Physics Letters B 843 (2023) 137880

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Measurement of the Higgs boson mass in the $H \to ZZ^* \to 4\ell$ decay channel using 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collisions recorded by the ATLAS detector at the LHC

The ATLAS Collaboration *

ARTICLE INFO

Article history:
Received 4 July 2022
Received in revised form 2 March 2023
Accepted 27 March 2023
Available online 12 June 2023
Editor: M. Doser

ABSTRACT

The mass of the Higgs boson is measured in the $H \to ZZ^* \to 4\ell$ decay channel. The analysis uses proton–proton collision data from the Large Hadron Collider at a centre-of-mass energy of 13 TeV recorded by the ATLAS detector between 2015 and 2018, corresponding to an integrated luminosity of 139 fb^{-1}. The measured value of the Higgs boson mass is $124.99 \pm 0.18(\text{stat.}) \pm 0.04(\text{syst.})$ GeV. In final states with muons, this measurement benefits from an improved momentum-scale calibration relative to that adopted in previous publications. The measurement also employs an analytic model that takes into account the invariant-mass resolution of the four-lepton system on a per-event basis and the output of a deep neural network discriminating signal from background events. This measurement is combined with the corresponding measurement using 7 and 8 TeV pp collision data, resulting in a Higgs boson mass of $124.94 \pm 0.17(\text{stat.}) \pm 0.03(\text{syst.})$ GeV.

Contents

1. Introduction

The observation of a Higgs boson, H, in 2012 by the ATLAS and CMS collaborations [1,2] in proton–proton (pp) collisions produced by the Large Hadron Collider (LHC) was a major step towards understanding the mechanism of the electroweak (EW) symmetry breaking [3–5]. An unknown parameter of the Standard Model (SM), the Higgs boson mass m_H is related to the SM vacuum stability [6] and its value is required for precise calculations of EW observables, including the production and decay properties of the Higgs boson itself. These calculations are needed to test the cou-

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

https://doi.org/10.1016/j.physletb.2023.137880
0370-2693/

pling structure of the SM Higgs boson, as suggested in Ref. [7] and references therein. Therefore, it is important to determine the Higgs boson mass experimentally.

The mass of the Higgs boson was measured to be 125.09 ± 0.24 GeV [8] in a combined analysis performed by the ATLAS and CMS collaborations using approximately 25 fb^{-1} of $\sqrt{s} = 7$ and 8 TeV pp collision data recorded in 2011 and 2012, respectively, commonly referred to as Run 1. The individual measurements, reported in Refs. [9,10], used the $H \to ZZ^* \to 4\ell$ (where $\ell = e$ or μ) and $H \to \gamma\gamma$ decay modes because of their excellent mass resolution.

The ATLAS Collaboration reported a measurement of m_H using the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ channels with 36.1 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data recorded in 2015 and 2016. This was combined with the Run 1 ATLAS measurement to obtain a value of $m_H = 124.97 \pm 0.24$ GeV [11]. The CMS Collaboration measured m_H using the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ channels with 35.9 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data recorded in 2016. This was combined with the Run 1 CMS measurement to obtain a value of $m_H = 125.38 \pm 0.14$ GeV [12].

This paper reports a new measurement of m_H in the $H \to ZZ^* \to 4\ell$ channel using a 139 fb^{-1} dataset of 13 TeV pp collisions produced by the LHC and recorded by the ATLAS detector between 2015 and 2018, commonly referred to as Run 2. Most of the techniques used in this analysis are described in detail in Ref. [13].

The $H \to ZZ^* \to 4\ell$ process is identified by selecting four leptons ($\ell = e, \mu$) in the final state, and by identifying one pair of same-flavour leptons that is consistent with arising from an on-shell Z-boson decay. The mass measurement is performed using an analytic model to describe the distribution of the reconstructed 4ℓ invariant mass, $m_{4\ell}$, as a function of m_H and to fit to the observed distribution. In comparison with the previous ATLAS result from the $H \to ZZ^* \to 4\ell$ channel [11], the measurement has been improved by using the complete Run 2 dataset and a new high-precision muon momentum calibration. The m_H uncertainty has also been reduced by introducing a neural-network-based classifier to discriminate between signal and background processes and by including the event-by-event invariant-mass resolution of the four-lepton system in the analytic model used to fit the collision data.

This paper is organised as follows. The ATLAS detector is described in Section 2, and the data samples and Monte Carlo simulations are presented in Section 3. The reconstruction of muons and electrons, as well as their calibration procedures, is discussed in Section 4, while the event selection is explained in Section 5. The statistical models describing the signal and background samples are defined in Section 6 and results of the measurement are presented in Section 7. The conclusions are provided in Section 8.

2. ATLAS detector

The ATLAS experiment [14] at the LHC is a multi-purpose particle detector with nearly 4π coverage in solid angle.[1] It includes an inner tracking detector (ID) used for charged-particle tracking, surrounded by a 2 T solenoid. Electromagnetic (EM) and hadronic calorimeters are placed outside the solenoid, followed by a muon spectrometer (MS).

The ID provides precise reconstruction of tracks within a pseudorapidity range $|\eta| \leq 2.5$. The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, the first hit normally being in the insertable B-layer (IBL) installed before Run 2 [15,16]. It is followed by the silicon microstrip tracker, which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$. The TRT also provides electron-identification information based on the detection of transition radiation X-ray photons.

The ATLAS calorimeter system covers the pseudorapidity range $|\eta| < 4.9$, with finer granularity over the region matching the inner detector. The lead/liquid-argon (LAr) EM calorimeter is divided into two half-barrels ($|\eta| < 1.475$) and two endcap components ($1.375 < |\eta| < 3.2$). It is segmented into three longitudinal (depth) sections over the region $|\eta| < 2.5$, and into two depth sections for $2.5 < |\eta| < 3.2$. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters extending the coverage to $|\eta| = 3.2$. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic energy measurements, respectively.

The muon spectrometer, located beyond the calorimeters, is designed to detect muons in the region $|\eta| < 2.7$ and to provide momentum measurements with a relative resolution better than 3% over a wide range of transverse momentum, p_{T}, and up to 10% at $p_{\mathrm{T}} \sim 1$ TeV. A system of three superconducting air-core toroidal magnets provides a magnetic field with a bending power of approximately 2.5 Tm in the barrel and up to 6 Tm in the endcaps.

A two-level trigger system [17] is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a maximum rate of about 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average. An extensive software suite [18] is used 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. Data and event simulation

This measurement uses data from pp collisions with a centre-of-mass energy of 13 TeV collected between 2015 and 2018 using single-lepton, dilepton, and trilepton triggers [19,20] as detailed in Ref. [13]. The combined efficiency of these triggers is approximately 98%, 99%, 97%, and 99% for the 4μ, $2\mu2e$, $2e2\mu$, and $4e$ final states, respectively, for the simulated $H \to ZZ^* \to 4\ell$ events passing the event selection described in Section 5 (assuming $m_H = 125$ GeV). After data-quality requirements are imposed, the integrated luminosity of the data sample is 139 fb^{-1} [21].

Details of the simulated Monte Carlo (MC) events used in this analysis can be found in Refs. [13,22]. Higgs boson production via the gluon–gluon fusion (ggF) process was modelled at next-to-next-to-leading-order (NLO) accuracy in the strong coupling constant α_s using the Powheg NNLOPS generator [23–31] with the PDF4LHC15nnlo set of parton distribution functions (PDFs) [32]. Higgs bosons produced via vector-boson fusion (VBF), in association with a vector boson (VH) or in association with a top-quark pair ($t\bar{t}H$), were simulated at NLO accuracy with the Powheg Box generator [25–27], using the PDF4LHC15nlo PDF set. The loop-induced $gg \to ZH$ process was simulated with the Powheg Box generator at leading-order (LO) accuracy. Higgs boson production in association with a top quark (tH) or with a bottom-quark pair ($b\bar{b}H$) was simulated at NLO accuracy using the MadGraph5_aMC@NLO generator [33,34] with the NNPDF3.0 PDF

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

set [35]. For all signal processes, the EvtGen 1.2.0 generator [36] was used for the simulation of the bottom- and charm-hadron decays. Correspondingly, the Pythia 8 generator [37] was used for the $H \to ZZ^* \to 4\ell$ decay as well as for parton showering, hadronisation, and simulation of the underlying event. Higgs bosons produced via the ggF and VBF processes or in association with a vector boson were simulated for a range of m_H values from 123 to 127 GeV. Higgs boson production in association with a top quark, a top-quark pair, or a bottom-quark pair were simulated assuming $m_H = 125$ GeV, as these processes make a negligible contribution. These samples are normalised to cross-sections obtained from the most recent predictions provided by the LHC Higgs Working Group [7].

The ZZ^* continuum background was modelled separately for quark-initiated ($qqZZ$), gluon-initiated ($ggZZ$), and vector boson scattering (EW ZZ) production. The $qqZZ$ process was modelled at NLO accuracy in α_s using the Sherpa 2.2.2 generator [38–41] with the NNPDF3.0nnlo PDF set. The $ggZZ$ process with 0 or 1 jet in the final state was modelled with a LO calculation using the same Sherpa generator setup, with higher-order corrections calculated using massless quark loops [42–44] in the heavy top-quark approximation [45]. The resulting $ggZZ$ cross-section was scaled by 1.7 ± 1.0 to account for the uncertainty in additional higher-order effects. Production of EW ZZ was modelled at LO accuracy with the Sherpa v2.2.2 with matching of the matrix element to the parton shower using the ME+PS@NLO prescription [46]. These samples were normalised to cross-sections obtained directly from the Sherpa simulation. Alternative $qqZZ$ samples, produced with the Powheg Box v2 and MadGraph5_aMC@NLO generators, are used for studies of the systematic uncertainties. For the nominal and alternative ZZ^* continuum samples, the Pythia 8 generator was used for parton showering, hadronisation, and simulation of the underlying event.

Backgrounds from WZ production and $t\bar{t}$ events were modelled using the Powheg Box v2 generator, while Z bosons produced in association with jets were simulated using the Sherpa 2.2.1 generator. Minor contributions from processes with three electroweak bosons, denoted by VVV, were modelled using Sherpa 2.2.2. Small backgrounds originating from top-quark production in association with one or more electroweak bosons or additional top quarks, such as ttZ, tWZ, $ttWW$, $ttWZ$, $ttZ\gamma$, $ttZZ$, ttt, $tttt$, and tZ (denoted by tXX), were simulated using the MadGraph5_aMC@NLO generator. The Pythia 8 generator was used for parton showering, hadronisation, and simulation of the underlying event.

Generated events were processed through the ATLAS detector simulation [47] within the Geant4 framework [48] and reconstructed in the same way as collision data. Additional pp interactions in the same or neighbouring bunch crossings, referred to as pile-up, are included in the simulation. The pile-up events were modelled using the Pythia 8 generator with the A3 set of tuned parameters [49] and the NNPDF2.3lo PDF set [50].

The normalisation of the non-resonant ZZ^* background component is determined by the fit of a signal and background model to the observed $m_{4\ell}$ distributions. The normalisations of the backgrounds from hadrons or hadron-decay products misidentified as prompt leptons, and from Z+jets, $t\bar{t}$ and WZ processes (referred to as the reducible background), are determined using data-driven techniques, and are explained in detail in Ref. [13].

4. Muon and electron reconstruction

Muon candidates are reconstructed using a combination of different algorithms [51]. The reconstruction of muon candidates within $|\eta| < 2.5$ is primarily performed by a global fit of reconstructed tracks in the ID and the MS. In the central detector region ($|\eta| < 0.1$), where the MS has reduced geometrical coverage, muons are also identified by matching a reconstructed ID track to either an MS track segment (‘segment-tagged muons’) or a calorimetric energy deposit consistent with a minimum-ionising particle (‘calorimeter-tagged muons’). Calorimeter-tagged muons are required to have $p_T > 15$ GeV. For both the segment-tagged and calorimeter-tagged muons, the muon momentum is measured from the ID track alone. In the forward MS region ($2.5 < |\eta| < 2.7$) outside the ID coverage, MS tracks with hits in three MS layers are accepted as ‘stand-alone muons’ and combined with track segments formed from hits in the silicon tracker, if they exist. Additionally, ‘loose’ muon-identification criteria [51] are applied to reject low-quality tracks that have missing hits in the MS or have poor agreement between the reconstructed MS and ID tracks. These requirements have an efficiency of at least 98% for muons with p_T above 5 GeV. Muons are required to be isolated by using both calorimeter-based and track-based isolation variables and applying the ‘PflowLoose’ criteria [51]. The efficiency of the isolation selection is about 85% for muons with p_T above 5 GeV and increases to >97% for muons with $p_T > 20$ GeV.

Although the detector is well aligned overall, there are residual local misalignments that effect the reconstructed muon-track sagitta [52,53] and introduce a small, charge-dependent, momentum bias. The bias is measured with an iterative procedure that minimises the observed width of the line-shape of $Z \to \mu^+\mu^-$ decays [54]. This correction, which is applied to the collision data, reduces the width of the dimuon invariant-mass distribution in Z-boson decays by approximately 1% [54]. A systematic uncertainty is assigned to this correction to cover residual differences between observed and simulated data. It is estimated to be, on average, 1% of the correction itself for muons from $Z \to \mu^+\mu^-$ decays.

Corrections are also applied to the reconstructed muon momentum in simulation in order to precisely match the data. These corrections to the simulated momentum resolution and momentum scale are parameterised as an expansion in powers of the muon p_T, with each coefficient measured as a function of η and ϕ. The corrections are extracted from large data samples of $J/\psi \to \mu^+\mu^-$ and $Z \to \mu^+\mu^-$ decays, using techniques that reduce any residual biases and by directly calibrating the global re-fitted track [54]. Compared to the previously used corrections, this reduces the associated uncertainties by approximately a factor of four.

The momentum-scale corrections range from 0.1% to 0.3% for muons with p_T between 5 and 100 GeV. These account for inaccuracies in the estimation of the energy loss in the traversed material, local magnetic field inaccuracies, and geometrical distortions. The corrections to the momentum resolution for muons with p_T of 5–100 GeV are at the percent level. The main sources of systematic uncertainty for these corrections are the residual biases in the calibration method and the consistency of calibrations using $J/\psi \to \mu^+\mu^-$ or $Z \to \mu^+\mu^-$ decays separately. For muons from $Z \to \mu^+\mu^-$ decays, which have an average p_T of approximately 45 GeV, the momentum scale is determined with a precision better than 0.01%. The resolution is known with a precision of 0.4% for muons with $|\eta| < 1$, while for muons in high-$|\eta|$ regions the precision is approximately 1%.

A reconstructed electron consists of a cluster of energy deposits in the calorimeter and a matched ID track [55]. Variable-size clusters are created dynamically from calorimeter-energy deposits, improving the invariant-mass resolution of the four-lepton system, especially when bremsstrahlung photons are present. Electron ID tracks are fitted using an optimised Gaussian-sum filter (GSF) [56] that accounts for non-linear effects arising from energy loss through bremsstrahlung. Quality criteria are used to improve the purity of selected electron candidates. The quality of an electron candidate is evaluated by using a likelihood method that employs measurements from the tracking system and the calorimeter system, and quantities that combine both tracking and calorimeter information [56]. The 'loose' likelihood criteria, together with track hit requirements, are applied to electron candidates. Electrons are required to be isolated using both the calorimeter-based and track-based isolation variables as discussed in Ref. [13].

The energy of electrons is estimated from the calorimeter energy clusters, using a combination of simulation-based and data-driven corrections [55,57]. A single simulation-based correction, which accounts for the energy lost in the material upstream of the calorimeter, the energy deposited in the cells neighbouring the cluster in η and ϕ, and the energy lost beyond the LAr calorimeter, is derived using multivariate regression algorithms. Data-driven corrections account for effects such as those associated with the material in front of the EM calorimeter and material between the presampler and the calorimeter, and the inter-calibration of the different calorimeter layers. The remaining energy-scale difference between data and simulation is parameterised by energy-independent linear corrections, defined in different regions of η. Similarly, deviations of the energy resolution in the simulation from that in the data are parameterised as an η-dependent additional term. The electron reconstruction efficiency is >97% for electron $p_\mathrm{T} > 18$ GeV and the additional identification efficiency varies between 75 and 90% for the kinematic region relevant to this analysis.

The main sources of systematic uncertainties in the electron-energy scale include uncertainties in the method used to extract the energy scale correction, as well as uncertainties due to the extrapolation of the energy scale from $Z \to e^+e^-$ events to electrons with different energies. A detailed explanation of these uncertainties can be found in Ref. [55]. In the case of electrons with E_T around 40 GeV, the total relative uncertainties range between 0.04% and 0.2% for most of the detector acceptance. For electrons with E_T around 10 GeV the relative uncertainty ranges between 0.3% and 0.8%.

Systematic uncertainties in the calorimeter-energy resolution for electrons arise from uncertainties in the modelling of the sampling term and in the measurement of the constant term in Z-boson decays, in the amount of material in front of the calorimeter, and in the modelling of the contribution to the resolution due to fluctuations in the pile-up from additional pp interactions in the same or neighbouring bunch crossings. The uncertainty in the energy resolution for electrons with transverse energy between 30 and 60 GeV varies between 5% and 10%.

5. Event selection

Events are required to contain at least four isolated leptons emerging from a common vertex and forming two pairs of oppositely charged same-flavour leptons. Electrons are required to be within the geometrical acceptance of the inner detector ($|\eta| < 2.47$) and to have $E_\mathrm{T} > 7$ GeV, while muons must be within the geometrical acceptance of the muon spectrometer ($|\eta| < 2.7$) and have $p_\mathrm{T} > 5$ GeV (except for calorimeter-tagged muons, as explained in Section 4). At most one calorimeter-tagged or standalone muon is allowed per Higgs boson candidate. The three higher-(p_T or E_T) leptons in each quadruplet are required to pass thresholds of 20, 15, and 10 GeV, respectively, and have $\Delta R(\ell, \ell') > 0.1$. These thresholds are chosen to maximise signal yield consistent with selecting events with high trigger efficiency. Contributions from misidentified leptons are reduced by requiring the lepton tracks to have low transverse-impact-parameter significances and to be compatible with originating from a common vertex. A detailed description of the event selection can be found in Ref. [13].

The lepton pair with an invariant mass closest to the Z-boson mass in each quadruplet is referred to as the leading dilepton, while the remaining pair is referred to as the subleading dilepton. The selected quadruplets are separated into four subchannels, according to the flavour of the leading and subleading pairs. In order of decreasing expected selection efficiency and resolution, they are 4μ, $2e2\mu$, $2\mu2e$, and $4e$. The $m_{4\ell}$ resolution is about 1.5 GeV for subchannels with a subleading muon pair (4μ and $2e2\mu$) and about 2.1 GeV for subchannels with a subleading electron pair ($2\mu2e$ and $4e$). Only one quadruplet is selected from each event, based on the mass of the leading dilepton, the final state, and, for events with additional leptons, the value of the LO matrix element, as described in Ref. [13].

Final-state radiation (FSR) photons are searched for in all events following the procedure described in Ref. [13]. FSR candidates are defined as collinear if their angular separation from the nearest lepton of the quadruplet satisfies $\Delta R < 0.15$, and non-collinear otherwise. Collinear FSR candidates are considered only for muons from the leading dilepton as the electron candidate reconstruction includes collinear FSR, while non-collinear FSR candidates are considered for both muons and electrons from either the leading or the subleading dilepton. Only one FSR candidate is included in the quadruplet as events with more than one FSR candidate are rare and have negligible effect on the four-lepton mass resolution. In cases where there are more than one FSR candidate preference is given to collinear FSR and to the candidate with the highest p_T. FSR photons are found in 4% of the events and their energy is included in the mass computation, improving the $m_{4\ell}$ resolution by about 1%.

