Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Search for Wγ resonances in proton-proton collisions at $\sqrt{s} = 13$ TeV using hadronic decays of Lorentz-boosted W bosons

The CMS Collaboration *
CERN, Geneva, Switzerland

ARTICLE INFO

Article history:
Received 19 June 2021
Received in revised form 22 December 2021
Accepted 6 January 2022
Available online xxxx
Editor: M. Doser

Keywords:
CMS
Wgamma resonances
BSM particles

ABSTRACT

A search for Wγ resonances in the mass range between 0.7 and 6.0 TeV is presented. The W boson is reconstructed via its hadronic decays, with the final-state products forming a single large-radius jet, owing to a high Lorentz boost of the W boson. The search is based on proton-proton collision data at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 137 fb^{-1}, collected with the CMS detector at the LHC in 2016–2018. The Wγ mass spectrum is parameterized with a smoothly falling background function and examined for the presence of resonance-like signals. No significant excess above the predicted background is observed. Model-specific upper limits at 95% confidence level on the product of the cross section and branching fraction to the Wγ channel are set. Limits for narrow resonances and for resonances with an intrinsic width equal to 5% of their mass, for spin-0 and spin-1 hypotheses, range between 0.17 fb at 6.0 TeV and 55 fb at 0.7 TeV. These are the most restrictive limits to date on the existence of such resonances over a large range of probed masses. In specific heavy scalar (vector) triplet benchmark models, narrow resonances with masses between 0.75 (1.15) and 1.40 (1.36) TeV are excluded for a range of model parameters. Model-independent limits on the product of the cross section, signal acceptance, and branching fraction to the Wγ channel are set for minimum Wγ mass thresholds between 1.5 and 8.0 TeV.

1. Introduction

Searches for new resonances predicted in theories beyond the standard model (SM) are among the key components of the physics program at the CERN LHC. Many of these searches have been carried out in the past decade, since the start of the LHC operation, and have helped to reshape the landscape of allowed beyond-the-SM physics. Experimental searches for the production of new resonances decaying into a pair of SM particles are a notable aspect of this program. In the case of a new resonance with significant couplings to quarks and gluons, it would be produced in quark-antiquark, quark-gluon, or gluon-gluon interactions in proton-proton (pp) collisions at the LHC and subsequently decay into a pair of jets. On the other hand, if the couplings to quarks and gluons were suppressed, other decay channels, including decays into pairs of vector bosons (diboson decays), would become dominant.

Diboson decays involving photons, i.e., Wγ, Zγ, Hγ, and γγ channels, are important parts of this search program, owing to the excellent detection efficiency and photon energy resolution of the ATLAS and CMS detectors. For example, searches in the γγ channel contributed significantly to the discovery of the Higgs boson by the ATLAS and CMS Collaborations in 2012 [1–3]. Nevertheless, the above-mentioned decay modes involving photons, in particular the Wγ decay mode, are generally less studied over a large range of masses than other diboson signatures. There are multiple beyond-the-SM theories that predict Wγ resonances, including new particles in models with an extended Higgs sector [4], such as charged Higgs bosons in generic two Higgs doublet models [5,6], as well as particles predicted in technicolor [7–10], heavy vector triplet [11], and electroweak singlet [12] models, or scalar "quirks" in folded supersymmetry [13]. A number of nonresonant Wγ analyses that mainly probe anomalous WWγ couplings have been conducted at the CERN Sp$\bar{\text{p}}$S, LEP, and LHC, as well as at the Fermilab Tevatron. However, searches for Wγ resonances at high mass have been conducted only by the ATLAS experiment, in the leptonic decay channel of the W boson at the center-of-mass energies of 7 TeV [14] and 8 TeV [15], and in the hadronic decay channel at 13 TeV [16]. The best 95% confidence level (CL) upper limits on the product of the cross section and branching fraction to Wγ for narrow spin-1 resonances in the leptonic channel are 6.0–0.5 fb in the 0.2–1.6 TeV mass range [15], while the analogous limits in

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

https://doi.org/10.1016/j.physletb.2022.136888

the hadronic channel [16] vary between 12 and 0.14 fb within the 1.0–6.8 TeV mass range probed.

In this Letter, we describe a search for Wγ resonances in the hadronic decay channel of the W boson using pp collision data at $\sqrt{s} = 13$ TeV delivered by the LHC in 2016–2018. The results of the search are interpreted in terms of limits on narrow and broad, spin-0 and spin-1 resonances in a mass range between 0.7 and 6.0 TeV. Narrow resonances are taken to be those with widths Γ_X that are negligible compared to the experimental resolution, while for broad resonances we consider the representative case for which $\Gamma_X/m_X = 5\%$, where m_X is the resonance mass. Given the large mass of the resonances probed in this analysis, the W boson is produced with a high Lorentz boost and is reconstructed as a single large-radius jet. The two-prong structure and mass of this jet are established using jet substructure techniques, allowing for the reduction of the dominant background from direct photon production, where a jet recoiling against a photon originates from quantum chromodynamics (QCD) radiation.

Digitized versions of tables and plots from this paper can be found in the HEPData database [17].

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (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 detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in η and 0.087 in azimuth (ϕ). In the η-ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map on to 5×5 arrays of ECAL crystals to form calorimeter towers projecting radially outwards from close to the nominal interaction point. For $|\eta| > 1.74$, the coverage of the towers increases progressively to a maximum of 0.174 in $\Delta\eta$ and $\Delta\phi$. Within each tower, the energy deposits in ECAL and HCAL cells are summed to define the calorimeter tower energies, and subsequently used to provide the energies and directions of hadronic jets.

Events of interest are selected using a two-tiered trigger system [18]. The first level (L1), 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 [19]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [18].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [20].

3. Data sets and event selection

The data used in this search correspond to an total integrated luminosity of 137 fb^{-1} and were recorded by the CMS experiment at $\sqrt{s} = 13$ TeV in 2016–2018 (36, 41, and 60 fb^{-1} in 2016, 2017, and 2018, respectively) [21–23]. The high instantaneous luminosity delivered by the LHC results in additional interactions in the same or neighboring bunch crossings as the hard scattering interactions (pileup). The average number of pileup interactions in the 2016 (2017 and 2018) data set is around 23 (32).

The data are selected via single-photon triggers that require the photon candidate to be within $|\eta| < 2.5$, and to have transverse momentum $p_T > 165$ or 175 GeV in 2016 and $p_T > 200$ GeV in 2017–2018. We determine the selection efficiencies for these triggers using unbiased data samples collected with single-muon triggers. The single-photon triggers are found to be 98–100% efficient with respect to the offline selection described below, for the entire mass range used in the analysis. The small residual inefficiency is taken into account when calculating the signal acceptance.

Simulated Monte Carlo (MC) signal samples are produced at leading order (LO) in perturbative QCD. They are used to optimize the analysis selection and to calculate the signal efficiency. Simulated signal events of spin-0 resonances decaying to Wγ are generated using electroweak triplet pseudo-Goldstone bosons π_3 [24] and a heavy (pseudo-)scalar $SU(2)_L$ triplet [25], while for spin-1 resonances, a heavy vector $SU(2)_L$ triplet [25] is used. Several signal samples are generated with masses ranging from 0.7 to 6.0 TeV. Two resonance width assumptions are used in the simulation: one, termed "narrow", has a width which is significantly smaller than the detector resolution that ranges between 3.75 and 5%, and the second, referred to as "broad", has $\Gamma_X/m_X = 5\%$. The latter choice is representative of broad resonances, for which the impact of the off-shell production on the signal efficiency becomes sizable.

Simulated background events do not enter the analyses directly, as the background is obtained from a fit to data. They are only used to assess the accuracy of the background model and to optimize the event selection. The dominant background from γ+jet production as well as the QCD multijet background from SM events composed uniquely of jets produced through the strong interaction which have a jet misidentified as a photon are generated at LO using MadGraph5_amc@nlo. Smaller backgrounds from W+jets and W+γproduction, as well as top quark backgrounds, are not simulated, as their contribution is far less than that of the dominant backgrounds and does not affect the search optimization procedure.

Both the signal and background samples are generated using MadGraph5_amc@nlo 2.2.2 (2.4.2) [26] with NNPDF3.0 NLO [27] (NNPDF3.1 NNLO [28]) parton distribution functions (PDFs) for 2016 (2017 and 2018) conditions. Fragmentation and hadronization are simulated with pythia 8.205 (8.230) [29] with the CUETP8M1 [30,31] (CP5 [32]) underlying event tune for 2016 (2017 and 2018) samples. All simulated samples are processed with the full CMS detector model based on Geant4 [33] and reconstructed with the same suite of programs as used for collision data. Pileup effects are taken into account by superimposing simulated minimum bias events on the hard scattering interaction, with the multiplicity distribution matching that observed in data.

A particle-flow (PF) event algorithm [34] is used, which 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.

The events must contain at least one reconstructed primary vertex with at least four associated tracks, with transverse (longitudinal) coordinates required to be within 2 (24) cm of the nominal collision point. The candidate vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [35,36] with the tracks assigned to candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_T of those jets.

Since the dominant background in the analysis is from direct photon production (γ+jets), rather than from sources with a misidentified photon, we chose a "loose" photon identification working point of a standard CMS sequential-selection algorithm, which maximizes the photon efficiency at the cost of a slightly higher misidentification rate compared to other available working points [37]. The identification is based on photon shower shape and isolation variables. The latter are computed from various types of PF candidates in a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the photon candidate, corrected for the pileup effects. In addition, a conversion-safe electron veto [37] is applied. The loose working point gives an efficiency of approximately 90% that does not depend on the photon p_T up to the highest values explored in the analysis, while reducing the background from misidentified photons by approximately a factor of 7. The photon candidates are required to have $p_T > 225$ GeV and to be within the barrel fiducial region of the ECAL ($|\eta| < 1.44$). Since events with a photon reconstructed in the endcap region suffer from high background from γ+jets, which peaks in the forward direction, they do not add to the sensitivity of the analysis and therefore are not included.

Large-radius jets (J) are used to reconstruct hadronically decaying, highly Lorentz-boosted W boson candidates. These jets are reconstructed from PF candidates clustered using the anti-k_T algorithm [35,36] with a distance parameter of 0.8. Charged hadrons not originating from the primary vertex are not considered in the jet clustering. The pileup per particle identification algorithm (PUPPI) [38,39] is used to mitigate the effect of pileup at the reconstructed particle level, making use of local energy distribution, event pileup properties, and tracking information. Charged particles identified to be originating from pileup vertices are discarded. The momenta of the neutral particles are 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 [38]. Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle-level jets. In situ measurements of the momentum balance in dijet, γ+jet, Z+jet, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are applied [40]. Additional quality criteria [41] are used to remove jets due to rare spurious noise patterns in the calorimeters, and also to suppress leptons misidentified as jets. The jet energy resolution typically amounts to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV. In each event, the jet selected to be the hadronic W candidate must have $p_T > 225$ GeV, to balance the p_T of the selected photon, and is required to be separated from the photon by a distance of $\Delta R > 1.1$ to reduce the contamination of the photon isolation cone with the jet constituents.

