EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

JHEP 09 (2019) 091
DOI: 10.1007/JHEP09(2019)091

CERN-EP-2019-044
12th June 2020

arXiv:1906.08589v3 [hep-ex] 11 Jun 2020

Search for diboson resonances in hadronic final states in 139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Narrow resonances decaying into WW, WZ or ZZ boson pairs are searched for in 139 fb^{-1} of proton–proton collision data at a centre-of-mass energy of $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider from 2015 to 2018. The diboson system is reconstructed using pairs of high transverse momentum, large-radius jets. These jets are built from a combination of calorimeter- and tracker-inputs compatible with the hadronic decay of a boosted W or Z boson, using jet mass and substructure properties. The search is performed for diboson resonances with masses greater than 1.3 TeV. No significant deviations from the background expectations are observed. Exclusion limits at the 95% confidence level are set on the production cross-section times branching ratio into dibosons for resonances in a range of theories beyond the Standard Model, with the highest excluded mass of a new gauge boson at 3.8 TeV in the context of mass-degenerate resonances that couple predominantly to gauge bosons.

© 2020 CERN for the benefit of the ATLAS Collaboration.
Reproduction of this article or parts of it is allowed as specified in the CC-BY-4.0 license.

1 Introduction

The discovery of new phenomena in high-energy proton–proton (pp) collisions is one of the main goals of the Large Hadron Collider (LHC). New heavy, TeV-scale, resonances of vector bosons VV (where V represents a W or a Z boson) are a possible signature of such new physics and are predicted in several extensions to the Standard Model (SM). These include extended gauge-symmetry models [1–3], Grand Unified theories [4–7], theories with warped extra dimensions [8–12], two-Higgs-doublet models [13], little-Higgs models [14], theories with new strong dynamics [15], including technicolour [16–18], and more generic composite Higgs models [19]. The data sample of 36.7 fb^{-1} of pp collisions collected in 2015 and 2016 at the LHC at $\sqrt{s} = 13$ TeV offered improved sensitivity to heavy diboson resonances compared with earlier results. The ATLAS and CMS collaborations performed searches in the fully hadronic final states using this data [20–22] but no significant deviation from a smooth background consistent with the SM expectation was observed. Searches by ATLAS [23, 24] and CMS [25, 26] for semileptonic decay modes of the boson pair, as well as statistical combinations of various decay channels [27], on the same data also did not reveal any hint of new physics.

This paper presents a search for narrow diboson resonances decaying into fully hadronic final states in 139 fb^{-1} of pp collision data collected by the ATLAS experiment between 2015 and 2018. The W and Z bosons produced in the decay of TeV-scale resonances are highly boosted, and are therefore reconstructed in ATLAS as a single large-radius-parameter jet. The signature of such heavy resonance decays is thus a resonant structure in the dijet invariant mass spectrum. Although the hadronic decays of vector bosons have the largest branching ratio (67% for W and 70% for Z bosons), they suffer from background contamination from the production of multijet events. This background is larger by several orders of magnitude, and to suppress it, the characteristic jet substructure of W/Z boson decays is used. Contributions to the background from SM processes containing bosons, V + jets, SM VV, $t\bar{t}$ and single top production, are significantly smaller.

To improve the sensitivity of this search, new techniques are used. Novel inputs are used for jet finding, which improve the jet substructure resolution of ATLAS in highly boosted topologies [28]. To further benefit from these developments, a new approach for identifying boosted boson candidates is introduced. The identification of the boosted boson candidates is validated using the known SM V + jets production.

To avoid limitations caused by poor modelling or limited numbers of Monte Carlo (MC) generated background events, the observed background is characterised by a parametric function fit to the smoothly falling dijet invariant mass distribution. To assess the sensitivity of the search, to optimise the event selection and for comparison with the observed data, three specific benchmark models are used: a spin-0 radion [29] decaying into WW or ZZ; a spin-1 Heavy Vector Triplet (HVT) Model [30] that provides signals such as $W' \rightarrow WZ$ and $Z' \rightarrow WW$; and a spin-2 graviton $G_{\text{KK}} \rightarrow WW$ or ZZ, corresponding to Kaluza–Klein (KK) modes [8, 9] of the Randall–Sundrum (RS) graviton [10–12]. These models assume production mechanisms either via gluon–gluon fusion or quark–antiquark annihilation.

2 ATLAS detector

The ATLAS detector [31] surrounds nearly the entire solid angle around the ATLAS collision point. It has an approximately cylindrical geometry[1] and consists of an inner tracking detector surrounded by electromagnetic and hadronic calorimeters and a muon spectrometer. The tracking detector is placed within a 2 T axial magnetic field provided by a superconducting solenoid and measures charged-particle trajectories with silicon pixel and silicon microstrip detectors that cover the pseudorapidity range $|\eta| < 2.5$, and with a straw-tube transition radiation tracker covering $|\eta| < 2.0$. A new innermost pixel layer [32, 33] inserted at a radius of 3.3 cm has been used since 2015.

Electromagnetic and hadronic calorimeter systems provide energy measurements with high granularity. The electromagnetic calorimeter is a liquid-argon (LAr) sampling calorimeter with lead absorbers, spanning $|\eta| < 3.2$ with barrel and endcap sections. The three-layer central hadronic calorimeter comprises scintillator tiles with steel absorbers and extends to $|\eta| = 1.7$. The hadronic endcap calorimeters measure particles in the region $1.5 < |\eta| < 3.2$ using liquid argon with copper absorbers. The forward calorimeters cover $3.1 < |\eta| < 4.9$, using LAr/copper modules for electromagnetic energy measurements and LAr/tungsten modules to measure hadronic energy.

The muon spectrometer surrounds the calorimetry system and provides precision muon tracking and triggering. It includes three large superconducting air-core toroids providing a magnetic field for accurate momentum measurements in tracking drift chambers arranged in a barrel, covering $|\eta| < 1.0$, and endcaps, extending to $|\eta| = 2.7$.

Events are recorded in ATLAS if they satisfy a two-level trigger requirement [34]. The level-1 trigger detects jet and particle signatures in the calorimeter and muon systems with a fixed latency of 2.5 μs, and is designed to reduce the event rate to about 100 kHz. Jets are identified at level-1 with a sliding-window algorithm, searching for local maxima in square regions with size $\Delta\eta \times \Delta\phi = 0.8 \times 0.8$. The subsequent high-level trigger consists of software-based trigger filters that reduce the event rate to one kHz.

3 Data

The search is performed using data collected by the ATLAS experiment from 2015 to 2018 from $\sqrt{s} = 13$ TeV LHC pp collisions. Events used in this search satisfied a single-jet trigger requiring at least one jet reconstructed at each trigger level. The final filter in the high-level trigger required a jet to satisfy a high transverse momentum (p_{T}) threshold, $p_{\mathrm{T}} \geq 360$ GeV (2015), $p_{\mathrm{T}} \geq 420$ GeV (2016), $p_{\mathrm{T}} \geq 440$ GeV (2017 and 2018), reconstructed with the anti-k_t algorithm [35] and a large radius parameter ($R = 1.0$). Calorimeter-cell energy clusters calibrated to the hadronic scale utilising the local cell signal weighting method [36] were used as inputs. These are referred to as topo-clusters in this paper. After requiring that the data were collected during stable beam conditions and the detector components relevant to the analysis were functional, the integrated luminosity was 3.2 fb^{-1} in 2015, 33.0 fb^{-1} in 2016, 44.3 fb^{-1} in 2017 and 58.5 fb^{-1} in 2018.

---

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

4 Simulation

4.1 Signal Models

MC simulation of signal events is used to optimise the sensitivity of the search and to interpret its results. Signals are simulated in three benchmark scenarios.

In the first scenario, the gravitational fluctuations in the extra dimension of the Randall–Sundrum framework correspond to scalar fields, known as the radion, which are massless in the simplest scenario. A fundamental problem in the original Randall–Sundrum framework is that it lacks a mechanism to stabilise the radius of the compactified extra dimension, r_c. One possible mechanism to achieve this is to introduce an additional bulk scalar radion, produced via gluon–gluon fusion, which has its interactions localised on the two ends of the extra dimension [37, 38]. This causes the radion field to acquire a mass term, which is typically much smaller than the first KK excitation mass. The coupling of the radion field to SM fields scales inversely proportional to the model parameter $\Lambda_\mathrm{R} = \sqrt{g} \times k \times \mathrm{e}^{-k\pi r_\mathrm{c}} \sqrt{M_5^3/k^3}$ where M_5 is the 5-dimensional Planck mass, which has been extensively studied in the literature [29, 39, 40], k the curvature factor, and g is the 5-dimensional metric. The size of the extra dimension, defined as $k\pi r_\mathrm{c}$, is another parameter of the model. In this analysis, the curvature factor is set to $k\pi r_\mathrm{c} = 35$, and $\Lambda_\mathrm{R} = 3$ TeV is used.

The couplings of the radion to fermions are proportional to the masses of the fermions, while the couplings are proportional to the square of the masses for bosons. For radion mass above ~ 1 TeV, the dominant decay mode is into pairs of bosons. The decay width of the radion is approximately 10% of its pole mass, resulting in observable mass peaks with a width comparable to the experimental resolution (see Section 6.3). The calculated production cross-section times branching ratio ($\sigma \times \mathcal{B}$) for a radion decaying into WW, with the W decaying hadronically, is 6.3 fb and 0.61 fb for radion masses of 2 TeV and 3 TeV, respectively. Corresponding values for a radion decaying into ZZ are 3.1 fb and 0.30 fb.

The second scenario is based on two benchmark models, A and B, of the HVT phenomenological Lagrangian [30]. The Lagrangian introduces a new heavy vector triplet V', where V' refers to W' and Z', produced via quark–antiquark annihilation, whose members are degenerate in mass, and parameterises its couplings to SM fields in a generic manner, such that a large class of extensions to the SM can be described.

Model A with the strength of the vector-boson interaction $g_V = 1$ [30] describes scenarios where the new triplet field couples weakly to the SM fields and arises from an extension of the SM gauge group, with the heavy vector bosons having comparable branching ratios into fermions and gauge bosons. For W' and Z' masses of interest, the width of the new heavy bosons is approximately 2.5%, which results in observable mass peaks with a width dominated by the experimental resolution. The branching fraction of the new heavy boson W' (Z') to each of the WZ and WH (WW and ZH) final states, where H represents the Higgs boson, is approximately 2%. The calculated $\sigma \times \mathcal{B}$ values for $W' \rightarrow WZ$, with W and Z bosons decaying hadronically, are 8.3 fb and 0.75 fb for W' masses of 2 TeV and 3 TeV, respectively. Corresponding values for $Z' \rightarrow WW$ are 3.8 fb and 0.34 fb.

Model B with $g_V = 3$ is representative of composite Higgs models, where the fermionic couplings to V' are suppressed. The width of the resonances are identical to Model A. For the W' and Z' masses of interest, the branching fraction of the new heavy boson W' (Z') to each of the WZ and WH (WW and ZH) final states is close to 50%. Resonance widths and experimental signatures are similar to those obtained for model A and the predicted $\sigma \times \mathcal{B}$ values for $W' \to WZ$, with hadronic W and Z decays, are 13 fb and 1.3 fb for W' masses of 2 TeV and 3 TeV, respectively. Corresponding values for $Z' \to WW$ are 6.0 fb and 0.55 fb.

The third scenario considered is the bulk RS model [10] that extends the original RS model [8, 41] with a warped extra dimension, by allowing the SM fields to propagate in the bulk of the extra dimension. This model is characterised by a dimensionless coupling constant $\kappa/\overline{M}_{\text{Pl}} \sim 1$, where κ is the curvature of the warped extra dimension, and $\overline{M}_{\text{Pl}}$ is the reduced Planck mass. In this model, a Kaluza–Klein graviton, G_{KK}, predominately produced via gluon–gluon fusion, decays into pairs of top quarks, pairs of Higgs bosons, WW and ZZ with significant branching fractions. The branching fraction of the G_{KK} to WW (ZZ) ranges from 24% to 20% (12% to 10%) as the mass increases. The decay width of the G_{KK} is approximately 6% of its pole mass, resulting in observable mass peaks with a width comparable to the experimental resolution, and $\sigma \times \mathcal{B}$ for $G_{\text{KK}} \to WW$, with the W decaying hadronically, is 1.29 fb and 0.06 fb for G_{KK} masses of 2 TeV and 3 TeV, respectively. Corresponding values for $G_{\text{KK}} \to ZZ$ are 0.65 fb and 0.03 fb.

4.2 Simulated event samples

For all MC samples, all hadronic decays were imposed at the generator level. MC samples for the radion, HVT, and RS models, were generated using MadGraph 2.2.2 [42] interfaced to Pythia 8.186 [43] for hadronisation using the leading-order (LO) NNPDF 2.3 parton distribution function (PDF) set [44] and the ATLAS A14 set of tuned parameters for the underlying event [45]. In all signal samples, the W and Z bosons are primarily longitudinally polarised. The procedure to derive the optimal boson identification criteria (Section 6.1) uses a dedicated sample of W' decaying only into W/Z bosons that in turn decay hadronically. Pythia 8.186 was used to generate this sample with the A14 set of tuned parameters for the underlying event and the NNPDF 2.3 LO PDF. The cross-section of the hard-scattering process was modified by applying an event-by-event weighting factor to broaden the width of the resonance and widen the p_{T} distribution of the electroweak bosons produced in its hadronic decays.

Pythia 8.186 with the NNPDF 2.3 LO PDF set and the A14 set of tuned parameters was used to generate and shower multijet background events. Samples of W+jets and Z+jets events were generated with Sherpa 2.2.5 [46–49] interfaced with the NNPDF 3.0 next-to-next-to-leading-order (NNLO) PDF set [50]. A $t\bar{t}$ sample generated with Powheg-Box v2 [51–53] with the NNPDF 3.0 next-to-leading-order (NLO) PDF [54], interfaced with Pythia 8.186 with the NNPDF 2.3 LO PDF and the A14 set of tuned parameters for parton showering is used for the V+jets study. EvtGen v1.2.0 [55] was used for properties of bottom and charm hadron decays, except for samples generated by Sherpa.

For all MC samples, the final-state particles produced by the generators were propagated through a detailed detector simulation based on GEANT4 [56, 57]. The mean number of pp interactions per bunch crossing, ‘pile-up’, was approximately 33 in the collision data being used for the analysis. The expected contribution from these minimum-bias pp interactions was accounted for by overlaying additional minimum-bias events generated with Pythia 8.186 using the ATLAS A3 [58] set of tuned parameter. The MC simulation events were weighted to match the distribution of the average number of interactions per bunch crossing observed in collision data. Simulated events were then reconstructed with the same algorithms as run on the collision data.

5 Reconstruction

The experimental signatures central to this analysis are hadronic jets. Since the decay products of TeV-scale resonances are highly boosted, their decay products become increasingly collimated and they are therefore reconstructed as a single large-radius jet. It is important that they can still be differentiated from multijet events where a jet is initiated by a single quark or gluon. This relies on both the energy and angular resolution of the detector used to reconstruct the jet. Although the analysis primarily relies on jets, reconstruction of lepton candidates is necessary to reject events that could bias the SM V+jets studies presented in Section 6.2.

5.1 Track-CaloClusters

In previous analyses, ATLAS has mainly focused on the use of calorimeter-based jet substructure, which exploits the exceptional energy resolution of the ATLAS calorimetry [36]. However, as the event becomes even more energetic, jets become so collimated that the calorimeter lacks the angular resolution to resolve the desired structure inside the jet. For boson jets with high transverse momentum, p_{T}, only a handful of calorimeter-cell clusters are created, each with limited angular resolution, but excellent energy resolution. On the other hand, the tracking detector has excellent angular resolution and good reconstruction efficiency at very high energy [59], while its momentum resolution deteriorates. By combining information from the ATLAS calorimeter and tracking detectors, the precision of jet substructure techniques can be improved for a wide range of energies. This analysis uses a new unified object built from both the tracking and the calorimeter information, referred to as Track-CaloClusters (TCCs) [28]. This procedure is a type of particle flow, complementary to the energy subtraction algorithm described in the ATLAS particle flow paper [60] which improves the energy resolution of low-energy jets. The two algorithms are designed to improve the jet reconstruction performance in very different energy regimes, reflected in their distinct four-momentum construction and energy sharing procedures. Energy sharing in the TCC approach is based solely on a weighting scheme where only the relative track momenta are used to spatially redistribute the energy measured in the calorimeter. In practice, this means that the TCC algorithm uses the spatial coordinates of the tracker and the energy scale of the calorimeter. A more detailed description of TCCs can be found in Ref. [28].

5.2 Jet reconstruction

This analysis uses anti-k_t, $R = 1.0$ jets reconstructed from both the combined and the neutral TCCs. Combined TCCs are four-momenta created by combining the angular information of tracks with the energy information of the calorimeters. Neutral TCCs are calorimeter topo-clusters that could not be matched to any track, most likely representing energy deposits from neutral particles. The use of combined and neutral TCCs captures most of the hard-scatter energy and provides the best representation of the total energy flow in the event, as there are both charged and neutral contributions. The combined TCC component is robust against effects from pile-up since only tracks consistent with coming from the primary vertex[2] are used. However, by including the neutral TCCs, these jets have a pile-up dependence similar to that of standard topo-cluster jets. Jets are therefore trimmed [61] to remove contributions from pile-up by

---

[2] If more than one vertex is reconstructed, the one with the highest sum of p_{T}^2 of the associated tracks is regarded as the primary vertex.

removing any $R = 0.2$ subjet with less than 5% of the p_{T} of the associated $R = 1.0$ jet. The clustering and trimming algorithms use the FastJet package [62]. The combination of pile-up suppression through track-to-primary-vertex matching and trimming makes these jets very robust against pile-up [28]. A MC-based particle-level energy and mass calibration is applied to the jets, as described in Ref. [63]. MC generator-level jets are built using the same algorithm and trimming procedure, with inputs of stable generator-level particles ($c\tau > 10$ mm) excluding muons and neutrinos, and excluding particles from pile-up. These serve as the reference in Figure 1. The energy and mass of MC generator-level jets also serves as reference to which reconstructed detector-level jets are corrected to in the above mentioned calibration procedure. Consequently, the mass of jets from V bosons is not expected to match the pole mass of the bosons.

Several jet properties can be used to discriminate hadronic decays of W and Z bosons from background jets. Two providing strong discrimination are the jet mass and D_2,[3] where the latter is defined as a ratio of two-point to three-point energy correlation functions that are based on the energies of the jets' constituents and their pairwise angular separations [64]. Signal jets are expected to peak at D_2 values below one, while jets from multijet background have significantly larger values. The radiation of a hard gluon can allow background jets to mimic a two-pronged structure and satisfy the tagging requirements described above. Discrimination between boson jets and multijet background from such gluon-initiated jets can be attained by selecting on the charged hadron multiplicity, in form of the track multiplicity (n_{trk}) of the untrimmed $R = 1.0$ jet, considering tracks with $p_{\mathrm{T}} > 0.5$ GeV consistent with coming from the primary vertex.

Figure 1 shows the striking improvement in D_2 resolutions[4] achieved with TCC jets. The mass resolution is superior to previously used jet mass variables (m_{comb} [65]) starting around a jet p_{T} of 2 TeV. Below 1 TeV, the mass resolution in TCC jets is degraded. For identifying hadronically decaying V bosons, the improvement in D_2 resolution far outweighs the slight degradation in mass resolution.

5.3 Leptons

Electron identification is based on matching tracks to energy clusters in the electromagnetic calorimeter and calculating a likelihood based on several properties of the electron candidate. Electrons are required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$, and to satisfy the 'medium' identification criterion [66] and the 'loose' track-based isolation [66].

Muon identification relies on matching tracks in the inner detector to muon spectrometer tracks or track segments. Muons are required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$, and to satisfy the 'loose' selection criterion [67] and the 'loose' track isolation [67].