Finally, the four-momenta of leptons in the leading pair are recomputed by performing a kinematic fit which constrains their invariant mass to the Z-boson mass, as discussed in Ref. [58]. The fit, which takes into account lepton and FSR kinematic information, their associated experimental uncertainties, and the Z-boson width, improves the $m_{4\ell}$ resolution by about 17% [9]. The lepton four-momenta reconstruction uncertainties were derived from simulation and are corrected to match those observed in data, using a large sample of Z-boson decays.

In the mass range $115 < m_{4\ell} < 130$ GeV, 313 candidate events are observed. The yield is in agreement with the expectation of 321 ± 14 events, 65% of which are predicted to originate from signal processes, assuming $m_H = 125$ GeV. The $m_{4\ell}$ distributions are shown in Fig. 1 for each final state and in Fig. 2 for the inclusive final state for the mass range of 105–160 GeV, which is used to determine the Higgs boson mass.

The dominant contribution to the background is non-resonant ZZ^* production, accounting for approximately 89% of the total background yield. The reducible background contributes approximately 9%. The VVV and tXX events are estimated to constitute approximately 2% of the total background. The residual combinatorial background, originating from events with additional prompt leptons, is found to be negligible [13].

5.1. Signal–background discriminant

To provide additional separation between the $H \to ZZ^* \to 4\ell$ signal and the $ZZ^* \to 4\ell$ background, a deep feed-forward neural network (NN) is employed. The NN is trained with Keras [59] using the TensorFlow [60] backend, following the method described in Ref. [13]. Signal events for training are taken from simulated samples with different masses of the Higgs boson, as described in Section 3, thus reducing the dependence of the discriminant on m_H.

The p_T and η of the four-lepton system are used as inputs to the NN, together with a matrix-element-based kinematic discriminant D_{ZZ^*} [58]. The discriminant D_{ZZ^*} is defined as $\ln(|\mathcal{M}_{HZZ^*}|^2/|\mathcal{M}_{ZZ^*}|^2)$ where $\mathcal{M}_{HZZ^*}$ denotes the matrix element for leading-order (LO) $H \to ZZ^* \to 4\ell$ production and $\mathcal{M}_{ZZ^*}$ the sum of the corresponding matrix elements for the $q\bar{q} \to ZZ^*$

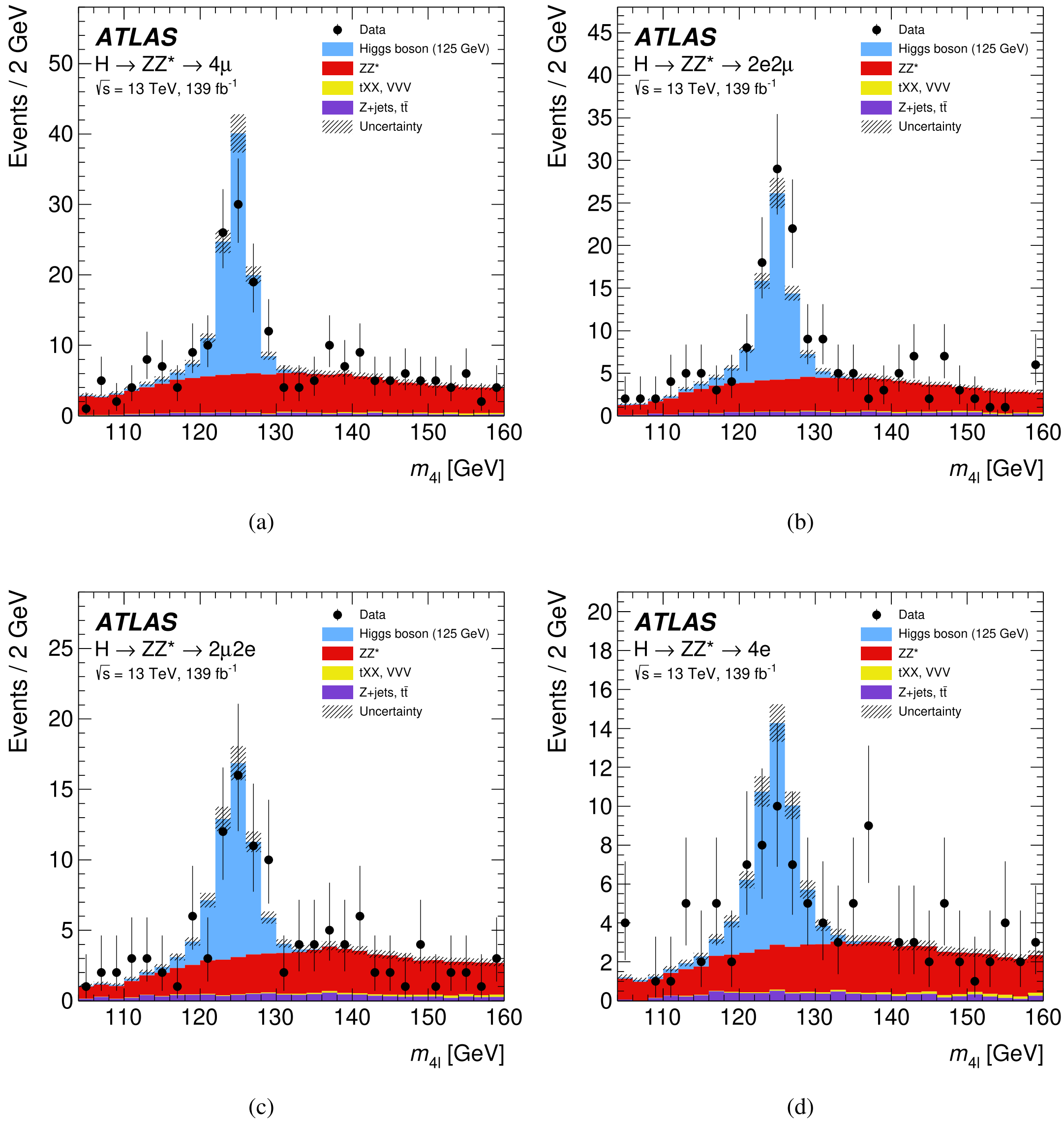


Fig. 1. The observed and expected (pre-fit) $m_{4\ell}$ distributions for the selected Higgs boson candidates, for the different decay final states (a) 4μ, (b) $2e2\mu$, (c) $2\mu 2e$, and (d) $4e$ events. The predicted number of events for these distributions is taken from simulation for the signal, ZZ^*, tXX, and VVV processes, while it is taken from the data-driven estimate (see Section 6) for the Z+jets and $t\bar{t}$ backgrounds. The total uncertainty in the prediction is shown by the hatched band, which also includes the theoretical uncertainties of the SM cross-section for the signal and the ZZ^* background. Higgs boson events in this plot are simulated with $m_H = 125$ GeV. The p-values quantifying the agreement between the data and MC predictions are (a) 0.81, (b) 0.43, (c) 0.77, and (d) 0.15.

and $gg \to ZZ^*$ continuum backgrounds, all calculated at LO with the MadGraph 2.2.1 generator [33].

The distribution of the output of the NN, D_{NN}, is shown in Fig. 3. The D_{NN} for each event is included in the final fit as an additional observable, as explained in Section 6. The additional separation between signal and background provided by the NN improves the precision of this measurement by 2%.

5.2. Event-level $m_{4\ell}$ resolution

The event-level $m_{4\ell}$ resolution, σ_i, is estimated using a quantile regression neural network (QRNN) [61]. The QRNN is trained on signal MC events using the Tensorflow library and the Keras Python application programming interface. The inputs are the p_{T}, η, and ϕ of the individual leptons, as well as the four-lepton momentum, constrained by the Z-boson mass constraint, and its uncertainty. The output of the QRNN for each final state is the predicted quantile of the difference between the reconstructed mass and the true mass of the four-lepton system. The targeted quantile is calibrated using a step-wise scanning procedure so that it results in an estimate that produces 68% confidence-level intervals when tested on simulated events.

The σ_i distributions are shown in Fig. 4. Each event is assigned the σ_i estimated by the QRNN and employed in the likelihood fit to m_H. Taking into account the per-event resolution reduces the total expected uncertainty in m_H by 1%.

6. Signal and background model

The Higgs boson $m_{4\ell}$ distribution is the result of the convolution of its theoretical line-shape, a narrow relativistic Breit–Wigner (BW) distribution of 4.1 MeV width [7] centred on m_H, with the detector response for the four-lepton invariant-mass distribution. The BW width is more than two orders of magnitude smaller than the $m_{4\ell}$ detector resolution. Therefore, the signal line-shape in $m_{4\ell}$ is completely dominated by the detector response.

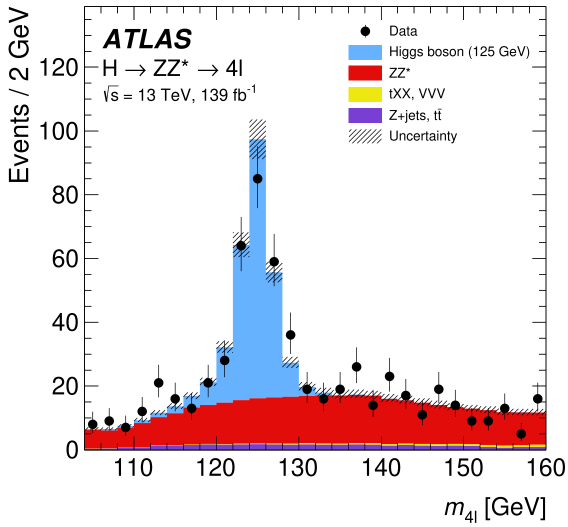


Fig. 2. The observed and expected (pre-fit) $m_{4\ell}$ distributions for the selected Higgs boson candidates. The predicted number of events for these distributions is taken from simulation for the signal, ZZ^*, tXX, and VVV processes, while it is taken from the data-driven estimate (see Section 6) for the Z+jets and $t\bar{t}$ backgrounds. The total uncertainty in the prediction is shown by the hatched band, which also includes the theoretical uncertainties of the SM cross-section for the signal and the ZZ^* background. Higgs boson events in this plot are simulated with $m_H = 125$ GeV. The p-value quantifying the agreement between the data and MC predictions is 0.36.

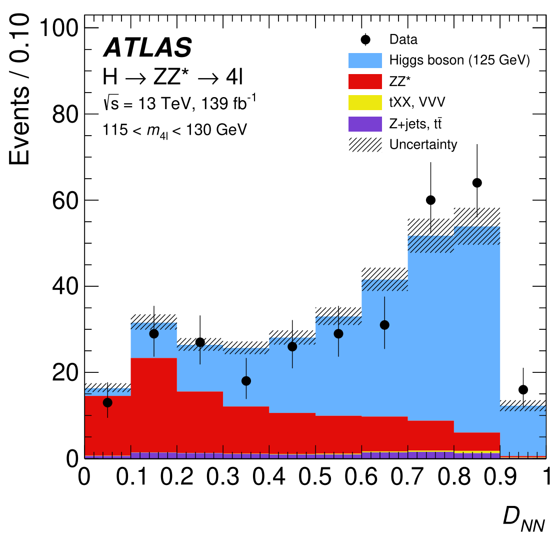


Fig. 3. The observed and expected (pre-fit) D_{NN} distributions for the selected Higgs boson candidates. The predicted number of events for these distributions is taken from simulation for the signal, ZZ^*, tXX, and VVV processes, while it is taken from the data-driven estimate (see Section 6) for the Z+jets and $t\bar{t}$ backgrounds. The total uncertainty in the prediction is shown by the hatched band, which also includes the theoretical uncertainties of the SM cross-section for the signal and the ZZ^* background. Higgs boson events in this plot are simulated with $m_H = 125$ GeV. The p-value quantifying the agreement between the data and MC predictions is 0.28.

The signal probability density function is modelled as a function of $m_{4\ell}$, signal versus ZZ^* discriminator D_{NN}, and the per-event resolution estimator σ_i. The model can be written as

$$\begin{aligned}
&\mathcal{P}(m_{4\ell}, D_{NN}, \sigma_i | m_H) \\
&\quad = \mathcal{P}(m_{4\ell} | D_{NN}, \sigma_i, m_H) \cdot \mathcal{P}(D_{NN} | \sigma_i, m_H) \cdot \mathcal{P}(\sigma_i | m_H) \\
&\quad \simeq \mathcal{P}(m_{4\ell} | D_{NN}, \sigma_i, m_H) \cdot \mathcal{P}(D_{NN} | m_H),
\end{aligned}$$

where the following approximations are used:

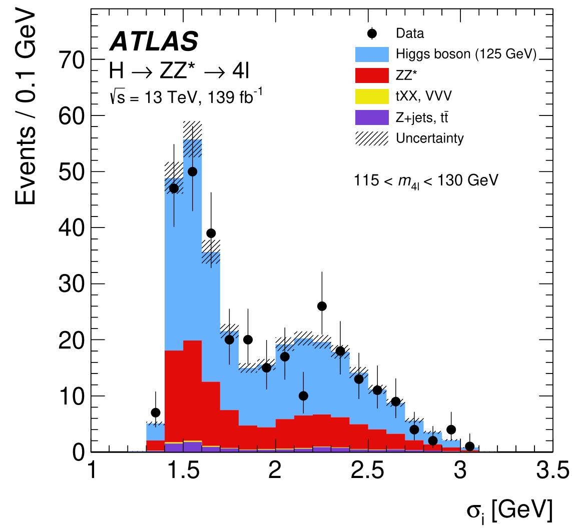


Fig. 4. The observed and expected (pre-fit) event-level resolution σ_i distributions predicted by the QRNN for the selected Higgs boson candidates. The predicted number of events for these distributions is taken from simulation for the signal, ZZ^*, tXX, and VVV processes, while it is taken from the data-driven estimate (see Section 6) for the Z+jets and $t\bar{t}$ backgrounds. The total uncertainty in the prediction is shown by the hatched band, which also includes the theoretical uncertainties of the SM cross-section for the signal and the ZZ^* background. Higgs boson events in this plot are simulated with $m_H = 125$ GeV. The 4μ and $2\mu 2e$ events typically have $\sigma_i \sim 1.5$ GeV, while the $2e2\mu$ and $4e$ events typically have $\sigma_i \sim 2.1$ GeV. The p-value quantifying the agreement between the data and MC predictions is 0.81.

- $\mathcal{P}(D_{NN}|\sigma_i, m_H) \simeq \mathcal{P}(D_{NN}|m_H)$ because the neural network discriminant does not directly depend on the per-event $m_{4\ell}$ resolution,
- $\mathcal{P}(\sigma_i|m_H) \simeq \mathcal{P}(\sigma_i)$ since the averaged per-event resolution does not depend on m_H within the range of 105 to 160 GeV used in this measurement, and
- $\mathcal{P}(\sigma_i)$ is omitted from the probability density function because it was observed that it has approximately the same distribution for signal and background events in the Higgs boson peak region. Dedicated checks of the assumption that $\mathcal{P}(\sigma_i)$ can be omitted have shown that this has negligible impact on the measurement.

The probability density function $\mathcal{P}(D_{NN}|m_H)$ is determined through interpolation between neighbouring m_H values using simulated data. The probability density function $\mathcal{P}(m_{4\ell}|D_{NN}, \sigma_i, m_H)$ in each subchannel is described by a double-sided Crystal Ball [62] probability density function that consists of a Gaussian core and two power-law tails.

The mean of the Gaussian core is parameterised as a function of m_H and D_{NN} for each subchannel λ as

$$a^\lambda \cdot (m_H - 125 \text{ GeV}) + b^\lambda(D_{NN}),$$

in order to decorrelate the uncertainties of the shifts in the mean reconstructed $m_{4\ell}$ due to the subchannel dependence from those due to the D_{NN} dependence. The a^λ parameters are consistent with unity within a few percent for all final states. The dependence of b^λ on D_{NN} is parameterised as a second-order polynomial, and its values lie in the 124–125 GeV range for the $2\mu 2e$ and $4e$ final states, and between 124.6 GeV and 125 GeV for the $2e2\mu$ and 4μ final states. The residual correlations between the m_H dependence of the mean and shape of the reconstructed $m_{4\ell}$ distribution, and the D_{NN} dependence of the mean have been checked with simulation and found to be negligible. The a^λ parameters and the b^λ functions are extracted from an unbinned maximum-likelihood fit to the combined ggF, VBF, and VH samples, which were simulated with different values of m_H, as described in Section 3.

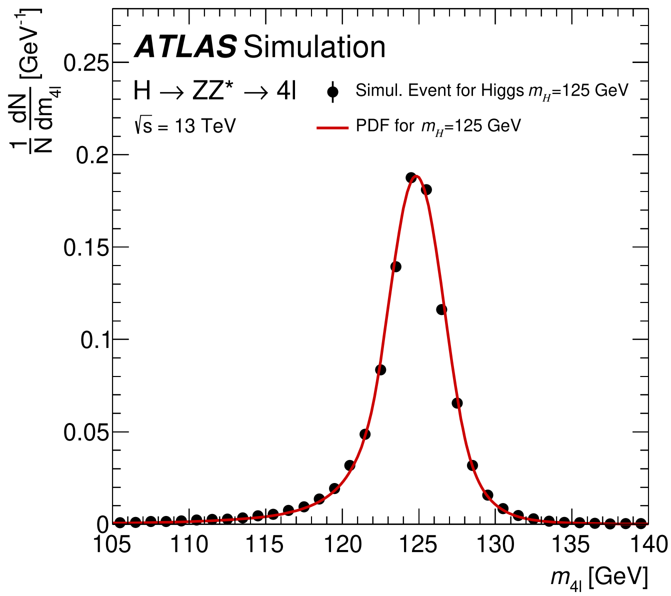


Fig. 5. The probability density function derived from signal MC simulation using the per-event resolution (red line) is shown in comparison with the $m_{4\ell}$ distribution in signal MC simulation (black points) for $m_H = 125$ GeV. The probability density function is derived for each channel separately and they are added together assuming predicted yields. Both the probability density function and the MC simulation are normalised to unity.

The standard deviation of the Gaussian core is expressed as a function of the predicted event-level resolution σ_i and is parameterised as a function of D_{NN} to account for a residual correlation between D_{NN} and σ_i. The parameters of the left tail of the double-sided Crystal Ball are parameterised as a function of D_{NN} only, which results in few percent variation as a function of D_{NN}, while those of the right tail are found to be constant for a given final state.

The parameters of the signal model for each subchannel are derived by a simultaneous maximum-likelihood fit to signal MC samples for m_H values ranging from 123 GeV to 127 GeV. The resulting probability density function is shown in Fig. 5 for the $m_H = 125$ GeV signal sample. The residual bias in the measured m_H for the derived model, estimated by pseudo-experiments sampling MC events, is at the level of 6 MeV and is treated as an additional systematic uncertainty. In the fit of the model to the data, m_H can vary freely while the other parameters are constrained to vary in accordance with the impact of the relevant systematic uncertainties. Negligible biases in m_H are observed when fitting the model to simulated Higgs signal samples with different values of m_H.

The probability density functions for the ZZ^* and $tXX + VVV$ backgrounds are estimated as a function of $m_{4\ell}$ and D_{NN} for each subchannel from MC simulation. The size of the background contributions from misidentified and non-isolated leptons is estimated from a data-control region [13], with the dependence on $m_{4\ell}$ and D_{NN} parameterised using simulated samples.

The probability density functions for the backgrounds are smoothed using an adaptive kernel estimation technique, employing Gaussian kernels [63] to reduce statistical fluctuations. The effects of uncertainties that modify the shapes of probability density functions are described by using non-linear moment morphing [64] to interpolate between the nominal probability density functions and those accounting for the relevant systematic variations. Such uncertainties include the theoretical and experimental uncertainties for the ZZ^* and $tXX + VVV$ probability density functions and imperfect knowledge of the relative background composition for the reducible background's probability density function.

