



Constraints on off-shell Higgs boson production and the Higgs boson total width in $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ final states with the ATLAS detector

The ATLAS Collaboration

A measurement of off-shell Higgs boson production in the $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ decay channels, where ℓ stands for either an electron or a muon, is performed using data from proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. The data were collected by the ATLAS experiment in 2015 and 2016 at the Large Hadron Collider, and they correspond to an integrated luminosity of 36.1 fb^{-1} . An observed (expected) upper limit on the off-shell Higgs signal strength, defined as the event yield normalised to the Standard Model prediction, of 3.8 (3.4) is obtained at 95% confidence level (CL). Assuming the ratio of the Higgs boson couplings to the Standard Model predictions is independent of the momentum transfer of the Higgs production mechanism considered in the analysis, a combination with the on-shell signal-strength measurements yields an observed (expected) 95% CL upper limit on the Higgs boson total width of 14.4 (15.2) MeV.

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1 Introduction

The observation of the Higgs boson by the ATLAS and CMS experiments [1, 2] at the Large Hadron Collider (LHC) marks a milestone towards the understanding of the mechanism of electroweak (EW) symmetry breaking [3–5]. Further studies of the spin, parity and couplings of the new particle have shown no significant deviation from the predictions for the Standard Model (SM) Higgs boson [6–10]. Efforts to measure the properties of the Higgs boson are primarily focused on on-shell production. For a Higgs boson at a mass of 125 GeV [10, 11], the expected natural width of the SM Higgs boson is $\Gamma_H^{\text{SM}} \sim 4.1$ MeV [12]. However, above 125 GeV off-shell production of the Higgs boson has a substantial cross section at the LHC [13–16], due to the increased phase space as the vector bosons ($V = W, Z$) and top quark decay products become on-shell with the increasing energy scale. This provides an opportunity to study the Higgs boson properties at higher energy scales. Off-shell production can provide sensitivity to new physics that alters the interactions between the Higgs boson and other fundamental particles in the high-mass region [17–24].

The measured off-shell event yield from gluon–gluon fusion (ggF) production normalised to the SM prediction, where this ratio is referred to as the signal strength $\mu_{\text{off-shell}}$, can be expressed as

$$\mu_{\text{off-shell}} = \frac{\sigma_{\text{off-shell}}^{gg \rightarrow H^* \rightarrow ZZ}}{\sigma_{\text{off-shell,SM}}^{gg \rightarrow H^* \rightarrow ZZ}} = \kappa_{g,\text{off-shell}}^2 \cdot \kappa_{Z,\text{off-shell}}^2,$$

where $\sigma_{\text{off-shell}}^{gg \rightarrow H^* \rightarrow ZZ}$ is the cross section of the off-shell Higgs boson production via ggF with subsequent decay into a ZZ pair, and $\kappa_{g,\text{off-shell}}$ and $\kappa_{Z,\text{off-shell}}$ are the off-shell coupling modifiers relative to the SM predictions associated with the $gg \rightarrow H^*$ production and the $H^* \rightarrow ZZ$ decay, respectively. The off-shell Higgs boson signal cannot be treated independently of the $gg \rightarrow ZZ$ background, as sizeable negative interference effects appear [13]. The interference term is assumed to be proportional to $\sqrt{\mu_{\text{off-shell}}} = \kappa_{g,\text{off-shell}} \cdot \kappa_{Z,\text{off-shell}}$. Similarly, $\mu_{\text{on-shell}}$ for the on-shell Higgs boson production via ggF is given by:

$$\mu_{\text{on-shell}} = \frac{\sigma_{\text{on-shell}}^{gg \rightarrow H \rightarrow ZZ^*}}{\sigma_{\text{on-shell,SM}}^{gg \rightarrow H \rightarrow ZZ^*}} = \frac{\kappa_{g,\text{on-shell}}^2 \cdot \kappa_{Z,\text{on-shell}}^2}{\Gamma_H / \Gamma_H^{\text{SM}}},$$

which depends on the Higgs boson total width Γ_H . A measurement of the relative off-shell and on-shell event yields, $\mu_{\text{off-shell}}/\mu_{\text{on-shell}}$, provides direct information about Γ_H , if one assumes identical on-shell and off-shell Higgs boson coupling modifiers [15, 25]. The above formalism describing the ratio of off-shell to on-shell cross sections also applies to the vector-boson fusion (VBF) production mode. As in the previous measurement [26], for a measurement of Γ_H it is necessary to assume that the on-shell and off-shell coupling modifiers are the same, and for an upper limit that the on-shell coupling modifiers are not larger than the off-shell couplings. It is also assumed that any new physics which modifies the off-shell signal strength and the off-shell couplings does not modify the relative phase of the interfering signal and background processes. Further, it is assumed that there are neither sizeable kinematic modifications to the off-shell signal nor new sizeable signals in the search region of this analysis unrelated to an enhanced off-shell signal strength.

The ATLAS and CMS experiments have presented studies of the off-shell production of the Higgs boson using Run-1 proton–proton (pp) collisions data [26–29]. ATLAS obtained an observed (expected) upper limit on the off-shell Higgs boson signal strength ($\mu_{\text{off-shell}}$) in the range of 5.1–8.6 (6.7–11.0) [26], using the ZZ and WW channels. This range is determined by the assumption that the $gg \rightarrow ZZ$ and $gg \rightarrow WW$

background K -factors, corresponding to the ratio of the next-to-leading-order (NLO) QCD predictions to the leading-order (LO) predictions, lie between one-half and twice the value of the $gg \rightarrow H^* \rightarrow ZZ(WW)$ signal K -factor. An observed (expected) 95% confidence level (CL) upper limit of $\Gamma_H < 23(33)$ MeV was obtained, assuming the $gg \rightarrow ZZ(WW)$ background K -factor is equal to the $gg \rightarrow H^* \rightarrow ZZ(WW)$ signal K -factor. CMS presented a similar study in the ZZ and WW channels, with observed (expected) 95% CL upper limit of $\Gamma_H < 13(26)$ MeV [29]. By comparison, the precision of Γ_H from direct on-shell Higgs boson mass measurements alone is approximately 1 GeV [9, 30, 31], limited by measurement resolution.

This Letter presents an analysis of off-shell Higgs boson production in the $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ final states ($\ell = e, \mu$), using 36.1 fb^{-1} of data collected by the ATLAS detector in pp collisions at $\sqrt{s} = 13 \text{ TeV}$. The off-shell region is defined by requiring the invariant mass of the ZZ system (m_{ZZ}) to be above the on-shell ZZ production threshold, hence well above the Higgs boson mass, and the on-shell region is defined by a mass window around the 125 GeV resonance. This analysis adopts the same methodology used in the Run-1 analysis reported in Ref. [26]. The analysis for the $ZZ \rightarrow 4\ell$ final state closely follows the Higgs boson measurements and high-mass search in the same final state described in Refs. [32, 33]. The off-shell Higgs signal strength is extracted using a matrix-element discriminant, defined in Section 4, in a mass region $220 \text{ GeV} < m_{4\ell} < 2000 \text{ GeV}$. The on-shell signal strength was measured in the $118 \text{ GeV} < m_{4\ell} < 129 \text{ GeV}$ region in Ref. [32]. The analysis of the $ZZ \rightarrow 2\ell 2\nu$ channel, described in Section 5, follows a strategy similar to that used in the search for heavy ZZ resonances described in Ref. [33]. For this channel, the signal strength is extracted from the transverse mass distribution in the 250 to 2000 GeV range. For off-shell production of the Higgs boson, the dominant processes of ggF and VBF are considered. Next-to-next-to-leading-order (NNLO) QCD and NLO EW corrections are known for the off-shell signal process $gg \rightarrow H^* \rightarrow ZZ$ [25]. More recently, NLO QCD corrections have also become available for the $gg \rightarrow ZZ$ background and for the signal–background interference [34, 35], for which additional details are given in Section 3. Given that the QCD corrections for the off-shell signal processes have only been calculated inclusively in the jet multiplicity, the analysis is performed inclusively in jet observables and the event selection is designed to minimise the dependence on the momentum of the ZZ system, which is sensitive to the jet multiplicity.

2 ATLAS detector

The ATLAS experiment is described in Ref. [36]. ATLAS is a multipurpose detector with a forward–backward symmetric cylindrical geometry and a solid-angle¹ coverage of nearly 4π . The inner tracking detector, covering the region $|\eta| < 2.5$, consists of a silicon pixel detector, a silicon microstrip detector and a straw-tube transition-radiation tracker. The innermost layer of the pixel detector, the insertable B-layer [37], was installed between Run 1 and Run 2 of the LHC. The inner detector is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by a finely segmented lead/liquid-argon (LAr) electromagnetic calorimeter covering the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter provides coverage in the central region $|\eta| < 1.7$. The endcap and forward regions, covering the pseudorapidity range $1.5 < |\eta| < 4.9$, are instrumented with electromagnetic and hadronic LAr calorimeters, with copper or tungsten as the absorber material. A muon spectrometer system incorporating

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

large superconducting toroidal air-core magnets surrounds the calorimeters. Three layers of precision wire chambers provide muon tracking in the range $|\eta| < 2.7$, while dedicated fast chambers are used for triggering in the region $|\eta| < 2.4$. The trigger system is composed of two stages [38]. The first stage, implemented with custom hardware, uses information from calorimeters and muon chambers to reduce the event rate from about 40 MHz to a maximum of 100 kHz. The second stage, called the high-level trigger, reduces the data acquisition rate to about 1 kHz on average. The high-level trigger is software-based and runs reconstruction algorithms similar to those used in the offline reconstruction.

3 Monte Carlo simulation and higher-order theory corrections

Monte Carlo (MC) samples of $gg \rightarrow (H^* \rightarrow)ZZ$ events, which include the SM Higgs boson signal, $gg \rightarrow H^* \rightarrow ZZ$, the continuum background, $gg \rightarrow ZZ$, and the signal-background interference contribution, were generated with the MC generator SHERPA-v2.2.2 + OPENLOOPS [39–42]. Matrix elements were calculated for zero jets and one jet at LO and merged with the SHERPA parton shower [43]. The NNPDF30NNLO [44] PDF set was used, and the QCD renormalisation and factorisation scales were set to $m_{ZZ}/2$.

The K -factor for the $gg \rightarrow H^* \rightarrow ZZ$ process is known up to NNLO in QCD as a function of m_{ZZ} [12, 25]. More recently, a NLO QCD calculation which includes the $gg \rightarrow ZZ$ continuum process has become available [34, 35] allowing m_{ZZ} differential K -factors to be calculated with an expansion in the inverse top mass ($1/m_t$) below $2m_t$, and assuming a massless-quark approximation above this threshold. This NLO QCD calculation was used to correct all three components with separate K -factors computed for the signal $gg \rightarrow H^* \rightarrow ZZ$ ($K^S(m_{ZZ})$), the background $gg \rightarrow ZZ$ ($K^B(m_{ZZ})$) and the interference ($K^I(m_{ZZ})$). Since the NNLO QCD correction is only known differentially in m_{ZZ} for the $gg \rightarrow H^* \rightarrow ZZ$ process and not for all three components in the off-shell region, an overall correction is applied by scaling the differential NLO QCD reweighted cross section by an additional factor of 1.2, which is assumed to be the same for the signal, background and interference. This additional constant scale factor is justified by the constant NNLO to NLO ratio of the QCD predictions over the data region considered in the analysis. Using these scaled NLO K -factors, the cross section for the $gg \rightarrow (H^* \rightarrow)ZZ$ process with any off-shell Higgs boson signal strength $\mu_{\text{off-shell}}$ can be obtained from a parameterisation of three SM MC samples: the $gg \rightarrow H^* \rightarrow ZZ$ signal ($\sigma_{gg \rightarrow H^* \rightarrow ZZ}^{\text{SM}}$), the $gg \rightarrow ZZ$ continuum background ($\sigma_{gg \rightarrow ZZ, \text{cont}}^{\text{SM}}$) and the full process with signal, background and interference $gg \rightarrow (H^* \rightarrow)ZZ$ ($\sigma_{gg \rightarrow (H^* \rightarrow)ZZ}^{\text{SM}}$), where the last sample is required to derive the interference sample:

$$\begin{aligned} \sigma_{gg \rightarrow (H^* \rightarrow)ZZ}(\mu_{\text{off-shell}}) &= \mu_{\text{off-shell}} \cdot 1.2 \cdot K^S(m_{ZZ}) \cdot \sigma_{gg \rightarrow H^* \rightarrow ZZ}^{\text{SM}} \\ &+ \sqrt{\mu_{\text{off-shell}}} \cdot 1.2 \cdot K^I(m_{ZZ}) \cdot \sigma_{gg \rightarrow ZZ, \text{Interference}}^{\text{SM}} \\ &+ 1.2 \cdot K^B(m_{ZZ}) \cdot \sigma_{gg \rightarrow ZZ, \text{cont}}^{\text{SM}}, \\ \sigma_{gg \rightarrow ZZ, \text{Interference}}^{\text{SM}} &= \sigma_{gg \rightarrow (H^* \rightarrow)ZZ}^{\text{SM}} - \sigma_{gg \rightarrow H^* \rightarrow ZZ}^{\text{SM}} - \sigma_{gg \rightarrow ZZ, \text{cont}}^{\text{SM}}. \end{aligned} \quad (1)$$

$$\sigma_{gg \rightarrow ZZ, \text{Interference}}^{\text{SM}} = \sigma_{gg \rightarrow (H^* \rightarrow)ZZ}^{\text{SM}} - \sigma_{gg \rightarrow H^* \rightarrow ZZ}^{\text{SM}} - \sigma_{gg \rightarrow ZZ, \text{cont}}^{\text{SM}}. \quad (2)$$

The electroweak $pp \rightarrow VV + 2j$ processes containing both the VBF-like events and events from associated Higgs production with vector bosons (VH), which includes on-shell Higgs boson production, were simulated using MADGRAPH5_aMC@NLO [45] with matrix elements calculated at LO. The QCD renormalisation and factorisation scales were set to m_W following the recommendation in Ref. [46] and the NNPDF23LO PDF set [47] was used. PYTHIA 8.186 [48] was used for parton showering and hadronisation,

with the A14 set of tuned parameters for the underlying event [49]. Due to the different Γ_H dependence, the on-shell and off-shell Higgs boson production processes are separated when weighting MC events as in Eqs. (1) by requiring that the generated Higgs boson mass satisfy $|m_H^{\text{gen.}} - 125 \text{ GeV}| < 1 \text{ GeV}$. This requirement is fully efficient in selecting the on-shell VH process. The cross section $\sigma_{pp \rightarrow VV+2j}(\mu_{\text{off-shell}})$ for the electroweak $pp \rightarrow VV + 2j$ process for any off-shell Higgs boson signal strength $\mu_{\text{off-shell}}$ is parameterised in the same way as for the $gg \rightarrow (H^* \rightarrow)ZZ$ process.

The $q\bar{q} \rightarrow ZZ$ background was simulated with SHERPA v2.2.2, using the NNPDF30NNLO PDF set for the hard-scattering process. NLO QCD accuracy is achieved in the matrix-element calculation for 0- and 1-jet final states and LO accuracy for 2- and 3-jet final states. The merging with the SHERPA parton shower was performed using the MEps@NLO prescription. NLO EW corrections are applied as a function of the particle-level m_{ZZ} [50, 51].

The WW and WZ backgrounds were simulated at NLO in QCD using the PowHEG-Box v2 event generator [52] with the CT10NLO PDF set [53] and PYTHIA 8.186 for parton showering and hadronisation. The non-perturbative effects were modelled with the AZNLO set of tuned parameters [54]. The interference between the $q\bar{q} \rightarrow ZZ$ and $q\bar{q} \rightarrow WW$ processes for the $2\ell 2\nu$ final state is found to be negligible and thus is not considered.

Events containing a single Z boson with associated jets ($Z + \text{jets}$) were simulated using the SHERPA v2.2.1 event generator. Matrix elements were calculated for up to two partons at NLO and four partons at LO using the COMIX [55] and OPENLOOPS [41] matrix-element generators and merged with the SHERPA parton shower [43] using the MEps@NLO prescription. The NNPDF30NNLO PDF set was used in conjunction with dedicated parton-shower tuning developed by the SHERPA authors. The $Z + \text{jets}$ events are normalised using the NNLO cross sections [56].

The triboson backgrounds ZZZ , WZZ , and WWZ with fully leptonic decays and at least four prompt charged leptons were modelled using SHERPA v2.1.1. The contribution from triboson backgrounds with one W or Z boson decaying hadronically is not included in the simulation, but the impact on the analysis is found to be negligible. For the fully leptonic $t\bar{t} + Z$ background, with four prompt charged leptons originating from the decays of the top quarks and Z boson, MADGRAPH5_aMC@NLO was used. The $t\bar{t}$ background, as well as the single-top and Wt production, were modelled using PowHEG-Box v2 interfaced to PYTHIA 6.428 [57] with the Perugia 2012 [58] set of tuned parameters for parton showering, hadronisation and the underlying event, and to EVTGEN v1.2.0 [59] for properties of the bottom and charm hadron decays.

The particle-level events produced by each MC event generator were processed through the ATLAS detector simulation within the GEANT 4 framework [60, 61] or the fast detector simulation package Atlfast-II [61]. Additional pp interactions in the same and nearby bunch crossings (pile-up) are included in the simulation. The pile-up events were generated using PYTHIA 8 with the A2 set of tuned parameters [62] and the MSTW2008LO PDF set [63]. The simulation samples were weighted to reproduce the observed distribution of the mean number of interactions per bunch crossing in the data.

4 $ZZ \rightarrow 4\ell$ analysis

The analysis for the $ZZ \rightarrow 4\ell$ final state closely follows the on-shell Higgs boson measurements and high-mass search in the same final state described in Refs. [32, 33], with the same event reconstruction, trigger and event selections, and background estimation methods. A matrix-element-based (ME-based)

discriminant computed at LO is constructed to enhance the separation between the $gg \rightarrow H^* \rightarrow ZZ$ signal and the $gg \rightarrow ZZ$ and $q\bar{q} \rightarrow ZZ$ backgrounds, and this discriminant is subsequently used in a binned maximum-likelihood fit for the final result. To minimise the dependence of the $gg \rightarrow ZZ$ kinematics on higher-order QCD effects, the analysis is performed inclusively, ignoring the number of jets in the events.

The analysis is split into three channels (4μ , $2e2\mu$, $4e$). Each electron (muon) must have transverse momentum $p_T > 7$ (5) GeV and be measured in the pseudorapidity range $|\eta| < 2.47$ ($|\eta| < 2.7$). The highest- p_T lepton in the quadruplet must satisfy $p_T > 20$ GeV, and the second (third) lepton in p_T order is required to have $p_T > 15$ GeV ($p_T > 10$ GeV). Lepton pairs are formed from same-flavour opposite-charge leptons. For each channel, the quadruplet with a lepton pair whose mass is closest to the Z boson mass is kept. This pair is referred to as the leading dilepton pair and its invariant mass, m_{12} , is required to be between 50 GeV and 106 GeV. The second (subleading) pair is chosen from the remaining leptons as the pair closest in mass to the Z boson and in the range $50 \text{ GeV} < m_{34} < 115 \text{ GeV}$. The off-shell region is defined as the range $220 \text{ GeV} < m_{4\ell} < 2000 \text{ GeV}$, while the on-shell region is defined as $118 \text{ GeV} < m_{4\ell} < 129 \text{ GeV}$.

The dominant background in the $ZZ \rightarrow 4\ell$ channel arises from $q\bar{q} \rightarrow ZZ$ events. This is modelled using MC simulation, accurate to NLO QCD and NLO EW corrections as explained in Section 3. Other backgrounds, such as triboson production, $t\bar{t}V$, Z + jets, and top quark production, constitute less than 2% of the total background in the off-shell signal region, and are either taken from simulation or from dedicated data control regions.

Figure 1(a) shows the observed and expected distributions of $m_{4\ell}$ combining all lepton channels in the off-shell region. The data are in agreement with the SM predictions, with two small excesses at $m_{4\ell}$ around 240 GeV and 700 GeV, each having a significance of about two standard deviations (2σ), as evaluated by the high-mass resonance search reported in Ref. [33]. Table 1 shows the expected and observed numbers of events in the signal region and additionally in the $400 \text{ GeV} < m_{4\ell} < 2000 \text{ GeV}$ mass range, which is enriched in signal. The latter mass region was chosen for this table since it is optimal for a counting experiment.

The matrix-element kinematic discriminant fully exploits the event kinematics in the centre-of-mass frame of the 4ℓ system. It is computed from eight kinematic observables: the three masses $m_{4\ell}$, m_{12} and m_{34} , and the leading Z boson production angle and four decay angles defined in Ref. [64]. These observables are used to calculate the matrix elements for the different processes with the MCFM program [15] at LO. The following matrix elements are calculated for each event in the mass range $220 \text{ GeV} < m_{4\ell} < 2000 \text{ GeV}$:

- $P_{q\bar{q}}$: the matrix element squared for the $q\bar{q} \rightarrow ZZ \rightarrow 4\ell$ process,
- P_{gg} : the matrix element squared for the $gg \rightarrow (H^* \rightarrow)ZZ \rightarrow 4\ell$ process, which includes the Higgs boson with SM couplings, the continuum background and their interference,
- P_H : the matrix element squared for the $gg \rightarrow H^* \rightarrow ZZ \rightarrow 4\ell$ process without continuum background or interference.

