Published for SISSA by Springer

Received: *March 10, 2018*
Revised: *May 18, 2018*
Accepted: *June 28, 2018*
Published: *July 11, 2018*

Search for a heavy resonance decaying into a Z boson and a vector boson in the $\nu\overline{\nu}\mathrm{q}\overline{\mathrm{q}}$ final state

The CMS collaboration

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

Abstract: A search is presented for a heavy resonance decaying into either a pair of Z bosons or a Z boson and a W boson (ZZ or WZ), with a Z boson decaying into a pair of neutrinos and the other boson decaying hadronically into two collimated quarks that are reconstructed as a highly energetic large-cone jet. The search is performed using the data collected with the CMS detector at the CERN LHC during 2016 in proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to a total integrated luminosity of 35.9 fb^{-1}. No excess is observed in data with regard to background expectations. Results are interpreted in scenarios of physics beyond the standard model. Limits at 95% confidence level on production cross sections are set at 0.9 fb (63 fb) for spin-1 W' bosons, included in the heavy vector triplet model, with mass 4.0 TeV (1.0 TeV), and at 0.5 fb (40 fb) for spin-2 bulk gravitons with mass 4.0 TeV (1.0 TeV). Lower limits are set on the masses of W' bosons in the context of two versions of the heavy vector triplet model of 3.1 TeV and 3.4 TeV, respectively.

Keywords: Beyond Standard Model, Hadron-Hadron scattering (experiments)

ArXiv ePrint: 1803.03838

https://doi.org/10.1007/JHEP07(2018)075

Contents

1 Introduction

Many models of physics beyond the standard model (BSM) predict the existence of additional heavy resonances that may decay into a pair of vector bosons. A particular class of models addresses the divergence of quantum mechanical corrections to the Higgs boson mass, known as the hierarchy problem, by introducing extra spatial dimensions (such as warped extra dimensions models [1, 2]), which predict the presence of additional massive particles.

The Randall-Sundrum model [3, 4] introduces one warped extra dimension to solve the hierarchy problem. In the four-dimensional bulk space, two branes are hypothesized: one whose fundamental scale is the Planck scale, and one at the TeV scale, where the standard model (SM) particles are confined. Spin-2 gravitons, expected to have a mass at the TeV scale, are allowed to propagate from the Planck brane to the TeV brane via the warped fourth spatial dimension. In the bulk warped extra dimension model, the SM particles can also propagate through the bulk multidimensional space. In this context, spin-2 bulk gravitons can be produced at a significant rate via gluon fusion, and can decay into a pair of vector bosons [5]. Two parameters are used to describe the model: the mass of the proposed spin-2 particle and $\widetilde{k} = k/\overline{M}_{\text{Pl}}$, where k is the curvature parameter of the five-dimensional space-time metric, and $\overline{M}_{\text{Pl}} = M_{\text{Pl}}/\sqrt{8\pi}$ is the reduced Planck mass.

Other theories extend the SM by adding fields to the SM Lagrangian, resulting in a larger symmetry. New vector bosons arise from the breaking of this symmetry. The heavy vector triplet (HVT) model [6] provides a framework for many BSM models, in particular those where heavy spin-1 partners of the vector bosons (W' and Z' bosons) [7, 8] are expected to be weakly coupled to SM particles (referred to as the "HVT model A" scenario), and the composite Higgs model [9, 10], where exotic vector bosons are strongly coupled to ordinary particles (the "HVT model B" scenario). Both scenarios are described by three Lagrangian parameters: the couplings of spin-1 particles to SM fermions (c_{F}) and to SM bosons (c_{H}), and the strength of the interaction (g_{V}). In the HVT model A scenario, $g_{\mathrm{V}} = 1$, $c_{\mathrm{F}} = -1.316$, and $c_{\mathrm{H}} = -0.556$; in HVT model B, $g_{\mathrm{V}} = 3$, $c_{\mathrm{F}} = 1.024$, and $c_{\mathrm{H}} = 0.976$ [6]. Previous searches performed at the CERN LHC looking for evidence for these models have set limits on the production cross section of the new heavy bosons (46.1 fb at a mass of 1.4 TeV and 0.7 fb at a mass of 4.1 TeV), and mass lower limits of 3.3 TeV (3.6 TeV) for HVT model A (model B) [11–15].

In this article, we present the results of a search for heavy resonances decaying into a pair of vector bosons, where one vector boson is a Z boson decaying into neutrinos, while the other boson V (either a W or Z boson) decays hadronically. The vector bosons are mostly produced in a back-to-back topology with large Lorentz boosts because of the large mass of the new particle (on the order of 1 TeV); this implies that the two quarks originating from the vector boson decay are close enough to be reconstructed within one single large-cone jet, an approach that, in this kinematic region, is more efficient than building the vector boson candidate as two distinct standard jets. Since neutrinos do not leave any visible signature in the detector, they are reconstructed as a large amount of missing transverse momentum ($\vec{p}_{\mathrm{T}}^{\text{miss}}$) recoiling against the hadronic component. The sensitivity of the search is enhanced by the relatively high branching fraction of the Z boson into neutrinos (20%) and of the other vector boson into a pair of quarks (≈70%). Jet substructure techniques [16] are exploited to improve the discrimination between signal events and SM background processes.

The contributions of the SM backgrounds, composed mainly of Z+jets and W+jets events, are estimated using a method that interpolates the data from control regions into the signal region with a fit constrained by the simulation.

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. Events of interest are selected using a two-tiered trigger system [17]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors. The second level, known as

JHEP07(2018)075

the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing.

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. [18].

3 Data and simulated samples

The analysis is performed on data collected in 2016 with the CMS detector during proton-proton collisions at the LHC at a center-of-mass energy of 13 TeV, corresponding to a total integrated luminosity of $35.9\,\mathrm{fb}^{-1}$.

Two signal models are simulated: the first considers a spin-1 HVT W' boson decaying into a W and a Z boson for both A and B scenarios, and the second considers a spin-2 bulk graviton G decaying into two Z bosons. Both processes are generated at leading order (LO) with the MadGraph5_aMC@NLO v2.2.2 [19] matrix element Monte Carlo (MC) generator for a range of different mass hypotheses for the resonances from 0.6 to 4.5 TeV. Signals are generated assuming the resonances have negligible width (0.1% of their masses) compared to the experimental resolution (4–8% depending on their masses); this assumption is the so-called "narrow-width approximation". The actual width of the spin-2 resonances may be larger depending on the value of the curvature parameter $\widetilde{k}$ in the model [1, 2], but this effect is only significant for values of $\widetilde{k}$ larger than 1, which are not considered in this analysis. For the background, events with a vector boson produced with additional partons are generated at next-to-leading order (NLO) in α_S with MadGraph5_aMC@NLO, using the FxFx merging scheme [20]. Electroweak corrections at NLO [21] are applied to these samples as a function of the transverse momentum p_{T} of the vector bosons. Top quark-antiquark ($\mathrm{t}\bar{\mathrm{t}}$) and single top quark events are simulated at NLO in the five-flavor scheme with POWHEG v2 [22–26]. Inclusive diboson production (WW, WZ, ZZ) is considered as well, and generated with PYTHIA 8.212 [27] at LO. The hadronization and fragmentation steps of all simulated samples are handled by PYTHIA with the CUETP8M1 [28] tune. The NNPDF3.1 [29] parton distribution functions are used in the simulations. The effect of additional proton-proton interactions within the same or nearby bunch crossings (pileup) is accounted for by adding simulated minimum bias events to the hard interaction. The frequency distributions of the pileup events are reweighted to match those observed in data. The simulation of the CMS detector is performed with Geant4 [30].

4 Event reconstruction

The particle-flow (PF) event algorithm [31] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained directly from the ECAL measurement, corrected for zero-suppression effects. 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 zero-suppression effects and 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.