Table 1
The observed and expected (pre-fit) yields for the different decay final states in the region with $m_{4\ell}$ between 115 and 130 GeV. The predicted number of events is taken from simulation for the signal, ZZ^*, tXX, and VVV processes, while for Z+jets and $t\bar{t}$ it is taken from the data-driven estimate (see Section 6). The uncertainty in the prediction includes the theoretical uncertainties of the SM cross-section for the signal and the ZZ^* background. Higgs boson yields are determined using simulation with $m_H = 125$ GeV.

Final state	Higgs	ZZ, tXX, VVV	Reducible backgrounds	Expected total yield	Observed yield
4μ	78 ± 5	38.7 ± 2.2	2.84 ± 0.17	120 ± 5	115
$2e2\mu$	53.4 ± 3.2	26.7 ± 1.4	3.02 ± 0.19	83.1 ± 3.5	94
$2\mu 2e$	41.2 ± 3.0	17.9 ± 1.3	3.4 ± 0.5	62.5 ± 3.3	59
$4e$	36.2 ± 2.7	15.7 ± 1.6	2.83 ± 0.35	54.8 ± 3.2	45
Total	209 ± 13	99 ± 6	12.2 ± 0.9	321 ± 14	313

The $m_{4\ell}$ distribution is described by the sum of a signal distribution and the distributions of the backgrounds. The normalisations of the signal contribution and the ZZ^* process in each subchannel are free parameters and extracted directly from the fit to data, while those of the reducible background in each channel are constrained according to estimates obtained from data, using minimal input from simulation and following the methodology described in Ref. [13]. The normalisation of the $tXX + VVV$ background is constrained according to the uncertainties in the theory prediction.

The fit model was validated by utilising a two-step unblinding process, where the same, unknown, bias is applied to all events in the observed dataset and the likelihood model, as described in Section 7, is fitted to it. No significant changes to the compatibility between channels or to any free or constrained parameters, with the exception of m_H, are observed when this bias is removed.

7. Results

The mass measurement is performed by maximising the profile-likelihood ratio [65,66]

$$\lambda(m_H) = \frac{\mathcal{L}\big(m_H, \hat{\hat{\theta}}(m_H)\big)}{\mathcal{L}\big(\hat{m}_H, \hat{\theta}\big)},$$

where $\hat{m}_H$ and $\hat{\theta}$ denote the unconditional maximum-likelihood estimates of the parameters of the likelihood function $\mathcal{L}$, while $\hat{\hat{\theta}}$ is the conditional maximum-likelihood estimate of the parameters θ for a fixed value of the parameter of interest, m_H. Systematic uncertainties and their correlations are modelled by introducing nuisance parameters θ with priors described by Gaussian or log-normal functions that reflect the uncertainties in the values of the nuisance parameters.

The estimate of m_H is extracted by performing a simultaneous unbinned maximum-likelihood fit to the four subchannels (4μ, $2e2\mu$, $2\mu 2e$, and $4e$) in the $m_{4\ell}$ range between 105 and 160 GeV. The expected and observed yields, along with the signal-to-background ratio, are shown in Table 1 for the signal region defined by limiting the data to $m_{4\ell}$ between 115 and 130 GeV.

The free parameters of the fit are m_H, the signal normalisation, and background normalisations for each of the four subchannels, while the nuisance parameters associated with the systematic uncertainties are constrained by their respective priors. Fig. 6 shows the $m_{4\ell}$ distribution of the data together with the result of the fit to the $H \to ZZ^* \to 4\ell$ candidates. The small shape fluctuations in the background prediction arise from the integrations of the background probability density functions; their effects on the mass fit are negligible. The fit results in

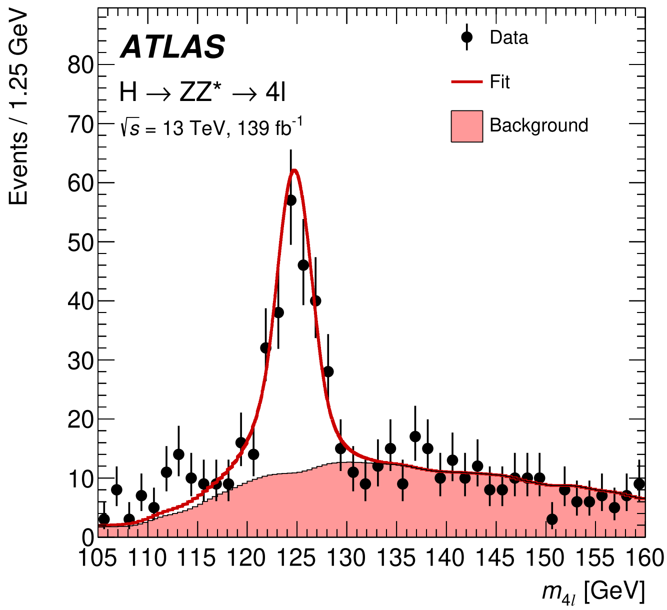


Fig. 6. The $m_{4\ell}$ data distribution from all subchannels combined (black points) is shown along with the signal-plus-background post-fit probability density function (red line). The p-value quantifying the agreement between the data and the fit model is 0.53.

$$m_H = 124.99 \pm 0.18(\text{stat.}) \pm 0.04(\text{syst.})\ \text{GeV}.$$

All fitted normalisations are found to be compatible with the SM expectations. By allowing the fit to determine the normalisation in each subchannel, the result is insensitive to the SM predictions for each subchannel. There is negligible change in the fit results if the relative fractions are constrained to the SM. The fit for m_H is also performed independently for each decay channel. The $m_{4\ell}$ distributions for the four channels are shown in Fig. 7. The resulting profile-likelihood-ratio variation as a function of m_H and the resulting fitted values are compared with those of the combined fit in Fig. 8. The m_H measurements from the individual channels are compatible with the combined measurement, with a p-value of 0.82.

The statistical uncertainty of m_H is estimated by fixing all nuisance parameters associated with systematic uncertainties to their best-fit values, leaving all remaining parameters unconstrained. Uncertainties on the Higgs boson signal originating from the QCD scale, PDF variations, and modelling of FSR account result in an uncertainty in m_H of 14 MeV. Other sources, including background modelling and simulation statistics, contribute less than 5 MeV. The systematic uncertainties are applied following the strategy detailed in Ref. [13]. The total systematic uncertainty is estimated by subtracting the square of the statistical uncertainty from the square of the total uncertainty and calculating the square root. Table 2 shows the leading contributions to the systematic uncertainty of m_H. The uncertainties in the electron energy scale and in the muon momentum scale, resolution, and sagitta bias correction are described in Section 4. Other sources, including background modelling and simulation statistics, contribute less than 5 MeV. The total uncertainty is in agreement with the expectation of 0.19 GeV and is dominated by the statistical component. Fig. 9 shows the distribution of the expected uncertainty in m_H obtained by fitting a set of pseudo-experiments assuming $m_H = 125$ GeV.

The result of this measurement is combined with the measurement of m_H using the Run 1 dataset in the same final states, which was $m_H = 124.51 \pm 0.52$ [9]. The correlation scheme for the systematic uncertainties of the two measurements follows the one used in Ref. [11], where only the uncertainties in the lepton calibration were considered correlated. In this combination, the electron calibration uncertainty is correlated between the two measurements, while the muon calibration systematic uncertainty is uncorrelated due to the use of improved and independent techniques, as described in Section 4. Systematic uncertainties are reduced by about 14% when using this correlation scheme. The combined result, calculated by combining the likelihoods of the two measurements is

Table 2
Largest contributions to the systematic uncertainty of m_H.

Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	±28
Electron energy scale	±19
Signal-process theory	±14

$$m_H = 124.94 \pm 0.17(\text{stat.}) \pm 0.03(\text{syst.})\ \text{GeV},$$

which has slightly smaller statistical and systematic uncertainties. The p-value for the two individual results, assuming the Higgs boson mass is the combined value, is 0.4.

8. Summary

The mass of the Higgs boson is measured from a maximum-likelihood fit to the invariant mass and the predicted invariant-mass resolution of the $H \to ZZ^* \to 4\ell$ decay channel. The results are obtained from the full Run 2 pp collision data sample recorded by the ATLAS experiment at the CERN Large Hadron Collider at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 139 fb^{-1}. The measurement is based on the latest calibrations of muons and electrons, and on improvements to the analysis techniques used to obtain the previous result using data collected by ATLAS in 2015 and 2016.

The measured value of the Higgs boson mass for the $H \to ZZ^* \to 4\ell$ channel is

$$m_H = 124.99 \pm 0.18(\text{stat.}) \pm 0.04(\text{syst.})\ \text{GeV}.$$

Thanks to a larger dataset, improved experimental techniques, and more precise lepton calibration, the statistical uncertainty of the measurement has been reduced by a factor of two and the systematic uncertainty by about 20% relative to the previous Run 2 published result.

This measurement is combined with the previous one obtained in the same channel with ATLAS Run 1 data. The result of the combination is

$$m_H = 124.94 \pm 0.17(\text{stat.}) \pm 0.03(\text{syst.})\ \text{GeV}.$$

This is the most precise measurement of m_H in the $H \to ZZ^* \to 4\ell$ channel by the ATLAS Collaboration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

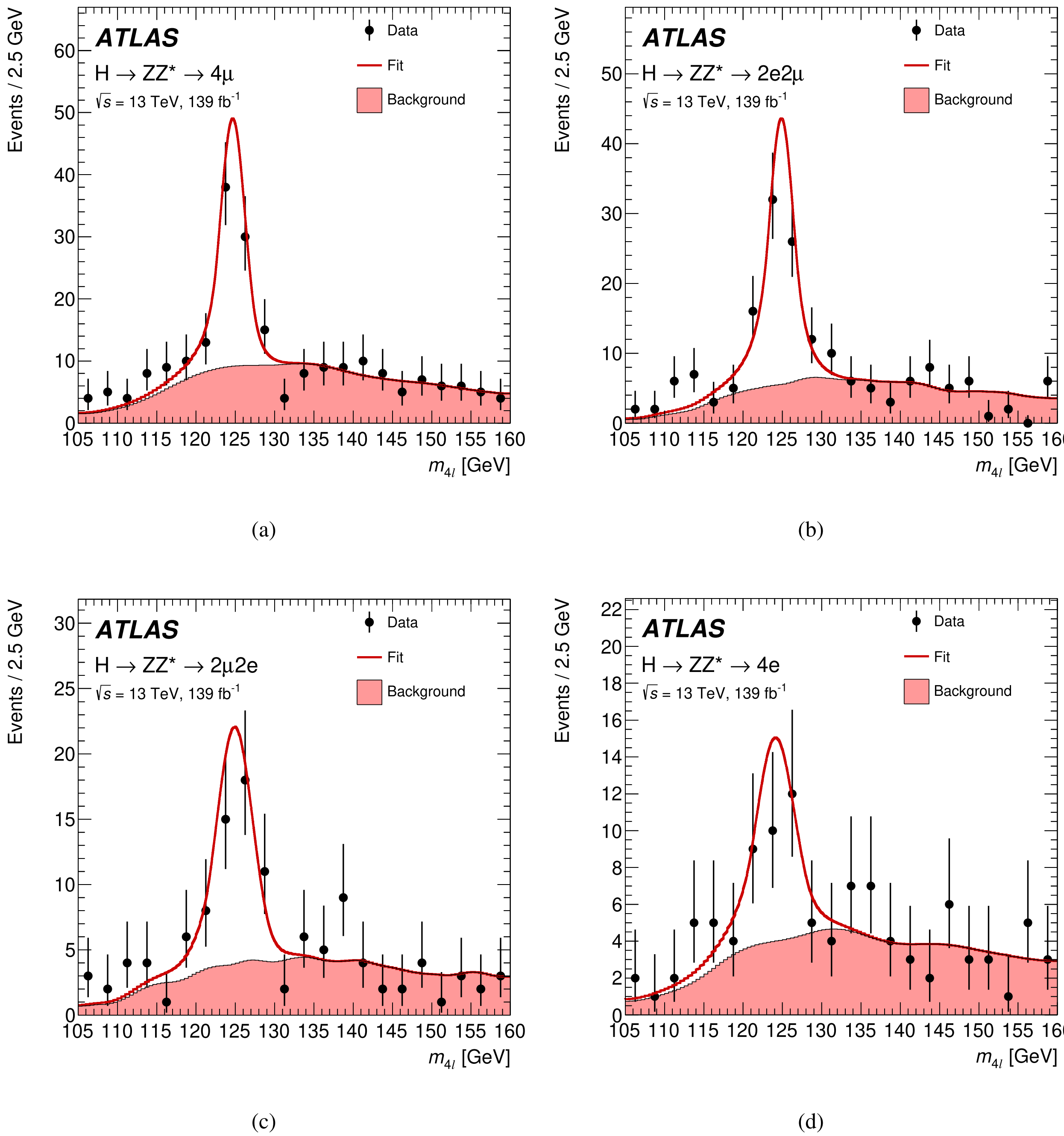
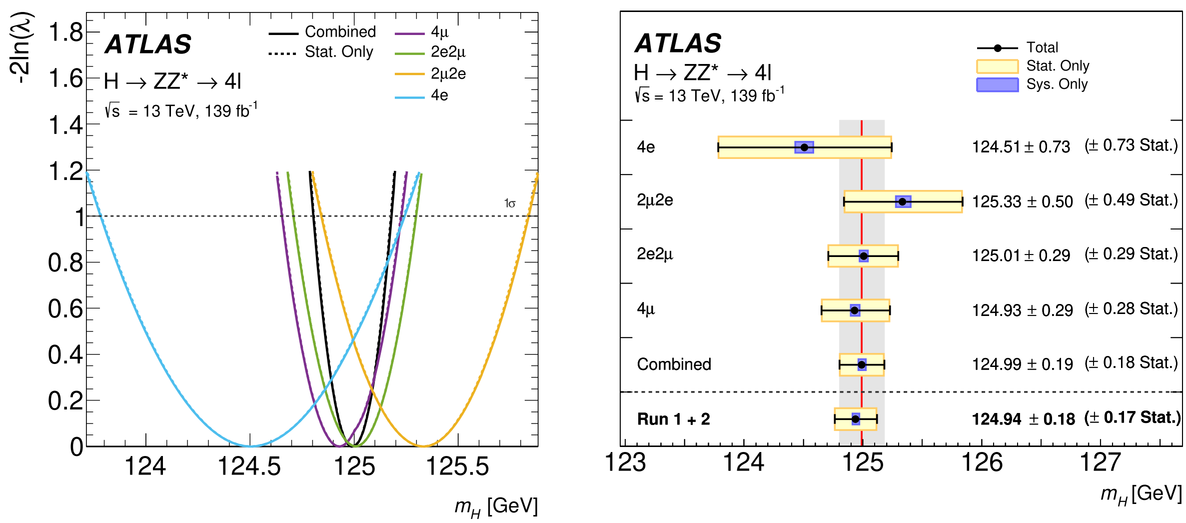


Fig. 7. The $m_{4\ell}$ data distribution (black points) for (a) 4μ, (b) $2e2\mu$, (c) $2\mu2e$, and (d) $4e$ events is shown along with the signal-plus-background post-fit probability density function (red line). The p-values quantifying the agreement between the data and the fit model are (a) 0.92, (b) 0.10, (c) 0.83, and (d) 0.97.

Acknowledgements

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

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; 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 Benoziyo 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 Knut and Alice Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; PRIMUS 21/SCI/017 and UNCE SCI/013, Czech Republic; COST, ERC, ERDF, Horizon 2020 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



(a) (b)

Fig. 8. The test statistic, $-2\ln(\lambda)$, values as a function of m_H are shown in (a) for the fit in each of the final states 4μ (purple), $2e2\mu$ (green), $2\mu 2e$ (orange), and $4e$ (blue), and for the combined fit (black), both with (solid lines) and without (dashed lines) systematic uncertainties. The horizontal dashed line indicates the location of the one-σ uncertainty. The fit results obtained in each final state are shown in (b) together with the combined result. The uncertainty bar on each point is the total statistical and systematic uncertainty; the brackets show the statistical uncertainty only. The vertical (red) line indicates the combined Run 2 result, and the grey band its total uncertainty.

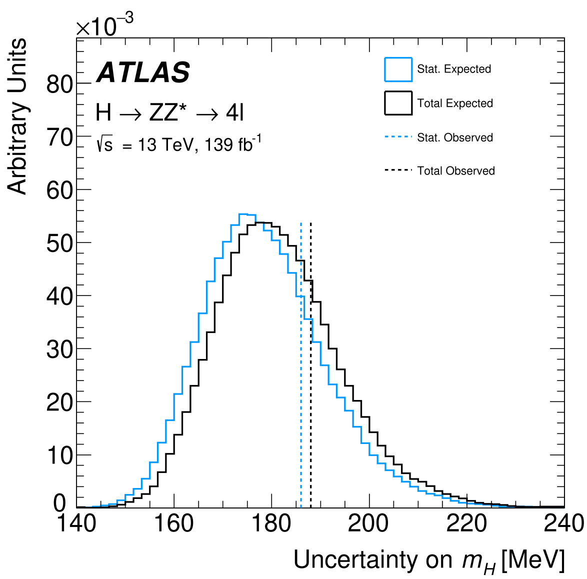


Fig. 9. The distributions of the total m_H uncertainty from pseudo-experiments assuming $m_H = 125$ GeV are shown, for when the fit does (black) and does not (blue) take into account systematic uncertainties. The solid lines correspond to the expected uncertainty distribution from pseudo-experiments, while the vertical dashed lines indicate the observed values of the uncertainties. The one-sided p-value for compatibility between the observed and expected total uncertainties is 0.28.

Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelser, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [67].

References

[1] ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1, arXiv:1207.7214 [hep-ex].
[2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716 (2012) 30, arXiv:1207.7235 [hep-ex].
[3] F. Englert, R. Brout, Broken symmetry and the mass of gauge vector mesons, Phys. Rev. Lett. 13 (1964) 321.
[4] P.W. Higgs, Broken symmetries and the masses of gauge bosons, Phys. Rev. Lett. 13 (1964) 508.
[5] G. Guralnik, C. Hagen, T. Kibble, Global conservation laws and massless particles, Phys. Rev. Lett. 13 (1964) 585.
[6] M. Sher, Electroweak Higgs potential and vacuum stability, Phys. Rep. (ISSN 0370-1573) 179 (1989) 273, https://www.sciencedirect.com/science/article/pii/0370157389900616.
[7] D. de Florian, et al., Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector, arXiv:1610.07922 [hep-ph], 2016.
[8] ATLAS CMS Collaborations, Combined measurement of the Higgs boson mass in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS experiments, Phys. Rev. Lett. 114 (2015) 191803, arXiv:1503.07589 [hep-ex].
[9] ATLAS Collaboration, Measurement of the Higgs boson mass from the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector, Phys. Rev. D 90 (2014) 052004, arXiv:1406.3827 [hep-ex].
[10] CMS Collaboration, Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV, Eur. Phys. J. C 75 (2015) 212, arXiv:1412.8662 [hep-ex].
[11] ATLAS Collaboration, Measurement of the Higgs boson mass in the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ channels with $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector, Phys. Lett. B 784 (2018) 345, arXiv:1806.00242 [hep-ex].
[12] CMS Collaboration, A measurement of the Higgs boson mass in the diphoton decay channel, Phys. Lett. B 805 (2020) 135425, arXiv:2002.06398 [hep-ex].
[13] ATLAS Collaboration, Higgs boson production cross-section measurements and their EFT interpretation in the 4ℓ decay channel at $\sqrt{s} = 13$ TeV with the ATLAS detector, Eur. Phys. J. C 80 (2020) 957, arXiv:2004.03447 [hep-ex], Erratum: Eur. Phys. J. C 81 (2021) 29.
[14] ATLAS Collaboration, The ATLAS experiment at the CERN Large Hadron Collider, J. Instrum. 3 (2008) S08003.
[15] ATLAS Collaboration, ATLAS insertable b-layer technical design report, ATLAS-TDR-19; CERN-LHCC-2010-013, https://cds.cern.ch/record/1291633, 2010, Addendum: ATLAS-TDR-19-ADD-1; CERN-LHCC-2012-009, https://cds.cern.ch/record/1451888, 2012.
[16] B. Abbott, et al., Production and integration of the ATLAS Insertable B-Layer, J. Instrum. 13 (2018) T05008, arXiv:1803.00844 [physics.ins-det].
[17] ATLAS Collaboration, Performance of the ATLAS trigger system in 2015, Eur. Phys. J. C 77 (2017) 317, arXiv:1611.09661 [hep-ex].