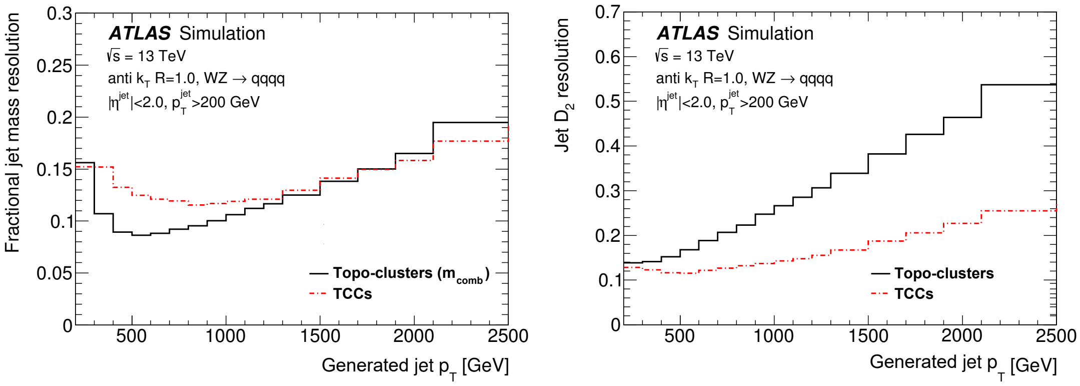
6 Event selection

To avoid contamination from non-collision backgrounds such as from calorimeter noise, beam halo, and cosmic rays, events containing an anti-k_t jet built from calorimeter-cell clusters with $R = 0.4$ and

---

[3] The angular exponent β, defined in Ref. [64], is set to unity.

[4] The resolution is defined as $R^r = [Q_{84}(\mathcal{R}^r) - Q_{16}(\mathcal{R}^r)]/[2 \times Q_{50}(\mathcal{R}^r)]$ and $R^d = 1/2\left[Q_{75}(\mathcal{R}^d) - Q_{25}(\mathcal{R}^d)\right]$ for the mass and D_2, respectively, where Q_x is the x% quantile boundary, meaning that Q_{50} is the median. The mass response is defined as $\mathcal{R}^r = m_{\mathrm{reco}}/m_{\mathrm{gen}}$, while the residual of D_2 is $\mathcal{R}^d = D_{2,\mathrm{reco}} - D_{2,\mathrm{gen}}$, where 'gen' and 'reco' refer to the generated and reconstructed properties of the jets.



(a) (b)

Figure 1: A comparison of (a) the fractional jet mass resolution for jets built from a linear combination of the calorimeter and track-only mass (Topo-clusters m_{comb}, solid line), and jets built using combined and neutral Track-CaloClusters objects (dashed lines) as a function of Monte Carlo generator-level jet p_{T}. The fractional jet resolution of the D_2 variable (b) is compared between Track-CaloClusters and pure calorimeter jets. Only the two jets with the highest p_{T} per event matched to a generated jet from a W or Z boson are shown.

$p_{\mathrm{T}} > 20$ GeV failing to meet the loose quality criteria for consistency with production in pp collisions are rejected [68]. In addition, events with at least one lepton meeting the requirements defined in Section 5.3 are rejected. There are no further requirements on leptons that are aligned with jets.

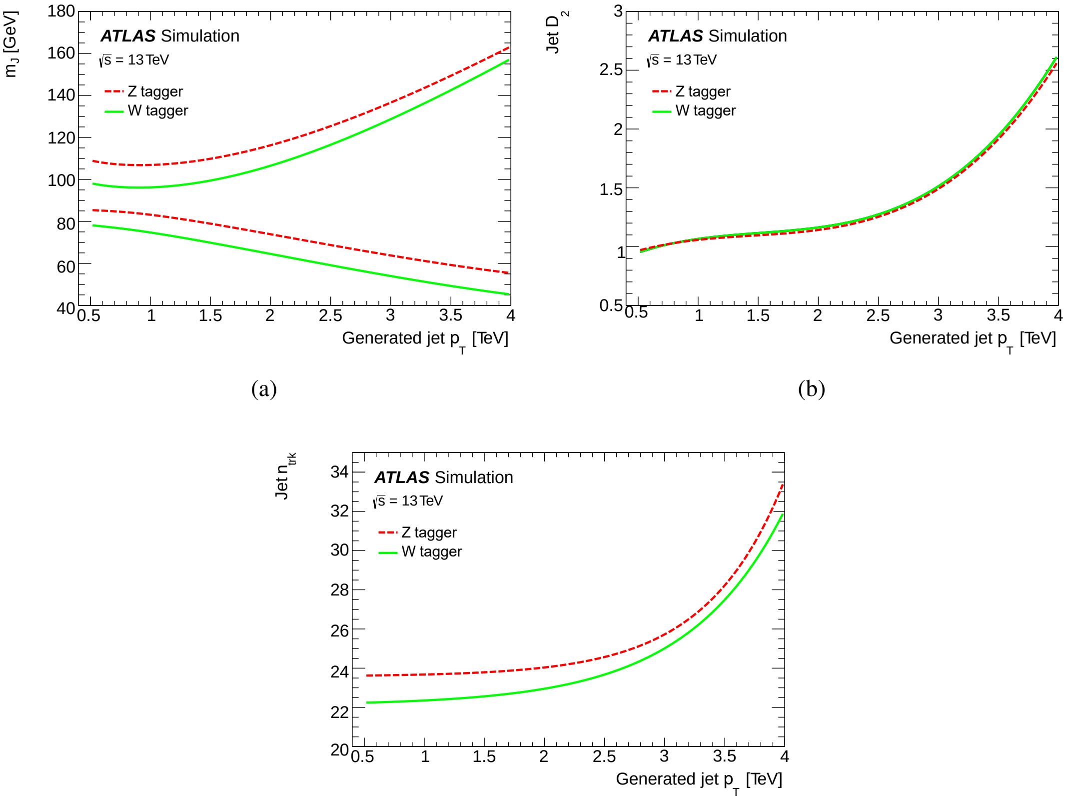
Events are required to have at least two anti-k_t, $R = 1.0$, jets originating from the primary vertex, one with $p_{\mathrm{T}} > 500$ GeV and the second with $p_{\mathrm{T}} > 200$ GeV. The leading (highest p_{T}) and subleading of these jets must satisfy $|\eta| < 2.0$ (to guarantee a good overlap with the tracking acceptance), have masses $m_{\mathrm{J}} > 50$ GeV, and their invariant mass, m_{JJ}, must be larger than 1.3 TeV. The last requirement ensures that the triggers in use are fully efficient for the backgrounds and the benchmark signals. These selections are referred to as pre-selections.

The pair of jets is then required to have a small separation in rapidity, $|\Delta y_{12}| < 1.2$. This requirement reduces the multijet background, which is mainly produced in t-channel processes with large rapidity differences, in contrast to signal events that are expected to be produced in s-channel processes with small rapidity differences. Additionally, to reject events with potentially badly reconstructed jets, a criterion is applied to the p_{T} asymmetry, $A = (p_{\mathrm{T1}} - p_{\mathrm{T2}})\,/\,(p_{\mathrm{T1}} + p_{\mathrm{T2}}) < 0.15$, where p_{T1} and p_{T2} are the transverse momenta of the leading and subleading jets, respectively.

6.1 Vector-boson identification

Jet substructure can be exploited to enhance the separation between signal boson jets and jets from multijet background. Several promising variables have been studied [63], with the largest sensitivity gain coming from the use of the three variables introduced in Section 5.2: jet mass, D_2, and n_{trk}.

A three-dimensional (jet mass, D_2, n_{trk}) tagger using TCC jets is optimised to provide maximum significance for boosted vector-boson jets relative to background jets. A measure of significance, independent of the cross-sections of the new processes being searched for, is selected: $\epsilon/(a/2 + \sqrt{B})$, where ϵ is the per-signal-jet selection efficiency for masses in the range of 0.5 TeV to 10 TeV in the W' model described



(a)

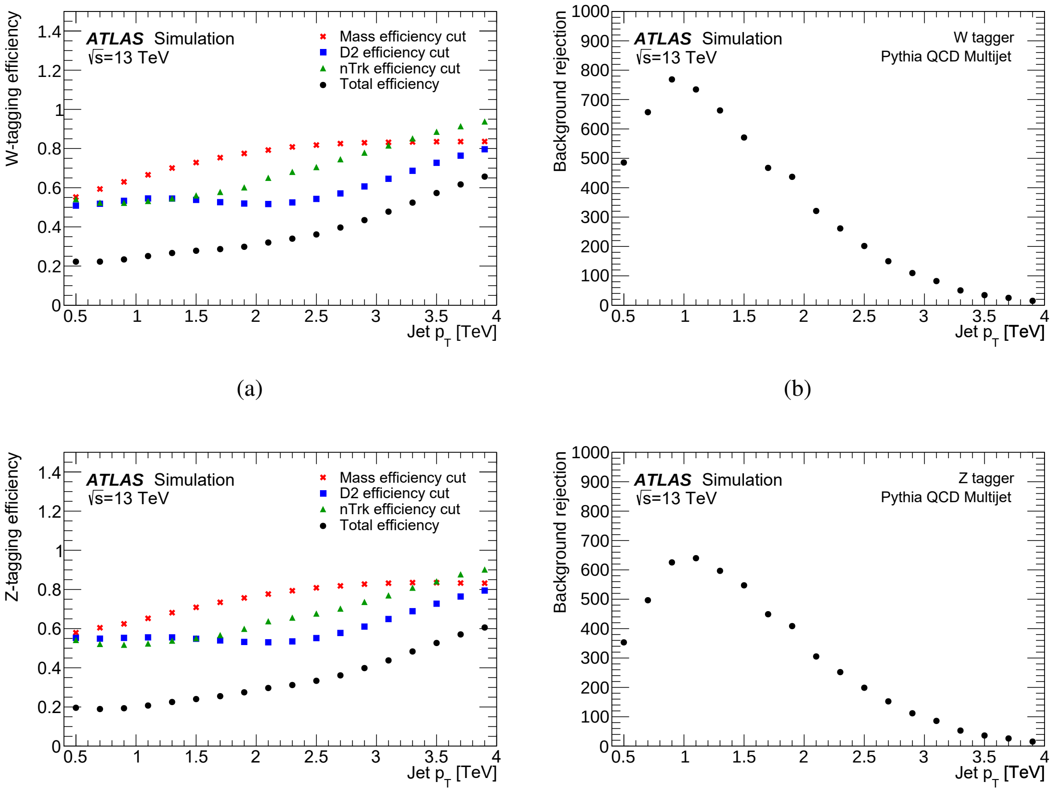
(b)

(c)

Figure 2: (a) Jet mass window, (b) D_2 selection and (c) n_{trk} selection of the W and Z taggers as a function of jet p_{T}. Jets selected in the analysis are required to have jet masses inside the jet mass window and D_2 and n_{trk} values below the shown values. The tagger is only valid for jets with a p_{T} between 0.5 TeV and 4.0 TeV and with $|\eta^{\mathrm{jet}}| < 2.0$.

in Section 4.1, a is the number of standard deviations corresponding to a one-sided Gaussian distribution, and B is the number of background jets after the selection [69] taken from MC simulation. This number does not rely on a specific signal, but is valid for all signals with similar experimental features. Compared with the often used $S/\sqrt{B}$, that breaks down for small values of B, as is the case here, this measure is more appropriate. A value of $a = 3$ is used, where the result of the optimisation is not very sensitive to the exact value. For each jet p_{T} bin, the optimal selection on the three variables is defined by the combination of selections that leads to the highest significance. This simultaneous treatment properly accounts for the correlations between the variables. The result of this optimisation does not depend on the pre-selections described at the beginning of this section. Next, the applied selection criteria on jet mass, D_2, and n_{trk} are parameterised with jet-p_{T}-dependent functions. For the jet mass, the function follows its approximate experimental resolution. For the latter two a simple higher-order polynomial is used. The resulting smooth selections for the W and Z boson taggers as a function of jet p_{T} are shown in Figure 2. Jets selected in the analysis are required to have jet masses inside the jet mass window and D_2 and n_{trk} values below the shown values. It should be noted that the W and Z boson mass windows overlap. This search is not sensitive to signatures containing massive particles with masses different from W/Z boson masses (for example top quarks or Higgs bosons).

Unlike previous boson taggers [20], the optimisation described above does not enforce a fixed signal



(a) (b)

(c) (d)

Figure 3: The (a) per-boson signal efficiency for the jet mass, D_2, and n_{trk} selections, as well as the combined efficiency and (b) background rejection (1/efficiency) of the W tagger for HVT $W' \to WZ \to qqqq$ and MC simulated multijets as a function of the jet p_{T}. Corresponding values for the Z tagger are shown in (c) and (d).

efficiency nor a fixed background rejection, but rather creates a smooth behaviour that maximises the analysis sensitivity. Figure 3 shows the resulting W and Z boson efficiencies and multijet background rejections (defined as 1/efficiency) as a function of jet p_{T}. The selection criteria retain about 20% efficiency for W and Z boson jets with $p_{\mathrm{T}} = 0.5$ TeV. At higher jet p_{T}, the signal efficiency increases, reaching an efficiency close to 60% for jets with a p_{T} of 4 TeV. This is due to the behaviour of the multijet background, which decreases rapidly for high dijet masses, and thus higher jet p_{T}. In the regime of $m_{\mathrm{JJ}} > 3.0$ TeV, where the number of background events is small, the tagger maintains a reasonable acceptance for signals with small cross-sections. This is also reflected in the background rejection as a function of jet p_{T}.

6.2 Measurement of boson-tagging efficiency

The modelling of the boson-tagging efficiency is evaluated in a data sample enriched in final states with a vector boson plus jets. This sample is obtained by requiring two large-radius jets with $|\eta| < 2.0$ and then requiring that the leading jet has $p_{\mathrm{T}} > 600$ GeV. A higher minimum p_{T} requirement is imposed on the leading jet than in the nominal event selection to obtain a sample with higher average leading jet p_{T} that better corresponds to the jet p_{T} values probed in the search. Events with identified leptons are vetoed.

Both jets are independently analysed for the presence of a vector boson by requiring them to satisfy the D_2 and n_{trk} selection for either a W or a Z boson. The opposite jet is required to not satisfy the same D_2 selection to guarantee independence of this control region from the main analysis signal region.

The mass distribution of the selected jets between 50 GeV and 200 GeV is fit by a signal-plus-background function, allowing the inclusive rate of $V+\text{jets}$ events to be measured. The contribution originating from $V+\text{jets}$ processes is modelled using a double-Gaussian distribution with the shape parameters determined from simulation, while the background contribution is fit to data using a fourth-order exponentiated polynomial. The relative rates of $W+\text{jets}$ and $Z+\text{jets}$ events in the fit are fixed from MC simulation. The ability of the fit to extract the correct $V+\text{jets}$ yield (also called MC closure) is tested in simulation by injecting signals of various strengths. Good linearity is found and the method is deemed reliable. By comparing the measured event yield in data and MC simulation, potential differences in the selection efficiency (s_{Tag}) can be probed. Expected contributions of about 5% from $t\bar{t}$ events are subtracted based on MC simulation. The cross-section of $V+\text{jets}$ at a V p_{T} of about 600 GeV is modelled with about 10% accuracy by the simulation [70]. Additional systematic uncertainties in the fitted $V+\text{jets}$ event yield from closure, from the uncertainty in the $t\bar{t}$ contribution, as well as from the fit parameterisation are considered. The relative efficiency of the D_2 and n_{trk} selections is extracted for V bosons with p_{T} starting from 600 GeV, while the analysis extends to $p_{\mathrm{T}} = 3.5$ TeV. To estimate the dependence of the modelling on the jet p_{T}, the distribution of the D_2 and n_{trk} variables is compared in an inclusive sample in data and MC simulation as a function of jet p_{T}. The observed residual mismodelling as a function of jet p_{T} is taken into account as an additional 5% uncertainty in the relative efficiency.

The fit to data is shown in Figure 4. This fit only extracts the overall yield, while the width and mean of the W/Z peaks are fixed from similar fits performed on MC simulation. The fitted relative efficiency of the D_2 and n_{trk} selections in data compared with MC simulation is $s_{\mathrm{Tag}} = 0.92 \pm 0.04\,(\text{stat}) \pm 0.02\,(\text{closure}) \pm 0.03\,(t\bar{t}) \pm 0.02\,(\text{fit}) \pm 0.05\,(p_{\mathrm{T}}\text{ range}) \pm 0.10\,(\text{theory})$, or $s_{\mathrm{Tag}} = 0.92 \pm 0.13$. This is applied as a scale-factor to the signal MC events, where the uncertainty in it reflects the uncertainty in the W/Z-tagging efficiency in the simulation. Additional fits allowing both the width and the mean of the W/Z peaks to float are used to compare the efficiency of the jet mass window of the boson taggers in data and simulation. Excellent agreement is found, and no additional uncertainty is assigned. The polarisation of the vector bosons in this control region will be different from those in different signal models, but as no other physics process has sufficient sensitivity to probe the data-to-simulation agreement it is assumed that the simulation models the polarisation effects sufficiently well that the scale-factors can be applied globally.

6.3 Signal and background selection efficiency

After boson tagging, the data is categorised into five non-exclusive signal regions (SRs): events with two jets identified as WW, ZZ, or WZ form three SRs, and events with two jets identified as either WZ or WW, and either WW or ZZ form two. The latter provides the highest sensitivity to the benchmark signals described in Section 4.1 while the others probe the individual decay channels. Only the boson-tagging requirement differs between the regions. The highest mass jet of the two highest p_{T} jets is considered as the candidate for the higher boson mass requirement. For the WZ selection this means that the highest mass jet must satisfy the Z boson selections and the second highest one the W boson selections. The selection requirements are summarised in Table 1.

The selection efficiency, defined as the number of selected events at different stages of the selection divided by the number of generated events, as a function of the resonance mass, is shown in Figure 5 for the HVT

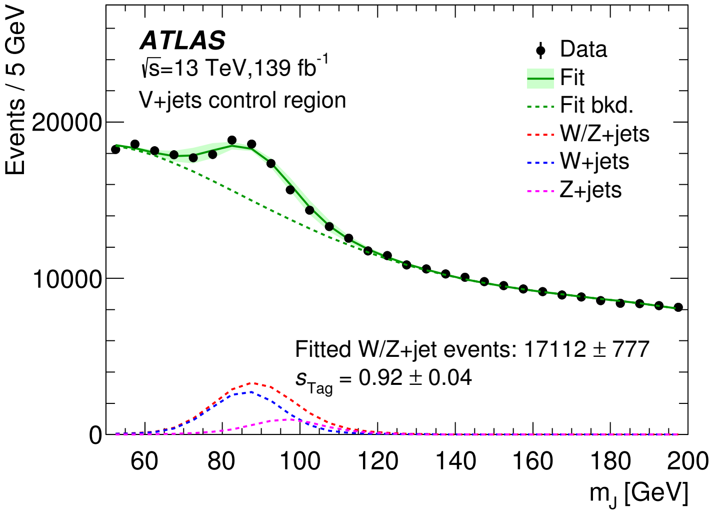
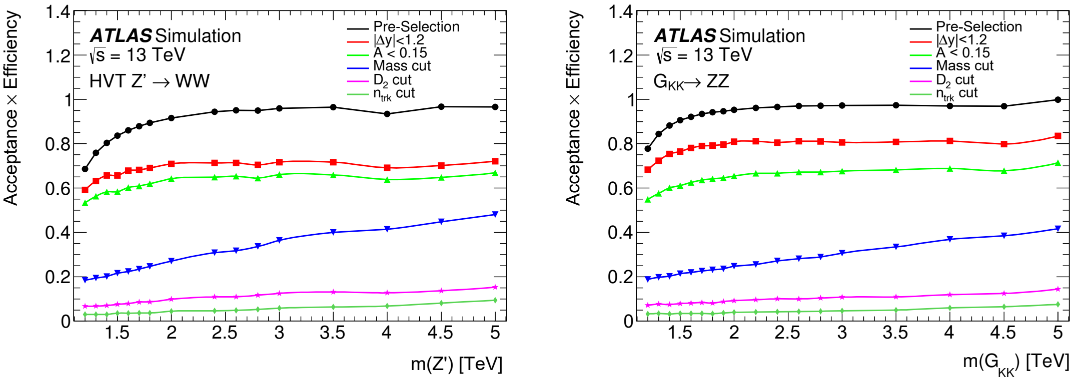


Figure 4: Jet mass distribution for data in the region enhanced in V + jets events after boson tagging based only on the D_2 and n_{trk} variables. The result of fitting to the sum of functions for the V + jets and background events is also shown. The shown fit uncertainty reflects the uncertainty in shape and positions of the W and Z peaks. At the bottom, the fitted contribution to the observed jet mass spectra from the V + jets signal is shown. The fitted relative efficiency of the D_2 and n_{trk} selections is $s_{\text{Tag}} = 0.92 \pm 0.04$, where the uncertainty is purely statistical.

Table 1: Event selection requirements and definition of the different regions used in the analysis. Different requirements are indicated for the highest-p_{T} (leading) jet with index 1 and the second highest-p_{T} (subleading) jet with index 2.