The ME-based discriminant is defined as in Ref. [15]:

$$D_{\text{ME}} = \log_{10} \left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}} \right),$$

where $c = 0.1$ is a constant whose value is chosen to balance the overall cross sections of the $q\bar{q} \rightarrow ZZ$ and $gg \rightarrow (H^* \rightarrow)ZZ$ processes. The value of c has a small effect on the analysis sensitivity. Figure 1(b)

shows the observed and expected distributions of D_{ME} . Events with a D_{ME} value between -4.5 and 0.5 are used for the final result.

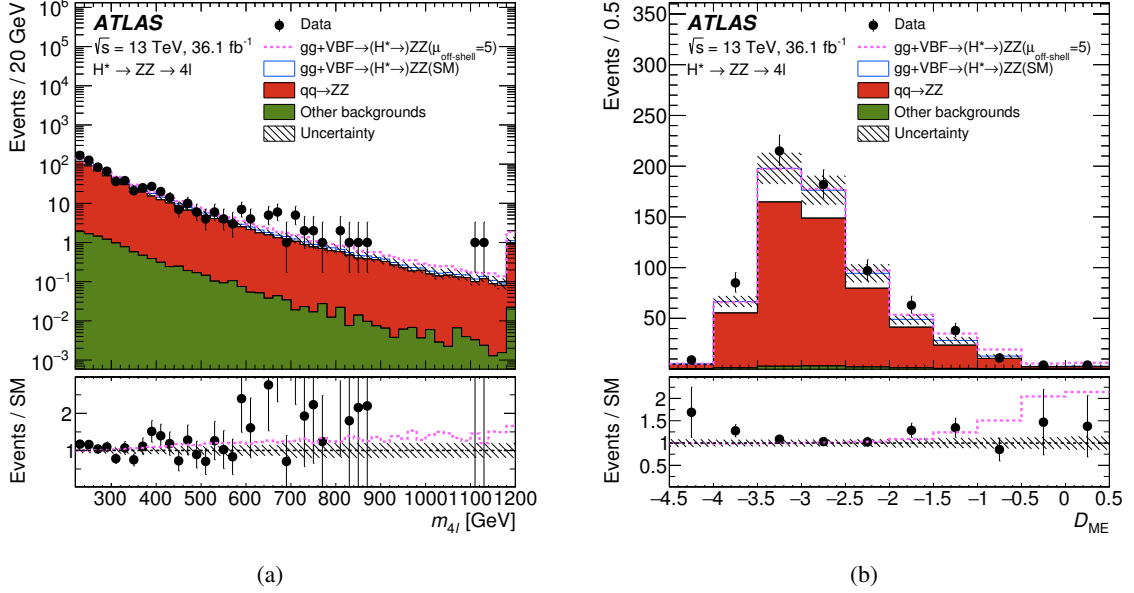


Figure 1: Observed distributions in the range $220 \text{ GeV} < m_{4\ell} < 2000 \text{ GeV}$ for (a) the four-lepton invariant mass $m_{4\ell}$ and (b) the ME-based discriminant D_{ME} combining all lepton final states, compared to the expected contributions from the SM including the Higgs boson (stacked). Events with $m_{4\ell} > 1200 \text{ GeV}$ are included in the last bin of the $m_{4\ell}$ distribution. The hatched area shows the combined statistical and systematic uncertainties. The dashed line corresponds to the total expected event yield, including all backgrounds and the Higgs boson with $\mu_{\text{off-shell}} = 5$. The ratio plot shows the observed data yield divided by the SM prediction (black points) as well as the total expected event yield with $\mu_{\text{off-shell}} = 5$ divided by the SM prediction (dashed line) in each bin.

5 $ZZ \rightarrow 2\ell 2\nu$ analysis

The analysis in the $ZZ \rightarrow 2\ell 2\nu$ final state closely follows the one performed to search for ZZ resonances [33]. The reconstruction, identification and selection of electrons, muons, jets, b -jets and missing transverse momentum are identical while the event selection is optimised for the current analysis.

To discriminate the signal from the background and enhance the sensitivity to off-shell Higgs boson production, the transverse mass of the ZZ system (m_{T}^{ZZ}) is used, defined as:

$$m_{\text{T}}^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + (p_{\text{T}}^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_{\text{T}}^{\text{miss}})^2} \right]^2 - \left| \vec{p}_{\text{T}}^{\ell\ell} + \vec{E}_{\text{T}}^{\text{miss}} \right|^2},$$

where $p_{\text{T}}^{\ell\ell}$ is the transverse momentum of the dilepton system, m_Z is the mass of the Z boson fixed to $m_Z = 91.187 \text{ GeV}$ [65] and $E_{\text{T}}^{\text{miss}}$ is the magnitude of the missing transverse momentum $\vec{E}_{\text{T}}^{\text{miss}}$. The latter is computed as the negative sum of transverse momenta of all the leptons and jets, as well as the tracks

originating from the primary vertex but not associated with any of the leptons or jets, the so-called soft term.

The event selection is designed to minimise the dependence on the p_T of the ZZ system, and thus is performed inclusively in number of jets. First, events with two opposite-charge leptons of the same flavour are selected with the requirement of $p_T > 30$ (20) GeV for the leading (sub-leading) lepton. The dilepton invariant mass $m_{\ell\ell}$ is required to be in the range $76 \text{ GeV} < m_{\ell\ell} < 106 \text{ GeV}$. Events with additional, loosely identified leptons with $p_T > 7 \text{ GeV}$ are rejected to reduce the amount of WZ background. The two Z bosons originating from the decay of an off-shell Higgs boson are boosted and tend to be back-to-back in the transverse plane. A series of selection requirements are applied to reduce the $Z + \text{jets}$ background: the two leptons are required to be produced with an angular separation of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.8$; E_T^{miss} is required to be larger than 175 GeV; the azimuthal angle between the transverse momentum of the dilepton system and the missing transverse momentum is required to be large, $\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{\text{miss}}) > 2.7$; $p_T^{\ell\ell}$ is required to be balanced by the E_T^{miss} and jets, $|p_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell} < 0.2$, where $p_T^{\text{miss,jet}} = |\vec{E}_T^{\text{miss}} + \sum_{\text{jet}} \vec{p}_T^{\text{jet}}|$; and $E_T^{\text{miss}}/H_T > 0.33$, where H_T is the scalar sum of lepton and jet transverse momenta. Finally, events with a b -jet with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$, identified by the MV2c10 algorithm [66, 67] with 85% tagging efficiency, are vetoed to suppress the top quark background.

The dominant backgrounds in the $ZZ \rightarrow 2\ell 2\nu$ channel consist of $q\bar{q} \rightarrow ZZ$ events, followed by WZ events. Other background processes with two genuine leptons not directly originating from a Z boson decay include WW , $t\bar{t}$, Wt and $Z \rightarrow \tau\tau$. The remaining background comes from $Z + \text{jets}$ with poorly reconstructed E_T^{miss} , $W + \text{jets}$ events with at least one misidentified electron or muon, semileptonic top decays, and multi-jet events.

The $q\bar{q} \rightarrow ZZ$ background is modelled in the same manner as for the $ZZ \rightarrow 4\ell$ channel. The WZ background is estimated with simulation using a normalisation correction factor extracted from a dedicated control region (CR). This WZ -enriched CR is defined by selecting $Z \rightarrow \ell\ell$ candidates with an additional electron or muon with $p_T > 20 \text{ GeV}$. Events with a b -jet are rejected to suppress leptonic $t\bar{t}$ decays and a $m_T(W) > 60 \text{ GeV}$ requirement is applied to reduce the $Z + \text{jets}$ contamination. The correction factor is then calculated in the CR as the number of data events, after subtracting the non- WZ contributions, divided by the predicted WZ yield, and is found to be 1.29. The statistical uncertainty of the WZ estimate is about 2%, while the systematic uncertainty is estimated to be 5% from theoretical and experimental uncertainties in the simulation-based transfer factor between the three-lepton control region and the two-lepton signal region.

The non-resonant- $\ell\ell$ background, including WW , $t\bar{t}$, Wt and $Z \rightarrow \tau\tau$ processes, is estimated from a control sample of $e\mu$ events, in the same manner as in Ref. [33], except that the $e\mu$ CR is defined by requiring $E_T^{\text{miss}} > 120 \text{ GeV}$. The background estimation is performed by extrapolating the result obtained with the relaxed E_T^{miss} requirement to the SR, extracting the efficiency of the E_T^{miss} selection criteria from MC simulation of the non-resonant- $\ell\ell$ background. The m_T^{ZZ} distributions for the non-resonant- $\ell\ell$ background are derived from the data CR and extrapolated to the SR. The total uncertainty in the non-resonant- $\ell\ell$ estimate is about 40%, including the statistical uncertainty of the data in the control region, the extrapolation and the method bias estimated from simulation. The m_T^{ZZ} distribution differences between data and simulation are taken as a shape uncertainty ($\sim 10\%$).

The $Z + \text{jets}$ background, expected to be $\sim 2\%$ of the total background, is estimated from a combination of MC and data-driven techniques. A $Z + \text{jets}$ enriched CR is defined by reversing the E_T^{miss}/H_T selection. Additionally, the b -jet veto and the requirement on $\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{\text{miss}})$ are removed to allow more data events. The estimation is performed by extrapolating the number of events observed in the CR, after subtracting

non- Z -boson backgrounds, to the SR with a correction factor based on simulation. The m_T^{ZZ} distribution for the Z + jets background is derived from simulation. The total uncertainty in the Z + jets estimate is about 50% (80%) for the ee ($\mu\mu$) channel, including the statistical uncertainty of the data in the control region and the extrapolation factor. The shape difference in m_T^{ZZ} between Z + jets MC events in the SR and those in the CR is taken into account as a systematic uncertainty.

Other backgrounds, such as triboson production, ttV , W + jets, and top quark processes other than pair production, constitute only a tiny fraction of the total background in the off-shell signal region, $< 1\%$, and are taken from simulation. The contribution from the on-shell Higgs production is negligible in the off-shell signal region.

The expected and observed numbers of events in the signal region for the $ZZ \rightarrow 2\ell 2\nu$ analysis are summarised in Table 1. Figure 2 shows the observed and expected distributions of m_T^{ZZ} in both the ee and $\mu\mu$ channels in the off-shell region.

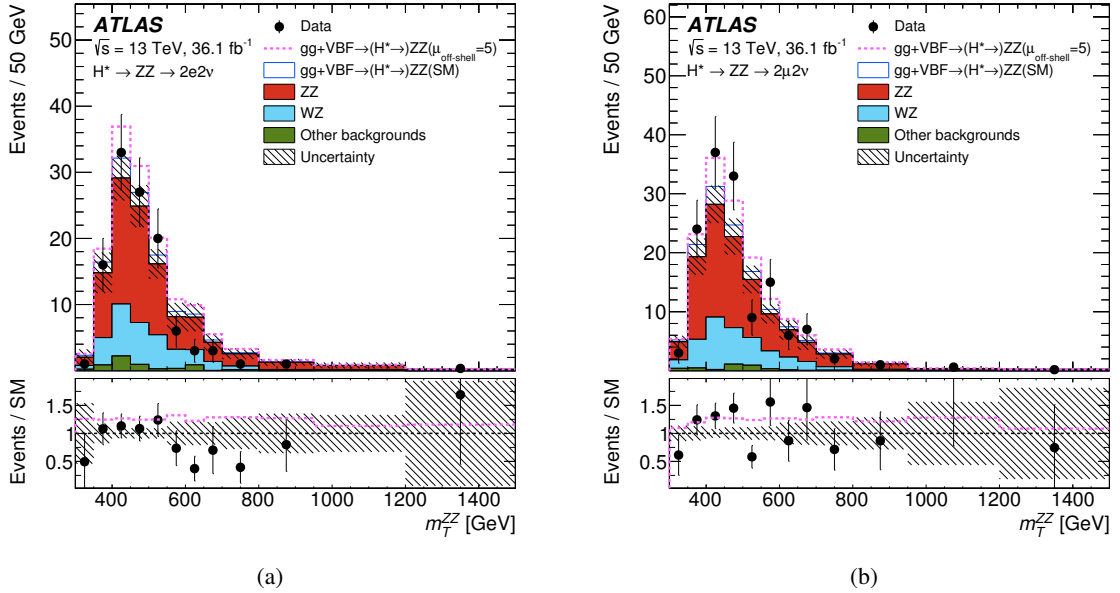


Figure 2: Observed transverse mass m_T^{ZZ} distribution in the (a) ee channel and (b) $\mu\mu$ channel of the $ZZ \rightarrow 2\ell 2\nu$ off-shell region, compared to the expected contributions from the SM including the Higgs boson (stacked). Events with $1500 < m_T^{ZZ} < 2000$ GeV are included in the last bin of the distribution. The hatched area shows the combined statistical and systematic uncertainties. The dashed line corresponds to the total expected event yield, including all backgrounds and the Higgs boson with $\mu_{\text{off-shell}} = 5$. The ratio plot shows the observed data yield divided by the SM prediction (black points) as well as the total expected event yield with $\mu_{\text{off-shell}} = 5$ divided by the SM prediction (dashed line) in each bin.

6 Systematic uncertainties

Systematic uncertainty sources impacting the analysis of both channels can be divided into two categories: uncertainties in the theoretical description of the signal and background processes and experimental uncertainties related to the detector or to the reconstruction algorithms. The largest systematic uncertainties

Table 1: The expected and observed numbers of events in the signal region for both final states. For the $ZZ \rightarrow 4\ell$ analysis, numbers are given for both the signal region and a signal-enriched region which covers the mass range $400 \text{ GeV} < m_{4\ell} < 2000 \text{ GeV}$. The other backgrounds in the $ZZ \rightarrow 4\ell$ final state include contributions from Z + jets and top quark processes, while in the $ZZ \rightarrow 2\ell 2\nu$ final state they include contributions from tri-boson production, the W + jets process, and top quark processes other than pair production. For the $ZZ \rightarrow 2\ell 2\nu$ analysis, the range $250 \text{ GeV} < m_{\text{T}}^{ZZ} < 2000 \text{ GeV}$ is considered. The upper part of the table contains the expected events for the $gg \rightarrow (H^* \rightarrow)ZZ$ and VBF ($H^* \rightarrow)ZZ$ processes which include the Higgs boson signal, background and interference for the SM predictions. The SM estimates for the signal (S) and background (B) event yields without interference are given in parentheses. The lower part of the table contains the corresponding predictions for $\mu_{\text{off-shell}} = 5$. The uncertainties in the number of expected events include the statistical uncertainties from MC samples and systematic uncertainties, summed in quadrature. Empty entries correspond to contributions with event yields smaller than 0.1 events.

Process	$ZZ \rightarrow 4\ell$		$ZZ \rightarrow 2\ell 2\nu$
	$m_{4\ell} > 220 \text{ GeV}$	$m_{4\ell} > 400 \text{ GeV}$	$m_{\text{T}}^{ZZ} > 250 \text{ GeV}$
$gg \rightarrow (H^* \rightarrow)ZZ$	96 ± 15	10.6 ± 2.0	22 ± 4
($gg \rightarrow H^* \rightarrow ZZ$ (S))	9.8 ± 1.5	5.9 ± 1.0	20.1 ± 3.3
($gg \rightarrow ZZ$ (B))	101 ± 16	11.8 ± 2.2	28 ± 6
VBF ($H^* \rightarrow)ZZ$	8.29 ± 0.34	3.07 ± 0.13	2.83 ± 0.14
(VBF $H^* \rightarrow ZZ$ (S))	1.67 ± 0.08	1.14 ± 0.04	5.45 ± 0.30
(VBF ZZ (B))	9.9 ± 0.4	4.17 ± 0.18	6.92 ± 0.35
$q\bar{q} \rightarrow ZZ$	520 ± 42	77 ± 8	132 ± 15
$q\bar{q} \rightarrow WZ$	-	-	68 ± 4
$WW/t\bar{t}/Wt/Z \rightarrow \tau\tau$	-	-	2.6 ± 1.0
Z + jets	-	-	6.0 ± 2.8
Other backgrounds	14.6 ± 0.7	2.15 ± 0.15	1.14 ± 0.08
Total Expected (SM)	639 ± 60	93 ± 10	234 ± 16
Observed	704	114	261
Other signal hypothesis			
$gg \rightarrow (H^* \rightarrow)ZZ$ ($\mu_{\text{off-shell}} = 5$)	117 ± 18	26 ± 5	61 ± 12
VBF ($H^* \rightarrow)ZZ$ ($\mu_{\text{off-shell}} = 5$)	11.0 ± 0.5	4.85 ± 0.22	8.8 ± 0.4

arise from the theoretical uncertainties in the gg -initiated ZZ processes and the $q\bar{q} \rightarrow ZZ$ background process. The uncertainties from experimental measurements are generally small compared to the theoretical uncertainties in this analysis.

The theoretical uncertainties originate from the PDF choice, the missing higher-order corrections, and the parton-shower modelling. The PDF uncertainty corresponds to the 68% CL variations of the nominal PDF set NNPDF30NNLO for both $q\bar{q} \rightarrow ZZ$ and $gg \rightarrow (H^* \rightarrow)ZZ$, as well as the difference from alternative PDF sets. The alternative PDF sets used are CT10NNLO [68] and MMHT2014NNLO [69]. The uncertainty due to PDF is found to be about 3% in the high-mass region considered. The uncertainty due to higher-order QCD corrections (QCD scale uncertainty) is estimated by varying the renormalisation and factorisation scales independently, ranging from a factor of one-half to two. The uncertainty in the K -factors due to the NLO QCD scale uncertainty is 10–20% as a function of m_{ZZ} for the gg -initiated ZZ processes in the probed high-mass region, and ranges from 5% to 10% as a function of m_{ZZ} for the $q\bar{q} \rightarrow ZZ$ background. The QCD scale uncertainties are treated as correlated among the gg -initiated ZZ processes, and uncorrelated with the $q\bar{q}$ -initiated ZZ process. There are a few additional normalisation

uncertainties associated with the NLO K -factors discussed in section 3. In the region below $2m_t$, the higher-order corrections are computed with a maximum jet transverse momentum of 150 GeV to ensure a good description by the $1/m_t$ expansion. The default scale uncertainty is therefore doubled for events which have a jet with $p_T > 150$ GeV, corresponding to about 8% of the events in this region. The scale uncertainty is also increased by 50% around the $2m_t$ threshold, with a Gaussian-smoothed transition decreasing to the default uncertainty within 50 GeV of the threshold. This is intended to allow for possible effects on the K -factor which have not been estimated as the top quark moves on-shell. It is assumed that the 10–20% NLO QCD scale uncertainty for the gg -initiated ZZ processes covers the assumption of massless loops above the $2m_t$ threshold, and as well the uncertainties in the 1.2 scale factor estimated only for the NNLO/NLO signal correction but also applied to the background and interference components. These NLO QCD scale uncertainties are larger than those associated with the NNLO QCD signal uncertainties. The EW correction uncertainty for $q\bar{q} \rightarrow ZZ$ is evaluated using the same method as in Ref. [26] and its impact is estimated to be about 1%. The parton-shower uncertainty is evaluated by varying parameters in the parton-shower tunes according to Refs. [49, 54] and found to be 2–3% in normalisation.

The theoretical uncertainties due to the missing higher-order corrections and PDF variations are small for VH -like and VBF-like processes $pp \rightarrow ZZ + 2j$; therefore, they are not included in the analysis.

For the $ZZ \rightarrow 4\ell$ analysis, the same sources of experimental uncertainty as in Ref. [32] are evaluated. The leading experimental systematic uncertainties are due to the electron and muon reconstruction and selection efficiency uncertainties, which are smaller than the uncertainties associated with the theoretical predictions.

Similarly, for the $ZZ \rightarrow 2\ell 2\nu$ channel, the same sources of experimental uncertainty as in Ref. [70] are evaluated. These experimental uncertainties affect the sensitivity of the $\mu_{\text{off-shell}}$ measurement only at the percent level.

The uncertainty in the combined 2015 and 2016 integrated luminosity is 2.1%, derived following a methodology similar to that detailed in Ref. [71], from a preliminary calibration of the luminosity scale using x – y beam-separation scans. This uncertainty is applied to the normalisation of the signal and also to background contributions whose normalisations are derived from MC simulations. A variation in the pile-up reweighting of MC events is included to cover the uncertainty in the ratio of the predicted and measured inelastic cross sections in Ref. [72].

