



# Measurement of the $W$ -boson mass and width with the ATLAS detector using proton–proton collisions at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration

Proton–proton data recorded by the ATLAS detector in 2011, at a centre-of-mass energy of 7 TeV, have been used for an improved determination of the  $W$ -boson mass and a first measurement of the  $W$ -boson width at the LHC. Recent fits to the proton parton distribution functions are incorporated in the measurement procedure and an improved statistical method is used to increase the measurement precision. The measurement of the  $W$ -boson mass yields a value of  $m_W = 80366.5 \pm 9.8$  (stat.)  $\pm 12.5$  (syst.) MeV =  $80366.5 \pm 15.9$  MeV, and the width is measured as  $\Gamma_W = 2202 \pm 32$  (stat.)  $\pm 34$  (syst.) MeV =  $2202 \pm 47$  MeV. The first uncertainty components are statistical and the second correspond to the experimental and physics-modelling systematic uncertainties. Both results are consistent with the expectation from fits to electroweak precision data. The present measurement of  $m_W$  is compatible with and supersedes the previous measurement performed using the same data.

# Contents

<b>1</b>	<b>Introduction</b>	<b>2</b>
<b>2</b>	<b>ATLAS detector</b>	<b>3</b>
<b>3</b>	<b>Measurement overview and analysis strategy</b>	<b>4</b>
3.1	Data samples and event simulation	4
3.2	Selection of electrons and muons and reconstruction of the recoil	5
3.3	$W$ -boson kinematics and event selection	5
3.4	$W$ -boson mass analysis updates	6
3.5	Statistical analysis	7
<b>4</b>	<b>Experimental corrections and uncertainties</b>	<b>9</b>
4.1	Uncertainty propagation	9
4.2	Sources of uncertainty	9
<b>5</b>	<b>Physics corrections and uncertainties</b>	<b>10</b>
5.1	Electroweak uncertainties	10
5.2	QCD model and uncertainties	10
<b>6</b>	<b>Improved measurement of the <math>W</math>-boson mass</b>	<b>11</b>
6.1	Results with CT10nnlo and consistency tests	11
6.2	Impact of updated parton distribution functions	12
6.3	Results and discussion	15
6.4	Combination	20
<b>7</b>	<b>Measurement of the <math>W</math>-boson width</b>	<b>21</b>
7.1	Overview	21
7.2	Results and discussion	22
7.3	Combination	24
<b>8</b>	<b>Simultaneous determination of the <math>W</math>-boson mass and width</b>	<b>26</b>
<b>9</b>	<b>Conclusion</b>	<b>27</b>

## 1 Introduction

At lowest order in the Standard Model (SM) electroweak theory [1–3] the  $W$ -boson mass,  $m_W$ , can be expressed solely as a function of the  $Z$ -boson mass,  $m_Z$ , the fine-structure constant,  $\alpha$ , and the Fermi constant,  $G_F$ . Higher-order corrections introduce an additional dependence of the  $W$ -boson mass on the gauge couplings and the masses of the heavy particles of the SM, such as the top-quark mass,  $m_t$ , and the Higgs boson mass,  $m_H$  [4, 5]. In extended theories, the loop corrections receive contributions from additional particles and interactions. The consistency of the SM and potential effects of new physics can therefore be probed by comparing the measured values of  $m_W$  with the results of global fits to the relevant physical parameters [6–8]. The SM fit yields  $m_W^{\text{SM}} = 80355 \pm 6$  MeV [6, 7]. The present

experimental situation is characterised by a significant tension between the precise measurement from the CDF Collaboration,  $m_W = 80433.5 \pm 9.4$  MeV [9], and the average of the LEP [10], D0 [11], ATLAS [12] and LHCb [13] measurements,  $m_W = 80369.2 \pm 13.3$  MeV [14].

The electroweak theory also predicts the total decay width of the  $W$  boson,  $\Gamma_W$ . It is expected to be equal to the sum of the partial widths over three generations of lepton doublets and two generations of quark doublets, yielding an expected value of  $\Gamma_W^{\text{SM}} = 2088 \pm 1$  MeV [6]. New particle candidates that couple to the  $W$  boson and are lighter than  $m_W$  would open a new decay channel and alter  $\Gamma_W$  [15]. Examples are supersymmetric models in which the  $W$  boson decays into the lightest super-partner of the charged gauge bosons and the lightest super-partner of the neutral gauge bosons [16]. The current world average of  $W$ -boson width determinations yields a value of  $\Gamma_W = 2085 \pm 42$  MeV [17], and is based on measurements at LEP-2 [10] and the Tevatron [18, 19]. No measurement of  $\Gamma_W$  has been previously performed at the Large Hadron Collider (LHC).

In this paper, an improved measurement of the  $W$ -boson mass as well as a first measurement of its width is presented, which is based on data from  $\sqrt{s} = 7$  TeV recorded by the ATLAS detector in 2011, i.e., the same data as was used for the first measurement of  $m_W$  at the LHC [12]. This was based on a  $\chi^2$  considering statistical uncertainties only, where systematic uncertainties were included a posteriori through variations of the physics and calibration models within their uncertainties (the so-called ‘offset’ method).

The present analysis uses an improved statistic based on the profile likelihood (PLH) [20]. This technique performs a simultaneous determination of  $m_W$  together with a set of nuisance parameters describing the experimental and modelling uncertainties. The nuisance parameters are adjusted to optimally describe the data, yielding an overall improved model and some reduction in uncertainty compared with the fitting technique used previously. With few sub-dominant exceptions, the sources of uncertainty considered in this measurement are either of experimental nature, or phenomenological, with model parameters derived from the data. A nuisance parameter representation is therefore adequate and the PLH technique can be applied. The measurement of  $\Gamma_W$  relies on the same PLH statistic and on the same physics, detector and background model as those used for the determination of  $m_W$ .

Recent parton distribution functions (PDFs) are studied within this work, and the dependence of the measurement results on the assumed PDF set is presented and discussed. The present analysis also aims at consolidating the earlier result of ATLAS, in the perspective of the latest measurement by CDF.

## 2 ATLAS detector

The ATLAS experiment [21] is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroid magnets<sup>1</sup>.

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range of  $|\eta| < 2.5$ . At small radii, a high-granularity silicon pixel detector covers the vertex

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

region and typically provides three measurements per track. It is followed by the silicon microstrip tracker, which usually provides eight measurement points per track. These silicon detectors are complemented by a gas-filled straw-tube transition radiation tracker, which enables radially extended track reconstruction within  $|\eta| = 2.0$ . The transition radiation tracker also provides electron identification information based on the fraction of hits (typically 35 in total) above a higher energy-deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range  $|\eta| < 4.9$ . Within the region  $|\eta| < 3.2$ , electromagnetic (EM) calorimetry is provided by high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering  $|\eta| < 1.8$  to correct for upstream energy-loss fluctuations. The EM calorimeter is divided into a barrel section covering  $|\eta| < 1.475$  and two endcap sections covering  $1.375 < |\eta| < 3.2$ . For  $|\eta| < 2.5$ , it is divided into three layers in depth, which are finely segmented in  $\eta$  and  $\phi$ . Hadronic calorimetry is provided by a steel/scintillator-tile calorimeter, segmented into three barrel structures within  $|\eta| = 1.7$  and two copper/LAr hadronic endcap calorimeters covering  $1.5 < |\eta| < 3.2$ . The solid-angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules in  $3.1 < |\eta| < 4.9$ , optimised for electromagnetic and hadronic measurements, respectively.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by superconducting air-core toroids. The precision chamber system covers the region  $|\eta| < 2.7$  with three layers of monitored drift tubes, complemented by cathode strip chambers in the forward region. The muon trigger system covers the range  $|\eta| < 2.4$  with resistive plate chambers in the barrel, and thin gap chambers in the endcap regions.

A three-level trigger system is used to select events for offline analysis [22]. The level-1 trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to a design value of at most 75 kHz. This is followed by two software-based trigger levels that together reduce the event rate to about 300 Hz. A software suite [23] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

## 3 Measurement overview and analysis strategy

### 3.1 Data samples and event simulation

The data sample consists of  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  candidate events, collected in 2011 with the ATLAS detector in proton–proton collisions at the LHC, at a centre-of-mass energy of  $\sqrt{s} = 7$  TeV. The data collected with all relevant detector systems operational correspond to approximately  $4.6 \text{ fb}^{-1}$  and  $4.1 \text{ fb}^{-1}$  of integrated luminosity in the electron and muon channels, respectively.

The POWHEG Monte Carlo (MC) generator (v1/r1556) [24–26] is used for the simulation of  $W$ - and  $Z$ -boson production and decay in the electron, muon, and  $\tau$ -lepton channels, and is interfaced to PYTHIA 8 (v8.170) for the modelling of the parton shower, hadronisation, and underlying event [27, 28]. Parton shower and underlying event parameters are set according to the AZNLO tune [29]. The CT10 PDF set [30] is used for the hard process, and the CTEQ6L1 PDF set [31] is used in the parton shower. The  $Z$ -boson simulation includes the effect of virtual photon exchange. The  $W$ - and  $Z$ -boson rapidity and  $p_T$  distributions are reweighted to optimise the description of the data, as described in Section 5.2. The change in the final-state distributions from updating the distributions to more recent PDFs is evaluated using POWHEG.

QED final-state radiation (FSR) is simulated using PHOTOS (v2.154) [32]. Decays of  $\tau$ -leptons are handled by PYTHIA 8, taking into account polarisation effects. The  $W$ - and  $Z$ -boson event yields are normalised according to their measured cross sections, and the experimental uncertainties of 1.8% and 2.3% are assigned to the  $W^+/Z$  and  $W^-/Z$  production cross-section ratios, respectively [33]. The  $W$ -boson production samples assume  $m_W = 80399$  MeV and  $\Gamma_W = 2085$  MeV.

Background processes such as top-quark pair and single-top-quark production are modelled using the MC@NLO MC generator (v4.01) [34–36], interfaced to HERWIG and JIMMY for the parton shower. Gauge-boson pair production ( $WW$ ,  $WZ$ ,  $ZZ$ ) is simulated with HERWIG (v6.520). The CT10 PDF set is used in all these samples.

The response of the ATLAS detector is simulated using a software suite [37] based on GEANT4 [38]. The hard-scattering process is overlaid with additional proton–proton interactions, simulated with PYTHIA 8 (v8.165) using the A2 tune [39]. The distribution of the average number of interactions per bunch crossing  $\langle\mu\rangle$  spans the range 2.5–16.0, with a mean value of approximately 9.0.

### 3.2 Selection of electrons and muons and reconstruction of the recoil

Object definitions are unchanged compared to Ref. [12]. Electron candidates are reconstructed from clusters of energy deposited in the electromagnetic calorimeter and associated with at least one track in the ID [40, 41]. Quality requirements are applied to the associated tracks in order to reject poorly reconstructed charged-particle trajectories. The energy of the electron is reconstructed from the energy collected in calorimeter cells within an area of size  $\Delta\eta \times \Delta\phi = 0.075 \times 0.175$  in the barrel, and  $0.125 \times 0.125$  in the endcaps. The energy measurement relies on a multivariate regression algorithm developed and optimised on simulated events. The kinematic properties of the reconstructed electron are inferred from the energy measured in the EM calorimeter and from the pseudorapidity and azimuth of the associated track. Electron candidates are required to fulfil tight identification requirements [40], and their transverse momentum,  $p_T^\ell$ , and pseudorapidity should satisfy  $p_T^\ell > 15$  GeV and  $|\eta| < 2.4$ . As in the previous result, the pseudorapidity range  $1.2 < |\eta| < 1.8$  is excluded from the measurement. Background from jets misidentified as electrons is reduced using additional isolation requirements using the activity in the ID and calorimeter nearby the electron candidates passing the kinematic and identification selections [12].

Muon candidates are reconstructed independently in the ID and in the MS, and a combined muon candidate is formed from the statistical combination of the ID and MS track parameters [42]. The kinematic properties of the reconstructed muon are defined using the ID track parameters alone, which allows a simpler calibration procedure. Muon candidates are required to have  $p_T^\ell > 20$  GeV and  $|\eta| < 2.4$  [12]. Similarly to the electrons, the multijet background is reduced by applying an isolation requirement [12].

The recoil,  $\vec{u}_T$ , is an estimator of the  $W$ - or  $Z$ -boson transverse momentum. It is reconstructed from the vector sum of the transverse energy of all clusters measured in the calorimeters, excluding clusters located at a distance  $\Delta R < 0.2$  from electron or muon candidates. The definition of  $\vec{u}_T$  does not involve the explicit reconstruction of jets to avoid possible  $p_T$  threshold effects.

### 3.3 $W$ -boson kinematics and event selection

The transverse momentum vector of charged leptons from the  $W$ -boson decay,  $\vec{p}_T^\ell$ , is measured as summarised in the previous section. The transverse momentum of the decay neutrino is inferred

from the missing transverse momentum vector,  $\vec{p}_T^{\text{miss}}$ , defined as  $\vec{p}_T^{\text{miss}} = -(\vec{p}_T^\ell + \vec{u}_T)$ . The  $W$ -boson transverse mass,  $m_T$ , is derived from  $p_T^{\text{miss}}$  and from the transverse momentum of the charged lepton as  $m_T = \sqrt{2p_T^\ell p_T^{\text{miss}}(1 - \cos \Delta\phi)}$ , where  $\Delta\phi$  is the azimuthal opening angle between the charged lepton and the missing transverse momentum.

The  $W$ -boson sample is collected using triggers requiring at least one muon candidate with transverse momentum larger than 18 GeV or at least one electron candidate with transverse momentum larger than 20 GeV. The transverse-momentum requirement for the electron candidate was raised to 22 GeV in later data-taking periods to cope with the increased instantaneous luminosity delivered by the LHC. Selected events are required to have a reconstructed primary vertex with at least three associated tracks.

The sample of  $W$ -boson candidate events is selected by requiring exactly one reconstructed electron or muon candidate with  $p_T^\ell > 30$  GeV. The leptons are required to match the corresponding trigger signal. The magnitude of the recoil is required to satisfy  $u_T < 30$  GeV, the missing transverse momentum  $p_T^{\text{miss}} > 30$  GeV and the transverse mass  $m_T > 60$  GeV. Approximately  $5.89 \times 10^6$  candidate events are selected in the  $W \rightarrow e\nu$  channel and  $7.84 \times 10^6$  events in the  $W \rightarrow \mu\nu$  channel.

### 3.4 $W$ -boson mass analysis updates

The selected  $W$ -boson event sample includes events from various background processes. Background contributions from  $Z$ -boson,  $W \rightarrow \tau\nu$ , boson pair, and top-quark production are estimated using simulation, and represent about 6.4% of the total sample in the muon channels, and about 3.1% in the electron channels. Contributions from multijet production are estimated with data-driven techniques, and are detailed in Ref. [12]. Compared with that reference, the multijet background yield was re-evaluated using the final luminosity calibration for Run 1 [43], resulting in a 1–2% decrease of the contamination of multijet background control regions by electroweak processes, and a corresponding 20% increase in the estimated multijet background yield in the electron channel. This background now represents 1.2% of the total sample, and agrees with the previous measurement within uncertainties. The multijet background in the muon channel is unaffected, due to the smaller contamination in this case. In addition, uncertainties in the multijet distributions were previously propagated to the  $m_W$  measurement through fluctuations of the extrapolation parameters; an eigenvector decomposition is used in the present analysis.

The results of Ref. [12] were obtained using the CT10nnlo PDF set and compared with results using the CT14 [44] and MMHT2014 PDF sets [45]. The present analysis extends the study of the PDF dependence of the fit results to the ATLASpdf21 [46], CT18, CT18A [47], MSHT20 [48], NNPDF3.1 [49] and NNPDF4.0 [50] sets.

In the previous measurement,  $m_W$  was determined with the  $W$ -boson width fixed to the SM prediction. In the present analysis, this assumption is relaxed by treating  $\Gamma_W$  as a source of systematic uncertainty, considering the SM value and uncertainty of  $\Gamma_W^{\text{SM}} = 2088 \pm 1$  MeV. The  $W$ -boson width is also extracted assuming the SM prediction and uncertainty of the  $W$ -boson mass,  $m_W^{\text{SM}} = 80355 \pm 6$  MeV.

Finally, an improved statistic is used for the fit as described in the following section.

Table 1: Summary of the 28 categories and kinematic distributions used in the  $m_W$  measurement for the electron and muon decay channels.

Decay channel	$W \rightarrow e\nu$	$W \rightarrow \mu\nu$
Kinematic distributions	$p_T^\ell, m_T$	$p_T^\ell, m_T$
Charge categories	$W^+, W^-$	$W^+, W^-$
$ \eta_\ell $ categories	[0, 0.6], [0.6, 1.2], [1.8, 2.4]	[0, 0.8], [0.8, 1.4], [1.4, 2.0], [2.0, 2.4]

### 3.5 Statistical analysis

The previous measurement used separate template fits to the  $p_T^\ell$  and  $m_T$  distributions observed in different event categories. The  $W$ -boson candidate events were classified according to the charge, flavour and pseudorapidity of the final state lepton, as summarised in Table 1. In the fit, the  $\chi^2$  of the comparison between data and simulation was minimised considering statistical uncertainties only; systematic uncertainties were included by varying the parameters determining the templates within their uncertainties, and repeating the fits.

The present analysis performs a simultaneous optimisation of  $m_W$  or  $\Gamma_W$ , and of nuisance parameters describing systematic uncertainties, through a global profile likelihood fit in all event categories for a given kinematic distribution. The likelihood function, which describes how compatible with each other the data and MC distributions are, is given by

$$\mathcal{L}(\vec{n}|\mu, \vec{\theta}) = \prod_j \prod_i \text{Poisson}(n_{ji} | v_{ji}(\mu, \vec{\theta})) \cdot \text{Gauss}(\vec{\theta}), \quad (1)$$

where  $\vec{n}$  represents the observed distributions in data, and  $n_{ji}$  is the number of events observed in data in bin  $i$  of the distribution in a given category  $j$ . It is the input to the Poisson distribution with expectation  $v_{ji}(\mu, \vec{\theta}) = S_{ji}(\mu, \vec{\theta}) + B_{ji}(\vec{\theta})$ , of  $S_{ji}$  events from signal and  $B_{ji}$  events from background contributions. The parameter of interest,  $\mu$ , represents variations in  $m_W$  or  $\Gamma_W$  with respect to a conventional reference,  $\mu_{\text{ref}}$ . Uncertainties of the signal and background distributions are encapsulated as nuisance parameters (NPs), denoted by  $\vec{\theta}$  in Eq. (1), for which a normal probability distribution is assumed. The expected number of events  $v_{ji}$  is parameterised as

$$v_{ji}(\mu, \vec{\theta}) = \Phi \times \left[ S_{ji}^{\text{nom}} + \mu \times (S_{ji}^\mu - S_{ji}^{\text{nom}}) \right] + \sum_s \theta_s \times (S_{ji}^s - S_{ji}^{\text{nom}}) + B_{ji}^{\text{nom}} + \sum_b \theta_b \times (B_{ji}^b - B_{ji}^{\text{nom}}), \quad (2)$$

where  $\Phi$  is an overall, unconstrained normalisation factor ensuring that the total  $W^\pm$  signal rate always adjusts to the number of events in data,  $S_{ji}^{\text{nom}}$  and  $B_{ji}^{\text{nom}}$  are the nominal distributions of signal and background, respectively, while  $s$  and  $b$  represent nuisance parameters acting on signal and background contributions.

Changes in  $\mu$  and  $\vec{\theta}$  lead to changes in the expected signal and background distributions, which are interpolated using a polynomial morphing procedure. Signal templates for arbitrary values of  $m_W$  or  $\Gamma_W$  are obtained from the same simulation sample through a reweighting of the  $W$ -boson Breit–Wigner

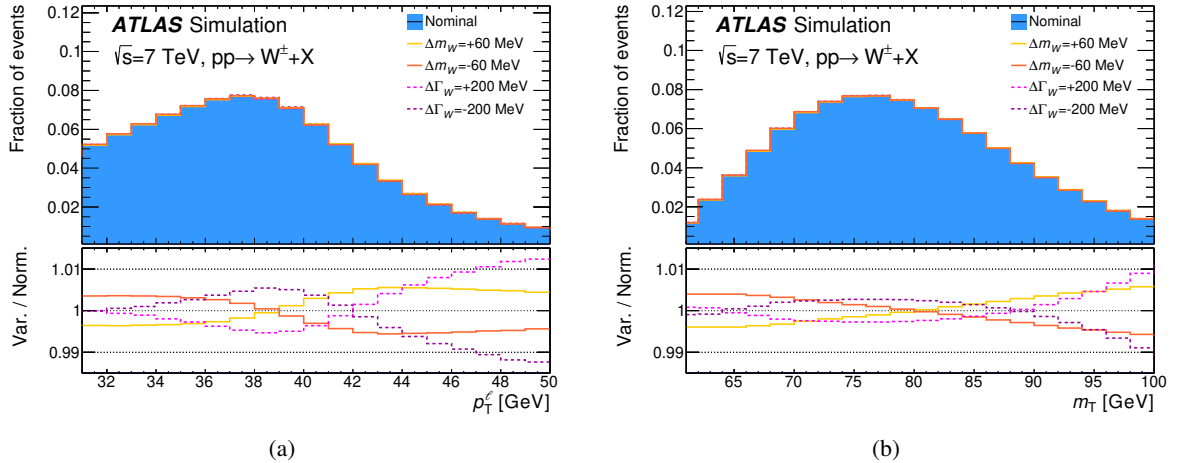


Figure 1: Simulated kinematic distributions of (a)  $p_T^\ell$  and (b)  $m_T$  in  $W^\pm \rightarrow \mu^\pm \nu$  events, for  $W$ -boson mass and width values of  $m_W = 80399$  MeV and  $\Gamma_W = 2085$  MeV. The ratio panels represent the relative effect of varying these parameters by  $\pm 60$  MeV and  $\pm 200$  MeV, respectively.

distribution. Templates representing systematic variations are determined from two-sided one- and two-sigma variations of the corresponding sources of uncertainty. The effect of varying  $m_W$  or  $\Gamma_W$  on the  $p_T^\ell$  and  $m_T$  distributions is illustrated in Figure 1. The procedure to interpolate between these points during the PLH fit was extensively tested, and excellent closure was observed.

As the new fitting method allows to better optimise the total uncertainty of the measurement due to the inclusion of NPs in the likelihood, the nominal fit ranges for the  $m_W$  measurement are re-evaluated. The updated optimal fit ranges are  $30 < p_T^\ell < 50$  GeV and  $60 < m_T < 100$  GeV, in contrast with  $32 < p_T^\ell < 45$  GeV and  $66 < m_T < 99$  GeV used in the previous measurement. For the determination of  $\Gamma_W$ , the same ranges are used as in the  $m_W$  measurement.

The baseline results rely on a numerical minimisation of the likelihood from Eq. (2). For ancillary studies, such as the decomposition of uncertainties, fit range variations, and to estimate the correlation between the  $m_T$  and  $p_T^\ell$  fits, the following assumptions are made: in the limit where all uncertainties are Gaussian and the dependence of  $v_{ji}(\mu, \vec{\theta})$  on  $\mu$  and  $\vec{\theta}$  is linear, the likelihood can be written as

$$-2 \ln \mathcal{L}(\vec{n} | \mu, \vec{\theta}) = \sum_j \sum_i \left( \frac{n_{ji} - v_{ji}(\mu_{\text{ref}}, \vec{0}) - \frac{\partial v_{ij}}{\partial \mu}(\mu - \mu_{\text{ref}}) - \sum_t \frac{\partial v_{ij}}{\partial \theta_t} \theta_t}{\sigma_{ji}} \right)^2 + \sum_t \theta_t^2, \quad (3)$$

and the minimisation and uncertainty estimation can be performed analytically [51]. This approach gives results within 2 MeV from the nominal fits and is much faster.

The decomposition of the post-fit uncertainties is performed according to the methods of Ref. [51]. The uncertainty components are defined to represent the contribution of the pre-fit uncertainty in the corresponding sources to the total uncertainty of the measurement, consistently with standard error propagation.



## 4 Experimental corrections and uncertainties

The  $p_{\text{T}}^{\ell}$  and  $m_{\text{T}}$  distributions are affected by the lepton energy calibration and by the calibration of the recoil. Lepton momentum corrections are derived exploiting  $Z \rightarrow \ell\ell$  event samples and the precisely measured value of  $m_Z$  [52], and the recoil response is calibrated using the expected momentum balance between  $u_{\text{T}}$  and  $p_{\text{T}}^{\ell\ell}$  [12]. Lepton identification and reconstruction efficiency corrections are determined from  $W$ - and  $Z$ -boson events using the tag-and-probe method [40, 42].

A precision on the energy and momentum scale for electrons and muons of  $O(10^{-4})$  is achieved, with somewhat larger uncertainty for the muons in the high- $\eta$  region. The response and resolution of  $u_{\text{T}} = |\vec{u}_{\text{T}}|$  is determined with a precision of a few percent. The experimental precision is limited by the finite size of the  $Z$ -boson sample, and by systematic uncertainties in the modelling of the distributions used in the calibration procedures.

### 4.1 Uncertainty propagation

Systematic uncertainties in the determination of  $m_W$  and  $\Gamma_W$  are evaluated by varying the calibration model parameters within their uncertainty. For two-sided systematic uncertainties, separate templates are produced for 68% confidence level (CL) upwards and downwards variations. Systematic uncertainties that are estimated independently in many kinematic bins are propagated through simultaneous random variations of the corresponding parameters within their uncertainty and generating templates for each variation. A principal component analysis (PCA) [53, 54] is used to transform these variations into a set of uncorrelated two-sided uncertainties, preserving the total uncertainty. This approach is used for the statistical uncertainties of the electron and muon efficiencies, as well as for the recoil calibration, and allows a faithful representation of these uncertainties using a reduced set of nuisance parameters.

Because of the finite size of the MC samples, some systematic variations contribute significant statistical fluctuations in the final-state distributions. A smoothing procedure is applied to remove such fluctuations, preserving the normalisation of each variation. For calibration systematic uncertainties, the effect of the upwards and downwards variations are symmetrised. The impact of the smoothing and symmetrisation procedures on the best-fit values and uncertainties are below 1 and 0.1 MeV, respectively.

The effect of each systematic variation is decomposed into corresponding uncertainties in the normalisation and in the shape of the final state distributions. Systematic uncertainties that yield differences smaller than 0.01% in the normalised  $p_{\text{T}}^{\ell}$  distribution and smaller than 0.02% in the normalised  $m_{\text{T}}$  distribution are removed, reducing the number of shape systematic variations by a factor of two, for a change in the total measurement uncertainty by less than 1% of itself. This pruning procedure simplifies the likelihood, stabilising and accelerating the fit procedure.

### 4.2 Sources of uncertainty

The electron calibration and selection efficiencies account for 75 sources of uncertainty in the  $p_{\text{T}}^{\ell}$  distribution and 58 in the  $m_{\text{T}}$  distribution, including the energy scale and resolution as well as the electron identification, isolation, and trigger efficiencies. Of these uncertainties, 23 originate from the energy calibration and are treated as two-sided systematic uncertainties, while 52 ( $p_{\text{T}}^{\ell}$ ) and 35 ( $m_{\text{T}}$ ) systematic variations come from the trigger, reconstruction, identification and isolation efficiencies. PCA is utilised to handle those

systematic variations. Similarly, the muon response and efficiencies contribute 83 ( $p_T^\ell$ ) and 76 ( $m_T$ ) sources of uncertainty, of which 6 are treated as two-sided uncertainties.

The calibration of the hadronic recoils yields 36 sources of systematic uncertainties for the  $m_T$  distributions, but only 7 sources for the  $p_T^\ell$  distributions since the impact on the latter are only due to the hadronic recoil requirement in the signal selection. Of these uncertainties, 3 are two-sided uncertainties, while 4 ( $p_T^\ell$ ) and 33 ( $m_T$ ) PCA variations are taken into account.

## 5 Physics corrections and uncertainties

### 5.1 Electroweak uncertainties

The dominant source of electroweak corrections to  $W$ -boson production originates from QED final-state radiation, and is simulated with `PHOTOS`. The effect of QED initial-state radiation (ISR) is also included through the `PYTHIA 8` parton shower (PS). Other sources of electroweak corrections are not included in the simulated event samples, and their full effects are considered as systematic uncertainties. Systematic uncertainties from missing higher-order electroweak corrections are estimated considering the same sources of uncertainty as in Ref. [12]. An improvement of the present analysis is that the corresponding uncertainties are evaluated at detector level instead of generator level, which was a simplification used in the previous analysis as these are not leading uncertainties. The detector-level systematic variations are obtained by applying detector response and efficiency migration matrices derived from samples of simulated signal events described in Section 3.1. Their impact on  $m_W$  is larger than for generator-level variations by typically 20%.

### 5.2 QCD model and uncertainties

The rapidity, transverse momentum and decay distributions of the simulated  $W$ - and  $Z$ -boson samples are reweighted to include the effects of higher-order QCD corrections, which improves the agreement between the data and simulation. The differential cross section as a function of the boson rapidity,  $d\sigma(y)/dy$ , and the coefficients describing angular distributions of decay leptons,  $A_i$  [55], are calculated at  $O(\alpha_s^2)$  in fixed-order QCD. The transverse-momentum spectrum at a given rapidity,  $d\sigma(p_T, y)/(dp_T dy) \cdot (d\sigma(y)/dy)^{-1}$ , is modelled using the `PYTHIA 8` MC generator, with parameters adjusted to reproduce the measured  $Z$ -boson  $p_T$  distribution at  $\sqrt{s} = 7$  TeV [29]. The resulting tune, called `AZ` in the following, predicts  $W$ -boson  $p_T$  distributions that agree with measurements at  $\sqrt{s} = 5.02$  and 13 TeV [56].

PDF uncertainties are calculated for the CT10, CT14, CT18, CT18A, MMHT2014, MSHT20, NNPDF3.1, NNPDF4.0 and ATLASpdf21 sets using the Hessian method [57], where each eigenvector of the PDF fit covariance matrix defines a pair of PDF uncertainty variations and a corresponding nuisance parameter in the PLH fit. The CT10, CT14, CT18 and CT18A variations correspond to 90% CL, and are rescaled to match the 68% CL. Given the precisely measured  $p_T^Z$  distribution, PDF uncertainty variations are constrained to leave the predicted  $p_T^Z$  distribution unchanged, and propagate only the part of the PDF uncertainty in the  $p_T^W$  distribution that is uncorrelated to  $p_T^Z$ . The uncertainties in the `AZ` tune parameters are propagated separately, as described below.

The `PYTHIA 8` parton shower model contributes additional sources of uncertainty in the  $p_T^W$  distribution. The `AZ` tune parameters are assumed universal between  $Z$ - and  $W$ -boson production, and their uncertainties

are propagated to the  $W$ -boson final-state distributions. The initial-state charm and bottom quark masses affect the  $p_T$  spectrum, and the corresponding uncertainties are estimated by varying their respective masses by  $\pm 0.5$  GeV and  $\pm 0.8$  GeV, respectively. Uncertainties in the shower evolution are parameterised through variations of the factorisation scale,  $\mu_F$ , by factors of 0.5 and 2.0 with respect to the central choice  $\mu_F^2 = p_{T,0}^2 + p_T^2$ , where  $p_{T,0}$  is an infrared cut-off, and  $p_T$  is the evolution variable of the parton shower [58]. The variations are applied independently to the light-quark, charm-quark and bottom-quark-induced processes, and are propagated considering only the relative impact on the  $p_T^W$  and  $p_T^Z$  distributions. Differences between the PYTHIA 8 and HERWIG 7 predictions for this ratio were found to be negligible.