Since the signal jets are merged products of the W boson decay, we require the jet mass to be within a certain range of the W boson mass to reduce the very large background from QCD jets, which have steeply falling jet mass distribution. To improve the signal and background separation, a jet grooming algorithm known as "soft drop" (SD) [42], with parameters $\beta = 0$ and $z_{cut} = 0.1$, is applied to recursively remove soft, wide-angle radiation from anti-k_T jets. The groomed jet mass (m_J^{SD}) is then computed from the four-momentum sum of the remaining jet constituents, whose energies are corrected with the same factor that has already been used in the generic jet reconstruction described above. The typical mass resolution for a W boson jet is 10% [43]. Finally, in order to avoid the region of rapidly varying efficiency near threshold, we require the invariant mass of the selected jet and photon ($m_{J\gamma}$) to exceed 0.6 TeV.

4. Analysis optimization

The analysis is optimized using a sequential selection on a number of kinematic variables. These variables fall into two classes: those related to the resonance decay kinematics and those related to the properties of a large-radius jet. The former are: pseudorapidities of the photon η_γ and the jet η_J, the cosine of the polar decay angle in the center-of-mass frame of the Jγ system with respect to the beam axis $\cos\theta_\gamma^*$, and the ratio of the photon transverse momentum p_T^γ to $m_{J\gamma}$. The last two variables mentioned are highly correlated and are both used to separate the mostly central s-channel signal events from the mostly forward t-channel direct photon background. For the purpose of tagging jets originating from the W boson decay (W jet tagging), selections are also applied on two variables related to the properties of a large-radius jet, which are the jet mass m_J^{SD} and the jet substructure variable τ_{21}. m_J^{SD} peaks at the W mass for the signal and falls rapidly for the QCD background. The variable τ_{21} is defined as the ratio of τ_2 to τ_1, where τ_N is a set of N-subjettiness [44] variables. Such variables are measures of how likely it is that a large-radius jet has a substructure of N subjets. For a jet with exactly N subjets, τ_N tends to small values, while τ_M values for $M \neq N$ are shifted to larger values. Thus, τ_{21} is expected to be generally smaller for a signal, which contains a jet produced by an overlap of the quark jets from a two-prong W boson decay, than for the background, which mostly consists of structureless QCD jets.

The optimization aims at maximizing the expected signal significance for a large range of tested masses, where the background yield (B) is typically much larger than that of the signal we probe (S), and is large enough to use the Gaussian approximation, i.e., maximizing $S/\sqrt{B}$. This figure of merit (FOM) has the advantage that its maximum is independent of the signal cross section. The optimization is based on the events in the control region (CR) in data, defined as the lower sideband of the W boson jet mass $40 < m_J^{SD} < 65$ GeV, which has negligible signal contamination for the range of the signal cross sections probed in this analysis, as well as events in the signal region (SR) in signal simulation samples, which is defined as $68 < m_J^{SD} < 94$ GeV, as determined via the optimization using the FOM described above. The CR and SR are illustrated in Fig. 1, which also shows the expected distributions in m_J^{SD} for the benchmark narrow spin-0 signals. It was demonstrated that the differences in this distribution between different signal spin and width hypotheses are negligible.

The optimization of the FOM uses simulated signal events and two different estimates of the background in the signal region. The first background estimate uses data events in the CR, which are expected to have similar distributions in the main analysis variables to those in the SR. To ensure the same normalization, a scale factor of approximately 0.86 is applied to the CR event yield to match that in the SR. This procedure was justified by comparing the kinematic distributions of simulated background events in the SR and CR and finding that they are quite similar. The second background sample uses simulated background events that have been rescaled to account for the missing higher-order effects, as well as for an imperfect description of the misidentification of jets as photons in the QCD multijet simulation. This is done by fitting the p_T^γ spectrum in data with the sum of these two backgrounds, with the normalizations allowed to float in the fit. Fig. 2 shows that before the optimization an adequate description of the SR data is achieved in the main kinematic variables used for the analysis optimization by using either MC simulation or CR data, with the exception of the τ_{21} variable, which has a different shape in the data CR

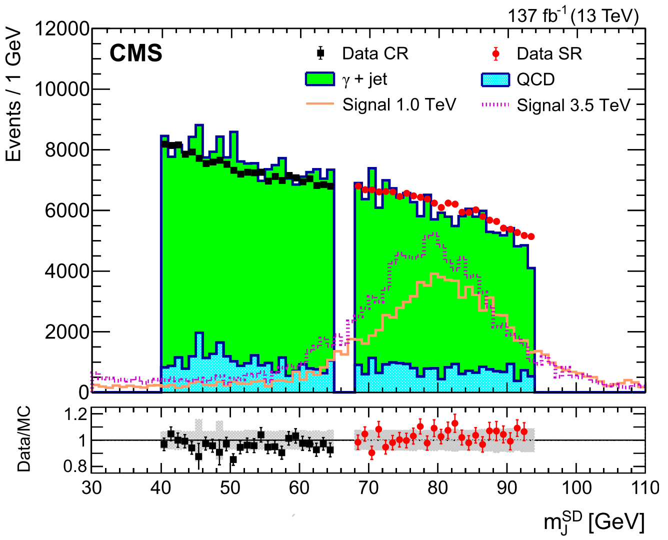

Fig. 1. Definitions of the signal and control regions in data, based on the jet mass m_J^{SD}. The stacked filled histograms represent dominant backgrounds from simulation, normalized to the p_T^γ spectrum in the signal region. The red circles (black squares) correspond to data in the signal (control) region. Benchmark narrow spin-0 signal distributions, normalized to a cross section of 2 pb for two masses, 1.0 and 3.5 TeV, are shown by the solid orange and dashed magenta lines, respectively. The lower panel shows the data-to-simulation ratio in the control and signal regions. The gray hatched band shows the statistical uncertainty in the background estimation, stemming from the limited size of the simulated samples.

due to a strong correlation of the τ_{21} variable with m_J^{SD}. Consequently, the optimization of the τ_{21} selection is performed only using simulated backgrounds. The residual discrepancies seen in other distributions are due to missing minor backgrounds and the limitations of the MC simulation modeling of the data. They are typically present near the kinematic limits of the corresponding variables, far from the region of optimal selections, and consequently do not bias the optimization procedure. Since neither the simulated backgrounds nor data CR events are used in the final analysis, beyond the optimization step, we find that the level of agreement between the data and simulated backgrounds is adequate. Fig. 2 also shows several benchmark signal points and, given the similarity of signal shapes for various spin and width combinations, the spin-0, narrow-width hypothesis is used, unless indicated otherwise in the legend.

For most of the variables, and the signal masses, widths, and spins probed, the maxima of the FOM distributions are fairly broad, which justifies using a single set of selections for all signal masses and spin/width hypotheses, without compromising the search performance. We have tested whether combining the input variables into a multivariate discriminant using a boosted decision tree with adaptive boosting, instead of selecting on individual variables, results in a gain in performance. However, the best gain we were able to achieve was only a 5% increase in the FOM value, which required separate discriminants constructed for each signal mass point. Consequently, a single set of selections on the individual variables was chosen, which simplifies the analysis without introducing a noticeable performance loss. The best selections chosen as a result of the above procedure are: $|\eta_\gamma| < 1.44$ (i.e., the photon in the ECAL barrel), $|\eta_J| < 2.0$, $\tau_{21} < 0.35$, $68 < m_J^{SD} < 94$ GeV, $p_T^\gamma/m_{J\gamma} > 0.37$, and $\cos\theta_\gamma^* < 0.6$. The use of these optimal selections combined improves the FOM by up to 90% for signals with masses ranging from 0.7 TeV to 3.5 TeV. The requirement on the τ_{21} variable alone improves the FOM by 40%, making it the most discriminating variable.

5. Signal and background modeling

We describe the shape of the $m_{J\gamma}$ distributions for the signals probed by fitting simulated signal samples with analytic functions. For narrow resonances, we use a sum of Crystal Ball (CB) [45] and Gaussian functions with different means. For broad resonances, we use a sum of CB and two Gaussian functions, where the two Gaussian functions have a common mean that may be different from that of the CB function. In order to obtain the signal shapes for the mass points where no simulated samples were generated, we use linear morphing between the adjacent simulated signal points [46]. The simulated signal samples for each of the three years of data taking reflect changes in MC tunes, pileup and trigger conditions, selection criteria, and detector performance along with time. We verify that the signal shape in simulation is consistent for the three years and use samples produced with the 2017 conditions as the signal model for all three data-taking years. Consequently, we also combine the $m_{J\gamma}$ spectra for the three data-taking periods and search for the presence of signal in this combined data set.

The overall signal acceptance $\mathcal{A}$, and the product of the acceptance and signal efficiency $\mathcal{A}\varepsilon$ for the optimal selection for spin-0 and spin-1 resonances, are shown as functions of the resonance mass in Fig. 3 (upper row). The latter ranges between 6.1 (10.0)% and 12.3 (16.4)% for spin-0 (spin-1) signals over the mass range probed. It was verified that for both $\mathcal{A}$ and $\mathcal{A}\varepsilon$ the differences between three years of data taking are small; thus the values for the 2017 data taking are used as the nominal ones. The efficiencies for narrow resonances are generally 1–2% higher than for the broad ones, mainly because of the long low-mass tail in the $m_{J\gamma}$ distribution for broad resonances, caused by the quickly falling PDFs convoluted with the Breit–Wigner resonant shape. In order to be less sensitive to the exact description of this tail, which depends on both the PDF choice and the parameterization of the signal resonance line-shape, we use a window of ±25% of the resonance mass, centered on the mass. The size of the window corresponds to roughly ±5 effective widths of a broad resonance. The window requirement is included in the definition of the signal acceptance. The W jet tagging efficiency ($\epsilon_{W\text{-tag}}$, which is a part of the overall efficiency) is shown in Fig. 3 (lower), which illustrate that a slight decrease in the overall product of the acceptance and efficiency at high masses is due to a less effective W tagging for very energetic jets.

After the final selection, the background shape of the $m_{J\gamma}$ spectrum in the SR is modeled by a background-only fit with a smooth, monotonically falling function. A variety of functional forms are considered for the background fit, and for each function, a goodness-of-fit (GOF) test based on the Kolmogorov–Smirnov statistic is performed in the SR. The nominal background fit function is chosen as the one with the best GOF achieved with the minimal number of parameters:

$$\frac{dN}{dm} = p_0 (m/\sqrt{s})^{p_1 + p_2 \log(m/\sqrt{s}) + p_3 \log^2(m/\sqrt{s})} \quad (1)$$

where p_i (with $i = 0$–3) are the free parameters of the fit. The best fit to data with the background-only hypothesis is shown in Fig. 4. This smooth background function provides an adequate description of the data in the entire mass range probed.