Signal region	Veto events with leptons: No e or μ with $p_{\text{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$ Event pre-selection: ≥ 2 large-R jets with $\lvert\eta\rvert < 2.0$ and mass > 50 GeV $p_{\text{T1}} > 500$ GeV and $p_{\text{T2}} > 200$ GeV $m_{\text{JJ}} > 1.3$ TeV Topology and boson tag: $\lvert\Delta y\rvert = \lvert y_1 - y_2\rvert < 1.2$ $A = (p_{\text{T1}} - p_{\text{T2}}) / (p_{\text{T1}} + p_{\text{T2}}) < 0.15$ Boson tag with D_2 variable, n_{trk} variable, and W or Z mass window
V+jets control region	Veto events with leptons: No e or μ with $p_{\text{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$ V+jets selection: ≥ 2 large-R jets with $\lvert\eta\rvert < 2.0$ $p_{\text{T1}} > 600$ GeV and $p_{\text{T2}} > 200$ GeV Boson tag with D_2 and n_{trk} variables on either jet Anti-boson tag with D_2 variable on other jet

Z' decaying into WW and for the bulk G_{KK} decaying into ZZ. Similar efficiencies are obtained in the WZ final state for the HVT model and in the WW final state for the bulk RS models. The figure shows that, among the different selection criteria described above, the boson tagging reduces the signal efficiency the most. However, this particular selection also provides the most significant suppression of the dominant multijet background. The resulting width of the m_{JJ} distributions in the signal region for a HVT model A $W' \to WZ$ (Bulk RS graviton $\to ZZ$) is about 6% (10%) of its mean value across the mass range studied, corresponding to about 120 GeV (200 GeV) at 2 TeV. Multijet background events are suppressed with a rejection factor greater than 10^5 across the entire m_{JJ} search range, as determined from simulation.



(a) (b)

Figure 5: The acceptance × efficiency for the selection, defined as the number of selected events at different stages of the selection divided by the number of generated events, for (a) HVT $Z' \to WW$ and (b) $G_{\mathrm{KK}} \to ZZ$ as a function of mass. The selections are applied in sequence and include pre-selections, topological selections on $|\Delta y_{12}|$, p_{T} asymmetry A, and boson tagging using jet mass, D_2, and n_{trk}.

7 Background parameterisation

The search for diboson resonances is performed by looking for narrow peaks above the smoothly falling m_{JJ} distribution expected from the SM. The background in the search is estimated empirically from the observed m_{JJ} spectrum in the signal region. The background estimation procedure is based on a binned maximum-likelihood fit of the following parameterised form to the observed m_{JJ} spectrum:

$$\frac{\mathrm{d}n}{\mathrm{d}x} = p_1(1-x)^{p_2-\xi p_3} x^{-p_3} \tag{1}$$

where $x = m_{\mathrm{JJ}}/\sqrt{s}$, p_1 is a normalisation factor, p_2 and p_3 are dimensionless shape parameters, and ξ is a constant. The value of ξ is derived in an iterative way, minimising the correlation between p_2 and p_3 in the fit, for each m_{JJ} distribution. It is confirmed that the complexity of this fit function is sufficient for the expected number of events in the signal regions by performing Wilks likelihood-ratio tests [71]. The fit is performed to the m_{JJ} distribution in each signal region in data with a constant bin size of 100 GeV. This choice is motivated by the experimental resolution.

The modelling of the parametric shape in Eq (1) is tested in dedicated fit control regions (CRs) in data. These CRs are designed to resemble the expected background in the SRs in both their shape and number of events, assuming that no signal contribution is present. Four regions are defined as shown in Figure 6, where A and B differ for each tested SR. A possible contamination in region A, C, or D from a potential beyond-the-SM signal is negligible. Region B corresponds to the nominal signal regions.

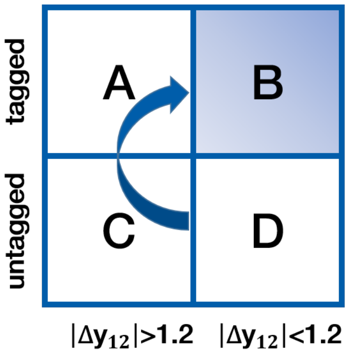


Figure 6: Four orthogonal regions used to build the fit control region for each signal region. A: $|\Delta y_{12}| > 1.2$ with both the jets boson-tagged, B: $|\Delta y_{12}| < 1.2$ with both the jets boson-tagged (this is the nominal signal region), C: $|\Delta y_{12}| > 1.2$ with the event not boson-tagged, D: $|\Delta y_{12}| < 1.2$ with the event not boson-tagged. Regions A and C are used to derive a per-event transfer factor from region D to the fit control region, which is representative of region B. A and C are also signal-depleted due to the $|\Delta y_{12}| > 1.2$ requirement.

The probability of misidentifying either the highest or second highest mass jet in an event as a W or Z boson in a data sample dominated by multijets is parameterised as a function of jet p_{T} using regions C and A. It is validated on data that such a probability is independent of $|\Delta y_{12}|$. Since a misidentification correlation between the two leading jets of the multijet background is observed after the pre-selections, the probability of the second highest mass jet is derived by requiring the highest mass jet to be in the mass window of the boson tagger. By applying per-jet weights, for the inverted selections, depending on the jet p_{T}, events of the region D are transformed to resemble region B – the fit CRs. To correctly take into account the expected statistical fluctuations and uncertainties, the CR distributions are assigned the correct Poisson errors, and fluctuated accordingly. The last step is repeated multiple times, fitting each distribution with the background fit function, and evaluating the goodness-of-fit χ^2/NDF. Bins with fewer than five events are combined with bins that contain at least five events to compute the number of degrees of freedom (NDF). On average, the χ^2/NDF is equal to unity with no cases for which the fit fails. Figure 7 shows the fit result performed in an example WZ fit CR. Similar results are obtained for the other CRs, confirming the ability of the chosen background fit function (Eq. (1)) to describe the expected background dijet mass spectra in the SRs. It is validated on both the data and the simulation that this parametric background description is valid up to 8.0 TeV, which is also the mass up to which the observed m_{JJ} spectra are fit.

The statistical uncertainty in the background expectation comes directly from the uncertainty in the fitted parameters of the background function, which assumes a smoothly falling m_{JJ} distribution. Possible additional uncertainties due to the background model are assessed by considering signal-plus-background fits (also called spurious signal tests) of the chosen function to the fit control regions of data in which a signal contribution is expected to be negligible. The background is modelled with Eq. (1) and the signal is modelled using resonance mass distributions from simulation. These procedures were estimated to introduce a bias smaller than 25% of the statistical uncertainty in the background estimate at any mass in the search region, and no additional uncertainty is assigned.

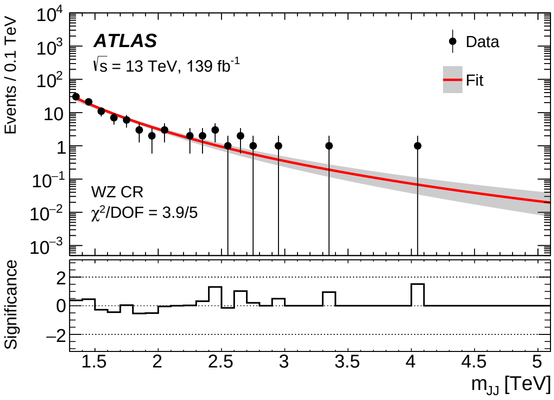


Figure 7: Comparison between fitted background shape and the m_{JJ} spectra in an example WZ fit control region in data. The fitted background distribution is normalised to the data shown in the displayed mass range. The shaded bands represent the uncertainty in the background expectation calculated from the maximum-likelihood function. The lower panel shows the significance, defined as the z-value as described in Ref. [72].

8 Systematic uncertainties

The uncertainties affecting the background modelling are taken directly from the errors in the fit parameters of the background estimation procedure described in Section 7. The systematic uncertainties in the expected signal yield and shapes arise from detector effects and MC modelling and are assessed and expressed in terms of nuisance parameters in the statistical analysis as described in Section 9.2. The dominant sources of uncertainty in the signal modelling arise from uncertainties in the large-R jet tagging efficiency and the jet p_{T} calibration. These two uncertainties, and the uncertainty in the fitted background, are also the only ones significantly affecting the statistical results.

The uncertainty in the jet p_{T} scale (Jp_{T}S) is evaluated using track-to-calorimeter double ratios between data and simulation [73]. The ratio of the calorimeter and track measures of jet p_{T} is expected to be the same in data and simulation and any observed differences are assigned as baseline systematic uncertainties. Uncertainties obtained from this procedure assume no correlation between the two p_{T} measures, while any residual correlation would modify them by a certain factor. An upper limit to the correlation between the two p_{T} measures is found to be at the percent level by comparing the results of this double-ratio procedure between jets built from TCC inputs and jets built from calorimeter-only inputs. Additional uncertainties due to the track reconstruction efficiency, track impact parameter resolution, and track fake rate are taken into account. The size of the total Jp_{T}S uncertainty varies with jet p_{T} and is between 2.5% and 5% for the full mass range.

The impact of the jet p_{T} resolution uncertainty is evaluated event-by-event by rerunning the analysis with an additional Gaussian smearing applied to the input jets' p_{T} to degrade the nominal resolution by the systematic uncertainty value. The systematic uncertainty in the width of the Gaussian distribution is an absolute 2% per jet, and is symmetrised.

Uncertainty in the jet mass scale and resolution influences the observed jet mass, affecting the boson-tagging efficiency. Any uncertainty in the value of the boson-tagging discriminant D_2 or n_{trk}, would also affect the selection efficiency of the analysis. A scale-factor for the W/Z-tagging efficiency is derived as described in Section 6.2. The changes to the overall yield is hence corrected by $0.85^{+0.23}_{-0.21}$ per event with the boson-tagging efficiency scale-factor, assuming full correlation between the two jets. The uncertainty in the scale-factor is assigned as a two-sided variation in the yield. Additional studies comparing jet properties in data and simulation confirm this uncertainty to be valid up to 7.0 TeV.

The uncertainty in the combined 2015–2018 integrated luminosity is 1.7% [74], obtained using the LUCID-2 detector [75] for the primary luminosity measurements. The uncertainty from the trigger selection is found to be negligible, as the minimum requirement on the dijet invariant mass of 1.3 TeV guarantees that the trigger is fully efficient.

Uncertainties in the behaviour of the PDFs at high Q^2 values can potentially have a large effect on the signal acceptance. This systematic uncertainty is estimated by taking the envelope formed by the largest deviations produced by the errors of three PDF sets, as set out by the PDF4LHC group [76]. A constant 1% uncertainty is applied in the case of the RS and radion models, and a pole-mass-dependent uncertainty ranging from 1%–12% is applied in the case of the HVT model. Systematic variations are used to cover uncertainties in the A14 tuned parameter values describing initial-state radiation, final-state radiation, and multi-parton interactions. The uncertainty in the signal acceptance is evaluated at the generator level, before boson-tagging requirements. Following the same procedure as for the PDFs, constant uncertainties of 3% (5%) are applied for the HVT (RS and radion) models.

9 Results

9.1 Background fit

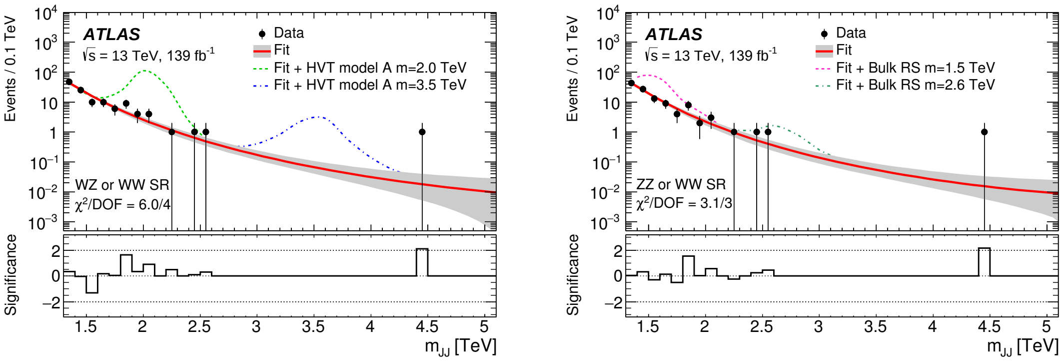
Figure 8 shows the comparison of the dijet mass distributions of the selected events in the combined $WW + WZ$ and $WW + ZZ$ signal regions with the expected background distribution from the background-only fits to the data. The fitted background functions shown, labelled ‘Fit’, are evaluated in bins between 1.3 TeV and 8.0 TeV. No events are observed beyond 5.0 TeV. A total of 119 and 113 events are observed above 1.3 TeV in the $WW + WZ$ and $WW + ZZ$ signal regions, respectively. Due to the non-exclusive selections of the boson taggers, about 50% of events satisfying the WW selection also satisfy the ZZ selection. The highest mass event at 4.4 TeV is the same for both signal regions, and it is compatible with the background expectation in the high mass region.

9.2 Statistical analysis

In the statistical analysis, the parameter of interest is the *signal strength*, which is defined as a scale-factor to the predicted signal normalisation of the model being tested. The analysis follows the *frequentist* approach with a test statistic based on the profile-likelihood ratio [77]. The test statistic extracts information about the signal strength from the binned maximum-likelihood fit of the signal-plus-background model to the data. The likelihood model is defined as,

$$\mathcal{L} = \prod_i P_{\mathrm{pois}}(n^i_{\mathrm{obs}}|n^i_{\mathrm{exp}}) \times G(\alpha) \times \mathcal{N}(\theta)$$

where $P_{\mathrm{pois}}(n^i_{\mathrm{obs}}|n^i_{\mathrm{exp}})$ is the Poisson probability to observe n^i_{obs} events if n^i_{exp} events are expected, $G(\alpha)$ are a series of Gaussian probability density functions modelling the systematic uncertainties, α, related to the



(a)

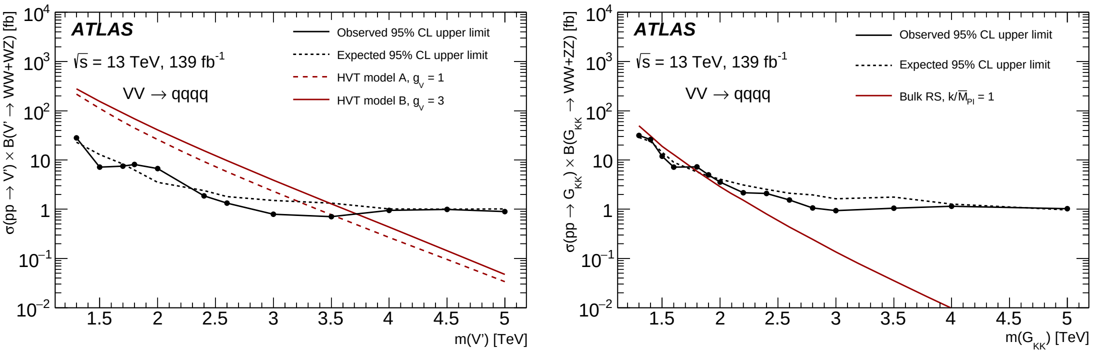
(b)

Figure 8: Background-only fits to the dijet mass (m_{JJ}) distributions in data after tagging in the combined (a) $WW+WZ$, and (b) $WW+ZZ$ signal region. The shaded bands represent the uncertainty in the background expectation calculated from the maximum-likelihood function. The lower panels show the significance, defined as the z-value as described in Ref. [68]. Selected theoretical signal distributions are overlaid on top of the background.

shape of the signal, and $\mathcal{N}(\theta)$ is a log-normal distribution for the nuisance parameters, θ, modelling the systematic uncertainty in the signal normalisation. The expected number of events is the bin-wise sum of those expected for the signal and background: $\mathbf{n}_{\mathrm{exp}} = \mathbf{n}_{\mathrm{sig}} + \mathbf{n}_{\mathrm{bg}}$. The expected number of background events in dijet mass bin i, n^{i}_{bg}, is obtained by integrating $\mathrm{d}n/\mathrm{d}x$ obtained from Eq. (1) over that bin. Thus $\mathbf{n}_{\mathrm{bg}}$ is a function of the dijet background parameters p_1, p_2 and p_3. The expected number of signal events, $\mathbf{n}_{\mathrm{sig}}$, is evaluated from MC simulation assuming the cross-section of the model under test multiplied by the signal strength, including the effects of the systematic uncertainties described in Section 8.

The significance of observed excesses over the background-only prediction is quantified using the local p_0-value, defined as the probability of the background-only model to produce a signal-like fluctuation at least as large as that observed in the data. The most extreme p_0 has a local significance of 1.8 standard deviations, and is found when testing the HVT $W' \rightarrow WW$ hypothesis at a resonance mass of 1.8 TeV. This is within the expected fluctuation of the background.

Limits at 95% confidence level (CL) on the production cross-section times branching fraction to diboson final states for the benchmark signals are set with sampling distributions generated using pseudo-experiments. All systematic uncertainties are considered. The uncertainty in the W/Z-tagging efficiency is dominant at lower masses, while the uncertainty in the background modelling has largest impact at high masses. Uncertainties in the jet p_{T} scale are at the percent level but are subordinate across the full mass range. The cross-section limits extracted for the different benchmark scenarios in the $WW + WZ$ and $WW + ZZ$ signal regions are shown in Figure 9 and Table 2. Table 3 presents the resonance mass ranges excluded at the 95% CL in the various signal regions and signal models considered in the search.



(a) (b)

Figure 9: Observed and expected limits at 95% CL on the cross-section times branching ratio for $WW + WZ$ production as a function of (a) $m_{\mathrm{V'}}$, and for $WW + ZZ$ production as a function of (b) the Bulk RS graviton $m_{\mathrm{G_{KK}}}$. The predicted cross-section times branching ratio is shown (a) as dashed and solid lines for the HVT models A with $g_V = 1$ and B with $g_V = 3$, respectively, and (b) as a solid line for the bulk RS model with $k/\overline{M}_{\mathrm{Pl}} = 1$.

Table 2: Observed and expected limits at 95% CL on cross-section times branching ratio for $WW + ZZ$ production for different radion masses m_{radion}, as well as the predicted cross-section times branching ratio.

Mass [TeV]	Observed Limit [fb]	Expected Limit [fb]	Prediction [fb]
2.0	5.72	5.75	9.4
3.0	1.86	2.85	0.92
4.0	1.98	2.34	0.089
5.0	1.98	2.02	0.012

Table 3: Observed excluded resonance masses (at 95% CL) in the individual and combined signal regions for the HVT, bulk RS and radion models.

Model	Signal Region	Excluded mass range [TeV]
Radion	WW	1.3–2.8
	ZZ	1.6–2.1
	$WW + ZZ$	1.3–3.0
HVT model A, $g_V = 1$	WW	1.3–2.9
	WZ	1.3–3.4
	$WW + WZ$	1.3–3.5
HVT model B, $g_V = 3$	WW	1.3–3.1
	WZ	1.3–3.6
	$WW + WZ$	1.3–3.8
Bulk RS, $k/\overline{M}_{\mathrm{Pl}} = 1$	WW	1.3–1.6
	ZZ	none
	$WW + ZZ$	1.3–1.8

10 Conclusion

A search for narrow heavy resonances decaying into dibosons in the all hadronic channel is performed using 139 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13$ TeV collected by the ATLAS experiment at the LHC from 2015 to 2018. The results of the search are shown for the $WW + WZ$, $WW + ZZ$ channels, and are interpreted in terms of a radion model, two HVT benchmark models, and a bulk G_{KK} model. The data are in agreement with the background expectations in all channels. Upper limits on the production cross-section times branching ratio to diboson final states for new resonances with masses greater than 1.3 TeV are set at the 95% CL. These results exclude at the 95% CL the production of $WW + WZ$ from the HVT model A (model B) with $g_V = 1$ ($g_V = 3$) with masses in the range of 1.3 TeV–3.5 TeV (1.3 TeV–3.8 TeV). Production of a G_{KK} in the bulk RS model with $k/\overline{M}_{\text{Pl}} = 1$ is excluded in the range 1.3 TeV–1.8 TeV, at the 95% CL. The production of $WW + ZZ$ from the scalar-like radion is excluded at the 95% CL in the range 1.3 TeV–3.0 TeV.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRT, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russia Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; ERC, ERDF, Horizon 2020, Marie Skłodowska-Curie Actions and COST, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya and PROMETEO Programme Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [78].