The accuracy of the next-to-next-to-leading-order (NNLO) predictions for the angular coefficients  $A_0$ – $A_7$  is validated by comparing to the corresponding measured values in  $Z$ -boson production [55]. The  $Z$ -boson data uncertainties are propagated to the  $W$ -boson predictions, which assumes that NNLO predictions have similar accuracy for the  $W$ - and  $Z$ -boson processes, and are validated within the experimental precision of the  $Z$ -boson data. The observed disagreement between data and prediction for the  $A_2$  coefficient is taken as additional uncertainty. Similarly to some experimental uncertainties, random angular coefficient variations are treated with a PCA to produce uncorrelated two-sided uncertainties.

The effect of missing higher-order corrections on the NNLO predictions of the normalised rapidity distributions and the effect of the LHC beam-energy uncertainty of 0.65% were both found to be negligible.

## 6 Improved measurement of the $W$ -boson mass

The improvements to the previous  $m_W$  measurement described in Sections 3.4 and 3.5 are implemented in several steps. The impact of the analysis updates is evaluated using the same statistical method as in the previous measurement, and yields a change of the measured  $W$ -boson mass from  $80369.5 \pm 18.5$  MeV to  $80371.9 \pm 18.7$  MeV, corresponding to a shift of 2.4 MeV and a minimal increase of the total uncertainty. The analysis is then repeated using the CT10nnlo PDF set and unchanged systematic uncertainties but implementing the PLH approach. This provides a test of the stability of the measurement under the change of statistic used in the fit. The final step consists of updating the measurement to more recent PDF sets, one of which is used to define a new baseline.

### 6.1 Results with CT10nnlo and consistency tests

The PLH fits using the CT10nnlo PDF set are first performed with statistical uncertainties only. Excellent consistency with the previous results is obtained, which provides a basic validation for the technical aspects of the fit. The comparison is repeated for fits including all systematic uncertainties, with the results summarised in Figure 2. The results of the PLH fits combining all categories yield  $m_W = 80357.0 \pm 15.8$  MeV and  $m_W = 80388.2 \pm 23.8$  MeV for the  $p_T^\ell$  and  $m_T$  distributions, respectively. Compared to the original ATLAS measurement, this corresponds to shifts of  $m_W$  of  $-12.4$  MeV and  $+12.5$  MeV, respectively, while the total uncertainties are reduced by about 3 MeV due to the profiling of some systematic uncertainties. Repeating the present analysis with the fit range used in Ref. [12] increases the difference by 3 MeV.

The compatibility between the present and previous results is tested by repeating the PLH fits for an ensemble of models where the preferred values of the nuisance parameters are varied randomly within their pre-fit uncertainties. As shown in Figure 3, the spread of fit results from pseudo-experiments with

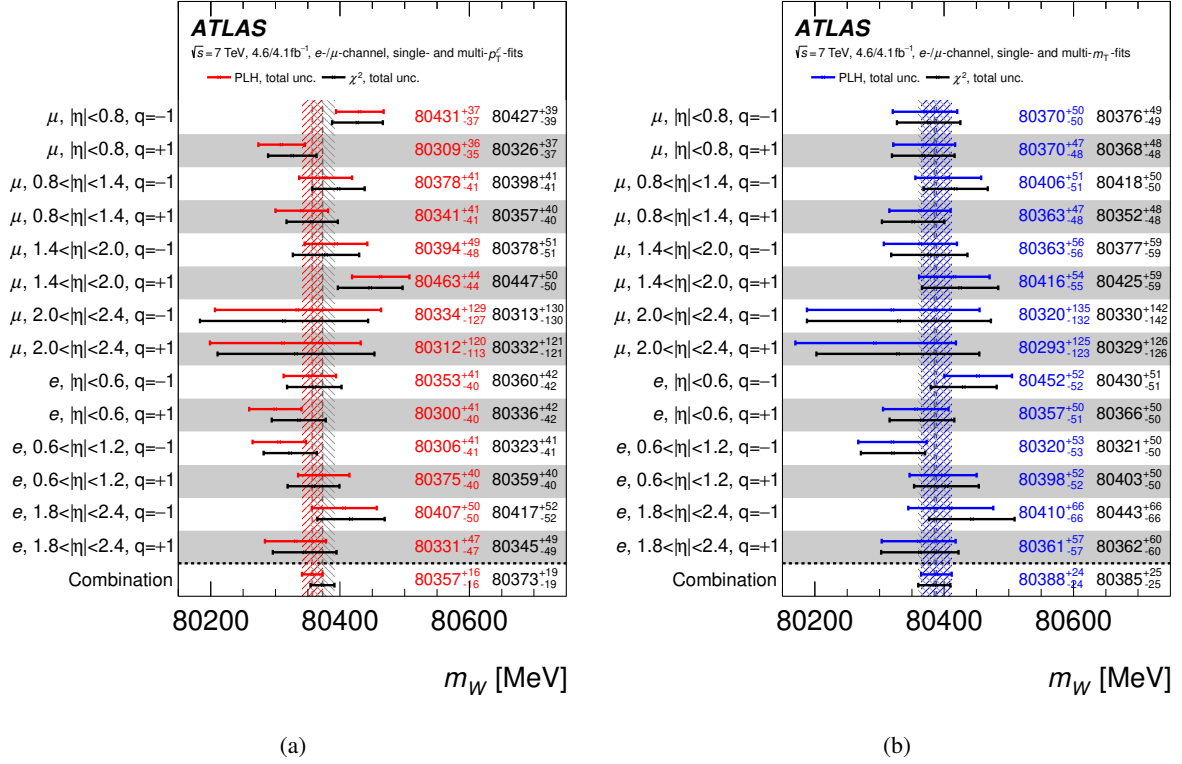


Figure 2: Overview of the  $m_W$  fit results in all categories for the (a)  $p_T^\ell$  and (b)  $m_T$  distributions, with the CT10nnlo PDF set, where  $q$  denotes the charge of the decay lepton. The results of the PLH fit are compared with the  $\chi^2$  fit, where systematic uncertainties are propagated using the offset method [12]. The points labelled as ‘Combination’ correspond to the result of a joint PLH fit to all categories and to a combination of individual  $\chi^2$  fits.

varied nuisance parameters is about 16 MeV, confirming that the change in central value introduced by the new statistical method corresponds to about one standard deviation. The distribution of the nuisance parameter pulls<sup>2</sup> is consistent with a normal distribution, indicating an overall correct estimate of the pre-fit uncertainties.

## 6.2 Impact of updated parton distribution functions

The impact of a change in the PDFs on the final state distributions is evaluated using POWHEG, both to calculate the extrapolation from the central CT10nnlo set to CT14, CT18, CT18A, MMHT2014, MSHT20, NNPDF3.1, NNPDF4.0 and ATLASpdf21, and to calculate the PDF uncertainty variations. All calculations are performed at generator level in full phase space, and the impact on the final-state distributions is evaluated using migration matrices as in Section 5.1. As in Section 5.2, the PDF extrapolations are constrained to leave  $p_T^Z$  unchanged. The impact of the extrapolations on the detector-level  $p_T^\ell$  distributions is illustrated in Figure 4.

<sup>2</sup> For a given nuisance parameter  $\theta$ , the pull is defined as  $\hat{\theta}/\sqrt{1-\sigma_\theta}$ , where  $\hat{\theta}$  and  $\sigma_\theta$  are the nuisance parameter post-fit value and uncertainty, respectively.

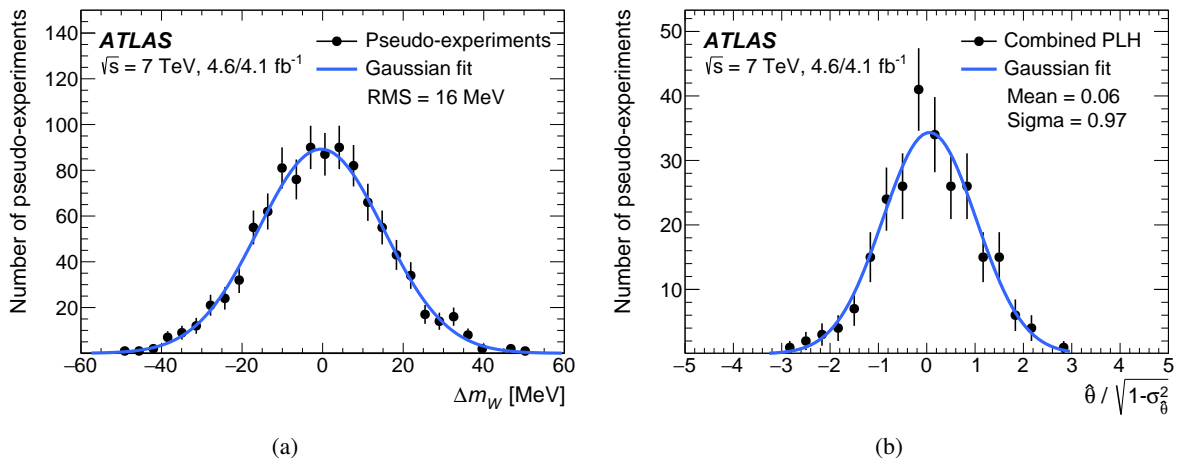


Figure 3: (a) Distribution of the difference  $\Delta m_W$  between the nominal  $m_W$  PLH fit result and results obtained for pseudo-experiments using random variations of the sources of systematic uncertainty. The  $p_T^\ell$  distribution is used. (b) Distribution of pull significances for the NPs in the combined PLH fit to the  $p_T^\ell$  distribution.

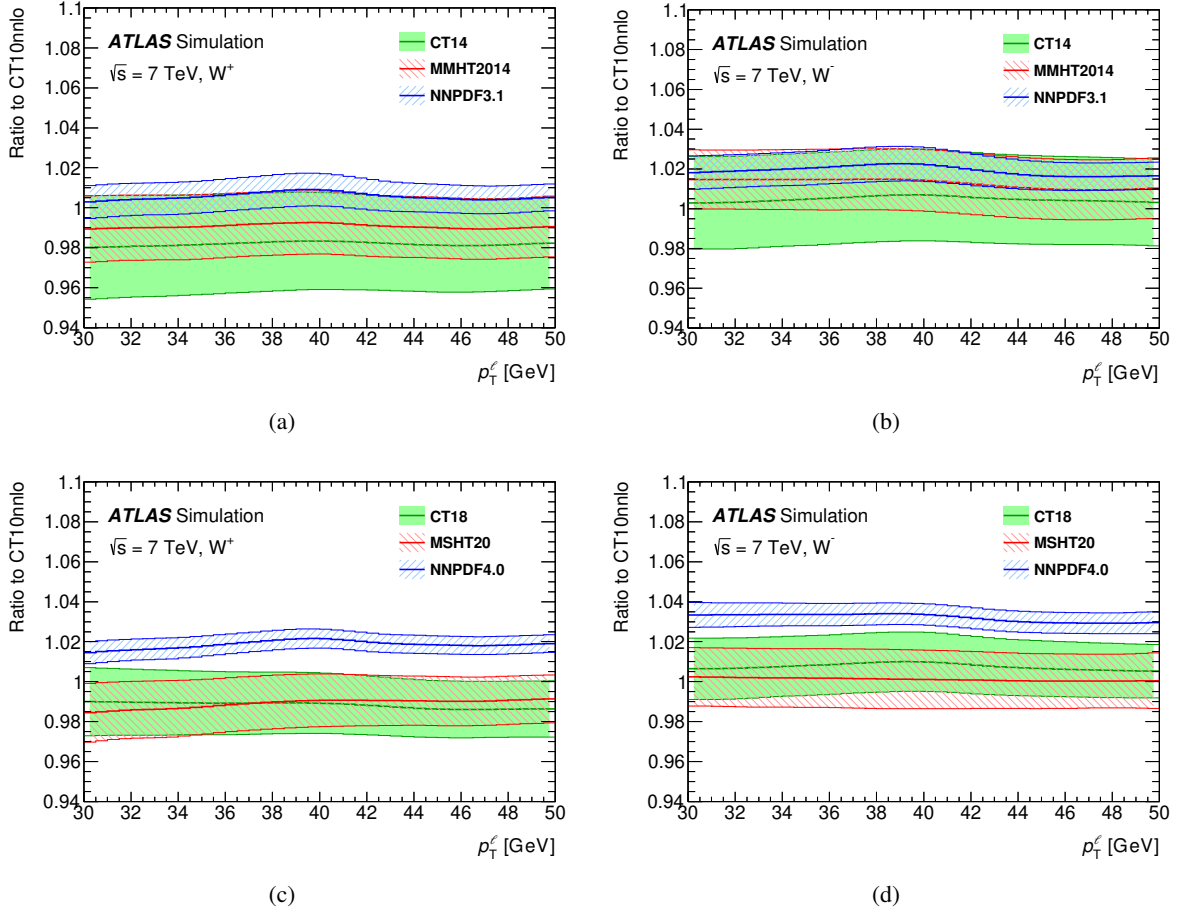


Figure 4: Relative effect, with respect to CT10nnlo, of the indicated PDF extrapolations on the detector-level,  $\eta$ -inclusive  $p_T^\ell$  distributions in (a,c)  $W^+$  events and (b,d)  $W^-$  events. The thick lines show the central PDF set, and the envelopes show the associated 68% CL uncertainty.

Table 2: Best-fit value of  $m_W$ , total and PDF uncertainties, in MeV, and goodness-of-fit for the  $p_T^\ell$  and  $m_T$  distributions and the PDF sets described in the text. Each fit uses 14 event categories with 40 bins, for 558 degrees of freedom.

PDF set	$p_T^\ell$ fit				$m_T$ fit			
	$m_W$	$\sigma_{\text{tot}}$	$\sigma_{\text{PDF}}$	$\chi^2/\text{n.d.f.}$	$m_W$	$\sigma_{\text{tot}}$	$\sigma_{\text{PDF}}$	$\chi^2/\text{n.d.f.}$
CT14	80358.3	+16.1 -16.2	4.6	543.3/558	80401.3	+24.3 -24.5	11.6	557.4/558
CT18	80362.0	+16.2 -16.2	4.9	529.7/558	80394.9	+24.3 -24.5	11.7	549.2/558
CT18A	80353.2	+15.9 -15.8	4.8	525.3/558	80384.8	+23.5 -23.8	10.9	548.4/558
MMHT2014	80361.6	+16.0 -16.0	4.5	539.8/558	80399.1	+23.2 -23.5	10.0	561.5/558
MSHT20	80359.0	+13.8 -15.4	4.3	550.2/558	80391.4	+23.6 -24.1	10.0	557.3/558
ATLASpdf21	80362.1	+16.9 -16.9	4.2	526.9/558	80405.5	+28.2 -27.7	13.2	544.9/558
NNPDF3.1	80347.5	+15.2 -15.7	4.8	523.1/558	80368.9	+22.7 -22.9	9.7	556.6/558
NNPDF4.0	80343.7	+15.0 -15.0	4.2	539.2/558	80363.1	+21.4 -22.1	7.7	558.8/558

### 6.3 Results and discussion

Fit results with updated PDF sets are listed in Table 2. A satisfactory fit quality is obtained for all PDF sets. Separate fits are performed to the  $p_T^\ell$  and  $m_T$  distributions as they are projections of the same data, and the corresponding statistical correlations cannot be accounted for in the framework of Eq. (1) in a straightforward way. Moreover, the PCA treatment applied for some classes of systematic uncertainties leads to different sets of nuisance parameters for the two distributions.

The best-fit values of  $m_W$  obtained with different PDF sets span a range of about 18 MeV for the  $p_T^\ell$  fits, and about 42 MeV for the  $m_T$  fits. This envelope is dominated by the NNPDF3.1 and NNPDF4.0 fits, which yield the lowest fit values; the range spanned by the other sets is only 9 MeV for  $p_T^\ell$  and 21 MeV for  $m_T$ .

The influence of the size of the initial PDF uncertainties on the best-fit values is studied in Figure 5, where the fits are repeated with pre-fit PDF uncertainties scaled by factors 1–3. Enlarged uncertainties allow the models to better adapt to the data, resulting in a reduced PDF model dependence. For scale factors of 2 and above, the residual model dependence is below 5 MeV for the  $p_T^\ell$  fits, and 25 MeV for  $m_T$  fits, with the total uncertainty increased by less than 1.5 MeV.

The baseline result is defined using CT18, which is compatible with the previous exercise and yields the most conservative uncertainty among the PDF sets considered except for ATLASpdf21. CT18 is also the only recent PDF set that does not include the  $W$ - and  $Z$ -boson cross sections measured by ATLAS at 7 TeV [33], which represent the same data as those used in the present analysis. The results for all measurement categories and for the CT18 PDF set are summarised in Figure 6. The post-fit,  $|\eta|$ -inclusive  $p_T^\ell$  distributions obtained with CT18 are shown in Figure 7, and agree with the data within the uncertainties. Similarly to CT10nnlo, the distribution of the nuisance parameter pulls is consistent with a normal distribution.

The compatibility of the results for  $m_W$  in the different measurement categories is verified by repeating the fit assuming independent parameters of interest in each category. The differences to the baseline fit are small compared with the measurement uncertainties. Partial fits are performed to the electron and muon channels separately. The electron and muon fit results are found to agree within one standard deviation. A similar exercise is performed for the  $W^+$  and  $W^-$  channels, and the same conclusion is obtained. Finally,

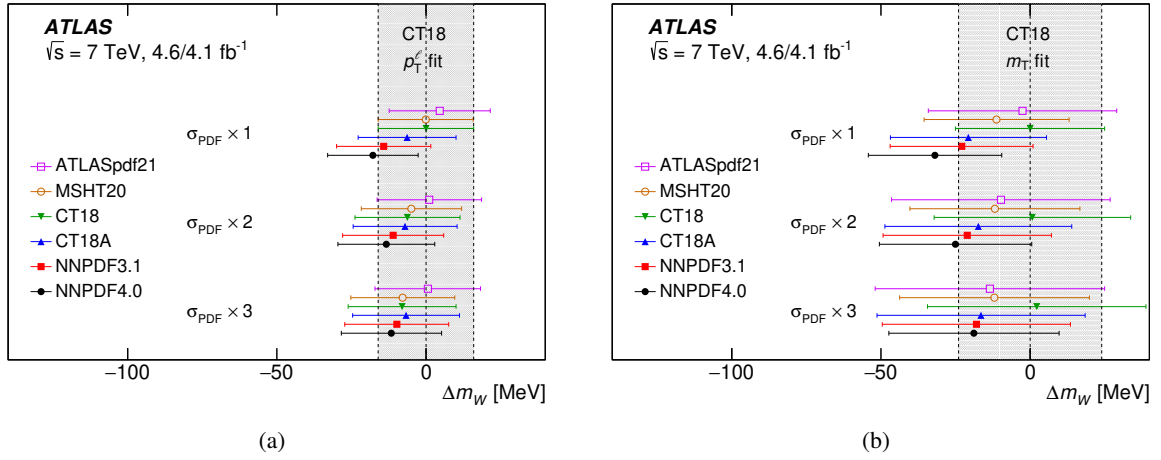


Figure 5: Variation of the fitted value of  $m_W$  with the PDF set used in the fit, for the (a)  $p_T^{\ell}$  and (b)  $m_T$  distributions and different scalings of the pre-fit PDF uncertainties. The reference value is defined by the CT18 PDF set.

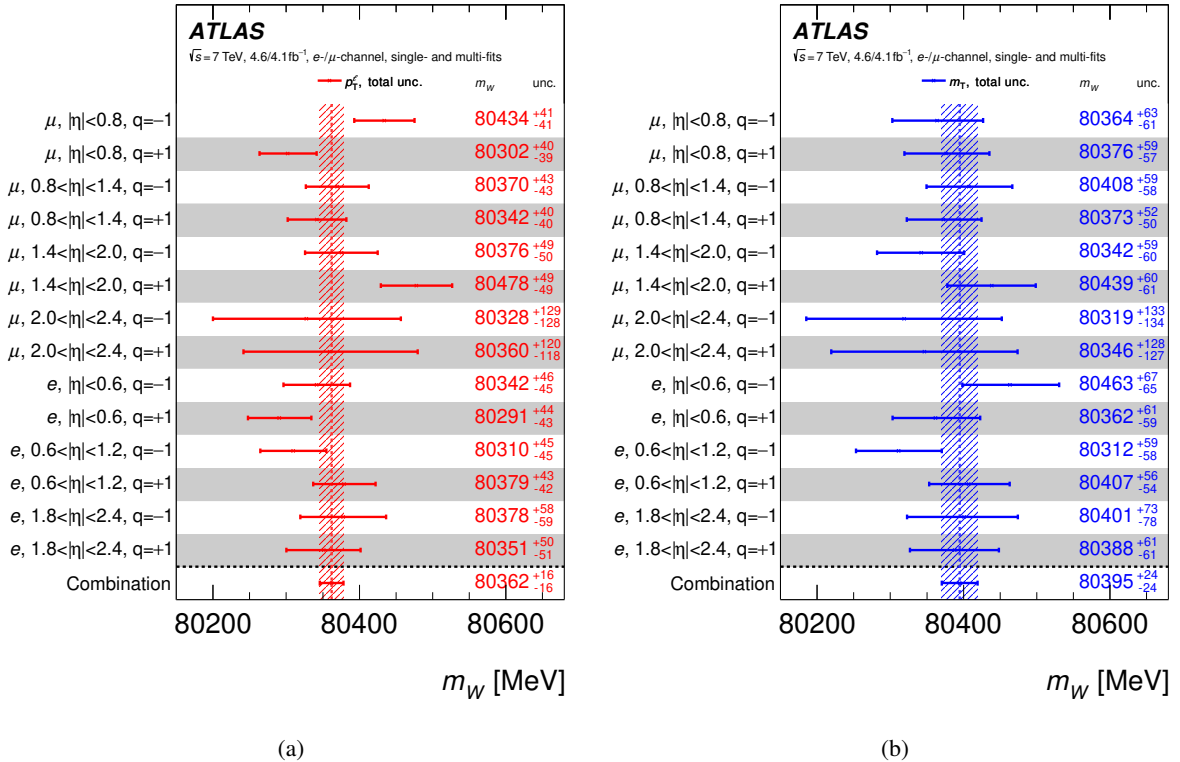


Figure 6: Overview of the  $m_W$  PLH fit results in all categories for the (a)  $p_T^{\ell}$  and (b)  $m_T$  distributions, with the CT18 PDF set. The points labelled as 'Combination' correspond to the result of a joint PLH fit to all categories.



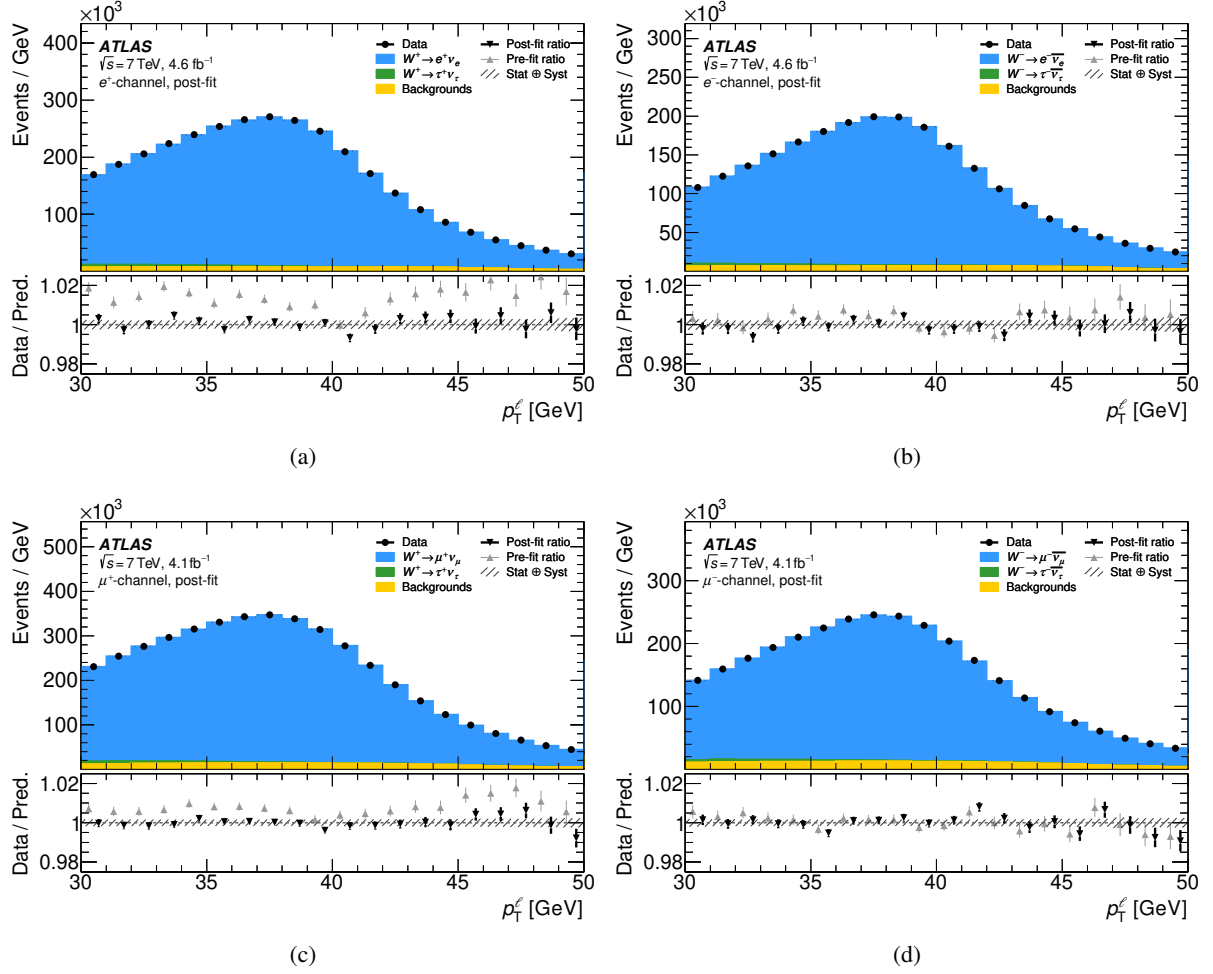


Figure 7: Post-fit distributions of  $p_T^l$  with data and MC for (a)  $W^+ \rightarrow e^+ \nu_e$ , (b)  $W^- \rightarrow e^- \bar{\nu}_e$ , (c)  $W^+ \rightarrow \mu^+ \nu_\mu$  and (d)  $W^- \rightarrow \mu^- \bar{\nu}_\mu$ , inclusive over all  $\eta$  regions, and using the CT18 PDF set. In the bottom panels, the darker points represent the post-fit ratio of data to MC, while the lighter points indicate the ratio before the fit. The hatched band represents the total uncertainty of the data.

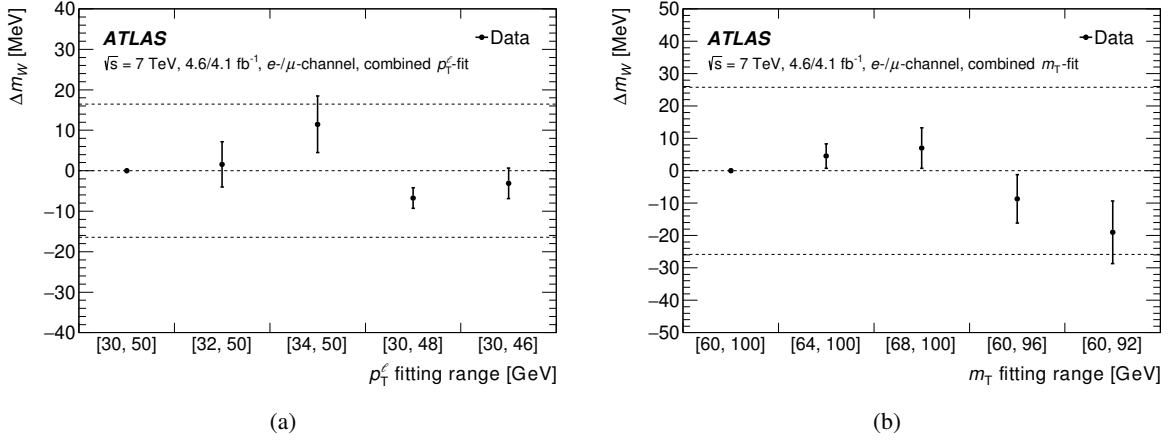


Figure 8: Difference  $\Delta m_W$  between the  $W$ -boson mass measured using the (a)  $p_T^\ell$  and (b)  $m_T$  distribution fit ranges indicated in the figure and the nominal fit range. The nominal ranges are  $30 < p_T^\ell < 50$  GeV and  $60 < m_T < 100$  GeV, respectively. The outer dashed lines indicate the total measurement uncertainty for the nominal range. Results are shown for the combined fit over all categories, and for the CT18 PDF set.

the dependence of the fit result on the  $p_T^\ell$  and  $m_T$  ranges used for the fit is shown in Figure 8, with good stability.

Figure 9 summarises the ten nuisance parameters that induce the largest shift of  $m_W$  in fits to the  $p_T^\ell$  and  $m_T$  distributions. They are related to electron and muon calibration uncertainties, to the uncertainty in charm-induced production for the  $p_T^W$  description, to specific eigenvectors (EV) of the CT18 PDF set, and to missing higher-order electroweak corrections. The corresponding nuisance parameter pulls are also shown. By construction, the PLH fits induce shifts of the nuisance parameters from their nominal value and significant deviations would indicate an underestimation of systematic uncertainties. All observed pulls are within the expectation.

While uncertainties in the PDFs and in the AZ tune parameters have well defined confidence intervals and can be treated as nuisance parameters, this is more questionable for the other uncertainties in the  $W$ -boson  $p_T$  distribution, i.e., the factorisation scale and quark-mass variations. It was verified that the impact of the latter on the final-state distributions is very similar, in shape, to that of the AZ tune parameters, and that these effects are thus not different from the other sources of uncertainty in this respect, and can be treated accordingly. The small post-fit value of the corresponding uncertainty is due to the strong discrimination between the effects of  $m_W$  and  $p_T^W$  variations on the  $p_T^\ell$  distribution.

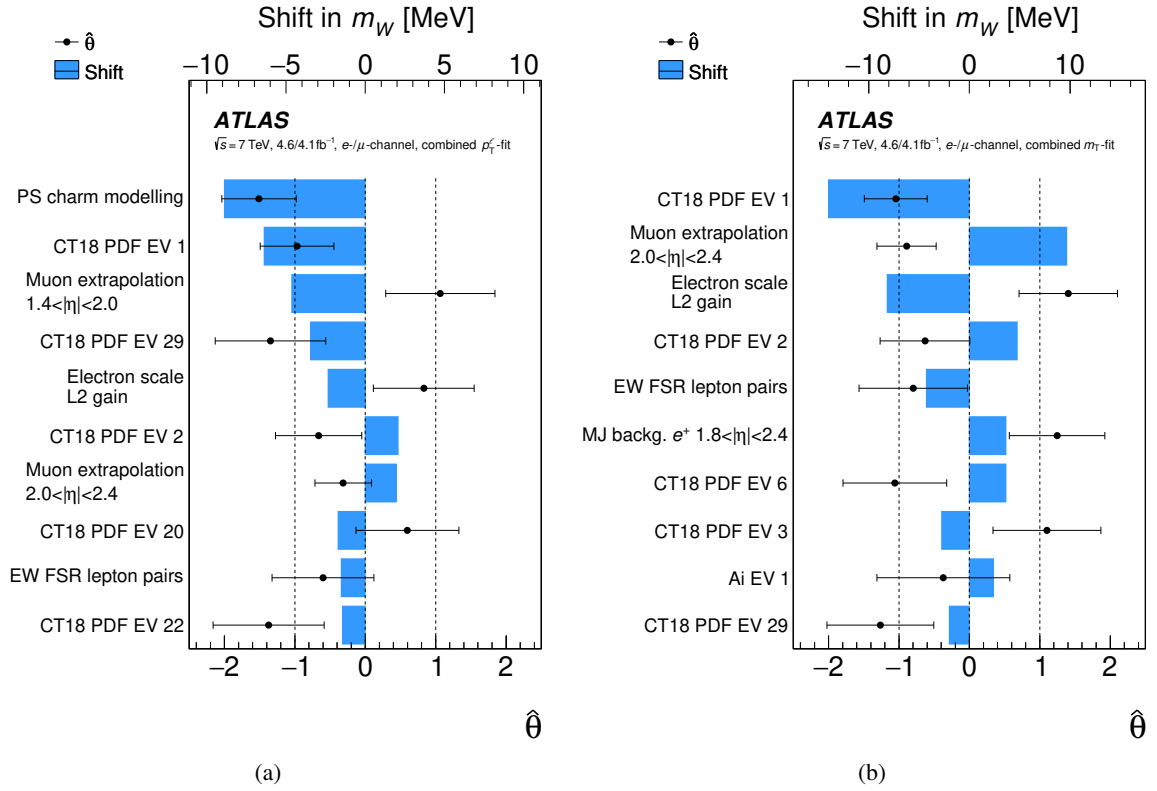


Figure 9: The ten nuisance parameters inducing the largest shifts on the fitted value of  $m_W$  in the combined PLH fits, using the (a)  $p_T^l$  and (b)  $m_T$  distributions and the CT18 PDF set. For a given NP  $\theta$ , the shift is defined as the product of its post-fit value  $\hat{\theta}$  and its pre-fit impact on  $m_W$ . The points, which are plotted according to the bottom horizontal scale, show  $\hat{\theta}$  for each of the nuisance parameters. The error bars show the corresponding post-fit uncertainties,  $\sigma_{\hat{\theta}}$ . The nuisance parameters are ranked according to the shift induced on  $m_W$ , the NPs with the largest shifts at the top.

