



Search for a standard model Higgs boson in the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ decay channel using 4.7 fb^{-1} of $\sqrt{s} = 7 \text{ TeV}$ data with the ATLAS detector [☆]

ATLAS Collaboration ^{*}

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ABSTRACT

A search for a Standard Model Higgs boson decaying via $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$, where ℓ represents electrons or muons, is presented. It is based on proton–proton collision data at $\sqrt{s} = 7 \text{ TeV}$, collected by the ATLAS experiment at the LHC during 2011 and corresponding to an integrated luminosity of 4.7 fb^{-1} . The data agree with the expected Standard Model backgrounds. Upper limits on the Higgs boson production cross section are derived for Higgs boson masses between 200 GeV and 600 GeV and the production of a Standard Model Higgs boson with a mass in the range 319–558 GeV is excluded at the 95% confidence level.

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1. Introduction

The search for the Higgs boson [1–3], which in the Standard Model (SM) gives mass to the weak vector bosons and fermions, is one of the most important aspects of the CERN Large Hadron Collider (LHC) physics programme. Direct searches performed at the CERN Large Electron–Positron Collider (LEP) have excluded, at a 95% confidence level (CL), the production of a SM Higgs boson with mass, m_H , less than 114.4 GeV [4]. Searches at the Fermilab Tevatron $p\bar{p}$ collider have excluded at 95% CL the region $156 < m_H < 177 \text{ GeV}$ [5,6]. At the LHC, the combination of ATLAS searches [7], using $1.0\text{--}4.9 \text{ fb}^{-1}$ of $\sqrt{s} = 7 \text{ TeV}$ data, excluded at the 95% CL the production of a SM Higgs boson in the regions $112.9 < m_H < 115.5 \text{ GeV}$, $131 < m_H < 238 \text{ GeV}$ and $251 < m_H < 466 \text{ GeV}$. The CMS combined result [8] using $4.6\text{--}4.8 \text{ fb}^{-1}$ of $\sqrt{s} = 7 \text{ TeV}$ data excluded the production of a SM Higgs boson at the 95% CL in the region $127 < m_H < 600 \text{ GeV}$.

The $ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ decay channel offers a substantial branching fraction in combination with a good separation from potential background processes owing to the large transverse momentum, p_T , of the electron or muon pair from the leptonic Z boson decay and the large missing transverse momentum from the Z boson decaying to neutrinos. Earlier results in this channel, published in Ref. [9], using 1.0 fb^{-1} , were subsequently updated in Ref. [7] with 2.0 fb^{-1} and exclude at the 95% CL the presence of a SM Higgs boson in the range $310 < m_H < 470 \text{ GeV}$. The most recent CMS analysis [10] in this channel based on 4.6 fb^{-1} excluded at 95% CL $270 < m_H < 440 \text{ GeV}$.

The data sample considered in the search presented in this Letter was recorded by the ATLAS experiment during the 2011 LHC run at a centre-of-mass energy $\sqrt{s} = 7 \text{ TeV}$. The integrated luminosity of the data sample, considering only data-taking periods where all relevant detector subsystems were operational, is 4.7 fb^{-1} with an uncertainty of 3.9% [11,12].

2. The ATLAS detector

The ATLAS detector [13] is a multi-purpose particle physics detector with forward–backward symmetric cylindrical geometry.¹ The inner tracking detector (ID) covers $|\eta| < 2.5$ and consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field. A high-granularity lead/liquid-argon (LAr) sampling calorimeter measures the energy and the position of electromagnetic showers with $|\eta| < 3.2$. LAr sampling calorimeters are also used to measure hadronic showers in the end-cap ($1.5 < |\eta| < 3.2$) and forward ($3.1 < |\eta| < 4.9$) regions, while an iron/scintillating-tile calorimeter measures hadronic showers in the central region ($|\eta| < 1.7$). The muon spectrometer surrounds the calorimeters and consists of three large superconducting air–core toroids, each with eight coils, a system of precision tracking chambers ($|\eta| < 2.7$), and fast tracking chambers for triggering ($|\eta| < 2.4$). A three-level trigger system selects events to be recorded for offline analysis.

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point. The z -axis is along the beam pipe, the x -axis points 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 beam pipe. The pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$ where θ is the polar angle.

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

3. Data and simulation samples

The $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ signal is modelled using the POWHEG [14,15] event generator, which includes matrix elements for the gluon fusion and vector-boson fusion (VBF) production mechanisms of the Higgs boson up to next-to-leading-order (NLO). POWHEG is interfaced to PYTHIA [16] for the modelling of parton showers. The modelling of final-state radiation is performed with PHOTOS [17], and TAUOLA [18,19] is used for the simulation of τ decays. The Higgs boson p_T spectrum in the gluon fusion process is reweighted to the calculation of Ref. [20], which provides QCD corrections up to NLO and QCD soft-gluon resummations up to next-to-next-to-leading logarithms (NNLL).

$H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$, $H \rightarrow ZZ \rightarrow \ell^+ \ell^- q \bar{q}$ and $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ samples are also simulated using the same generators as for the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ samples. These channels, together with the $H \rightarrow ZZ \rightarrow \tau^+ \tau^- \nu \bar{\nu}$ final state, which is included in the $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ samples, contribute to the signal yield and are considered as part of the signal. In particular, $H \rightarrow W^+ W^- \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ decays contribute as much as 70% to the signal expectation after the full selection for $m_H = 200$ GeV, decreasing to 13% at $m_H = 300$ GeV, and to less than 4.5% for Higgs boson masses larger than 400 GeV. Statistical independence of the analysis with respect to other ATLAS Higgs boson searches [21–23] is ensured through mutually exclusive selection requirements on the dilepton invariant mass, the number of leptons and the missing transverse momentum in the event.

The Higgs boson production cross sections and decay branching ratios, as well as their uncertainties, are taken from Refs. [24,25]. The cross sections for the gluon fusion process have been calculated to NLO in QCD in Refs. [26–28], and to next-to-next-to-leading-order (NNLO) in Refs. [29–31]. In addition, QCD soft-gluon resummations, calculated in the NNLL approximation [32], are applied for the gluon fusion process. NLO electroweak (EW) corrections are also applied [33,34]. These results are compiled in Refs. [35–37] and assume factorisation between QCD and EW corrections. The cross sections for VBF processes are calculated with full NLO QCD and EW corrections [38–40], and approximate NNLO QCD corrections are included [41]. The uncertainty in the production cross section due to the choice of QCD scale is typically $^{+12}_{-8}\%$ for the gluon fusion process, and $\pm 1\%$ for the VBF process [24]. The uncertainty in the production cross section due to the parton distribution function (PDF) and α_s is $\pm 8\%$ for gluon-initiated processes and $\pm 4\%$ for quark-initiated processes [42–45]. The Higgs boson decay branching ratio [46] to the four-fermion final state is predicted by PROPHECY4F [47,48].

The Higgs boson cross sections are calculated with a zero-width approximation. For the Higgs decay, a relativistic Breit–Wigner line shape is applied at the event-generator level. It has been suggested [25,49–51] that effects related to off-shell Higgs boson production and interference with other SM processes may become sizeable for the highest Higgs boson masses ($m_H > 400$ GeV) considered in this search. Currently, in the absence of a full lineshape calculation for the production mechanisms as well as a correct account of the interference with SM ZZ production, an estimate of the possible size of such effects is included as a signal normalisation systematic uncertainty, following a parameterisation as a function of m_H : $1.5 \times [m_H/\text{TeV}]^3$, for $m_H \geq 300$ GeV [25].

Different event generators are chosen to model a range of important background processes. The ALPGEN generator [52] interfaced to HERWIG [53] for parton showers and hadronisation is used to simulate inclusive W/Z boson backgrounds. MC@NLO [54], interfaced to HERWIG and JIMMY [55], is used for the production of top-pair, single-top and diboson (WW , WZ and ZZ) backgrounds. PYTHIA is used to simulate $b\bar{b}$ and $c\bar{c}$ samples as well as alterna-

tive samples for the inclusive Z boson and ZZ backgrounds. All simulated background samples are scaled to the highest-precision calculations available for the relevant process. An overview of the relevant predictions and their uncertainties is given in Ref. [56].

Generated events are simulated using the ATLAS detector simulation [57] within the GEANT4 framework [58]. Additional pp interactions in the same and nearby bunch crossings (pile-up) are included in the simulation. The Monte Carlo (MC) samples are reweighted to reproduce the observed distribution of the number of interactions per bunch crossing in the data.

Data used for the search in the muon channel are collected using a single muon trigger with a p_T threshold of 18 GeV, while in the electron case a logical OR between a single electron trigger with a threshold varying from 20 to 22 GeV and a dielectron trigger with a p_T threshold of 12 GeV is used.

The overall trigger efficiencies are estimated from MC events after correction of the simulated lepton trigger efficiencies to those observed in data. For signal events passing the full selection criteria, the trigger efficiency is close to 100% in the electron channel and between 94% and 97% in the muon channel. The systematic uncertainties on the trigger efficiency are negligible when compared to the other selection uncertainties.

During the course of the 2011 data-taking, the average number of pile-up interactions increased due to increased beam currents and stronger beam focusing. This changed the average number of interactions per bunch crossing at the start of a fill, from about six in the earlier periods to about 15 in the later periods. The missing transverse momentum resolution is affected by the level of pile-up, resulting in a significant change in the signal-to-background ratio between the earlier and the later periods. To retain the best sensitivity, the search is therefore split between the earlier (2.3 fb^{-1}) and the later (2.4 fb^{-1}) periods, hereafter referred to as the “low pile-up data” and the “high pile-up data”, respectively. The selection is unaltered between the periods.

4. Lepton identification and event selection

Electron candidates consist of clusters of energy deposited in the electromagnetic calorimeter that are associated with tracks reconstructed in the ID. The electron candidates must satisfy a set of identification criteria [59] that require the shower profiles to be consistent with those expected for electromagnetic showers and a well-reconstructed ID track pointing to the corresponding cluster. Furthermore, the electron candidates are required to have $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.47$. The electron transverse momentum is computed from the cluster energy and the track direction at the interaction point.

Muons are identified by reconstructing tracks in the muon spectrometer. These tracks are then extrapolated back to the beam line to find a matching ID track. Details of muon reconstruction and identification can be found in Ref. [60]. Only muons with $p_T > 20$ GeV and $|\eta| < 2.5$ are considered.

Jets are used in this analysis to reject backgrounds from events with heavy-quark decays or from events with fake missing transverse momentum E_T^{miss} due to mis-measured jets. For this purpose, jets are reconstructed from clusters of energy deposits in the calorimeters using the anti- k_t algorithm [61] with a radius parameter $R = 0.4$. Jets are calibrated using p_T - and η -dependent correction factors based on MC simulation and validated with data [62]; this calibration corrects for effects of energy from additional proton–proton interactions. Only jets with $p_T > 25$ GeV and $|\eta| < 2.5$ are considered.

Two conditions are applied to remove leptons associated with jets, such as those originating from semi-leptonic decays of b -hadrons. Leptons are not considered in the analysis if the scalar

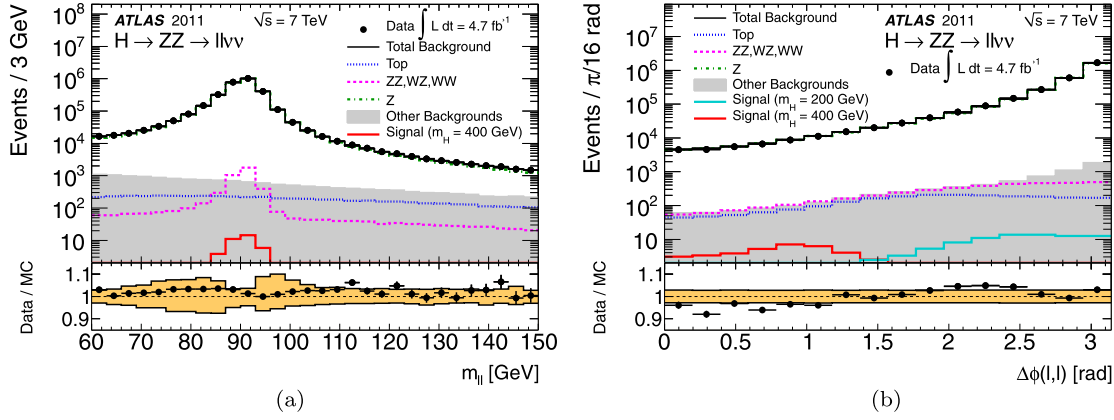


Fig. 1. (a) The dilepton invariant mass distribution for events with exactly two oppositely-charged electrons or muons. (b) The azimuthal separation between leptons for events with exactly two oppositely-charged electrons or muons with an invariant mass satisfying $|m_Z - m_{\ell\ell}| < 15$ GeV. The inset at the bottom of the figures shows the ratio of the data to the combined background expectations as well as a band corresponding to the combined systematic uncertainties. In both figures the line corresponding to the Z boson background is mostly hidden under the line for the total background. The background contribution labelled “Other Backgrounds” includes multijet and inclusive W boson production.

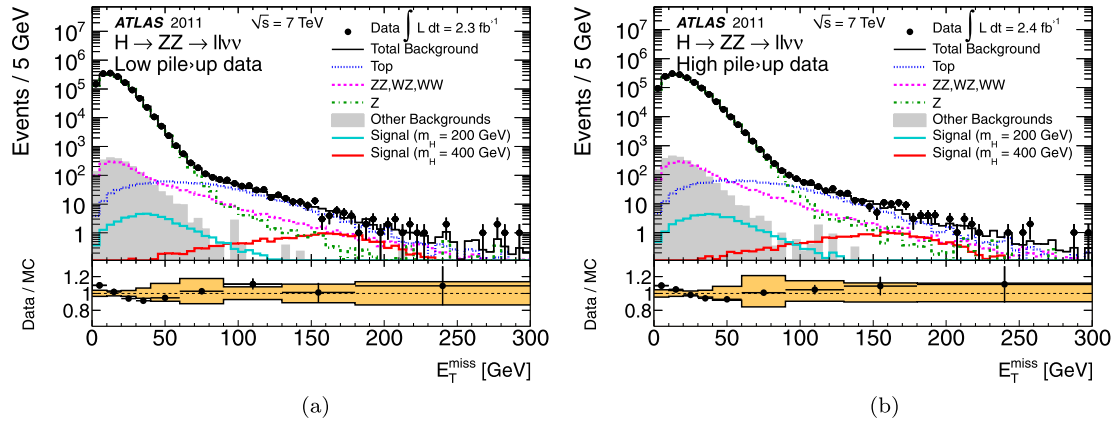


Fig. 2. The E_T^{miss} distributions for events with exactly two oppositely-charged electrons or muons satisfying $|m_Z - m_{\ell\ell}| < 15$ GeV, for (a) the low pile-up data and (b) the high pile-up data. The insets at the bottom show the ratio of the data to the combined background expectations as well as a band corresponding to the combined systematic uncertainties. The background contribution labelled “Other Backgrounds” includes multijet and inclusive W boson production.

sum of ID track momenta, not associated with the lepton, in a cone of $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.2$ around the lepton direction is greater than 10% of the p_T of the lepton itself or if the lepton is within a distance $\Delta R = 0.4$ of the nearest jet.

The missing transverse momentum is measured as the negative vectorial sum of the transverse momenta measured in all cells in the calorimeters with $|\eta| < 4.9$, calibrated appropriately based on their identification as electrons, photons, τ -leptons, jets or unassociated calorimeter cells, and all selected muons in the event [63]. Calorimeter deposits associated with muons are subtracted to avoid double counting.

Events are required to contain a reconstructed primary vertex, with at least three associated tracks with $p_T > 0.4$ GeV, and exactly two oppositely-charged electrons or muons, consistent with having originated from the primary vertex. Furthermore, events are rejected if they contain a third lepton, as defined above, but with a loosened p_T requirement of at least 10 GeV. The dilepton mass distribution is shown in Fig. 1(a). Inclusive Z boson production is the dominant background at this stage of the analysis. To suppress backgrounds from top, inclusive W boson, and multijet production, the dilepton invariant mass, $m_{\ell\ell}$, is required to satisfy $|m_Z - m_{\ell\ell}| < 15$ GeV.

To reduce the background from top quark production, events with one or more b -tagged jets are rejected, where the b -tagging is based on a multivariate algorithm which uses information from

both the impact parameter with respect to the primary vertex of tracks associated to the jet and the presence of displaced secondary vertices associated to the jet’s tracks. Jets with a loosened p_T threshold of 20 GeV and $|\eta| < 2.5$ are considered in the b -tag veto. The selection applied on the b -tagging discriminant achieves an efficiency of about 85% (50%) for identifying b -jets (c -jets) [64] and a light-jet rejection factor of about ten [65] in inclusive top-pair events.

To exploit the mass-dependent kinematic features of $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ production, the search is subdivided into a low Higgs boson mass region ($m_H < 280$ GeV) and a high Higgs boson mass region ($m_H \geq 280$ GeV), where dedicated selection criteria are applied to two important discriminating variables used to reduce the background contributions: E_T^{miss} and the azimuthal angle between the two leptons, $\Delta\phi(\ell, \ell)$. Events can contribute to one or both search regions depending on whether they satisfy the selection criteria applied on these variables. Figs. 1(b) and 2 show the distributions of these variables after the application of the $m_{\ell\ell}$ window. Since inclusive Z boson production gives rise to a steeply falling E_T^{miss} distribution, systematic uncertainties on the E_T^{miss} reconstruction are particularly important in order to estimate this background correctly.