[18] ATLAS Collaboration, The ATLAS collaboration software and firmware, ATL-SOFT-PUB-2021-001, https://cds.cern.ch/record/2767187, 2021.
[19] ATLAS Collaboration, Performance of the ATLAS muon triggers in Run 2, J. Instrum. 15 (2020) P09015, arXiv:2004.13447 [hep-ex].
[20] ATLAS Collaboration, Performance of electron and photon triggers in ATLAS during LHC Run 2, Eur. Phys. J. C 80 (2020) 47, arXiv:1909.00761 [hep-ex].
[21] ATLAS Collaboration, ATLAS data quality operations and performance for 2015–2018 data-taking, J. Instrum. 15 (2020) P04003, arXiv:1911.04632 [physics.ins-det].
[22] ATLAS Collaboration, Measurements of the Higgs boson inclusive and differential fiducial cross sections in the 4ℓ decay channel at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 80 (2020) 942, arXiv:2004.03969 [hep-ex].
[23] K. Hamilton, P. Nason, E. Re, G. Zanderighi, NNLOPS simulation of Higgs boson production, J. High Energy Phys. 10 (2013) 222, arXiv:1309.0017 [hep-ph].
[24] K. Hamilton, P. Nason, G. Zanderighi, Finite quark-mass effects in the NNLOPS POWHEG+MiNLO Higgs generator, J. High Energy Phys. 05 (2015) 140, arXiv:1501.04637 [hep-ph].
[25] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, J. High Energy Phys. 06 (2010) 043, arXiv:1002.2581 [hep-ph].
[26] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040, arXiv:{hep-ph/0409146}.
[27] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 070, arXiv:0709.2092 [hep-ph].
[28] K. Hamilton, P. Nason, G. Zanderighi, MINLO: multi-scale improved NLO, J. High Energy Phys. 10 (2012) 155, arXiv:1206.3572 [hep-ph].
[29] J.M. Campbell, et al., NLO Higgs boson production plus one and two jets using the POWHEG BOX, MadGraph4 and MCFM, J. High Energy Phys. 07 (2012) 092, arXiv:1202.5475 [hep-ph].
[30] K. Hamilton, P. Nason, C. Oleari, G. Zanderighi, Merging H/W/Z + 0 and 1 jet at NLO with no merging scale: a path to parton shower + NNLO matching, J. High Energy Phys. 05 (2013) 082, arXiv:1212.4504 [hep-ph].
[31] S. Catani, M. Grazzini, Next-to-next-to-leading-order subtraction formalism in hadron collisions and its application to Higgs-boson production at the Large Hadron Collider, Phys. Rev. Lett. 98 (2007) 222002, arXiv:{hep-ph/0703012} [hep-ph].
[32] J. Butterworth, et al., PDF4LHC recommendations for LHC Run II, J. Phys. G 43 (2016) 023001, arXiv:1510.03865 [hep-ph].
[33] J. Alwall, et al., The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079, arXiv:1405.0301 [hep-ph].
[34] M. Wiesemann, et al., Higgs production in association with bottom quarks, J. High Energy Phys. 02 (2015) 132, arXiv:1409.5301 [hep-ph].
[35] R.D. Ball, et al., Parton distributions for the LHC run II, J. High Energy Phys. 04 (2015) 040, arXiv:1410.8849 [hep-ph].
[36] D.J. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Methods A 462 (2001) 152.
[37] T. Sjöstrand, S. Mrenna, P. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. 178 (2008) 852, arXiv:0710.3820 [hep-ph].
[38] T. Gleisberg, et al., Event generation with SHERPA 1.1, J. High Energy Phys. 02 (2009) 007, arXiv:0811.4622 [hep-ph].
[39] T. Gleisberg, S. Höche, Comix, a new matrix element generator, J. High Energy Phys. 12 (2008) 039, arXiv:0808.3674 [hep-ph].
[40] F. Cascioli, P. Maierhöfer, S. Pozzorini, Scattering amplitudes with open loops, Phys. Rev. Lett. 108 (2012) 111601, arXiv:1111.5206 [hep-ph].
[41] E. Bothmann, et al., Event generation with Sherpa 2.2, SciPost Phys. 7 (2019) 034, arXiv:1905.09127 [hep-ph].
[42] F. Caola, K. Melnikov, R. Röntsch, L. Tancredi, QCD corrections to ZZ production in gluon fusion at the LHC, Phys. Rev. D 92 (2015) 094028, arXiv:1509.06734 [hep-ph].
[43] F. Caola, K. Melnikov, R. Röntsch, L. Tancredi, QCD corrections to W^+W^- production through gluon fusion, Phys. Lett. B 754 (2016) 275, arXiv:1511.08617 [hep-ph].
[44] J.M. Campbell, R.K. Ellis, M. Czakon, S. Kirchner, Two loop correction to interference in gg $\to ZZ$, J. High Energy Phys. 08 (2016) 011, arXiv:1605.01380 [hep-ph].
[45] K. Melnikov, M. Dowling, Production of two Z-bosons in gluon fusion in the heavy top quark approximation, Phys. Lett. B 744 (2015) 43, arXiv:1503.01274 [hep-ph].
[46] S. Höche, F. Krauss, M. Schönherr, F. Siegert, QCD matrix elements + parton showers. The NLO case, J. High Energy Phys. 04 (2013) 027, arXiv:1207.5030 [hep-ph].
[47] ATLAS Collaboration, The ATLAS simulation infrastructure, Eur. Phys. J. C 70 (2010) 823, arXiv:1005.4568 [physics.ins-det].
[48] GEANT4 Collaboration, S. Agostinelli, et al., GEANT4 – a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250.
[49] ATLAS Collaboration, The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie–Landshoff diffractive model, ATL-PHYS-PUB-2016-017, https://cds.cern.ch/record/2206965, 2016.
[50] R.D. Ball, et al., Parton distributions with LHC data, Nucl. Phys. B 867 (2013) 244, arXiv:1207.1303 [hep-ph].
[51] ATLAS Collaboration, Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 81 (2021) 578, arXiv:2012.00578 [hep-ex].
[52] ATLAS Collaboration, Alignment of the ATLAS inner detector in Run-2, Eur. Phys. J. C 80 (2020) 1194, arXiv:2007.07624 [hep-ex].
[53] ATLAS Collaboration, Performance of the muon spectrometer alignment in 2017 and 2018 data, ATL-MUON-PUB-2021-002, https://cds.cern.ch/record/2753329, 2021.
[54] ATLAS Collaboration, Studies of the muon momentum calibration and performance of the ATLAS detector with pp collisions at $\sqrt{s} = 13$ TeV, arXiv:2212.07338 [hep-ex], 2022.
[55] ATLAS Collaboration, Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data, J. Instrum. 14 (2019) P12006, arXiv:1908.00005 [hep-ex].
[56] ATLAS Collaboration, Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton–proton collision data at $\sqrt{s} =$ 13 TeV, Eur. Phys. J. C 79 (2019) 639, arXiv:1902.04655 [hep-ex].
[57] ATLAS Collaboration, Electron and photon energy calibration with the ATLAS detector using 2015–2016 LHC proton–proton collision data, J. Instrum. 14 (2019) P03017, arXiv:1812.03848 [hep-ex].
[58] ATLAS Collaboration, Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector, Phys. Rev. D 91 (2015) 012006, arXiv:1408.5191 [hep-ex].
[59] F. Chollet, et al., https://keras.io, 2015.
[60] Martin Abadi, et al., TensorFlow: large-scale machine learning on heterogeneous systems, Software available from tensorflow.org, https://www.tensorflow.org/, 2015.
[61] H. White, Nonparametric estimation of conditional quantiles using neural networks, in: Computing Science and Statistics, Springer New York, New York, NY, 1992, p. 190.
[62] ATLAS Collaboration, Search for scalar diphoton resonances in the mass range 65–600 GeV with the ATLAS detector in pp collision data at $\sqrt{s} = 8$ TeV, Phys. Rev. Lett. 113 (2014) 171801, arXiv:1407.6583 [hep-ex].
[63] K. Cranmer, Kernel estimation in high-energy physics, Comput. Phys. Commun. 136 (2001) 198, arXiv:{hep-ex/0011057} [hep-ex].
[64] M. Baak, S. Gadatsch, R. Harrington, W. Verkerke, Interpolation between multi-dimensional histograms using a new non-linear moment morphing method, Nucl. Instrum. Methods A (ISSN 0168-9002) 771 (2015) 39, https://doi.org/10.1016/j.nima.2014.10.033.
[65] ATLAS Collaboration, Combined search for the Standard Model Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, Phys. Rev. D 86 (2012) 032003, arXiv:1207.0319 [hep-ex].
[66] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C 71 (2011) 1554, arXiv:1007.1727 [physics.data-an], Erratum: Eur. Phys. J. C 73 (2013) 2501.
[67] ATLAS Collaboration, ATLAS computing acknowledgements, ATL-SOFT-PUB-2021-003, https://cds.cern.ch/record/2776662.

The ATLAS Collaboration

G. Aad [101], B. Abbott [119], D.C. Abbott [102], K. Abeling [55], S.H. Abidi [29], A. Aboulhorma [35e], H. Abramowicz [150], H. Abreu [149], Y. Abulaiti [116], A.C. Abusleme Hoffman [136a], B.S. Acharya [68a,68b,p], B. Achkar [55], C. Adam Bourdarios [4], L. Adamczyk [84a], L. Adamek [154], S.V. Addepalli [26], J. Adelman [114], A. Adiguzel [21c], S. Adorni [56], T. Adye [133], A.A. Affolder [135], Y. Afik [36], M.N. Agaras [13], J. Agarwala [72a,72b], A. Aggarwal [99], C. Agheorghiesei [27c], J.A. Aguilar-Saavedra [129f], A. Ahmad [36], F. Ahmadov [38,x], W.S. Ahmed [103], S. Ahuja [94], X. Ai [48], G. Aielli [75a,75b], I. Aizenberg [168], M. Akbiyik [99], T.P.A. Åkesson [97], A.V. Akimov [37], K. Al Khoury [41], G.L. Alberghi [23b], J. Albert [164], P. Albicocco [53], S. Alderweireldt [52], M. Aleksa [36], I.N. Aleksandrov [38], C. Alexa [27b], T. Alexopoulos [10], A. Alfonsi [113], F. Alfonsi [23b], M. Alhroob [119], B. Ali [131], S. Ali [147], M. Aliev [37], G. Alimonti [70a], W. Alkakhi [55], C. Allaire [66], B.M.M. Allbrooke [145], P.P. Allport [20], A. Aloisio [71a,71b], F. Alonso [89], C. Alpigiani [137], E. Alunno Camelia [75a,75b], M. Alvarez Estevez [98], M.G. Alviggi [71a,71b], M. Aly [100], Y. Amaral Coutinho [81b], A. Ambler [103], C. Amelung [36], M. Amerl [1], C.G. Ames [108], D. Amidei [105], S.P. Amor Dos Santos [129a], S. Amoroso [48], K.R. Amos [162], V. Ananiev [124], C. Anastopoulos [138], T. Andeen [11], J.K. Anders [19], S.Y. Andrean [47a,47b], A. Andreazza [70a,70b], S. Angelidakis [9], A. Angerami [41,z], A.V. Anisenkov [37], A. Annovi [73a], C. Antel [56], M.T. Anthony [138], E. Antipov [120], M. Antonelli [53], D.J.A. Antrim [17a], F. Anulli [74a], M. Aoki [82], T. Aoki [152], J.A. Aparisi Pozo [162], M.A. Aparo [145], L. Aperio Bella [48], C. Appelt [18], N. Aranzabal [36], V. Araujo Ferraz [81a], C. Arcangeletti [53], A.T.H. Arce [51], E. Arena [91], J-F. Arguin [107], S. Argyropoulos [54], J.-H. Arling [48], A.J. Armbruster [36], O. Arnaez [154], H. Arnold [113], Z.P. Arrubarrena Tame [108], G. Artoni [74a,74b], H. Asada [110], K. Asai [117], S. Asai [152], N.A. Asbah [61], J. Assahsah [35d], K. Assamagan [29], R. Astalos [28a], R.J. Atkin [33a], M. Atkinson [161], N.B. Atlay [18], H. Atmani [62b], P.A. Atmasiddha [105], K. Augsten [131], S. Auricchio [71a,71b], A.D. Auriol [20], V.A. Austrup [170], G. Avner [149], G. Avolio [36], K. Axiotis [56], M.K. Ayoub [14c], G. Azuelos [107,ac], D. Babal [28a], H. Bachacou [134], K. Bachas [151,r], A. Bachiu [34], F. Backman [47a,47b], A. Badea [61], P. Bagnaia [74a,74b], M. Bahmani [18], A.J. Bailey [162], V.R. Bailey [161], J.T. Baines [133], C. Bakalis [10], O.K. Baker [171], P.J. Bakker [113], E. Bakos [15], D. Bakshi Gupta [8], S. Balaji [146], R. Balasubramanian [113], E.M. Baldin [37], P. Balek [132], E. Ballabene [70a,70b], F. Balli [134], L.M. Baltes [63a], W.K. Balunas [32], J. Balz [99], E. Banas [85], M. Bandieramonte [128], A. Bandyopadhyay [24], S. Bansal [24], L. Barak [150], E.L. Barberio [104], D. Barberis [57b,57a], M. Barbero [101], G. Barbour [95], K.N. Barends [33a], T. Barillari [109], M-S. Barisits [36], T. Barklow [142], R.M. Barnett [17a], P. Baron [121], D.A. Baron Moreno [100], A. Baroncelli [62a], G. Barone [29], A.J. Barr [125], L. Barranco Navarro [47a,47b], F. Barreiro [98], J. Barreiro Guimarães da Costa [14a], U. Barron [150], M.G. Barros Teixeira [129a], S. Barsov [37], F. Bartels [63a], R. Bartoldus [142], A.E. Barton [90], P. Bartos [28a], A. Basalaev [48], A. Basan [99], M. Baselga [49], I. Bashta [76a,76b], A. Bassalat [66,b], M.J. Basso [154], C.R. Basson [100], R.L. Bates [59], S. Batlamous [35e], J.R. Batley [32], B. Batool [140], M. Battaglia [135], D. Battulga [18], M. Bauce [74a,74b], P. Bauer [24], A. Bayirli [21a], J.B. Beacham [51], T. Beau [126], P.H. Beauchemin [157], F. Becherer [54], P. Bechtle [24], H.P. Beck [19,q], K. Becker [166], A.J. Beddall [21d], V.A. Bednyakov [38], C.P. Bee [144], L.J. Beemster [15], T.A. Beermann [36], M. Begalli [81d], M. Begel [29], A. Behera [144], J.K. Behr [48], C. Beirao Da Cruz E Silva [36], J.F. Beirer [55,36], F. Beisiegel [24], M. Belfkir [158], G. Bella [150], L. Bellagamba [23b], A. Bellerive [34], P. Bellos [20], K. Beloborodov [37], K. Belotskiy [37], N.L. Belyaev [37], D. Benchekroun [35a], F. Bendebba [35a], Y. Benhammou [150], D.P. Benjamin [29], M. Benoit [29], J.R. Bensinger [26], S. Bentvelsen [113], L. Beresford [36], M. Beretta [53], D. Berge [18], E. Bergeaas Kuutmann [160], N. Berger [4], B. Bergmann [131], J. Beringer [17a], S. Berlendis [7], G. Bernardi [5], C. Bernius [142], F.U. Bernlochner [24], T. Berry [94], P. Berta [132], A. Berthold [50], I.A. Bertram [90], S. Bethke [109], A. Betti [74a,74b], A.J. Bevan [93], M. Bhamjee [33c], S. Bhatta [144], D.S. Bhattacharya [165], P. Bhattarai [26], V.S. Bhopatkar [120], R. Bi [29,af], R.M. Bianchi [128], O. Biebel [108], R. Bielski [122], M. Biglietti [76a], T.R.V. Billoud [131], M. Bindi [55], A. Bingul [21b], C. Bini [74a,74b], S. Biondi [23b,23a], A. Biondini [91], C.J. Birch-sykes [100], G.A. Bird [20,133], M. Birman [168], T. Bisanz [36], E. Bisceglie [43b,43a], D. Biswas [169,l], A. Bitadze [100], K. Bjørke [124], I. Bloch [48], C. Blocker [26], A. Blue [59], U. Blumenschein [93], J. Blumenthal [99], G.J. Bobbink [113], V.S. Bobrovnikov [37], M. Boehler [54], D. Bogavac [36], A.G. Bogdanchikov [37], C. Bohm [47a], V. Boisvert [94], P. Bokan [48], T. Bold [84a], M. Bomben [5], M. Bona [93], M. Boonekamp [134], C.D. Booth [94], A.G. Borbély [59], H.M. Borecka-Bielska [107], L.S. Borgna [95], G. Borissov [90], D. Bortoletto [125], D. Boscherini [23b], M. Bosman [13], J.D. Bossio Sola [36], K. Bouaouda [35a], N. Bouchhar [162], J. Boudreau [128], E.V. Bouhova-Thacker [90], D. Boumediene [40], R. Bouquet [5], A. Boveia [118], J. Boyd [36], D. Boye [29], I.R. Boyko [38], J. Bracinik [20], N. Brahimi [62d], G. Brandt [170], O. Brandt [32], F. Braren [48], B. Brau [102], J.E. Brau [122], K. Brendlinger [48], R. Brener [168], L. Brenner [113], R. Brenner [160], S. Bressler [168], B. Brickwedde [99], D. Britton [59], D. Britzger [109], I. Brock [24], G. Brooijmans [41], W.K. Brooks [136f], E. Brost [29], T.L. Bruckler [125], P.A. Bruckman de Renstrom [85], B. Brüers [48], D. Bruncko [28b,*], A. Bruni [23b], G. Bruni [23b], M. Bruschi [23b], N. Bruscino [74a,74b], L. Bryngemark [142], T. Buanes [16], Q. Buat [137], P. Buchholz [140], A.G. Buckley [59], I.A. Budagov [38,*], M.K. Bugge [124], O. Bulekov [37], B.A. Bullard [61], S. Burdin [91], C.D. Burgard [48], A.M. Burger [40], B. Burghgrave [8], J.T.P. Burr [32], C.D. Burton [11], J.C. Burzynski [141], E.L. Busch [41], V. Büscher [99], P.J. Bussey [59], J.M. Butler [25], C.M. Buttar [59], J.M. Butterworth [95], W. Buttinger [133], C.J. Buxo Vazquez [106], A.R. Buzykaev [37], G. Cabras [23b],

