



Evidence for the production of three massive vector bosons with the ATLAS detector

The ATLAS Collaboration ^{*}



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ABSTRACT

A search for the production of three massive vector bosons in proton–proton collisions is performed using data at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider in the years 2015–2017, corresponding to an integrated luminosity of 79.8 fb^{-1} . Events with two same-sign leptons ℓ (electrons or muons) and at least two reconstructed jets are selected to search for $WWW \rightarrow \ell\nu\ell\nu q\bar{q}$. Events with three leptons without any same-flavour opposite-sign lepton pairs are used to search for $WWW \rightarrow \ell\nu\ell\nu\nu$, while events with three leptons and at least one same-flavour opposite-sign lepton pair and one or more reconstructed jets are used to search for $WWZ \rightarrow \ell\nu q\bar{q}\ell$. Finally, events with four leptons are analysed to search for $WWZ \rightarrow \ell\nu\ell\nu\ell$ and $WZZ \rightarrow q\bar{q}\ell\ell\ell$. Evidence for the joint production of three massive vector bosons is observed with a significance of 4.1 standard deviations, where the expectation is 3.1 standard deviations.

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1. Introduction

The joint production of three vector bosons is a rare process in the Standard Model (SM). Studies of triboson production can test the non-Abelian gauge structure of the SM theory and any deviations from the SM prediction would provide hints of new physics at higher energy scales [1–4]. Triboson production has been studied at the Large Hadron Collider (LHC) using proton–proton (pp) collision data taken at $\sqrt{s} = 8$ TeV for processes such as $\gamma\gamma\gamma$ [5], $W\gamma\gamma$ [6,7], $Z\gamma\gamma$ [8,7], $WW\gamma$ and $WZ\gamma$ [9,10], and WWW [11].

This letter presents the first evidence for the joint production of three massive vector bosons in pp collisions using the dataset collected with the ATLAS detector between 2015 and 2017 at $\sqrt{s} = 13$ TeV. At leading order (LO) in quantum chromodynamics (QCD), the production of three massive vector bosons (VVV , with $V = W, Z$) can proceed via the radiation of each vector boson from a fermion, from an associated boson production with an intermediate boson ($W, Z/\gamma^*$ or H) decaying into two vector bosons, or from a quartic gauge coupling vertex. Representative Feynman diagrams are shown in Fig. 1.

Two dedicated searches are performed, one for the $W^\pm W^\pm W^\mp$ (denoted as WWW) process and one for the $W^\pm W^\mp Z$ (denoted as WWZ) and $W^\pm ZZ$ (denoted as WZZ) processes. To search for the WWW process, events with two same-sign leptons with at least two jets resulting from $WWW \rightarrow \ell\nu\ell\nu q\bar{q}$ ($\ell = e, \mu$, including $\tau \rightarrow \ell\nu\nu$) or three leptons resulting from $WWW \rightarrow \ell\nu\ell\nu\nu$ are

considered and are hereafter referred to as the $\ell\nu\ell\nu q\bar{q}$ and $\ell\nu\ell\nu\nu$ channels, respectively. To search for the WWZ and WZZ (denoted as WVZ) processes, events with three or four leptons resulting from $WVZ \rightarrow \ell\nu q\bar{q}\ell$, $WWZ \rightarrow \ell\nu\ell\nu\ell$, and $WZZ \rightarrow q\bar{q}\ell\ell\ell$ are used. Selection criteria are chosen in order to ensure there is no overlap between different channels. A discriminant that separates the WWW or WVZ signal from the background is defined in each channel. The discriminants are combined using a binned maximum-likelihood fit, which allows the signal yield and the background normalisations to be extracted. The combined observable is the signal strength parameter μ defined as the ratio of the measured WVV cross section to its SM expectation, where one common ratio is assumed for WWW and WVZ .

2. The ATLAS detector, data and simulation samples

The ATLAS detector [12–14] is a multi-purpose particle detector comprised of an inner detector (ID) surrounded by a 2 T superconducting solenoid, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS) with one barrel and two endcap air-core toroids. The ID consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker, and covers $|\eta| < 2.5$ in pseudorapidity.¹ The calorimeter system covers the

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

^{*} E-mail address: atlas.publications@cern.ch.

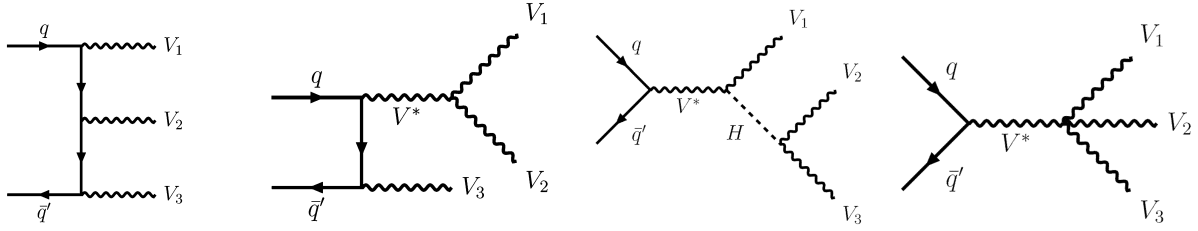


Fig. 1. Representative Feynman diagrams at LO for the production of three massive vector bosons, including diagrams sensitive to triple and quartic gauge couplings.

pseudorapidity range $|\eta| < 4.9$. The MS provides muon triggering capability for $|\eta| < 2.4$ and muon identification and measurement for $|\eta| < 2.7$. A two-level trigger system [15], using custom hardware followed by a software-based trigger level, is used to reduce the event rate to an average of around 1 kHz for offline storage.

The data used were collected between 2015 and 2017 in pp collisions at $\sqrt{s} = 13$ TeV. Only events recorded with a fully operational detector and stable beams are included. Candidate events are selected by single isolated-lepton (e or μ) triggers with transverse momentum thresholds varying from $p_T = 20$ GeV to 26 GeV (depending on the lepton flavour and run period) or single-lepton triggers with thresholds of $p_T = 50$ GeV for muons and $p_T = 60$ GeV for electrons. Due to the presence of two, three or four leptons in the final state, these single-lepton triggers are fully efficient for the triboson signals in the signal regions defined in Sections 4 and 5. The resulting total integrated luminosity is 79.8 fb^{-1} .

Signal and background processes were simulated with several Monte Carlo (MC) event generators, while the ATLAS detector response was modelled [16] with GEANT4 [17]. The effect of multiple pp interactions in the same and neighbouring bunch crossings (pile-up) was included by overlaying minimum-bias events simulated with PYTHIA 8.186 [18] interfaced to EVTGEN 1.2.0 [19], referred to as PYTHIA 8.1 in the following, and using the A3 [20] set of tuned MC parameters, on each generated event in all samples. Triboson signal events [21] were generated using SHERPA 2.2.2 [22–24] with the NNPDF3.0NNLO [25] parton distribution function (PDF) set, where all three bosons are on-mass-shell, using a factorised approach [26]. Events with an off-mass-shell boson through $WH \rightarrow WVV^*$ and $ZH \rightarrow ZVV^*$ were generated using POWHEG-Box 2 [27–32] interfaced to PYTHIA 8.1 for the WWW analysis, while for the WVZ analysis only PYTHIA 8.1 was used. The generator was interfaced to the CT10 [33] (NNPDF2.3LO [34]) PDF and the AZNLO [35] (A14 [36]) set of tuned MC parameters for the WWW (WVZ) analysis. Both on-mass-shell and off-mass-shell processes were generated at next-to-leading order (NLO) QCD accuracy [37–40] and are included in the signal definition. The expected cross sections for WWW and WVZ production are 0.50 pb and 0.29 pb, respectively, with an uncertainty of $\sim 10\%$, evaluated by varying parameters in the simulation related to the renormalisation and factorisation scales, parton shower and PDF sets.

Diboson (WW , WZ , ZZ) [26], $W/Z + \gamma$ [21] and single boson ($W/Z + \text{jets}$) [41] production, as well as electroweak production of $W^\pm W^\pm + 2$ jets, $WZ + 2$ jets, and $ZZ + 2$ jets, were modelled using SHERPA 2.2.2 with the NNPDF3.0NNLO PDF set. In order to improve the agreement between the simulated and observed jet multiplicity distributions for the $WZ \rightarrow \ell\nu\ell\ell$ and $ZZ \rightarrow \ell\ell\ell\ell$ events, a jet-multiplicity based reweighting was applied to the simulated WZ and ZZ samples. Top-quark pair events ($t\bar{t}$) were generated using POWHEG-Box 2 [42] interfaced to PYTHIA 8.230 [43]

POWHEG-Box 2 interfaced to PYTHIA 8.230 and EVTGEN 1.6.0. The NNPDF3.0NLO PDF set was used for the matrix-element calculation, while the NNPDF2.3LO PDF set was used for the showering with the A14 set of tuned parameters. Other background processes containing top quarks were generated with MADGRAPH5_aMC@NLO [44] interfaced to PYTHIA 8, at LO ($t\bar{t}\gamma$, tZ , $t\bar{t}WW$, and $t\bar{t}t\bar{t}$) or at NLO ($t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$), with MADGRAPH5_aMC@NLO interfaced to HERWIG [45] (tWZ and tWH) or with POWHEG-Box 2 [46] interfaced to PYTHIA 6 (tW).

3. Object definitions and selection criteria

Selected events are required to contain at least one reconstructed primary vertex. If more than one vertex is found, the vertex with the largest p_T^2 sum of associated ID tracks is selected as the primary vertex.

Electrons are reconstructed as energy clusters in the EM calorimeter that are matched to tracks found in the ID. Muons are reconstructed by combining tracks reconstructed in the ID with tracks or track segments found in the MS. Leptons need to satisfy $p_T > 15$ GeV and have $|\eta| < 2.47$ for electrons (electrons within the transition region between the barrel and endcap calorimeters, $1.37 < |\eta| < 1.52$, are excluded) and $|\eta| < 2.5$ for muons. Leptons are required to be consistent with originating from the primary vertex by imposing requirements on the transverse impact parameter, d_0 , its uncertainty, σ_{d_0} , the longitudinal impact parameter, z_0 , and the polar angle θ . These requirements are $|d_0|/\sigma_{d_0} < 5$ and $|z_0 \times \sin\theta| < 0.5$ mm for electrons, and $|d_0|/\sigma_{d_0} < 3$ and $|z_0 \times \sin\theta| < 0.5$ mm for muons. Electrons have to satisfy the likelihood-based “Tight” quality definition which results in efficiencies of 58% at $E_T = 4.5$ GeV to 88% at $E_T = 100$ GeV [47]. For the WWW (WVZ) analysis, muons are required to pass the “Medium” (“Loose”) identification criteria which results in efficiencies of approximately 96% (98%) for muons from a $Z \rightarrow \mu\mu$ sample [48].

To reject jets misidentified as leptons or leptons from hadron decays (including b - and c -hadron decays), referred to as “non-prompt” leptons in the following, leptons are required to be isolated from other particles in both the calorimeters and the ID. The lepton isolation cone size is at most $\Delta R = 0.2$, except for the muon isolation in the ID, where it is at most $\Delta R = 0.3$. Electrons are required to pass the “Fix (Loose)” isolation requirement [49] and muons are required to pass the “Gradient” (“FixedCutLoose”) isolation requirement [48] for the WWW (WVZ) analysis. The identification and isolation requirements for muons are more restrictive in the WWW analysis because a larger contamination from non-prompt leptons is expected. The electron Fix (Loose) isolation requirement results in an efficiency above 95% [47]. The muon isolation efficiency is above 90% (99%) for the Gradient isolation criteria for muons with p_T of 25 GeV (60 GeV), and the FixedCutLoose efficiency is above 95% [48].

A dedicated boosted decision tree (BDT), termed “non-prompt lepton BDT” [50], is used to reject leptons likely to originate from heavy-flavour decays. In addition, electrons have to pass the “charge misidentification suppression BDT” [49] to reject electrons

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 $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

likely to have the electric charge wrongly measured. The non-prompt lepton BDT uses isolation and b -tagging information derived from energy deposits and tracks in a cone around the lepton direction. The charge misidentification suppression BDT uses the electron track impact parameter, the track curvature significance, the cluster width and the quality of the matching between the cluster and its associated track. Leptons passing all requirements listed above are referred to as “nominal” leptons. The combination of isolation, non-prompt lepton BDT and charge misidentification suppression BDT criteria results in an efficiency of 65% (89%) for electrons with $p_T > 20$ GeV (80 GeV) [47]. The combination of isolation and non-prompt lepton BDT results in an efficiency of 65% (99%) for muons that have the Gradient isolation with p_T of 20 GeV (100 GeV), and an efficiency of 74% (99%) for muons that have the FixedCutLoose isolation with p_T of 20 GeV (80 GeV) [48].

Jets are reconstructed from calibrated topological clusters built from energy deposits in the calorimeter [51] using the anti- k_t algorithm with a radius parameter of 0.4 [52,53] and calibrated using the techniques described in Ref. [54]. Jet candidates are required to have $p_T > 20$ GeV and $|\eta| < 2.5$. To reject jets likely to be arising from pile-up collisions, an additional criterion using the jet vertex tagger [55] discriminant is applied for jets with $p_T < 60$ GeV and $|\eta| < 2.4$. Jets containing b -hadrons (b -jets) are identified by a multivariate discriminant combining information from algorithms using secondary vertices reconstructed within the jet and track impact parameters [56,57], with an efficiency of 85% (70%) for the WW (WVZ) analysis.

The missing transverse momentum, whose magnitude is denoted E_T^{miss} , is defined as the negative vector sum of the p_T of all reconstructed and calibrated objects in the event. This sum includes a term to account for the energy from low-momentum particles that are not associated with any of the selected objects, and is calculated from ID tracks matched to the reconstructed primary vertex in the event [58]. The sum also includes jets with $|\eta| > 2.5$ and $p_T > 30$ GeV.

The object reconstruction and identification algorithms do not always result in unambiguous identifications. An overlap removal algorithm is therefore applied. Electrons sharing a track with any muons are removed. Any jet within $\Delta R < 0.2$ of an electron is removed and electrons within $\Delta R < 0.4$ of any remaining jets are removed. Jets with less than three associated tracks and within $\Delta R < 0.2$ of a muon are removed, and muons within $\Delta R < 0.4$ of any of the remaining jets are removed.

At least one reconstructed “trigger” lepton with a minimum p_T is required to match within $\Delta R < 0.15$ a lepton with the same flavour reconstructed by the trigger algorithm. The thresholds for the trigger (other) leptons are 27 GeV (20 GeV) for the WW analysis, and from 21 GeV to 27 GeV (15 GeV), depending on the run period and lepton flavour, for the WVZ analysis.

4. Analysis targeting WW

The experimental signature of the $lvlvqq$ process is the presence of two same-sign leptons, E_T^{miss} , and two jets. The signature of the $lvlvll$ process is the presence of three leptons and E_T^{miss} . To reduce the background contributions from processes that have more than two (three) leptons in the $lvlvqq$ ($lvlvll$) channel a “veto lepton” definition is introduced. Compared with the nominal lepton selection criteria described in Section 3, the veto lepton p_T threshold is lowered to 7 GeV, and the isolation, non-prompt lepton BDT, charge misidentification suppression BDT, and impact parameter requirements are removed. For veto electrons, the likelihood-based Loose identification definition [49] is used. For veto muons, the Loose identification definition [48] is used, and the pseudorapidity range is extended to $|\eta| < 2.7$.

