



# Search for high-mass dilepton resonances using $139 \text{ fb}^{-1}$ of $pp$ collision data collected at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector

The ATLAS Collaboration\*

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## ABSTRACT

A search for high-mass dielectron and dimuon resonances in the mass range of 250 GeV to 6 TeV is presented. The data were recorded by the ATLAS experiment in proton–proton collisions at a centre-of-mass energy of  $\sqrt{s} = 13 \text{ TeV}$  during Run 2 of the Large Hadron Collider and correspond to an integrated luminosity of  $139 \text{ fb}^{-1}$ . A functional form is fitted to the dilepton invariant-mass distribution to model the contribution from background processes, and a generic signal shape is used to determine the significance of observed deviations from this background estimate. No significant deviation is observed and upper limits are placed at the 95% confidence level on the fiducial cross-section times branching ratio for various resonance width hypotheses. The derived limits are shown to be applicable to spin-0, spin-1 and spin-2 signal hypotheses. For a set of benchmark models, the limits are converted into lower limits on the resonance mass and reach 4.5 TeV for the  $E_6$ -motivated  $Z'_\psi$  boson. Also presented are limits on Heavy Vector Triplet model couplings.

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## 1. Introduction

Searches in the dilepton (dielectron and dimuon) final state have a long and illustrious history with the discovery of the  $J/\psi$  meson in 1974 [1,2] and  $\Upsilon$  meson in 1977 [3] as well as the  $Z$  boson in 1983 [4,5]. As these were key steps which led to the establishment of the Standard Model (SM) of particle physics, the study of the same final state could help to pave the way to a better understanding of the physics processes beyond it.

Various models predict resonances which decay into dileptons and can be categorised according to their spin. A new high-mass spin-0 resonance,  $H$ , introduced as part of an extended scalar sector in some models, such as the Minimal Supersymmetric SM (MSSM) [6], has higher decay rate into a pair of muons rather than electrons. The majority of searches for new neutral high-mass resonances have focused on a new spin-1 vector boson, generally referred to as  $Z'$ , that appears in models with extended gauge symmetries. Typical benchmark models include the Sequential Standard Model  $Z'_{\text{SSM}}$  boson [7], which has the same fermion couplings as the SM  $Z$  boson, a  $Z'_X$  and a  $Z'_\psi$  boson of an  $E_6$ -motivated Grand Unification model [8], or a  $Z'_{\text{HVT}}$  boson of the Heavy Vector Triplet model [9]. In the first two models, the  $Z'$  boson is a singlet, associated with a new  $U(1)$  gauge group, and generally its couplings to the SM  $W$  and  $Z$  bosons are assumed to be zero. The

$Z'_{\text{HVT}}$  boson is a neutral member of a new  $SU(2)$  gauge group, i.e. part of a triplet and cannot exist without two new charged heavy bosons,  $W'_{\text{HVT}}{}^\pm$ , with which it is nearly degenerate in mass. New spin-2 resonances, excited states of the graviton, are introduced in the Randall–Sundrum model [10] with a warped extra dimension. In experimental terms the described scenarios would result in a local excess of signal candidates over a smoothly falling dilepton mass spectrum. This search has a clean experimental signature with a fully reconstructable final state and excellent detection efficiency.

This Letter presents a search for a new resonance decaying into two electrons or two muons in  $139 \text{ fb}^{-1}$  of data collected in proton–proton ( $pp$ ) collisions at the LHC at a centre-of-mass energy  $\sqrt{s} = 13 \text{ TeV}$ . Previous searches with  $36.1 \text{ fb}^{-1}$  of  $pp$  collision data at  $\sqrt{s} = 13 \text{ TeV}$  conducted by the ATLAS and CMS experiments [11,12] showed no significant excess and led to lower limits of up to 3.8 TeV for the mass of the  $Z'_\psi$  boson. The analysis presented in this Letter, compared with that published in Ref. [11], benefits from: a factor of four increase in integrated luminosity; several improvements in the reconstruction software, including the use of a new dynamical, topological cell-clustering algorithm for electron reconstruction [13] and an improved treatment of the relative alignment of the inner tracker and the muon tracking detectors in the muon reconstruction; the use of invariant-mass sidebands of the expected signal in data to constrain the fit parameters of the background distribution, which is described by a smooth functional form instead of relying on simulation; and a generic

\* E-mail address: [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch).

**Table 1**

The event generators used for simulation of the signal and background processes. The acronyms ME and PS stand for matrix element and parton shower. The top-quark mass is set to 172.5 GeV.

	ME Generator and ME PDFs	PS and non-perturbative effect with PDFs
<b>Background process</b>		
NLO Drell–Yan	POWHEG-Box [23,24], CT10 [25], PHOTOS	PYTHIA v8.186 [26], CTEQ6L1 [27,28], EVTGEN1.2.0
$t\bar{t}$	POWHEG-Box, NNPDF3.0NLO [29]	PYTHIA v8.230, NNPDF23LO [30], EVTGEN1.6.0
Single top $s$ -channel, $Wt$	POWHEG-Box, NNPDF3.0NLO	PYTHIA v8.230, NNPDF23LO, EVTGEN1.6.0
Single top $t$ -channel	POWHEG-Box, NNPDF3.04fNLO, MADSPIN	PYTHIA v8.230, NNPDF23LO, EVTGEN1.6.0
Diboson ( $WW$ , $WZ$ and $ZZ$ )	SHERPA 2.1.1 [31], CT10	SHERPA 2.1.1, CT10
<b>Signal process</b>		
LO Drell–Yan	PYTHIA v8.186, NNPDF23LO	PYTHIA v8.186, NNPDF23LO, EVTGEN1.2.0
Randall–Sundrum $G^* \rightarrow \ell\ell$	PYTHIA v8.210, NNPDF23LO	PYTHIA v8.210, NNPDF23LO, EVTGEN1.2.0
MSSM $gg \rightarrow H \rightarrow \ell\ell$	POWHEG-Box, CT10	PYTHIA v8.212, CTEQ6L1, EVTGEN1.2.0

signal line shape described by a non-relativistic Breit–Wigner function convolved with the detector resolution, which simplifies reinterpretations of the result.

## 2. ATLAS detector

ATLAS [14–16] is a multipurpose detector with a forward–backward symmetric cylindrical geometry with respect to the LHC beam axis.<sup>1</sup> The innermost layers consist of tracking detectors in the pseudorapidity range  $|\eta| < 2.5$ . This inner detector (ID) is surrounded by a thin superconducting solenoid that provides a 2 T axial magnetic field. It is enclosed by the electromagnetic and hadronic calorimeters, which cover  $|\eta| < 4.9$ . The outermost layers of ATLAS consist of an external muon spectrometer (MS) within  $|\eta| < 2.7$ , incorporating three large toroidal magnetic assemblies with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 Tm for most of the acceptance. The MS includes precision tracking chambers and fast detectors for triggering. A two-level trigger system [17] reduces the recorded event rate to an average of 1 kHz.

## 3. Data and simulation

The dataset used in this analysis was collected during LHC Run 2 in stable beam conditions and with all detector systems operating normally. The event quality was checked to remove events with noise bursts or coherent noise in the calorimeters. Events in the dielectron channel were recorded using a dielectron trigger based on the ‘very loose’ or ‘loose’ identification criteria [17] with transverse energy ( $E_T$ ) thresholds between 12 and 24 GeV for both electrons, depending on the data-taking period. Events in the dimuon channel are required to pass at least one of two single-muon triggers: the first requires a transverse momentum ( $p_T$ ) of at least 50 GeV, while the second has a threshold lowered to 26 GeV but requires the muon candidate to be isolated [17]. The integrated luminosity of the dataset is determined to be  $139.0 \pm 2.4 \text{ fb}^{-1}$ , following a methodology similar to that detailed in Ref. [18], and using the LUCID-2 detector for the baseline luminosity measurements [19], from calibration of the luminosity scale using x-y beam-separation scans.

While the search in this analysis is carried out entirely in a data-driven way, simulated event samples for the signal and back-

ground processes are used to determine appropriate functions to fit the data, study background compositions and to evaluate the signal efficiency. The main backgrounds in decreasing order of importance are Drell–Yan (DY), top-quark pair ( $t\bar{t}$ ), single-top-quark and diboson production. Multi-jet and  $W$  + jets processes in the dielectron channel are estimated with a data-driven method [11]. Multi-jet and  $W$  + jets processes in the dimuon channel as well as processes with  $\tau$ -leptons in both channels have a negligible impact and are not considered. The Monte Carlo (MC) event generators for the hard-scatter process, showering and parton distribution functions (PDFs) are listed in Table 1. The ‘afterburner’ generators such as PHOTOS [20] for the final-state photon radiation (FSR) modelling, MADSPIN [21] to preserve top-quark spin correlations, and EVTGEN [22], used for the modelling of  $c$ - and  $b$ -hadron decays, are also reported.

The DY [32] and diboson [33] samples are generated in slices of dilepton mass to increase the sample size in the high-mass region. Next-to-next-to-leading-order (NNLO) corrections in quantum chromodynamic (QCD) theory and next-to-leading-order (NLO) corrections in electroweak (EW) theory, are calculated and applied to the DY events. The corrections are computed with VRAP v0.9 [34] and the CT14 NNLO PDF set [35] in the case of QCD effects whereas they are computed with MCSANC [36] in the case of quantum electrodynamic effects due to initial state radiation, interference between initial and final state radiation, and Sudakov logarithm single-loop corrections. The top-quark samples [37] are normalised to the cross-sections calculated at NNLO in QCD including resummation of the next-to-next-to-leading logarithmic soft gluon terms as provided by TOP++2.0 [38].