References

[1] 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, [Erratum: Z. Phys. C 47 (1990) 676].

[2] E. Eichten, I. Hinchliffe, K. D. Lane and C. Quigg, *Super Collider Physics*, Rev. Mod. Phys. **56** (1984) 579, [Addendum: Rev. Mod. Phys. 58 (1986) 1065].

[3] C. Quigg, *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions*, Princeton University Press, 2013, ISBN: 978-0-691-13548-9, 978-1-4008-4822-5, URL: `http://chrisquigg.com/gauge-theories/`.

[4] J. C. Pati and A. Salam, *Lepton Number as the Fourth Color*, Phys. Rev. D **10** (1974) 275, [Erratum: Phys. Rev. D 11 (1975) 703].

[5] H. Georgi and S. L. Glashow, *Unity of All Elementary Particle Forces*, Phys. Rev. Lett. **32** (1974) 438.

[6] H. Georgi, *The State of the Art - Gauge Theories. (Talk)*, AIP Conf. Proc. **23** (1975) 575.

[7] H. Fritzsch and P. Minkowski, *Unified Interactions of Leptons and Hadrons*, Annals Phys. **93** (1975) 193.

[8] L. Randall and R. Sundrum, *Large Mass Hierarchy from a Small Extra Dimension*, Phys. Rev. Lett. **83** (1999) 3370, arXiv: `hep-ph/9905221 [hep-ph]`.

[9] T. Han, J. D. Lykken and R.-J. Zhang, *On Kaluza-Klein states from large extra dimensions*, Phys. Rev. D **59** (1999) 105006, arXiv: `hep-ph/9811350 [hep-ph]`.

[10] K. Agashe, H. Davoudiasl, G. Perez and A. Soni, *Warped Gravitons at the LHC and Beyond*, Phys. Rev. D **76** (2007) 036006, arXiv: `hep-ph/0701186 [hep-ph]`.

[11] O. Antipin, D. Atwood and A. Soni, *Search for RS gravitons via $W_L W_L$ decays*, Phys. Lett. B **666** (2008) 155, arXiv: `0711.3175 [hep-ph]`.

[12] O. Antipin and A. Soni, *Towards establishing the spin of warped gravitons*, JHEP **10** (2008) 018, arXiv: `0806.3427 [hep-ph]`.

[13] G. C. Branco et al., *Theory and phenomenology of two-Higgs-doublet models*, Phys. Rept. **516** (2012) 1, arXiv: `1106.0034 [hep-ph]`.

[14] M. Perelstein, *Little Higgs models and their phenomenology*, Prog. Part. Nucl. Phys. **58** (2007) 247, arXiv: `hep-ph/0512128 [hep-ph]`.

[15] F. Sannino, *Technicolor and Beyond: Unification in Theory Space*, J. Phys. Conf. Ser. **259** (2010) 012003, arXiv: `1010.3461 [hep-ph]`.

[16] E. Eichten and K. Lane, *Low-scale technicolor at the Tevatron and LHC*, Phys. Lett. B **669** (2008) 235, arXiv: `0706.2339 [hep-ph]`.

[17] S. Catterall, L. Del Debbio, J. Giedt and L. Keegan, *Monte Carlo renormalization group minimal walking technicolor*, Phys. Rev. D **85** (2012) 094501, arXiv: `1108.3794 [hep-ph]`.

[18] J. R. Andersen et al., *Discovering Technicolor*, Eur. Phys. J. Plus **126** (2011) 81, arXiv: `1104.1255 [hep-ph]`.

[19] D. Barducci, A. Belyaev, S. Moretti, S. De Curtis and G. M. Pruna, *LHC physics of extra gauge bosons in the 4D Composite Higgs Model*, EPJ Web Conf. **60** (2013) 20049, arXiv: `1307.1782 [hep-ph]`.

[20] ATLAS Collaboration, *Search for diboson resonances with boson-tagged jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys. Lett. B **777** (2018) 91, arXiv: `1708.04445 [hep-ex]`.

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

[22] C. Collaboration, *A multi-dimensional search for new heavy resonances decaying to boosted WW, WZ, or ZZ boson pairs in the dijet final state at 13 TeV*, (2019), arXiv: `1906.05977 [hep-ex]`.

[23] ATLAS Collaboration, *Search for WW/WZ resonance production in $\ell\nu qq$ final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, JHEP **03** (2018) 042, arXiv: `1710.07235 [hep-ex]`.

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

[25] CMS Collaboration, *Search for a heavy resonance decaying into a Z boson and a Z or W boson in $2\ell 2q$ final states at $\sqrt{s} = 13$ TeV*, JHEP **09** (2018) 101, arXiv: `1803.10093 [hep-ex]`.

[26] CMS Collaboration, *Search for a heavy resonance decaying into a Z boson and a vector boson in the $\nu\bar{\nu}q\bar{q}$ final state*, JHEP **07** (2018) 075, arXiv: `1803.03838 [hep-ex]`.

[27] ATLAS Collaboration, *Combination of searches for heavy resonances decaying into bosonic and leptonic final states using $36\,fb^{-1}$ of proton–proton collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys. Rev. D **98** (2018) 052008, arXiv: `1808.02380 [hep-ex]`.

[28] ATLAS Collaboration, *Improving jet substructure performance in ATLAS using Track-CaloClusters*, ATL-PHYS-PUB-2017-015, 2017, URL: `https://cds.cern.ch/record/2275636`.

[29] A. Carvalho, *Gravity particles from Warped Extra Dimensions, predictions for LHC*, tech. rep., arXiv: `1404.0102 [hep-ph]`.

[30] D. Pappadopulo, A. Thamm, R. Torre and A. Wulzer, *Heavy Vector Triplets: Bridging Theory and Data*, JHEP **09** (2014) 060, arXiv: `1402.4431 [hep-ph]`.

[31] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.

[32] B. Abbott et al., *Production and Integration of the ATLAS Insertable B-Layer*, JINST **13** (2018) T05008, arXiv: `1803.00844 [physics.ins-det]`.

[33] ATLAS Collaboration, *ATLAS Insertable B-Layer Technical Design Report (ATLAS-TDR-19)*, (2010), URL: `https://cds.cern.ch/record/1291633`, ATLAS Insertable B-Layer Technical Design Report Addendum, (ATLAS-TDR-19-ADD-1), URL: `https://cds.cern.ch/record/1451888`.

[34] ATLAS Collaboration, *Performance of the ATLAS trigger system in 2015*, Eur. Phys. J. C **77** (2017) 317, arXiv: `1611.09661 [hep-ex]`.

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

[36] ATLAS Collaboration, *Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1*, Eur. Phys. J. C **77** (2017) 490, arXiv: `1603.02934 [hep-ex]`.

[37] W. D. Goldberger and M. B. Wise, *Modulus stabilization with bulk fields*, Phys. Rev. Lett. **83** (1999) 4922, arXiv: `hep-ph/9907447 [hep-ph]`.

[38] W. D. Goldberger and M. B. Wise, *Phenomenology of a stabilized modulus*, Phys. Lett. **B475** (2000) 275, arXiv: `hep-ph/9911457 [hep-ph]`.

[39] V. Barger and M. Ishida, *Randall-Sundrum Reality at the LHC*, Phys. Lett. B **709** (2012) 185, arXiv: `1110.6452 [hep-ph]`.

[40] C. Csáki, J. Hubisz and S. J. Lee, *Radion phenomenology in realistic warped space models*, Phys. Rev. D **76** (2007) 125015, arXiv: `0705.3844 [hep-ph]`.

[41] L. Randall and R. Sundrum, *An Alternative to Compactification*, Phys. Rev. Lett. **83** (1999) 4690, arXiv: `hep-th/9906064 [hep-th]`.

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

[43] T. Sjöstrand, S. Mrenna and P. Z. Skands, *A Brief Introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178** (2008) 852, arXiv: `0710.3820 [hep-ph]`.

[44] S. Carrazza, S. Forte and J. Rojo, 'Parton Distributions and Event Generators', *Proceedings, 43rd International Symposium on Multiparticle Dynamics (ISMD 13)*, 2013 89, arXiv: `1311.5887 [hep-ph]`.

[45] ATLAS Collaboration, *ATLAS Pythia 8 tunes to* 7 *TeV data*, ATL-PHYS-PUB-2014-021, 2014, URL: `https://cds.cern.ch/record/1966419`.

[46] T. Gleisberg et al., *Event generation with SHERPA 1.1*, JHEP **02** (2009) 007, arXiv: `0811.4622 [hep-ph]`.

[47] S. Höche, F. Krauss, S. Schumann and F. Siegert, *QCD matrix elements and truncated showers*, JHEP **05** (2009) 053, arXiv: `0903.1219 [hep-ph]`.

[48] T. Gleisberg and S. Höche, *Comix, a new matrix element generator*, JHEP **12** (2008) 039, arXiv: `0808.3674 [hep-ph]`.

[49] S. Schumann and F. Krauss, *A Parton shower algorithm based on Catani-Seymour dipole factorisation*, JHEP **03** (2008) 038, arXiv: `0709.1027 [hep-ph]`.

[50] H.-L. Lai et al., *New parton distributions for collider physics*, Phys. Rev. D **82** (2010) 074024, arXiv: `1007.2241 [hep-ph]`.

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

[52] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, JHEP **11** (2007) 070, arXiv: `0709.2092 [hep-ph]`.

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

[54] R. D. Ball et al., *Parton distributions for the LHC Run II*, JHEP **04** (2015) 040, arXiv: `1410.8849 [hep-ph]`.

[55] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. A **462** (2001) 152.

[56] S. Agostinelli et al., *GEANT4 – a simulation toolkit*, Nucl. Instrum. Meth. A **506** (2003) 250.

[57] ATLAS Collaboration, *The ATLAS Simulation Infrastructure*, Eur. Phys. J. C **70** (2010) 823, arXiv: `1005.4568 [physics.ins-det]`.

[58] ATLAS Collaboration, *The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie–Landshoff diffractive model*, ATL-PHYS-PUB-2016-017, 2016, URL: `https://cds.cern.ch/record/2206965`.

[59] ATLAS Collaboration, *Performance of the ATLAS track reconstruction algorithms in dense environments in LHC Run 2*, Eur. Phys. J. C **77** (2017) 673, arXiv: `1704.07983 [hep-ex]`.

[60] ATLAS Collaboration, *Jet reconstruction and performance using particle flow with the ATLAS Detector*, Eur. Phys. J. C **77** (2017) 466, arXiv: `1703.10485 [hep-ex]`.

[61] D. Krohn, J. Thaler and L.-T. Wang, *Jet Trimming*, JHEP **02** (2010) 084, arXiv: `0912.1342 [hep-ph]`.

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

[63] ATLAS Collaboration, *Identification of Boosted, Hadronically-Decaying W and Z Bosons in* $\sqrt{s} = 13$ *TeV Monte Carlo Simulations for ATLAS*, ATL-PHYS-PUB-2015-033, 2015, URL: `https://cds.cern.ch/record/2041461`.

[64] A. J. Larkoski, G. P. Salam and J. Thaler, *Energy Correlation Functions for Jet Substructure*, JHEP **06** (2013) 108, arXiv: `1305.0007 [hep-ph]`.

[65] ATLAS Collaboration, *Performance of top-quark and* W*-boson tagging with ATLAS in Run 2 of the LHC*, Eur. Phys. J. C **79** (2019) 375, arXiv: `1808.07858 [hep-ex]`.

[66] A. Collaboration, *Electron and photon performance measurements with the ATLAS detector using the 2015-2017 LHC proton-proton collision data*, (2019), arXiv: `1908.00005 [hep-ex]`.

[67] ATLAS Collaboration, *Muon reconstruction performance of the ATLAS detector in proton–proton collision data at* $\sqrt{s} = 13$ *TeV*, Eur. Phys. J. C **76** (2016) 292, arXiv: `1603.05598 [hep-ex]`.

[68] ATLAS Collaboration, *Selection of jets produced in* 13 *TeV proton–proton collisions with the ATLAS detector*, ATLAS-CONF-2015-029, 2015, URL: `https://cds.cern.ch/record/2037702`.

[69] G. Punzi, *Sensitivity of searches for new signals and its optimization*, eConf C030908 (2003) MODT002, 79(2003), arXiv: `physics/0308063 [physics]`.

[70] J. M. Lindert et al., *Precise predictions for* $V+$ *jets dark matter backgrounds*, Eur. Phys. J. C **77** (2017) 829, arXiv: `1705.04664 [hep-ph]`.

[71] S. S. Wilks, *The Large-Sample Distribution of the Likelihood Ratio for Testing Composite Hypotheses*, Annals Math. Statist. **9** (1938) 60.

[72] G. Choudalakis and D. Casadei, *Plotting the Differences Between Data and Expectation*, Eur. Phys. J. Plus **127** (2012) 25, arXiv: `1111.2062 [physics.data-an]`.

[73] ATLAS Collaboration, *Performance of jet substructure techniques for large-R jets in proton–proton collisions at* $\sqrt{s} = 7$ *TeV using the ATLAS detector*, JHEP **09** (2013) 076, arXiv: `1306.4945 [hep-ex]`.

[74] ATLAS Collaboration, *Luminosity determination in pp collisions at* $\sqrt{s} = 13$ *TeV using the ATLAS detector at the LHC*, ATLAS-CONF-2019-021, 2019, URL: `https://cds.cern.ch/record/2677054`.

[75] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS*, JINST **13** (2018) P07017.

[76] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, J. Phys. G **43** (2016) 023001, arXiv: `1510.03865 [hep-ph]`.

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

[78] ATLAS Collaboration, *ATLAS Computing Acknowledgements*, ATL-GEN-PUB-2016-002, URL: `https://cds.cern.ch/record/2202407`.

The ATLAS Collaboration

G. Aad[101], B. Abbott[128], D.C. Abbott[102], O. Abdinov[13,*], A. Abed Abud[70a,70b], K. Abeling[53], D.K. Abhayasinghe[93], S.H. Abidi[167], O.S. AbouZeid[40], N.L. Abraham[156], H. Abramowicz[161], H. Abreu[160], Y. Abulaiti[6], B.S. Acharya[66a,66b,n], B. Achkar[53], S. Adachi[163], L. Adam[99], C. Adam Bourdarios[132], L. Adamczyk[83a], L. Adamek[167], J. Adelman[121], M. Adersberger[114], A. Adiguzel[12c,ai], S. Adorni[54], T. Adye[144], A.A. Affolder[146], Y. Afik[160], C. Agapopoulou[132], M.N. Agaras[38], A. Aggarwal[119], C. Agheorghiesei[27c], J.A. Aguilar-Saavedra[140f,140a,ah], F. Ahmadov[79], W.S. Ahmed[103], X. Ai[15a], G. Aielli[73a,73b], S. Akatsuka[85], T.P.A. Åkesson[96], E. Akilli[54], A.V. Akimov[110], K. Al Khoury[132], G.L. Alberghi[23b,23a], J. Albert[176], M.J. Alconada Verzini[88], S. Alderweireldt[36], M. Aleksa[36], I.N. Aleksandrov[79], C. Alexa[27b], D. Alexandre[19], T. Alexopoulos[10], A. Alfonsi[120], M. Alhroob[128], B. Ali[142], G. Alimonti[68a], J. Alison[37], S.P. Alkire[148], C. Allaire[132], B.M.M. Allbrooke[156], B.W. Allen[131], P.P. Allport[21], A. Aloisio[69a,69b], A. Alonso[40], F. Alonso[88], C. Alpigiani[148], A.A. Alshehri[57], M. Alvarez Estevez[98], D. Álvarez Piqueras[174], M.G. Alviggi[69a,69b], Y. Amaral Coutinho[80b], A. Ambler[103], L. Ambroz[135], C. Amelung[26], D. Amidei[105], S.P. Amor Dos Santos[140a], S. Amoroso[46], C.S. Amrouche[54], F. An[78], C. Anastopoulos[149], N. Andari[145], T. Andeen[11], C.F. Anders[61b], J.K. Anders[20], A. Andreazza[68a,68b], V. Andrei[61a], C.R. Anelli[176], S. Angelidakis[38], A. Angerami[39], A.V. Anisenkov[122b,122a], A. Annovi[71a], C. Antel[61a], M.T. Anthony[149], M. Antonelli[51], D.J.A. Antrim[171], F. Anulli[72a], M. Aoki[81], J.A. Aparisi Pozo[174], L. Aperio Bella[36], G. Arabidze[106], J.P. Araque[140a], V. Araujo Ferraz[80b], R. Araujo Pereira[80b], C. Arcangeletti[51], A.T.H. Arce[49], F.A. Arduh[88], J-F. Arguin[109], S. Argyropoulos[77], J.-H. Arling[46], A.J. Armbruster[36], L.J. Armitage[92], A. Armstrong[171], O. Arnaez[167], H. Arnold[120], A. Artamonov[111,*], G. Artoni[135], S. Artz[99], S. Asai[163], N. Asbah[59], E.M. Asimakopoulou[172], L. Asquith[156], K. Assamagan[29], R. Astalos[28a], R.J. Atkin[33a], M. Atkinson[173], N.B. Atlay[151], H. Atmani[132], K. Augsten[142], G. Avolio[36], R. Avramidou[60a], M.K. Ayoub[15a], A.M. Azoulay[168b], G. Azuelos[109,ax], M.J. Baca[21], H. Bachacou[145], K. Bachas[67a,67b], M. Backes[135], F. Backman[45a,45b], P. Bagnaia[72a,72b], M. Bahmani[84], H. Bahrasemani[152], A.J. Bailey[174], V.R. Bailey[173], J.T. Baines[144], M. Bajic[40], C. Bakalis[10], O.K. Baker[183], P.J. Bakker[120], D. Bakshi Gupta[8], S. Balaji[157], E.M. Baldin[122b,122a], P. Balek[180], F. Balli[145], W.K. Balunas[135], J. Balz[99], E. Banas[84], A. Bandyopadhyay[24], Sw. Banerjee[181,i], A.A.E. Bannoura[182], L. Barak[161], W.M. Barbe[38], E.L. Barberio[104], D. Barberis[55b,55a], M. Barbero[101], T. Barillari[115], M-S. Barisits[36], J. Barkeloo[131], T. Barklow[153], R. Barnea[160], S.L. Barnes[60c], B.M. Barnett[144], R.M. Barnett[18], Z. Barnovska-Blenessy[60a], A. Baroncelli[60a], G. Barone[29], A.J. Barr[135], L. Barranco Navarro[45a,45b], F. Barreiro[98], J. Barreiro Guimarães da Costa[15a], S. Barsov[138], R. Bartoldus[153], G. Bartolini[101], A.E. Barton[89], P. Bartos[28a], A. Basalaev[46], A. Bassalat[132,aq], R.L. Bates[57], S.J. Batista[167], S. Batlamous[35e], J.R. Batley[32], B. Batool[151], M. Battaglia[146], M. Bauce[72a,72b], F. Bauer[145], K.T. Bauer[171], H.S. Bawa[31,l], J.B. Beacham[49], T. Beau[136], P.H. Beauchemin[170], F. Becherer[52], P. Bechtle[24], H.C. Beck[53], H.P. Beck[20,r], K. Becker[52], M. Becker[99], C. Becot[46], A. Beddall[12d], A.J. Beddall[12a], V.A. Bednyakov[79], M. Bedognetti[120], C.P. Bee[155], T.A. Beermann[76], M. Begalli[80b], M. Begel[29], A. Behera[155], J.K. Behr[46], F. Beisiegel[24], A.S. Bell[94], G. Bella[161], L. Bellagamba[23b], A. Bellerive[34], P. Bellos[9], K. Beloborodov[122b,122a], K. Belotskiy[112], N.L. Belyaev[112], D. Benchekroun[35a], N. Benekos[10], Y. Benhammou[161], D.P. Benjamin[6], M. Benoit[54], J.R. Bensinger[26], S. Bentvelsen[120], L. Beresford[135], M. Beretta[51], D. Berge[46], E. Bergeaas Kuutmann[172], N. Berger[5], B. Bergmann[142], L.J. Bergsten[26], J. Beringer[18], S. Berlendis[7], N.R. Bernard[102], G. Bernardi[136], C. Bernius[153], T. Berry[93], P. Berta[99], C. Bertella[15a], I.A. Bertram[89], G.J. Besjes[40], O. Bessidskaia Bylund[182], N. Besson[145], A. Bethani[100], S. Bethke[115], A. Betti[24], A.J. Bevan[92], J. Beyer[115], R. Bi[139], R.M. Bianchi[139], O. Biebel[114], D. Biedermann[19], R. Bielski[36], K. Bierwagen[99], N.V. Biesuz[71a,71b], M. Biglietti[74a], T.R.V. Billoud[109], M. Bindi[53], A. Bingul[12d], C. Bini[72a,72b],