To select $lvlvqq$ candidates, events are required to have exactly two nominal leptons with $p_T > 20$ GeV and the same electric charge, at least two jets, and no identified b -jets. Four regions are considered, based on the lepton flavour, namely ee , $e\mu$, μe , and $\mu\mu$, where $e\mu$ denotes the highest- p_T (leading) lepton being an electron, while μe denotes the leading lepton being a muon. Events with an additional veto lepton are removed. The invariant mass of the dilepton system is required to be in the range $40 < m_{\ell\ell} < 400$ GeV. The upper mass limit reduces the contribution from the WZ +jets process. The leading (sub-leading) jet must have $p_T > 30$ (20) GeV and $|\eta| < 2.5$. The dijet system, formed by the two jets with the largest p_T , is required to have $m_{jj} < 300$ GeV and $|\Delta\eta_{jj}| < 1.5$, where m_{jj} is the dijet invariant mass and $\Delta\eta_{jj}$ is the pseudorapidity separation between the two jets. The cuts applied on the dijet system mainly reduce the contributions from the same-sign WW vector boson scattering process. Additionally, in the ee final state, E_T^{miss} is required to be above 55 GeV and $m_{\ell\ell}$ must satisfy $m_{\ell\ell} < 80$ GeV or $m_{\ell\ell} > 100$ GeV, to reduce contamination from $Z \rightarrow ee$ where the charge of one electron is misidentified. This $m_{\ell\ell}$ cut is not applied in the $\mu\mu$ final state, since the muon charge misidentification rate is found to be negligible, nor is it applied in the $e\mu$ and μe final states, where the contamination from Z events is small.

To select $lvlvll$ candidates, events are required to have exactly three nominal leptons with $p_T > 20$ GeV and no identified b -jets. Events with an additional veto lepton are removed. To reduce the contribution from the $WZ \rightarrow lvll$ process, events are required to have no same-flavour opposite-sign (SFOS) lepton pairs, and thus only $\mu^\pm e^\mp e^\mp$ and $e^\pm \mu^\mp \mu^\mp$ events are selected.

A major background originates from the WZ +jets $\rightarrow lvll$ +jets process, contributing to the $lvlvqq$ channel when one lepton is not reconstructed or identified, or to the $lvlvll$ channel, when a Z boson decays into a pair of τ leptons both of which decay to an electron or muon. Simulation is used to estimate this background. The WZ +jets modelling is tested in a WZ -dominated validation region defined by selecting events with exactly three nominal leptons with one SFOS lepton pair. In addition, events are required to have no b -jets reconstructed, $E_T^{\text{miss}} > 55$ GeV and the tripleton invariant mass $m_{\ell\ell\ell} > 110$ GeV. Data and simulation agree in this validation region, as shown in Fig. 2(a) for the leading lepton p_T distribution.

Contributions from SM processes that produce at least one non-prompt lepton are estimated using a data-driven method as described in Ref. [59] by introducing “fake” leptons. The definitions of nominal and fake leptons are mutually exclusive. Fake electrons have to satisfy the likelihood-based Medium [49] but fail the Tight identification, and the isolation, non-prompt lepton BDT and charge misidentification suppression BDT requirements are removed. Fake muons have the impact parameter requirements loosened to $|d_0|/\sigma_{d_0} < 10$, and both isolation and non-prompt lepton BDT requirements are removed. Additionally, they have to fail the nominal muon definition. Simulation shows that the $t\bar{t}$ process is the dominant contributor of events with fake leptons, with more than 90% in the $lvlvqq$ channel and more than 95% in the $lvlvll$ channel originating from this process. Events containing one (two) nominal lepton(s) and one fake lepton with $p_T > 20$ GeV are scaled by a “fake factor” to predict the non-prompt lepton background contribution in the $lvlvqq$ ($lvlvll$) channel. The fake factor is the ratio of the number of non-prompt leptons passing the nominal lepton criteria over the number passing the fake lepton criteria. Its value is derived from two $t\bar{t}$ -enriched regions selected with two or three leptons (no SFOS lepton pairs) and exactly one b -jet. One of the same-sign leptons passes either nominal or fake lepton criteria, while the other lepton(s) must pass the nominal lepton

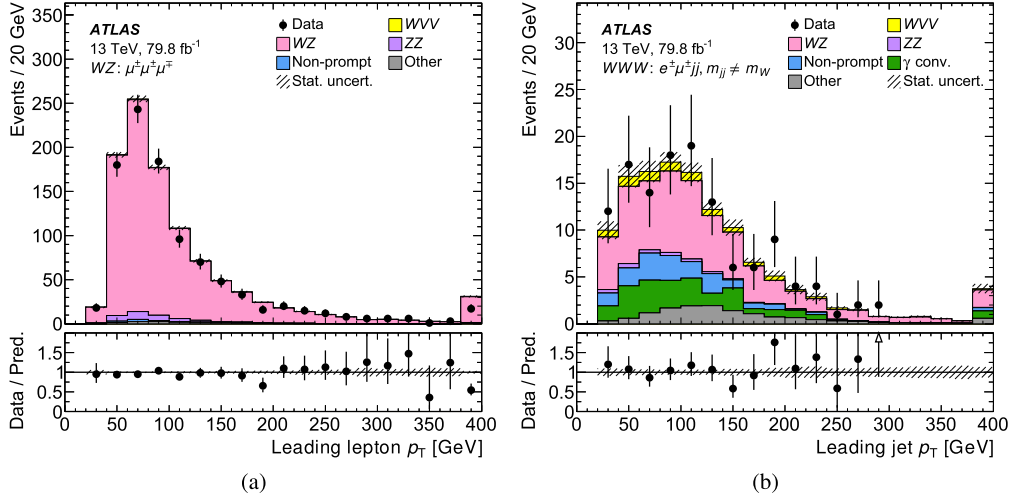


Fig. 2. Comparison between data and prediction of (a) the leading lepton p_T distribution in the WZ validation region and (b) the leading jet p_T distribution in the W sideband region. The contribution denoted “Other” is dominated by the $W^\pm W^\pm + 2$ jets process for the W sideband region. The contribution denoted “ γ -conv.” is described in the text. Predictions from simulation are scaled to the integrated luminosity of the data using the theoretical cross sections of each sample. The hatched area represents the statistical uncertainty in the prediction due to the limited number of simulated events. The last bin contains the overflow. The bottom panel displays the ratio of data to the total prediction.

criteria. The fake factor is found to be 0.017 ± 0.010 for electrons and 0.035 ± 0.005 for muons.

Events resulting from the $V\gamma jj$ production can pass the ee , $e\mu$ or μe signal selection criteria if the photon is misreconstructed as an electron. This contribution (referred to as “ γ conv.”) is evaluated using a data-driven method similar to the non-prompt lepton background evaluation by introducing “photon-like” electrons. A photon-like electron is an object reconstructed like a nominal electron except that the track has no hit in the innermost layer of the pixel detector and the non-prompt lepton BDT and charge misidentification suppression BDT requirements are not applied. The photon fake factor is determined in two regions selected with two nominal muons, no b -jets, and one nominal or photon-like electron. The trilepton invariant mass is required to satisfy $80 \text{ GeV} < m_{e\mu\mu} < 100 \text{ GeV}$. Most of these events contain a $Z \rightarrow \mu\mu$ decay, where one muon radiates a photon, which is misreconstructed as an electron.

The charge misidentification background originates from processes that produce oppositely-charged prompt leptons, where one lepton’s charge is misidentified and results in final states with two same-sign leptons. The background is estimated using a data-driven technique as described in Ref. [11].

All $\ell\nu\ell\nu qq$ candidates with $m_{jj} < 50 \text{ GeV}$ or $m_{jj} > 120 \text{ GeV}$ (denoted as the “ W sideband” region) are used to validate the modelling of different backgrounds described above. Data and prediction agree, as shown in Fig. 2(b) for the leading jet p_T distribution. Events with $m_{jj} < 300 \text{ GeV}$ are used in the fit to extract the signal.

5. Analysis targeting WWZ and WZZ

The experimental signature of the $WWZ \rightarrow \ell\nu qq\ell\ell$, $WWZ \rightarrow \ell\nu\ell\nu\ell\ell$, and $WZZ \rightarrow qq\ell\ell\ell\ell$ processes is the presence of three or four charged leptons. In order to increase the signal acceptance, “loose” leptons are defined in addition to nominal leptons, the latter being a subset of the former. Loose leptons have both the isolation and non-prompt lepton BDT requirements removed. In addition, loose electrons are required to pass the likelihood-based Loose identification definition and the charge misidentification suppression BDT requirement is removed.

Six regions are defined with either three or four loose leptons, sensitive to triboson final states containing Z bosons. Among all possible SFOS lepton pairs, the one with $m_{\ell\ell}$ closest to the Z boson mass is defined as the best Z candidate. In all regions, the presence of such a best Z candidate with $|m_{\ell\ell} - 91.2 \text{ GeV}| < 10 \text{ GeV}$, is required. Furthermore, any SFOS lepton pair combination is required to have a minimum invariant mass of $m_{\ell\ell} > 12 \text{ GeV}$. Events with b -tagged jets are vetoed.

For the three-lepton channel, the lepton which is not part of the best Z candidate is required to be a nominal lepton. The scalar sum of the transverse momenta of all leptons and jets (H_T) is required to be larger than 200 GeV. This significantly reduces the contribution of the $Z \rightarrow \ell\ell$ processes with one additional non-prompt lepton. Three regions are defined according to the number of jets in the event: one jet (3ℓ -1j), two jets (3ℓ -2j), and at least three jets (3ℓ -3j).

For the four-lepton channel, the third and fourth leading leptons are required to be nominal leptons. The two leptons which are not part of the best Z candidate definition are required to have opposite charges. These “other leptons” are used to define three regions, depending on whether they are different-flavour (4ℓ -DF), or same-flavour and their mass lies within a window of 10 GeV around the Z boson mass (4ℓ -SF-Z) or their mass is outside this window (4ℓ -SF-noZ).

In each of the six regions the distribution p_T of a dedicated BDT discriminant, separating the WWZ signal from the dominating diboson background, is fed as input to the binned maximum-likelihood fit to extract the signal. For the three-lepton channels, 13, 15, and 12 input variables are used for the 3ℓ -1j, 3ℓ -2j, and 3ℓ -3j final states, respectively, while for the four-lepton channels, six input variables are used for each of the 4ℓ -DF, 4ℓ -SF-Z and 4ℓ -SF-noZ final states. These input variables are listed in Table 1.

Due to the required presence of nominal leptons in the three- and four-lepton channels, backgrounds with a Z boson and non-prompt leptons are reduced. The remaining backgrounds are dominated by processes with prompt leptons and thus all backgrounds are estimated using simulation. The WZ +jets and Z +jets backgrounds are validated in a region defined in the same way as the 3ℓ -1j region, with the exception that no requirement on H_T is applied, the third-highest- p_T lepton is required to have a small transverse momentum ($10 \text{ GeV} < p_T < 15 \text{ GeV}$), and the invariant mass

Table 1

List of input variables used in the multivariate analysis for each of the WVZ channels, denoted by \times . The subscripts 1, 2 and 3 refer to the leading, subleading and third leading lepton or jet. The definitions of “best Z candidate” and “other leptons” are given in the text. The variable $m_T(W_\ell)$ is the W -boson transverse mass of the leptonically decaying W -boson candidate. Among the invariant masses formed by all possible jet pairs, the one closest to the W -boson mass defines the “ m_{jj} of best W candidate” and the smallest one defines the “smallest m_{jj} ”. Finally, the leptonic and hadronic H_T are calculated as the scalar sum of the p_T of all leptons or all jets, respectively.

Variable	3 ℓ -1j	3 ℓ -2j	3 ℓ -3j	4 ℓ DF	4 ℓ SF on-shell	4 ℓ SF off-shell
$p_T(\ell_1)$	\times	\times				
$p_T(\ell_2)$	\times	\times	\times			
$p_T(\ell_3)$	\times	\times	\times			
Sum of $p_T(\ell)$	\times	\times	\times			
$m_{\ell_1\ell_2}$	\times	\times				
$m_{\ell_1\ell_3}$	\times	\times				
$m_{\ell_2\ell_3}$	\times	\times				
$m_{\ell\ell}$ of best Z candidate					\times	\times
$m_{\ell\ell}$ of other leptons				\times	\times	\times
$m_{3\ell}$	\times	\times	\times			
$m_{4\ell}$				\times	\times	\times
Sum of lepton charges	\times	\times	\times			
$p_T(j_1)$	\times	\times				
$p_T(j_2)$		\times	\times			
Sum of $p_T(j)$			\times			
Number of jets			\times	\times	\times	\times
$m_{j_1j_2}$		\times				
$m_T(W_\ell)$		\times				
m_{jj} of best W candidate			\times			
Smallest m_{jj}			\times			
E_T^{miss}		\times	\times	\times	\times	\times
H_T	\times	\times			\times	\times
Leptonic H_T				\times		
Hadronic H_T				\times		
Invariant mass of all leptons, jets and E_T^{miss}	\times		\times			
Invariant mass of the best Z leptons and j_1	\times					

of the three leptons has to be smaller than 150 GeV. Data and expectation agree in the 3 ℓ -1j validation region, as shown in Fig. 3(a) for the transverse momentum distribution of the third-highest- p_T lepton.

The $t\bar{t}Z$ background is determined in a region defined like the 3 ℓ -3j region with the exception that no requirement on H_T is applied, and at least four jets are required, of which at least two are b -tagged. This region is included as a single-bin control region (CR) in the fit model, outlined in Section 6. Data and expectation agree, as shown in Fig. 3(b) for the $t\bar{t}Z$ control region.

6. Signal extraction and combination

The WWW , WWZ and WZZ regions are combined using the profile likelihood method described in Ref. [60] based on a simultaneous fit to distributions in the signal and background control regions. A total of eleven signal regions are considered: four regions (ee , $e\mu$, μe , and $\mu\mu$) for the $\ell\nu\ell\nu q\bar{q}$ channel, one region ($\mu e e$ and $e\mu\mu$ combined) for the $\ell\nu\ell\nu\nu$ channel, three regions (3 ℓ -1j, 3 ℓ -2j, and 3 ℓ -3j) for the WVZ three-lepton channel, and three regions (4 ℓ -DF, 4 ℓ -SF-Z, and 4 ℓ -SF-noZ) for the WVZ four-lepton channel. One control region is considered: the $t\bar{t}Z$ control region described in Section 5. The distributions used in the fit are the m_{jj} distributions for the $\ell\nu\ell\nu q\bar{q}$ channel and the BDT distributions for the WVZ three-lepton and four-lepton channels. The number of selected events in the $\ell\nu\ell\nu\nu$ channel and the $t\bar{t}Z$ control region are each included as a single bin in the fit. In total, 186 bins are used in the combined fit.

A binned likelihood function $\mathcal{L}(\mu, \theta)$ is constructed as a product of Poisson probability terms over all bins considered. This likelihood function depends on the signal-strength parameter μ , a multiplicative factor that scales the number of expected signal events, and θ , a set of nuisance parameters that encode the effect of systematic uncertainties in the signal and background expectations. The nuisance parameters are implemented in the likelihood

function as Gaussian, log-normal or Poisson constraints. The same value for $\mu = \mu_{WVV}$ is assumed for the on- and off-mass-shell WWW , WWZ and WZZ processes. Correlations of systematic uncertainties arising from common sources are maintained across processes and channels.

Experimental uncertainties are related to the lepton trigger, reconstruction and identification efficiencies [49,48], lepton isolation criteria [50], lepton energy (momentum) scale and resolution [48, 61], jet energy scale and resolution [54], jet vertex tagging [55, 62], b -tagging [57], modelling of pile-up and missing transverse momentum [58], and integrated luminosity [63,64]. Nuisance parameters related to these uncertainties are treated as correlated between all channels. The time-dependence of the efficiencies, scales and resolutions across the various run periods is taken into account.

For each of the background processes evaluated using simulation, a nuisance parameter representing its normalisation uncertainty is included. The following prior uncertainties in the normalisations are assumed: 20% for WZ and ZZ ; 40% for Z +jets, 10% [65] for WtZ , 30% [66,67] for tZ , 11% [68] for $t\bar{t}Z$, and 30% for VH not producing three massive bosons. For dominant backgrounds from the WZ and ZZ processes, the simultaneous fit model has the power to constrain their normalisations at the $\sim 5\%$ level, independently of the assumed prior. In addition, shape-only variations for backgrounds from the WZ and ZZ processes are derived from alternative samples, generated using POWHEG [69] with PYTHIA 8 for the parton shower to account for differences in the modelling of diboson production and showering. Shape variations due to renormalisation and factorisation scales are also considered for these two processes. The prior uncertainties assumed for Z +jets and VH cover the observed data/simulation agreement in validation regions, and the calculations in Ref. [68], respectively. The impact of these uncertainties on the measurement is small.

