



Combination of searches for heavy resonances decaying to WW , WZ , ZZ , WH , and ZH boson pairs in proton–proton collisions at $\sqrt{s} = 8$ and 13 TeV

The CMS Collaboration*

CERN, Switzerland

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ABSTRACT

A statistical combination of searches is presented for massive resonances decaying to WW , WZ , ZZ , WH , and ZH boson pairs in proton–proton collision data collected by the CMS experiment at the LHC. The data were taken at centre-of-mass energies of 8 and 13 TeV, corresponding to respective integrated luminosities of 19.7 and up to 2.7 fb^{-1} . The results are interpreted in the context of heavy vector triplet and singlet models that mimic properties of composite-Higgs models predicting W' and Z' bosons decaying to WZ , WW , WH , and ZH bosons. A model with a bulk graviton that decays into WW and ZZ is also considered. This is the first combined search for WW , WZ , WH , and ZH resonances and yields lower limits on masses at 95% confidence level for W' and Z' singlets at 2.3 TeV, and for a triplet at 2.4 TeV. The limits on the production cross section of a narrow bulk graviton resonance with the curvature scale of the warped extra dimension $\tilde{k} = 0.5$, in the mass range of 0.6 to 4.0 TeV, are the most stringent published to date.

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1. Introduction

Hypotheses for physics beyond the standard model (SM) predict the existence of heavy resonances that decay to any combination of two among the massive vector bosons (W or Z , collectively referred to as V) or to a V and the scalar SM Higgs boson (H). Among the considered models are those dealing with warped extra dimensions (WED) [1,2] and composite-Higgs bosons [3–6]. Searches for such VV and VH resonances in different final states have previously been performed by the ATLAS [7–12] and CMS [13–20] experiments at the CERN LHC. As all of these searches have similar sensitivities, a statistical combination of the CMS results is provided to improve the overall result. The current status of heavy diboson searches at CMS is also of interest in this respect, with recent work in the all-jet VV [21] and lepton+jet WH [16] decay channels showing possible enhancements.

The benchmark models considered in combining the results are a heavy vector triplet (HVT) model [22] and the bulk scenario [23–25] (G_{bulk} graviton) in the Randall–Sundrum (RS) WED model [1,2]. The HVT model generalizes a large number of models that predict spin-1 resonances, such as those in composite-Higgs

theories, which can arise as a singlet, either W' or Z' [26–28], or as a V' triplet (where V' represents W' and Z' bosons) [22]. The HVT and G_{bulk} models are considered as benchmarks for diboson resonances with spin 1 ($W' \rightarrow WZ$ or WH , $Z' \rightarrow WW$ or ZH), and spin 2 ($G_{\text{bulk}} \rightarrow WW$ or ZZ), respectively, produced via quark–antiquark annihilation ($q\bar{q} \rightarrow W'$, $q\bar{q} \rightarrow Z'$) and gluon–gluon fusion ($gg \rightarrow G_{\text{bulk}}$).

The analyses included in this statistical combination are based on proton–proton (pp) collision data collected by the CMS experiment [29] at $\sqrt{s} = 8$ and 13 TeV, corresponding to respective integrated luminosities of 19.7 and $2.3\text{--}2.7\text{ fb}^{-1}$. Of the 2.7 fb^{-1} recorded at 13 TeV, the detector was fully operational for 2.3 fb^{-1} , while 0.4 fb^{-1} were collected with only the central part of the detector ($|\eta| < 3$) in optimal condition. The signal corresponds to a narrow charge 0 or 1 resonance with a mass $> 0.6\text{ TeV}$ that decays to any of the two high energy W , Z , or Higgs bosons, where narrow refers to the assumption that the natural relative width is smaller than the typical experimental resolution of 5%, which is true for a large fraction of the parameter space of the reference models. For the mass range under study, the particles emerging from the boson decays are highly collimated, requiring special reconstruction and identification techniques that are in common in these kinds of analyses.

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

Table 1

Summary of the properties of the heavy-resonance models considered in the combination. The polarization of the produced W and Z bosons in these models is primarily longitudinal, as decays to transverse polarizations are suppressed.

Model	Particles	Spin	Charge	Main production mode	Main decay mode
HVT model A, $g_V = 1$	W' singlet	1	± 1	$q\bar{q}'$	$q\bar{q}'$
	Z' singlet	1	0	$q\bar{q}$	$q\bar{q}$
	W' and Z' triplet	1	$\pm 1, 0$	$q\bar{q}', q\bar{q}$	$q\bar{q}', q\bar{q}$
HVT model B, $g_V = 3$	W' singlet	1	± 1	$q\bar{q}'$	WZ, WH
	Z' singlet	1	0	$q\bar{q}$	WW, ZH
	W' and Z' triplet	1	$\pm 1, 0$	$q\bar{q}', q\bar{q}$	WZ, WH, WW, ZH
RS bulk, $\tilde{k} = 0.5$	G_{bulk}	2	0	gg	WW, ZZ

Analyses were performed using all-lepton, lepton+jet, and all-jet final states that include decays of W and Z bosons into charged leptons ($\ell = e$ or μ) and neutrinos (ν), as well as the reconstructed jets evolved from the $q\bar{q}^{(\prime)}$ products of the boson decays. The latter include $W \rightarrow q\bar{q}'$ and $Z \rightarrow q\bar{q}$. The analyses use $H \rightarrow b\bar{b}$ and $H \rightarrow WW \rightarrow q\bar{q}'q\bar{q}'$ decays of the Higgs boson, which are labeled as $b\bar{b}$ or $q\bar{q}'q\bar{q}'$, together with a vector boson decaying to hadrons. Final states with the Higgs boson decaying into a $\tau^+\tau^-$ lepton pair are also considered. In all, we combine results from the following final states: $3\ell\nu$ (8 TeV) [13]; $\ell\ell q\bar{q}$ (8 TeV) [14]; $\ell\nu q\bar{q}$ (8 TeV) [14]; $q\bar{q}q\bar{q}$ (8 TeV) [15]; $\ell\nu b\bar{b}$ (8 TeV) [16]; $q\bar{q}\tau\tau$ (8 TeV) [17]; $q\bar{q}b\bar{b}$ and $6q$ (8 TeV) [18]; $\ell\nu q\bar{q}$ (13 TeV) [19]; $q\bar{q}q\bar{q}$ (13 TeV) [19]; and $\ell\ell b\bar{b}$, $\ell\nu b\bar{b}$, and $\nu\nu b\bar{b}$ (13 TeV) [20]. Since some more forward parts of the detector, which provide information for the calculation of the missing transverse momentum, were not in optimal condition for a fraction of the 2015 data-taking period, the analyses of 13 TeV data in the $\ell\nu q\bar{q}$, $\ell\nu b\bar{b}$, $\ell\ell b\bar{b}$, and $\nu\nu b\bar{b}$ decay channels are based on the dataset corresponding to the integrated luminosity of 2.3 fb^{-1} rather than 2.7 fb^{-1} .

Given the limited experimental jet mass resolution, the $W \rightarrow q\bar{q}'$ and $Z \rightarrow q\bar{q}$ candidates cannot be fully differentiated, and individual analyses can be sensitive to several different interpretations in the same model. For example, the final state $\ell\nu q\bar{q}$ is sensitive to HVT W' decays to a WZ boson pair as well as to Z' decays to WW boson pairs. The sum of contributions from multiple signals with their respective efficiencies is sought in the combination. For this reason, separate interpretations are given below for a vector triplet V' and for vector singlets (W' or Z').

This letter is structured as follows. After a brief introduction to the benchmark models in Section 2, a summary of the analyses entering the combination is given in Section 3. The combining procedure is described in Section 4, and finally the results and summary are provided in Sections 5 and 6.

2. Theoretical models

As indicated above, heavy diboson resonances are expected in a large class of models that attempt to accommodate the difference between the electroweak and Planck scales. We perform the combination in the context of seven benchmark theories formulated to cover different spin, production, and decay options for resonances decaying to VV and VH. The properties of models for spin-1 and spin-2 resonances are briefly discussed in the following two subsections, with benchmark resonances summarized in Table 1. For both spin-1 and spin-2 resonances, the signal cross sections used in this paper are given in Tables A.1 and A.2 of the Appendix.

2.1. Spin-1 resonances

Several extensions of the SM such as composite-Higgs [3–6] and little Higgs [30,31] models can be generalized through a phe-

nomenological Lagrangian that describes the production and decay of spin-1 heavy resonances, such as a charged W' and a neutral Z' , using the HVT model.

The HVT couplings are described in terms of four parameters:

- (i) c_H describes interactions of the new resonance with the Higgs boson or longitudinally polarized SM vector bosons;
- (ii) c_F describes the interactions of the new resonance with fermions;
- (iii) g_V gives the typical strength of the new interaction and
- (iv) m_V is the mass of the new resonance.

The W' and Z' bosons couple to the fermions through the combination of parameters $g^2 c_F / g_V$ and to the H and vector bosons through $g_V c_H$, where g is the $SU(2)_L$ gauge coupling. The Higgs boson is assumed to be part of a Higgs doublet field. Therefore, its dynamics are related to the Goldstone bosons in the same doublet by SM symmetry. Those Goldstone bosons are equivalent to the corresponding longitudinally polarized W and Z bosons in the high energy limit according to the “Equivalence Theorem” [32]. The coupling of the Higgs boson to the W' and Z' resonances can thus be described by the same coupling as used for the longitudinal W and Z bosons.