S. Cabrera Urbán [162], D. Caforio [58], H. Cai [128], Y. Cai [14a,14d], V.M.M. Cairo [36], O. Cakir [3a], N. Calace [36], P. Calafiura [17a], G. Calderini [126], P. Calfayan [67], G. Callea [59], L.P. Caloba [81b], D. Calvet [40], S. Calvet [40], T.P. Calvet [101], M. Calvetti [73a,73b], R. Camacho Toro [126], S. Camarda [36], D. Camarero Munoz [26], P. Camarri [75a,75b], M.T. Camerlingo [76a,76b], D. Cameron [124], C. Camincher [164], M. Campanelli [95], A. Camplani [42], V. Canale [71a,71b], A. Canesse [103], M. Cano Bret [79], J. Cantero [162], Y. Cao [161], F. Capocasa [26], M. Capua [43b,43a], A. Carbone [70a,70b], R. Cardarelli [75a], J.C.J. Cardenas [8], F. Cardillo [162], T. Carli [36], G. Carlino [71a], J.I. Carlotto [13], B.T. Carlson [128,s], E.M. Carlson [164,155a], L. Carminati [70a,70b], M. Carnesale [74a,74b], S. Caron [112], E. Carquin [136f], S. Carrá [70a,70b], G. Carratta [23b,23a], F. Carrio Argos [33g], J.W.S. Carter [154], T.M. Carter [52], M.P. Casado [13,i], A.F. Casha [154], E.G. Castiglia [171], F.L. Castillo [63a], L. Castillo Garcia [13], V. Castillo Gimenez [162], N.F. Castro [129a,129e], A. Catinaccio [36], J.R. Catmore [124], V. Cavaliere [29], N. Cavalli [23b,23a], V. Cavasinni [73a,73b], E. Celebi [21a], F. Celli [125], M.S. Centonze [69a,69b], K. Cerny [121], A.S. Cerqueira [81a], A. Cerri [145], L. Cerrito [75a,75b], F. Cerutti [17a], A. Cervelli [23b], S.A. Cetin [21d], Z. Chadi [35a], D. Chakraborty [114], M. Chala [129f], J. Chan [169], W.Y. Chan [152], J.D. Chapman [32], B. Chargeishvili [148b], D.G. Charlton [20], T.P. Charman [93], M. Chatterjee [19], S. Chekanov [6], S.V. Chekulaev [155a], G.A. Chelkov [38,a], A. Chen [105], B. Chen [150], B. Chen [164], C. Chen [62a], H. Chen [14c], H. Chen [29], J. Chen [62c], J. Chen [26], S. Chen [152], S.J. Chen [14c], X. Chen [62c], X. Chen [14b,ab], Y. Chen [62a], C.L. Cheng [169], H.C. Cheng [64a], S. Cheong [142], A. Cheplakov [38], E. Cheremushkina [48], E. Cherepanova [113], R. Cherkaoui El Moursli [35e], E. Cheu [7], K. Cheung [65], L. Chevalier [134], V. Chiarella [53], G. Chiarelli [73a], N. Chiedde [101], G. Chiodini [69a], A.S. Chisholm [20], A. Chitan [27b], M. Chitishvili [162], Y.H. Chiu [164], M.V. Chizhov [38], K. Choi [11], A.R. Chomont [74a,74b], Y. Chou [102], E.Y.S. Chow [113], T. Chowdhury [33g], L.D. Christopher [33g], K.L. Chu [64a], M.C. Chu [64a], X. Chu [14a,14d], J. Chudoba [130], J.J. Chwastowski [85], D. Cieri [109], K.M. Ciesla [84a], V. Cindro [92], A. Ciocio [17a], F. Cirotto [71a,71b], Z.H. Citron [168,m], M. Citterio [70a], D.A. Ciubotaru [27b], B.M. Ciungu [154], A. Clark [56], P.J. Clark [52], J.M. Clavijo Columbie [48], S.E. Clawson [100], C. Clement [47a,47b], J. Clercx [48], L. Clissa [23b,23a], Y. Coadou [101], M. Cobal [68a,68c], A. Coccaro [57b], R.F. Coelho Barrue [129a], R. Coelho Lopes De Sa [102], S. Coelli [70a], H. Cohen [150], A.E.C. Coimbra [70a,70b], B. Cole [41], J. Collot [60], P. Conde Muiño [129a,129g], M.P. Connell [33c], S.H. Connell [33c], I.A. Connelly [59], E.I. Conroy [125], F. Conventi [71a,ad], H.G. Cooke [20], A.M. Cooper-Sarkar [125], F. Cormier [163], L.D. Corpe [36], M. Corradi [74a,74b], E.E. Corrigan [97], F. Corriveau [103,w], A. Cortes-Gonzalez [18], M.J. Costa [162], F. Costanza [4], D. Costanzo [138], B.M. Cote [118], G. Cowan [94], J.W. Cowley [32], K. Cranmer [116], S. Crépé-Renaudin [60], F. Crescioli [126], M. Cristinziani [140], M. Cristoforetti [77a,77b,d], V. Croft [157], G. Crosetti [43b,43a], A. Cueto [36], T. Cuhadar Donszelmann [159], H. Cui [14a,14d], Z. Cui [7], A.R. Cukierman [142], W.R. Cunningham [59], F. Curcio [43b,43a], P. Czodrowski [36], M.M. Czurylo [63b], M.J. Da Cunha Sargedas De Sousa [62a], J.V. Da Fonseca Pinto [81b], C. Da Via [100], W. Dabrowski [84a], T. Dado [49], S. Dahbi [33g], T. Dai [105], C. Dallapiccola [102], M. Dam [42], G. D'amen [29], V. D'Amico [108], J. Damp [99], J.R. Dandoy [127], M.F. Daneri [30], M. Danninger [141], V. Dao [36], G. Darbo [57b], S. Darmora [6], S.J. Das [29], S. D'Auria [70a,70b], C. David [155b], T. Davidek [132], D.R. Davis [51], B. Davis-Purcell [34], I. Dawson [93], K. De [8], R. De Asmundis [71a], M. De Beurs [113], N. De Biase [48], S. De Castro [23b,23a], N. De Groot [112], P. de Jong [113], H. De la Torre [106], A. De Maria [14c], A. De Salvo [74a], U. De Sanctis [75a,75b], A. De Santo [145], J.B. De Vivie De Regie [60], D.V. Dedovich [38], J. Degens [113], A.M. Deiana [44], F. Del Corso [23b,23a], J. Del Peso [98], F. Del Rio [63a], F. Deliot [134], C.M. Delitzsch [49], M. Della Pietra [71a,71b], D. Della Volpe [56], A. Dell'Acqua [36], L. Dell'Asta [70a,70b], M. Delmastro [4], P.A. Delsart [60], S. Demers [171], M. Demichev [38], S.P. Denisov [37], L. D'Eramo [114], D. Derendarz [85], F. Derue [126], P. Dervan [91], K. Desch [24], K. Dette [154], C. Deutsch [24], P.O. Deviveiros [36], F.A. Di Bello [74a,74b], A. Di Ciaccio [75a,75b], L. Di Ciaccio [4], A. Di Domenico [74a,74b], C. Di Donato [71a,71b], A. Di Girolamo [36], G. Di Gregorio [73a,73b], A. Di Luca [77a,77b], B. Di Micco [76a,76b], R. Di Nardo [76a,76b], C. Diaconu [101], F.A. Dias [113], T. Dias Do Vale [141], M.A. Diaz [136a,136b], F.G. Diaz Capriles [24], M. Didenko [162], E.B. Diehl [105], L. Diehl [54], S. Díez Cornell [48], C. Diez Pardos [140], C. Dimitriadi [24,160], A. Dimitrievska [17a], W. Ding [14b], J. Dingfelder [24], I-M. Dinu [27b], S.J. Dittmeier [63b], F. Dittus [36], F. Djama [101], T. Djobava [148b], J.I. Djuvsland [16], C. Doglioni [100,97], J. Dolejsi [132], Z. Dolezal [132], M. Donadelli [81c], B. Dong [62c], J. Donini [40], A. D'Onofrio [14c], M. D'Onofrio [91], J. Dopke [133], A. Doria [71a], M.T. Dova [89], A.T. Doyle [59], M.A. Draguet [125], E. Drechsler [141], E. Dreyer [168], I. Drivas-koulouris [10], A.S. Drobac [157], M. Drozdova [56], D. Du [62a], T.A. du Pree [113], F. Dubinin [37], M. Dubovsky [28a], E. Duchovni [168], G. Duckeck [108], O.A. Ducu [27b], D. Duda [109], A. Dudarev [36], M. D'uffizi [100], L. Duflot [66], M. Dührssen [36], C. Dülsen [170], A.E. Dumitriu [27b], M. Dunford [63a], S. Dungs [49], K. Dunne [47a,47b], A. Duperrin [101], H. Duran Yildiz [3a], M. Düren [58],

A. Durglishvili [148b], B.L. Dwyer [114], G.I. Dyckes [17a], M. Dyndal [84a], S. Dysch [100], B.S. Dziedzic [85], Z.O. Earnshaw [145], B. Eckerova [28a], M.G. Eggleston [51], E. Egidio Purcino De Souza [81b], L.F. Ehrke [56], G. Eigen [16], K. Einsweiler [17a], T. Ekelof [160], P.A. Ekman [97], Y. El Ghazali [35b], H. El Jarrari [35e,147], A. El Moussaouy [35a], V. Ellajosyula [160], M. Ellert [160], F. Ellinghaus [170], A.A. Elliot [93], N. Ellis [36], J. Elmsheuser [29], M. Elsing [36], D. Emeliyanov [133], A. Emerman [41], Y. Enari [152], I. Ene [17a], S. Epari [13], J. Erdmann [49,aa], A. Ereditato [19], P.A. Erland [85], M. Errenst [170], M. Escalier [66], C. Escobar [162], E. Etzion [150], G. Evans [129a], H. Evans [67], M.O. Evans [145], A. Ezhilov [37], S. Ezzarqtouni [35a], F. Fabbri [59], L. Fabbri [23b,23a], G. Facini [95], V. Fadeyev [135], R.M. Fakhrutdinov [37], S. Falciano [74a], P.J. Falke [24], S. Falke [36], J. Faltova [132], Y. Fan [14a], Y. Fang [14a,14d], G. Fanourakis [46], M. Fanti [70a,70b], M. Faraj [68a,68b], A. Farbin [8], A. Farilla [76a], T. Farooque [106], S.M. Farrington [52], F. Fassi [35e], D. Fassouliotis [9], M. Faucci Giannelli [75a,75b], W.J. Fawcett [32], L. Fayard [66], P. Federicova [130], O.L. Fedin [37,a], G. Fedotov [37], M. Feickert [161], L. Feligioni [101], A. Fell [138], D.E. Fellers [122], C. Feng [62b], M. Feng [14b], Z. Feng [113], M.J. Fenton [159], A.B. Fenyuk [37], L. Ferencz [48], S.W. Ferguson [45], J. Ferrando [48], A. Ferrari [160], P. Ferrari [113,112], R. Ferrari [72a], D. Ferrere [56], C. Ferretti [105], F. Fiedler [99], A. Filipčič [92], E.K. Filmer [1], F. Filthaut [112], M.C.N. Fiolhais [129a,129c,c], L. Fiorini [162], F. Fischer [140], W.C. Fisher [106], T. Fitschen [20], I. Fleck [140], P. Fleischmann [105], T. Flick [170], L. Flores [127], M. Flores [33d], L.R. Flores Castillo [64a], F.M. Follega [77a,77b], N. Fomin [16], J.H. Foo [154], B.C. Forland [67], A. Formica [134], A.C. Forti [100], E. Fortin [101], A.W. Fortman [61], M.G. Foti [17a], L. Fountas [9], D. Fournier [66], H. Fox [90], P. Francavilla [73a,73b], S. Francescato [61], M. Franchini [23b,23a], S. Franchino [63a], D. Francis [36], L. Franco [112], L. Franconi [19], M. Franklin [61], G. Frattari [26], A.C. Freegard [93], P.M. Freeman [20], W.S. Freund [81b], N. Fritzsche [50], A. Froch [54], D. Froidevaux [36], J.A. Frost [125], Y. Fu [62a], M. Fujimoto [117], E. Fullana Torregrosa [162,*], J. Fuster [162], A. Gabrielli [23b,23a], A. Gabrielli [154], P. Gadow [48], G. Gagliardi [57b,57a], L.G. Gagnon [17a], G.E. Gallardo [125], E.J. Gallas [125], B.J. Gallop [133], R. Gamboa Goni [93], K.K. Gan [118], S. Ganguly [152], J. Gao [62a], Y. Gao [52], F.M. Garay Walls [136a,136b], B. Garcia [29,af], C. García [162], J.E. García Navarro [162], J.A. García Pascual [14a], M. Garcia-Sciveres [17a], R.W. Gardner [39], D. Garg [79], R.B. Garg [142], S. Gargiulo [54], C.A. Garner [154], V. Garonne [29], S.J. Gasiorowski [137], P. Gaspar [81b], G. Gaudio [72a], V. Gautam [13], P. Gauzzi [74a,74b], I.L. Gavrilenko [37], A. Gavrilyuk [37], C. Gay [163], G. Gaycken [48], E.N. Gazis [10], A.A. Geanta [27b,27e], C.M. Gee [135], J. Geisen [97], M. Geisen [99], C. Gemme [57b], M.H. Genest [60], S. Gentile [74a,74b], S. George [94], W.F. George [20], T. Geralis [46], L.O. Gerlach [55], P. Gessinger-Befurt [36], M. Ghasemi Bostanabad [164], M. Ghneimat [140], K. Ghorbanian [93], A. Ghosal [140], A. Ghosh [159], A. Ghosh [7], B. Giacobbe [23b], S. Giagu [74a,74b], N. Giangiacomi [154], P. Giannetti [73a], A. Giannini [62a], S.M. Gibson [94], M. Gignac [135], D.T. Gil [84b], A.K. Gilbert [84a], B.J. Gilbert [41], D. Gillberg [34], G. Gilles [113], N.E.K. Gillwald [48], L. Ginabat [126], D.M. Gingrich [2,ac], M.P. Giordani [68a,68c], P.F. Giraud [134], G. Giugliarelli [68a,68c], D. Giugni [70a], F. Giuli [36], I. Gkialas [9,j], L.K. Gladilin [37], C. Glasman [98], G.R. Gledhill [122], M. Glisic [122], I. Gnesi [43b,f], Y. Go [29,af], M. Goblirsch-Kolb [26], B. Gocke [49], D. Godin [107], S. Goldfarb [104], T. Golling [56], M.G.D. Gololo [33g], D. Golubkov [37], J.P. Gombas [106], A. Gomes [129a,129b], G. Gomes Da Silva [140], A.J. Gomez Delegido [162], R. Goncalves Gama [55], R. Gonçalo [129a,129c], G. Gonella [122], L. Gonella [20], A. Gongadze [38], F. Gonnella [20], J.L. Gonski [41], R.Y. González Andana [52], S. González de la Hoz [162], S. Gonzalez Fernandez [13], R. Gonzalez Lopez [91], C. Gonzalez Renteria [17a], R. Gonzalez Suarez [160], S. Gonzalez-Sevilla [56], G.R. Gonzalvo Rodriguez [162], L. Goossens [36], N.A. Gorasia [20], P.A. Gorbounov [37], B. Gorini [36], E. Gorini [69a,69b], A. Gorišek [92], A.T. Goshaw [51], M.I. Gostkin [38], C.A. Gottardo [36], M. Gouighri [35b], V. Goumarre [48], A.G. Goussiou [137], N. Govender [33c], C. Goy [4], I. Grabowska-Bold [84a], K. Graham [34], E. Gramstad [124], S. Grancagnolo [18], M. Grandi [145], V. Gratchev [37,*], P.M. Gravila [27f], F.G. Gravili [69a,69b], H.M. Gray [17a], M. Greco [69a,69b], C. Grefe [24], I.M. Gregor [48], P. Grenier [142], C. Grieco [13], A.A. Grillo [135], K. Grimm [31,n], S. Grinstein [13,u], J.-F. Grivaz [66], E. Gross [168], J. Grosse-Knetter [55], C. Grud [105], A. Grummer [111], J.C. Grundy [125], L. Guan [105], W. Guan [169], C. Gubbels [163], J.G.R. Guerrero Rojas [162], G. Guerrieri [68a,68b], F. Guescini [109], R. Gugel [99], J.A.M. Guhit [105], A. Guida [48], T. Guillemin [4], E. Guilloton [166,133], S. Guindon [36], F. Guo [14a,14d], J. Guo [62c], L. Guo [66], Y. Guo [105], R. Gupta [48], S. Gurbuz [24], S.S. Gurdasani [54], G. Gustavino [36], M. Guth [56], P. Gutierrez [119], L.F. Gutierrez Zagazeta [127], C. Gutschow [95], C. Guyot [134], C. Gwenlan [125], C.B. Gwilliam [91], E.S. Haaland [124], A. Haas [116], M. Habedank [48], C. Haber [17a], H.K. Hadavand [8], A. Hadef [99], S. Hadzic [109], E.H. Haines [95], M. Haleem [165], J. Haley [120], J.J. Hall [138], G.D. Hallewell [101], L. Halser [19], K. Hamano [164], H. Hamdaoui [35e], M. Hamer [24], G.N. Hamity [52], J. Han [62b], K. Han [62a], L. Han [14c], L. Han [62a], S. Han [17a], Y.F. Han [154], K. Hanagaki [82], M. Hance [135], D.A. Hangal [41,z], H. Hanif [141], M.D. Hank [39], R. Hankache [100], J.B. Hansen [42], J.D. Hansen [42], P.H. Hansen [42], K. Hara [156],