Spin-1 signal templates are obtained by a matrix-element reweighting [11] of the leading-order (LO) DY samples generated in slices of dilepton mass. These signal templates are used only for cross-section and efficiency calculations. The relative natural width ( $\Gamma_{Z'}/m_{Z'}$ ) for the benchmark models considered varies between 0.5% for  $Z'_\psi$  and 3% for  $Z'_{SSM}$ . Interference effects between the resonant signal and the background processes are neglected. Higher-order QCD corrections for all the spin-1 signals are computed with the same methodology as for the DY background. For the HVT model, these corrections are not applied, which ensures consistent treatment with the other signal channels in an eventual combination, similar to that described in Ref. [39]. Electroweak corrections are not applied to the signal samples due to their large model dependence. Spin-0 signal efficiencies are obtained from samples of the MSSM gluon–gluon fusion production of a heavy Higgs boson decaying into dilepton pairs,  $gg \rightarrow H \rightarrow \ell\ell$ , produced in the mass range  $m_H = 400\text{--}1000 \text{ GeV}$  and with relative natural width ( $\Gamma_H/m_H$ ) varying between zero and 20%. Spin-2 signal efficiencies are obtained from Randall–Sundrum graviton  $G^* \rightarrow \ell\ell$  samples produced in the mass range  $m_{G^*} = 750\text{--}5000 \text{ GeV}$  and with coupling strengths,  $k/\bar{m}_{\text{Pl}}$ , of 0.1, 0.2 and 0.3, where  $k$  is a

<sup>1</sup> 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 upwards. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ . Angular distance is measured in units of  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .

scale that defines the warp factor of the extra dimension and  $\bar{m}_{\text{Pl}}$  is the reduced Planck mass.

Simulated event samples include the effect of multiple  $pp$  interactions in the same or neighbouring bunch crossings. These effects are collectively referred to as pile-up. The simulation of pile-up collisions was performed with PYTHIA v8.186 using the ATLAS A3 set of tuned parameters [40] and the NNPDF23LO PDF set, and weighted to reproduce the average number of pile-up interactions per bunch crossing observed in data. The generated events were passed through a full detector simulation [41] based on GEANT 4 [42]. Spin-0 and spin-2 MC signal samples were produced with a fast parameterisation of the calorimeter response [43].

Very large generator-level-only MC samples (with more than 55 times the data events) for NLO DY events are used for the background studies described in Section 6. These samples could not be produced with the full detector simulation due to the large number of events required.

#### 4. Event selection

The selection of dilepton events closely follows that described in Ref. [11]. An event is selected if at least one  $pp$  interaction vertex is reconstructed. The primary vertex is chosen to be the vertex with the highest summed  $p_T^2$  of tracks with transverse momentum  $p_T > 0.5$  GeV which are associated with the vertex.

Electron candidates are reconstructed from ID tracks that are matched to clusters of energy deposited in the electromagnetic calorimeter with energy deposition consistent with that of an electromagnetic shower [44]. Reconstructed electrons must have  $E_T > 30$  GeV, satisfy  $|\eta| < 2.47$  in order to pass through the fine-granularity region of the EM calorimeter, and be outside the range  $1.37 < |\eta| < 1.52$  corresponding to the transition region between the barrel and endcap EM calorimeters. The calorimeter granularity in the excluded transition region is reduced, and the presence of significant additional inactive material degrades the electron identification capabilities and energy resolution. The ‘medium’ electron working point used for the final selection has an identification and reconstruction efficiency for prompt electrons above 92% for  $E_T > 80$  GeV.

Muon candidates are identified by matching ID tracks to tracks reconstructed in the MS [45]. Muon candidates must have  $p_T > 30$  GeV and  $|\eta| < 2.5$ . To ensure optimal muon momentum resolution at high  $p_T$ , the ‘high  $p_T$ ’ identification working point is used. It requires at least three hits in each of three layers of precision tracking chambers in the MS, and specific regions of the MS where the alignment is suboptimal are vetoed as a precaution. These requirements reject about 80% (13%) of the muon candidates in (outside) the barrel–endcap overlap region,  $1.01 < |\eta| < 1.1$ . The muon ‘high  $p_T$ ’ working point has an  $\eta$ -averaged efficiency of 69% at 1 TeV which decreases to 64% at 2.5 TeV due to increased occasional catastrophic energy loss at high  $p_T$ . Additionally, a ‘good muon’ selection requires that the uncertainty in the charge-to-momentum ratio of muon candidates is less than a  $p_T$ -dependent value. This selection is fully efficient below 1 TeV, but introduces an additional inefficiency of 7% at 2.5 TeV.

Electron (muon) candidate tracks must be consistent with the primary vertex both along the beamline, where the longitudinal impact parameter  $z_0$  is required to satisfy  $|z_0 \sin\theta| < 0.5$  mm, and in the transverse plane, where the transverse impact parameter significance  $|d_0/\sigma(d_0)|$  is required to be less than 5 (3). To reduce background from misidentified jets as well as from light- and heavy-flavour hadron decays inside jets, lepton candidates are required to be isolated. Electrons must pass the ‘gradient’ isolation working point which targets an  $E_T$ -dependent value of the iso-

lation efficiency, uniform in  $\eta$ , using a combination of track and calorimeter isolation requirements [44]. For muons, the summed scalar  $p_T$  of good-quality tracks with  $p_T > 1$  GeV originating from the primary vertex within a cone of variable size<sup>2</sup>  $\Delta R$  around the muon, but excluding the muon-candidate track itself, must be less than 6% of the  $p_T$  of the muon candidate. The efficiency of this selection is above 99% for both electrons and muons with  $p_T > 60$  GeV. Corrections are applied to electron (muon) candidates to match the energy (momentum) scale and resolution between simulation and data. These corrections are derived in an energy independent way for electrons [46]. For muons, the correction is determined as a function of  $p_T$  up to 300 GeV, from a fit to  $Z \rightarrow \mu\mu$  data with templates derived from simulation [45]. At high transverse momentum, the calibrations are dominated by corrections extracted from alignment studies, using special runs with the toroidal magnetic field off. Corrections to the lepton efficiencies in the simulation are derived from the data for electron  $E_T$  (muon  $p_T$ ) up to 150 (200) GeV [44,45]. The simulation is used to extrapolate to higher electron  $E_T$  (muon  $p_T$ ) and to study systematic effects.

The events are required to contain at least two same-flavour leptons. If additional leptons are present in the event, the two same-flavour leptons with the largest  $E_T$  ( $p_T$ ) in the electron (muon) channel are selected to form the dilepton pair. If two different-flavour pairs are found, the dielectron pair is kept, because of the better resolution and higher efficiency for electrons. A selected muon pair is required to be oppositely charged. For an electron pair, the opposite-charge requirement is not applied because of the higher probability of charge misidentification for high- $E_T$  electrons. The reconstructed mass of the dilepton system after the full analysis selection,  $m_{\ell\ell}$ , is required to be above 225 GeV to avoid the  $Z$  boson peak region, which cannot be described by the same parameterisation as the high-mass part of the dilepton distributions.

#### 5. Reconstructed dilepton mass modelling

The relative dilepton mass resolution is defined as  $(m_{\ell\ell} - m_{\ell\ell}^{\text{true}})/m_{\ell\ell}^{\text{true}}$ , where  $m_{\ell\ell}^{\text{true}}$  is the generated dilepton mass at Born level before FSR. The mass resolution is parameterised as a sum of a Gaussian distribution, which describes the detector response, and a Crystal Ball function composed of a secondary Gaussian distribution with a power-law low-mass tail, which accounts for bremsstrahlung effects in the dielectron channel or for the effect of poorly reconstructed muons. The parameterisation of the relative dilepton mass resolution as a function of  $m_{\ell\ell}^{\text{true}}$  is determined by a simultaneous fit of the function described above to NLO DY MC events. The MC sample is separated in 200  $m_{\ell\ell}^{\text{true}}$  bins of equal size on a logarithmic scale in the range of 130 GeV to 6 TeV. This procedure is repeated to evaluate the uncertainty on the fit parameters by shifting individually the lepton energy and momentum scale and resolutions by their uncertainties.

#### 6. Signal and background modelling

A resonant signal is searched for by fitting the data dilepton mass distribution. The fit function consists of a smooth functional form for the background, and a generic signal shape. The generic signal shapes are constructed from non-relativistic Breit–Wigner functions of various widths convolved with the detector resolution, obtained as described in the previous section. The shape of

<sup>2</sup>  $\Delta R$  has a maximum value of 0.3 and decreases as a function of  $p_T$  as  $10\text{GeV}/p_T[\text{GeV}]$ .

**Table 2**

The relative impact of  $\pm 1\sigma$  variation of systematic uncertainties on the signal yield in percent for zero (10%) relative width signals at the pole masses of 300 GeV, 2 and 5 TeV for dielectron and dimuon channels. Sources of uncertainties leading to an impact smaller than 0.5% on the signal yield at any point of the mass spectrum are not shown. A signal is injected at the cross-section limit.

Uncertainty source for $m_X$ [GeV]	Dielectron			Dimuon		
	300	2000	5000	300	2000	5000
Spurious signal	$\pm 12.5$ (12.0)	$\pm 4.6$ (10.8)	$\pm 0.1$ (1.0)	$\pm 11.7$ (11.0)	$\pm 3.8$ (3.5)	$\pm 2.1$ (2.2)
Lepton identification	$\pm 1.6$ (1.6)	$\pm 5.6$ (5.6)	$\pm 5.6$ (5.6)	$\pm 1.8$ (1.8)	$+12$ $\left(\begin{smallmatrix} +12 \\ -10 \end{smallmatrix}\right)$	$+25$ $\left(\begin{smallmatrix} +25 \\ -20 \end{smallmatrix}\right)$
Isolation	$\pm 0.3$ (0.3)	$\pm 1.1$ (1.2)	$\pm 1.1$ (1.1)	$\pm 0.4$ (0.4)	$\pm 0.4$ (0.4)	$\pm 0.4$ (0.5)
Luminosity	$\pm 1.7$ (1.7)	$\pm 1.7$ (1.7)	$\pm 1.7$ (1.7)	$\pm 1.7$ (1.7)	$\pm 1.7$ (1.7)	$\pm 1.7$ (1.7)
Electron energy scale	$-1.7$ $\left(\begin{smallmatrix} +1.0 \\ -1.8 \end{smallmatrix}\right)$	$-1.9$ $\left(\begin{smallmatrix} +1.7 \\ -2.9 \end{smallmatrix}\right)$	$+0.1$ ( $\pm 0.8$ )	-	-	-
Electron energy resolution	$+7.9$ $\left(\begin{smallmatrix} +1.1 \\ -0.9 \end{smallmatrix}\right)$	$+9.0$ $\left(\begin{smallmatrix} +0.7 \\ -0.5 \end{smallmatrix}\right)$	$+0.4$ ( $\pm 0.1$ )	-	-	-
Muon ID resolution	-	-	-	$+0.8$ $\left(\begin{smallmatrix} +0.3 \\ -0.8 \end{smallmatrix}\right)$	$+0.9$ $\left(\begin{smallmatrix} +0.7 \\ -1.1 \end{smallmatrix}\right)$	$+0.6$ $\left(\begin{smallmatrix} +0.5 \\ -0.3 \end{smallmatrix}\right)$
Muon MS resolution	-	-	-	$+2.8$ $\left(\begin{smallmatrix} +1.0 \\ -1.3 \end{smallmatrix}\right)$	$+3.2$ $\left(\begin{smallmatrix} +2.6 \\ -2.4 \end{smallmatrix}\right)$	$\pm 2.4$ (2.1)
'Good muon' requirement	-	-	-	$\pm 0.6$ (0.6)	$+9.0$ $\left(\begin{smallmatrix} +9.0 \\ -8.2 \end{smallmatrix}\right)$	$+55$ $\left(\begin{smallmatrix} +55 \\ -35 \end{smallmatrix}\right)$

the dilepton invariant mass distribution for a signal resonance with intrinsic width that is negligible compared with the detector resolution (zero-width signal) is obtained from the mass resolution only.