7 Results

The results for the $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ analyses are first translated into limits on the off-shell signal strength $\mu_{\text{off-shell}}$. A single off-shell signal-strength parameter is applied for all production modes, assuming that the ratio of the off-shell production rates via the ggF process to those via the VBF process are as predicted in the SM, namely $\mu_{\text{off-shell}}^{\text{ggF}}/\mu_{\text{off-shell}}^{\text{VBF}} = 1$. In a second step, the off-shell analyses are combined with the on-shell $ZZ^* \rightarrow 4\ell$ [73] analysis, where the on-shell Higgs signal strength is measured to be $\mu_{\text{on-shell}} = 1.28^{+0.21}_{-0.19}$. The combination with the on-shell analysis is performed with two assumptions that correspond to different interpretations of the results. In the first combination, the parameter of interest is the ratio of off-shell to on-shell signal strengths, which can be interpreted as the Higgs boson width normalised to its SM prediction: $\mu_{\text{off-shell}}/\mu_{\text{on-shell}} = \Gamma_H/\Gamma_H^{\text{SM}}$. This interpretation assumes that the off- and on-shell coupling modifiers are the same for both ggF and VBF production modes (i.e., $\kappa_{g,\text{on-shell}} = \kappa_{g,\text{off-shell}} = \kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}$). In the second combination, the parameter of interest is

the ratio of off-shell to on-shell signal strengths for the ggF production only, $R_{gg} = \mu_{\text{off-shell}}^{\text{ggF}} / \mu_{\text{on-shell}}^{\text{ggF}}$, which can be interpreted as the ratio of off-shell to on-shell gluon couplings: $R_{gg} = \kappa_{g,\text{off-shell}}^2 / \kappa_{g,\text{on-shell}}^2$. In this case the coupling scale factors $\kappa_V = \kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}$ associated with on- and off-shell VBF production and the $H^{(*)} \rightarrow ZZ$ decay are assumed to be the same and fitted to the data (profiled). This also assumes that the total width is equal to the SM prediction.

The statistical analysis is based on the framework described in Refs. [74–76]. A binned likelihood function is constructed as a product of Poisson probability terms over all bins of the fit templates considered. This function depends on the parameter of interest μ , corresponding to one of the different interpretations discussed above ($\mu_{\text{off-shell}}$, $\Gamma_H / \Gamma_H^{\text{SM}}$ and R_{gg}), and θ , a set of nuisance parameters that encode the effects of systematic uncertainties on the signal and expected backgrounds, as described in Section 6. The nuisance parameters are constrained using either Gaussian or log-normal terms.

In the $ZZ \rightarrow 4\ell$ channel, a binned maximum-likelihood fit to the D_{ME} distribution is performed to extract the limits on μ . The fit model accounts for signal and background processes, including $gg \rightarrow (H^* \rightarrow)ZZ$, VBF $(H^* \rightarrow)ZZ$, $q\bar{q} \rightarrow ZZ$ and other backgrounds. The probability density functions of the signal-related processes $gg \rightarrow (H^* \rightarrow)ZZ$ and VBF $(H^* \rightarrow)ZZ$ are parameterised as a function of the off-shell Higgs boson signal strength $\mu_{\text{off-shell}}$ as given in Eqs. (1) and (2). In the $ZZ \rightarrow 2\ell 2\nu$ channel, a similar maximum-likelihood fit to the m_{T}^{ZZ} distribution is performed. The modelling of the dominant signal and background processes is the same as in the $ZZ \rightarrow 4\ell$ channel. The likelihood function for the combination of the $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ channels is the product of the Poisson likelihoods of these individual channels. The main common theoretical and experimental systematic uncertainties are treated as correlated within different channels.

The PDF uncertainties and uncertainties from higher-order QCD corrections applied to the $q\bar{q} \rightarrow ZZ$ process are considered correlated between the on-shell and off-shell measurements. Given the different theoretical computations, the corresponding uncertainties are considered uncorrelated for the gg-initiated ZZ processes between the on-shell and off-shell measurements, and the impact of such a correlation effect is found to be small. In addition to the main theoretical uncertainties, the common experimental systematic uncertainties are treated as correlated between the on-shell and off-shell measurements.

Hypothesis testing and confidence intervals are based on the profile likelihood ratio [77]. The parameters of interest are different in the various tests, while the remaining parameters are profiled. All 95% CL upper limits are derived using the CL_s method [78], based on the ratio of one-sided p -values: $R_{\text{CL}_s}(\mu) = p_\mu / (1 - p_1)$ where p_μ is the p -value for testing a given $\mu = \mu_{\text{off-shell}}$ or $\mu = \Gamma_H / \Gamma_H^{\text{SM}}$ (the non-SM hypothesis) and p_1 is the p -value derived from the same test statistic under the SM hypothesis of $\mu_{\text{off-shell}} = 1$ in the first case and $\Gamma_H / \Gamma_H^{\text{SM}} = 1$ in the second case.²

The negative log-likelihood, $-2 \ln \lambda$, is scanned as a function of a single parameter of interest, chosen to be $\mu_{\text{off-shell}}$, $\Gamma_H / \Gamma_H^{\text{SM}}$ or R_{gg} . The results are shown in Figure 3 for observed and expected values. The results based on the CL_s method for the two individual analyses and their combination are reported in Table 2. As a result of the small data excess observed in the off-shell region, the observed limits on $\mu_{\text{off-shell}}$ are less stringent than the expected ones. The observed (expected) limit on $\Gamma_H / \Gamma_H^{\text{SM}}$ is 3.5 (3.7) at the 95% CL. Due to the fact that the measured on-shell signal strength $\mu_{\text{on-shell}}$ is larger than one [32], the observed limit on $\Gamma_H / \Gamma_H^{\text{SM}}$ is smaller than the expected limit. The limit on $\Gamma_H / \Gamma_H^{\text{SM}}$ can be translated into a limit on the total width of the Higgs boson, leading to an observed (expected) 95% CL upper limit on the Higgs boson total width of 14.4 (15.2) MeV.

² In the context of this analysis the alternative hypothesis is given by the SM value(s) for all relevant parameters of the fit model.

These results are significantly improved compared to the Run-1 publication [26], the expected limit being about a factor two better.

If instead of constraining the $q\bar{q} \rightarrow ZZ$ background to the theoretical expectation, the normalisation is left as a free parameter in the profile likelihood fit, the upper limits on $\mu_{\text{on-shell}}$ are about 4% worse in the $ZZ \rightarrow 4\ell$ channel. If only the NLO K -factor are applied to the SM prediction of the gg -initiated ZZ processes, without the additional NNLO/NLO K -factor of 1.2 (Section 3), the upper limits on $\mu_{\text{off-shell}}$ and $\Gamma_H/\Gamma_H^{\text{SM}}$ are about 10% worse.

Table 2: The 95% CL upper limits on $\mu_{\text{off-shell}}$, $\Gamma_H/\Gamma_H^{\text{SM}}$ and R_{gg} . Both the observed and expected limits are given. The 1σ (2σ) uncertainties represent 68% (95%) confidence intervals for the expected limit. The upper limits are evaluated using the CL_s method, with the SM values as the alternative hypothesis for each interpretation.

		Observed	Median	Expected	
				$\pm 1\sigma$	$\pm 2\sigma$
$\mu_{\text{off-shell}}$	$ZZ \rightarrow 4\ell$ analysis	4.5	4.3	[3.3, 5.4]	[2.7, 7.1]
	$ZZ \rightarrow 2\ell 2\nu$ analysis	5.3	4.4	[3.4, 5.5]	[2.8, 7.0]
	Combined	3.8	3.4	[2.7, 4.2]	[2.3, 5.3]
$\Gamma_H/\Gamma_H^{\text{SM}}$	Combined	3.5	3.7	[2.9, 4.8]	[2.4, 6.5]
R_{gg}	Combined	4.3	4.1	[3.3, 5.6]	[2.7, 8.2]

The impact of the various systematic uncertainties on the expected limit in the $\mu_{\text{off-shell}}$ fit are listed in Table 3. The values in this table were derived by fixing all the nuisance parameters associated with the systematic uncertainties to the values derived from the SM-conditional fit to the data, with the exception of the one under study. The uncertainties with the largest impact on the sensitivity of $\mu_{\text{off-shell}}$ are the theoretical uncertainties of the gg - and $q\bar{q}$ -initiated ZZ processes.

Table 3: The expected 95% CL upper limit on $\mu_{\text{off-shell}}$ with a ranked listing of the impact of the leading systematic uncertainty individually, comparing with no systematic uncertainty or all systematic uncertainties. The upper limits are evaluated using the CL_s method.

Systematic uncertainty	95% CL upper limit on $\mu_{\text{off-shell}}$		
	$ZZ \rightarrow 4\ell$	$ZZ \rightarrow 2\ell 2\nu$	Combined
QCD scale $q\bar{q} \rightarrow ZZ$	4.2	3.9	3.2
QCD scale $gg \rightarrow (H^* \rightarrow)ZZ$	4.2	3.6	3.1
Luminosity	4.1	3.5	3.1
Remaining systematic uncertainties	4.1	3.5	3.0
All systematic uncertainties	4.3	4.4	3.4
No systematic uncertainties	4.0	3.4	3.0

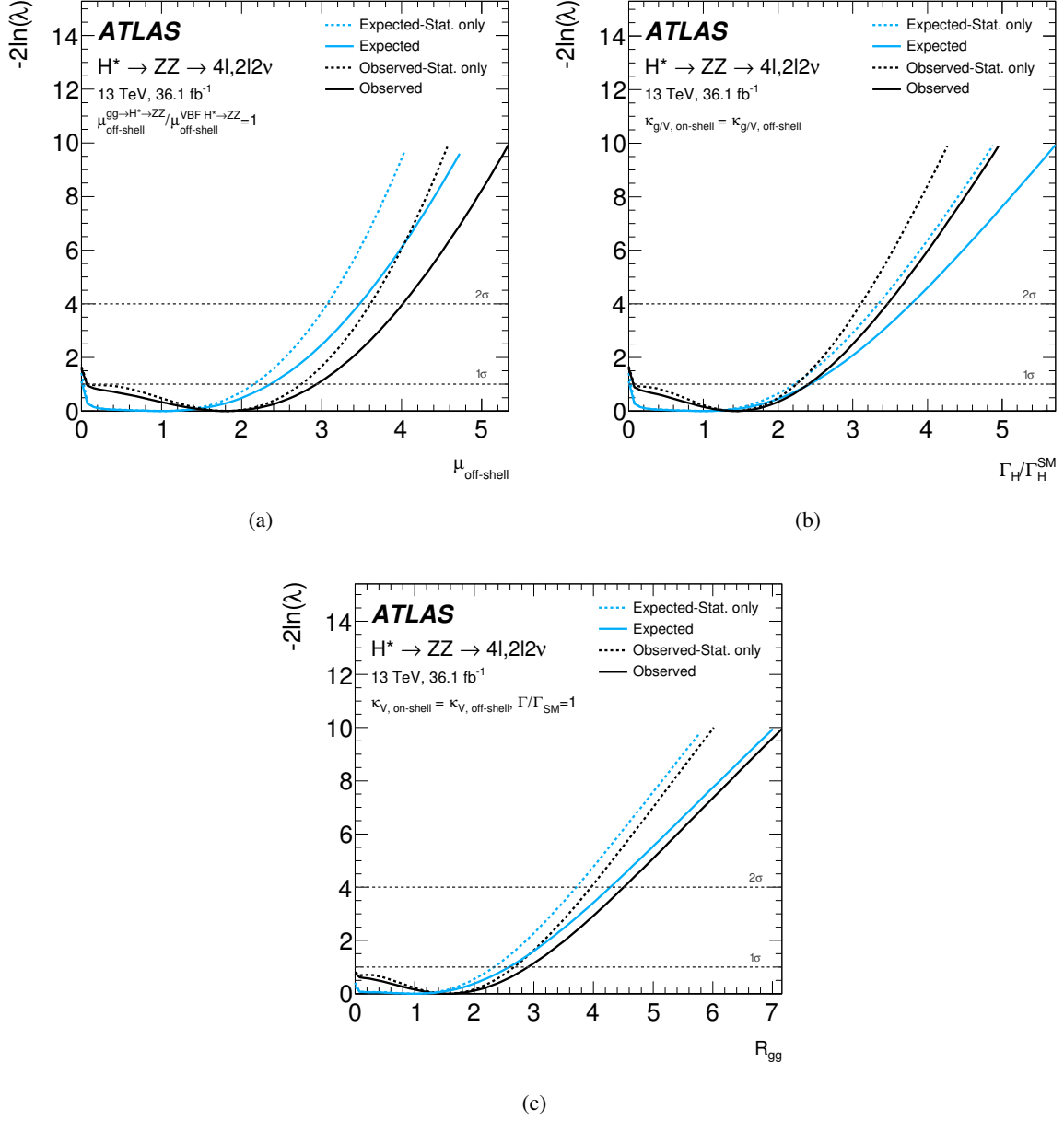


Figure 3: Scan of the negative log-likelihood, $-2 \ln \lambda$, for the (a) off-shell Higgs signal strength, $\mu_{\text{off-shell}}$ (b) $\Gamma_H/\Gamma_H^{\text{SM}}$ ratio (c) $R_{gg} = \kappa_{g,\text{off-shell}}^2/\kappa_{g,\text{on-shell}}^2$. The solid lower black (upper blue) line represents the observed (expected) value including all systematic uncertainties, while the dashed lower black (upper blue) line is for the observed (expected) value without systematic uncertainties (lower and upper refer here to the position of the lines in the legend). The double minimum structure of the scan when the parameter of interest approaches zero is the consequence of the parametrisation as shown in Eqs. (1).

8 Conclusion

A determination of the off-shell Higgs boson signal strength in the $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ final states and their combination is presented. The result is based on pp collision data collected by the ATLAS experiment at the LHC, corresponding to an integrated luminosity of 36.1 fb^{-1} at a collision energy of $\sqrt{s} = 13 \text{ TeV}$. Using the CL_s method, the observed (expected) 95% confidence level (CL) upper limit on the off-shell signal strength is 3.8 (3.4). Assuming the ratio of the relevant Higgs boson couplings to the SM predictions are constant with energy from on-shell production to the high-mass range considered in this analysis, a combination with the on-shell measurements yields an observed (expected) 95% CL upper limit on the Higgs boson total width of 14.4 (15.2) MeV.

Assuming that the total width of the Higgs boson is as expected in the SM, and the coupling scale factors associated with on- and off-shell VBF production and the $H^{(*)} \rightarrow ZZ$ decay are the same, the same combination can be interpreted as a limit on the ratio of the off-shell to the on-shell couplings to gluons $R_{gg} = \kappa_{g,\text{off-shell}}^2 / \kappa_{g,\text{on-shell}}^2$. An observed (expected) limit of 4.3 (4.1) at 95% CL on R_{gg} is obtained.

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The ATLAS Collaboration

M. Aaboud^{34d}, G. Aad⁹⁹, B. Abbott¹²⁴, O. Abidinov^{13,*}, B. Abeloos¹²⁸, D.K. Abhayasinghe⁹¹, S.H. Abidi¹⁶⁴, O.S. AbouZeid³⁹, N.L. Abraham¹⁵³, H. Abramowicz¹⁵⁸, H. Abreu¹⁵⁷, Y. Abulaiti⁶, B.S. Acharya^{64a,64b,n}, S. Adachi¹⁶⁰, L. Adam⁹⁷, L. Adamczyk^{81a}, J. Adelman¹¹⁹, M. Adersberger¹¹², A. Adiguzel^{12c,ag}, T. Adye¹⁴¹, A.A. Affolder¹⁴³, Y. Afik¹⁵⁷, C. Agheorghiesei^{27c}, J.A. Aguilar-Saavedra^{136f,136a}, F. Ahmadov^{77,ae}, G. Aielli^{71a,71b}, S. Akatsuka⁸³, T.P.A. Åkesson⁹⁴, E. Akilli⁵², A.V. Akimov¹⁰⁸, G.L. Alberghi^{23b,23a}, J. Albert¹⁷³, P. Albicocco⁴⁹, M.J. Alconada Verzini⁸⁶, S. Alderweireldt¹¹⁷, M. Aleksa³⁵, I.N. Aleksandrov⁷⁷, C. Alexa^{27b}, T. Alexopoulos¹⁰, M. Alhroob¹²⁴, B. Ali¹³⁸, G. Alimonti^{66a}, J. Alison³⁶, S.P. Alkire¹⁴⁵, C. Allaire¹²⁸, B.M.M. Allbrooke¹⁵³, B.W. Allen¹²⁷, P.P. Allport²¹, A. Aloisio^{67a,67b}, A. Alonso³⁹, F. Alonso⁸⁶, C. Alpigiani¹⁴⁵, A.A. Alshehri⁵⁵, M.I. Alstady⁹⁹, B. Alvarez Gonzalez³⁵, D. Álvarez Piqueras¹⁷¹, M.G. Alviggi^{67a,67b}, B.T. Amadio¹⁸, Y. Amaral Coutinho^{78b}, A. Ambler¹⁰¹, L. Ambroz¹³¹, C. Amelung²⁶, D. Amidei¹⁰³, S.P. Amor Dos Santos^{136a,136c}, S. Amoroso⁴⁴, C.S. Amrouche⁵², C. Anastopoulos¹⁴⁶, L.S. Ancu⁵², N. Andari¹⁴², T. Andeen¹¹, C.F. Anders^{59b}, J.K. Anders²⁰, K.J. Anderson³⁶, A. Andreazza^{66a,66b}, V. Andrei^{59a}, C.R. Anelli¹⁷³, S. Angelidakis³⁷, I. Angelozzi¹¹⁸, A. Angerami³⁸, A.V. Anisenkov^{120b,120a}, A. Annovi^{69a}, C. Antel^{59a}, M.T. Anthony¹⁴⁶, M. Antonelli⁴⁹, D.J.A. Antrim¹⁶⁸, F. Anulli^{70a}, M. Aoki⁷⁹, J.A. Aparisi Pozo¹⁷¹, L. Aperio Bella³⁵, G. Arabidze¹⁰⁴, J.P. Araque^{136a}, V. Araujo Ferraz^{78b}, R. Araujo Pereira^{78b}, A.T.H. Arce⁴⁷, R.E. Ardell⁹¹, F.A. Arduh⁸⁶, J-F. Arguin¹⁰⁷, S. Argyropoulos⁷⁵, A.J. Armbruster³⁵, L.J. Armitage⁹⁰, A. Armstrong¹⁶⁸, O. Arnaez¹⁶⁴, H. Arnold¹¹⁸, M. Arratia³¹, O. Arslan²⁴, A. Artamonov^{109,*}, G. Artoni¹³¹, S. Artz⁹⁷, S. Asai¹⁶⁰, N. Asbah⁵⁷, E.M. Asimakopoulou¹⁶⁹, L. Asquith¹⁵³, K. Assamagan²⁹, R. Astalos^{28a}, R.J. Atkin^{32a}, M. Atkinson¹⁷⁰, N.B. Atlay¹⁴⁸, K. Augsten¹³⁸, G. Avolio³⁵, R. Avramidou^{58a}, M.K. Ayoub^{15a}, G. Azuelos^{107,ar}, A.E. Baas^{59a}, M.J. Baca²¹, H. Bachacou¹⁴², K. Bachas^{65a,65b}, M. Backes¹³¹, P. Bagnaia^{70a,70b}, M. Bahmani⁸², H. Bahrasemani¹⁴⁹, A.J. Bailey¹⁷¹, J.T. Baines¹⁴¹, M. Bajic³⁹, C. Bakalis¹⁰, O.K. Baker¹⁸⁰, P.J. Bakker¹¹⁸, D. Bakshi Gupta⁹³, S. Balaji¹⁵⁴, E.M. Baldin^{120b,120a}, P. Balek¹⁷⁷, F. Balli¹⁴², W.K. Balunas¹³³, J. Balz⁹⁷, E. Banas⁸², A. Bandyopadhyay²⁴, S. Banerjee^{178j}, A.A.E. Bannoura¹⁷⁹, L. Barak¹⁵⁸, W.M. Barbe³⁷, E.L. Barberio¹⁰², D. Barberis^{53b,53a}, M. Barbero⁹⁹, T. Barillari¹¹³, M-S. Barisits³⁵, J. Barkeloo¹²⁷, T. Barklow¹⁵⁰, R. Barnea¹⁵⁷, S.L. Barnes^{58c}, B.M. Barnett¹⁴¹, R.M. Barnett¹⁸, Z. Barnovska-Blenessy^{58a}, A. Baroncelli^{72a}, G. Barone²⁶, A.J. Barr¹³¹, L. Barranco Navarro¹⁷¹, F. Barreiro⁹⁶, J. Barreiro Guimarães da Costa^{15a}, R. Bartoldus¹⁵⁰, A.E. Barton⁸⁷, P. Bartos^{28a}, A. Basalae¹³⁴, A. Bassalat¹²⁸, R.L. Bates⁵⁵, S.J. Batista¹⁶⁴, S. Batlamous^{34e}, J.R. Batley³¹, M. Battaglia¹⁴³, M. Bause^{70a,70b}, F. Bauer¹⁴², K.T. Bauer¹⁶⁸, H.S. Bawa^{150,l}, J.B. Beacham¹²², T. Beau¹³², P.H. Beauchemin¹⁶⁷, P. Bechtel²⁴, H.C. Beck⁵¹, H.P. Beck^{20,q}, K. Becker⁵⁰, M. Becker⁹⁷, C. Becot⁴⁴, A. Beddall^{12d}, A.J. Beddall^{12a}, V.A. Bednyakov⁷⁷, M. Bedognetti¹¹⁸, C.P. Bee¹⁵², T.A. Beermann³⁵, M. Begalli^{78b}, M. Begel²⁹, A. Behera¹⁵², J.K. Behr⁴⁴, A.S. Bell⁹², G. Bella¹⁵⁸, L. Bellagamba^{23b}, A. Bellerive³³, M. Bellomo¹⁵⁷, P. Bellos⁹, K. Belotskiy¹¹⁰, N.L. Belyaev¹¹⁰, O. Benary^{158,*}, D. Bencheikroun^{34a}, M. Bender¹¹², N. Benekos¹⁰, Y. Benhammou¹⁵⁸, E. Benhar Noccioli¹⁸⁰, J. Benitez⁷⁵, D.P. Benjamin⁴⁷, M. Benoit⁵², J.R. Bensinger²⁶, S. Bentvelsen¹¹⁸, L. Beresford¹³¹, M. Beretta⁴⁹, D. Berge⁴⁴, E. Bergeas Kuutmann¹⁶⁹, N. Berger⁵, L.J. Bergsten²⁶, J. Beringer¹⁸, S. Berlendis⁷, N.R. Bernard¹⁰⁰, G. Bernardi¹³², C. Bernius¹⁵⁰, F.U. Bernlochner²⁴, T. Berry⁹¹, P. Berta⁹⁷, C. Bertella^{15a}, G. Bertoli^{43a,43b}, I.A. Bertram⁸⁷, G.J. Besjes³⁹, O. Bessidskaia Bylund¹⁷⁹, M. Bessner⁴⁴, N. Besson¹⁴², A. Bethani⁹⁸, S. Bethke¹¹³, A. Betti²⁴, A.J. Bevan⁹⁰, J. Beyer¹¹³, R.M. Bianchi¹³⁵, O. Biebel¹¹², D. Biedermann¹⁹, R. Bielski³⁵, K. Bierwagen⁹⁷, N.V. Biesuz^{69a,69b}, M. Biglietti^{72a}, T.R.V. Billoud¹⁰⁷, M. Bindi⁵¹, A. Bingul^{12d}, C. Bini^{70a,70b}, S. Biondi^{23b,23a}, M. Birman¹⁷⁷, T. Bisanz⁵¹, J.P. Biswal¹⁵⁸, C. Bittrich⁴⁶, D.M. Bjergaard⁴⁷,