The dominant contribution to the E_T^{miss} uncertainty comes from the knowledge of the jet energy scale. A degradation of the E_T^{miss} resolution is observed in the data taken during the periods with a

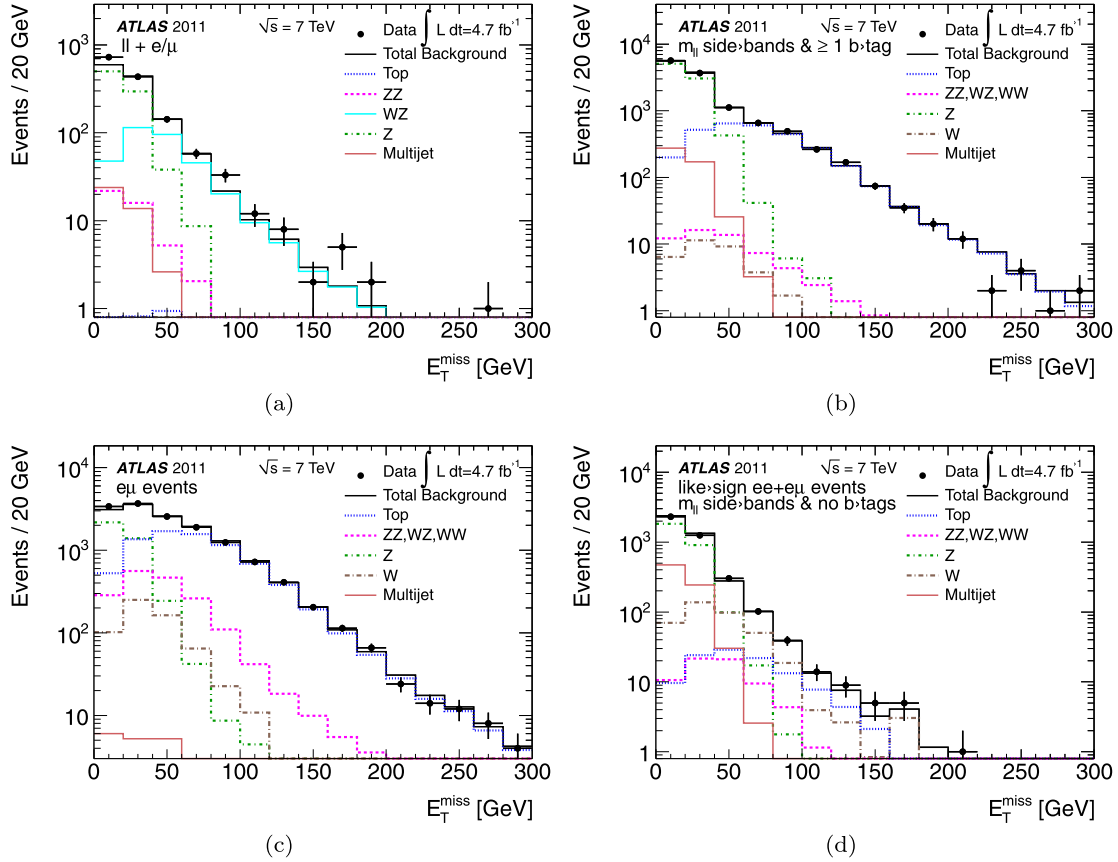


Fig. 3. The E_T^{miss} distribution in the different control regions: Figure (a) is a WZ control region with events containing exactly three leptons. Figure (b) is a top-quark control region populated with events containing at least one b -jet and a lepton pair in the sidebands of dilepton mass distribution. Figure (c) is a second top-quark control region populated with events with an oppositely-charged $e\mu$ pair. Figure (d) is an inclusive W boson control region populated with events with no b -tagged jets and a same-charge ee or $e\mu$ pair in the sidebands of dilepton mass distribution.

larger average number of interactions per bunch crossing, as is illustrated in Fig. 2. In particular, this increases the background from inclusive Z boson production in the high pile-up periods, mostly in the low mass search region.

Fig. 2 shows that, at high E_T^{miss} , the data and the combined background expectation agree within systematic uncertainties. In the low m_H region, events are required to satisfy $E_T^{\text{miss}} > 66$ GeV, whilst in the high m_H region the requirement is $E_T^{\text{miss}} > 82$ GeV. These selection criteria reduce significantly the backgrounds from processes with no or modest genuine missing transverse momentum originating from unobserved neutrinos. In the low m_H region a significant fraction of signal events is also removed by this criterion.

The boost of the Z bosons originating from a Higgs boson decay increases with m_H , thus reducing the expected opening angle between the leptons. In the low (high) m_H region an upper bound, $\Delta\phi(\ell, \ell) < 2.64$ (2.25), is therefore applied. In the low m_H region a lower bound, $\Delta\phi(\ell, \ell) > 1$, is also applied, to reduce backgrounds from events in which the lepton pair did not originate from a Z boson decay. In the high m_H region, events are also rejected if the azimuthal angle between the missing transverse momentum vector and the direction of the $Z \rightarrow \ell\ell$ boson candidate is $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\ell\ell}) < 1$.

Finally, to further reduce the background from events with fake E_T^{miss} due to mis-measured jets, events are rejected if the azimuthal angle between \vec{p}_T^{miss} and the nearest jet in the event satisfies $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}}) < 1.5$ for the low m_H search and $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}}) < 0.5$ for the high m_H region.

The efficiency of the event selection is very similar in the electron and muon channels, ranging from 3.1% for $m_H = 200$ GeV to about 43% for $m_H = 600$ GeV.

5. Background normalisation and control regions

Standard Model pair-production of Z bosons has a final state identical to the signal, and is therefore expected to survive most of the applied selection criteria and form a continuum in the transverse mass distribution (defined in Section 7). The normalisation for this background is obtained from a calculation including next-to-leading-order terms [66] with an additional 6% term to account for missing quark-box diagrams ($gg \rightarrow ZZ$) [67]. An 11% normalisation uncertainty is assigned to this background. This combines the theoretical uncertainty for Z pair production estimated in Ref. [25] with an additional modelling uncertainty related to the used Monte Carlo model, estimated from comparison to other models. The ZZ background is taken from the MC simulation. A systematic uncertainty to account for shape uncertainties is derived using PYTHIA as an alternative event generator. WW and WZ backgrounds are normalised in a similar way. For the WZ background the normalisation is verified using a control sample in which the presence of exactly three leptons is required, where the minimum p_T for the third lepton is 10 GeV. Fig. 3(a) shows the E_T^{miss} distribution in this control region, which is dominated by WZ background for $E_T^{\text{miss}} > 40$ GeV and is well modelled by the MC simulations, in the high E_T^{miss} region.

The background from top-quark events is taken from the MC prediction. This prediction is verified to agree with data in two

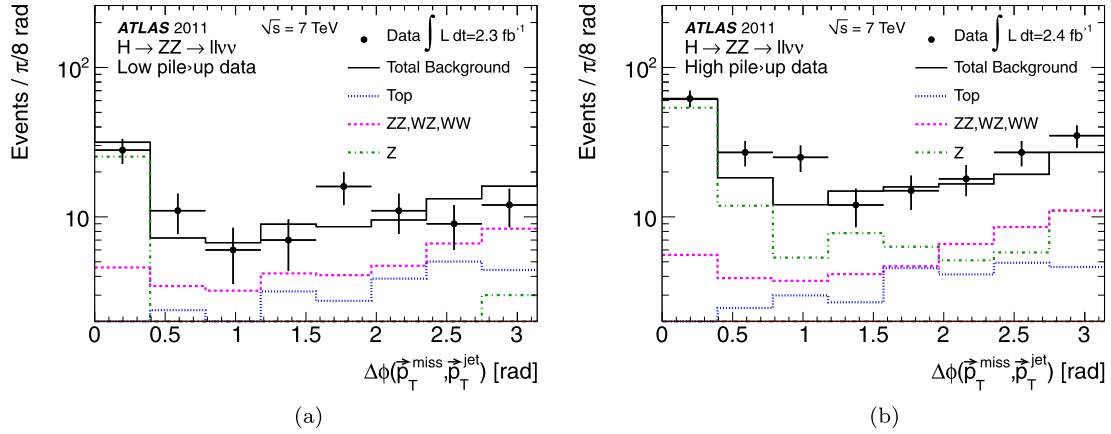


Fig. 4. The azimuthal separation between the missing transverse momentum vector, \vec{p}_T^{miss} , and the nearest jet in the event $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}})$ after the E_T^{miss} requirement, for the high m_H search region. Figure (a) refers to the low pile-up data and figure (b) to the high pile-up data.

Table 1

The expected number of background and signal events along with the observed numbers of candidates in the data, separated into the low and high m_H search regions and the low and high pile-up periods. The quoted uncertainties are statistical and systematic, respectively.

Source	Low m_H search		High m_H search	
	Low pile-up data	High pile-up data	Low pile-up data	High pile-up data
Z	$40.1 \pm 5.0 \pm 7.9$	$265 \pm 13 \pm 67$	$0.8 \pm 0.3 \pm 0.8$	$11.6 \pm 2.1 \pm 2.9$
W	$4.6 \pm 2.2 \pm 4.6$	$5.8 \pm 1.8 \pm 5.8$	$1.5 \pm 0.8 \pm 1.5$	$2.2 \pm 1.3 \pm 2.2$
Top	$23.2 \pm 1.3 \pm 5.4$	$27.9 \pm 1.3 \pm 5.3$	$16.0 \pm 1.1 \pm 4.0$	$17.2 \pm 1.0 \pm 3.9$
Multijet	$1.1 \pm 0.2 \pm 0.5$	$1.1 \pm 0.2 \pm 0.6$	$0.1 \pm 0.1 \pm 0.0$	$0.1 \pm 0.1 \pm 0.0$
ZZ	$33.4 \pm 0.7 \pm 3.9$	$36.7 \pm 0.7 \pm 4.3$	$28.4 \pm 0.6 \pm 3.4$	$31.9 \pm 0.7 \pm 3.8$
WZ	$23.3 \pm 1.0 \pm 2.8$	$25.2 \pm 1.0 \pm 3.0$	$17.1 \pm 0.8 \pm 2.1$	$18.9 \pm 0.8 \pm 2.3$
WW	$25.5 \pm 0.8 \pm 3.0$	$32.4 \pm 0.9 \pm 3.8$	$9.4 \pm 0.5 \pm 1.1$	$13.3 \pm 0.5 \pm 1.6$
Total	$151 \pm 6 \pm 11$	$394 \pm 13 \pm 67$	$73.3 \pm 1.8 \pm 6.1$	$95.2 \pm 2.9 \pm 6.9$
Data	158	442	77	109
m_H [GeV]	Signal expectation			
200	$10.3 \pm 0.2 \pm 1.8$	$11.1 \pm 0.2 \pm 1.9$		
300			$16.4 \pm 0.3 \pm 2.9$	$17.5 \pm 0.3 \pm 3.1$
400			$14.4 \pm 0.2 \pm 2.5$	$15.4 \pm 0.2 \pm 2.7$
500			$6.2 \pm 0.1 \pm 1.1$	$6.5 \pm 0.1 \pm 1.1$
600			$2.7 \pm 0.0 \pm 0.5$	$2.9 \pm 0.0 \pm 0.5$

independent control samples: the first uses the dilepton mass sideband and requires at least one identified b -jet (Fig. 3(b)), while the second selects events containing oppositely-charged electron–muon pairs (Fig. 3(c)).

Additional backgrounds can arise from multijet events or inclusive W boson production due to heavy flavour decays or jets misidentified as leptons. The normalisation of the inclusive W boson background in this search is obtained from a control sample of events with a like-sign electron–electron or electron–muon pair in the sidebands of the dilepton mass distribution and with no b -tagged jets. Fig. 3(d) shows the E_T^{miss} distribution following this procedure. At large E_T^{miss} this distribution is dominated by the inclusive W boson background.

The multijet background in the electron channel is determined using a data sample based on a loosened electron selection. This sample, which is dominated by jet events, is scaled to describe the tails of the $m_{\ell\ell}$ distribution. In the muon channel, the background from heavy flavour decays is studied using simulation, whereas other muon sources from multijet events are constrained using a sample of like-sign muon pairs in data. In both cases the background is found to be negligible.

The background from inclusive Z boson production is taken from the MC prediction and verified in a control region populated with events rejected by the $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}})$ selection criterion after the E_T^{miss} requirement. The full $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}})$ distribution is

shown in Fig. 4. At low $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}})$, where the inclusive Z boson background dominates, a small discrepancy is observed between the data and the expected backgrounds. This discrepancy is within the systematic uncertainties applied on the inclusive Z boson background.

The signal efficiencies and overall background expectations are similar in the electron and muon channels; therefore only combined results are presented. The numbers of candidate $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ events selected in data and the expected yields from signal and background processes are shown in Table 1.

6. Systematic uncertainties

The systematic uncertainties applied in this search include experimental uncertainties related to the selection and calibration of electrons, muons and jets, which are also all explicitly propagated to the E_T^{miss} calculation. Uncertainties on the $b(c)$ -tagging efficiency as well as the light-jet mis-tagging rate are also applied.

Normalisation uncertainties for the signal (gluon fusion $^{+14\%}_{-10\%}$ and VBF 4%) [24] and for the diboson backgrounds (11%, see Section 5) are obtained from theory; uncertainties for the inclusive Z boson production (2.5%), top quark production (9%), inclusive W boson production (100%) and for multijet production in the electron channel (50%) are estimated from data. These normalisation uncertainties are not the full systematic uncertainties applied

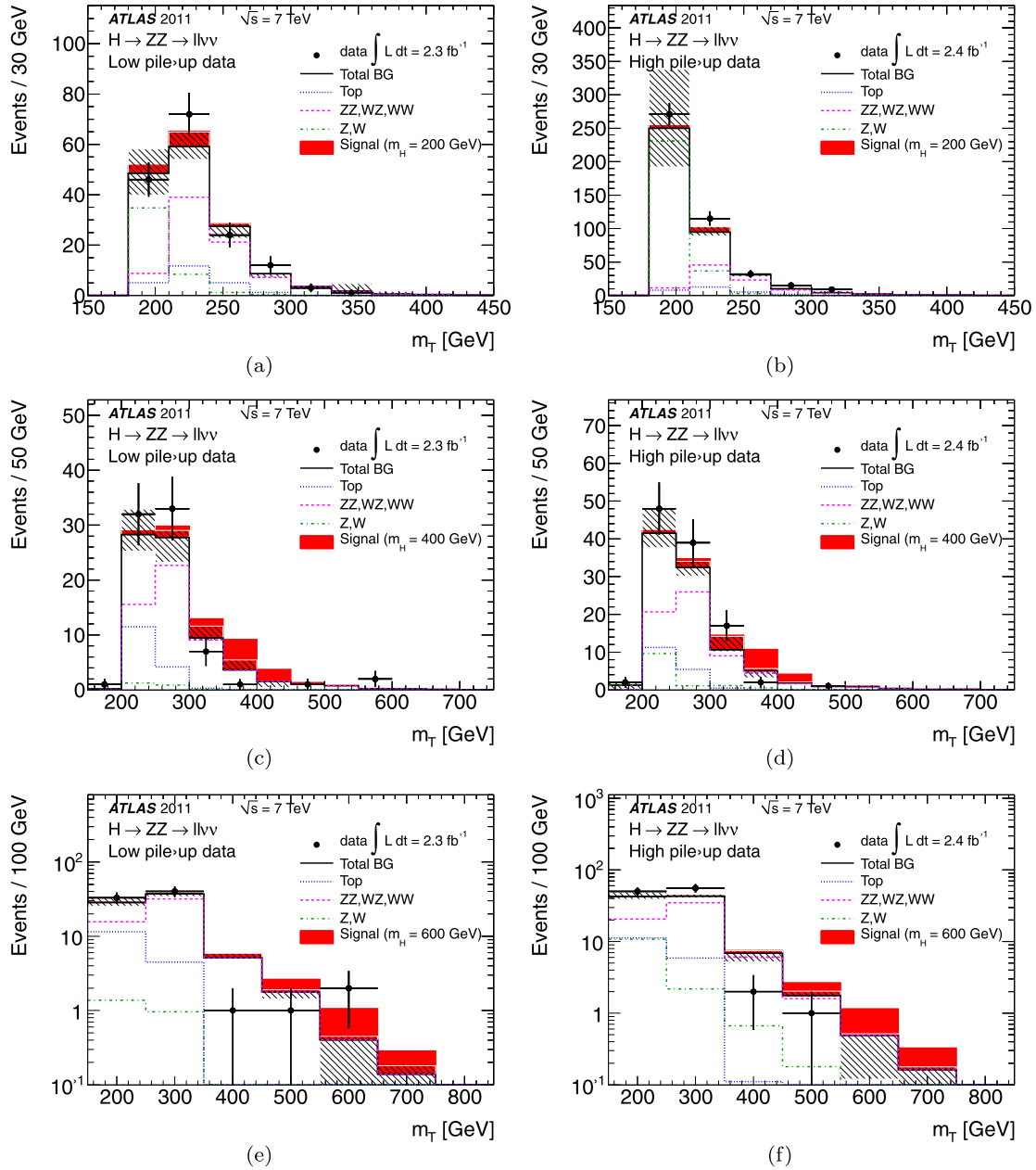


Fig. 5. The transverse mass distribution of $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ candidates. Figures (a) and (b) refer to the low m_H search region and figures (c) to (f) to the high m_H search region. The top, centre and bottom figures show the expected signal for a Higgs boson with a mass of 200 GeV, 400 GeV and 600 GeV, respectively. Figures on the left correspond to the low pile-up data and figures on the right to the high pile-up data. The hashed area represents the combined systematic uncertainties on the total expected background.

on these backgrounds. Where a normalisation uncertainty is obtained from data, additional detector related systematic uncertainties are applied if they are likely to affect the background in the control region and in the signal region differently. Where a normalisation error is taken from theory, full detector related systematic uncertainties are applied.

