



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

The CMS Collaboration*

Abstract

A search for a massive resonance decaying into a standard-model-like Higgs boson (H) and a W or Z boson is reported. The analysis is performed on a data sample corresponding to an integrated luminosity of 19.7 fb^{-1} , collected in proton-proton collisions at a centre-of-mass energy of 8 TeV with the CMS detector at the LHC. Signal events, in which the decay products of Higgs, W, or Z bosons at high Lorentz boost are contained within single reconstructed jets, are identified using jet substructure techniques, including the tagging of b hadrons. This is the first search for heavy resonances decaying into HW or HZ resulting in an all-jet final state, as well as the first application of jet substructure techniques to identify $H \rightarrow WW^* \rightarrow 4q$ decays at high Lorentz boost. No significant signal is observed and limits are set at 95% confidence level on the production cross sections of W' and Z' in a model with mass-degenerate charged and neutral spin-1 resonances. Resonance masses are excluded for W' in the interval [1.0, 1.6] TeV, for Z' in the intervals [1.0, 1.1] and [1.3, 1.5] TeV, and for mass-degenerate W' and Z' in the interval [1.0, 1.7] TeV.

Published in the Journal of High Energy Physics as doi:10.1007/JHEP02(2016)145.

1 Introduction

Several theories of physics beyond the standard model (SM) predict the existence of vector resonances with masses above 1 TeV that decay into a W or Z vector boson (V) and a SM-like Higgs boson (H). Here we present a search for the production of such resonances in proton-proton (pp) collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV. The data sample, corresponding to an integrated luminosity of 19.7 fb^{-1} , was collected with the CMS detector at the CERN LHC.

The composite Higgs [1–3] and little Higgs models [4–6] address the hierarchy problem and predict many new particles, including additional gauge bosons, e.g. heavy spin-1 W' or Z' bosons (V'). These models can be generalized in the heavy vector triplet (HVT) framework [7]. Of particular interest for this search is the HVT scenario B model, where the branching fractions $\mathcal{B}(W' \rightarrow WH)$ and $\mathcal{B}(Z' \rightarrow ZH)$ dominate over the corresponding branching fractions to fermions, and are comparable to $\mathcal{B}(W' \rightarrow WZ)$ and $\mathcal{B}(Z' \rightarrow WW)$. In this scenario, experimental constraints from searches for boson decay channels are more stringent than those from fermion decay channels. Several searches [8–12] for $W' \rightarrow WZ$ based upon the Extended Gauge Boson (EGB) reference model [13] have excluded resonance masses below 1.7 TeV. Unlike the HVT scenario B model, the EGB model has enhanced fermionic couplings and the mass limit is not directly comparable to this work. Model independent limits on the cross section for the resonant production $\ell\nu + \text{jets}$ [14] can be used to extract resonance mass limits on the processes $W' \rightarrow WZ$ and $Z' \rightarrow WW$ of 1.7 TeV and 1.1 TeV, respectively. A search for $Z' \rightarrow ZH \rightarrow q\bar{q}\tau\tau$ was reported in Ref. [15] and interpreted in the context of HVT scenario model B; however, no resonance mass limit could be set with the sensitivity achieved. Finally, a recent search [16] combining leptonic decays of W and Z bosons, and two b-tagged jets forming a $H \rightarrow b\bar{b}$ candidate excluded HVT model A with coupling constant $g_V = 1$ for heavy vector boson masses below $m_{V^0} < 1360$ GeV and $m_{V^{\pm}} < 1470$ GeV.

The signal of interest is a narrow heavy vector resonance V' decaying into VH , where the V decays to a pair of quarks and the H decays either to a pair of b quarks, or to a pair of W bosons, which further decay into quarks. The H in the HVT framework does not have properties that are identical to those of a SM Higgs boson. We make the assumption that the state observed by the LHC Collaborations [17, 18] is the same as the one described by the HVT framework and that, in accord with present measurements [19, 20], its properties are similar to those of a SM Higgs boson.

In the decay of massive V' bosons produced in the pp collisions at the LHC, the momenta of the daughter V and H are large enough (>200 GeV) that their hadronic decay products are reconstructed as single jets [21]. Because this results in a dijet topology, traditional analysis techniques relying on resolved jets are no longer applicable. The signal is characterized by a peak in the dijet invariant mass (m_{jj}) distribution over a continuous background from mainly QCD multijet events. The sensitivity to b-quark jets from H decays is enhanced through subjet or jet b tagging [22]. Jets from $W/Z \rightarrow \bar{q}q'$, $H \rightarrow b\bar{b}$, and $H \rightarrow WW^* \rightarrow 4q$ decays are identified with jet substructure techniques [23, 24].

This is the first search for heavy resonances decaying via VH into all-jet final states and it incorporates the first application of jet substructure techniques to identify $H \rightarrow WW^* \rightarrow 4q$ at a high Lorentz boost.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field 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. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. 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. [25].

3 Signal model and simulation

In the HVT framework, the production cross sections of W' and Z' bosons and their decay branching fractions depend on three parameters in addition to the resonance masses: the strength of couplings to quarks (c_q), to the H (c_H), and on their self-coupling (g_V). In the HVT model B, where $g_V = 3$ and $c_q = -c_H = 1$, W' and Z' preferentially couple to bosons (W/Z/H), giving rise to diboson final states. This feature reproduces the properties of the W' and Z' bosons predicted by the minimal composite Higgs model. In this case, the production cross sections for Z' , W'^- , and W'^+ are respectively 165, 87, and 248 fb for a signal of resonance mass $m_{V'} = 1$ TeV. Their branching fractions to VH and decay width are respectively 51.7%, 50.8%, 50.8% and 35.0, 34.9, 34.9 GeV. The resonances are assumed to be narrow, i.e., with natural widths smaller than the experimental resolution in m_{jj} for masses considered in this analysis.

We consider the W' and Z' resonances separately, and report limits for each candidate individually to permit the reinterpretation of our results in different scenarios with different numbers of spin-1 resonances.

Signal events are simulated using the MADGRAPH 5.1.5.11 [26] Monte Carlo event generator to generate partons that are then showered with PYTHIA 6.426 [27] to produce final state particles. These events are then processed through a GEANT4 [28] based simulation of the CMS detector. The MADGRAPH input parameters are provided in Ref. [29] and the H mass is assumed to be 125 GeV. Samples showered with HERWIG++ 2.5.0 [30] are used to evaluate the systematic uncertainty associated with the hadronization. Tune Z2* [31] is used in PYTHIA, while the version 23 tune [30] is used in HERWIG++. The CTEQ6L1 [32] parton distribution functions (PDF) are used for MADGRAPH, PYTHIA and HERWIG++. Signal events are generated from resonance mass 1.0 to 2.6 TeV in steps of 0.1 TeV. Signals with resonance masses between the generated values are interpolated.

The distribution of the background is modelled from the data. However, simulated samples of multijet and $t\bar{t}$ events, generated using MADGRAPH 5v1.3.30 [26] and POWHEG 1.0 [33–35], respectively, and interfaced to PYTHIA for parton showering and hadronization, serve to provide guidance and cross-checks.

4 Event reconstruction and selection

The event selection, in the online trigger as well as offline, utilizes a global event description by combining information from the individual subdetectors. Online, events are selected by at least one of two specific triggers: one based on the scalar sum of the transverse momenta p_T of

the jets (H_T), which requires $H_T > 650$ GeV; the other on the invariant mass of the two jets with highest p_T , which requires $m_{jj} > 750$ GeV.

The offline reconstruction is described below.

Events must have at least one primary vertex reconstructed with $|z| < 24$ cm. The primary vertex used in the event reconstruction is the one with the largest summed p_T^2 of associated tracks. Individual particle candidates are reconstructed and identified using the particle-flow algorithm [36, 37], and divided into five categories: muons, electrons, photons (including those that convert into e^+e^- pairs), charged hadrons, and neutral hadrons. Charged particle candidates associated with a primary vertex different from the one considered for the event reconstruction are discarded, which reduces contamination from additional pp interactions in the same bunch crossings (pileup).

Jets are clustered from the remaining particle flow candidates, except those identified as isolated muons, using the Cambridge–Aachen (CA) [38, 39] jet clustering algorithm as implemented in FASTJET [40, 41]. This algorithm starts from a set of particles as “protojets”. It combines them iteratively with each other into new protojets until the distance of the resulting protojet to the closest remaining protojet is larger than the distance parameter of the CA algorithm. A distance parameter of 0.8 is used (CA8 jets). An event-by-event correction based on the jet area method [42–44] is applied to remove the remaining energy deposited by neutral particles originating from pileup. The pileup-subtracted jet four-momenta are then corrected to account for the difference between the measured and true energies of hadrons [44]. Jet identification criteria [45] are applied to the two highest p_T jets in order to remove spurious events associated with calorimeter noise.

The jet reconstruction efficiencies (estimated from simulation) are larger than 99.9%, and contribute negligibly to the systematic uncertainties for signal events.

Events are selected by requiring at least two jets each with $p_T > 30$ GeV/ c and pseudorapidity $|\eta| < 2.5$. The two highest p_T jets are required to have a pseudorapidity separation $|\Delta\eta| < 1.3$ to reduce background from multijet events [46]. The invariant mass of these two jets is required to satisfy $m_{jj} > 890$ GeV/ c^2 . The trigger efficiency for the events passing the preselection requirements exceeds 99%.

To enable the results to be applied to other models of similar final states, we utilize simulations to derive the geometrical acceptances and the W/Z and H selection efficiencies. These are presented separately in Figs. 1, 6, and 7, respectively.

For the purpose of reinterpreting the result, the global efficiency is presented approximated by the product of acceptances and the W/Z and H selection efficiency, restricted to final states where the W/Z and H bosons decay hadronically. The products of acceptances and the W/Z and H tagging efficiency, ignoring the correlations between detector acceptance and W/Z or H tagging, agree to better than 10% with the full event simulation. In the interpretations reported in this paper, the global efficiency is estimated from the full simulation of signal events, such that the correlations between the acceptance and W/Z and H selection efficiency are properly taken into account. However, when re-interpreting this search in terms of an arbitrary model, an additional uncertainty of 10% should be folded in, to allow for the possible effect of correlations.

The acceptance, shown in Fig. 1 as a function of the dijet resonance mass for several signals, takes into account the angular acceptance ($|\eta| < 2.5$, $|\Delta\eta| < 1.3$).