J.E. Black¹⁵⁰, K.M. Black²⁵, T. Blazek^{28a}, I. Bloch⁴⁴, C. Blocker²⁶, A. Blue⁵⁵, U. Blumenschein⁹⁰, Dr. Blunier^{144a}, G.J. Bobbink¹¹⁸, V.S. Bobrovnikov^{120b,120a}, S.S. Bocchetta⁹⁴, A. Bocci⁴⁷, D. Boerner¹⁷⁹, D. Bogavac¹¹², A.G. Bogdanchikov^{120b,120a}, C. Bohm^{43a}, V. Boisvert⁹¹, P. Bokan^{169,x}, T. Bold^{81a}, A.S. Boldyrev¹¹¹, A.E. Bolz^{59b}, M. Bomben¹³², M. Bona⁹⁰, J.S. Bonilla¹²⁷, M. Boonekamp¹⁴², A. Borisov¹⁴⁰, G. Borissov⁸⁷, J. Bortfeldt³⁵, D. Bortoletto¹³¹, V. Bortolotto^{71a,71b}, D. Boscherini^{23b}, M. Bosman¹⁴, J.D. Bossio Sola³⁰, K. Bouaouda^{34a}, J. Boudreau¹³⁵, E.V. Bouhova-Thacker⁸⁷, D. Boumediene³⁷, C. Bourdarios¹²⁸, S.K. Boutle⁵⁵, A. Boveia¹²², J. Boyd³⁵, D. Boye^{32b}, I.R. Boyko⁷⁷, A.J. Bozson⁹¹, J. Bracinik²¹, N. Brahimi⁹⁹, A. Brandt⁸, G. Brandt¹⁷⁹, O. Brandt^{59a}, F. Braren⁴⁴, U. Bratzler¹⁶¹, B. Brau¹⁰⁰, J.E. Brau¹²⁷, W.D. Breaden Madden⁵⁵, K. Brendlinger⁴⁴, L. Brenner⁴⁴, R. Brenner¹⁶⁹, S. Bressler¹⁷⁷, B. Brickwedde⁹⁷, D.L. Briglin²¹, D. Britton⁵⁵, D. Britzger^{59b}, I. Brock²⁴, R. Brock¹⁰⁴, G. Brooijmans³⁸, T. Brooks⁹¹, W.K. Brooks^{144b}, E. Brost¹¹⁹, J.H. Broughton²¹, P.A. Bruckman de Renstrom⁸², D. Bruncko^{28b}, A. Bruni^{23b}, G. Bruni^{23b}, L.S. Bruni¹¹⁸, S. Bruno^{71a,71b}, B.H. Brunt³¹, M. Bruschi^{23b}, N. Bruscino¹³⁵, P. Bryant³⁶, L. Bryngemark⁴⁴, T. Buanes¹⁷, Q. Buat³⁵, P. Buchholz¹⁴⁸, A.G. Buckley⁵⁵, I.A. Budagov⁷⁷, F. Buehrer⁵⁰, M.K. Bugge¹³⁰, O. Bulekov¹¹⁰, D. Bullock⁸, T.J. Burch¹¹⁹, S. Burdin⁸⁸, C.D. Burgard¹¹⁸, A.M. Burger⁵, B. Burghgrave¹¹⁹, K. Burka⁸², S. Burke¹⁴¹, I. Burmeister⁴⁵, J.T.P. Burr¹³¹, V. Büscher⁹⁷, E. Buschmann⁵¹, P. Bussey⁵⁵, J.M. Butler²⁵, C.M. Buttar⁵⁵, J.M. Butterworth⁹², P. Butti³⁵, W. Buttinger³⁵, A. Buzatu¹⁵⁵, A.R. Buzykaev^{120b,120a}, G. Cabras^{23b,23a}, S. Cabrera Urbán¹⁷¹, D. Caforio¹³⁸, H. Cai¹⁷⁰, V.M.M. Cairo², O. Cakir^{4a}, N. Calace⁵², P. Calafiura¹⁸, A. Calandri⁹⁹, G. Calderini¹³², P. Calfayan⁶³, G. Callea^{40b,40a}, L.P. Caloba^{78b}, S. Calvente Lopez⁹⁶, D. Calvet³⁷, S. Calvet³⁷, T.P. Calvet¹⁵², M. Calvetti^{69a,69b}, R. Camacho Toro¹³², S. Camarda³⁵, P. Camarri^{71a,71b}, D. Cameron¹³⁰, R. Caminal Armadans¹⁰⁰, C. Camincher³⁵, S. Campana³⁵, M. Campanelli⁹², A. Camplani³⁹, A. Campoverde¹⁴⁸, V. Canale^{67a,67b}, M. Cano Bret^{58c}, J. Cantero¹²⁵, T. Cao¹⁵⁸, Y. Cao¹⁷⁰, M.D.M. Capeans Garrido³⁵, I. Caprini^{27b}, M. Caprini^{27b}, M. Capua^{40b,40a}, R.M. Carbone³⁸, R. Cardarelli^{71a}, F.C. Cardillo¹⁴⁶, I. Carli¹³⁹, T. Carli³⁵, G. Carlino^{67a}, B.T. Carlson¹³⁵, L. Carminati^{66a,66b}, R.M.D. Carney^{43a,43b}, S. Caron¹¹⁷, E. Carquin^{144b}, S. Carrá^{66a,66b}, G.D. Carrillo-Montoya³⁵, D. Casadei^{32b}, M.P. Casado^{14,f}, A.F. Casha¹⁶⁴, D.W. Casper¹⁶⁸, R. Castelijin¹¹⁸, F.L. Castillo¹⁷¹, V. Castillo Gimenez¹⁷¹, N.F. Castro^{136a,136e}, A. Catinaccio³⁵, J.R. Catmore¹³⁰, A. Cattai³⁵, J. Caudron²⁴, V. Cavaliere²⁹, E. Cavallaro¹⁴, D. Cavalli^{66a}, M. Cavalli-Sforza¹⁴, V. Cavasinni^{69a,69b}, E. Celebi^{12b}, F. Ceradini^{72a,72b}, L. Cerda Alberich¹⁷¹, A.S. Cerqueira^{78a}, A. Cerri¹⁵³, L. Cerrito^{71a,71b}, F. Cerutti¹⁸, A. Cervelli^{23b,23a}, S.A. Cetin^{12b}, A. Chafaq^{34a}, D. Chakraborty¹¹⁹, S.K. Chan⁵⁷, W.S. Chan¹¹⁸, Y.L. Chan^{61a}, J.D. Chapman³¹, B. Chargeishvili^{156b}, D.G. Charlton²¹, C.C. Chau³³, C.A. Chavez Barajas¹⁵³, S. Che¹²², A. Chegwidan¹⁰⁴, S. Chekanov⁶, S.V. Chekulaev^{165a}, G.A. Chelkov^{77,aq}, M.A. Chelstowska³⁵, C. Chen^{58a}, C.H. Chen⁷⁶, H. Chen²⁹, J. Chen^{58a}, J. Chen³⁸, S. Chen¹³³, S.J. Chen^{15c}, X. Chen^{15b,ap}, Y. Chen⁸⁰, Y-H. Chen⁴⁴, H.C. Cheng¹⁰³, H.J. Cheng^{15d}, A. Cheplakov⁷⁷, E. Cheremushkina¹⁴⁰, R. Cherkaoui El Moursli^{34e}, E. Cheu⁷, K. Cheung⁶², L. Chevalier¹⁴², V. Chiarella⁴⁹, G. Chiarelli^{69a}, G. Chiodini^{65a}, A.S. Chisholm^{35,21}, A. Chitan^{27b}, I. Chiu¹⁶⁰, Y.H. Chiu¹⁷³, M.V. Chizhov⁷⁷, K. Choi⁶³, A.R. Chomont¹²⁸, S. Chouridou¹⁵⁹, Y.S. Chow¹¹⁸, V. Christodoulou⁹², M.C. Chu^{61a}, J. Chudoba¹³⁷, A.J. Chuinard¹⁰¹, J.J. Chwastowski⁸², L. Chytka¹²⁶, D. Cinca⁴⁵, V. Cindro⁸⁹, I.A. Cioară²⁴, A. Ciocio¹⁸, F. Ciotto^{67a,67b}, Z.H. Citron¹⁷⁷, M. Citterio^{66a}, A. Clark⁵², M.R. Clark³⁸, P.J. Clark⁴⁸, C. Clement^{43a,43b}, Y. Coadou⁹⁹, M. Cobal^{64a,64c}, A. Coccaro^{53b,53a}, J. Cochran⁷⁶, H. Cohen¹⁵⁸, A.E.C. Coimbra¹⁷⁷, L. Colasurdo¹¹⁷, B. Cole³⁸, A.P. Colijn¹¹⁸, J. Collot⁵⁶, P. Conde Muiño^{136a,136b}, E. Coniavitis⁵⁰, S.H. Connell^{32b}, I.A. Connelly⁹⁸, S. Constantinescu^{27b}, F. Conventi^{67a,as}, A.M. Cooper-Sarkar¹³¹, F. Cormier¹⁷², K.J.R. Cormier¹⁶⁴, L.D. Corpe⁹², M. Corradi^{70a,70b}, E.E. Corrigan⁹⁴, F. Corriveau^{101,ac}, A. Cortes-Gonzalez³⁵, M.J. Costa¹⁷¹, F. Costanza⁵, D. Costanzo¹⁴⁶, G. Cottin³¹, G. Cowan⁹¹, B.E. Cox⁹⁸, J. Crane⁹⁸, K. Cranmer¹²¹, S.J. Crawley⁵⁵, R.A. Creager¹³³, G. Cree³³, S. Crépe-Renaudin⁵⁶, F. Crescioli¹³², M. Cristinziani²⁴, V. Croft¹²¹, G. Crosetti^{40b,40a}, A. Cueto⁹⁶,

T. Cuhadar Donszelmann¹⁴⁶, A.R. Cukierman¹⁵⁰, S. Czekerda⁸², P. Czodrowski³⁵,
 M.J. Da Cunha Sargedas De Sousa^{58b,136b}, C. Da Via⁹⁸, W. Dabrowski^{81a}, T. Dado^{28a,x}, S. Dahbi^{34e},
 T. Dai¹⁰³, F. Dallaire¹⁰⁷, C. Dallapiccola¹⁰⁰, M. Dam³⁹, G. D'amen^{23b,23a}, J. Damp⁹⁷, J.R. Dandoy¹³³,
 M.F. Daneri³⁰, N.P. Dang^{178j}, N.D. Dann⁹⁸, M. Danninger¹⁷², V. Dao³⁵, G. Darbo^{53b}, S. Darmora⁸,
 O. Dartsis⁵, A. Dattagupta¹²⁷, T. Daubney⁴⁴, S. D'Auria⁵⁵, W. Davey²⁴, C. David⁴⁴, T. Davidek¹³⁹,
 D.R. Davis⁴⁷, E. Dawe¹⁰², I. Dawson¹⁴⁶, K. De⁸, R. De Asmundis^{67a}, A. De Benedetti¹²⁴,
 M. De Beurs¹¹⁸, S. De Castro^{23b,23a}, S. De Cecco^{70a,70b}, N. De Groot¹¹⁷, P. de Jong¹¹⁸, H. De la Torre¹⁰⁴,
 F. De Lorenzi⁷⁶, A. De Maria^{51,s}, D. De Pedis^{70a}, A. De Salvo^{70a}, U. De Sanctis^{71a,71b},
 M. De Santis^{71a,71b}, A. De Santo¹⁵³, K. De Vasconcelos Corga⁹⁹, J.B. De Vivie De Regie¹²⁸,
 C. Debenedetti¹⁴³, D.V. Dedovich⁷⁷, N. Dehghanian³, M. Del Gaudio^{40b,40a}, J. Del Peso⁹⁶,
 Y. Delabat Diaz⁴⁴, D. Delgove¹²⁸, F. Deliot¹⁴², C.M. Delitzsch⁷, M. Della Pietra^{67a,67b}, D. Della Volpe⁵²,
 A. Dell'Acqua³⁵, L. Dell'Asta²⁵, M. Delmastro⁵, C. Delporte¹²⁸, P.A. Delsart⁵⁶, D.A. DeMarco¹⁶⁴,
 S. Demers¹⁸⁰, M. Demichev⁷⁷, S.P. Denisov¹⁴⁰, D. Denysiuk¹¹⁸, L. D'Eramo¹³², D. Derendarz⁸²,
 J.E. Derkaoui^{34d}, F. Derue¹³², P. Dervan⁸⁸, K. Desch²⁴, C. Deterre⁴⁴, K. Dette¹⁶⁴, M.R. Devesa³⁰,
 P.O. Deviveiros³⁵, A. Dewhurst¹⁴¹, S. Dhaliwal²⁶, F.A. Di Bello⁵², A. Di Ciaccio^{71a,71b}, L. Di Ciaccio⁵,
 W.K. Di Clemente¹³³, C. Di Donato^{67a,67b}, A. Di Girolamo³⁵, G. Di Gregorio^{69a,69b}, B. Di Micco^{72a,72b},
 R. Di Nardo¹⁰⁰, K.F. Di Petrillo⁵⁷, R. Di Sipio¹⁶⁴, D. Di Valentino³³, C. Diaconu⁹⁹, M. Diamond¹⁶⁴,
 F.A. Dias³⁹, T. Dias Do Vale^{136a}, M.A. Diaz^{144a}, J. Dickinson¹⁸, E.B. Diehl¹⁰³, J. Dietrich¹⁹,
 S. Díez Cornell⁴⁴, A. Dimitrievska¹⁸, J. Dingfelder²⁴, F. Dittus³⁵, F. Djama⁹⁹, T. Djobava^{156b},
 J.I. Djuvsland^{59a}, M.A.B. Do Vale^{78c}, M. Dobre^{27b}, D. Dodsworth²⁶, C. Doglioni⁹⁴, J. Dolejsi¹³⁹,
 Z. Dolezal¹³⁹, M. Donadelli^{78d}, J. Donini³⁷, A. D'onofrio⁹⁰, M. D'Onofrio⁸⁸, J. Dopke¹⁴¹, A. Doria^{67a},
 M.T. Dova⁸⁶, A.T. Doyle⁵⁵, E. Drechsler⁵¹, E. Dreyer¹⁴⁹, T. Dreyer⁵¹, Y. Du^{58b}, F. Dubinin¹⁰⁸,
 M. Dubovsky^{28a}, A. Dubreuil⁵², E. Duchovni¹⁷⁷, G. Duckeck¹¹², A. Ducourthial¹³², O.A. Ducu^{107,w},
 D. Duda¹¹³, A. Dudarev³⁵, A.C. Dudder⁹⁷, E.M. Duffield¹⁸, L. Duflot¹²⁸, M. Dührssen³⁵, C. Dülzen¹⁷⁹,
 M. Dumancic¹⁷⁷, A.E. Dumitriu^{27b,d}, A.K. Duncan⁵⁵, M. Dunford^{59a}, A. Duperrin⁹⁹, H. Duran Yildiz^{4a},
 M. Düren⁵⁴, A. Durglishvili^{156b}, D. Duschinger⁴⁶, B. Dutta⁴⁴, D. Duvnjak¹, M. Dyndal⁴⁴, S. Dysch⁹⁸,
 B.S. Dziedzic⁸², C. Eckardt⁴⁴, K.M. Ecker¹¹³, R.C. Edgar¹⁰³, T. Eifert³⁵, G. Eigen¹⁷, K. Einsweiler¹⁸,
 T. Ekelof¹⁶⁹, M. El Kacimi^{34c}, R. El Kosseifi⁹⁹, V. Ellajosyula⁹⁹, M. Ellert¹⁶⁹, F. Ellinghaus¹⁷⁹,
 A.A. Elliot⁹⁰, N. Ellis³⁵, J. Elmsheuser²⁹, M. Elsing³⁵, D. Emeliyanov¹⁴¹, Y. Enari¹⁶⁰, J.S. Ennis¹⁷⁵,
 M.B. Epland⁴⁷, J. Erdmann⁴⁵, A. Ereditato²⁰, S. Errede¹⁷⁰, M. Escalier¹²⁸, C. Escobar¹⁷¹,
 O. Estrada Pastor¹⁷¹, A.I. Etienne¹⁴², E. Etzion¹⁵⁸, H. Evans⁶³, A. Ezhilov¹³⁴, M. Ezzi^{34e}, F. Fabbri⁵⁵,
 L. Fabbri^{23b,23a}, V. Fabiani¹¹⁷, G. Facini⁹², R.M. Faisca Rodrigues Pereira^{136a}, R.M. Fakhruddinov¹⁴⁰,
 S. Falciano^{70a}, P.J. Falke⁵, S. Falke⁵, J. Faltova¹³⁹, Y. Fang^{15a}, M. Fanti^{66a,66b}, A. Farbin⁸, A. Farilla^{72a},
 E.M. Farina^{68a,68b}, T. Farooque¹⁰⁴, S. Farrell¹⁸, S.M. Farrington¹⁷⁵, P. Farthouat³⁵, F. Fassi^{34e},
 P. Fassnacht³⁵, D. Fassouliotis⁹, M. Fauci Giannelli⁴⁸, A. Favareto^{53b,53a}, W.J. Fawcett³¹, L. Fayard¹²⁸,
 O.L. Fedin^{134,o}, W. Fedorko¹⁷², M. Feickert⁴¹, S. Feigl¹³⁰, L. Feligioni⁹⁹, C. Feng^{58b}, E.J. Feng³⁵,
 M. Feng⁴⁷, M.J. Fenton⁵⁵, A.B. Fenyuk¹⁴⁰, L. Feremenga⁸, J. Ferrando⁴⁴, A. Ferrari¹⁶⁹, P. Ferrari¹¹⁸,
 R. Ferrari^{68a}, D.E. Ferreira de Lima^{59b}, A. Ferrer¹⁷¹, D. Ferrere⁵², C. Ferretti¹⁰³, F. Fiedler⁹⁷,
 A. Filipčić⁸⁹, F. Filthaut¹¹⁷, K.D. Finelli²⁵, M.C.N. Fiolhais^{136a,136c,a}, L. Fiorini¹⁷¹, C. Fischer¹⁴,
 W.C. Fisher¹⁰⁴, N. Flaschel⁴⁴, I. Fleck¹⁴⁸, P. Fleischmann¹⁰³, R.R.M. Fletcher¹³³, T. Flick¹⁷⁹,
 B.M. Flierl¹¹², L.M. Flores¹³³, L.R. Flores Castillo^{61a}, F.M. Follega^{73a,73b}, N. Fomin¹⁷,
 G.T. Forcolin^{73a,73b}, A. Formica¹⁴², F.A. Förster¹⁴, A.C. Forti⁹⁸, A.G. Foster²¹, D. Fournier¹²⁸, H. Fox⁸⁷,
 S. Fracchia¹⁴⁶, P. Francavilla^{69a,69b}, M. Franchini^{23b,23a}, S. Franchino^{59a}, D. Francis³⁵, L. Franconi¹⁴³,
 M. Franklin⁵⁷, M. Frate¹⁶⁸, M. Fraternali^{68a,68b}, A.N. Fray⁹⁰, D. Freeborn⁹²,
 S.M. Fressard-Batraneanu³⁵, B. Freund¹⁰⁷, W.S. Freund^{78b}, E.M. Freundlich⁴⁵, D.C. Frizzell¹²⁴,
 D. Froidevaux³⁵, J.A. Frost¹³¹, C. Fukunaga¹⁶¹, E. Fullana Torregrosa¹⁷¹, T. Fusayasu¹¹⁴, J. Fuster¹⁷¹,
 O. Gabizon¹⁵⁷, A. Gabrielli^{23b,23a}, A. Gabrielli¹⁸, G.P. Gach^{81a}, S. Gadatsch⁵², P. Gadow¹¹³,