For the signal, an additional uncertainty is applied to account for the possible effect of theoretical uncertainties on the acceptance. This uncertainty is estimated from signal samples containing variations in the modelling of initial- and final-state radiation, the renormalisation and factorisation scales, which are varied to half and twice their nominal values, as well as variations in the underlying event tune, which was changed from the default AUET2B [68] to PERUGIA2011 [69], both based on LHC data. An overall uncertainty of 8.4% (3.4%) is assigned in the low (high) mass search

regions, obtained by the addition in quadrature of the largest deviations observed for each variation.

The luminosity uncertainty is 3.7% and 4.1% for the low and high pile-up data, respectively, based on the calibration described in Refs. [11,12]. Where appropriate, systematic uncertainties are treated as correlated between the signal and the different background expectations. The total systematic uncertainty on the signal and on each of the background contributions can be seen in Table 1. In most cases the assigned normalisation uncertainties dominate the total systematic uncertainty, except for the inclusive Z boson background, for which the jet energy scale and resolution uncertainties dominate, and the top-quark background for which the b -tagging uncertainty dominates. In the low m_H search using the high pile-up data, the uncertainty on the inclusive Z boson background uncertainty dominates the overall uncertainty.

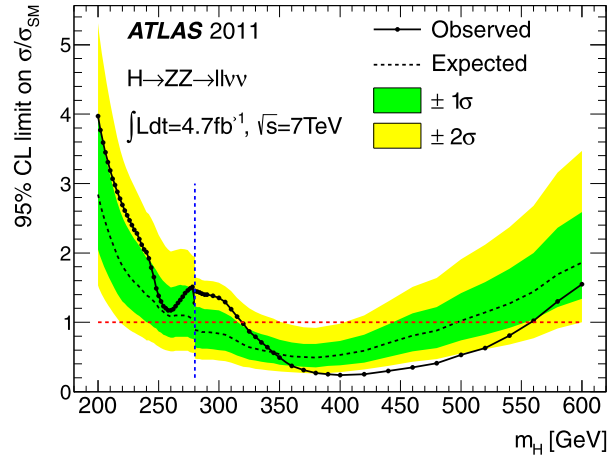


Fig. 6. Observed and expected 95% CL upper limits on the Higgs boson production cross section divided by the SM prediction, together with the green (inner) and yellow (outer) bands which indicate the $\pm 1\sigma$ and $\pm 2\sigma$ fluctuations, respectively, around the median sensitivity. The limits are based on 4.7 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$. The line at 280 GeV indicates the transition from the low m_H to the high m_H search region.

7. Results

After the event selection, the Higgs boson search is performed by looking for an excess of data over the SM background expectation in the transverse mass distribution of the selected $ee\nu\nu$ and $\mu\mu\nu\nu$ events. The transverse mass is calculated from the lepton pair and the \vec{p}_T^{miss} vector as:

$$m_T^2 \equiv \left[\sqrt{m_Z^2 + |\vec{p}_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_T^{\text{miss}}|^2} \right]^2 - [\vec{p}_T^{\ell\ell} + \vec{p}_T^{\text{miss}}]^2.$$

Fig. 5 shows the m_T distributions in the low and high m_H search regions with the expected signal for a Higgs boson mass of 200 GeV, 400 GeV and 600 GeV. The low pile-up and high pile-up data are shown separately.

The number and distribution of candidate $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ events observed in the data agree with the expected backgrounds. No indication of an excess is seen, with a smallest p_0 -value of 0.05 at $m_H = 280$ GeV, where p_0 represents the probability that a background-only experiment would yield a result that is more signal-like than the observed result. Upper limits are set on the Higgs boson production cross section relative to its predicted SM value as a function of m_H . The limits are extracted from a maximum likelihood fit to the m_T distribution following the CL_s modified frequentist formalism [70] with the profile likelihood test statistic [71]. All systematic uncertainties are taken into account. The likelihood function includes the parameters that describe the systematic uncertainties and their correlations. No significant pulls are observed on any of these parameters.

Fig. 6 shows the expected and observed limits at the 95% CL. Bands are shown, indicating the expected sensitivity with $\pm 1\sigma$ and $\pm 2\sigma$ fluctuations. At low values of m_H the transverse mass resolution induces correlations in the observed limit between neighbouring mass points. While at high values of m_H , where the observed limits are lower than expected over a broad range, the width of the SM Higgs is large and these correlations are therefore stronger. The mass range between 280–497 GeV is expected to be excluded while observation shows that a SM Higgs is excluded at the 95% CL in the range of 319–558 GeV.

8. Summary

Results of a search for a heavy SM Higgs boson with a mass in the range $200 < m_H < 600$ GeV decaying to $ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ have

been presented. These results are based on a data sample corresponding to an integrated luminosity of 4.7 fb^{-1} and $\sqrt{s} = 7 \text{ TeV}$, recorded with the ATLAS detector at the LHC. No evidence for a signal is observed and cross section limits are placed over the mass range considered in this search, excluding the production of a SM Higgs boson in the region $319 < m_H < 558$ GeV at the 95% CL.

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Biesiada¹⁴, M. Biglietti^{134a}, H. Bilokon⁴⁷, M. Bindi^{19a,19b}, S. Binet¹¹⁵, A. Bingul^{18c}, C. Bini^{132a,132b}, C. Biscarat¹⁷⁸, U. Bitenc⁴⁸, K.M. Black²¹, R.E. Blair⁵, J.-B. Blanchard¹³⁶, G. Blanchot²⁹, T. Blazek^{144a}, C. Blocker²², J. Blocki³⁸, A. Blondel⁴⁹, W. Blum⁸¹, U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁵, V.B. Bobrovnikov¹⁰⁷, S.S. Bocchetta⁷⁹, A. Bocci⁴⁴, C.R. Boddy¹¹⁸, M. Boehler⁴¹, J. Boek¹⁷⁵, N. Boelaert³⁵, J.A. Bogaerts²⁹, A. Bogdanchikov¹⁰⁷, A. Bogouch^{90,*}, C. Boehm^{146a}, J. Boehm¹²⁵, V. Boisvert⁷⁶, T. Bold³⁷, V. Boldea^{25a}, N.M. Bolnet¹³⁶, M. Bomben⁷⁸, M. Bona⁷⁵, M. Bondioli¹⁶³, M. Boonekamp¹³⁶, C.N. Booth¹³⁹, S. Bordini⁷⁸, C. Borer¹⁶, A. Borisov¹²⁸, G. Borissov⁷¹, I. Borjanovic^{12a}, M. Borri⁸², S. Borroni⁸⁷, V. Bortolotto^{134a,134b}, K. Bos¹⁰⁵, D. Boscherini^{19a}, M. Bosman¹¹, H. Boterenbrood¹⁰⁵, D. Botterill¹²⁹, J. Bouchami⁹³, J. Boudreau¹²³, E.V. Bouhova-Thacker⁷¹, D. Boumediene³³, C. Bourdarios¹¹⁵, N. Bousson⁸³, A. Boveia³⁰, J. Boyd²⁹, I.R. Boyko⁶⁴, N.I. Bozhko¹²⁸, I. Bozovic-Jelisavcic^{12b}, J. Bracinik¹⁷, P. Branchini^{134a}, A. Brandt⁷, G. Brandt¹¹⁸, O. Brandt⁵⁴, U. Bratzler¹⁵⁶, B. Brau⁸⁴, J.E. Brau¹¹⁴, H.M. Braun¹⁷⁵, B. Brelier¹⁵⁸, J. Bremer²⁹, K. Brendlinger¹²⁰, R. Brenner¹⁶⁶, S. Bressler¹⁷², D. Britton⁵³, F.M. Brochu²⁷, I. Brock²⁰, R. Brock⁸⁸, E. Brodet¹⁵³, F. Broggi^{89a}, C. Bromberg⁸⁸, J. Bronner⁹⁹, G. Brooijmans³⁴, W.K. Brooks^{31b}, G. Brown⁸², H. Brown⁷, P.A. Bruckman de Renstrom³⁸, D. Bruncko^{144b}, R. Bruneliere⁴⁸, S. Brunet⁶⁰, A. Bruni^{19a}, G. Bruni^{19a}, M. Bruschi^{19a}, T. Buanes¹³, Q. Buat⁵⁵, F. Bucci⁴⁹, J. Buchanan¹¹⁸, P. Buchholz¹⁴¹, R.M. Buckingham¹¹⁸, A.G. Buckley⁴⁵, S.I. Buda^{25a}, I.A. Budagov⁶⁴, B. Budick¹⁰⁸, V. Büscher⁸¹, L. Bugge¹¹⁷, O. Bulekov⁹⁶, A.C. Bundock⁷³, M. Bunse⁴², T. Buran¹¹⁷, H. Burckhart²⁹, S. Burdin⁷³, T. Burgess¹³, S. Burke¹²⁹, E. Busato³³, P. Bussey⁵³, C.P. Buszello¹⁶⁶, B. Butler¹⁴³, J.M. Butler²¹, C.M. Buttar⁵³, J.M. Butterworth⁷⁷, W. Buttinger²⁷, S. Cabrera Urbán¹⁶⁷, D. Caforio^{19a,19b}, O. Cakir^{3a}, P. Calafiura¹⁴, G. Calderini⁷⁸, P. Calfayan⁹⁸, R. Calkins¹⁰⁶, L.P. Caloba^{23a}, R. Caloi^{132a,132b}, D. Calvet³³, S. Calvet³³, R. Camacho Toro³³, P. Camarri^{133a,133b}, D. Cameron¹¹⁷, L.M. Caminada¹⁴, S. Campana²⁹, M. Campanelli⁷⁷, V. Canale^{102a,102b}, F. Canelli^{30,g}, A. Canepa^{159a}, J. Cantero⁸⁰, L. Capasso^{102a,102b},

M.D.M. Capeans Garrido²⁹, I. Caprini^{25a}, M. Caprini^{25a}, D. Capriotti⁹⁹, M. Capua^{36a,36b}, R. Caputo⁸¹,
 R. Cardarelli^{133a}, T. Carli²⁹, G. Carlino^{102a}, L. Carminati^{89a,89b}, B. Caron⁸⁵, S. Caron¹⁰⁴, E. Carquin^{31b},
 G.D. Carrillo Montoya¹⁷³, A.A. Carter⁷⁵, J.R. Carter²⁷, J. Carvalho^{124a,h}, D. Casadei¹⁰⁸, M.P. Casado¹¹,
 M. Cascella^{122a,122b}, C. Caso^{50a,50b,*}, A.M. Castaneda Hernandez^{173,i}, E. Castaneda-Miranda¹⁷³,
 V. Castillo Gimenez¹⁶⁷, N.F. Castro^{124a}, G. Cataldi^{72a}, P. Catastini⁵⁷, A. Catinaccio²⁹, J.R. Catmore²⁹,
 A. Cattai²⁹, G. Cattani^{133a,133b}, S. Caughron⁸⁸, P. Cavalleri⁷⁸, D. Cavalli^{89a}, M. Cavalli-Sforza¹¹,
 V. Cavasinni^{122a,122b}, F. Ceradini^{134a,134b}, A.S. Cerqueira^{23b}, A. Cerri²⁹, L. Cerrito⁷⁵, F. Cerutti⁴⁷,
 S.A. Cetin^{18b}, A. Chafaq^{135a}, D. Chakraborty¹⁰⁶, I. Chalupkova¹²⁶, K. Chan², B. Chapleau⁸⁵,
 J.D. Chapman²⁷, J.W. Chapman⁸⁷, E. Chareyre⁷⁸, D.G. Charlton¹⁷, V. Chavda⁸², C.A. Chavez Barajas²⁹,
 S. Cheatham⁸⁵, S. Chekanov⁵, S.V. Chekulaev^{159a}, G.A. Chelkov⁶⁴, M.A. Chelstowska¹⁰⁴, C. Chen⁶³,
 H. Chen²⁴, S. Chen^{32c}, X. Chen¹⁷³, A. Cheplakov⁶⁴, R. Cherkaoui El Moursli^{135e}, V. Chernyatin²⁴,
 E. Cheu⁶, S.L. Cheung¹⁵⁸, L. Chevalier¹³⁶, G. Chiefari^{102a,102b}, L. Chikovani^{51a}, J.T. Childers²⁹,
 A. Chilingarov⁷¹, G. Chiodini^{72a}, A.S. Chisholm¹⁷, R.T. Chislett⁷⁷, M.V. Chizhov⁶⁴, G. Choudalakis³⁰,
 S. Chouridou¹³⁷, I.A. Christidi⁷⁷, A. Christov⁴⁸, D. Chromek-Burckhart²⁹, M.L. Chu¹⁵¹, J. Chudoba¹²⁵,
 G. Ciapetti^{132a,132b}, A.K. Ciftci^{3a}, R. Ciftci^{3a}, D. Cinca³³, V. Cindro⁷⁴, C. Ciocca^{19a}, A. Ciocio¹⁴,
 M. Cirilli⁸⁷, M. Citterio^{89a}, M. Ciubancan^{25a}, A. Clark⁴⁹, P.J. Clark⁴⁵, W. Cleland¹²³, J.C. Clemens⁸³,
 B. Clement⁵⁵, C. Clement^{146a,146b}, Y. Coadou⁸³, M. Cobal^{164a,164c}, A. Coccaro¹³⁸, J. Cochran⁶³, P. Coe¹¹⁸,
 J.G. Cogan¹⁴³, J. Coggeshall¹⁶⁵, E. Cogneras¹⁷⁸, J. Colas⁴, A.P. Colijn¹⁰⁵, N.J. Collins¹⁷, C. Collins-Tooth⁵³,
 J. Collot⁵⁵, G. Colon⁸⁴, P. Conde Muiño^{124a}, E. Coniavitis¹¹⁸, M.C. Conidi¹¹, S.M. Consonni^{89a,89b},
 V. Consorti⁴⁸, S. Constantinescu^{25a}, C. Conta^{119a,119b}, G. Conti⁵⁷, F. Conventi^{102a,j}, M. Cooke¹⁴,
 B.D. Cooper⁷⁷, A.M. Cooper-Sarkar¹¹⁸, K. Copic¹⁴, T. Cornelissen¹⁷⁵, M. Corradi^{19a}, F. Corriveau^{85,k},
 A. Cortes-Gonzalez¹⁶⁵, G. Cortiana⁹⁹, G. Costa^{89a}, M.J. Costa¹⁶⁷, D. Costanzo¹³⁹, T. Costin³⁰, D. Côté²⁹,
 L. Courneyea¹⁶⁹, G. Cowan⁷⁶, C. Cowden²⁷, B.E. Cox⁸², K. Cranmer¹⁰⁸, F. Crescioli^{122a,122b},
 M. Cristinziani²⁰, G. Crosetti^{36a,36b}, R. Crupi^{72a,72b}, S. Crépé-Renaudin⁵⁵, C.-M. Cuciuc^{25a},
 C. Cuenca Almenar¹⁷⁶, T. Cuhadar Donszelmann¹³⁹, M. Curatolo⁴⁷, C.J. Curtis¹⁷, C. Cuthbert¹⁵⁰,
 P. Cwetanski⁶⁰, H. Czirr¹⁴¹, P. Czodrowski⁴³, Z. Czyzula¹⁷⁶, S. D'Auria⁵³, M. D'Onofrio⁷³,
 A. D'Orazio^{132a,132b}, C. Da Via⁸², W. Dabrowski³⁷, A. Dafinca¹¹⁸, T. Dai⁸⁷, C. Dallapiccola⁸⁴, M. Dam³⁵,
 M. Dameri^{50a,50b}, D.S. Damiani¹³⁷, H.O. Danielsson²⁹, V. Dao⁴⁹, G. Darbo^{50a}, G.L. Darlea^{25b},
 W. Davey²⁰, T. Davidek¹²⁶, N. Davidson⁸⁶, R. Davidson⁷¹, E. Davies^{118,c}, M. Davies⁹³, A.R. Davison⁷⁷,
 Y. Davygora^{58a}, E. Dawe¹⁴², I. Dawson¹³⁹, R.K. Daya-Ishmukhametova²², K. De⁷, R. de Asmundis^{102a},
 S. De Castro^{19a,19b}, S. De Cecco⁷⁸, J. de Graat⁹⁸, N. De Groot¹⁰⁴, P. de Jong¹⁰⁵, C. De La Taille¹¹⁵,
 H. De la Torre⁸⁰, F. De Lorenzi⁶³, L. de Mora⁷¹, L. De Nooij¹⁰⁵, D. De Pedis^{132a}, A. De Salvo^{132a},
 U. De Sanctis^{164a,164c}, A. De Santo¹⁴⁹, J.B. De Vivie De Regie¹¹⁵, G. De Zorzi^{132a,132b}, W.J. Dearnaley⁷¹,
 R. Debbe²⁴, C. Debenedetti⁴⁵, B. Dechenaux⁵⁵, D.V. Dedovich⁶⁴, J. Degenhardt¹²⁰, C. Del Papa^{164a,164c},
 J. Del Peso⁸⁰, T. Del Prete^{122a,122b}, T. Delemontex⁵⁵, M. Deliyergiyev⁷⁴, A. Dell'Acqua²⁹, L. Dell'Asta²¹,
 M. Della Pietra^{102a,j}, D. della Volpe^{102a,102b}, M. Delmastro⁴, P.A. Delsart⁵⁵, C. Deluca¹⁴⁸, S. Demers¹⁷⁶,
 M. Demichev⁶⁴, B. Demirköz^{11,l}, J. Deng¹⁶³, S.P. Denisov¹²⁸, D. Derendarz³⁸, J.E. Derkaoui^{135d},
 F. Derue⁷⁸, P. Dervan⁷³, K. Desch²⁰, E. Devetak¹⁴⁸, P.O. Deviveiros¹⁰⁵, A. Dewhurst¹²⁹, B. DeWilde¹⁴⁸,
 S. Dhaliwal¹⁵⁸, R. Dhullipudi^{24,m}, A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁴, A. Di Girolamo²⁹,
 B. Di Girolamo²⁹, S. Di Luise^{134a,134b}, A. Di Mattia¹⁷³, B. Di Micco²⁹, R. Di Nardo⁴⁷,
 A. Di Simone^{133a,133b}, R. Di Sipio^{19a,19b}, M.A. Diaz^{31a}, F. Diblen^{18c}, E.B. Diehl⁸⁷, J. Dietrich⁴¹,
 T.A. Dietzsch^{58a}, S. Diglio⁸⁶, K. Dindar Yagci³⁹, J. Dingfelder²⁰, C. Dionisi^{132a,132b}, P. Dita^{25a}, S. Dita^{25a},
 F. Dittus²⁹, F. Djama⁸³, T. Djobava^{51b}, M.A.B. do Vale^{23c}, A. Do Valle Wemans^{124a,n}, T.K.O. Doan⁴,
 M. Dobbs⁸⁵, R. Dobinson^{29,*}, D. Dobos²⁹, E. Dobson^{29,o}, J. Dodd³⁴, C. Doglioni⁴⁹, T. Doherty⁵³,
 Y. Doi^{65,*}, J. Dolejsi¹²⁶, I. Dolenc⁷⁴, Z. Dolezal¹²⁶, B.A. Dolgoshein^{96,*}, T. Dohmae¹⁵⁵, M. Donadelli^{23d},
 M. Donega¹²⁰, J. Donini³³, J. Dopke²⁹, A. Doria^{102a}, A. Dos Anjos¹⁷³, A. Dotti^{122a,122b}, M.T. Dova⁷⁰,
 A.D. Doxiadis¹⁰⁵, A.T. Doyle⁵³, M. Dris⁹, J. Dubbert⁹⁹, S. Dube¹⁴, E. Duchovni¹⁷², G. Duckeck⁹⁸,
 A. Dudarev²⁹, F. Dudziak⁶³, M. Dührssen²⁹, I.P. Duerdoth⁸², L. Dufloc¹¹⁵, M.-A. Dufour⁸⁵, M. Dunford²⁹,
 H. Duran Yildiz^{3a}, R. Duxfield¹³⁹, M. Dwuznik³⁷, F. Dydak²⁹, M. Düren⁵², J. Ebke⁹⁸, S. Eckweiler⁸¹,
 K. Edmonds⁸¹, C.A. Edwards⁷⁶, N.C. Edwards⁵³, W. Ehrenfeld⁴¹, T. Eifert¹⁴³, G. Eigen¹³, K. Einsweiler¹⁴,
 E. Eisenhandler⁷⁵, T. Ekelof¹⁶⁶, M. El Kacimi^{135c}, M. Ellert¹⁶⁶, S. Elles⁴, F. Ellinghaus⁸¹, K. Ellis⁷⁵,
 N. Ellis²⁹, J. Elmsheuser⁹⁸, M. Elsing²⁹, D. Emeliyanov¹²⁹, R. Engelmann¹⁴⁸, A. Engl⁹⁸, B. Epp⁶¹,