Jets are reconstructed from PF inputs, using FastJet 3.1 [32] to cluster jets with the anti-k_{T} algorithm [33], with two distance parameters: 0.4 ("AK4" jets) and 0.8 ("AK8" jets). The jet momentum is determined as the four-vector sum of all particle momenta in the jet, and is found from simulation to be within 2 to 10% of the momentum of the quark that initiated the jet, over the whole p_{T} spectrum and detector acceptance. The raw jet energies are further corrected to establish a relative uniform response of the calorimeter in η and a calibrated absolute response in p_{T} [34]. Charged particles not associated to the primary vertex are removed from the jet [35]. An additional offset correction is applied to the jet energies to subtract the contribution from pileup [35]. The jet energy scale (JES) is calculated using a detailed MC simulation of the detector, and further adjusted using the p_{T} balance in dijet, multijet, photon+jet and leptonically decaying Z+jet events in data [36]. A smearing procedure has been applied to jets in the simulated samples in order to account for small differences between the jet momentum resolutions observed in simulation and in data. The jet energy resolution (JER) is ≈15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV [36].

A minimum threshold on the energy recorded in the HCAL is applied to remove spurious jet-like features originating from isolated noise patterns in certain regions. Jets are required to have more than one PF constituent, and they are required to have less than 80% of their total energy originating from neutral hadrons, less than 99% from electrons, and more than 20% from charged hadrons.

The jet mass reconstruction is optimized for this analysis using a combination of a jet grooming technique [37, 38] and pileup mitigation [39]. In the jet grooming algorithm, the constituents of the AK8 jets are reclustered using the Cambridge-Aachen algorithm [40, 41]. The "modified mass drop tagger" algorithm [37], also known as the "soft drop" algorithm, with angular exponent $\beta = 0$, soft cutoff threshold $z_{\mathrm{cut}} < 0.1$, and characteristic radius $R_0 = 0.8$ [38], is applied to remove soft, wide-angle radiation from the jet. The pileup mitigation is performed by the "pileup per particle identification" algorithm [39], a method that assigns a weight to each charged or neutral particle, which is determined by the probability for the particle to have originated from the primary vertex of the hard interaction. Finally, the jet mass is corrected with p_{T}-dependent factors [42] to account for the small difference observed in the reconstructed vector boson mass between data and simulated events in a $\mathrm{t\bar{t}}$ control sample, in which one W boson, originating from the top or antitop quark, decays into leptons and the other W boson decays hadronically.

The missing transverse momentum vector is defined as the negative sum of the p_{T} of all PF candidates in the event: $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\Sigma_i \vec{p}_{\mathrm{T}}^{\,i}$; its magnitude is referred to as $p_{\mathrm{T}}^{\mathrm{miss}}$. This raw quantity is corrected by propagating the effect of the jet energy corrections. Uncertainties in the $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ determination arise from mismeasurements caused by detector alignment, unclustered energy deposits, and contributions coming from pileup [43]. Events with spurious missing momentum related to detector noise and badly reconstructed events are rejected [43].

5 Event selection

Events are required to satisfy criteria at the HLT trigger level on either $p_{\mathrm{T}}^{\text{miss}}$ or the missing hadronic activity, $H_{\mathrm{T}}^{\text{miss}}$, which is defined as the magnitude of the transverse component of the negative sum of the three-momenta of all the objects identified as jets at trigger level. To avoid inefficiencies due to the prescaling of the triggers during high-luminosity LHC operation, several triggers are used, variously requiring $H_{\mathrm{T}}^{\text{miss}}$ or $p_{\mathrm{T}}^{\text{miss}} > 90$, 110, 120 GeV, or $p_{\mathrm{T}}^{\text{miss}} > 170$ GeV, in order to have at least one nonprescaled trigger at any given time.

The $p_{\mathrm{T}}^{\text{miss}}$ trigger efficiency has been measured with data events satisfying one or more single-muon triggers. A W leptonic decay topology is selected ($\mathrm{W} \to \mu\nu$), since it ensures the presence of $p_{\mathrm{T}}^{\text{miss}}$ in the event, due to the neutrino. One muon identified by offline algorithms is required: this not only guarantees that the sample does not overlap with the search region of the analysis (where events with muons are rejected), but also reduces the contamination from particles or jets misidentified as leptons at the trigger level. The additional condition of having at least one AK8 jet is applied, in order to select events with a topology similar to that of the considered search. The combination of $p_{\mathrm{T}}^{\text{miss}}$ triggers reaches a plateau in efficiency of 96% around $p_{\mathrm{T}}^{\text{miss}} > 200$ GeV, which is chosen as the minimum $p_{\mathrm{T}}^{\text{miss}}$ threshold for the event selection. An independent efficiency measurement has been performed using a data set satisfying single-electron triggers, and the discrepancy with the result based on the muon data set is taken as a systematic uncertainty, which amounts to 1%.

The AK8 jets are required to satisfy $p_{\mathrm{T}} > 200$ GeV and $|\eta| < 2.4$. The largest-p_{T} AK8 jet in the event is assumed to be the hadronically decaying boson (V) candidate.

The jet mass (m_{j}) is used to define the search region. Since the analysis searches for a diboson resonance where one vector boson decays hadronically, the mass of the jet candidate is expected to lie within a window around the nominal masses of the W and Z bosons, chosen to be between 65 and 105 GeV. Two control regions are defined that are expected to be depleted in signal: the "low sideband", which lies in the m_{j} range 30–65 GeV, and the "high sideband", with m_{j} above 135 GeV. These sidebands play a crucial role in the background estimation. The region 105–135 GeV is excluded from the sideband selections in order to not overlap with other diboson searches aiming at a final state containing a hadronically decaying Higgs boson. This exclusion allows the results to be combined with those of other searches in a straightforward manner. The region under 30 GeV is discarded, since jets are not reconstructed sufficiently well in this region.

Jet substructure is exploited to further improve the ability to identify signal events. The τ_{21} N-subjettiness ratio [16] distinguishes jets with two separable substructure components from jets with only one substructure component. In the former case, the τ_{21} distribution is peaked towards a small fraction of unity; in the latter case, it has a broader shape, centered around larger values closer to 1. Two exclusive search categories are defined: a low-purity category ($0.35 < \tau_{21} < 0.75$) and a high-purity category ($\tau_{21} < 0.35$).

In principle, the high-purity category is the most sensitive to the signals explored; nevertheless, the low-purity category allows us to retain a significant part of the signal efficiency, especially for very heavy resonances (3–4 TeV). As a consequence, the signal sensitivity improves by up to 40% when the categories are combined. Multiplicative scale factors [42] are used to correct observed discrepancies between data and simulation, and are measured to be 0.99 ± 0.11 for events falling into the high-purity category and 1.03 ± 0.23 for those in the low-purity category. They have been measured with MC simulation and top quark-enriched data samples, and are applied to simulated backgrounds.

The reconstructed $\vec{p}_{\mathrm{T}}$ of the invisibly decaying Z boson is set equal to $\vec{p}_{\mathrm{T}}^{\text{miss}}$. Thus, instead of the invariant mass, the resulting reconstructed VZ candidate mass is the transverse mass $m_{\mathrm{T}}^{\mathrm{VZ}}$:

$$m_{\mathrm{T}}^{\mathrm{VZ}} = \sqrt{2E_{\mathrm{T}}^{\mathrm{j}} p_{\mathrm{T}}^{\text{miss}} \left(1 - \cos\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\mathrm{j}}, \vec{p}_{\mathrm{T}}^{\,\text{miss}})\right)}, \tag{5.1}$$

where $E_{\mathrm{T}}^{\mathrm{j}} = E^{\mathrm{j}} \sin\theta$ and $\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\mathrm{j}}, \vec{p}_{\mathrm{T}}^{\,\text{miss}})$ is the azimuthal angle between the $\vec{p}_{\mathrm{T}}^{\,\text{miss}}$ and the leading AK8 jet transverse momentum vector.

The AK4 jets are used for background suppression; they are required to satisfy $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$. If the event contains an AK4 jet passing a loose b tagging criterion using the combined secondary vertex (CSVv2) [44, 45] algorithm, and it does not overlap with the AK8 jet identified as the V candidate, the event is discarded, since this suggests that the event is more likely to have originated from a top quark decay. Scale factors are applied to correct for the different b tagging efficiency in data and simulated samples [44, 45].