D. Harada [56], T. Harenberg [170], S. Harkusha [37], Y.T. Harris [125], N.M. Harrison [118], P.F. Harrison [166], N.M. Hartman [142], N.M. Hartmann [108], Y. Hasegawa [139], A. Hasib [52], S. Haug [19], R. Hauser [106], M. Havranek [131], C.M. Hawkes [20], R.J. Hawkings [36], S. Hayashida [110], D. Hayden [106], C. Hayes [105], R.L. Hayes [163], C.P. Hays [125], J.M. Hays [93], H.S. Hayward [91], F. He [62a], Y. He [153], Y. He [126], M.P. Heath [52], V. Hedberg [97], A.L. Heggelund [124], N.D. Hehir [93], C. Heidegger [54], K.K. Heidegger [54], W.D. Heidorn [80], J. Heilman [34], S. Heim [48], T. Heim [17a], J.G. Heinlein [127], J.J. Heinrich [122], L. Heinrich [109], J. Hejbal [130], L. Helary [48], A. Held [169], S. Hellesund [124], C.M. Helling [163], S. Hellman [47a,47b], C. Helsens [36], R.C.W. Henderson [90], L. Henkelmann [32], A.M. Henriques Correia [36], H. Herde [97], Y. Hernández Jiménez [144], M.G. Herrmann [108], T. Herrmann [50], G. Herten [54], R. Hertenberger [108], L. Hervas [36], N.P. Hessey [155a], H. Hibi [83], E. Higón-Rodriguez [162], S.J. Hillier [20], I. Hinchliffe [17a], F. Hinterkeuser [24], M. Hirose [123], S. Hirose [156], D. Hirschbuehl [170], T.G. Hitchings [100], B. Hiti [92], J. Hobbs [144], R. Hobincu [27e], N. Hod [168], M.C. Hodgkinson [138], B.H. Hodkinson [32], A. Hoecker [36], J. Hofer [48], D. Hohn [54], T. Holm [24], M. Holzbock [109], L.B.A.H. Hommels [32], B.P. Honan [100], J. Hong [62c], T.M. Hong [128], Y. Hong [55], J.C. Honig [54], A. Hönle [109], B.H. Hooberman [161], W.H. Hopkins [6], Y. Horii [110], S. Hou [147], A.S. Howard [92], J. Howarth [59], J. Hoya [6], M. Hrabovsky [121], A. Hrynevich [48], T. Hryn'ova [4], P.J. Hsu [65], S.-C. Hsu [137], Q. Hu [41,z], Y.F. Hu [14a,14d,ae], D.P. Huang [95], S. Huang [64b], X. Huang [14c], Y. Huang [62a], Y. Huang [14a], Z. Huang [100], Z. Hubacek [131], M. Huebner [24], F. Huegging [24], T.B. Huffman [125], M. Huhtinen [36], S.K. Huiberts [16], R. Hulsken [103], N. Huseynov [12,a], J. Huston [106], J. Huth [61], R. Hyneman [142], S. Hyrych [28a], G. Iacobucci [56], G. Iakovidis [29], I. Ibragimov [140], L. Iconomidou-Fayard [66], P. Iengo [71a,71b], R. Iguchi [152], T. Iizawa [56], Y. Ikegami [82], A. Ilg [19], N. Ilic [154], H. Imam [35a], T. Ingebretsen Carlson [47a,47b], G. Introzzi [72a,72b], M. Iodice [76a], V. Ippolito [74a,74b], M. Ishino [152], W. Islam [169], C. Issever [18,48], S. Istin [21a,ah], H. Ito [167], J.M. Iturbe Ponce [64a], R. Iuppa [77a,77b], A. Ivina [168], J.M. Izen [45], V. Izzo [71a], P. Jacka [130,131], P. Jackson [1], R.M. Jacobs [48], B.P. Jaeger [141], C.S. Jagfeld [108], G. Jäkel [170], K. Jakobs [54], T. Jakoubek [168], J. Jamieson [59], K.W. Janas [84a], G. Jarlskog [97], A.E. Jaspan [91], M. Javurkova [102], F. Jeanneau [134], L. Jeanty [122], J. Jejelava [148a,y], P. Jenni [54,g], C.E. Jessiman [34], S. Jézéquel [4], J. Jia [144], X. Jia [61], X. Jia [14a,14d], Z. Jia [14c], Y. Jiang [62a], S. Jiggins [52], J. Jimenez Pena [109], S. Jin [14c], A. Jinaru [27b], O. Jinnouchi [153], P. Johansson [138], K.A. Johns [7], D.M. Jones [32], E. Jones [166], P. Jones [32], R.W.L. Jones [90], T.J. Jones [91], R. Joshi [118], J. Jovicevic [15], X. Ju [17a], J.J. Junggeburth [36], A. Juste Rozas [13,u], S. Kabana [136e], A. Kaczmarska [85], M. Kado [74a,74b], H. Kagan [118], M. Kagan [142], A. Kahn [41], A. Kahn [127], C. Kahra [99], T. Kaji [167], E. Kajomovitz [149], N. Kakati [168], C.W. Kalderon [29], A. Kamenshchikov [154], S. Kanayama [153], N.J. Kang [135], Y. Kano [110], D. Kar [33g], K. Karava [125], M.J. Kareem [155b], E. Karentzos [54], I. Karkanias [151], S.N. Karpov [38], Z.M. Karpova [38], V. Kartvelishvili [90], A.N. Karyukhin [37], E. Kasimi [151], C. Kato [62d], J. Katzy [48], S. Kaur [34], K. Kawade [139], K. Kawagoe [88], T. Kawamoto [134], G. Kawamura [55], E.F. Kay [164], F.I. Kaya [157], S. Kazakos [13], V.F. Kazanin [37], Y. Ke [144], J.M. Keaveney [33a], R. Keeler [164], G.V. Kehris [61], J.S. Keller [34], A.S. Kelly [95], D. Kelsey [145], J.J. Kempster [20], K.E. Kennedy [41], P.D. Kennedy [99], O. Kepka [130], B.P. Kerridge [166], S. Kersten [170], B.P. Kerševan [92], S. Keshri [66], L. Keszeghova [28a], S. Ketabchi Haghighat [154], M. Khandoga [126], A. Khanov [120], A.G. Kharlamov [37], T. Kharlamova [37], E.E. Khoda [137], T.J. Khoo [18], G. Khoriauli [165], J. Khubua [148b], Y.A.R. Khwaira [66], M. Kiehn [36], A. Kilgallon [122], D.W. Kim [47a,47b], E. Kim [153], Y.K. Kim [39], N. Kimura [95], A. Kirchhoff [55], D. Kirchmeier [50], C. Kirfel [24], J. Kirk [133], A.E. Kiryunin [109], T. Kishimoto [152], D.P. Kisliuk [154], C. Kitsaki [10], O. Kivernyk [24], M. Klassen [63a], C. Klein [34], L. Klein [165], M.H. Klein [105], M. Klein [91], S.B. Klein [56], U. Klein [91], P. Klimek [36], A. Klimentov [29], F. Klimpel [109], T. Klingl [24], T. Klioutchnikova [36], F.F. Klitzner [108], P. Kluit [113], S. Kluth [109], E. Kneringer [78], T.M. Knight [154], A. Knue [54], D. Kobayashi [88], R. Kobayashi [86], M. Kocian [142], P. Kodyš [132], D.M. Koeck [145], P.T. Koenig [24], T. Koffas [34], N.M. Köhler [36], M. Kolb [134], I. Koletsou [4], T. Komarek [121], K. Köneke [54], A.X.Y. Kong [1], T. Kono [117], N. Konstantinidis [95], B. Konya [97], R. Kopeliansky [67], S. Koperny [84a], K. Korcyl [85], K. Kordas [151], G. Koren [150], A. Korn [95], S. Korn [55], I. Korolkov [13], N. Korotkova [37], B. Kortman [113], O. Kortner [109], S. Kortner [109], W.H. Kostecka [114], V.V. Kostyukhin [140], A. Kotsokechagia [134], A. Kotwal [51], A. Koulouris [36], A. Kourkoumeli-Charalampidi [72a,72b], C. Kourkoumelis [9], E. Kourlitis [6], O. Kovanda [145], R. Kowalewski [164], W. Kozanecki [134], A.S. Kozhin [37], V.A. Kramarenko [37], G. Kramberger [92], P. Kramer [99], M.W. Krasny [126], A. Krasznahorkay [36], J.A. Kremer [99], T. Kresse [50], J. Kretzschmar [91], K. Kreul [18], P. Krieger [154], F. Krieter [108], S. Krishnamurthy [102], A. Krishnan [63b], M. Krivos [132], K. Krizka [17a], K. Kroeninger [49], H. Kroha [109], J. Kroll [130], J. Kroll [127], K.S. Krowpman [106], U. Kruchonak [38], H. Krüger [24], N. Krumnack [80], M.C. Kruse [51], J.A. Krzysiak [85], A. Kubota [153], O. Kuchinskaia [37], S. Kuday [3a], D. Kuechler [48], J.T. Kuechler [48], S. Kuehn [36],

T. Kuhl [48], V. Kukhtin [38], Y. Kulchitsky [37,a], S. Kuleshov [136d,136b], M. Kumar [33g], N. Kumari [101], A. Kupco [130], T. Kupfer [49], A. Kupich [37], O. Kuprash [54], H. Kurashige [83], L.L. Kurchaninov [155a], Y.A. Kurochkin [37], A. Kurova [37], M. Kuze [153], A.K. Kvam [102], J. Kvita [121], T. Kwan [103], K.W. Kwok [64a], N.G. Kyriacou [105], L.A.O. Laatu [101], C. Lacasta [162], F. Lacava [74a,74b], H. Lacker [18], D. Lacour [126], N.N. Lad [95], E. Ladygin [38], B. Laforge [126], T. Lagouri [136e], S. Lai [55], I.K. Lakomiec [84a], N. Lalloue [60], J.E. Lambert [119], S. Lammers [67], W. Lampl [7], C. Lampoudis [151], A.N. Lancaster [114], E. Lançon [29], U. Landgraf [54], M.P.J. Landon [93], V.S. Lang [54], R.J. Langenberg [102], A.J. Lankford [159], F. Lanni [36], K. Lantzsch [24], A. Lanza [72a], A. Lapertosa [57b,57a], J.F. Laporte [134], T. Lari [70a], F. Lasagni Manghi [23b], M. Lassnig [36], V. Latonova [130], T.S. Lau [64a], A. Laudrain [99], A. Laurier [34], S.D. Lawlor [94], Z. Lawrence [100], M. Lazzaroni [70a,70b], B. Le [100], B. Leban [92], A. Lebedev [80], M. LeBlanc [36], T. LeCompte [6], F. Ledroit-Guillon [60], A.C.A. Lee [95], G.R. Lee [16], L. Lee [61], S.C. Lee [147], S. Lee [47a,47b], T.F. Lee [91], L.L. Leeuw [33c], H.P. Lefebvre [94], M. Lefebvre [164], C. Leggett [17a], K. Lehmann [141], G. Lehmann Miotto [36], M. Leigh [56], W.A. Leight [102], A. Leisos [151,t], M.A.L. Leite [81c], C.E. Leitgeb [48], R. Leitner [132], K.J.C. Leney [44], T. Lenz [24], S. Leone [73a], C. Leonidopoulos [52], A. Leopold [143], C. Leroy [107], R. Les [106], C.G. Lester [32], M. Levchenko [37], J. Levêque [4], D. Levin [105], L.J. Levinson [168], M.P. Lewicki [85], D.J. Lewis [4], A. Li [5], B. Li [14b], B. Li [62b], C. Li [62a], C-Q. Li [62c], H. Li [62a], H. Li [62b], H. Li [14c], H. Li [62b], J. Li [62c], K. Li [137], L. Li [62c], M. Li [14a,14d], Q.Y. Li [62a], S. Li [62d,62c,e], T. Li [62b], X. Li [103], Z. Li [62b], Z. Li [125], Z. Li [103], Z. Li [91], Z. Li [14a,14d], Z. Liang [14a], M. Liberatore [48], B. Liberti [75a], K. Lie [64c], J. Lieber Marin [81b], K. Lin [106], R.A. Linck [67], R.E. Lindley [7], J.H. Lindon [2], A. Linss [48], E. Lipeles [127], A. Lipniacka [16], A. Lister [163], J.D. Little [4], B. Liu [14a], B.X. Liu [141], D. Liu [62d,62c], J.B. Liu [62a], J.K.K. Liu [32], K. Liu [62d,62c], M. Liu [62a], M.Y. Liu [62a], P. Liu [14a], Q. Liu [62d,137,62c], X. Liu [62a], Y. Liu [48], Y. Liu [14c,14d], Y.L. Liu [105], Y.W. Liu [62a], M. Livan [72a,72b], J. Llorente Merino [141], S.L. Lloyd [93], E.M. Lobodzinska [48], P. Loch [7], S. Loffredo [75a,75b], T. Lohse [18], K. Lohwasser [138], M. Lokajicek [130], J.D. Long [161], I. Longarini [74a,74b], L. Longo [69a,69b], R. Longo [161], I. Lopez Paz [36], A. Lopez Solis [48], J. Lorenz [108], N. Lorenzo Martinez [4], A.M. Lory [108], A. Lösle [54], X. Lou [47a,47b], X. Lou [14a,14d], A. Lounis [66], J. Love [6], P.A. Love [90], J.J. Lozano Bahilo [162], G. Lu [14a,14d], M. Lu [79], S. Lu [127], Y.J. Lu [65], H.J. Lubatti [137], C. Luci [74a,74b], F.L. Lucio Alves [14c], A. Lucotte [60], F. Luehring [67], I. Luise [144], O. Lukianchuk [66], O. Lundberg [143], B. Lund-Jensen [143], N.A. Luongo [122], M.S. Lutz [150], D. Lynn [29], H. Lyons [91], R. Lysak [130], E. Lytken [97], F. Lyu [14a], V. Lyubushkin [38], T. Lyubushkina [38], H. Ma [29], L.L. Ma [62b], Y. Ma [95], D.M. Mac Donell [164], G. Maccarrone [53], J.C. MacDonald [138], R. Madar [40], W.F. Mader [50], J. Maeda [83], T. Maeno [29], M. Maerker [50], V. Magerl [54], J. Magro [68a,68c], H. Maguire [138], D.J. Mahon [41], C. Maidantchik [81b], A. Maio [129a,129b,129d], K. Maj [84a], O. Majersky [28a], S. Majewski [122], N. Makovec [66], V. Maksimovic [15], B. Malaescu [126], Pa. Malecki [85], V.P. Maleev [37], F. Malek [60], D. Malito [43b,43a], U. Mallik [79], C. Malone [32], S. Maltezos [10], S. Malyukov [38], J. Mamuzic [13], G. Mancini [53], G. Manco [72a,72b], J.P. Mandalia [93], I. Mandić [92], L. Manhaes de Andrade Filho [81a], I.M. Maniatis [151], M. Manisha [134], J. Manjarres Ramos [50], D.C. Mankad [168], A. Mann [108], B. Mansoulie [134], S. Manzoni [36], A. Marantis [151], G. Marchiori [5], M. Marcisovsky [130], L. Marcoccia [75a,75b], C. Marcon [70a,70b], M. Marinescu [20], M. Marjanovic [119], Z. Marshall [17a], S. Marti-Garcia [162], T.A. Martin [166], V.J. Martin [52], B. Martin dit Latour [16], L. Martinelli [74a,74b], M. Martinez [13,u], P. Martinez Agullo [162], V.I. Martinez Outschoorn [102], P. Martinez Suarez [13], S. Martin-Haugh [133], V.S. Martoiu [27b], A.C. Martyniuk [95], A. Marzin [36], S.R. Maschek [109], L. Masetti [99], T. Mashimo [152], J. Masik [100], A.L. Maslennikov [37], L. Massa [23b], P. Massarotti [71a,71b], P. Mastrandrea [73a,73b], A. Mastroberardino [43b,43a], T. Masubuchi [152], T. Mathisen [160], N. Matsuzawa [152], J. Maurer [27b], B. Maček [92], D.A. Maximov [37], R. Mazini [147], I. Maznas [151], M. Mazza [106], S.M. Mazza [135], C. Mc Ginn [29,af], J.P. Mc Gowan [103], S.P. Mc Kee [105], W.P. McCormack [17a], E.F. McDonald [104], A.E. McDougall [113], J.A. Mcfayden [145], G. Mchedlidze [148b], R.P. Mckenzie [33g], T.C. Mclachlan [48], D.J. Mclaughlin [95], K.D. McLean [164], S.J. McMahon [133], P.C. McNamara [104], C.M. Mcpartland [91], R.A. McPherson [164,w], T. Megy [40], S. Mehlhase [108], A. Mehta [91], B. Meirose [45], D. Melini [149], B.R. Mellado Garcia [33g], A.H. Melo [55], F. Meloni [48], E.D. Mendes Gouveia [129a], A.M. Mendes Jacques Da Costa [20], H.Y. Meng [154], L. Meng [90], S. Menke [109], M. Mentink [36], E. Meoni [43b,43a], C. Merlassino [125], L. Merola [71a,71b], C. Meroni [70a], G. Merz [105], O. Meshkov [37], J.K.R. Meshreki [140], J. Metcalfe [6], A.S. Mete [6], C. Meyer [67], J-P. Meyer [134], M. Michetti [18], R.P. Middleton [133], L. Mijović [52], G. Mikenberg [168], M. Mikestikova [130], M. Mikuž [92], H. Mildner [138], A. Milic [36], C.D. Milke [44], D.W. Miller [39], L.S. Miller [34], A. Milov [168], D.A. Milstead [47a,47b], T. Min [14c], A.A. Minaenko [37], I.A. Minashvili [148b], L. Mince [59], A.I. Mincer [116], B. Mindur [84a], M. Mineev [38], Y. Mino [86], L.M. Mir [13], M. Miralles Lopez [162], M. Mironova [125], M.C. Missio [112], T. Mitani [167], A. Mitra [166], V.A. Mitsou [162], O. Miu [154], P.S. Miyagawa [93], Y. Miyazaki [88], A. Mizukami [82], J.U. Mjörnmark [97], T. Mkrtchyan [63a], T. Mlinarevic [95], M. Mlynarikova [36], T. Moa [47a,47b], S. Mobius [55], K. Mochizuki [107], P. Moder [48], P. Mogg [108], A.F. Mohammed [14a,14d], S. Mohapatra [41], G. Mokgatitswane [33g], B. Mondal [140], S. Mondal [131], K. Mönig [48], E. Monnier [101], L. Monsonis Romero [162], J. Montejo Berlingen [36], M. Montella [118], F. Monticelli [89], N. Morange [66], A.L. Moreira De Carvalho [129a], M. Moreno Llácer [162], C. Moreno Martinez [56], P. Morettini [57b], S. Morgenstern [166], M. Morii [61], M. Morinaga [152], V. Morisbak [124], A.K. Morley [36], F. Morodei [74a,74b], L. Morvaj [36], P. Moschovakos [36], B. Moser [36], M. Mosidze [148b], T. Moskalets [54], P. Moskvitina [112], J. Moss [31,o], E.J.W. Moyse [102], S. Muanza [101], J. Mueller [128], D. Muenstermann [90], R. Müller [19], G.A. Mullier [97], J.J. Mullin [127], D.P. Mungo [154], J.L. Munoz Martinez [13], D. Munoz Perez [162], F.J. Munoz Sanchez [100], M. Murin [100], W.J. Murray [166,133], A. Murrone [70a,70b], J.M. Muse [119], M. Muškinja [17a], C. Mwewa [29], A.G. Myagkov [37,a], A.J. Myers [8], A.A. Myers [128], G. Myers [67], M. Myska [131], B.P. Nachman [17a], O. Nackenhorst [49], A. Nag [50], K. Nagai [125], K. Nagano [82], J.L. Nagle [29,af], E. Nagy [101], A.M. Nairz [36], Y. Nakahama [82], K. Nakamura [82], H. Nanjo [123], R. Narayan [44], E.A. Narayanan [111], I. Naryshkin [37], M. Naseri [34], C. Nass [24], G. Navarro [22a], J. Navarro-Gonzalez [162], R. Nayak [150], A. Nayaz [18], P.Y. Nechaeva [37], F. Nechansky [48], L. Nedic [125], T.J. Neep [20], A. Negri [72a,72b], M. Negrini [23b], C. Nellist [112], C. Nelson [103], K. Nelson [105], S. Nemecek [130], M. Nessi [36,h], M.S. Neubauer [161], F. Neuhaus [99], J. Neundorf [48], R. Newhouse [163], P.R. Newman [20], C.W. Ng [128], Y.S. Ng [18], Y.W.Y. Ng [48], B. Ngair [35e], H.D.N. Nguyen [107], R.B. Nickerson [125], R. Nicolaidou [134], J. Nielsen [135], M. Niemeyer [55], N. Nikiforou [36], V. Nikolaenko [37,a], I. Nikolic-Audit [126], K. Nikolopoulos [20], P. Nilsson [29], H.R. Nindhito [56], A. Nisati [74a], N. Nishu [2], R. Nisius [109], J-E. Nitschke [50], E.K. Nkadimeng [33g], S.J. Noacco Rosende [89], T. Nobe [152], D.L. Noel [32], Y. Noguchi [86], T. Nommensen [146], M.A. Nomura [29], M.B. Norfolk [138], R.R.B. Norisam [95], B.J. Norman [34], J. Novak [92], T. Novak [48], O. Novgorodova [50], L. Novotny [131], R. Novotny [111], L. Nozka [121], K. Ntekas [159], N.M.J. Nunes De Moura Junior [81b], E. Nurse [95], F.G. Oakham [34,ac], J. Ocariz [126], A. Ochi [83], I. Ochoa [129a], S. Oerdek [160], A. Ogrodnik [84a], A. Oh [100], C.C. Ohm [143], H. Oide [153], R. Oishi [152], M.L. Ojeda [48], Y. Okazaki [86], M.W. O'Keefe [91], Y. Okumura [152], A. Olariu [27b], L.F. Oleiro Seabra [129a], S.A. Olivares Pino [136e], D. Oliveira Damazio [29], D. Oliveira Goncalves [81a], J.L. Oliver [159], M.J.R. Olsson [159], A. Olszewski [85], J. Olszowska [85,*], Ö.O. Öncel [54], D.C. O'Neil [141], A.P. O'Neill [19], A. Onofre [129a,129e], P.U.E. Onyisi [11], M.J. Oreglia [39], G.E. Orellana [89], D. Orestano [76a,76b], N. Orlando [13], R.S. Orr [154], V. O'Shea [59], R. Ospanov [62a], G. Otero y Garzon [30], H. Otono [88], P.S. Ott [63a], G.J. Ottino [17a], M. Ouchrif [35d], J. Ouellette [29,af], F. Ould-Saada [124], M. Owen [59], R.E. Owen [133], K.Y. Oyulmaz [21a], V.E. Ozcan [21a], N. Ozturk [8], S. Ozturk [21d], J. Pacalt [121], H.A. Pacey [32], K. Pachal [51], A. Pacheco Pages [13], C. Padilla Aranda [13], G. Padovano [74a,74b], S. Pagan Griso [17a], G. Palacino [67], A. Palazzo [69a,69b], S. Palazzo [52], S. Palestini [36], M. Palka [84b], J. Pan [171], T. Pan [64a], D.K. Panchal [11], C.E. Pandini [113], J.G. Panduro Vazquez [94], H. Pang [14b], P. Pani [48], G. Panizzo [68a,68c], L. Paolozzi [56], C. Papadatos [107], S. Parajuli [44], A. Paramonov [6], C. Paraskevopoulos [10], D. Paredes Hernandez [64b], T.H. Park [154], M.A. Parker [32], F. Parodi [57b,57a], E.W. Parrish [114], V.A. Parrish [52], J.A. Parsons [41], U. Parzefall [54], B. Pascual Dias [107], L. Pascual Dominguez [150], V.R. Pascuzzi [17a], F. Pasquali [113], E. Pasqualucci [74a], S. Passaggio [57b], F. Pastore [94], P. Pasuwan [47a,47b], P. Patel [85], J.R. Pater [100], J. Patton [91], T. Pauly [36], J. Pearkes [142], M. Pedersen [124], R. Pedro [129a], S.V. Peleganchuk [37], O. Penc [36], E.A. Pender [52], C. Peng [64b], H. Peng [62a], K.E. Penski [108], M. Penzin [37], B.S. Peralva [81d], A.P. Pereira Peixoto [60], L. Pereira Sanchez [47a,47b], D.V. Perepelitsa [29,af], E. Perez Codina [155a], M. Perganti [10], L. Perini [70a,70b,*], H. Pernegger [36], S. Perrella [36], A. Perrevoort [112], O. Perrin [40], K. Peters [48], R.F.Y. Peters [100], B.A. Petersen [36], T.C. Petersen [42], E. Petit [101], V. Petousis [131], C. Petridou [151], A. Petrukhin [140], M. Pettee [17a], N.E. Pettersson [36], A. Petukhov [37], K. Petukhova [132], A. Peyaud [134], R. Pezoa [136f], L. Pezzotti [36], G. Pezzullo [171], T.M. Pham [169], T. Pham [104], P.W. Phillips [133], M.W. Phipps [161], G. Piacquadio [144], E. Pianori [17a], F. Piazza [70a,70b], R. Piegaia [30], D. Pietreanu [27b], A.D. Pilkington [100], M. Pinamonti [68a,68c], J.L. Pinfold [2], B.C. Pinheiro Pereira [129a], C. Pitman Donaldson [95], D.A. Pizzi [34], L. Pizzimento [75a,75b], A. Pizzini [113], M.-A. Pleier [29], V. Plesanovs [54], V. Pleskot [132], E. Plotnikova [38], G. Poddar [4], R. Poettgen [97], L. Poggioli [126], I. Pogrebnyak [106], D. Pohl [24], I. Pokharel [55], S. Polacek [132], G. Polesello [72a], A. Poley [141,155a], R. Polifka [131], A. Polini [23b], C.S. Pollard [125], Z.B. Pollock [118], V. Polychronakos [29], E. Pompa Pacchi [74a,74b], D. Ponomarenko [37], L. Pontecorvo [36], S. Popa [27a], G.A. Popeneciu [27d], D.M. Portillo Quintero [155a], S. Pospisil [131], P. Postolache [27c], K. Potamianos [125], I.N. Potrap [38], C.J. Potter [32], H. Potti [1], T. Poulsen [48], J. Poveda [162], M.E. Pozo Astigarraga [36], A. Prades Ibanez [162], M.M. Prapa [46], J. Pretel [54], D. Price [100], M. Primavera [69a], M.A. Principe Martin [98], R. Privara [121], M.L. Proffitt [137], N. Proklova [127], K. Prokofiev [64c],