A. Eppig⁸⁷, J. Erdmann⁵⁴, A. Ereditato¹⁶, D. Eriksson^{146a}, J. Ernst¹, M. Ernst²⁴, J. Ernwein¹³⁶,
 D. Errede¹⁶⁵, S. Errede¹⁶⁵, E. Ertel⁸¹, M. Escalier¹¹⁵, C. Escobar¹²³, X. Espinal Curull¹¹, B. Esposito⁴⁷,
 F. Etienne⁸³, A.I. Etievre¹³⁶, E. Etzion¹⁵³, D. Evangelakou⁵⁴, H. Evans⁶⁰, L. Fabbri^{19a,19b}, C. Fabre²⁹,
 R.M. Fakhruddinov¹²⁸, S. Falciano^{132a}, Y. Fang¹⁷³, M. Fanti^{89a,89b}, A. Farbin⁷, A. Farilla^{134a}, J. Farley¹⁴⁸,
 T. Farooque¹⁵⁸, S. Farrell¹⁶³, S.M. Farrington¹¹⁸, P. Farthouat²⁹, P. Fassnacht²⁹, D. Fassouliotis⁸,
 B. Fatholahzadeh¹⁵⁸, A. Favareto^{89a,89b}, L. Fayard¹¹⁵, S. Fazio^{36a,36b}, R. Febbraro³³, P. Federic^{144a},
 O.L. Fedin¹²¹, W. Fedorko⁸⁸, M. Fehling-Kaschek⁴⁸, L. Feligioni⁸³, D. Fellmann⁵, C. Feng^{32d}, E.J. Feng³⁰,
 A.B. Fenyuk¹²⁸, J. Ferencei^{144b}, W. Fernando⁵, S. Ferrag⁵³, J. Ferrando⁵³, V. Ferrara⁴¹, A. Ferrari¹⁶⁶,
 P. Ferrari¹⁰⁵, R. Ferrari^{119a}, D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁷, D. Ferrere⁴⁹, C. Ferretti⁸⁷,
 A. Ferretto Parodi^{50a,50b}, M. Fiascaris³⁰, F. Fiedler⁸¹, A. Filipčič⁷⁴, F. Filthaut¹⁰⁴, M. Fincke-Keeler¹⁶⁹,
 M.C.N. Fiolhais^{124a,h}, L. Fiorini¹⁶⁷, A. Firan³⁹, G. Fischer⁴¹, M.J. Fisher¹⁰⁹, M. Flechl⁴⁸, I. Fleck¹⁴¹,
 J. Fleckner⁸¹, P. Fleischmann¹⁷⁴, S. Fleischmann¹⁷⁵, T. Flick¹⁷⁵, A. Floderus⁷⁹, L.R. Flores Castillo¹⁷³,
 M.J. Flowerdew⁹⁹, T. Fonseca Martin¹⁶, A. Formica¹³⁶, A. Forti⁸², D. Fortin^{159a}, D. Fournier¹¹⁵, H. Fox⁷¹,
 P. Francavilla¹¹, S. Franchino^{119a,119b}, D. Francis²⁹, T. Frank¹⁷², M. Franklin⁵⁷, S. Franz²⁹,
 M. Fraternali^{119a,119b}, S. Fratina¹²⁰, S.T. French²⁷, C. Friedrich⁴¹, F. Friedrich⁴³, R. Froeschl²⁹,
 D. Froidevaux²⁹, J.A. Frost²⁷, C. Fukunaga¹⁵⁶, E. Fullana Torregrosa²⁹, B.G. Fulsom¹⁴³, J. Fuster¹⁶⁷,
 C. Gabaldon²⁹, O. Gabizon¹⁷², T. Gadfort²⁴, S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰, C. Galea⁹⁸,
 E.J. Gallas¹¹⁸, V. Gallo¹⁶, B.J. Gallop¹²⁹, P. Gallus¹²⁵, K.K. Gan¹⁰⁹, Y.S. Gao^{143,e}, A. Gaponenko¹⁴,
 F. Garberon¹⁷⁶, M. Garcia-Sciveres¹⁴, C. García¹⁶⁷, J.E. García Navarro¹⁶⁷, R.W. Gardner³⁰, N. Garelli²⁹,
 H. Garitaonandia¹⁰⁵, V. Garonne²⁹, J. Garvey¹⁷, C. Gatti⁴⁷, G. Gaudio^{119a}, B. Gaur¹⁴¹, L. Gauthier¹³⁶,
 P. Gauzzi^{132a,132b}, I.L. Gavrilenko⁹⁴, C. Gay¹⁶⁸, G. Gaycken²⁰, E.N. Gazis⁹, P. Ge^{32d}, Z. Gece¹⁶⁸,
 C.N.P. Gee¹²⁹, D.A.A. Geerts¹⁰⁵, Ch. Geich-Gimbel²⁰, K. Gellerstedt^{146a,146b}, C. Gemme^{50a},
 A. Gemmell⁵³, M.H. Genest⁵⁵, S. Gentile^{132a,132b}, M. George⁵⁴, S. George⁷⁶, P. Gerlach¹⁷⁵,
 A. Gershon¹⁵³, C. Geweniger^{58a}, H. Ghazlane^{135b}, N. Ghodbane³³, B. Giacobbe^{19a}, S. Giagu^{132a,132b},
 V. Giakoumopoulou⁸, V. Giangiobbe¹¹, F. Gianotti²⁹, B. Gibbard²⁴, A. Gibson¹⁵⁸, S.M. Gibson²⁹,
 D. Gillberg²⁸, A.R. Gillman¹²⁹, D.M. Gingrich^{2,d}, J. Ginzburg¹⁵³, N. Giokaris⁸, M.P. Giordani^{164c},
 R. Giordano^{102a,102b}, F.M. Giorgi¹⁵, P. Giovannini⁹⁹, P.F. Giraud¹³⁶, D. Giugni^{89a}, M. Giunta⁹³,
 P. Giusti^{19a}, B.K. Gjelsten¹¹⁷, L.K. Gladilin⁹⁷, C. Glasman⁸⁰, J. Glatzer⁴⁸, A. Glazov⁴¹, K.W. Glitza¹⁷⁵,
 G.L. Glonti⁶⁴, J.R. Goddard⁷⁵, J. Godfrey¹⁴², J. Godlewski²⁹, M. Goebel⁴¹, T. Göpfert⁴³, C. Goeringer⁸¹,
 C. Gössling⁴², T. Göttfert⁹⁹, S. Goldfarb⁸⁷, T. Golling¹⁷⁶, A. Gomes^{124a,b}, L.S. Gomez Fajardo⁴¹,
 R. Gonçalves⁷⁶, J. Goncalves Pinto Firmino Da Costa⁴¹, L. Gonella²⁰, S. Gonzalez¹⁷³,
 S. González de la Hoz¹⁶⁷, G. Gonzalez Parra¹¹, M.L. Gonzalez Silva²⁶, S. Gonzalez-Sevilla⁴⁹,
 J.J. Goodson¹⁴⁸, L. Goossens²⁹, P.A. Gorbounov⁹⁵, H.A. Gordon²⁴, I. Gorelov¹⁰³, G. Gorfine¹⁷⁵,
 B. Gorini²⁹, E. Gorini^{72a,72b}, A. Gorišek⁷⁴, E. Gornicki³⁸, B. Gosdzik⁴¹, A.T. Goshaw⁵, M. Gosselink¹⁰⁵,
 M.I. Gostkin⁶⁴, I. Gough Eschrich¹⁶³, M. Gouighri^{135a}, D. Goujdami^{135c}, M.P. Goulette⁴⁹,
 A.G. Goussiou¹³⁸, C. Goy⁴, S. Gozpinar²², I. Grabowska-Bold³⁷, P. Grafström²⁹, K.-J. Grah⁴¹,
 F. Grancagnolo^{72a}, S. Grancagnolo¹⁵, V. Grassi¹⁴⁸, V. Gratchev¹²¹, N. Grau³⁴, H.M. Gray²⁹, J.A. Gray¹⁴⁸,
 E. Graziani^{134a}, O.G. Grebenyuk¹²¹, T. Greenshaw⁷³, Z.D. Greenwood^{24,m}, K. Gregersen³⁵, I.M. Gregor⁴¹,
 P. Grenier¹⁴³, J. Griffiths¹³⁸, N. Grigalashvili⁶⁴, A.A. Grillo¹³⁷, S. Grinstein¹¹, Y.V. Grishkevich⁹⁷,
 J.-F. Grivaz¹¹⁵, E. Gross¹⁷², J. Grosse-Knetter⁵⁴, J. Groth-Jensen¹⁷², K. Grybel¹⁴¹, D. Guest¹⁷⁶,
 C. Guicheney³³, A. Guida^{72a,72b}, S. Guindon⁵⁴, H. Guler^{85,p}, J. Gunther¹²⁵, B. Guo¹⁵⁸, J. Guo³⁴,
 V.N. Gushchin¹²⁸, P. Gutierrez¹¹¹, N. Guttman¹⁵³, O. Gutzwiller¹⁷³, C. Guyot¹³⁶, C. Gwenlan¹¹⁸,
 C.B. Gwilliam⁷³, A. Haas¹⁴³, S. Haas²⁹, C. Haber¹⁴, H.K. Hadavand³⁹, D.R. Hadley¹⁷, P. Haefner⁹⁹,
 F. Hahn²⁹, S. Haider²⁹, Z. Hajduk³⁸, H. Hakobyan¹⁷⁷, D. Hall¹¹⁸, J. Haller⁵⁴, K. Hamacher¹⁷⁵,
 P. Hamal¹¹³, M. Hamer⁵⁴, A. Hamilton^{145b,q}, S. Hamilton¹⁶¹, L. Han^{32b}, K. Hanagaki¹¹⁶, K. Hanawa¹⁶⁰,
 M. Hance¹⁴, C. Handel⁸¹, P. Hanke^{58a}, J.R. Hansen³⁵, J.B. Hansen³⁵, J.D. Hansen³⁵, P.H. Hansen³⁵,
 P. Hansson¹⁴³, K. Hara¹⁶⁰, G.A. Hare¹³⁷, T. Harenberg¹⁷⁵, S. Harkusha⁹⁰, D. Harper⁸⁷,
 R.D. Harrington⁴⁵, O.M. Harris¹³⁸, K. Harrison¹⁷, J. Hartert⁴⁸, F. Hartjes¹⁰⁵, T. Haruyama⁶⁵, A. Harvey⁵⁶,
 S. Hasegawa¹⁰¹, Y. Hasegawa¹⁴⁰, S. Hassani¹³⁶, S. Haug¹⁶, M. Hauschild²⁹, R. Hauser⁸⁸, M. Havranek²⁰,
 C.M. Hawkes¹⁷, R.J. Hawkins²⁹, A.D. Hawkins⁷⁹, D. Hawkins¹⁶³, T. Hayakawa⁶⁶, T. Hayashi¹⁶⁰,
 D. Hayden⁷⁶, H.S. Hayward⁷³, S.J. Haywood¹²⁹, M. He^{32d}, S.J. Head¹⁷, V. Hedberg⁷⁹, L. Heelan⁷,
 S. Heim⁸⁸, B. Heinemann¹⁴, S. Heisterkamp³⁵, L. Helary⁴, C. Heller⁹⁸, M. Heller²⁹, S. Hellman^{146a,146b},

