



Search for pair-produced long-lived neutral particles decaying to jets in the ATLAS hadronic calorimeter in pp collisions at $\sqrt{s} = 8$ TeV



ATLAS Collaboration ^{*}

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ABSTRACT

The ATLAS detector at the Large Hadron Collider at CERN is used to search for the decay of a scalar boson to a pair of long-lived particles, neutral under the Standard Model gauge group, in 20.3 fb^{-1} of data collected in proton–proton collisions at $\sqrt{s} = 8$ TeV. This search is sensitive to long-lived particles that decay to Standard Model particles producing jets at the outer edge of the ATLAS electromagnetic calorimeter or inside the hadronic calorimeter. No significant excess of events is observed. Limits are reported on the product of the scalar boson production cross section times branching ratio into long-lived neutral particles as a function of the proper lifetime of the particles. Limits are reported for boson masses from 100 GeV to 900 GeV, and a long-lived neutral particle mass from 10 GeV to 150 GeV.

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1. Introduction

The discovery of the Higgs boson [1–3] by the ATLAS and CMS experiments [4,5] in 2012 identified the last piece of the highly successful Standard Model (SM). Subsequent measurements of the Higgs boson branching ratios and couplings, while consistent with the SM expectations, allow for a substantial branching ratio to exotic particles. This letter describes a search for decays of the Higgs boson and other scalar bosons to non-SM states that in turn decay to SM particles.

A number of extensions of the SM involve a hidden sector that is weakly coupled to the SM, with the two connected via a communicator particle. This letter considers models containing a hidden sector with a confining gauge interaction that is otherwise invisible to the SM. The communicator is chosen to be a SM-sector scalar boson, Φ [6–9]. The communicator mixes with a hidden-sector scalar boson, Φ_{hs} , which decays into detectable SM particles. This search considers communicator masses between 100 GeV and 900 GeV. A Φ mass close to the mass of the discovered Higgs boson is included to search for exotic decays of the Higgs boson.

A Hidden Valley (HV) model [8,9] is used as the benchmark model. The lightest HV particles form an isospin triplet of pseudoscalar particles which are called valley pions (π_{ν}) because of their similarity to the SM triplet. The π_{ν} are pair-produced ($\Phi_{\text{hs}} \rightarrow \pi_{\nu}\pi_{\nu}$) and each decays to a pair of SM fermions. The π_{ν} possess Yukawa couplings to fermions and therefore preferentially decay to accessible heavy fermions, primarily $b\bar{b}$, $c\bar{c}$ and $\tau^+\tau^-$.

The lifetime of the π_{ν} is unconstrained and could be quite long. A long-lived π_{ν} can result in signatures that traditional searches fail to detect. If a π_{ν} decays in the inner detector or muon spectrometer, it can be reconstructed as a displaced vertex. However, standard vertex-finding algorithms [10] are not likely to reconstruct it without modification. Likewise, a π_{ν} decay deep inside the calorimeter is reconstructed as a jet with an unusual energy signature that most traditional searches reject as having poor data quality. This search focusses on final states where both π_{ν} decay in the hadronic calorimeter or near the outer edge of the electromagnetic calorimeter. Each heavy fermion pair from a π_{ν} decay is reconstructed as a single calorimeter jet with three characteristic properties: a narrow radius, no tracks from charged particles matched to the jet, and little or no energy deposited in the electromagnetic calorimeter.

Scalar boson masses ranging from 100 GeV to 900 GeV are considered in addition to the Higgs boson's mass (generated at $m_H = 126$ GeV) and π_{ν} masses between 10 GeV and 150 GeV are studied. Other searches for pairs of displaced vertices generated by pair-produced neutral, long-lived particles were performed in ATLAS [11] and CMS [12] at the LHC and in D0 [13] and CDF [14] at the Tevatron. The Tevatron experiments and CMS searched for displaced vertices in their tracking system only, which results in a corresponding proper decay length range of a few meters. CMS also looked at the multi-lepton decay channel, another possible decay of HV particles. The previous ATLAS analysis, based on 7 TeV data, used the muon spectrometer and is sensitive to proper decay lengths between 0.5 m and 27 m, depending on the benchmark model. No evidence of physics beyond the SM was found.

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

2. The ATLAS detector

The ATLAS detector [15] is a multi-purpose detector at the LHC, consisting of several sub-detectors. From the interaction point (IP) outwards there are an inner detector (ID), electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The ID, immersed in a 2 T axial magnetic field, provides tracking and vertex information for charged particles within the pseudorapidity¹ (η) region $|\eta| < 2.5$. It consists of three different tracking detectors. From small radii outwards, these are a silicon pixel detector, a silicon microstrip tracker (SCT) and a transition radiation tracker (TRT).