A set of selection criteria has been applied to improve the background rejection. By requiring a minimum azimuthal angular separation of 0.5 between $\vec{p}_{\mathrm{T}}^{\,\text{miss}}$ and the $\vec{p}_{\mathrm{T}}$ of the AK4 jets outside the cone of the leading AK8 jet, the contribution of background events originating from soft multijet radiation is reduced from 30% to 2% or 3%, depending on the purity category. The single top quark and $\mathrm{t\bar{t}}$ contributions are approximately halved by applying the loose b tag veto described above. Background contributions are further suppressed by requiring a back-to-back topology in the transverse plane between the V and Z candidates, specifically, $\Delta\phi > 2$.

Final states with photons, electrons, muons, and hadronically decaying tau leptons are rejected in this analysis. The identification of these objects is performed using the variables described in ref. [31]. An event is discarded if it contains at least one photon with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$ and $|\eta| < 2.5$, at least one electron with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.5$, at least one muon with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.4$, or at least one hadronically decaying tau lepton with $p_{\mathrm{T}} > 18\,\mathrm{GeV}$ and $|\eta| < 2.4$.

The main discriminating variables used to perform the background prediction, m_{j} and τ_{21}, are compared in data and MC simulation in figure 1. Two signal hypotheses, a spin-1 W′ boson and a spin-2 bulk graviton, are displayed as well. They are characterized by jet mass spectra peaking at the W mass and at the Z mass, respectively, and by a τ_{21} distribution reflecting the two-prong structure of the jet produced in the vector boson hadronic decay, significantly different from the background. The discrepancy visible between the data and the background prediction is due to the imperfect modeling of the jet substruc-

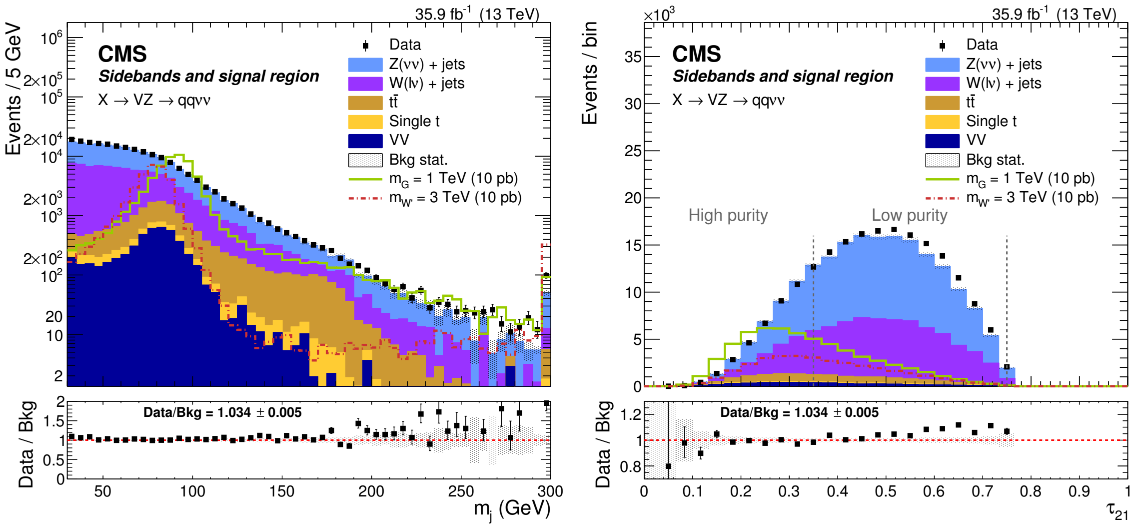

Figure 1. Comparison of data and simulated events. Left: the corrected mass of the leading AK8 jet, interpreted as the hadronically decaying vector boson. Right: the distribution of the τ_{21} subjettiness of the vector boson candidate, which is used to define low- and high-purity categories. The background processes predicted by the SM are depicted as colored filled histograms. The shaded area on top of the histograms represents the statistical uncertainty associated to MC simulations. Overflows are shown in the rightmost bin. Two possible signal hypotheses are shown: a spin-1 W′ boson with a mass of 3 TeV and a spin-2 bulk graviton with a mass of 1 TeV. The data points are shown by the black markers, along with their associated statistical uncertainties. In the bottom panels, the ratio between data and MC predictions is calculated for each bin.

ture and momentum in simulation. Agreement is achieved when a hybrid data/simulation background estimation approach, described in section 6, is applied.

6 Background estimation

This analysis searches for a localized excess in data in the transverse mass spectrum of the VZ system. Hence, accurate background modeling is crucial to the analysis.

The main irreducible background is from events in which a Z boson is produced along with additional jets ("Z+jets") and decays into neutrinos. The second dominant contribution comes from events in which a W boson is produced along with additional jets ("W+jets") and decays leptonically, with the charged lepton falling outside the detector acceptance or not correctly identified. Since the production mechanisms of these two processes are the same, these two categories of events are grouped together as "V+jets" events. Smaller background contributions come from events in which at least one top quark (either a tt̄ pair or a single top quark, indicated as "Top" background) or a pair of vector bosons (WW, WZ, or ZZ, which we call "VV" background) is produced; these are referred to as "secondary backgrounds".

The background estimation technique [46], which is now known as the "α method", takes advantage of the data sidebands to predict the normalization and $m_{\mathrm{T}}^{\mathrm{VZ}}$ shape of the

V+jets background distributions, which are poorly populated by simulations in phase space regions with large transverse momentum. The normalization and shape of the secondary backgrounds are determined from MC simulation. This data-driven approach allows us to improve the agreement between data and predictions, especially in the higher tails of the momentum distributions.

The background prediction is performed in two steps for each of the two purity categories. First, the mass spectrum of the AK8 jet is the variable chosen to predict the background event yield in the signal region. Then, once the normalization is determined, the transverse mass distribution of the diboson candidates is used to predict the background shapes in the signal region.

To perform the normalization prediction, the m_{j} distribution of each background is fitted in simulated samples with an empirical probability density function (pdf), converted into an extended likelihood in order to allow the event yield to vary in the fit. The main background is modeled by using two alternative functional forms, and the difference between the two yield predictions is considered as a systematic uncertainty and propagated to the final results. The m_{j} spectrum of the V+jets background is smoothly falling in the low-purity category; hence, it is modeled as a power law (main function) or as a Gaussian peak added to a falling exponential (alternative function), in order to check that a different description of the slope of the spectrum near the signal region does not significantly affect the final result. In the high-purity category, the m_{j} spectrum has a peaking component, so it is described by a broad Gaussian peak, centered at approximately 150 GeV, added to a falling exponential (main function), or by an exponential function convolved with an error function to describe the turn-on effect at low mass (alternative function). The top quark and diboson backgrounds are modeled as Gaussian peaks, centered on the top quark and W or Z masses, respectively, added to a smoothly falling exponential background.

Once the extended likelihoods for the main and secondary backgrounds are added together, an extended maximum likelihood fit is performed in the data sidebands. The parameters related to the V+jets background and its normalization are allowed to vary according to data, whereas those describing the secondary backgrounds are fixed to the theoretical predictions. The expected number of background events in the signal region is then evaluated by integrating the final extended likelihood that describes the total background.

The results of the background estimation are presented in figure 2 as smooth functions, and are compared to data. The fit to the data is performed in the sideband regions described in section 5. Data are compared to the α method background predictions in the signal region (SR), while the Higgs region is excluded from the analysis. It can be seen that the data agree with the background estimates.

The final step consists in predicting the functional shape of the m_{T} spectrum of the total background. First, the distribution of $m_{\mathrm{T}}^{\mathrm{VZ}}$ is described separately for each background using MC simulation, both in the signal region and sidebands. The general background shape expected for all SM processes is an exponentially falling function with two parameters, of the form $e^{-x/(a+bx)}$.