The production of W' and Z' bosons at hadron colliders is expected to be dominated by the process $q\bar{q}^{(\prime)} \rightarrow W'$ or Z' . Two benchmark models are studied, denoted A and B, that were suggested in Ref. [22]. In model A, weakly coupled vector resonances arise from an extension of the SM gauge group. In model B, the heavy vector triplet is produced by a strong coupling mechanism, as embodied in theories such as in the composite-Higgs model. Consequently, in model A the branching fractions to fermions and SM massive bosons are comparable, whereas in model B, fermionic couplings are suppressed. Therefore, in the context of WW, WZ, ZH, and WH resonance searches, model B is of more interest, since model A is strongly constrained by searches in final states with fermions. In both options, the heavy resonances couple as SM custodial triplets, so that W' and Z' are expected to be approximately degenerate in mass, and the branching fractions $\mathcal{B}(W' \rightarrow WH)$ and $\mathcal{B}(Z' \rightarrow ZH)$ to be comparable to $\mathcal{B}(W' \rightarrow WZ)$ and $\mathcal{B}(Z' \rightarrow WW)$. We consider model A ($c_H = -g^2/g_V^2$, $c_F = -1.3$) with parameter $g_V = 1$, and model B ($c_H = -1$, $c_F = 1$) with parameter $g_V = 3$. A value of $g_V = 3$ is chosen for model B to represent strongly coupled electroweak symmetry breaking, e.g. composite-Higgs models, while assuring small natural widths relative to the experimental resolution. We also consider heavy resonances that couple to W' and Z' as singlets, i.e. expecting only one charged or neutral resonance at a given mass, as summarized in Table 1.

Previous searches for a W' boson decaying into a pair of SM massive bosons (WZ, WH) provide a lower mass limit of 1.8 TeV in model A ($g_V = 1$) and 2.3 TeV in model B ($g_V = 3$), where the

results from 8 TeV data [7–9,13,15,16] are most stringent at low resonance masses, while 13 TeV analyses [10,11,19,20] dominate at higher resonance masses. Searches for a Z' boson decaying into a pair of SM massive bosons (WW, ZH) yield lower mass limits of 1.4 and 2.0 TeV in models A and B, respectively, based on 8 TeV [12,17,18] and 13 TeV [10,11,19,20] data. For a heavy vector triplet resonance, the most stringent lower mass limits of 2.35 TeV (model A) and 2.60 TeV (model B) are obtained from a combination of VV searches at 13 TeV [10].

2.2. Spin-2 resonances

Massive spin-2 resonances can be motivated in WED models through Kaluza–Klein (KK) gravitons [1,2], which correspond to a tower of KK excitations of a spin-2 graviton. The original RS model (here denoted as RS1) can be extended to the bulk scenario (G_{bulk}), which addresses the flavor structure of the SM through the localization of fermions in the warped extra dimension [23–25].

These WED models have two free parameters: the mass of the first mode of the KK graviton, m_G , and the ratio $\tilde{k} \equiv k/\bar{m}_{\text{Pl}}$, where k is the curvature scale of the WED and $\bar{m}_{\text{Pl}} \equiv m_{\text{Pl}}/\sqrt{8\pi}$ is the reduced Planck mass. The constant $\tilde{k}$ acts as the coupling constant of the model, on which the production cross sections and widths of the graviton depend quadratically. For models with $\tilde{k} \lesssim 0.5$, the natural width of the resonance is sufficiently small to be neglected relative to detector resolution.

In the bulk scenario, coupling of the graviton to light fermions is highly suppressed, and the decay into photons is negligible, while in the RS1 scenario, the graviton decays to photon and fermion pairs dominate. In the context of WW and ZZ resonance searches, the bulk scenario is of great interest, since RS1 is already strongly constrained through searches in final states with fermions and photons [33–35]. The production of gravitons at hadron colliders in the bulk scenario is dominated by gluon–gluon fusion, and the branching fraction $\mathcal{B}(G_{\text{bulk}} \rightarrow WW) \approx 2\mathcal{B}(G_{\text{bulk}} \rightarrow ZZ)$. The decay mode into a pair of Higgs bosons, which is not studied in this paper, has a branching fraction comparable to $\mathcal{B}(G_{\text{bulk}} \rightarrow ZZ)$.

For $\tilde{k} = 1$, where the bulk graviton has comparable or larger width than the detector resolution, the most stringent lower limit of 1.1 TeV on its mass is set by a combination of searches in the diboson final state [10]. The most stringent limits on the cross section for narrow bulk graviton resonances for $\tilde{k} \leq 0.5$ are also determined through searches in the diboson final state [14,15,19]; however, the integrated luminosity of the dataset is not large enough to allow us to obtain mass limits for this resonance.

3. Data analyses

3.1. 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, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [29].

3.2. Analysis techniques

This paper combines searches for heavy resonances over a background spectrum described by steeply falling distributions of the invariant mass of two reconstructed W, Z, or Higgs bosons in several decay modes. The $Z \rightarrow \ell\ell$ candidates are reconstructed from electron [36] or muon [37] candidates, while $W \rightarrow \ell\nu$ candidates are formed from the combination of electron or muon candidates with missing transverse momentum [38], where the longitudinal momentum of the neutrino is constrained such that the $\ell\nu$ invariant mass is equal to the W mass [39]. The selection criteria for leptons are such that they ensure disjoint datasets for the searches in lepton+jet final states with 0, 1, and 2 leptons. The contributions from $H \rightarrow \tau\tau$ candidates are constructed from e and μ decays of $\tau \rightarrow \ell\bar{\nu}_\ell\nu_\tau$, and from $\tau \rightarrow q\bar{q}'\nu_\tau$ candidates, in combination with missing transverse momentum. The $W \rightarrow q\bar{q}'$, $Z \rightarrow q\bar{q}$, $H \rightarrow b\bar{b}$, and $H \rightarrow WW \rightarrow q\bar{q}'q\bar{q}'$ candidates are reconstructed from QCD-evolved jets [40], as described in detail in the following.

Since the W, Z, and Higgs bosons originating from decays of heavy resonances tend to have large Lorentz boosts, their decay products have a small angular separation, requiring special reconstruction techniques. For highly boosted W, Z, and Higgs bosons decaying to electron, muon, and tau candidates, identification and isolation requirements are formulated such that any other nearby reconstructed lepton is excluded from the computation of quantities used for identification and isolation. This method retains high identification efficiency, while maintaining the same misidentification probability when two leptons are very collimated.

When W, Z, or Higgs bosons decay to quark–antiquark pairs, the showers of hadrons originating from these pairs merge into single large-radius jets that are reconstructed using two jet algorithms [41]. The Cambridge–Aachen [42] and the anti- k_T [43] algorithms with a distance parameter of 0.8 are used for the 8 and 13 TeV data, respectively, providing comparable jet reconstruction performance. Jet momenta are corrected for additional pp collisions (pileup) that overlap the event of interest, as specified in Ref. [44]. To discriminate against quark and gluon jet background, selections on the pruned jet mass [45,46] and the N-subjettiness ratio τ_2/τ_1 [47] are applied. The jet pruning algorithm reclusters the jet constituents, while applying additional requirements to eliminate soft, large-angle QCD radiation that increases the jet mass relative to the initial V or H, quark, or gluon jet mass. The variable τ_2/τ_1 indicates the probability of a jet to be composed of two hard subjets rather than just one hard jet. A jet is a candidate V jet if its pruned mass, m_{jet} , is compatible within resolution with the W or Z mass. The specific selection depends on the analysis channel. For example, the 13 TeV analyses define the window in the range $65 < m_{\text{jet}} < 105$ GeV. In the 13 TeV data, to further enhance analysis sensitivity to different signal hypotheses, two distinct categories enriched in W or Z bosons are defined through two disjoint ranges in m_{jet} . Sensitivity is then further improved in both 8 and 13 TeV data by categorizing events according to the τ_2/τ_1 variable into a low purity (LP) and a high purity (HP) category. Although the HP category dominates the total sensitivity of the analyses, the LP category is retained, since it provides improved sensitivity for high-mass resonances. The optimal selection criteria for m_{jet} and τ_2/τ_1 depend on signal and background yields and therefore differ across analyses. As a consequence, the efficiencies for identifying W and Z bosons can be different. The total efficiency of the m_{jet} and τ_2/τ_1 HP selection criteria for a jet with p_T of 1 TeV originating from the decay of a heavy resonance ranges from 45% to 75%, with a mistagging rate of 2% to 7% [40,48].

A category enriched in Higgs bosons is identified through a pruned-jet mass window around the Higgs boson mass, ensuring a

Table 2

Summary of signal efficiencies in analysis channels for 2TeV resonances in the different models under study. For analyses that define high-purity (HP) and low-purity (LP) categories, both efficiencies are quoted in the form HP/LP. Signal efficiencies are given in percent, and include the SM branching fractions of the bosons to the final state in the analysis channel, effects from detector acceptance, as well as reconstruction and selection efficiencies. Dashes indicate negligible signal contributions that are not considered in the overall combination. Channels marked with an asterisk have been reinterpreted for this combination, as described in the text later.