To allow for a generic resonance search, a fiducial region at particle level is defined following the selection criteria applied to the reconstructed lepton candidates: each electron and muon candidate needs to pass  $|\eta| < 2.5$  and  $E_T(p_T) > 30$  GeV, and the dilepton mass has to satisfy  $m_{\ell\ell}^{\text{true}} > m_X - 2\Gamma_X$ , where  $m_X$  and  $\Gamma_X$  represent the pole mass and width of a hypothetical resonance  $X$ , respectively. This selection is added in order to reduce the model dependence from off-shell effects.

The nominal combined reconstruction and identification efficiency in the fiducial region is extracted from the DY sample and thus assumes the kinematics of a spin-1 boson. For the dielectron (dimuon) channels, it varies from 64% (54%) at 225 GeV to 74% (38%) at 6 TeV for the zero-width signals. For a spin-1 signal with 10% relative width, the efficiency changes by less than 0.5% relative to a signal with zero width for both channels over most of the considered invariant-mass range. Only above 5 TeV in the dimuon channel are the variations as large as 2% in absolute efficiency. For the spin-0 and spin-2 samples, width-related variations are below 1%. For the dielectron channel, spin-0 and spin-2 efficiencies are higher than the corresponding spin-1 values by at most 4%. For the dimuon channel, efficiencies for spin-0 and spin-2 signals are at most 1% lower than the corresponding spin-1 values. The systematic uncertainties of the overall efficiency are due to the uncertainties in the trigger, isolation, identification, and reconstruction efficiencies.

The smooth functional form for the background is based on fit performance studies on a MC background template. The associated uncertainties are also estimated through these studies. In order to minimise the statistical uncertainties in this procedure, the background template for DY is produced from large-statistics samples simulated only at generator level and smeared by the experimental dilepton mass resolution, described in the previous section, with mass-dependent acceptance and efficiency corrections applied. A similar procedure is applied to the generator-level dilepton mass distribution in the  $t\bar{t}$  sample exploiting the larger number of events from the generator-level mass distribution. The distributions from the diboson and single-top simulated samples and, in the electron channel, a template for multi-jet and  $W + \text{jet}$  processes are also considered. All MC-based contributions are scaled by their respective cross-sections and summed together to obtain the background template for the choice of the smooth functional form.

In order to select the background functional form, a fit to the dilepton mass background template is performed, under the signal plus background hypothesis, for various functional forms, following the procedure outlined in Ref. [47]. The chosen functional form is the one with the smallest absolute number of fitted signal events ('spurious signal'), which are determined as a function of  $m_{\ell\ell}$ :

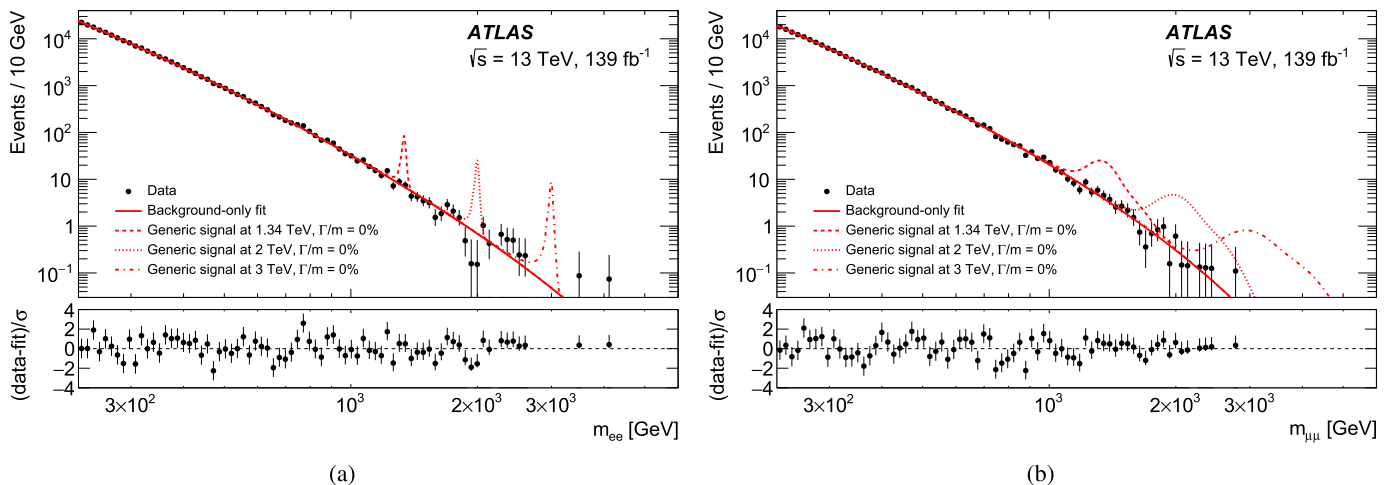
$$f_{\ell\ell}(m_{\ell\ell}) = f_{\text{BW},Z}(m_{\ell\ell}) \cdot (1 - x^c)^b \cdot x^{\sum_{i=0}^3 p_i \log(x)^i}, \quad (1)$$

where  $x = m_{\ell\ell}/\sqrt{s}$  and parameters  $b$  and  $p_i$  with  $i = 0, \dots, 3$  are left free in the fit to data and independent for dielectron and dimuon channels. The parameter  $c$  is 1 for the dielectron and 1/3 for the dimuon channel. The function  $f_{\text{BW},Z}(m_{\ell\ell})$  is a non-relativistic Breit–Wigner function with  $m_Z = 91.1876$  GeV and  $\Gamma_Z = 2.4952$  GeV [48]. The normalisation of the background function is such that the integral  $a$  corresponds to the total number of background events. To further validate this functional form an extra degree of freedom ( $i = 4$ ) is added to the fit function before the final data analysis, to check if it improves the likelihood value of the fit by more than  $2\sigma$ . To check the fit stability in the high-mass region, signal injection tests are performed at various mass points. No significant bias in the number of extracted signal events is observed.

Uncertainties related to the background modelling are propagated into the determination of the spurious signal. Smooth templates for systematic shape uncertainties are produced using the same procedure as for the nominal templates. The uncertainties considered include variations due to PDFs [11] and normalisation of the  $t\bar{t}$  background component [49]. Uncertainties on the multi-jet and  $W + \text{jet}$  background contributions [11] are also considered in the dielectron channel. For the selected function, the largest spurious signal (accounting for all systematic variations) is required to be less than 30% of the statistical uncertainty in the fitted signal yield (from the background distribution) for the zero-width signal. This criterion is relaxed to 50% for signals of greater width. The systematic uncertainty of the background estimate is mass dependent and corresponds to a functional interpolation between the highest maxima among the spurious-signal-yield distributions for all systematic variations. The spurious-signal yield is calculated independently for the relative signal width assumptions between zero and 10% in steps of 0.5%.

The impact of systematic uncertainties on the signal yield is shown in Table 2. Only systematic uncertainties which change the fitted signal yield by more than 0.5% at any point in the mass spectrum are considered. The largest systematic uncertainty at low mass in both channels originates from the spurious signals. The





**Fig. 1.** Distribution of the (a) dielectron and (b) dimuon invariant mass for events passing the full selection. Generic zero-width signal shapes, scaled to 20 times the value of the corresponding expected upper limit at 95% CL on the fiducial cross-section times branching ratio, with pole masses of  $m_X = 1.34, 2$  and  $3\text{ TeV}$  as well as background-only fits are superimposed. The data points are plotted at the centre of each bin. The error bars indicate statistical uncertainties only. The differences between the data and the fit results in units of standard deviations of the statistical uncertainty are shown in the bottom panels.

largest systematic uncertainty in the dielectron channel at high mass originates from the electron identification efficiency. The uncertainty associated with the ‘good muon’ requirement is dominant in the dimuon channel at high mass. This uncertainty is estimated with a conservative approach in a dataset collected in 2015–2016, corresponding to  $36\text{ fb}^{-1}$ , by comparing efficiencies obtained in data and in simulation.

## 7. Statistical analysis

The numbers of signal and background events, as a function of the signal mass and width hypothesis, are estimated from simultaneous maximum-likelihood fits of the signal-plus-background models to the data  $m_{\ell\ell}$  distribution. Systematic uncertainties are included in the fits via nuisance parameters constrained by penalty terms which are either Gaussian (e.g. energy and momentum scale uncertainties) or log-normal (efficiency and resolution uncertainties). Potential mismodelling of the background estimate is accounted for through an additional nuisance parameter allowing non-zero signal normalisation under the null hypothesis constrained by the measured spurious signal. Dielectron and dimuon channels are considered both as independent channels and in a combined approach, under a lepton-flavour universality assumption [7,8].