JHEP07(2018)075

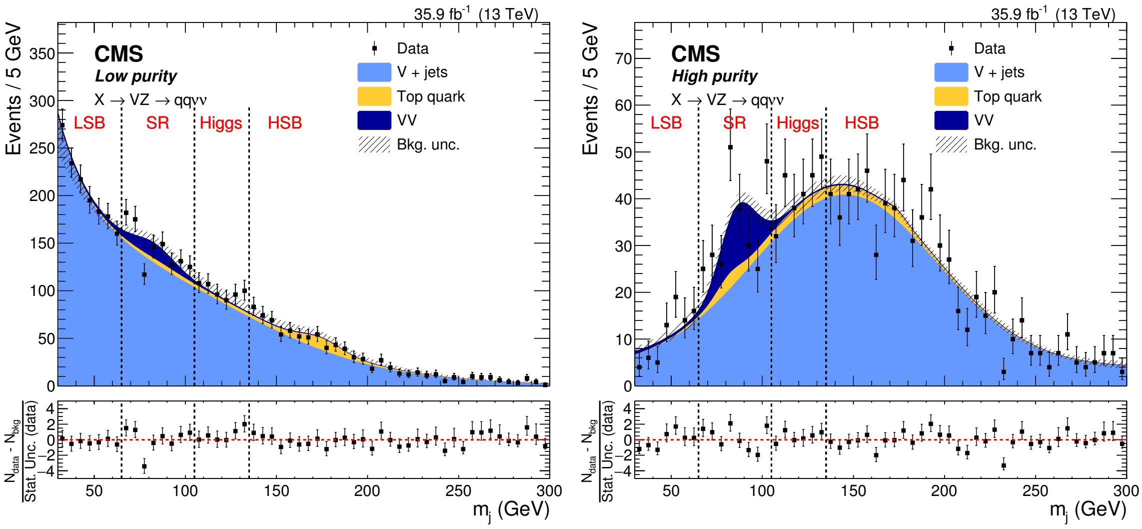

Figure 2. Background yield prediction in the signal region obtained with the α method, in the low-purity (left) and high-purity (right) categories. Background processes predicted by the SM are depicted as colored areas bounded by smooth functions. The bottom panels show fit residuals normalized to their uncertainties.

The α function is defined as the ratio between the V+jets background pdf in the signal region ($f_{\mathrm{SR}}^{\mathrm{V+jets}}$) and that in the sidebands ($f_{\mathrm{SB}}^{\mathrm{V+jets}}$), predicted from simulation:

$$\alpha(m_{\mathrm{T}}^{\mathrm{VZ}}) = \frac{f_{\mathrm{SR}}^{\mathrm{V+jets}}(m_{\mathrm{T}}^{\mathrm{VZ}})}{f_{\mathrm{SB}}^{\mathrm{V+jets}}(m_{\mathrm{T}}^{\mathrm{VZ}})}. \tag{6.1}$$

The α ratio can be interpreted as a transfer function from the sidebands to the signal region, accounting for the small kinematical differences in the two regions of the V+jets background. The typical correction resulting from using the α ratio is on the order of 1–5 per mil. A simultaneous fit to MC simulation and data sidebands is performed in order to extract the α function and the main background parameters respectively, while the secondary background shapes are taken from predictions from MC simulation, as described in the following equation:

$$f_{\mathrm{SR}}^{\mathrm{data}}(m_{\mathrm{T}}^{\mathrm{VZ}}) = \left[f_{\mathrm{SB}}^{\mathrm{data}}(m_{\mathrm{T}}^{\mathrm{VZ}}) - f_{\mathrm{SB}}^{\mathrm{Top}}(m_{\mathrm{T}}^{\mathrm{VZ}}) - f_{\mathrm{SB}}^{\mathrm{VV}}(m_{\mathrm{T}}^{\mathrm{VZ}})\right]\alpha(m_{\mathrm{T}}^{\mathrm{VZ}}) + f_{\mathrm{SR}}^{\mathrm{Top}}(m_{\mathrm{T}}^{\mathrm{VZ}}) + f_{\mathrm{SR}}^{\mathrm{VV}}(m_{\mathrm{T}}^{\mathrm{VZ}}). \tag{6.2}$$

The background estimation obtained with the α method, i.e., the predicted spectrum of $m_{\mathrm{T}}^{\mathrm{VZ}}$ in the background-only hypothesis, is compared with data in figure 3, and no significant excess is observed with regard to the SM expectations.

The robustness of the α method is tested by splitting the low sideband into two subregions, one considered as a narrower lower sideband (30–50 GeV) and the other (50–65 GeV) taken as a validation region. The predictions obtained by applying the α method in the narrow lower sideband and the high sideband are then compared to data distributions in the validation region, and are found to agree.

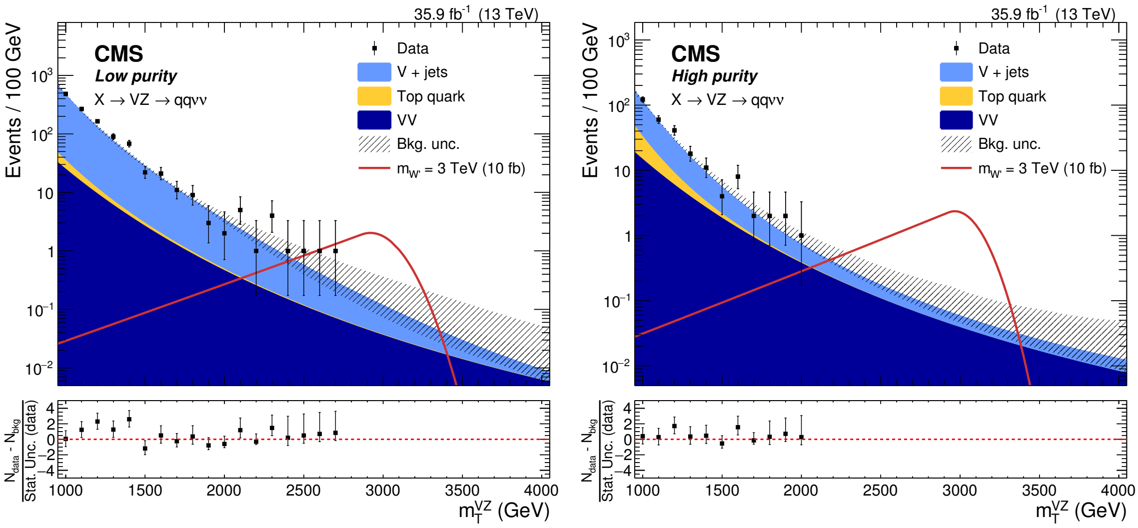

Figure 3. Expected background shapes as a function of the transverse mass of the diboson candidate obtained using the α method in the low-purity (left) and high-purity (right) categories, represented as colored areas bounded by smooth functions. As a reference, the expected distribution of a W′ with a mass of 3 TeV decaying into a W boson and a Z boson is displayed. Data are shown as black markers.

7 Systematic uncertainties

The background normalization is predicted from a set of simultaneous fits to the simulated and data samples, so the uncertainty in the normalization is estimated by propagating all the uncertainties affecting the main and the secondary background fits. The statistical uncertainty in the fit, determined by the number of data events in the sidebands, contributes to the uncertainty in the main background event yield by 5% and 15% for the low- and high-purity categories, respectively. A second source of uncertainty is the absolute difference in the V+jets event yield prediction between the main function and the alternative function used to fit the m_j spectrum of the V+jets background in the simulated samples. It amounts to 5% and 4% for the low- and high-purity categories, respectively. The uncertainties related to the number of expected events from the secondary backgrounds amount to 68% and 48% for the low- and high-purity categories, respectively, for the top quark background yield, and to 11% and 19%, respectively, for the diboson background yield. Given that the secondary backgrounds are a small fraction of the total, the overall impact of the uncertainties in their event yields is negligible.

The uncertainties in the parameters describing the shape of the m_T^VZ distribution of the main background are obtained by propagating the uncertainties related to each parameter of the simultaneous fit to simulation and data sidebands. These parameters are then decorrelated by diagonalizing their covariance matrix with a linear transformation.

The normalizations of the secondary backgrounds and of the signal are affected by a 1% uncertainty in the trigger efficiency, calculated as described in section 5.