Uncertainties in data-driven background evaluations mainly come from statistical and systematic uncertainties in the charge

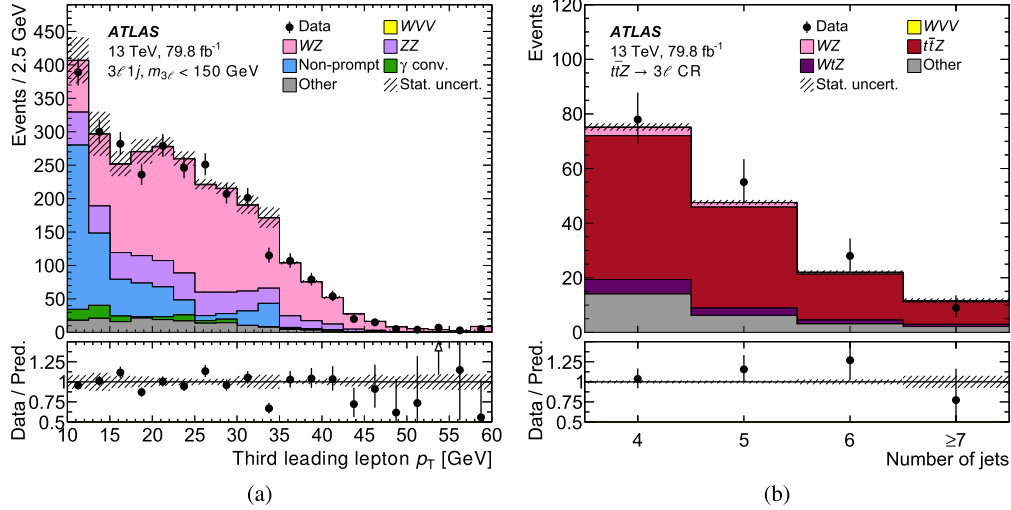


Fig. 3. Data compared with expectations for (a) the transverse momentum of the third-highest- p_T lepton in the 3ℓ -1j region with the additional requirement $m_{\ell\ell\ell} < 150$ GeV, no requirement on H_T , and including the $10 \text{ GeV} < p_T < 15 \text{ GeV}$ validation region and (b) the number of jets in the $t\bar{t}Z$ control region. The contributions denoted “Other” are dominated by (a) the tZ and VH processes, where the Higgs boson does not decay to two massive bosons, and (b) the tZ process. Predictions from simulation are scaled to the integrated luminosity of the data using the theoretical cross sections of each sample. The hatched area represents the statistical uncertainty in the prediction due to the limited number of simulated events. The last bin contains the overflow. The bottom panel displays the ratio of data to the total prediction.

Table 2

Post-fit background, signal and observed yields for the $\ell\nu\ell\nu q\bar{q}$ and $\ell\nu\ell\nu\ell\nu$ channels. Uncertainties in the predictions include both statistical and systematic uncertainties added in quadrature; correlations among systematic uncertainties are taken into account in the calculation of the total.

	$e\bar{e}$	$e\mu$	μe	$\mu\mu$	$\mu e\bar{e} + e\mu\mu$
WWW	9.9 ± 3.3	26 ± 9	23 ± 8	30 ± 10	15 ± 5
WZ	37.4 ± 2.2	121 ± 6	96 ± 5	119 ± 6	8.6 ± 0.5
ZZ	0.46 ± 0.05	5.11 ± 0.25	3.44 ± 0.18	4.12 ± 0.24	0.69 ± 0.03
Non-prompt	6.1 ± 3.0	35 ± 5	17 ± 9	37 ± 7	9.4 ± 1.5
γ conv.	20.9 ± 1.9	35.0 ± 3.1	76 ± 7	-	1.06 ± 0.11
Other	12.9 ± 1.0	25.7 ± 1.7	20.3 ± 1.3	25.3 ± 1.6	3.5 ± 0.4
Total	88 ± 4	249 ± 9	237 ± 10	216 ± 9	38 ± 4
Data	87	239	235	237	27

Table 3

Post-fit background, signal and observed yields for the three-lepton and four-lepton channels as well as the $t\bar{t}Z$ control region. Uncertainties in the predictions include both statistical and systematic uncertainties added in quadrature; correlations among systematic uncertainties are taken into account in the calculation of the total.

	4 ℓ -DF	4 ℓ -SF-Z	4 ℓ -SF-noZ	3 ℓ -1j	3 ℓ -2j	3 ℓ -3j	$t\bar{t}Z$ CR
WVZ	9.6 ± 3.5	5.0 ± 1.8	10 ± 4	62 ± 23	85 ± 30	84 ± 30	-
WZ	1.11 ± 0.13	-	1.08 ± 0.14	2580 ± 80	1830 ± 60	1110 ± 50	5.7 ± 0.4
ZZ	6.7 ± 0.4	933 ± 28	310 ± 10	344 ± 12	182 ± 13	98 ± 12	0.58 ± 0.06
$t\bar{t}Z$	5.1 ± 0.5	0.55 ± 0.08	4.5 ± 0.5	7.6 ± 1.1	22.6 ± 2.5	82 ± 8	122 ± 9
tWZ	1.9 ± 0.4	0.23 ± 0.10	1.6 ± 0.4	4.2 ± 0.9	11.2 ± 2.2	20 ± 4	10.3 ± 0.8
Non-prompt	-	-	0.18 ± 0.12	130 ± 50	77 ± 28	59 ± 24	0.47 ± 0.18
γ conv.	-	-	-	42 ± 8	32 ± 7	9.6 ± 3.4	0.4 ± 0.6
Other	0.4 ± 0.4	1.8 ± 1.1	1.0 ± 0.7	200 ± 15	182 ± 16	120 ± 10	24.4 ± 2.5
Total	24.8 ± 3.5	941 ± 27	329 ± 10	3370 ± 70	2430 ± 40	1580 ± 40	160 ± 10
Data	28	912	360	3351	2438	1572	170

misidentification rate, lepton fake factor, and photon-like electron scale factor. Additional uncertainties come from the statistical uncertainties come from the statistical uncertainties in the sub-samples used to extrapolate the background evaluations to the signal region. Nuisance parameters are treated as correlated for backgrounds evaluated using the same method and from the same systematic sources.

Shape-only variations of the signal distributions due to QCD renormalisation and factorisation scales, PDF, and parton-shower matching scales are considered in the simultaneous fit. The corresponding nuisance parameters are treated as correlated between the $\ell\nu\ell\nu q\bar{q}$ and $\ell\nu\ell\nu\ell\nu$ channels in the WWW analysis and between three-lepton and four-lepton channels in the WVZ analysis. These parameters are treated as uncorrelated between the WWW and WVZ analyses.

Tables 2 and 3 show the post-fit background, signal and observed yields for the signal regions and the background control region. The contribution to the WVZ signal from VH associated production is $\sim 40\%$ in the WWW fiducial regions and $\sim 30\%$ in the WVZ fiducial regions. Contributions from SM processes producing the same detector signature as events in these signal regions (or the $t\bar{t}Z$ control region) besides those listed are combined into “Other”. The uncertainties shown include both statistical and systematic uncertainties. Data and predictions agree in all channels.

Fig. 4 shows the comparison between data and post-fit prediction of the combined m_{jj} distribution for the $\ell\nu\ell\nu q\bar{q}$ channel, the number of selected events for the $\ell\nu\ell\nu\ell\nu$ channel, and the BDT output distributions in the 3 ℓ -2j and 4 ℓ -DF regions for the WVZ analysis. The 3 ℓ -2j and 4 ℓ -DF regions are chosen since they have

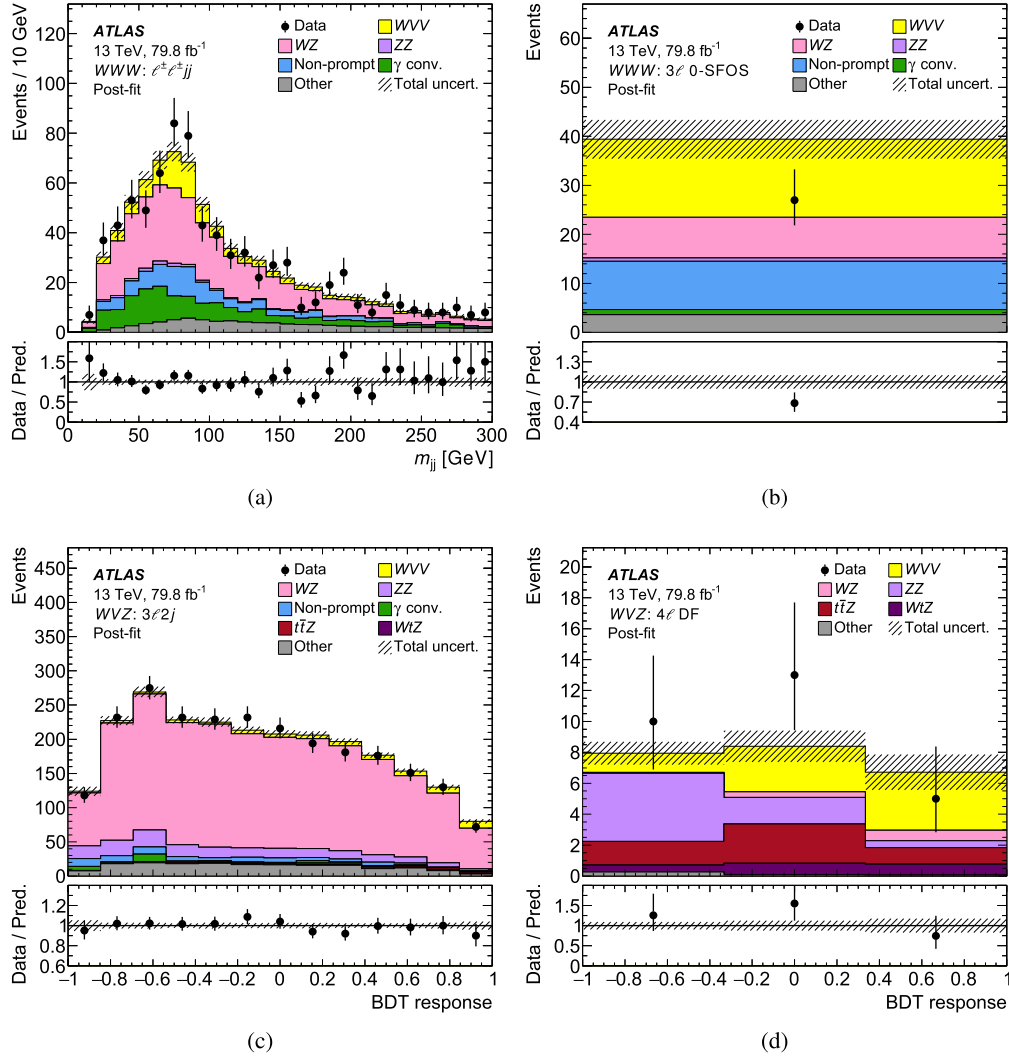


Fig. 4. Post-fit distribution of (a) m_{jj} for the $WVV \rightarrow \ell\nu\ell\nu qq$ analysis ($ee, e\mu, \mu e, \mu\mu$ combined), (b) number of events for the $WVV \rightarrow \ell\nu\ell\nu\ell\nu$ analysis, and the BDT response in the (c) $3\ell-2j$ and (d) $4\ell-DF$ channels for the WVZ analysis. The contributions denoted “Other” are dominated by the (a) $W^\pm W^\pm + 2\text{jets}$, (b) $t\bar{t}W$ and (c) $t\bar{t}Z$ process, respectively. The uncertainty band includes both statistical and systematic uncertainties as obtained by the fit.

the best sensitivity among the three-lepton and four-lepton channels. Data and predictions agree in all distributions.

The overall observed (expected) significance for WVV production is found to be 4.1σ (3.1σ), constituting evidence for the production of three massive vector bosons. The combined best-fit signal strength for the WVV process, obtained by the fit to the eleven signal regions and one control region, is $\mu_{WVV} = 1.40^{+0.39}_{-0.37}$ with respect to the SM prediction (Section 2). The compatibility of the individual signal strengths is 0.13, determined by repeating the fit, assuming individual signal strengths, and evaluating the p -value of the χ^2 of the comparison. The statistical uncertainty in the measured signal strength is $^{+0.25}_{-0.24}$ and the systematic uncertainty is $^{+0.30}_{-0.27}$. The impact of the most important groups of systematic uncertainties on the measured value of μ_{WVV} is shown in Table 4. The largest systematic uncertainties come from uncertainties related to data-driven background evaluations affecting the WVV channels, from theoretical uncertainties related to renormalisation and factorisation scale variations and experimental uncertainties. The impact of each systematic uncertainty on the result is assessed and the ranking for the nuisance parameters with the largest contribution to the uncertainty in μ_{WVV} is shown in Fig. 5.

Table 4

Summary of the effects of the most important groups of systematic uncertainties in μ_{WVV} : Uncertainties related to data-driven background evaluations affecting the WVV channels (data-driven); theoretical uncertainties related to renormalisation and factorisation scale variations, mostly in the diboson background, evaluated using simulations (theory); experimental uncertainties in the signal and background evaluations (instrumental); the statistical uncertainty in simulated events (MC stat. uncertainty); and modelling uncertainty evaluated by comparing different event generators (generators).

Uncertainty source	$\Delta\mu_{WVV}$	
Data-driven	+0.14	-0.14
Theory	+0.15	-0.13
Instrumental	+0.12	-0.09
MC stat. uncertainty	+0.06	-0.04
Generators	+0.04	-0.03
Total systematic uncertainty	+0.30	-0.27

Additional fits are performed separately in the WVV and the WVZ channels. For these fits the other signal strength is fixed to its SM expectation. For the fits of the WVV channels, the WZ control region defined in Section 4 is used in the fit. The inclusion of the WZ control region helps constraining the overall normalisation of the WZ +jets background, which in the combined fit is constrained by the WVZ three-lepton signal regions. The $t\bar{t}Z$ con-

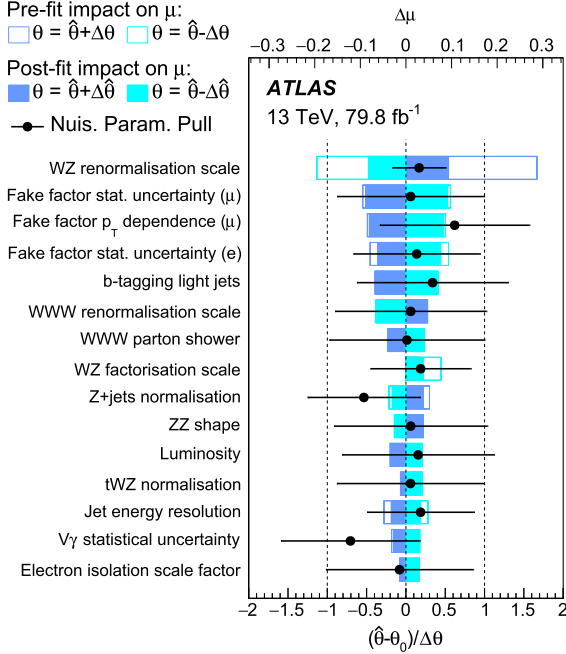


Fig. 5. Impact of systematic uncertainties on the fitted signal-strength parameter μ for the combined WVV fit to data. The systematic uncertainties are listed in decreasing order of their post-fit impact in the fit, and only the 15 most important are displayed. The effect of varying each nuisance parameter θ is shown, where θ_0 is the pre-fit value, $\hat{\theta}$ is the post-fit value, and $\Delta\theta$ and $\Delta\hat{\theta}$ are the pre- and post-fit uncertainties, respectively.

control region is used in the WVZ fit, however, it is not used in the WWW fit. The observed (expected) significance is 3.2σ (2.4σ) for WWW production and 3.2σ (2.0σ) for WVZ production.