Channel	Ref.	Efficiency [%]					
		HVT				RS bulk	
		W'		Z'		G _{bulk}	
		WZ	WH	WW	ZH	WW	ZZ
$3\ell\nu$ (8 TeV)	[13]	0.6	–	–	–	–	–
$\ell\ell q\bar{q}$ (8 TeV)	[14]	*1.1/–	–	–	*0.2/–	–	3.0/1.0
$\ell\nu q\bar{q}$ (8 TeV)	[14]	*4.8/–	–	*9.4/–	–	10.6/7.1	–
$q\bar{q}q\bar{q}$ (8 TeV)	[15]	5.9/5.5	*0.8/0.7	*5.7/5.3	*0.8/0.7	3.8/3.1	5.7/4.2
$\ell\nu b\bar{b}$ (8 TeV)	[16]	–	0.9	–	–	–	–
$q\bar{q}\tau\tau$ (8 TeV)	[17]	–	*1.2	–	1.3	–	–
$q\bar{q}b\bar{b}/6q$ (8 TeV)	[18]	–	3.0/1.8	–	1.7/1.1	–	–
$\ell\nu q\bar{q}$ (13 TeV)	[19]	10.2	1.7	19.4	–	18.1	–
$q\bar{q}q\bar{q}$ (13 TeV)	[19]	9.7/12.3	1.8/2.5	8.2/10.6	1.9/2.6	8.7/12.4	11.0/13.5
$\ell\ell b\bar{b}$ (13 TeV)	[20]	–	–	–	1.5	–	–
$\ell\nu b\bar{b}$ (13 TeV)	[20]	–	4.0	–	–	–	–
$\nu\nu b\bar{b}$ (13 TeV)	[20]	–	–	–	4.2	–	–

separate selection relative to V jet identification. For example, the searches in the $\nu\nu b\bar{b}$, $\ell\nu b\bar{b}$, and $\ell\ell b\bar{b}$ final states at 13 TeV [20] define the window in the range $105 < m_{\text{jet}} < 135$ GeV. In addition, for the $b\bar{b}$ final state, further discrimination against background is gained by applying a b tagging algorithm [49–51] to the two individual subjects into which the H-jet candidate is split. The b tagging algorithm discriminates jets originating from b quarks against those originating from lighter quarks or gluons. To distinguish $H \rightarrow WW \rightarrow q\bar{q}'q\bar{q}'$ jets from background, a technique similar to V jet identification is applied using the τ_4/τ_2 N-subjettiness ratio [18]. The selection efficiencies for each signal and channel are summarized in Table 2.

In all-jet final states [15,18,19], the background expectation is dominated by multijet production, which is estimated through a fit of a signal+background hypothesis to the data, where the background is described by a smoothly falling parametric function. In lepton+jet ($\ell\nu q\bar{q}$, $\ell\ell q\bar{q}$, $\nu\nu b\bar{b}$, $\ell\nu b\bar{b}$, $\ell\ell b\bar{b}$, and $q\bar{q}\tau\tau$) final states [14,16,17,19,20], the dominant backgrounds from V+jets production are estimated using data in the sidebands of m_{jet} . The contamination from WH and ZH resonances decaying into lepton+jet final states in the high sideband defined in the $\ell\nu q\bar{q}$ and $\ell\ell q\bar{q}$ analyses has been evaluated considering the cross sections excluded by the $\ell\nu b\bar{b}$ and $\ell\ell b\bar{b}$ searches. The impact of this contamination on the resulting background estimate is found to be negligible. In all-lepton final states [13], the dominant background from SM diboson production is estimated using simulated events.

3.3. Reinterpretations

In this subsection, we discuss analyses that have been reinterpreted for this paper since not all signal models presented in this combination were considered in the originally published analyses.

In the searches for new heavy resonances decaying into pairs of vector bosons in lepton+jet ($\ell\nu q\bar{q}$ and $\ell\ell q\bar{q}$) final states [14] at $\sqrt{s} = 8$ TeV, 95% confidence level (CL) exclusion limits are obtained for the production cross section of a bulk graviton. Using a parametrization for the reconstruction efficiency as a function of W and Z boson kinematics, a reinterpretation is performed in the context of the HVT model described in Section 2.1, which predicts the production of charged and neutral spin-1 resonances decaying preferably to WW and WZ pairs. This reinterpretation is obtained

by rescaling the bulk-graviton signal efficiencies by factors taking into account the different kinematics of W and Z bosons from W' and Z' production relative to graviton production. The scale factors are obtained for each value of the sought resonance by means of the tables published in Ref. [14]. Signal shapes are unchanged by the combination process, and the effect of the scaling factor on the signal efficiency takes into account the differences in acceptance for the various signals and masses. Since the parametrization is restricted to the HP category of the analyses, the LP category is not used for the HVT W' and Z' interpretations of these channels. The m_{jet} window that defines the signal regions of the analysis channels is chosen such that the $\ell\nu q\bar{q}$ channel is sensitive to both the charged and the neutral resonances predicted in the HVT model. This additional signal efficiency is taken into account in the combination presented in Section 5.2.

The searches for heavy resonances decaying into pairs of vector bosons in the lepton+jet ($\ell\nu q\bar{q}$ and $\ell\ell q\bar{q}$) [14,19] and all-jet ($q\bar{q}q\bar{q}$) [15,19] final states at 8 and 13 TeV are also sensitive to the WH and ZH signatures, since a small fraction of jets initiated by Higgs bosons have a pruned jet mass in the W or Z range. These searches are therefore reinterpreted for WH and ZH signals, to profit from this additional sensitivity. The efficiencies of these additional signals for the analyses selections are calculated and indicated in Table 2 with an asterisk. This contribution is found to be negligible for the search in the $\ell\nu q\bar{q}$ final state at 8 TeV, as in this analysis events are rejected if the boson jet satisfies b tagging requirements. The fraction of jets initiated by Z bosons that have a pruned jet mass in the Higgs boson mass range is found to be negligible and therefore this contribution is not taken into account in the combination.

The search for resonances in the $q\bar{q}\tau\tau$ final state [18] is optimized for a Z' resonance decaying to a ZH pair. However, given the large m_{jet} window ($65 < m_{\text{jet}} < 105$ GeV) used to tag the $Z \rightarrow q\bar{q}$ decays, this analysis channel is also sensitive to the production of the charged spin-1 W' resonance decaying to a WH pair predicted in HVT models. Similarly, the search in the all-jet final state with 8 TeV data is optimized for the $W' \rightarrow WZ$ signal hypothesis, while being sensitive as well to a Z' resonance decaying to WW. This overlap is taken into account in the statistical combination described in Section 5.2. For all the other analyses, limits have been

Table 3

Correlation across analyses of systematic uncertainties in the signal prediction affecting the event yield in the signal region and the reconstructed diboson invariant mass distribution. A “yes” signifies 100% correlation, and “no” means uncorrelated.

Source	Quantity	8 and 13 TeV	e and μ	HP and LP	W-, Z-, and H-enriched
Lepton trigger	yield	no	no	yes	yes
Lepton identification	yield	no	no	yes	yes
Lepton momentum scale	yield, shape	no	no	yes	yes
Jet energy scale	yield, shape	no	yes	yes	yes
Jet energy resolution	yield, shape	no	yes	yes	yes
Jet mass scale	yield	no	yes	yes	yes
Jet mass resolution	yield	no	yes	yes	yes
b tagging	yield	no	yes	yes	yes
W tagging τ_{21} (HP/LP)	yield	no	yes	yes	yes
Integrated luminosity	yield	no	yes	yes	yes
Pileup	yield	no	yes	yes	yes
PDF	yield	yes	yes	yes	yes
μ_f and μ_r scales	yield	yes	yes	yes	yes

previously obtained in the same models as those considered in this letter and a reinterpretation is not needed.

4. Combination procedure

We search for a peak on top of a falling background spectrum by means of a fit to the data. The likelihood function is constructed using the diboson invariant mass distribution in data, the background prediction, and the resonant line-shape, to assess the presence of a potential diboson resonance. We define the likelihood function $\mathcal{L}$ as

$$\mathcal{L}(\text{data} | \mu s(\theta) + b(\theta)) = \mathcal{P}(\text{data} | \mu s(\theta) + b(\theta)) p(\tilde{\theta} | \theta), \quad (1)$$

where “data” stands for the observed data; θ represents the full ensemble of nuisance parameters; $s(\theta)$ and $b(\theta)$ are the expected signal and background yields; μ is a scale factor for the signal strength; $\mathcal{P}(\text{data} | \mu s(\theta) + b(\theta))$ is the product of Poisson probabilities over all bins of diboson invariant mass distributions in all channels (or over all events for channels with unbinned distributions); and $p(\tilde{\theta} | \theta)$ is the probability density function for all nuisance parameters to measure a value $\tilde{\theta}$ given its true value θ [52]. After maximizing the likelihood function, the best-fit value of $\mu = \sigma_{\text{best-fit}} / \sigma_{\text{theory}}$ corresponds therefore to the ratio of the best-fit signal cross section $\sigma_{\text{best-fit}}$ to the predicted cross section σ_{theory} , assuming that all branching fractions are as predicted by the relevant signal models.

The treatment of the background in the maximum likelihood fit depends on the analysis channel. In the $q\bar{q}q\bar{q}$, $q\bar{q}b\bar{b}$, and $6q$ analyses, the parameters in the background function are left floating in the fit, such that the background prediction is obtained simultaneously with μ , in each hypothesis [15]. In the remaining analyses ($\ell\nu q\bar{q}$, $\ell\ell q\bar{q}$, $\ell\ell b\bar{b}$, $\ell\nu b\bar{b}$, $\nu\nu b\bar{b}$), the background is estimated using sidebands in data, and the uncertainties related to its parametrized distribution are treated as nuisance parameters constrained through Gaussian probability density functions in the fit [14]. The likelihoods from all analysis channels are combined.

The asymptotic approximation [53] of the CL_s criterion [54,55] is used to obtain limits on the signal scale factor μ that take into account the ratio of the theoretical predictions for the production cross sections at 8 and 13 TeV.

Systematic uncertainties in the signal and background yields are treated as nuisance parameters constrained through log-normal probability density functions. All such parameters are profiled (re-fitted as a function of the parameter of interest μ) in the maximization of the likelihood function. When the likelihoods from different analysis channels are combined, the correlation of systematic effects across those channels is taken into account by treating

the uncertainties as fully correlated (associated with the same nuisance parameter) or fully uncorrelated (associated with different nuisance parameters). Table 3 summarizes which uncertainties are treated as correlated among 8 and 13 TeV analyses, e and μ channels, HP and LP categories, and mass categories enriched in W, Z, and Higgs bosons in the combination. Additional categorization within individual analyses is described in their corresponding papers. The nuisance parameters treated as correlated between 8 and 13 TeV analyses are those related to the parton distribution functions (PDFs) and the choice of the factorization (μ_f) and renormalization (μ_r) scales used to estimate the signal cross sections. The signal cross sections and their associated uncertainties are reevaluated for this combination at both 8 and 13 TeV, estimating thereby their full impact on the expected signal yield rather than just the impact on the signal acceptance. The PDF uncertainties are evaluated using the NNPDF 3.0 [56] PDFs. The uncertainty related to the choice of μ_f and μ_r scales is evaluated following [57,58] by changing the default choice of scales in six combinations of (μ_f, μ_r) by factors of (0.5, 0.5), (0.5, 1), (1, 0.5), (2, 2), (2, 1), and (1, 2). The experimental uncertainties are all treated as uncorrelated between 8 and 13 TeV analyses. The case where the most important uncertainties are treated as fully correlated among 8 and 13 TeV analyses has been studied and found to have negligible impact on the results. After the combined fit, no nuisance parameter was found to differ significantly from its expectation and from the fit result in individual analyses.