The impact of the uncertainties in the p_T of the reconstructed bosons is evaluated by simultaneously varying their p_T within their uncertainties, since $\vec{p}_\mathrm{T}^\text{miss}$ is influenced by the p_T corrections applied to all the hadronic objects present in the event. The uncertainties related to JES and JER are evaluated by varying their numerical values within their uncertainties. They have a negligible impact (less than 1%) on both the normalization of the signal and secondary backgrounds, and on their shape; namely, on the parameters describing the exponential behavior of the spectra. The uncertainty in $\vec{p}_\mathrm{T}^\text{miss}$ arising from unclustered energy deposits is also negligibly small. Uncertainties related to the m_j corrections are considered, and they affect the signal and background yields by 1%. Uncertainties related to the jet mass smearing affect the signal yield by 5.1%, the top quark backgrounds by 3.1%, and the diboson backgrounds by 2.0%. Jet mass smearing uncertainties affect the parameters describing the top quark and diboson background shapes by 4% and 1%, respectively.

The uncertainty related to the τ_{21} scale factors, as described in section 5, has the largest single impact on the final results. An additional source of uncertainty comes from the jet p_T dependence of the τ_{21} scale factors. The τ_{21} distributions are modeled at higher p_T regimes (above 200 GeV), where the event yield is very small in data, by using an alternative showering scheme (HERWIG++ [47]) and compared to PYTHIA. The discrepancy between the predictions is parameterized as a function of the jet p_T. In this analysis, the uncertainties due to the τ_{21} scale factor extrapolations at high p_T amount to 9–20%, depending on the purity category.

The uncertainty in the b tagging efficiency affecting the veto applied to AK4 jets impacts the signal normalization by 1%, the diboson background normalization by less than 1%, and the top quark background normalization by 2%.

A minor source of uncertainty comes from the uncertainty in the total inelastic proton-proton cross section at 13 TeV, which affects the pileup distribution, and thus the normalization of the simulated samples. It amounts to less than 1% for diboson, top quark, and signal samples.

A 3% uncertainty is assigned to the efficiency of vetoing hadronically decaying tau leptons. The uncertainty in the measurement of the integrated luminosity amounts to 2.5% [48].

The renormalization and factorization scales used in the simulation are varied by a factor of 2 and a factor of 0.5, both separately and independently. Per-event weights are extracted and propagated to the invariant mass distributions. These scale variations affect the shape of the top quark background by a total of 1%, and its normalization by 7% (renormalization scale) and 3% (factorization scale); they both affect the diboson background normalization by 1%. The uncertainty related to the choice of the parton distribution functions used in simulation is estimated by following the prescriptions in ref. [49], using the NNPDF3.1 [29] set. The parameters describing the parton distribution functions are varied together within their uncertainties, and the resulting variations are used as a set of per-event weights, applied to the invariant mass distributions. These uncertainties affect the normalization of the top quark and diboson backgrounds by 0.3% each; the effect on the top quark and diboson background shapes is negligibly small. Uncertainties of 15% [50, 51] and 10% [52–54] are assigned to the normalization of the diboson and top quark backgrounds, respectively, from the knowledge of the production cross section.

8 Results

An unbinned profile likelihood fit is performed on the final spectra of the transverse mass of the diboson candidates. The signals are modeled with a Crystal Ball function [55], i.e., a function with a Gaussian core and a power-law behavior in the low tail. Systematic uncertainties are treated as nuisance parameters constrained with a log-normal distribution and profiled during the minimization. The background-only hypothesis is tested in the data, where the low- and high-purity categories have been combined. The asymptotic modified frequentist approach [56–58], or $\mathrm{CL_s}$ criterion, is used to quote 95% confidence level (CL) limits.

The observed and expected limits on the product of the cross section and branching fraction ($\sigma\mathcal{B}(\mathrm{W}' \to \mathrm{W_{had}Z_{inv}})$) for a spin-1 W′ decaying into W and Z bosons that in turn decay in the hadronic and invisible channels, respectively, as a function of the mass of the resonance, are shown in figure 4 (left). The hypothesis of a heavy spin-1 resonance, predicted by the HVT model A scenario, is rejected at 95% CL for masses smaller than 3.1 TeV, while the W′ described in the HVT model B context is excluded up to 3.4 TeV. At these mass values, the product of cross section and branching fraction are expected to be 1.4 fb and 1.1 fb, respectively.

The observed and expected limits on the product of the cross section and branching fraction ($\sigma\mathcal{B}(\mathrm{G} \to \mathrm{Z_{had}Z_{inv}})$) for a spin-2 bulk graviton decaying into a pair of Z bosons, where one Z boson decays hadronically and the other invisibly, are shown in figure 4 (right), as a function of the mass of the resonance. The theoretical predictions for the curvature parameter hypothesis $\widetilde{k} = 0.5$ are shown for comparison.

The results of this search complement those published by the ATLAS collaboration [59], which were obtained from an investigation of the same final state, using different jet substructure and background estimation techniques. The limits obtained here are the best single limits obtained in this final state.

9 Summary

A search has been made for heavy diboson resonances (WZ, ZZ) decaying into a pair of vector bosons, one of which is a Z boson decaying into $\nu\overline{\nu}$ and the other is a W or Z boson that decays into $\mathrm{q\overline{q}}$. The data were collected by the CMS detector from proton-proton collisions produced at the LHC at a center-of-mass energy of 13 TeV. In this analysis, the hadronically decaying W or Z boson is reconstructed as a large-cone jet. The invisible decay of the Z boson manifests itself as a large amount of missing transverse momentum recoiling against the jet. The transverse components of the VZ system momentum are used to define the transverse mass variable, where a search for a localized excess is performed. The expected background is described with a hybrid data/simulation approach that takes advantage of data sidebands to predict the background normalization and shape in the signal region. To improve the discovery potential, two purity categories are defined, based on a jet substructure observable. An unbinned maximum likelihood fit is performed. No excess is observed in data compared to standard model predictions. Upper limits are

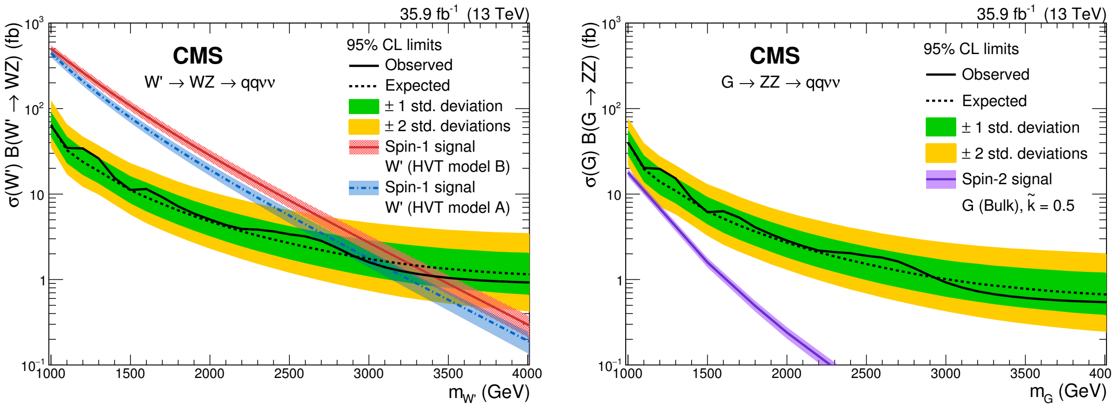

Figure 4. The observed and expected limits on the product of the cross section and branching fraction $\sigma\mathcal{B}(\mathrm{W'} \to \mathrm{W_{had}Z_{inv}})$ for a spin-1 HVT signal hypothesis (left) and $\sigma\mathcal{B}(\mathrm{G} \to \mathrm{Z_{had}Z_{inv}})$ for a spin-2 bulk graviton signal hypothesis (right), as a function of the W′ and G mass, respectively. The low- and high-purity categories have been combined. The inner and outer shaded bands indicate the 68% and 95% uncertainty intervals associated with the expected limits. Theoretical predictions are shown for: (left) the two HVT models considered, model A (blue dotted-and-dashed line) and model B (red solid line), and (right) a graviton model with a curvature parameter of $\tilde{k} = 0.5$ (violet solid line).

established at 95% confidence level on the product of the production cross section and branching fraction for a spin-1 heavy vector triplet (HVT) W′ boson and spin-2 bulk graviton, which are in the range 0.9–63 fb and 0.5–40 fb, respectively, depending on the resonance mass. The existence of a W′ boson is excluded at 95% confidence level up to a mass of 3.1 TeV in the HVT model A and up to 3.4 TeV in the HVT model B.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid 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 and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, 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); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (U.S.A.).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. 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 Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; 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 and 125105 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; 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 Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

References

[1] K. Agashe, H. Davoudiasl, G. Perez and A. Soni, *Warped gravitons at the LHC and beyond*, *Phys. Rev.* **D 76** (2007) 036006 [hep-ph/0701186] [INSPIRE].