The two highest p_T jets are chosen as candidates for the hadronically decaying W/Z and H

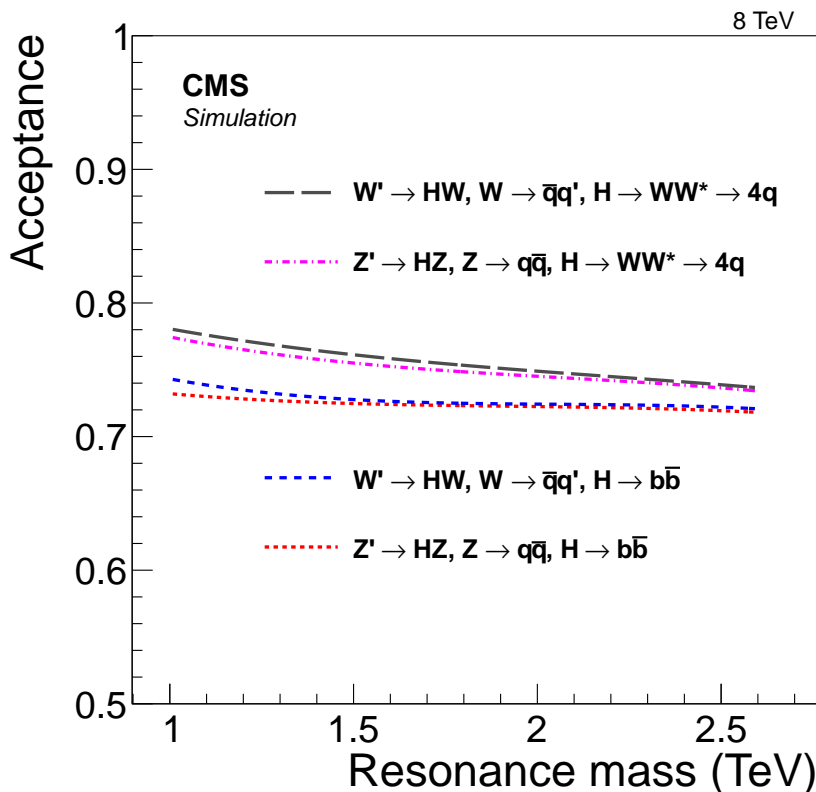


Figure 1: The fraction of simulated signal events for hadronically decaying W/Z and H bosons, reconstructed as two jets, that pass the geometrical acceptance criteria ($|\eta| < 2.5$, $|\Delta\eta| < 1.3$), shown as a function of the resonance mass.

bosons, and W/Z and H tagging algorithms based on jet substructure are applied.

Information characterizing jet substructure is derived using three separate algorithms, producing the variables *pruned jet mass*, *subject b tagging*, and *N -subjettiness*. The combined use of these variables in event selection strongly suppresses the background from QCD dijet production. All three characterizations of jet substructure are defined and discussed in detail in the following paragraphs.

As the mass of the V or H boson is larger than the mass of a typical QCD jet, the jet mass is the primary observable that distinguishes such a jet from a QCD jet. The bulk of the V or H jet mass arises from the kinematics of the two or more jet cores that correspond to the decay quarks. In contrast, the QCD jet mass arises mostly from soft gluon radiation. For this reason, the use of jet pruning [47, 48] improves discrimination by removing the softer radiation, as this shifts the jet mass of QCD jets to smaller values, while maintaining the jet mass for V and H jets close to the masses of W , Z or H bosons. Jet pruning is implemented by applying additional cuts in the process of CA jet clustering. These cuts remove protojets that would have a large angle and low p_T with respect to the combination with another protojet. The details of this procedure are given in Ref. [24]. The distributions of the pruned jet mass (m_j) for simulated signal and background samples, are shown in Fig. 2. Jets from boosted W and Z decays are expected to generate peaks at $m_j \approx 80$ and $m_j \approx 90$ GeV, respectively. Jets from boosted H decays are expected to peak at $m_j \approx 120$ GeV. Hadronic top-quark jets, where the b quark and the two different light quarks from the $t \rightarrow Wb \rightarrow q\bar{q}'b$ decay are required to be within a reconstructed CA8 jet, peak at $m_j \approx 175$ GeV. The peak around 20 GeV arises from unmerged

light jets, mostly associated with quark- and gluon-induced jets from multijet events, but also from quark jets from W , Z , and H bosons in the cases where the decay products do not end up in a single jet. The contribution from bosons depends on their spin and polarization. All peaks are slightly shifted to lower masses because of the removal of soft radiation in jet pruning. If the pruned jet has a mass (m_j) within $70 < m_j < 100 \text{ GeV}/c^2$ ($110 < m_j < 135 \text{ GeV}/c^2$), it is tagged as a W/Z (H) candidate.

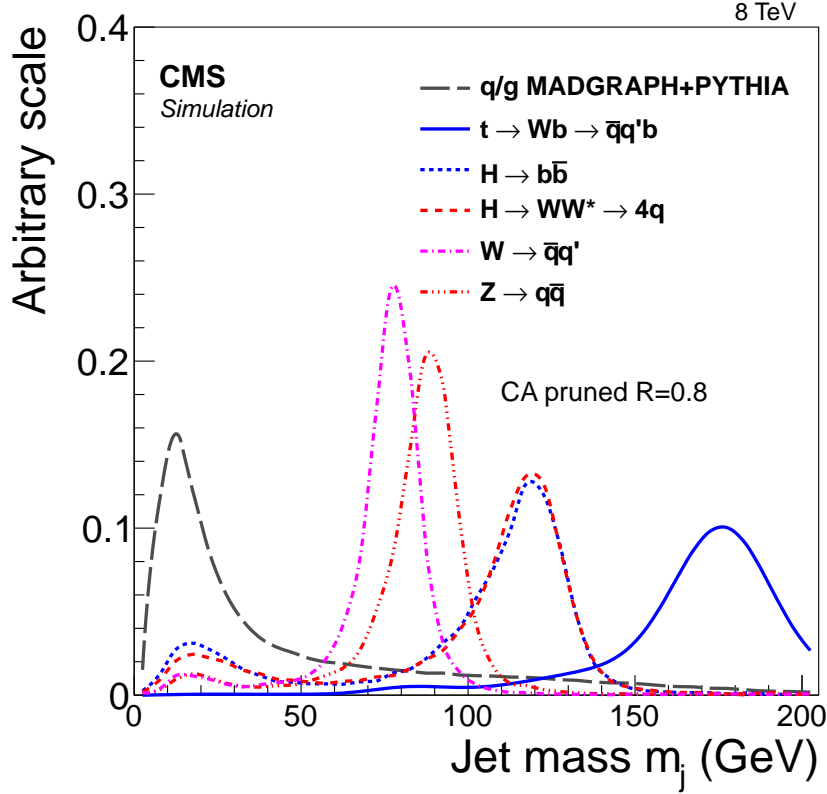


Figure 2: Distribution of pruned jet mass in simulation of signal and background processes. All simulated distributions are normalized to 1. The W/Z , H , and top-quark jets are required to match respective generator level particles in the event. The W/Z and H jets are from $1.5 \text{ TeV } W' \rightarrow WH$ and $Z' \rightarrow ZH$ signal samples.

Jet pruning can also provide a good delineation of subjets within the CA8 jet.

To tag jets from $H \rightarrow b\bar{b}$ decays, denoted as H_{bb} jets, the pruned subjets, given by reversing the last step of the CA8 pruning recombination algorithm, are used as the basis for b tagging. Jets arising from the hadronization of b quarks (b jets) are identified using the “Combined Secondary Vertex” b -tagging algorithm [49], which uses information from tracks and secondary vertices associated with jets to build a likelihood-based discriminator to distinguish between jets from b quarks and those from charm or light quarks and gluons. The b -tagging discriminator can take values between 0 and 1 with higher values indicating higher probability for the jet to originate from a b quark. The “loose” working point of the b -tagging algorithm [49] is chosen and is found to be optimal for both subjet and jet b tagging. It has a b -tagging efficiency of $\approx 85\%$, with mistagging probabilities of $\approx 40\%$ for c -quark jets and $\approx 10\%$ for light-quark and gluon jets at jet p_T near 80 GeV . The ratio of b -tagging efficiencies for data and simulation is applied as a scale factor [22] to the simulated signal events. To identify CA8 jets originating from $H \rightarrow b\bar{b}$ decays, we apply b tagging either to the two subjets or to the CA8 jet, based

on the angular separation of the two subjets (ΔR) [22]. If ΔR is larger (smaller) than 0.3, the b-tagging algorithm is applied to both of the subjets (the single CA8 jet).

While the pruned jet mass is a powerful discriminant against QCD multijet backgrounds, the substructure of jets arising from V and H decays provides additional discrimination. In $H \rightarrow WW^* \rightarrow 4q$ decays, the boosted H decays into a final state of four quarks merged together, denoted as an H_{WW} jet, and has a different substructure than jets from $V/H \rightarrow \bar{q}q'$ decays. We quantify how well the constituents of a given jet can be arranged into N subjets by reconstructing the full set of jet constituents (before pruning) with the k_T algorithm [50] and halting the reclustering when N distinguishable protojets are formed. The directions of the N jets are used as the reference axes to compute the N -subjettiness [51–53] τ_N of the original jet, defined as

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k}), \quad (1)$$

where $p_{T,k}$ is the p_T of the k^{th} constituent of the original jet and $\Delta R_{n,k}$ is its angular distance from the axis of the n^{th} subjet (with $n = 1, 2, \dots, N$). The normalization factor d_0 for τ_N is $d_0 = \sum_k p_{T,k} R_0$, with R_0 set to 0.8, the distance parameter of the CA algorithm. To improve the discriminating power, we perform a one-pass optimization of the directions of the subjets' axes by minimizing τ_N [24, 52]. By using the smallest $\Delta R_{n,k}$ to weight the value of $p_{T,k}$ in Eq. (1), τ_N yields small values when the jet originates from the hadronization of N or fewer quarks. The $\tau_{ij} = \tau_i/\tau_j$ ratios τ_{21} , τ_{31} , τ_{32} , τ_{41} , τ_{42} , and τ_{43} have been studied to identify the best discriminators for jets from $W/Z \rightarrow \bar{q}q'$ and $H \rightarrow WW^* \rightarrow 4q$ decays.

We find that τ_{21} is the most suitable variable for identifying $W/Z \rightarrow \bar{q}q'$ jets [12]. The distribution of τ_{21} for the $W/Z \rightarrow \bar{q}q'$ signal, shown in Fig. 3, peaks below 0.4 and is almost fully contained within $\tau_{21} < 0.75$, where we place our cut. In contrast, the QCD background peaks around 0.6. The figure shows only W/Z candidate jets with the pruned jet mass in the W/Z boson mass window. For this reason, the jets matched to the top quark are mostly true W bosons, and appear signal-like. However, they represent only a small fraction of the top quarks from $t\bar{t}$ events (cf. Fig. 2), since in the kinematic regime considered in this search, the top quarks are highly boosted and the b jet rarely fails to merge with the W jet. The overall contribution from $t\bar{t}$, after the full selection, is 1–3%.

For $H \rightarrow WW^* \rightarrow 4q$ events, we find that the ratio τ_{42} works best to discriminate between four-pronged $H \rightarrow WW^* \rightarrow 4q$ and QCD jets. The discriminating power of τ_{42} can be seen in Fig. 4. The τ_{42} distribution of H_{WW} jets tends to peak around 0.55. By contrast, τ_{42} distributions of multijet background and W/Z jets have a larger fraction of events at large values of τ_{42} , especially after requiring a pruned jet mass in the range [110, 135] GeV. Jets from unmatched $t\bar{t}$ events peak together with QCD jets, since they contain a mixture of b-quark jets and W -jets, but relatively few fully merged top-quark jets. However, the τ_{42} distribution for matched top-quark jets tends to peak at smaller values, since for the same jet τ_{42} is nearly always less than τ_{32} , which is small for hadronic top-quark jets.

In Fig. 4, the comparison between dijet data and the QCD multijet simulation shows that the simulated distribution is well reproduced, though shifted towards higher values of τ_{42} as compared with the data. A similar level of disagreement is known for the modelling of τ_{21} in QCD simulation in Ref. [12]. The disagreement does not affect this analysis since the background is estimated from data. For the signal scale factor, the uncertainties from the modelling of τ_{42} are taken into account.