5. Results

We evaluate the combined significance of the 8 and 13 TeV CMS searches for all signal hypotheses. The ATLAS Collaboration reported an excess in the all-jet $VV \rightarrow q\bar{q}q\bar{q}$ search, corresponding to a local significance of 3.4 standard deviations (s.d.) for a W' resonance with a mass of 2 TeV [21]. Similarly, the CMS experiment reported a local deviation of 2.2 s.d. in the lepton+jet $WH \rightarrow \ell\nu b\bar{b}$ search for a W' resonance with a mass of 1.8 TeV [16]. The present combination does not confirm these small excesses (within the context of the models considered), as the highest combined significance in the mass range of the reported excesses is found to be for a W' resonance at 1.8 TeV with a local significance of 0.8 standard deviations.

In the following, we present for each channel 95% CL exclusion limits on the signal strength μ in Eq. (1), expressed as the exclusion limit on the ratio $\sigma_{95\%} / \sigma_{\text{theory}}$ of the signal cross section to the predicted cross section, assuming that all branching fractions are as predicted by the relevant signal models.

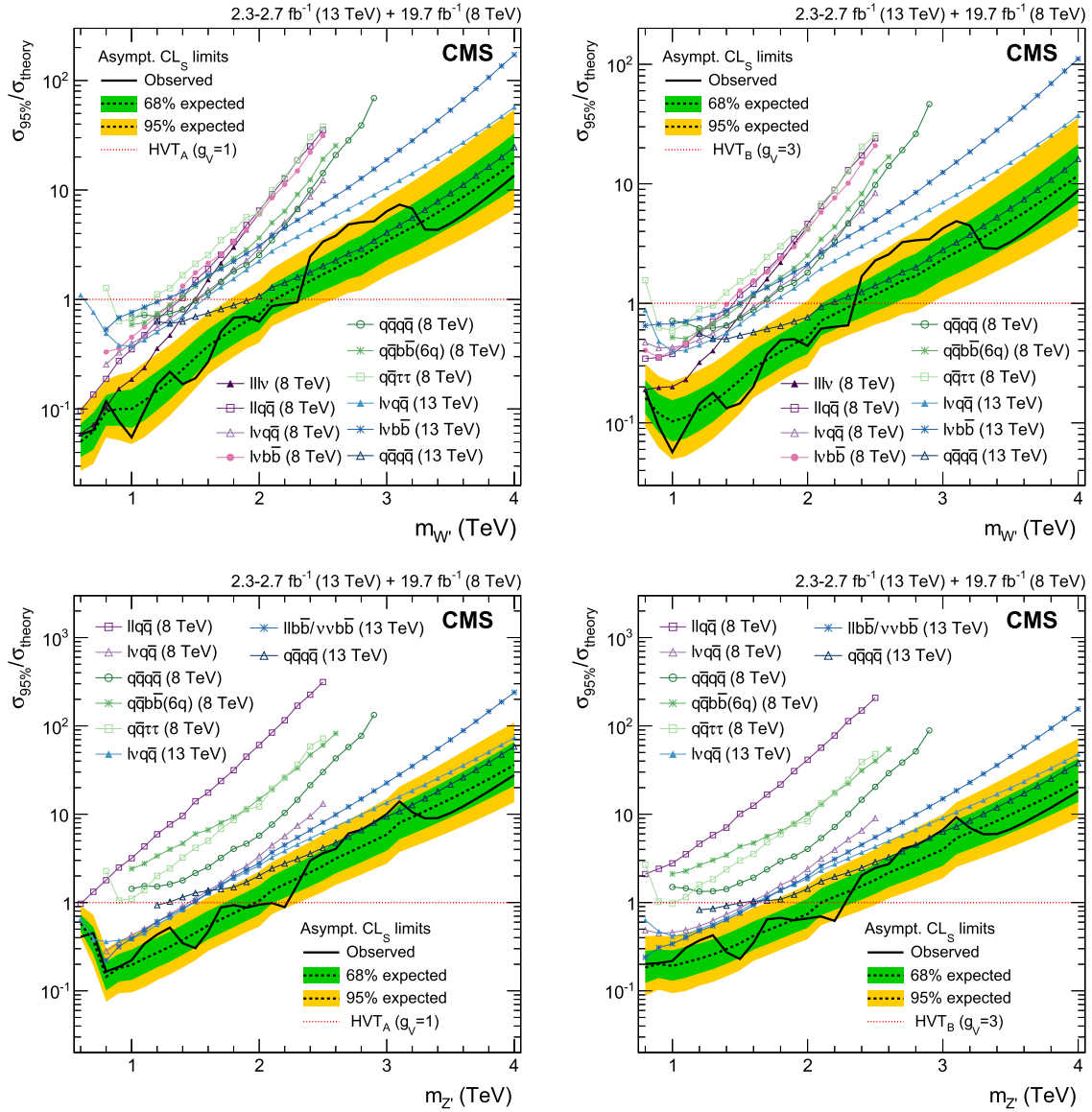


Fig. 1. Exclusion limits at 95% CL for HVT models A (left) and B (right) on the signal strengths for the singlets $W' \rightarrow WZ$ and WH (upper), and $Z' \rightarrow WW$ and ZH (lower) as a function of the resonance mass, obtained by combining the 8 and 13 TeV analyses. The signal strength is expressed as the ratio $\sigma_{95\%}/\sigma_{\text{theory}}$ of the signal cross section to the predicted cross section, assuming that all branching fractions are as predicted by the relevant signal models. The curves with symbols refer to the expected limits obtained by the analyses that are inputs to the combinations. The thick solid (dashed) line represents the combined observed (expected) limits.

Table 4

Lower limits at 95% CL on the resonance masses in HVT models A and B. The 68% quantiles defined as the intervals containing the central 68% of the distribution of limits expected under the background-only hypothesis are also reported.

Model	Observed limit [TeV]	Expected limit [TeV]	68% quantile
Singlet W' (model A)	2.3	2.1	[1.9, 2.3]
Singlet Z' (model A)	2.2	2.0	[1.8, 2.2]
Triplet W' and Z' (model A)	2.4	2.4	[2.1, 2.7]
Singlet W' (model B)	2.3	2.4	[2.1, 2.7]
Singlet Z' (model B)	2.3	2.1	[1.9, 2.3]
Triplet W' and Z' (model B)	2.4	2.6	[2.3, 2.9]

5.1. Limits on W' and Z' singlets

Fig. 1 (upper) shows a comparison and combination of results obtained in the 8 and 13 TeV searches for a W' singlet resonance in HVT models A and B. The 95% CL exclusion limits on the sig-

nal strengths are given for the mass ranges $0.6 < m_{W'} < 4.0$ TeV for model A and $0.8 < m_{W'} < 4.0$ TeV for model B. Table 4 summarizes the lower limits on the resonance masses. Below mass values of ≈ 1.4 TeV, the most sensitive channel is the $3\ell\nu$ final state at 8 TeV. At higher masses, the $qqqq$ search at 13 TeV dominates the