[2] A.L. Fitzpatrick, J. Kaplan, L. Randall and L.-T. Wang, *Searching for the Kaluza-Klein graviton in bulk RS models*, *JHEP* **09** (2007) 013 [hep-ph/0701150] [INSPIRE].

[3] L. Randall and R. Sundrum, *A large mass hierarchy from a small extra dimension*, *Phys. Rev. Lett.* **83** (1999) 3370 [hep-ph/9905221] [INSPIRE].

[4] L. Randall and R. Sundrum, *An alternative to compactification*, *Phys. Rev. Lett.* **83** (1999) 4690 [hep-th/9906064] [INSPIRE].

[5] O. Antipin, D. Atwood and A. Soni, *Search for RS gravitons via W_LW_L decays*, *Phys. Lett.* **B 666** (2008) 155 [arXiv:0711.3175] [INSPIRE].

[6] D. Pappadopulo, A. Thamm, R. Torre and A. Wulzer, *Heavy vector triplets: bridging theory and data*, *JHEP* **09** (2014) 060 [arXiv:1402.4431] [INSPIRE].

[7] V.D. Barger, W.-Y. Keung and E. Ma, *A gauge model with light W and Z bosons*, *Phys. Rev.* **D 22** (1980) 727 [INSPIRE].

[8] C. Grojean, E. Salvioni and R. Torre, *A weakly constrained W' at the early LHC*, *JHEP* **07** (2011) 002 [arXiv:1103.2761] [INSPIRE].

[9] R. Contino, D. Marzocca, D. Pappadopulo and R. Rattazzi, *On the effect of resonances in composite Higgs phenomenology*, *JHEP* **10** (2011) 081 [arXiv:1109.1570] [INSPIRE].

[10] B. Bellazzini, C. Csáki and J. Serra, *Composite Higgses*, *Eur. Phys. J.* **C 74** (2014) 2766 [arXiv:1401.2457] [INSPIRE].

[11] CMS collaboration, *Search for massive resonances decaying into WW, WZ, ZZ, qW and qZ with dijet final states at $\sqrt{s} = 13$ TeV*, *Phys. Rev.* **D 97** (2018) 072006 [arXiv:1708.05379] [INSPIRE].

[12] CMS collaboration, *Search for heavy resonances that decay into a vector boson and a Higgs boson in hadronic final states at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J.* **C 77** (2017) 636 [arXiv:1707.01303] [INSPIRE].

[13] ATLAS collaboration, *Search for heavy resonances decaying to a W or Z boson and a Higgs boson in the $q\bar{q}^{(\prime)}b\bar{b}$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Phys. Lett.* **B 774** (2017) 494 [arXiv:1707.06958] [INSPIRE].

[14] CMS collaboration, *Search for heavy resonances decaying into a vector boson and a Higgs boson in final states with charged leptons, neutrinos and b quarks*, *Phys. Lett.* **B 768** (2017) 137 [arXiv:1610.08066] [INSPIRE].

[15] CMS collaboration, *Search for a heavy resonance decaying to a pair of vector bosons in the lepton plus merged jet final state at $\sqrt{s} = 13$ TeV*, *JHEP* **05** (2018) 088 [arXiv:1802.09407] [INSPIRE].

[16] J. Thaler and K. Van Tilburg, *Identifying boosted objects with N-subjettiness*, *JHEP* **03** (2011) 015 [arXiv:1011.2268] [INSPIRE].

[17] CMS collaboration, *The CMS trigger system*, 2017 *JINST* **12** P01020 [arXiv:1609.02366] [INSPIRE].

[18] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [INSPIRE].

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

[20] R. Frederix and S. Frixione, *Merging meets matching in MC@NLO*, *JHEP* **12** (2012) 061 [arXiv:1209.6215] [INSPIRE].

[21] S. Kallweit, J.M. Lindert, S. Pozzorini, M. Schönherr and P. Maierhöfer, *NLO QCD+EW automation and precise predictions for V+multijet production*, in *Proceedings, 50th Rencontres de Moriond, QCD and high energy interactions*, La Thuile, Italy, 21–28 March 2015, pg. 121 [arXiv:1505.05704] [INSPIRE].

[22] P. Nason, *A new method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **11** (2004) 040 [`hep-ph/0409146`] [INSPIRE].

[23] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070 [`arXiv:0709.2092`] [INSPIRE].

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

[25] J.M. Campbell, R.K. Ellis, P. Nason and E. Re, *Top-pair production and decay at NLO matched with parton showers*, *JHEP* **04** (2015) 114 [`arXiv:1412.1828`] [INSPIRE].

[26] E. Re, *Single-top Wt-channel production matched with parton showers using the POWHEG method*, *Eur. Phys. J.* **C 71** (2011) 1547 [`arXiv:1009.2450`] [INSPIRE].

[27] T. Sjöstrand, S. Mrenna and P.Z. Skands, *A brief introduction to PYTHIA* 8.1, *Comput. Phys. Commun.* **178** (2008) 852 [`arXiv:0710.3820`] [INSPIRE].

[28] CMS collaboration, *Event generator tunes obtained from underlying event and multiparton scattering measurements*, *Eur. Phys. J.* **C 76** (2016) 155 [`arXiv:1512.00815`] [INSPIRE].

[29] NNPDF collaboration, R.D. Ball et al., *Parton distributions from high-precision collider data*, *Eur. Phys. J.* **C 77** (2017) 663 [`arXiv:1706.00428`] [INSPIRE].

[30] GEANT4 collaboration, S. Agostinelli et al., *GEANT4: a simulation toolkit*, *Nucl. Instrum. Meth.* **A 506** (2003) 250 [INSPIRE].

[31] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector*, 2017 *JINST* **12** P10003 [`arXiv:1706.04965`] [INSPIRE].

[32] M. Cacciari, G.P. Salam and G. Soyez, *FastJet user manual*, *Eur. Phys. J.* **C 72** (2012) 1896 [`arXiv:1111.6097`] [INSPIRE].

[33] M. Cacciari, G.P. Salam and G. Soyez, *The anti-k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [`arXiv:0802.1189`] [INSPIRE].

[34] CMS collaboration, *Determination of jet energy calibration and transverse momentum resolution in CMS*, 2011 *JINST* **6** P11002 [`arXiv:1107.4277`] [INSPIRE].

[35] CMS collaboration, *Pileup removal algorithms*, CMS-PAS-JME-14-001, CERN, Geneva, Switzerland, (2014).

[36] CMS collaboration, *Jet energy scale and resolution in the CMS experiment in pp collisions at* 8 *TeV*, 2017 *JINST* **12** P02014 [`arXiv:1607.03663`] [INSPIRE].

[37] M. Dasgupta, A. Fregoso, S. Marzani and G.P. Salam, *Towards an understanding of jet substructure*, *JHEP* **09** (2013) 029 [`arXiv:1307.0007`] [INSPIRE].

[38] A.J. Larkoski, S. Marzani, G. Soyez and J. Thaler, *Soft drop*, *JHEP* **05** (2014) 146 [`arXiv:1402.2657`] [INSPIRE].

[39] D. Bertolini, P. Harris, M. Low and N. Tran, *Pileup per particle identification*, *JHEP* **10** (2014) 059 [`arXiv:1407.6013`] [INSPIRE].

[40] Y.L. Dokshitzer, G.D. Leder, S. Moretti and B.R. Webber, *Better jet clustering algorithms*, *JHEP* **08** (1997) 001 [`hep-ph/9707323`] [INSPIRE].

[41] M. Wobisch and T. Wengler, *Hadronization corrections to jet cross-sections in deep inelastic scattering*, in *Monte Carlo generators for HERA physics. Proceedings, Workshop*, Hamburg, Germany, 1998–1999, pg. 270 [`hep-ph/9907280`] [INSPIRE].