Table 3: Uncertainty correlation between the  $p_T^\ell$  and  $m_T$  fits, combination weights and combination results for  $m_W$  and the indicated PDF sets.

PDF set	Correlation	weight ( $p_T^\ell$ )	weight ( $m_T$ )	Combined $m_W$ [MeV]
CT14	52.2%	88%	12%	$80363.6 \pm 15.9$
CT18	50.4%	86%	14%	$80366.5 \pm 15.9$
CT18A	53.4%	88%	12%	$80357.2 \pm 15.6$
MMHT2014	56.0%	88%	12%	$80366.2 \pm 15.8$
MSHT20	57.6%	97%	3%	$80359.3 \pm 14.6$
ATLASpdf21	42.8%	87%	13%	$80367.6 \pm 16.6$
NNPDF3.1	56.8%	89%	11%	$80349.6 \pm 15.3$
NNPDF4.0	59.5%	90%	10%	$80345.6 \pm 14.9$

## 6.4 Combination

All event categories are statistically independent as long as only the  $p_T^\ell$  or only the  $m_T$  distributions are considered. The correlation between the final  $p_T^\ell$ - and  $m_T$ -based results for  $m_W$  is determined from an ensemble of fit results obtained by fluctuating the data and the most probable values of the nuisance parameters within their respective uncertainties. The  $p_T^\ell$  and  $m_T$  results are then combined using the BLUE prescription [59]. The results of this procedure are given in Table 3. The weight of the  $p_T^\ell$  fit ranges from 86% to 97%, depending on the PDF set, and dominates the final result. For the CT18 PDF set, the final result is:

$$m_W = 80366.5 \pm 9.8 \text{ (stat.)} \pm 12.5 \text{ (syst.) MeV} = 80366.5 \pm 15.9 \text{ MeV,}$$

where the first uncertainty component is statistical and the second corresponds to the total systematic uncertainties.

The decomposition of the post-fit uncertainties is performed according to Ref. [51] and shown in Table 4. Statistical uncertainties contribute about 10 MeV in the present fit. This is in contrast with 6 MeV obtained from fits considering statistical uncertainties only, with all nuisance parameters fixed to their best-fit values. The increase reflects the larger number of parameters determined from the same data. Correspondingly, the systematic uncertainty components are smaller than systematic ‘impacts’ conventionally reported for PLH fits.<sup>3</sup> Systematic uncertainties contribute about 13 MeV, dominated by PDF uncertainties, missing higher-order electroweak corrections, and electron and muon calibration uncertainties.

The fits are performed assuming the SM value for the  $W$ -boson width,  $\Gamma_W^{\text{SM}} = 2088 \pm 1$  MeV [6]. The fitted value of  $m_W$  varies with the assumed value for  $\Gamma_W$  following  $\Delta m_W = -0.06 \Delta \Gamma_W$ . Assuming an alternate SM prediction of  $\Gamma_W^{\text{SM}} = 2091 \pm 1$  MeV, as obtained in Ref. [7], does not change the measured value of the  $W$ -boson mass significantly.

The compatibility of the measured value of the  $W$ -boson mass using the CT18 PDF set with the Standard Model expectation is illustrated in Figure 10(a), together with selected previous measurements. The two-dimensional 68% and 95% confidence limits for the predictions of  $m_W$  and  $m_t$  in the context of the

<sup>3</sup> Impacts are obtained from the quadratic subtraction between the total fit uncertainty and the uncertainty of a fit with selected nuisance parameters removed and overestimate the genuine systematic uncertainty.

Table 4: Uncertainty components for the  $p_T^\ell$ ,  $m_T$  and combined  $m_W$  measurements using the CT18 PDF set. The first columns give the total, statistical and overall systematic uncertainty in the measurements. The following columns show the contributions of modelling and experimental systematic uncertainties, grouped into categories.

Unc. [MeV ]	Total	Stat.	Syst.	PDF	$A_i$	Backg.	EW	$e$	$\mu$	$u_T$	Lumi	$\Gamma_W$	PS
$p_T^\ell$	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
$m_T$	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

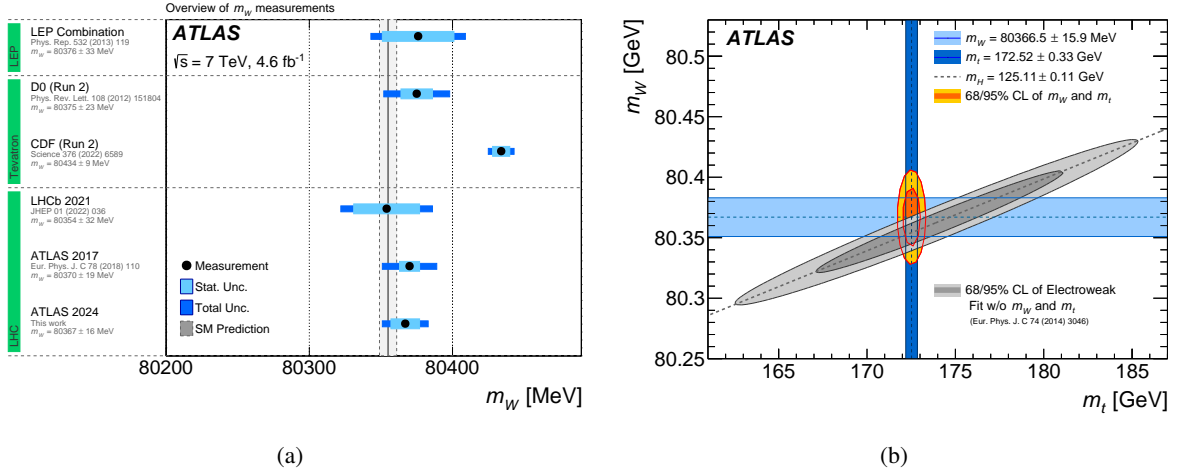


Figure 10: (a) Present measured value of  $m_W$ , compared to SM prediction from the global electroweak fit [6], and to the measurements of LEP [10], Tevatron [18, 19] and the LHC [12, 13]. (b) The 68% and 95% confidence level contours of the  $m_W$  and  $m_t$  indirect determinations from the global electroweak fit [7], compared to the 68% and 95% confidence-level contours of the present ATLAS measurement of  $m_W$ , the ATLAS measurement of  $m_H$  [61] and the LHC measurement of  $m_t$  [60].

Standard Model electroweak fit are shown in Figure 10(b), and are compared to the present measurement of  $m_W$  and to the combined value of the LHC top-quark mass determinations at 7 and 8 TeV [60].

## 7 Measurement of the $W$ -boson width

### 7.1 Overview

The  $p_T^\ell$  and  $m_T$  distributions are not only sensitive to  $m_W$  but also to  $\Gamma_W$ , as shown in Figure 1. In particular, the high tails of the  $p_T^\ell$  and  $m_T$  distributions are sensitive to changes of  $\Gamma_W$ . The fit to the  $m_T$  distribution is expected to be more sensitive, because events with high  $m_T$  are more likely to come from the tail of the  $W$ -boson Breit–Wigner distribution than events with high  $p_T^\ell$ . The measurement of  $\Gamma_W$  relies on the same statistical framework, the same calibration, and the same distributions as the previously presented measurement of  $m_W$ . However,  $\Gamma_W$  is left free in the fit, while the  $W$ -boson mass is treated as NP and set to its SM expectation within the global electroweak fit,  $m_W^{\text{SM}} = 80355 \pm 6$  MeV [6]. The templates are generated with different values of  $\Gamma_W$ , centred around the reference value used in the Monte Carlo signal

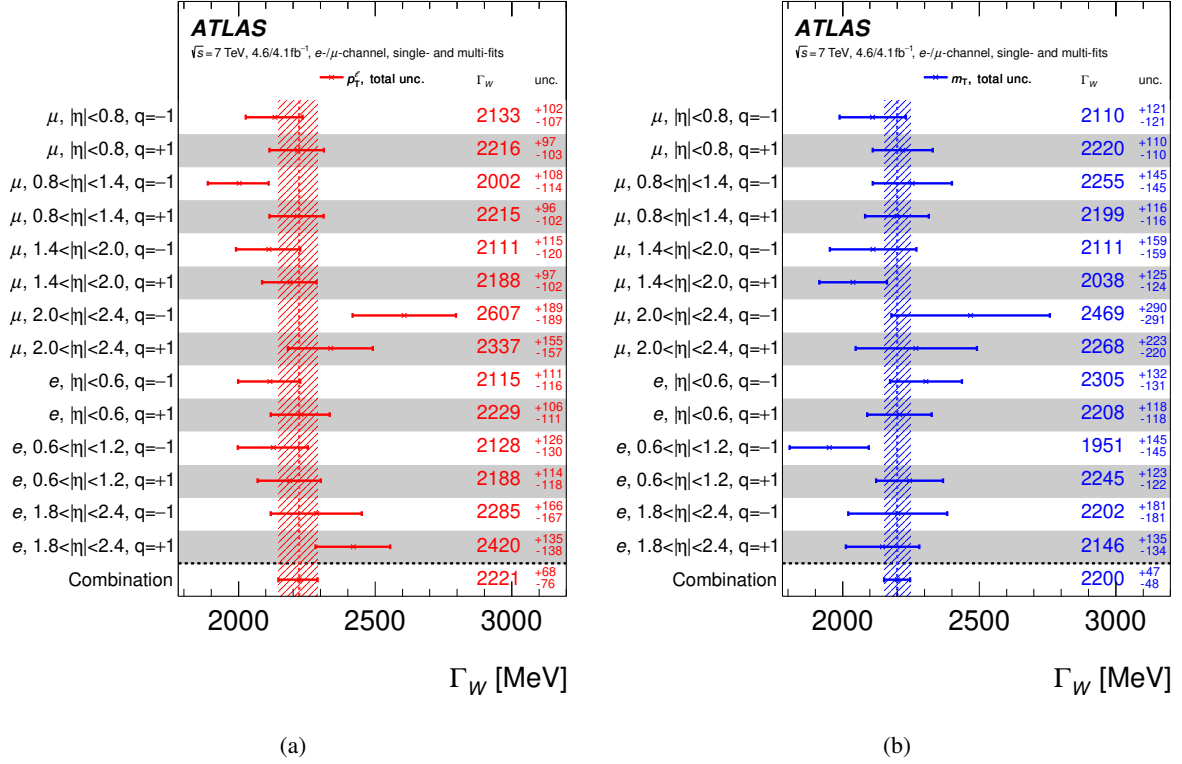


Figure 11: Overview of the  $\Gamma_W$  PLH fit results in all categories for the (a)  $p_T^\ell$  and (b)  $m_T$  distributions, with the CT18 PDF set. The points labelled as ‘Combination’ correspond to the result of a joint PLH fit to all categories.

samples. All results are obtained using the same fit ranges as in the  $m_W$  measurement:  $60 < m_T < 100$  GeV and  $30 < p_T^\ell < 50$  GeV. The choice of fitting range is driven by the uncertainties in the lepton performance and the hadronic recoil.

## 7.2 Results and discussion

The results for each measurement category including all systematic uncertainties for the CT18 PDF set are summarised in Figure 11 yielding the values of  $\Gamma_W = 2221^{+68}_{-76}$  MeV and  $\Gamma_W = 2200^{+47}_{-48}$  MeV for  $p_T^\ell$  and  $m_T$  distributions respectively. Good agreement between the categories can be observed.

Contrary to  $m_W$ , the fitted value of  $\Gamma_W$  depends more strongly on the assumed value of the mass. The fitted value of  $\Gamma_W$  varies with the assumed value for  $m_W$  following  $\Delta\Gamma_W = -1.25 \Delta m_W$ . In the Standard Model, the predicted value of  $m_W$  mainly depends on the assumed value of  $m_t$ . The present result is based on Ref. [6], which uses  $m_t = 172.6$  GeV and is close to the LHC combined value used in Figure 10(b). Using  $m_t = 171.8$  GeV [62] or  $m_t = 173.1$  GeV [63] yields  $m_W^{\text{SM}} = 80350$  MeV or 80360 MeV, respectively, with corresponding variations of  $\Gamma_W$  by  $\pm 6$  MeV.

The impact of different PDF sets (CT14, CT18, CT18A, MMHT2014, MSHT20, ATLASpdf21, NNPDF3.1, NNPDF4.0) on the  $\Gamma_W$  measurement is also studied. The results of full fits for all considered PDF sets are summarised in Table 5, with again a satisfactory fit quality for all PDF sets. The PDF dependence of the fit

Table 5: Best-fit value of  $\Gamma_W$ , total and PDF uncertainties, in MeV, and goodness-of-fit for the  $p_T^\ell$  and  $m_T$  distributions and the PDF sets described in the text. Each fit uses 14 event categories with 40 bins, for 558 degrees of freedom.

PDF set	$p_T^\ell$ fit				$m_T$ fit			
	$\Gamma_W$	$\sigma_{\text{tot}}$	$\sigma_{\text{PDF}}$	$\chi^2/\text{n.d.f.}$	$\Gamma_W$	$\sigma_{\text{tot}}$	$\sigma_{\text{PDF}}$	$\chi^2/\text{n.d.f.}$
CT14	2228	+67 -83	24	550.0/558	2202	+48 -48	5	556.8/558
CT18	2221	+68 -76	21	534.5/558	2200	+47 -48	5	548.8/558
CT18A	2207	+68 -75	18	533.0/558	2181	+47 -48	5	550.6/558
MMHT2014	2155	+71 -78	19	546.0/558	2186	+48 -48	5	562.2/558
MSHT20	2206	+66 -79	15	556.5/558	2179	+47 -48	4	559.4/558
ATLASpdf21	2213	+67 -73	18	531.3/558	2190	+47 -48	6	545.6/558
NNPDF31	2203	+65 -78	20	531.7/558	2180	+47 -47	6	560.4/558
NNPDF40	2182	+69 -68	12	550.5/558	2184	+47 -47	4	564.0/558

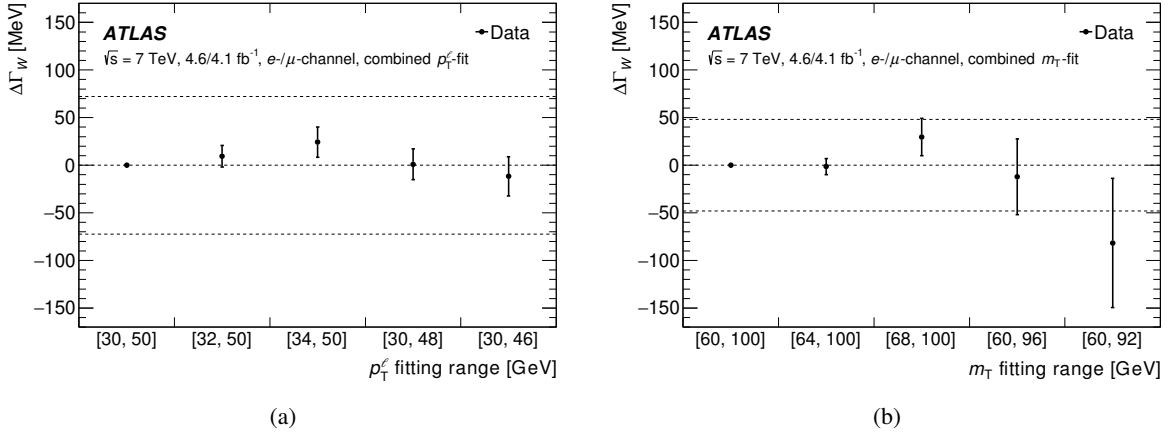


Figure 12: Difference  $\Delta\Gamma_W$  between the  $W$ -boson width measured using the (a)  $p_T^\ell$  and (b)  $m_T$  distribution fit ranges indicated in the figure and the nominal fit range. The nominal ranges are  $30 < p_T^\ell < 50$  GeV and  $60 < m_T < 100$  GeV, respectively. The outer dashed lines indicate the total measurement uncertainty for the nominal range. Results are shown for the combined fit over all categories, and for the CT18 PDF set.

result is weaker than for  $m_W$ , and all central values are well within the uncertainties obtained with CT18. The CT18 PDF set is chosen for the baseline result, consistently with the  $m_W$  measurement.

Partial fits are performed to the electron and muon channels separately. These fit results are found to agree within one standard deviation. Similarly, separate fits are performed in the  $W^+$  and  $W^-$  channels. The results for the two charges are consistent within the 68% CL contour of the two-dimensional likelihood function for the  $m_T$  fits, while for the  $p_T^\ell$  fits the consistency between the two charges is within two standard deviations. Finally, the dependence of the measurement result on the  $m_T$  and  $p_T^\ell$  ranges used for the fit is studied in Figure 12, with stable results.

Figure 13 summarises the ten nuisance parameters that induce the largest shift of  $\Gamma_W$  in fits to the  $p_T^\ell$  and  $m_T$  distributions. The largest shifts are related to the multijet (MJ) background, to the lepton calibration,

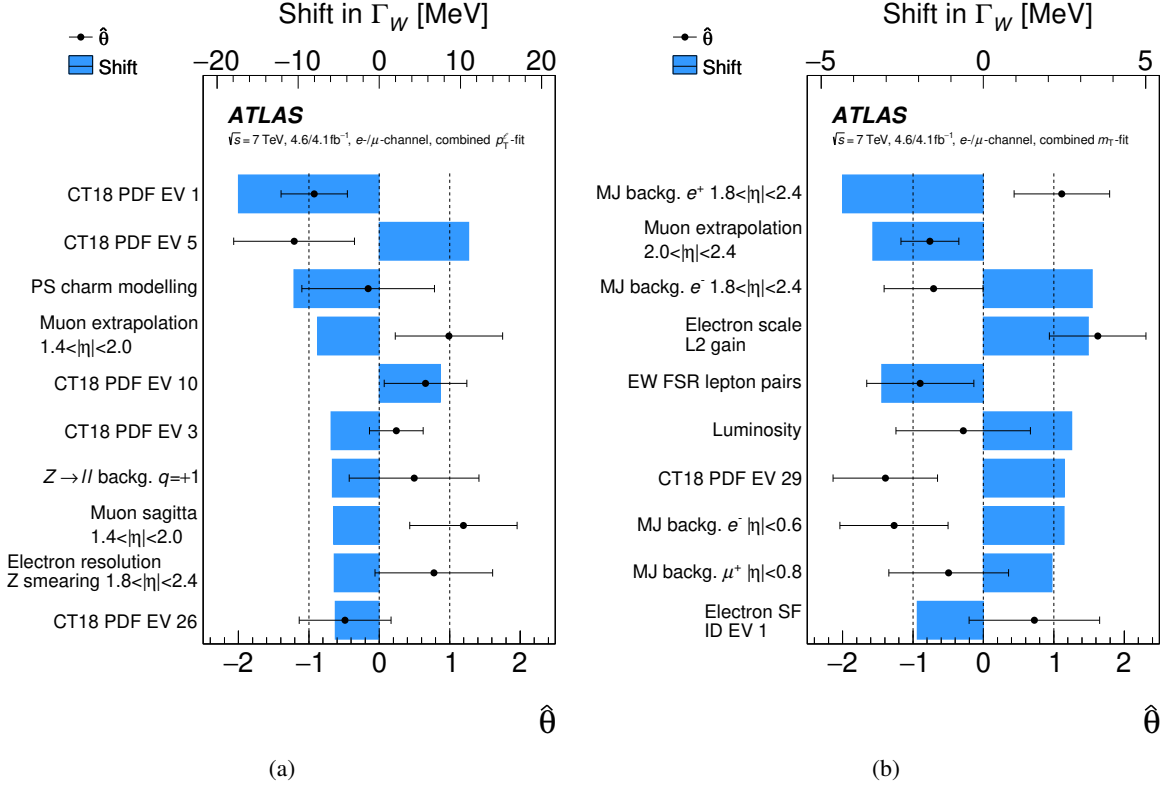


Figure 13: The ten nuisance parameters inducing the largest shifts on the fitted value of  $\Gamma_W$  in the combined PLH fits, using the (a)  $p_T^\ell$  and (b)  $m_T$  distributions and the CT18 PDF set. For a given NP  $\theta$ , the shift is defined as the product of its post-fit value  $\hat{\theta}$  and its pre-fit impact on  $\Gamma_W$ . The points, which are plotted according to the bottom horizontal scale, show  $\hat{\theta}$  for each of the nuisance parameters. The error bars show the corresponding post-fit uncertainties,  $\sigma_{\hat{\theta}}$ . The nuisance parameters are ranked according to the shift induced on  $\Gamma_W$ , the NPs with the largest shifts at the top.

to specific eigenvectors of the CT18 PDF set, to the luminosity, and to the uncertainty in charm-induced production for the  $p_T^W$  description.

The decomposition of post-fit uncertainties is done with the same method as in the  $m_W$  measurement, see Section 6.4. A summary of the uncertainties contributed by various sources is given in Table 6. The measurement is dominated by systematic uncertainties for the  $p_T^\ell$  distribution, while for the  $m_T$  distribution statistical and systematic uncertainties are of similar magnitude. The dominant systematic uncertainties are due to the parton shower modelling for  $p_T^\ell$ , and lepton and recoil performance for  $m_T$ , respectively.

An overview of selected pre- and post-fit distributions of  $m_T$  is shown in Figure 14, where a general better agreement can be observed for the post-fit case. The post-fit distributions use the final measured value of  $\Gamma_W$ .

### 7.3 Combination

The combination of results obtained from  $p_T^\ell$  and  $m_T$  distributions follows the procedure described in Section 6.4. The  $p_T^\ell$  and  $m_T$  results are fully compatible with each other. The results for all considered



Table 6: Uncertainty components for the  $p_T^\ell$ ,  $m_T$  and combined  $\Gamma_W$  measurements using the CT18 PDF set. The first columns give the total, statistical and overall systematic uncertainty in the measurements. The following columns show the contributions of modelling and experimental systematic uncertainties, grouped into categories.

Unc. [MeV]	Total	Stat.	Syst.	PDF	$A_i$	Backg.	EW	$e$	$\mu$	$u_T$	Lumi	$m_W$	PS
$p_T^\ell$	72	27	66	21	14	10	5	13	12	12	10	6	55
$m_T$	48	36	32	5	7	10	3	13	9	18	9	6	12
Combined	47	32	34	7	8	9	3	13	9	17	9	6	18

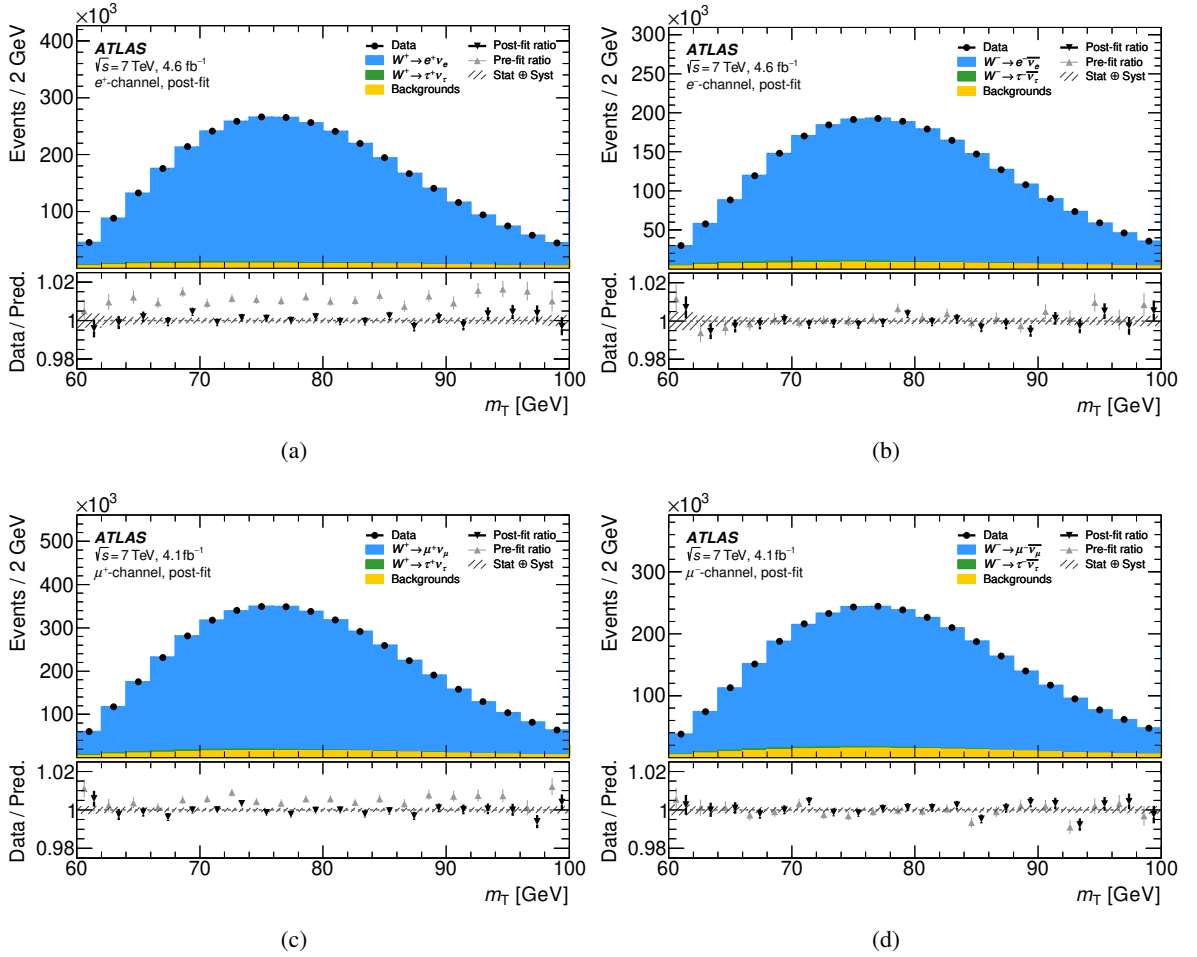


Figure 14: Post-fit distributions of  $m_T$  with data and MC for (a)  $W^+ \rightarrow e^+ \nu_e$ , (b)  $W^- \rightarrow e^- \bar{\nu}_e$ , (c)  $W^+ \rightarrow \mu^+ \nu_\mu$  and (d)  $W^- \rightarrow \mu^- \bar{\nu}_\mu$ , inclusive over all  $\eta$  regions, and using the CT18 PDF set. In the bottom panels, the darker points represent the post-fit ratio of data to MC, while the lighter points indicate the ratio before the fit. The hatched band represents the total uncertainty of the data.

Table 7: Uncertainty correlation between the  $p_T^\ell$  and  $m_T$  fits, combination weights and combination results for  $\Gamma_W$  and the indicated PDF sets.

PDF set	Correlation	weight ( $m_T$ )	weight ( $p_T^\ell$ )	Combined $\Gamma_W$ [MeV ]
CT14	50.3%	88%	12%	$2204 \pm 47$
CT18	51.5%	87%	13%	$2202 \pm 47$
CT18A	50.0%	86%	14%	$2184 \pm 47$
MMHT2014	50.8%	88%	13%	$2182 \pm 47$
MSHT20	53.6%	89%	11%	$2181 \pm 47$
ATLASpdf21	49.5%	84%	16%	$2193 \pm 46$
NNPDF31	49.9%	86%	14%	$2182 \pm 46$
NNPDF40	51.4%	85%	15%	$2184 \pm 46$

PDF sets are presented in Table 7. The weight of the  $m_T$  fit ranges from 84% to 89%, depending on the PDF set, and dominates the final result. For CT18, the final result yields:

$$\Gamma_W = 2202 \pm 32 \text{ (stat.)} \pm 34 \text{ (syst.) MeV} = 2202 \pm 47 \text{ MeV,}$$

where the first uncertainty component is statistical and the second corresponds to the total systematic uncertainties. The compatibility of the measured value with the SM expectation is illustrated in Figure 15(a), together with selected previous measurements.

## 8 Simultaneous determination of the $W$ -boson mass and width

The previously described determination of  $m_W$  assumes for the  $W$ -boson width its SM value and uncertainty, and similarly the  $\Gamma_W$  measurement uses the SM prediction for  $m_W$ . To further test the interplay between the two observables, the PLH fit is also performed with both  $m_W$  and  $\Gamma_W$  free in the fit. This fit with two parameters of interest relies on the same experimental calibrations and physics modelling. The fit yields values of  $m_W = 80351.8 \pm 16.7$  MeV and  $\Gamma_W = 2216 \pm 73$  MeV for the  $p_T^\ell$  distributions and  $m_W = 80369.4 \pm 26.8$  MeV and  $\Gamma_W = 2186 \pm 53$  MeV for the  $m_T$  distributions using the CT18 PDF set. Compared with the separate  $m_W$  and  $\Gamma_W$  fits, the decrease of  $m_W$  by 10 MeV and 25 MeV for the  $p_T^\ell$  and  $m_T$  distributions, respectively, is consistent with the larger measured value of  $\Gamma_W$  following the observed anti-correlation of  $m_W$  and  $\Gamma_W$ . The increase in total uncertainty is due to the removal of the constraints on  $\Gamma_W$  and  $m_W$  in the fit.

The combination of results obtained from  $p_T^\ell$  and  $m_T$  distributions follows the procedure described in Section 6.4. The  $p_T^\ell$  and  $m_T$  results are fully compatible with each other.