6. Systematic uncertainties

In order to prove that no systematic bias arises from the choice of the background fit function, an alternative fit function that performed relatively well in the GOF test is used to generate a large number of $m_{J\gamma}$ spectra, with or without signal injection. The spectra are then fit to the sum of the chosen background function

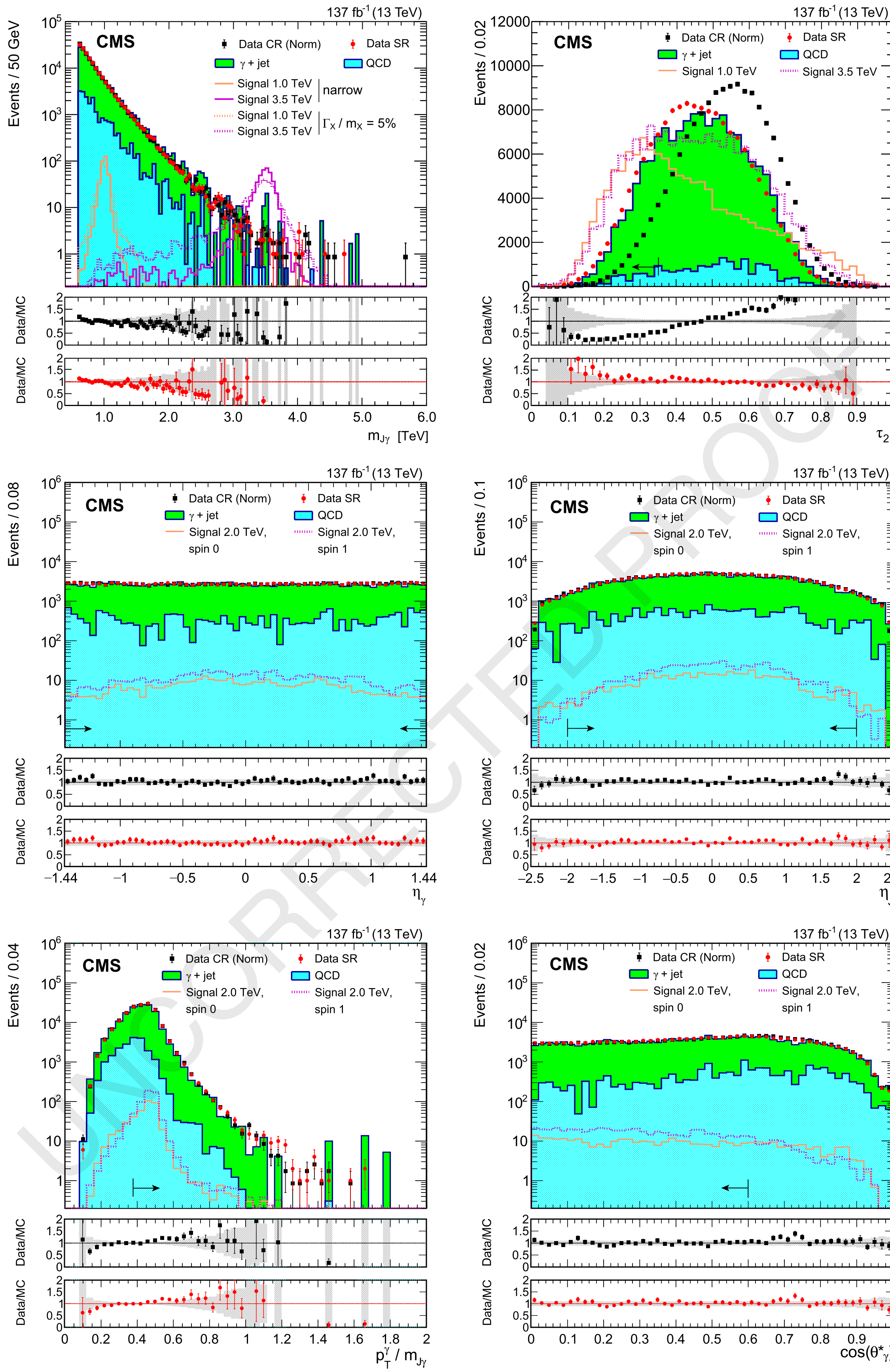

Fig. 2. Distributions of some of the kinematic variables used in the analysis. Upper row: $m_{J\gamma}$ (left), τ_{21} (right); middle row: η_γ (left), η_J (right); lower row: $p_T^\gamma/m_{J\gamma}$ (left), $\cos\theta^*_\gamma$ (right), except that the yield in the control region is normalized to that in the signal region. Several benchmark signals are also shown, as indicated by the legend. By default, the spin-0, narrow width hypothesis is used unless indicated otherwise. Signals are normalized to a cross section of 5 fb, except for the τ_{21} distribution, for which the normalization is 2 pb. Optimized selections are indicated with the black arrows. The two lower panels show the data-to-simulation ratio in the control and signal regions, respectively. The gray hatched band shows the statistical uncertainty in the background estimation, stemming from the limited size of the simulated samples.

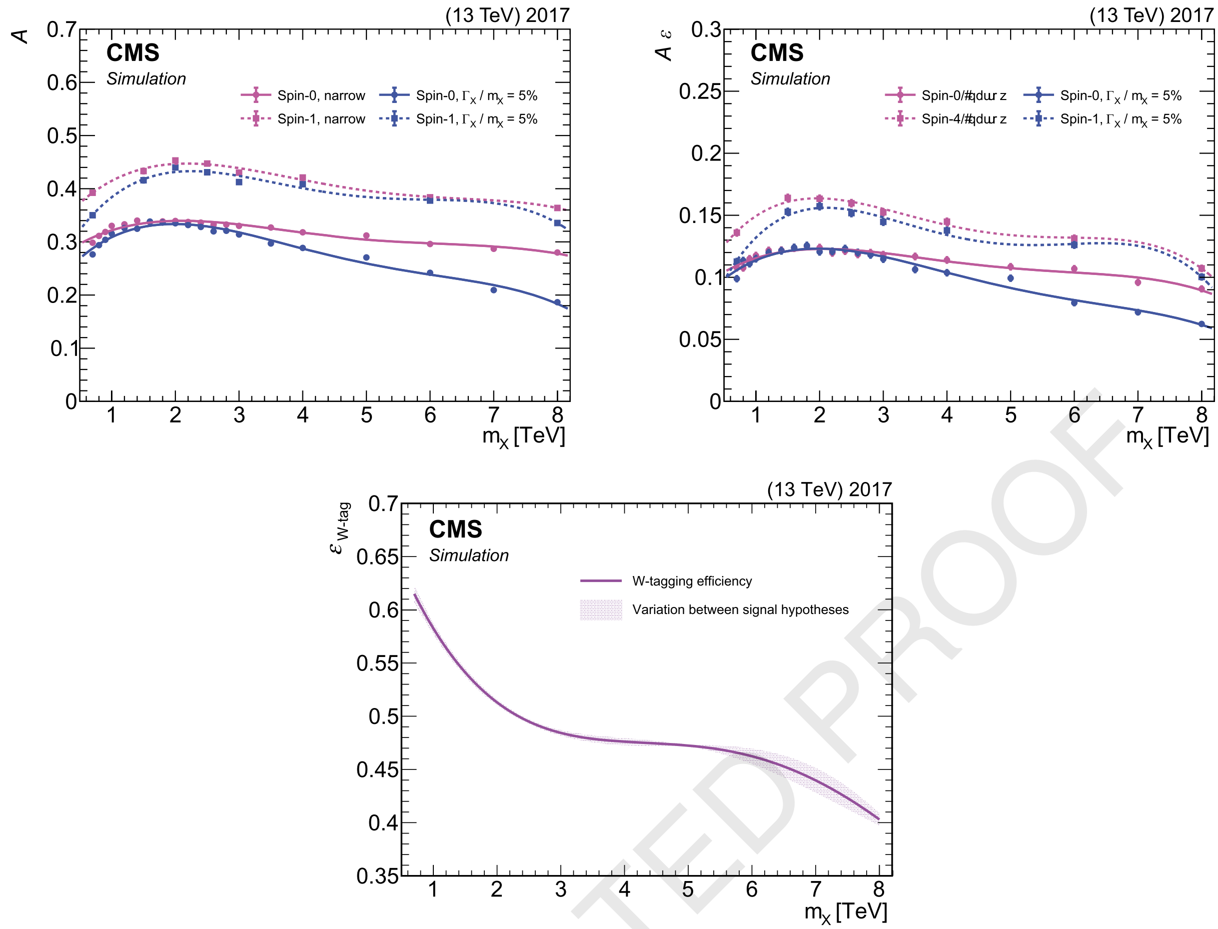

Fig. 3. Signal acceptance $\mathcal{A}$ (upper left), the product of the signal acceptance and selection efficiency $\mathcal{A}\varepsilon$ (upper right), and the W tagging efficiency (lower) for spin-0 (solid lines) and spin-1 (dashed lines) resonances, for the narrow (pink) and broad (blue) hypotheses. The curves are obtained by fitting fourth-order polynomials to the set of discrete mass points, for which simulated signal samples are available. For the W tagging efficiency, the average value obtained for the different spin and width hypotheses and the spread of the individual efficiencies about the average are shown with the solid line and the shaded band, respectively.

and a signal template with the mass and normalization allowed to float. The signal significance is extracted from each fit and the distributions of the pull of the signal yield are constructed, where the pull is defined as the difference between the injected and extracted signal normalizations, divided by the statistical uncertainty in the extracted signal normalization from the fit. We observe that the distributions of the pulls are consistent with a Gaussian function with a zero mean and a standard deviation of unity, and thus conclude that any systematic bias from the background fitting procedure is negligible compared to the statistical uncertainties in the fit. We therefore use the latter as the only uncertainties associated with the background estimate.

The systematic uncertainty associated with the background shape is evaluated via likelihood profiling. This procedure refits for the optimal values of the background parameters for each signal mass hypothesis with the parameters of the background function allowed to vary freely in the fit, thus accounting for the uncertainty in the background prediction.

There are several sources of uncertainties in the description of the signal. Most of the uncertainties mainly affect the signal yield and have only a small impact on the shape of the signal mass distribution. These include the integrated luminosity, trigger plateau efficiency, photon identification efficiency, pileup description, choice of PDFs, and the efficiency of tagging the W boson jet, including the efficiencies of the SR selection on the $m_{\mathrm{J}}^{\mathrm{SD}}$ and of the τ_{21} requirement. Uncertainties affecting both the yield and the shape of the signal distributions include the jet and photon energy scales and resolutions.

The uncertainties in the integrated luminosity are 2.5% [21], 2.3% [22], and 2.5% [23] in 2016, 2017, and 2018, respectively. The efficiency of the trigger is obtained using an independent suite of triggers. A systematic uncertainty of 1.0 (2.3)% is assigned to the trigger efficiency in 2016 and 2018 (2017) data taking, based on the difference between the observed plateau value and unity. The uncertainty due to the photon identification efficiency is obtained by comparing the efficiency in simulation with that in $\mathrm{Z} \to \mathrm{ee}$ events, where electrons are reconstructed as photons. It amounts to a 3–6% uncertainty in the signal yield.