[42] CMS collaboration, *Identification techniques for highly boosted W bosons that decay into hadrons*, *JHEP* **12** (2014) 017 [arXiv:1410.4227] [INSPIRE].

[43] CMS collaboration, *Performance of missing energy reconstruction in 13 TeV pp collision data using the CMS detector*, CMS-PAS-JME-16-004, CERN, Geneva, Switzerland, (2016).

[44] CMS collaboration, *Identification of b-quark jets with the CMS experiment*, 2013 *JINST* **8** P04013 [arXiv:1211.4462] [INSPIRE].

[45] CMS collaboration, *Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV*, 2018 *JINST* **13** P05011 [arXiv:1712.07158] [INSPIRE].

[46] CMS collaboration, *Search for a Higgs boson in the mass range from 145 to 1000 GeV decaying to a pair of W or Z bosons*, *JHEP* **10** (2015) 144 [arXiv:1504.00936] [INSPIRE].

[47] M. Bahr et al., *HERWIG++ physics and manual*, *Eur. Phys. J.* **C 58** (2008) 639 [arXiv:0803.0883] [INSPIRE].

[48] CMS collaboration, *CMS luminosity measurements for the 2016 data taking period*, CMS-PAS-LUM-17-001, CERN, Geneva, Switzerland, (2017).

[49] J. Butterworth et al., *PDF4LHC recommendations for LHC run II*, *J. Phys.* **G 43** (2016) 023001 [arXiv:1510.03865] [INSPIRE].

[50] CMS collaboration, *Measurement of the ZZ production cross section and $Z \to \ell^+\ell^-\ell'^+\ell'^-$ branching fraction in pp collisions at $\sqrt{s} = 13$ TeV*, *Phys. Lett.* **B 763** (2016) 280 [*Erratum ibid.* **B 772** (2017) 884] [arXiv:1607.08834] [INSPIRE].

[51] CMS collaboration, *Measurement of the WZ production cross section in pp collisions at $\sqrt{s} = 13$ TeV*, *Phys. Lett.* **B 766** (2017) 268 [arXiv:1607.06943] [INSPIRE].

[52] CMS collaboration, *Cross section measurement of t-channel single top quark production in pp collisions at $\sqrt{s} = 13$ TeV*, *Phys. Lett.* **B 772** (2017) 752 [arXiv:1610.00678] [INSPIRE].

[53] CMS collaboration, *Measurement of the $t\bar{t}$ production cross section using events in the $e\mu$ final state in pp collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J.* **C 77** (2017) 172 [arXiv:1611.04040] [INSPIRE].

[54] CMS collaboration, *Measurement of the $t\bar{t}$ production cross section using events with one lepton and at least one jet in pp collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **09** (2017) 051 [arXiv:1701.06228] [INSPIRE].

[55] M.J. Oreglia, *A study of the reactions $\psi' \to \gamma\gamma\psi$*, Ph.D. thesis, SLAC report SLAC-236, Stanford University, Stanford, U.S.A., (1980) [INSPIRE].

[56] A.L. Read, *Presentation of search results: the CL_s technique*, *J. Phys.* **G 28** (2002) 2693 [INSPIRE].

[57] T. Junk, *Confidence level computation for combining searches with small statistics*, *Nucl. Instrum. Meth.* **A 434** (1999) 435 [hep-ex/9902006] [INSPIRE].

[58] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J.* **C 71** (2011) 1554 [*Erratum ibid.* **C 73** (2013) 2501] [arXiv:1007.1727] [INSPIRE].

[59] ATLAS collaboration, *Searches for heavy ZZ and ZW resonances in the $\ell\ell qq$ and $\nu\nu qq$ final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **03** (2018) 009 [arXiv:1708.09638] [INSPIRE].

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

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

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, T. Seva, E. Starling, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov[2], D. Poyraz, C. Roskas, S. Salva, D. Trocino, M. Tytgat, W. Verbeke, N. Zaganidis

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

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[3], E. Coelho, E.M. Da Costa, G.G. Da Silveira[4], D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas

Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

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

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

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

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

University of Sofia, Sofia, Bulgaria

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

Beihang University, Beijing, China

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

Institute of High Energy Physics, Beijing, China

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

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

Y. Ban, G. Chen, J. Li, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, F. Zhang[5]

Tsinghua University, Beijing, China

Y. Wang

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez, M.A. Segura Delgado

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

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

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

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

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

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

S. Khalil[8], M.A. Mahmoud[9,10], A. Mahrous[11]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

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

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

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

A. Abdulsalam[12], C. Amendola, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

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

J.-L. Agram[13], J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte[13], X. Coubez, F. Drouhin[13], J.-C. Fontaine[13], D. Gelé, U. Goerlach, M. Jansová, P. Juillot, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov[14], V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Georgian Technical University, Tbilisi, Georgia

A. Khvedelidze[7]

Tbilisi State University, Tbilisi, Georgia

D. Lomidze

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

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov[14]

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

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

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

G. Flügge, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, A. Stahl[15]

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras[16], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo[17], J. Garay Garcia, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel[18], H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann[18], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, R. Shevchenko, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo[15], T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Teilchenphysik, Karlsruhe, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, R. Friese, M. Giffels, M.A. Harrendorf, F. Hartmann[15], S.M. Heindl, U. Husemann, F. Kassel[15], S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

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

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

K. Kousouris

University of Ioánnina, Ioánnina, Greece

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

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

M. Csanad, N. Filipovic, G. Pasztor, O. Surányi, G.I. Veres[19]

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath[20], Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi[19]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi[21], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

M. Bartók[19], P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati[22], P. Mal, K. Mandal, A. Nayak[23], D.K. Sahoo[22], N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Indian Institute of Technology Madras, Madras, India
P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty[15], P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity[24], G. Majumder, K. Mazumdar, T. Sarkar[24], N. Wickramage[25]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[26], E. Eskandari Tadavani, S.M. Etesami[26], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi[27], F. Rezaei Hosseinabadi, B. Safarzadeh[28], M. Zeinali

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

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], F. Errico[a,b], L. Fiore[a], G. Iaselli[a,c], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], A. Sharma[a], L. Silvestris[a,15], R. Venditti[a], P. Verwilligen[a]

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

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b], S. Costa[a,b], A. Di Mattia[a], F. Giordano[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

JHEP07(2018)075

INFN Sezione di Firenze ^{a}, Università di Firenze ^{b}, Firenze, Italy

G. Barbagli^{a}, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^{a}, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, P. Lenzi^{a,b}, M. Meschini^{a}, S. Paoletti^{a}, L. Russo^{a,29}, G. Sguazzoni^{a}, D. Strom^{a}, L. Viliani^{a}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera^{15}

INFN Sezione di Genova ^{a}, Università di Genova ^{b}, Genova, Italy

V. Calvelli^{a,b}, F. Ferro^{a}, F. Ravera^{a,b}, E. Robutti^{a}, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca ^{a}, Università di Milano-Bicocca ^{b}, Milano, Italy

A. Benaglia^{a}, A. Beschi^{b}, L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b,15}, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^{a}, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^{a}, R.A. Manzoni^{a,b}, D. Menasce^{a}, L. Moroni^{a}, M. Paganoni^{a,b}, K. Pauwels^{a,b}, D. Pedrini^{a}, S. Pigazzini^{a,b,30}, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}

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

S. Buontempo^{a}, N. Cavallo^{a,c}, S. Di Guida^{a,d,15}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, A.O.M. Iorio^{a,b}, W.A. Khan^{a}, L. Lista^{a}, S. Meola^{a,d,15}, P. Paolucci^{a,15}, C. Sciacca^{a,b}, F. Thyssen^{a}

INFN Sezione di Padova ^{a}, Università di Padova ^{b}, Padova, Italy, Università di Trento ^{c}, Trento, Italy

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

INFN Sezione di Pavia ^{a}, Università di Pavia ^{b}, Pavia, Italy

A. Braghieri^{a}, A. Magnani^{a}, 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,b}, P. Vitulo^{a,b}

INFN Sezione di Perugia ^{a}, Università di Perugia ^{b}, Perugia, Italy

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

INFN Sezione di Pisa ^{a}, Università di Pisa ^{b}, Scuola Normale Superiore di Pisa ^{c}, Pisa, Italy