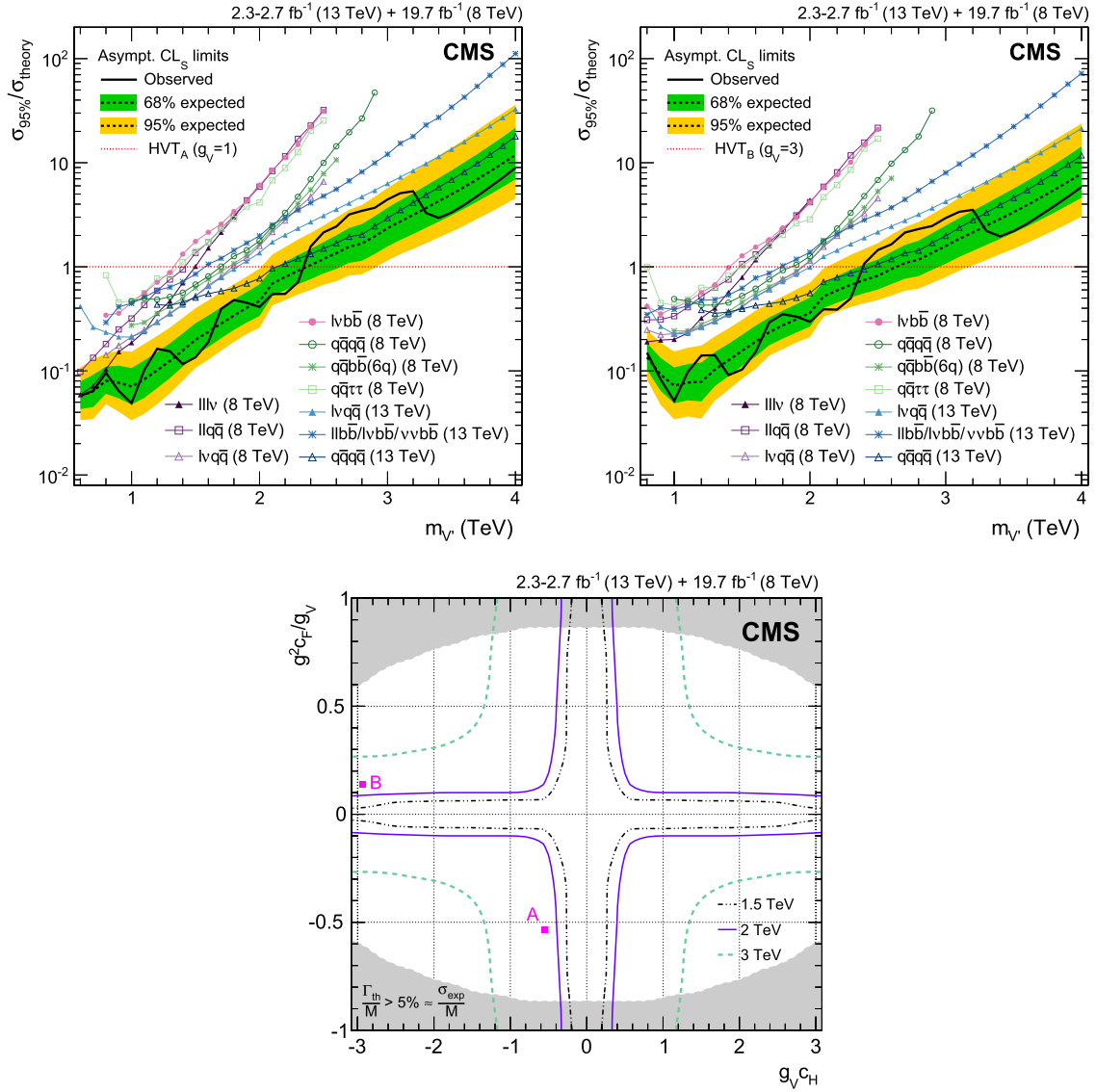


Fig. 2. Exclusion limits at 95% CL on the signal strengths in HVT models A (upper left) and B (upper right) for the triplet V' , as a function of the resonance mass, obtained by combining the 8 and 13 TeV diboson searches. The signal strength is expressed as the ratio $\sigma_{95\%}/\sigma_{\text{theory}}$ of the signal cross section to the predicted cross section, assuming that all branching fractions are as predicted by the relevant signal models. In the upper plots, the curves with symbols refer to the expected limits obtained by the analyses that are inputs to the combinations. The thick solid (dashed) line represents the combined observed (expected) limits. In the lower plot, exclusion regions in the plane of the HVT-model couplings (g_{VCH} , g^2_{CF}/g_V) for three resonance masses of 1.5, 2.0, and 3.0 TeV, where g denotes the weak gauge coupling. The points A and B of the benchmark models used in the analysis are also shown. The boundaries of the regions excluded in this search are indicated by the solid, dashed, and dashed-dotted lines. The areas indicated by the solid shading correspond to regions where the resonance width is predicted to be more than 5% of the resonance mass, in which the narrow-resonance assumption is not satisfied.

sensitivity. The overall sensitivity benefits from the combination for resonance masses up to ≈ 2 TeV, lowering the exclusion limit on the cross section by up to a factor of ≈ 3 relative to the most sensitive single channel, as several channels of similar sensitivity are combined in this mass range. Above resonance masses of 2 TeV, the 8 TeV analyses do not have significant sensitivity compared to the $q\bar{q}q\bar{q}$ search at 13 TeV.

Fig. 1 (lower) shows the analogous results for a Z' singlet resonance for final states of WW and ZH in the HVT models A and B. The $l\nu q\bar{q}$ channel at 8 TeV and the $q\bar{q}q\bar{q}$, $l\nu q\bar{q}$, $l\bar{l}b\bar{b}$, and $\nu\nu b\bar{b}$ channels at 13 TeV dominate the sensitivity over the whole range, with 8 and 13 TeV analyses giving almost equal contributions for masses below 2 TeV. Above this value, the sensitivity arises mainly from the 13 TeV data. As in the W' analyses, the mass limit is not affected by the combination compared to what is obtained from the 13 TeV searches.

5.2. Limits on the heavy vector triplet V'

Fig. 2 (upper) shows the comparison and combination of the results obtained in the 8 and 13 TeV searches for resonances in a heavy vector triplet. The lower limits on the resonance masses for HVT models A and B are quoted in Table 4. As for the W' and Z' cases, the observed mass limit of 2.4 TeV for both models obtained combining the 8 and 13 TeV searches is dominated essentially by the 13 TeV analyses alone.

Fig. 2 (lower) displays a scan of the coupling parameters and the corresponding observed 95% CL exclusion contours in the HVT models from the combination of the 8 and 13 TeV analyses. The parameters are defined as g_{VCH} and g^2_{CF}/g_V in terms of the coupling strengths of the new resonance to the H and V, and to fermions, respectively, given in Section 2.1. The range is limited by the assumption that the resonance sought is narrow. The shaded

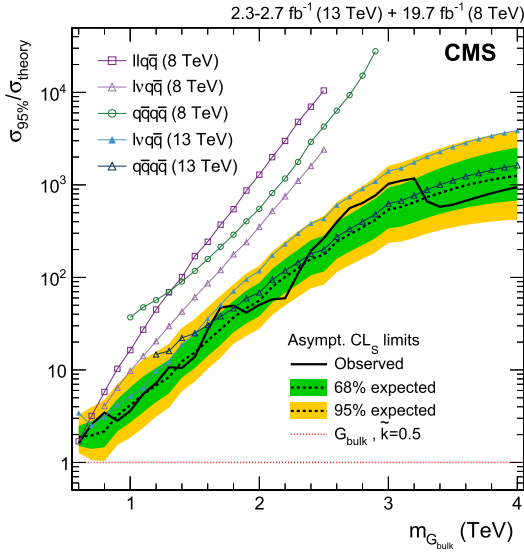


Fig. 3. Exclusion limits at 95% CL on the signal strength in the bulk graviton model with $\tilde{k} = 0.5$, as a function of the resonance mass, obtained by combining the 8 and 13 TeV diboson searches. The signal strength is expressed as the ratio $\sigma_{95\%}/\sigma_{\text{theory}}$ of the signal cross section to the predicted cross section, assuming that all branching fractions are as predicted by the relevant signal models. The curves with symbols refer to the expected limits obtained by the analyses that are inputs to the combination. The thick solid (dashed) line represents the combined observed (expected) limits.

area represents the region where the theoretical width is larger than the experimental resolution of the searches, and therefore where the narrow-resonance assumption is not satisfied. This contour is defined by a predicted resonance width, relative to its mass, of 5%, corresponding to the best detector resolution of the searches.

5.3. Limits on the bulk graviton

Fig. 3 shows a comparison and combination of results obtained in the 8 and 13 TeV VV searches in the bulk graviton model with $\tilde{k} = 0.5$. The sensitivity arises mainly from the 13 TeV $q\bar{q}q\bar{q}$ and $\ell\nu q\bar{q}$ channels. The 13 TeV searches supersede the 8 TeV combination down to masses of 0.7 TeV, since in this model, the signal is produced via gluon–gluon fusion, in contrast to the $q\bar{q}$ annihilation process responsible for the production of HVT resonances. The combination yields the most stringent limits to date on signal strengths for narrow bulk graviton resonances ($\tilde{k} = 0.5$) in the mass range from 0.6 to 4.0 TeV.

6. Summary

A statistical combination of searches for massive narrow resonances decaying to WW, ZZ, WZ, WH, and ZH boson pairs in the mass range 0.6–4.0 TeV has been presented. The searches are based on proton–proton collision data collected by the CMS experiment at centre-of-mass energies of 8 and 13 TeV, corresponding to integrated luminosities of 19.7 and up to 2.7 fb^{-1} , respectively. The results of the searches and of the combination are interpreted in the context of heavy vector singlet and triplet models predicting W' and Z' bosons decaying to WZ, WH, WW, and ZH, and a model with a bulk graviton that decays into WW and ZZ. The small excesses observed with 8 TeV data by the ATLAS and CMS experiments [16,21] at 1.8–2.0 TeV are not confirmed by the analyses performed with 13 TeV data. This is the first combined search for WW, WZ, WH, and ZH resonances and yields 95% confidence level lower limits in the heavy vector triplet model B on

the masses of W' and Z' singlets at 2.3 TeV, and on a heavy vector triplet at 2.4 TeV. The limits on the production cross section of a narrow bulk graviton resonance with the curvature scale of the warped extra dimension $\tilde{k} = 0.5$, in the mass range of 0.6 to 4.0 TeV, are the most stringent published to date. The statistical combination of VV and VH resonance searches in several distinct final states was found to yield a significant gain in sensitivity and therefore represents a powerful tool for future resonance searches with the large expected diboson event data sample at the LHC.

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Appendix A. Signal cross section tables

Table A.1

Signal cross sections in units of fb at 8 TeV center-of-mass energy. HVT model A and model B cross sections are quoted in the form $\sigma_{\text{Model A}}/\sigma_{\text{Model B}}$.

Mass [TeV]	Cross section at 8 TeV [fb]				
	HVT A/B				RS bulk
	W'		Z'		G _{bulk}
	WZ	WH	WW	ZH	WW ZZ
0.6	1786/–	1377/–	874/–	746/–	80.7 42.4
0.8	483/262	413/337	235/131	213/180	12.3 6.32
1.0	168/155	151/171	80.0/74.6	74.9/85.6	2.75 1.41
1.5	19.4/24.8	18.4/25.5	8.85/11.4	8.58/11.9	0.142 0.0719
2.0	2.98/4.19	2.89/4.25	1.34/1.89	1.31/1.93	0.0126 0.00627
2.5	0.494/0.725	0.485/0.731	0.227/0.333	0.224/0.338	0.00140 0.000709
3.0	0.0801/0.120	0.0791/0.121	0.0395/0.0594	0.0392/0.0600	– –

Table A.2

Signal cross sections in units of fb at 13 TeV center-of-mass energy. HVT model A and model B cross sections are quoted in the form $\sigma_{\text{Model A}}/\sigma_{\text{Model B}}$.