Table 5 and Fig. 6(a) summarise the observed and expected significances with respect to the background-only hypothesis and the observed best-fit values of the signal strength for the individual and combined fits. The measured signal strengths from the individual fits are converted to inclusive cross-section measurements using the signal samples described in Section 2 and the central values of the theoretical predictions. All uncertainties

Table 5

Observed and expected significances with respect to the SM background-only hypothesis for the four WVV channels entering the fit.

Decay channel	Significance	
	Observed	Expected
WWW combined	3.2σ	2.4σ
$WWW \rightarrow \ell\nu\ell\nu qq$	4.0σ	1.7σ
$WWW \rightarrow \ell\nu\ell\nu\nu\nu$	1.0σ	2.0σ
WVZ combined	3.2σ	2.0σ
$WVZ \rightarrow \ell\nu qq\ell\ell$	0.5σ	1.0σ
$WVZ \rightarrow \ell\nu\ell\nu\ell\ell qq\ell\ell\ell\ell$	3.5σ	1.8σ
WVV combined	4.1σ	3.1σ

determined in the fit are included in the conversion, except for the normalisation uncertainty in the signal prediction. The results are: $\sigma_{WWW} = 0.65^{+0.16}_{-0.15}$ (stat.) $^{+0.16}_{-0.14}$ (syst.) pb and $\sigma_{WWZ} = 0.55 \pm 0.14$ (stat.) $^{+0.15}_{-0.13}$ (syst.) pb. For the σ_{WWZ} extraction, the WZZ normalisation is fixed to the SM expectation. The cross section of the latter is not reported, since there is not enough sensitivity to this channel to quote a separate cross-section value.

Fig. 6(b) shows the data, background and signal yields, where the discriminant bins in all signal regions are combined into bins of $\log_{10}(S/B)$, S being the expected signal yield and B the background yield. The background and signal yields are shown after the global signal-plus-background fit to the data.

7. Conclusion

In conclusion, a search for the joint production of three massive vector bosons (W or Z) in proton–proton collisions using 79.8 fb^{-1} of data at $\sqrt{s} = 13 \text{ TeV}$ collected by the ATLAS detector at the LHC, is presented. Events with two, three or four reconstructed electrons or muons are analysed. Evidence for the production of three massive vector bosons is observed with a combined significance of 4.1 standard deviations, where the expectation is 3.1 standard deviations. The measured production cross sections are $\sigma_{WWW} = 0.65^{+0.23}_{-0.21}$ pb, and $\sigma_{WWZ} = 0.55^{+0.21}_{-0.19}$ pb, in agreement with the Standard Model predictions.

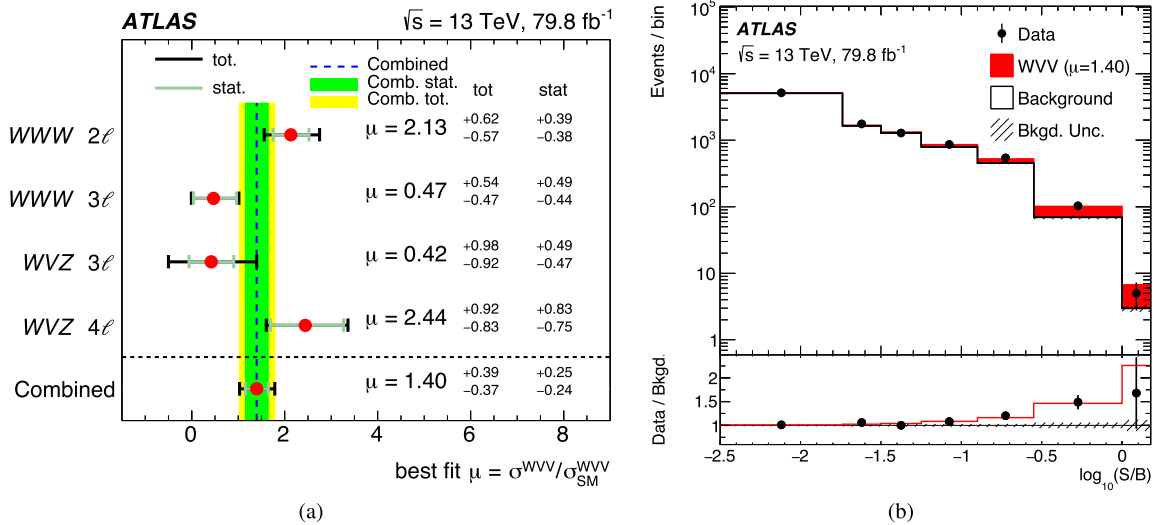


Fig. 6. (a) Extracted signal strengths μ for the four analysis regions and for the combination. (b) Event yields as a function of $\log_{10}(S/B)$ for data, background B and the signal S . Events in all eleven signal regions are included. The background and signal yields are shown after the global signal-plus-background fit. The hatched band corresponds to the systematic uncertainties, and the statistical uncertainties are represented by the error bars on the data points. The lower panel shows the ratio of the data to the expected background estimated from the fit, compared to the expected distribution including the signal (red line).

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G. Aad¹⁰¹, B. Abbott¹²⁸, D.C. Abbott¹⁰², O. Abidinov^{13,*}, A. Abed Abud^{70a,70b}, K. Abeling⁵³, D.K. Abhayasinghe⁹³, S.H. Abidi¹⁶⁷, O.S. AbouZeid⁴⁰, N.L. Abraham¹⁵⁶, H. Abramowicz¹⁶¹, H. Abreu¹⁶⁰, Y. Abulaiti⁶, B.S. Acharya^{66a,66b,o}, B. Achkar⁵³, S. Adachi¹⁶³, L. Adam⁹⁹, L. Adamczyk^{83a}, L. Adamek¹⁶⁷, J. Adelman¹²¹, M. Adersberger¹¹⁴, A. Adiguzel^{12c,aj}, S. Adorni⁵⁴, T. Adye¹⁴⁴, A.A. Affolder¹⁴⁶, Y. Afik¹⁶⁰, C. Agapopoulou¹³², M.N. Agaras³⁸, A. Aggarwal¹¹⁹, C. Agheorghiesei^{27c}, J.A. Aguilar-Saavedra^{140f,140a,ai}, F. Ahmadov⁷⁹, W.S. Ahmed¹⁰³, X. Ai^{15a}, G. Aielli^{73a,73b}, S. Akatsuka⁸⁵, T.P.A. Åkesson⁹⁶, E. Akilli⁵⁴, A.V. Akimov¹¹⁰, K. Al Khoury¹³², G.L. Alberghi^{23b,23a}, J. Albert¹⁷⁶, M.J. Alconada Verzini⁸⁸, S. Alderweireldt³⁶, M. Aleksa³⁶, I.N. Aleksandrov⁷⁹, C. Alexa^{27b}, D. Alexandre¹⁹, T. Alexopoulos¹⁰, A. Alfonsi¹²⁰, M. Alhroob¹²⁸, B. Ali¹⁴², G. Alimonti^{68a}, J. Alison³⁷, S.P. Alkire¹⁴⁸, C. Allaire¹³², B.M.M. Allbrooke¹⁵⁶, B.W. Allen¹³¹, P.P. Allport²¹, A. Aloisio^{69a,69b}, A. Alonso⁴⁰, F. Alonso⁸⁸, C. Alpigiani¹⁴⁸, A.A. Alshehri⁵⁷, M. Alvarez Estevez⁹⁸, D. Álvarez Piqueras¹⁷⁴, M.G. Alvigi^{69a,69b}, Y. Amaral Coutinho^{80b}, A. Ambler¹⁰³, L. Ambroz¹³⁵, C. Amelung²⁶, D. Amidei¹⁰⁵, S.P. Amor Dos Santos^{140a}, S. Amoroso⁴⁶, C.S. Amrouche⁵⁴, F. An⁷⁸, C. Anastopoulos¹⁴⁹, N. Andari¹⁴⁵, T. Andeen¹¹, C.F. Anders^{61b}, J.K. Anders²⁰, A. Andreazza^{68a,68b}, V. Andrei^{61a}, C.R. Anelli¹⁷⁶, S. Angelidakis³⁸, A. Angerami³⁹, A.V. Anisenkov^{122b,122a}, A. Annovi^{71a}, C. Antel^{61a}, M.T. Anthony¹⁴⁹, M. Antonelli⁵¹, D.J.A. Antrim¹⁷¹, F. Anulli^{72a}, M. Aoki⁸¹, J.A. Aparisi Pozo¹⁷⁴, L. Aperio Bella³⁶, G. Arabidze¹⁰⁶, J.P. Araque^{140a}, V. Araujo Ferraz^{80b}, R. Araujo Pereira^{80b}, C. Arcangeletti⁵¹, A.T.H. Arce⁴⁹, F.A. Arduh⁸⁸, J-F. Arguin¹⁰⁹, S. Argyropoulos⁷⁷, J.-H. Arling⁴⁶, A.J. Armbruster³⁶, L.J. Armitage⁹², A. Armstrong¹⁷¹, O. Arnaez¹⁶⁷, H. Arnold¹²⁰, A. Artamonov^{111,*}, G. Artoni¹³⁵, S. Artz⁹⁹, S. Asai¹⁶³, N. Asbah⁵⁹, E.M. Asimakopoulou¹⁷², L. Asquith¹⁵⁶, K. Assamagan²⁹, R. Astalos^{28a}, R.J. Atkin^{33a}, M. Atkinson¹⁷³, N.B. Atlay¹⁵¹, H. Atmani¹³², K. Augsten¹⁴², G. Avolio³⁶, R. Avramidou^{60a}, M.K. Ayoub^{15a}, A.M. Azoulay^{168b}, G. Azeleos^{109,ax}, M.J. Baca²¹, H. Bachacou¹⁴⁵, K. Bachas^{67a,67b}, M. Backes¹³⁵, F. Backman^{45a,45b}, P. Bagnaia^{72a,72b}, M. Bahmani⁸⁴, H. Bahrasemani¹⁵², A.J. Bailey¹⁷⁴, V.R. Bailey¹⁷³, J.T. Baines¹⁴⁴, M. Bajic⁴⁰, C. Bakalis¹⁰, O.K. Baker¹⁸³, P.J. Bakker¹²⁰, D. Bakshi Gupta⁸, S. Balaji¹⁵⁷, E.M. Baldin^{122b,122a}, P. Balek¹⁸⁰, F. Balli¹⁴⁵, W.K. Balunas¹³⁵, J. Balz⁹⁹, E. Banas⁸⁴, A. Bandyopadhyay²⁴, S. Banerjee^{181,j}, A.A.E. Bannoura¹⁸², L. Barak¹⁶¹, W.M. Barbe³⁸, E.L. Barberio¹⁰⁴,