G. Proto [75a,75b], S. Protopopescu [29], J. Proudfoot [6], M. Przybycien [84a], J.E. Puddefoot [138], D. Pudzha [37], P. Puzo [66], D. Pyatiizbyantseva [37], J. Qian [105], D. Qichen [100], Y. Qin [100], T. Qiu [93], A. Quadt [55], M. Queitsch-Maitland [100], G. Quetant [56], G. Rabanal Bolanos [61], D. Rafanoharana [54], F. Ragusa [70a,70b], J.L. Rainbolt [39], J.A. Raine [56], S. Rajagopalan [29], E. Ramakoti [37], K. Ran [48,14d], N.P. Rapheeha [33g], V. Raskina [126], D.F. Rassloff [63a], S. Rave [99], B. Ravina [55], I. Ravinovich [168], M. Raymond [36], A.L. Read [124], N.P. Readioff [138], D.M. Rebuzzi [72a,72b], G. Redlinger [29], K. Reeves [45], J.A. Reidelsturz [170], D. Reikher [150], A. Reiss [99], A. Rej [140], C. Rembser [36], A. Renardi [48], M. Renda [27b], M.B. Rendel [109], F. Renner [48], A.G. Rennie [59], S. Resconi [70a], M. Ressegotti [57b,57a], E.D. Resseguie [17a], S. Rettie [36], B. Reynolds [118], E. Reynolds [17a], M. Rezaei Estabragh [170], O.L. Rezanova [37], P. Reznicek [132], E. Ricci [77a,77b], R. Richter [109], S. Richter [47a,47b], E. Richter-Was [84b], M. Ridel [126], P. Rieck [116], P. Riedler [36], M. Rijssenbeek [144], A. Rimoldi [72a,72b], M. Rimoldi [48], L. Rinaldi [23b,23a], T.T. Rinn [29], M.P. Rinnagel [108], G. Ripellino [143], I. Riu [13], P. Rivadeneira [48], J.C. Rivera Vergara [164], F. Rizatdinova [120], E. Rizvi [93], C. Rizzi [56], B.A. Roberts [166], B.R. Roberts [17a], S.H. Robertson [103,w], M. Robin [48], D. Robinson [32], C.M. Robles Gajardo [136f], M. Robles Manzano [99], A. Robson [59], A. Rocchi [75a,75b], C. Roda [73a,73b], S. Rodriguez Bosca [63a], Y. Rodriguez Garcia [22a], A. Rodriguez Rodriguez [54], A.M. Rodríguez Vera [155b], S. Roe [36], J.T. Roemer [159], A.R. Roepe-Gier [119], J. Roggel [170], O. Røhne [124], R.A. Rojas [164], B. Roland [54], C.P.A. Roland [67], J. Roloff [29], A. Romaniouk [37], E. Romano [72a,72b], M. Romano [23b], A.C. Romero Hernandez [161], N. Rompotis [91], L. Roos [126], S. Rosati [74a], B.J. Rosser [39], E. Rossi [4], E. Rossi [71a,71b], L.P. Rossi [57b], L. Rossini [48], R. Rosten [118], M. Rotaru [27b], B. Rottler [54], D. Rousseau [66], D. Rousso [32], G. Rovelli [72a,72b], A. Roy [161], A. Rozanov [101], Y. Rozen [149], X. Ruan [33g], A. Rubio Jimenez [162], A.J. Ruby [91], V.H. Ruelas Rivera [18], T.A. Ruggeri [1], F. Rühr [54], A. Ruiz-Martinez [162], A. Rummler [36], Z. Rurikova [54], N.A. Rusakovich [38], H.L. Russell [164], J.P. Rutherfoord [7], K. Rybacki [90], M. Rybar [132], E.B. Rye [124], A. Ryzhov [37], J.A. Sabater Iglesias [56], P. Sabatini [162], L. Sabetta [74a,74b], H.F-W. Sadrozinski [135], F. Safai Tehrani [74a], B. Safarzadeh Samani [145], M. Safdari [142], S. Saha [103], M. Sahinsoy [109], M. Saimpert [134], M. Saito [152], T. Saito [152], D. Salamani [36], G. Salamanna [76a,76b], A. Salnikov [142], J. Salt [162], A. Salvador Salas [13], D. Salvatore [43b,43a], F. Salvatore [145], A. Salzburger [36], D. Sammel [54], D. Sampsonidis [151], D. Sampsonidou [62d,62c], J. Sánchez [162], A. Sanchez Pineda [4], V. Sanchez Sebastian [162], H. Sandaker [124], C.O. Sander [48], J.A. Sandesara [102], M. Sandhoff [170], C. Sandoval [22b], D.P.C. Sankey [133], A. Sansoni [53], L. Santi [74a,74b], C. Santoni [40], H. Santos [129a,129b], S.N. Santpur [17a], A. Santra [168], K.A. Saoucha [138], J.G. Saraiva [129a,129d], J. Sardain [7], O. Sasaki [82], K. Sato [156], C. Sauer [63b], F. Sauerburger [54], E. Sauvan [4], P. Savard [154,ac], R. Sawada [152], C. Sawyer [133], L. Sawyer [96], I. Sayago Galvan [162], C. Sbarra [23b], A. Sbrizzi [23b,23a], T. Scanlon [95], J. Schaarschmidt [137], P. Schacht [109], D. Schaefer [39], U. Schäfer [99], A.C. Schaffer [66], D. Schaile [108], R.D. Schamberger [144], E. Schanet [108], C. Scharf [18], M.M. Schefer [19], V.A. Schegelsky [37], D. Scheirich [132], F. Schenck [18], M. Schernau [159], C. Scheulen [55], C. Schiavi [57b,57a], Z.M. Schillaci [26], E.J. Schioppa [69a,69b], M. Schioppa [43b,43a], B. Schlag [99], K.E. Schleicher [54], S. Schlenker [36], M.A. Schmidt [170], K. Schmieden [99], C. Schmitt [99], S. Schmitt [48], L. Schoeffel [134], A. Schoening [63b], P.G. Scholer [54], E. Schopf [125], M. Schott [99], J. Schovancova [36], S. Schramm [56], F. Schroeder [170], H-C. Schultz-Coulon [63a], M. Schumacher [54], B.A. Schumm [135], Ph. Schune [134], A. Schwartzman [142], T.A. Schwarz [105], Ph. Schwemling [134], R. Schwienhorst [106], A. Sciandra [135], G. Sciolla [26], F. Scuri [73a], F. Scutti [104], C.D. Sebastiani [91], K. Sedlaczek [49], P. Seema [18], S.C. Seidel [111], A. Seiden [135], B.D. Seidlitz [41], T. Seiss [39], C. Seitz [48], J.M. Seixas [81b], G. Sekhniaidze [71a], S.J. Sekula [44], L. Selem [4], N. Semprini-Cesari [23b,23a], S. Sen [51], D. Sengupta [56], V. Senthilkumar [162], L. Serin [66], L. Serkin [68a,68b], M. Sessa [76a,76b], H. Severini [119], S. Sevova [142], F. Sforza [57b,57a], A. Sfyrla [56], E. Shabalina [55], R. Shaheen [143], J.D. Shahinian [127], N.W. Shaikh [47a,47b], D. Shaked Renous [168], L.Y. Shan [14a], M. Shapiro [17a], A. Sharma [36], A.S. Sharma [163], P. Sharma [79], S. Sharma [48], P.B. Shatalov [37], K. Shaw [145], S.M. Shaw [100], Q. Shen [62c,5], P. Sherwood [95], L. Shi [95], C.O. Shimmin [171], Y. Shimogama [167], J.D. Shinner [94], I.P.J. Shipsey [125], S. Shirabe [60], M. Shiyakova [38], J. Shlomi [168], M.J. Shochet [39], J. Shojaii [104], D.R. Shope [124], S. Shrestha [118,ag], E.M. Shrif [33g], M.J. Shroff [164], P. Sicho [130], A.M. Sickles [161], E. Sideras Haddad [33g], A. Sidoti [23b], F. Siegert [50], Dj. Sijacki [15], R. Sikora [84a], F. Sili [89], J.M. Silva [20], M.V. Silva Oliveira [36], S.B. Silverstein [47a], S. Simion [66], R. Simoniello [36], E.L. Simpson [59], N.D. Simpson [97], S. Simsek [21d], S. Sindhu [55], P. Sinervo [154], V. Sinetckii [37], S. Singh [141], S. Singh [154], S. Sinha [48], S. Sinha [33g], M. Sioli [23b,23a], I. Siral [36], S.Yu. Sivoklokov [37,*], J. Sjölin [47a,47b], A. Skaf [55], E. Skorda [97], P. Skubic [119], M. Slawinska [85], V. Smakhtin [168], B.H. Smart [133], J. Smiesko [36], S.Yu. Smirnov [37], Y. Smirnov [37], L.N. Smirnova [37,a], O. Smirnova [97], A.C. Smith [41], E.A. Smith [39], H.A. Smith [125], J.L. Smith [91], R. Smith [142],

M. Smizanska [90], K. Smolek [131], A. Smykiewicz [85], A.A. Snesarev [37], H.L. Snoek [113], S. Snyder [29], R. Sobie [164,w], A. Soffer [150], C.A. Solans Sanchez [36], E.Yu. Soldatov [37], U. Soldevila [162], A.A. Solodkov [37], S. Solomon [54], A. Soloshenko [38], K. Solovieva [54], O.V. Solovyanov [37], V. Solovyev [37], P. Sommer [36], A. Sonay [13], W.Y. Song [155b], A. Sopczak [131], A.L. Sopio [95], F. Sopkova [28b], V. Sothilingam [63a], S. Sottocornola [72a,72b], R. Soualah [115b], Z. Soumaimi [35e], D. South [48], S. Spagnolo [69a,69b], M. Spalla [109], F. Spanò [94], D. Sperlich [54], G. Spigo [36], M. Spina [145], S. Spinali [90], D.P. Spiteri [59], M. Spousta [132], E.J. Staats [34], A. Stabile [70a,70b], R. Stamen [63a], M. Stamenkovic [113], A. Stampekis [20], M. Standke [24], E. Stanecka [85], M.V. Stange [50], B. Stanislaus [17a], M.M. Stanitzki [48], M. Stankaityte [125], B. Stapf [48], E.A. Starchenko [37], G.H. Stark [135], J. Stark [101], D.M. Starko [155b], P. Staroba [130], P. Starovoitov [63a], S. Stärz [103], R. Staszewski [85], G. Stavropoulos [46], J. Steentoft [160], P. Steinberg [29], A.L. Steinhebel [122], B. Stelzer [141,155a], H.J. Stelzer [128], O. Stelzer-Chilton [155a], H. Stenzel [58], T.J. Stevenson [145], G.A. Stewart [36], M.C. Stockton [36], G. Stoicea [27b], M. Stolarski [129a], S. Stonjek [109], A. Straessner [50], J. Strandberg [143], S. Strandberg [47a,47b], M. Strauss [119], T. Strebler [101], P. Strizenec [28b], R. Ströhmer [165], D.M. Strom [122], L.R. Strom [48], R. Stroynowski [44], A. Strubig [47a,47b], S.A. Stucci [29], B. Stugu [16], J. Stupak [119], N.A. Styles [48], D. Su [142], S. Su [62a], W. Su [62d,137,62c], X. Su [62a,66], K. Sugizaki [152], V.V. Sulin [37], M.J. Sullivan [91], D.M.S. Sultan [77a,77b], L. Sultanaliyeva [37], S. Sultansoy [3b], T. Sumida [86], S. Sun [105], S. Sun [169], O. Sunneborn Gudnadottir [160], M.R. Sutton [145], M. Svatos [130], M. Swiatlowski [155a], T. Swirski [165], I. Sykora [28a], M. Sykora [132], T. Sykora [132], D. Ta [99], K. Tackmann [48,v], A. Taffard [159], R. Tafirout [155a], J.S. Tafoya Vargas [66], R.H.M. Taibah [126], R. Takashima [87], K. Takeda [83], E.P. Takeva [52], Y. Takubo [82], M. Talby [101], A.A. Talyshev [37], K.C. Tam [64b], N.M. Tamir [150], A. Tanaka [152], J. Tanaka [152], R. Tanaka [66], M. Tanasini [57b,57a], J. Tang [62c], Z. Tao [163], S. Tapia Araya [80], S. Tapprogge [99], A. Tarek Abouelfadl Mohamed [106], S. Tarem [149], K. Tariq [62b], G. Tarna [101,27b], G.F. Tartarelli [70a], P. Tas [132], M. Tasevsky [130], E. Tassi [43b,43a], A.C. Tate [161], G. Tateno [152], Y. Tayalati [35e], G.N. Taylor [104], W. Taylor [155b], H. Teagle [91], A.S. Tee [169], R. Teixeira De Lima [142], P. Teixeira-Dias [94], J.J. Teoh [154], K. Terashi [152], J. Terron [98], S. Terzo [13], M. Testa [53], R.J. Teuscher [154,w], A. Thaler [78], O. Theiner [56], N. Themistokleous [52], T. Theveneaux-Pelzer [18], O. Thielmann [170], D.W. Thomas [94], J.P. Thomas [20], E.A. Thompson [48], P.D. Thompson [20], E. Thomson [127], E.J. Thorpe [93], Y. Tian [55], V. Tikhomirov [37,a], Yu.A. Tikhonov [37], S. Timoshenko [37], E.X.L. Ting [1], P. Tipton [171], S. Tisserant [101], S.H. Tlou [33g], A. Tnourji [40], K. Todome [23b,23a], S. Todorova-Nova [132], S. Todt [50], M. Togawa [82], J. Tojo [88], S. Tokár [28a], K. Tokushuku [82], R. Tombs [32], M. Tomoto [82,110], L. Tompkins [142], K.W. Topolnicki [84b], P. Tornambe [102], E. Torrence [122], H. Torres [50], E. Torró Pastor [162], M. Toscani [30], C. Tosciri [39], D.R. Tovey [138], A. Traeet [16], I.S. Trandafir [27b], T. Trefzger [165], A. Tricoli [29], I.M. Trigger [155a], S. Trincaz-Duvoid [126], D.A. Trischuk [26], B. Trocmé [60], A. Trofymov [66], C. Troncon [70a], L. Truong [33c], M. Trzebinski [85], A. Trzupek [85], F. Tsai [144], M. Tsai [105], A. Tsiamis [151], P.V. Tsiareshka [37], S. Tsigaridas [155a], A. Tsirigotis [151,t], V. Tsiskaridze [144], E.G. Tskhadadze [148a], M. Tsopoulou [151], Y. Tsujikawa [86], I.I. Tsukerman [37], V. Tsulaia [17a], S. Tsuno [82], O. Tsur [149], D. Tsybychev [144], Y. Tu [64b], A. Tudorache [27b], V. Tudorache [27b], A.N. Tuna [36], S. Turchikhin [38], I. Turk Cakir [3a], R. Turra [70a], T. Turtuvshin [38], P.M. Tuts [41], S. Tzamarias [151], P. Tzanis [10], E. Tzovara [99], K. Uchida [152], F. Ukegawa [156], P.A. Ulloa Poblete [136c], G. Unal [36], M. Unal [11], A. Undrus [29], G. Unel [159], J. Urban [28b], P. Urquijo [104], G. Usai [8], R. Ushioda [153], M. Usman [107], Z. Uysal [21b], V. Vacek [131], B. Vachon [103], K.O.H. Vadla [124], T. Vafeiadis [36], C. Valderanis [108], E. Valdes Santurio [47a,47b], M. Valente [155a], S. Valentinetti [23b,23a], A. Valero [162], A. Vallier [101], J.A. Valls Ferrer [162], T.R. Van Daalen [137], P. Van Gemmeren [6], M. Van Rijnbach [124,36], S. Van Stroud [95], I. Van Vulpen [113], M. Vanadia [75a,75b], W. Vandelli [36], M. Vandenbroucke [134], E.R. Vandewall [120], D. Vannicola [150], L. Vannoli [57b,57a], R. Vari [74a], E.W. Varnes [7], C. Varni [17a], T. Varol [147], D. Varouchas [66], L. Varriale [162], K.E. Varvell [146], M.E. Vasile [27b], L. Vaslin [40], G.A. Vasquez [164], F. Vazeille [40], T. Vazquez Schroeder [36], J. Veatch [31], V. Vecchio [100], M.J. Veen [102], I. Veliscek [125], L.M. Veloce [154], F. Veloso [129a,129c], S. Veneziano [74a], A. Ventura [69a,69b], A. Verbytskyi [109], M. Verducci [73a,73b], C. Vergis [24], M. Verissimo De Araujo [81b], W. Verkerke [113], J.C. Vermeulen [113], C. Vernieri [142], P.J. Verschuuren [94], M. Vessella [102], M.C. Vetterli [141,ac], A. Vgenopoulos [151], N. Viaux Maira [136f], T. Vickey [138], O.E. Vickey Boeriu [138], G.H.A. Viehhauser [125], L. Vigani [63b], M. Villa [23b,23a], M. Villaplana Perez [162], E.M. Villhauer [52], E. Vilucchi [53], M.G. Vincter [34], G.S. Virdee [20], A. Vishwakarma [52], C. Vittori [23b,23a], I. Vivarelli [145], V. Vladimirov [166], E. Voevodina [109], F. Vogel [108], P. Vokac [131], J. Von Ahnen [48], E. Von Toerne [24], B. Vormwald [36], V. Vorobel [132], K. Vorobev [37], M. Vos [162], J.H. Vossebeld [91], M. Vozak [113], L. Vozdecky [93], N. Vranjes [15], M. Vranjes Milosavljevic [15], M. Vreeswijk [113], R. Vuillermet [36],