Mass [TeV]	Cross section at 13 TeV [fb]				
	HVT A/B				RS bulk
	W'		Z'		G _{bulk}
	WZ	WH	WW	ZH	WW ZZ
0.6	4170/–	3215/–	2097/–	1789/–	406.8 203.4
0.8	1258/680	1074/878	635/354	576/485	76.1 38.0
1.0	492/464	443/501	247/229	231/264	20.5 10.2
1.5	81.7/105	77.8/108	39.8/51.1	38.6/53.6	1.80 0.901
2.0	19.8/27.9	19.2/28.3	9.32/13.1	9.16/13.5	0.240 0.120
2.5	5.70/8.37	5.60/8.44	2.61/3.84	2.58/3.90	0.0449 0.0224
3.0	1.79/2.68	1.77/2.70	0.808/1.21	0.801/1.23	0.00982 0.00491
3.5	0.584/0.888	0.579/0.891	0.264/0.402	0.262/0.405	0.00420 0.00210
4.0	0.192/0.296	0.191/0.296	0.0887/0.136	0.0883/0.137	0.00244 0.00122

References

- [1] L. Randall, R. Sundrum, A large mass hierarchy from a small extra dimension, Phys. Rev. Lett. 83 (1999) 3370, <http://dx.doi.org/10.1103/PhysRevLett.83.3370>, arXiv:hep-ph/9905221.
- [2] L. Randall, R. Sundrum, An alternative to compactification, Phys. Rev. Lett. 83 (1999) 4690, <http://dx.doi.org/10.1103/PhysRevLett.83.4690>, arXiv:hep-th/9906064.
- [3] B. Bellazzini, C. Csáki, J. Serra, Composite Higgses, Eur. Phys. J. C 74 (2014) 2766, <http://dx.doi.org/10.1140/epjc/s10052-014-2766-x>, arXiv:1401.2457.
- [4] R. Contino, D. Marzocca, D. Pappadopulo, R. Rattazzi, On the effect of resonances in composite Higgs phenomenology, J. High Energy Phys. 10 (2011) 081, [http://dx.doi.org/10.1007/JHEP10\(2011\)081](http://dx.doi.org/10.1007/JHEP10(2011)081), arXiv:1109.1570.
- [5] D. Marzocca, M. Serone, J. Shu, General composite Higgs models, J. High Energy Phys. 08 (2012) 013, [http://dx.doi.org/10.1007/JHEP08\(2012\)013](http://dx.doi.org/10.1007/JHEP08(2012)013), arXiv:1205.0770.
- [6] D. Greco, D. Liu, Hunting composite vector resonances at the LHC: naturalness facing data, J. High Energy Phys. 12 (2014) 126, [http://dx.doi.org/10.1007/JHEP12\(2014\)126](http://dx.doi.org/10.1007/JHEP12(2014)126), arXiv:1410.2883.
- [7] ATLAS Collaboration, Combination of searches for WW, WZ, and ZZ resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Phys. Lett. B 755 (2016) 285, <http://dx.doi.org/10.1016/j.physletb.2016.02.015>, arXiv:1512.05099.
- [8] ATLAS Collaboration, Search for production of WW/WZ resonances decaying to a lepton, neutrino and jets in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Eur. Phys. J. C 75 (2015) 209, <https://doi.org/10.1140/epjc/s10052-015-3425-6>, arXiv:1503.04677, Erratum: <https://doi.org/10.1140/epjc/s10052-015-3593-4>.
- [9] ATLAS Collaboration, Search for WZ resonances in the fully leptonic channel using pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Phys. Lett. B 737 (2014) 223, <http://dx.doi.org/10.1016/j.physletb.2014.08.039>, arXiv:1406.4456.
- [10] ATLAS Collaboration, Searches for heavy diboson resonances in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 09 (2016) 173, [http://dx.doi.org/10.1007/JHEP09\(2016\)173](http://dx.doi.org/10.1007/JHEP09(2016)173), arXiv:1606.04833.
- [11] ATLAS Collaboration, Search for new resonances decaying to a W or Z boson and a Higgs boson in the $\ell^+\ell^-\text{b}\bar{\text{b}}$, $\ell\nu\text{b}\bar{\text{b}}$, and $\nu\bar{\nu}\text{b}\bar{\text{b}}$ channels with pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B 765 (2017) 32, <http://dx.doi.org/10.1016/j.physletb.2016.11.045>, arXiv:1607.05621.
- [12] ATLAS Collaboration, Search for a new resonance decaying to a W or Z boson and a Higgs boson in the $\ell\ell/\ell\nu/\nu\nu + \text{b}\bar{\text{b}}$ final states with the ATLAS detector, Eur. Phys. J. C 75 (2015) 263, <http://dx.doi.org/10.1140/epjc/s10052-015-3474-x>, arXiv:1503.08089.
- [13] CMS Collaboration, Search for new resonances decaying via WZ to leptons in proton–proton collisions at $\sqrt{s} = 8$ TeV, Phys. Lett. B 740 (2015) 83, <http://dx.doi.org/10.1016/j.physletb.2014.11.026>, arXiv:1407.3476.
- [14] CMS Collaboration, Search for massive resonances decaying into pairs of boosted bosons in semi-leptonic final states at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 08 (2014) 174, [http://dx.doi.org/10.1007/JHEP08\(2014\)174](http://dx.doi.org/10.1007/JHEP08(2014)174), arXiv:1405.3447.
- [15] CMS Collaboration, Search for massive resonances in dijet systems containing jets tagged as W or Z boson decays in pp collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 08 (2014) 173, [http://dx.doi.org/10.1007/JHEP08\(2014\)173](http://dx.doi.org/10.1007/JHEP08(2014)173), arXiv:1405.1994.
- [16] CMS Collaboration, Search for massive WH resonances decaying into the $\ell\nu\text{b}\bar{\text{b}}$ final state at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C 76 (2016) 237, <http://dx.doi.org/10.1140/epjc/s10052-016-4067-z>, arXiv:1601.06431.
- [17] CMS Collaboration, Search for narrow high-mass resonances in proton–proton collisions at $\sqrt{s} = 8$ TeV decaying to a Z and a Higgs boson, Phys. Lett. B 748 (2015) 255, <http://dx.doi.org/10.1016/j.physletb.2015.07.011>, arXiv:1502.04994.
- [18] CMS Collaboration, Search for a massive resonance decaying into a Higgs boson and a W or Z boson in hadronic final states in proton–proton collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 02 (2016) 145, [http://dx.doi.org/10.1007/JHEP02\(2016\)145](http://dx.doi.org/10.1007/JHEP02(2016)145), arXiv:1506.01443.
- [19] CMS Collaboration, Search for massive resonances decaying into WW, WZ or ZZ bosons in proton–proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 03 (2017) 162, [http://dx.doi.org/10.1007/JHEP03\(2017\)162](http://dx.doi.org/10.1007/JHEP03(2017)162), arXiv:1612.09159.
- [20] 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, <http://dx.doi.org/10.1016/j.physletb.2017.02.040>, arXiv:1610.08066.
- [21] ATLAS Collaboration, Search for high-mass diboson resonances with boson-tagged jets in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, J. High Energy Phys. 12 (2015) 055, [http://dx.doi.org/10.1007/JHEP12\(2015\)055](http://dx.doi.org/10.1007/JHEP12(2015)055), arXiv:1506.00962.
- [22] D. Pappadopulo, A. Thamm, R. Torre, A. Wulzer, Heavy vector triplets: bridging theory and data, J. High Energy Phys. 09 (2014) 060, [http://dx.doi.org/10.1007/JHEP09\(2014\)060](http://dx.doi.org/10.1007/JHEP09(2014)060), arXiv:1402.4431.