The significance of a signal is summarised by a  $p$ -value, the probability of observing an excess at least as signal-like as the one observed in data, in the absence of signal. The local  $p$ -value of the background-only hypothesis ( $p_0$ ) is determined from a profile-likelihood-ratio-test statistic [50] as detailed in Ref. [51] in the asymptotic approximation. Global significance values are also computed in the asymptotic approximation to account for the trial factors due to scanning the signal mass hypothesis [52]. Upper limits at the 95% confidence level (CL) are set on the fiducial cross-section times branching ratio into the corresponding dilepton final state, given the integrated luminosity of the data and the signal efficiency. The limits are evaluated with the modified frequentist  $\text{CL}_s$  method [53] using the asymptotic approximation to the test-statistic distribution [50]. Cross-checks with sampling distributions generated using pseudo-experiments are used to test the accuracy of this approximation for the high-mass part of the dilepton spectra. The approximation is found to lead to limits that are stronger than those obtained with pseudo-experiments above  $3\text{ TeV}$ . This effect reaches 25% (35%) at  $5\text{ TeV}$  ( $6\text{ TeV}$ ) for the combined dilepton

channel. The impact of this approximation on the mass limits is below  $100\text{ GeV}$ .

## 8. Results

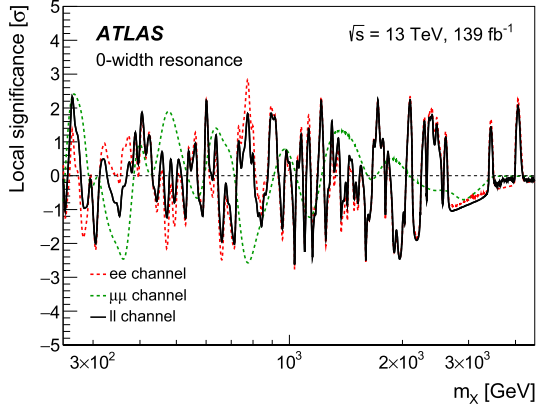
The dilepton invariant-mass distributions for the events that pass the full analysis selection are shown in Fig. 1. The event with highest reconstructed mass is a dielectron candidate with  $m_{ee} = 4.06\text{ TeV}$ , formed of two electrons with  $E_T = 2.01\text{ TeV}$  and  $E_T = 1.92\text{ TeV}$  in the barrel region of the calorimeter. The event with highest reconstructed mass in the dimuon channel has an invariant mass of  $m_{\mu\mu} = 2.75\text{ TeV}$ . Both muon candidates are in the barrel section of the muon spectrometer and their transverse momenta are  $p_T = 1.82\text{ TeV}$  and  $p_T = 1.04\text{ TeV}$ .

The fit to data<sup>3</sup> is performed in bins of  $1\text{ GeV}$  and uses the function in Eq. (1). In both channels, validation tests using the extension of the functional form described in Section 6 did not yield any significant improvement, so the function in Eq. (1) is used without modification.

The probability that the data are compatible with the background-only hypothesis is shown in Fig. 2 as a function of pole mass for zero-width signals. No significant excess is observed. The largest deviations from the background-only hypothesis in the dielectron, dimuon and combined dilepton channels are observed at masses of  $774\text{ GeV}$ ,  $267\text{ GeV}$  and  $264\text{ GeV}$  for zero-width signals with a local  $p_0$  of  $2.9\sigma$ ,  $2.4\sigma$  and  $2.3\sigma$  and a global significance of  $0.1\sigma$ ,  $0.3\sigma$ , and zero, respectively.

Fig. 3 shows the upper limits on the fiducial cross-section times branching ratio to two leptons of a single flavour for generic resonances of various relative widths as a function of their mass. The observed limits for pole masses ranging from  $250$  to  $750\text{ GeV}$  are obtained with a spacing of  $1\text{ GeV}$ . The granularity is reduced above that mass, but remains below the experimental resolution of the  $ee$  channel. The observed limit on the fiducial cross-section times branching ratio ranges from  $3.6$  ( $13.1$ )  $\text{fb}$  at  $250\text{ GeV}$  to about  $0.014$  ( $0.018$ )  $\text{fb}$  at  $6\text{ TeV}$  for the zero ( $10\%$ ) relative width signal in the combined dilepton channel. The impact of systematic uncertainties

<sup>3</sup> The resulting fit parameters for dielectron channel are:  $a = 178000 \pm 400$ ,  $b = 1.5 \pm 1.0$ ,  $p_0 = -12.38 \pm 0.09$ ,  $p_1 = -4.295 \pm 0.014$ ,  $p_2 = -0.9191 \pm 0.0027$ ,  $p_3 = -0.0845 \pm 0.0005$ ; for dimuon channel are:  $a = 138700 \pm 400$ ,  $b = 11.8 \pm 0.5$ ,  $p_0 = -7.38 \pm 0.12$ ,  $p_1 = -4.132 \pm 0.017$ ,  $p_2 = -1.0637 \pm 0.0029$ ,  $p_3 = -0.1022 \pm 0.0005$ .



**Fig. 2.** Probability that the observed spectrum is compatible with the background-only hypothesis for the dielectron, dimuon and combined dilepton channels. The local  $p_0$  is quantified in standard deviations  $\sigma$  as a function of pole mass  $m_\chi$ .

on this search is small across all mass and width assumptions, resulting in the expected limits on the fiducial cross-section times branching ratio to dileptons being (4–7)% weaker than those without systematic uncertainties. As all studied signal spin hypotheses (0, 1, 2) have efficiency values which are consistent within 4%, the limits shown above can be used for reinterpretation of models with such new resonances.

The generic cross-section limits at  $\Gamma/m = 0.5\%$ ,  $1.2\%$  and  $3.0\%$  are compared with the model predictions of  $Z'_\psi$ ,  $Z'_\chi$  and  $Z'_{SSM}$ , respectively, to obtain mass limits. The cross-section values for the model predictions are obtained in the fiducial volume, for compatibility with the definition of the generic signal model. Mass limits are calculated as the intersection between the expected and observed limits with the model prediction. Table 3 lists the mass limits for the three tested models in all three channels. These exceed previously reported results [11] by 500–800 GeV.

The generic cross-section limits shown in Fig. 3 are smoothly interpolated via Delaunay triangulation [54] to produce limits in between the tested widths. The results are converted into exclusion contours in the HVT model coupling space presented in Fig. 4, where  $g_\ell$ ,  $g_q$  and  $g_h$  correspond to the coupling strengths between the triplet field and the lepton, quark and Higgs and vector-boson fields, respectively. In the tested  $\{g_q, g_\ell\}$  plane the relative width always remains below 10%, and in the  $\{g_h, g_f\}$

**Table 3**

Observed and expected 95% CL lower limits on  $m_{Z'}$  for three  $Z'$  gauge boson models, quoted to the nearest 100 GeV in the  $ee$  and  $\mu\mu$  channels as well as their combination ( $\ell\ell$ ).

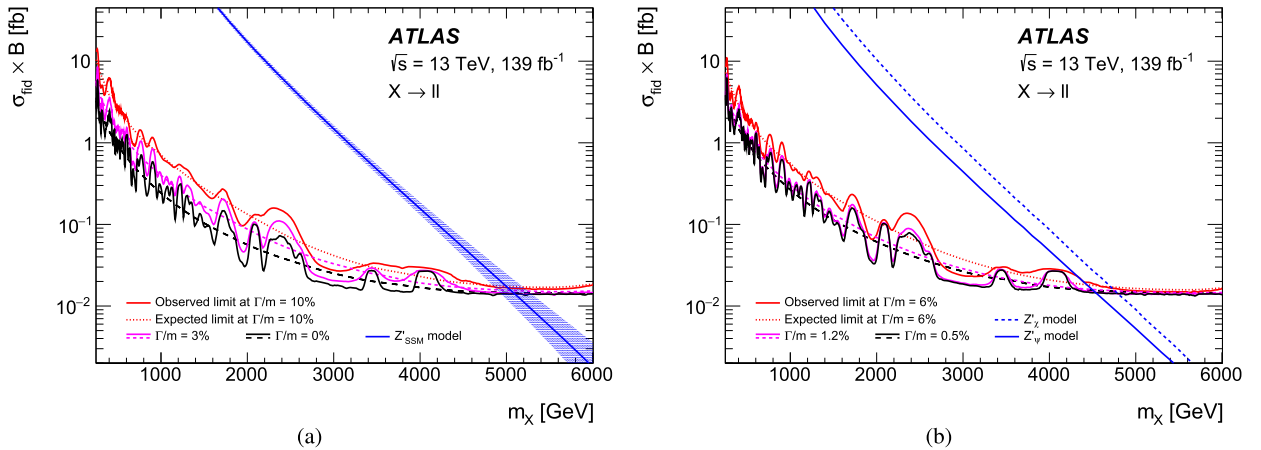
Model	Lower limits on $m_{Z'}$ [TeV]					
	$ee$		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
$Z'_\psi$	4.1	4.3	4.0	4.0	4.5	4.5
$Z'_\chi$	4.6	4.6	4.2	4.2	4.8	4.8
$Z'_{SSM}$	4.9	4.9	4.5	4.5	5.1	5.1

( $g_f \equiv g_\ell = g_q$ ) it only exceeds 10% in regions ( $|g_f| > 0.9$  and  $|g_h| > 2.5$ ) well outside the limit contours. The observed limits can be compared with the limits obtained for the combination of the  $\ell\ell$  and  $\ell\nu$  channels in Ref. [39] (provided in brackets): for  $g_h = 0$  and  $m_{Z'_{HVT}} = 3$  TeV, 4 TeV and 5 TeV the  $|g_f|$  values above 0.07 (0.06), 0.23 (0.15) and 0.49 (0.42) are excluded at 95% CL, respectively. The resulting dilepton-only limits are slightly weaker than those for the  $\ell\ell$  and  $\ell\nu$  channels combined, even with a four times larger dataset, because of the higher  $W'_{HVT} \rightarrow \ell\nu$  cross-section in this model.