O. Vujinovic [99], I. Vukotic [39], S. Wada [156], C. Wagner [102], W. Wagner [170], S. Wahdan [170], H. Wahlberg [89], R. Wakasa [156], M. Wakida [110], V.M. Walbrecht [109], J. Walder [133], R. Walker [108], W. Walkowiak [140], A.M. Wang [61], A.Z. Wang [169], C. Wang [62a], C. Wang [62c], H. Wang [17a], J. Wang [64a], P. Wang [44], R.-J. Wang [99], R. Wang [61], R. Wang [6], S.M. Wang [147], S. Wang [62b], T. Wang [62a], W.T. Wang [79], W.X. Wang [62a], X. Wang [14c], X. Wang [161], X. Wang [62c], Y. Wang [62d], Y. Wang [14c], Z. Wang [105], Z. Wang [62d,51,62c], Z. Wang [105], A. Warburton [103], R.J. Ward [20], N. Warrack [59], A.T. Watson [20], M.F. Watson [20], G. Watts [137], B.M. Waugh [95], A.F. Webb [11], C. Weber [29], M.S. Weber [19], S.M. Weber [63a], C. Wei [62a], Y. Wei [125], A.R. Weidberg [125], J. Weingarten [49], M. Weirich [99], C. Weiser [54], C.J. Wells [48], T. Wenaus [29], B. Wendland [49], T. Wengler [36], N.S. Wenke [109], N. Wermes [24], M. Wessels [63a], K. Whalen [122], A.M. Wharton [90], A.S. White [61], A. White [8], M.J. White [1], D. Whiteson [159], L. Wickremasinghe [123], W. Wiedenmann [169], C. Wiel [50], M. Wielers [133], N. Wieseotte [99], C. Wiglesworth [42], L.A.M. Wiik-Fuchs [54], D.J. Wilbern [119], H.G. Wilkens [36], D.M. Williams [41], H.H. Williams [127], S. Williams [32], S. Willocq [102], P.J. Windischhofer [125], F. Winklmeier [122], B.T. Winter [54], J.K. Winter [100], M. Wittgen [142], M. Wobisch [96], R. Wölker [125], J. Wollrath [159], M.W. Wolter [85], H. Wolters [129a,129c], V.W.S. Wong [163], A.F. Wongel [48], S.D. Worm [48], B.K. Wosiek [85], K.W. Woźniak [85], K. Wraight [59], J. Wu [14a,14d], M. Wu [64a], M. Wu [112], S.L. Wu [169], X. Wu [56], Y. Wu [62a], Z. Wu [134,62a], J. Wuerzinger [125], T.R. Wyatt [100], B.M. Wynne [52], S. Xella [42], L. Xia [14c], M. Xia [14b], J. Xiang [64c], X. Xiao [105], M. Xie [62a], X. Xie [62a], S. Xin [14a,14d], J. Xiong [17a], I. Xiotidis [145], D. Xu [14a], H. Xu [62a], H. Xu [62a], L. Xu [62a], R. Xu [127], T. Xu [105], W. Xu [105], Y. Xu [14b], Z. Xu [62b], Z. Xu [14a], B. Yabsley [146], S. Yacoob [33a], N. Yamaguchi [88], Y. Yamaguchi [153], H. Yamauchi [156], T. Yamazaki [17a], Y. Yamazaki [83], J. Yan [62c], S. Yan [125], Z. Yan [25], H.J. Yang [62c,62d], H.T. Yang [17a], S. Yang [62a], T. Yang [64c], X. Yang [62a], X. Yang [14a], Y. Yang [44], Z. Yang [62a,105], W-M. Yao [17a], Y.C. Yap [48], H. Ye [14c], H. Ye [55], J. Ye [44], S. Ye [29], X. Ye [62a], Y. Yeh [95], I. Yeletskikh [38], B.K. Yeo [17a], M.R. Yexley [90], P. Yin [41], K. Yorita [167], C.J.S. Young [54], C. Young [142], M. Yuan [105], R. Yuan [62b,k], L. Yue [95], X. Yue [63a], M. Zaazoua [35e], B. Zabinski [85], E. Zaid [52], T. Zakareishvili [148b], N. Zakharchuk [34], S. Zambito [56], J.A. Zamora Saa [136d], J. Zang [152], D. Zanzi [54], O. Zaplatilek [131], S.V. Zeißner [49], C. Zeitnitz [170], J.C. Zeng [161], D.T. Zenger Jr [26], O. Zenin [37], T. Ženiš [28a], S. Zenz [93], S. Zerradi [35a], D. Zerwas [66], B. Zhang [14c], D.F. Zhang [138], G. Zhang [14b], J. Zhang [62b], J. Zhang [6], K. Zhang [14a,14d], L. Zhang [14c], P. Zhang [14a,14d], R. Zhang [169], S. Zhang [105], T. Zhang [152], X. Zhang [62c], X. Zhang [62b], Y. Zhang [62c,5], Z. Zhang [17a], Z. Zhang [66], H. Zhao [137], P. Zhao [51], T. Zhao [62b], Y. Zhao [135], Z. Zhao [62a], A. Zhemchugov [38], X. Zheng [62a], Z. Zheng [142], D. Zhong [161], B. Zhou [105], C. Zhou [169], H. Zhou [7], N. Zhou [62c], Y. Zhou [7], C.G. Zhu [62b], C. Zhu [14a,14d], H.L. Zhu [62a], H. Zhu [14a], J. Zhu [105], Y. Zhu [62c], Y. Zhu [62a], X. Zhuang [14a], K. Zhukov [37], V. Zhulanov [37], N.I. Zimine [38], J. Zinsser [63b], M. Ziolkowski [140], L. Živković [15], A. Zoccoli [23b,23a], K. Zoch [56], T.G. Zorbas [138], O. Zormpa [46], W. Zou [41], L. Zwalinski [36]

[1] *Department of Physics, University of Adelaide, Adelaide; Australia*
[2] *Department of Physics, University of Alberta, Edmonton AB; Canada*
[3] [(a)] *Department of Physics, Ankara University, Ankara;* [(b)] *Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye*
[4] *LAPP, Univ. Savoie Mont Blanc, CNRS/IN2P3, Annecy; France*
[5] *APC, Université Paris Cité, CNRS/IN2P3, Paris; France*
[6] *High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America*
[7] *Department of Physics, University of Arizona, Tucson AZ; United States of America*
[8] *Department of Physics, University of Texas at Arlington, Arlington TX; United States of America*
[9] *Physics Department, National and Kapodistrian University of Athens, Athens; Greece*
[10] *Physics Department, National Technical University of Athens, Zografou; Greece*
[11] *Department of Physics, University of Texas at Austin, Austin TX; United States of America*
[12] *Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan*
[13] *Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain*
[14] [(a)] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;* [(b)] *Physics Department, Tsinghua University, Beijing;* [(c)] *Department of Physics, Nanjing University, Nanjing;* [(d)] *University of Chinese Academy of Science (UCAS), Beijing; China*
[15] *Institute of Physics, University of Belgrade, Belgrade; Serbia*
[16] *Department for Physics and Technology, University of Bergen, Bergen; Norway*
[17] [(a)] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA;* [(b)] *University of California, Berkeley CA; United States of America*
[18] *Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany*
[19] *Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland*
[20] *School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom*
[21] [(a)] *Department of Physics, Bogazici University, Istanbul;* [(b)] *Department of Physics Engineering, Gaziantep University, Gaziantep;* [(c)] *Department of Physics, Istanbul University, Istanbul;* [(d)] *Istinye University, Sariyer, Istanbul; Türkiye*
[22] [(a)] *Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá;* [(b)] *Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia*
[23] [(a)] *Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna;* [(b)] *INFN Sezione di Bologna; Italy*
[24] *Physikalisches Institut, Universität Bonn, Bonn; Germany*
[25] *Department of Physics, Boston University, Boston MA; United States of America*
[26] *Department of Physics, Brandeis University, Waltham MA; United States of America*
[27] [(a)] *Transilvania University of Brasov, Brasov;* [(b)] *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;* [(c)] *Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;* [(d)] *National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;* [(e)] *University Politehnica Bucharest, Bucharest;* [(f)] *West University in Timisoara, Timisoara;* [(g)] *Faculty of Physics, University of Bucharest, Bucharest; Romania*

[28] [(a)] Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; [(b)] Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic
[29] Physics Department, Brookhaven National Laboratory, Upton NY; United States of America
[30] 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
[31] California State University, CA; United States of America
[32] Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom
[33] [(a)] Department of Physics, University of Cape Town, Cape Town; [(b)] 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
[34] Department of Physics, Carleton University, Ottawa ON; Canada
[35] [(a)] Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; [(b)] Faculté des Sciences, Université Ibn-Tofail, Kénitra; [(c)] Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; [(d)] 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
[36] CERN, Geneva; Switzerland
[37] Affiliated with an institute covered by a cooperation agreement with CERN
[38] Affiliated with an international laboratory covered by a cooperation agreement with CERN
[39] Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America
[40] LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France
[41] Nevis Laboratory, Columbia University, Irvington NY; United States of America
[42] Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark
[43] [(a)] Dipartimento di Fisica, Università della Calabria, Rende; [(b)] INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy
[44] Physics Department, Southern Methodist University, Dallas TX; United States of America
[45] Physics Department, University of Texas at Dallas, Richardson TX; United States of America
[46] National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece
[47] [(a)] Department of Physics, Stockholm University; [(b)] Oskar Klein Centre, Stockholm; Sweden
[48] Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
[49] Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany
[50] Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany
[51] Department of Physics, Duke University, Durham NC; United States of America
[52] SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom
[53] INFN e Laboratori Nazionali di Frascati, Frascati; Italy
[54] Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
[55] II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
[56] Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
[57] [(a)] Dipartimento di Fisica, Università di Genova, Genova; [(b)] INFN Sezione di Genova; Italy
[58] II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany
[59] SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
[60] LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France
[61] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America
[62] [(a)] Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; [(b)] Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; [(c)] School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; [(d)] Tsung-Dao Lee Institute, Shanghai; China
[63] [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany
[64] [(a)] Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; [(b)] Department of Physics, University of Hong Kong, Hong Kong; [(c)] Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China
[65] Department of Physics, National Tsing Hua University, Hsinchu; Taiwan
[66] IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France
[67] Department of Physics, Indiana University, Bloomington IN; United States of America
[68] [(a)] INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; [(b)] ICTP, Trieste; [(c)] Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy
[69] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
[70] [(a)] INFN Sezione di Milano; [(b)] Dipartimento di Fisica, Università di Milano, Milano; Italy
[71] [(a)] INFN Sezione di Napoli; [(b)] Dipartimento di Fisica, Università di Napoli, Napoli; Italy
[72] [(a)] INFN Sezione di Pavia; [(b)] Dipartimento di Fisica, Università di Pavia, Pavia; Italy
[73] [(a)] INFN Sezione di Pisa; [(b)] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
[74] [(a)] INFN Sezione di Roma; [(b)] Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
[75] [(a)] INFN Sezione di Roma Tor Vergata; [(b)] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
[76] [(a)] INFN Sezione di Roma Tre; [(b)] Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
[77] [(a)] INFN-TIFPA; [(b)] Università degli Studi di Trento, Trento; Italy
[78] Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria
[79] University of Iowa, Iowa City IA; United States of America
[80] Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
[81] [(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; Brazil
[82] KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
[83] Graduate School of Science, Kobe University, Kobe; Japan
[84] [(a)] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; [(b)] Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland
[85] Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
[86] Faculty of Science, Kyoto University, Kyoto; Japan
[87] Kyoto University of Education, Kyoto; Japan
[88] Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan
[89] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina
[90] Physics Department, Lancaster University, Lancaster; United Kingdom
[91] Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom
[92] Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia
[93] School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom
[94] Department of Physics, Royal Holloway University of London, Egham; United Kingdom
[95] Department of Physics and Astronomy, University College London, London; United Kingdom
[96] Louisiana Tech University, Ruston LA; United States of America
[97] Fysiska institutionen, Lunds universitet, Lund; Sweden

[98] Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain
[99] Institut für Physik, Universität Mainz, Mainz; Germany
[100] School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom
[101] CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France
[102] Department of Physics, University of Massachusetts, Amherst MA; United States of America
[103] Department of Physics, McGill University, Montreal QC; Canada
[104] School of Physics, University of Melbourne, Victoria; Australia
[105] Department of Physics, University of Michigan, Ann Arbor MI; United States of America
[106] Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
[107] Group of Particle Physics, University of Montreal, Montreal QC; Canada
[108] Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany
[109] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany
[110] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan
[111] Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America
[112] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands
[113] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands
[114] Department of Physics, Northern Illinois University, DeKalb IL; United States of America
[115] [(a)] New York University Abu Dhabi, Abu Dhabi; [(b)] University of Sharjah, Sharjah; United Arab Emirates
[116] Department of Physics, New York University, New York NY; United States of America
[117] Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan
[118] Ohio State University, Columbus OH; United States of America
[119] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America
[120] Department of Physics, Oklahoma State University, Stillwater OK; United States of America
[121] Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic
[122] Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America
[123] Graduate School of Science, Osaka University, Osaka; Japan
[124] Department of Physics, University of Oslo, Oslo; Norway
[125] Department of Physics, Oxford University, Oxford; United Kingdom
[126] LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France
[127] Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America
[128] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America
[129] [(a)] Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; [(b)] Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; [(c)] Departamento de Física, Universidade de Coimbra, Coimbra; [(d)] Centro de Física Nuclear da Universidade de Lisboa, Lisboa; [(e)] Departamento de Física, Universidade do Minho, Braga; [(f)] Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); [(g)] Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal
[130] Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic
[131] Czech Technical University in Prague, Prague; Czech Republic
[132] Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic
[133] Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom
[134] IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France
[135] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America
[136] [(a)] Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; [(b)] Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago; [(c)] Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena; [(d)] Universidad Andres Bello, Department of Physics, Santiago; [(e)] Instituto de Alta Investigación, Universidad de Tarapacá, Arica; [(f)] Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile
[137] Department of Physics, University of Washington, Seattle WA; United States of America
[138] Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
[139] Department of Physics, Shinshu University, Nagano; Japan
[140] Department Physik, Universität Siegen, Siegen; Germany
[141] Department of Physics, Simon Fraser University, Burnaby BC; Canada
[142] SLAC National Accelerator Laboratory, Stanford CA; United States of America
[143] Department of Physics, Royal Institute of Technology, Stockholm; Sweden
[144] Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America
[145] Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom
[146] School of Physics, University of Sydney, Sydney; Australia
[147] Institute of Physics, Academia Sinica, Taipei; Taiwan
[148] [(a)] E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; [(b)] High Energy Physics Institute, Tbilisi State University, Tbilisi; [(c)] University of Georgia, Tbilisi; Georgia
[149] Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel
[150] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel
[151] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece
[152] International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan
[153] Department of Physics, Tokyo Institute of Technology, Tokyo; Japan
[154] Department of Physics, University of Toronto, Toronto ON; Canada
[155] [(a)] TRIUMF, Vancouver BC; [(b)] Department of Physics and Astronomy, York University, Toronto ON; Canada
[156] Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan
[157] Department of Physics and Astronomy, Tufts University, Medford MA; United States of America
[158] United Arab Emirates University, Al Ain; United Arab Emirates
[159] Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
[160] Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
[161] Department of Physics, University of Illinois, Urbana IL; United States of America
[162] Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia; Spain
[163] Department of Physics, University of British Columbia, Vancouver BC; Canada
[164] Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
[165] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
[166] Department of Physics, University of Warwick, Coventry; United Kingdom
[167] Waseda University, Tokyo; Japan
[168] Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel
[169] Department of Physics, University of Wisconsin, Madison WI; United States of America
[170] Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
[171] Department of Physics, Yale University, New Haven CT; United States of America

[a] Also Affiliated with an institute covered by a cooperation agreement with CERN.
[b] Also at An-Najah National University, Nablus; Palestine.
[c] Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
[d] Also at Bruno Kessler Foundation, Trento; Italy.
[e] Also at Center for High Energy Physics, Peking University; China.
[f] Also at Centro Studi e Ricerche Enrico Fermi; Italy.
[g] Also at CERN, Geneva; Switzerland.
[h] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[i] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[j] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[k] Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[l] Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
[m] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
[n] Also at Department of Physics, California State University, East Bay; United States of America.
[o] Also at Department of Physics, California State University, Sacramento; United States of America.
[p] Also at Department of Physics, King's College London, London; United Kingdom.
[q] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[r] Also at Department of Physics, University of Thessaly; Greece.
[s] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
[t] Also at Hellenic Open University, Patras; Greece.
[u] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[v] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[w] Also at Institute of Particle Physics (IPP); Canada.
[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 RWTH Aachen University, III. Physikalisches Institut A, Aachen; Germany.
[ab] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[ac] Also at TRIUMF, Vancouver BC; Canada.
[ad] Also at Università di Napoli Parthenope, Napoli; Italy.
[ae] Also at University of Chinese Academy of Sciences (UCAS), Beijing; China.
[af] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[ag] Also at Washington College, Maryland; United States of America.
[ah] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
[*] Deceased.