We select “high (low)-purity” W/Z jets by requiring $\tau_{21} \leq 0.5$ ($0.5 < \tau_{21} < 0.75$), denoted as the HP (LP) V tag. Given the shape of τ_{21} distribution for the W/Z signal, the HP V tag category

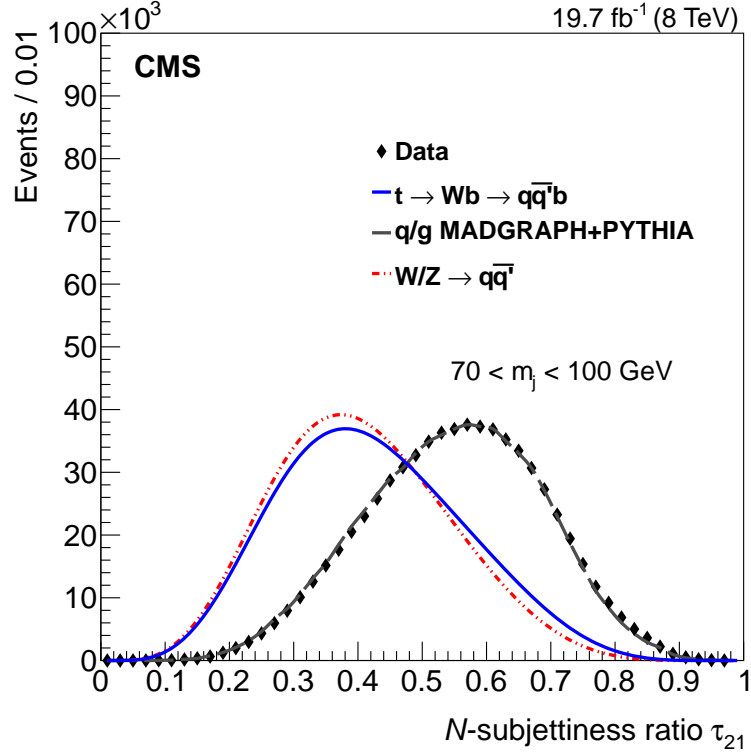


Figure 3: Distribution of the N -subjettiness ratio $\tau_{21} = \tau_2/\tau_1$, where τ_N is given in Eq. (1), for simulated signal and background processes, and for data. The jets for which τ_{21} is calculated are required to satisfy the W/Z pruned jet mass requirement. The W/Z and top-quark jets are required to match respective generator level particles in the event. All simulated distributions are scaled to the number of events in data.

has a higher efficiency than the LP V tag category. We select HP (LP) H_{WW} jets by requiring $\tau_{42} \leq 0.55$ ($0.55 < \tau_{42} < 0.65$), denoted as the HP (LP) H tag. Here also the HP category has a higher efficiency than the LP category.

Cross-talk between the H decay channels is possible; for example, two-pronged H decays (e.g. $H \rightarrow b\bar{b}$, $H \rightarrow c\bar{c}$) can be reconstructed as four-pronged $H \rightarrow WW^* \rightarrow 4q$, as shown in Fig. 5. Because of its large branching fraction, $H \rightarrow b\bar{b}$ contributes a non-negligible number of events to the $H \rightarrow WW^* \rightarrow 4q$ tagged sample. In order to combine events from $H \rightarrow b\bar{b}$ and $H \rightarrow WW^* \rightarrow 4q$ channels into a single joint likelihood, these categories must be mutually exclusive. Since the $H \rightarrow b\bar{b}$ tagger has significantly lower background than $H \rightarrow WW^* \rightarrow 4q$, it takes precedence in selecting events. We first identify the events that pass the $H \rightarrow b\bar{b}$ tagger, and only if they fail we test them for the presence of the $H \rightarrow WW^* \rightarrow 4q$ tag. Thus we arrive at the final division of events into five mutually exclusive categories. These event categories and their nomenclature are summarized in Table 1.

The LP V tag and LP H tag category is not included in this analysis, since it is dominated by background and therefore its contribution to the expected significance of the signal is negligible. Other H decay modes like $H \rightarrow gg$, $H \rightarrow \tau\tau$, $H \rightarrow ZZ^*$, and $H \rightarrow c\bar{c}$ together contribute 2–7% of the total $H \rightarrow b\bar{b}$ tagged events, and 18–24% of the total $H \rightarrow WW^* \rightarrow 4q$ tagged events, as shown in Fig. 5. In this analysis, we only consider the $H \rightarrow b\bar{b}$ and $H \rightarrow WW^* \rightarrow 4q$ channels. Other H channels passing the tagging requirements are conservatively viewed as background and included as systematic uncertainties, discussed in Section 6.

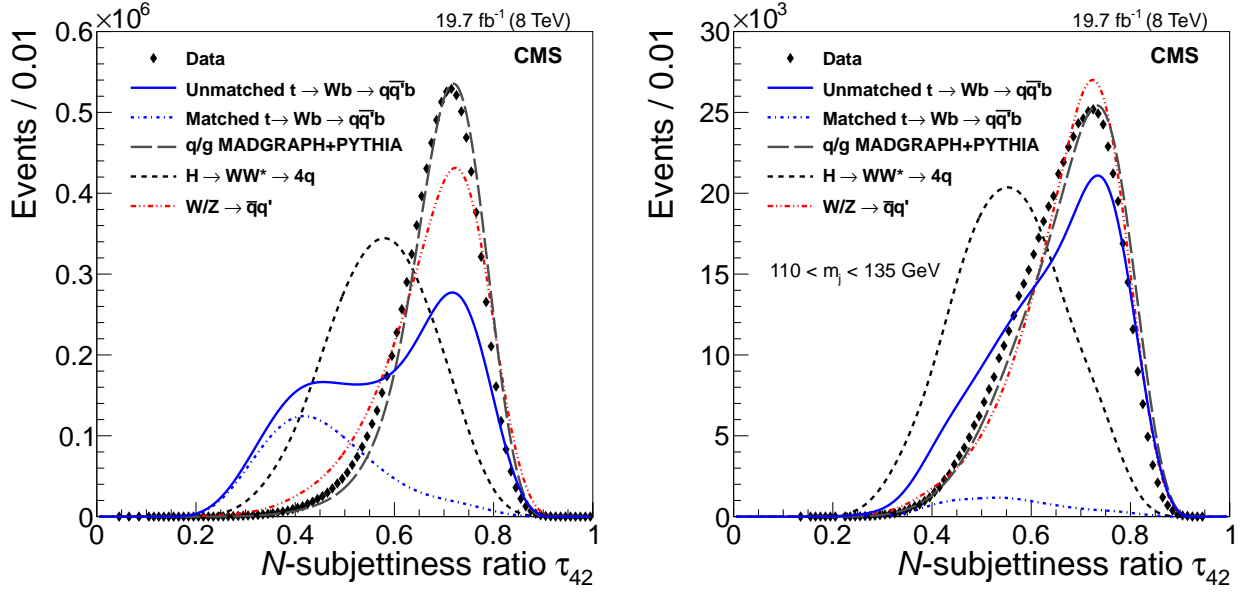


Figure 4: Distributions of τ_{42} in data and in simulations of signal (2 TeV) and background events, without applying the pruned jet mass requirement (left) and with the pruned jet mass requirement applied (right). Matched top-quark, W/Z, and H_{WW} jets are required to be consistent with their generator level particles, respectively. All simulated distributions are scaled to the number of events in data, except that matched top-quark background is scaled to the fraction of unmatched $t\bar{t}$ events times the number of data events.

Table 1: Summary of event categories and their nomenclature used in the paper. The jet mass cut is $70 < m_j < 100 \text{ GeV}/c^2$ for the V tag and $110 < m_j < 135 \text{ GeV}/c^2$ for the H tag.

Categories	V tag	H tag
$V^{\text{HP}}H_{bb}$	$\tau_{21} \leq 0.5$	b tag
$V^{\text{LP}}H_{bb}$	$0.5 < \tau_{21} < 0.75$	b tag
$V^{\text{HP}}H_{WW}^{\text{HP}}$	$\tau_{21} \leq 0.5$	$\tau_{42} \leq 0.55$
$V^{\text{LP}}H_{WW}^{\text{HP}}$	$0.5 < \tau_{21} < 0.75$	$\tau_{42} \leq 0.55$
$V^{\text{HP}}H_{WW}^{\text{LP}}$	$\tau_{21} \leq 0.5$	$0.55 < \tau_{42} < 0.65$

The expected tag probabilities of the W, Z, and H selection criteria for signal and data events in different event categories are shown in Figs. 6 and 7, as a function of m_{jj} . The W/Z and $H \rightarrow WW^* \rightarrow 4q$ tagging efficiencies for signal events in the $H \rightarrow WW^* \rightarrow 4q$ categories fall at high p_T , primarily because the τ_{42} distribution is p_T -dependent.

The Monte Carlo modelling of V-tag efficiency is validated using high- p_T $W \rightarrow \bar{q}q'$ decays selected from a data sample enriched in semileptonic $t\bar{t}$ events [24]. Scale factors of 0.86 ± 0.07 and 1.39 ± 0.75 are applied to the simulated events in the HP and LP V tag categories, respectively, to match the tagging efficiencies in the top pair data. The decay of $H \rightarrow WW^* \rightarrow 4q$ produces a hard W jet accompanied by two soft jets from the off-shell W boson. As the $H \rightarrow WW^* \rightarrow 4q$ tagger is also based on the N -subjettiness variables, and the measured ratio τ_{42}/τ_{21} is well modelled by QCD simulation, it is reasonable to assume that the mismodelling of the shower by PYTHIA is similar to that in the case of V tagging. The $H \rightarrow WW^* \rightarrow 4q$ tagging efficiency scale factors are extrapolated using the same technique as for V tagging for both the HP and LP categories, respectively, with additional systematic uncertainties, which are discussed in Section 6.

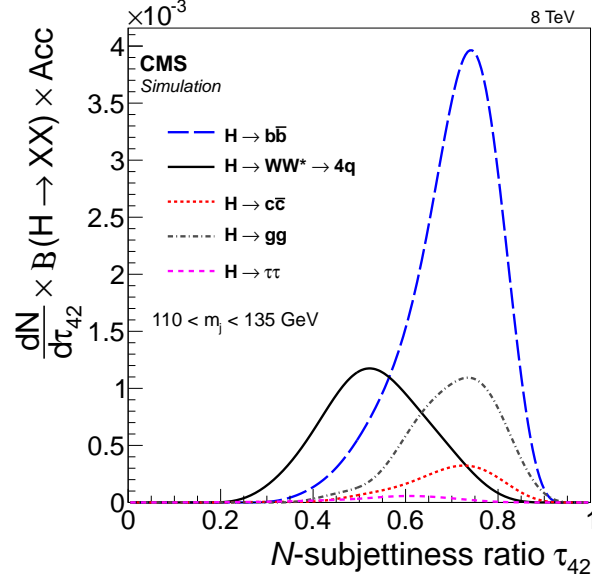


Figure 5: Comparison of τ_{42} distributions for signal events failing the $H \rightarrow b\bar{b}$ requirement. These events are from the $H \rightarrow WW^* \rightarrow 4q$, $H \rightarrow b\bar{b}$, $H \rightarrow gg$, $H \rightarrow c\bar{c}$, and $H \rightarrow \tau\tau$ channels. The H jets are from a 1.5 TeV resonance decaying to VH. All curves are normalized to the product of the corresponding branching fraction and acceptance.