D. Hellmich²⁰, C. Helsens¹¹, R.C.W. Henderson⁷¹, M. Henke^{58a}, A. Henrichs⁵⁴,
 A.M. Henriques Correia²⁹, S. Henrot-Versille¹¹⁵, F. Henry-Couannier⁸³, C. Hensel⁵⁴, T. Henß¹⁷⁵,
 C.M. Hernandez⁷, Y. Hernández Jiménez¹⁶⁷, R. Herrberg¹⁵, G. Hertzen⁴⁸, R. Hertenberger⁹⁸, L. Hervas²⁹,
 G.G. Hesketh⁷⁷, N.P. Hessey¹⁰⁵, E. Higón-Rodríguez¹⁶⁷, J.C. Hill²⁷, K.H. Hiller⁴¹, S. Hillert²⁰,
 S.J. Hillier¹⁷, I. Hinchliffe¹⁴, E. Hines¹²⁰, M. Hirose¹¹⁶, F. Hirsch⁴², D. Hirschbuehl¹⁷⁵, J. Hobbs¹⁴⁸,
 N. Hod¹⁵³, M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker²⁹, M.R. Hoferkamp¹⁰³, J. Hoffman³⁹,
 D. Hoffmann⁸³, M. Hohlfeld⁸¹, M. Holder¹⁴¹, S.O. Holmgren^{146a}, T. Holy¹²⁷, J.L. Holzbauer⁸⁸,
 T.M. Hong¹²⁰, L. Hooft van Huysduynen¹⁰⁸, C. Horn¹⁴³, S. Horner⁴⁸, J.-Y. Hostachy⁵⁵, S. Hou¹⁵¹,
 A. Hoummada^{135a}, J. Howarth⁸², I. Hristova¹⁵, J. Hrivnac¹¹⁵, I. Hruska¹²⁵, T. Hryn'ova⁴, P.J. Hsu⁸¹,
 S.-C. Hsu¹⁴, Z. Hubacek¹²⁷, F. Hubaut⁸³, F. Huegging²⁰, A. Huettmann⁴¹, T.B. Huffman¹¹⁸,
 E.W. Hughes³⁴, G. Hughes⁷¹, M. Huhtinen²⁹, M. Hurwitz¹⁴, U. Husemann⁴¹, N. Huseynov^{64,r},
 J. Huston⁸⁸, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis⁹, M. Ibbotson⁸², I. Ibragimov¹⁴¹,
 L. Iconomidou-Fayard¹¹⁵, J. Idarraga¹¹⁵, P. Iengo^{102a}, O. Igonkina¹⁰⁵, Y. Ikegami⁶⁵, M. Ikeno⁶⁵,
 D. Iliadis¹⁵⁴, N. Ilic¹⁵⁸, T. Ince²⁰, J. Inigo-Golfín²⁹, P. Ioannou⁸, M. Iodice^{134a}, K. Iordanidou⁸,
 V. Ippolito^{132a,132b}, A. Irlés Quiles¹⁶⁷, C. Isaksson¹⁶⁶, A. Ishikawa⁶⁶, M. Ishino⁶⁷, R. Ishmukhametov³⁹,
 C. Issever¹¹⁸, S. Istin^{18a}, A.V. Ivashin¹²⁸, W. Iwanski³⁸, H. Iwasaki⁶⁵, J.M. Izen⁴⁰, V. Izzo^{102a},
 B. Jackson¹²⁰, J.N. Jackson⁷³, P. Jackson¹⁴³, M.R. Jaekel²⁹, V. Jain⁶⁰, K. Jakobs⁴⁸, S. Jakobsen³⁵,
 J. Jakubek¹²⁷, D.K. Jana¹¹¹, E. Jansen⁷⁷, H. Jansen²⁹, A. Jantsch⁹⁹, M. Janus⁴⁸, G. Jarlskog⁷⁹, L. Jeanty⁵⁷,
 I. Jen-La Plante³⁰, P. Jenni²⁹, A. Jeremie⁴, P. Jež³⁵, S. Jézéquel⁴, M.K. Jha^{19a}, H. Ji¹⁷³, W. Ji⁸¹, J. Jia¹⁴⁸,
 Y. Jiang^{32b}, M. Jimenez Belenguer⁴¹, S. Jin^{32a}, O. Jinnouchi¹⁵⁷, M.D. Joergensen³⁵, D. Joffe³⁹,
 L.G. Johansen¹³, M. Johansen^{146a,146b}, K.E. Johansson^{146a}, P. Johansson¹³⁹, S. Johnert⁴¹, K.A. Johns⁶,
 K. Jon-And^{146a,146b}, G. Jones¹¹⁸, R.W.L. Jones⁷¹, T.J. Jones⁷³, C. Joram²⁹, P.M. Jorge^{124a}, K.D. Joshi⁸²,
 J. Jovicevic¹⁴⁷, T. Jovin^{12b}, X. Ju¹⁷³, C.A. Jung⁴², R.M. Jungst²⁹, V. Juranek¹²⁵, P. Jussel⁶¹,
 A. Juste Rozas¹¹, S. Kabana¹⁶, M. Kaci¹⁶⁷, A. Kaczmarska³⁸, P. Kadlecik³⁵, M. Kado¹¹⁵, H. Kagan¹⁰⁹,
 M. Kagan⁵⁷, E. Kajomovitz¹⁵², S. Kalinin¹⁷⁵, L.V. Kalinovskaya⁶⁴, S. Kama³⁹, N. Kanaya¹⁵⁵, M. Kaneda²⁹,
 S. Kaneti²⁷, T. Kanno¹⁵⁷, V.A. Kantserov⁹⁶, J. Kanzaki⁶⁵, B. Kaplan¹⁷⁶, A. Kapliy³⁰, J. Kaplon²⁹, D. Kar⁵³,
 M. Karagounis²⁰, K. Karakostas⁹, M. Karnevskiy⁴¹, V. Kartvelishvili⁷¹, A.N. Karyukhin¹²⁸, L. Kashif¹⁷³,
 G. Kasieczka^{58b}, R.D. Kass¹⁰⁹, A. Kastanas¹³, M. Kataoka⁴, Y. Kataoka¹⁵⁵, E. Katsoufis⁹, J. Katzy⁴¹,
 V. Kaushik⁶, K. Kawagoe⁶⁹, T. Kawamoto¹⁵⁵, G. Kawamura⁸¹, M.S. Kayl¹⁰⁵, V.A. Kazanin¹⁰⁷,
 M.Y. Kazarinov⁶⁴, R. Keeler¹⁶⁹, R. Kehoe³⁹, M. Keil⁵⁴, G.D. Kekelidze⁶⁴, J.S. Keller¹³⁸, J. Kennedy⁹⁸,
 M. Kenyon⁵³, O. Kepka¹²⁵, N. Kerschen²⁹, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁵, K. Kessoku¹⁵⁵, J. Keung¹⁵⁸,
 F. Khalil-zada¹⁰, H. Khandanyan¹⁶⁵, A. Khanov¹¹², D. Kharchenko⁶⁴, A. Khodinov⁹⁶, A. Khomich^{58a},
 T.J. Khoo²⁷, G. Khoraiuli²⁰, A. Khoroshilov¹⁷⁵, V. Khovanskiy⁹⁵, E. Khramov⁶⁴, J. Khubua^{51b},
 H. Kim^{146a,146b}, M.S. Kim², S.H. Kim¹⁶⁰, N. Kimura¹⁷¹, O. Kind¹⁵, B.T. King⁷³, M. King⁶⁶, R.S.B. King¹¹⁸,
 J. Kirk¹²⁹, A.E. Kiryunin⁹⁹, T. Kishimoto⁶⁶, D. Kisielewska³⁷, T. Kittelmann¹²³, A.M. Kiver¹²⁸,
 E. Kladiva^{144b}, M. Klein⁷³, U. Klein⁷³, K. Kleinknecht⁸¹, M. Klemetti⁸⁵, A. Klier¹⁷², P. Klimek^{146a,146b},
 A. Klimentov²⁴, R. Klingenberg⁴², J.A. Klinger⁸², E.B. Klinkby³⁵, T. Klioutchnikova²⁹, P.F. Klok¹⁰⁴,
 S. Klous¹⁰⁵, E.-E. Kluge^{58a}, T. Kluge⁷³, P. Kluit¹⁰⁵, S. Kluth⁹⁹, N.S. Knecht¹⁵⁸, E. Kneringer⁶¹,
 E.B.F.G. Knoop⁸³, A. Knue⁵⁴, B.R. Ko⁴⁴, T. Kobayashi¹⁵⁵, M. Kobel⁴³, M. Kocian¹⁴³, P. Kodys¹²⁶,
 K. Köneke²⁹, A.C. König¹⁰⁴, S. Koenig⁸¹, L. Köpke⁸¹, F. Koetsveld¹⁰⁴, P. Koevesarki²⁰, T. Koffas²⁸,
 E. Koffeman¹⁰⁵, L.A. Kogan¹¹⁸, S. Kohlmann¹⁷⁵, F. Kohn⁵⁴, Z. Kohout¹²⁷, T. Kohriki⁶⁵, T. Koi¹⁴³,
 G.M. Kolachev¹⁰⁷, H. Kolanoski¹⁵, V. Kolesnikov⁶⁴, I. Koletsou^{89a}, J. Koll⁸⁸, M. Kollerfrath⁴⁸,
 A.A. Komar⁹⁴, Y. Komori¹⁵⁵, T. Kondo⁶⁵, T. Kono^{41,s}, A.I. Kononov⁴⁸, R. Konoplich^{108,t},
 N. Konstantinidis⁷⁷, A. Kootz¹⁷⁵, S. Koperny³⁷, K. Korcyl³⁸, K. Kordas¹⁵⁴, A. Korn¹¹⁸, A. Korol¹⁰⁷,
 I. Korolkov¹¹, E.V. Korolkova¹³⁹, V.A. Korotkov¹²⁸, O. Kortner⁹⁹, S. Kortner⁹⁹, V.V. Kostyukhin²⁰,
 S. Kotov⁹⁹, V.M. Kotov⁶⁴, A. Kotwal⁴⁴, C. Kourkoumelis⁸, V. Kouskoura¹⁵⁴, A. Koutsman^{159a},
 R. Kowalewski¹⁶⁹, T.Z. Kowalski³⁷, W. Kozanecki¹³⁶, A.S. Kozhin¹²⁸, V. Kral¹²⁷, V.A. Kramarenko⁹⁷,
 G. Kramberger⁷⁴, M.W. Krasny⁷⁸, A. Krasznahorkay¹⁰⁸, J. Kraus⁸⁸, J.K. Kraus²⁰, F. Krejci¹²⁷,
 J. Kretzschmar⁷³, N. Krieger⁵⁴, P. Krieger¹⁵⁸, K. Kroeninger⁵⁴, H. Kroha⁹⁹, J. Kroll¹²⁰, J. Kroseberg²⁰,
 J. Krstic^{12a}, U. Kruchonak⁶⁴, H. Krüger²⁰, T. Kruker¹⁶, N. Krumnack⁶³, Z.V. Krumshteyn⁶⁴, A. Kruth²⁰,
 T. Kubota⁸⁶, S. Kudah^{3a}, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl⁴¹, D. Kuhn⁶¹, V. Kukhtin⁶⁴, Y. Kulchitsky⁹⁰,
 S. Kuleshov^{31b}, C. Kummer⁹⁸, M. Kuna⁷⁸, J. Kunkle¹²⁰, A. Kupco¹²⁵, H. Kurashige⁶⁶, M. Kurata¹⁶⁰,

Y.A. Kurochkin⁹⁰, V. Kus¹²⁵, E.S. Kuwertz¹⁴⁷, M. Kuze¹⁵⁷, J. Kvita¹⁴², R. Kwee¹⁵, A. La Rosa⁴⁹,
 L. La Rotonda^{36a,36b}, L. Labarga⁸⁰, J. Labbe⁴, S. Lablak^{135a}, C. Lacasta¹⁶⁷, F. Lacava^{132a,132b}, H. Lacker¹⁵,
 D. Lacour⁷⁸, V.R. Lacuesta¹⁶⁷, E. Ladygin⁶⁴, R. Lafaye⁴, B. Laforge⁷⁸, T. Lagouri⁸⁰, S. Lai⁴⁸, E. Laisne⁵⁵,
 M. Lamanna²⁹, L. Lambourne⁷⁷, C.L. Lampen⁶, W. Lampl⁶, E. Lancon¹³⁶, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵,
 J.L. Lane⁸², C. Lange⁴¹, A.J. Lankford¹⁶³, F. Lanni²⁴, K. Lantzschi¹⁷⁵, S. Laplace⁷⁸, C. Lapoire²⁰,
 J.F. Laporte¹³⁶, T. Lari^{89a}, A. Larner¹¹⁸, M. Lassnig²⁹, P. Laurelli⁴⁷, V. Lavorini^{36a,36b}, W. Lavrijsen¹⁴,
 P. Laycock⁷³, O. Le Dortz⁷⁸, E. Le Guirriec⁸³, C. Le Maner¹⁵⁸, E. Le Menedeu¹¹, T. LeCompte⁵,
 F. Ledroit-Guillon⁵⁵, H. Lee¹⁰⁵, J.S.H. Lee¹¹⁶, S.C. Lee¹⁵¹, L. Lee¹⁷⁶, M. Lefebvre¹⁶⁹, M. Legendre¹³⁶,
 B.C. LeGeyt¹²⁰, F. Legger⁹⁸, C. Leggett¹⁴, M. Lehmacher²⁰, G. Lehmann Miotto²⁹, X. Lei⁶,
 M.A.L. Leite^{23d}, R. Leitner¹²⁶, D. Lellouch¹⁷², B. Lemmer⁵⁴, V. Lendermann^{58a}, K.J.C. Leney^{145b},
 T. Lenz¹⁰⁵, G. Lenzen¹⁷⁵, B. Lenzi²⁹, K. Leonhardt⁴³, S. Leontsinis⁹, F. Lepold^{58a}, C. Leroy⁹³,
 J.-R. Lessard¹⁶⁹, C.G. Lester²⁷, C.M. Lester¹²⁰, J. Levêque⁴, D. Levin⁸⁷, L.J. Levinson¹⁷², A. Lewis¹¹⁸,
 G.H. Lewis¹⁰⁸, A.M. Leyko²⁰, M. Leyton¹⁵, B. Li⁸³, H. Li^{173,u}, S. Li^{32b,v}, X. Li⁸⁷, Z. Liang^{118,w}, H. Liao³³,
 B. Liberti^{133a}, P. Lichard²⁹, M. Lichtnecker⁹⁸, K. Lie¹⁶⁵, W. Liebig¹³, C. Limbach²⁰, A. Limosani⁸⁶,
 M. Limper⁶², S.C. Lin^{151,x}, F. Linde¹⁰⁵, J.T. Linnemann⁸⁸, E. Lipeles¹²⁰, A. Lipniacka¹³, T.M. Liss¹⁶⁵,
 D. Lissauer²⁴, A. Lister⁴⁹, A.M. Litke¹³⁷, C. Liu²⁸, D. Liu¹⁵¹, H. Liu⁸⁷, J.B. Liu⁸⁷, M. Liu^{32b}, Y. Liu^{32b},
 M. Livan^{119a,119b}, S.S.A. Livermore¹¹⁸, A. Lleres⁵⁵, J. Llorente Merino⁸⁰, S.L. Lloyd⁷⁵, E. Lobodzinska⁴¹,
 P. Loch⁶, W.S. Lockman¹³⁷, T. Loddenkoetter²⁰, F.K. Loebinger⁸², A. Loginov¹⁷⁶, C.W. Loh¹⁶⁸, T. Lohse¹⁵,
 K. Lohwasser⁴⁸, M. Lokajicek¹²⁵, V.P. Lombardo⁴, R.E. Long⁷¹, L. Lopes^{124a}, D. Lopez Mateos⁵⁷,
 J. Lorenz⁹⁸, N. Lorenzo Martinez¹¹⁵, M. Losada¹⁶², P. Loscutoff¹⁴, F. Lo Sterzo^{132a,132b}, M.J. Losty^{159a},
 X. Lou⁴⁰, A. Lounis¹¹⁵, K.F. Loureiro¹⁶², J. Love²¹, P.A. Love⁷¹, A.J. Lowe^{143,e}, F. Lu^{32a}, H.J. Lubatti¹³⁸,
 C. Luci^{132a,132b}, A. Lucotte⁵⁵, A. Ludwig⁴³, D. Ludwig⁴¹, I. Ludwig⁴⁸, J. Ludwig⁴⁸, F. Luehring⁶⁰,
 G. Luijckx¹⁰⁵, W. Lukas⁶¹, D. Lumb⁴⁸, L. Luminari^{132a}, E. Lund¹¹⁷, B. Lund-Jensen¹⁴⁷, B. Lundberg⁷⁹,
 J. Lundberg^{146a,146b}, J. Lundquist³⁵, M. Lungwitz⁸¹, D. Lynn²⁴, J. Lys¹⁴, E. Lytken⁷⁹, H. Ma²⁴, L.L. Ma¹⁷³,
 J.A. Macana Goia⁹³, G. Maccarrone⁴⁷, A. Macchiolo⁹⁹, B. Maček⁷⁴, J. Machado Miguens^{124a},
 R. Mackeprang³⁵, R.J. Madaras¹⁴, W.F. Mader⁴³, R. Maenner^{58c}, T. Maeno²⁴, P. Mättig¹⁷⁵, S. Mättig⁴¹,
 L. Magnoni²⁹, E. Magradze⁵⁴, K. Mahboubi⁴⁸, S. Mahmoud⁷³, G. Mahout¹⁷, C. Maiani¹³⁶,
 C. Maidantchik^{23a}, A. Maio^{124a,b}, S. Majewski²⁴, Y. Makida⁶⁵, N. Makovec¹¹⁵, P. Mal¹³⁶, B. Malaescu²⁹,
 Pa. Malecki³⁸, P. Malecki³⁸, V.P. Maleev¹²¹, F. Malek⁵⁵, U. Mallik⁶², D. Malon⁵, C. Malone¹⁴³,
 S. Maltezos⁹, V. Malyshev¹⁰⁷, S. Malyukov²⁹, R. Mameghani⁹⁸, J. Mamuzic^{12b}, A. Manabe⁶⁵,
 L. Mandelli^{89a}, I. Mandić⁷⁴, R. Mandrysch¹⁵, J. Maneira^{124a}, P.S. Mangedard⁸⁸,
 L. Manhaes de Andrade Filho^{23a}, A. Mann⁵⁴, P.M. Manning¹³⁷, A. Manousakis-Katsikakis⁸,
 B. Mansoulie¹³⁶, A. Mapelli²⁹, L. Mapelli²⁹, L. March⁸⁰, J.F. Marchand²⁸, F. Marchese^{133a,133b},
 G. Marchiori⁷⁸, M. Marcisovsky¹²⁵, C.P. Marino¹⁶⁹, F. Marroquim^{23a}, Z. Marshall²⁹, F.K. Martens¹⁵⁸,
 S. Marti-Garcia¹⁶⁷, B. Martin²⁹, B. Martin⁸⁸, J.P. Martin⁹³, T.A. Martin¹⁷, V.J. Martin⁴⁵,
 B. Martin dit Latour⁴⁹, S. Martin-Haugh¹⁴⁹, M. Martinez¹¹, V. Martinez Outschoorn⁵⁷,
 A.C. Martyniuk¹⁶⁹, M. Marx⁸², F. Marzano^{132a}, A. Marzin¹¹¹, L. Masetti⁸¹, T. Mashimo¹⁵⁵,
 R. Mashinistov⁹⁴, J. Masik⁸², A.L. Maslennikov¹⁰⁷, I. Massa^{19a,19b}, G. Massaro¹⁰⁵, N. Massol⁴,
 P. Mastrandrea^{132a,132b}, A. Mastroberardino^{36a,36b}, T. Masubuchi¹⁵⁵, P. Matricon¹¹⁵, H. Matsunaga¹⁵⁵,
 T. Matsushita⁶⁶, C. Mattravers^{118,c}, J. Maurer⁸³, S.J. Maxfield⁷³, A. Mayne¹³⁹, R. Mazini¹⁵¹, M. Mazur²⁰,
 L. Mazzaferro^{133a,133b}, M. Mazzanti^{89a}, S.P. Mc Kee⁸⁷, A. McCarn¹⁶⁵, R.L. McCarthy¹⁴⁸, T.G. McCarthy²⁸,
 N.A. McCubbin¹²⁹, K.W. McFarlane⁵⁶, J.A. McFayden¹³⁹, H. McGlone⁵³, G. Mchedlidze^{51b},
 T. McLaughlan¹⁷, S.J. McMahon¹²⁹, R.A. McPherson^{169,k}, A. Meade⁸⁴, J. Mechnich¹⁰⁵, M. Mechtel¹⁷⁵,
 M. Medinnis⁴¹, R. Meera-Lebbai¹¹¹, T. Meguro¹¹⁶, R. Mehdiev⁹³, S. Mehlhase³⁵, A. Mehta⁷³,
 K. Meier^{58a}, B. Meirose⁷⁹, C. Melachrinou³⁰, B.R. Mellado Garcia¹⁷³, F. Meloni^{89a,89b},
 L. Mendoza Navas¹⁶², Z. Meng^{151,u}, A. Mengarelli^{19a,19b}, S. Menke⁹⁹, E. Meoni¹¹, K.M. Mercurio⁵⁷,
 P. Mermod⁴⁹, L. Merola^{102a,102b}, C. Meroni^{89a}, F.S. Merritt³⁰, H. Merritt¹⁰⁹, A. Messina^{29,y},
 J. Metcalfe¹⁰³, A.S. Mete⁶³, C. Meyer⁸¹, C. Meyer³⁰, J.-P. Meyer¹³⁶, J. Meyer¹⁷⁴, J. Meyer⁵⁴,
 T.C. Meyer²⁹, W.T. Meyer⁶³, J. Miao^{32d}, S. Michal²⁹, L. Micu^{25a}, R.P. Middleton¹²⁹, S. Migas⁷³,
 L. Mijović⁴¹, G. Mikenberg¹⁷², M. Mikesikova¹²⁵, M. Mikuž⁷⁴, D.W. Miller³⁰, R.J. Miller⁸⁸,
 W.J. Mills¹⁶⁸, C. Mills⁵⁷, A. Milov¹⁷², D.A. Milstead^{146a,146b}, D. Milstein¹⁷², A.A. Minaenko¹²⁸,
 M. Miñano Moya¹⁶⁷, I.A. Minashvili⁶⁴, A.I. Mincer¹⁰⁸, B. Mindur³⁷, M. Mineev⁶⁴, Y. Ming¹⁷³,