The uncertainty due to the description of pileup in the simulated samples is estimated by changing the value of the total inelastic cross section by $\pm 4.6\%$ [47] and recalculating the signal efficiency after the corresponding change in the pileup distribution. The resulting uncertainty is 1.0–1.5 (1.0–2.0)% for narrow (broad) resonances. The PDF uncertainty is determined using the PDF4LHC prescription [48]. Only the effect on the signal acceptance is included as a source of the experimental uncertainty, and amounts to 2%. The uncertainty in the W jet tagging efficiency mainly originates from the τ_{21} selection efficiency. It amounts to an uncertainty of 3.2–11% in the signal yield.

The uncertainty in the jet energy scale is obtained by varying the energy scale of the jet corresponding to the W candidate by a p_{T}- and η-dependent correction [40]. The uncertainty due to the jet energy resolution is obtained by smearing the momentum of

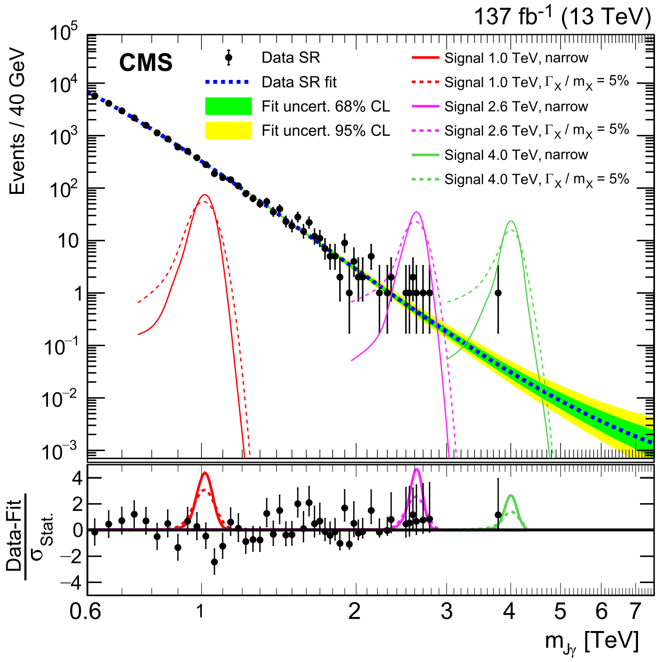

Fig. 4. Background-only fit to data (black points) with the chosen background function. The green (inner) and yellow (outer) bands show, respectively, the 68 and 95% confidence level statistical uncertainties in the fit. The lower panel contains the pull distribution, defined as the difference between the data yield and the background prediction, divided by their combined uncertainty. Expected signal shapes are also shown in the lower panel for three different resonance mass hypotheses, 1.0 TeV (red), 2.6 TeV (magenta), and 4.0 TeV (green), and for both the narrow (solid) and broad (dashed) cases. Signal normalizations are set to 15, 1.0, and 0.30 fb, respectively, for illustrative purposes.

the W jet in simulation to match that in data. The combined effect on the signal yield is 1.3%, which is the major source of the uncertainty in the signal shapes. The effects of the photon energy scale and resolution are accounted for in a similar fashion; they are significantly less important than those stemming from the jets, because of a much higher precision of the photon energy reconstruction [37].

Given that the signal is extracted from the $m_{J\gamma}$ spectrum combined over the three data-taking periods, we take into account correlations between the uncertainties across the three years, and use the luminosity-weighted linear (quadratic) average for correlated (uncorrelated) uncertainties. The integrated luminosity uncertainty has both correlated and uncorrelated components, resulting in the overall uncertainty of 1.8% when applied to the full data set. The trigger and W tagging efficiencies, as well as the jet energy scale and resolution uncertainties, are treated as uncorrelated across the three years, while the rest are treated as fully correlated. A summary of the systematic uncertainties, as well as the effect of the year-to-year correlations, is given in Table 1.

7. Results

We set model-specific upper limits on the product of the cross section and branching fraction for both narrow and broad, spin-0 and spin-1 resonances using the modified frequentist CL_s criterion [49–51], with a likelihood ratio in the asymptotic approximation [52] used as a test statistic. The yield (shape) uncertainties are incorporated as nuisance parameters with log-normal (Gaussian) priors. These limits, at 95% CL, are shown in Fig. 5, separately for the spin-0 and spin-1 hypotheses, as well as for narrow and broad resonances, and are the most restrictive limits to date on the existence of Wγ resonances over the majority of the masses probed. The p-values for the background-only fit are shown in Fig. 6 for

Table 1
Systematic uncertainties affecting the signal description. Uncertainties marked with "†" affect both the yield and the shape of the signal distribution, while the rest only affect the signal yield. In cases where the uncertainty is different for various data-taking periods, the three numbers given in the second column correspond to the 2016/2017/2018 data taking, while the third column shows the combined uncertainties across the three years, taking into account the year-to-year correlations. The effect on the signal yield is the same for all the signal hypotheses studied.

Source	Effect on the signal yield (%)	Combined (%)
Integrated luminosity	2.5/2.3/2.5	1.8
Trigger efficiency	1.0/2.3/1.0	0.9
Photon ident. efficiency	4.7/6.0/3.0	4.4
Pileup	1.0/2.0/1.0	1.3
PDF	2.0	2.0
W tagging efficiency	11/7.4/3.2	3.9
Jet energy scale and resolution†	1.3	0.8
Photon energy scale and resolution†	0.5/1.0/1.0	0.9
Total	12.6/10.6/5.8	6.7

the narrow (left) and broad (right) resonances for both spin hypotheses. The largest excess seen in the limit plots has a mass around 1.58 TeV, with a local significance of 2.8 (3.1) standard deviations for narrow (broad) signals for both spin hypotheses. After taking into account the look-elsewhere effect [53], the global significance of the excess is estimated to be 1.1 (1.7) standard deviations, favoring its interpretation as a statistical fluctuation in data.

In the case of narrow resonances, we compare these limits with the predictions of two of the models described in Ref. [25], which we use as benchmarks. In the spin-0 case, a scalar or pseudoscalar $SU(2)_L$ triplet ϕ^{α} that couples to the SM vector boson fields via anomaly-induced interactions $\phi^a W^a_{\mu\nu}\widetilde{B}^{\mu\nu}/\Lambda$ and to the SM fermionic fields with an effective coupling y_m/Λ, is considered. Here, Λ is the ultraviolet cutoff of the model, chosen to be 2, 4, or 5 times the resonance mass, while y_m is set to 0.10 or 0.15 to suppress fermionic decays. In the spin-1 case, a vector $SU(2)_L$ triplet V^a_μ that couples to the SM vector boson fields via a higher-dimensional operator $c_W V^{a\nu}_\mu W^{a\alpha}_\nu B^\mu_\alpha/\Lambda^2$ and to the SM fermionic fields directly with the coupling g_m is considered. Similar to the scalar triplet case, we set Λ to 4 or 5 times the resonance mass, c_W to 1, and g_m to 0.10 or 0.15. Additionally, we set the coupling of the vector triplet to the Higgs boson c_h to zero. These choices of parameters assure narrow resonances in the mass range of interest, with sizable branching fractions to Wγ. As a result of this search, benchmark heavy scalar (vector) triplet bosons with masses between 0.75 (1.15) and 1.40 (1.36) TeV are excluded at 95% CL, as shown in Fig. 5. Spin-0 π_3 states of Ref. [24] are beyond the sensitivity of this search, as they decay predominantly into hadronic final states and the branching fraction into the Wγ channel is suppressed.

The asymptotic CL_s approach tends to overestimate the limits in the bins with low event count. For the narrow (broad) spin-0 signal hypothesis, it is found that the asymptotic approximation yields more stringent cross section limits compared to a full CL_s approach above 2.6 (3.2) TeV. The limits are 10 (16)% more stringent at 3.5 TeV and the difference increases to 31% at 6.0 TeV in both cases. Similar behavior is expected for the spin-1 signal hypothesis. The asymptotic approximation has negligible impact on the mass exclusions in the benchmark models, as these limits are well below 2.6 TeV.

Model-independent upper limits on the product of the cross section, branching fraction, and signal acceptance are set in the context of a simple counting experiment that considers the number of events observed and expected above a variable Jγ invariant mass threshold. These limits allow the interpretation of our results in nonresonant and other resonant models by estimating their acceptance for the selections used in this analysis. Since the exact