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 ¹⁷⁴, 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,
 R.L. Bates ⁵⁷, S.J. Batista ¹⁶⁷, S. Batlamous ^{35e}, J.R. Batley ³², B. Batool ¹⁵¹, M. Battaglia ¹⁴⁶, M. Baucé ^{72a,72b},
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 M. Begalli ^{80b}, M. Begel ²⁹, A. Behera ¹⁵⁵, J.K. Behr ⁴⁶, F. Beisiegel ²⁴, A.S. Bell ⁹⁴, G. Bella ¹⁶¹,
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 D. Bencheikroun ^{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,
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 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,
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 V.S. Bobrovnikov ^{122b,122a}, S.S. Bocchetta ⁹⁶, A. Bocci ⁴⁹, D. Boerner ⁴⁶, D. Bogavac ¹⁴,
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 M. Bosman ¹⁴, J.D. Bossio Sola ¹⁰³, K. Bouaouda ^{35a}, J. Boudreau ¹³⁹, E.V. Bouhova-Thacker ⁸⁹,
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 B. Brau ¹⁰², J.E. Brau ¹³¹, W.D. Breaden Madden ⁵⁷, K. Brendlinger ⁴⁶, L. Brenner ⁴⁶, R. Brenner ¹⁷²,
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 N. Brusino ¹³⁹, P. Bryant ³⁷, L. Bryngemark ⁹⁶, T. Buanes ¹⁷, Q. Buat ³⁶, P. Buchholz ¹⁵¹, A.G. Buckley ⁵⁷,
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 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,
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 M.D.M. Capeans Garrido ³⁶, M. Capua ^{41b,41a}, R. Cardarelli ^{73a}, F.C. Cardillo ¹⁴⁹, 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},
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 F.L. Castillo ¹⁷⁴, V. Castillo Gimenez ¹⁷⁴, N.F. Castro ^{140a,140e}, A. Catinaccio ³⁶, J.R. Catmore ¹³⁴, A. Cattai ³⁶,
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 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 ^{15d}, A. Cheplakov ⁷⁹, E. Cheremushkina ¹²³,
 R. Cherkaoui El Moursli ^{35e}, E. Cheu ⁷, K. Cheung ⁶⁴, T.J.A. Chevaléras 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}, 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. Ciroto ^{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,g}, 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,ae}, 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. Crépe-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. Dabhi ^{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. Dartsis 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, M. Del Gaudio ^{41b,41a}, J. Del Peso ⁹⁸, Y. Delabat Diaz ⁴⁶, D. Delgove ¹³², F. Deliot ^{145,r}, 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. Dyckes ¹³⁷, M. Dyndal ³⁶, S. Dysch ¹⁰⁰, B.S. Dzedzic ⁸⁴, K.M. Ecker ¹¹⁵, R.C. Edgar ¹⁰⁵, T. Eifert ³⁶, G. Eigen ¹⁷, K. Einsweiler ¹⁸, T. Ekelof ¹⁷², 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. Fakhruddinov 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,p}, 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,a}, 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.M. 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.m},
 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 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,i}, E.L. Gkoukousis ¹⁴, P. Gkoutoumis 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. Gonçalves ^{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,
 C. Gössling ⁴⁷, M.I. Gostkin ⁷⁹, C.A. Gottardo ²⁴, M. Gouighri ^{35b}, D. Goujdami ^{35c}, A.G. Goussiou ¹⁴⁸,
 N. Govender ^{33b,b}, 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,
 N.A. Grieser ¹²⁸, J. Griffiths ⁸, A.A. Grillo ¹⁴⁶, K. Grimm ^{31,l}, S. Grinstein ^{14,y}, 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. Guillemain ⁵, S. Guindon ³⁶,
 U. Gul ⁵⁷, J. Guo ^{60c}, W. Guo ¹⁰⁵, Y. Guo ^{60a,t}, Z. Guo ¹⁰¹, R. Gupta ⁴⁶, S. Gurbuz ^{12c}, G. Gustavino ¹²⁸,
 P. Gutierrez ¹²⁸, C. Gutsche 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. Hadeef ^{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,al}, L. Han ^{60a}, S. Han ^{15d}, K. Hanagaki ^{81,w}, M. Hance ¹⁴⁶,
 D.M. Handl ¹¹⁴, B. Haney ¹³⁷, R. Hankache ¹³⁶, P. Hanke ^{61a}, 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. Hawking 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, 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. Helsen 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-Rodríguez 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. Hubaut¹⁰¹, M. Huebner²⁴, F. Huegging²⁴, T.B. Huffman¹³⁵, M. Huhtinen³⁶, R.F.H. Hunter³⁴, P. Huo¹⁵⁵, A.M. Hupe³⁴, N. Huseynov^{79,ag}, J. Huston¹⁰⁶, J. Huth⁵⁹, R. Hyneman¹⁰⁵, S. Hyrych^{28a}, G. Iacobucci⁵⁴, G. Iakovidis²⁹, I. Ibragimov¹⁵¹, L. Iconomidou-Fayard¹³², Z. Idrissi^{35e}, P. Iengo³⁶, R. Ignazzi⁴⁰, O. Igonkina^{120,aa}, R. Iguchi¹⁶³, T. Iizawa⁵⁴, Y. Ikegami⁸¹, M. Ikeno⁸¹, D. Iliadis¹⁶², N. Ilic¹¹⁹, F. Iltzsche⁴⁸, G. Introzzi^{70a,70b}, M. Iodice^{74a}, K. Iordanidou^{168a}, V. Ippolito^{72a,72b}, M.F. Isacson¹⁷², M. Ishino¹⁶³, M. Ishitsuka¹⁶⁵, W. Islam¹²⁹, C. Issever¹³⁵, S. Istin¹⁶⁰, F. Ito¹⁶⁹, J.M. Iturbe Ponce^{63a}, R. Iuppa^{75a,75b}, A. Ivina¹⁸⁰, H. Iwasaki⁸¹, J.M. Izen⁴³, V. Izzo^{69a}, P. Jacka¹⁴¹, P. Jackson¹, R.M. Jacobs²⁴, B.P. Jaeger¹⁵², V. Jain², G. Jäkel¹⁸², K.B. Jakobi⁹⁹, K. Jakobs⁵², S. Jakobsen⁷⁶, T. Jakoubek¹⁴¹, J. Jamieson⁵⁷, K.W. Janas^{83a}, R. Jansky⁵⁴, J. Janssen²⁴, M. Janus⁵³, P.A. Janus^{83a}, G. Jarlskog⁹⁶, N. Javadov^{79,ag}, T. Javůrek³⁶, M. Javurkova⁵², F. Jeanneau¹⁴⁵, L. Jeanty¹³¹, J. Jejelava^{159a,ah}, A. Jelinskas¹⁷⁸, P. Jenni^{52,c}, J. Jeong⁴⁶, N. Jeong⁴⁶, S. Jézéquel⁵, H. Ji¹⁸¹, J. Jia¹⁵⁵, H. Jiang⁷⁸, Y. Jiang^{60a}, Z. Jiang^{153,q}, S. Jiggins⁵², F.A. Jimenez Morales³⁸, J. Jimenez Pena¹⁷⁴, S. Jin^{15c}, A. Jinaru^{27b}, O. Jinnouchi¹⁶⁵, H. Jivan^{33c}, P. Johansson¹⁴⁹, K.A. Johns⁷, C.A. Johnson⁶⁵, K. Jon-And^{45a,45b}, R.W.L. Jones⁸⁹, S.D. Jones¹⁵⁶, S. Jones⁷, T.J. Jones⁹⁰, J. Jongmanns^{61a}, P.M. Jorge^{140a}, J. Jovicevic³⁶, X. Ju¹⁸, J.J. Junggeburth¹¹⁵, A. Juste Rozas^{14,y}, A. Kaczmarska⁸⁴, M. Kado¹³², H. Kagan¹²⁶, M. Kagan¹⁵³, C. Kahra⁹⁹, T. Kaji¹⁷⁹, E. Kajomovitz¹⁶⁰, C.W. Kalderon⁹⁶, A. Kaluza⁹⁹, A. Kamenshchikov¹²³, L. Kanjir⁹¹, Y. Kano¹⁶³, V.A. Kantserov¹¹², J. Kanzaki⁸¹, L.S. Kaplan¹⁸¹, D. Kar^{33c}, M.J. Kareem^{168b}, E. Karentzos¹⁰, S.N. Karpov⁷⁹, Z.M. Karpova⁷⁹, V. Kartvelishvili⁸⁹, A.N. Karyukhin¹²³, L. Kashif¹⁸¹, R.D. Kass¹²⁶, A. Kastanas^{45a,45b}, Y. Kataoka¹⁶³, C. Kato^{60d,60c}, J. Katzy⁴⁶, K. Kawade⁸², K. Kawagoe⁸⁷, T. Kawaguchi¹¹⁷, T. Kawamoto¹⁶³, G. Kawamura⁵³, E.F. Kay¹⁷⁶, V.F. Kazanin^{122b,122a}, R. Keeler¹⁷⁶, R. Kehoe⁴², J.S. Keller³⁴, E. Kellermann⁹⁶, D. Kelsey¹⁵⁶, J.J. Kempster²¹, J. Kendrick²¹, O. Kepka¹⁴¹, S. Kersten¹⁸², B.P. Kerševan⁹¹, S. Ketabchi Haghighat¹⁶⁷, M. Khader¹⁷³, F. Khalil-Zada¹³, M.K. Khandoga¹⁴⁵, A. Khanov¹²⁹, A.G. Kharlamov^{122b,122a}, T. Kharlamova^{122b,122a}, E.E. Khoda¹⁷⁵, A. Khodinov¹⁶⁶, T.J. Khoo⁵⁴, E. Khramov⁷⁹, J. Khubua^{159b}, S. Kido⁸², M. Kiehn⁵⁴, C.R. Kilby⁹³, Y.K. Kim³⁷, N. Kimura^{66a,66c}, O.M. Kind¹⁹, B.T. King⁹⁰, D. Kirchmeier⁴⁸, J. Kirk¹⁴⁴, A.E. Kiryunin¹¹⁵, T. Kishimoto¹⁶³, D.P. Kisiuk¹⁶⁷, V. Kitali⁴⁶, O. Kivernyk⁵, E. Kladiva^{28b,*}, T. Klapdor-Kleingrothaus⁵², M. Klassen^{61a}, M.H. Klein¹⁰⁵, M. Klein⁹⁰, U. Klein⁹⁰, K. Kleinknecht⁹⁹, P. Klimek¹²¹, A. Klimentov²⁹, T. Klingl²⁴, T. Klioutchnikova³⁶, F.F. Klitzner¹¹⁴, P. Kluit¹²⁰, S. Kluth¹¹⁵, E. Kneringer⁷⁶, E.B.F.G. Knoop¹⁰¹, A. Knue⁵², D. Kobayashi⁸⁷, T. Kobayashi¹⁶³, M. Kobel⁴⁸, M. Kocian¹⁵³, P. Kodys¹⁴³, P.T. Koenig²⁴, T. Koffas³⁴, N.M. Köhler¹¹⁵, T. Koi¹⁵³, M. Kolb^{61b}, I. Koletsou⁵, T. Komarek¹³⁰, T. Kondo⁸¹, N. Kondrashova^{60c}, K. Köneke⁵², A.C. König¹¹⁹, T. Kono¹²⁵, R. Konoplich^{124,ao}, V. Konstantinides⁹⁴, N. Konstantinidis⁹⁴, B. Konya⁹⁶, R. Kopeliansky⁶⁵, S. Koperny^{83a}, K. Korcyl⁸⁴, K. Kordas¹⁶², G. Koren¹⁶¹, A. Korn⁹⁴, I. Korolkov¹⁴, E.V. Korolkova¹⁴⁹, N. Korotkova¹¹³, O. Kortner¹¹⁵, S. Kortner¹¹⁵, T. Kosek¹⁴³, V.V. Kostyukhin²⁴, A. Kotwal⁴⁹, A. Koulouris¹⁰, A. Kourkoumeli-Charalampidi^{70a,70b}, C. Kourkoumelis⁹, E. Kourlitis¹⁴⁹, V. Kouskoura²⁹, A.B. Kowalewska⁸⁴, R. Kowalewski¹⁷⁶, C. Kozakai¹⁶³, W. Kozanecki¹⁴⁵, A.S. Kozhin¹²³, V.A. Kramarenko¹¹³, G. Kramberger⁹¹, D. Krasnoperstev^{60a}, M.W. Krasny¹³⁶, A. Krasznahorkay³⁶, D. Krauss¹¹⁵, J.A. Kremer^{83a}, J. Kretschmar⁹⁰, P. Krieger¹⁶⁷, F. Krieter¹¹⁴, A. Krishnan^{61b}, K. Krizka¹⁸, K. Kroeninger⁴⁷, H. Kroha¹¹⁵, J. Kroll¹⁴¹, J. Kroll¹³⁷, J. Krstic¹⁶, U. Kruchonak⁷⁹, H. Krüger²⁴, N. Krumnack⁷⁸, M.C. Kruse⁴⁹, J.A. Krzysiak⁸⁴, T. Kubota¹⁰⁴, S. Kudah^{4b}, J.T. Kuechler⁴⁶, S. Kuehn³⁶, A. Kugel^{61a}, T. Kuhl⁴⁶, V. Kukhtin⁷⁹, R. Kukla¹⁰¹, Y. Kulchitsky^{107,ak}, S. Kuleshov^{147b}, Y.P. Kulinich¹⁷³, M. Kuna⁵⁸, T. Kunigo⁸⁵, A. Kupco¹⁴¹, T. Kupfer⁴⁷, O. Kuprash⁵², H. Kurashige⁸², L.L. Kurchaninov^{168a}, Y.A. Kurochkin¹⁰⁷, A. Kurova¹¹², M.G. Kurth^{15d}, E.S. Kuwertz³⁶, M. Kuze¹⁶⁵, A.K. Kvam¹⁴⁸, J. Kvita¹³⁰, T. Kwan¹⁰³, A. La Rosa¹¹⁵, L. La Rotonda^{41b,41a}, F. La Ruffa^{41b,41a}, C. Lacasta¹⁷⁴, F. Lacava^{72a,72b}, D.P.J. Lack¹⁰⁰, H. Lacker¹⁹, D. Lacour¹³⁶, E. Ladygin⁷⁹, R. Lafaye⁵, B. Laforge¹³⁶, T. Lagouri^{33c}, S. Lai⁵³, S. Lammers⁶⁵, W. Lampl⁷, C. Lampoudis¹⁶², E. Lançon²⁹, U. Landgraf⁵², M.P.J. Landon⁹², M.C. Lanfermann⁵⁴, V.S. Lang⁴⁶, J.C. Lange⁵³, R.J. Langenberg³⁶, A.J. Lankford¹⁷¹, F. Lanni²⁹, K. Lantsch²⁴, A. Lanza^{70a}, A. Lapertosa^{55b,55a}, S. Laplace¹³⁶, J.F. Laporte¹⁴⁵, T. Lari^{68a}, F. Lasagni Manghi^{23b,23a}, M. Lassnig³⁶, T.S. Lau^{63a}, A. Laudrain¹³², A. Laurier³⁴, M. Lavourga^{69a,69b}, M. Lazzaroni^{68a,68b}, B. Le¹⁰⁴, O. Le Dortz¹³⁶, E. Le Guirriec¹⁰¹, M. LeBlanc⁷, T. LeCompte⁶, F. Ledroit-Guillon⁵⁸, C.A. Lee²⁹, G.R. Lee¹⁷, L. Lee⁵⁹, S.C. Lee¹⁵⁸, S.J. Lee³⁴, B. Lefebvre^{168a}, M. Lefebvre¹⁷⁶, F. Legger¹¹⁴, C. Leggett¹⁸, K. Lehmann¹⁵², N. Lehmann¹⁸², G. Lehmann Miotto³⁶, W.A. Leight⁴⁶, A. Leisos^{162,x}, M.A.L. Leite^{80d}, R. Leitner¹⁴³, D. Lellouch¹⁸⁰,