For the CT18 PDF set, the combination yields values of

$$m_W = 80354.8 \pm 16.1 \text{ MeV}$$

and

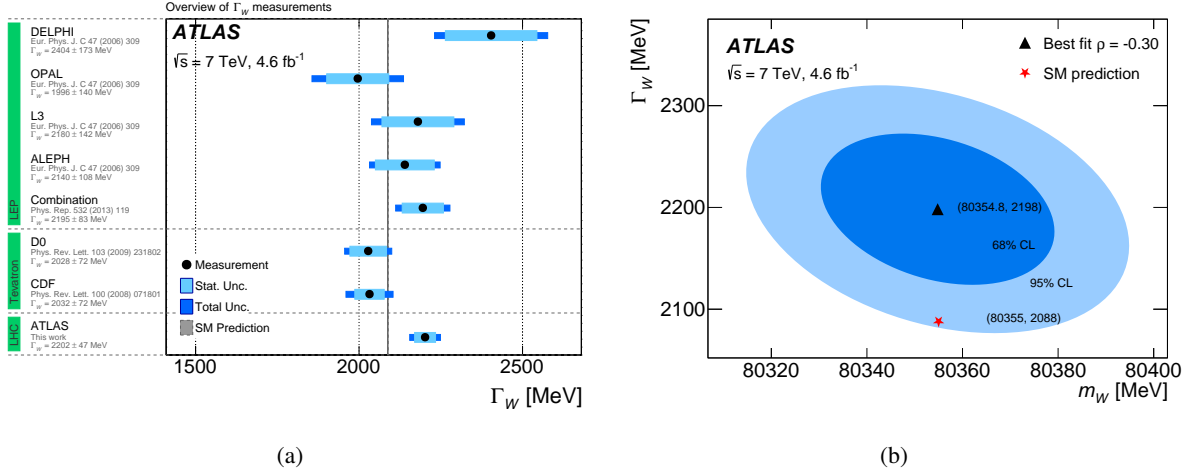


Figure 15: (a) Present measurement of  $\Gamma_W$ , compared to the SM prediction from the global electroweak fit [6], and to the measurements of LEP [10] and Tevatron [64]. (b) 68% and 95% CL uncertainty contours for the simultaneous determination of  $m_W$  and  $\Gamma_W$  using the CT18 PDF set and combining results from the  $p_T^\ell$  and  $m_T$  distributions. The triangular marker represents the best fit, while the star corresponds to the SM prediction of Ref. [6].

$$\Gamma_W = 2198 \pm 49 \text{ MeV},$$

with a correlation of  $-30\%$  that reflects the negative slope of the dependencies reported in Sections 6.4 and 7.2. The 68% and 95% CL uncertainty contours are shown in Figure 15(b).

## 9 Conclusion

This paper reports on a first measurement of the  $W$ -boson width at the LHC as well as the reanalysis of the data used in the published  $W$ -boson mass measurement, using an improved fitting technique and updated parton distribution functions. Both measurements are based on proton–proton collision data at a centre-of-mass energy of  $\sqrt{s} = 7$  TeV recorded by the ATLAS detector at the LHC in 2011, and corresponding to an integrated luminosity of  $4.6 \text{ fb}^{-1}$  and  $4.1 \text{ fb}^{-1}$  in the electron and muon channels, respectively.

The measurements of  $m_W$  using the  $p_T^\ell$  and  $m_T$  distributions are found to be consistent and their combination yields

$$m_W = 80366.5 \pm 9.8 \text{ (stat.)} \pm 12.5 \text{ (syst.) MeV} = 80366.5 \pm 15.9 \text{ MeV}.$$

The present result is compatible with and supersedes the previous measurement of  $m_W$  at ATLAS using the same data. No significant deviation from the SM expectation is observed. The PDF dependence of the  $m_W$  result is driven by the pre-fit PDF uncertainties, and is strongly reduced when allowing for enlarged uncertainties. The final results are obtained using the CT18 PDF set, which is the most conservative PDF set for these measurements and compatible with the fits using enlarged PDF uncertainties of other sets.

The measurements of  $\Gamma_W$  using the  $p_T^\ell$  and  $m_T$  distributions are also found to be consistent and their combination yields a value of

$$\Gamma_W = 2202 \pm 32 \text{ (stat.)} \pm 34 \text{ (syst.) MeV} = 2202 \pm 47 \text{ MeV.}$$

It is the currently most precise single measurement of  $\Gamma_W$  and agrees with the SM expectation of  $\Gamma_W^{\text{SM}} = 2088 \pm 1 \text{ MeV}$  within two standard deviations. The dependence of  $\Gamma_W$  on the assumed PDF set is weak compared with the measurement uncertainties.

## Acknowledgements

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

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [65].

We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benozziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEiN, Poland; FCT, Portugal; MNE/IFA, Romania; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taipei; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, United States of America.

Individual groups and members have received support from BCKDF, CANARIE, CRC and DRAC, Canada; PRIMUS 21/SCI/017, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; Norwegian Financial Mechanism 2014-2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

In addition, individual members wish to acknowledge support from CERN: European Organization for Nuclear Research (CERN PJAS); Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1190886, FONDECYT 1210400, FONDECYT 1230987); China: National Natural Science Foundation of China (NSFC - 12175119, NSFC 12275265); Czech Republic: Ministry of Education Youth and Sports (FORTE CZ.02.01.01/00/22\_008/0004632); European Union: European Research Council (ERC - 948254, ERC 101089007), Horizon 2020 Framework Programme (MUCCA - CHIST-ERA-19-XAI-00), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU);

France: Agence Nationale de la Recherche (ANR-20-CE31-0013, ANR-21-CE31-0022), Investissements d’Avenir Labex (ANR-11-LABX-0012); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG - 469666862, DFG - CR 312/5-2); Italy: Istituto Nazionale di Fisica Nucleare (ICSC, NextGenerationEU); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI 22H01227, JSPS KAKENHI 22KK0227, JSPS KAKENHI JP21H05085, JSPS KAKENHI JP22H04944); Netherlands: Netherlands Organisation for Scientific Research (NWO Veni 2020 - VI.Veni.202.179); Norway: Research Council of Norway (RCN-314472); Poland: Polish National Agency for Academic Exchange (PPN/PPO/2020/1/00002/U/00001), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, UMO-2020/37/B/ST2/01043, UMO-2021/40/C/ST2/00187, UMO-2022/47/O/ST2/00148); Slovenia: Slovenian Research Agency (ARIS grant J1-3010); Spain: Generalitat Valenciana (Artemisa, FEDER, IDIFEDER/2018/048), Ministry of Science and Innovation (RYC2019-028510-I, RYC2020-030254-I), PROMETEO and GenT Programmes Generalitat Valenciana (CIDEAGENT/2019/023, CIDEAGENT/2019/027); Sweden: Swedish Research Council (VR 2022-03845, VR 2023-03403), Knut and Alice Wallenberg Foundation (KAW 2022.0358); Switzerland: Swiss National Science Foundation (SNSF - PCEFP2\_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust RPG-2020-004); United States of America: Neubauer Family Foundation.

## References

- [1] S. L. Glashow, *Partial-symmetries of weak interactions*, *Nucl. Phys.* **22** (1961) 579.
- [2] A. Salam and J. C. Ward, *Electromagnetic and weak interactions*, *Phys. Lett.* **13** (1964) 168.
- [3] S. Weinberg, *A Model of Leptons*, *Phys. Rev. Lett.* **19** (1967) 1264.
- [4] A. Sirlin, *Radiative corrections in the  $SU(2)_L \times U(1)$  theory: A simple renormalization framework*, *Phys. Rev. D* **22** (1980) 971.
- [5] M. Awramik, M. Czakon, A. Freitas and G. Weiglein, *Precise prediction for the  $W$ -boson mass in the standard model*, *Phys. Rev. D* **69** (2004) 053006, arXiv: [hep-ph/0311148](https://arxiv.org/abs/hep-ph/0311148).
- [6] J. de Blas et al., *Global analysis of electroweak data in the Standard Model*, *Phys. Rev. D* **106** (2022) 033003, arXiv: [2112.07274](https://arxiv.org/abs/2112.07274) [[hep-ph](#)].
- [7] The GFitter Group, J. Haller et al., *Update of the global electroweak fit and constraints on two-Higgs-doublet models*, *Eur. Phys. J. C* **78** (2018) 675, arXiv: [1803.01853](https://arxiv.org/abs/1803.01853) [[hep-ph](#)].
- [8] J. Erler, ‘Global Fits to Electroweak Data Using GAPP’, *QCD and weak boson physics in Run II. Proceedings, Batavia, IL, March 4-6, June 3-4, November 4-6, 1999*, arXiv: [hep-ph/0005084](https://arxiv.org/abs/hep-ph/0005084) [[hep-ph](#)].
- [9] CDF Collaboration, *High-precision measurement of the  $W$  boson mass with the CDF II detector*, *Science* **376** (2022) 170.
- [10] The ALEPH Collaboration, The DELPHI Collaboration, The L3 Collaboration, The OPAL Collaboration, The LEP Electroweak Working Group, *Electroweak measurements in electron-positron collisions at  $W$ -boson-pair energies at LEP*, *Phys. Rept.* **532** (2013) 119, arXiv: [1302.3415](https://arxiv.org/abs/1302.3415) [[hep-ex](#)].

- [11] D0 Collaboration, *Measurement of the W Boson Mass with the D0 Detector*, *Phys. Rev. Lett.* **108** (2012) 151804, arXiv: [1203.0293 \[hep-ex\]](#).
- [12] ATLAS Collaboration, *Measurement of the W-boson mass in pp collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector*, *Eur. Phys. J. C* **78** (2018) 110, arXiv: [1701.07240 \[hep-ex\]](#),  
Erratum: *Eur. Phys. J. C* **78** (2018) 898.
- [13] LHCb Collaboration, *Measurement of the W boson mass*, *JHEP* **01** (2022) 036, arXiv: [2109.01113 \[hep-ex\]](#).
- [14] S. Amoroso et al., *Compatibility and combination of world W-boson mass measurements*, (2023), arXiv: [2308.09417 \[hep-ex\]](#).
- [15] M. E. Peskin and T. Takeuchi, *Estimation of oblique electroweak corrections*, *Phys. Rev. D* **46** (1992) 381.
- [16] S. Heinemeyer, W. Hollik, G. Weiglein and L. Zeune, *Implications of LHC search results on the W boson mass prediction in the MSSM*, *JHEP* **12** (2013) 084, arXiv: [1311.1663 \[hep-ph\]](#).
- [17] Particle Data Group, R. L. Workman et al., *Review of Particle Physics*, *PTEP* **2022** (2022) 083C01.
- [18] CDF Collaboration, *Precise measurement of the W-boson mass with the CDF II detector*, *Phys. Rev. Lett.* **108** (2012) 151803, arXiv: [1203.0275 \[hep-ex\]](#).
- [19] D0 Collaboration, *Measurement of the W boson mass with the D0 detector*, *Phys. Rev. D* **89** (2014) 012005, arXiv: [1310.8628 \[hep-ex\]](#).
- [20] W. A. Rolke, A. M. López and J. Conrad, *Limits and confidence intervals in the presence of nuisance parameters*, *Nucl. Instrum. Meth. A* **551** (2005) 493, arXiv: [physics/0403059](#).
- [21] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *JINST* **3** (2008) S08003.
- [22] ATLAS Collaboration, *Performance of the ATLAS Trigger System in 2010*, *Eur. Phys. J. C* **72** (2012) 1849, arXiv: [1110.1530 \[hep-ex\]](#).
- [23] ATLAS Collaboration, *The ATLAS Collaboration Software and Firmware*, ATL-SOFT-PUB-2021-001, 2021, URL: <https://cds.cern.ch/record/2767187>.
- [24] P. Nason, *A new method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **11** (2004) 040, arXiv: [hep-ph/0409146](#).
- [25] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070, arXiv: [0709.2092 \[hep-ph\]](#).
- [26] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043, arXiv: [1002.2581 \[hep-ph\]](#).
- [27] T. Sjöstrand, S. Mrenna and P. Skands, *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006) 026, arXiv: [hep-ph/0603175](#).
- [28] T. Sjöstrand, S. Mrenna and P. Skands, *A brief introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852, arXiv: [0710.3820 \[hep-ph\]](#).

- [29] ATLAS Collaboration, *Measurement of the  $Z/\gamma^*$  boson transverse momentum distribution in  $pp$  collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector*, *JHEP* **09** (2014) 145, arXiv: [1406.3660 \[hep-ex\]](#).
- [30] H.-L. Lai et al., *New parton distributions for collider physics*, *Phys. Rev. D* **82** (2010) 074024, arXiv: [1007.2241 \[hep-ph\]](#).
- [31] J. Pumplin et al., *New Generation of Parton Distributions with Uncertainties from Global QCD Analysis*, *JHEP* **07** (2002) 012, arXiv: [hep-ph/0201195](#).
- [32] P. Golonka and Z. Was, *PHOTOS Monte Carlo: a precision tool for QED corrections in Z and W decays*, *Eur. Phys. J. C* **45** (2006) 97, arXiv: [hep-ph/0506026](#).
- [33] ATLAS Collaboration, *Precision measurement and interpretation of inclusive  $W^+$ ,  $W^-$  and  $Z/\gamma^*$  production cross sections with the ATLAS detector*, *Eur. Phys. J. C* **77** (2017) 367, arXiv: [1612.03016 \[hep-ex\]](#).
- [34] S. Frixione and B. R. Webber, *Matching NLO QCD computations and parton shower simulations*, *JHEP* **06** (2002) 029, arXiv: [hep-ph/0204244](#).
- [35] S. Frixione, P. Nason and B. R. Webber, *Matching NLO QCD and parton showers in heavy flavour production*, *JHEP* **08** (2003) 007, arXiv: [hep-ph/0305252](#).
- [36] S. Frixione, E. Laenen, P. Motylinski and B. R. Webber, *Single-top production in MC@NLO*, *JHEP* **03** (2006) 092, arXiv: [hep-ph/0512250](#).
- [37] ATLAS Collaboration, *The ATLAS Simulation Infrastructure*, *Eur. Phys. J. C* **70** (2010) 823, arXiv: [1005.4568 \[physics.ins-det\]](#).
- [38] S. Agostinelli et al., *GEANT4—a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250.
- [39] ATLAS Collaboration, *Summary of ATLAS Pythia 8 tunes*, ATL-PHYS-PUB-2012-003, 2012, URL: <https://cds.cern.ch/record/1474107>.
- [40] ATLAS Collaboration, *Electron reconstruction and identification efficiency measurements with the ATLAS detector using the 2011 LHC proton–proton collision data*, *Eur. Phys. J. C* **74** (2014) 2941, arXiv: [1404.2240 \[hep-ex\]](#).
- [41] ATLAS Collaboration, *Electron and photon energy calibration with the ATLAS detector using LHC Run 1 data*, *Eur. Phys. J. C* **74** (2014) 3071, arXiv: [1407.5063 \[hep-ex\]](#).
- [42] ATLAS Collaboration, *Measurement of the muon reconstruction performance of the ATLAS detector using 2011 and 2012 LHC proton–proton collision data*, *Eur. Phys. J. C* **74** (2014) 3130, arXiv: [1407.3935 \[hep-ex\]](#).
- [43] ATLAS Collaboration, *Improved luminosity determination in  $pp$  collisions at  $\sqrt{s} = 7$  TeV using the ATLAS detector at the LHC*, *Eur. Phys. J. C* **73** (2013) 2518, arXiv: [1302.4393 \[hep-ex\]](#).
- [44] S. Dulat et al., *New parton distribution functions from a global analysis of quantum chromodynamics*, *Phys. Rev. D* **93** (2016) 033006, arXiv: [1506.07443 \[hep-ph\]](#).

- [45] L. A. Harland-Lang, A. D. Martin, P. Motylinski and R. S. Thorne, *Parton distributions in the LHC era: MMHT 2014 PDFs*, *Eur. Phys. J. C* **75** (2015) 204, arXiv: [1412.3989 \[hep-ph\]](#).
- [46] ATLAS Collaboration, *Determination of the parton distribution functions of the proton using diverse ATLAS data from pp collisions at  $\sqrt{s} = 7, 8$  and 13 TeV*, *Eur. Phys. J. C* **82** (2022) 438, arXiv: [2112.11266 \[hep-ex\]](#).
- [47] T.-J. Hou et al., *New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC*, *Phys. Rev. D* **103** (2021) 014013, arXiv: [1912.10053 \[hep-ph\]](#).
- [48] S. Bailey, T. Cridge, L. A. Harland-Lang, A. D. Martin and R. S. Thorne, *Parton distributions from LHC, HERA, Tevatron and fixed target data: MSHT20 PDFs*, *Eur. Phys. J. C* **81** (2021) 341, arXiv: [2012.04684 \[hep-ph\]](#).
- [49] NNPDF Collaboration, *Parton distributions from high-precision collider data*, *Eur. Phys. J. C* **77** (2017) 663, arXiv: [1706.00428 \[hep-ph\]](#).
- [50] NNPDF Collaboration, R. D. Ball et al., *The path to proton structure at 1% accuracy*, *Eur. Phys. J. C* **82** (2022) 428, arXiv: [2109.02653 \[hep-ph\]](#).
- [51] A. Pinto et al., *Uncertainty components in profile likelihood fits*, (2023), arXiv: [2307.04007 \[physics.data-an\]](#).
- [52] The ALEPH Collaboration, The DELPHI Collaboration, The L3 Collaboration, The OPAL Collaboration, The SLD Collaboration, The LEP Electroweak Working Group, The SLD Electroweak and Heavy Flavour Groups, *Precision electroweak measurements on the Z resonance*, *Phys. Rept.* **427** (2006) 257, arXiv: [hep-ex/0509008](#).
- [53] K. Pearson, *LIII. On lines and planes of closest fit to systems of points in space*, *London Edinburgh Dublin Philos. Mag. & J. Sci.* **2** (1901) 559.
- [54] H. Hotelling, *Analysis of a complex of statistical variables into principal components*, *J. Educ. Psychol.* (1933) 417.
- [55] ATLAS Collaboration, *Measurement of the angular coefficients in Z-boson events using electron and muon pairs from data taken at  $\sqrt{s} = 8$  TeV with the ATLAS detector*, *JHEP* **08** (2016) 159, arXiv: [1606.00689 \[hep-ex\]](#).
- [56] ATLAS Collaboration, *Precise measurements of W and Z transverse momentum spectra with the ATLAS detector at  $\sqrt{s} = 5.02$  TeV and 13 TeV*, CERN-EP-2024-080, 2024.
- [57] J. Pumplin et al., *Uncertainties of predictions from parton distribution functions. II. The Hessian method*, *Phys. Rev. D* **65** (2001) 014013, arXiv: [hep-ph/0101032](#).
- [58] T. Sjöstrand and P. Z. Skands, *Transverse-momentum-ordered showers and interleaved multiple interactions*, *Eur. Phys. J. C* **39** (2005) 129, arXiv: [hep-ph/0408302](#).
- [59] L. Lyons, D. Gibaut and P. Clifford, *How to combine correlated estimates of a single physical quantity*, *Nucl. Instrum. Meth. A* **270** (1988) 110.
- [60] ATLAS and CMS Collaborations, *Combination of measurements of the top quark mass from data collected by the ATLAS and CMS experiments at  $\sqrt{s}=7$  and 8 TeV*, (2024), arXiv: [2402.08713 \[hep-ex\]](#).



- [61] ATLAS Collaboration, *Combined Measurement of the Higgs Boson Mass from the  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ^* \rightarrow 4\ell$  Decay Channels with the ATLAS Detector Using  $\sqrt{s}=7, 8,$  and 13 TeV pp Collision Data*, *Phys. Rev. Lett.* **131** (2023) 251802, arXiv: [2308.04775](https://arxiv.org/abs/2308.04775) [[hep-ex](#)].
- [62] J. de Blas, M. Pierini, L. Reina and L. Silvestrini, *Impact of the Recent Measurements of the Top-Quark and W-Boson Masses on Electroweak Precision Fits*, *Phys. Rev. Lett.* **129** (2022) 271801, arXiv: [2204.04204](https://arxiv.org/abs/2204.04204) [[hep-ph](#)].
- [63] J. de Blas et al., *The Global Electroweak and Higgs Fits in the LHC era*, *PoS EPS-HEP2017* (2017) 467, ed. by P. Checchia et al., arXiv: [1710.05402](https://arxiv.org/abs/1710.05402) [[hep-ph](#)].
- [64] The Tevatron Electroweak Working Group, *Combination of CDF and D0 Results on the Width of the W boson*, 2010, arXiv: [1003.2826](https://arxiv.org/abs/1003.2826) [[hep-ex](#)].
- [65] ATLAS Collaboration, *ATLAS Computing Acknowledgements*, ATL-SOFT-PUB-2023-001, 2023, URL: <https://cds.cern.ch/record/2869272>.

## The ATLAS Collaboration

G. Aad <sup>103</sup>, E. Aakvaag <sup>16</sup>, B. Abbott <sup>121</sup>, S. Abdelhameed <sup>117a</sup>, K. Abeling <sup>55</sup>, N.J. Abicht <sup>49</sup>, S.H. Abidi <sup>29</sup>, M. Aboeela <sup>44</sup>, A. Aboulhorma <sup>35e</sup>, H. Abramowicz <sup>152</sup>, H. Abreu <sup>151</sup>, Y. Abulaiti <sup>118</sup>, B.S. Acharya <sup>69a,69b,k</sup>, A. Ackermann <sup>63a</sup>, C. Adam Bourdarios <sup>4</sup>, L. Adamczyk <sup>86a</sup>, S.V. Addepalli <sup>26</sup>, M.J. Addison <sup>102</sup>, J. Adelman <sup>116</sup>, A. Adiguzel <sup>21c</sup>, T. Adye <sup>135</sup>, A.A. Affolder <sup>137</sup>, Y. Afik <sup>39</sup>, M.N. Agaras <sup>13</sup>, J. Agarwala <sup>73a,73b</sup>, A. Aggarwal <sup>101</sup>, C. Agheorghiesei <sup>27c</sup>, A. Ahmad <sup>36</sup>, F. Ahmadov <sup>38,x</sup>, W.S. Ahmed <sup>105</sup>, S. Ahuja <sup>96</sup>, X. Ai <sup>62e</sup>, G. Aielli <sup>76a,76b</sup>, A. Aikot <sup>164</sup>, M. Ait Tamliah <sup>35e</sup>, B. Aitbenchikh <sup>35a</sup>, M. Akbiyik <sup>101</sup>, T.P.A. Åkesson <sup>99</sup>, A.V. Akimov <sup>37</sup>, D. Akiyama <sup>169</sup>, N.N. Akolkar <sup>24</sup>, S. Aktas <sup>21a</sup>, K. Al Houry <sup>41</sup>, G.L. Alberghi <sup>23b</sup>, J. Albert <sup>166</sup>, P. Albicocco <sup>53</sup>, G.L. Albouy <sup>60</sup>, S. Alderweireldt <sup>52</sup>, Z.L. Alegria <sup>122</sup>, M. Aleksa <sup>36</sup>, I.N. Aleksandrov <sup>38</sup>, C. Alexa <sup>27b</sup>, T. Alexopoulos <sup>10</sup>, F. Alfonsi <sup>23b</sup>, M. Algren <sup>56</sup>, M. Alhroob <sup>168</sup>, B. Ali <sup>133</sup>, H.M.J. Ali <sup>92</sup>, S. Ali <sup>31</sup>, S.W. Alibocus <sup>93</sup>, M. Aliev <sup>33c</sup>, G. Alimonti <sup>71a</sup>, W. Alkahi <sup>55</sup>, C. Allaire <sup>66</sup>, B.M.M. Allbrooke <sup>147</sup>, J.F. Allen <sup>52</sup>, C.A. Allendes Flores <sup>138f</sup>, P.P. Allport <sup>20</sup>, A. Aloisio <sup>72a,72b</sup>, F. Alonso <sup>91</sup>, C. Alpigiani <sup>139</sup>, Z.M.K. Alsolami <sup>92</sup>, M. Alvarez Estevez <sup>100</sup>, A. Alvarez Fernandez <sup>101</sup>, M. Alves Cardoso <sup>56</sup>, M.G. Alvigi <sup>72a,72b</sup>, M. Aly <sup>102</sup>, Y. Amaral Coutinho <sup>83b</sup>, A. Ambler <sup>105</sup>, C. Amelung <sup>36</sup>, M. Amerl <sup>102</sup>, C.G. Ames <sup>110</sup>, D. Amidei <sup>107</sup>, K.J. Amirie <sup>156</sup>, S.P. Amor Dos Santos <sup>131a</sup>, K.R. Amos <sup>164</sup>, S. An <sup>84</sup>, V. Ananiev <sup>126</sup>, C. Anastopoulos <sup>140</sup>, T. Andeen <sup>11</sup>, J.K. Anders <sup>36</sup>, S.Y. Andrean <sup>47a,47b</sup>, A. Andreazza <sup>71a,71b</sup>, S. Angelidakis <sup>9</sup>, A. Angerami <sup>41,z</sup>, A.V. Anisenkov <sup>37</sup>, A. Annovi <sup>74a</sup>, C. Antel <sup>56</sup>, E. Antipov <sup>146</sup>, M. Antonelli <sup>53</sup>, F. Anulli <sup>75a</sup>, M. Aoki <sup>84</sup>, T. Aoki <sup>154</sup>, M.A. Aparo <sup>147</sup>, L. Aperio Bella <sup>48</sup>, C. Appelt <sup>18</sup>, A. Apyan <sup>26</sup>, S.J. Arbiol Val <sup>87</sup>, C. Arcangeletti <sup>53</sup>, A.T.H. Arce <sup>51</sup>, E. Arena <sup>93</sup>, J-F. Arguin <sup>109</sup>, S. Argyropoulos <sup>54</sup>, J.-H. Arling <sup>48</sup>, O. Arnaez <sup>4</sup>, H. Arnold <sup>115</sup>, G. Artoni <sup>75a,75b</sup>, H. Asada <sup>112</sup>, K. Asai <sup>119</sup>, S. Asai <sup>154</sup>, N.A. Asbah <sup>36</sup>, K. Assamagan <sup>29</sup>, R. Astalos <sup>28a</sup>, K.S.V. Astrand <sup>99</sup>, S. Atashi <sup>160</sup>, R.J. Atkin <sup>33a</sup>, M. Atkinson <sup>163</sup>, H. Atmani <sup>35f</sup>, P.A. Atmasiddha <sup>129</sup>, K. Augsten <sup>133</sup>, S. Auricchio <sup>72a,72b</sup>, A.D. Auriol <sup>20</sup>, V.A. Austrup <sup>102</sup>, G. Avolio <sup>36</sup>, K. Axiotis <sup>56</sup>, G. Azuelos <sup>109,ad</sup>, D. Babal <sup>28b</sup>, H. Bachacou <sup>136</sup>, K. Bachas <sup>153,o</sup>, A. Bachi <sup>34</sup>, F. Backman <sup>47a,47b</sup>, A. Badea <sup>39</sup>, T.M. Baer <sup>107</sup>, P. Bagnaia <sup>75a,75b</sup>, M. Bahmani <sup>18</sup>, D. Bahner <sup>54</sup>, K. Bai <sup>124</sup>, J.T. Baines <sup>135</sup>, L. Baines <sup>95</sup>, O.K. Baker <sup>173</sup>, E. Bakos <sup>15</sup>, D. Bakshi Gupta <sup>8</sup>, V. Balakrishnan <sup>121</sup>, R. Balasubramanian <sup>115</sup>, E.M. Baldin <sup>37</sup>, P. Balek <sup>86a</sup>, E. Ballabene <sup>23b,23a</sup>, F. Balli <sup>136</sup>, L.M. Baltos <sup>63a</sup>, W.K. Balunas <sup>32</sup>, J. Balz <sup>101</sup>, I. Bamwidhi <sup>117b</sup>, E. Banas <sup>87</sup>, M. Bandieramonte <sup>130</sup>, A. Bandyopadhyay <sup>24</sup>, S. Bansal <sup>24</sup>, L. Barak <sup>152</sup>, M. Barakat <sup>48</sup>, E.L. Barberio <sup>106</sup>, D. Barberis <sup>57b,57a</sup>, M. Barbero <sup>103</sup>, M.Z. Barel <sup>115</sup>, K.N. Barends <sup>33a</sup>, T. Barillari <sup>111</sup>, M-S. Barisits <sup>36</sup>, T. Barklow <sup>144</sup>, P. Baron <sup>123</sup>, D.A. Baron Moreno <sup>102</sup>, A. Baroncelli <sup>62a</sup>, G. Barone <sup>29</sup>, A.J. Barr <sup>127</sup>, J.D. Barr <sup>97</sup>, F. Barreiro <sup>100</sup>, J. Barreiro Guimarães da Costa <sup>14a</sup>, U. Barron <sup>152</sup>, M.G. Barros Teixeira <sup>131a</sup>, S. Barsov <sup>37</sup>, F. Bartels <sup>63a</sup>, R. Bartoldus <sup>144</sup>, A.E. Barton <sup>92</sup>, P. Bartos <sup>28a</sup>, A. Basan <sup>101</sup>, M. Baselga <sup>49</sup>, A. Bassalat <sup>66,b</sup>, M.J. Basso <sup>157a</sup>, R. Bate <sup>165</sup>, R.L. Bates <sup>59</sup>, S. Batlamous <sup>100</sup>, B. Batool <sup>142</sup>, M. Battaglia <sup>137</sup>, D. Battulga <sup>18</sup>, M. Baucé <sup>75a,75b</sup>, M. Bauer <sup>36</sup>, P. Bauer <sup>24</sup>, L.T. Bazzano Hurrell <sup>30</sup>, J.B. Beacham <sup>51</sup>, T. Beau <sup>128</sup>, J.Y. Beaucamp <sup>91</sup>, P.H. Beauchemin <sup>159</sup>, P. Bechtel <sup>24</sup>, H.P. Beck <sup>19,n</sup>, K. Becker <sup>168</sup>, A.J. Beddall <sup>82</sup>, V.A. Bednyakov <sup>38</sup>, C.P. Bee <sup>146</sup>, L.J. Beemster <sup>15</sup>, T.A. Beermann <sup>36</sup>, M. Begalli <sup>83d</sup>, M. Beger <sup>29</sup>, A. Behera <sup>146</sup>, J.K. Behr <sup>48</sup>, J.F. Beirer <sup>36</sup>, F. Beisiegel <sup>24</sup>, M. Belfkir <sup>117b</sup>, G. Bella <sup>152</sup>, L. Bellagamba <sup>23b</sup>, A. Bellerive <sup>34</sup>, P. Bellos <sup>20</sup>, K. Beloborodov <sup>37</sup>, D. Benckekroun <sup>35a</sup>, F. Bendebba <sup>35a</sup>, Y. Benhammou <sup>152</sup>,