- [23] K. Agashe, H. Davoudiasl, G. Perez, A. Soni, Warped gravitons at the LHC and beyond, *Phys. Rev. D* 76 (2007) 036006, <http://dx.doi.org/10.1103/PhysRevD.76.036006>, arXiv:hep-ph/0701186.
- [24] A.L. Fitzpatrick, J. Kaplan, L. Randall, L.-T. Wang, Searching for the Kaluza–Klein graviton in bulk RS models, *J. High Energy Phys.* 09 (2007) 013, <http://dx.doi.org/10.1088/1126-6708/2007/09/013>, arXiv:hep-ph/0701150.
- [25] O. Antipin, D. Atwood, A. Soni, Search for RS gravitons via $W_L W_L$ decays, *Phys. Lett. B* 666 (2008) 155, <http://dx.doi.org/10.1016/j.physletb.2008.07.009>, arXiv:0711.3175.
- [26] C. Grojean, E. Salvioni, R. Torre, A weakly constrained W' at the early LHC, *J. High Energy Phys.* 07 (2011) 002, [http://dx.doi.org/10.1007/JHEP07\(2011\)002](http://dx.doi.org/10.1007/JHEP07(2011)002), arXiv:1103.2761.
- [27] P. Langacker, The physics of heavy Z' gauge bosons, *Rev. Mod. Phys.* 81 (2009) 1199, <http://dx.doi.org/10.1103/RevModPhys.81.1199>, arXiv:0801.1345.
- [28] E. Salvioni, G. Villadoro, F. Zwirner, Minimal Z' models: present bounds and early LHC reach, *J. High Energy Phys.* 11 (2009) 068, <http://dx.doi.org/10.1088/1126-6708/2009/11/068>, arXiv:0909.1320.
- [29] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* 3 (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [30] M. Schmaltz, D. Tucker-Smith, Little Higgs theories, *Annu. Rev. Nucl. Part. Sci.* 55 (2005) 229, <http://dx.doi.org/10.1146/annurev.nucl.55.090704.151502>, arXiv:hep-ph/0502182.
- [31] N. Arkani-Hamed, A.G. Cohen, E. Katz, A.E. Nelson, The Littlest Higgs, *J. High Energy Phys.* 07 (2002) 034, <http://dx.doi.org/10.1088/1126-6708/2002/07/034>, arXiv:hep-ph/0206021.
- [32] M.S. Chanowitz, M.K. Gaillard, The TeV physics of strongly interacting W 's and Z 's, *Nucl. Phys. B* 261 (1985), [http://dx.doi.org/10.1016/0550-3213\(85\)90580-2](http://dx.doi.org/10.1016/0550-3213(85)90580-2).
- [33] CMS Collaboration, Search for dijet resonances in proton–proton collisions at $\sqrt{s} = 13$ TeV and constraints on dark matter and other models, accepted by *Phys. Lett. B* (2017), <http://dx.doi.org/10.1016/j.physletb.2017.02.012>, arXiv:1611.03568.
- [34] CMS Collaboration, Search for narrow resonances in dilepton mass spectra in proton–proton collisions at $\sqrt{s} = 13$ TeV and combination with 8 TeV data, *Phys. Lett. B* 768 (2017) 57, <http://dx.doi.org/10.1016/j.physletb.2017.02.010>, arXiv:1609.05391.
- [35] CMS Collaboration, Search for high-mass diphoton resonances in proton–proton collisions at 13 TeV and combination with 8 TeV search, *Phys. Lett. B* 767 (2017) 147, <http://dx.doi.org/10.1016/j.physletb.2017.01.027>, arXiv:1609.02507.
- [36] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV, *J. Instrum.* 10 (2015) P06005, <http://dx.doi.org/10.1088/1748-0221/10/06/P06005>, arXiv:1502.02701.
- [37] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV, *J. Instrum.* 7 (2012) P10002, <http://dx.doi.org/10.1088/1748-0221/7/10/P10002>, arXiv:1206.4071.
- [38] CMS Collaboration, Performance of the CMS missing transverse momentum reconstruction in pp data at $\sqrt{s} = 8$ TeV, *J. Instrum.* 10 (2015) P02006, <http://dx.doi.org/10.1088/1748-0221/10/02/P02006>, arXiv:1411.0511.
- [39] Particle Data Group, C. Patrignani, et al., Review of particle physics, *Chin. Phys. C* 40 (2016) 100001, <http://dx.doi.org/10.1088/1674-1137/40/10/100001>.
- [40] CMS Collaboration, Identification techniques for highly boosted W bosons that decay into hadrons, *J. High Energy Phys.* 12 (2014) 017, [http://dx.doi.org/10.1007/JHEP12\(2014\)017](http://dx.doi.org/10.1007/JHEP12(2014)017), arXiv:1410.4227.
- [41] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, *Eur. Phys. J. C* 72 (2012) 1896, <http://dx.doi.org/10.1140/epjc/s10052-012-1896-2>, arXiv:1111.6097.
- [42] M. Wobisch, T. Wengler, Hadronization corrections to jet cross sections in deep-inelastic scattering, in: A.T. Doyle, G. Grindhammer, G. Ingelman, H. Jung (Eds.), *Proceedings of the Workshop on Monte Carlo Generators for HERA Physics*, 1999, Hamburg, Germany. URL: http://inspirehep.net/record/484872/files/arXiv:hep-ph_9907280.pdf, arXiv:hep-ph/9907280.
- [43] M. Cacciari, G.P. Salam, G. Soyez, The anti- k_t jet clustering algorithm, *J. High Energy Phys.* 04 (2008) 063, <http://dx.doi.org/10.1088/1126-6708/2008/04/063>, arXiv:0802.1189.
- [44] CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, *J. Instrum.* 6 (2011) P11002, <http://dx.doi.org/10.1088/1748-0221/6/11/P11002>, arXiv:1107.4277.
- [45] S.D. Ellis, C.K. Vermilion, J.R. Walsh, Techniques for improved heavy particle searches with jet substructure, *Phys. Rev. D* 80 (2009) 051501, <http://dx.doi.org/10.1103/PhysRevD.80.051501>, arXiv:0903.5081.
- [46] S.D. Ellis, C.K. Vermilion, J.R. Walsh, Recombination algorithms and jet substructure: pruning as a tool for heavy particle searches, *Phys. Rev. D* 81 (2010) 094023, <http://dx.doi.org/10.1103/PhysRevD.81.094023>, arXiv:0912.0033.
- [47] J. Thaler, K. Van Tilburg, Identifying boosted objects with N-subjettiness, *J. High Energy Phys.* 03 (2011) 015, [http://dx.doi.org/10.1007/JHEP03\(2011\)015](http://dx.doi.org/10.1007/JHEP03(2011)015), arXiv:1011.2268.
- [48] CMS Collaboration, Jet algorithms performance in 13 TeV data, CMS Physics Analysis Summary CMS-PAS-JME-16-003 (2017), URL: <http://cds.cern.ch/record/2256875>.
- [49] CMS Collaboration, Identification of b-quark jets with the CMS experiment, *J. Instrum.* 8 (2013) P04013, <http://dx.doi.org/10.1088/1748-0221/8/04/P04013>, arXiv:1211.4462.
- [50] CMS Collaboration, Performance of b tagging at $\sqrt{s} = 8$ TeV in multijet, $t\bar{t}$ and boosted topology events, CMS Physics Analysis Summary CMS-PAS-BTV-13-001 (2013), URL: <http://cdsweb.cern.ch/record/1581306>.
- [51] CMS Collaboration, Identification of b quark jets at the CMS experiment in the LHC Run 2, CMS Physics Analysis Summary CMS-PAS-BTV-15-001 (2016), URL: <http://cds.cern.ch/record/2138504>.
- [52] ATLAS, CMS Collaborations LHC Higgs Combination Group, Procedure for the LHC Higgs Boson Search Combination in Summer 2011, Technical Report ATL-PHYS-PUB-2011-11, CMS-NOTE-2011-005, 2011, URL: <http://cds.cern.ch/record/1379837>.
- [53] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* 71 (2011) 1554, <https://doi.org/10.1140/epjc/s10052-011-1554-0>, arXiv:1007.1727, Erratum: <https://doi.org/10.1140/epjc/s10052-013-2501-z>.
- [54] T. Junk, Confidence level computation for combining searches with small statistics, *Nucl. Instrum. Methods A* 434 (1999) 435, [http://dx.doi.org/10.1016/S0168-9002\(99\)00498-2](http://dx.doi.org/10.1016/S0168-9002(99)00498-2), arXiv:hep-ex/9902006.
- [55] A.L. Read, Presentation of search results: the CL_s technique, *J. Phys. G* 28 (2002) 2693, <http://dx.doi.org/10.1088/0954-3889/28/10/313>.
- [56] R.D. Ball, V. Bertone, F. Cerutti, L. Del Debbio, S. Forte, A. Guffanti, J.I. Latorre, J. Rojo, M. Ubiali, Impact of heavy quark masses on parton distributions and LHC phenomenology, *Nucl. Phys. B* 849 (2011) 296, <http://dx.doi.org/10.1016/j.nuclphysb.2011.03.021>, arXiv:1101.1300.
- [57] M. Cacciari, S. Frixione, M.L. Mangano, P. Nason, G. Ridolfi, The $t\bar{t}$ cross-section at 1.8 and 1.96 TeV: a study of the systematics due to parton densities and scale dependence, *J. High Energy Phys.* 04 (2004) 068, <http://dx.doi.org/10.1088/1126-6708/2004/04/068>, arXiv:hep-ph/0303085.
- [58] S. Catani, D. de Florian, M. Grazzini, P. Nason, Soft-gluon resummation for Higgs boson production at hadron colliders, *J. High Energy Phys.* 07 (2003) 028, <http://dx.doi.org/10.1088/1126-6708/2003/07/028>, arXiv:hep-ph/0306211.

The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, H. Rohringer, J. Schieck¹, J. Strauss, W. Waltenberger, C.-E. Wulz¹

Institut für Hochenergiephysik, Wien, Austria

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

Institute for Nuclear Problems, Minsk, Belarus

N. Shumeiko

National Centre for Particle and High Energy Physics, Minsk, Belarus

S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang²

Université Libre de Bruxelles, Bruxelles, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, S. Salva, R. Schöffbeck, M. Tytgat, W. Van Driessche, W. Verbeke, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, M. Vidal Marono, S. Wertz

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

N. Beliy

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, A. Custódio, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, C. Mora Herrera, L. Mundim, H. Nogima, A. Santoro, A. Sznajder, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

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

^a Universidade Estadual Paulista, São Paulo, Brazil

^b Universidade Federal do ABC, São Paulo, Brazil

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

W. Fang⁵, X. Gao⁵

Beihang University, Beijing, China

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

Institute of High Energy Physics, Beijing, China

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez

Universidad de Los Andes, Bogota, Colombia

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

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger⁶, M. Finger Jr.⁶

Charles University, Prague, Czech Republic

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

Y. Assran^{7,8}, M.A. Mahmoud^{9,8}, A. Mahrous¹⁰

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, E. Tuominen, J. Tuominiemi, E. Tuovinen

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

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, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

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

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, P. Miné, M. Nguyen, C. Ochando,

G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

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

J.-L. Agram¹¹, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹¹, X. Coubez, J.-C. Fontaine¹¹, D. Gelé, U. Goerlach, A.-C. Le Bihan, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, B. Courbon, 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. Popov¹², V. Sordini, M. Vander Donckt, S. Viret

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

A. Khvedelidze⁶

Georgian Technical University, Tbilisi, Georgia

I. Bagaturia¹³

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

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

A. Albert, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

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

G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, A. Stahl¹⁴

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

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras¹⁵, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo¹⁶, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, A. Harb, J. Hauk, M. Hempel¹⁷, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁷, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann¹⁷, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

S. Bein, V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹⁴, 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, L. Vanelderen, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, S. Baur, C. Baus, J. Berger, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann¹⁴, S.M. Heindl, U. Husemann, F. Kassel¹⁴, 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