L.M. Mir¹¹, G. Mirabelli^{132a}, J. Mitrevski¹³⁷, V.A. Mitsou¹⁶⁷, S. Mitsui⁶⁵, P.S. Miyagawa¹³⁹,
 K. Miyazaki⁶⁶, J.U. Mjörnmark⁷⁹, T. Moa^{146a,146b}, S. Moed⁵⁷, V. Moeller²⁷, K. Mönig⁴¹, N. Möser²⁰,
 S. Mohapatra¹⁴⁸, W. Mohr⁴⁸, R. Moles-Valls¹⁶⁷, J. Molina-Perez²⁹, J. Monk⁷⁷, E. Monnier⁸³,
 S. Montesano^{89a,89b}, F. Monticelli⁷⁰, S. Monzani^{19a,19b}, R.W. Moore², G.F. Moorhead⁸⁶,
 C. Mora Herrera⁴⁹, A. Moraes⁵³, N. Morange¹³⁶, J. Morel⁵⁴, G. Morello^{36a,36b}, D. Moreno⁸¹,
 M. Moreno Llácer¹⁶⁷, P. Morettini^{50a}, M. Morgenstern⁴³, M. Morii⁵⁷, J. Morin⁷⁵, A.K. Morley²⁹,
 G. Mornacchi²⁹, J.D. Morris⁷⁵, L. Morvaj¹⁰¹, H.G. Moser⁹⁹, M. Mosidze^{51b}, J. Moss¹⁰⁹, R. Mount¹⁴³,
 E. Mountricha^{9,z}, S.V. Mouraviev⁹⁴, E.J.W. Moyse⁸⁴, F. Mueller^{58a}, J. Mueller¹²³, K. Mueller²⁰,
 T.A. Müller⁹⁸, T. Mueller⁸¹, D. Muenstermann²⁹, Y. Munwes¹⁵³, W.J. Murray¹²⁹, I. Mussche¹⁰⁵,
 E. Musto^{102a,102b}, A.G. Myagkov¹²⁸, M. Myska¹²⁵, J. Nadal¹¹, K. Nagai¹⁶⁰, K. Nagano⁶⁵, A. Nagarkar¹⁰⁹,
 Y. Nagasaka⁵⁹, M. Nagel⁹⁹, A.M. Nairz²⁹, Y. Nakahama²⁹, K. Nakamura¹⁵⁵, T. Nakamura¹⁵⁵,
 I. Nakano¹¹⁰, G. Nanava²⁰, A. Napier¹⁶¹, R. Narayan^{58b}, M. Nash^{77,c}, T. Nattermann²⁰, T. Naumann⁴¹,
 G. Navarro¹⁶², H.A. Neal⁸⁷, P.Yu. Nechaeva⁹⁴, T.J. Neep⁸², A. Negri^{119a,119b}, G. Negri²⁹, S. Nektarijevic⁴⁹,
 A. Nelson¹⁶³, T.K. Nelson¹⁴³, S. Nemecek¹²⁵, P. Nemethy¹⁰⁸, A.A. Nepomuceno^{23a}, M. Nessi^{29,aa},
 M.S. Neubauer¹⁶⁵, A. Neusiedl⁸¹, R.M. Neves¹⁰⁸, P. Nevski²⁴, P.R. Newman¹⁷, V. Nguyen Thi Hong¹³⁶,
 R.B. Nickerson¹¹⁸, R. Nicolaidou¹³⁶, L. Nicolas¹³⁹, B. Nicquevert²⁹, F. Niedercorn¹¹⁵, J. Nielsen¹³⁷,
 N. Nikiforou³⁴, A. Nikiforov¹⁵, V. Nikolaenko¹²⁸, I. Nikolic-Audit⁷⁸, K. Nikolics⁴⁹, K. Nikolopoulos²⁴,
 H. Nilsen⁴⁸, P. Nilsson⁷, Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, T. Nishiyama⁶⁶, R. Nisius⁹⁹, L. Nodulman⁵,
 M. Nomachi¹¹⁶, I. Nomidis¹⁵⁴, M. Nordberg²⁹, P.R. Norton¹²⁹, J. Novakova¹²⁶, M. Nozaki⁶⁵, L. Nozka¹¹³,
 I.M. Nugent^{159a}, A.-E. Nuncio-Quiroz²⁰, G. Nunes Hanninger⁸⁶, T. Nunnemann⁹⁸, E. Nurse⁷⁷,
 B.J. O'Brien⁴⁵, S.W. O'Neale^{17,*}, D.C. O'Neil¹⁴², V. O'Shea⁵³, L.B. Oakes⁹⁸, F.G. Oakham^{28,d},
 H. Oberlack⁹⁹, J. Ocariz⁷⁸, A. Ochi⁶⁶, S. Oda¹⁵⁵, S. Odaka⁶⁵, J. Odier⁸³, H. Ogren⁶⁰, A. Oh⁸², S.H. Oh⁴⁴,
 C.C. Ohm^{146a,146b}, T. Ohshima¹⁰¹, S. Okada⁶⁶, H. Okawa¹⁶³, Y. Okumura¹⁰¹, T. Okuyama¹⁵⁵,
 A. Olariu^{25a}, A.G. Olchevski⁶⁴, S.A. Olivares Pino^{31a}, M. Oliveira^{124a,h}, D. Oliveira Damazio²⁴,
 E. Oliver Garcia¹⁶⁷, D. Olivito¹²⁰, A. Olszewski³⁸, J. Olszowska³⁸, A. Onofre^{124a,ab}, P.U.E. Onyisi³⁰,
 C.J. Oram^{159a}, M.J. Oreglia³⁰, Y. Oren¹⁵³, D. Orestano^{134a,134b}, N. Orlando^{72a,72b}, I. Orlov¹⁰⁷,
 C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁸, B. Osculati^{50a,50b}, R. Ospanov¹²⁰, C. Osuna¹¹, G. Otero y Garzon²⁶,
 J.P. Ottersbach¹⁰⁵, M. Ouchrif^{135d}, E.A. Ouellette¹⁶⁹, F. Ould-Saada¹¹⁷, A. Ouraou¹³⁶, Q. Ouyang^{32a},
 A. Ovcharova¹⁴, M. Owen⁸², S. Owen¹³⁹, V.E. Ozcan^{18a}, N. Ozturk⁷, A. Pacheco Pages¹¹,
 C. Padilla Aranda¹¹, S. Pagan Griso¹⁴, E. Paganis¹³⁹, F. Paige²⁴, P. Pais⁸⁴, K. Pajchel¹¹⁷, G. Palacino^{159b},
 C.P. Paleari⁶, S. Palestini²⁹, D. Pallin³³, A. Palma^{124a}, J.D. Palmer¹⁷, Y.B. Pan¹⁷³, E. Panagiotopoulou⁹,
 N. Panikashvili⁸⁷, S. Panitkin²⁴, D. Pantea^{25a}, A. Papadelis^{146a}, Th.D. Papadopoulou⁹, A. Paramonov⁵,
 D. Paredes Hernandez³³, W. Park^{24,ac}, M.A. Parker²⁷, F. Parodi^{50a,50b}, J.A. Parsons³⁴, U. Parzefall⁴⁸,
 S. Pashapour⁵⁴, E. Pasqualucci^{132a}, S. Passaggio^{50a}, A. Passeri^{134a}, F. Pastore^{134a,134b}, Fr. Pastore⁷⁶,
 G. Pásztor^{49,ad}, S. Pataraja¹⁷⁵, N. Patel¹⁵⁰, J.R. Pater⁸², S. Patricelli^{102a,102b}, T. Pauly²⁹, M. Pecsny^{144a},
 M.I. Pedraza Morales¹⁷³, S.V. Peleganchuk¹⁰⁷, D. Pelikan¹⁶⁶, H. Peng^{32b}, B. Penning³⁰, A. Penson³⁴,
 J. Penwell⁶⁰, M. Perantoni^{23a}, K. Perez^{34,ae}, T. Perez Cavalcanti⁴¹, E. Perez Codina^{159a},
 M.T. Pérez García-Estañ¹⁶⁷, V. Perez Reale³⁴, L. Perini^{89a,89b}, H. Pernegger²⁹, R. Perrino^{72a}, P. Perrodo⁴,
 S. Persema^{3a}, V.D. Peshekhonov⁶⁴, K. Peters²⁹, B.A. Petersen²⁹, J. Petersen²⁹, T.C. Petersen³⁵, E. Petit⁴,
 A. Petridis¹⁵⁴, C. Petridou¹⁵⁴, E. Petrolu^{132a}, F. Petrucci^{134a,134b}, D. Petschull⁴¹, M. Petteini¹⁴²,
 R. Pezoa^{31b}, A. Phan⁸⁶, P.W. Phillips¹²⁹, G. Piacquadio²⁹, A. Picazio⁴⁹, E. Piccaro⁷⁵, M. Piccinini^{19a,19b},
 S.M. Piec⁴¹, R. Piegaia²⁶, D.T. Pignotti¹⁰⁹, J.E. Pilcher³⁰, A.D. Pilkington⁸², J. Pina^{124a,b},
 M. Pinamonti^{164a,164c}, A. Pinder¹¹⁸, J.L. Pinfold², B. Pinto^{124a}, C. Pizio^{89a,89b}, M. Plamondon¹⁶⁹,
 M.-A. Pleier²⁴, E. Plotnikova⁶⁴, A. Poblaguev²⁴, S. Poddar^{58a}, F. Podlyski³³, L. Poggioli¹¹⁵,
 T. Poghosyan²⁰, M. Pohl⁴⁹, F. Polci⁵⁵, G. Polesello^{119a}, A. Policicchio^{36a,36b}, A. Polini^{19a}, J. Poll⁷⁵,
 V. Polychronakos²⁴, D.M. Pomarede¹³⁶, D. Pomeroy²², K. Pommès²⁹, L. Pontecorvo^{132a}, B.G. Pope⁸⁸,
 G.A. Popeneciu^{25a}, D.S. Popovic^{12a}, A. Poppleton²⁹, X. Portell Bueso²⁹, G.E. Pospelov⁹⁹, S. Pospisil¹²⁷,
 I.N. Potrap⁹⁹, C.J. Potter¹⁴⁹, C.T. Potter¹¹⁴, G. Poulard²⁹, J. Poveda¹⁷³, V. Pozdnyakov⁶⁴, R. Prabhu⁷⁷,
 P. Pralavorio⁸³, A. Pranko¹⁴, S. Prasad²⁹, R. Pravahan²⁴, S. Prell⁶³, K. Pretzl¹⁶, D. Price⁶⁰, J. Price⁷³,
 L.E. Price⁵, D. Prieur¹²³, M. Primavera^{72a}, K. Prokofiev¹⁰⁸, F. Prokoshin^{31b}, S. Protopopescu²⁴,
 J. Proudfoot⁵, X. Prudent⁴³, M. Przybycien³⁷, H. Przysiezniak⁴, S. Psoroulas²⁰, E. Ptacek¹¹⁴,
 E. Pueschel⁸⁴, J. Purdham⁸⁷, M. Purohit^{24,ac}, P. Puze¹¹⁵, Y. Pylypchenko⁶², J. Qian⁸⁷, Z. Qin⁴¹,