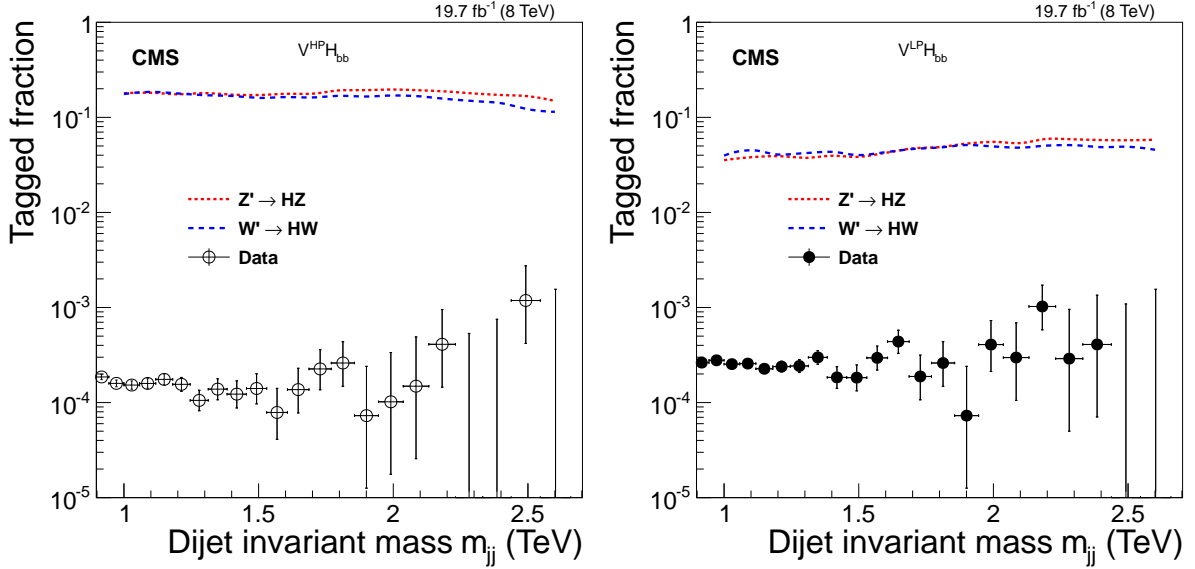


Figure 6: Tagged fractions in $H \rightarrow b\bar{b}, W/Z \rightarrow \bar{q}q'$ signal channels and data as a function of dijet invariant mass, for categories of $V^{HP}H_{bb}$ (left) and $V^{LP}H_{bb}$ (right). Horizontal bars through the data points indicate the bin width.

5 Resonance search in the dijet mass spectrum

The resolution for the m_{jj} reconstruction is in the range 5–10% for all the five categories. The dominant background in this analysis is from multijet events with an additional 1–3% contribution from $t\bar{t}$ events. The background is modelled by a smoothly falling distribution for each

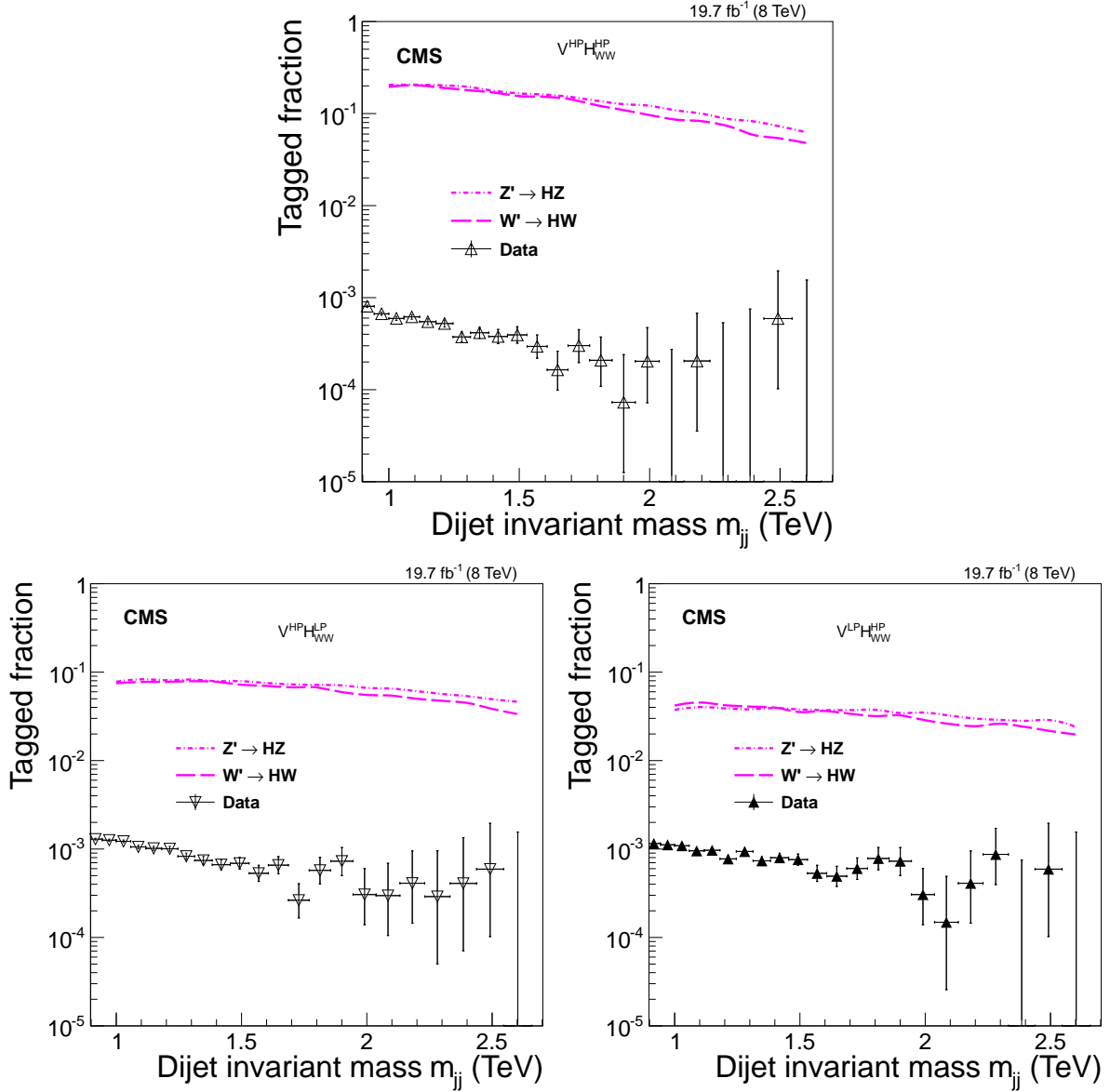


Figure 7: Tagged fractions in $H \rightarrow WW^* \rightarrow 4q, W/Z \rightarrow \bar{q}q'$ signal channels and data as a function of dijet invariant mass, for categories of $V^{\text{HP}} H_{\text{WW}}^{\text{HP}}$ (top), $V^{\text{HP}} H_{\text{WW}}^{\text{LP}}$ (bottom left) and $V^{\text{LP}} H_{\text{WW}}^{\text{HP}}$ (bottom right). Horizontal bars through the data points indicate the bin width.

event category, given by the empirical probability density function

$$P_D(m_{jj}) = \frac{P_0(1 - m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2}}. \quad (2)$$

The background model includes the small $t\bar{t}$ background, which falls smoothly in a similar way to the multijet background.

Each event category has separate normalization P_0 and shape parameters P_1 and P_2 . This parameterization was deployed successfully in a number of searches based on dijet mass spectra [46]. A Fisher F-test [54] is used to check that no additional parameters are needed to model the individual background distributions, compared with the four-parameter function

used in [46]. We have also tested an alternative function $P_E(m_{jj}) = P_0/(m_{jj}/\sqrt{s} + P_1)^{P_2}$, and found it less favored by the F-test.

The use of the alternative function in the analysis produces negligible changes in the final result and therefore, no systematic uncertainty is associated with this choice.

We search for a peak on top of the falling background spectrum by means of a binned maximum likelihood fit to the data.

The binned likelihood is given by

$$\mathcal{L} = \prod_i \frac{\lambda_i^{n_i} e^{-\lambda_i}}{n_i!}, \quad (3)$$

where $\lambda_i = \mu N_i(S) + N_i(B)$, μ is a scale factor for the signal, $N_i(S)$ is the number of events expected from the signal, and $N_i(B)$ is the number expected from multijet background. The variable n_i quantifies the number of observed events in the i^{th} m_{jj} bin. The number of background events $N_i(B)$ is described by the functional form of Eq. (2). The signal shape for each narrow-width resonance hypothesis is obtained by fitting the m_{jj} distribution from simulated events with a sum of a Gaussian and a Crystal Ball probability density function. The resulting shape is fixed and, as such, used in the combined signal and background fit. This procedure is repeated for each resonance hypothesis, sampling resonance masses from 1.0 to 2.6 TeV in steps of 50 GeV. While maximizing the likelihood, μ and the parameters of the background function are left unconstrained. The shape of the resonance is additionally modified to account for systematic uncertainties (described below); parameters controlling each source of systematic uncertainty are also allowed to vary in the fit, albeit within constraints. For presentational purposes, a binning according to m_{jj} resolution is used in this paper. However, the likelihood is calculated in bins of 1 GeV in m_{jj} , approximating an unbinned analysis, while keeping it computationally manageable.

Figs. 8 and 9 show the m_{jj} distributions in data. The solid curves represent the results of the maximum likelihood fit to the data, fixing the number of expected signal events to zero, while the bottom panels show the corresponding pull distributions, quantifying the agreement between the background-only hypothesis and the data. The expected distributions of $H \rightarrow b\bar{b}$, $W/Z \rightarrow \bar{q}q'$ and $H \rightarrow WW^* \rightarrow 4q$, $W/Z \rightarrow \bar{q}q'$ signals at 1.0, 1.5 and 2.0 TeV in each category, scaled to their corresponding cross sections are given by the dashed and dash-dotted curves. The resonance masses in VH_{bb} channels are slightly lower than those of the VH_{WW} channels because of missing neutrinos in b-hadron decays and partial misreconstruction of two-pronged $H \rightarrow b\bar{b}$ decays.

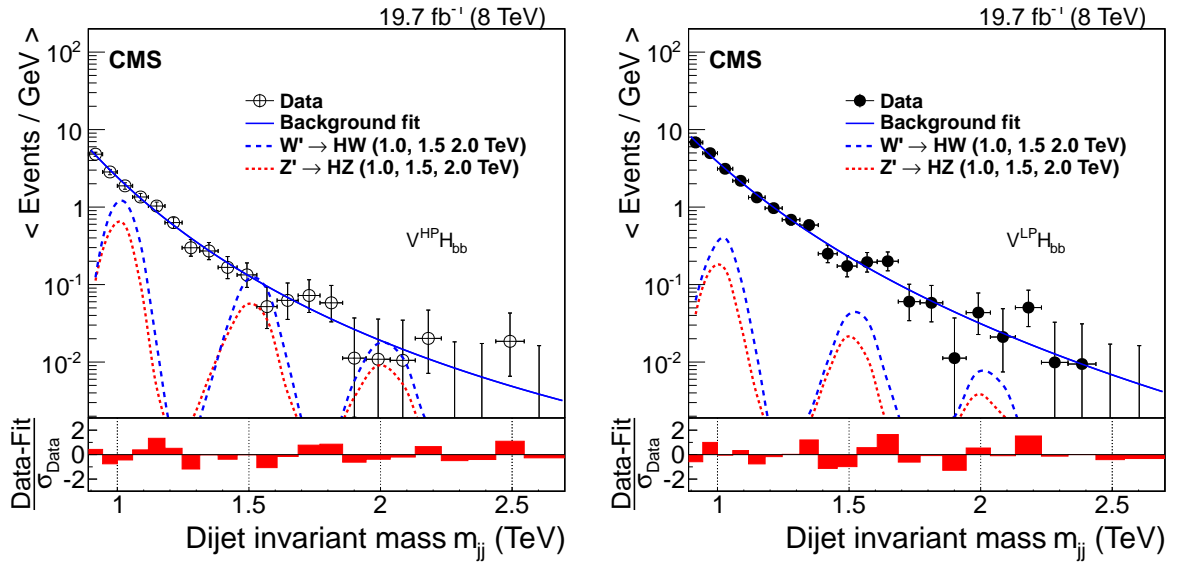


Figure 8: Distributions in m_{jj} are shown for $V^{\text{HP}}H_{bb}$ category (left), $V^{\text{LP}}H_{bb}$ category (right). The solid curves represent the results of fitting Eq. (2) to the data. The distributions for $H \rightarrow b\bar{b}, W/Z \rightarrow \bar{q}q'$ contributions, scaled to their corresponding cross sections, are given by the dashed curves. The vertical axis displays the number of events per bin, divided by the bin width. Horizontal bars through the data points indicate the bin width. The corresponding pull distributions $\frac{\text{Data-Fit}}{\sigma_{\text{Data}}}$, where σ_{Data} represents the statistical uncertainty in the data in a bin in m_{jj} , are shown below each m_{jj} plot.