S. Biondi[23b,23a], M. Birman[180], T. Bisanz[53], J.P. Biswal[161], A. Bitadze[100], C. Bittrich[48], K. Bjørke[134], K.M. Black[25], T. Blazek[28a], I. Bloch[46], C. Blocker[26], A. Blue[57], U. Blumenschein[92], G.J. Bobbink[120], V.S. Bobrovnikov[122b,122a], S.S. Bocchetta[96], A. Bocci[49], D. Boerner[46], D. Bogavac[14], A.G. Bogdanchikov[122b,122a], C. Bohm[45a], V. Boisvert[93], P. Bokan[53,172], T. Bold[83a], A.S. Boldyrev[113], A.E. Bolz[61b], M. Bomben[136], M. Bona[92], J.S. Bonilla[131], M. Boonekamp[145], H.M. Borecka-Bielska[90], A. Borisov[123], G. Borissov[89], J. Bortfeldt[36], D. Bortoletto[135], V. Bortolotto[73a,73b], D. Boscherini[23b], M. Bosman[14], J.D. Bossio Sola[103], K. Bouaouda[35a], J. Boudreau[139], E.V. Bouhova-Thacker[89], D. Boumediene[38], S.K. Boutle[57], A. Boveia[126], J. Boyd[36], D. Boye[33b,ar], I.R. Boyko[79], A.J. Bozson[93], J. Bracinik[21], N. Brahimi[101], G. Brandt[182], O. Brandt[61a], F. Braren[46], B. Brau[102], J.E. Brau[131], W.D. Breaden Madden[57], K. Brendlinger[46], L. Brenner[46], R. Brenner[172], S. Bressler[180], B. Brickwedde[99], D.L. Briglin[21], D. Britton[57], D. Britzger[115], I. Brock[24], R. Brock[106], G. Brooijmans[39], W.K. Brooks[147b], E. Brost[121], J.H Broughton[21], P.A. Bruckman de Renstrom[84], D. Bruncko[28b], A. Bruni[23b], G. Bruni[23b], L.S. Bruni[120], S. Bruno[73a,73b], B.H. Brunt[32], M. Bruschi[23b], N. Bruscino[139], P. Bryant[37], L. Bryngemark[96], T. Buanes[17], Q. Buat[36], P. Buchholz[151], A.G. Buckley[57], I.A. Budagov[79], M.K. Bugge[134], F. Bührer[52], O. Bulekov[112], T.J. Burch[121], S. Burdin[90], C.D. Burgard[120], A.M. Burger[129], B. Burghgrave[8], K. Burka[84], J.T.P. Burr[46], J.C. Burzynski[102], V. Büscher[99], E. Buschmann[53], P.J. Bussey[57], J.M. Butler[25], C.M. Buttar[57], J.M. Butterworth[94], P. Butti[36], W. Buttinger[36], A. Buzatu[158], A.R. Buzykaev[122b,122a], G. Cabras[23b,23a], S. Cabrera Urbán[174], D. Caforio[56], H. Cai[173], V.M.M. Cairo[153], O. Cakir[4a], N. Calace[36], P. Calafiura[18], A. Calandri[101], G. Calderini[136], P. Calfayan[65], G. Callea[57], L.P. Caloba[80b], S. Calvente Lopez[98], D. Calvet[38], S. Calvet[38], T.P. Calvet[155], M. Calvetti[71a,71b], R. Camacho Toro[136], S. Camarda[36], D. Camarero Munoz[98], P. Camarri[73a,73b], D. Cameron[134], R. Caminal Armadans[102], C. Camincher[36], S. Campana[36], M. Campanelli[94], A. Camplani[40], A. Campoverde[151], V. Canale[69a,69b], A. Canesse[103], M. Cano Bret[60c], J. Cantero[129], T. Cao[161], Y. Cao[173], M.D.M. Capeans Garrido[36], M. Capua[41b,41a], R. Cardarelli[73a], F.C. Cardillo[149], G. Carducci[41b,41a], I. Carli[143], T. Carli[36], G. Carlino[69a], B.T. Carlson[139], L. Carminati[68a,68b], R.M.D. Carney[45a,45b], S. Caron[119], E. Carquin[147b], S. Carrá[46], J.W.S. Carter[167], M.P. Casado[14,e], A.F. Casha[167], D.W. Casper[171], R. Castelijn[120], F.L. Castillo[174], V. Castillo Gimenez[174], N.F. Castro[140a,140e], A. Catinaccio[36], J.R. Catmore[134], A. Cattai[36], J. Caudron[24], V. Cavaliere[29], E. Cavallaro[14], M. Cavalli-Sforza[14], V. Cavasinni[71a,71b], E. Celebi[12b], F. Ceradini[74a,74b], L. Cerda Alberich[174], K. Cerny[130], A.S. Cerqueira[80a], A. Cerri[156], L. Cerrito[73a,73b], F. Cerutti[18], A. Cervelli[23b,23a], S.A. Cetin[12b], D. Chakraborty[121], S.K. Chan[59], W.S. Chan[120], W.Y. Chan[90], J.D. Chapman[32], B. Chargeishvili[159b], D.G. Charlton[21], T.P. Charman[92], C.C. Chau[34], S. Che[126], A. Chegwidden[106], S. Chekanov[6], S.V. Chekulaev[168a], G.A. Chelkov[79,aw], M.A. Chelstowska[36], B. Chen[78], C. Chen[60a], C.H. Chen[78], H. Chen[29], J. Chen[60a], J. Chen[39], S. Chen[137], S.J. Chen[15c], X. Chen[15b,av], Y. Chen[82], Y-H. Chen[46], H.C. Cheng[63a], H.J. Cheng[15a,15d], A. Cheplakov[79], E. Cheremushkina[123], R. Cherkaoui El Moursli[35e], E. Cheu[7], K. Cheung[64], T.J.A. Chevalérias[145], L. Chevalier[145], V. Chiarella[51], G. Chiarelli[71a], G. Chiodini[67a], A.S. Chisholm[36,21], A. Chitan[27b], I. Chiu[163], Y.H. Chiu[176], M.V. Chizhov[79], K. Choi[65], A.R. Chomont[72a,72b], S. Chouridou[162], Y.S. Chow[120], M.C. Chu[63a], X. Chu[15a], J. Chudoba[141], A.J. Chuinard[103], J.J. Chwastowski[84], L. Chytka[130], K.M. Ciesla[84], D. Cinca[47], V. Cindro[91], I.A. Cioară[27b], A. Ciocio[18], F. Cirotto[69a,69b], Z.H. Citron[180], M. Citterio[68a], D.A. Ciubotaru[27b], B.M. Ciungu[167], A. Clark[54], M.R. Clark[39], P.J. Clark[50], C. Clement[45a,45b], Y. Coadou[101], M. Cobal[66a,66c], A. Coccaro[55b], J. Cochran[78], H. Cohen[161], A.E.C. Coimbra[36], L. Colasurdo[119], B. Cole[39], A.P. Colijn[120], J. Collot[58], P. Conde Muiño[140a,f], E. Coniavitis[52], S.H. Connell[33b], I.A. Connelly[57], S. Constantinescu[27b], F. Conventi[69a,ay], A.M. Cooper-Sarkar[135], F. Cormier[175], K.J.R. Cormier[167], L.D. Corpe[94], M. Corradi[72a,72b], E.E. Corrigan[96], F. Corriveau[103,ad], A. Cortes-Gonzalez[36], M.J. Costa[174], F. Costanza[5], D. Costanzo[149], G. Cowan[93], J.W. Cowley[32], J. Crane[100], K. Cranmer[124], S.J. Crawley[57], R.A. Creager[137], S. Crépé-Renaudin[58], F. Crescioli[136], M. Cristinziani[24], V. Croft[120], G. Crosetti[41b,41a], A. Cueto[5], T. Cuhadar Donszelmann[149], A.R. Cukierman[153], S. Czekierda[84], P. Czodrowski[36], M.J. Da Cunha Sargedas De Sousa[60b], J.V. Da Fonseca Pinto[80b], C. Da Via[100], W. Dabrowski[83a], T. Dado[28a], S. Dahbi[35e], T. Dai[105], C. Dallapiccola[102], M. Dam[40], G. D'amen[23b,23a], V. D'Amico[74a,74b], J. Damp[99], J.R. Dandoy[137], M.F. Daneri[30], N.P. Dang[181], N.D Dann[100], M. Danninger[175], V. Dao[36], G. Darbo[55b], O. Dartsi[5], A. Dattagupta[131], T. Daubney[46], S. D'Auria[68a,68b], W. Davey[24], C. David[46], T. Davidek[143], D.R. Davis[49], I. Dawson[149], K. De[8], R. De Asmundis[69a], M. De Beurs[120], S. De Castro[23b,23a], S. De Cecco[72a,72b], N. De Groot[119], P. de Jong[120], H. De la Torre[106], A. De Maria[15c], D. De Pedis[72a], A. De Salvo[72a], U. De Sanctis[73a,73b], M. De Santis[73a,73b], A. De Santo[156], K. De Vasconcelos Corga[101], J.B. De Vivie De Regie[132], C. Debenedetti[146], D.V. Dedovich[79], A.M. Deiana[42], M. Del Gaudio[41b,41a], J. Del Peso[98], Y. Delabat Diaz[46], D. Delgove[132], F. Deliot[145,q], C.M. Delitzsch[7], M. Della Pietra[69a,69b], D. Della Volpe[54], A. Dell'Acqua[36], L. Dell'Asta[73a,73b], M. Delmastro[5], C. Delporte[132], P.A. Delsart[58], D.A. DeMarco[167], S. Demers[183], M. Demichev[79], G. Demontigny[109], S.P. Denisov[123], D. Denysiuk[120], L. D'Eramo[136], D. Derendarz[84], J.E. Derkaoui[35d], F. Derue[136], P. Dervan[90], K. Desch[24], C. Deterre[46], K. Dette[167], C. Deutsch[24], M.R. Devesa[30], P.O. Deviveiros[36], A. Dewhurst[144], S. Dhaliwal[26], F.A. Di Bello[54], A. Di Ciaccio[73a,73b], L. Di Ciaccio[5], W.K. Di Clemente[137], C. Di Donato[69a,69b], A. Di Girolamo[36], G. Di Gregorio[71a,71b], B. Di Micco[74a,74b], R. Di Nardo[102], K.F. Di Petrillo[59], R. Di Sipio[167], D. Di Valentino[34], C. Diaconu[101], F.A. Dias[40], T. Dias Do Vale[140a], M.A. Diaz[147a], J. Dickinson[18], E.B. Diehl[105], J. Dietrich[19], S. Díez Cornell[46], A. Dimitrievska[18], W. Ding[15b], J. Dingfelder[24], F. Dittus[36], F. Djama[101], T. Djobava[159b], J.I. Djuvsland[17], M.A.B. Do Vale[80c], M. Dobre[27b], D. Dodsworth[26], C. Doglioni[96], J. Dolejsi[143], Z. Dolezal[143], M. Donadelli[80d], J. Donini[38], A. D'onofrio[92], M. D'Onofrio[90], J. Dopke[144], A. Doria[69a], M.T. Dova[88], A.T. Doyle[57], E. Drechsler[152], E. Dreyer[152], T. Dreyer[53], A.S. Drobac[170], Y. Duan[60b], F. Dubinin[110], M. Dubovsky[28a], A. Dubreuil[54], E. Duchovni[180], G. Duckeck[114], A. Ducourthial[136], O.A. Ducu[109], D. Duda[115], A. Dudarev[36], A.C. Dudder[99], E.M. Duffield[18], L. Duflot[132], M. Dührssen[36], C. Dülsen[182], M. Dumancic[180], A.E. Dumitriu[27b], A.K. Duncan[57], M. Dunford[61a], A. Duperrin[101], H. Duran Yildiz[4a], M. Düren[56], A. Durglishvili[159b], D. Duschinger[48], B. Dutta[46], D. Duvnjak[1], G.I. Dyckes[137], M. Dyndal[36], S. Dysch[100], B.S. Dziedzic[84], K.M. Ecker[115], R.C. Edgar[105], T. Eifert[36], G. Eigen[17], K. Einsweiler[18], T. Ekelof[172], H. El Jarrari[35e], M. El Kacimi[35c], R. El Kosseifi[101], V. Ellajosyula[172], M. Ellert[172], F. Ellinghaus[182], A.A. Elliot[92], N. Ellis[36], J. Elmsheuser[29], M. Elsing[36], D. Emeliyanov[144], A. Emerman[39], Y. Enari[163], J.S. Ennis[178], M.B. Epland[49], J. Erdmann[47], A. Ereditato[20], M. Errenst[36], M. Escalier[132], C. Escobar[174], O. Estrada Pastor[174], E. Etzion[161], H. Evans[65], A. Ezhilov[138], F. Fabbri[57], L. Fabbri[23b,23a], V. Fabiani[119], G. Facini[94], R.M. Faisca Rodrigues Pereira[140a], R.M. Fakhrutdinov[123], S. Falciano[72a], P.J. Falke[5], S. Falke[5], J. Faltova[143], Y. Fang[15a], Y. Fang[15a], G. Fanourakis[44], M. Fanti[68a,68b], A. Farbin[8], A. Farilla[74a], E.M. Farina[70a,70b], T. Farooque[106], S. Farrell[18], S.M. Farrington[178], P. Farthouat[36], F. Fassi[35e], P. Fassnacht[36], D. Fassouliotis[9], M. Faucci Giannelli[50], W.J. Fawcett[32], L. Fayard[132], O.L. Fedin[138,o], W. Fedorko[175], M. Feickert[42], S. Feigl[134], L. Feligioni[101], A. Fell[149], C. Feng[60b], E.J. Feng[36], M. Feng[49], M.J. Fenton[57], A.B. Fenyuk[123], J. Ferrando[46], A. Ferrante[173], A. Ferrari[172], P. Ferrari[120], R. Ferrari[70a], D.E. Ferreira de Lima[61b], A. Ferrer[174], D. Ferrere[54], C. Ferretti[105], F. Fiedler[99], A. Filipčič[91], F. Filthaut[119], K.D. Finelli[25], M.C.N. Fiolhais[140a], L. Fiorini[174], F. Fischer[114], W.C. Fisher[106], I. Fleck[151], P. Fleischmann[105], R.R.M. Fletcher[137], T. Flick[182], B.M. Flierl[114], L.F. Flores[137], L.R. Flores Castillo[63a], F.M. Follega[75a,75b], N. Fomin[17], J.H. Foo[167], G.T. Forcolin[75a,75b], A. Formica[145], F.A. Förster[14], A.C. Forti[100], A.G. Foster[21], M.G. Foti[135], D. Fournier[132], H. Fox[89], P. Francavilla[71a,71b], S. Francescato[72a,72b], M. Franchini[23b,23a], S. Franchino[61a], D. Francis[36], L. Franconi[20], M. Franklin[59], A.N. Fray[92], B. Freund[109], W.S. Freund[80b], E.M. Freundlich[47], D.C. Frizzell[128], D. Froidevaux[36], J.A. Frost[135], C. Fukunaga[164], E. Fullana Torregrosa[174], E. Fumagalli[55b,55a], T. Fusayasu[116], J. Fuster[174], A. Gabrielli[23b,23a], A. Gabrielli[18], G.P. Gach[83a], S. Gadatsch[54], P. Gadow[115], G. Gagliardi[55b,55a], L.G. Gagnon[109], C. Galea[27b], B. Galhardo[140a], G.E. Gallardo[135], E.J. Gallas[135], B.J. Gallop[144], P. Gallus[142], G. Galster[40], R. Gamboa Goni[92], K.K. Gan[126], S. Ganguly[180], J. Gao[60a], Y. Gao[90], Y.S. Gao[31,l], C. García[174], J.E. García Navarro[174], J.A. García Pascual[15a], C. Garcia-Argos[52], M. Garcia-Sciveres[18], R.W. Gardner[37], N. Garelli[153], S. Gargiulo[52], V. Garonne[134], A. Gaudiello[55b,55a], G. Gaudio[70a], I.L. Gavrilenko[110], A. Gavrilyuk[111], C. Gay[175], G. Gaycken[24], E.N. Gazis[10], A.A. Geanta[27b], C.N.P. Gee[144], J. Geisen[53], M. Geisen[99], M.P. Geisler[61a], C. Gemme[55b], M.H. Genest[58], C. Geng[105], S. Gentile[72a,72b], S. George[93], T. Geralis[44], L.O. Gerlach[53], P. Gessinger-Befurt[99], G. Gessner[47], S. Ghasemi[151], M. Ghasemi Bostanabad[176], M. Ghneimat[24], A. Ghosh[132], A. Ghosh[77], B. Giacobbe[23b], S. Giagu[72a,72b], N. Giangiacomi[23b,23a], P. Giannetti[71a], A. Giannini[69a,69b], S.M. Gibson[93], M. Gignac[146], D. Gillberg[34], G. Gilles[182], D.M. Gingrich[3,ax], M.P. Giordani[66a,66c], F.M. Giorgi[23b], P.F. Giraud[145], G. Giugliarelli[66a,66c], D. Giugni[68a], F. Giuli[73a,73b], S. Gkaitatzis[162], I. Gkialas[9,h], E.L. Gkougkousis[14], P. Gkountoumis[10], L.K. Gladilin[113], C. Glasman[98], J. Glatzer[14], P.C.F. Glaysher[46], A. Glazov[46], M. Goblirsch-Kolb[26], S. Goldfarb[104], T. Golling[54], D. Golubkov[123], A. Gomes[140a,140b], R. Goncalves Gama[53], R. Gonçalo[140a,140b], G. Gonella[52], L. Gonella[21], A. Gongadze[79], F. Gonnella[21], J.L. Gonski[59], S. González de la Hoz[174], S. Gonzalez-Sevilla[54], G.R. Gonzalvo Rodriguez[174], L. Goossens[36], P.A. Gorbounov[111], H.A. Gordon[29], B. Gorini[36], E. Gorini[67a,67b], A. Gorišek[91], A.T. Goshaw[49], M.I. Gostkin[79], C.A. Gottardo[24], M. Gouighri[35b], D. Goujdami[35c], A.G. Goussiou[148], N. Govender[33b,a], C. Goy[5], E. Gozani[160], I. Grabowska-Bold[83a], E.C. Graham[90], J. Gramling[171], E. Gramstad[134], S. Grancagnolo[19], M. Grandi[156], V. Gratchev[138], P.M. Gravila[27f], F.G. Gravili[67a,67b], C. Gray[57], H.M. Gray[18], C. Grefe[24], K. Gregersen[96], I.M. Gregor[46], P. Grenier[153], K. Grevtsov[46], C. Grieco[14], N.A. Grieser[128], J. Griffiths[8], A.A. Grillo[146], K. Grimm[31,k], S. Grinstein[14,x], J.-F. Grivaz[132], S. Groh[99], E. Gross[180], J. Grosse-Knetter[53], Z.J. Grout[94], C. Grud[105], A. Grummer[118], L. Guan[105], W. Guan[181], J. Guenther[36], A. Guerguichon[132], F. Guescini[115], D. Guest[171], R. Gugel[52], T. Guillemin[5], S. Guindon[36], U. Gul[57], J. Guo[60c], W. Guo[105], Y. Guo[60a,s], Z. Guo[101], R. Gupta[46], S. Gurbuz[12c], G. Gustavino[128], P. Gutierrez[128], C. Gutschow[94], C. Guyot[145], M.P. Guzik[83a], C. Gwenlan[135], C.B. Gwilliam[90], A. Haas[124], C. Haber[18], H.K. Hadavand[8], N. Haddad[35e], A. Hadef[60a], S. Hageböck[36], M. Hagihara[169], M. Haleem[177], J. Haley[129], G. Halladjian[106], G.D. Hallewell[101], K. Hamacher[182], P. Hamal[130], K. Hamano[176], H. Hamdaoui[35e], G.N. Hamity[149], K. Han[60a,ak], L. Han[60a], S. Han[15a,15d], K. Hanagaki[81,v], M. Hance[146], D.M. Handl[114], B. Haney[137], R. Hankache[136], E. Hansen[96], J.B. Hansen[40], J.D. Hansen[40], M.C. Hansen[24], P.H. Hansen[40], E.C. Hanson[100], K. Hara[169], A.S. Hard[181], T. Harenberg[182], S. Harkusha[107], P.F. Harrison[178], N.M. Hartmann[114], Y. Hasegawa[150], A. Hasib[50], S. Hassani[145], S. Haug[20], R. Hauser[106], L.B. Havener[39], M. Havranek[142], C.M. Hawkes[21], R.J. Hawkings[36], D. Hayden[106], C. Hayes[155], R.L. Hayes[175], C.P. Hays[135], J.M. Hays[92], H.S. Hayward[90], S.J. Haywood[144], F. He[60a], M.P. Heath[50], V. Hedberg[96], L. Heelan[8], S. Heer[24], K.K. Heidegger[52], W.D. Heidorn[78], J. Heilman[34], S. Heim[46], T. Heim[18], B. Heinemann[46,as], J.J. Heinrich[131], L. Heinrich[36], C. Heinz[56], J. Hejbal[141], L. Helary[61b], A. Held[175], S. Hellesund[134], C.M. Helling[146], S. Hellman[45a,45b], C. Helsens[36], R.C.W. Henderson[89], Y. Heng[181], S. Henkelmann[175], A.M. Henriques Correia[36], G.H. Herbert[19], H. Herde[26], V. Herget[177], Y. Hernández Jiménez[33c], H. Herr[99], M.G. Herrmann[114], T. Herrmann[48], G. Herten[52], R. Hertenberger[114], L. Hervas[36], T.C. Herwig[137], G.G. Hesketh[94], N.P. Hessey[168a], A. Higashida[163], S. Higashino[81], E. Higón-Rodriguez[174], K. Hildebrand[37], E. Hill[176], J.C. Hill[32], K.K. Hill[29], K.H. Hiller[46], S.J. Hillier[21], M. Hils[48], I. Hinchliffe[18], F. Hinterkeuser[24], M. Hirose[133], S. Hirose[52], D. Hirschbuehl[182], B. Hiti[91], O. Hladik[141], D.R. Hlaluku[33c], X. Hoad[50], J. Hobbs[155], N. Hod[180], M.C. Hodgkinson[149], A. Hoecker[36], F. Hoenig[114], D. Hohn[52], D. Hohov[132], T.R. Holmes[37], M. Holzbock[114], L.B.A.H Hommels[32], S. Honda[169], T. Honda[81], T.M. Hong[139], A. Hönle[115], B.H. Hooberman[173], W.H. Hopkins[6], Y. Horii[117], P. Horn[48], L.A. Horyn[37], J-Y. Hostachy[58], A. Hostiuc[148], S. Hou[158], A. Hoummada[35a], J. Howarth[100], J. Hoya[88], M. Hrabovsky[130], J. Hrdinka[76], I. Hristova[19], J. Hrivnac[132], A. Hrynevich[108], T. Hryn'ova[5], P.J. Hsu[64], S.-C. Hsu[148], Q. Hu[29], S. Hu[60c], Y. Huang[15a], Z. Hubacek[142], F. Hubaut[101], M. Huebner[24], F. Huegging[24], T.B. Huffman[135], M. Huhtinen[36], R.F.H. Hunter[34], P. Huo[155], A.M. Hupe[34], N. Huseynov[79,af], J. Huston[106], J. Huth[59], R. Hyneman[105],