K. Androsov^{a}, P. Azzurri^{a,15}, G. Bagliesi^{a}, T. Boccali^{a}, L. Borrello, R. Castaldi^{a}, M.A. Ciocci^{a,b}, R. Dell'Orso^{a}, G. Fedi^{a}, L. Giannini^{a,c}, A. Giassi^{a}, M.T. Grippo^{a,29}, F. Ligabue^{a,c}, T. Lomtadze^{a}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^{a}, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,31}, P. Spagnolo^{a}, R. Tenchini^{a}, G. Tonelli^{a,b}, A. Venturi^{a}, P.G. Verdini^{a}

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

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

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

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

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

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

Kyungpook National University

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

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

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

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

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

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

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

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali[32], F. Mohamad Idris[33], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

Reyes-Almanza, R, Ramirez-Sanchez, G., Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[34], Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

S. Bheesette, P.H. Butler

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

K. Bunkowski, A. Byszuk[35], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

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

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, V. Alexakhin, P. Bunin, M. Gavrilenko, A. Golunov, I. Golutvin, N. Gorbounov, I. Gorbunov, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev[36,37], P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Y. Ivanov, V. Kim[38], E. Kuznetsova[39], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev, A. Bylinkin[37]

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
R. Chistov[40], M. Danilov[40], P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin[37], I. Dremin[37], M. Kirakosyan[37], S.V. Rusakov, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[41], L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov[42], D. Shtol[42], Y. Skovpen[42]

State Research Center of Russian Federation, Institute for High Energy Physics of NRC "Kurchatov Institute", Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[43], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, I. Bachiller, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi, A. Álvarez Fernández

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

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

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

I.J. Cabrillo, A. Calderon, B. Chazin Quero, E. Curras, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, P. Harris, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban[18], J. Kieseler, V. Knünz, A. Kornmayer, M.J. Kortelainen, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic[44], F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Rabady, A. Racz, T. Reis, G. Rolandi[45], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[46], A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Tsirou, V. Veckalns[47], M. Verweij, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl[†], L. Caminada[48], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

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

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

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler[49], M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, D. Pinna, G. Rauco, P. Robmann, D. Salerno,

K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

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

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

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

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

M.N. Bakirci[50], A. Bat, F. Boran, S. Cerci[51], S. Damarseckin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, I. Hos[52], E.E. Kangal[53], O. Kara, U. Kiminsu, M. Oglakci, G. Onengut[54], K. Ozdemir[55], S. Ozturk[50], A. Polatoz, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar[56], K. Ocalan[57], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya[58], O. Kaya[59], S. Tekten, E.A. Yetkin[60]

Istanbul Technical University, Istanbul, Turkey

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

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

B. Grynyov

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

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold[61], S. Paramesvaran, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev[62], C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom
G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko[6], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta[63], T. Virdee[15], N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, U.S.A.
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

Catholic University of America, Washington DC, U.S.A.
R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, U.S.A.
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

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

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

University of California, Davis, Davis, U.S.A.
R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, D. Stolp, K. Tos, M. Tripathi, Z. Wang

University of California, Los Angeles, U.S.A.
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

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

University of California, San Diego, La Jolla, U.S.A.
J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[64], J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, U.S.A.

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

California Institute of Technology, Pasadena, U.S.A.

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

Carnegie Mellon University, Pittsburgh, U.S.A.

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

University of Colorado Boulder, Boulder, U.S.A.

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

Cornell University, Ithaca, U.S.A.

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

Fermi National Accelerator Laboratory, Batavia, U.S.A.

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

University of Florida, Gainesville, U.S.A.

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

Florida International University, Miami, U.S.A.

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

Florida State University, Tallahassee, U.S.A.

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

Florida Institute of Technology, Melbourne, U.S.A.

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

University of Illinois at Chicago (UIC), Chicago, U.S.A.

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

The University of Iowa, Iowa City, U.S.A.

B. Bilki[65], W. Clarida, K. Dilsiz[66], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[67], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul[68], Y. Onel, F. Ozok[69], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, U.S.A.

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

The University of Kansas, Lawrence, U.S.A.

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

Kansas State University, Manhattan, U.S.A.

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

Lawrence Livermore National Laboratory, Livermore, U.S.A.

F. Rebassoo, D. Wright

University of Maryland, College Park, U.S.A.

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

Massachusetts Institute of Technology, Cambridge, U.S.A.

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, U.S.A.
A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Mississippi, Oxford, U.S.A.
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, U.S.A.
E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, U.S.A.
J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, U.S.A.
G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, A. Massironi, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, U.S.A.
S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, U.S.A.
R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[36], M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, U.S.A.
J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, B. Liu, W. Luo, B.L. Winer, H.W. Wulsin

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

University of Puerto Rico, Mayaguez, U.S.A.
S. Malik, S. Norberg

Purdue University, West Lafayette, U.S.A.
A. Barker, V.E. Barnes, S. Das, S. Folgueras, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, U.S.A.
T. Cheng, N. Parashar, J. Stupak

Rice University, Houston, U.S.A.
Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Guilbaud, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

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

The Rockefeller University, New York, U.S.A.
R. Ciesielski, K. Goulianos, C. Mesropian

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

University of Tennessee, Knoxville, U.S.A.
A.G. Delannoy, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, U.S.A.
O. Bouhali[70], A. Castaneda Hernandez[70], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[71], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov

Texas Tech University, Lubbock, U.S.A.
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, U.S.A.
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, U.S.A.
M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, U.S.A.
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, U.S.A.
M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, V. Rekovic, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

---

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria

2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
7: Also at Joint Institute for Nuclear Research, Dubna, Russia
8: Also at Zewail City of Science and Technology, Zewail, Egypt
9: Also at Fayoum University, El-Fayoum, Egypt
10: Now at British University in Egypt, Cairo, Egypt
11: Now at Helwan University, Cairo, Egypt
12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
13: Also at Université de Haute Alsace, Mulhouse, France
14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
22: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
23: Also at Institute of Physics, Bhubaneswar, India
24: Also at University of Visva-Bharati, Santiniketan, India
25: Also at University of Ruhuna, Matara, Sri Lanka
26: Also at Isfahan University of Technology, Isfahan, Iran
27: Also at Yazd University, Yazd, Iran
28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
29: Also at Università degli Studi di Siena, Siena, Italy
30: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy
31: Also at Purdue University, West Lafayette, U.S.A.
32: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
36: Also at Institute for Nuclear Research, Moscow, Russia
37: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
39: Also at University of Florida, Gainesville, U.S.A.
40: Also at P.N. Lebedev Physical Institute, Moscow, Russia
41: Also at California Institute of Technology, Pasadena, U.S.A.
42: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
43: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
44: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

45: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
46: Also at National and Kapodistrian University of Athens, Athens, Greece
47: Also at Riga Technical University, Riga, Latvia
48: Also at Universität Zürich, Zurich, Switzerland
49: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
50: Also at Gaziosmanpasa University, Tokat, Turkey
51: Also at Adiyaman University, Adiyaman, Turkey
52: Also at Istanbul Aydin University, Istanbul, Turkey
53: Also at Mersin University, Mersin, Turkey
54: Also at Cag University, Mersin, Turkey
55: Also at Piri Reis University, Istanbul, Turkey
56: Also at Izmir Institute of Technology, Izmir, Turkey
57: Also at Necmettin Erbakan University, Konya, Turkey
58: Also at Marmara University, Istanbul, Turkey
59: Also at Kafkas University, Kars, Turkey
60: Also at Istanbul Bilgi University, Istanbul, Turkey
61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
63: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
64: Also at Utah Valley University, Orem, U.S.A.
65: Also at Beykent University, Istanbul, Turkey
66: Also at Bingol University, Bingol, Turkey
67: Also at Erzincan University, Erzincan, Turkey
68: Also at Sinop University, Sinop, Turkey
69: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
70: Also at Texas A&M University at Qatar, Doha, Qatar
71: Also at Kyungpook National University, Daegu, Korea

JHEP07(2018)075