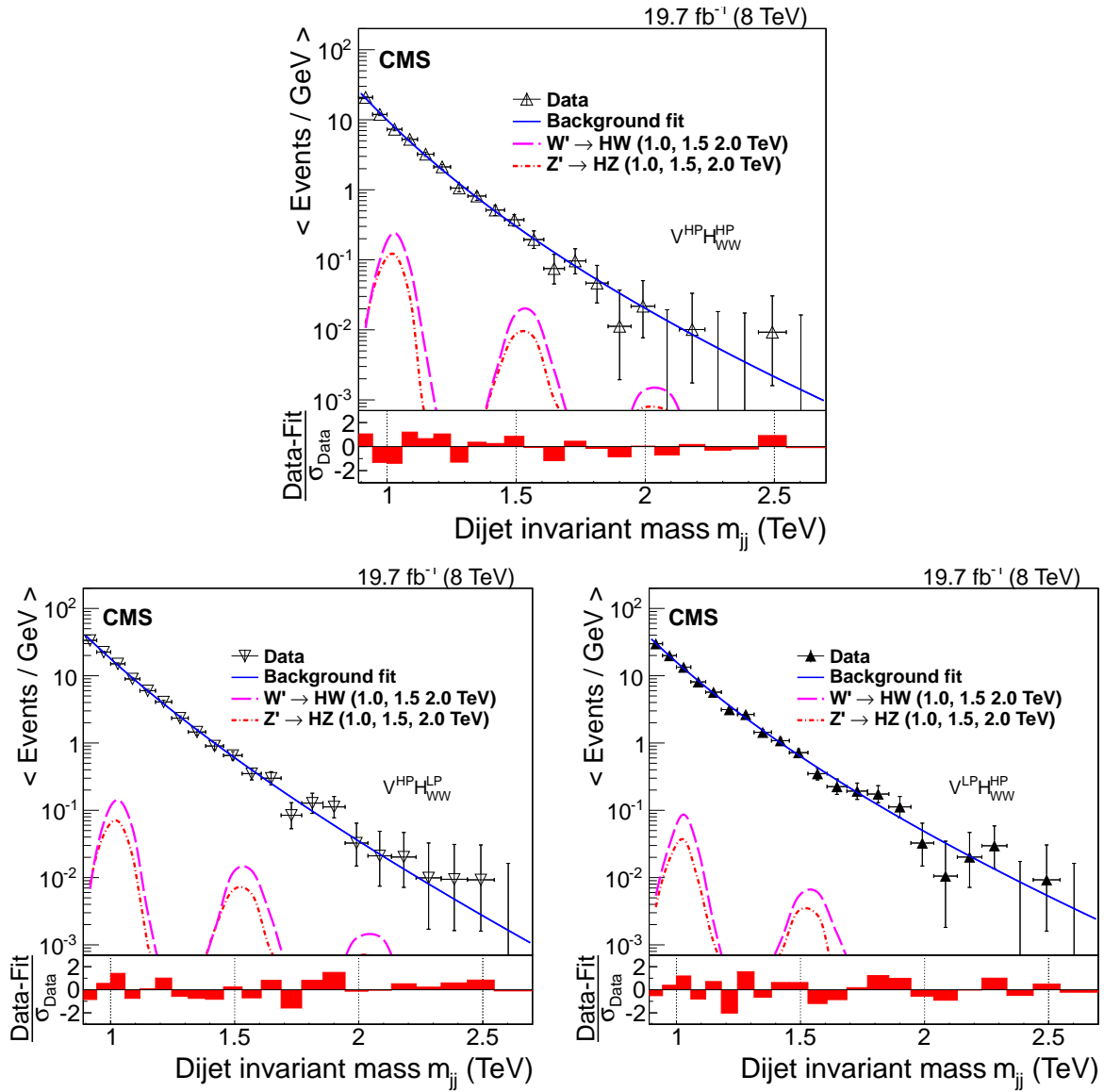


Figure 9: Distributions in m_{jj} are shown for $V^{\text{HP}}H_{\text{WW}}^{\text{HP}}$ (top), $V^{\text{HP}}H_{\text{WW}}^{\text{LP}}$ (bottom left), and $V^{\text{LP}}H_{\text{WW}}^{\text{HP}}$ (bottom right). The solid curves represent the results of fitting Eq. (2) to the data. The distributions for $H \rightarrow WW^* \rightarrow 4q, W/Z \rightarrow \bar{q}q'$ contributions, scaled to their corresponding cross sections, are given by the dashed and dash-dotted curves. The vertical axis displays the number of events per bin, divided by the bin width. Horizontal bars through the data points indicate the bin width. The corresponding pull distributions $\frac{\text{Data-Fit}}{\sigma_{\text{Data}}}$, where σ_{Data} represents the statistical uncertainty in the data in a bin in m_{jj} , are shown below each m_{jj} plot.

6 Systematic uncertainties

The largest contributions to the systematic uncertainty are associated with the modelling of the signal, namely: the efficiencies of W/Z, H, and b tagging; the choice of PDF; the jet energy scale (JES); the jet energy resolution (JER); the pileup corrections; the cross-talk between different signal contributions; and the integrated luminosity.

The uncertainty in the efficiency for W/Z tagging is estimated using a control sample enriched with $t\bar{t}$ events described in Ref. [24]. Uncertainties of 7.5% and 54% in the respective scale factors for HP and LP V tag include contributions from control-sample statistical uncertainties, and the uncertainties in the JES and JER for pruned jets [12]. The uncertainty due to the extrapolation of the simulated W/Z-tagging efficiency to higher jet p_T is estimated by studying the W/Z-tagging efficiency as a function of p_T for two different showering and hadronization models using PYTHIA 6 and HERWIG++, respectively. The results show that the differences are within 4% (12%) for the HP (LP) V tagging [24].

We extrapolate the $H \rightarrow WW^* \rightarrow 4q$ tagging efficiency scale factor in the same way as the W/Z-tagging efficiency, with an additional systematic uncertainty based on the difference between PYTHIA 6 and HERWIG++ in modelling $H \rightarrow WW^* \rightarrow 4q$ decay. This is evaluated to be $\approx 7\%$ for the HP and LP H tag. The uncertainty from the pruned jet mass requirement in the $H \rightarrow WW^* \rightarrow 4q$ search is already included in the extrapolated scale factor uncertainty of the V-tag.

The uncertainty in the efficiency of $H \rightarrow b\bar{b}$ tagging can be separated into two categories: the efficiency related to the b tagging and the efficiency related to the pruned H mass tag. The first is obtained by varying the b-tagging scale factors within the associated uncertainties [22] and amounts to 15%. The second is assumed to be similar to the mass selection efficiency of W jets estimated in Ref. [24], additionally accounting for the difference in fragmentation of light quarks and b quarks, which amounts to 2.6% per jet.

Because of the rejection of charged particles not originating from the primary vertex, and the application of pruning, the dependence of the W/Z- and H-tagging efficiencies on pileup is weak and the uncertainty in the modelling of the pileup distribution is $\leq 1.5\%$ per jet.

In this analysis, we only consider $H \rightarrow b\bar{b}$ and $H \rightarrow WW^* \rightarrow 4q$ decays. Other H decay channels that pass H taggers are viewed as nuisance signals, and a corresponding cross-talk systematic uncertainty is assigned. We evaluate this uncertainty as a ratio of expected nuisance signal events with respect to the total expected signal events, taking into account the branching fractions, acceptances and tagging efficiencies. The contamination from cross-talk is estimated to be 2–7% in the $VH_{b\bar{b}}$ categories, and 18–24% in the VH_{WW} categories, and we take the maximum as the uncertainty. The analysis is potentially 7% (24%) more sensitive than quoted, but since it is not clear how well the efficiency for the nuisance signals is understood, they are neglected, yielding a conservative limit on new physics. When the $VH_{b\bar{b}}$ and VH_{WW} categories are combined together, the 24% uncertainty becomes a small effect, based on a quantitative measure of sensitivity suggested in Ref. [55]:

$$P = \frac{\mathcal{B}(H \rightarrow XX) \epsilon_S}{1 + \sqrt{N_B}} \quad (4)$$

where $\mathcal{B}(H \rightarrow XX)$ is the branching fraction for the H decay channel, ϵ_S is the signal tagging efficiency, and N_B is the corresponding background yield. The values of P for each channel are shown in Table 2.

The JES has an uncertainty of 1–2% [44, 56], and its p_T and η dependence is propagated to the reconstructed value of m_{jj} , yielding an uncertainty of 1%, independent of the resonance mass.

Table 2: Summary of the values P for a Z' signal at 1.5 TeV resonance mass and the corresponding background yield in all five categories.

Signal/Categories	$V^{\text{HP}}H_{bb}$	$V^{\text{LP}}H_{bb}$	$V^{\text{HP}}H_{WW}^{\text{HP}}$	$V^{\text{HP}}H_{WW}^{\text{LP}}$	$V^{\text{LP}}H_{WW}^{\text{HP}}$
$H \rightarrow b\bar{b}, Z \rightarrow q\bar{q}$	2.3×10^{-2}	4.8×10^{-3}	1.0×10^{-3}	1.6×10^{-3}	3.9×10^{-4}
$H \rightarrow WW^* \rightarrow 4q, Z \rightarrow q\bar{q}$	5.6×10^{-4}	≈ 0	2.6×10^{-3}	9.8×10^{-4}	4.5×10^{-4}

The impact of this uncertainty on the calculated limits is estimated by changing the dijet mass in the analysis within its uncertainty. The JER is known to a precision of 10%, and its non-Gaussian features observed in data are well described by the CMS simulation [44]. The effect of the JER uncertainty on the limits is estimated by changing the reconstructed resonance width within its uncertainty. The integrated luminosity has an uncertainty of 2.6% [57], which is also taken into account in the analysis.

The uncertainty related to the PDF used to model the signal acceptance is estimated from the CT10 [58], MSTW08 [59], and NNPDF21 [60] PDF sets. The envelope of the upward and downward variations of the estimated acceptance for the three sets is assigned as uncertainty [61] and found to be 5–15% in the resonance mass range of interest. A summary of all systematic uncertainties is given in Table 3 and 4. Among these uncertainties, the JES and JER are applied as shape uncertainties, while others are applied as uncertainty in the event yield.