S. Hyrych[28a], G. Iacobucci[54], G. Iakovidis[29], I. Ibragimov[151], L. Iconomidou-Fayard[132], Z. Idrissi[35e], P.I. Iengo[36], R. Ignazzi[40], O. Igonkina[120,z,*], R. Iguchi[163], T. Iizawa[54], Y. Ikegami[81], M. Ikeno[81], D. Iliadis[162], N. Ilic[119], F. Iltzsche[48], G. Introzzi[70a,70b], M. Iodice[74a], K. Iordanidou[168a], V. Ippolito[72a,72b], M.F. Isacson[172], M. Ishino[163], M. Ishitsuka[165], W. Islam[129], C. Issever[135], S. Istin[160], F. Ito[169], J.M. Iturbe Ponce[63a], R. Iuppa[75a,75b], A. Ivina[180], H. Iwasaki[81], J.M. Izen[43], V. Izzo[69a], P. Jacka[141], P. Jackson[1], R.M. Jacobs[24], B.P. Jaeger[152], V. Jain[2], G. Jäkel[182], K.B. Jakobi[99], K. Jakobs[52], S. Jakobsen[76], T. Jakoubek[141], J. Jamieson[57], K.W. Janas[83a], R. Jansky[54], J. Janssen[24], M. Janus[53], P.A. Janus[83a], G. Jarlskog[96], N. Javadov[79,af], T. Javůrek[36], M. Javurkova[52], F. Jeanneau[145], L. Jeanty[131], J. Jejelava[159a,ag], A. Jelinskas[178], P. Jenni[52,b], J. Jeong[46], N. Jeong[46], S. Jézéquel[5], H. Ji[181], J. Jia[155], H. Jiang[78], Y. Jiang[60a], Z. Jiang[153,p], S. Jiggins[52], F.A. Jimenez Morales[38], J. Jimenez Pena[174], S. Jin[15c], A. Jinaru[27b], O. Jinnouchi[165], H. Jivan[33c], P. Johansson[149], K.A. Johns[7], C.A. Johnson[65], K. Jon-And[45a,45b], R.W.L. Jones[89], S.D. Jones[156], S. Jones[7], T.J. Jones[90], J. Jongmanns[61a], P.M. Jorge[140a], J. Jovicevic[36], X. Ju[18], J.J. Junggeburth[115], A. Juste Rozas[14,x], A. Kaczmarska[84], M. Kado[72a,72b], H. Kagan[126], M. Kagan[153], C. Kahra[99], T. Kaji[179], E. Kajomovitz[160], C.W. Kalderon[96], A. Kaluza[99], A. Kamenshchikov[123], L. Kanjir[91], Y. Kano[163], V.A. Kantserov[112], J. Kanzaki[81], L.S. Kaplan[181], D. Kar[33c], M.J. Kareem[168b], E. Karentzos[10], S.N. Karpov[79], Z.M. Karpova[79], V. Kartvelishvili[89], A.N. Karyukhin[123], L. Kashif[181], R.D. Kass[126], A. Kastanas[45a,45b], Y. Kataoka[163], C. Kato[60d,60c], J. Katzy[46], K. Kawade[82], K. Kawagoe[87], T. Kawaguchi[117], T. Kawamoto[163], G. Kawamura[53], E.F. Kay[176], V.F. Kazanin[122b,122a], R. Keeler[176], R. Kehoe[42], J.S. Keller[34], E. Kellermann[96], D. Kelsey[156], J.J. Kempster[21], J. Kendrick[21], O. Kepka[141], S. Kersten[182], B.P. Kerševan[91], S. Ketabchi Haghighat[167], M. Khader[173], F. Khalil-Zada[13], M. Khandoga[145], A. Khanov[129], A.G. Kharlamov[122b,122a], T. Kharlamova[122b,122a], E.E. Khoda[175], A. Khodinov[166], T.J. Khoo[54], E. Khramov[79], J. Khubua[159b], S. Kido[82], M. Kiehn[54], C.R. Kilby[93], Y.K. Kim[37], N. Kimura[66a,66c], O.M. Kind[19], B.T. King[90,*], D. Kirchmeier[48], J. Kirk[144], A.E. Kiryunin[115], T. Kishimoto[163], D.P. Kisliuk[167], V. Kitali[46], O. Kivernyk[5], E. Kladiva[28b,*], T. Klapdor-Kleingrothaus[52], M. Klassen[61a], M.H. Klein[105], M. Klein[90], U. Klein[90], K. Kleinknecht[99], P. Klimek[121], A. Klimentov[29], T. Klingl[24], T. Klioutchnikova[36], F.F. Klitzner[114], P. Kluit[120], S. Kluth[115], E. Kneringer[76], E.B.F.G. Knoops[101], A. Knue[52], D. Kobayashi[87], T. Kobayashi[163], M. Kobel[48], M. Kocian[153], P. Kodys[143], P.T. Koenig[24], T. Koffas[34], N.M. Köhler[115], T. Koi[153], M. Kolb[61b], I. Koletsou[5], T. Komarek[130], T. Kondo[81], N. Kondrashova[60c], K. Köneke[52], A.C. König[119], T. Kono[125], R. Konoplich[124,an], V. Konstantinides[94], N. Konstantinidis[94], B. Konya[96], R. Kopeliansky[65], S. Koperny[83a], K. Korcyl[84], K. Kordas[162], G. Koren[161], A. Korn[94], I. Korolkov[14], E.V. Korolkova[149], N. Korotkova[113], O. Kortner[115], S. Kortner[115], T. Kosek[143], V.V. Kostyukhin[24], A. Kotwal[49], A. Koulouris[10], A. Kourkoumeli-Charalampidi[70a,70b], C. Kourkoumelis[9], E. Kourlitis[149], V. Kouskoura[29], A.B. Kowalewska[84], R. Kowalewski[176], C. Kozakai[163], W. Kozanecki[145], A.S. Kozhin[123], V.A. Kramarenko[113], G. Kramberger[91], D. Krasnopevtsev[60a], M.W. Krasny[136], A. Krasznahorkay[36], D. Krauss[115], J.A. Kremer[83a], J. Kretzschmar[90], P. Krieger[167], F. Krieter[114], A. Krishnan[61b], K. Krizka[18], K. Kroeninger[47], H. Kroha[115], J. Kroll[141], J. Kroll[137], J. Krstic[16], U. Kruchonak[79], H. Krüger[24], N. Krumnack[78], M.C. Kruse[49], J.A. Krzysiak[84], T. Kubota[104], S. Kuday[4b], J.T. Kuechler[46], S. Kuehn[36], A. Kugel[61a], T. Kuhl[46], V. Kukhtin[79], R. Kukla[101], Y. Kulchitsky[107,aj], S. Kuleshov[147b], Y.P. Kulinich[173], M. Kuna[58], T. Kunigo[85], A. Kupco[141], T. Kupfer[47], O. Kuprash[52], H. Kurashige[82], L.L. Kurchaninov[168a], Y.A. Kurochkin[107], A. Kurova[112], M.G. Kurth[15a,15d], E.S. Kuwertz[36], M. Kuze[165], A.K. Kvam[148], J. Kvita[130], T. Kwan[103], A. La Rosa[115], L. La Rotonda[41b,41a], F. La Ruffa[41b,41a], C. Lacasta[174], F. Lacava[72a,72b], D.P.J. Lack[100], H. Lacker[19], D. Lacour[136], E. Ladygin[79], R. Lafaye[5], B. Laforge[136], T. Lagouri[33c], S. Lai[53], S. Lammers[65], W. Lampl[7], C. Lampoudis[162], E. Lançon[29], U. Landgraf[52], M.P.J. Landon[92], M.C. Lanfermann[54], V.S. Lang[46], J.C. Lange[53], R.J. Langenberg[36], A.J. Lankford[171], F. Lanni[29], K. Lantzsch[24], A. Lanza[70a], A. Lapertosa[55b,55a], S. Laplace[136], J.F. Laporte[145], T. Lari[68a], F. Lasagni Manghi[23b,23a], M. Lassnig[36], T.S. Lau[63a], A. Laudrain[132], A. Laurier[34], M. Lavorgna[69a,69b],

M. Lazzaroni[68a,68b], B. Le[104], E. Le Guirriec[101], M. LeBlanc[7], T. LeCompte[6], F. Ledroit-Guillon[58], C.A. Lee[29], G.R. Lee[17], L. Lee[59], S.C. Lee[158], S.J. Lee[34], B. Lefebvre[168a], M. Lefebvre[176], F. Legger[114], C. Leggett[18], K. Lehmann[152], N. Lehmann[182], G. Lehmann Miotto[36], W.A. Leight[46], A. Leisos[162,w], M.A.L. Leite[80d], C.E. Leitgeb[114], R. Leitner[143], D. Lellouch[180,*], K.J.C. Leney[42], T. Lenz[24], B. Lenzi[36], R. Leone[7], S. Leone[71a], C. Leonidopoulos[50], A. Leopold[136], G. Lerner[156], C. Leroy[109], R. Les[167], C.G. Lester[32], M. Levchenko[138], J. Levêque[5], D. Levin[105], L.J. Levinson[180], D.J. Lewis[21], B. Li[15b], B. Li[105], C-Q. Li[60a], F. Li[60c], H. Li[60a], H. Li[60b], J. Li[60c], K. Li[153], L. Li[60c], M. Li[15a], Q. Li[15a,15d], Q.Y. Li[60a], S. Li[60d,60c], X. Li[46], Y. Li[46], Z. Li[60b], Z. Liang[15a], B. Liberti[73a], A. Liblong[167], K. Lie[63c], S. Liem[120], C.Y. Lin[32], K. Lin[106], T.H. Lin[99], R.A. Linck[65], J.H. Lindon[21], A.L. Lionti[54], E. Lipeles[137], A. Lipniacka[17], M. Lisovyi[61b], T.M. Liss[173,au], A. Lister[175], A.M. Litke[146], J.D. Little[8], B. Liu[78,ac], B.L Liu[6], H.B. Liu[29], H. Liu[105], J.B. Liu[60a], J.K.K. Liu[135], K. Liu[136], M. Liu[60a], P. Liu[18], Y. Liu[15a,15d], Y.L. Liu[105], Y.W. Liu[60a], M. Livan[70a,70b], A. Lleres[58], J. Llorente Merino[15a], S.L. Lloyd[92], C.Y. Lo[63b], F. Lo Sterzo[42], E.M. Lobodzinska[46], P. Loch[7], S. Loffredo[73a,73b], T. Lohse[19], K. Lohwasser[149], M. Lokajicek[141], J.D. Long[173], R.E. Long[89], L. Longo[36], K.A. Looper[126], J.A. Lopez[147b], I. Lopez Paz[100], A. Lopez Solis[149], J. Lorenz[114], N. Lorenzo Martinez[5], M. Losada[22], P.J. Lösel[114], A. Lösle[52], X. Lou[46], X. Lou[15a], A. Lounis[132], J. Love[6], P.A. Love[89], J.J. Lozano Bahilo[174], M. Lu[60a], Y.J. Lu[64], H.J. Lubatti[148], C. Luci[72a,72b], A. Lucotte[58], C. Luedtke[52], F. Luehring[65], I. Luise[136], L. Luminari[72a], B. Lund-Jensen[154], M.S. Lutz[102], D. Lynn[29], R. Lysak[141], E. Lytken[96], F. Lyu[15a], V. Lyubushkin[79], T. Lyubushkina[79], H. Ma[29], L.L. Ma[60b], Y. Ma[60b], G. Maccarrone[51], A. Macchiolo[115], C.M. Macdonald[149], J. Machado Miguens[137], D. Madaffari[174], R. Madar[38], W.F. Mader[48], N. Madysa[48], J. Maeda[82], K. Maekawa[163], S. Maeland[17], T. Maeno[29], M. Maerker[48], A.S. Maevskiy[113], V. Magerl[52], N. Magini[78], D.J. Mahon[39], C. Maidantchik[80b], T. Maier[114], A. Maio[140a,140b,140d], O. Majersky[28a], S. Majewski[131], Y. Makida[81], N. Makovec[132], B. Malaescu[136], Pa. Malecki[84], V.P. Maleev[138], F. Malek[58], U. Mallik[77], D. Malon[6], C. Malone[32], S. Maltezos[10], S. Malyukov[36], J. Mamuzic[174], G. Mancini[51], I. Mandić[91], L. Manhaes de Andrade Filho[80a], I.M. Maniatis[162], J. Manjarres Ramos[48], K.H. Mankinen[96], A. Mann[114], A. Manousos[76], B. Mansoulie[145], I. Manthos[162], S. Manzoni[120], A. Marantis[162], G. Marceca[30], L. Marchese[135], G. Marchiori[136], M. Marcisovsky[141], C. Marcon[96], C.A. Marin Tobon[36], M. Marjanovic[38], Z. Marshall[18], M.U.F Martensson[172], S. Marti-Garcia[174], C.B. Martin[126], T.A. Martin[178], V.J. Martin[50], B. Martin dit Latour[17], L. Martinelli[74a,74b], M. Martinez[14,x], V.I. Martinez Outschoorn[102], S. Martin-Haugh[144], V.S. Martoiu[27b], A.C. Martyniuk[94], A. Marzin[36], S.R. Maschek[115], L. Masetti[99], T. Mashimo[163], R. Mashinistov[110], J. Masik[100], A.L. Maslennikov[122b,122a], L.H. Mason[104], L. Massa[73a,73b], P. Massarotti[69a,69b], P. Mastrandrea[71a,71b], A. Mastroberardino[41b,41a], T. Masubuchi[163], A. Matic[114], P. Mättig[24], J. Maurer[27b], B. Maček[91], D.A. Maximov[122b,122a], R. Mazini[158], I. Maznas[162], S.M. Mazza[146], S.P. Mc Kee[105], T.G. McCarthy[115], L.I. McClymont[94], W.P. McCormack[18], E.F. McDonald[104], J.A. Mcfayden[36], M.A. McKay[42], K.D. McLean[176], S.J. McMahon[144], P.C. McNamara[104], C.J. McNicol[178], R.A. McPherson[176,ad], J.E. Mdhluli[33c], Z.A. Meadows[102], S. Meehan[148], T. Megy[52], S. Mehlhase[114], A. Mehta[90], T. Meideck[58], B. Meirose[43], D. Melini[174], B.R. Mellado Garcia[33c], J.D. Mellenthin[53], M. Melo[28a], F. Meloni[46], A. Melzer[24], S.B. Menary[100], E.D. Mendes Gouveia[140a,140e], L. Meng[36], X.T. Meng[105], S. Menke[115], E. Meoni[41b,41a], S. Mergelmeyer[19], S.A.M. Merkt[139], C. Merlassino[20], P. Mermod[54], L. Merola[69a,69b], C. Meroni[68a], O. Meshkov[113,110], J.K.R. Meshreki[151], A. Messina[72a,72b], J. Metcalfe[6], A.S. Mete[171], C. Meyer[65], J. Meyer[160], J-P. Meyer[145], H. Meyer Zu Theenhausen[61a], F. Miano[156], R.P. Middleton[144], L. Mijović[50], G. Mikenberg[180], M. Mikestikova[141], M. Mikuž[91], H. Mildner[149], M. Milesi[104], A. Milic[167], D.A. Millar[92], D.W. Miller[37], A. Milov[180], D.A. Milstead[45a,45b], R.A. Mina[153,p], A.A. Minaenko[123], M. Miñano Moya[174], I.A. Minashvili[159b], A.I. Mincer[124], B. Mindur[83a], M. Mineev[79], Y. Minegishi[163], Y. Ming[181], L.M. Mir[14], A. Mirto[67a,67b], K.P. Mistry[137], T. Mitani[179], J. Mitrevski[114], V.A. Mitsou[174], M. Mittal[60c], A. Miucci[20], P.S. Miyagawa[149], A. Mizukami[81], J.U. Mjörnmark[96], T. Mkrtchyan[184], M. Mlynarikova[143], T. Moa[45a,45b],