A. Quadt⁵⁴, D.R. Quarrie¹⁴, W.B. Quayle¹⁷³, F. Quinonez^{31a}, M. Raas¹⁰⁴, V. Radescu⁴¹, P. Radloff¹¹⁴,
 T. Rador^{18a}, F. Ragusa^{89a,89b}, G. Rahal¹⁷⁸, A.M. Rahimi¹⁰⁹, D. Rahm²⁴, S. Rajagopalan²⁴,
 M. Rammensee⁴⁸, M. Rammes¹⁴¹, A.S. Randle-Conde³⁹, K. Randrianarivony²⁸, F. Rauscher⁹⁸,
 T.C. Rave⁴⁸, M. Raymond²⁹, A.L. Read¹¹⁷, D.M. Rebuffi^{119a,119b}, A. Redelbach¹⁷⁴, G. Redlinger²⁴,
 R. Reece¹²⁰, K. Reeves⁴⁰, E. Reinherz-Aronis¹⁵³, A. Reinsch¹¹⁴, I. Reisinger⁴², C. Rembser²⁹, Z.L. Ren¹⁵¹,
 A. Renaud¹¹⁵, M. Rescigno^{132a}, S. Resconi^{89a}, B. Resende¹³⁶, P. Reznicek⁹⁸, R. Rezvani¹⁵⁸, R. Richter⁹⁹,
 E. Richter-Was^{4,af}, M. Ridel⁷⁸, M. Rijpstra¹⁰⁵, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{119a,119b}, L. Rinaldi^{19a},
 R.R. Rios³⁹, I. Riu¹¹, G. Rivoltella^{89a,89b}, F. Rizatdinova¹¹², E. Rizvi⁷⁵, S.H. Robertson^{85,k},
 A. Robichaud-Veronneau¹¹⁸, D. Robinson²⁷, J.E.M. Robinson⁷⁷, A. Robson⁵³, J.G. Rocha de Lima¹⁰⁶,
 C. Roda^{122a,122b}, D. Roda Dos Santos²⁹, A. Roe⁵⁴, S. Roe²⁹, O. Röhne¹¹⁷, S. Rolli¹⁶¹, A. Romaniouk⁹⁶,
 M. Romano^{19a,19b}, G. Romeo²⁶, E. Romero Adam¹⁶⁷, L. Roos⁷⁸, E. Ros¹⁶⁷, S. Rosati^{132a}, K. Rosbach⁴⁹,
 A. Rose¹⁴⁹, M. Rose⁷⁶, G.A. Rosenbaum¹⁵⁸, E.I. Rosenberg⁶³, P.L. Rosendahl¹³, O. Rosenthal¹⁴¹,
 L. Rossetlet⁴⁹, V. Rossetti¹¹, E. Rossi^{132a,132b}, L.P. Rossi^{50a}, M. Rotaru^{25a}, I. Roth¹⁷², J. Rothberg¹³⁸,
 D. Rousseau¹¹⁵, C.R. Royon¹³⁶, A. Rozanov⁸³, Y. Rozen¹⁵², X. Ruan^{32a,ag}, F. Rubbo¹¹, I. Rubinskiy⁴¹,
 B. Ruckert⁹⁸, N. Ruckstuhl¹⁰⁵, V.I. Rud⁹⁷, C. Rudolph⁴³, G. Rudolph⁶¹, F. Rühr⁶, F. Ruggieri^{134a,134b},
 A. Ruiz-Martinez⁶³, L. Rumyantsev⁶⁴, K. Runge⁴⁸, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁴, J.P. Rutherford⁶,
 C. Ruwiedel¹⁴, P. Ruzicka¹²⁵, Y.F. Ryabov¹²¹, P. Ryan⁸⁸, M. Rybar¹²⁶, G. Rybkin¹¹⁵, N.C. Ryder¹¹⁸,
 A.F. Saavedra¹⁵⁰, I. Sadeh¹⁵³, H.F.-W. Sadrozinski¹³⁷, R. Sadykov⁶⁴, F. Safai Tehrani^{132a}, H. Sakamoto¹⁵⁵,
 G. Salamanna⁷⁵, A. Salamon^{133a}, M. Saleem¹¹¹, D. Salek²⁹, D. Salihagic⁹⁹, A. Salnikov¹⁴³, J. Salt¹⁶⁷,
 B.M. Salvachua Ferrando⁵, D. Salvatore^{36a,36b}, F. Salvatore¹⁴⁹, A. Salvucci¹⁰⁴, A. Salzburger²⁹,
 D. Sampsonidis¹⁵⁴, B.H. Samset¹¹⁷, A. Sanchez^{102a,102b}, V. Sanchez Martinez¹⁶⁷, H. Sandaker¹³,
 H.G. Sander⁸¹, M.P. Sanders⁹⁸, M. Sandhoff¹⁷⁵, T. Sandoval²⁷, C. Sandoval¹⁶², R. Sandstroem⁹⁹,
 D.P.C. Sankey¹²⁹, A. Sansoni⁴⁷, C. Santamarina Rios⁸⁵, C. Santoni³³, R. Santonico^{133a,133b}, H. Santos^{124a},
 J.G. Saraiva^{124a}, T. Sarangi¹⁷³, E. Sarkisyan-Grinbaum⁷, F. Sarri^{122a,122b}, G. Sartisohn¹⁷⁵, O. Sasaki⁶⁵,
 N. Sasao⁶⁷, I. Satsounkevitch⁹⁰, G. Sauvage⁴, E. Sauvan⁴, J.B. Sauvan¹¹⁵, P. Savard^{158,d}, V. Savinov¹²³,
 D.O. Savu²⁹, L. Sawyer^{24,m}, D.H. Saxon⁵³, J. Saxon¹²⁰, C. Sbarra^{19a}, A. Sbrizzi^{19a,19b}, O. Scallon⁹³,
 D.A. Scannicchio¹⁶³, M. Scarcella¹⁵⁰, J. Schaarschmidt¹¹⁵, P. Schacht⁹⁹, D. Schaefer¹²⁰, U. Schäfer⁸¹,
 S. Schaepe²⁰, S. Schaezel^{58b}, A.C. Schaffer¹¹⁵, D. Schaile⁹⁸, R.D. Schamberger¹⁴⁸, A.G. Schamov¹⁰⁷,
 V. Scharf^{58a}, V.A. Schegelsky¹²¹, D. Scheirich⁸⁷, M. Schernau¹⁶³, M.I. Scherzer³⁴, C. Schiavi^{50a,50b},
 J. Schieck⁹⁸, M. Schioppa^{36a,36b}, S. Schlenker²⁹, E. Schmidt⁴⁸, K. Schmieden²⁰, C. Schmitt⁸¹,
 S. Schmitt^{58b}, M. Schmitz²⁰, A. Schöning^{58b}, M. Schott²⁹, D. Schouten^{159a}, J. Schovancova¹²⁵,
 M. Schram⁸⁵, C. Schroeder⁸¹, N. Schroer^{58c}, M.J. Schultens²⁰, J. Schultes¹⁷⁵, H.-C. Schultz-Coulon^{58a},
 H. Schulz¹⁵, J.W. Schumacher²⁰, M. Schumacher⁴⁸, B.A. Schumm¹³⁷, Ph. Schune¹³⁶,
 C. Schwanenberger⁸², A. Schwartzman¹⁴³, Ph. Schwemling⁷⁸, R. Schwienhorst⁸⁸, R. Schwierz⁴³,
 J. Schwindling¹³⁶, T. Schwindt²⁰, M. Schwoerer⁴, G. Sciolla²², W.G. Scott¹²⁹, J. Searcy¹¹⁴, G. Sedov⁴¹,
 E. Sedykh¹²¹, S.C. Seidel¹⁰³, A. Seiden¹³⁷, F. Seifert⁴³, J.M. Seixas^{23a}, G. Sekhniaidze^{102a}, S.J. Sekula³⁹,
 K.E. Selbach⁴⁵, D.M. Seliverstov¹²¹, B. Sellden^{146a}, G. Sellers⁷³, M. Seman^{144b},
 N. Semprini-Cesari^{19a,19b}, C. Serfon⁹⁸, L. Serin¹¹⁵, L. Serkin⁵⁴, R. Seuster⁹⁹, H. Severini¹¹¹, A. Sfyrla²⁹,
 E. Shabalina⁵⁴, M. Shamim¹¹⁴, L.Y. Shan^{32a}, J.T. Shank²¹, Q.T. Shao⁸⁶, M. Shapiro¹⁴, P.B. Shatalov⁹⁵,
 K. Shaw^{164a,164c}, D. Sherman¹⁷⁶, P. Sherwood⁷⁷, A. Shibata¹⁰⁸, H. Shichi¹⁰¹, S. Shimizu²⁹,
 M. Shimojima¹⁰⁰, T. Shin⁵⁶, M. Shiyakova⁶⁴, A. Shmeleva⁹⁴, M.J. Shochet³⁰, D. Short¹¹⁸, S. Shrestha⁶³,
 E. Shulga⁹⁶, M.A. Shupe⁶, P. Sicho¹²⁵, A. Sidoti^{132a}, F. Siegert⁴⁸, Dj. Sijacki^{12a}, O. Silbert¹⁷², J. Silva^{124a},
 Y. Silver¹⁵³, D. Silverstein¹⁴³, S.B. Silverstein^{146a}, V. Simak¹²⁷, O. Simard¹³⁶, Lj. Simic^{12a}, S. Simion¹¹⁵,
 B. Simmons⁷⁷, R. Simoniello^{89a,89b}, M. Simonyan³⁵, P. Sinervo¹⁵⁸, N.B. Sinev¹¹⁴, V. Sipica¹⁴¹,
 G. Siragusa¹⁷⁴, A. Sircar²⁴, A.N. Sisakyan⁶⁴, S.Yu. Sivoklov⁹⁷, J. Sjölin^{146a,146b}, T.B. Sjusen¹³,
 L.A. Skinnari¹⁴, H.P. Skottowe⁵⁷, K. Skovpen¹⁰⁷, P. Skubic¹¹¹, M. Slater¹⁷, T. Slavicek¹²⁷, K. Sliwa¹⁶¹,
 V. Smakhtin¹⁷², B.H. Smart⁴⁵, S.Yu. Smirnov⁹⁶, Y. Smirnov⁹⁶, L.N. Smirnova⁹⁷, O. Smirnova⁷⁹,
 B.C. Smith⁵⁷, D. Smith¹⁴³, K.M. Smith⁵³, M. Smizanska⁷¹, K. Smolek¹²⁷, A.A. Snesev⁹⁴, S.W. Snow⁸²,
 J. Snow¹¹¹, S. Snyder²⁴, R. Sobie^{169,k}, J. Sodomka¹²⁷, A. Soffer¹⁵³, C.A. Solans¹⁶⁷, M. Solar¹²⁷, J. Solc¹²⁷,
 E.Yu. Soldatov⁹⁶, U. Soldevila¹⁶⁷, E. Solfaroli Camillocci^{132a,132b}, A.A. Solodkov¹²⁸, O.V. Solovyanov¹²⁸,
 N. Soni², V. Sopko¹²⁷, B. Sopko¹²⁷, M. Sosebee⁷, R. Soualah^{164a,164c}, A. Soukharev¹⁰⁷,
 S. Spagnolo^{72a,72b}, F. Spanò⁷⁶, R. Spighi^{19a}, G. Spigo²⁹, F. Spila^{132a,132b}, R. Spiwoks²⁹, M. Spousta¹²⁶,

T. Spreitzer¹⁵⁸, B. Spurlock⁷, R.D. St. Denis⁵³, J. Stahlman¹²⁰, R. Stamen^{58a}, E. Stanecka³⁸, R.W. Stanek⁵,
 C. Stanescu^{134a}, M. Stanescu-Bellu⁴¹, S. Stapnes¹¹⁷, E.A. Starchenko¹²⁸, J. Stark⁵⁵, P. Staroba¹²⁵,
 P. Starovoitov⁴¹, A. Stauder⁹⁸, P. Stavina^{144a}, G. Steele⁵³, P. Steinbach⁴³, P. Steinberg²⁴, I. Stekl¹²⁷,
 B. Stelzer¹⁴², H.J. Stelzer⁸⁸, O. Stelzer-Chilton^{159a}, H. Stenzel⁵², S. Stern⁹⁹, G.A. Stewart²⁹,
 J.A. Stillings²⁰, M.C. Stockton⁸⁵, K. Stoerig⁴⁸, G. Stoicea^{25a}, S. Stonjek⁹⁹, P. Strachota¹²⁶, A.R. Stradling⁷,
 A. Straessner⁴³, J. Strandberg¹⁴⁷, S. Strandberg^{146a,146b}, A. Strandlie¹¹⁷, M. Strang¹⁰⁹, E. Strauss¹⁴³,
 M. Strauss¹¹¹, P. Strizenec^{144b}, R. Ströhmer¹⁷⁴, D.M. Strom¹¹⁴, J.A. Strong^{76,*}, R. Stroynowski³⁹,
 J. Strube¹²⁹, B. Stugu¹³, I. Stumer^{24,*}, J. Stupak¹⁴⁸, P. Sturm¹⁷⁵, N.A. Styles⁴¹, D.A. Soh^{151,w}, D. Su¹⁴³,
 H.S. Subramania², A. Succurro¹¹, Y. Sugaya¹¹⁶, C. Suhr¹⁰⁶, K. Suita⁶⁶, M. Suk¹²⁶, V.V. Sulin⁹⁴,
 S. Sultansoy^{3d}, T. Sumida⁶⁷, X. Sun⁵⁵, J.E. Sundermann⁴⁸, K. Suruliz¹³⁹, G. Susinno^{36a,36b},
 M.R. Sutton¹⁴⁹, Y. Suzuki⁶⁵, Y. Suzuki⁶⁶, M. Svatos¹²⁵, S. Swedish¹⁶⁸, I. Sykora^{144a}, T. Sykora¹²⁶,
 J. Sánchez¹⁶⁷, D. Ta¹⁰⁵, K. Tackmann⁴¹, A. Taffard¹⁶³, R. Tafirot^{159a}, N. Taiblum¹⁵³, Y. Takahashi¹⁰¹,
 H. Takai²⁴, R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹⁴⁰, Y. Takubo⁶⁵, M. Talby⁸³, A. Talyshev^{107,f},
 M.C. Tamsett²⁴, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁵, S. Tanaka¹³¹, S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴², K. Tani⁶⁶,
 N. Tannoury⁸³, S. Tapprogge⁸¹, D. Tardif¹⁵⁸, S. Tarem¹⁵², F. Tarrade²⁸, G.F. Tartarelli^{89a}, P. Tas¹²⁶,
 M. Tasevsky¹²⁵, E. Tassi^{36a,36b}, M. Tatarkhanov¹⁴, Y. Tayalati^{135d}, C. Taylor⁷⁷, F.E. Taylor⁹²,
 G.N. Taylor⁸⁶, W. Taylor^{159b}, M. Teinturier¹¹⁵, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶,
 K.K. Temming⁴⁸, H. Ten Kate²⁹, P.K. Teng¹⁵¹, S. Terada⁶⁵, K. Terashi¹⁵⁵, J. Terron⁸⁰, M. Testa⁴⁷,
 R.J. Teuscher^{158,k}, J. Therhaag²⁰, T. Theveneaux-Pelzer⁷⁸, M. Thioye¹⁷⁶, S. Thoma⁴⁸, J.P. Thomas¹⁷,
 E.N. Thompson³⁴, P.D. Thompson¹⁷, P.D. Thompson¹⁵⁸, A.S. Thompson⁵³, L.A. Thomsen³⁵,
 E. Thomson¹²⁰, M. Thomson²⁷, R.P. Thun⁸⁷, F. Tian³⁴, M.J. Tibbetts¹⁴, T. Tic¹²⁵, V.O. Tikhomirov⁹⁴,
 Y.A. Tikhonov^{107,f}, S. Timoshenko⁹⁶, P. Tipton¹⁷⁶, F.J. Tique Aires Viegas²⁹, S. Tisserant⁸³, T. Todorov⁴,
 S. Todorova-Nova¹⁶¹, B. Toggerson¹⁶³, J. Tojo⁶⁹, S. Tokár^{144a}, K. Tokunaga⁶⁶, K. Tokushuku⁶⁵,
 K. Tollefson⁸⁸, M. Tomoto¹⁰¹, L. Tompkins³⁰, K. Toms¹⁰³, A. Tonoyan¹³, C. Topfel¹⁶, N.D. Topilin⁶⁴,
 I. Torchiani²⁹, E. Torrence¹¹⁴, H. Torres⁷⁸, E. Torrón Pastor¹⁶⁷, J. Toth^{83,ad}, F. Touchard⁸³, D.R. Tovey¹³⁹,
 T. Trefzger¹⁷⁴, L. Tremblet²⁹, A. Tricoli²⁹, I.M. Trigger^{159a}, S. Trincaz-Duvoid⁷⁸, M.F. Tripiana⁷⁰,
 W. Trischuk¹⁵⁸, B. Trocmé⁵⁵, C. Troncon^{89a}, M. Trottier-McDonald¹⁴², M. Trzebinski³⁸, A. Trzupek³⁸,
 C. Tsarouchas²⁹, J.C.-L. Tseng¹¹⁸, M. Tsiakiris¹⁰⁵, P.V. Tsiarehka⁹⁰, D. Tsiou^{4,ah}, G. Tsipolitis⁹,
 V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁵, V. Tsulaia¹⁴, J.-W. Tsung²⁰, S. Tsuno⁶⁵,
 D. Tsybychev¹⁴⁸, A. Tua¹³⁹, A. Tudorache^{25a}, V. Tudorache^{25a}, J.M. Tuggle³⁰, M. Turala³⁸, D. Turecek¹²⁷,
 I. Turk Cakir^{3e}, E. Turlay¹⁰⁵, R. Turra^{89a,89b}, P.M. Tuts³⁴, A. Tykhonov⁷⁴, M. Tylmad^{146a,146b},
 M. Tyndel¹²⁹, G. Tzanakos⁸, K. Uchida²⁰, I. Ueda¹⁵⁵, R. Ueno²⁸, M. Ugland¹³, M. Uhlenbrock²⁰,
 M. Uhrmacher⁵⁴, F. Ukegawa¹⁶⁰, G. Unal²⁹, A. Undrus²⁴, G. Unel¹⁶³, Y. Unno⁶⁵, D. Urbaniec³⁴,
 G. Usai⁷, M. Uslenghi^{119a,119b}, L. Vacavant⁸³, V. Vacek¹²⁷, B. Vachon⁸⁵, S. Vahsen¹⁴, J. Valenta¹²⁵,
 P. Valente^{132a}, S. Valentinetti^{19a,19b}, S. Valkar¹²⁶, E. Valladolid Gallego¹⁶⁷, S. Vallecorsa¹⁵²,
 J.A. Valls Ferrer¹⁶⁷, H. van der Graaf¹⁰⁵, E. van der Kraaij¹⁰⁵, R. Van Der Leeuw¹⁰⁵, E. van der Poel¹⁰⁵,
 D. van der Ster²⁹, N. van Eldik²⁹, P. van Gemmeren⁵, I. van Vulpen¹⁰⁵, M. Vanadia⁹⁹, W. Vandelli²⁹,
 A. Vaniachine⁵, P. Vankov⁴¹, F. Vannucci⁷⁸, R. Vari^{132a}, T. Varol⁸⁴, D. Varouchas¹⁴, A. Vartapetian⁷,
 K.E. Varvell¹⁵⁰, V.I. Vassilakopoulos⁵⁶, F. Vazeille³³, T. Vazquez Schroeder⁵⁴, G. Vegni^{89a,89b},
 J.J. Veillet¹¹⁵, F. Veloso^{124a}, R. Veness²⁹, S. Veneziano^{132a}, A. Ventura^{72a,72b}, D. Ventura⁸⁴,
 M. Venturi⁴⁸, N. Venturi¹⁵⁸, V. Vercesi^{119a}, M. Verducci¹³⁸, W. Verkerke¹⁰⁵, J.C. Vermeulen¹⁰⁵,
 A. Vest⁴³, M.C. Vetterli^{142,d}, I. Vichou¹⁶⁵, T. Vickey^{145b,ai}, O.E. Vickey Boeriu^{145b}, G.H.A. Viehhauser¹¹⁸,
 S. Viel¹⁶⁸, M. Villa^{19a,19b}, M. Villaplana Perez¹⁶⁷, E. Vilucchi⁴⁷, M.G. Vincker²⁸, E. Vinek²⁹,
 V.B. Vinogradov⁶⁴, M. Virchaux^{136,*}, J. Virzi¹⁴, O. Vitells¹⁷², M. Viti⁴¹, I. Vivarelli⁴⁸, F. Vives Vaque²,
 S. Vlachos⁹, D. Vladoiu⁹⁸, M. Vlasak¹²⁷, A. Vogel²⁰, P. Vokac¹²⁷, G. Volpi⁴⁷, M. Volpi⁸⁶, G. Volpini^{89a},
 H. von der Schmitt⁹⁹, J. von Loeben⁹⁹, H. von Radziewski⁴⁸, E. von Toerne²⁰, V. Vorobel¹²⁶,
 V. Vorwerk¹¹, M. Vos¹⁶⁷, R. Voss²⁹, T.T. Voss¹⁷⁵, J.H. Vosseveld⁷³, N. Vranjes¹³⁶,
 M. Vranjes Milosavljevic¹⁰⁵, V. Vrba¹²⁵, M. Vreeswijk¹⁰⁵, T. Vu Anh⁴⁸, R. Vuillermet²⁹, I. Vukotic¹¹⁵,
 W. Wagner¹⁷⁵, P. Wagner¹²⁰, H. Wahlen¹⁷⁵, S. Wahrmund⁴³, J. Wakabayashi¹⁰¹, S. Walch⁸⁷,
 J. Walder⁷¹, R. Walker⁹⁸, W. Walkowiak¹⁴¹, R. Wall¹⁷⁶, P. Waller⁷³, C. Wang⁴⁴, H. Wang¹⁷³,
 H. Wang^{32b,aj}, J. Wang¹⁵¹, J. Wang⁵⁵, R. Wang¹⁰³, S.M. Wang¹⁵¹, T. Wang²⁰, A. Warburton⁸⁵,
 C.P. Ward²⁷, M. Warsinsky⁴⁸, A. Washbrook⁴⁵, C. Wasicki⁴¹, P.M. Watkins¹⁷, A.T. Watson¹⁷,