Table 3: Systematic uncertainties common to all categories.

Source	HP uncertainties (%)	LP uncertainties (%)
JES	1	1
JER	10	10
Pileup	≤ 3.0	≤ 3.0
PDF	5–15	5–15
Integrated luminosity	2.6	2.6
W tagging	7.5	54
W tag p_T dependence	4	12

Table 4: Systematic uncertainties(%) for $X \rightarrow VH$ signals, in which $H \rightarrow b\bar{b}$ and $H \rightarrow WW^* \rightarrow 4q$. Numbers in parentheses represent the uncertainty for the corresponding LP category. If LP has the same uncertainty as HP, only the HP uncertainty is presented here.

Source	Final state		
	$H \rightarrow b\bar{b}$ VH_{bb}	$H \rightarrow WW^* \rightarrow 4q$ VH_{WW}	$H \rightarrow WW^* \rightarrow 4q$ VH_{WW}
$H \rightarrow b\bar{b}$ mass scale	2.6	—	—
H(4q) tagging	—	7.5 (54)	7.5 (54)
H(4q)-tag τ_{42} extrapolation	—	7	7
Cross-talk	7	24	24
b tagging	≤ 15	≤ 15	—

7 Results

The asymptotic approximation [62] of the LHC CL_s criterion [63, 64] is used to set upper limits on the cross section for resonance production. The dominant sources of systematic uncertainties are treated as nuisance parameters associated with log-normal priors in those variables. For a given value of the signal cross section, the nuisance parameters are fixed to the values that

maximize the likelihood, a method referred to as profiling. The dependence of the likelihood on parameters used to describe the background in Eq. (2) is treated in the same manner, and no additional systematic uncertainty is assigned to the parameterization of the background.

Events from the 5 categories of Table 1 are combined into a common likelihood, with the uncertainties of the HP and LP H tag (V tag) efficiencies considered to be anticorrelated between HP and LP tagging because events failing the HP τ_{42} (τ_{21}) selection migrate to the LP category and the fraction of events failing both HP and LP requirements is small compared to the HP and LP events. The branching fractions of $H \rightarrow WW^* \rightarrow 4q$ and $H \rightarrow b\bar{b}$ decays are taken as fixed values in joint likelihood. The remaining systematic uncertainties in the signal are fully correlated across all channels. The variables describing the background uncertainties are treated as uncorrelated. Fig. 10 shows the observed and background-only expected upper limits on the production cross sections for Z' and W' , including both $H \rightarrow b\bar{b}$ and $H \rightarrow WW^* \rightarrow 4q$ decays, computed at 95% confidence level (CL), with the predicted cross sections for the benchmark models overlaid for comparison. In the HVT model scenario B, W' and Z' are degenerate in resonance mass, thus we compute the limit on their combined cross section under this hypothesis, shown in Fig. 11. Table 5 shows the exclusion ranges on resonance masses.

Table 5: Summary of observed lower limits on resonance masses at 95% CL and their expected values, assuming a null hypothesis. The analysis is sensitive to resonances heavier than 1 TeV.

Process	Observed lower mass limit (TeV)	Expected lower mass limit (TeV)
$W' \rightarrow HW$	[1.0, 1.6]	1.7
$Z' \rightarrow HZ$	[1.0, 1.1], [1.3, 1.5]	1.3
$V' \rightarrow VH$	[1.0, 1.7]	1.9

8 Summary

A search for a massive resonance decaying into a standard model-like Higgs boson and a W or Z boson is presented. A data sample corresponding to an integrated luminosity of 19.7 fb^{-1} collected in proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$ with the CMS detector has been used to measure the W/Z and Higgs boson-tagged dijet mass spectra using the two highest p_T jets within the pseudorapidity range $|\eta| < 2.5$ and with pseudorapidity separation $|\Delta\eta| < 1.3$. The QCD background is suppressed using jet substructure tagging techniques, which identify boosted bosons decaying into hadrons. In particular, the mass of pruned jets and the N -subjettiness ratios τ_{21} and τ_{42} , as well as b tagging applied to the subjects of the Higgs boson jet, are used to discriminate against the otherwise overwhelming QCD background. The remaining QCD background is estimated from a fit to the dijet mass distributions using a smooth function. We have searched for the signal as a peak on top of the smoothly falling QCD background. No significant signal is observed. In the HVT model B, a Z' is excluded in resonance mass intervals [1.0, 1.1] and [1.3, 1.5] TeV, while a W' is excluded in the interval [1.0, 1.6] TeV. A mass degenerate W' plus Z' particle is excluded in the interval [1.0, 1.7] TeV.

This is the first search for heavy resonances decaying into a Higgs boson and a vector boson (W/Z) resulting in a hadronic final state, as well as the first application of jet substructure techniques to identify $H \rightarrow WW^* \rightarrow 4q$ decays of the Higgs boson at high Lorentz boost.

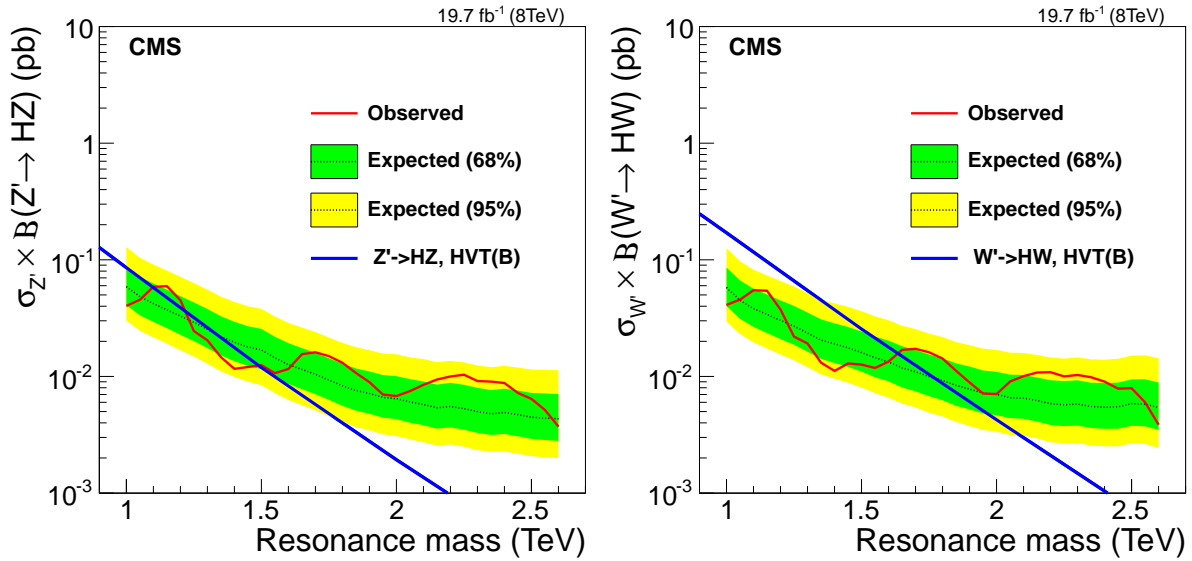


Figure 10: Expected and observed upper limits on the production cross sections for $Z' \rightarrow HZ$ (left) and $W' \rightarrow HW$ (right), including all five decay categories. Branching fractions of H and V decays have been taken into account. The theoretical predictions of the HVT model scenario B are also shown.

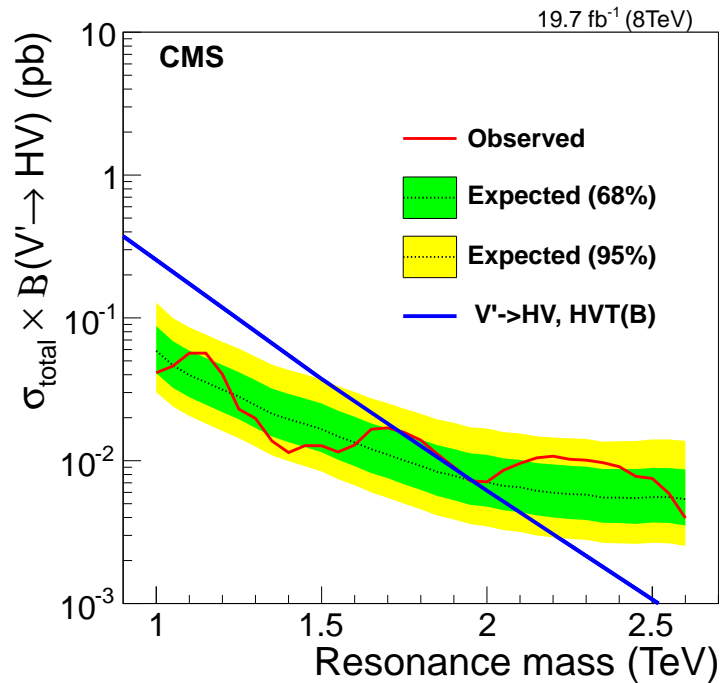


Figure 11: Expected and observed upper limits on the production cross section for $V' \rightarrow VH$, obtained by combining W' and Z' channels together. Branching fractions of H and V decays have been taken into account. The theoretical prediction of the HVT model scenario B is also shown.

Acknowledgments

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

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; and the National Priorities Research Program by Qatar National Research Fund.

References

- [1] R. Contino, D. Marzocca, D. Pappadopulo, and R. Rattazzi, "On the effect of resonances in composite Higgs phenomenology", *JHEP* **10** (2011) 081, doi:10.1007/JHEP10(2011)081, arXiv:1109.1570.
- [2] D. Marzocca, M. Serone, and J. Shu, "General composite Higgs models", *JHEP* **08** (2012) 013, doi:10.1007/JHEP08(2012)013, arXiv:1205.0770.
- [3] B. Bellazzini, C. Csáki, and J. Serra, "Composite Higgses", *Eur. Phys. J. C* **74** (2014) 2766, doi:10.1140/epjc/s10052-014-2766-x, arXiv:1401.2457.
- [4] T. Han, H. E. Logan, B. McElrath, and L.-T. Wang, "Phenomenology of the little Higgs model", *Phys. Rev. D* **67** (2003) 095004, doi:10.1103/PhysRevD.67.095004, arXiv:hep-ph/0301040.
- [5] M. Schmaltz and D. Tucker-Smith, "Little Higgs review", *Ann. Rev. Nucl. Part. Sci.* **55** (2005) 229, doi:10.1146/annurev.nucl.55.090704.151502, arXiv:hep-ph/0502182.