K. Mochizuki[109], P. Mogg[52], S. Mohapatra[39], R. Moles-Valls[24], M.C. Mondragon[106], K. Mönig[46], J. Monk[40], E. Monnier[101], A. Montalbano[152], J. Montejo Berlingen[36], M. Montella[94], F. Monticelli[88], S. Monzani[68a], N. Morange[132], D. Moreno[22], M. Moreno Llácer[36], C. Moreno Martinez[14], P. Morettini[55b], M. Morgenstern[120], S. Morgenstern[48], D. Mori[152], M. Morii[59], M. Morinaga[179], V. Morisbak[134], A.K. Morley[36], G. Mornacchi[36], A.P. Morris[94], L. Morvaj[155], P. Moschovakos[36], B. Moser[120], M. Mosidze[159b], T. Moskalets[145], H.J. Moss[149], J. Moss[31,m], K. Motohashi[165], E. Mountricha[36], E.J.W. Moyse[102], S. Muanza[101], J. Mueller[139], R.S.P. Mueller[114], D. Muenstermann[89], G.A. Mullier[96], J.L. Munoz Martinez[14], F.J. Munoz Sanchez[100], P. Murin[28b], W.J. Murray[178,144], A. Murrone[68a,68b], M. Muškinja[18], C. Mwewa[33a], A.G. Myagkov[123,ao], J. Myers[131], M. Myska[142], B.P. Nachman[18], O. Nackenhorst[47], A.Nag Nag[48], K. Nagai[135], K. Nagano[81], Y. Nagasaka[62], M. Nagel[52], E. Nagy[101], A.M. Nairz[36], Y. Nakahama[117], K. Nakamura[81], T. Nakamura[163], I. Nakano[127], H. Nanjo[133], F. Napolitano[61a], R.F. Naranjo Garcia[46], R. Narayan[42], D.I. Narrias Villar[61a], I. Naryshkin[138], T. Naumann[46], G. Navarro[22], H.A. Neal[105,*], P.Y. Nechaeva[110], F. Nechansky[46], T.J. Neep[21], A. Negri[70a,70b], M. Negrini[23b], C. Nellist[53], M.E. Nelson[135], S. Nemecek[141], P. Nemethy[124], M. Nessi[36,d], M.S. Neubauer[173], M. Neumann[182], P.R. Newman[21], T.Y. Ng[63c], Y.S. Ng[19], Y.W.Y. Ng[171], H.D.N. Nguyen[101], T. Nguyen Manh[109], E. Nibigira[38], R.B. Nickerson[135], R. Nicolaidou[145], D.S. Nielsen[40], J. Nielsen[146], N. Nikiforou[11], V. Nikolaenko[123,ao], I. Nikolic-Audit[136], K. Nikolopoulos[21], P. Nilsson[29], H.R. Nindhito[54], Y. Ninomiya[81], A. Nisati[72a], N. Nishu[60c], R. Nisius[115], I. Nitsche[47], T. Nitta[179], T. Nobe[163], Y. Noguchi[85], I. Nomidis[136], M.A. Nomura[29], M. Nordberg[36], N. Norjoharuddeen[135], T. Novak[91], O. Novgorodova[48], R. Novotny[142], L. Nozka[130], K. Ntekas[171], E. Nurse[94], F.G. Oakham[34,ax], H. Oberlack[115], J. Ocariz[136], A. Ochi[82], I. Ochoa[39], J.P. Ochoa-Ricoux[147a], K. O'Connor[26], S. Oda[87], S. Odaka[81], S. Oerdek[53], A. Ogrodnik[83a], A. Oh[100], S.H. Oh[49], C.C. Ohm[154], H. Oide[55b,55a], M.L. Ojeda[167], H. Okawa[169], Y. Okazaki[85], Y. Okumura[163], T. Okuyama[81], A. Olariu[27b], L.F. Oleiro Seabra[140a], S.A. Olivares Pino[147a], D. Oliveira Damazio[29], J.L. Oliver[1], M.J.R. Olsson[171], A. Olszewski[84], J. Olszowska[84], D.C. O'Neil[152], A. Onofre[140a,140e], K. Onogi[117], P.U.E. Onyisi[11], H. Oppen[134], M.J. Oreglia[37], G.E. Orellana[88], D. Orestano[74a,74b], N. Orlando[14], R.S. Orr[167], V. O'Shea[57], R. Ospanov[60a], G. Otero y Garzon[30], H. Otono[87], M. Ouchrif[35d], J. Ouellette[29], F. Ould-Saada[134], A. Ouraou[145], Q. Ouyang[15a], M. Owen[57], R.E. Owen[21], V.E. Ozcan[12c], N. Ozturk[8], J. Pacalt[130], H.A. Pacey[32], K. Pachal[49], A. Pacheco Pages[14], C. Padilla Aranda[14], S. Pagan Griso[18], M. Paganini[183], G. Palacino[65], S. Palazzo[50], S. Palestini[36], M. Palka[83b], D. Pallin[38], I. Panagoulias[10], C.E. Pandini[36], J.G. Panduro Vazquez[93], P. Pani[46], G. Panizzo[66a,66c], L. Paolozzi[54], C. Papadatos[109], K. Papageorgiou[9,h], A. Paramonov[6], D. Paredes Hernandez[63b], S.R. Paredes Saenz[135], B. Parida[166], T.H. Park[167], A.J. Parker[89], M.A. Parker[32], F. Parodi[55b,55a], E.W.P. Parrish[121], J.A. Parsons[39], U. Parzefall[52], L. Pascual Dominguez[136], V.R. Pascuzzi[167], J.M.P. Pasner[146], E. Pasqualucci[72a], S. Passaggio[55b], F. Pastore[93], P. Pasuwan[45a,45b], S. Pataraia[99], J.R. Pater[100], A. Pathak[181], T. Pauly[36], B. Pearson[115], M. Pedersen[134], L. Pedraza Diaz[119], R. Pedro[140a], T. Peiffer[53], S.V. Peleganchuk[122b,122a], O. Penc[141], H. Peng[60a], B.S. Peralva[80a], M.M. Perego[132], A.P. Pereira Peixoto[140a], D.V. Perepelitsa[29], F. Peri[19], L. Perini[68a,68b], H. Pernegger[36], S. Perrella[69a,69b], K. Peters[46], R.F.Y. Peters[100], B.A. Petersen[36], T.C. Petersen[40], E. Petit[101], A. Petridis[1], C. Petridou[162], P. Petroff[132], M. Petrov[135], F. Petrucci[74a,74b], M. Pettee[183], N.E. Pettersson[102], K. Petukhova[143], A. Peyaud[145], R. Pezoa[147b], L. Pezzotti[70a,70b], T. Pham[104], F.H. Phillips[106], P.W. Phillips[144], M.W. Phipps[173], G. Piacquadio[155], E. Pianori[18], A. Picazio[102], R.H. Pickles[100], R. Piegaia[30], D. Pietreanu[27b], J.E. Pilcher[37], A.D. Pilkington[100], M. Pinamonti[73a,73b], J.L. Pinfold[3], M. Pitt[180], L. Pizzimento[73a,73b], M.-A. Pleier[29], V. Pleskot[143], E. Plotnikova[79], D. Pluth[78], P. Podberezko[122b,122a], R. Poettgen[96], R. Poggi[54], L. Poggioli[132], I. Pogrebnyak[106], D. Pohl[24], I. Pokharel[53], G. Polesello[70a], A. Poley[18], A. Policicchio[72a,72b], R. Polifka[143], A. Polini[23b], C.S. Pollard[46], V. Polychronakos[29], D. Ponomarenko[112], L. Pontecorvo[36], S. Popa[27a], G.A. Popeneciu[27d], D.M. Portillo Quintero[58], S. Pospisil[142], K. Potamianos[46], I.N. Potrap[79], C.J. Potter[32], H. Potti[11],

T. Poulsen[96], J. Poveda[36], T.D. Powell[149], G. Pownall[46], M.E. Pozo Astigarraga[36], P. Pralavorio[101], S. Prell[78], D. Price[100], M. Primavera[67a], S. Prince[103], M.L. Proffitt[148], N. Proklova[112], K. Prokofiev[63c], F. Prokoshin[79], S. Protopopescu[29], J. Proudfoot[6], M. Przybycien[83a], D. Pudzha[138], A. Puri[173], P. Puzo[132], J. Qian[105], Y. Qin[100], A. Quadt[53], M. Queitsch-Maitland[46], A. Qureshi[1], P. Rados[104], F. Ragusa[68a,68b], G. Rahal[97], J.A. Raine[54], S. Rajagopalan[29], A. Ramirez Morales[92], K. Ran[15a,15d], T. Rashid[132], S. Raspopov[5], M.G. Ratti[68a,68b], D.M. Rauch[46], F. Rauscher[114], S. Rave[99], B. Ravina[149], I. Ravinovich[180], J.H. Rawling[100], M. Raymond[36], A.L. Read[134], N.P. Readioff[58], M. Reale[67a,67b], D.M. Rebuzzi[70a,70b], A. Redelbach[177], G. Redlinger[29], K. Reeves[43], L. Rehnisch[19], J. Reichert[137], D. Reikher[161], A. Reiss[99], A. Rej[151], C. Rembser[36], M. Renda[27b], M. Rescigno[72a], S. Resconi[68a], E.D. Resseguie[137], S. Rettie[175], E. Reynolds[21], O.L. Rezanova[122b,122a], P. Reznicek[143], E. Ricci[75a,75b], R. Richter[115], S. Richter[46], E. Richter-Was[83b], O. Ricken[24], M. Ridel[136], P. Rieck[115], C.J. Riegel[182], O. Rifki[46], M. Rijssenbeek[155], A. Rimoldi[70a,70b], M. Rimoldi[46], L. Rinaldi[23b], G. Ripellino[154], B. Ristić[89], E. Ritsch[36], I. Riu[14], J.C. Rivera Vergara[176], F. Rizatdinova[129], E. Rizvi[92], C. Rizzi[36], R.T. Roberts[100], S.H. Robertson[103,ad], M. Robin[46], D. Robinson[32], J.E.M. Robinson[46], C.M. Robles Gajardo[147b], A. Robson[57], E. Rocco[99], C. Roda[71a,71b], S. Rodriguez Bosca[174], A. Rodriguez Perez[14], D. Rodriguez Rodriguez[174], A.M. Rodríguez Vera[168b], S. Roe[36], O. Røhne[134], R. Röhrig[115], C.P.A. Roland[65], J. Roloff[59], A. Romaniouk[112], M. Romano[23b,23a], N. Rompotis[90], M. Ronzani[124], L. Roos[136], S. Rosati[72a], K. Rosbach[52], G. Rosin[102], B.J. Rosser[137], E. Rossi[46], E. Rossi[74a,74b], E. Rossi[69a,69b], L.P. Rossi[55b], L. Rossini[68a,68b], R. Rosten[14], M. Rotaru[27b], J. Rothberg[148], D. Rousseau[132], G. Rovelli[70a,70b], D. Roy[33c], A. Rozanov[101], Y. Rozen[160], X. Ruan[33c], F. Rubbo[153], F. Rühr[52], A. Ruiz-Martinez[174], A. Rummler[36], Z. Rurikova[52], N.A. Rusakovich[79], H.L. Russell[103], L. Rustige[38,47], J.P. Rutherfoord[7], E.M. Rüttinger[46,j], Y.F. Ryabov[138], M. Rybar[39], G. Rybkin[132], A. Ryzhov[123], G.F. Rzehorz[53], P. Sabatini[53], G. Sabato[120], S. Sacerdoti[132], H.F-W. Sadrozinski[146], R. Sadykov[79], F. Safai Tehrani[72a], B. Safarzadeh Samani[156], P. Saha[121], S. Saha[103], M. Sahinsoy[61a], A. Sahu[182], M. Saimpert[46], M. Saito[163], T. Saito[163], H. Sakamoto[163], A. Sakharov[124,an], D. Salamani[54], G. Salamanna[74a,74b], J.E. Salazar Loyola[147b], P.H. Sales De Bruin[172], A. Salnikov[153], J. Salt[174], D. Salvatore[41b,41a], F. Salvatore[156], A. Salvucci[63a,63b,63c], A. Salzburger[36], J. Samarati[36], D. Sammel[52], D. Sampsonidis[162], D. Sampsonidou[162], J. Sánchez[174], A. Sanchez Pineda[66a,66c], H. Sandaker[134], C.O. Sander[46], I.G. Sanderswood[89], M. Sandhoff[182], C. Sandoval[22], D.P.C. Sankey[144], M. Sannino[55b,55a], Y. Sano[117], A. Sansoni[51], C. Santoni[38], H. Santos[140a,140b], S.N. Santpur[18], A. Santra[174], A. Sapronov[79], J.G. Saraiva[140a,140d], O. Sasaki[81], K. Sato[169], E. Sauvan[5], P. Savard[167,ax], N. Savic[115], R. Sawada[163], C. Sawyer[144], L. Sawyer[95,al], C. Sbarra[23b], A. Sbrizzi[23a], T. Scanlon[94], J. Schaarschmidt[148], P. Schacht[115], B.M. Schachtner[114], D. Schaefer[37], L. Schaefer[137], J. Schaeffer[99], S. Schaepe[36], U. Schäfer[99], A.C. Schaffer[132], D. Schaile[114], R.D. Schamberger[155], N. Scharmberg[100], V.A. Schegelsky[138], D. Scheirich[143], F. Schenck[19], M. Schernau[171], C. Schiavi[55b,55a], S. Schier[146], L.K. Schildgen[24], Z.M. Schillaci[26], E.J. Schioppa[36], M. Schioppa[41b,41a], K.E. Schleicher[52], S. Schlenker[36], K.R. Schmidt-Sommerfeld[115], K. Schmieden[36], C. Schmitt[99], S. Schmitt[46], S. Schmitz[99], J.C. Schmoeckel[46], U. Schnoor[52], L. Schoeffel[145], A. Schoening[61b], P.G. Scholer[52], E. Schopf[135], M. Schott[99], J.F.P. Schouwenberg[119], J. Schovancova[36], S. Schramm[54], F. Schroeder[182], A. Schulte[99], H-C. Schultz-Coulon[61a], M. Schumacher[52], B.A. Schumm[146], Ph. Schune[145], A. Schwartzman[153], T.A. Schwarz[105], Ph. Schwemling[145], R. Schwienhorst[106], A. Sciandra[146], G. Sciolla[26], M. Scodeggio[46], M. Scornajenghi[41b,41a], F. Scuri[71a], F. Scutti[104], L.M. Scyboz[115], C.D. Sebastiani[72a,72b], P. Seema[19], S.C. Seidel[118], A. Seiden[146], T. Seiss[37], J.M. Seixas[80b], G. Sekhniaidze[69a], K. Sekhon[105], S.J. Sekula[42], N. Semprini-Cesari[23b,23a], S. Sen[49], S. Senkin[38], C. Serfon[76], L. Serin[132], L. Serkin[66a,66b], M. Sessa[60a], H. Severini[128], F. Sforza[170], A. Sfyrla[54], E. Shabalina[53], J.D. Shahinian[146], N.W. Shaikh[45a,45b], D. Shaked Renous[180], L.Y. Shan[15a], R. Shang[173], J.T. Shank[25], M. Shapiro[18], A. Sharma[135], A.S. Sharma[1], P.B. Shatalov[111], K. Shaw[156], S.M. Shaw[100], A. Shcherbakova[138], Y. Shen[128], N. Sherafati[34], A.D. Sherman[25], P. Sherwood[94], L. Shi[158,at], S. Shimizu[81], C.O. Shimmin[183], Y. Shimogama[179], M. Shimojima[116], I.P.J. Shipsey[135], S. Shirabe[87], M. Shiyakova[79,aa], J. Shlomi[180], A. Shmeleva[110], M.J. Shochet[37], S. Shojaii[104], D.R. Shope[128], S. Shrestha[126], E.M. Shrif[33c], E. Shulga[180], P. Sicho[141], A.M. Sickles[173], P.E. Sidebo[154], E. Sideras Haddad[33c], O. Sidiropoulou[36], A. Sidoti[23b,23a], F. Siegert[48], Dj. Sijacki[16], M. Silva Jr.[181], M.V. Silva Oliveira[80a], S.B. Silverstein[45a], S. Simion[132], E. Simioni[99], R. Simoniello[99], S. Simsek[12b], P. Sinervo[167], V. Sinetckii[113,110], N.B. Sinev[131], M. Sioli[23b,23a], I. Siral[105], S.Yu. Sivoklokov[113], J. Sjölin[45a,45b], E. Skorda[96], P. Skubic[128], M. Slawinska[84], K. Sliwa[170], R. Slovak[143], V. Smakhtin[180], B.H. Smart[144], J. Smiesko[28a], N. Smirnov[112], S.Yu. Smirnov[112], Y. Smirnov[112], L.N. Smirnova[113,t], O. Smirnova[96], J.W. Smith[53], M. Smizanska[89], K. Smolek[142], A. Smykiewicz[84], A.A. Snesarev[110], H.L. Snoek[120], I.M. Snyder[131], S. Snyder[29], R. Sobie[176,ad], A.M. Soffa[171], A. Soffer[161], A. Søgaard[50], F. Sohns[53], C.A. Solans Sanchez[36], E.Yu. Soldatov[112], U. Soldevila[174], A.A. Solodkov[123], A. Soloshenko[79], O.V. Solovyanov[123], V. Solovyev[138], P. Sommer[149], H. Son[170], W. Song[144], W.Y. Song[168b], A. Sopczak[142], F. Sopkova[28b], C.L. Sotiropoulou[71a,71b], S. Sottocornola[70a,70b], R. Soualah[66a,66c,g], A.M. Soukharev[122b,122a], D. South[46], S. Spagnolo[67a,67b], M. Spalla[115], M. Spangenberg[178], F. Spanò[93], D. Sperlich[52], T.M. Spieker[61a], R. Spighi[23b], G. Spigo[36], M. Spina[156], D.P. Spiteri[57], M. Spousta[143], A. Stabile[68a,68b], B.L. Stamas[121], R. Stamen[61a], M. Stamenkovic[120], E. Stanecka[84], R.W. Stanek[6], B. Stanislaus[135], M.M. Stanitzki[46], M. Stankaityte[135], B. Stapf[120], E.A. Starchenko[123], G.H. Stark[146], J. Stark[58], S.H Stark[40], P. Staroba[141], P. Starovoitov[61a], S. Stärz[103], R. Staszewski[84], G. Stavropoulos[44], M. Stegler[46], P. Steinberg[29], A.L. Steinhebel[131], B. Stelzer[152], H.J. Stelzer[139], O. Stelzer-Chilton[168a], H. Stenzel[56], T.J. Stevenson[156], G.A. Stewart[36], M.C. Stockton[36], G. Stoicea[27b], M. Stolarski[140a], P. Stolte[53], S. Stonjek[115], A. Straessner[48], J. Strandberg[154], S. Strandberg[45a,45b], M. Strauss[128], P. Strizenec[28b], R. Ströhmer[177], D.M. Strom[131], R. Stroynowski[42], A. Strubig[50], S.A. Stucci[29], B. Stugu[17], J. Stupak[128], N.A. Styles[46], D. Su[153], S. Suchek[61a], V.V. Sulin[110], M.J. Sullivan[90], D.M.S. Sultan[54], S. Sultansoy[4c], T. Sumida[85], S. Sun[105], X. Sun[3], K. Suruliz[156], C.J.E. Suster[157], M.R. Sutton[156], S. Suzuki[81], M. Svatos[141], M. Swiatlowski[37], S.P. Swift[2], T. Swirski[177], A. Sydorenko[99], I. Sykora[28a], M. Sykora[143], T. Sykora[143], D. Ta[99], K. Tackmann[46,y], J. Taenzer[161], A. Taffard[171], R. Tafirout[168a], H. Takai[29], R. Takashima[86], K. Takeda[82], T. Takeshita[150], E.P. Takeva[50], Y. Takubo[81], M. Talby[101], A.A. Talyshev[122b,122a], N.M. Tamir[161], J. Tanaka[163], M. Tanaka[165], R. Tanaka[132], S. Tapia Araya[173], S. Tapprogge[99], A. Tarek Abouelfadl Mohamed[136], S. Tarem[160], G. Tarna[27b,c], G.F. Tartarelli[68a], P. Tas[143], M. Tasevsky[141], T. Tashiro[85], E. Tassi[41b,41a], A. Tavares Delgado[140a,140b], Y. Tayalati[35e], A.J. Taylor[50], G.N. Taylor[104], W. Taylor[168b], A.S. Tee[89], R. Teixeira De Lima[153], P. Teixeira-Dias[93], H. Ten Kate[36], J.J. Teoh[120], S. Terada[81], K. Terashi[163], J. Terron[98], S. Terzo[14], M. Testa[51], R.J. Teuscher[167,ad], S.J. Thais[183], T. Theveneaux-Pelzer[46], F. Thiele[40], D.W. Thomas[93], J.O. Thomas[42], J.P. Thomas[21], A.S. Thompson[57], P.D. Thompson[21], L.A. Thomsen[183], E. Thomson[137], Y. Tian[39], R.E. Ticse Torres[53], V.O. Tikhomirov[110,ap], Yu.A. Tikhonov[122b,122a], S. Timoshenko[112], P. Tipton[183], S. Tisserant[101], K. Todome[23b,23a], S. Todorova-Nova[5], S. Todt[48], J. Tojo[87], S. Tokár[28a], K. Tokushuku[81], E. Tolley[126], K.G. Tomiwa[33c], M. Tomoto[117], L. Tompkins[153,p], K. Toms[118], B. Tong[59], P. Tornambe[102], E. Torrence[131], H. Torres[48], E. Torró Pastor[148], C. Tosciri[135], J. Toth[101,ab], D.R. Tovey[149], A. Traeet[17], C.J. Treado[124], T. Trefzger[177], F. Tresoldi[156], A. Tricoli[29], I.M. Trigger[168a], S. Trincaz-Duvoid[136], W. Trischuk[167], B. Trocmé[58], A. Trofymov[132], C. Troncon[68a], M. Trovatelli[176], F. Trovato[156], L. Truong[33b], M. Trzebinski[84], A. Trzupek[84], F. Tsai[46], J.C-L. Tseng[135], P.V. Tsiareshka[107,aj], A. Tsirigotis[162], N. Tsirintanis[9], V. Tsiskaridze[155], E.G. Tskhadadze[159a], M. Tsopoulou[162], I.I. Tsukerman[111], V. Tsulaia[18], S. Tsuno[81], D. Tsybychev[155], Y. Tu[63b], A. Tudorache[27b], V. Tudorache[27b], T.T. Tulbure[27a], A.N. Tuna[59], S. Turchikhin[79], D. Turgeman[180], I. Turk Cakir[4b,u], R.J. Turner[21], R.T. Turra[68a], P.M. Tuts[39], S Tzamarias[162], E. Tzovara[99], G. Ucchielli[47], K. Uchida[163], I. Ueda[81], M. Ughetto[45a,45b], F. Ukegawa[169], G. Unal[36], A. Undrus[29], G. Unel[171], F.C. Ungaro[104], Y. Unno[81], K. Uno[163], J. Urban[28b], P. Urquijo[104], G. Usai[8], J. Usui[81], Z. Uysal[12d], L. Vacavant[101],