G. Gagliardi^{53b,53a}, L.G. Gagnon¹⁰⁷, C. Galea^{27b}, B. Galhardo^{136a,136c}, E.J. Gallas¹³¹, B.J. Gallop¹⁴¹, P. Gallus¹³⁸, G. Galster³⁹, R. Gamboa Goni⁹⁰, K.K. Gan¹²², S. Ganguly¹⁷⁷, J. Gao^{58a}, Y. Gao⁸⁸, Y.S. Gao^{150,1}, C. García¹⁷¹, J.E. García Navarro¹⁷¹, J.A. García Pascual^{15a}, M. Garcia-Sciveres¹⁸, R.W. Gardner³⁶, N. Garelli¹⁵⁰, V. Garonne¹³⁰, K. Gasnikova⁴⁴, A. Gaudiello^{53b,53a}, G. Gaudio^{68a}, I.L. Gavrilenko¹⁰⁸, A. Gavrilyuk¹⁰⁹, C. Gay¹⁷², G. Gaycken²⁴, E.N. Gazis¹⁰, C.N.P. Gee¹⁴¹, J. Geisen⁵¹, M. Geisen⁹⁷, M.P. Geisler^{59a}, K. Gellerstedt^{43a,43b}, C. Gemme^{53b}, M.H. Genest⁵⁶, C. Geng¹⁰³, S. Gentile^{70a,70b}, S. George⁹¹, D. Gerbaudo¹⁴, G. Gessner⁴⁵, S. Ghasemi¹⁴⁸, M. Ghasemi Bostanabad¹⁷³, M. Ghneimat²⁴, B. Giacobbe^{23b}, S. Giagu^{70a,70b}, N. Giangiacomi^{23b,23a}, P. Giannetti^{69a}, A. Giannini^{67a,67b}, S.M. Gibson⁹¹, M. Gignac¹⁴³, D. Gillberg³³, G. Gilles¹⁷⁹, D.M. Gingrich^{3,ar}, M.P. Giordani^{64a,64c}, F.M. Giorgi^{23b}, P.F. Giraud¹⁴², P. Giromini⁵⁷, G. Giugliarelli^{64a,64c}, D. Giugni^{66a}, F. Giuli¹³¹, M. Giulini^{59b}, S. Gkaitatzis¹⁵⁹, I. Gkialas^{9,i}, E.L. Gkougkousis¹⁴, P. Gkoutoumis¹⁰, L.K. Gladilin¹¹¹, C. Glasman⁹⁶, J. Glatzer¹⁴, P.C.F. Glaysheer⁴⁴, A. Glazov⁴⁴, M. Goblirsch-Kolb²⁶, J. Godlewski⁸², S. Goldfarb¹⁰², T. Golling⁵², D. Golubkov¹⁴⁰, A. Gomes^{136a,136b,136d}, R. Goncalves Gama^{78a}, R. Gonçalves^{136a}, G. Gonella⁵⁰, L. Gonella²¹, A. Gongadze⁷⁷, F. Gonnella²¹, J.L. Gonski⁵⁷, S. González de la Hoz¹⁷¹, S. Gonzalez-Sevilla⁵², L. Goossens³⁵, P.A. Gorbounov¹⁰⁹, H.A. Gordon²⁹, B. Gorini³⁵, E. Gorini^{65a,65b}, A. Gorišek⁸⁹, A.T. Goshaw⁴⁷, C. Gössling⁴⁵, M.I. Gostkin⁷⁷, C.A. Gottardo²⁴, C.R. Goudet¹²⁸, D. Goudami^{34c}, A.G. Goussiou¹⁴⁵, N. Govender^{32b,b}, C. Goy⁵, E. Gozani¹⁵⁷, I. Grabowska-Bold^{81a}, P.O.J. Gradin¹⁶⁹, E.C. Graham⁸⁸, J. Gramling¹⁶⁸, E. Gramstad¹³⁰, S. Grancagnolo¹⁹, V. Gratchev¹³⁴, P.M. Gravila^{27f}, F.G. Gravili^{65a,65b}, C. Gray⁵⁵, H.M. Gray¹⁸, Z.D. Greenwood^{93,ai}, C. Grefe²⁴, K. Gregersen⁹⁴, I.M. Gregor⁴⁴, P. Grenier¹⁵⁰, K. Grevtsov⁴⁴, N.A. Grieser¹²⁴, J. Griffiths⁸, A.A. Grillo¹⁴³, K. Grimm¹⁵⁰, S. Grinstein^{14,y}, Ph. Gris³⁷, J.-F. Grivaz¹²⁸, S. Groh⁹⁷, E. Gross¹⁷⁷, J. Grosse-Knetter⁵¹, G.C. Grossi⁹³, Z.J. Grout⁹², C. Grud¹⁰³, A. Grummer¹¹⁶, L. Guan¹⁰³, W. Guan¹⁷⁸, J. Guenther³⁵, A. Guerguichon¹²⁸, F. Guescini^{165a}, D. Guest¹⁶⁸, R. Gugel⁵⁰, B. Gui¹²², T. Guillemin⁵, S. Guindon³⁵, U. Gul⁵⁵, C. Gumpert³⁵, J. Guo^{58c}, W. Guo¹⁰³, Y. Guo^{58a,r}, Z. Guo⁹⁹, R. Gupta⁴¹, S. Gurbuz^{12c}, G. Gustavino¹²⁴, B.J. Gutelman¹⁵⁷, P. Gutierrez¹²⁴, C. Gutschow⁹², C. Guyot¹⁴², M.P. Guzik^{81a}, C. Gwenlan¹³¹, C.B. Gwilliam⁸⁸, A. Haas¹²¹, C. Haber¹⁸, H.K. Hadavand⁸, N. Haddad^{34e}, A. Hadeef^{58a}, S. Hageböck²⁴, M. Hagihara¹⁶⁶, H. Hakobyan^{181,*}, M. Haleem¹⁷⁴, J. Haley¹²⁵, G. Halladjian¹⁰⁴, G.D. Hallowell⁹⁹, K. Hamacher¹⁷⁹, P. Hamal¹²⁶, K. Hamano¹⁷³, A. Hamilton^{32a}, G.N. Hamity¹⁴⁶, K. Han^{58a,ah}, L. Han^{58a}, S. Han^{15d}, K. Hanagaki^{79,u}, M. Hance¹⁴³, D.M. Handl¹¹², B. Haney¹³³, R. Hankache¹³², P. Hanke^{59a}, E. Hansen⁹⁴, J.B. Hansen³⁹, J.D. Hansen³⁹, M.C. Hansen²⁴, P.H. Hansen³⁹, K. Hara¹⁶⁶, A.S. Hard¹⁷⁸, T. Harenberg¹⁷⁹, S. Harkusha¹⁰⁵, P.F. Harrison¹⁷⁵, N.M. Hartmann¹¹², Y. Hasegawa¹⁴⁷, A. Hasib⁴⁸, S. Hassani¹⁴², S. Haug²⁰, R. Hauser¹⁰⁴, L. Hauswald⁴⁶, L.B. Havener³⁸, M. Havranek¹³⁸, C.M. Hawkes²¹, R.J. Hawkings³⁵, D. Hayden¹⁰⁴, C. Hayes¹⁵², C.P. Hays¹³¹, J.M. Hays⁹⁰, H.S. Hayward⁸⁸, S.J. Haywood¹⁴¹, M.P. Heath⁴⁸, V. Hedberg⁹⁴, L. Heelan⁸, S. Heer²⁴, K.K. Heidegger⁵⁰, J. Heilman³³, S. Heim⁴⁴, T. Heim¹⁸, B. Heinemann^{44,am}, J.J. Heinrich¹¹², L. Heinrich¹²¹, C. Heinz⁵⁴, J. Hejbal¹³⁷, L. Helary³⁵, A. Held¹⁷², S. Hellesund¹³⁰, S. Hellman^{43a,43b}, C. Helsen³⁵, R.C.W. Henderson⁸⁷, Y. Heng¹⁷⁸, S. Henkelmann¹⁷², A.M. Henriques Correia³⁵, G.H. Herbert¹⁹, H. Herde²⁶, V. Herget¹⁷⁴, Y. Hernández Jiménez^{32c}, H. Herr⁹⁷, M.G. Herrmann¹¹², G. Herten⁵⁰, R. Hertenberger¹¹², L. Hervas³⁵, T.C. Herwig¹³³, G.G. Hesketh⁹², N.P. Hessey^{165a}, J.W. Hetherly⁴¹, S. Higashino⁷⁹, E. Higón-Rodríguez¹⁷¹, K. Hildebrand³⁶, E. Hill¹⁷³, J.C. Hill³¹, K.K. Hill²⁹, K.H. Hiller⁴⁴, S.J. Hillier²¹, M. Hils⁴⁶, I. Hinchliffe¹⁸, M. Hirose¹²⁹, D. Hirschbuehl¹⁷⁹, B. Hiti⁸⁹, O. Hladik¹³⁷, D.R. Hlaluku^{32c}, X. Hoad⁴⁸, J. Hobbs¹⁵², N. Hod^{165a}, M.C. Hodgkinson¹⁴⁶, A. Hoecker³⁵, M.R. Hoefkamp¹¹⁶, F. Hoenig¹¹², D. Hohn²⁴, D. Hohov¹²⁸, T.R. Holmes³⁶, M. Holzbock¹¹², M. Homann⁴⁵, S. Honda¹⁶⁶, T. Honda⁷⁹, T.M. Hong¹³⁵, A. Hönle¹¹³, B.H. Hooberman¹⁷⁰, W.H. Hopkins¹²⁷, Y. Horii¹¹⁵, P. Horn⁴⁶, A.J. Horton¹⁴⁹, L.A. Horyn³⁶, J.-Y. Hostachy⁵⁶, A. Hostiuc¹⁴⁵, S. Hou¹⁵⁵, A. Hoummada^{34a}, J. Howarth⁹⁸, J. Hoya⁸⁶, M. Hrabovsky¹²⁶, I. Hristova¹⁹, J. Hrivnac¹²⁸, A. Hrynevich¹⁰⁶, T. Hryn'ova⁵,

P.J. Hsu⁶², S.-C. Hsu¹⁴⁵, Q. Hu²⁹, S. Hu^{58c}, Y. Huang^{15a}, Z. Hubacek¹³⁸, F. Hubaut⁹⁹, M. Huebner²⁴, F. Huegging²⁴, T.B. Huffman¹³¹, E.W. Hughes³⁸, M. Huhtinen³⁵, R.F.H. Hunter³³, P. Huo¹⁵², A.M. Hupe³³, N. Huseynov^{77,ae}, J. Huston¹⁰⁴, J. Huth⁵⁷, R. Hyneman¹⁰³, G. Iacobucci⁵², G. Iakovidis²⁹, I. Ibragimov¹⁴⁸, L. Iconomidou-Fayard¹²⁸, Z. Idrissi^{34e}, P. Iengo³⁵, R. Ignazzi³⁹, O. Igonkina^{118,aa}, R. Iguchi¹⁶⁰, T. Iizawa⁵², Y. Ikegami⁷⁹, M. Ikeno⁷⁹, D. Iliadis¹⁵⁹, N. Ilic¹⁵⁰, F. Iltzsche⁴⁶, G. Introzzi^{68a,68b}, M. Iodice^{72a}, K. Iordanidou³⁸, V. Ippolito^{70a,70b}, M.F. Isacson¹⁶⁹, N. Ishijima¹²⁹, M. Ishino¹⁶⁰, M. Ishitsuka¹⁶², W. Islam¹²⁵, C. Issever¹³¹, S. Istin¹⁵⁷, F. Ito¹⁶⁶, J.M. Iturbe Ponce^{61a}, R. Iuppa^{73a,73b}, A. Ivina¹⁷⁷, H. Iwasaki⁷⁹, J.M. Izen⁴², V. Izzo^{67a}, P. Jacka¹³⁷, P. Jackson¹, R.M. Jacobs²⁴, V. Jain², G. Jäkel¹⁷⁹, K.B. Jakobi⁹⁷, K. Jakobs⁵⁰, S. Jakobsen⁷⁴, T. Jakoubek¹³⁷, D.O. Jamin¹²⁵, D.K. Jana⁹³, R. Jansky⁵², J. Janssen²⁴, M. Janus⁵¹, P.A. Janus^{81a}, G. Jarlskog⁹⁴, N. Javadov^{77,ae}, T. Javůrek³⁵, M. Javurkova⁵⁰, F. Jeanneau¹⁴², L. Jeanty¹⁸, J. Jejelava^{156a,af}, A. Jelinskas¹⁷⁵, P. Jenni^{50,c}, J. Jeong⁴⁴, N. Jeong⁴⁴, S. Jézéquel⁵, H. Ji¹⁷⁸, J. Jia¹⁵², H. Jiang⁷⁶, Y. Jiang^{58a}, Z. Jiang^{150,p}, S. Jiggins⁵⁰, F.A. Jimenez Morales³⁷, J. Jimenez Pena¹⁷¹, S. Jin^{15c}, A. Jinaru^{27b}, O. Jinnouchi¹⁶², H. Jivan^{32c}, P. Johansson¹⁴⁶, K.A. Johns⁷, C.A. Johnson⁶³, W.J. Johnson¹⁴⁵, K. Jon-And^{43a,43b}, R.W.L. Jones⁸⁷, S.D. Jones¹⁵³, S. Jones⁷, T.J. Jones⁸⁸, J. Jongmanns^{59a}, P.M. Jorge^{136a,136b}, J. Jovicevic^{165a}, X. Ju¹⁸, J.J. Junggeburth¹¹³, A. Juste Rozas^{14,y}, A. Kaczmarska⁸², M. Kado¹²⁸, H. Kagan¹²², M. Kagan¹⁵⁰, T. Kaji¹⁷⁶, E. Kajomovitz¹⁵⁷, C.W. Kalderon⁹⁴, A. Kaluza⁹⁷, S. Kama⁴¹, A. Kamenshchikov¹⁴⁰, L. Kanjir⁸⁹, Y. Kano¹⁶⁰, V.A. Kantserov¹¹⁰, J. Kanzaki⁷⁹, B. Kaplan¹²¹, L.S. Kaplan¹⁷⁸, D. Kar^{32c}, M.J. Kareem^{165b}, E. Karentzos¹⁰, S.N. Karpov⁷⁷, Z.M. Karpova⁷⁷, V. Kartvelishvili⁸⁷, A.N. Karyukhin¹⁴⁰, L. Kashif¹⁷⁸, R.D. Kass¹²², A. Kastanas^{43a,43b}, Y. Kataoka¹⁶⁰, C. Kato^{58d,58c}, J. Katzy⁴⁴, K. Kawade⁸⁰, K. Kawagoe⁸⁵, T. Kawamoto¹⁶⁰, G. Kawamura⁵¹, E.F. Kay⁸⁸, V.F. Kazanin^{120b,120a}, R. Keeler¹⁷³, R. Kehoe⁴¹, J.S. Keller³³, E. Kellermann⁹⁴, J.J. Kempster²¹, J. Kendrick²¹, O. Kepka¹³⁷, S. Kersten¹⁷⁹, B.P. Kerševan⁸⁹, R.A. Keyes¹⁰¹, M. Khader¹⁷⁰, F. Khalil-Zada¹³, A. Khanov¹²⁵, A.G. Kharlamov^{120b,120a}, T. Kharlamova^{120b,120a}, E.E. Khoda¹⁷², A. Khodinov¹⁶³, T.J. Khoo⁵², E. Khramov⁷⁷, J. Khubua^{156b}, S. Kido⁸⁰, M. Kiehn⁵², C.R. Kilby⁹¹, Y.K. Kim³⁶, N. Kimura^{64a,64c}, O.M. Kind¹⁹, B.T. King⁸⁸, D. Kirchmeier⁴⁶, J. Kirk¹⁴¹, A.E. Kiryunin¹¹³, T. Kishimoto¹⁶⁰, D. Kisielewska^{81a}, V. Kitali⁴⁴, O. Kivernyk⁵, E. Kladiva^{28b}, T. Klapdor-Kleingrothaus⁵⁰, M.H. Klein¹⁰³, M. Klein⁸⁸, U. Klein⁸⁸, K. Kleinknecht⁹⁷, P. Klimek¹¹⁹, A. Klimentov²⁹, R. Klingenberg^{45,*}, T. Klingl²⁴, T. Klioutchnikova³⁵, F.F. Klitzner¹¹², P. Kluit¹¹⁸, S. Kluth¹¹³, E. Kneringer⁷⁴, E.B.F.G. Knoops⁹⁹, A. Knue⁵⁰, A. Kobayashi¹⁶⁰, D. Kobayashi⁸⁵, T. Kobayashi¹⁶⁰, M. Kobel⁴⁶, M. Kocian¹⁵⁰, P. Kodys¹³⁹, P.T. Koenig²⁴, T. Koffas³³, E. Koffeman¹¹⁸, N.M. Köhler¹¹³, T. Koi¹⁵⁰, M. Kolb^{59b}, I. Koletsou⁵, T. Kondo⁷⁹, N. Kondrashova^{58c}, K. Köneke⁵⁰, A.C. König¹¹⁷, T. Kono⁷⁹, R. Konoplich^{121,aj}, V. Konstantinides⁹², N. Konstantinidis⁹², B. Konya⁹⁴, R. Kopeliansky⁶³, S. Koperny^{81a}, K. Korcyl⁸², K. Kordas¹⁵⁹, G. Koren¹⁵⁸, A. Korn⁹², I. Korolkov¹⁴, E.V. Korolkova¹⁴⁶, N. Korotkova¹¹¹, O. Kortner¹¹³, S. Kortner¹¹³, T. Kosek¹³⁹, V.V. Kostyukhin²⁴, A. Kotwal⁴⁷, A. Koulouris¹⁰, A. Kourkoulis-Charalampidi^{68a,68b}, C. Kourkoulis⁹, E. Kourlitis¹⁴⁶, V. Kouskoura²⁹, A.B. Kowalewska⁸², R. Kowalewski¹⁷³, T.Z. Kowalski^{81a}, C. Kozakai¹⁶⁰, W. Kozanecki¹⁴², A.S. Kozhin¹⁴⁰, V.A. Kramarenko¹¹¹, G. Kramberger⁸⁹, D. Krasnopevtsev^{58a}, M.W. Krasny¹³², A. Krasznahorkay³⁵, D. Krauss¹¹³, J.A. Kremer^{81a}, J. Kretzschmar⁸⁸, P. Krieger¹⁶⁴, K. Krizka¹⁸, K. Kroeninger⁴⁵, H. Kroha¹¹³, J. Kroll¹³⁷, J. Kroll¹³³, J. Krstic¹⁶, U. Kruchonak⁷⁷, H. Krüger²⁴, N. Krumnack⁷⁶, M.C. Kruse⁴⁷, T. Kubota¹⁰², S. Kuday^{4b}, J.T. Kuechler¹⁷⁹, S. Kuehn³⁵, A. Kugel^{59a}, F. Kuger¹⁷⁴, T. Kuhl⁴⁴, V. Kukhtin⁷⁷, R. Kukla⁹⁹, Y. Kulchitsky¹⁰⁵, S. Kuleshov^{144b}, Y.P. Kulinich¹⁷⁰, M. Kuna⁵⁶, T. Kunigo⁸³, A. Kupco¹³⁷, T. Kupfer⁴⁵, O. Kuprash¹⁵⁸, H. Kurashige⁸⁰, L.L. Kurchaninov^{165a}, Y.A. Kurochkin¹⁰⁵, M.G. Kurth^{15d}, E.S. Kuwertz³⁵, M. Kuze¹⁶², J. Kvita¹²⁶, T. Kwan¹⁰¹, A. La Rosa¹¹³, J.L. La Rosa Navarro^{78d}, L. La Rotonda^{40b,40a}, F. La Ruffa^{40b,40a}, C. Lacasta¹⁷¹, F. Lacava^{70a,70b}, J. Lacey⁴⁴, D.P.J. Lack⁹⁸, H. Lacker¹⁹, D. Lacour¹³², E. Ladygin⁷⁷, R. Lafaye⁵, B. Laforge¹³², T. Lagouri^{32c}, S. Lai⁵¹, S. Lammers⁶³, W. Lampl⁷, E. Lançon²⁹,