K.J.C. Leney⁴², T. Lenz²⁴, B. Lenzi³⁶, R. Leone⁷, S. Leone^{71a}, C. Leonidopoulos⁵⁰, A. Leopold¹³⁶,
 G. Lerner¹⁵⁶, C. Leroy¹⁰⁹, R. Les¹⁶⁷, C.G. Lester³², M. Levchenko¹³⁸, J. Levêque⁵, D. Levin¹⁰⁵,
 L.J. Levinson¹⁸⁰, D.J. Lewis²¹, B. Li^{15b}, B. Li¹⁰⁵, C-Q. Li^{60a}, F. Li^{60c}, H. Li^{60a}, H. Li^{60b}, J. Li^{60c}, K. Li¹⁵³,
 L. Li^{60c}, M. Li^{15a}, Q. Li^{15d}, Q.Y. Li^{60a}, S. Li^{60d,60c}, X. Li⁴⁶, Y. Li⁴⁶, Z. Li^{60b}, Z. Liang^{15a}, B. Liberti^{73a},
 A. Liblong¹⁶⁷, K. Lie^{63c}, S. Liem¹²⁰, C.Y. Lin³², K. Lin¹⁰⁶, T.H. Lin⁹⁹, R.A. Linck⁶⁵, J.H. Lindon²¹,
 A.L. Lioni⁵⁴, E. Lipeles¹³⁷, A. Lipniacka¹⁷, M. Lisovyi^{61b}, T.M. Liss^{173,au}, A. Lister¹⁷⁵, A.M. Litke¹⁴⁶,
 J.D. Little⁸, B. Liu^{78,ad}, B.L. Liu⁶, H.B. Liu²⁹, H. Liu¹⁰⁵, J.B. Liu^{60a}, J.K.K. Liu¹³⁵, K. Liu¹³⁶, M. Liu^{60a},
 P. Liu¹⁸, Y. Liu^{15d}, Y.L. Liu¹⁰⁵, Y.W. Liu^{60a}, M. Livan^{70a,70b}, A. Lleres⁵⁸, J. Llorente Merino^{15a},
 S.L. Lloyd⁹², C.Y. Lo^{63b}, F. Lo Sterzo⁴², E.M. Lobodzinska⁴⁶, P. Loch⁷, S. Loffredo^{73a,73b}, T. Lohse¹⁹,
 K. Lohwasser¹⁴⁹, M. Lokajicek¹⁴¹, J.D. Long¹⁷³, R.E. Long⁸⁹, L. Longo³⁶, K.A. Looper¹²⁶, J.A. Lopez^{147b},
 I. Lopez Paz¹⁰⁰, A. Lopez Solis¹⁴⁹, J. Lorenz¹¹⁴, N. Lorenzo Martinez⁵, M. Losada²², P.J. Lösel¹¹⁴,
 A. Lösle⁵², X. Lou⁴⁶, X. Lou^{15a}, A. Lounis¹³², J. Love⁶, P.A. Love⁸⁹, J.J. Lozano Bahilo¹⁷⁴, M. Lu^{60a},
 Y.J. Lu⁶⁴, H.J. Lubatti¹⁴⁸, C. Luci^{72a,72b}, A. Lucotte⁵⁸, C. Luedtke⁵², F. Luehring⁶⁵, I. Luise¹³⁶,
 L. Luminari^{72a}, B. Lund-Jensen¹⁵⁴, M.S. Lutz¹⁰², D. Lynn²⁹, R. Lysak¹⁴¹, E. Lytken⁹⁶, F. Lyu^{15a},
 V. Lyubushkin⁷⁹, T. Lyubushkina⁷⁹, H. Ma²⁹, L.L. Ma^{60b}, Y. Ma^{60b}, G. Maccarrone⁵¹, A. Macchiolo¹¹⁵,
 C.M. Macdonald¹⁴⁹, J. Machado Miguens¹³⁷, D. Madaffari¹⁷⁴, R. Madar³⁸, W.F. Mader⁴⁸, N. Madysa⁴⁸,
 J. Maeda⁸², K. Maekawa¹⁶³, S. Maeland¹⁷, T. Maeno²⁹, M. Maerker⁴⁸, A.S. Maevskiy¹¹³, V. Magerl⁵²,
 N. Magini⁷⁸, D.J. Mahon³⁹, C. Maidantchik^{80b}, T. Maier¹¹⁴, A. Maio^{140a,140b,140d}, O. Majersky^{28a},
 S. Majewski¹³¹, Y. Makida⁸¹, N. Makovec¹³², B. Malaescu¹³⁶, Pa. Malecki⁸⁴, V.P. Maleev¹³⁸, F. Malek⁵⁸,
 U. Mallik⁷⁷, D. Malon⁶, C. Malone³², S. Maltezos¹⁰, S. Malyukov³⁶, J. Mamuzic¹⁷⁴, G. Mancini⁵¹,
 I. Mandić⁹¹, L. Manhaes de Andrade Filho^{80a}, I.M. Maniatis¹⁶², J. Manjarres Ramos⁴⁸, K.H. Mankinen⁹⁶,
 A. Mann¹¹⁴, A. Manousos⁷⁶, B. Mansoulie¹⁴⁵, I. Manthos¹⁶², S. Manzoni¹²⁰, A. Marantis¹⁶²,
 G. Marceca³⁰, L. Marchese¹³⁵, G. Marchiori¹³⁶, M. Marcisovsky¹⁴¹, C. Marcon⁹⁶, C.A. Marin Tobon³⁶,
 M. Marjanovic³⁸, F. Marroquim^{80b}, Z. Marshall¹⁸, M.U.F. Martensson¹⁷², S. Marti-Garcia¹⁷⁴,
 C.B. Martin¹²⁶, T.A. Martin¹⁷⁸, V.J. Martin⁵⁰, B. Martin dit Latour¹⁷, L. Martinelli^{74a,74b},
 M. Martinez^{14,y}, V.I. Martinez Outschoorn¹⁰², S. Martin-Haugh¹⁴⁴, V.S. Martoiu^{27b}, A.C. Martyniuk⁹⁴,
 A. Marzin³⁶, S.R. Maschek¹¹⁵, L. Masetti⁹⁹, T. Mashimo¹⁶³, R. Mashinistov¹¹⁰, J. Masik¹⁰⁰,
 A.L. Maslennikov^{122b,122a}, L.H. Mason¹⁰⁴, L. Massa^{73a,73b}, P. Massarotti^{69a,69b}, P. Mastrandrea^{71a,71b},
 A. Mastroberardino^{41b,41a}, T. Masubuchi¹⁶³, A. Matic¹¹⁴, P. Mättig²⁴, J. Maurer^{27b}, B. Maček⁹¹,
 S.J. Maxfield⁹⁰, D.A. Maximov^{122b,122a}, R. Mazini¹⁵⁸, I. Maznas¹⁶², S.M. Mazza¹⁴⁶, S.P. Mc Kee¹⁰⁵,
 A. McCarn Deiana⁴², T.G. McCarthy¹¹⁵, L.I. McClymont⁹⁴, W.P. McCormack¹⁸, E.F. McDonald¹⁰⁴,
 J.A. Mcfayden³⁶, G. Mchedlidze⁵³, M.A. McKay⁴², K.D. McLean¹⁷⁶, S.J. McMahon¹⁴⁴, P.C. McNamara¹⁰⁴,
 C.J. McNicol¹⁷⁸, R.A. McPherson^{176,ae}, J.E. Mdhluli^{33c}, Z.A. Meadows¹⁰², S. Meehan¹⁴⁸, T.M. Megy⁵²,
 S. Mehlhase¹¹⁴, A. Mehta⁹⁰, T. Meideck⁵⁸, B. Meirose⁴³, D. Melini¹⁷⁴, B.R. Mellado Garcia^{33c},
 J.D. Mellenthin⁵³, M. Melo^{28a}, F. Meloni⁴⁶, A. Melzer²⁴, S.B. Menary¹⁰⁰, E.D. Mendes Gouveia^{140a,140e},
 L. Meng³⁶, X.T. Meng¹⁰⁵, S. Menke¹¹⁵, E. Meoni^{41b,41a}, S. Mergelmeyer¹⁹, S.A.M. Merkt¹³⁹,
 C. Merlassino²⁰, P. Mermod⁵⁴, L. Merola^{69a,69b}, C. Meroni^{68a}, O. Meshkov^{113,110}, J.K.R. Meshreki¹⁵¹,
 A. Messina^{72a,72b}, J. Metcalfe⁶, A.S. Mete¹⁷¹, C. Meyer⁶⁵, J. Meyer¹⁶⁰, J-P. Meyer¹⁴⁵,
 H. Meyer Zu Theenhausen^{61a}, F. Miano¹⁵⁶, R.P. Middleton¹⁴⁴, L. Mijović⁵⁰, G. Mikenberg¹⁸⁰,
 M. Mikesikova¹⁴¹, M. Mikuz⁹¹, H. Mildner¹⁴⁹, M. Milesi¹⁰⁴, A. Milic¹⁶⁷, D.A. Millar⁹², D.W. Miller³⁷,
 A. Milov¹⁸⁰, D.A. Milstead^{45a,45b}, R.A. Mina^{153,q}, A.A. Minaenko¹²³, M. Miñano Moya¹⁷⁴,
 I.A. Minashvili^{159b}, A.I. Mincer¹²⁴, B. Mindur^{83a}, M. Mineev⁷⁹, Y. Minegishi¹⁶³, Y. Ming¹⁸¹, L.M. Mir¹⁴,
 A. Mirto^{67a,67b}, K.P. Mistry¹³⁷, T. Mitani¹⁷⁹, J. Mitrevski¹¹⁴, V.A. Mitsou¹⁷⁴, M. Mittal^{60c}, A. Miucci²⁰,
 P.S. Miyagawa¹⁴⁹, A. Mizukami⁸¹, J.U. Mjörnmark⁹⁶, T. Mkrtychyan¹⁸⁴, M. Mlynarikova¹⁴³, T. Moa^{45a,45b},
 K. Mochizuki¹⁰⁹, P. Mogg⁵², S. Mohapatra³⁹, R. Moles-Valls²⁴, M.C. Mondragon¹⁰⁶, K. Mönig⁴⁶,
 J. Monk⁴⁰, E. Monnier¹⁰¹, A. Montalbano¹⁵², J. Montejo Berlingen³⁶, M. Montella⁹⁴, F. Monticelli⁸⁸,
 S. Monzani^{68a}, N. Morange¹³², D. Moreno²², M. Moreno Llácer³⁶, C. Moreno Martinez¹⁴,
 P. Morettini^{55b}, M. Morgenstern¹²⁰, S. Morgenstern⁴⁸, D. Mori¹⁵², M. Morii⁵⁹, M. Morinaga¹⁷⁹,
 V. Morisbak¹³⁴, A.K. Morley³⁶, G. Mornacchi³⁶, A.P. Morris⁹⁴, L. Morvaj¹⁵⁵, P. Moschovakos³⁶,
 B. Moser¹²⁰, M. Mosidze^{159b}, T. Moskalets¹⁴⁵, H.J. Moss¹⁴⁹, J. Moss^{31,n}, K. Motohashi¹⁶⁵,
 E. Mountricha³⁶, E.J.W. Moyse¹⁰², S. Muanza¹⁰¹, J. Mueller¹³⁹, R.S.P. Mueller¹¹⁴, D. Muenstermann⁸⁹,
 G.A. Mullier⁹⁶, J.L. Munoz Martinez¹⁴, F.J. Munoz Sanchez¹⁰⁰, P. Murin^{28b}, W.J. Murray^{178,144},

A. Murrone^{68a,68b}, M. Muškinja¹⁸, C. Mwewa^{33a}, A.G. Myagkov^{123,ap}, J. Myers¹³¹, M. Myska¹⁴²,
 B.P. Nachman¹⁸, O. Nackenhorst⁴⁷, A. Nag Nag⁴⁸, K. Nagai¹³⁵, K. Nagano⁸¹, Y. Nagasaka⁶², M. Nagel⁵²,
 E. Nagy¹⁰¹, A.M. Nairz³⁶, Y. Nakahama¹¹⁷, K. Nakamura⁸¹, T. Nakamura¹⁶³, I. Nakano¹²⁷, H. Nanjo¹³³,
 F. Napolitano^{61a}, R.F. Naranjo Garcia⁴⁶, R. Narayan⁴², D.I. Narrias Villar^{61a}, I. Naryshkin¹³⁸,
 T. Naumann⁴⁶, G. Navarro²², H.A. Neal^{105,*}, P.Y. Nechaeva¹¹⁰, F. Nechansky⁴⁶, T.J. Neep²¹,
 A. Negri^{70a,70b}, M. Negrini^{23b}, C. Nellist⁵³, M.E. Nelson¹³⁵, S. Nemecek¹⁴¹, P. Nemethy¹²⁴, M. Nessi^{36,e},
 M.S. Neubauer¹⁷³, M. Neumann¹⁸², P.R. Newman²¹, T.Y. Ng^{63c}, Y.S. Ng¹⁹, Y.W.Y. Ng¹⁷¹,
 H.D.N. Nguyen¹⁰¹, T. Nguyen Manh¹⁰⁹, E. Nibigira³⁸, R.B. Nickerson¹³⁵, R. Nicolaidou¹⁴⁵, D.S. Nielsen⁴⁰,
 J. Nielsen¹⁴⁶, N. Nikiforou¹¹, V. Nikolaenko^{123,ap}, I. Nikolic-Audit¹³⁶, K. Nikolopoulos²¹, P. Nilsson²⁹,
 H.R. Nindhito⁵⁴, Y. Ninomiya⁸¹, A. Nisati^{72a}, N. Nishu^{60c}, R. Nisius¹¹⁵, I. Nitsche⁴⁷, T. Nitta¹⁷⁹,
 T. Nobe¹⁶³, Y. Noguchi⁸⁵, I. Nomidis¹³⁶, M.A. Nomura²⁹, M. Nordberg³⁶, N. Norjoharuddeen¹³⁵,
 T. Novak⁹¹, O. Novgorodova⁴⁸, R. Novotny¹⁴², L. Nozka¹³⁰, K. Ntekas¹⁷¹, E. Nurse⁹⁴, F.G. Oakham^{34,ax},
 H. Oberlack¹¹⁵, J. Ocariz¹³⁶, A. Ochi⁸², I. Ochoa³⁹, J.P. Ochoa-Ricoux^{147a}, K. O'Connor²⁶, S. Oda⁸⁷,
 S. Odaka⁸¹, S. Oerdek⁵³, A. Ogrodnik^{83a}, A. Oh¹⁰⁰, S.H. Oh⁴⁹, C.C. Ohm¹⁵⁴, H. Oide^{55b,55a},
 M.L. Ojeda¹⁶⁷, H. Okawa¹⁶⁹, Y. Okazaki⁸⁵, Y. Okumura¹⁶³, T. Okuyama⁸¹, A. Olariu^{27b},
 L.F. Oleiro Seabra^{140a}, S.A. Olivares Pino^{147a}, D. Oliveira Damazio²⁹, J.L. Oliver¹, M.J.R. Olsson¹⁷¹,
 A. Olszewski⁸⁴, J. Olszowska⁸⁴, D.C. O'Neil¹⁵², A. Onofre^{140a,140e}, K. Onogi¹¹⁷, P.U.E. Onyisi¹¹,
 H. Oppen¹³⁴, M.J. Oreglia³⁷, G.E. Orellana⁸⁸, Y. Oren¹⁶¹, D. Orestano^{74a,74b}, N. Orlando¹⁴, R.S. Orr¹⁶⁷,
 V. O'Shea⁵⁷, R. Ospanov^{60a}, G. Otero y Garzon³⁰, H. Otono⁸⁷, M. Ouchrif^{35d}, F. Ould-Saada¹³⁴,
 A. Ouraou¹⁴⁵, Q. Ouyang^{15a}, M. Owen⁵⁷, R.E. Owen²¹, V.E. Ozcan^{12c}, N. Ozturk⁸, J. Pacalt¹³⁰,
 H.A. Pacey³², K. Pachal⁴⁹, A. Pacheco Pages¹⁴, C. Padilla Aranda¹⁴, S. Pagan Griso¹⁸, M. Paganini¹⁸³,
 G. Palacino⁶⁵, S. Palazzo⁵⁰, S. Palestini³⁶, M. Palka^{83b}, D. Pallin³⁸, I. Panagoulas¹⁰, C.E. Pandini³⁶,
 J.G. Panduro Vazquez⁹³, P. Pani⁴⁶, G. Panizzo^{66a,66c}, L. Paolozzi⁵⁴, C. Papadatos¹⁰⁹, K. Papageorgiou^{9,i},
 A. Paramonov⁶, D. Paredes Hernandez^{63b}, S.R. Paredes Saenz¹³⁵, B. Parida¹⁶⁶, T.H. Park¹⁶⁷,
 A.J. Parker⁸⁹, M.A. Parker³², F. Parodi^{55b,55a}, E.W.P. Parrish¹²¹, J.A. Parsons³⁹, U. Parzefall⁵²,
 L. Pascual Dominguez¹³⁶, V.R. Pascuzzi¹⁶⁷, J.M.P. Pasner¹⁴⁶, E. Pasqualucci^{72a}, S. Passaggio^{55b},
 F. Pastore⁹³, P. Pasuwan^{45a,45b}, S. Patariaia⁹⁹, J.R. Pater¹⁰⁰, A. Pathak^{181,j}, T. Pauly³⁶, B. Pearson¹¹⁵,
 M. Pedersen¹³⁴, L. Pedraza Diaz¹¹⁹, R. Pedro^{140a}, T. Peiffer⁵³, S.V. Peleganchuk^{122b,122a}, O. Penc¹⁴¹,
 H. Peng^{60a}, B.S. Peralva^{80a}, M.M. Perego¹³², A.P. Pereira Peixoto^{140a}, D.V. Perepelitsa²⁹, F. Peri¹⁹,
 L. Perini^{68a,68b}, H. Pernegger³⁶, S. Perrella^{69a,69b}, K. Peters⁴⁶, R.F.Y. Peters¹⁰⁰, B.A. Petersen³⁶,
 T.C. Petersen⁴⁰, E. Petit⁵⁸, A. Petridis¹, C. Petridou¹⁶², P. Petroff¹³², M. Petrov¹³⁵, F. Petrucci^{74a,74b},
 M. Pettee¹⁸³, N.E. Pettersson¹⁰², K. Petukhova¹⁴³, A. Peyaud¹⁴⁵, R. Pezoa^{147b}, L. Pezzotti^{70a,70b},
 T. Pham¹⁰⁴, F.H. Phillips¹⁰⁶, P.W. Phillips¹⁴⁴, M.W. Phipps¹⁷³, G. Piacquadio¹⁵⁵, E. Pianori¹⁸,
 A. Picazio¹⁰², R.H. Pickles¹⁰⁰, R. Piegai³⁰, D. Pietreanu^{27b}, J.E. Pilcher³⁷, A.D. Pilkington¹⁰⁰,
 M. Pinamonti^{73a,73b}, J.L. Pinfold³, M. Pitt¹⁸⁰, L. Pizzimento^{73a,73b}, M.-A. Pleier²⁹, V. Pleskot¹⁴³,
 E. Plotnikova⁷⁹, D. Pluth⁷⁸, P. Podberezko^{122b,122a}, R. Poettgen⁹⁶, R. Poggi⁵⁴, L. Poggioli¹³²,
 I. Pogrebnyak¹⁰⁶, D. Pohl²⁴, I. Pokharel⁵³, G. Polesello^{70a}, A. Poley¹⁸, A. Policicchio^{72a,72b}, R. Polifka¹⁴³,
 A. Polini^{23b}, C.S. Pollard⁴⁶, V. Polychronakos²⁹, D. Ponomarenko¹¹², L. Pontecorvo³⁶, S. Popa^{27a},
 G.A. Popeneciu^{27d}, D.M. Portillo Quintero⁵⁸, S. Pospisil¹⁴², K. Potamianos⁴⁶, I.N. Potrap⁷⁹, C.J. Potter³²,
 H. Potti¹¹, T. Poulsen⁹⁶, J. Poveda³⁶, T.D. Powell¹⁴⁹, G. Pownall⁴⁶, M.E. Pozo Astigarraga³⁶,
 P. Pralavorio¹⁰¹, S. Prell⁷⁸, D. Price¹⁰⁰, M. Primavera^{67a}, S. Prince¹⁰³, M.L. Proffitt¹⁴⁸, N. Proklova¹¹²,
 K. Prokofiev^{63c}, F. Prokoshin^{147b}, S. Protopopescu²⁹, J. Proudfoot⁶, M. Przybycien^{83a}, D. Pudzha¹³⁸,
 A. Puri¹⁷³, P. Puzo¹³², J. Qian¹⁰⁵, Y. Qin¹⁰⁰, A. Quadt⁵³, M. Queitsch-Maitland⁴⁶, A. Qureshi¹,
 P. Rados¹⁰⁴, F. Ragusa^{68a,68b}, G. Rahal⁹⁷, J.A. Raine⁵⁴, S. Rajagopalan²⁹, A. Ramirez Morales⁹²,
 K. Ran^{15d}, T. Rashid¹³², S. Raspopov⁵, M.G. Ratti^{68a,68b}, D.M. Rauch⁴⁶, F. Rauscher¹¹⁴, S. Rave⁹⁹,
 B. Ravina¹⁴⁹, I. Ravinovich¹⁸⁰, J.H. Rawling¹⁰⁰, M. Raymond³⁶, A.L. Read¹³⁴, N.P. Readioff⁵⁸,
 M. Reale^{67a,67b}, D.M. Rebuzzi^{70a,70b}, A. Redelbach¹⁷⁷, G. Redlinger²⁹, K. Reeves⁴³, L. Rehnisch¹⁹,
 J. Reichert¹³⁷, D. Reikher¹⁶¹, A. Reiss⁹⁹, A. Rej¹⁵¹, C. Rembser³⁶, M. Renda^{27b}, M. Rescigno^{72a},
 S. Resconi^{68a}, E.D. Resseguie¹³⁷, S. Rettie¹⁷⁵, E. Reynolds²¹, O.L. Rezanova^{122b,122a}, P. Reznicek¹⁴³,
 E. Ricci^{75a,75b}, R. Richter¹¹⁵, S. Richter⁴⁶, E. Richter-Was^{83b}, O. Ricken²⁴, M. Ridel¹³⁶, P. Rieck¹¹⁵,
 C.J. Riegel¹⁸², O. Rifki⁴⁶, M. Rijssenbeek¹⁵⁵, A. Rimoldi^{70a,70b}, M. Rimoldi⁴⁶, L. Rinaldi^{23b},
 G. Ripellino¹⁵⁴, B. Ristić⁸⁹, E. Ritsch³⁶, I. Riu¹⁴, J.C. Rivera Vergara¹⁷⁶, F. Rizatdinova¹²⁹, E. Rizvi⁹²,