V. Vacek[142], B. Vachon[103], K.O.H. Vadla[134], A. Vaidya[94], C. Valderanis[114], E. Valdes Santurio[45a,45b], M. Valente[54], S. Valentinetti[23b,23a], A. Valero[174], L. Valéry[46], R.A. Vallance[21], A. Vallier[36], J.A. Valls Ferrer[174], T.R. Van Daalen[14], P. Van Gemmeren[6], I. Van Vulpen[120], M. Vanadia[73a,73b], W. Vandelli[36], A. Vaniachine[166], D. Vannicola[72a,72b], R. Vari[72a], E.W. Varnes[7], C. Varni[55b,55a], T. Varol[42], D. Varouchas[132], K.E. Varvell[157], M.E. Vasile[27b], G.A. Vasquez[176], J.G. Vasquez[183], F. Vazeille[38], D. Vazquez Furelos[14], T. Vazquez Schroeder[36], J. Veatch[53], V. Vecchio[74a,74b], M.J. Veen[120], L.M. Veloce[167], F. Veloso[140a,140c], S. Veneziano[72a], A. Ventura[67a,67b], N. Venturi[36], A. Verbytskyi[115], V. Vercesi[70a], M. Verducci[74a,74b], C.M. Vergel Infante[78], C. Vergis[24], W. Verkerke[120], A.T. Vermeulen[120], J.C. Vermeulen[120], M.C. Vetterli[152,ax], N. Viaux Maira[147b], M. Vicente Barreto Pinto[54], T. Vickey[149], O.E. Vickey Boeriu[149], G.H.A. Viehhauser[135], L. Vigani[135], M. Villa[23b,23a], M. Villaplana Perez[68a,68b], E. Vilucchi[51], M.G. Vincter[34], V.B. Vinogradov[79], A. Vishwakarma[46], C. Vittori[23b,23a], I. Vivarelli[156], M. Vogel[182], P. Vokac[142], S.E. von Buddenbrock[33c], E. Von Toerne[24], V. Vorobel[143], K. Vorobev[112], M. Vos[174], J.H. Vossebeld[90], M. Vozak[100], N. Vranjes[16], M. Vranjes Milosavljevic[16], V. Vrba[142], M. Vreeswijk[120], T. Šfiligoj[91], R. Vuillermet[36], I. Vukotic[37], T. Ženiš[28a], L. Živković[16], P. Wagner[24], W. Wagner[182], J. Wagner-Kuhr[114], H. Wahlberg[88], K. Wakamiya[82], V.M. Walbrecht[115], J. Walder[89], R. Walker[114], S.D. Walker[93], W. Walkowiak[151], V. Wallangen[45a,45b], A.M. Wang[59], C. Wang[60b], F. Wang[181], H. Wang[18], H. Wang[3], J. Wang[157], J. Wang[61b], P. Wang[42], Q. Wang[128], R.-J. Wang[99], R. Wang[60a], R. Wang[6], S.M. Wang[158], W.T. Wang[60a], W. Wang[15c,ae], W.X. Wang[60a,ae], Y. Wang[60a,am], Z. Wang[60c], C. Wanotayaroj[46], A. Warburton[103], C.P. Ward[32], D.R. Wardrope[94], N. Warrack[57], A. Washbrook[50], A.T. Watson[21], M.F. Watson[21], G. Watts[148], B.M. Waugh[94], A.F. Webb[11], S. Webb[99], C. Weber[183], M.S. Weber[20], S.A. Weber[34], S.M. Weber[61a], A.R. Weidberg[135], J. Weingarten[47], M. Weirich[99], C. Weiser[52], P.S. Wells[36], T. Wenaus[29], T. Wengler[36], S. Wenig[36], N. Wermes[24], M.D. Werner[78], M. Wessels[61a], T.D. Weston[20], K. Whalen[131], N.L. Whallon[148], A.M. Wharton[89], A.S. White[105], A. White[8], M.J. White[1], D. Whiteson[171], B.W. Whitmore[89], F.J. Wickens[144], W. Wiedenmann[181], M. Wielers[144], N. Wieseotte[99], C. Wiglesworth[40], L.A.M. Wiik-Fuchs[52], F. Wilk[100], H.G. Wilkens[36], L.J. Wilkins[93], H.H. Williams[137], S. Williams[32], C. Willis[106], S. Willocq[102], J.A. Wilson[21], I. Wingerter-Seez[5], E. Winkels[156], F. Winklmeier[131], O.J. Winston[156], B.T. Winter[52], M. Wittgen[153], M. Wobisch[95], A. Wolf[99], T.M.H. Wolf[120], R. Wolff[101], R.W. Wölker[135], J. Wollrath[52], M.W. Wolter[84], H. Wolters[140a,140c], V.W.S. Wong[175], N.L. Woods[146], S.D. Worm[21], B.K. Wosiek[84], K.W. Woźniak[84], K. Wraight[57], S.L. Wu[181], X. Wu[54], Y. Wu[60a], T.R. Wyatt[100], B.M. Wynne[50], S. Xella[40], Z. Xi[105], L. Xia[178], D. Xu[15a], H. Xu[60a,c], L. Xu[29], T. Xu[145], W. Xu[105], Z. Xu[60b], Z. Xu[153], B. Yabsley[157], S. Yacoob[33a], K. Yajima[133], D.P. Yallup[94], D. Yamaguchi[165], Y. Yamaguchi[165], A. Yamamoto[81], T. Yamanaka[163], F. Yamane[82], M. Yamatani[163], T. Yamazaki[163], Y. Yamazaki[82], Z. Yan[25], H.J. Yang[60c,60d], H.T. Yang[18], S. Yang[77], X. Yang[60b,58], Y. Yang[163], W-M. Yao[18], Y.C. Yap[46], Y. Yasu[81], E. Yatsenko[60c,60d], J. Ye[42], S. Ye[29], I. Yeletskikh[79], M.R. Yexley[89], E. Yigitbasi[25], K. Yorita[179], K. Yoshihara[137], C.J.S. Young[36], C. Young[153], J. Yu[78], R. Yuan[60b], X. Yue[61a], S.P.Y. Yuen[24], B. Zabinski[84], G. Zacharis[10], E. Zaffaroni[54], J. Zahreddine[136], A.M. Zaitsev[123,ao], T. Zakareishvili[159b], N. Zakharchuk[34], S. Zambito[59], D. Zanzi[36], D.R. Zaripovas[57], S.V. Zeißner[47], C. Zeitnitz[182], G. Zemaityte[135], J.C. Zeng[173], O. Zenin[123], D. Zerwas[132], M. Zgubič[135], D.F. Zhang[15b], F. Zhang[181], G. Zhang[60a], G. Zhang[15b], H. Zhang[15c], J. Zhang[6], L. Zhang[15c], L. Zhang[60a], M. Zhang[173], R. Zhang[60a], R. Zhang[24], X. Zhang[60b], Y. Zhang[15a,15d], Z. Zhang[63a], Z. Zhang[132], P. Zhao[49], Y. Zhao[60b], Z. Zhao[60a], A. Zhemchugov[79], Z. Zheng[105], D. Zhong[173], B. Zhou[105], C. Zhou[181], M.S. Zhou[15a,15d], M. Zhou[155], N. Zhou[60c], Y. Zhou[7], C.G. Zhu[60b], H.L. Zhu[60a], H. Zhu[15a], J. Zhu[105], Y. Zhu[60a], X. Zhuang[15a], K. Zhukov[110], V. Zhulanov[122b,122a], D. Zieminska[65], N.I. Zimine[79], S. Zimmermann[52], Z. Zinonos[115], M. Ziolkowski[151], G. Zobernig[181], A. Zoccoli[23b,23a], K. Zoch[53], T.G. Zorbas[149], R. Zou[37], L. Zwalinski[36].

[1] Department of Physics, University of Adelaide, Adelaide; Australia.

[2]Physics Department, SUNY Albany, Albany NY; United States of America.
[3]Department of Physics, University of Alberta, Edmonton AB; Canada.
[4](a)Department of Physics, Ankara University, Ankara;(b)Istanbul Aydin University, Istanbul;(c)Division of Physics, TOBB University of Economics and Technology, Ankara; Turkey.
[5]LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.
[6]High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.
[7]Department of Physics, University of Arizona, Tucson AZ; United States of America.
[8]Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.
[9]Physics Department, National and Kapodistrian University of Athens, Athens; Greece.
[10]Physics Department, National Technical University of Athens, Zografou; Greece.
[11]Department of Physics, University of Texas at Austin, Austin TX; United States of America.
[12](a)Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul;(b)Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul;(c)Department of Physics, Bogazici University, Istanbul;(d)Department of Physics Engineering, Gaziantep University, Gaziantep; Turkey.
[13]Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[14]Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.
[15](a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;(b)Physics Department, Tsinghua University, Beijing;(c)Department of Physics, Nanjing University, Nanjing;(d)University of Chinese Academy of Science (UCAS), Beijing; China.
[16]Institute of Physics, University of Belgrade, Belgrade; Serbia.
[17]Department for Physics and Technology, University of Bergen, Bergen; Norway.
[18]Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA; United States of America.
[19]Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
[20]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
[21]School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
[22]Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogota; Colombia.
[23](a)INFN Bologna and Universita' di Bologna, Dipartimento di Fisica;(b)INFN Sezione di Bologna; Italy.
[24]Physikalisches Institut, Universität Bonn, Bonn; Germany.
[25]Department of Physics, Boston University, Boston MA; United States of America.
[26]Department of Physics, Brandeis University, Waltham MA; United States of America.
[27](a)Transilvania University of Brasov, Brasov;(b)Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;(c)Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;(d)National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;(e)University Politehnica Bucharest, Bucharest;(f)West University in Timisoara, Timisoara; Romania.
[28](a)Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
[29]Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
[30]Departamento de Física, Universidad de Buenos Aires, Buenos Aires; Argentina.
[31]California State University, CA; United States of America.
[32]Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
[33](a)Department of Physics, University of Cape Town, Cape Town;(b)Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;(c)School of Physics, University of the

Witwatersrand, Johannesburg; South Africa.
[34]Department of Physics, Carleton University, Ottawa ON; Canada.
[35](a)Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;(b)Faculté des Sciences, Université Ibn-Tofail, Kénitra;(c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;(d)Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;(e)Faculté des sciences, Université Mohammed V, Rabat; Morocco.
[36]CERN, Geneva; Switzerland.
[37]Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
[38]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
[39]Nevis Laboratory, Columbia University, Irvington NY; United States of America.
[40]Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
[41](a)Dipartimento di Fisica, Università della Calabria, Rende;(b)INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
[42]Physics Department, Southern Methodist University, Dallas TX; United States of America.
[43]Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
[44]National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
[45](a)Department of Physics, Stockholm University;(b)Oskar Klein Centre, Stockholm; Sweden.
[46]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
[47]Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund; Germany.
[48]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
[49]Department of Physics, Duke University, Durham NC; United States of America.
[50]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
[51]INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
[52]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
[53]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
[54]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[55](a)Dipartimento di Fisica, Università di Genova, Genova;(b)INFN Sezione di Genova; Italy.
[56]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
[57]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
[58]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
[59]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
[60](a)Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;(b)Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;(c)School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai;(d)Tsung-Dao Lee Institute, Shanghai; China.
[61](a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;(b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
[62]Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima; Japan.
[63](a)Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;(b)Department of Physics, University of Hong Kong, Hong Kong;(c)Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.
[64]Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
[65]Department of Physics, Indiana University, Bloomington IN; United States of America.
[66](a)INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;(b)ICTP, Trieste;(c)Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.

[67][a]INFN Sezione di Lecce;[b]Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
[68][a]INFN Sezione di Milano;[b]Dipartimento di Fisica, Università di Milano, Milano; Italy.
[69][a]INFN Sezione di Napoli;[b]Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
[70][a]INFN Sezione di Pavia;[b]Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
[71][a]INFN Sezione di Pisa;[b]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
[72][a]INFN Sezione di Roma;[b]Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
[73][a]INFN Sezione di Roma Tor Vergata;[b]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
[74][a]INFN Sezione di Roma Tre;[b]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
[75][a]INFN-TIFPA;[b]Università degli Studi di Trento, Trento; Italy.
[76]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck; Austria.
[77]University of Iowa, Iowa City IA; United States of America.
[78]Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
[79]Joint Institute for Nuclear Research, Dubna; Russia.
[80][a]Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;[b]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;[c]Universidade Federal de São João del Rei (UFSJ), São João del Rei;[d]Instituto de Física, Universidade de São Paulo, São Paulo; Brazil.
[81]KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
[82]Graduate School of Science, Kobe University, Kobe; Japan.
[83][a]AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow;[b]Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
[84]Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
[85]Faculty of Science, Kyoto University, Kyoto; Japan.
[86]Kyoto University of Education, Kyoto; Japan.
[87]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
[88]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
[89]Physics Department, Lancaster University, Lancaster; United Kingdom.
[90]Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
[91]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
[92]School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
[93]Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
[94]Department of Physics and Astronomy, University College London, London; United Kingdom.
[95]Louisiana Tech University, Ruston LA; United States of America.
[96]Fysiska institutionen, Lunds universitet, Lund; Sweden.
[97]Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne; France.
[98]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
[99]Institut für Physik, Universität Mainz, Mainz; Germany.
[100]School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
[101]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
[102]Department of Physics, University of Massachusetts, Amherst MA; United States of America.
[103]Department of Physics, McGill University, Montreal QC; Canada.
[104]School of Physics, University of Melbourne, Victoria; Australia.
[105]Department of Physics, University of Michigan, Ann Arbor MI; United States of America.

[106]Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[107]B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk; Belarus.
[108]Research Institute for Nuclear Problems of Byelorussian State University, Minsk; Belarus.
[109]Group of Particle Physics, University of Montreal, Montreal QC; Canada.
[110]P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow; Russia.
[111]Institute for Theoretical and Experimental Physics of the National Research Centre Kurchatov Institute, Moscow; Russia.
[112]National Research Nuclear University MEPhI, Moscow; Russia.
[113]D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.
[114]Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
[115]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
[116]Nagasaki Institute of Applied Science, Nagasaki; Japan.
[117]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
[118]Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
[119]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
[120]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
[121]Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
[122](a)Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk;(b)Novosibirsk State University Novosibirsk; Russia.
[123]Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino; Russia.
[124]Department of Physics, New York University, New York NY; United States of America.
[125]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
[126]Ohio State University, Columbus OH; United States of America.
[127]Faculty of Science, Okayama University, Okayama; Japan.
[128]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
[129]Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
[130]Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc; Czech Republic.
[131]Center for High Energy Physics, University of Oregon, Eugene OR; United States of America.
[132]LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
[133]Graduate School of Science, Osaka University, Osaka; Japan.
[134]Department of Physics, University of Oslo, Oslo; Norway.
[135]Department of Physics, Oxford University, Oxford; United Kingdom.
[136]LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.
[137]Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
[138]Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg; Russia.
[139]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
[140](a)Laboratório de Instrumentação e Física Experimental de Partículas - LIP;(b)Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;(c)Departamento de Física, Universidade de Coimbra, Coimbra;(d)Centro de Física Nuclear da Universidade de Lisboa, Lisboa;(e)Departamento de

Física, Universidade do Minho, Braga;(f)Universidad de Granada, Granada (Spain);(g)Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica; Portugal.

[141]Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.

[142]Czech Technical University in Prague, Prague; Czech Republic.

[143]Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.

[144]Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.

[145]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.

[146]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.

[147](a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;(b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.

[148]Department of Physics, University of Washington, Seattle WA; United States of America.

[149]Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

[150]Department of Physics, Shinshu University, Nagano; Japan.

[151]Department Physik, Universität Siegen, Siegen; Germany.

[152]Department of Physics, Simon Fraser University, Burnaby BC; Canada.

[153]SLAC National Accelerator Laboratory, Stanford CA; United States of America.

[154]Physics Department, Royal Institute of Technology, Stockholm; Sweden.

[155]Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.

[156]Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.

[157]School of Physics, University of Sydney, Sydney; Australia.

[158]Institute of Physics, Academia Sinica, Taipei; Taiwan.

[159](a)E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;(b)High Energy Physics Institute, Tbilisi State University, Tbilisi; Georgia.

[160]Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.

[161]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.

[162]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.

[163]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.

[164]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.

[165]Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.

[166]Tomsk State University, Tomsk; Russia.

[167]Department of Physics, University of Toronto, Toronto ON; Canada.

[168](a)TRIUMF, Vancouver BC;(b)Department of Physics and Astronomy, York University, Toronto ON; Canada.

[169]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.

[170]Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.

[171]Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.

[172]Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.

[173]Department of Physics, University of Illinois, Urbana IL; United States of America.

[174]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.

[175]Department of Physics, University of British Columbia, Vancouver BC; Canada.

[176]Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.

[177]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.

[178]Department of Physics, University of Warwick, Coventry; United Kingdom.
[179]Waseda University, Tokyo; Japan.
[180]Department of Particle Physics, Weizmann Institute of Science, Rehovot; Israel.
[181]Department of Physics, University of Wisconsin, Madison WI; United States of America.
[182]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
[183]Department of Physics, Yale University, New Haven CT; United States of America.
[184]Yerevan Physics Institute, Yerevan; Armenia.
[a] Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town; South Africa.
[b] Also at CERN, Geneva; Switzerland.
[c] Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
[d] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[e] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[f] Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.
[g] Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates.
[h] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[i] Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
[j] Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
[k] Also at Department of Physics, California State University, East Bay; United States of America.
[l] Also at Department of Physics, California State University, Fresno; United States of America.
[m] Also at Department of Physics, California State University, Sacramento; United States of America.
[n] Also at Department of Physics, King's College London, London; United Kingdom.
[o] Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia.
[p] Also at Department of Physics, Stanford University, Stanford CA; United States of America.
[q] Also at Department of Physics, University of Adelaide, Adelaide; Australia.
[r] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[s] Also at Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
[t] Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.
[u] Also at Giresun University, Faculty of Engineering, Giresun; Turkey.
[v] Also at Graduate School of Science, Osaka University, Osaka; Japan.
[w] Also at Hellenic Open University, Patras; Greece.
[x] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[y] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[z] Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
[aa] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
[ab] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.
[ac] Also at Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; China.
[ad] Also at Institute of Particle Physics (IPP); Canada.
[ae] Also at Institute of Physics, Academia Sinica, Taipei; Taiwan.
[af] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[ag] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.

[ah] Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid; Spain.
[ai] Also at Istanbul University, Dept. of Physics, Istanbul; Turkey.
[aj] Also at Joint Institute for Nuclear Research, Dubna; Russia.
[ak] Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
[al] Also at Louisiana Tech University, Ruston LA; United States of America.
[am] Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.
[an] Also at Manhattan College, New York NY; United States of America.
[ao] Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
[ap] Also at National Research Nuclear University MEPhI, Moscow; Russia.
[aq] Also at Physics Department, An-Najah National University, Nablus; Palestine.
[ar] Also at Physics Dept, University of South Africa, Pretoria; South Africa.
[as] Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
[at] Also at School of Physics, Sun Yat-sen University, Guangzhou; China.
[au] Also at The City College of New York, New York NY; United States of America.
[av] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[aw] Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
[ax] Also at TRIUMF, Vancouver BC; Canada.
[ay] Also at Universita di Napoli Parthenope, Napoli; Italy.
[*] Deceased