- [6] M. Perelstein, “Little Higgs models and their phenomenology”, *Prog. Part. Nucl. Phys.* **58** (2007) 247, doi:10.1016/j.pnpnp.2006.04.001, arXiv:hep-ph/0512128.
- [7] D. Pappadopulo, A. Thamm, R. Torre, and A. Wulzer, “Heavy vector triplets: bridging theory and data”, *JHEP* **09** (2014) 60, doi:10.1007/JHEP09(2014)060, arXiv:1402.4431.
- [8] 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, doi:10.1016/j.physletb.2014.11.026, arXiv:1407.3476.
- [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, doi:10.1016/j.physletb.2014.08.039, arXiv:1406.4456.
- [10] ATLAS Collaboration, “Search for resonant diboson production in the $\ell\ell q\bar{q}$ final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **75** (2015) 69, doi:10.1140/epjc/s10052-015-3261-8, arXiv:1409.6190.
- [11] ATLAS Collaboration, “Search for resonant diboson production in the $WW/WZ \rightarrow \ell\nu jj$ decay channels with the ATLAS detector at $\sqrt{s} = 7$ TeV”, *Phys. Rev. D* **87** (2013) 112006, doi:10.1103/PhysRevD.87.112006, arXiv:1305.0125.
- [12] 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”, *JHEP* **08** (2014) 173, doi:10.1007/JHEP08(2014)173, arXiv:1405.1994.
- [13] G. Altarelli, B. Mele, and M. Ruiz-Altaba, “Searching for new heavy vector bosons in $p\bar{p}$ colliders”, *Z. Phys. C* **45** (1989) 109, doi:10.1007/BF01556677.
- [14] CMS Collaboration, “Search for massive resonances decaying into pairs of boosted bosons in semi-leptonic final states at $\sqrt{s} = 8$ TeV”, *JHEP* **08** (2014) 174, doi:10.1007/JHEP08(2014)174, arXiv:1405.3447.
- [15] CMS Collaboration, “Search for narrow high-mass resonances in proton-proton collisions at $\sqrt{s} = 8$ TeV decaying to Z and Higgs bosons”, (2015). arXiv:1502.04994. Submitted to *Phys. Lett. B*.
- [16] ATLAS Collaboration, “Search for a new resonance decaying to a W or Z boson and a Higgs boson in the $\ell\ell/\ell\nu/\nu\nu + b\bar{b}$ final states with the ATLAS Detector”, (2015). arXiv:1503.08089. Submitted to EPJC.
- [17] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.
- [18] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
- [19] CMS Collaboration, “Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV”, (2014). arXiv:1411.3441. Submitted to *Phys. Rev. D*.

- [20] CMS Collaboration, “Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV”, (2014). arXiv:1412.8662. Submitted to EPJC.
- [21] M. Gouzevitch et al., “Scale-invariant resonance tagging in multijet events and new physics in Higgs pair production”, *JHEP* **07** (2013) 148, doi:10.1007/JHEP07(2013)148, arXiv:1303.6636.
- [22] 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.
- [23] CMS Collaboration, “Study of Jet Substructure in pp Collisions at 7 TeV in CMS”, CMS Physics Analysis Summary CMS-PAS-JME-10-013, 2010.
- [24] CMS Collaboration, “Identification techniques for highly boosted W bosons that decay into hadrons”, *JHEP* **12** (2014) 017, doi:10.1007/JHEP12(2014)017, arXiv:1410.4227.
- [25] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [26] J. Alwall et al., “MadGraph 5: going beyond”, *JHEP* **06** (2011) 128, doi:10.1007/JHEP06(2011)128, arXiv:1106.0522.
- [27] T. Sjöstrand, S. Mrenna, and P. Z. Skands, “PYTHIA 6.4 physics and manual”, *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.
- [28] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [29] D. Pappadopulo, A. Thamm, R. Torre, and A. Wulzer, “Resources for Heavy Vector Triplets”.
<https://rtorre.web.cern.ch/rtorre/Riccardotorre/heptools.html>.
- [30] S. Gieseke et al., “Herwig++ 2.5 Release Note”, (2011). arXiv:1102.1672.
- [31] R. Field, “Early LHC Underlying Event Data – Findings and Surprises”, in *Proceedings of the Hadron Collider Physics Symposium*. 2010. arXiv:1010.3558.
- [32] J. Pumplin et al., “New generation of parton distributions with uncertainties from global QCD analysis”, *JHEP* **07** (2002) 012, doi:10.1088/1126-6708/2002/07/012, arXiv:hep-ph/0201195.
- [33] P. Nason, “A New method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [34] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [35] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.

- [36] CMS Collaboration, "Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and E_T^{miss} ", CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009.
- [37] CMS Collaboration, "Commissioning of the Particle-flow Event Reconstruction with the first LHC collisions recorded in the CMS detector", CMS Physics Analysis Summary CMS-PAS-PFT-10-001, 2010.
- [38] M. Wobisch and T. Wengler, "Hadronization corrections to jet cross-sections in deep inelastic scattering", (1998). arXiv:hep-ph/9907280.
- [39] Y. L. Dokshitzer, G. D. Leder, S. Moretti, and B. R. Webber, "Better jet clustering algorithms", *JHEP* **08** (1997) 001, doi:10.1088/1126-6708/1997/08/001, arXiv:hep-ph/9707323.
- [40] M. Cacciari and G. P. Salam, "Dispelling the N^3 myth for the k_t jet-finder", *Phys. Lett. B* **641** (2006) 57, doi:10.1016/j.physletb.2006.08.037, arXiv:hep-ph/0512210.
- [41] M. Cacciari, G. P. Salam, and G. Soyez, "FastJet user manual", *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [42] M. Cacciari, G. P. Salam, and G. Soyez, "The catchment area of jets", *JHEP* **04** (2008) 005, doi:10.1088/1126-6708/2008/04/005, arXiv:0802.1188.
- [43] M. Cacciari and G. P. Salam, "Pileup subtraction using jet areas", *Phys. Lett. B* **659** (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378.
- [44] CMS Collaboration, "Determination of jet energy calibration and transverse momentum resolution in CMS", *J. Instrum.* **6** (2011) P11002, doi:10.1088/1748-0221/6/11/P11002.
- [45] CMS Collaboration, "Jet Performance in pp Collisions at $\sqrt{s}=7$ TeV", CMS Physics Analysis Summary CMS-PAS-JME-10-003, 2010.
- [46] CMS Collaboration, "Search for narrow resonances using the dijet mass spectrum in pp collisions at $\sqrt{s} = 8$ TeV", *Phys. Rev. D* **87** (2013) 114015, doi:10.1103/PhysRevD.87.114015, arXiv:1302.4794.
- [47] S. D. Ellis, C. K. Vermilion, and J. R. Walsh, "Techniques for improved heavy particle searches with jet substructure", *Phys. Rev. D* **80** (2009) 051501, doi:10.1103/PhysRevD.80.051501, arXiv:0903.5081.
- [48] S. D. Ellis, C. K. Vermilion, and J. R. Walsh, "Recombination algorithms and jet substructure: Pruning as a tool for heavy particle searches", *Phys. Rev. D* **81** (2010) 094023, doi:10.1103/PhysRevD.81.094023, arXiv:0912.0033.
- [49] CMS Collaboration, "Identification of b-quark jets with the CMS experiment", *JINST* **8** (2013) P04013, doi:10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.
- [50] M. Cacciari, G. P. Salam, and G. Soyez, "The anti- k_t jet clustering algorithm", *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [51] J. Thaler and K. Van Tilburg, "Identifying boosted objects with N-subjettiness", *JHEP* **03** (2011) 015, doi:10.1007/JHEP03(2011)015, arXiv:1011.2268.

- [52] J. Thaler and K. Van Tilburg, “Maximizing boosted top identification by minimizing N -subjettiness”, *JHEP* **02** (2012) 093, doi:10.1007/JHEP02(2012)093, arXiv:1108.2701.
- [53] I. W. Stewart, F. J. Tackmann, and W. J. Waalewijn, “ N -Jettiness: An Inclusive Event Shape to Veto Jets”, *Phys. Rev. Lett.* **105** (2010) 092002, doi:10.1103/PhysRevLett.105.092002, arXiv:1004.2489.
- [54] R. G. Lomax and D. L. Hahs-Vaughn, “Statistical Concepts: A Second Course”. Routledge Academic, third edition, 2007.
- [55] G. Punzi, “Sensitivity of searches for new signals and its optimization”, in *Statistical Problems in Particle Physics, Astrophysics, and Cosmology*, L. Lyons, R. Mount, and R. Reitmeyer, eds., p. 79. 2003. arXiv:physics/0308063.
- [56] CMS Collaboration, “Status of the 8 TeV Jet Energy Corrections and Uncertainties based on 11 fb^{-1} of data in CMS”, CMS Detector Performance Note CMS-DP-2013-011, 2013.
- [57] CMS Collaboration, “CMS Luminosity Based on Pixel Cluster Counting - Summer 2013 Update”, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013.
- [58] H.-L. Lai et al., “New parton distributions for collider physics”, *Phys. Rev. D* **82** (2010) 074024, doi:10.1103/PhysRevD.82.074024, arXiv:1007.2241.
- [59] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, “Parton distributions for the LHC”, *Eur. Phys. J. C* **63** (2009) 189, doi:10.1140/epjc/s10052-009-1072-5, arXiv:0901.0002.
- [60] NNPDF Collaboration, “Fitting parton distribution data with multiplicative normalization uncertainties”, *JHEP* **05** (2010) 075, doi:10.1007/JHEP05(2010)075, arXiv:0912.2276.
- [61] S. Alekhin et al., “The PDF4LHC Working Group Interim Report”, (2011). arXiv:1101.0536.
- [62] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:physics/1007.1727.
- [63] A. L. Read, “Presentation of search results: the CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [64] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, V. Knünz, A. König, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady², B. Rahbaran, H. Rohringer, J. Schieck¹, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

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

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

S. Alderweireldt, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, S. Ochesanu, R. Rougny, M. Van De Klundert, H. Van Haeevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium

P. Barria, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, D. Dobur, G. Fasanella, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè, A. Randle-conde, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang, F. Zenoni

Ghent University, Ghent, Belgium

K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

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

S. Basegmez, C. Beluffi³, O. Bondu, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silva, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco⁴, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaître, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrkowski, A. Popov⁵, L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium

N. Bely, T. Caebergs, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, C. Hensel, C. Mora Herrera, A. Moraes, M.E. Pol, P. Rebello Teles

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁶, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁶, A. Vilela Pereira

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

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

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Aleksandrov, V. Genchev², R. Hadjiiska, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria

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

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina⁷, F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang

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

C. Asawatrangkuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, F. Zhang⁸, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

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

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

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, K. Kadija, J. Luetic, L. Sudic

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Bodlak, M. Finger, M. Finger Jr.⁹

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

A. Ali^{10,11}, R. Aly¹², S. Aly¹², S. Elgammal¹¹, A. Ellithi Kamel¹³, A. Lotfy¹⁴, M.A. Mahmoud¹⁴, A. Radi^{11,10}, E. Salama^{10,11}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland

J. Talvitie, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms, O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram¹⁵, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹⁵, J.-C. Fontaine¹⁵, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin², K. Skovpen, P. Van Hove

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

S. Gadrat

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

S. Beauceron, N. Beaupere, C. Bernet⁷, G. Boudoul², E. Bouvier, S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

I. Bagaturia¹⁶

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

C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov⁵

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

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

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann², A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, J. Garay

Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel¹⁷, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁷, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, R. Mankel, I. Marfin¹⁷, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, B. Roland, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, C. Wissing

University of Hamburg, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, H. Kirschenmann, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, D. Nowatschin, J. Ott, T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vaneldereren, A. Vanhoefer

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann², U. Husemann, I. Katkov⁵, A. Kornmayer², P. Lobelle Pardo, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, C. Wöhrmann, R. Wolf

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

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

University of Athens, Athens, Greece

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioánnina, Greece

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

Wigner Research Centre for Physics, Budapest, Hungary

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

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²⁰, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary

M. Bartók²¹, A. Makovec, P. Raics, Z.L. Trocsanyi

National Institute of Science Education and Research, Bhubaneswar, India

P. Mal, K. Mandal, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

Ashok Kumar, Arun Kumar, A. Bhardwaj, B.C. Choudhary, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik²², R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu²³, G. Kole, S. Kumar, M. Maity²², G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Sur, B. Sutar, N. Wickramage²⁴