I.J. Watson¹⁵⁰, M.F. Watson¹⁷, G. Watts¹³⁸, S. Watts⁸², A.T. Waugh¹⁵⁰, B.M. Waugh⁷⁷, M. Weber¹²⁹, M.S. Weber¹⁶, P. Weber⁵⁴, A.R. Weidberg¹¹⁸, P. Weigell⁹⁹, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Wellenstein²², P.S. Wells²⁹, T. Wenaus²⁴, D. Wendland¹⁵, Z. Weng^{151,w}, T. Wengler²⁹, S. Wenig²⁹, N. Wermes²⁰, M. Werner⁴⁸, P. Werner²⁹, M. Werth¹⁶³, M. Wessels^{58a}, J. Wetter¹⁶¹, C. Weydert⁵⁵, K. Whalen²⁸, S.J. Wheeler-Ellis¹⁶³, A. White⁷, M.J. White⁸⁶, S. White^{122a,122b}, S.R. Whitehead¹¹⁸, D. Whiteson¹⁶³, D. Whittington⁶⁰, F. Wicek¹¹⁵, D. Wicke¹⁷⁵, F.J. Wickens¹²⁹, W. Wiedenmann¹⁷³, M. Wielers¹²⁹, P. Wienemann²⁰, C. Wiglesworth⁷⁵, L.A.M. Wiik-Fuchs⁴⁸, P.A. Wijeratne⁷⁷, A. Wildauer¹⁶⁷, M.A. Wildt^{41,s}, I. Wilhelm¹²⁶, H.G. Wilkens²⁹, J.Z. Will⁹⁸, E. Williams³⁴, H.H. Williams¹²⁰, W. Willis³⁴, S. Willocq⁸⁴, J.A. Wilson¹⁷, M.G. Wilson¹⁴³, A. Wilson⁸⁷, I. Wingerter-Seez⁴, S. Winkelmann⁴⁸, F. Winklmeier²⁹, M. Wittgen¹⁴³, M.W. Wolter³⁸, H. Wolters^{124a,h}, W.C. Wong⁴⁰, G. Wooden⁸⁷, B.K. Wosiek³⁸, J. Wotschack²⁹, M.J. Woudstra⁸², K.W. Wozniak³⁸, K. Wraight⁵³, C. Wright⁵³, M. Wright⁵³, B. Wrona⁷³, S.L. Wu¹⁷³, X. Wu⁴⁹, Y. Wu^{32b,ak}, E. Wulf³⁴, B.M. Wynne⁴⁵, S. Xella³⁵, M. Xiao¹³⁶, S. Xie⁴⁸, C. Xu^{32b,z}, D. Xu¹³⁹, B. Yabsley¹⁵⁰, S. Yacoob^{145b}, M. Yamada⁶⁵, H. Yamaguchi¹⁵⁵, A. Yamamoto⁶⁵, K. Yamamoto⁶³, S. Yamamoto¹⁵⁵, T. Yamamura¹⁵⁵, T. Yamanaka¹⁵⁵, J. Yamaoka⁴⁴, T. Yamazaki¹⁵⁵, Y. Yamazaki⁶⁶, Z. Yan²¹, H. Yang⁸⁷, U.K. Yang⁸², Y. Yang⁶⁰, Z. Yang^{146a,146b}, S. Yanush⁹¹, L. Yao^{32a}, Y. Yao¹⁴, Y. Yasu⁶⁵, G.V. Ybeles Smit¹³⁰, J. Ye³⁹, S. Ye²⁴, M. Yilmaz^{3c}, R. Yoosoofmiya¹²³, K. Yorita¹⁷¹, R. Yoshida⁵, C. Young¹⁴³, C.J. Young¹¹⁸, S. Youssef²¹, D. Yu²⁴, J. Yu⁷, J. Yu¹¹², L. Yuan⁶⁶, A. Yurkewicz¹⁰⁶, B. Zabinski³⁸, R. Zaidan⁶², A.M. Zaitsev¹²⁸, Z. Zajacova²⁹, L. Zanello^{132a,132b}, A. Zaytsev¹⁰⁷, C. Zeitnitz¹⁷⁵, M. Zeman¹²⁵, A. Zemla³⁸, C. Zender²⁰, O. Zenin¹²⁸, T. Ženiš^{144a}, Z. Zinonos^{122a,122b}, S. Zenz¹⁴, D. Zerwas¹¹⁵, G. Zevi della Porta⁵⁷, Z. Zhan^{32d}, D. Zhang^{32b,aj}, H. Zhang⁸⁸, J. Zhang⁵, X. Zhang^{32d}, Z. Zhang¹¹⁵, L. Zhao¹⁰⁸, T. Zhao¹³⁸, Z. Zhao^{32b}, A. Zhemchugov⁶⁴, J. Zhong¹¹⁸, B. Zhou⁸⁷, N. Zhou¹⁶³, Y. Zhou¹⁵¹, C.G. Zhu^{32d}, H. Zhu⁴¹, J. Zhu⁸⁷, Y. Zhu^{32b}, X. Zhuang⁹⁸, V. Zhuravlov⁹⁹, D. Zieminska⁶⁰, R. Zimmermann²⁰, S. Zimmermann²⁰, S. Zimmermann⁴⁸, M. Ziolkowski¹⁴¹, R. Zitoun⁴, L. Živković³⁴, V.V. Zmouchko^{128,*}, G. Zobernig¹⁷³, A. Zoccoli^{19a,19b}, M. zur Nedden¹⁵, V. Zutshi¹⁰⁶, L. Zwalinski²⁹

¹ University at Albany, Albany, NY, United States

² Department of Physics, University of Alberta, Edmonton AB, Canada

³ (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Dumlupinar University, Kutahya; (c) Department of Physics, Gazi University, Ankara; (d) Division of Physics, TOBB University of Economics and Technology, Ankara; (e) Turkish Atomic Energy Authority, Ankara, Turkey

⁴ LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

⁵ High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States

⁶ Department of Physics, University of Arizona, Tucson, AZ, United States

⁷ Department of Physics, The University of Texas at Arlington, Arlington, TX, United States

⁸ Physics Department, University of Athens, Athens, Greece

⁹ Physics Department, National Technical University of Athens, Zografou, Greece

¹⁰ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹¹ Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain

¹² (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

¹³ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁴ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States

¹⁵ Department of Physics, Humboldt University, Berlin, Germany

¹⁶ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁷ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

¹⁸ (a) Department of Physics, Bogazici University, Istanbul; (b) Division of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep;

(d) Department of Physics, Istanbul Technical University, Istanbul, Turkey

¹⁹ (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy

²⁰ Physikalisches Institut, University of Bonn, Bonn, Germany

²¹ Department of Physics, Boston University, Boston, MA, United States

²² Department of Physics, Brandeis University, Waltham, MA, United States

²³ (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil

²⁴ Physics Department, Brookhaven National Laboratory, Upton, NY, United States

²⁵ (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania

²⁶ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

²⁷ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

²⁸ Department of Physics, Carleton University, Ottawa ON, Canada

²⁹ CERN, Geneva, Switzerland

³⁰ Enrico Fermi Institute, University of Chicago, Chicago, IL, United States

³¹ (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

³² (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong, China

³³ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France

³⁴ Nevis Laboratory, Columbia University, Irvington, NY, United States

³⁵ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

³⁶ (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy

- ³⁷ AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
- ³⁸ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ³⁹ Physics Department, Southern Methodist University, Dallas, TX, United States
- ⁴⁰ Physics Department, University of Texas at Dallas, Richardson, TX, United States
- ⁴¹ DESY, Hamburg and Zeuthen, Germany
- ⁴² Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴³ Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
- ⁴⁴ Department of Physics, Duke University, Durham, NC, United States
- ⁴⁵ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁶ Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3 2700 Wiener Neustadt, Austria
- ⁴⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
- ⁴⁹ Section de Physique, Université de Genève, Geneva, Switzerland
- ⁵⁰ ^(a) INFN Sezione di Genova; ^(b) Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁵¹ ^(a) E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵² II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵³ SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁴ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁵ Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- ⁵⁶ Department of Physics, Hampton University, Hampton, VA, United States
- ⁵⁷ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
- ⁵⁸ ^(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁵⁹ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶⁰ Department of Physics, Indiana University, Bloomington, IN, United States
- ⁶¹ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶² University of Iowa, Iowa City, IA, United States
- ⁶³ Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
- ⁶⁴ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁵ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁶ Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁷ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁸ Kyoto University of Education, Kyoto, Japan
- ⁶⁹ Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷⁰ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷¹ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷² ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷³ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁴ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁵ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁶ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁷ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁷⁸ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁷⁹ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸⁰ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸¹ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸² School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸³ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁴ Department of Physics, University of Massachusetts, Amherst, MA, United States
- ⁸⁵ Department of Physics, McGill University, Montreal QC, Canada
- ⁸⁶ School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁷ Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- ⁸⁸ Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- ⁸⁹ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹⁰ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- ⁹¹ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- ⁹² Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
- ⁹³ Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹⁴ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁵ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁶ Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- ⁹⁷ Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- ⁹⁸ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ⁹⁹ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰⁰ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰¹ Graduate School of Science, Nagoya University, Nagoya, Japan
- ¹⁰² ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- ¹⁰³ Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- ¹⁰⁴ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁵ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁶ Department of Physics, Northern Illinois University, DeKalb, IL, United States
- ¹⁰⁷ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹⁰⁸ Department of Physics, New York University, New York, NY, United States
- ¹⁰⁹ Ohio State University, Columbus, OH, United States
- ¹¹⁰ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹¹ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
- ¹¹² Department of Physics, Oklahoma State University, Stillwater, OK, United States
- ¹¹³ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁴ Center for High Energy Physics, University of Oregon, Eugene, OR, United States

- 115 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
 116 Graduate School of Science, Osaka University, Osaka, Japan
 117 Department of Physics, University of Oslo, Oslo, Norway
 118 Department of Physics, Oxford University, Oxford, United Kingdom
 119 ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
 120 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
 121 Petersburg Nuclear Physics Institute, Gatchina, Russia
 122 ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
 123 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
 124 ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; ^(b) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Portugal
 125 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
 126 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
 127 Czech Technical University in Prague, Praha, Czech Republic
 128 State Research Center Institute for High Energy Physics, Protvino, Russia
 129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
 130 Physics Department, University of Regina, Regina SK, Canada
 131 Ritsumeikan University, Kusatsu, Shiga, Japan
 132 ^(a) INFN Sezione di Roma I; ^(b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
 133 ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
 134 ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
 135 ^(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, 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-Agdal, Rabat, Morocco
 136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique), Gif-sur-Yvette, France
 137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
 138 Department of Physics, University of Washington, Seattle, WA, United States
 139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
 140 Department of Physics, Shinshu University, Nagano, Japan
 141 Fachbereich Physik, Universität Siegen, Siegen, Germany
 142 Department of Physics, Simon Fraser University, Burnaby BC, Canada
 143 SLAC National Accelerator Laboratory, Stanford, CA, United States
 144 ^(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
 145 ^(a) Department of Physics, University of Johannesburg, Johannesburg; ^(b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
 146 ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
 147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
 148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
 149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
 150 School of Physics, University of Sydney, Sydney, Australia
 151 Institute of Physics, Academia Sinica, Taipei, Taiwan
 152 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
 153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
 154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
 155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
 156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
 157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
 158 Department of Physics, University of Toronto, Toronto ON, Canada
 159 ^(a) TRIUMF, Vancouver BC; ^(b) Department of Physics and Astronomy, York University, Toronto ON, Canada
 160 Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan
 161 Science and Technology Center, Tufts University, Medford, MA, United States
 162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
 163 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
 164 ^(a) INFN Gruppo Collegato di Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
 165 Department of Physics, University of Illinois, Urbana, IL, United States
 166 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
 167 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
 168 Department of Physics, University of British Columbia, Vancouver BC, Canada
 169 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
 170 Department of Physics, University of Warwick, Coventry, United Kingdom
 171 Waseda University, Tokyo, Japan
 172 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
 173 Department of Physics, University of Wisconsin, Madison, WI, United States
 174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
 175 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
 176 Department of Physics, Yale University, New Haven CT, United States
 177 Yerevan Physics Institute, Yerevan, Armenia
 178 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

^a Also at Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa, Portugal.

^b Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal.

^c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

^d Also at TRIUMF, Vancouver BC, Canada.

^e Also at Department of Physics, California State University, Fresno, CA, United States.

^f Also at Novosibirsk State University, Novosibirsk, Russia.

^g Also at Fermilab, Batavia, IL, United States.

^h Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

- ⁱ Also at Department of Physics, UASLP, San Luis Potosi, Mexico.
- ^j Also at Università di Napoli Parthenope, Napoli, Italy.
- ^k Also at Institute of Particle Physics (IPP), Canada.
- ^l Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
- ^m Also at Louisiana Tech University, Ruston, LA, United States.
- ⁿ Also at Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
- ^o Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
- ^p Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada.
- ^q Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
- ^r Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
- ^s Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
- ^t Also at Manhattan College, New York, NY, United States.
- ^u Also at School of Physics, Shandong University, Shandong, China.
- ^v Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
- ^w Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
- ^x Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^y Also at INFN Sezione di Roma I, Italy.
- ^z Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique), Gif-sur-Yvette, France.
- ^{aa} Also at Section de Physique, Université de Genève, Geneva, Switzerland.
- ^{ab} Also at Departamento de Física, Universidade de Minho, Braga, Portugal.
- ^{ac} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
- ^{ad} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- ^{ae} Also at California Institute of Technology, Pasadena, CA, United States.
- ^{af} Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
- ^{ag} Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
- ^{ah} Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
- ^{ai} Also at Department of Physics, Oxford University, Oxford, United Kingdom.
- ^{aj} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^{ak} Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
- * Deceased.