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

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

S. Kesisoglou, A. Panagiotou, N. Saoulidou

National and Kapodistrian University of Athens, Athens, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis

University of Ioánnina, Ioánnina, Greece

M. Csanad, N. Filipovic, G. Pasztor

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

G. Bencze, C. Hajdu, D. Horvath¹⁸, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁹, A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi²⁰, A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók¹⁹, P. Raics, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

S. Choudhury, J.R. Komaragiri

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati²¹, S. Bhowmik, P. Mal, K. Mandal, A. Nayak²², D.K. Sahoo²¹, N. Sahoo, S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

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

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

R. Bhattacharya, S. Bhattacharya, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹⁴, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity²³,
G. Majumder, K. Mazumdar, T. Sarkar²³, N. Wickramage²⁴

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kotheekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani²⁵, E. Eskandari Tadavani, S.M. Etesami²⁵, M. Khakzad, M. Mohammadi Najafabadi,
M. Naseri, S. Paktinat Mehdiabadi²⁶, F. Rezaei Hosseinabadi, B. Safarzadeh²⁷, M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, C. Calabria^{a,b}, C. Caputo^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c},
M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, 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,b}, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,14},
R. Venditti^a, P. Verwilligen^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b},
P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a,
A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^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,b,14}

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, 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}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, 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,28}, G. Sguazzoni^a, D. Strom^a, L. Viliani^{a,b,14}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁴

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

L. Brianza^{a,b,14}, F. Brivio^{a,b}, V. Ciriolo, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b,14}, 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, D. Pedrini^a, S. Pigazzini^{a,b}, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}

^a INFN Sezione di Milano-Bicocca, Milano, Italy

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,14}, 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,14}, P. Paolucci^{a,14}, C. Sciacca^{a,b}, F. Thyssen^a

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi^{a,14}, 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}, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, M. Gulmini^{a,29}, S. Lacaprara^a, M. Margoni^{a,b}, G. Maron^{a,29}, A.T. Meneguzzo^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, S. Ventura^a, M. Zanetti^{a,b}, P. Zotto^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, Italy

A. Braghieri^a, F. Fallavollita^{a,b}, A. Magnani^{a,b}, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

L. Alunni Solestizi^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Saha^a, A. Santocchia^{a,b}, D. Spiga

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsov^a, P. Azzurri^{a,14}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, A. Giassi^a, M.T. Grippo^{a,28}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,30}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, D. Del Re^{a,b,14}, 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}

^a INFN Sezione di Roma, Rome, Italy

^b Sapienza Università di Roma, Rome, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c,14}, 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}, F. Ravera^{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}

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

S. Belforte ^a, M. Casarsa ^a, F. Cossutti ^a, G. Della Ricca ^{a,b}, A. Zanetti ^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

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

Kyungpook National University, Daegu, Republic of Korea

A. Lee

Chonbuk National University, Jeonju, Republic of Korea

H. Kim, D.H. Moon

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

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

Hanyang University, Seoul, Republic of 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

Korea University, Seoul, Republic of Korea

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

Seoul National University, Seoul, Republic of Korea

M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali ³¹, F. Mohamad Idris ³², W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz ³³, R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

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

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

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

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

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

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

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk³⁴, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura,
M. Olszewski, A. Pyskir, M. Walczak

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

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

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev,
A. Malakhov, V. Matveev^{35,36}, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov,
N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

Y. Ivanov, V. Kim³⁷, E. Kuznetsova³⁸, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov,
L. Uvarov, S. Vavilov, A. Vorobyev

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

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov,
A. Pashenkov, D. Tisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms,
E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

T. Aushev, A. Bylinkin³⁶

Moscow Institute of Physics and Technology, Moscow, Russia

M. Chadeeva³⁹, E. Popova, E. Tarkovskii

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

V. Andreev, M. Azarkin³⁶, I. Dremin³⁶, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin⁴⁰, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin,
O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

V. Blinov⁴¹, Y. Skovpen⁴¹, D. Shtol⁴¹

Novosibirsk State University (NSU), Novosibirsk, Russia

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

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic⁴², P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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

J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, Spain

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

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

D. Abbaneo, E. Auffray, P. Baillon, A.H. Ball, D. Barney, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco⁴³, M. Dobson, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, P. Harris, J. Hegeman, V. Innocente, P. Janot, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer¹⁴, M.J. Kortelainen, 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. Milenovic⁴⁴, F. Moortgat, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi⁴⁵, M. Rovere, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, P. Sphicas⁴⁶, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsiros, V. Veckalns⁴⁷, G.I. Veres¹⁹, M. Verweij, N. Wardle, A. Zagozdzinska³⁴, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, 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. Rossini, M. Schönenberger, A. Starodumov⁴⁸, V.R. Tavolaro, K. Theofilatos, R. Wallny

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁴⁹, L. Caminada, M.F. Canelli, A. De Cosa, S. Donato, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Yang, A. Zucchetta

Universität Zürich, Zurich, Switzerland

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

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

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

A. Adiguzel, F. Boran, S. Cerci⁵⁰, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos⁵¹, E.E. Kangal⁵², O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut⁵³, K. Ozdemir⁵⁴, D. Sunar Cerci⁵⁰, H. Topakli⁵⁵, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Bilin, G. Karapinar⁵⁶, K. Ocalan⁵⁷, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya⁵⁸, O. Kaya⁵⁹, E.A. Yetkin⁶⁰

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold⁶¹, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁶², C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, 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, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko⁴⁸, J. Pela, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶³, T. Virdee¹⁴, J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

Baylor University, Waco, USA

R. Bartek, A. Dominguez

Catholic University of America, Washington, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

Brown University, Providence, USA

D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi

University of California, Davis, Davis, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Los Angeles, USA

E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁴, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

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

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

D. Anderson, J. Bendavid, A. Bornheim, J.M. Lawhorn, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, 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, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, I. Fisk, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, 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, S. Maruyama, 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

Fermi National Accelerator Laboratory, Batavia, USA

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

University of Florida, Gainesville, USA

S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

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

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

B. Bilki⁶⁵, W. Clarida, K. Dilsiz⁶⁶, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶⁷, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁶⁸, Y. Onel, F. Ozok⁶⁹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

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

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, 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

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, 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. Stephens, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁵, M. Planer, A. Reinsvold, R. Ruchti, N. Rupprecht, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

A. Benaglia, S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, A. Svyatkovskiy, C. Tully

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, J.F. Schulte, J. Sun, F. Wang, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, N. Parashar, J. Stupak

Purdue University Northwest, Hammond, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, J. Roberts, J. Rorie, Z. Tu, J. Zabel

Rice University, Houston, USA

B. Betchart, 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

University of Rochester, Rochester, USA

R. Ciesielski, K. Goulianos, C. Mesropian

The Rockefeller University, New York, USA

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

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

M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

University of Tennessee, Knoxville, USA

O. Bouhali⁷⁰, A. Castaneda Hernandez⁷⁰, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷¹, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, C. Dragoiu, P.R. Dudero, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

C. Clarke, R. Harr, P.E. Karchin, J. Sturdy, S. Zaleski

Wayne State University, Detroit, USA

D.A. Belknap, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin – Madison, Madison, WI, USA

- ¹ Also at Vienna University of Technology, Vienna, Austria.
- ² Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
- ³ Also at Universidade Estadual de Campinas, Campinas, Brazil.
- ⁴ Also at Universidade Federal de Pelotas, Pelotas, Brazil.
- ⁵ Also at Université Libre de Bruxelles, Bruxelles, Belgium.
- ⁶ Also at Joint Institute for Nuclear Research, Dubna, Russia.
- ⁷ Also at Suez University, Suez, Egypt.
- ⁸ Now at British University in Egypt, Cairo, Egypt.
- ⁹ Also at Fayoum University, El-Fayoum, Egypt.
- ¹⁰ Now at Helwan University, Cairo, Egypt.
- ¹¹ Also at Université de Haute Alsace, Mulhouse, France.
- ¹² Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
- ¹³ Also at Ilia State University, Tbilisi, Georgia.
- ¹⁴ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- ¹⁵ Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
- ¹⁶ Also at University of Hamburg, Hamburg, Germany.
- ¹⁷ Also at Brandenburg University of Technology, Cottbus, Germany.
- ¹⁸ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ¹⁹ Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
- ²⁰ Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
- ²¹ Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.
- ²² Also at Institute of Physics, Bhubaneswar, India.
- ²³ Also at University of Visva-Bharati, Santiniketan, India.
- ²⁴ Also at University of Ruhuna, Matara, Sri Lanka.
- ²⁵ Also at Isfahan University of Technology, Isfahan, Iran.
- ²⁶ Also at Yazd University, Yazd, Iran.
- ²⁷ Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- ²⁸ Also at Università degli Studi di Siena, Siena, Italy.
- ²⁹ Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
- ³⁰ Also at Purdue University, West Lafayette, USA.
- ³¹ Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- ³² Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- ³³ Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
- ³⁴ Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- ³⁵ Also at Institute for Nuclear Research, Moscow, Russia.
- ³⁶ Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ³⁷ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ³⁸ Also at University of Florida, Gainesville, USA.
- ³⁹ Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ⁴⁰ Also at California Institute of Technology, Pasadena, USA.
- ⁴¹ Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ⁴² Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ⁴³ Also at INFN Sezione di Roma; Sapienza Università di Roma, Rome, Italy.
- 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 Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ⁴⁹ Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- ⁵⁰ Also at Adiyaman University, Adiyaman, Turkey.
- ⁵¹ Also at Istanbul Aydin University, Istanbul, Turkey.
- ⁵² Also at Mersin University, Mersin, Turkey.
- ⁵³ Also at Cag University, Mersin, Turkey.
- ⁵⁴ Also at Piri Reis University, Istanbul, Turkey.
- ⁵⁵ Also at Gaziosmanpasa University, Tokat, 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, USA.

⁶⁵ Also at BEYKENT UNIVERSITY, Istanbul, Turkey.

⁶⁶ Also at Bingöl University, Bingöl, 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.