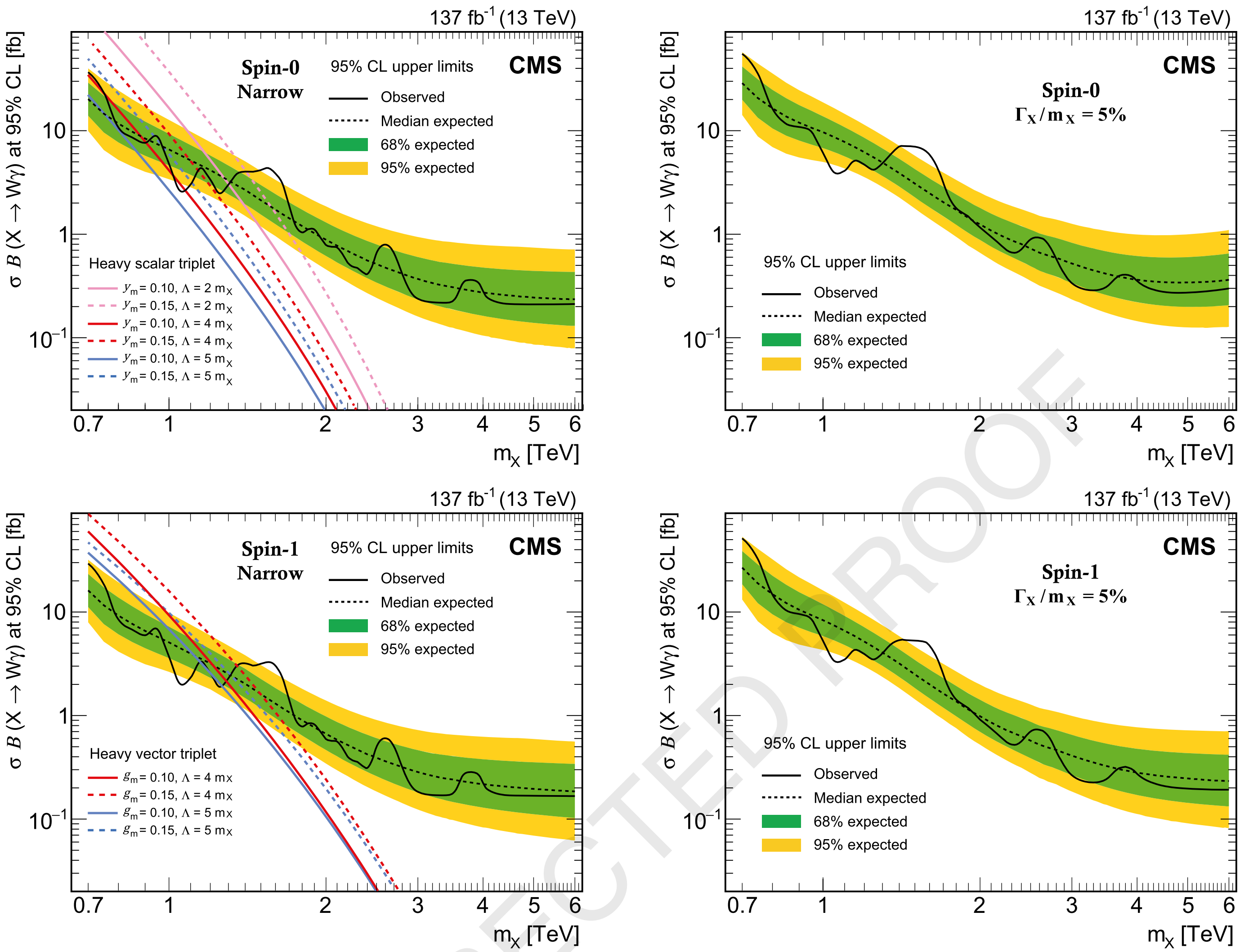

Fig. 5. Expected and observed 95% confidence level limits on $\sigma\mathcal{B}(X \to W\gamma)$ for the spin-0 (upper row) and spin-1 (lower row) resonances for the narrow (left column) and broad (right column) resonance cases. Also shown, for spin-0 (spin-1) narrow-resonance case, theoretical cross sections for heavy scalar (vector) triplet resonance production in the benchmark model of Ref. [25], which can be probed by this search.

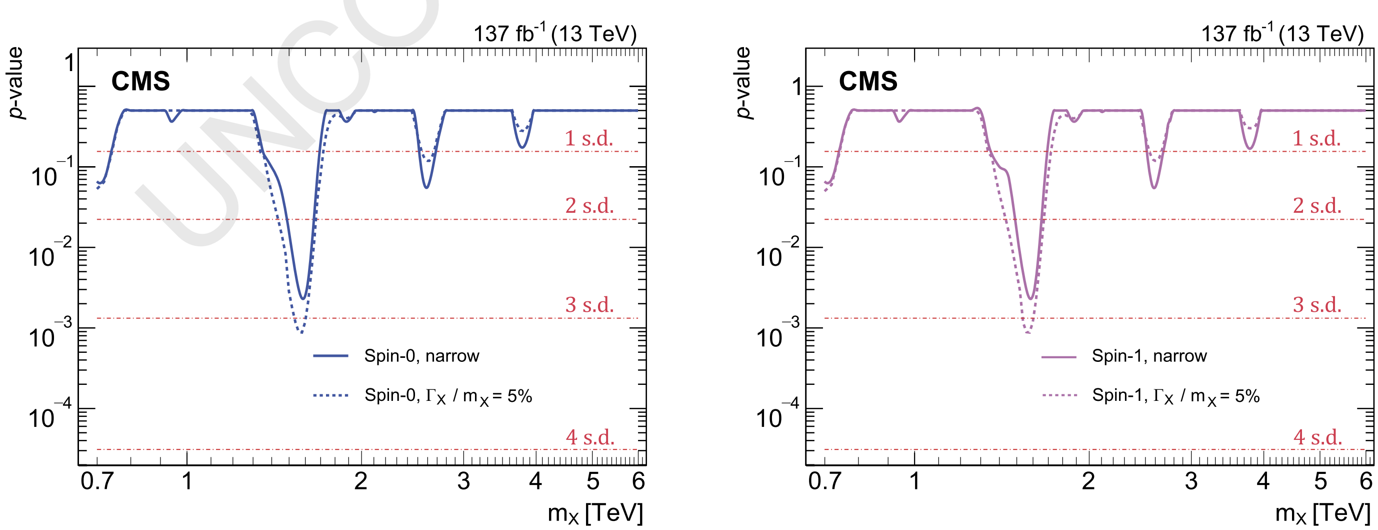

Fig. 6. Observed local *p*-values for spin-0 (left) and spin-1 (right) resonance hypotheses. The largest excess observed at 1.58 TeV corresponds to a local significance of 2.8 (3.1) standard deviations (s.d.) for narrow (broad) signals, for both spin hypotheses.

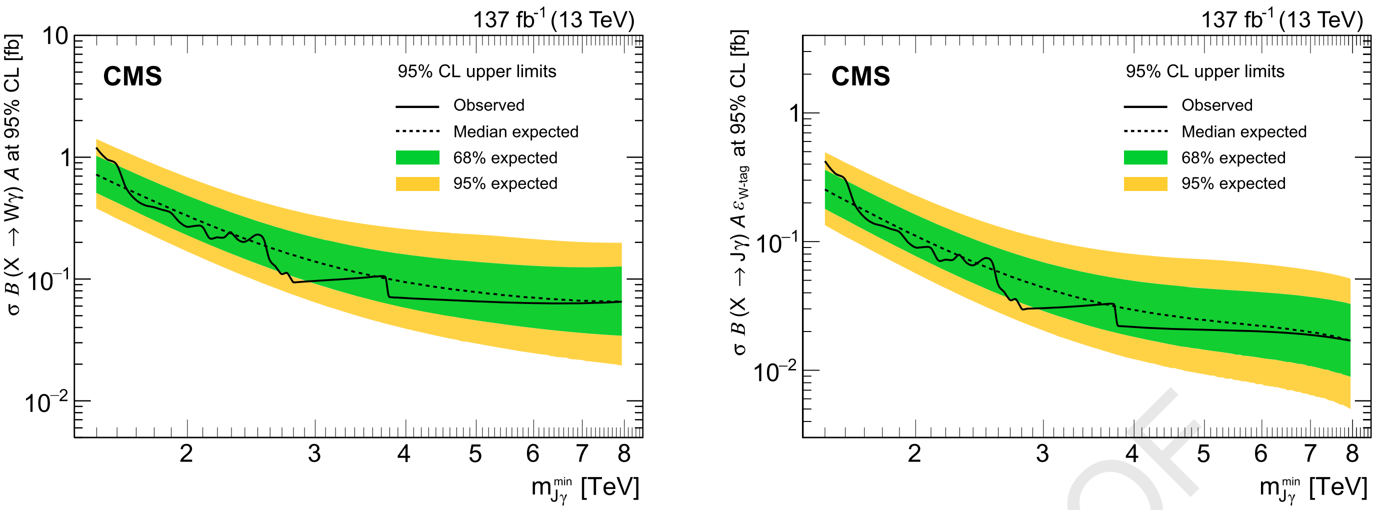

Fig. 7. Expected and observed 95% confidence level model-independent limits on $\sigma\mathcal{B}(\mathrm{X}\to\mathrm{W}\gamma)\mathcal{A}$ (left) and $\sigma\mathcal{B}(\mathrm{X}\to\mathrm{J}\gamma)\mathcal{A}\epsilon_{\mathrm{W\text{-}tag}}$ (right), as a function of the minimum invariant mass requirement on the Jγ system.

description of the signal shape is no longer important in the region where little background is expected, these limits are continued up to the mass threshold of 8.0 TeV, thus extending the mass range of phenomena that can be investigated. To make this interpretation possible for a broad set of models, we treat the W tagging efficiency as a part of either the experimental efficiency or the signal acceptance. The former case, shown in Fig. 7 (left), would apply to models yielding signatures with a hadronically decaying Lorentz-boosted W boson, as the W tagging efficiency in this case should be very similar to that in the model-specific analysis. The latter case, shown in Fig. 7 (right), would apply to an even broader set of models, e.g., the ones predicting Zγ signatures, by accounting for the efficiency of tagging a Z boson using our W tagging requirements as a part of the signal acceptance.

8. Summary

A search for Wγ resonances in the mass range between 0.7 and 6.0 TeV has been presented. The W boson is reconstructed from its hadronic decay, in which the final-state products form a single large-radius jet owing to the large Lorentz boost of the W boson. The search is based on proton-proton collision data collected at $\sqrt{s} = 13$ TeV with the CMS detector at the LHC in 2016–2018, corresponding to an integrated luminosity of 137 fb^{-1}. No significant excess above the smoothly falling background is observed. Limits at 95% confidence level on the product of the cross section and branching fraction for Wγ resonances are set, ranging from 37 (55) to 0.21 (0.30) fb for the narrow (broad) spin-0 hypothesis, and from 29 (51) to 0.17 (0.19) fb for the narrow (broad) spin-1 hypothesis. The results reported are the most restrictive limits to date on the existence of such resonances over a large range of probed masses. In specific narrow-resonance benchmark models, heavy scalar (vector) triplet resonances with masses between 0.75 (1.15) and 1.40 (1.35) TeV are excluded for a range of model parameters probed. In addition, model-independent limits are set on the product of the cross section, branching fraction, and signal acceptance, as functions of the minimum invariant mass of the jet-photon system, making possible the interpretation of these results in the context of a broader class of models predicting similar signatures.