K.C. Benkendorfer <sup>61</sup>, L. Beresford <sup>48</sup>, M. Beretta <sup>53</sup>, E. Bergeaas Kuutmann <sup>162</sup>, N. Berger <sup>4</sup>,  
 B. Bergmann <sup>133</sup>, J. Beringer <sup>17a</sup>, G. Bernardi <sup>5</sup>, C. Bernius <sup>144</sup>, F.U. Bernlochner <sup>24</sup>,  
 F. Bernon <sup>36,103</sup>, A. Berrocal Guardia <sup>13</sup>, T. Berry <sup>96</sup>, P. Berta <sup>134</sup>, A. Berthold <sup>50</sup>, S. Bethke <sup>111</sup>,  
 A. Betti <sup>75a,75b</sup>, A.J. Bevan <sup>95</sup>, N.K. Bhalla <sup>54</sup>, M. Bhamjee <sup>33c</sup>, S. Bhatta <sup>146</sup>,  
 D.S. Bhattacharya <sup>167</sup>, P. Bhattarai <sup>144</sup>, K.D. Bhide <sup>54</sup>, V.S. Bhopatkar <sup>122</sup>, R.M. Bianchi <sup>130</sup>,  
 G. Bianco <sup>23b,23a</sup>, O. Biebel <sup>110</sup>, R. Bielski <sup>124</sup>, M. Biglietti <sup>77a</sup>, C.S. Billingsley <sup>44</sup>, M. Bindi <sup>55</sup>,  
 A. Bingul <sup>21b</sup>, C. Bini <sup>75a,75b</sup>, A. Biondini <sup>93</sup>, C.J. Birch-sykes <sup>102</sup>, G.A. Bird <sup>32</sup>, M. Birman <sup>170</sup>,  
 M. Biros <sup>134</sup>, S. Biryukov <sup>147</sup>, T. Bisanz <sup>49</sup>, E. Bisceglie <sup>43b,43a</sup>, J.P. Biswal <sup>135</sup>, D. Biswas <sup>142</sup>,  
 I. Bloch <sup>48</sup>, A. Blue <sup>59</sup>, U. Blumenschein <sup>95</sup>, J. Blumenthal <sup>101</sup>, V.S. Bobrovnikov <sup>37</sup>,  
 M. Boehler <sup>54</sup>, B. Boehm <sup>167</sup>, D. Bogavac <sup>36</sup>, A.G. Bogdanchikov <sup>37</sup>, C. Bohm <sup>47a</sup>,  
 V. Boisvert <sup>96</sup>, P. Bokan <sup>36</sup>, T. Bold <sup>86a</sup>, M. Bomben <sup>5</sup>, M. Bona <sup>95</sup>, M. Boonekamp <sup>136</sup>,  
 C.D. Booth <sup>96</sup>, A.G. Borbély <sup>59</sup>, I.S. Bordulev <sup>37</sup>, H.M. Borecka-Bielska <sup>109</sup>, G. Borissov <sup>92</sup>,  
 D. Bortoletto <sup>127</sup>, D. Boscherini <sup>23b</sup>, M. Bosman <sup>13</sup>, J.D. Bossio Sola <sup>36</sup>, K. Bouaouda <sup>35a</sup>,  
 N. Bouchhar <sup>164</sup>, L. Boudet <sup>4</sup>, J. Boudreau <sup>130</sup>, E.V. Bouhova-Thacker <sup>92</sup>, D. Boumediene <sup>40</sup>,  
 R. Bouquet <sup>57b,57a</sup>, A. Boveia <sup>120</sup>, J. Boyd <sup>36</sup>, D. Boye <sup>29</sup>, I.R. Boyko <sup>38</sup>, L. Bozianu <sup>56</sup>,  
 J. Bracinik <sup>20</sup>, N. Brahimí <sup>4</sup>, G. Brandt <sup>172</sup>, O. Brandt <sup>32</sup>, F. Braren <sup>48</sup>, B. Brau <sup>104</sup>,  
 J.E. Brau <sup>124</sup>, R. Brenner <sup>170</sup>, L. Brenner <sup>115</sup>, R. Brenner <sup>162</sup>, S. Bressler <sup>170</sup>, D. Britton <sup>59</sup>,  
 D. Britzger <sup>111</sup>, I. Brock <sup>24</sup>, G. Brooijmans <sup>41</sup>, E. Brost <sup>29</sup>, L.M. Brown <sup>166</sup>, L.E. Bruce <sup>61</sup>,  
 T.L. Bruckler <sup>127</sup>, P.A. Bruckman de Renstrom <sup>87</sup>, B. Brüers <sup>48</sup>, A. Bruni <sup>23b</sup>, G. Bruni <sup>23b</sup>,  
 M. Bruschi <sup>23b</sup>, N. Bruscinò <sup>75a,75b</sup>, T. Buanes <sup>16</sup>, Q. Buat <sup>139</sup>, D. Buchin <sup>111</sup>, A.G. Buckley <sup>59</sup>,  
 O. Bulekov <sup>37</sup>, B.A. Bullard <sup>144</sup>, S. Burdin <sup>93</sup>, C.D. Burgard <sup>49</sup>, A.M. Burger <sup>36</sup>,  
 B. Burghgrave <sup>8</sup>, O. Burlayenko <sup>54</sup>, J.T.P. Burr <sup>32</sup>, J.C. Burzynski <sup>143</sup>, E.L. Busch <sup>41</sup>,  
 V. Büscher <sup>101</sup>, P.J. Bussey <sup>59</sup>, J.M. Butler <sup>25</sup>, C.M. Buttar <sup>59</sup>, J.M. Butterworth <sup>97</sup>,  
 W. Buttinger <sup>135</sup>, C.J. Buxo Vazquez <sup>108</sup>, A.R. Buzykaev <sup>37</sup>, S. Cabrera Urbán <sup>164</sup>,  
 L. Cadamuro <sup>66</sup>, D. Caforio <sup>58</sup>, H. Cai <sup>130</sup>, Y. Cai <sup>14a,14e</sup>, Y. Cai <sup>14c</sup>, V.M.M. Cairo <sup>36</sup>,  
 O. Cakir <sup>3a</sup>, N. Calace <sup>36</sup>, P. Calafiura <sup>17a</sup>, G. Calderini <sup>128</sup>, P. Calfayan <sup>68</sup>, G. Callea <sup>59</sup>,  
 L.P. Caloba <sup>83b</sup>, D. Calvet <sup>40</sup>, S. Calvet <sup>40</sup>, M. Calvetti <sup>74a,74b</sup>, R. Camacho Toro <sup>128</sup>,  
 S. Camarda <sup>36</sup>, D. Camarero Munoz <sup>26</sup>, P. Camarri <sup>76a,76b</sup>, M.T. Camerlingo <sup>72a,72b</sup>,  
 D. Cameron <sup>36</sup>, C. Camincher <sup>166</sup>, M. Campanelli <sup>97</sup>, A. Camplani <sup>42</sup>, V. Canale <sup>72a,72b</sup>,  
 A.C. Canbay <sup>3a</sup>, E. Canonero <sup>96</sup>, J. Cantero <sup>164</sup>, Y. Cao <sup>163</sup>, F. Capocasa <sup>26</sup>, M. Capua <sup>43b,43a</sup>,  
 A. Carbone <sup>71a,71b</sup>, R. Cardarelli <sup>76a</sup>, J.C.J. Cardenas <sup>8</sup>, G. Carducci <sup>43b,43a</sup>, T. Carli <sup>36</sup>,  
 G. Carlino <sup>72a</sup>, J.I. Carlotto <sup>13</sup>, B.T. Carlson <sup>130,p</sup>, E.M. Carlson <sup>166,157a</sup>, J. Carmignani <sup>93</sup>,  
 L. Carminati <sup>71a,71b</sup>, A. Carnelli <sup>136</sup>, M. Carnesale <sup>75a,75b</sup>, S. Caron <sup>114</sup>, E. Carquin <sup>138f</sup>,  
 S. Carrá <sup>71a</sup>, G. Carratta <sup>23b,23a</sup>, A.M. Carroll <sup>124</sup>, T.M. Carter <sup>52</sup>, M.P. Casado <sup>13,h</sup>,  
 M. Caspar <sup>48</sup>, F.L. Castillo <sup>4</sup>, L. Castillo Garcia <sup>13</sup>, V. Castillo Gimenez <sup>164</sup>, N.F. Castro <sup>131a,131e</sup>,  
 A. Catinaccio <sup>36</sup>, J.R. Catmore <sup>126</sup>, T. Cavaliere <sup>4</sup>, V. Cavaliere <sup>29</sup>, N. Cavalli <sup>23b,23a</sup>,  
 Y.C. Cekmecelioglu <sup>48</sup>, E. Celebi <sup>21a</sup>, S. Cella <sup>36</sup>, F. Celli <sup>127</sup>, M.S. Centonze <sup>70a,70b</sup>,  
 V. Cepaitis <sup>56</sup>, K. Cerny <sup>123</sup>, A.S. Cerqueira <sup>83a</sup>, A. Cerri <sup>147</sup>, L. Cerrito <sup>76a,76b</sup>, F. Cerutti <sup>17a</sup>,  
 B. Cervato <sup>142</sup>, A. Cervelli <sup>23b</sup>, G. Cesarini <sup>53</sup>, S.A. Cetin <sup>82</sup>, D. Chakraborty <sup>116</sup>, J. Chan <sup>17a</sup>,  
 W.Y. Chan <sup>154</sup>, J.D. Chapman <sup>32</sup>, E. Chapon <sup>136</sup>, B. Chargeishvili <sup>150b</sup>, D.G. Charlton <sup>20</sup>,  
 M. Chatterjee <sup>19</sup>, C. Chauhan <sup>134</sup>, Y. Che <sup>14c</sup>, S. Chekanov <sup>6</sup>, S.V. Chekulaev <sup>157a</sup>,  
 G.A. Chelkov <sup>38,a</sup>, A. Chen <sup>107</sup>, B. Chen <sup>152</sup>, B. Chen <sup>166</sup>, H. Chen <sup>14c</sup>, H. Chen <sup>29</sup>,  
 J. Chen <sup>62c</sup>, J. Chen <sup>143</sup>, M. Chen <sup>127</sup>, S. Chen <sup>154</sup>, S.J. Chen <sup>14c</sup>, X. Chen <sup>62c,136</sup>,  
 X. Chen <sup>14b,ac</sup>, Y. Chen <sup>62a</sup>, C.L. Cheng <sup>171</sup>, H.C. Cheng <sup>64a</sup>, S. Cheong <sup>144</sup>, A. Cheplakov <sup>38</sup>,  
 E. Cheremushkina <sup>48</sup>, E. Cherepanova <sup>115</sup>, R. Cherkaoui El Moursli <sup>35e</sup>, E. Cheu <sup>7</sup>, K. Cheung <sup>65</sup>,  
 L. Chevalier <sup>136</sup>, V. Chiarella <sup>53</sup>, G. Chiarelli <sup>74a</sup>, N. Chiedde <sup>103</sup>, G. Chiodini <sup>70a</sup>,  
 A.S. Chisholm <sup>20</sup>, A. Chitan <sup>27b</sup>, M. Chitishvili <sup>164</sup>, M.V. Chizhov <sup>38</sup>, K. Choi <sup>11</sup>, Y. Chou <sup>139</sup>,

E.Y.S. Chow [id114](#), K.L. Chu [id170](#), M.C. Chu [id64a](#), X. Chu [id14a,14e](#), J. Chudoba [id132](#),  
 J.J. Chwastowski [id87](#), D. Cieri [id111](#), K.M. Ciesla [id86a](#), V. Cindro [id94](#), A. Ciocio [id17a](#), F. Ciroto [id72a,72b](#),  
 Z.H. Citron [id170](#), M. Citterio [id71a](#), D.A. Ciubotaru [id27b](#), A. Clark [id56](#), P.J. Clark [id52](#), C. Clarry [id156](#),  
 J.M. Clavijo Columbie [id48](#), S.E. Clawson [id48](#), C. Clement [id47a,47b](#), J. Clercx [id48](#), Y. Coadou [id103](#),  
 M. Cobal [id69a,69c](#), A. Cocco [id57b](#), R.F. Coelho Barrue [id131a](#), R. Coelho Lopes De Sa [id104](#),  
 S. Coelli [id71a](#), B. Cole [id41](#), J. Collot [id60](#), P. Conde Muiño [id131a,131g](#), M.P. Connell [id33c](#),  
 S.H. Connell [id33c](#), E.I. Conroy [id127](#), F. Conventi [id72a,ae](#), H.G. Cooke [id20](#), A.M. Cooper-Sarkar [id127](#),  
 F.A. Corchia [id23b,23a](#), A. Cordeiro Oudot Choi [id128](#), L.D. Corpe [id40](#), M. Corradi [id75a,75b](#),  
 F. Corriveau [id105,v](#), A. Cortes-Gonzalez [id18](#), M.J. Costa [id164](#), F. Costanza [id4](#), D. Costanzo [id140](#),  
 B.M. Cote [id120](#), J. Couthures [id4](#), G. Cowan [id96](#), K. Cranmer [id171](#), D. Cremonini [id23b,23a](#),  
 S. Crépe-Renaudin [id60](#), F. Crescioli [id128](#), M. Cristinziani [id142](#), M. Cristoforetti [id78a,78b](#), V. Croft [id115](#),  
 J.E. Crosby [id122](#), G. Crosetti [id43b,43a](#), A. Cueto [id100](#), Z. Cui [id7](#), W.R. Cunningham [id59](#), F. Curcio [id164](#),  
 J.R. Curran [id52](#), P. Czodrowski [id36](#), M.M. Czurylo [id36](#), M.J. Da Cunha Sargedas De Sousa [id57b,57a](#),  
 J.V. Da Fonseca Pinto [id83b](#), C. Da Via [id102](#), W. Dabrowski [id86a](#), T. Dado [id49](#), S. Dahbi [id149](#),  
 T. Dai [id107](#), D. Dal Santo [id19](#), C. Dallapiccola [id104](#), M. Dam [id42](#), G. D'amen [id29](#), V. D'Amico [id110](#),  
 J. Damp [id101](#), J.R. Dandoy [id34](#), D. Dannheim [id36](#), M. Danninger [id143](#), V. Dao [id36](#), G. Darbo [id57b](#),  
 S.J. Das [id29,af](#), F. Dattola [id48](#), S. D'Auria [id71a,71b](#), A. D'avanzo [id72a,72b](#), C. David [id33a](#), T. Davidek [id134](#),  
 I. Dawson [id95](#), H.A. Day-hall [id133](#), K. De [id8](#), R. De Asmundis [id72a](#), N. De Biase [id48](#),  
 S. De Castro [id23b,23a](#), N. De Groot [id114](#), P. de Jong [id115](#), H. De la Torre [id116](#), A. De Maria [id14c](#),  
 A. De Salvo [id75a](#), U. De Sanctis [id76a,76b](#), F. De Santis [id70a,70b](#), A. De Santo [id147](#),  
 J.B. De Vivie De Regie [id60](#), D.V. Dedovich [id38](#), J. Degens [id93](#), A.M. Deiana [id44](#), F. Del Corso [id23b,23a](#),  
 J. Del Peso [id100](#), F. Del Rio [id63a](#), L. Delagrangue [id128](#), F. Deliot [id136](#), C.M. Delitzsch [id49](#),  
 M. Della Pietra [id72a,72b](#), D. Della Volpe [id56](#), A. Dell'Acqua [id36](#), L. Dell'Asta [id71a,71b](#), M. Delmastro [id4](#),  
 P.A. Delsart [id60](#), S. Demers [id173](#), M. Demichev [id38](#), S.P. Denisov [id37](#), L. D'Eramo [id40](#),  
 D. Derendarz [id87](#), F. Derue [id128](#), P. Dervan [id93](#), K. Desch [id24](#), C. Deutsch [id24](#), F.A. Di Bello [id57b,57a](#),  
 A. Di Ciaccio [id76a,76b](#), L. Di Ciaccio [id4](#), A. Di Domenico [id75a,75b](#), C. Di Donato [id72a,72b](#),  
 A. Di Girolamo [id36](#), G. Di Gregorio [id36](#), A. Di Luca [id78a,78b](#), B. Di Micco [id77a,77b](#), R. Di Nardo [id77a,77b](#),  
 M. Diamantopoulou [id34](#), F.A. Dias [id115](#), T. Dias Do Vale [id143](#), M.A. Diaz [id138a,138b](#),  
 F.G. Diaz Capriles [id24](#), M. Didenko [id164](#), E.B. Diehl [id107](#), S. Díez Cornell [id48](#), C. Diez Pardo [id142](#),  
 C. Dimitriadi [id162,24](#), A. Dimitrievska [id20](#), J. Dingfelder [id24](#), I-M. Dinu [id27b](#), S.J. Dittmeier [id63b](#),  
 F. Dittus [id36](#), M. Divisek [id134](#), F. Djama [id103](#), T. Djobava [id150b](#), C. Doglioni [id102,99](#),  
 A. Dohnalova [id28a](#), J. Dolejsi [id134](#), Z. Dolezal [id134](#), K. Domijan [id86a](#), K.M. Dona [id39](#),  
 M. Donadelli [id83c](#), B. Dong [id108](#), J. Donini [id40](#), A. D'Onofrio [id72a,72b](#), M. D'Onofrio [id93](#),  
 J. Dopke [id135](#), A. Doria [id72a](#), N. Dos Santos Fernandes [id131a](#), P. Dougan [id102](#), M.T. Dova [id91](#),  
 A.T. Doyle [id59](#), M.A. Draguet [id127](#), E. Dreyer [id170](#), I. Drivas-koulouris [id10](#), M. Drnevich [id118](#),  
 M. Drozdova [id56](#), D. Du [id62a](#), T.A. du Pree [id115](#), F. Dubinin [id37](#), M. Dubovsky [id28a](#), E. Duchovni [id170](#),  
 G. Duckeck [id110](#), O.A. Ducu [id27b](#), D. Duda [id52](#), A. Dudarev [id36](#), E.R. Duden [id26](#), M. D'uffizi [id102](#),  
 L. Duflo [id66](#), M. Dührssen [id36](#), I. Duminica [id27g](#), A.E. Dumitriu [id27b](#), M. Dunford [id63a](#), S. Dungs [id49](#),  
 K. Dunne [id47a,47b](#), A. Duperrin [id103](#), H. Duran Yildiz [id3a](#), M. Düren [id58](#), A. Durglishvili [id150b](#),  
 B.L. Dwyer [id116](#), G.I. Dyckes [id17a](#), M. Dyndal [id86a](#), B.S. Dziedzic [id36](#), Z.O. Earnshaw [id147](#),  
 G.H. Eberwein [id127](#), B. Eckerova [id28a](#), S. Eggebrecht [id55](#), E. Egidio Purcino De Souza [id128](#),  
 L.F. Ehrke [id56](#), G. Eigen [id16](#), K. Einsweiler [id17a](#), T. Ekelof [id162](#), P.A. Ekman [id99](#), S. El Farkh [id35b](#),  
 Y. El Ghazali [id35b](#), H. El Jarrari [id36](#), A. El Moussaouy [id109](#), V. Ellajosyula [id162](#), M. Ellert [id162](#),  
 F. Ellinghaus [id172](#), N. Ellis [id36](#), J. Elmsheuser [id29](#), M. Elsayy [id117a](#), M. Elsing [id36](#),  
 D. Emelianov [id135](#), Y. Enari [id154](#), I. Ene [id17a](#), S. Epari [id13](#), P.A. Erland [id87](#), M. Errenst [id172](#),  
 M. Escalier [id66](#), C. Escobar [id164](#), E. Etzion [id152](#), G. Evans [id131a](#), H. Evans [id68](#), L.S. Evans [id96](#),  
 A. Ezhilov [id37](#), S. Ezzarqtouni [id35a](#), F. Fabbri [id23b,23a](#), L. Fabbri [id23b,23a](#), G. Facini [id97](#),

V. Fadeyev <sup>137</sup>, R.M. Fakhruddinov <sup>37</sup>, D. Fakoudis <sup>101</sup>, S. Falciano <sup>75a</sup>,  
 L.F. Falda Ulhoa Coelho <sup>36</sup>, F. Fallavollita <sup>111</sup>, J. Faltova <sup>134</sup>, C. Fan <sup>163</sup>, Y. Fan <sup>14a</sup>,  
 Y. Fang <sup>14a,14e</sup>, M. Fanti <sup>71a,71b</sup>, M. Faraj <sup>69a,69b</sup>, Z. Farazpay <sup>98</sup>, A. Farbin <sup>8</sup>, A. Farilla <sup>77a</sup>,  
 T. Farooque <sup>108</sup>, S.M. Farrington <sup>52</sup>, F. Fassi <sup>35e</sup>, D. Fassouliotis <sup>9</sup>, M. Faucci Giannelli <sup>76a,76b</sup>,  
 W.J. Fawcett <sup>32</sup>, L. Fayard <sup>66</sup>, P. Federic <sup>134</sup>, P. Federicova <sup>132</sup>, O.L. Fedin <sup>37,a</sup>, M. Feickert <sup>171</sup>,  
 L. Feligioni <sup>103</sup>, D.E. Fellers <sup>124</sup>, C. Feng <sup>62b</sup>, M. Feng <sup>14b</sup>, Z. Feng <sup>115</sup>, M.J. Fenton <sup>160</sup>,  
 L. Ferencz <sup>48</sup>, R.A.M. Ferguson <sup>92</sup>, S.I. Fernandez Luengo <sup>138f</sup>, P. Fernandez Martinez <sup>13</sup>,  
 M.J.V. Fernoux <sup>103</sup>, J. Ferrando <sup>92</sup>, A. Ferrari <sup>162</sup>, P. Ferrari <sup>115,114</sup>, R. Ferrari <sup>73a</sup>, D. Ferrere <sup>56</sup>,  
 C. Ferretti <sup>107</sup>, F. Fiedler <sup>101</sup>, P. Fiedler <sup>133</sup>, A. Filipčič <sup>94</sup>, E.K. Filmer <sup>1</sup>, F. Filthaut <sup>114</sup>,  
 M.C.N. Fiolhais <sup>131a,131c,c</sup>, L. Fiorini <sup>164</sup>, W.C. Fisher <sup>108</sup>, T. Fitschen <sup>102</sup>, P.M. Fitzhugh <sup>136</sup>,  
 I. Fleck <sup>142</sup>, P. Fleischmann <sup>107</sup>, T. Flick <sup>172</sup>, M. Flores <sup>33d,aa</sup>, L.R. Flores Castillo <sup>64a</sup>,  
 L. Flores Sanz De Acedo <sup>36</sup>, F.M. Follega <sup>78a,78b</sup>, N. Fomin <sup>16</sup>, J.H. Foo <sup>156</sup>, A. Formica <sup>136</sup>,  
 A.C. Forti <sup>102</sup>, E. Fortin <sup>36</sup>, A.W. Fortman <sup>17a</sup>, M.G. Foti <sup>17a</sup>, L. Fountas <sup>9,i</sup>, D. Fournier <sup>66</sup>,  
 H. Fox <sup>92</sup>, P. Francavilla <sup>74a,74b</sup>, S. Francescato <sup>61</sup>, S. Franchellucci <sup>56</sup>, M. Franchini <sup>23b,23a</sup>,  
 S. Franchino <sup>63a</sup>, D. Francis <sup>36</sup>, L. Franco <sup>114</sup>, V. Franco Lima <sup>36</sup>, L. Franconi <sup>48</sup>, M. Franklin <sup>61</sup>,  
 G. Frattari <sup>26</sup>, Y.Y. Frid <sup>152</sup>, J. Friend <sup>59</sup>, N. Fritzsche <sup>50</sup>, A. Froch <sup>54</sup>, D. Froidevaux <sup>36</sup>,  
 J.A. Frost <sup>127</sup>, Y. Fu <sup>62a</sup>, S. Fuenzalida Garrido <sup>138f</sup>, M. Fujimoto <sup>103</sup>, K.Y. Fung <sup>64a</sup>,  
 E. Furtado De Simas Filho <sup>83e</sup>, M. Furukawa <sup>154</sup>, J. Fuster <sup>164</sup>, A. Gabrielli <sup>23b,23a</sup>,  
 A. Gabrielli <sup>156</sup>, P. Gadow <sup>36</sup>, G. Gagliardi <sup>57b,57a</sup>, L.G. Gagnon <sup>17a</sup>, S. Gaid <sup>161</sup>,  
 S. Galantzan <sup>152</sup>, E.J. Gallas <sup>127</sup>, B.J. Gallop <sup>135</sup>, K.K. Gan <sup>120</sup>, S. Ganguly <sup>154</sup>, Y. Gao <sup>52</sup>,  
 F.M. Garay Walls <sup>138a,138b</sup>, B. Garcia <sup>29</sup>, C. García <sup>164</sup>, A. Garcia Alonso <sup>115</sup>,  
 A.G. Garcia Caffaro <sup>173</sup>, J.E. García Navarro <sup>164</sup>, M. Garcia-Sciveres <sup>17a</sup>, G.L. Gardner <sup>129</sup>,  
 R.W. Gardner <sup>39</sup>, N. Garelli <sup>159</sup>, D. Garg <sup>80</sup>, R.B. Garg <sup>144</sup>, J.M. Gargan <sup>52</sup>, C.A. Garner <sup>156</sup>,  
 C.M. Garvey <sup>33a</sup>, V.K. Gassmann <sup>159</sup>, G. Gaudio <sup>73a</sup>, V. Gautam <sup>13</sup>, P. Gauzzi <sup>75a,75b</sup>,  
 I.L. Gavrilenko <sup>37</sup>, A. Gavrilyuk <sup>37</sup>, C. Gay <sup>165</sup>, G. Gaycken <sup>48</sup>, E.N. Gazis <sup>10</sup>, A.A. Geanta <sup>27b</sup>,  
 C.M. Gee <sup>137</sup>, A. Gekow <sup>120</sup>, C. Gemme <sup>57b</sup>, M.H. Genest <sup>60</sup>, A.D. Gentry <sup>113</sup>, S. George <sup>96</sup>,  
 W.F. George <sup>20</sup>, T. Geralis <sup>46</sup>, P. Gessinger-Befurt <sup>36</sup>, M.E. Geyik <sup>172</sup>, M. Ghani <sup>168</sup>,  
 K. Ghorbanian <sup>95</sup>, A. Ghosal <sup>142</sup>, A. Ghosh <sup>160</sup>, A. Ghosh <sup>7</sup>, B. Giacobbe <sup>23b</sup>, S. Giagu <sup>75a,75b</sup>,  
 T. Giani <sup>115</sup>, P. Giannetti <sup>74a</sup>, A. Giannini <sup>62a</sup>, S.M. Gibson <sup>96</sup>, M. Gignac <sup>137</sup>, D.T. Gil <sup>86b</sup>,  
 A.K. Gilbert <sup>86a</sup>, B.J. Gilbert <sup>41</sup>, D. Gillberg <sup>34</sup>, G. Gilles <sup>115</sup>, L. Ginabat <sup>128</sup>,  
 D.M. Gingrich <sup>2,ad</sup>, M.P. Giordani <sup>69a,69c</sup>, P.F. Giraud <sup>136</sup>, G. Giugliarelli <sup>69a,69c</sup>, D. Giugni <sup>71a</sup>,  
 F. Giuli <sup>36</sup>, I. Gkialas <sup>9,i</sup>, L.K. Gladilin <sup>37</sup>, C. Glasman <sup>100</sup>, G.R. Gledhill <sup>124</sup>, G. Glemža <sup>48</sup>,  
 M. Glisic <sup>124</sup>, I. Gnesi <sup>43b,e</sup>, Y. Go <sup>29</sup>, M. Goblirsch-Kolb <sup>36</sup>, B. Gocke <sup>49</sup>, D. Godin <sup>109</sup>,  
 B. Gokturk <sup>21a</sup>, S. Goldfarb <sup>106</sup>, T. Golling <sup>56</sup>, M.G.D. Gololo <sup>33g</sup>, D. Golubkov <sup>37</sup>,  
 J.P. Gombas <sup>108</sup>, A. Gomes <sup>131a,131b</sup>, G. Gomes Da Silva <sup>142</sup>, A.J. Gomez Delegido <sup>164</sup>,  
 R. Gonçalves <sup>131a</sup>, L. Gonella <sup>20</sup>, A. Gongadze <sup>150c</sup>, F. Gonnella <sup>20</sup>, J.L. Gonski <sup>144</sup>,  
 R.Y. González Andana <sup>52</sup>, S. González de la Hoz <sup>164</sup>, R. Gonzalez Lopez <sup>93</sup>,  
 C. Gonzalez Renteria <sup>17a</sup>, M.V. Gonzalez Rodrigues <sup>48</sup>, R. Gonzalez Suarez <sup>162</sup>,  
 S. Gonzalez-Sevilla <sup>56</sup>, L. Goossens <sup>36</sup>, B. Gorini <sup>36</sup>, E. Gorini <sup>70a,70b</sup>, A. Gorišek <sup>94</sup>,  
 T.C. Gosart <sup>129</sup>, A.T. Goshaw <sup>51</sup>, M.I. Gostkin <sup>38</sup>, S. Goswami <sup>122</sup>, C.A. Gottardo <sup>36</sup>,  
 S.A. Gotz <sup>110</sup>, M. Gouighri <sup>35b</sup>, V. Goumarre <sup>48</sup>, A.G. Goussiou <sup>139</sup>, N. Govender <sup>33c</sup>,  
 I. Grabowska-Bold <sup>86a</sup>, K. Graham <sup>34</sup>, E. Gramstad <sup>126</sup>, S. Grancagnolo <sup>70a,70b</sup>, C.M. Grant <sup>1,136</sup>,  
 P.M. Gravila <sup>27f</sup>, F.G. Gravili <sup>70a,70b</sup>, H.M. Gray <sup>17a</sup>, M. Greco <sup>70a,70b</sup>, C. Grefe <sup>24</sup>,  
 A.S. Grefsrud <sup>16</sup>, I.M. Gregor <sup>48</sup>, K.T. Greif <sup>160</sup>, P. Grenier <sup>144</sup>, S.G. Grewe <sup>111</sup>, A.A. Grillo <sup>137</sup>,  
 K. Grimm <sup>31</sup>, S. Grinstein <sup>13,r</sup>, J.-F. Grivaz <sup>66</sup>, E. Gross <sup>170</sup>, J. Grosse-Knetter <sup>55</sup>,  
 J.C. Grundy <sup>127</sup>, L. Guan <sup>107</sup>, J.G.R. Guerrero Rojas <sup>164</sup>, G. Guerrieri <sup>69a,69c</sup>, F. Guescini <sup>111</sup>,  
 R. Gugel <sup>101</sup>, J.A.M. Guhit <sup>107</sup>, A. Guida <sup>18</sup>, E. Guilloton <sup>168</sup>, S. Guindon <sup>36</sup>, F. Guo <sup>14a,14e</sup>,