U. Landgraf⁵⁰, M.P.J. Landon⁹⁰, M.C. Lanfermann⁵², V.S. Lang⁴⁴, J.C. Lange¹⁴, R.J. Langenberg³⁵, A.J. Lankford¹⁶⁸, F. Lanni²⁹, K. Lantzsch²⁴, A. Lanza^{68a}, A. Lapertosa^{53b,53a}, S. Laplace¹³², J.F. Laporte¹⁴², T. Lari^{66a}, F. Lasagni Manghi^{23b,23a}, M. Lassnig³⁵, T.S. Lau^{61a}, A. Laudrain¹²⁸, M. Lavorgna^{67a,67b}, A.T. Law¹⁴³, M. Lazzaroni^{66a,66b}, B. Le¹⁰², O. Le Dortz¹³², E. Le Guirriec⁹⁹, E.P. Le Quilleuc¹⁴², M. LeBlanc⁷, T. LeCompte⁶, F. Ledroit-Guillon⁵⁶, C.A. Lee²⁹, G.R. Lee^{144a}, L. Lee⁵⁷, S.C. Lee¹⁵⁵, B. Lefebvre¹⁰¹, M. Lefebvre¹⁷³, F. Legger¹¹², C. Leggett¹⁸, K. Lehmann¹⁴⁹, N. Lehmann¹⁷⁹, G. Lehmann Miotto³⁵, W.A. Leight⁴⁴, A. Leisos^{159,v}, M.A.L. Leite^{78d}, R. Leitner¹³⁹, D. Lellouch¹⁷⁷, B. Lemmer⁵¹, K.J.C. Leney⁹², T. Lenz²⁴, B. Lenzi³⁵, R. Leone⁷, S. Leone^{69a}, C. Leonidopoulos⁴⁸, G. Lerner¹⁵³, C. Leroy¹⁰⁷, R. Les¹⁶⁴, A.A.J. Lesage¹⁴², C.G. Lester³¹, M. Levchenko¹³⁴, J. Levêque⁵, D. Levin¹⁰³, L.J. Levinson¹⁷⁷, D. Lewis⁹⁰, B. Li¹⁰³, C-Q. Li^{58a}, H. Li^{58b}, L. Li^{58c}, M. Li^{15a}, Q. Li^{15d}, Q.Y. Li^{58a}, S. Li^{58d,58c}, X. Li^{58c}, Y. Li¹⁴⁸, Z. Liang^{15a}, B. Liberti^{71a}, A. Liblong¹⁶⁴, K. Lie^{61c}, S. Liem¹¹⁸, A. Limosani¹⁵⁴, C.Y. Lin³¹, K. Lin¹⁰⁴, T.H. Lin⁹⁷, R.A. Linck⁶³, J.H. Lindon²¹, B.E. Lindquist¹⁵², A.L. Lioni⁵², E. Lipeles¹³³, A. Lipniacka¹⁷, M. Lisovyi^{59b}, T.M. Liss^{170,ao}, A. Lister¹⁷², A.M. Litke¹⁴³, J.D. Little⁸, B. Liu⁷⁶, B.L. Liu⁶, H.B. Liu²⁹, H. Liu¹⁰³, J.B. Liu^{58a}, J.K.K. Liu¹³¹, K. Liu¹³², M. Liu^{58a}, P. Liu¹⁸, Y. Liu^{15a}, Y.L. Liu^{58a}, Y.W. Liu^{58a}, M. Livan^{68a,68b}, A. Lleres⁵⁶, J. Llorente Merino^{15a}, S.L. Lloyd⁹⁰, C.Y. Lo^{61b}, F. Lo Sterzo⁴¹, E.M. Lobodzinska⁴⁴, P. Loch⁷, A. Loesle⁵⁰, T. Lohse¹⁹, K. Lohwasser¹⁴⁶, M. Lokajicek¹³⁷, B.A. Long²⁵, J.D. Long¹⁷⁰, R.E. Long⁸⁷, L. Longo^{65a,65b}, K.A. Looper¹²², J.A. Lopez^{144b}, I. Lopez Paz¹⁴, A. Lopez Solis¹⁴⁶, J. Lorenz¹¹², N. Lorenzo Martinez⁵, M. Losada²², P.J. Lösel¹¹², X. Lou⁴⁴, X. Lou^{15a}, A. Lounis¹²⁸, J. Love⁶, P.A. Love⁸⁷, J.J. Lozano Bahilo¹⁷¹, H. Lu^{61a}, M. Lu^{58a}, N. Lu¹⁰³, Y.J. Lu⁶², H.J. Lubatti¹⁴⁵, C. Luci^{70a,70b}, A. Lucotte⁵⁶, C. Luedtke⁵⁰, F. Luehring⁶³, I. Luise¹³², L. Luminari^{70a}, B. Lund-Jensen¹⁵¹, M.S. Lutz¹⁰⁰, P.M. Luzi¹³², D. Lynn²⁹, R. Lysak¹³⁷, E. Lytken⁹⁴, F. Lyu^{15a}, V. Lyubushkin⁷⁷, H. Ma²⁹, L.L. Ma^{58b}, Y. Ma^{58b}, G. Maccarrone⁴⁹, A. Macchiolo¹¹³, C.M. Macdonald¹⁴⁶, J. Machado Miguens^{133,136b}, D. Madaffari¹⁷¹, R. Madar³⁷, W.F. Mader⁴⁶, A. Madsen⁴⁴, N. Madysa⁴⁶, J. Maeda⁸⁰, K. Maekawa¹⁶⁰, S. Maeland¹⁷, T. Maeno²⁹, A.S. Maevskiy¹¹¹, V. Magerl⁵⁰, C. Maidantchik^{78b}, T. Maier¹¹², A. Maio^{136a,136b,136d}, O. Majersky^{28a}, S. Majewski¹²⁷, Y. Makida⁷⁹, N. Makovec¹²⁸, B. Malaescu¹³², Pa. Malecki⁸², V.P. Maleev¹³⁴, F. Malek⁵⁶, U. Mallik⁷⁵, D. Malon⁶, C. Malone³¹, S. Maltezos¹⁰, S. Malyukov³⁵, J. Mamuzic¹⁷¹, G. Mancini⁴⁹, I. Mandic⁸⁹, J. Maneira^{136a}, L. Manhaes de Andrade Filho^{78a}, J. Manjarres Ramos⁴⁶, K.H. Mankinen⁹⁴, A. Mann¹¹², A. Manousos⁷⁴, B. Mansoulie¹⁴², J.D. Mansour^{15a}, M. Mantoani⁵¹, S. Manzoni^{66a,66b}, A. Marantis¹⁵⁹, G. Marceca³⁰, L. March⁵², L. Marchese¹³¹, G. Marchiori¹³², M. Marcisovsky¹³⁷, C.A. Marin Tobon³⁵, M. Marjanovic³⁷, D.E. Marley¹⁰³, F. Marroquim^{78b}, Z. Marshall¹⁸, M.U.F. Martensson¹⁶⁹, S. Marti-Garcia¹⁷¹, C.B. Martin¹²², T.A. Martin¹⁷⁵, V.J. Martin⁴⁸, B. Martin dit Latour¹⁷, M. Martinez^{14,y}, V.I. Martinez Outschoorn¹⁰⁰, S. Martin-Haugh¹⁴¹, V.S. Martoiu^{27b}, A.C. Martyniuk⁹², A. Marzin³⁵, L. Masetti⁹⁷, T. Mashimo¹⁶⁰, R. Mashinistov¹⁰⁸, J. Masik⁹⁸, A.L. Maslennikov^{120b,120a}, L.H. Mason¹⁰², L. Massa^{71a,71b}, P. Massarotti^{67a,67b}, P. Mastrandrea⁵, A. Mastroberardino^{40b,40a}, T. Masubuchi¹⁶⁰, P. Mättig¹⁷⁹, J. Maurer^{27b}, B. Maček⁸⁹, S.J. Maxfield⁸⁸, D.A. Maximov^{120b,120a}, R. Mazini¹⁵⁵, I. Maznas¹⁵⁹, S.M. Mazza¹⁴³, N.C. Mc Fadden¹¹⁶, G. Mc Goldrick¹⁶⁴, S.P. Mc Kee¹⁰³, A. McCarn¹⁰³, T.G. McCarthy¹¹³, L.I. McClymont⁹², E.F. McDonald¹⁰², J.A. Mcfayden³⁵, G. Mchedlidze⁵¹, M.A. McKay⁴¹, K.D. McLean¹⁷³, S.J. McMahon¹⁴¹, P.C. McNamara¹⁰², C.J. McNicol¹⁷⁵, R.A. McPherson^{173,ac}, J.E. Mdhluli^{32c}, Z.A. Meadows¹⁰⁰, S. Meehan¹⁴⁵, T.M. Megy⁵⁰, S. Mehlhase¹¹², A. Mehta⁸⁸, T. Meideck⁵⁶, B. Meirose⁴², D. Melini^{171,g}, B.R. Mellado Garcia^{32c}, J.D. Mellenthin⁵¹, M. Melo^{28a}, F. Meloni⁴⁴, A. Melzer²⁴, S.B. Menary⁹⁸, E.D. Mendes Gouveia^{136a}, L. Meng⁸⁸, X.T. Meng¹⁰³, A. Mengarelli^{23b,23a}, S. Menke¹¹³, E. Meoni^{40b,40a}, S. Mergelmeyer¹⁹, C. Merlassino²⁰, P. Mermod⁵², L. Merola^{67a,67b}, C. Meroni^{66a}, F.S. Merritt³⁶, A. Messina^{70a,70b}, J. Metcalfe⁶, A.S. Mete¹⁶⁸, C. Meyer¹³³, J. Meyer¹⁵⁷, J-P. Meyer¹⁴², H. Meyer Zu Theenhausen^{59a}, F. Miano¹⁵³, R.P. Middleton¹⁴¹, L. Mijović⁴⁸, G. Mikenberg¹⁷⁷, M. Mikestikova¹³⁷, M. Mikuž⁸⁹,

M. Milesi¹⁰², A. Milic¹⁶⁴, D.A. Millar⁹⁰, D.W. Miller³⁶, A. Milov¹⁷⁷, D.A. Milstead^{43a,43b},
A.A. Minaenko¹⁴⁰, M. Miñano Moya¹⁷¹, I.A. Minashvili^{156b}, A.I. Mincer¹²¹, B. Mindur^{81a},
M. Mineev⁷⁷, Y. Minegishi¹⁶⁰, Y. Ming¹⁷⁸, L.M. Mir¹⁴, A. Mirto^{65a,65b}, K.P. Mistry¹³³, T. Mitani¹⁷⁶,
J. Mitrevski¹¹², V.A. Mitsou¹⁷¹, A. Miucci²⁰, P.S. Miyagawa¹⁴⁶, A. Mizukami⁷⁹, J.U. Mjörnmark⁹⁴,
T. Mkrtchyan¹⁸¹, M. Mlynarikova¹³⁹, T. Moa^{43a,43b}, K. Mochizuki¹⁰⁷, P. Mogg⁵⁰, S. Mohapatra³⁸,
S. Molander^{43a,43b}, R. Moles-Valls²⁴, M.C. Mondragon¹⁰⁴, K. Mönig⁴⁴, J. Monk³⁹, E. Monnier⁹⁹,
A. Montalbano¹⁴⁹, J. Montejó Berlingen³⁵, F. Monticelli⁸⁶, S. Monzani^{66a}, N. Morange¹²⁸, D. Moreno²²,
M. Moreno Llácer³⁵, P. Morettini^{53b}, M. Morgenstern¹¹⁸, S. Morgenstern⁴⁶, D. Mori¹⁴⁹, M. Morii⁵⁷,
M. Morinaga¹⁷⁶, V. Morisbak¹³⁰, A.K. Morley³⁵, G. Mornacchi³⁵, A.P. Morris⁹², J.D. Morris⁹⁰,
L. Morvaj¹⁵², P. Moschovakos¹⁰, M. Mosidze^{156b}, H.J. Moss¹⁴⁶, J. Moss^{150,m}, K. Motohashi¹⁶²,
R. Mount¹⁵⁰, E. Mountricha³⁵, E.J.W. Moyse¹⁰⁰, S. Muanza⁹⁹, F. Mueller¹¹³, J. Mueller¹³⁵,
R.S.P. Mueller¹¹², D. Muenstermann⁸⁷, G.A. Mullier⁹⁴, F.J. Munoz Sanchez⁹⁸, P. Murin^{28b},
W.J. Murray^{175,141}, A. Murrone^{66a,66b}, M. Muškinja⁸⁹, C. Mwewa^{32a}, A.G. Myagkov^{140,ak}, J. Myers¹²⁷,
M. Myska¹³⁸, B.P. Nachman¹⁸, O. Nackenhorst⁴⁵, K. Nagai¹³¹, K. Nagano⁷⁹, Y. Nagasaka⁶⁰, M. Nagel⁵⁰,
E. Nagy⁹⁹, A.M. Nairz³⁵, Y. Nakahama¹¹⁵, K. Nakamura⁷⁹, T. Nakamura¹⁶⁰, I. Nakano¹²³, H. Nanjo¹²⁹,
F. Napolitano^{59a}, R.F. Naranjo Garcia⁴⁴, R. Narayan¹¹, D.I. Narrias Villar^{59a}, I. Naryshkin¹³⁴,
T. Naumann⁴⁴, G. Navarro²², R. Nayyar⁷, H.A. Neal¹⁰³, P.Y. Nechaeva¹⁰⁸, T.J. Neep¹⁴², A. Negri^{68a,68b},
M. Negrini^{23b}, S. Nektarijevic¹¹⁷, C. Nellist⁵¹, M.E. Nelson¹³¹, S. Nemecek¹³⁷, P. Nemethy¹²¹,
M. Nessi^{35,e}, M.S. Neubauer¹⁷⁰, M. Neumann¹⁷⁹, P.R. Newman²¹, T.Y. Ng^{61c}, Y.S. Ng¹⁹,
H.D.N. Nguyen⁹⁹, T. Nguyen Manh¹⁰⁷, E. Nibigira³⁷, R.B. Nickerson¹³¹, R. Nicolaidou¹⁴²,
D.S. Nielsen³⁹, J. Nielsen¹⁴³, N. Nikiforou¹¹, V. Nikolaenko^{140,ak}, I. Nikolic-Audit¹³²,
K. Nikolopoulos²¹, P. Nilsson²⁹, Y. Ninomiya⁷⁹, A. Nisati^{70a}, N. Nishu^{58c}, R. Nisius¹¹³, I. Nitsche⁴⁵,
T. Nitta¹⁷⁶, T. Nobe¹⁶⁰, Y. Noguchi⁸³, M. Nomachi¹²⁹, I. Nomidis¹³², M.A. Nomura²⁹, T. Nooney⁹⁰,
M. Nordberg³⁵, N. Norjoharuddeen¹³¹, T. Novak⁸⁹, O. Novgorodova⁴⁶, R. Novotny¹³⁸, L. Nozka¹²⁶,
K. Ntekas¹⁶⁸, E. Nurse⁹², F. Nuti¹⁰², F.G. Oakham^{33,ar}, H. Oberlack¹¹³, T. Obermann²⁴, J. Ocariz¹³²,
A. Ochi⁸⁰, I. Ochoa³⁸, J.P. Ochoa-Ricoux^{144a}, K. O'Connor²⁶, S. Oda⁸⁵, S. Odaka⁷⁹, S. Oerdek⁵¹,
A. Oh⁹⁸, S.H. Oh⁴⁷, C.C. Ohm¹⁵¹, H. Oide^{53b,53a}, M.L. Ojeda¹⁶⁴, H. Okawa¹⁶⁶, Y. Okazaki⁸³,
Y. Okumura¹⁶⁰, T. Okuyama⁷⁹, A. Olariu^{27b}, L.F. Oleiro Seabra^{136a}, S.A. Olivares Pino^{144a},
D. Oliveira Damazio²⁹, J.L. Oliver¹, M.J.R. Olsson³⁶, A. Olszewski⁸², J. Olszowska⁸², D.C. O'Neil¹⁴⁹,
A. Onofre^{136a,136e}, K. Onogi¹¹⁵, P.U.E. Onyisi¹¹, H. Oppen¹³⁰, M.J. Oreglia³⁶, G.E. Orellana⁸⁶,
Y. Oren¹⁵⁸, D. Orestano^{72a,72b}, E.C. Orgill⁹⁸, N. Orlando^{61b}, A.A. O'Rourke⁴⁴, R.S. Orr¹⁶⁴,
B. Osculati^{53b,53a,*}, V. O'Shea⁵⁵, R. Ospanov^{58a}, G. Otero y Garzon³⁰, H. Otono⁸⁵, M. Ouchrif^{34d},
F. Ould-Saada¹³⁰, A. Ouraou¹⁴², Q. Ouyang^{15a}, M. Owen⁵⁵, R.E. Owen²¹, V.E. Ozcan^{12c}, N. Ozturk⁸,
J. Pacalt¹²⁶, H.A. Pacey³¹, K. Pachal¹⁴⁹, A. Pacheco Pages¹⁴, L. Pacheco Rodriguez¹⁴²,
C. Padilla Aranda¹⁴, S. Pagan Griso¹⁸, M. Paganini¹⁸⁰, G. Palacino⁶³, S. Palazzo^{40b,40a}, S. Palestini³⁵,
M. Palka^{81b}, D. Pallin³⁷, I. Panagoulas¹⁰, C.E. Pandini³⁵, J.G. Panduro Vazquez⁹¹, P. Pani³⁵,
G. Panizzo^{64a,64c}, L. Paolozzi⁵², T.D. Papadopolou¹⁰, K. Papageorgiou^{9,i}, A. Paramonov⁶,
D. Paredes Hernandez^{61b}, S.R. Paredes Saenz¹³¹, B. Parida¹⁶³, A.J. Parker⁸⁷, K.A. Parker⁴⁴,
M.A. Parker³¹, F. Parodi^{53b,53a}, J.A. Parsons³⁸, U. Parzefall⁵⁰, V.R. Pascuzzi¹⁶⁴, J.M.P. Pasner¹⁴³,
E. Pasqualucci^{70a}, S. Passaggio^{53b}, F. Pastore⁹¹, P. Pasuwan^{43a,43b}, S. Pataria⁹⁷, J.R. Pater⁹⁸,
A. Pathak^{178,j}, T. Pauly³⁵, B. Pearson¹¹³, M. Pedersen¹³⁰, L. Pedraza Diaz¹¹⁷, R. Pedro^{136a,136b},
S.V. Peleganchuk^{120b,120a}, O. Penc¹³⁷, C. Peng^{15d}, H. Peng^{58a}, B.S. Peralva^{78a}, M.M. Perego¹⁴²,
A.P. Pereira Peixoto^{136a}, D.V. Perepelitsa²⁹, F. Peri¹⁹, L. Perini^{66a,66b}, H. Pernegger³⁵, S. Perrella^{67a,67b},
V.D. Peshekhonov^{77,*}, K. Peters⁴⁴, R.F.Y. Peters⁹⁸, B.A. Petersen³⁵, T.C. Petersen³⁹, E. Petit⁵⁶,
A. Petridis¹, C. Petridou¹⁵⁹, P. Petroff¹²⁸, M. Petrov¹³¹, F. Petrucci^{72a,72b}, M. Pettee¹⁸⁰,
N.E. Pettersson¹⁰⁰, A. Peyaud¹⁴², R. Pezoa^{144b}, T. Pham¹⁰², F.H. Phillips¹⁰⁴, P.W. Phillips¹⁴¹,
M.W. Phipps¹⁷⁰, G. Piacquadio¹⁵², E. Pianori¹⁸, A. Picazio¹⁰⁰, M.A. Pickering¹³¹, R.H. Pickles⁹⁸,