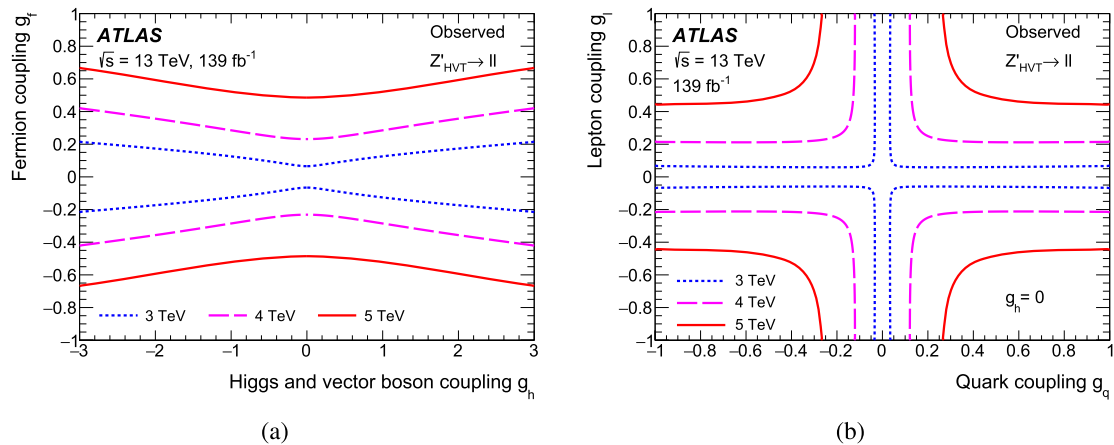
A complete set of tables and figures (including additional results for the dielectron and dimuon channels) are available at the Durham HepData repository [55].

## 9. Conclusions

The ATLAS detector at LHC is used to search for new resonances with mass larger than 250 GeV decaying into a pair of electrons or muons in  $139 \text{ fb}^{-1}$  of proton–proton collision data at a centre-of-mass energy  $\sqrt{s} = 13$  TeV. A functional form is fitted to the dilepton invariant-mass distribution in data events to model the contribution from background processes. A generic signal shape is used to determine the significance of observed deviations from the background estimate. No significant deviation is observed. Limits are set on the fiducial cross-section times branching ratio to dielectrons and dimuons for generic resonances with a relative natural width in the range of zero to 10%. These limits are shown to be applicable to spin-0, spin-1 and spin-2 signal hypotheses. Limits on the Heavy Vector Triplet model couplings and on the masses of vector resonances are inferred. In particular, the results imply a lower limit of 4.5 (5.1) TeV on  $m_{Z'}$  for the  $Z'_\psi$  ( $Z'_{SSM}$ ) boson at 95% confidence level. These are the most stringent limits to date.



**Fig. 3.** Upper limits at 95% CL on the fiducial cross-section times branching ratio as a function of pole mass for (a) the zero-width, 3%, 10% and (b) 0.5%, 1.2%, 6% relative width signals for the combined dilepton channel. Observed limits are shown as a solid line and expected limits as a dotted/dashed line. Also shown are theoretical cross-sections for (a)  $Z'_{SSM}$  ( $\Gamma/m = 3.0\%$ ) and (b)  $Z'_\chi$  ( $\Gamma/m = 1.2\%$ ) and  $Z'_\psi$  ( $\Gamma/m = 0.5\%$ ) in the fiducial region. The signal theoretical uncertainties are shown as a band on the  $Z'_{SSM}$  theory line and are derived as in Ref. [11]. They are shown for illustration purposes, but are not included in the limit calculation.



**Fig. 4.** Observed 95% exclusion contours in the HVT parameter space (a)  $\{g_h, g_f\}$  with  $g_f \equiv g_e = g_q$  and (b)  $\{g_q, g_\ell\}$  with  $g_h$  set to zero, for resonance masses of 3, 4, and 5 TeV for the dilepton channel. The area outside the curves is excluded.

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## The ATLAS Collaboration

G. Aad<sup>101</sup>, B. Abbott<sup>128</sup>, D.C. Abbott<sup>102</sup>, O. Abidinov<sup>13,\*</sup>, A. Abed Abud<sup>70a,70b</sup>, K. Abeling<sup>53</sup>, D.K. Abhayasinghe<sup>93</sup>, S.H. Abidi<sup>167</sup>, O.S. AbouZeid<sup>40</sup>, N.L. Abraham<sup>156</sup>, H. Abramowicz<sup>161</sup>, H. Abreu<sup>160</sup>, Y. Abulaiti<sup>6</sup>, B.S. Acharya<sup>66a,66b,n</sup>, B. Achkar<sup>53</sup>, S. Adachi<sup>163</sup>, L. Adam<sup>99</sup>, C. Adam Bourdarios<sup>132</sup>, L. Adamczyk<sup>83a</sup>, L. Adamek<sup>167</sup>, J. Adelman<sup>121</sup>, M. Adersberger<sup>114</sup>, A. Adiguzel<sup>12c,ai</sup>, S. Adorni<sup>54</sup>, T. Adye<sup>144</sup>, A.A. Affolder<sup>146</sup>, Y. Afik<sup>160</sup>, C. Agapopoulou<sup>132</sup>, M.N. Agarar<sup>38</sup>, A. Aggarwal<sup>119</sup>, C. Agheorghiesei<sup>27c</sup>, J.A. Aguilar-Saavedra<sup>140f,140a,ah</sup>, F. Ahmadov<sup>79</sup>, W.S. Ahmed<sup>103</sup>, X. Ai<sup>15a</sup>, G. Aielli<sup>73a,73b</sup>, S. Akatsuka<sup>85</sup>, T.P.A. Åkesson<sup>96</sup>, E. Akilli<sup>54</sup>, A.V. Akimov<sup>110</sup>, K. Al Khoury<sup>132</sup>, G.L. Alberghi<sup>23b,23a</sup>, J. Albert<sup>176</sup>, M.J. Alconada Verzini<sup>88</sup>, S. Alderweireldt<sup>119</sup>, M. Aleksa<sup>36</sup>, I.N. Aleksandrov<sup>79</sup>, C. Alexa<sup>27b</sup>, D. Alexandre<sup>19</sup>, T. Alexopoulos<sup>10</sup>, A. Alfonsi<sup>120</sup>, M. Alhroob<sup>128</sup>, B. Ali<sup>142</sup>, G. Alimonti<sup>68a</sup>, J. Alison<sup>37</sup>, S.P. Alkire<sup>148</sup>, C. Allaire<sup>132</sup>, B.M.M. Allbrooke<sup>156</sup>, B.W. Allen<sup>131</sup>, P.P. Allport<sup>21</sup>, A. Aloisio<sup>69a,69b</sup>, A. Alonso<sup>40</sup>, F. Alonso<sup>88</sup>, C. Alpigiani<sup>148</sup>, A.A. Alshehri<sup>57</sup>, M. Alvarez Estevez<sup>98</sup>, B. Alvarez Gonzalez<sup>36</sup>, D. Álvarez Piqueras<sup>174</sup>, M.G. Alvigi<sup>69a,69b</sup>, Y. Amaral Coutinho<sup>80b</sup>, A. Ambler<sup>103</sup>, L. Ambroz<sup>135</sup>, C. Amelung<sup>26</sup>, D. Amidei<sup>105</sup>, S.P. Amor Dos Santos<sup>140a</sup>, S. Amoroso<sup>46</sup>, C.S. Amrouche<sup>54</sup>, F. An<sup>78</sup>, C. Anastopoulos<sup>149</sup>, N. Andari<sup>145</sup>, T. Andeen<sup>11</sup>, C.F. Anders<sup>61b</sup>, J.K. Anders<sup>20</sup>, A. Andreazza<sup>68a,68b</sup>, V. Andrei<sup>61a</sup>, C.R. Anelli<sup>176</sup>, S. Angelidakis<sup>38</sup>, A. Angerami<sup>39</sup>, A.V. Anisenkov<sup>122b,122a</sup>, A. Annovi<sup>71a</sup>, C. Antel<sup>61a</sup>, M.T. Anthony<sup>149</sup>, M. Antonelli<sup>51</sup>, D.J.A. Antrim<sup>171</sup>, F. Anulli<sup>72a</sup>, M. Aoki<sup>81</sup>, J.A. Aparisi Pozo<sup>174</sup>, L. Aperio Bella<sup>36</sup>, G. Arabidze<sup>106</sup>, J.P. Araque<sup>140a</sup>, V. Araujo Ferraz<sup>80b</sup>, R. Araujo Pereira<sup>80b</sup>, C. Arcangeletti<sup>51</sup>, A.T.H. Arce<sup>49</sup>, F.A. Arduh<sup>88</sup>, J-F. Arguin<sup>109</sup>, S. Argyropoulos<sup>77</sup>, J.-H. Arling<sup>46</sup>, A.J. Armbruster<sup>36</sup>, L.J. Armitage<sup>92</sup>, A. Armstrong<sup>171</sup>, O. Arnaez<sup>167</sup>, H. Arnold<sup>120</sup>, A. Artamonov<sup>111,\*</sup>, G. Artoni<sup>135</sup>, S. Artz<sup>99</sup>, S. Asai<sup>163</sup>, N. Asbah<sup>59</sup>, E.M. Asimakopoulou<sup>172</sup>, L. Asquith<sup>156</sup>, K. Assamagan<sup>29</sup>, R. Astalos<sup>28a</sup>, R.J. Atkin<sup>33a</sup>, M. Atkinson<sup>173</sup>, N.B. Atlay<sup>151</sup>, H. Atmani<sup>132</sup>, K. Augsten<sup>142</sup>, G. Avolio<sup>36</sup>, R. Avramidou<sup>60a</sup>, M.K. Ayoub<sup>15a</sup>, A.M. Azoulay<sup>168b</sup>, G. Azuelos<sup>109,ax</sup>, M.J. Baca<sup>21</sup>, H. Bachacou<sup>145</sup>, K. Bachas<sup>67a,67b</sup>, M. Backes<sup>135</sup>, F. Backman<sup>45a,45b</sup>, P. Bagnaia<sup>72a,72b</sup>, M. Bahmani<sup>84</sup>, H. Bahrasemani<sup>152</sup>, A.J. Bailey<sup>174</sup>,