J. Guo <sup>62c</sup>, L. Guo <sup>48</sup>, Y. Guo <sup>107</sup>, R. Gupta <sup>130</sup>, S. Gurbuz <sup>24</sup>, S.S. Gurdasani <sup>54</sup>,  
 G. Gustavino <sup>36</sup>, M. Guth <sup>56</sup>, P. Gutierrez <sup>121</sup>, L.F. Gutierrez Zagazeta <sup>129</sup>, M. Gutsche <sup>50</sup>,  
 C. Gutschow <sup>97</sup>, C. Gwenlan <sup>127</sup>, C.B. Gwilliam <sup>93</sup>, E.S. Haaland <sup>126</sup>, A. Haas <sup>118</sup>,  
 M. Habedank <sup>48</sup>, C. Haber <sup>17a</sup>, H.K. Hadavand <sup>8</sup>, A. Hadeef <sup>50</sup>, S. Hadzic <sup>111</sup>, A.I. Hagan <sup>92</sup>,  
 J.J. Hahn <sup>142</sup>, E.H. Haines <sup>97</sup>, M. Haleem <sup>167</sup>, J. Haley <sup>122</sup>, J.J. Hall <sup>140</sup>, G.D. Hallewell <sup>103</sup>,  
 L. Halser <sup>19</sup>, K. Hamano <sup>166</sup>, M. Hamer <sup>24</sup>, G.N. Hamity <sup>52</sup>, E.J. Hampshire <sup>96</sup>, J. Han <sup>62b</sup>,  
 K. Han <sup>62a</sup>, L. Han <sup>14c</sup>, L. Han <sup>62a</sup>, S. Han <sup>17a</sup>, Y.F. Han <sup>156</sup>, K. Hanagaki <sup>84</sup>, M. Hance <sup>137</sup>,  
 D.A. Hangal <sup>41</sup>, H. Hanif <sup>143</sup>, M.D. Hank <sup>129</sup>, J.B. Hansen <sup>42</sup>, P.H. Hansen <sup>42</sup>, K. Hara <sup>158</sup>,  
 D. Harada <sup>56</sup>, T. Harenberg <sup>172</sup>, S. Harkusha <sup>37</sup>, M.L. Harris <sup>104</sup>, Y.T. Harris <sup>127</sup>, J. Harrison <sup>13</sup>,  
 N.M. Harrison <sup>120</sup>, P.F. Harrison <sup>168</sup>, N.M. Hartman <sup>111</sup>, N.M. Hartmann <sup>110</sup>, R.Z. Hasan <sup>96,135</sup>,  
 Y. Hasegawa <sup>141</sup>, S. Hassan <sup>16</sup>, R. Hauser <sup>108</sup>, C.M. Hawkes <sup>20</sup>, R.J. Hawkings <sup>36</sup>,  
 Y. Hayashi <sup>154</sup>, S. Hayashida <sup>112</sup>, D. Hayden <sup>108</sup>, C. Hayes <sup>107</sup>, R.L. Hayes <sup>115</sup>, C.P. Hays <sup>127</sup>,  
 J.M. Hays <sup>95</sup>, H.S. Hayward <sup>93</sup>, F. He <sup>62a</sup>, M. He <sup>14a,14e</sup>, Y. He <sup>155</sup>, Y. He <sup>48</sup>, Y. He <sup>97</sup>,  
 N.B. Heatley <sup>95</sup>, V. Hedberg <sup>99</sup>, A.L. Heggelund <sup>126</sup>, N.D. Hehir <sup>95,\*</sup>, C. Heidegger <sup>54</sup>,  
 K.K. Heidegger <sup>54</sup>, W.D. Heidorn <sup>81</sup>, J. Heilman <sup>34</sup>, S. Heim <sup>48</sup>, T. Heim <sup>17a</sup>, J.G. Heinlein <sup>129</sup>,  
 J.J. Heinrich <sup>124</sup>, L. Heinrich <sup>111,ab</sup>, J. Hejbal <sup>132</sup>, A. Held <sup>171</sup>, S. Hellesund <sup>16</sup>,  
 C.M. Helling <sup>165</sup>, S. Hellman <sup>47a,47b</sup>, R.C.W. Henderson <sup>92</sup>, L. Henkelmann <sup>32</sup>,  
 A.M. Henriques Correia <sup>36</sup>, H. Herde <sup>99</sup>, Y. Hernández Jiménez <sup>146</sup>, L.M. Herrmann <sup>24</sup>,  
 T. Herrmann <sup>50</sup>, G. Herten <sup>54</sup>, R. Hertenberger <sup>110</sup>, L. Hervas <sup>36</sup>, M.E. Hesping <sup>101</sup>,  
 N.P. Hesse <sup>157a</sup>, M. Hidaoui <sup>35b</sup>, E. Hill <sup>156</sup>, S.J. Hillier <sup>20</sup>, J.R. Hinds <sup>108</sup>, F. Hinterkeuser <sup>24</sup>,  
 M. Hirose <sup>125</sup>, S. Hirose <sup>158</sup>, D. Hirschbuehl <sup>172</sup>, T.G. Hitchings <sup>102</sup>, B. Hiti <sup>94</sup>, J. Hobbs <sup>146</sup>,  
 R. Hobincu <sup>27e</sup>, N. Hod <sup>170</sup>, M.C. Hodgkinson <sup>140</sup>, B.H. Hodgkinson <sup>127</sup>, A. Hoecker <sup>36</sup>,  
 D.D. Hofer <sup>107</sup>, J. Hofer <sup>48</sup>, T. Holm <sup>24</sup>, M. Holzbock <sup>111</sup>, L.B.A.H. Hommels <sup>32</sup>,  
 B.P. Honan <sup>102</sup>, J.J. Hong <sup>68</sup>, J. Hong <sup>62c</sup>, T.M. Hong <sup>130</sup>, B.H. Hooberman <sup>163</sup>,  
 W.H. Hopkins <sup>6</sup>, M.C. Hoppesch <sup>163</sup>, Y. Horii <sup>112</sup>, S. Hou <sup>149</sup>, A.S. Howard <sup>94</sup>, J. Howarth <sup>59</sup>,  
 J. Hoya <sup>6</sup>, M. Hrabovsky <sup>123</sup>, A. Hrynevich <sup>48</sup>, T. Hryn'ova <sup>4</sup>, P.J. Hsu <sup>65</sup>, S.-C. Hsu <sup>139</sup>,  
 T. Hsu <sup>66</sup>, M. Hu <sup>17a</sup>, Q. Hu <sup>62a</sup>, S. Huang <sup>64b</sup>, X. Huang <sup>14a,14e</sup>, Y. Huang <sup>140</sup>, Y. Huang <sup>101</sup>,  
 Y. Huang <sup>14a</sup>, Z. Huang <sup>102</sup>, Z. Hubacek <sup>133</sup>, M. Huebner <sup>24</sup>, F. Hugging <sup>24</sup>, T.B. Huffman <sup>127</sup>,  
 C.A. Hugli <sup>48</sup>, M. Huhtinen <sup>36</sup>, S.K. Huiberts <sup>16</sup>, R. Hulsken <sup>105</sup>, N. Huseynov <sup>12</sup>, J. Huston <sup>108</sup>,  
 J. Huth <sup>61</sup>, R. Hyneman <sup>144</sup>, G. Iacobucci <sup>56</sup>, G. Iakovidis <sup>29</sup>, L. Iconomidou-Fayard <sup>66</sup>,  
 J.P. Iddon <sup>36</sup>, P. Iengo <sup>72a,72b</sup>, R. Iguchi <sup>154</sup>, T. Iizawa <sup>127</sup>, Y. Ikegami <sup>84</sup>, N. Ilic <sup>156</sup>,  
 H. Imam <sup>35a</sup>, M. Ince Lezki <sup>56</sup>, T. Ingebretsen Carlson <sup>47a,47b</sup>, G. Introzzi <sup>73a,73b</sup>, M. Iodice <sup>77a</sup>,  
 V. Ippolito <sup>75a,75b</sup>, R.K. Irwin <sup>93</sup>, M. Ishino <sup>154</sup>, W. Islam <sup>171</sup>, C. Issever <sup>18,48</sup>, S. Istin <sup>21a,ah</sup>,  
 H. Ito <sup>169</sup>, R. Iuppa <sup>78a,78b</sup>, A. Ivina <sup>170</sup>, J.M. Izen <sup>45</sup>, V. Izzo <sup>72a</sup>, P. Jacka <sup>132</sup>, P. Jackson <sup>1</sup>,  
 C.S. Jagfeld <sup>110</sup>, G. Jain <sup>157a</sup>, P. Jain <sup>48</sup>, K. Jakobs <sup>54</sup>, T. Jakoubek <sup>170</sup>, J. Jamieson <sup>59</sup>,  
 M. Javurkova <sup>104</sup>, L. Jeanty <sup>124</sup>, J. Jejelava <sup>150a,y</sup>, P. Jenni <sup>54,f</sup>, C.E. Jessiman <sup>34</sup>, C. Jia <sup>62b</sup>,  
 J. Jia <sup>146</sup>, X. Jia <sup>61</sup>, X. Jia <sup>14a,14e</sup>, Z. Jia <sup>14c</sup>, C. Jiang <sup>52</sup>, S. Jiggins <sup>48</sup>, J. Jimenez Pena <sup>13</sup>,  
 S. Jin <sup>14c</sup>, A. Jinaru <sup>27b</sup>, O. Jinnouchi <sup>155</sup>, P. Johansson <sup>140</sup>, K.A. Johns <sup>7</sup>, J.W. Johnson <sup>137</sup>,  
 D.M. Jones <sup>147</sup>, E. Jones <sup>48</sup>, P. Jones <sup>32</sup>, R.W.L. Jones <sup>92</sup>, T.J. Jones <sup>93</sup>, H.L. Joos <sup>55,36</sup>,  
 R. Joshi <sup>120</sup>, J. Jovicevic <sup>15</sup>, X. Ju <sup>17a</sup>, J.J. Junggeburth <sup>104</sup>, T. Junkermann <sup>63a</sup>,  
 A. Juste Rozas <sup>13,r</sup>, M.K. Juzek <sup>87</sup>, S. Kabana <sup>138e</sup>, A. Kaczmarek <sup>87</sup>, M. Kado <sup>111</sup>,  
 H. Kagan <sup>120</sup>, M. Kagan <sup>144</sup>, A. Kahn <sup>129</sup>, C. Kahra <sup>101</sup>, T. Kaji <sup>154</sup>, E. Kajomovitz <sup>151</sup>,  
 N. Kakati <sup>170</sup>, I. Kalaitzidou <sup>54</sup>, C.W. Kalderon <sup>29</sup>, N.J. Kang <sup>137</sup>, D. Kar <sup>33g</sup>, K. Karava <sup>127</sup>,  
 M.J. Kareem <sup>157b</sup>, E. Karentzos <sup>54</sup>, O. Karkout <sup>115</sup>, S.N. Karpov <sup>38</sup>, Z.M. Karpova <sup>38</sup>,  
 V. Kartvelishvili <sup>92</sup>, A.N. Karyukhin <sup>37</sup>, E. Kasimi <sup>153</sup>, J. Katzy <sup>48</sup>, S. Kaur <sup>34</sup>, K. Kawade <sup>141</sup>,  
 M.P. Kawale <sup>121</sup>, C. Kawamoto <sup>88</sup>, T. Kawamoto <sup>62a</sup>, E.F. Kay <sup>36</sup>, F.I. Kaya <sup>159</sup>, S. Kazakos <sup>108</sup>,  
 V.F. Kazanin <sup>37</sup>, Y. Ke <sup>146</sup>, J.M. Keaveney <sup>33a</sup>, R. Keeler <sup>166</sup>, G.V. Kehris <sup>61</sup>, J.S. Keller <sup>34</sup>,

A.S. Kelly<sup>97</sup>, J.J. Kempster<sup>147</sup>, P.D. Kennedy<sup>101</sup>, O. Kepka<sup>132</sup>, B.P. Kerridge<sup>135</sup>, S. Kersten<sup>172</sup>,  
 B.P. Kerševan<sup>94</sup>, L. Keszezhova<sup>28a</sup>, S. Ketabchi Haghighat<sup>156</sup>, R.A. Khan<sup>130</sup>, A. Khanov<sup>122</sup>,  
 A.G. Kharlamov<sup>37</sup>, T. Kharlamova<sup>37</sup>, E.E. Khoda<sup>139</sup>, M. Kholodenko<sup>37</sup>, T.J. Khoo<sup>18</sup>,  
 G. Khoriauli<sup>167</sup>, J. Khubua<sup>150b</sup>, Y.A.R. Khwaira<sup>128</sup>, B. Kibirige<sup>33g</sup>, D.W. Kim<sup>47a,47b</sup>,  
 Y.K. Kim<sup>39</sup>, N. Kimura<sup>97</sup>, M.K. Kingston<sup>55</sup>, A. Kirchhoff<sup>55</sup>, C. Kirfel<sup>24</sup>, F. Kirfel<sup>24</sup>,  
 J. Kirk<sup>135</sup>, A.E. Kiryunin<sup>111</sup>, C. Kitsaki<sup>10</sup>, O. Kivernyk<sup>24</sup>, M. Klassen<sup>159</sup>, C. Klein<sup>34</sup>,  
 L. Klein<sup>167</sup>, M.H. Klein<sup>44</sup>, S.B. Klein<sup>56</sup>, U. Klein<sup>93</sup>, P. Klimek<sup>36</sup>, A. Klimentov<sup>29</sup>,  
 T. Klioutchnikova<sup>36</sup>, P. Kluit<sup>115</sup>, S. Kluth<sup>111</sup>, E. Kneringer<sup>79</sup>, T.M. Knight<sup>156</sup>, A. Knue<sup>49</sup>,  
 R. Kobayashi<sup>88</sup>, D. Kobylanskii<sup>170</sup>, S.F. Koch<sup>127</sup>, M. Kocian<sup>144</sup>, P. Kodyš<sup>134</sup>,  
 D.M. Koeck<sup>124</sup>, P.T. Koenig<sup>24</sup>, T. Koffas<sup>34</sup>, O. Kolay<sup>50</sup>, I. Koletsou<sup>4</sup>, T. Komarek<sup>123</sup>,  
 K. Köneke<sup>54</sup>, A.X.Y. Kong<sup>1</sup>, T. Kono<sup>119</sup>, N. Konstantinidis<sup>97</sup>, P. Kontaxakis<sup>56</sup>, B. Konya<sup>99</sup>,  
 R. Kopeliansky<sup>41</sup>, S. Koperny<sup>86a</sup>, K. Korcyl<sup>87</sup>, K. Kordas<sup>153,d</sup>, A. Korn<sup>97</sup>, S. Korn<sup>55</sup>,  
 I. Korolkov<sup>13</sup>, N. Korotkova<sup>37</sup>, B. Kortman<sup>115</sup>, O. Kortner<sup>111</sup>, S. Kortner<sup>111</sup>,  
 W.H. Kostecka<sup>116</sup>, V.V. Kostyukhin<sup>142</sup>, A. Kotsokechagia<sup>136</sup>, A. Koulouris<sup>36</sup>,  
 A. Kourkoumeli-Charalampidi<sup>73a,73b</sup>, C. Kourkoumelis<sup>9</sup>, E. Kourlitis<sup>111,ab</sup>, O. Kovanda<sup>124</sup>,  
 R. Kowalewski<sup>166</sup>, W. Kozanecki<sup>136</sup>, A.S. Kozhin<sup>37</sup>, V.A. Kramarenko<sup>37</sup>, G. Kramberger<sup>94</sup>,  
 P. Kramer<sup>101</sup>, M.W. Krasny<sup>128</sup>, A. Krasznahorkay<sup>36</sup>, J.W. Kraus<sup>172</sup>, J.A. Kremer<sup>48</sup>,  
 T. Kresse<sup>50</sup>, J. Kretschmar<sup>93</sup>, K. Kreul<sup>18</sup>, P. Krieger<sup>156</sup>, S. Krishnamurthy<sup>104</sup>,  
 M. Krivos<sup>134</sup>, K. Krizka<sup>20</sup>, K. Kroeninger<sup>49</sup>, H. Kroha<sup>111</sup>, J. Kroll<sup>132</sup>, J. Kroll<sup>129</sup>,  
 K.S. Krowpman<sup>108</sup>, U. Kruchonak<sup>38</sup>, H. Krüger<sup>24</sup>, N. Krumnack<sup>81</sup>, M.C. Kruse<sup>51</sup>,  
 O. Kuchinskaia<sup>37</sup>, S. Kудay<sup>3a</sup>, S. Kuehn<sup>36</sup>, R. Kuesters<sup>54</sup>, T. Kuhl<sup>48</sup>, V. Kukhtin<sup>38</sup>,  
 Y. Kulchitsky<sup>37,a</sup>, S. Kuleshov<sup>138d,138b</sup>, M. Kumar<sup>33g</sup>, N. Kumari<sup>48</sup>, P. Kumari<sup>157b</sup>,  
 A. Kupco<sup>132</sup>, T. Kupfer<sup>49</sup>, A. Kupich<sup>37</sup>, O. Kuprash<sup>54</sup>, H. Kurashige<sup>85</sup>, L.L. Kurchaninov<sup>157a</sup>,  
 O. Kurdysh<sup>66</sup>, Y.A. Kurochkin<sup>37</sup>, A. Kurova<sup>37</sup>, M. Kuze<sup>155</sup>, A.K. Kvam<sup>104</sup>, J. Kvita<sup>123</sup>,  
 T. Kwan<sup>105</sup>, N.G. Kyriacou<sup>107</sup>, L.A.O. Laatu<sup>103</sup>, C. Lacasta<sup>164</sup>, F. Lacava<sup>75a,75b</sup>,  
 H. Lacker<sup>18</sup>, D. Lacour<sup>128</sup>, N.N. Lad<sup>97</sup>, E. Ladygin<sup>38</sup>, A. Lafarge<sup>40</sup>, B. Laforge<sup>128</sup>,  
 T. Lagouri<sup>173</sup>, F.Z. Lahbabi<sup>35a</sup>, S. Lai<sup>55</sup>, J.E. Lambert<sup>166</sup>, S. Lammers<sup>68</sup>, W. Lampl<sup>7</sup>,  
 C. Lampoudis<sup>153,d</sup>, G. Lamprinoudis<sup>101</sup>, A.N. Lancaster<sup>116</sup>, E. Lançon<sup>29</sup>, U. Landgraf<sup>54</sup>,  
 M.P.J. Landon<sup>95</sup>, V.S. Lang<sup>54</sup>, O.K.B. Langrekken<sup>126</sup>, A.J. Lankford<sup>160</sup>, F. Lanni<sup>36</sup>,  
 K. Lantzsck<sup>24</sup>, A. Lanza<sup>73a</sup>, J.F. Laporte<sup>136</sup>, T. Lari<sup>71a</sup>, F. Lasagni Manghi<sup>23b</sup>,  
 M. Lassnig<sup>36</sup>, V. Latonova<sup>132</sup>, A. Laudrain<sup>101</sup>, A. Laurier<sup>151</sup>, S.D. Lawlor<sup>140</sup>,  
 Z. Lawrence<sup>102</sup>, R. Lazaridou<sup>168</sup>, M. Lazzaroni<sup>71a,71b</sup>, B. Le<sup>102</sup>, E.M. Le Boulicaut<sup>51</sup>,  
 L.T. Le Pottier<sup>17a</sup>, B. Leban<sup>23b,23a</sup>, A. Lebedev<sup>81</sup>, M. LeBlanc<sup>102</sup>, F. Ledroit-Guillon<sup>60</sup>,  
 S.C. Lee<sup>149</sup>, S. Lee<sup>47a,47b</sup>, T.F. Lee<sup>93</sup>, L.L. Leeuw<sup>33c</sup>, H.P. Lefebvre<sup>96</sup>, M. Lefebvre<sup>166</sup>,  
 C. Leggett<sup>17a</sup>, G. Lehmann Miotto<sup>36</sup>, M. Leigh<sup>56</sup>, W.A. Leight<sup>104</sup>, W. Leinonen<sup>114</sup>,  
 A. Leisos<sup>153,q</sup>, M.A.L. Leite<sup>83c</sup>, C.E. Leitgeb<sup>18</sup>, R. Leitner<sup>134</sup>, K.J.C. Leney<sup>44</sup>, T. Lenz<sup>24</sup>,  
 S. Leone<sup>74a</sup>, C. Leonidopoulos<sup>52</sup>, A. Leopold<sup>145</sup>, C. Leroy<sup>109</sup>, R. Les<sup>108</sup>, C.G. Lester<sup>32</sup>,  
 M. Levchenko<sup>37</sup>, J. Levêque<sup>4</sup>, L.J. Levinson<sup>170</sup>, G. Levrini<sup>23b,23a</sup>, M.P. Lewicki<sup>87</sup>,  
 C. Lewis<sup>139</sup>, D.J. Lewis<sup>4</sup>, A. Li<sup>5</sup>, B. Li<sup>62b</sup>, C. Li<sup>62a</sup>, C-Q. Li<sup>111</sup>, H. Li<sup>62a</sup>, H. Li<sup>62b</sup>,  
 H. Li<sup>14c</sup>, H. Li<sup>14b</sup>, H. Li<sup>62b</sup>, J. Li<sup>62c</sup>, K. Li<sup>139</sup>, L. Li<sup>62c</sup>, M. Li<sup>14a,14e</sup>, S. Li<sup>14a,14e</sup>,  
 S. Li<sup>62d,62c</sup>, T. Li<sup>5</sup>, X. Li<sup>105</sup>, Z. Li<sup>127</sup>, Z. Li<sup>105</sup>, Z. Li<sup>14a,14e</sup>, S. Liang<sup>14a,14e</sup>, Z. Liang<sup>14a</sup>,  
 M. Liberatore<sup>136</sup>, B. Liberti<sup>76a</sup>, K. Lie<sup>64c</sup>, J. Lieber Marin<sup>83e</sup>, H. Lien<sup>68</sup>, H. Lin<sup>107</sup>,  
 K. Lin<sup>108</sup>, R.E. Lindley<sup>7</sup>, J.H. Lindon<sup>2</sup>, E. Lipeles<sup>129</sup>, A. Lipniacka<sup>16</sup>, A. Lister<sup>165</sup>,  
 J.D. Little<sup>68</sup>, B. Liu<sup>14a</sup>, B.X. Liu<sup>14d</sup>, D. Liu<sup>62d,62c</sup>, E.H.L. Liu<sup>20</sup>, J.B. Liu<sup>62a</sup>,  
 J.K.K. Liu<sup>32</sup>, K. Liu<sup>62d</sup>, K. Liu<sup>62d,62c</sup>, M. Liu<sup>62a</sup>, M.Y. Liu<sup>62a</sup>, P. Liu<sup>14a</sup>, Q. Liu<sup>62d,139,62c</sup>,  
 X. Liu<sup>62a</sup>, X. Liu<sup>62b</sup>, Y. Liu<sup>14d,14e</sup>, Y.L. Liu<sup>62b</sup>, Y.W. Liu<sup>62a</sup>, J. Llorente Merino<sup>143</sup>,  
 S.L. Lloyd<sup>95</sup>, E.M. Lobodzinska<sup>48</sup>, P. Loch<sup>7</sup>, T. Lohse<sup>18</sup>, K. Lohwasser<sup>140</sup>, E. Loiacono<sup>48</sup>,

M. Lokajicek [id](#)<sup>132,\*</sup>, J.D. Lomas [id](#)<sup>20</sup>, J.D. Long [id](#)<sup>163</sup>, I. Longarini [id](#)<sup>160</sup>, R. Longo [id](#)<sup>163</sup>,  
I. Lopez Paz [id](#)<sup>67</sup>, A. Lopez Solis [id](#)<sup>48</sup>, N. Lorenzo Martinez [id](#)<sup>4</sup>, A.M. Lory [id](#)<sup>110</sup>, M. Losada [id](#)<sup>117a</sup>,  
G. Löschcke Centeno [id](#)<sup>147</sup>, O. Loseva [id](#)<sup>37</sup>, X. Lou [id](#)<sup>47a,47b</sup>, X. Lou [id](#)<sup>14a,14e</sup>, A. Lounis [id](#)<sup>66</sup>,  
P.A. Love [id](#)<sup>92</sup>, G. Lu [id](#)<sup>14a,14e</sup>, M. Lu [id](#)<sup>66</sup>, S. Lu [id](#)<sup>129</sup>, Y.J. Lu [id](#)<sup>65</sup>, H.J. Lubatti [id](#)<sup>139</sup>, C. Luci [id](#)<sup>75a,75b</sup>,  
F.L. Lucio Alves [id](#)<sup>14c</sup>, F. Luehring [id](#)<sup>68</sup>, I. Luise [id](#)<sup>146</sup>, O. Lukianchuk [id](#)<sup>66</sup>, O. Lundberg [id](#)<sup>145</sup>,  
B. Lund-Jensen [id](#)<sup>145</sup>, N.A. Luongo [id](#)<sup>6</sup>, M.S. Lutz [id](#)<sup>36</sup>, A.B. Lux [id](#)<sup>25</sup>, D. Lynn [id](#)<sup>29</sup>, R. Lysak [id](#)<sup>132</sup>,  
E. Lytken [id](#)<sup>99</sup>, V. Lyubushkin [id](#)<sup>38</sup>, T. Lyubushkina [id](#)<sup>38</sup>, M.M. Lyukova [id](#)<sup>146</sup>, M.Firdaus M. Soberi [id](#)<sup>52</sup>,  
H. Ma [id](#)<sup>29</sup>, K. Ma [id](#)<sup>62a</sup>, L.L. Ma [id](#)<sup>62b</sup>, W. Ma [id](#)<sup>62a</sup>, Y. Ma [id](#)<sup>122</sup>, G. Maccarrone [id](#)<sup>53</sup>, J.C. MacDonald [id](#)<sup>101</sup>,  
P.C. Machado De Abreu Farias [id](#)<sup>83e</sup>, R. Madar [id](#)<sup>40</sup>, T. Madula [id](#)<sup>97</sup>, J. Maeda [id](#)<sup>85</sup>, T. Maeno [id](#)<sup>29</sup>,  
H. Maguire [id](#)<sup>140</sup>, V. Maiboroda [id](#)<sup>136</sup>, A. Maio [id](#)<sup>131a,131b,131d</sup>, K. Maj [id](#)<sup>86a</sup>, O. Majersky [id](#)<sup>48</sup>,  
S. Majewski [id](#)<sup>124</sup>, N. Makovec [id](#)<sup>66</sup>, V. Maksimovic [id](#)<sup>15</sup>, B. Malaescu [id](#)<sup>128</sup>, Pa. Malecki [id](#)<sup>87</sup>,  
V.P. Maleev [id](#)<sup>37</sup>, F. Malek [id](#)<sup>60,m</sup>, M. Mali [id](#)<sup>94</sup>, D. Malito [id](#)<sup>96</sup>, U. Mallik [id](#)<sup>80</sup>, S. Maltezos [id](#)<sup>10</sup>,  
S. Malyukov [id](#)<sup>38</sup>, J. Mamuzic [id](#)<sup>13</sup>, G. Mancini [id](#)<sup>53</sup>, M.N. Mancini [id](#)<sup>26</sup>, G. Manco [id](#)<sup>73a,73b</sup>,  
J.P. Mandalia [id](#)<sup>95</sup>, I. Mandić [id](#)<sup>94</sup>, L. Manhaes de Andrade Filho [id](#)<sup>83a</sup>, I.M. Maniatis [id](#)<sup>170</sup>,  
J. Manjarres Ramos [id](#)<sup>90</sup>, D.C. Mankad [id](#)<sup>170</sup>, A. Mann [id](#)<sup>110</sup>, S. Manzoni [id](#)<sup>36</sup>, L. Mao [id](#)<sup>62c</sup>,  
X. Mapekula [id](#)<sup>33c</sup>, A. Marantis [id](#)<sup>153,q</sup>, G. Marchiori [id](#)<sup>5</sup>, M. Marcisovsky [id](#)<sup>132</sup>, C. Marcon [id](#)<sup>71a</sup>,  
M. Marinescu [id](#)<sup>20</sup>, S. Marium [id](#)<sup>48</sup>, M. Marjanovic [id](#)<sup>121</sup>, A. Markhoos [id](#)<sup>54</sup>, M. Markovitch [id](#)<sup>66</sup>,  
E.J. Marshall [id](#)<sup>92</sup>, Z. Marshall [id](#)<sup>17a</sup>, S. Marti-Garcia [id](#)<sup>164</sup>, T.A. Martin [id](#)<sup>135</sup>, V.J. Martin [id](#)<sup>52</sup>,  
B. Martin dit Latour [id](#)<sup>16</sup>, L. Martinelli [id](#)<sup>75a,75b</sup>, M. Martinez [id](#)<sup>13,r</sup>, P. Martinez Agullo [id](#)<sup>164</sup>,  
V.I. Martinez Outschoorn [id](#)<sup>104</sup>, P. Martinez Suarez [id](#)<sup>13</sup>, S. Martin-Haugh [id](#)<sup>135</sup>, G. Martinovicova [id](#)<sup>134</sup>,  
V.S. Martoiu [id](#)<sup>27b</sup>, A.C. Martyniuk [id](#)<sup>97</sup>, A. Marzin [id](#)<sup>36</sup>, D. Mascione [id](#)<sup>78a,78b</sup>, L. Masetti [id](#)<sup>101</sup>,  
T. Mashimo [id](#)<sup>154</sup>, J. Masik [id](#)<sup>102</sup>, A.L. Maslennikov [id](#)<sup>37</sup>, P. Massarotti [id](#)<sup>72a,72b</sup>, P. Mastrandrea [id](#)<sup>74a,74b</sup>,  
A. Mastroberardino [id](#)<sup>43b,43a</sup>, T. Masubuchi [id](#)<sup>154</sup>, T. Mathisen [id](#)<sup>162</sup>, J. Matousek [id](#)<sup>134</sup>, N. Matsuzawa [id](#)<sup>154</sup>,  
J. Maurer [id](#)<sup>27b</sup>, A.J. Maury [id](#)<sup>66</sup>, B. Maček [id](#)<sup>94</sup>, D.A. Maximov [id](#)<sup>37</sup>, A.E. May [id](#)<sup>102</sup>, R. Mazini [id](#)<sup>149</sup>,  
I. Maznas [id](#)<sup>116</sup>, M. Mazza [id](#)<sup>108</sup>, S.M. Mazza [id](#)<sup>137</sup>, E. Mazzeo [id](#)<sup>71a,71b</sup>, C. Mc Ginn [id](#)<sup>29</sup>,  
J.P. Mc Gowan [id](#)<sup>166</sup>, S.P. Mc Kee [id](#)<sup>107</sup>, C.C. McCracken [id](#)<sup>165</sup>, E.F. McDonald [id](#)<sup>106</sup>,  
A.E. McDougall [id](#)<sup>115</sup>, J.A. Mcfayden [id](#)<sup>147</sup>, R.P. McGovern [id](#)<sup>129</sup>, G. Mchedlidze [id](#)<sup>150b</sup>,  
R.P. Mckenzie [id](#)<sup>33g</sup>, T.C. Mclachlan [id](#)<sup>48</sup>, D.J. Mclaughlin [id](#)<sup>97</sup>, S.J. McMahon [id](#)<sup>135</sup>,  
C.M. Mcpartland [id](#)<sup>93</sup>, R.A. McPherson [id](#)<sup>166,v</sup>, S. Mehlhase [id](#)<sup>110</sup>, A. Mehta [id](#)<sup>93</sup>, D. Melini [id](#)<sup>164</sup>,  
B.R. Mellado Garcia [id](#)<sup>33g</sup>, A.H. Melo [id](#)<sup>55</sup>, F. Meloni [id](#)<sup>48</sup>, A.M. Mendes Jacques Da Costa [id](#)<sup>102</sup>,  
H.Y. Meng [id](#)<sup>156</sup>, L. Meng [id](#)<sup>92</sup>, S. Menke [id](#)<sup>111</sup>, M. Mentink [id](#)<sup>36</sup>, E. Meoni [id](#)<sup>43b,43a</sup>, G. Mercado [id](#)<sup>116</sup>,  
S. Merianos [id](#)<sup>153</sup>, C. Merlassino [id](#)<sup>69a,69c</sup>, L. Merola [id](#)<sup>72a,72b</sup>, C. Meroni [id](#)<sup>71a,71b</sup>, J. Metcalfe [id](#)<sup>6</sup>,  
A.S. Mete [id](#)<sup>6</sup>, E. Meuser [id](#)<sup>101</sup>, C. Meyer [id](#)<sup>68</sup>, J-P. Meyer [id](#)<sup>136</sup>, R.P. Middleton [id](#)<sup>135</sup>, L. Mijović [id](#)<sup>52</sup>,  
G. Mikenberg [id](#)<sup>170</sup>, M. Mikestikova [id](#)<sup>132</sup>, M. Mikuž [id](#)<sup>94</sup>, H. Mildner [id](#)<sup>101</sup>, A. Milic [id](#)<sup>36</sup>,  
D.W. Miller [id](#)<sup>39</sup>, E.H. Miller [id](#)<sup>144</sup>, L.S. Miller [id](#)<sup>34</sup>, A. Milov [id](#)<sup>170</sup>, D.A. Milstead [id](#)<sup>47a,47b</sup>, T. Min [id](#)<sup>14c</sup>,  
A.A. Minaenko [id](#)<sup>37</sup>, I.A. Minashvili [id](#)<sup>150b</sup>, L. Mince [id](#)<sup>59</sup>, A.I. Mincer [id](#)<sup>118</sup>, B. Mindur [id](#)<sup>86a</sup>,  
M. Mineev [id](#)<sup>38</sup>, Y. Mino [id](#)<sup>88</sup>, L.M. Mir [id](#)<sup>13</sup>, M. Miralles Lopez [id](#)<sup>59</sup>, M. Mironova [id](#)<sup>17a</sup>, A. Mishima [id](#)<sup>154</sup>,  
M.C. Missio [id](#)<sup>114</sup>, A. Mitra [id](#)<sup>168</sup>, V.A. Mitsou [id](#)<sup>164</sup>, Y. Mitsumori [id](#)<sup>112</sup>, O. Miu [id](#)<sup>156</sup>,  
P.S. Miyagawa [id](#)<sup>95</sup>, T. Mkrtychyan [id](#)<sup>63a</sup>, M. Mlinarevic [id](#)<sup>97</sup>, T. Mlinarevic [id](#)<sup>97</sup>, M. Mlynarikova [id](#)<sup>36</sup>,  
S. Mobius [id](#)<sup>19</sup>, P. Mogg [id](#)<sup>110</sup>, M.H. Mohamed Farook [id](#)<sup>113</sup>, A.F. Mohammed [id](#)<sup>14a,14e</sup>, S. Mohapatra [id](#)<sup>41</sup>,  
G. Mokgatitswane [id](#)<sup>33g</sup>, L. Moleri [id](#)<sup>170</sup>, B. Mondal [id](#)<sup>142</sup>, S. Mondal [id](#)<sup>133</sup>, K. Mönig [id](#)<sup>48</sup>,  
E. Monnier [id](#)<sup>103</sup>, L. Monsonis Romero [id](#)<sup>164</sup>, J. Montejo Berlingen [id](#)<sup>13</sup>, M. Montella [id](#)<sup>120</sup>,  
F. Montekali [id](#)<sup>77a,77b</sup>, F. Monticelli [id](#)<sup>91</sup>, S. Monzani [id](#)<sup>69a,69c</sup>, N. Morange [id](#)<sup>66</sup>,  
A.L. Moreira De Carvalho [id](#)<sup>48</sup>, M. Moreno Llácer [id](#)<sup>164</sup>, C. Moreno Martinez [id](#)<sup>56</sup>, P. Morettini [id](#)<sup>57b</sup>,  
S. Morgenstern [id](#)<sup>36</sup>, M. Morii [id](#)<sup>61</sup>, M. Morinaga [id](#)<sup>154</sup>, F. Morodei [id](#)<sup>75a,75b</sup>, L. Morvaj [id](#)<sup>36</sup>,  
P. Moschovakos [id](#)<sup>36</sup>, B. Moser [id](#)<sup>36</sup>, M. Mosidze [id](#)<sup>150b</sup>, T. Moskalets [id](#)<sup>54</sup>, P. Moskvitina [id](#)<sup>114</sup>,  
J. Moss [id](#)<sup>31,j</sup>, P. Moszkowicz [id](#)<sup>86a</sup>, A. Moussa [id](#)<sup>35d</sup>, E.J.W. Moyse [id](#)<sup>104</sup>, O. Mtintsilana [id](#)<sup>33g</sup>,