C. Rizzi³⁶, R.T. Roberts¹⁰⁰, S.H. Robertson^{103,ae}, M. Robin⁴⁶, D. Robinson³², J.E.M. Robinson⁴⁶, C.M. Robles Gajardo^{147b}, A. Robson⁵⁷, E. Rocco⁹⁹, C. Roda^{71a,71b}, S. Rodriguez Bosca¹⁷⁴, A. Rodriguez Perez¹⁴, D. Rodriguez Rodriguez¹⁷⁴, A.M. Rodríguez Vera^{168b}, S. Roe³⁶, O. Røhne¹³⁴, R. Röhrig¹¹⁵, C.P.A. Roland⁶⁵, J. Roloff⁵⁹, A. Romaniouk¹¹², M. Romano^{23b,23a}, N. Rompotis⁹⁰, M. Ronzani¹²⁴, L. Roos¹³⁶, S. Rosati^{72a}, K. Rosbach⁵², G. Rosin¹⁰², B.J. Rosser¹³⁷, E. Rossi⁴⁶, E. Rossi^{74a,74b}, E. Rossi^{69a,69b}, L.P. Rossi^{55b}, L. Rossini^{68a,68b}, R. Rosten¹⁴, M. Rotaru^{27b}, J. Rothberg¹⁴⁸, D. Rousseau¹³², G. Rovelli^{70a,70b}, D. Roy^{33c}, A. Rozanov¹⁰¹, Y. Rozen¹⁶⁰, X. Ruan^{33c}, F. Rubbo¹⁵³, F. Rühr⁵², A. Ruiz-Martinez¹⁷⁴, A. Rummler³⁶, Z. Rurikova⁵², N.A. Rusakovich⁷⁹, H.L. Russell¹⁰³, L. Rustige^{38,47}, J.P. Rutherford⁷, E.M. Rüttinger^{46,k}, Y.F. Ryabov¹³⁸, M. Rybar³⁹, G. Rybkin¹³², A. Ryzhov¹²³, G.F. Rzehorz⁵³, P. Sabatini⁵³, G. Sabato¹²⁰, S. Sacerdoti¹³², H.F.-W. Sadrozinski¹⁴⁶, R. Sadykov⁷⁹, F. Safai Tehrani^{72a}, B. Safarzadeh Samani¹⁵⁶, P. Saha¹²¹, S. Saha¹⁰³, M. Sahinsoy^{61a}, A. Sahu¹⁸², M. Saimpert⁴⁶, M. Saito¹⁶³, T. Saito¹⁶³, H. Sakamoto¹⁶³, A. Sakharov^{124,ao}, D. Salamani⁵⁴, G. Salamanna^{74a,74b}, J.E. Salazar Loyola^{147b}, P.H. Sales De Bruin¹⁷², A. Salnikov¹⁵³, J. Salt¹⁷⁴, D. Salvatore^{41b,41a}, F. Salvatore¹⁵⁶, A. Salvucci^{63a,63b,63c}, A. Salzburger³⁶, J. Samarati³⁶, D. Sammel⁵², D. Sampsonidis¹⁶², D. Sampsonidou¹⁶², J. Sánchez¹⁷⁴, A. Sanchez Pineda^{66a,66c}, H. Sandaker¹³⁴, C.O. Sander⁴⁶, I.G. Sanderswood⁸⁹, M. Sandhoff¹⁸², C. Sandoval²², D.P.C. Sankey¹⁴⁴, M. Sannino^{55b,55a}, Y. Sano¹¹⁷, A. Sansoni⁵¹, C. Santoni³⁸, H. Santos^{140a,140b}, S.N. Santpur¹⁸, A. Santra¹⁷⁴, A. Saprosov⁷⁹, J.G. Saraiva^{140a,140d}, O. Sasaki⁸¹, K. Sato¹⁶⁹, E. Sauvan⁵, P. Savard^{167,ax}, N. Savic¹¹⁵, R. Sawada¹⁶³, C. Sawyer¹⁴⁴, L. Sawyer^{95,am}, C. Sbarra^{23b}, A. Sbrizzi^{23a}, T. Scanlon⁹⁴, J. Schaarschmidt¹⁴⁸, P. Schacht¹¹⁵, B.M. Schachtner¹¹⁴, D. Schaefer³⁷, L. Schaefer¹³⁷, J. Schaeffer⁹⁹, S. Schaepe³⁶, U. Schäfer⁹⁹, A.C. Schaffer¹³², D. Schaile¹¹⁴, R.D. Schamberger¹⁵⁵, N. Scharmberg¹⁰⁰, V.A. Schegelsky¹³⁸, D. Scheirich¹⁴³, F. Schenck¹⁹, M. Schernau¹⁷¹, C. Schiavi^{55b,55a}, S. Schier¹⁴⁶, L.K. Schildgen²⁴, Z.M. Schillaci²⁶, E.J. Schioppa³⁶, M. Schioppa^{41b,41a}, K.E. Schleicher⁵², S. Schlenker³⁶, K.R. Schmidt-Sommerfeld¹¹⁵, K. Schmieden³⁶, C. Schmitt⁹⁹, S. Schmitt⁴⁶, S. Schmitz⁹⁹, J.C. Schmoeckel⁴⁶, U. Schnoor⁵², L. Schoeffel¹⁴⁵, A. Schoening^{61b}, P.G. Scholer⁵², E. Schopf¹³⁵, M. Schott⁹⁹, J.F.P. Schouwenberg¹¹⁹, J. Schovancova³⁶, S. Schramm⁵⁴, F. Schroeder¹⁸², A. Schulte⁹⁹, H.-C. Schultz-Coulon^{61a}, M. Schumacher⁵², B.A. Schumm¹⁴⁶, Ph. Schune¹⁴⁵, A. Schwartzman¹⁵³, T.A. Schwarz¹⁰⁵, Ph. Schwemling¹⁴⁵, R. Schwienhorst¹⁰⁶, A. Sciandra¹⁴⁶, G. Sciolla²⁶, M. Scodreggio⁴⁶, M. Scornajenghi^{41b,41a}, F. Scuri^{71a}, F. Scutti¹⁰⁴, L.M. Scyboz¹¹⁵, C.D. Sebastiani^{72a,72b}, P. Seema¹⁹, S.C. Seidel¹¹⁸, A. Seiden¹⁴⁶, T. Seiss³⁷, J.M. Seixas^{80b}, G. Sekhniaidze^{69a}, K. Sekhon¹⁰⁵, S.J. Sekula⁴², N. Semprini-Cesari^{23b,23a}, S. Sen⁴⁹, S. Senkin³⁸, C. Serfon⁷⁶, L. Serin¹³², L. Serkin^{66a,66b}, M. Sessa^{60a}, H. Severini¹²⁸, F. Sforza¹⁷⁰, A. Sfyrila⁵⁴, E. Shabalina⁵³, J.D. Shahinian¹⁴⁶, N.W. Shaikh^{45a,45b}, D. Shaked Renous¹⁸⁰, L.Y. Shan^{15a}, R. Shang¹⁷³, J.T. Shank²⁵, M. Shapiro¹⁸, A.S. Sharma¹, A. Sharma¹³⁵, P.B. Shatalov¹¹¹, K. Shaw¹⁵⁶, S.M. Shaw¹⁰⁰, A. Shcherbakova¹³⁸, Y. Shen¹²⁸, N. Sherafati³⁴, A.D. Sherman²⁵, P. Sherwood⁹⁴, L. Shi^{158,at}, S. Shimizu⁸¹, C.O. Shimmin¹⁸³, Y. Shimogama¹⁷⁹, M. Shimojima¹¹⁶, I.P.J. Shipsey¹³⁵, S. Shirabe⁸⁷, M. Shiyakova^{79,ab}, J. Shlomi¹⁸⁰, A. Shmeleva¹¹⁰, M.J. Shochet³⁷, S. Shojaii¹⁰⁴, D.R. Shope¹²⁸, S. Shrestha¹²⁶, E. Shulga¹¹², P. Sicho¹⁴¹, A.M. Sickles¹⁷³, P.E. Sidebo¹⁵⁴, E. Sideras Haddad^{33c}, O. Sidiropoulou³⁶, A. Sidoti^{23b,23a}, F. Siegert⁴⁸, Dj. Sijacki¹⁶, M. Silva Jr.¹⁸¹, M.V. Silva Oliveira^{80a}, S.B. Silverstein^{45a}, S. Simion¹³², E. Simioni⁹⁹, R. Simoniello⁹⁹, P. Sinervo¹⁶⁷, N.B. Sinev¹³¹, M. Sioli^{23b,23a}, I. Siral¹⁰⁵, S.Yu. Sivoklov¹¹³, J. Sjölin^{45a,45b}, E. Skorda⁹⁶, P. Skubic¹²⁸, M. Slawinska⁸⁴, K. Sliwa¹⁷⁰, R. Slovak¹⁴³, V. Smakhtin¹⁸⁰, B.H. Smart¹⁴⁴, J. Smiesko^{28a}, N. Smirnov¹¹², S.Yu. Smirnov¹¹², Y. Smirnov¹¹², L.N. Smirnova^{113,u}, O. Smirnova⁹⁶, J.W. Smith⁵³, M. Smizanska⁸⁹, K. Smolek¹⁴², A. Smykiewicz⁸⁴, A.A. Snesarev¹¹⁰, H.L. Snoek¹²⁰, I.M. Snyder¹³¹, S. Snyder²⁹, R. Sobie^{176,ae}, A.M. Soffa¹⁷¹, A. Soffer¹⁶¹, A. Søgaard⁵⁰, F. Sohns⁵³, C.A. Solans Sanchez³⁶, E.Yu. Soldatov¹¹², U. Soldevila¹⁷⁴, A.A. Solodkov¹²³, A. Soloshenko⁷⁹, O.V. Solovyanov¹²³, V. Solovyev¹³⁸, P. Sommer¹⁴⁹, H. Son¹⁷⁰, W. Song¹⁴⁴, W.Y. Song^{168b}, A. Sopczak¹⁴², F. Sopkova^{28b}, C.L. Sotiropoulou^{71a,71b}, S. Sottocornola^{70a,70b}, R. Soualah^{66a,66c,h}, A.M. Soukharev^{122b,122a}, D. South⁴⁶, S. Spagnolo^{67a,67b}, M. Spalla¹¹⁵, M. Spangenberg¹⁷⁸, F. Spanò⁹³, D. Sperlich⁵², T.M. Spieker^{61a}, R. Spighi^{23b}, G. Spigo³⁶, M. Spina¹⁵⁶, D.P. Spiteri⁵⁷, M. Spousta¹⁴³, A. Stabile^{68a,68b}, B.L. Stamas¹²¹, R. Stamen^{61a}, M. Stamenkovic¹²⁰, E. Stanecka⁸⁴, R.W. Stanek⁶, B. Stanislaus¹³⁵, M.M. Stanitzki⁴⁶, M. Stankaityte¹³⁵, B. Stapf¹²⁰, E.A. Starchenko¹²³, G.H. Stark¹⁴⁶, J. Stark⁵⁸, S.H. Stark⁴⁰, P. Staroba¹⁴¹, P. Starovoitov^{61a}, S. Stärz¹⁰³, R. Staszewski⁸⁴, G. Stavropoulos⁴⁴, M. Stegler⁴⁶, P. Steinberg²⁹,