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

S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami²⁵, A. Fahim²⁶, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh²⁷, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, C. Calabria^{a,b}, C. Caputo^{a,b}, S.S. Chhibra^{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,c}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b,2}, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,2}, R. Venditti^{a,b}, P. Verwilligen^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, C. Battilana, A.C. Benvenuti^a, 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, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b}, R. Travaglini^{a,b}

INFN Sezione di Catania ^a, Università di Catania ^b, CSFNSM ^c, Catania, Italy

G. Cappello^a, M. Chiorboli^{a,b}, S. Costa^{a,b}, F. Giordano^{a,c,2}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

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

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, V. Gori^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,b}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

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

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

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

M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^{a,2}, R. Gerosa^{a,b}, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M.T. Lucchini^{a,b,2}, S. Malvezzi^a, R.A. Manzoni^{a,b}, B. Marzocchi^{a,b,2}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, T. Tabarelli de Fatis^{a,b}

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

S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,2}, M. Esposito^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, G. Lanza^a, L. Lista^a, S. Meola^{a,d,2}, M. Merola^a, P. Paolucci^{a,2}, C. Sciacca^{a,b}

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

P. Azzi^{a,2}, D. Bisello^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, F. Gonella^a, A. Gozzelino^a, K. Kanishchev^{a,c}, S. Lacaprara^a, M. Margoni^{a,b}, G. Maron^{a,28}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, M. Zanetti, P. Zotto^{a,b}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

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

M. Gabusi^{a,b}, A. Magnani^a, S.P. Ratti^{a,b}, V. Re^a, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^a, P. Vitulo^{a,b}

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

L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b,2}, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b,2}

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

K. Androsov^{a,29}, P. Azzurri^a, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, G. Broccoli^{a,c}, R. Castaldi^a, M.A. Ciocci^{a,29}, R. Dell'Orso^a, S. Donato^{a,c,2}, G. Fedi, F. Fiori^{a,c}, L. Foà^{a,c†}, A. Giassi^a, M.T. Grippo^{a,29}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, C.S. Moon^{a,30}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,31}, A.T. Serban^a, P. Spagnolo^a, P. Squillacioti^{a,29}, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

INFN Sezione di Roma ^a, Università di Roma ^b, Roma, Italy

L. Barone^{a,b}, F. Cavallari^a, G. D'imperio^{a,b}, D. Del Re^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, C. Jorda^a, E. Longo^{a,b}, F. Margaroli^{a,b}, P. Meridiani^a, F. Micheli^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}, L. Soffi^{a,b}, P. Traczyk^{a,b,2}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, S. Casasso^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, P. De Remigis^a, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b,2}, C. Mariotti^a, S. Maselli^a, G. Mazza^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^a, M.M. Obertino^{a,c}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, V. Candelise^{a,b,2}, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, C. La Licata^{a,b}, M. Marone^{a,b}, A. Schizzi^{a,b}, T. Umer^{a,b}, A. Zanetti^a

Kangwon National University, Chunchon, Korea

S. Chang, A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea

H. Kim, T.J. Kim, M.S. Ryu

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

S. Song

Korea University, Seoul, Korea

S. Choi, Y. Go, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea

H.D. Yoo

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania

A. Juodagalvis, J. Vaitkus

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

Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali³², F. Mohamad Idris, W.A.T. Wan Abdullah

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

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, A. Hernandez-Almada, R. Lopez-Fernandez, G. Ramirez Sanchez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarguen

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

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler, S. Reucroft

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

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland

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

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

G. Brona, K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev³³, P. Moiseenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, T. Toriashvili³⁴, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim³⁵, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

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

A. Bylinkin

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁶, I. Dremin³⁶, M. Kirakosyan, A. Leonidov³⁶, G. Mesyats, S.V. Rusakov, A. Vinogradov

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

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin³⁷, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin

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

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

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

P. Adzic³⁸, M. Ekmedzic, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, 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, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizán Garcia

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, G.M. Berruti, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi³⁹, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi⁴⁰, M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas⁴¹, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres¹⁹, N. Wardle, H.K. Wöhri, A. Zagozdzińska⁴², W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

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

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, N. Mohr, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, M. Rossini, A. Starodumov⁴³, M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁴⁴, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, D. Salerno, S. Taroni, Y. Yang

National Central University, Chung-Li, Taiwan

M. Cardaci, K.H. Chen, T.H. Doan, C. Ferro, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Chang, Y.H. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.f. Tsai, Y.M. Tzeng, R. Wilken

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

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci⁴⁵, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler,

E. Gurpinar, I. Hos, E.E. Kangal⁴⁶, G. Onengut⁴⁷, K. Ozdemir⁴⁸, A. Polatoz, D. Sunar Cerci⁴⁹, M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, B. Bilin, S. Bilmis, B. Isildak⁵⁰, G. Karapinar⁵¹, U.E. Surat, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E.A. Albayrak⁵², E. Gülmez, M. Kaya⁵³, O. Kaya⁵⁴, T. Yetkin⁵⁵

Istanbul Technical University, Istanbul, Turkey

K. Cankocak, Y.O. Günaydin⁵⁶, F.I. Vardarli

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

B. Grynyov

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

L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold⁵⁷, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁵⁸, C. Brew, R.M. Brown, 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, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, M. Citron, D. Colling, L. Corpe, N. Cripps, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas⁵⁷, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko⁴³, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, P. Sharp[†], A. Tapper, K. Uchida, M. Vazquez Acosta, T. Virdee, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika, T. Scarborough

The University of Alabama, Tuscaloosa, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA

A. Avetisyan, T. Bose, C. Fantasia, D. Gastler, P. Lawson, D. Rankin, C. Richardson, J. Rohlf, J. St. John, L. Sulak, D. Zou

Brown University, Providence, USA

J. Alimena, E. Berry, S. Bhattacharya, D. Cutts, Z. Demiragli, N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Sagir, T. Sinthuprasith

University of California, Davis, Davis, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova Rikova, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, S. Sumowidagdo, H. Wei, S. Wimpenny

University of California, San Diego, La Jolla, USA

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, D. Kovalskyi, J. Letts, I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵⁹, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, W. To, C. West, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, J.G. Smith, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, L. Skinnari, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klima, B. Kreis, S. Kwan[†], S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, A. Whitbeck, F. Yang, H. Yin

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic⁶⁰, G. Mitselmakher, L. Muniz, D. Rank, A. Rinkevicius, L. Shchutska, M. Snowball, D. Sperka, S.J. Wang, J. Yelton

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

A. Ackert, J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA

V. Bhopatkar, M. Hohlmann, H. Kalakhety, D. Mareskas-palcek, T. Roy, F. Yumiceva

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

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas, Z. Wu, M. Zakaria

The University of Iowa, Iowa City, USA

B. Bilki⁶¹, W. Clarida, K. Dilsiz, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶², A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁵², A. Penzo, S. Sen, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA

I. Anderson, B.A. Barnett, B. Blumenfeld, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, K. Nash, M. Osherson, M. Swartz, M. Xiao, Y. Xin

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, D. Noonan, S. Sanders, R. Stringer, Q. Wang, J.S. Wood

Kansas State University, Manhattan, USA

I. Chakaberia, A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, N. Skhirtladze, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA

D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, Y. Lu, A.C. Mignerey, K. Pedro, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA

A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, C. McGinn, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

University of Minnesota, Minneapolis, USA

B. Dahmes, A. Finkel, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, S. Nourbakhsh, R. Rusack, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, J. Monroy, F. Ratnikov, G.R. Snow

State University of New York at Buffalo, Buffalo, USA

M. Alyari, J. Dolen, J. George, A. Godshalk, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Trovato, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA

A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³³, T. Pearson, M. Planer, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

Purdue University, West Lafayette, USA

V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D.H. Miller, N. Neumeister, F. Primavera, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki

Purdue University Calumet, Hammond, USA

N. Parashar, J. Stupak

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, M. Verzetti, D. Vishnevskiy

The Rockefeller University, New York, USA

L. Demortier

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

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

M. Foerster, K. Rose, S. Spanier, A. York

Texas A&M University, College Station, USA

O. Bouhali⁶³, A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁶⁴, V. Krutelyov, R. Montalvo, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, I. Suarez, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duerdo, J. Faulkner, K. Kovitanggoon, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

Vanderbilt University, Nashville, USA

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, E. Wolfe, J. Wood, F. Xia

Wayne State University, Detroit, USA

C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin, Madison, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, A. Christian, S. Dasu, L. Dodd, S. Duric, E. Friis, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Ruggles, T. Sarangi, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased

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

2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

6: Also at Universidade Estadual de Campinas, Campinas, Brazil

7: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

8: Also at Université Libre de Bruxelles, Bruxelles, Belgium

9: Also at Joint Institute for Nuclear Research, Dubna, Russia

10: Also at Ain Shams University, Cairo, Egypt

11: Now at British University in Egypt, Cairo, Egypt

12: Now at Helwan University, Cairo, Egypt

-
- 13: Also at Cairo University, Cairo, Egypt
 - 14: Now at Fayoum University, El-Fayoum, Egypt
 - 15: Also at Université de Haute Alsace, Mulhouse, France
 - 16: Also at Ilia State University, Tbilisi, Georgia
 - 17: Also at Brandenburg University of Technology, Cottbus, Germany
 - 18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
 - 19: Also at Eötvös Loránd University, Budapest, Hungary
 - 20: Also at University of Debrecen, Debrecen, Hungary
 - 21: Also at Wigner Research Centre for Physics, Budapest, Hungary
 - 22: Also at University of Visva-Bharati, Santiniketan, India
 - 23: Now at King Abdulaziz University, Jeddah, Saudi Arabia
 - 24: Also at University of Ruhuna, Matara, Sri Lanka
 - 25: Also at Isfahan University of Technology, Isfahan, Iran
 - 26: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
 - 27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
 - 28: Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
 - 29: Also at Università degli Studi di Siena, Siena, Italy
 - 30: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
 - 31: Also at Purdue University, West Lafayette, USA
 - 32: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
 - 33: Also at Institute for Nuclear Research, Moscow, Russia
 - 34: Also at Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
 - 35: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
 - 36: Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
 - 37: Also at California Institute of Technology, Pasadena, USA
 - 38: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
 - 39: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
 - 40: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
 - 41: Also at University of Athens, Athens, Greece
 - 42: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
 - 43: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
 - 44: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
 - 45: Also at Gaziosmanpasa University, Tokat, Turkey
 - 46: Also at Mersin University, Mersin, Turkey
 - 47: Also at Cag University, Mersin, Turkey
 - 48: Also at Piri Reis University, Istanbul, Turkey
 - 49: Also at Adiyaman University, Adiyaman, Turkey
 - 50: Also at Ozyegin University, Istanbul, Turkey
 - 51: Also at Izmir Institute of Technology, Izmir, Turkey
 - 52: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
 - 53: Also at Marmara University, Istanbul, Turkey
 - 54: Also at Kafkas University, Kars, Turkey
 - 55: Also at Yildiz Technical University, Istanbul, Turkey
 - 56: Also at Kahramanmaras Sütcü Imam University, Kahramanmaras, Turkey
 - 57: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
 - 58: Also at School of Physics and Astronomy, University of Southampton, Southampton,

United Kingdom

59: Also at Utah Valley University, Orem, USA

60: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

61: Also at Argonne National Laboratory, Argonne, USA

62: Also at Erzincan University, Erzincan, Turkey

63: Also at Texas A&M University at Qatar, Doha, Qatar

64: Also at Kyungpook National University, Daegu, Korea