S. Muanza <sup>id103</sup>, J. Mueller <sup>id130</sup>, D. Muenstermann <sup>id92</sup>, R. Müller <sup>id19</sup>, G.A. Mullier <sup>id162</sup>, A.J. Mullin<sup>32</sup>, J.J. Mullin<sup>129</sup>, D.P. Mungo <sup>id156</sup>, D. Munoz Perez <sup>id164</sup>, F.J. Munoz Sanchez <sup>id102</sup>, M. Murin <sup>id102</sup>, W.J. Murray <sup>id168,135</sup>, M. Muškinja <sup>id94</sup>, C. Mwewa <sup>id29</sup>, A.G. Myagkov <sup>id37,a</sup>, A.J. Myers <sup>id8</sup>, G. Myers <sup>id107</sup>, M. Myska <sup>id133</sup>, B.P. Nachman <sup>id17a</sup>, O. Nackenhorst <sup>id49</sup>, K. Nagai <sup>id127</sup>, K. Nagano <sup>id84</sup>, J.L. Nagle <sup>id29,af</sup>, E. Nagy <sup>id103</sup>, A.M. Nairz <sup>id36</sup>, Y. Nakahama <sup>id84</sup>, K. Nakamura <sup>id84</sup>, K. Nakkalil <sup>id5</sup>, H. Nanjo <sup>id125</sup>, E.A. Narayanan <sup>id113</sup>, I. Naryshkin <sup>id37</sup>, L. Nasella <sup>id71a,71b</sup>, M. Naseri <sup>id34</sup>, S. Nasri <sup>id117b</sup>, C. Nass <sup>id24</sup>, G. Navarro <sup>id22a</sup>, J. Navarro-Gonzalez <sup>id164</sup>, R. Nayak <sup>id152</sup>, A. Nayaz <sup>id18</sup>, P.Y. Nechaeva <sup>id37</sup>, S. Nechaeva <sup>id23b,23a</sup>, F. Nechansky <sup>id48</sup>, L. Nedic <sup>id127</sup>, T.J. Neep <sup>id20</sup>, A. Negri <sup>id73a,73b</sup>, M. Negrini <sup>id23b</sup>, C. Nellist <sup>id115</sup>, C. Nelson <sup>id105</sup>, K. Nelson <sup>id107</sup>, S. Nemecek <sup>id132</sup>, M. Nessi <sup>id36,g</sup>, M.S. Neubauer <sup>id163</sup>, F. Neuhaus <sup>id101</sup>, J. Neundorf <sup>id48</sup>, P.R. Newman <sup>id20</sup>, C.W. Ng <sup>id130</sup>, Y.W.Y. Ng <sup>id48</sup>, B. Ngair <sup>id117a</sup>, H.D.N. Nguyen <sup>id109</sup>, R.B. Nickerson <sup>id127</sup>, R. Nicolaidou <sup>id136</sup>, J. Nielsen <sup>id137</sup>, M. Niemeyer <sup>id55</sup>, J. Niermann <sup>id55</sup>, N. Nikiforou <sup>id36</sup>, V. Nikolaenko <sup>id37,a</sup>, I. Nikolic-Audit <sup>id128</sup>, K. Nikolopoulos <sup>id20</sup>, P. Nilsson <sup>id29</sup>, I. Ninca <sup>id48</sup>, G. Ninio <sup>id152</sup>, A. Nisati <sup>id75a</sup>, N. Nishu <sup>id2</sup>, R. Nisius <sup>id111</sup>, J-E. Nitschke <sup>id50</sup>, E.K. Nkadimeng <sup>id33g</sup>, T. Nobe <sup>id154</sup>, T. Nommensen <sup>id148</sup>, M.B. Norfolk <sup>id140</sup>, R.R.B. Norisam <sup>id97</sup>, B.J. Norman <sup>id34</sup>, M. Noury <sup>id35a</sup>, J. Novak <sup>id94</sup>, T. Novak <sup>id94</sup>, L. Novotny <sup>id133</sup>, R. Novotny <sup>id113</sup>, L. Nozka <sup>id123</sup>, K. Ntekas <sup>id160</sup>, N.M.J. Nunes De Moura Junior <sup>id83b</sup>, J. Ocariz <sup>id128</sup>, A. Ochi <sup>id85</sup>, I. Ochoa <sup>id131a</sup>, S. Oerdek <sup>id48,s</sup>, J.T. Offermann <sup>id39</sup>, A. Ogrodnik <sup>id134</sup>, A. Oh <sup>id102</sup>, C.C. Ohm <sup>id145</sup>, H. Oide <sup>id84</sup>, R. Oishi <sup>id154</sup>, M.L. Ojeda <sup>id48</sup>, Y. Okumura <sup>id154</sup>, L.F. Oleiro Seabra <sup>id131a</sup>, S.A. Olivares Pino <sup>id138d</sup>, G. Oliveira Correa <sup>id13</sup>, D. Oliveira Damazio <sup>id29</sup>, D. Oliveira Goncalves <sup>id83a</sup>, J.L. Oliver <sup>id160</sup>, Ö.O. Öncel <sup>id54</sup>, A.P. O’Neill <sup>id19</sup>, A. Onofre <sup>id131a,131e</sup>, P.U.E. Onyisi <sup>id11</sup>, M.J. Oreglia <sup>id39</sup>, G.E. Orellana <sup>id91</sup>, D. Orestano <sup>id77a,77b</sup>, N. Orlando <sup>id13</sup>, R.S. Orr <sup>id156</sup>, V. O’Shea <sup>id59</sup>, L.M. Osojnak <sup>id129</sup>, R. Ospanov <sup>id62a</sup>, G. Otero y Garzon <sup>id30</sup>, H. Otono <sup>id89</sup>, P.S. Ott <sup>id63a</sup>, G.J. Ottino <sup>id17a</sup>, M. Ouchrif <sup>id35d</sup>, F. Ould-Saada <sup>id126</sup>, T. Ovsiannikova <sup>id139</sup>, M. Owen <sup>id59</sup>, R.E. Owen <sup>id135</sup>, V.E. Ozcan <sup>id21a</sup>, F. Ozturk <sup>id87</sup>, N. Ozturk <sup>id8</sup>, S. Ozturk <sup>id82</sup>, H.A. Pacey <sup>id127</sup>, A. Pacheco Pages <sup>id13</sup>, C. Padilla Aranda <sup>id13</sup>, G. Padovano <sup>id75a,75b</sup>, S. Pagan Griso <sup>id17a</sup>, G. Palacino <sup>id68</sup>, A. Palazzo <sup>id70a,70b</sup>, J. Pampel <sup>id24</sup>, J. Pan <sup>id173</sup>, T. Pan <sup>id64a</sup>, D.K. Panchal <sup>id11</sup>, C.E. Pandini <sup>id115</sup>, J.G. Panduro Vazquez <sup>id135</sup>, H.D. Pandya <sup>id1</sup>, H. Pang <sup>id14b</sup>, P. Pani <sup>id48</sup>, G. Panizzo <sup>id69a,69c</sup>, L. Panwar <sup>id128</sup>, L. Paolozzi <sup>id56</sup>, S. Parajuli <sup>id163</sup>, A. Paramonov <sup>id6</sup>, C. Paraskevopoulos <sup>id53</sup>, D. Paredes Hernandez <sup>id64b</sup>, A. Pareti <sup>id73a,73b</sup>, K.R. Park <sup>id41</sup>, T.H. Park <sup>id156</sup>, M.A. Parker <sup>id32</sup>, F. Parodi <sup>id57b,57a</sup>, E.W. Parrish <sup>id116</sup>, V.A. Parrish <sup>id52</sup>, J.A. Parsons <sup>id41</sup>, U. Parzefall <sup>id54</sup>, B. Pascual Dias <sup>id109</sup>, L. Pascual Dominguez <sup>id100</sup>, E. Pasqualucci <sup>id75a</sup>, S. Passaggio <sup>id57b</sup>, F. Pastore <sup>id96</sup>, P. Patel <sup>id87</sup>, U.M. Patel <sup>id51</sup>, J.R. Pater <sup>id102</sup>, T. Pauly <sup>id36</sup>, C.I. Pazos <sup>id159</sup>, J. Pearkes <sup>id144</sup>, M. Pedersen <sup>id126</sup>, R. Pedro <sup>id131a</sup>, S.V. Peleganchuk <sup>id37</sup>, O. Penc <sup>id36</sup>, E.A. Pender <sup>id52</sup>, G.D. Penn <sup>id173</sup>, K.E. Penski <sup>id110</sup>, M. Penzin <sup>id37</sup>, B.S. Peralva <sup>id83d</sup>, A.P. Pereira Peixoto <sup>id139</sup>, L. Pereira Sanchez <sup>id144</sup>, D.V. Perepelitsa <sup>id29,af</sup>, E. Perez Codina <sup>id157a</sup>, M. Perganti <sup>id10</sup>, H. Pernegger <sup>id36</sup>, S. Perrella <sup>id75a,75b</sup>, O. Perrin <sup>id40</sup>, K. Peters <sup>id48</sup>, R.F.Y. Peters <sup>id102</sup>, B.A. Petersen <sup>id36</sup>, T.C. Petersen <sup>id42</sup>, E. Petit <sup>id103</sup>, V. Petousis <sup>id133</sup>, C. Petridou <sup>id153,d</sup>, T. Petru <sup>id134</sup>, A. Petrukhin <sup>id142</sup>, M. Pettee <sup>id17a</sup>, N.E. Pettersson <sup>id36</sup>, A. Petukhov <sup>id37</sup>, K. Petukhova <sup>id134</sup>, R. Pezoa <sup>id138f</sup>, L. Pezzotti <sup>id36</sup>, G. Pezzullo <sup>id173</sup>, T.M. Pham <sup>id171</sup>, T. Pham <sup>id106</sup>, P.W. Phillips <sup>id135</sup>, G. Piacquadio <sup>id146</sup>, E. Pianori <sup>id17a</sup>, F. Piazza <sup>id124</sup>, R. Piegai <sup>id30</sup>, D. Pietreanu <sup>id27b</sup>, A.D. Pilkington <sup>id102</sup>, M. Pinamonti <sup>id69a,69c</sup>, J.L. Pinfeld <sup>id2</sup>, B.C. Pinheiro Pereira <sup>id131a</sup>, A.E. Pinto Pinoargote <sup>id136,136</sup>, L. Pintucci <sup>id69a,69c</sup>, K.M. Piper <sup>id147</sup>, A. Pirttikoski <sup>id56</sup>, D.A. Pizzi <sup>id34</sup>, L. Pizzimento <sup>id64b</sup>, A. Pizzini <sup>id115</sup>, M.-A. Pleier <sup>id29</sup>, V. Pleskot <sup>id134</sup>, E. Plotnikova<sup>38</sup>, G. Poddar <sup>id95</sup>, R. Poettgen <sup>id99</sup>, L. Poggioli <sup>id128</sup>, I. Pokharel <sup>id55</sup>, S. Polacek <sup>id134</sup>, G. Polesello <sup>id73a</sup>, A. Poley <sup>id143,157a</sup>, A. Polini <sup>id23b</sup>, C.S. Pollard <sup>id168</sup>, Z.B. Pollock <sup>id120</sup>, E. Pompa Pacchi <sup>id75a,75b</sup>, N.I. Pond <sup>id97</sup>, D. Ponomarenko <sup>id114</sup>, L. Pontecorvo <sup>id36</sup>, S. Popa <sup>id27a</sup>, G.A. Popeneciu <sup>id27d</sup>, A. Poreba <sup>id36</sup>,

D.M. Portillo Quintero [ID157a](#), S. Pospisil [ID133](#), M.A. Postill [ID140](#), P. Postolache [ID27c](#), K. Potamianos [ID168](#),  
 P.A. Potepa [ID86a](#), I.N. Potrap [ID38](#), C.J. Potter [ID32](#), H. Potti [ID1](#), J. Poveda [ID164](#), M.E. Pozo Astigarraga [ID36](#),  
 A. Prades Ibanez [ID164](#), J. Pretel [ID54](#), D. Price [ID102](#), M. Primavera [ID70a](#), M.A. Principe Martin [ID100](#),  
 R. Privara [ID123](#), T. Procter [ID59](#), M.L. Proffitt [ID139](#), N. Proklova [ID129](#), K. Prokofiev [ID64c](#), G. Proto [ID111](#),  
 J. Proudfoot [ID6](#), M. Przybycien [ID86a](#), W.W. Przygoda [ID86b](#), A. Psallidas [ID46](#), J.E. Puddefoot [ID140](#),  
 D. Pudzha [ID37](#), D. Pyatiizbyantseva [ID37](#), J. Qian [ID107](#), D. Qichen [ID102](#), Y. Qin [ID13](#), T. Qiu [ID52](#),  
 A. Quadt [ID55](#), M. Queitsch-Maitland [ID102](#), G. Quetant [ID56](#), R.P. Quinn [ID165](#), G. Rabanal Bolanos [ID61](#),  
 D. Rafanoharana [ID54](#), F. Raffaelli [ID76a,76b](#), F. Ragusa [ID71a,71b](#), J.L. Rainbolt [ID39](#), J.A. Raine [ID56](#),  
 S. Rajagopalan [ID29](#), E. Ramakoti [ID37](#), I.A. Ramirez-Berend [ID34](#), K. Ran [ID48,14e](#), N.P. Rapheeha [ID33g](#),  
 H. Rasheed [ID27b](#), V. Raskina [ID128](#), D.F. Rassloff [ID63a](#), A. Rastogi [ID17a](#), S. Rave [ID101](#), B. Ravina [ID55](#),  
 I. Ravinovich [ID170](#), M. Raymond [ID36](#), A.L. Read [ID126](#), N.P. Readioff [ID140](#), D.M. Rebutzi [ID73a,73b](#),  
 G. Redlinger [ID29](#), A.S. Reed [ID111](#), K. Reeves [ID26](#), J.A. Reidelsturz [ID172](#), D. Reikher [ID152](#), A. Rej [ID49](#),  
 C. Rembser [ID36](#), M. Renda [ID27b](#), M.B. Rendel [ID111](#), F. Renner [ID48](#), A.G. Rennie [ID160](#), A.L. Rescia [ID48](#),  
 S. Resconi [ID71a](#), M. Ressegotti [ID57b,57a](#), S. Rettie [ID36](#), J.G. Reyes Rivera [ID108](#), E. Reynolds [ID17a](#),  
 O.L. Rezanova [ID37](#), P. Reznicek [ID134](#), H. Riani [ID35d](#), N. Ribaric [ID92](#), E. Ricci [ID78a,78b](#), R. Richter [ID111](#),  
 S. Richter [ID47a,47b](#), E. Richter-Was [ID86b](#), M. Ridel [ID128](#), S. Ridouani [ID35d](#), P. Rieck [ID118](#), P. Riedler [ID36](#),  
 E.M. Riefel [ID47a,47b](#), J.O. Rieger [ID115](#), M. Rijssenbeek [ID146](#), M. Rimoldi [ID36](#), L. Rinaldi [ID23b,23a](#),  
 T.T. Rinn [ID29](#), M.P. Rinnagel [ID110](#), G. Ripellino [ID162](#), I. Riu [ID13](#), J.C. Rivera Vergara [ID166](#),  
 F. Rizatdinova [ID122](#), E. Rizvi [ID95](#), B.R. Roberts [ID17a](#), S.H. Robertson [ID105,v](#), D. Robinson [ID32](#),  
 C.M. Robles Gajardo [ID138f](#), M. Robles Manzano [ID101](#), A. Robson [ID59](#), A. Rocchi [ID76a,76b](#), C. Roda [ID74a,74b](#),  
 S. Rodriguez Bosca [ID36](#), Y. Rodriguez Garcia [ID22a](#), A. Rodriguez Rodriguez [ID54](#),  
 A.M. Rodríguez Vera [ID116](#), S. Roe [ID36](#), J.T. Roemer [ID160](#), A.R. Roepe-Gier [ID137](#), J. Roggel [ID172](#),  
 O. Røhne [ID126](#), R.A. Rojas [ID104](#), C.P.A. Roland [ID128](#), J. Roloff [ID29](#), A. Romaniouk [ID37](#),  
 E. Romano [ID73a,73b](#), M. Romano [ID23b](#), A.C. Romero Hernandez [ID163](#), N. Rompotis [ID93](#), L. Roos [ID128](#),  
 S. Rosati [ID75a](#), B.J. Rosser [ID39](#), E. Rossi [ID127](#), E. Rossi [ID72a,72b](#), L.P. Rossi [ID61](#), L. Rossini [ID54](#),  
 R. Rosten [ID120](#), M. Rotaru [ID27b](#), B. Rottler [ID54](#), C. Rougier [ID90](#), D. Rousseau [ID66](#), D. Rousso [ID48](#),  
 A. Roy [ID163](#), S. Roy-Garand [ID156](#), A. Rozanov [ID103](#), Z.M.A. Rozario [ID59](#), Y. Rozen [ID151](#),  
 A. Rubio Jimenez [ID164](#), A.J. Ruby [ID93](#), V.H. Ruelas Rivera [ID18](#), T.A. Ruggeri [ID1](#), A. Ruggiero [ID127](#),  
 A. Ruiz-Martinez [ID164](#), A. Rummler [ID36](#), Z. Rurikova [ID54](#), N.A. Rusakovich [ID38](#), H.L. Russell [ID166](#),  
 G. Russo [ID75a,75b](#), J.P. Rutherford [ID7](#), S. Rutherford Colmenares [ID32](#), M. Rybar [ID134](#), E.B. Rye [ID126](#),  
 A. Ryzhov [ID44](#), J.A. Sabater Iglesias [ID56](#), P. Sabatini [ID164](#), H.F.W. Sadrozinski [ID137](#),  
 F. Safai Tehrani [ID75a](#), B. Safarzadeh Samani [ID135](#), S. Saha [ID1](#), M. Sahinsoy [ID111](#), A. Saibel [ID164](#),  
 M. Saimpert [ID136](#), M. Saito [ID154](#), T. Saito [ID154](#), A. Sala [ID71a,71b](#), D. Salamani [ID36](#), A. Salnikov [ID144](#),  
 J. Salt [ID164](#), A. Salvador Salas [ID152](#), D. Salvatore [ID43b,43a](#), F. Salvatore [ID147](#), A. Salzburger [ID36](#),  
 D. Sammel [ID54](#), E. Sampson [ID92](#), D. Sampsonidis [ID153,d](#), D. Sampsonidou [ID124](#), J. Sánchez [ID164](#),  
 V. Sanchez Sebastian [ID164](#), H. Sandaker [ID126](#), C.O. Sander [ID48](#), J.A. Sandesara [ID104](#), M. Sandhoff [ID172](#),  
 C. Sandoval [ID22b](#), L. Sanfilippo [ID63a](#), D.P.C. Sankey [ID135](#), T. Sano [ID88](#), A. Sansoni [ID53](#), L. Santi [ID75a,75b](#),  
 C. Santoni [ID40](#), H. Santos [ID131a,131b](#), A. Santra [ID170](#), E. Sanzani [ID23b,23a](#), K.A. Saoucha [ID161](#),  
 J.G. Saraiva [ID131a,131d](#), J. Sardain [ID7](#), O. Sasaki [ID84](#), K. Sato [ID158](#), C. Sauer [ID63b](#), E. Sauvan [ID4](#),  
 P. Savard [ID156,ad](#), R. Sawada [ID154](#), C. Sawyer [ID135](#), L. Sawyer [ID98](#), C. Sbarra [ID23b](#), A. Sbrizzi [ID23b,23a](#),  
 T. Scanlon [ID97](#), J. Schaarschmidt [ID139](#), U. Schäfer [ID101](#), A.C. Schaffer [ID66,44](#), D. Schaile [ID110](#),  
 R.D. Schamberger [ID146](#), C. Scharf [ID18](#), M.M. Schefer [ID19](#), V.A. Schegelsky [ID37](#), D. Scheirich [ID134](#),  
 M. Schernau [ID160](#), C. Scheulen [ID55](#), C. Schiavi [ID57b,57a](#), M. Schioppa [ID43b,43a](#), B. Schlag [ID144,1](#),  
 K.E. Schleicher [ID54](#), S. Schlenker [ID36](#), J. Schmeing [ID172](#), M.A. Schmidt [ID172](#), K. Schmieden [ID101](#),  
 C. Schmitt [ID101](#), N. Schmitt [ID101](#), S. Schmitt [ID48](#), L. Schoeffel [ID136](#), A. Schoening [ID63b](#),  
 P.G. Scholer [ID34](#), E. Schopf [ID127](#), M. Schott [ID24](#), J. Schovancova [ID36](#), S. Schramm [ID56](#), T. Schroer [ID56](#),  
 H-C. Schultz-Coulon [ID63a](#), M. Schumacher [ID54](#), B.A. Schumm [ID137](#), Ph. Schune [ID136](#), A.J. Schuy [ID139](#),

H.R. Schwartz <sup>137</sup>, A. Schwartzman <sup>144</sup>, T.A. Schwarz <sup>107</sup>, Ph. Schwemling <sup>136</sup>,  
 R. Schwienhorst <sup>108</sup>, A. Sciandra <sup>29</sup>, G. Sciolla <sup>26</sup>, F. Scuri <sup>74a</sup>, C.D. Sebastiani <sup>93</sup>,  
 K. Sedlaczek <sup>116</sup>, S.C. Seidel <sup>113</sup>, A. Seiden <sup>137</sup>, B.D. Seidlitz <sup>41</sup>, C. Seitz <sup>48</sup>, J.M. Seixas <sup>83b</sup>,  
 G. Sekhniaidze <sup>72a</sup>, L. Selem <sup>60</sup>, N. Semprini-Cesari <sup>23b,23a</sup>, D. Sengupta <sup>56</sup>, V. Senthilkumar <sup>164</sup>,  
 L. Serin <sup>66</sup>, M. Sessa <sup>76a,76b</sup>, H. Severini <sup>121</sup>, F. Sforza <sup>57b,57a</sup>, A. Sfyrta <sup>56</sup>, Q. Sha <sup>14a</sup>,  
 E. Shabalina <sup>55</sup>, A.H. Shah <sup>32</sup>, R. Shaheen <sup>145</sup>, J.D. Shahinian <sup>129</sup>, D. Shaked Renous <sup>170</sup>,  
 L.Y. Shan <sup>14a</sup>, M. Shapiro <sup>17a</sup>, A. Sharma <sup>36</sup>, A.S. Sharma <sup>165</sup>, P. Sharma <sup>80</sup>, P.B. Shatalov <sup>37</sup>,  
 K. Shaw <sup>147</sup>, S.M. Shaw <sup>102</sup>, Q. Shen <sup>62c,5</sup>, D.J. Sheppard <sup>143</sup>, P. Sherwood <sup>97</sup>, L. Shi <sup>97</sup>,  
 X. Shi <sup>14a</sup>, C.O. Shimmin <sup>173</sup>, J.D. Shinner <sup>96</sup>, I.P.J. Shipsey <sup>127</sup>, S. Shirabe <sup>89</sup>,  
 M. Shiyakova <sup>38,t</sup>, M.J. Shochet <sup>39</sup>, J. Shojaii <sup>106</sup>, D.R. Shope <sup>126</sup>, B. Shrestha <sup>121</sup>,  
 S. Shrestha <sup>120,ag</sup>, M.J. Shroff <sup>166</sup>, P. Sicho <sup>132</sup>, A.M. Sickles <sup>163</sup>, E. Sideras Haddad <sup>33g</sup>,  
 A.C. Sidley <sup>115</sup>, A. Sidoti <sup>23b</sup>, F. Siegert <sup>50</sup>, Dj. Sijacki <sup>15</sup>, F. Sili <sup>91</sup>, J.M. Silva <sup>52</sup>,  
 M.V. Silva Oliveira <sup>29</sup>, S.B. Silverstein <sup>47a</sup>, S. Simion <sup>66</sup>, R. Simoniello <sup>36</sup>, E.L. Simpson <sup>102</sup>,  
 H. Simpson <sup>147</sup>, L.R. Simpson <sup>107</sup>, N.D. Simpson <sup>99</sup>, S. Simsek <sup>82</sup>, S. Sindhu <sup>55</sup>, P. Sinervo <sup>156</sup>,  
 S. Singh <sup>156</sup>, S. Sinha <sup>48</sup>, S. Sinha <sup>102</sup>, M. Sioli <sup>23b,23a</sup>, I. Siral <sup>36</sup>, E. Sitnikova <sup>48</sup>,  
 J. Sjölin <sup>47a,47b</sup>, A. Skaf <sup>55</sup>, E. Skorda <sup>20</sup>, P. Skubic <sup>121</sup>, M. Slawinska <sup>87</sup>, V. Smakhtin <sup>170</sup>,  
 B.H. Smart <sup>135</sup>, S.Yu. Smirnov <sup>37</sup>, Y. Smirnov <sup>37</sup>, L.N. Smirnova <sup>37,a</sup>, O. Smirnova <sup>99</sup>,  
 A.C. Smith <sup>41</sup>, D.R. Smith <sup>160</sup>, E.A. Smith <sup>39</sup>, H.A. Smith <sup>127</sup>, J.L. Smith <sup>102</sup>, R. Smith <sup>144</sup>,  
 M. Smizanska <sup>92</sup>, K. Smolek <sup>133</sup>, A.A. Snesarev <sup>37</sup>, S.R. Snider <sup>156</sup>, H.L. Snoek <sup>115</sup>,  
 S. Snyder <sup>29</sup>, R. Sobie <sup>166,v</sup>, A. Soffer <sup>152</sup>, C.A. Solans Sanchez <sup>36</sup>, E.Yu. Soldatov <sup>37</sup>,  
 U. Soldevila <sup>164</sup>, A.A. Solodkov <sup>37</sup>, S. Solomon <sup>26</sup>, A. Soloshenko <sup>38</sup>, K. Solovieva <sup>54</sup>,  
 O.V. Solovyanov <sup>40</sup>, P. Sommer <sup>36</sup>, A. Sonay <sup>13</sup>, W.Y. Song <sup>157b</sup>, A. Sopczak <sup>133</sup>, A.L. Soppio <sup>97</sup>,  
 F. Sopkova <sup>28b</sup>, J.D. Sorenson <sup>113</sup>, I.R. Sotarriva Alvarez <sup>155</sup>, V. Sothilingam <sup>63a</sup>,  
 O.J. Soto Sandoval <sup>138c,138b</sup>, S. Sottocornola <sup>68</sup>, R. Soualah <sup>161</sup>, Z. Soumami <sup>35e</sup>, D. South <sup>48</sup>,  
 N. Soybelman <sup>170</sup>, S. Spagnolo <sup>70a,70b</sup>, M. Spalla <sup>111</sup>, D. Sperlich <sup>54</sup>, G. Spigo <sup>36</sup>, S. Spinali <sup>92</sup>,  
 D.P. Spiteri <sup>59</sup>, M. Spousta <sup>134</sup>, E.J. Staats <sup>34</sup>, R. Stamen <sup>63a</sup>, A. Stampeki <sup>20</sup>, M. Standke <sup>24</sup>,  
 E. Stanecka <sup>87</sup>, W. Stanek-Maslouska <sup>48</sup>, M.V. Stange <sup>50</sup>, B. Stanislaus <sup>17a</sup>, M.M. Stanitzki <sup>48</sup>,  
 B. Stapf <sup>48</sup>, E.A. Starchenko <sup>37</sup>, G.H. Stark <sup>137</sup>, J. Stark <sup>90</sup>, P. Staroba <sup>132</sup>, P. Starovoitov <sup>63a</sup>,  
 S. Stärz <sup>105</sup>, R. Staszewski <sup>87</sup>, G. Stavropoulos <sup>46</sup>, J. Steentoft <sup>162</sup>, P. Steinberg <sup>29</sup>,  
 B. Stelzer <sup>143,157a</sup>, H.J. Stelzer <sup>130</sup>, O. Stelzer-Chilton <sup>157a</sup>, H. Stenzel <sup>58</sup>, T.J. Stevenson <sup>147</sup>,  
 G.A. Stewart <sup>36</sup>, J.R. Stewart <sup>122</sup>, M.C. Stockton <sup>36</sup>, G. Stoicea <sup>27b</sup>, M. Stolarski <sup>131a</sup>,  
 S. Stonjek <sup>111</sup>, A. Straessner <sup>50</sup>, J. Strandberg <sup>145</sup>, S. Strandberg <sup>47a,47b</sup>, M. Stratmann <sup>172</sup>,  
 M. Strauss <sup>121</sup>, T. Strebler <sup>103</sup>, P. Strizenec <sup>28b</sup>, R. Ströhmer <sup>167</sup>, D.M. Strom <sup>124</sup>,  
 R. Stroynowski <sup>44</sup>, A. Strubig <sup>47a,47b</sup>, S.A. Stucci <sup>29</sup>, B. Stugu <sup>16</sup>, J. Stupak <sup>121</sup>, N.A. Styles <sup>48</sup>,  
 D. Su <sup>144</sup>, S. Su <sup>62a</sup>, W. Su <sup>62d</sup>, X. Su <sup>62a</sup>, D. Suchy <sup>28a</sup>, K. Sugizaki <sup>154</sup>, V.V. Sulin <sup>37</sup>,  
 M.J. Sullivan <sup>93</sup>, D.M.S. Sultan <sup>127</sup>, L. Sultanaliyeva <sup>37</sup>, S. Sultansoy <sup>3b</sup>, T. Sumida <sup>88</sup>,  
 S. Sun <sup>107</sup>, S. Sun <sup>171</sup>, O. Sunneborn Gudnadottir <sup>162</sup>, N. Sur <sup>103</sup>, M.R. Sutton <sup>147</sup>,  
 H. Suzuki <sup>158</sup>, M. Svatos <sup>132</sup>, M. Swiatlowski <sup>157a</sup>, T. Swirski <sup>167</sup>, I. Sykora <sup>28a</sup>, M. Sykora <sup>134</sup>,  
 T. Sykora <sup>134</sup>, D. Ta <sup>101</sup>, K. Tackmann <sup>48,s</sup>, A. Taffard <sup>160</sup>, R. Tafirout <sup>157a</sup>,  
 J.S. Tafoya Vargas <sup>66</sup>, Y. Takubo <sup>84</sup>, M. Talby <sup>103</sup>, A.A. Talyshev <sup>37</sup>, K.C. Tam <sup>64b</sup>,  
 N.M. Tamir <sup>152</sup>, A. Tanaka <sup>154</sup>, J. Tanaka <sup>154</sup>, R. Tanaka <sup>66</sup>, M. Tanasini <sup>146</sup>, Z. Tao <sup>165</sup>,  
 S. Tapia Araya <sup>138f</sup>, S. Tapprogge <sup>101</sup>, A. Tarek Abouelfadl Mohamed <sup>108</sup>, S. Tarem <sup>151</sup>,  
 K. Tariq <sup>14a</sup>, G. Tarna <sup>27b</sup>, G.F. Tartarelli <sup>71a</sup>, M.J. Tartarin <sup>90</sup>, P. Tas <sup>134</sup>, M. Tasevsky <sup>132</sup>,  
 E. Tassi <sup>43b,43a</sup>, A.C. Tate <sup>163</sup>, G. Tateno <sup>154</sup>, Y. Tayalati <sup>35e,u</sup>, G.N. Taylor <sup>106</sup>, W. Taylor <sup>157b</sup>,  
 A.S. Tee <sup>171</sup>, R. Teixeira De Lima <sup>144</sup>, P. Teixeira-Dias <sup>96</sup>, J.J. Teoh <sup>156</sup>, K. Terashi <sup>154</sup>,  
 J. Terron <sup>100</sup>, S. Terzo <sup>13</sup>, M. Testa <sup>53</sup>, R.J. Teuscher <sup>156,v</sup>, A. Thaler <sup>79</sup>, O. Theiner <sup>56</sup>,  
 N. Themistokleous <sup>52</sup>, T. Thevenaux-Pelzer <sup>103</sup>, O. Thielmann <sup>172</sup>, D.W. Thomas <sup>96</sup>,