Declaration of competing interest

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

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TÜBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 765710 and 824093 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S. - FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; The Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Science and Higher Education and the National Science Center, contracts Opus 2014/15/B/ST2/03998 and 2015/19/B/ST2/02861 (Poland); the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education, project no. 0723-2020-0041 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] ATLAS Collaboration, Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1, https://doi.org/10.1016/j.physletb.2012.08.020, arXiv:1207.7214.
[2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716 (2012) 30, https://doi.org/10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
[3] CMS Collaboration, Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV, J. High Energy Phys. 06 (2013) 081, https://doi.org/10.1007/JHEP06(2013)081, arXiv:1303.4571.
[4] J.F. Gunion, G.L. Kane, J. Wudka, Search techniques for charged and neutral intermediate mass Higgs bosons, Nucl. Phys. B 299 (1988) 231, https://doi.org/10.1016/0550-3213(88)90284-2.
[5] J.F. Gunion, H.E. Haber, G.L. Kane, S. Dawson, The Higgs Hunter's Guide, Frontiers in Physics, vol. 80, Westview Press, Boulder, Colorado, 2000.
[6] M. Capdequi Peyranere, H.E. Haber, P. Irulegui, $H^\pm \to W^\pm \gamma$ and $H^\pm \to W^\pm Z$ in two Higgs doublet models. 1. The large fermion mass limit, Phys. Rev. D 44 (1991) 191, https://doi.org/10.1103/PhysRevD.44.191.
[7] S. Weinberg, Implications of dynamical symmetry breaking, Phys. Rev. D 13 (1976) 974, https://doi.org/10.1103/PhysRevD.13.974; https://dx.doi.org/10.1103/PhysRevD.19.1277 (Addendum).
[8] L. Susskind, Dynamics of spontaneous symmetry breaking in the Weinberg–Salam theory, Phys. Rev. D 20 (1979) 2619, https://doi.org/10.1103/PhysRevD.20.2619.
[9] K.D. Lane, E. Eichten, Two scale technicolor, Phys. Lett. B 222 (1989) 274, https://doi.org/10.1016/0370-2693(89)91265-3.
[10] E. Eichten, K. Lane, Low-scale technicolor at the Tevatron and LHC, Phys. Lett. B 669 (2008) 235, https://doi.org/10.1016/j.physletb.2008.09.047, arXiv:0706.2339.
[11] D. Pappadopulo, A. Thamm, R. Torre, A. Wulzer, Heavy vector triplets: bridging theory and data, J. High Energy Phys. 09 (2014) 060, https://doi.org/10.1007/JHEP09(2014)060, arXiv:1402.4431.
[12] K. Howe, S. Knapen, D.J. Robinson, Diphotons from electroweak triplet-singlet mixing, Phys. Rev. D 94 (2016) 035021, https://doi.org/10.1103/PhysRevD.94.035021, arXiv:1603.08932.
[13] G. Burdman, Z. Chacko, H.-S. Goh, R. Harnik, C.A. Krenke, The quirky collider signals of folded supersymmetry, Phys. Rev. D 78 (2008) 075028, https://doi.org/10.1103/PhysRevD.78.075028, arXiv:0805.4667.
[14] ATLAS Collaboration, Measurements of $W\gamma$ and $Z\gamma$ production in pp collisions at $\sqrt{s}$=7 TeV with the ATLAS detector at the LHC, Phys. Rev. D 87 (2013) 112003, https://doi.org/10.1103/PhysRevD.87.112003, arXiv:1302.1283; https://dx.doi.org/10.1103/PhysRevD.91.119901 (Erratum).
[15] ATLAS Collaboration, Search for new resonances in $W\gamma$ and $Z\gamma$ final states in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Phys. Lett. B 738 (2014) 428, https://doi.org/10.1016/j.physletb.2014.10.002, arXiv:1407.8150.
[16] ATLAS Collaboration, Search for heavy resonances decaying to a photon and a hadronically decaying $Z/W/H$ boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. D 98 (2018) 032015, https://doi.org/10.1103/PhysRevD.98.032015, arXiv:1805.01908.
[17] HEPData record for this analysis, https://doi.org/10.17182/hepdata.106162, 2021.
[18] CMS Collaboration, The CMS trigger system, J. Instrum. 12 (2017) P01020, https://doi.org/10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
[19] CMS Collaboration, Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 15 (2020) P10017, https://doi.org/10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
[20] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.
[21] CMS Collaboration, CMS luminosity measurements for the 2016 data-taking period, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017, http://cds.cern.ch/record/2257069.
[22] CMS Collaboration, CMS luminosity measurements for the 2017 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018, https://cds.cern.ch/record/2621960.
[23] CMS Collaboration, CMS luminosity measurements for the 2018 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-18-001, 2018, https://cds.cern.ch/record/2676164.
[24] N. Arkani-Hamed, R.T. D'Agnolo, M. Low, D. Pinner, Unification and new particles at the LHC, J. High Energy Phys. 11 (2016) 082, https://doi.org/10.1007/JHEP11(2016)082, arXiv:1608.01675.
[25] R.M. Capdevilla, R. Harnik, A. Martin, The radiation valley and exotic resonances in $W\gamma$ production at the LHC, J. High Energy Phys. 03 (2020) 117, https://doi.org/10.1007/JHEP03(2020)117, arXiv:1912.08234.
[26] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079, https://doi.org/10.1007/JHEP07(2014)079, arXiv:1405.0301.
[27] R.D. Ball, et al., NNPDF, Parton distributions for the LHC Run II, J. High Energy Phys. 04 (2015) 040, https://doi.org/10.1007/JHEP04(2015)040, arXiv:1410.8849.
[28] R.D. Ball, et al., NNPDF, Parton distributions from high-precision collider data, Eur. Phys. J. C 77 (2017) 663, https://doi.org/10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
[29] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, https://doi.org/10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
[30] P. Skands, S. Carrazza, J. Rojo, Tuning PYTHIA 8.1: the Monash 2013 tune, Eur. Phys. J. C 74 (2014) 3024, https://doi.org/10.1140/epjc/s10052-014-3024-y, arXiv:1404.5630.
[31] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, Eur. Phys. J. C 76 (2016) 155, https://doi.org/10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
[32] CMS Collaboration, Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements, Eur. Phys. J. C 80 (2020) 4, https://doi.org/10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
[33] S. Agostinelli, et al., GEANT4, GEANT4 — a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250, https://doi.org/10.1016/S0168-9002(03)01368-8.
[34] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. 12 (2017) P10003, https://doi.org/10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
[35] M. Cacciari, G.P. Salam, G. Soyez, The anti-k_t jet clustering algorithm, J. High Energy Phys. 04 (2008) 063, https://doi.org/10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
[36] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, Eur. Phys. J. C 72 (2012) 1896, https://doi.org/10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
[37] CMS Collaboration, Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV, J. Instrum. 10 (2015) P08010, https://doi.org/10.1088/1748-0221/10/08/P08010, arXiv:1502.02702.
[38] CMS Collaboration, Pileup mitigation at CMS in 13 TeV data, J. Instrum. 15 (2020) P09018, https://doi.org/10.1088/1748-0221/15/09/p09018, arXiv:2003.00503.
[39] D. Bertolini, P. Harris, M. Low, N. Tran, Pileup per particle identification, J. High Energy Phys. 10 (2014) 059, https://doi.org/10.1007/JHEP10(2014)059, arXiv:1407.6013.
[40] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. 12 (2017) P02014, https://doi.org/10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
[41] CMS Collaboration, Jet algorithms performance in 13 TeV data, CMS Physics Analysis Summary CMS-PAS-JME-16-003, 2017, https://cds.cern.ch/record/2256875.
[42] A.J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft drop, J. High Energy Phys. 05 (2014) 146, https://doi.org/10.1007/JHEP05(2014)146, arXiv:1402.2657.

[43] CMS Collaboration, Search for a massive resonance decaying to a pair of Higgs bosons in the four b quark final state in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B 781 (2018) 244, https://doi.org/10.1016/j.physletb.2018.03.084, arXiv:1710.04960.
[44] J. Thaler, K. Van Tilburg, Identifying boosted objects with N-subjettiness, J. High Energy Phys. 03 (2011) 015, https://doi.org/10.1007/JHEP03(2011)015, arXiv:1011.2268.
[45] M.J. Oreglia, A study of the reactions $\psi' \to \gamma\gamma\psi$, Ph.D. thesis, Stanford University, 1980, http://www.slac.stanford.edu/pubs/slacreports/slac-r-236.html, SLAC Report SLAC-R-236.
[46] A.L. Read, Linear interpolation of histograms, Nucl. Instrum. Methods A 425 (1999) 357, https://doi.org/10.1016/S0168-9002(98)01347-3.
[47] CMS Collaboration, Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 07 (2018) 161, https://doi.org/10.1007/JHEP07(2018)161, arXiv:1802.02613.
[48] J. Butterworth, et al., PDF4LHC recommendations for LHC Run II, J. Phys. G 43 (2016) 023001, https://doi.org/10.1088/0954-3899/43/2/023001, arXiv:1510.03865.
[49] T. Junk, Confidence level computation for combining searches with small statistics, Nucl. Instrum. Methods A 434 (1999) 435, https://doi.org/10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
[50] A.L. Read, Presentation of search results: the CL_s technique, J. Phys. G 28 (2002) 2693, https://doi.org/10.1088/0954-3899/28/10/313.
[51] ATLAS and CMS Collaborations, Procedure for the LHC Higgs boson search combination in Summer 2011, ATL-PHYS-PUB-2011-011, CMS NOTE-2011/005, 2011, https://cdsweb.cern.ch/record/1379837.
[52] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C 71 (2011) 1554, https://doi.org/10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727; https://doi.org/10.1140/epjc/s10052-013-2501-z (Erratum).
[53] E. Gross, O. Vitells, Trial factors for the look elsewhere effect in high energy physics, Eur. Phys. J. C 70 (2010) 525, https://doi.org/10.1140/epjc/s10052-010-1470-8, arXiv:1005.1891.

The CMS Collaboration

A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth [1], M. Jeitler [1], N. Krammer, L. Lechner, D. Liko, I. Mikulec, F.M. Pitters, J. Schieck [1], R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz [1]

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, A. Litomin, V. Makarenko

Institute for Nuclear Problems, Minsk, Belarus

M.R. Darwish [2], E.A. De Wolf, X. Janssen, T. Kello [3], A. Lelek, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, E.S. Bols, J. D'Hondt, J. De Clercq, M. Delcourt, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, P. Van Mulders

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, L. Favart, A. Grebenyuk, A.K. Kalsi, K. Lee, M. Mahdavikhorrami, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, M. Gruchala, G. Mestdach, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Ghent University, Ghent, Belgium

A. Bethani, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, M. Teklishyn, P. Vischia, S. Wertz, S. Wuyckens

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

G.A. Alves, C. Hensel, A. Moraes

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato [4], E.M. Da Costa, G.G. Da Silveira [5], D. De Jesus Damiao, S. Fonseca De Souza, D. Matos Figueiredo, C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

C.A. Bernardes [a], L. Calligaris [a], T.R. Fernandez Perez Tomei [a], E.M. Gregores [a,b], D.S. Lemos [a], P.G. Mercadante [a,b], S.F. Novaes [a], Sandra S. Padula [a]

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

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

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

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

University of Sofia, Sofia, Bulgaria

T. Cheng, W. Fang [3], Q. Guo, T. Javaid [6], M. Mittal, H. Wang, L. Yuan

Beihang University, Beijing, China

M. Ahmad, G. Bauer, C. Dozen [7], Z. Hu, J. Martins [8], Y. Wang, K. Yi [9,10]

Department of Physics, Tsinghua University, Beijing, China

E. Chapon, G.M. Chen [6], H.S. Chen [6], M. Chen, A. Kapoor, D. Leggat, H. Liao, Z.-A. Liu [6], R. Sharma, A. Spiezia, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, S. Zhang [6], J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin, Q. Li, M. Lu, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

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

Z. You

Sun Yat-Sen University, Guangzhou, China

X. Gao [3], H. Okawa

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

M. Xiao

Zhejiang University, Hangzhou, China

C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

J. Jaramillo, J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

Universidad de Antioquia, Medellin, Colombia

D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak

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

Z. Antunovic, M. Kovac, T. Sculac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov [11], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka

University of Cyprus, Nicosia, Cyprus

M. Finger [12], M. Finger Jr. [12], A. Kveton

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

S. Abu Zeid [13], S. Elgammal [14], E. Salama [14,13]

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

M.A. Mahmoud, Y. Mohammed

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

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, J. Pata, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

E. Brücken, F. Garcia, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, H. Petrow, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro [15], M. Titov, G.B. Yu

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

S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, C. Charlot, O. Davignon, B. Diab, G. Falmagne, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, I. Kucher, A. Lobanov, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