V.R. Bailey<sup>173</sup>, J.T. Baines<sup>144</sup>, M. Bajic<sup>40</sup>, C. Bakalis<sup>10</sup>, O.K. Baker<sup>183</sup>, P.J. Bakker<sup>120</sup>, D. Bakshi Gupta<sup>8</sup>, S. Balaji<sup>157</sup>, E.M. Baldin<sup>122b,122a</sup>, P. Balek<sup>180</sup>, F. Balli<sup>145</sup>, W.K. Balunas<sup>135</sup>, J. Balz<sup>99</sup>, E. Banas<sup>84</sup>, A. Bandyopadhyay<sup>24</sup>, Sw. Banerjee<sup>181,i</sup>, A.A.E. Bannoura<sup>182</sup>, L. Barak<sup>161</sup>, W.M. Barbe<sup>38</sup>, E.L. Barberio<sup>104</sup>, D. Barberis<sup>55b,55a</sup>, M. Barbero<sup>101</sup>, T. Barillari<sup>115</sup>, M-S. Barisits<sup>36</sup>, J. Barkeloo<sup>131</sup>, T. Barklow<sup>153</sup>, R. Barnea<sup>160</sup>, S.L. Barnes<sup>60c</sup>, B.M. Barnett<sup>144</sup>, R.M. Barnett<sup>18</sup>, Z. Barnovska-Blenessy<sup>60a</sup>, A. Baroncelli<sup>60a</sup>, G. Barone<sup>29</sup>, A.J. Barr<sup>135</sup>, L. Barranco Navarro<sup>174</sup>, F. Barreiro<sup>98</sup>, J. Barreiro Guimarães da Costa<sup>15a</sup>, S. Barsov<sup>138</sup>, R. Bartoldus<sup>153</sup>, G. Bartolini<sup>101</sup>, A.E. Barton<sup>89</sup>, P. Bartos<sup>28a</sup>, A. Basalae<sup>46</sup>, A. Bassalat<sup>132,ag</sup>, R.L. Bates<sup>57</sup>, S.J. Batista<sup>167</sup>, S. Batlamous<sup>35e</sup>, J.R. Batley<sup>32</sup>, B. Batool<sup>151</sup>, M. Battaglia<sup>146</sup>, M. Baucé<sup>72a,72b</sup>, F. Bauer<sup>145</sup>, K.T. Bauer<sup>171</sup>, H.S. Bawa<sup>31,l</sup>, J.B. Beacham<sup>49</sup>, T. Beau<sup>136</sup>, P.H. Beauchemin<sup>170</sup>, F. Becherer<sup>52</sup>, P. Bechtel<sup>24</sup>, H.C. Beck<sup>53</sup>, H.P. Beck<sup>20,r</sup>, K. Becker<sup>52</sup>, M. Becker<sup>99</sup>, C. Becot<sup>46</sup>, A. Beddall<sup>12d</sup>, A.J. Beddall<sup>12a</sup>, V.A. Bednyakov<sup>79</sup>, M. Bedognetti<sup>120</sup>, C.P. Bee<sup>155</sup>, T.A. Beermann<sup>76</sup>, M. Begalli<sup>80b</sup>, M. Begel<sup>29</sup>, A. Behera<sup>155</sup>, J.K. Behr<sup>46</sup>, F. Beisiegel<sup>24</sup>, A.S. Bell<sup>94</sup>, G. Bella<sup>161</sup>, L. Bellagamba<sup>23b</sup>, A. Bellerive<sup>34</sup>, P. Bellos<sup>9</sup>, K. Beloborodov<sup>122b,122a</sup>, K. Belotskiy<sup>112</sup>, N.L. Belyaev<sup>112</sup>, D. Bencheekroun<sup>35a</sup>, N. Benekos<sup>10</sup>, Y. Benhammou<sup>161</sup>, D.P. Benjamin<sup>6</sup>, M. Benoit<sup>54</sup>, J.R. Bensinger<sup>26</sup>, S. Bentvelsen<sup>120</sup>, L. Beresford<sup>135</sup>, M. Beretta<sup>51</sup>, D. Berge<sup>46</sup>, E. Bergeaas Kuutmann<sup>172</sup>, N. Berger<sup>5</sup>, B. Bergmann<sup>142</sup>, L.J. Bergsten<sup>26</sup>, J. Beringer<sup>18</sup>, S. Berlendis<sup>7</sup>, N.R. Bernard<sup>102</sup>, G. Bernardi<sup>136</sup>, C. Bernius<sup>153</sup>, F.U. Bernlochner<sup>24</sup>, T. Berry<sup>93</sup>, P. Berta<sup>99</sup>, C. Bertella<sup>15a</sup>, I.A. Bertram<sup>89</sup>, G.J. Besjes<sup>40</sup>, O. Bessidskaia Bylund<sup>182</sup>, N. Besson<sup>145</sup>, A. Bethani<sup>100</sup>, S. Bethke<sup>115</sup>, A. Betti<sup>24</sup>, A.J. Bevan<sup>92</sup>, J. Beyer<sup>115</sup>, R. Bi<sup>139</sup>, R.M. Bianchi<sup>139</sup>, O. Biebel<sup>114</sup>, D. Biedermann<sup>19</sup>, R. Bielski<sup>36</sup>, K. Bierwagen<sup>99</sup>, N.V. Biesuz<sup>71a,71b</sup>, M. Biglietti<sup>74a</sup>, T.R.V. Billoud<sup>109</sup>, M. Bindi<sup>53</sup>, A. Bingul<sup>12d</sup>, C. Bini<sup>72a,72b</sup>, S. Biondi<sup>23b,23a</sup>, M. Birman<sup>180</sup>, T. Bisanz<sup>53</sup>, J.P. Biswal<sup>161</sup>, A. Bitadze<sup>100</sup>, C. Bittrich<sup>48</sup>, K. Björke<sup>134</sup>, K.M. Black<sup>25</sup>, T. Blazek<sup>28a</sup>, I. Bloch<sup>46</sup>, C. Blocker<sup>26</sup>, A. Blue<sup>57</sup>, U. Blumenschein<sup>92</sup>, G.J. Bobbink<sup>120</sup>, V.S. Bobrovnikov<sup>122b,122a</sup>, S.S. Bocchetta<sup>96</sup>, A. Bocci<sup>49</sup>, D. Boerner<sup>46</sup>, D. Bogavac<sup>14</sup>, A.G. Bogdanchikov<sup>122b,122a</sup>, C. Böhm<sup>45a</sup>, V. Boisvert<sup>93</sup>, P. Bokan<sup>53,172</sup>, T. Bold<sup>83a</sup>, A.S. Boldyrev<sup>113</sup>, A.E. Bolz<sup>61b</sup>, M. Bomben<sup>136</sup>, M. Bona<sup>92</sup>, J.S. Bonilla<sup>131</sup>, M. Boonekamp<sup>145</sup>, H.M. Borecka-Bielska<sup>90</sup>, A. Borisov<sup>123</sup>, G. Borissov<sup>89</sup>, J. Bortfeldt<sup>36</sup>, D. Bortoletto<sup>135</sup>, V. Bortolotto<sup>73a,73b</sup>, D. Boscherini<sup>23b</sup>, M. Bosman<sup>14</sup>, J.D. Bossio Sola<sup>103</sup>, K. Bouaouda<sup>35a</sup>, J. Boudreau<sup>139</sup>, E.V. Bouhova-Thacker<sup>89</sup>, D. Boumediene<sup>38</sup>, S.K. Boutle<sup>57</sup>, A. Boveia<sup>126</sup>, J. Boyd<sup>36</sup>, D. Boye<sup>33b,ar</sup>, I.R. Boyko<sup>79</sup>, A.J. Bozson<sup>93</sup>, J. Bracinik<sup>21</sup>, N. Brahimi<sup>101</sup>, G. Brandt<sup>182</sup>, O. Brandt<sup>61a</sup>, F. Braren<sup>46</sup>, U. Bratzler<sup>164</sup>, B. Brau<sup>102</sup>, J.E. Brau<sup>131</sup>, W.D. Breaden Madden<sup>57</sup>, K. Brendlinger<sup>46</sup>, L. Brenner<sup>46</sup>, R. Brenner<sup>172</sup>, S. Bressler<sup>180</sup>, B. Brickwedde<sup>99</sup>, D.L. Briglin<sup>21</sup>, D. Britton<sup>57</sup>, D. Britzger<sup>115</sup>, I. Brock<sup>24</sup>, R. Brock<sup>106</sup>, G. Brooijmans<sup>39</sup>, W.K. Brooks<sup>147b</sup>, E. Brost<sup>121</sup>, J.H. Broughton<sup>21</sup>, P.A. Bruckman de Renstrom<sup>84</sup>, D. Bruncko<sup>28b</sup>, A. Bruni<sup>23b</sup>, G. Bruni<sup>23b</sup>, L.S. Bruni<sup>120</sup>, S. Bruno<sup>73a,73b</sup>, B.H. Brunt<sup>32</sup>, M. Bruschi<sup>23b</sup>, N. Bruscino<sup>139</sup>, P. Bryant<sup>37</sup>, L. Bryngemark<sup>96</sup>, T. Buanes<sup>17</sup>, Q. Buat<sup>36</sup>, P. Buchholz<sup>151</sup>, A.G. Buckley<sup>57</sup>, I.A. Budagov<sup>79</sup>, M.K. Bugge<sup>134</sup>, F. Bühner<sup>52</sup>, O. Bulekov<sup>112</sup>, T.J. Burch<sup>121</sup>, S. Burdin<sup>90</sup>, C.D. Burgard<sup>120</sup>, A.M. Burger<sup>129</sup>, B. Burghgrave<sup>8</sup>, K. Burka<sup>84</sup>, J.T.P. Burr<sup>46</sup>, V. Büscher<sup>99</sup>, E. Buschmann<sup>53</sup>, P.J. Bussey<sup>57</sup>, J.M. Butler<sup>25</sup>, C.M. Buttar<sup>57</sup>, J.M. Butterworth<sup>94</sup>, P. Butti<sup>36</sup>, W. Buttinger<sup>36</sup>, A. Buzatu<sup>158</sup>, A.R. Buzykaev<sup>122b,122a</sup>, G. Cabras<sup>23b,23a</sup>, S. Cabrera Urbán<sup>174</sup>, D. Caforio<sup>56</sup>, H. Cai<sup>173</sup>, V.M.M. Cairo<sup>153</sup>, O. Cakir<sup>4a</sup>, N. Calace<sup>36</sup>, P. Calafiura<sup>18</sup>, A. Calandri<sup>101</sup>, G. Calderini<sup>136</sup>, P. Calfayan<sup>65</sup>, G. Callea<sup>57</sup>, L.P. Caloba<sup>80b</sup>, S. Calvente Lopez<sup>98</sup>, D. Calvet<sup>38</sup>, S. Calvet<sup>38</sup>, T.P. Calvet<sup>155</sup>, M. Calvetti<sup>71a,71b</sup>, R. Camacho Toro<sup>136</sup>, S. Camarda<sup>36</sup>, D. Camarero Munoz<sup>98</sup>, P. Camarri<sup>73a,73b</sup>, D. Cameron<sup>134</sup>, R. Caminal Armadans<sup>102</sup>, C. Camincher<sup>36</sup>, S. Campana<sup>36</sup>, M. Campanelli<sup>94</sup>, A. Camplani<sup>40</sup>, A. Campoverde<sup>151</sup>, V. Canale<sup>69a,69b</sup>, A. Canesse<sup>103</sup>, M. Cano Bret<sup>60c</sup>, J. Cantero<sup>129</sup>, T. Cao<sup>161</sup>, Y. Cao<sup>173</sup>, M.D.M. Capeans Garrido<sup>36</sup>, M. Capua<sup>41b,41a</sup>, R. Cardarelli<sup>73a</sup>, F.C. Cardillo<sup>149</sup>, I. Carli<sup>143</sup>, T. Carli<sup>36</sup>, G. Carlino<sup>69a</sup>, B.T. Carlson<sup>139</sup>, L. Carminati<sup>68a,68b</sup>, R.M.D. Carney<sup>45a,45b</sup>, S. Caron<sup>119</sup>, E. Carquin<sup>147b</sup>, S. Carrá<sup>68a,68b</sup>, J.W.S. Carter<sup>167</sup>, M.P. Casado<sup>14,e</sup>, A.F. Casha<sup>167</sup>, D.W. Casper<sup>171</sup>, R. Castelijin<sup>120</sup>, F.L. Castillo<sup>174</sup>, V. Castillo Gimenez<sup>174</sup>, N.F. Castro<sup>140a,140e</sup>, A. Catinaccio<sup>36</sup>, J.R. Catmore<sup>134</sup>, A. Cattai<sup>36</sup>, J. Caudron<sup>24</sup>, V. Cavaliere<sup>29</sup>, E. Cavallaro<sup>14</sup>, D. Cavalli<sup>68a</sup>, M. Cavalli-Sforza<sup>14</sup>, V. Cavasinni<sup>71a,71b</sup>, E. Celebi<sup>12b</sup>, F. Ceradini<sup>74a,74b</sup>, L. Cerda Alberich<sup>174</sup>, K. Cerny<sup>130</sup>, A.S. Cerqueira<sup>80a</sup>, A. Cerri<sup>156</sup>, L. Cerrito<sup>73a,73b</sup>, F. Cerutti<sup>18</sup>, A. Cervelli<sup>23b,23a</sup>, S.A. Cetin<sup>12b</sup>, D. Chakraborty<sup>121</sup>, S.K. Chan<sup>59</sup>, W.S. Chan<sup>120</sup>, W.Y. Chan<sup>90</sup>, J.D. Chapman<sup>32</sup>, B. Chargeishvili<sup>159b</sup>, D.G. Charlton<sup>21</sup>, T.P. Charman<sup>92</sup>, C.C. Chau<sup>34</sup>, S. Che<sup>126</sup>, A. Chegwidden<sup>106</sup>, S. Chekanov<sup>6</sup>, S.V. Chekulaev<sup>168a</sup>, G.A. Chelkov<sup>79,aw</sup>, M.A. Chelstowska<sup>36</sup>, B. Chen<sup>78</sup>,