A.L. Steinhebel¹³¹, B. Stelzer¹⁵², H.J. Stelzer¹³⁹, O. Stelzer-Chilton^{168a}, H. Stenzel⁵⁶, T.J. Stevenson¹⁵⁶,
 G.A. Stewart³⁶, M.C. Stockton³⁶, G. Stoica^{27b}, M. Stolarski^{140a}, P. Stolte⁵³, S. Stonjek¹¹⁵,
 A. Straessner⁴⁸, J. Strandberg¹⁵⁴, S. Strandberg^{45a,45b}, M. Strauss¹²⁸, P. Strizenec^{28b}, R. Ströhmer¹⁷⁷,
 D.M. Strom¹³¹, R. Stroynowski⁴², A. Strubig⁵⁰, S.A. Stucci²⁹, B. Stugu¹⁷, J. Stupak¹²⁸, N.A. Styles⁴⁶,
 D. Su¹⁵³, S. Suchek^{61a}, V.V. Sulin¹¹⁰, M.J. Sullivan⁹⁰, D.M.S. Sultan⁵⁴, S. Sultansoy^{4c}, T. Sumida⁸⁵,
 S. Sun¹⁰⁵, X. Sun³, K. Suruliz¹⁵⁶, C.J.E. Suster¹⁵⁷, M.R. Sutton¹⁵⁶, S. Suzuki⁸¹, M. Svatos¹⁴¹,
 M. Swiatlowski³⁷, S.P. Swift², T. Swirski¹⁷⁷, A. Sydorenko⁹⁹, I. Sykora^{28a}, M. Sykora¹⁴³, T. Sykora¹⁴³,
 D. Ta⁹⁹, K. Tackmann^{46,z}, J. Taenzer¹⁶¹, A. Taffard¹⁷¹, R. Tafirotout^{168a}, H. Takai²⁹, R. Takashima⁸⁶,
 K. Takeda⁸², T. Takeshita¹⁵⁰, E.P. Takeva⁵⁰, Y. Takubo⁸¹, M. Talby¹⁰¹, A.A. Talyshev^{122b,122a},
 N.M. Tamir¹⁶¹, J. Tanaka¹⁶³, M. Tanaka¹⁶⁵, R. Tanaka¹³², S. Tapia Araya¹⁷³, S. Tapprogge⁹⁹,
 A. Tarek Abouelfadl Mohamed¹³⁶, S. Tarem¹⁶⁰, G. Tarna^{27b,d}, G.F. Tartarelli^{68a}, P. Tas¹⁴³,
 M. Tasevsky¹⁴¹, T. Tashiro⁸⁵, E. Tassi^{41b,41a}, A. Tavares Delgado^{140a,140b}, Y. Tayalati^{35e}, A.J. Taylor⁵⁰,
 G.N. Taylor¹⁰⁴, W. Taylor^{168b}, A.S. Tee⁸⁹, R. Teixeira De Lima¹⁵³, P. Teixeira-Dias⁹³, H. Ten Kate³⁶,
 J.J. Teoh¹²⁰, S. Terada⁸¹, K. Terashi¹⁶³, J. Terron⁹⁸, S. Terzo¹⁴, M. Testa⁵¹, R.J. Teuscher^{167,ae},
 S.J. Thais¹⁸³, T. Theveneaux-Pelzer⁴⁶, F. Thiele⁴⁰, D.W. Thomas⁹³, J.O. Thomas⁴², J.P. Thomas²¹,
 A.S. Thompson⁵⁷, P.D. Thompson²¹, L.A. Thomsen¹⁸³, E. Thomson¹³⁷, Y. Tian³⁹, R.E. Ticse Torres⁵³,
 V.O. Tikhomirov^{110,aq}, Yu.A. Tikhonov^{122b,122a}, S. Timoshenko¹¹², P. Tipton¹⁸³, S. Tisserant¹⁰¹,
 K. Todome^{23b,23a}, S. Todorova-Nova⁵, S. Todt⁴⁸, J. Tojo⁸⁷, S. Tokár^{28a}, K. Tokushuku⁸¹, E. Tolley¹²⁶,
 K.G. Tomiwa^{33c}, M. Tomoto¹¹⁷, L. Tompkins^{153,q}, K. Toms¹¹⁸, B. Tong⁵⁹, P. Tornambe¹⁰², E. Torrence¹³¹,
 H. Torres⁴⁸, E. Torrón Pastor¹⁴⁸, C. Tosciri¹³⁵, J. Toth^{101,ac}, D.R. Tovey¹⁴⁹, A. Traet¹⁷, C.J. Treado¹²⁴,
 T. Trefzger¹⁷⁷, F. Tresoldi¹⁵⁶, A. Tricoli²⁹, I.M. Trigger^{168a}, S. Trincz-Duvoid¹³⁶, W. Trischuk¹⁶⁷,
 B. Trocmé⁵⁸, A. Trofymov¹³², C. Troncon^{68a}, M. Trovatelli¹⁷⁶, F. Trovato¹⁵⁶, L. Truong^{33b},
 M. Trzebinski⁸⁴, A. Trzupek⁸⁴, F. Tsai⁴⁶, J.C.-L. Tseng¹³⁵, P.V. Tsiarshka^{107,ak}, A. Tsirigotis¹⁶²,
 N. Tsirintanis⁹, V. Tsiskaridze¹⁵⁵, E.G. Tskhadadze^{159a}, M. Tsopoulou¹⁶², I.I. Tsukerman¹¹¹, V. Tsulaia¹⁸,
 S. Tsuno⁸¹, D. Tsybychev¹⁵⁵, Y. Tu^{63b}, A. Tudorache^{27b}, V. Tudorache^{27b}, T.T. Tulbure^{27a}, A.N. Tuna⁵⁹,
 S. Turchikhin⁷⁹, D. Turgeman¹⁸⁰, I. Turk Cakir^{4b,v}, R.J. Turner²¹, R.T. Turra^{68a}, P.M. Tuts³⁹,
 S. Tzamarias¹⁶², E. Tzovara⁹⁹, G. Ucchielli⁴⁷, K. Uchida¹⁶³, I. Ueda⁸¹, M. Ughetto^{45a,45b}, F. Ukegawa¹⁶⁹,
 G. Unal³⁶, A. Undrus²⁹, G. Unel¹⁷¹, F.C. Ungaro¹⁰⁴, Y. Unno⁸¹, K. Uno¹⁶³, J. Urban^{28b}, P. Urquijo¹⁰⁴,
 G. Usai⁸, J. Usui⁸¹, L. Vacavant¹⁰¹, V. Vacek¹⁴², B. Vachon¹⁰³, K.O.H. Vadla¹³⁴, A. Vaidya⁹⁴,
 C. Valderanis¹¹⁴, E. Valdes Santurio^{45a,45b}, M. Valente⁵⁴, S. Valentineti^{23b,23a}, A. Valero¹⁷⁴, L. Valéry⁴⁶,
 R.A. Vallance²¹, A. Vallier³⁶, J.A. Valls Ferrer¹⁷⁴, T.R. Van Daalen¹⁴, P. Van Gemmeren⁶,
 I. Van Vulpen¹²⁰, M. Vanadia^{73a,73b}, W. Vandelli³⁶, A. Vaniachine¹⁶⁶, D. Vannicola^{72a,72b}, R. Vari^{72a},
 E.W. Varnes⁷, C. Varni^{55b,55a}, T. Varol⁴², D. Varouchas¹³², K.E. Varvell¹⁵⁷, M.E. Vasile^{27b},
 G.A. Vasquez¹⁷⁶, J.G. Vasquez¹⁸³, F. Vazeille³⁸, D. Vazquez Furelos¹⁴, T. Vazquez Schroeder³⁶,
 J. Veatch⁵³, V. Vecchio^{74a,74b}, M.J. Veen¹²⁰, L.M. Veloce¹⁶⁷, F. Veloso^{140a,140c}, S. Veneziano^{72a},
 A. Ventura^{67a,67b}, N. Venturi³⁶, A. Verbytskyi¹¹⁵, V. Vercesi^{70a}, M. Verducci^{74a,74b},
 C.M. Vergel Infante⁷⁸, C. Vergis²⁴, W. Verkerke¹²⁰, A.T. Vermeulen¹²⁰, J.C. Vermeulen¹²⁰,
 M.C. Vetterli^{152,ax}, N. Viaux Maira^{147b}, M. Vicente Barreto Pinto⁵⁴, T. Vickey¹⁴⁹, O.E. Vickey Boeriu¹⁴⁹,
 G.H.A. Viehhauser¹³⁵, L. Vigani¹³⁵, M. Villa^{23b,23a}, M. Villaplana Perez^{68a,68b}, E. Vilucchi⁵¹,
 M.G. Vincter³⁴, V.B. Vinogradov⁷⁹, A. Vishwakarma⁴⁶, C. Vittori^{23b,23a}, I. Vivarelli¹⁵⁶, M. Vogel¹⁸²,
 P. Vokac¹⁴², S.E. von Buddenbrock^{33c}, E. Von Toerne²⁴, V. Vorobel¹⁴³, K. Vorobev¹¹², M. Vos¹⁷⁴,
 J.H. Vosseveld⁹⁰, M. Vozak¹⁰⁰, N. Vranjes¹⁶, M. Vranjes Milosavljevic¹⁶, V. Vrba¹⁴², M. Vreeswijk¹²⁰,
 T. Šfiligoj⁹¹, R. Vuillermet³⁶, I. Vukotic³⁷, T. Ženiš^{28a}, L. Živković¹⁶, P. Wagner²⁴, W. Wagner¹⁸²,
 J. Wagner-Kuhr¹¹⁴, H. Wahlberg⁸⁸, K. Wakamiya⁸², V.M. Walbrecht¹¹⁵, J. Walder⁸⁹, R. Walker¹¹⁴,
 S.D. Walker⁹³, W. Walkowiak¹⁵¹, V. Wallangen^{45a,45b}, A.M. Wang⁵⁹, C. Wang^{60b}, F. Wang¹⁸¹,
 H. Wang¹⁸, H. Wang³, J. Wang¹⁵⁷, J. Wang^{61b}, P. Wang⁴², Q. Wang¹²⁸, R.-J. Wang⁹⁹, R. Wang^{60a},
 R. Wang⁶, S.M. Wang¹⁵⁸, W.T. Wang^{60a}, W. Wang^{15c,af}, W.X. Wang^{60a,af}, Y. Wang^{60a,an}, Z. Wang^{60c},
 C. Wanotayaraj⁴⁶, A. Warburton¹⁰³, C.P. Ward³², D.R. Wardrope⁹⁴, N. Warrack⁵⁷, A. Washbrook⁵⁰,
 A.T. Watson²¹, M.F. Watson²¹, G. Watts¹⁴⁸, B.M. Waugh⁹⁴, A.F. Webb¹¹, S. Webb⁹⁹, C. Weber¹⁸³,
 M.S. Weber²⁰, S.A. Weber³⁴, S.M. Weber^{61a}, A.R. Weidberg¹³⁵, J. Weingarten⁴⁷, M. Weirich⁹⁹,
 C. Weiser⁵², P.S. Wells³⁶, T. Wenaus²⁹, T. Wengler³⁶, S. Wenig³⁶, N. Wermes²⁴, M.D. Werner⁷⁸,
 P. Werner³⁶, M. Wessels^{61a}, T.D. Weston²⁰, K. Whalen¹³¹, N.L. Whallon¹⁴⁸, A.M. Wharton⁸⁹,

A.S. White¹⁰⁵, A. White⁸, M.J. White¹, D. Whiteson¹⁷¹, B.W. Whitmore⁸⁹, F.J. Wickens¹⁴⁴,
W. Wiedenmann¹⁸¹, M. Wielers¹⁴⁴, N. Wieseotte⁹⁹, C. Wiglesworth⁴⁰, L.A.M. Wiik-Fuchs⁵², F. Wilk¹⁰⁰,
H.G. Wilkens³⁶, L.J. Wilkins⁹³, H.H. Williams¹³⁷, S. Williams³², C. Willis¹⁰⁶, S. Willocq¹⁰²,
J.A. Wilson²¹, I. Wingerter-Seez⁵, E. Winkels¹⁵⁶, F. Winklmeier¹³¹, O.J. Winston¹⁵⁶, B.T. Winter⁵²,
M. Wittgen¹⁵³, M. Wobisch⁹⁵, A. Wolf⁹⁹, T.M.H. Wolf¹²⁰, R. Wolff¹⁰¹, R.W. Wölker¹³⁵, J. Wollrath⁵²,
M.W. Wolter⁸⁴, H. Wolters^{140a,140c}, V.W.S. Wong¹⁷⁵, N.L. Woods¹⁴⁶, S.D. Worm²¹, B.K. Wosiek⁸⁴,
K.W. Woźniak⁸⁴, K. Wraight⁵⁷, S.L. Wu¹⁸¹, X. Wu⁵⁴, Y. Wu^{60a}, T.R. Wyatt¹⁰⁰, B.M. Wynne⁵⁰, S. Xella⁴⁰,
Z. Xi¹⁰⁵, L. Xia¹⁷⁸, D. Xu^{15a}, H. Xu^{60a,d}, L. Xu²⁹, T. Xu¹⁴⁵, W. Xu¹⁰⁵, Z. Xu^{60b}, Z. Xu¹⁵³, B. Yabsley¹⁵⁷,
S. Yacoob^{33a}, K. Yajima¹³³, D.P. Yallup⁹⁴, D. Yamaguchi¹⁶⁵, Y. Yamaguchi¹⁶⁵, A. Yamamoto⁸¹,
T. Yamanaka¹⁶³, F. Yamane⁸², M. Yamatani¹⁶³, T. Yamazaki¹⁶³, Y. Yamazaki⁸², Z. Yan²⁵, H.J. Yang^{60c,60d},
H.T. Yang¹⁸, S. Yang⁷⁷, X. Yang^{60b,58}, Y. Yang¹⁶³, W.-M. Yao¹⁸, Y.C. Yap⁴⁶, Y. Yasu⁸¹, E. Yatsenko^{60c,60d},
J. Ye⁴², S. Ye²⁹, I. Yeletsikh⁷⁹, M.R. Yexley⁸⁹, E. Yigitbasi²⁵, K. Yorita¹⁷⁹, K. Yoshihara¹³⁷,
C.J.S. Young³⁶, C. Young¹⁵³, J. Yu⁷⁸, R. Yuan^{60b}, X. Yue^{61a}, S.P.Y. Yuen²⁴, B. Zabinski⁸⁴, G. Zacharis¹⁰,
E. Zaffaroni⁵⁴, J. Zahreddine¹³⁶, A.M. Zaitsev^{123,ap}, T. Zakareishvili^{159b}, N. Zakharchuk³⁴, S. Zambito⁵⁹,
D. Zanzi³⁶, D.R. Zaripovas⁵⁷, S.V. Zeiβner⁴⁷, C. Zeitnitz¹⁸², G. Zemaityte¹³⁵, J.C. Zeng¹⁷³, O. Zenin¹²³,
D. Zerwas¹³², M. Zgubič¹³⁵, D.F. Zhang^{15b}, F. Zhang¹⁸¹, G. Zhang^{60a}, G. Zhang^{15b}, H. Zhang^{15c},
J. Zhang⁶, L. Zhang^{15c}, L. Zhang^{60a}, M. Zhang¹⁷³, R. Zhang^{60a}, R. Zhang²⁴, X. Zhang^{60b}, Y. Zhang^{15d},
Z. Zhang^{63a}, Z. Zhang¹³², P. Zhao⁴⁹, Y. Zhao^{60b}, Z. Zhao^{60a}, A. Zhemchugov⁷⁹, Z. Zheng¹⁰⁵,
D. Zhong¹⁷³, B. Zhou¹⁰⁵, C. Zhou¹⁸¹, M.S. Zhou^{15d}, M. Zhou¹⁵⁵, N. Zhou^{60c}, Y. Zhou⁷, C.G. Zhu^{60b},
H.L. Zhu^{60a}, H. Zhu^{15a}, J. Zhu¹⁰⁵, Y. Zhu^{60a}, X. Zhuang^{15a}, K. Zhukov¹¹⁰, V. Zhulanov^{122b,122a},
D. Zieminska⁶⁵, N.I. Zimine⁷⁹, S. Zimmermann⁵², Z. Zinonos¹¹⁵, M. Ziolkowski¹⁵¹, G. Zobernig¹⁸¹,
A. Zoccoli^{23b,23a}, K. Zoch⁵³, T.G. Zorbas¹⁴⁹, R. Zou³⁷, L. Zwalinski³⁶

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 Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia

²³ (a) INFN Bologna and Università 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 Teórica 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 Experimental Physics of the National Research Centre Kurchatov Institute, Moscow, Russia

- 112 National Research Nuclear University MEPhI, Moscow, Russia
- 113 D.V. Skobel'syn 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 Institut", 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. Javakishvili 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 Borough of Manhattan Community College, City University of New York, New York NY; United States of America.

^b Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town; South Africa.

- ^c Also at CERN, Geneva; Switzerland.
- ^d Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
- ^e Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ^f Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
- ^g Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.
- ^h Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates.
- ⁱ Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
- ^j Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
- ^k Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
- ^l Also at Department of Physics, California State University, East Bay; United States of America.
- ^m Also at Department of Physics, California State University, Fresno; United States of America.
- ⁿ Also at Department of Physics, California State University, Sacramento; United States of America.
- ^o Also at Department of Physics, King's College London, London; United Kingdom.
- ^p Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia.
- ^q Also at Department of Physics, Stanford University, Stanford CA; United States of America.
- ^r Also at Department of Physics, University of Adelaide, Adelaide; Australia.
- ^s Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
- ^t Also at Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
- ^u Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.
- ^v Also at Giresun University, Faculty of Engineering, Giresun; Turkey.
- ^w Also at Graduate School of Science, Osaka University, Osaka; Japan.
- ^x Also at Hellenic Open University, Patras; Greece.
- ^y Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
- ^z Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
- ^{aa} Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
- ^{ab} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
- ^{ac} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.
- ^{ad} Also at Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; China.
- ^{ae} Also at Institute of Particle Physics (IPP); Canada.
- ^{af} Also at Institute of Physics, Academia Sinica, Taipei; Taiwan.
- ^{ag} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- ^{ah} Also at Institute of Theoretical Physics, Ilija State University, Tbilisi; Georgia.
- ^{ai} Also at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid; Spain.
- ^{aj} Also at Istanbul University, Dept. of Physics, Istanbul; Turkey.
- ^{ak} Also at Joint Institute for Nuclear Research, Dubna; Russia.
- ^{al} Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
- ^{am} Also at Louisiana Tech University, Ruston LA; United States of America.
- ^{an} Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.
- ^{ao} Also at Manhattan College, New York NY; United States of America.
- ^{ap} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
- ^{aq} Also at National Research Nuclear University MEPhI, Moscow; Russia.
- ^{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 Università di Napoli Parthenope, Napoli; Italy.
- * Deceased.