R. Piegaia³⁰, J.E. Pilcher³⁶, A.D. Pilkington⁹⁸, M. Pinamonti^{71a,71b}, J.L. Pinfeld³, M. Pitt¹⁷⁷, L. Pizzimento^{71a,71b}, M-A. Pleier²⁹, V. Pleskot¹³⁹, E. Plotnikova⁷⁷, D. Pluth⁷⁶, P. Podberezko^{120b,120a}, R. Poettgen⁹⁴, R. Poggi⁵², L. Poggioli¹²⁸, I. Pogrebnyak¹⁰⁴, D. Pohl²⁴, I. Pokharel⁵¹, G. Polesello^{68a}, A. Poley¹⁸, A. Policicchio^{70a,70b}, R. Polifka³⁵, A. Polini^{23b}, C.S. Pollard⁴⁴, V. Polychronakos²⁹, D. Ponomarenko¹¹⁰, L. Pontecorvo^{70a}, G.A. Popeneciu^{27d}, D.M. Portillo Quintero¹³², S. Pospisil¹³⁸, K. Potamianos⁴⁴, I.N. Potrap⁷⁷, C.J. Potter³¹, H. Potti¹¹, T. Poulsen⁹⁴, J. Poveda³⁵, T.D. Powell¹⁴⁶, M.E. Pozo Astigarraga³⁵, P. Pralavorio⁹⁹, S. Prell⁷⁶, D. Price⁹⁸, M. Primavera^{65a}, S. Prince¹⁰¹, N. Proklova¹¹⁰, K. Prokofiev^{61c}, F. Prokoshin^{144b}, S. Protopopescu²⁹, J. Proudfoot⁶, M. Przybycien^{81a}, A. Puri¹⁷⁰, P. Puzo¹²⁸, J. Qian¹⁰³, Y. Qin⁹⁸, A. Quadri⁵¹, M. Queitsch-Maitland⁴⁴, A. Qureshi¹, P. Rados¹⁰², F. Ragusa^{66a,66b}, G. Rahal⁹⁵, J.A. Raine⁵², S. Rajagopalan²⁹, A. Ramirez Morales⁹⁰, T. Rashid¹²⁸, S. Raspopov⁵, M.G. Ratti^{66a,66b}, D.M. Rauch⁴⁴, F. Rauscher¹¹², S. Rave⁹⁷, B. Ravina¹⁴⁶, I. Ravinovitch¹⁷⁷, J.H. Rawling⁹⁸, M. Raymond³⁵, A.L. Read¹³⁰, N.P. Readoff⁵⁶, M. Reale^{65a,65b}, D.M. Rebuffi^{68a,68b}, A. Redelbach¹⁷⁴, G. Redlinger²⁹, R. Reece¹⁴³, R.G. Reed^{32c}, K. Reeves⁴², L. Rehnisch¹⁹, J. Reichert¹³³, D. Reikher¹⁵⁸, A. Reiss⁹⁷, C. Rembser³⁵, H. Ren^{15d}, M. Rescigno^{70a}, S. Resconi^{66a}, E.D. Resseguie¹³³, S. Rettie¹⁷², E. Reynolds²¹, O.L. Rezanova^{120b,120a}, P. Reznicek¹³⁹, E. Ricci^{73a,73b}, R. Richter¹¹³, S. Richter⁴⁴, E. Richter-Was^{81b}, O. Ricken²⁴, M. Ridet¹³², P. Rieck¹¹³, C.J. Riegel¹⁷⁹, O. Rifki⁴⁴, M. Rijssenbeek¹⁵², A. Rimoldi^{68a,68b}, M. Rimoldi²⁰, L. Rinaldi^{23b}, G. Ripellino¹⁵¹, B. Ristić⁸⁷, E. Ritsch³⁵, I. Riu¹⁴, J.C. Rivera Vergara^{144a}, F. Rizatdinova¹²⁵, E. Rizvi⁹⁰, C. Rizzi¹⁴, R.T. Roberts⁹⁸, S.H. Robertson^{101,ac}, D. Robinson³¹, J.E.M. Robinson⁴⁴, A. Robson⁵⁵, E. Rocco⁹⁷, C. Roda^{69a,69b}, Y. Rodina⁹⁹, S. Rodriguez Bosca¹⁷¹, A. Rodriguez Perez¹⁴, D. Rodriguez Rodriguez¹⁷¹, A.M. Rodríguez Vera^{165b}, S. Roe³⁵, C.S. Rogan⁵⁷, O. Røhne¹³⁰, R. Röhrig¹¹³, C.P.A. Roland⁶³, J. Roloff⁵⁷, A. Romaniouk¹¹⁰, M. Romano^{23b,23a}, N. Rompotis⁸⁸, M. Ronzani¹²¹, L. Roos¹³², S. Rosati^{70a}, K. Rosbach⁵⁰, P. Rose¹⁴³, N-A. Rosien⁵¹, B.J. Rosser¹³³, E. Rossi⁴⁴, E. Rossi^{72a,72b}, E. Rossi^{67a,67b}, L.P. Rossi^{53b}, L. Rossini^{66a,66b}, J.H.N. Rosten³¹, R. Rosten¹⁴, M. Rotaru^{27b}, J. Rothberg¹⁴⁵, D. Rousseau¹²⁸, D. Roy^{32c}, A. Rozanov⁹⁹, Y. Rozen¹⁵⁷, X. Ruan^{32c}, F. Rubbo¹⁵⁰, F. Rühr⁵⁰, A. Ruiz-Martinez¹⁷¹, Z. Rurikova⁵⁰, N.A. Rusakovitch⁷⁷, H.L. Russell¹⁰¹, J.P. Rutherford⁷, E.M. Rüttinger^{44,k}, Y.F. Ryabov¹³⁴, M. Rybar¹⁷⁰, G. Rybkin¹²⁸, S. Ryu⁶, A. Ryzhov¹⁴⁰, G.F. Rzehorz⁵¹, P. Sabatini⁵¹, G. Sabato¹¹⁸, S. Sacerdoti¹²⁸, H.F-W. Sadrozinski¹⁴³, R. Sadykov⁷⁷, F. Safai Tehrani^{70a}, P. Saha¹¹⁹, M. Sahinsoy^{59a}, A. Sahu¹⁷⁹, M. Saimpert⁴⁴, M. Saito¹⁶⁰, T. Saito¹⁶⁰, H. Sakamoto¹⁶⁰, A. Sakharov^{121,aj}, D. Salamani⁵², G. Salamanna^{72a,72b}, J.E. Salazar Loyola^{144b}, P.H. Sales De Bruin¹⁶⁹, D. Salihagic¹¹³, A. Salnikov¹⁵⁰, J. Salt¹⁷¹, D. Salvatore^{40b,40a}, F. Salvatore¹⁵³, A. Salvucci^{61a,61b,61c}, A. Salzburger³⁵, J. Samarati³⁵, D. Sammel⁵⁰, D. Sampsonidis¹⁵⁹, D. Sampsonidou¹⁵⁹, J. Sánchez¹⁷¹, A. Sanchez Pineda^{64a,64c}, H. Sandaker¹³⁰, C.O. Sander⁴⁴, M. Sandhoff¹⁷⁹, C. Sandoval²², D.P.C. Sankey¹⁴¹, M. Sannino^{53b,53a}, Y. Sano¹¹⁵, A. Sansoni⁴⁹, C. Santoni³⁷, H. Santos^{136a}, I. Santoyo Castillo¹⁵³, A. Santra¹⁷¹, A. Sapronov⁷⁷, J.G. Saraiva^{136a,136d}, O. Sasaki⁷⁹, K. Sato¹⁶⁶, E. Sauvan⁵, P. Savard^{164,ar}, N. Savic¹¹³, R. Sawada¹⁶⁰, C. Sawyer¹⁴¹, L. Sawyer^{93,ai}, C. Sbarra^{23b}, A. Sbrizzi^{23b,23a}, T. Scanlon⁹², J. Schaarschmidt¹⁴⁵, P. Schacht¹¹³, B.M. Schachtner¹¹², D. Schaefer³⁶, L. Schaefer¹³³, J. Schaeffer⁹⁷, S. Schaepe³⁵, U. Schäfer⁹⁷, A.C. Schaffer¹²⁸, D. Schaile¹¹², R.D. Schamberger¹⁵², N. Scharmberg⁹⁸, V.A. Schegelsky¹³⁴, D. Scheirich¹³⁹, F. Schenck¹⁹, M. Schernau¹⁶⁸, C. Schiavi^{53b,53a}, S. Schier¹⁴³, L.K. Schildgen²⁴, Z.M. Schillaci²⁶, E.J. Schioppa³⁵, M. Schioppa^{40b,40a}, K.E. Schleicher⁵⁰, S. Schlenker³⁵, K.R. Schmidt-Sommerfeld¹¹³, K. Schmieden³⁵, C. Schmitt⁹⁷, S. Schmitt⁴⁴, S. Schmitz⁹⁷, J.C. Schmoeckel⁴⁴, U. Schnoor⁵⁰, L. Schoeffel¹⁴², A. Schoening^{59b}, E. Schopf¹³¹, M. Schott⁹⁷, J.F.P. Schouwenberg¹¹⁷, J. Schovancova³⁵, S. Schramm⁵², A. Schulte⁹⁷, H-C. Schultz-Coulon^{59a}, M. Schumacher⁵⁰, B.A. Schumm¹⁴³, Ph. Schune¹⁴², A. Schwartzman¹⁵⁰, T.A. Schwarz¹⁰³, Ph. Schwemling¹⁴², R. Schwienhorst¹⁰⁴, A. Sciandra²⁴, G. Sciolla²⁶, M. Scornajenghi^{40b,40a}, F. Scuri^{69a}, F. Scutti¹⁰², L.M. Scyboz¹¹³, J. Searcy¹⁰³, C.D. Sebastiani^{70a,70b}, P. Seema¹⁹, S.C. Seidel¹¹⁶,

A. Seiden¹⁴³, T. Seiss³⁶, J.M. Seixas^{78b}, G. Sekhniaidze^{67a}, K. Sekhon¹⁰³, S.J. Sekula⁴¹, N. Semprini-Cesari^{23b,23a}, S. Sen⁴⁷, S. Senkin³⁷, C. Serfon¹³⁰, L. Serin¹²⁸, L. Serkin^{64a,64b}, M. Sessa^{58a}, H. Severini¹²⁴, F. Sforza¹⁶⁷, A. Sfyrila⁵², E. Shabalina⁵¹, J.D. Shahinian¹⁴³, N.W. Shaikh^{43a,43b}, L.Y. Shan^{15a}, R. Shang¹⁷⁰, J.T. Shank²⁵, M. Shapiro¹⁸, A.S. Sharma¹, A. Sharma¹³¹, P.B. Shatalov¹⁰⁹, K. Shaw¹⁵³, S.M. Shaw⁹⁸, A. Shcherbakova¹³⁴, Y. Shen¹²⁴, N. Sherafati³³, A.D. Sherman²⁵, P. Sherwood⁹², L. Shi^{155,an}, S. Shimizu⁷⁹, C.O. Shimmin¹⁸⁰, M. Shimojima¹¹⁴, I.P.J. Shipsey¹³¹, S. Shirabe⁸⁵, M. Shiyakova⁷⁷, J. Shlomi¹⁷⁷, A. Shmeleva¹⁰⁸, D. Shoaleh Saadi¹⁰⁷, M.J. Shochet³⁶, S. Shojaii¹⁰², D.R. Shope¹²⁴, S. Shrestha¹²², E. Shulga¹¹⁰, P. Sicho¹³⁷, A.M. Sickles¹⁷⁰, P.E. Sidebo¹⁵¹, E. Sideras Haddad^{32c}, O. Sidiropoulou³⁵, A. Sidoti^{23b,23a}, F. Siegert⁴⁶, Dj. Sijacki¹⁶, J. Silva^{136a}, M. Silva Jr.¹⁷⁸, M.V. Silva Oliveira^{78a}, S.B. Silverstein^{43a}, S. Simion¹²⁸, E. Simioni⁹⁷, M. Simon⁹⁷, R. Simoniello⁹⁷, P. Sinervo¹⁶⁴, N.B. Sinev¹²⁷, M. Sioli^{23b,23a}, G. Siragusa¹⁷⁴, I. Siral¹⁰³, S.Yu. Sivoklov¹¹¹, J. Sjölin^{43a,43b}, P. Skubic¹²⁴, M. Slater²¹, T. Slavicek¹³⁸, M. Slawinska⁸², K. Sliwa¹⁶⁷, R. Slovak¹³⁹, V. Smakhtin¹⁷⁷, B.H. Smart⁵, J. Smiesko^{28a}, N. Smirnov¹¹⁰, S.Yu. Smirnov¹¹⁰, Y. Smirnov¹¹⁰, L.N. Smirnova¹¹¹, O. Smirnova⁹⁴, J.W. Smith⁵¹, M.N.K. Smith³⁸, M. Smizanska⁸⁷, K. Smolek¹³⁸, A. Smykiewicz⁸², A.A. Snegarev¹⁰⁸, I.M. Snyder¹²⁷, S. Snyder²⁹, R. Sobie^{173,ac}, A.M. Soffa¹⁶⁸, A. Soffer¹⁵⁸, A. Søggaard⁴⁸, D.A. Soh¹⁵⁵, G. Sokhrannyi⁸⁹, C.A. Solans Sanchez³⁵, M. Solar¹³⁸, E.Yu. Soldatov¹¹⁰, U. Soldevila¹⁷¹, A.A. Solodkov¹⁴⁰, A. Soloshenko⁷⁷, O.V. Solovyanov¹⁴⁰, V. Solov'yev¹³⁴, P. Sommer¹⁴⁶, H. Son¹⁶⁷, W. Song¹⁴¹, W.Y. Song^{165b}, A. Sopczak¹³⁸, F. Sopkova^{28b}, C.L. Sotiropoulou^{69a,69b}, S. Sottocornola^{68a,68b}, R. Soualah^{64a,64c,h}, A.M. Soukharev^{120b,120a}, D. South⁴⁴, B.C. Sowden⁹¹, S. Spagnolo^{65a,65b}, M. Spalla¹¹³, M. Spangenberg¹⁷⁵, F. Spanò⁹¹, D. Sperlich¹⁹, F. Spettel¹¹³, T.M. Spieker^{59a}, R. Spighi^{23b}, G. Spigo³⁵, L.A. Spiller¹⁰², D.P. Spiteri⁵⁵, M. Spousta¹³⁹, A. Stabile^{66a,66b}, R. Stamen^{59a}, S. Stamm¹⁹, E. Stanecka⁸², R.W. Stanek⁶, C. Stanescu^{72a}, B. Stanislaus¹³¹, M.M. Stanitzki⁴⁴, B. Stapf¹¹⁸, S. Stapnes¹³⁰, E.A. Starchenko¹⁴⁰, G.H. Stark³⁶, J. Stark⁵⁶, S.H. Stark³⁹, P. Staroba¹³⁷, P. Starovoitov^{59a}, S. Stärz³⁵, R. Staszewski⁸², M. Stegler⁴⁴, P. Steinberg²⁹, B. Stelzer¹⁴⁹, H.J. Stelzer³⁵, O. Stelzer-Chilton^{165a}, H. Stenzel⁵⁴, T.J. Stevenson⁹⁰, G.A. Stewart⁵⁵, M.C. Stockton¹²⁷, G. Stoicea^{27b}, P. Stolte⁵¹, S. Stonjek¹¹³, A. Straessner⁴⁶, J. Strandberg¹⁵¹, S. Strandberg^{43a,43b}, M. Strauss¹²⁴, P. Strizenec^{28b}, R. Ströhmer¹⁷⁴, D.M. Strom¹²⁷, R. Stroynowski⁴¹, A. Strubig⁴⁸, S.A. Stucci²⁹, B. Stugu¹⁷, J. Stupak¹²⁴, N.A. Styles⁴⁴, D. Su¹⁵⁰, J. Su¹³⁵, S. Suchek^{59a}, Y. Sugaya¹²⁹, M. Suk¹³⁸, V.V. Sulin¹⁰⁸, M.J. Sullivan⁸⁸, D.M.S. Sultan⁵², S. Sultansoy^{4c}, T. Sumida⁸³, S. Sun¹⁰³, X. Sun³, K. Suruliz¹⁵³, C.J.E. Suster¹⁵⁴, M.R. Sutton¹⁵³, S. Suzuki⁷⁹, M. Svatos¹³⁷, M. Swiatlowski³⁶, S.P. Swift², A. Sydorenko⁹⁷, I. Sykora^{28a}, T. Sykora¹³⁹, D. Ta⁹⁷, K. Tackmann^{44,z}, J. Taenzer¹⁵⁸, A. Taffard¹⁶⁸, R. Tahirout^{165a}, E. Tahirovic⁹⁰, N. Taiblum¹⁵⁸, H. Takai²⁹, R. Takashima⁸⁴, E.H. Takasugi¹¹³, K. Takeda⁸⁰, T. Takeshita¹⁴⁷, Y. Takubo⁷⁹, M. Talby⁹⁹, A.A. Talyshchev^{120b,120a}, J. Tanaka¹⁶⁰, M. Tanaka¹⁶², R. Tanaka¹²⁸, B.B. Tannenwald¹²², S. Tapia Araya^{144b}, S. Tapprogge⁹⁷, A. Tarek Abouelfadl Mohamed¹³², S. Tarem¹⁵⁷, G. Tarna^{27b,d}, G.F. Tartarelli^{66a}, P. Tas¹³⁹, M. Tasevsky¹³⁷, T. Tashiro⁸³, E. Tassi^{40b,40a}, A. Tavares Delgado^{136a,136b}, Y. Tayalati^{34e}, A.C. Taylor¹¹⁶, A.J. Taylor⁴⁸, G.N. Taylor¹⁰², P.T.E. Taylor¹⁰², W. Taylor^{165b}, A.S. Tee⁸⁷, P. Teixeira-Dias⁹¹, H. Ten Kate³⁵, P.K. Teng¹⁵⁵, J.J. Teoh¹¹⁸, S. Terada⁷⁹, K. Terashi¹⁶⁰, J. Terron⁹⁶, S. Terzo¹⁴, M. Testa⁴⁹, R.J. Teuscher^{164,ac}, S.J. Thais¹⁸⁰, T. Theveneaux-Pelzer⁴⁴, F. Thiele³⁹, D.W. Thomas⁹¹, J.P. Thomas²¹, A.S. Thompson⁵⁵, P.D. Thompson²¹, L.A. Thomsen¹⁸⁰, E. Thomson¹³³, Y. Tian³⁸, R.E. Ticse Torres⁵¹, V.O. Tikhomirov^{108,al}, Yu.A. Tikhonov^{120b,120a}, S. Timoshenko¹¹⁰, P. Tipton¹⁸⁰, S. Tisserant⁹⁹, K. Todome¹⁶², S. Todorova-Nova⁵, S. Todt⁴⁶, J. Tojo⁸⁵, S. Tokár^{28a}, K. Tokushuku⁷⁹, E. Tolley¹²², K.G. Tomiwa^{32c}, M. Tomoto¹¹⁵, L. Tompkins^{150,p}, K. Toms¹¹⁶, B. Tong⁵⁷, P. Tornambe⁵⁰, E. Torrence¹²⁷, H. Torres⁴⁶, E. Torró Pastor¹⁴⁵, C. Toscizi¹³¹, J. Toth^{99,ab}, F. Touchard⁹⁹, D.R. Tovey¹⁴⁶, C.J. Treado¹²¹, T. Trefzger¹⁷⁴, F. Tresoldi¹⁵³, A. Tricoli²⁹, I.M. Trigger^{165a}, S. Trincas-Duvoid¹³², M.F. Tripiana¹⁴, W. Trischuk¹⁶⁴, B. Trocmé⁵⁶, A. Trofymov¹²⁸, C. Troncon^{66a}, M. Trovatelli¹⁷³, F. Trovato¹⁵³, L. Truong^{32b}, M. Trzebinski⁸², A. Trzupek⁸², F. Tsai⁴⁴, J.C.-L. Tseng¹³¹,