J.P. Thomas <sup>20</sup>, E.A. Thompson <sup>17a</sup>, P.D. Thompson <sup>20</sup>, E. Thomson <sup>129</sup>, R.E. Thornberry<sup>44</sup>, C. Tian <sup>62a</sup>, Y. Tian <sup>55</sup>, V. Tikhomirov <sup>37,a</sup>, Yu.A. Tikhonov <sup>37</sup>, S. Timoshenko<sup>37</sup>, D. Timoshyn <sup>134</sup>, E.X.L. Ting <sup>1</sup>, P. Tipton <sup>173</sup>, A. Tishelman-Charny <sup>29</sup>, S.H. Tlou <sup>33g</sup>, K. Todome <sup>155</sup>, S. Todorova-Nova <sup>134</sup>, S. Todt<sup>50</sup>, L. Toffolin <sup>69a,69c</sup>, M. Togawa <sup>84</sup>, J. Tojo <sup>89</sup>, S. Tokár <sup>28a</sup>, K. Tokushuku <sup>84</sup>, O. Toldaiev <sup>68</sup>, R. Tombs <sup>32</sup>, M. Tomoto <sup>84,112</sup>, L. Tompkins <sup>144,1</sup>, K.W. Topolnicki <sup>86b</sup>, E. Torrence <sup>124</sup>, H. Torres <sup>90</sup>, E. Torró Pastor <sup>164</sup>, M. Toscani <sup>30</sup>, C. Tosciri <sup>39</sup>, M. Tost <sup>11</sup>, D.R. Tovey <sup>140</sup>, A. Traeet<sup>16</sup>, I.S. Trandafir <sup>27b</sup>, T. Trefzger <sup>167</sup>, A. Tricoli <sup>29</sup>, I.M. Trigger <sup>157a</sup>, S. Trincaz-Duvoid <sup>128</sup>, D.A. Trischuk <sup>26</sup>, B. Trocmé <sup>60</sup>, L. Truong <sup>33c</sup>, M. Trzebinski <sup>87</sup>, A. Trzupiek <sup>87</sup>, F. Tsai <sup>146</sup>, M. Tsai <sup>107</sup>, A. Tsiamis <sup>153,d</sup>, P.V. Tsiareshka<sup>37</sup>, S. Tsigaridas <sup>157a</sup>, A. Tsirigotis <sup>153,q</sup>, V. Tsiskaridze <sup>156</sup>, E.G. Tskhadadze <sup>150a</sup>, M. Tsopoulou <sup>153</sup>, Y. Tsujikawa <sup>88</sup>, I.I. Tsukerman <sup>37</sup>, V. Tsulaia <sup>17a</sup>, S. Tsuno <sup>84</sup>, K. Tsuru <sup>119</sup>, D. Tsybychev <sup>146</sup>, Y. Tu <sup>64b</sup>, A. Tudorache <sup>27b</sup>, V. Tudorache <sup>27b</sup>, A.N. Tuna <sup>61</sup>, S. Turchikhin <sup>57b,57a</sup>, I. Turk Cakir <sup>3a</sup>, R. Turra <sup>71a</sup>, T. Turtuvshin <sup>38,w</sup>, P.M. Tuts <sup>41</sup>, S. Tzamarias <sup>153,d</sup>, E. Tzovara <sup>101</sup>, F. Ukegawa <sup>158</sup>, P.A. Ulloa Poblete <sup>138c,138b</sup>, E.N. Umaka <sup>29</sup>, G. Unal <sup>36</sup>, A. Undrus <sup>29</sup>, G. Unel <sup>160</sup>, J. Urban <sup>28b</sup>, P. Urrejola <sup>138a</sup>, G. Usai <sup>8</sup>, R. Ushioda <sup>155</sup>, M. Usman <sup>109</sup>, Z. Uysal <sup>82</sup>, V. Vacek <sup>133</sup>, B. Vachon <sup>105</sup>, T. Vafeiadis <sup>36</sup>, A. Vaitkus <sup>97</sup>, C. Valderanis <sup>110</sup>, E. Valdes Santurio <sup>47a,47b</sup>, M. Valente <sup>157a</sup>, S. Valentinetti <sup>23b,23a</sup>, A. Valero <sup>164</sup>, E. Valiente Moreno <sup>164</sup>, A. Vallier <sup>90</sup>, J.A. Valls Ferrer <sup>164</sup>, D.R. Van Arneman <sup>115</sup>, T.R. Van Daalen <sup>139</sup>, A. Van Der Graaf <sup>49</sup>, P. Van Gemmeren <sup>6</sup>, M. Van Rijnbach <sup>36</sup>, S. Van Stroud <sup>97</sup>, I. Van Vulpen <sup>115</sup>, P. Vana <sup>134</sup>, M. Vanadia <sup>76a,76b</sup>, W. Vandelli <sup>36</sup>, E.R. Vandewall <sup>122</sup>, D. Vannicola <sup>152</sup>, L. Vannoli <sup>53</sup>, R. Vari <sup>75a</sup>, E.W. Varnes <sup>7</sup>, C. Varni <sup>17b</sup>, T. Varol <sup>149</sup>, D. Varouchas <sup>66</sup>, L. Variiale <sup>164</sup>, K.E. Varvell <sup>148</sup>, M.E. Vasile <sup>27b</sup>, L. Vaslin<sup>84</sup>, G.A. Vasquez <sup>166</sup>, A. Vasyukov <sup>38</sup>, R. Vavricka<sup>101</sup>, T. Vazquez Schroeder <sup>36</sup>, J. Veatch <sup>31</sup>, V. Vecchio <sup>102</sup>, M.J. Veen <sup>104</sup>, I. Veliscek <sup>29</sup>, L.M. Veloce <sup>156</sup>, F. Veloso <sup>131a,131c</sup>, S. Veneziano <sup>75a</sup>, A. Ventura <sup>70a,70b</sup>, S. Ventura Gonzalez <sup>136</sup>, A. Verbytskyi <sup>111</sup>, M. Verducci <sup>74a,74b</sup>, C. Vergis <sup>95</sup>, M. Verissimo De Araujo <sup>83b</sup>, W. Verkerke <sup>115</sup>, J.C. Vermeulen <sup>115</sup>, C. Vernieri <sup>144</sup>, M. Vessella <sup>104</sup>, M.C. Vetterli <sup>143,ad</sup>, A. Vgenopoulos <sup>153,d</sup>, N. Viaux Maira <sup>138f</sup>, T. Vickey <sup>140</sup>, O.E. Vickey Boeriu <sup>140</sup>, G.H.A. Viehhauser <sup>127</sup>, L. Vigani <sup>63b</sup>, M. Villa <sup>23b,23a</sup>, M. Villaplana Perez <sup>164</sup>, E.M. Villhauer<sup>52</sup>, E. Vilucchi <sup>53</sup>, M.G. Vincter <sup>34</sup>, A. Visibile<sup>115</sup>, C. Vittori <sup>36</sup>, I. Vivarelli <sup>23b,23a</sup>, E. Voevodina <sup>111</sup>, F. Vogel <sup>110</sup>, J.C. Voigt <sup>50</sup>, P. Vokac <sup>133</sup>, Yu. Volkotrub <sup>86b</sup>, J. Von Ahnen <sup>48</sup>, E. Von Toerne <sup>24</sup>, B. Vormwald <sup>36</sup>, V. Vorobel <sup>134</sup>, K. Vorobev <sup>37</sup>, M. Vos <sup>164</sup>, K. Voss <sup>142</sup>, M. Vozak <sup>115</sup>, L. Vozdecky <sup>121</sup>, N. Vranjes <sup>15</sup>, M. Vranjes Milosavljevic <sup>15</sup>, M. Vreeswijk <sup>115</sup>, N.K. Vu <sup>62d,62c</sup>, R. Vuillermet <sup>36</sup>, O. Vujinovic <sup>101</sup>, I. Vukotic <sup>39</sup>, S. Wada <sup>158</sup>, C. Wagner<sup>104</sup>, J.M. Wagner <sup>17a</sup>, W. Wagner <sup>172</sup>, S. Wahdan <sup>172</sup>, H. Wahlberg <sup>91</sup>, M. Wakida <sup>112</sup>, J. Walder <sup>135</sup>, R. Walker <sup>110</sup>, W. Walkowiak <sup>142</sup>, A. Wall <sup>129</sup>, E.J. Wallin <sup>99</sup>, T. Wamorkar <sup>6</sup>, A.Z. Wang <sup>137</sup>, C. Wang <sup>101</sup>, C. Wang <sup>11</sup>, H. Wang <sup>17a</sup>, J. Wang <sup>64c</sup>, R. Wang <sup>61</sup>, R. Wang <sup>6</sup>, S.M. Wang <sup>149</sup>, S. Wang <sup>62b</sup>, S. Wang <sup>14a</sup>, T. Wang <sup>62a</sup>, W.T. Wang <sup>80</sup>, W. Wang <sup>14a</sup>, X. Wang <sup>14c</sup>, X. Wang <sup>163</sup>, X. Wang <sup>62c</sup>, Y. Wang <sup>62d</sup>, Y. Wang <sup>14c</sup>, Z. Wang <sup>107</sup>, Z. Wang <sup>62d,51,62c</sup>, Z. Wang <sup>107</sup>, A. Warburton <sup>105</sup>, R.J. Ward <sup>20</sup>, N. Warrack <sup>59</sup>, S. Waterhouse <sup>96</sup>, A.T. Watson <sup>20</sup>, H. Watson <sup>59</sup>, M.F. Watson <sup>20</sup>, E. Watton <sup>59,135</sup>, G. Watts <sup>139</sup>, B.M. Waugh <sup>97</sup>, J.M. Webb <sup>54</sup>, C. Weber <sup>29</sup>, H.A. Weber <sup>18</sup>, M.S. Weber <sup>19</sup>, S.M. Weber <sup>63a</sup>, C. Wei <sup>62a</sup>, Y. Wei <sup>54</sup>, A.R. Weidberg <sup>127</sup>, E.J. Weik <sup>118</sup>, J. Weingarten <sup>49</sup>, C. Weiser <sup>54</sup>, C.J. Wells <sup>48</sup>, T. Wenaus <sup>29</sup>, B. Wendland <sup>49</sup>, T. Wengler <sup>36</sup>, N.S. Wenke<sup>111</sup>, N. Wermes <sup>24</sup>, M. Wessels <sup>63a</sup>, A.M. Wharton <sup>92</sup>, A.S. White <sup>61</sup>, A. White <sup>8</sup>, M.J. White <sup>1</sup>, D. Whiteson <sup>160</sup>, L. Wickremasinghe <sup>125</sup>, W. Wiedenmann <sup>171</sup>, M. Wielers <sup>135</sup>, C. Wiglesworth <sup>42</sup>, D.J. Wilbern<sup>121</sup>, H.G. Wilkens <sup>36</sup>, J.J.H. Wilkinson <sup>32</sup>, D.M. Williams <sup>41</sup>, H.H. Williams<sup>129</sup>, S. Williams <sup>32</sup>, S. Willocq <sup>104</sup>, B.J. Wilson <sup>102</sup>, P.J. Windischhofer <sup>39</sup>,

F.I. Winkel <sup>30</sup>, F. Winklmeier <sup>124</sup>, B.T. Winter <sup>54</sup>, J.K. Winter <sup>102</sup>, M. Wittgen <sup>144</sup>, M. Wobisch <sup>98</sup>, T. Wojtkowski <sup>60</sup>, Z. Wolffs <sup>115</sup>, J. Wollrath <sup>160</sup>, M.W. Wolter <sup>87</sup>, H. Wolters <sup>131a,131c</sup>, M.C. Wong <sup>137</sup>, E.L. Woodward <sup>41</sup>, S.D. Worm <sup>48</sup>, B.K. Wosiek <sup>87</sup>, K.W. Woźniak <sup>87</sup>, S. Wozniowski <sup>55</sup>, K. Wraight <sup>59</sup>, C. Wu <sup>20</sup>, M. Wu <sup>14d</sup>, M. Wu <sup>114</sup>, S.L. Wu <sup>171</sup>, X. Wu <sup>56</sup>, Y. Wu <sup>62a</sup>, Z. Wu <sup>4</sup>, J. Wuerzinger <sup>111,ab</sup>, T.R. Wyatt <sup>102</sup>, B.M. Wynne <sup>52</sup>, S. Xella <sup>42</sup>, L. Xia <sup>14c</sup>, M. Xia <sup>14b</sup>, J. Xiang <sup>64c</sup>, M. Xie <sup>62a</sup>, S. Xin <sup>14a,14e</sup>, A. Xiong <sup>124</sup>, J. Xiong <sup>17a</sup>, D. Xu <sup>14a</sup>, H. Xu <sup>62a</sup>, L. Xu <sup>62a</sup>, R. Xu <sup>129</sup>, T. Xu <sup>107</sup>, Y. Xu <sup>14b</sup>, Z. Xu <sup>52</sup>, Z. Xu <sup>14c</sup>, B. Yabsley <sup>148</sup>, S. Yacoob <sup>33a</sup>, Y. Yamaguchi <sup>155</sup>, E. Yamashita <sup>154</sup>, H. Yamauchi <sup>158</sup>, T. Yamazaki <sup>17a</sup>, Y. Yamazaki <sup>85</sup>, J. Yan <sup>62c</sup>, S. Yan <sup>59</sup>, Z. Yan <sup>104</sup>, H.J. Yang <sup>62c,62d</sup>, H.T. Yang <sup>62a</sup>, S. Yang <sup>62a</sup>, T. Yang <sup>64c</sup>, X. Yang <sup>36</sup>, X. Yang <sup>14a</sup>, Y. Yang <sup>44</sup>, Y. Yang <sup>62a</sup>, Z. Yang <sup>62a</sup>, W-M. Yao <sup>17a</sup>, H. Ye <sup>14c</sup>, H. Ye <sup>55</sup>, J. Ye <sup>14a</sup>, S. Ye <sup>29</sup>, X. Ye <sup>62a</sup>, Y. Yeh <sup>97</sup>, I. Yeletsikh <sup>38</sup>, B.K. Yeo <sup>17b</sup>, M.R. Yexley <sup>97</sup>, T.P. Yildirim <sup>127</sup>, P. Yin <sup>41</sup>, K. Yorita <sup>169</sup>, S. Younas <sup>27b</sup>, C.J.S. Young <sup>36</sup>, C. Young <sup>144</sup>, C. Yu <sup>14a,14e</sup>, Y. Yu <sup>62a</sup>, M. Yuan <sup>107</sup>, R. Yuan <sup>62d,62c</sup>, L. Yue <sup>97</sup>, M. Zaazoua <sup>62a</sup>, B. Zabinski <sup>87</sup>, E. Zaid <sup>52</sup>, Z.K. Zak <sup>87</sup>, T. Zakareishvili <sup>164</sup>, N. Zakharchuk <sup>34</sup>, S. Zambito <sup>56</sup>, J.A. Zamora Saa <sup>138d,138b</sup>, J. Zang <sup>154</sup>, D. Zanzi <sup>54</sup>, O. Zaplatilek <sup>133</sup>, C. Zeitnitz <sup>172</sup>, H. Zeng <sup>14a</sup>, J.C. Zeng <sup>163</sup>, D.T. Zenger Jr <sup>26</sup>, O. Zenin <sup>37</sup>, T. Ženiš <sup>28a</sup>, S. Zenz <sup>95</sup>, S. Zerradi <sup>35a</sup>, D. Zerwas <sup>66</sup>, M. Zhai <sup>14a,14e</sup>, D.F. Zhang <sup>140</sup>, J. Zhang <sup>62b</sup>, J. Zhang <sup>6</sup>, K. Zhang <sup>14a,14e</sup>, L. Zhang <sup>62a</sup>, L. Zhang <sup>14c</sup>, P. Zhang <sup>14a,14e</sup>, R. Zhang <sup>171</sup>, S. Zhang <sup>107</sup>, S. Zhang <sup>90</sup>, T. Zhang <sup>154</sup>, X. Zhang <sup>62c</sup>, X. Zhang <sup>62b</sup>, Y. Zhang <sup>62c</sup>, Y. Zhang <sup>97</sup>, Y. Zhang <sup>14c</sup>, Z. Zhang <sup>17a</sup>, Z. Zhang <sup>62b</sup>, Z. Zhang <sup>66</sup>, H. Zhao <sup>139</sup>, T. Zhao <sup>62b</sup>, Y. Zhao <sup>137</sup>, Z. Zhao <sup>62a</sup>, Z. Zhao <sup>62a</sup>, A. Zhemchugov <sup>38</sup>, J. Zheng <sup>14c</sup>, K. Zheng <sup>163</sup>, X. Zheng <sup>62a</sup>, Z. Zheng <sup>144</sup>, D. Zhong <sup>163</sup>, B. Zhou <sup>107</sup>, H. Zhou <sup>7</sup>, N. Zhou <sup>62c</sup>, Y. Zhou <sup>14b</sup>, Y. Zhou <sup>14c</sup>, Y. Zhou <sup>7</sup>, C.G. Zhu <sup>62b</sup>, J. Zhu <sup>107</sup>, X. Zhu <sup>62d</sup>, Y. Zhu <sup>62c</sup>, Y. Zhu <sup>62a</sup>, X. Zhuang <sup>14a</sup>, K. Zhukov <sup>37</sup>, N.I. Zimine <sup>38</sup>, J. Zinsser <sup>63b</sup>, M. Ziolkowski <sup>142</sup>, L. Živković <sup>15</sup>, A. Zoccoli <sup>23b,23a</sup>, K. Zoch <sup>61</sup>, T.G. Zorbas <sup>140</sup>, O. Zormpa <sup>46</sup>, W. Zou <sup>41</sup>, L. Zwalinski <sup>36</sup>.

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

<sup>2</sup>Department of Physics, University of Alberta, Edmonton AB; Canada.

<sup>3(a)</sup>Department of Physics, Ankara University, Ankara; <sup>(b)</sup>Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye.

<sup>4</sup>LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.

<sup>5</sup>APC, Université Paris Cité, CNRS/IN2P3, Paris; 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>Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

<sup>13</sup>Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.

<sup>14(a)</sup>Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup>Physics Department, Tsinghua University, Beijing; <sup>(c)</sup>Department of Physics, Nanjing University, Nanjing; <sup>(d)</sup>School of Science, Shenzhen Campus of Sun Yat-sen University; <sup>(e)</sup>University of Chinese Academy of Science (UCAS), Beijing; China.

<sup>15</sup>Institute of Physics, University of Belgrade, Belgrade; Serbia.

<sup>16</sup>Department for Physics and Technology, University of Bergen, Bergen; Norway.

- <sup>17</sup>(*a*) Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; (*b*) University of California, Berkeley CA; United States of America.
- <sup>18</sup>Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
- <sup>19</sup>Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
- <sup>20</sup>School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
- <sup>21</sup>(*a*) Department of Physics, Bogazici University, Istanbul; (*b*) Department of Physics Engineering, Gaziantep University, Gaziantep; (*c*) Department of Physics, Istanbul University, Istanbul; Türkiye.
- <sup>22</sup>(*a*) Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; (*b*) Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia.
- <sup>23</sup>(*a*) Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; (*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*) National University of Science and Technology Politehnica, Bucharest; (*f*) West University in Timisoara, Timisoara; (*g*) Faculty of Physics, University of Bucharest, Bucharest; 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>Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), 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*) iThemba Labs, Western Cape; (*c*) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; (*d*) National Institute of Physics, University of the Philippines Diliman (Philippines); (*e*) University of South Africa, Department of Physics, Pretoria; (*f*) University of Zululand, KwaDlangezwa; (*g*) School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
- <sup>34</sup>Department of Physics, Carleton University, Ottawa ON; Canada.
- <sup>35</sup>(*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*) LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; (*e*) Faculté des sciences, Université Mohammed V, Rabat; (*f*) Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
- <sup>36</sup>CERN, Geneva; Switzerland.
- <sup>37</sup>Affiliated with an institute covered by a cooperation agreement with CERN.
- <sup>38</sup>Affiliated with an international laboratory covered by a cooperation agreement with CERN.
- <sup>39</sup>Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
- <sup>40</sup>LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
- <sup>41</sup>Nevis Laboratory, Columbia University, Irvington NY; United States of America.
- <sup>42</sup>Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
- <sup>43</sup>(*a*) Dipartimento di Fisica, Università della Calabria, Rende; (*b*) INFN Gruppo Collegato di Cosenza,

Laboratori Nazionali di Frascati; Italy.

<sup>44</sup>Physics Department, Southern Methodist University, Dallas TX; United States of America.

<sup>45</sup>Physics Department, University of Texas at Dallas, Richardson TX; United States of America.

<sup>46</sup>National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.

<sup>47</sup>(<sup>a</sup>) Department of Physics, Stockholm University; (<sup>b</sup>) Oskar Klein Centre, Stockholm; Sweden.

<sup>48</sup>Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.

<sup>49</sup>Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany.

<sup>50</sup>Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.

<sup>51</sup>Department of Physics, Duke University, Durham NC; United States of America.

<sup>52</sup>SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.

<sup>53</sup>INFN e Laboratori Nazionali di Frascati, Frascati; Italy.

<sup>54</sup>Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.

<sup>55</sup>II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.

<sup>56</sup>Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.

<sup>57</sup>(<sup>a</sup>) Dipartimento di Fisica, Università di Genova, Genova; (<sup>b</sup>) INFN Sezione di Genova; Italy.

<sup>58</sup>II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.

<sup>59</sup>SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.

<sup>60</sup>LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.

<sup>61</sup>Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.

<sup>62</sup>(<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, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; (<sup>d</sup>) Tsung-Dao Lee Institute, Shanghai; (<sup>e</sup>) School of Physics and Microelectronics, Zhengzhou University; China.

<sup>63</sup>(<sup>a</sup>) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (<sup>b</sup>) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.

<sup>64</sup>(<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.

<sup>65</sup>Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.

<sup>66</sup>IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.

<sup>67</sup>Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain.

<sup>68</sup>Department of Physics, Indiana University, Bloomington IN; United States of America.

<sup>69</sup>(<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.

<sup>70</sup>(<sup>a</sup>) INFN Sezione di Lecce; (<sup>b</sup>) Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.

<sup>71</sup>(<sup>a</sup>) INFN Sezione di Milano; (<sup>b</sup>) Dipartimento di Fisica, Università di Milano, Milano; Italy.

<sup>72</sup>(<sup>a</sup>) INFN Sezione di Napoli; (<sup>b</sup>) Dipartimento di Fisica, Università di Napoli, Napoli; Italy.

<sup>73</sup>(<sup>a</sup>) INFN Sezione di Pavia; (<sup>b</sup>) Dipartimento di Fisica, Università di Pavia, Pavia; Italy.

<sup>74</sup>(<sup>a</sup>) INFN Sezione di Pisa; (<sup>b</sup>) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.

<sup>75</sup>(<sup>a</sup>) INFN Sezione di Roma; (<sup>b</sup>) Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.

<sup>76</sup>(<sup>a</sup>) INFN Sezione di Roma Tor Vergata; (<sup>b</sup>) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.

<sup>77</sup>(<sup>a</sup>) INFN Sezione di Roma Tre; (<sup>b</sup>) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.

- <sup>78</sup>(*a*) INFN-TIFPA; (*b*) Università degli Studi di Trento, Trento; Italy.
- <sup>79</sup>Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.
- <sup>80</sup>University of Iowa, Iowa City IA; United States of America.
- <sup>81</sup>Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
- <sup>82</sup>Istinye University, Sariyer, Istanbul; Türkiye.
- <sup>83</sup>(*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*) Instituto de Física, Universidade de São Paulo, São Paulo; (*d*) Rio de Janeiro State University, Rio de Janeiro; (*e*) Federal University of Bahia, Bahia; Brazil.
- <sup>84</sup>KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
- <sup>85</sup>Graduate School of Science, Kobe University, Kobe; Japan.
- <sup>86</sup>(*a*) AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow; (*b*) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
- <sup>87</sup>Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
- <sup>88</sup>Faculty of Science, Kyoto University, Kyoto; Japan.
- <sup>89</sup>Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
- <sup>90</sup>L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
- <sup>91</sup>Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
- <sup>92</sup>Physics Department, Lancaster University, Lancaster; United Kingdom.
- <sup>93</sup>Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
- <sup>94</sup>Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
- <sup>95</sup>School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
- <sup>96</sup>Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
- <sup>97</sup>Department of Physics and Astronomy, University College London, London; United Kingdom.
- <sup>98</sup>Louisiana Tech University, Ruston LA; United States of America.
- <sup>99</sup>Fysiska institutionen, Lunds universitet, Lund; Sweden.
- <sup>100</sup>Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
- <sup>101</sup>Institut für Physik, Universität Mainz, Mainz; Germany.
- <sup>102</sup>School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
- <sup>103</sup>CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
- <sup>104</sup>Department of Physics, University of Massachusetts, Amherst MA; United States of America.
- <sup>105</sup>Department of Physics, McGill University, Montreal QC; Canada.
- <sup>106</sup>School of Physics, University of Melbourne, Victoria; Australia.
- <sup>107</sup>Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
- <sup>108</sup>Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
- <sup>109</sup>Group of Particle Physics, University of Montreal, Montreal QC; Canada.
- <sup>110</sup>Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
- <sup>111</sup>Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
- <sup>112</sup>Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
- <sup>113</sup>Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
- <sup>114</sup>Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.
- <sup>115</sup>Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam;



Netherlands.

<sup>116</sup>Department of Physics, Northern Illinois University, DeKalb IL; United States of America.

<sup>117</sup>(<sup>a</sup>)New York University Abu Dhabi, Abu Dhabi;(<sup>b</sup>)United Arab Emirates University, Al Ain; United Arab Emirates.

<sup>118</sup>Department of Physics, New York University, New York NY; United States of America.

<sup>119</sup>Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.

<sup>120</sup>Ohio State University, Columbus OH; United States of America.

<sup>121</sup>Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.

<sup>122</sup>Department of Physics, Oklahoma State University, Stillwater OK; United States of America.

<sup>123</sup>Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.

<sup>124</sup>Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.

<sup>125</sup>Graduate School of Science, Osaka University, Osaka; Japan.

<sup>126</sup>Department of Physics, University of Oslo, Oslo; Norway.

<sup>127</sup>Department of Physics, Oxford University, Oxford; United Kingdom.

<sup>128</sup>LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.

<sup>129</sup>Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.

<sup>130</sup>Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.

<sup>131</sup>(<sup>a</sup>)Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;(<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>)Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);(<sup>g</sup>)Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.

<sup>132</sup>Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.

<sup>133</sup>Czech Technical University in Prague, Prague; Czech Republic.

<sup>134</sup>Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.

<sup>135</sup>Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.

<sup>136</sup>IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.

<sup>137</sup>Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.

<sup>138</sup>(<sup>a</sup>)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;(<sup>b</sup>)Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago;(<sup>c</sup>)Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena;(<sup>d</sup>)Universidad Andres Bello, Department of Physics, Santiago;(<sup>e</sup>)Instituto de Alta Investigación, Universidad de Tarapacá, Arica;(<sup>f</sup>)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.

<sup>139</sup>Department of Physics, University of Washington, Seattle WA; United States of America.

<sup>140</sup>Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

<sup>141</sup>Department of Physics, Shinshu University, Nagano; Japan.

<sup>142</sup>Department Physik, Universität Siegen, Siegen; Germany.

<sup>143</sup>Department of Physics, Simon Fraser University, Burnaby BC; Canada.

<sup>144</sup>SLAC National Accelerator Laboratory, Stanford CA; United States of America.

<sup>145</sup>Department of Physics, Royal Institute of Technology, Stockholm; Sweden.

<sup>146</sup>Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.

- <sup>147</sup>Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
- <sup>148</sup>School of Physics, University of Sydney, Sydney; Australia.
- <sup>149</sup>Institute of Physics, Academia Sinica, Taipei; Taiwan.
- <sup>150</sup><sup>(a)</sup>E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; <sup>(b)</sup>High Energy Physics Institute, Tbilisi State University, Tbilisi; <sup>(c)</sup>University of Georgia, Tbilisi; Georgia.
- <sup>151</sup>Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
- <sup>152</sup>Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
- <sup>153</sup>Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
- <sup>154</sup>International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
- <sup>155</sup>Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.
- <sup>156</sup>Department of Physics, University of Toronto, Toronto ON; Canada.
- <sup>157</sup><sup>(a)</sup>TRIUMF, Vancouver BC; <sup>(b)</sup>Department of Physics and Astronomy, York University, Toronto ON; Canada.
- <sup>158</sup>Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.
- <sup>159</sup>Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
- <sup>160</sup>Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.
- <sup>161</sup>University of Sharjah, Sharjah; United Arab Emirates.
- <sup>162</sup>Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
- <sup>163</sup>Department of Physics, University of Illinois, Urbana IL; United States of America.
- <sup>164</sup>Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
- <sup>165</sup>Department of Physics, University of British Columbia, Vancouver BC; Canada.
- <sup>166</sup>Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
- <sup>167</sup>Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
- <sup>168</sup>Department of Physics, University of Warwick, Coventry; United Kingdom.
- <sup>169</sup>Waseda University, Tokyo; Japan.
- <sup>170</sup>Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.
- <sup>171</sup>Department of Physics, University of Wisconsin, Madison WI; United States of America.
- <sup>172</sup>Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
- <sup>173</sup>Department of Physics, Yale University, New Haven CT; United States of America.
- <sup>a</sup> Also Affiliated with an institute covered by a cooperation agreement with CERN.
- <sup>b</sup> Also at An-Najah National University, Nablus; Palestine.
- <sup>c</sup> Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
- <sup>d</sup> Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
- <sup>e</sup> Also at Centro Studi e Ricerche Enrico Fermi; Italy.
- <sup>f</sup> Also at CERN, Geneva; Switzerland.
- <sup>g</sup> Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- <sup>h</sup> Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
- <sup>i</sup> Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
- <sup>j</sup> Also at Department of Physics, California State University, Sacramento; United States of America.
- <sup>k</sup> Also at Department of Physics, King's College London, London; United Kingdom.
- <sup>l</sup> Also at Department of Physics, Stanford University, Stanford CA; United States of America.

- m* Also at Department of Physics, Stellenbosch University; South Africa.
- n* Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
- o* Also at Department of Physics, University of Thessaly; Greece.
- p* Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
- q* Also at Hellenic Open University, Patras; Greece.
- r* Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
- s* Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
- t* Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
- u* Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
- v* Also at Institute of Particle Physics (IPP); Canada.
- w* Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.
- x* Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- y* Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
- z* Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
- aa* Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
- ab* Also at Technical University of Munich, Munich; Germany.
- ac* Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
- ad* Also at TRIUMF, Vancouver BC; Canada.
- ae* Also at Università di Napoli Parthenope, Napoli; Italy.
- af* Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
- ag* Also at Washington College, Chestertown, MD; United States of America.
- ah* Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
- \* Deceased