C. Chen <sup>60a</sup>, C.H. Chen <sup>78</sup>, H. Chen <sup>29</sup>, J. Chen <sup>60a</sup>, J. Chen <sup>39</sup>, S. Chen <sup>137</sup>, S.J. Chen <sup>15c</sup>, X. Chen <sup>15b,av</sup>, Y. Chen <sup>82</sup>, Y.-H. Chen <sup>46</sup>, H.C. Cheng <sup>63a</sup>, H.J. Cheng <sup>15a,15d</sup>, A. Cheplakov <sup>79</sup>, E. Cheremushkina <sup>123</sup>, R. Cherkaoui El Moursli <sup>35e</sup>, E. Cheu <sup>7</sup>, K. Cheung <sup>64</sup>, T.J.A. Chevaléras <sup>145</sup>, L. Chevalier <sup>145</sup>, V. Chiarella <sup>51</sup>, G. Chiarelli <sup>71a</sup>, G. Chiodini <sup>67a</sup>, A.S. Chisholm <sup>36,21</sup>, A. Chitan <sup>27b</sup>, I. Chiu <sup>163</sup>, Y.H. Chiu <sup>176</sup>, M.V. Chizhov <sup>79</sup>, K. Choi <sup>65</sup>, A.R. Chomont <sup>72a,72b</sup>, S. Chouridou <sup>162</sup>, Y.S. Chow <sup>120</sup>, M.C. Chu <sup>63a</sup>, J. Chudoba <sup>141</sup>, A.J. Chuinard <sup>103</sup>, J.J. Chwastowski <sup>84</sup>, L. Chytka <sup>130</sup>, K.M. Ciesla <sup>84</sup>, D. Cinca <sup>47</sup>, V. Cindro <sup>91</sup>, I.A. Cioară <sup>27b</sup>, A. Ciocio <sup>18</sup>, F. Ciotto <sup>69a,69b</sup>, Z.H. Citron <sup>180</sup>, M. Citterio <sup>68a</sup>, D.A. Ciubotaru <sup>27b</sup>, B.M. Ciungu <sup>167</sup>, A. Clark <sup>54</sup>, M.R. Clark <sup>39</sup>, P.J. Clark <sup>50</sup>, C. Clement <sup>45a,45b</sup>, Y. Coadou <sup>101</sup>, M. Cobal <sup>66a,66c</sup>, A. Coccaro <sup>55b</sup>, J. Cochran <sup>78</sup>, H. Cohen <sup>161</sup>, A.E.C. Coimbra <sup>36</sup>, L. Colasurdo <sup>119</sup>, B. Cole <sup>39</sup>, A.P. Colijn <sup>120</sup>, J. Collot <sup>58</sup>, P. Conde Muñio <sup>140a,f</sup>, E. Coniavitis <sup>52</sup>, S.H. Connell <sup>33b</sup>, I.A. Connelly <sup>57</sup>, S. Constantinescu <sup>27b</sup>, F. Conventi <sup>69a,ay</sup>, A.M. Cooper-Sarkar <sup>135</sup>, F. Cormier <sup>175</sup>, K.J.R. Cormier <sup>167</sup>, L.D. Corpe <sup>94</sup>, M. Corradi <sup>72a,72b</sup>, E.E. 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M. Weirich<sup>99</sup>, C. Weiser<sup>52</sup>, P.S. Wells<sup>36</sup>, T. Wenaus<sup>29</sup>, T. Wengler<sup>36</sup>, S. Wenig<sup>36</sup>, N. Wermes<sup>24</sup>, M.D. Werner<sup>78</sup>, P. Werner<sup>36</sup>, M. Wessels<sup>61a</sup>, T.D. Weston<sup>20</sup>, K. Whalen<sup>131</sup>, N.L. Whallon<sup>148</sup>, A.M. Wharton<sup>89</sup>, A.S. White<sup>105</sup>, A. White<sup>8</sup>, M.J. White<sup>1</sup>, D. Whiteson<sup>171</sup>, B.W. Whitmore<sup>89</sup>, F.J. Wickens<sup>144</sup>, W. Wiedenmann<sup>181</sup>, M. Wielers<sup>144</sup>, N. Wieseotte<sup>99</sup>, C. Wigglesworth<sup>40</sup>, L.A.M. Wiik-Fuchs<sup>52</sup>, F. Wilk<sup>100</sup>, H.G. Wilkens<sup>36</sup>, L.J. Wilkins<sup>93</sup>, H.H. Williams<sup>137</sup>, S. Williams<sup>32</sup>, C. Willis<sup>106</sup>, S. Willocq<sup>102</sup>, J.A. Wilson<sup>21</sup>, I. Wingerter-Seez<sup>5</sup>, E. Winkels<sup>156</sup>, F. Winklmeier<sup>131</sup>, O.J. Winston<sup>156</sup>, B.T. Winter<sup>52</sup>, M. Wittgen<sup>153</sup>, M. Wobisch<sup>95</sup>, A. Wolf<sup>99</sup>, T.M.H. Wolf<sup>120</sup>, R. Wolff<sup>101</sup>, R.W. Wölker<sup>135</sup>, J. Wollrath<sup>52</sup>, M.W. Wolter<sup>84</sup>, H. Wolters<sup>140a,140c</sup>, V.W.S. Wong<sup>175</sup>, N.L. Woods<sup>146</sup>, S.D. Worm<sup>21</sup>, B.K. Wosiek<sup>84</sup>, K.W. Woźniak<sup>84</sup>, K. Wraight<sup>57</sup>, S.L. Wu<sup>181</sup>, X. Wu<sup>54</sup>, Y. Wu<sup>60a</sup>, T.R. Wyatt<sup>100</sup>, B.M. Wynne<sup>50</sup>, S. Xella<sup>40</sup>, Z. Xi<sup>105</sup>, L. Xia<sup>178</sup>, D. Xu<sup>15a</sup>, H. Xu<sup>60a,c</sup>, L. Xu<sup>29</sup>, T. Xu<sup>145</sup>, W. Xu<sup>105</sup>, Z. Xu<sup>60b</sup>, Z. Xu<sup>153</sup>, B. Yabsley<sup>157</sup>, S. Yacoob<sup>33a</sup>, K. Yajima<sup>133</sup>, D.P. Yallup<sup>94</sup>, D. Yamaguchi<sup>165</sup>, Y. Yamaguchi<sup>165</sup>, A. Yamamoto<sup>81</sup>, T. Yamanaka<sup>163</sup>, F. Yamane<sup>82</sup>, M. Yamatani<sup>163</sup>, T. Yamazaki<sup>163</sup>, Y. Yamazaki<sup>82</sup>, Z. Yan<sup>25</sup>, H.J. Yang<sup>60c,60d</sup>, H.T. Yang<sup>18</sup>, S. Yang<sup>77</sup>, X. Yang<sup>60b,58</sup>, Y. Yang<sup>163</sup>, W.-M. Yao<sup>18</sup>, Y.C. Yap<sup>46</sup>, Y. Yasu<sup>81</sup>, E. Yatsenko<sup>60c,60d</sup>, J. Ye<sup>42</sup>, S. Ye<sup>29</sup>, I. Yeletsikh<sup>79</sup>, M.R. Yexley<sup>89</sup>, E. Yigitbasi<sup>25</sup>, E. Yildirim<sup>99</sup>, K. Yorita<sup>179</sup>, K. Yoshihara<sup>137</sup>, C.J.S. Young<sup>36</sup>, C. Young<sup>153</sup>, J. Yu<sup>78</sup>, R. Yuan<sup>60b</sup>, X. Yue<sup>61a</sup>, S.P.Y. Yuen<sup>24</sup>, B. Zabinski<sup>84</sup>, G. Zacharis<sup>10</sup>, E. Zaffaroni<sup>54</sup>, J. Zahreddine<sup>136</sup>, A.M. Zaitsev<sup>123,ao</sup>, T. Zakareishvili<sup>159b</sup>, N. Zakharchuk<sup>34</sup>, S. Zambito<sup>59</sup>, D. Zanzi<sup>36</sup>, D.R. Zaripovas<sup>57</sup>, S.V. Zeiβner<sup>47</sup>, C. Zeitnitz<sup>182</sup>, G. Zemaityte<sup>135</sup>, J.C. Zeng<sup>173</sup>, O. Zenin<sup>123</sup>, D. Zerwas<sup>132</sup>, M. Zgubič<sup>135</sup>, D.F. Zhang<sup>15b</sup>, F. Zhang<sup>181</sup>, G. Zhang<sup>60a</sup>, G. Zhang<sup>15b</sup>, H. Zhang<sup>15c</sup>, J. Zhang<sup>6</sup>, L. Zhang<sup>15c</sup>, L. Zhang<sup>60a</sup>, M. Zhang<sup>173</sup>, R. Zhang<sup>60a</sup>, R. Zhang<sup>24</sup>, X. Zhang<sup>60b</sup>, Y. Zhang<sup>15a,15d</sup>, Z. Zhang<sup>63a</sup>, Z. Zhang<sup>132</sup>, P. Zhao<sup>49</sup>, Y. Zhao<sup>60b</sup>, Z. Zhao<sup>60a</sup>, A. Zhemchugov<sup>79</sup>, Z. Zheng<sup>105</sup>, D. Zhong<sup>173</sup>, B. Zhou<sup>105</sup>, C. Zhou<sup>181</sup>, M.S. Zhou<sup>15a,15d</sup>, M. Zhou<sup>155</sup>, N. Zhou<sup>60c</sup>, Y. Zhou<sup>7</sup>, C.G. Zhu<sup>60b</sup>, H.L. Zhu<sup>60a</sup>, H. Zhu<sup>15a</sup>, J. Zhu<sup>105</sup>, Y. Zhu<sup>60a</sup>, X. Zhuang<sup>15a</sup>, K. Zhukov<sup>110</sup>, V. Zhulanov<sup>122b,122a</sup>, D. Zieminska<sup>65</sup>, N.I. Zimine<sup>79</sup>, S. Zimmermann<sup>52</sup>, Z. Zinonos<sup>115</sup>, M. Ziolkowski<sup>151</sup>, G. Zobernig<sup>181</sup>, A. Zoccoli<sup>23b,23a</sup>, K. Zoch<sup>53</sup>, T.G. Zorbas<sup>149</sup>, R. Zou<sup>37</sup>, L. Zwalinski<sup>36</sup>