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

J.-L. Agram [16], J. Andrea, D. Apparu, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, J.-C. Fontaine [16], U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

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

E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, K. Shchablo, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

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

A. Khvedelidze [12], Z. Tsamalaidze [12]

Georgian Technical University, Tbilisi, Georgia

L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M.P. Rauch, M. Teroerde

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

D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, F. Ivone, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, W. Haj Ahmad [17], O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl [18], T. Ziemons

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

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras [19], V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, V. Danilov, M.M. Defranchis, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, E. Gallo [20], A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari [21], N.Z. Jomhari, H. Jung, A. Kasem [19], M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann [22], T. Madlener, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otarid, D. Pérez Adán, D. Pitzl, A. Raspereza, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, V. Scheurer, C. Schwanenberger [20], A. Singh, R.E. Sosa Ricardo, N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wuchterl, R. Zlebcik

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, K. De Leo, T. Dreyer, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, V. Kutzner, J. Lange, T. Lange, A. Malara, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, M. Schröder, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, A. Tews, B. Vormwald, I. Zoi

University of Hamburg, Hamburg, Germany

J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer [†], A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, J.o. Gosewisch, A. Gottmann, F. Hartmann [18], C. Heidecker, U. Husemann, I. Katkov [23], P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, Th. Müller, M. Neukum, G. Quast, K. Rabbertz, J. Rauser, D. Savoiu, D. Schäfer, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, J. Van Der Linden, R.F. Von Cube, M. Wassmer, M. Weber, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, A. Stakia

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

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, E. Vourliotis

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos, J. Strologas

University of Ioánnina, Ioánnina, Greece

M. Csanad, K. Farkas, M.M.A. Gadallah [24], S. Lökös [25], P. Major, K. Mandal, A. Mehta, G. Pasztor, A.J. Rádl, O. Surányi, G.I. Veres

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

M. Bartók [26], G. Bencze, C. Hajdu, D. Horvath [27], F. Sikler, V. Veszpremi, G. Vesztergombi [†]

Wigner Research Centre for Physics, Budapest, Hungary

S. Czellar, J. Karancsi [26], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi [28], B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo [29], F. Nemes [29], T. Novak

Karoly Robert Campus, MATE Institute of Technology, Hungary

S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati [30], D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu [31], A. Nayak [31], P. Saha, N. Sur, S.K. Swain

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

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra [32], R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Meena, K. Sandeep, J.B. Singh, A.K. Virdi

Panjab University, Chandigarh, India

A. Ahmed, A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

University of Delhi, Delhi, India

M. Bharti [33], R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, B. Gomber [34], M. Maity [35], S. Nandan, P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan, B. Singh [33], S. Thakur [33]

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Indian Institute of Technology Madras, Madras, India

D. Dutta, V. Jha, V. Kumar, D.K. Mishra, K. Naskar [36], P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, G.B. Mohanty, U. Sarkar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy

Tata Institute of Fundamental Research-B, Mumbai, India

S. Dube, B. Kansal, S. Pandey, A. Rane, A. Rastogi, S. Sharma

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

H. Bakhshiansohi [37], M. Zeinali [38]

Department of Physics, Isfahan University of Technology, Isfahan, Iran

S. Chenarani [39], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], R. Aly [a,b,40], C. Aruta [a,b], A. Colaleo [a], D. Creanza [a,c], N. De Filippis [a,c], M. De Palma [a,b], A. Di Florio [a,b], A. Di Pilato [a,b], W. Elmetenawee [a,b], L. Fiore [a], A. Gelmi [a,b], M. Gul [a], G. Iaselli [a,c], M. Ince [a,b], S. Lezki [a,b], G. Maggi [a,c], M. Maggi [a], I. Margjeka [a,b], V. Mastrapasqua [a,b], J.A. Merlin [a], S. My [a,b], S. Nuzzo [a,b], A. Pellecchia [a,b], A. Pompili [a,b], G. Pugliese [a,c], A. Ranieri [a], G. Selvaggi [a,b], L. Silvestris [a], F.M. Simone [a,b], R. Venditti [a], P. Verwilligen [a]

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

G. Abbiendi [a], C. Battilana [a,b], D. Bonacorsi [a,b], L. Borgonovi [a], S. Braibant-Giacomelli [a,b], L. Brigliadori [a], R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], C. Ciocca [a], M. Cuffiani [a,b], G.M. Dallavalle [a], T. Diotalevi [a,b], F. Fabbri [a], A. Fanfani [a,b], E. Fontanesi [a,b], P. Giacomelli [a], L. Giommi [a,b], C. Grandi [a], L. Guiducci [a,b], F. Iemmi [a,b], S. Lo Meo [a,41], S. Marcellini [a], G. Masetti [a], F.L. Navarria [a,b], A. Perrotta [a], F. Primavera [a,b], A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b], N. Tosi [a]

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

S. Albergo [a,b,42], S. Costa [a,b,42], A. Di Mattia [a], R. Potenza [a,b], A. Tricomi [a,b,42], C. Tuve [a,b]

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

G. Barbagli [a], A. Cassese [a], R. Ceccarelli [a,b], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], F. Fiori [a,b], E. Focardi [a,b], G. Latino [a,b], P. Lenzi [a,b], M. Lizzo [a,b], M. Meschini [a], S. Paoletti [a], R. Seidita [a,b], G. Sguazzoni [a], L. Viliani [a]

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

L. Benussi, S. Bianco, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo [a,b], F. Ferro [a], R. Mulargia [a,b], E. Robutti [a], S. Tosi [a,b]

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

A. Benaglia [a], F. Brivio [a,b], F. Cetorelli [a,b], V. Ciriolo [a,b,18], F. De Guio [a,b], M.E. Dinardo [a,b], P. Dini [a], S. Gennai [a], A. Ghezzi [a,b], P. Govoni [a,b], L. Guzzi [a,b], M. Malberti [a], S. Malvezzi [a], A. Massironi [a], D. Menasce [a], F. Monti [a,b], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], S. Ragazzi [a,b], T. Tabarelli de Fatis [a,b], D. Valsecchi [a,b,18], D. Zuolo [a,b]

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

S. Buontempo [a], F. Carnevali [a,b], N. Cavallo [a,c], A. De Iorio [a,b], F. Fabozzi [a,c], A.O.M. Iorio [a,b], L. Lista [a,b], S. Meola [a,d,18], P. Paolucci [a,18], B. Rossi [a], C. Sciacca [a,b]

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

P. Azzi [a], N. Bacchetta [a], D. Bisello [a,b], P. Bortignon [a], A. Bragagnolo [a,b], R. Carlin [a,b], P. Checchia [a], P. De Castro Manzano [a], T. Dorigo [a], F. Gasparini [a,b], U. Gasparini [a,b], S.Y. Hoh [a,b], L. Layer [a,43], M. Margoni [a,b], A.T. Meneguzzo [a,b], M. Presilla [a,b], P. Ronchese [a,b], R. Rossin [a,b], F. Simonetto [a,b], G. Strong [a], M. Tosi [a,b], H. Yarar [a,b], M. Zanetti [a,b], P. Zotto [a,b], A. Zucchetta [a,b], G. Zumerle [a,b]

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

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

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

G.M. Bilei [a], D. Ciangottini [a,b], L. Fanò [a,b], P. Lariccia [a,b], G. Mantovani [a,b], V. Mariani [a,b], M. Menichelli [a], F. Moscatelli [a], A. Piccinelli [a,b], A. Rossi [a,b], A. Santocchia [a,b], D. Spiga [a], T. Tedeschi [a,b]

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

P. Azzurri [a], G. Bagliesi [a], V. Bertacchi [a,c], L. Bianchini [a], T. Boccali [a], E. Bossini, R. Castaldi [a], M.A. Ciocci [a,b], R. Dell'Orso [a], M.R. Di Domenico [a,d], S. Donato [a], A. Giassi [a], M.T. Grippo [a], F. Ligabue [a,c], E. Manca [a,c], G. Mandorli [a,c], A. Messineo [a,b], F. Palla [a], S. Parolia [a,b], G. Ramirez-Sanchez [a,c], A. Rizzi [a,b], G. Rolandi [a,c], S. Roy Chowdhury [a,c], A. Scribano [a], N. Shafiei [a,b], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], N. Turini [a,d], A. Venturi [a], P.G. Verdini [a]

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

M. Campana [a,b], F. Cavallari [a], M. Cipriani [a,b], D. Del Re [a,b], E. Di Marco [a], M. Diemoz [a], E. Longo [a,b], P. Meridiani [a], G. Organtini [a,b], F. Pandolfi [a], R. Paramatti [a,b], C. Quaranta [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b], L. Soffi [a], R. Tramontano [a,b]

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

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], A. Bellora [a,b], J. Berenguer Antequera [a,b], C. Biino [a], A. Cappati [a,b], N. Cartiglia [a], S. Cometti [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], B. Kiani [a,b], F. Legger [a], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b], E. Monteil [a,b], M. Monteno [a], M.M. Obertino [a,b], G. Ortona [a], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], G.L. Pinna Angioni [a,b], M. Ruspa [a,c], R. Salvatico [a,b], K. Shchelina [a,b], F. Siviero [a,b], V. Sola [a], A. Solano [a,b], D. Soldi [a,b], A. Staiano [a], M. Tornago [a,b], D. Trocino [a,b]

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

S. Belforte [a], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a], A. Da Rold [a,b], G. Della Ricca [a,b], G. Sorrentino [a,b], F. Vazzoler [a,b]

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

S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, B.C. Radburn-Smith, S. Sekmen, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon

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

T.J. Kim, J. Park

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Korea University, Seoul, Republic of Korea

J. Goh, A. Gurtu

Kyung Hee University, Department of Physics, Seoul, Republic of Korea

H.S. Kim, Y. Kim

Sejong University, Seoul, Republic of Korea

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

Seoul National University, Seoul, Republic of Korea

D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, Y. Roh, D. Song, I.J. Watson

University of Seoul, Seoul, Republic of Korea

S. Ha, H.D. Yoo

Yonsei University, Department of Physics, Seoul, Republic of Korea

Y. Choi, Y. Jeong, H. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

T. Beyrouthy, Y. Maghrbi

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

V. Veckalns [44]

Riga Technical University, Riga, Latvia

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

Vilnius University, Vilnius, Lithuania

N. Bin Norjoharuddeen, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz [45], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

J. Mijuskovic [46], N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

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

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

V. Avati, L. Grzanka, M. Malawski

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, O. Toldaiev, J. Varela

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

S. Afanasiev, D. Budkouski, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev [47,48], V. Palichik, V. Perelygin, M. Savina, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, A. Zarubin, I. Zhizhin

Joint Institute for Nuclear Research, Dubna, Russia

G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim [49], E. Kuznetsova [50], V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

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

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov [†], A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko [51], V. Popov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

O. Bychkova, M. Chadeeva [52], P. Parygin, E. Popova, V. Rusinov

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

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin [53], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