P.V. Tsiareshka¹⁰⁵, A. Tsirigotis¹⁵⁹, N. Tsirintanis⁹, V. Tsiskaridze¹⁵², E.G. Tskhadadze^{156a}, I.I. Tsukerman¹⁰⁹, V. Tsulaia¹⁸, S. Tsuno⁷⁹, D. Tsybychev^{152,163}, Y. Tu^{61b}, A. Tudorache^{27b}, V. Tudorache^{27b}, T.T. Tulbure^{27a}, A.N. Tuna⁵⁷, S. Turchikhin⁷⁷, D. Turgeman¹⁷⁷, I. Turk Cakir^{4b,t}, R. Turra^{66a}, P.M. Tuts³⁸, E. Tzovara⁹⁷, G. Uccchielli^{23b,23a}, I. Ueda⁷⁹, M. Ughetto^{43a,43b}, F. Ukegawa¹⁶⁶, G. Unal³⁵, A. Undrus²⁹, G. Unel¹⁶⁸, F.C. Ungaro¹⁰², Y. Unno⁷⁹, K. Uno¹⁶⁰, J. Urban^{28b}, P. Urquijo¹⁰², P. Urrejola⁹⁷, G. Usai⁸, J. Usui⁷⁹, L. Vacavant⁹⁹, V. Vacek¹³⁸, B. Vachon¹⁰¹, K.O.H. Vadla¹³⁰, A. Vaidya⁹², C. Valderanis¹¹², E. Valdes Santurio^{43a,43b}, M. Valente⁵², S. Valentinetti^{23b,23a}, A. Valero¹⁷¹, L. Valéry⁴⁴, R.A. Vallance²¹, A. Vallier⁵, J.A. Valls Ferrer¹⁷¹, T.R. Van Daalen¹⁴, H. Van der Graaf¹¹⁸, P. Van Gemmeren⁶, J. Van Nieuwkoop¹⁴⁹, I. Van Vulpen¹¹⁸, M. Vanadia^{71a,71b}, W. Vandelli³⁵, A. Vaniachine¹⁶³, P. Vankov¹¹⁸, R. Vari^{70a}, E.W. Varnes⁷, C. Varni^{53b,53a}, T. Varol⁴¹, D. Varouchas¹²⁸, K.E. Varvell¹⁵⁴, G.A. Vasquez^{144b}, J.G. Vasquez¹⁸⁰, F. Vazeille³⁷, D. Vazquez Furelos¹⁴, T. Vazquez Schroeder¹⁰¹, J. Veatch⁵¹, V. Vecchio^{72a,72b}, L.M. Veloce¹⁶⁴, F. Veloso^{136a,136c}, S. Veneziano^{70a}, A. Ventura^{65a,65b}, M. Venturi¹⁷³, N. Venturi³⁵, V. Vercesi^{68a}, M. Verducci^{72a,72b}, C.M. Vergel Infante⁷⁶, C. Vergis²⁴, W. Verkerke¹¹⁸, A.T. Vermeulen¹¹⁸, J.C. Vermeulen¹¹⁸, M.C. Vetterli^{149,ar}, N. Viaux Maira^{144b}, M. Vicente Barreto Pinto⁵², I. Vichou^{170,*}, T. Vickey¹⁴⁶, O.E. Vickey Boeriu¹⁴⁶, G.H.A. Viehhauser¹³¹, S. Viel¹⁸, L. Vigani¹³¹, M. Villa^{23b,23a}, M. Villaplana Perez^{66a,66b}, E. Vilucchi⁴⁹, M.G. Vinciter³³, V.B. Vinogradov⁷⁷, A. Vishwakarma⁴⁴, C. Vittori^{23b,23a}, I. Vivarelli¹⁵³, S. Vlachos¹⁰, M. Vogel¹⁷⁹, P. Vokac¹³⁸, G. Volpi¹⁴, S.E. von Buddenbrock^{32c}, E. Von Toerne²⁴, V. Vorobel¹³⁹, K. Vorobev¹¹⁰, M. Vos¹⁷¹, J.H. Vosseveld⁸⁸, N. Vranjes¹⁶, M. Vranjes Milosavljevic¹⁶, V. Vrba¹³⁸, M. Vreeswijk¹¹⁸, T. Šfiligoj⁸⁹, R. Vuillermet³⁵, I. Vukotic³⁶, T. Ženiš^{28a}, L. Živković¹⁶, P. Wagner²⁴, W. Wagner¹⁷⁹, J. Wagner-Kuhr¹¹², H. Wahlberg⁸⁶, S. Wahrmond⁴⁶, K. Wakamiya⁸⁰, V.M. Walbrecht¹¹³, J. Walder⁸⁷, R. Walker¹¹², S.D. Walker⁹¹, W. Walkowiak¹⁴⁸, V. Wallangen^{43a,43b}, A.M. Wang⁵⁷, C. Wang^{58b,d}, F. Wang¹⁷⁸, H. Wang¹⁸, H. Wang³, J. Wang¹⁵⁴, J. Wang^{59b}, P. Wang⁴¹, Q. Wang¹²⁴, R.-J. Wang¹³², R. Wang^{58a}, R. Wang⁶, S.M. Wang¹⁵⁵, W.T. Wang^{58a}, W. Wang^{15c,ad}, W.X. Wang^{58a,ad}, Y. Wang^{58a}, Z. Wang^{58c}, C. Wanotayaroj⁴⁴, A. Warburton¹⁰¹, C.P. Ward³¹, D.R. Wardrope⁹², A. Washbrook⁴⁸, P.M. Watkins²¹, A.T. Watson²¹, M.F. Watson²¹, G. Watts¹⁴⁵, S. Watts⁹⁸, B.M. Waugh⁹², A.F. Webb¹¹, S. Webb⁹⁷, C. Weber¹⁸⁰, M.S. Weber²⁰, S.A. Weber³³, S.M. Weber^{59a}, A.R. Weidberg¹³¹, B. Weinert⁶³, J. Weingarten⁵¹, M. Weirich⁹⁷, C. Weiser⁵⁰, P.S. Wells³⁵, T. Wenaus²⁹, T. Wengler³⁵, S. Wenig³⁵, N. Wermes²⁴, M.D. Werner⁷⁶, P. Werner³⁵, M. Wessels^{59a}, T.D. Weston²⁰, K. Whalen¹²⁷, N.L. Whallon¹⁴⁵, A.M. Wharton⁸⁷, A.S. White¹⁰³, A. White⁸, M.J. White¹, R. White^{144b}, D. Whiteson¹⁶⁸, B.W. Whitmore⁸⁷, F.J. Wickens¹⁴¹, W. Wiedenmann¹⁷⁸, M. Wielers¹⁴¹, C. Wiglesworth³⁹, L.A.M. Wiik-Fuchs⁵⁰, F. Wilk⁹⁸, H.G. Wilkens³⁵, L.J. Wilkins⁹¹, H.H. Williams¹³³, S. Williams³¹, C. Willis¹⁰⁴, S. Willocq¹⁰⁰, J.A. Wilson²¹, I. Wingerter-Seez⁵, E. Winkels¹⁵³, F. Winklmeier¹²⁷, O.J. Winston¹⁵³, B.T. Winter²⁴, M. Wittgen¹⁵⁰, M. Wobisch⁹³, A. Wolf⁹⁷, T.M.H. Wolf¹¹⁸, R. Wolff⁹⁹, M.W. Wolter⁸², H. Wolters^{136a,136c}, V.W.S. Wong¹⁷², N.L. Woods¹⁴³, S.D. Worm²¹, B.K. Wosiek⁸², K.W. Woźniak⁸², K. Wraight⁵⁵, M. Wu³⁶, S.L. Wu¹⁷⁸, X. Wu⁵², Y. Wu^{58a}, T.R. Wyatt⁹⁸, B.M. Wynne⁴⁸, S. Xella³⁹, Z. Xi¹⁰³, L. Xia¹⁷⁵, D. Xu^{15a}, H. Xu^{58a}, L. Xu²⁹, T. Xu¹⁴², W. Xu¹⁰³, B. Yabsley¹⁵⁴, S. Yacoob^{32a}, K. Yajima¹²⁹, D.P. Yallup⁹², D. Yamaguchi¹⁶², Y. Yamaguchi¹⁶², A. Yamamoto⁷⁹, T. Yamanaka¹⁶⁰, F. Yamane⁸⁰, M. Yamatani¹⁶⁰, T. Yamazaki¹⁶⁰, Y. Yamazaki⁸⁰, Z. Yan²⁵, H.J. Yang^{58c,58d}, H.T. Yang¹⁸, S. Yang⁷⁵, Y. Yang¹⁶⁰, Z. Yang¹⁷, W.-M. Yao¹⁸, Y.C. Yap⁴⁴, Y. Yasu⁷⁹, E. Yatsenko^{58c,58d}, J. Ye⁴¹, S. Ye²⁹, I. Yeletsikh⁷⁷, E. Yigitbasi²⁵, E. Yildirim⁹⁷, K. Yorita¹⁷⁶, K. Yoshihara¹³³, C.J.S. Young³⁵, C. Young¹⁵⁰, J. Yu⁸, J. Yu⁷⁶, X. Yue^{59a}, S.P.Y. Yuen²⁴, B. Zabinski⁸², G. Zacharis¹⁰, E. Zaffaroni⁵², R. Zaidan¹⁴, A.M. Zaitsev^{140,ak}, T. Zakareishvili^{156b}, N. Zakharchuk³³, J. Zalieckas¹⁷, S. Zambito⁵⁷, D. Zanzi³⁵, D.R. Zaripovas⁵⁵, S.V. Zeiβner⁴⁵, C. Zeitnitz¹⁷⁹, G. Zemaityte¹³¹, J.C. Zeng¹⁷⁰, Q. Zeng¹⁵⁰, O. Zenin¹⁴⁰, D. Zerwas¹²⁸, M. Zgubić¹³¹, D.F. Zhang^{58b}, D. Zhang¹⁰³, F. Zhang¹⁷⁸, G. Zhang^{58a}, H. Zhang^{15c}, J. Zhang⁶, L. Zhang^{15c}, L. Zhang^{58a}, M. Zhang¹⁷⁰,

P. Zhang^{15c}, R. Zhang^{58a}, R. Zhang²⁴, X. Zhang^{58b}, Y. Zhang^{15d}, Z. Zhang¹²⁸, P. Zhao⁴⁷, X. Zhao⁴¹, Y. Zhao^{58b,128,ah}, Z. Zhao^{58a}, A. Zhemchugov⁷⁷, Z. Zheng¹⁰³, D. Zhong¹⁷⁰, B. Zhou¹⁰³, C. Zhou¹⁷⁸, L. Zhou⁴¹, M.S. Zhou^{15d}, M. Zhou¹⁵², N. Zhou^{58c}, Y. Zhou⁷, C.G. Zhu^{58b}, H.L. Zhu^{58a}, H. Zhu^{15a}, J. Zhu¹⁰³, Y. Zhu^{58a}, X. Zhuang^{15a}, K. Zhukov¹⁰⁸, V. Zhulanov^{120b,120a}, A. Zibell¹⁷⁴, D. Zieminska⁶³, N.I. Zimine⁷⁷, S. Zimmermann⁵⁰, Z. Zinonos¹¹³, M. Zinser⁹⁷, M. Ziolkowski¹⁴⁸, G. Zobernig¹⁷⁸, A. Zoccoli^{23b,23a}, K. Zoch⁵¹, T.G. Zorbas¹⁴⁶, R. Zou³⁶, M. Zur Nedden¹⁹, L. Zwalinski³⁵.

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

²Physics Department, SUNY Albany, Albany NY; United States of America.

³Department of Physics, University of Alberta, Edmonton AB; Canada.

^{4(a)}Department of Physics, Ankara University, Ankara;^(b)Istanbul Aydin University, Istanbul;^(c)Division of Physics, TOBB University of Economics and Technology, Ankara; Turkey.

⁵LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.

⁶High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.

⁷Department of Physics, University of Arizona, Tucson AZ; United States of America.

⁸Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.

⁹Physics Department, National and Kapodistrian University of Athens, Athens; Greece.

¹⁰Physics Department, National Technical University of Athens, Zografou; Greece.

¹¹Department of Physics, University of Texas at Austin, Austin TX; United States of America.

^{12(a)}Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul;^(b)Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul;^(c)Department of Physics, Bogazici University, Istanbul;^(d)Department of Physics Engineering, Gaziantep University, Gaziantep; Turkey.

¹³Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

¹⁴Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.

^{15(a)}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;^(b)Physics Department, Tsinghua University, Beijing;^(c)Department of Physics, Nanjing University, Nanjing;^(d)University of Chinese Academy of Science (UCAS), Beijing; China.

¹⁶Institute of Physics, University of Belgrade, Belgrade; Serbia.

¹⁷Department for Physics and Technology, University of Bergen, Bergen; Norway.

¹⁸Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA; United States of America.

¹⁹Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.

²⁰Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.

²¹School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.

²²Centro de Investigaciones, Universidad Antonio Nariño, Bogota; Colombia.

^{23(a)}Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna;^(b)INFN Sezione di Bologna; Italy.

²⁴Physikalisches Institut, Universität Bonn, Bonn; Germany.

²⁵Department of Physics, Boston University, Boston MA; United States of America.

²⁶Department of Physics, Brandeis University, Waltham MA; United States of America.

^{27(a)}Transilvania University of Brasov, Brasov;^(b)Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;^(c)Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;^(d)National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;^(e)University Politehnica Bucharest, Bucharest;^(f)West University in Timisoara, Timisoara; Romania.

- ^{28(a)}Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;^(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
- ²⁹Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
- ³⁰Departamento de Física, Universidad de Buenos Aires, Buenos Aires; Argentina.
- ³¹Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
- ^{32(a)}Department of Physics, University of Cape Town, Cape Town;^(b)Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;^(c)School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
- ³³Department of Physics, Carleton University, Ottawa ON; Canada.
- ^{34(a)}Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;^(b)Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN), Rabat;^(c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;^(d)Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;^(e)Faculté des sciences, Université Mohammed V, Rabat; Morocco.
- ³⁵CERN, Geneva; Switzerland.
- ³⁶Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
- ³⁷LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
- ³⁸Nevis Laboratory, Columbia University, Irvington NY; United States of America.
- ³⁹Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
- ^{40(a)}Dipartimento di Fisica, Università della Calabria, Rende;^(b)INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
- ⁴¹Physics Department, Southern Methodist University, Dallas TX; United States of America.
- ⁴²Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
- ^{43(a)}Department of Physics, Stockholm University;^(b)Oskar Klein Centre, Stockholm; Sweden.
- ⁴⁴Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
- ⁴⁵Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund; Germany.
- ⁴⁶Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
- ⁴⁷Department of Physics, Duke University, Durham NC; United States of America.
- ⁴⁸SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
- ⁴⁹INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
- ⁵⁰Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
- ⁵¹II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
- ⁵²Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ^{53(a)}Dipartimento di Fisica, Università di Genova, Genova;^(b)INFN Sezione di Genova; Italy.
- ⁵⁴II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
- ⁵⁵SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
- ⁵⁶LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
- ⁵⁷Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
- ^{58(a)}Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;^(b)Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;^(c)School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai;^(d)Tsung-Dao Lee Institute, Shanghai; China.
- ^{59(a)}Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;^(b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.

- ⁶⁰Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima; Japan.
- ^{61(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.
- ⁶²Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
- ⁶³Department of Physics, Indiana University, Bloomington IN; United States of America.
- ^{64(a)}INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b)ICTP, Trieste; ^(c)Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine; Italy.
- ^{65(a)}INFN Sezione di Lecce; ^(b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
- ^{66(a)}INFN Sezione di Milano; ^(b)Dipartimento di Fisica, Università di Milano, Milano; Italy.
- ^{67(a)}INFN Sezione di Napoli; ^(b)Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
- ^{68(a)}INFN Sezione di Pavia; ^(b)Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
- ^{69(a)}INFN Sezione di Pisa; ^(b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
- ^{70(a)}INFN Sezione di Roma; ^(b)Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
- ^{71(a)}INFN Sezione di Roma Tor Vergata; ^(b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
- ^{72(a)}INFN Sezione di Roma Tre; ^(b)Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
- ^{73(a)}INFN-TIFPA; ^(b)Università degli Studi di Trento, Trento; Italy.
- ⁷⁴Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck; Austria.
- ⁷⁵University of Iowa, Iowa City IA; United States of America.
- ⁷⁶Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
- ⁷⁷Joint Institute for Nuclear Research, Dubna; Russia.
- ^{78(a)}Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; ^(b)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(c)Universidade Federal de São João del Rei (UFSJ), São João del Rei; ^(d)Instituto de Física, Universidade de São Paulo, São Paulo; Brazil.
- ⁷⁹KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
- ⁸⁰Graduate School of Science, Kobe University, Kobe; Japan.
- ^{81(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.
- ⁸²Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
- ⁸³Faculty of Science, Kyoto University, Kyoto; Japan.
- ⁸⁴Kyoto University of Education, Kyoto; Japan.
- ⁸⁵Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
- ⁸⁶Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
- ⁸⁷Physics Department, Lancaster University, Lancaster; United Kingdom.
- ⁸⁸Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
- ⁸⁹Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
- ⁹⁰School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
- ⁹¹Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
- ⁹²Department of Physics and Astronomy, University College London, London; United Kingdom.
- ⁹³Louisiana Tech University, Ruston LA; United States of America.
- ⁹⁴Fysiska institutionen, Lunds universitet, Lund; Sweden.

- ⁹⁵Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne; France.
- ⁹⁶Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
- ⁹⁷Institut für Physik, Universität Mainz, Mainz; Germany.
- ⁹⁸School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
- ⁹⁹CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
- ¹⁰⁰Department of Physics, University of Massachusetts, Amherst MA; United States of America.
- ¹⁰¹Department of Physics, McGill University, Montreal QC; Canada.
- ¹⁰²School of Physics, University of Melbourne, Victoria; Australia.
- ¹⁰³Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
- ¹⁰⁴Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
- ¹⁰⁵B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk; Belarus.
- ¹⁰⁶Research Institute for Nuclear Problems of Byelorussian State University, Minsk; Belarus.
- ¹⁰⁷Group of Particle Physics, University of Montreal, Montreal QC; Canada.
- ¹⁰⁸P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow; Russia.
- ¹⁰⁹Institute for Theoretical and Experimental Physics (ITEP), Moscow; Russia.
- ¹¹⁰National Research Nuclear University MEPhI, Moscow; Russia.
- ¹¹¹D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.
- ¹¹²Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
- ¹¹³Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
- ¹¹⁴Nagasaki Institute of Applied Science, Nagasaki; Japan.
- ¹¹⁵Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
- ¹¹⁶Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
- ¹¹⁷Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
- ¹¹⁸Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
- ¹¹⁹Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
- ^{120(a)}Budker Institute of Nuclear Physics, SB RAS, Novosibirsk; ^(b)Novosibirsk State University Novosibirsk; Russia.
- ¹²¹Department of Physics, New York University, New York NY; United States of America.
- ¹²²Ohio State University, Columbus OH; United States of America.
- ¹²³Faculty of Science, Okayama University, Okayama; Japan.
- ¹²⁴Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
- ¹²⁵Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
- ¹²⁶Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc; Czech Republic.
- ¹²⁷Center for High Energy Physics, University of Oregon, Eugene OR; United States of America.
- ¹²⁸LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
- ¹²⁹Graduate School of Science, Osaka University, Osaka; Japan.
- ¹³⁰Department of Physics, University of Oslo, Oslo; Norway.
- ¹³¹Department of Physics, Oxford University, Oxford; United Kingdom.
- ¹³²LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.
- ¹³³Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.

- ¹³⁴Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg; Russia.
- ¹³⁵Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
- ^{136(a)}Laboratório de Instrumentação e Física Experimental de Partículas - LIP;^(b)Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;^(c)Departamento de Física, Universidade de Coimbra, Coimbra;^(d)Centro de Física Nuclear da Universidade de Lisboa, Lisboa;^(e)Departamento de Física, Universidade do Minho, Braga;^(f)Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);^(g)Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica; Portugal.
- ¹³⁷Institute of Physics, Academy of Sciences of the Czech Republic, Prague; Czech Republic.
- ¹³⁸Czech Technical University in Prague, Prague; Czech Republic.
- ¹³⁹Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
- ¹⁴⁰State Research Center Institute for High Energy Physics, NRC KI, Protvino; Russia.
- ¹⁴¹Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
- ¹⁴²IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
- ¹⁴³Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.
- ^{144(a)}Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;^(b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.
- ¹⁴⁵Department of Physics, University of Washington, Seattle WA; United States of America.
- ¹⁴⁶Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
- ¹⁴⁷Department of Physics, Shinshu University, Nagano; Japan.
- ¹⁴⁸Department Physik, Universität Siegen, Siegen; Germany.
- ¹⁴⁹Department of Physics, Simon Fraser University, Burnaby BC; Canada.
- ¹⁵⁰SLAC National Accelerator Laboratory, Stanford CA; United States of America.
- ¹⁵¹Physics Department, Royal Institute of Technology, Stockholm; Sweden.
- ¹⁵²Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.
- ¹⁵³Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
- ¹⁵⁴School of Physics, University of Sydney, Sydney; Australia.
- ¹⁵⁵Institute of Physics, Academia Sinica, Taipei; Taiwan.
- ^{156(a)}E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;^(b)High Energy Physics Institute, Tbilisi State University, Tbilisi; Georgia.
- ¹⁵⁷Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
- ¹⁵⁸Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
- ¹⁵⁹Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
- ¹⁶⁰International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
- ¹⁶¹Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.
- ¹⁶²Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.
- ¹⁶³Tomsk State University, Tomsk; Russia.
- ¹⁶⁴Department of Physics, University of Toronto, Toronto ON; Canada.
- ^{165(a)}TRIUMF, Vancouver BC;^(b)Department of Physics and Astronomy, York University, Toronto ON; Canada.
- ¹⁶⁶Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.

- ¹⁶⁷Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
- ¹⁶⁸Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.
- ¹⁶⁹Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
- ¹⁷⁰Department of Physics, University of Illinois, Urbana IL; United States of America.
- ¹⁷¹Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
- ¹⁷²Department of Physics, University of British Columbia, Vancouver BC; Canada.
- ¹⁷³Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
- ¹⁷⁴Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
- ¹⁷⁵Department of Physics, University of Warwick, Coventry; United Kingdom.
- ¹⁷⁶Waseda University, Tokyo; Japan.
- ¹⁷⁷Department of Particle Physics, Weizmann Institute of Science, Rehovot; Israel.
- ¹⁷⁸Department of Physics, University of Wisconsin, Madison WI; United States of America.
- ¹⁷⁹Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
- ¹⁸⁰Department of Physics, Yale University, New Haven CT; United States of America.
- ¹⁸¹Yerevan Physics Institute, Yerevan; Armenia.
- ^a Also at Borough of Manhattan Community College, City University of New York, NY; United States of America.
- ^b Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town; South Africa.
- ^c Also at CERN, Geneva; Switzerland.
- ^d Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
- ^e Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ^f Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
- ^g Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); Spain.
- ^h Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates.
- ⁱ Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
- ^j Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
- ^k Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
- ^l Also at Department of Physics, California State University, Fresno CA; United States of America.
- ^m Also at Department of Physics, California State University, Sacramento CA; United States of America.
- ⁿ Also at Department of Physics, King's College London, London; United Kingdom.
- ^o Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia.
- ^p Also at Department of Physics, Stanford University; United States of America.
- ^q Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
- ^r Also at Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
- ^s Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
- ^t Also at Giresun University, Faculty of Engineering, Giresun; Turkey.
- ^u Also at Graduate School of Science, Osaka University, Osaka; Japan.
- ^v Also at Hellenic Open University, Patras; Greece.
- ^w Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; Romania.
- ^x Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.

- ^y Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
- ^z Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
- ^{aa} Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
- ^{ab} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.
- ^{ac} Also at Institute of Particle Physics (IPP); Canada.
- ^{ad} Also at Institute of Physics, Academia Sinica, Taipei; Taiwan.
- ^{ae} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- ^{af} Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
- ^{ag} Also at Istanbul University, Dept. of Physics, Istanbul; Turkey.
- ^{ah} Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
- ^{ai} Also at Louisiana Tech University, Ruston LA; United States of America.
- ^{aj} Also at Manhattan College, New York NY; United States of America.
- ^{ak} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
- ^{al} Also at National Research Nuclear University MEPhI, Moscow; Russia.
- ^{am} Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
- ^{an} Also at School of Physics, Sun Yat-sen University, Guangzhou; China.
- ^{ao} Also at The City College of New York, New York NY; United States of America.
- ^{ap} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
- ^{aq} Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
- ^{ar} Also at TRIUMF, Vancouver BC; Canada.
- ^{as} Also at Università di Napoli Parthenope, Napoli; Italy.
- * Deceased