<sup>1</sup> Department of Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup> Physics Department, SUNY Albany, Albany, NY, United States of America

<sup>3</sup> Department of Physics, University of Alberta, Edmonton, AB, Canada

<sup>4</sup> (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

<sup>5</sup> LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France

<sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States of America

<sup>7</sup> Department of Physics, University of Arizona, Tucson, AZ, United States of America

<sup>8</sup> Department of Physics, University of Texas at Arlington, Arlington, TX, United States of America

<sup>9</sup> Physics Department, National and Kapodistrian University of Athens, Athens, Greece

<sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece

<sup>11</sup> Department of Physics, University of Texas at Austin, Austin, TX, United States of America

<sup>12</sup> (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

<sup>13</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>14</sup> Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain

<sup>15</sup> (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

<sup>16</sup> Institute of Physics, University of Belgrade, Belgrade, Serbia

<sup>17</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway

<sup>18</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States of America

<sup>19</sup> Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany

<sup>20</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

<sup>21</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

<sup>22</sup> Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia

<sup>23</sup> (a) INFN Bologna and Università di Bologna, Dipartimento di Fisica; (b) INFN Sezione di Bologna, Italy

<sup>24</sup> Physikalisches Institut, Universität Bonn, Bonn, Germany

<sup>25</sup> Department of Physics, Boston University, Boston, MA, United States of America

<sup>26</sup> Department of Physics, Brandeis University, Waltham, MA, United States of America

<sup>27</sup> (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

<sup>28</sup> (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

<sup>29</sup> Physics Department, Brookhaven National Laboratory, Upton, NY, United States of America

<sup>30</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

<sup>31</sup> California State University, CA, United States of America

<sup>32</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

<sup>33</sup> (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

<sup>34</sup> Department of Physics, Carleton University, Ottawa, ON, Canada

- 35 <sup>(a)</sup> *Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca*; <sup>(b)</sup> *Faculté des Sciences, Université Ibn-Tofail, Kénitra*;  
<sup>(c)</sup> *Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech*; <sup>(d)</sup> *Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda*; <sup>(e)</sup> *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 <sup>(a)</sup> *Dipartimento di Fisica, Università della Calabria, Rende*; <sup>(b)</sup> *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 <sup>(a)</sup> *Department of Physics, Stockholm University*; <sup>(b)</sup> *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 <sup>(a)</sup> *Dipartimento di Fisica, Università di Genova, Genova*; <sup>(b)</sup> *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 <sup>(a)</sup> *Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei*; <sup>(b)</sup> *Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao*; <sup>(c)</sup> *School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai*; <sup>(d)</sup> *Tsung-Dao Lee Institute, Shanghai, China*
- 61 <sup>(a)</sup> *Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg*; <sup>(b)</sup> *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- 62 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- 63 <sup>(a)</sup> *Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong*; <sup>(b)</sup> *Department of Physics, University of Hong Kong, Hong Kong*; <sup>(c)</sup> *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 <sup>(a)</sup> *INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine*; <sup>(b)</sup> *ICTP, Trieste*; <sup>(c)</sup> *Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
- 67 <sup>(a)</sup> *INFN Sezione di Lecce*; <sup>(b)</sup> *Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- 68 <sup>(a)</sup> *INFN Sezione di Milano*; <sup>(b)</sup> *Dipartimento di Fisica, Università di Milano, Milano, Italy*
- 69 <sup>(a)</sup> *INFN Sezione di Napoli*; <sup>(b)</sup> *Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
- 70 <sup>(a)</sup> *INFN Sezione di Pavia*; <sup>(b)</sup> *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- 71 <sup>(a)</sup> *INFN Sezione di Pisa*; <sup>(b)</sup> *Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- 72 <sup>(a)</sup> *INFN Sezione di Roma*; <sup>(b)</sup> *Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
- 73 <sup>(a)</sup> *INFN Sezione di Roma Tor Vergata*; <sup>(b)</sup> *Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- 74 <sup>(a)</sup> *INFN Sezione di Roma Tre*; <sup>(b)</sup> *Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- 75 <sup>(a)</sup> *INFN-TIFPA*; <sup>(b)</sup> *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 <sup>(a)</sup> *Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora*; <sup>(b)</sup> *Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro*;  
<sup>(c)</sup> *Universidade Federal de São João del Rei (UFSJ), São João del Rei*; <sup>(d)</sup> *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 <sup>(a)</sup> *AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow*; <sup>(b)</sup> *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 and Experimental Physics of the National Research Centre Kurchatov Institute, Moscow, Russia
- 112 National Research Nuclear University MEPhI, Moscow, Russia
- 113 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- 114 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 115 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- 116 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 117 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- 118 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States of America
- 119 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- 120 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- 121 Department of Physics, Northern Illinois University, DeKalb, IL, United States of America
- 122 <sup>(a)</sup> Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk; <sup>(b)</sup> Novosibirsk State University Novosibirsk, Russia
- 123 Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia
- 124 Department of Physics, New York University, New York, NY, United States of America
- 125 Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
- 126 Ohio State University, Columbus, OH, United States of America
- 127 Faculty of Science, Okayama University, Okayama, Japan
- 128 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States of America
- 129 Department of Physics, Oklahoma State University, Stillwater, OK, United States of America
- 130 Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
- 131 Center for High Energy Physics, University of Oregon, Eugene, OR, United States of America
- 132 LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- 133 Graduate School of Science, Osaka University, Osaka, Japan
- 134 Department of Physics, University of Oslo, Oslo, Norway
- 135 Department of Physics, Oxford University, Oxford, United Kingdom
- 136 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
- 137 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States of America
- 138 Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg, Russia
- 139 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States of America
- 140 <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas – LIP; <sup>(b)</sup> Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Departamento de Física, Universidade de Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Universidad de Granada, Granada (Spain); <sup>(g)</sup> 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 <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> 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 <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> 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 <sup>(a)</sup> TRIUMF, Vancouver, BC; <sup>(b)</sup> 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

<sup>184</sup> Yerevan Physics Institute, Yerevan, Armenia

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