V. Blinov [54], T. Dimova [54], L. Kardapoltsev [54], I. Ovtin [54], Y. Skovpen [54]

Novosibirsk State University (NSU), Novosibirsk, Russia

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

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

A. Babaev, V. Okhotnikov, L. Sukhikh

National Research Tomsk Polytechnic University, Tomsk, Russia

V. Borchsh, V. Ivanchenko, E. Tcherniaev

Tomsk State University, Tomsk, Russia

P. Adzic [55], M. Dordevic, P. Milenovic, J. Milosevic, V. Milosevic

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, L. Urda Gómez, C. Willmott

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

J.F. de Trocóniz, R. Reyes-Almanza

Universidad Autónoma de Madrid, Madrid, Spain

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza, A. Trapote

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, J.M. Vizan Garcia

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

M.K. Jayananda, B. Kailasapathy [56], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

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

T.K. Aarrestad, D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon [†], A.H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco, A. Bocci, E. Brondolin, T. Camporesi, M. Capeans Garrido, G. Cerminara, S.S. Chhibra, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, A. David, A. De Roeck,

M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita [57], D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, S. Mallios, M. Mannelli, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas [58], S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, M. Verzetti, J. Wanczyk [59], K.A. Wozniak, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada [60], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, M. Missiroli, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

K. Androsov [59], M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, F. Eble, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, C. Martin Perez, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, G. Perrin, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, J. Steggemann [59], R. Wallny, D.H. Zhu

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

C. Amsler [61], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, A. Jofrehei, B. Kilminster, S. Leontsinis, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, G. Rauco, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, Y. Takahashi

Universität Zürich, Zurich, Switzerland

C. Adloff [62], C.M. Kuo, W. Lin, A. Roy, T. Sarkar [35], S.S. Yu

National Central University, Chung-Li, Taiwan

L. Ceard, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, E. Yazgan, P.r. Yu

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

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

F. Boran, S. Damarseckin [63], Z.S. Demiroglu, F. Dolek, I. Dumanoglu [64], E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar Guler [65], I. Hos [66], C. Isik, E.E. Kangal [67], O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir [68], A. Polatoz, A.E. Simsek, B. Tali [69], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Isildak [70], G. Karapinar [71], K. Ocalan [72], M. Yalvac [73]

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya [74], O. Kaya [75], Ö. Özçelik, S. Tekten [76], E.A. Yetkin [77]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak [64], Y. Komurcu, S. Sen [78]

Istanbul Technical University, Istanbul, Turkey

F. Aydogmus Sen, S. Cerci [69], B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci [69]

Istanbul University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

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

E. Bhal, S. Bologna, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou [79], J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [80], C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, V. Cepaitis, G.S. Chahal [81], D. Colling, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash [82], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, A. Tapper, K. Uchida, T. Virdee [18], N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

Imperial College, London, United Kingdom

J.E. Cole, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

Brunel University, Uxbridge, United Kingdom

S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, N. Pastika, S. Sawant, C. Smith, C. Sutantawibul, J. Wilson

Baylor University, Waco, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

Catholic University of America, Washington, DC, USA

A. Buccilli, O. Charaf, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio [83], C. West

The University of Alabama, Tuscaloosa, USA

A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, D. Gastler, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan, D. Zou

Boston University, Boston, USA

G. Benelli, B. Burkle, X. Coubez [19], D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan [84], E. Laird, G. Landsberg, K.T. Lau, J. Lee, J. Luo, M. Narain, S. Sagir [85], E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

Brown University, Providence, USA

C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, M. Tripathi, Y. Yao, F. Zhang

University of California, Davis, Davis, USA

M. Bachtis, R. Cousins, A. Dasgupta, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Los Angeles, USA

K. Burt, Y. Chen, R. Clare, J.W. Gary, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, W. Si, S. Wimpenny, Y. Zhang

University of California, Riverside, Riverside, USA

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, J. Duarte, R. Gerosa, L. Giannini, D. Gilbert, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, B.V. Sathia Narayanan, V. Sharma, M. Tadel, A. Vartak, F. Würthwein, Y. Xiang, A. Yagil

University of California, San Diego, La Jolla, USA

N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, B. Marsh, H. Mei, M. Oshiro, A. Ovcharova, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang

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

A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, J. Ngadiuba, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, Z. Zhang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, E. MacDonald, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, Y. Cheng, J. Chu, D.J. Cranshaw, K. Mcdermott, J. Monroy, J.R. Patterson, D. Quach, J. Reichert, A. Ryd, W. Sun, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, K.F. Di Petrillo, V.D. Elvira, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, P. Klabbers, T. Klijnsma, B. Klima, M.J. Kortelainen, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, J. Lykken, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena [53], O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, 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, H.A. Weber, A. Woodard

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Sturdy, J. Wang, E. Yigitbasi, X. Zuo

University of Florida, Gainesville, USA

T. Adams, A. Askew, D. Diaz, R. Habibullah, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida State University, Tallahassee, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy [13], M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu, Z. Ye

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

M. Alhusseini, K. Dilsiz [86], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili [87], A. Moeller, J. Nachtman, H. Ogul [88], Y. Onel, F. Ozok [89], A. Penzo, C. Snyder, E. Tiras [90], J. Wetzel

The University of Iowa, Iowa City, USA

O. Amram, B. Blumenfeld, L. Corcodilos, J. Davis, M. Eminizer, A.V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, M. Swartz, T.Á. Vámi

Johns Hopkins University, Baltimore, USA

C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

The University of Kansas, Lawrence, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

University of Maryland, College Park, USA

D. Abercrombie, G. Andreassi, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, B. Maier, A.C. Marini, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Tatar, J. Wang, Z. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, USA

R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

K. Bloom, M. Bryson, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, C. Joo, I. Kravchenko, M. Musich, J.E. Siado, G.R. Snow [†], W. Tabb, F. Yan

University of Nebraska-Lincoln, Lincoln, USA

G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, J. Li, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

Northwestern University, Evanston, USA

R. Band, R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko [47], R. Ruchti, P. Siddireddy, M. Wayne, A. Wightman, M. Wolf, M. Zarucki, L. Zygala

University of Notre Dame, Notre Dame, USA

B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, A. Lefeld, B.L. Winer, B.R. Yates

The Ohio State University, Columbus, USA

F.M. Addesa, B. Bonham, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, D. Stickland, C. Tully

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, S. Karmarkar, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, C.C. Peng, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic [15], J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, USA

J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA

A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts [†], W. Shi, A.G. Stahl Leiton

Rice University, Houston, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

University of Rochester, Rochester, USA

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban [22], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

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

H. Acharya, A.G. Delannoy, S. Spanier

University of Tennessee, Knoxville, USA

O. Bouhali [91], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon [92], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Texas Tech University, Lubbock, USA

E. Appelt, S. Greene, A. Gurrola, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, B. Tannenwald, E. Wolfe

University of Virginia, Charlottesville, USA

P.E. Karchin, N. Poudyal, P. Thapa

Wayne State University, Detroit, USA

K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, P. Everaerts, F. Fienga, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, W. Vetens

University of Wisconsin – Madison, Madison, WI, USA

[†] Deceased.
[1] Also at TU Wien, Wien, Austria.
[2] Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt, Alexandria, Egypt.
[3] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[4] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[5] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[6] Also at University of Chinese Academy of Sciences, Beijing, China.
[7] Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China.
[8] Also at UFMS, Nova Andradina, Brazil.
[9] Also at Nanjing Normal University Department of Physics, Nanjing, China.
[10] Now at The University of Iowa, Iowa City, USA.
[11] Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia.
[12] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[13] Also at Ain Shams University, Cairo, Egypt.
[14] Now at British University in Egypt, Cairo, Egypt.
[15] Also at Purdue University, West Lafayette, USA.
[16] Also at Université de Haute Alsace, Mulhouse, France.
[17] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[18] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[19] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[20] Also at University of Hamburg, Hamburg, Germany.
[21] Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran.
[22] Also at Brandenburg University of Technology, Cottbus, Germany.
[23] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[24] Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[25] Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary.
[26] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary.
[27] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[28] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary.
[29] Also at Wigner Research Centre for Physics, Budapest, Hungary.
[30] Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India.
[31] Also at Institute of Physics, Bhubaneswar, India.
[32] Also at G.H.G. Khalsa College, Punjab, India.
[33] Also at Shoolini University, Solan, India.
[34] Also at University of Hyderabad, Hyderabad, India.

[35] Also at University of Visva-Bharati, Santiniketan, India.
[36] Also at Indian Institute of Technology (IIT), Mumbai, India.
[37] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[38] Also at Sharif University of Technology, Tehran, Iran.
[39] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[40] Now at INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy.
[41] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[42] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[43] Also at Università di Napoli 'Federico II', NAPOLI, Italy.
[44] Also at Riga Technical University, Riga, Latvia, Riga, Latvia.
[45] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[46] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
[47] Also at Institute for Nuclear Research, Moscow, Russia.
[48] Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[49] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[50] Also at University of Florida, Gainesville, USA.
[51] Also at Imperial College, London, United Kingdom.
[52] Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[53] Also at California Institute of Technology, Pasadena, USA.
[54] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[55] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[56] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[57] Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy, Pavia, Italy.
[58] Also at National and Kapodistrian University of Athens, Athens, Greece.
[59] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[60] Also at Universität Zürich, Zurich, Switzerland.
[61] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria.
[62] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[63] Also at Şırnak University, Sirnak, Turkey.
[64] Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey.
[65] Also at Konya Technical University, Konya, Turkey.
[66] Also at Istanbul University – Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[67] Also at Mersin University, Mersin, Turkey.
[68] Also at Piri Reis University, Istanbul, Turkey.
[69] Also at Adiyaman University, Adiyaman, Turkey.
[70] Also at Ozyegin University, Istanbul, Turkey.
[71] Also at Izmir Institute of Technology, Izmir, Turkey.
[72] Also at Necmettin Erbakan University, Konya, Turkey.
[73] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey, Yozgat, Turkey.
[74] Also at Marmara University, Istanbul, Turkey.
[75] Also at Milli Savunma University, Istanbul, Turkey.
[76] Also at Kafkas University, Kars, Turkey.
[77] Also at Istanbul Bilgi University, Istanbul, Turkey.
[78] Also at Hacettepe University, Ankara, Turkey.
[79] Also at Vrije Universiteit Brussel, Brussel, Belgium.
[80] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[81] Also at IPPP Durham University, Durham, United Kingdom.
[82] Also at Monash University, Faculty of Science, Clayton, Australia.
[83] Also at Università di Torino, TORINO, Italy.
[84] Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA.
[85] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[86] Also at Bingol University, Bingol, Turkey.
[87] Also at Georgian Technical University, Tbilisi, Georgia.
[88] Also at Sinop University, Sinop, Turkey.
[89] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[90] Also at Erciyes University, KAYSERI, Turkey.
[91] Also at Texas A&M University at Qatar, Doha, Qatar.
[92] Also at Kyungpook National University, Daegu, Korea, Daegu, Republic of Korea.