The calorimeter provides coverage over the range $|\eta| < 4.9$. It consists of a lead/liquid-argon electromagnetic calorimeter (ECal) at smaller radii surrounded by a hadronic calorimeter (HCal) at larger radii comprising a steel and scintillator-tile system in the barrel region ($|\eta| < 1.7$) and a liquid-argon system with copper absorbers in the endcaps ($1.5 < |\eta| < 3.2$). The ECal spans the range $1.5 \text{ m} < r < 2.0 \text{ m}$ in the barrel and $3.6 \text{ m} < |z| < 4.25 \text{ m}$ in the endcaps. The HCal covers $2.25 \text{ m} < r < 4.25 \text{ m}$ in the barrel and $4.3 \text{ m} < |z| < 6.05 \text{ m}$ in the endcaps. There is also a forward calorimeter (FCal), with coverage between $3.1 < |\eta| < 4.9$, which uses copper absorbers in the first layer, and tungsten absorbers in the second and third layers, and liquid-argon as the active medium in all layers. Muon identification and momentum measurement are provided by the MS, which extends to $|\eta| = 2.7$. It consists of a three-layer system of gas-filled precision-tracking chambers. The region $|\eta| < 2.4$ is also covered by separate trigger chambers.

A sequential three-level trigger system selects events to be recorded for offline analysis. The first level consists of custom hardware that implements selection on jets, electrons, photons, τ leptons, muons, and missing transverse momentum or large total transverse energy. The second and third levels add charged particle track finding and refine the first-level selections with progressively more detailed algorithms.

3. Data and simulation samples

All data used in this analysis were collected during the 2012 LHC proton–proton run at a centre-of-mass energy of 8 TeV. After data quality requirements are applied, the sample corresponds to an integrated luminosity of 20.3 fb^{-1} . The HV Monte Carlo (MC) samples are generated with PYTHIA 8.165 [16] and the PDF MSTW2008 [17] to simulate gluon fusion $gg \rightarrow \Phi$ production and the Φ_{HS} decay $\Phi_{\text{HS}} \rightarrow \pi_\nu \pi_\nu$ for different Φ and π_ν masses (Table 1). Φ masses below 300 GeV are considered low-mass samples and the rest are considered high-mass samples. The π_ν lifetime is fixed in each sample to ensure decays throughout the ATLAS detector. The Φ is simulated in PYTHIA by replacing the Higgs boson with the Φ and having the Φ decay to π_ν 100% of the time. The Φ samples are produced with cross sections calculated at next-to-next-to-leading-logarithmic accuracy in QCD processes and at next-to-leading-order in electro-weak processes assuming the Φ at each mass has the same properties as the SM Higgs boson [18]. After generation the events are passed through a detailed simulation of the detector response with GEANT4 [19,20] and the same reconstruction algorithms as are used on the data. GEANT4 needed no modification to simulate the signal as all decay particles are SM

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

Table 1

The Φ mass or Higgs boson mass, Φ gluon fusion production cross section, and π_ν mass of each benchmark Hidden Valley model generated. The cross-sections are based on the assumption in the benchmarked model that the Φ boson production mechanism is the same as the Higgs boson production mechanism. The decay branching ratios of the π_ν as a function of the π_ν mass are listed in the second table as determined in the simulation samples.

m_H [GeV]	σ [pb]	π_ν Mass [GeV]
126	19.0	10, 25, 40

Φ Mass [GeV]	σ [pb]	π_ν Mass [GeV]
100	29.7	10, 25
140	15.4	10, 20, 40
300	3.59	50
600	0.52	50, 150
900	0.06	50, 150

π_ν Mass [GeV]	BR $b\bar{b}$ [%]	BR $\tau^+\tau^-$ [%]	BR $c\bar{c}$ [%]
10	70.0	16.4	13.4
20	86.3	8.0	5.6
25	86.6	8.1	5.3
40	86.5	8.5	5.0
50	86.2	8.8	4.9
150	84.8	10.2	4.8

particles. All MC samples are reweighted to reproduce the number of interactions per bunch crossing observed in the data.

4. Trigger and event selection

Candidate events are collected using a dedicated trigger, called the *CalRatio* trigger [21], which looks specifically for long-lived neutral particles that decay near the outer radius of the ECal or within the HCal. The trigger is tuned to look for events containing at least one narrow jet with little energy deposited in the ECal and no charged tracks pointing towards the jet. At the first level the trigger selects only narrow jets by requiring at least 40 GeV of transverse energy (E_T) in the calorimeter in a 0.2×0.2 ($\Delta\eta \times \Delta\phi$) region using topological jets [15,22], in contrast to the default algorithm in which the energy in a 0.4×0.4 region is summed. The 40 GeV E_T threshold requirement is fully efficient at an offline jet E_T of 60 GeV. To select jets with a high fraction of their energy in the HCal the second level of the trigger requires these narrow jets to have $\log_{10}(E_H/E_{EM}) > 1.2$, where E_H/E_{EM} is the ratio of the energy deposited in the HCal (E_H) to the energy deposited in the ECal (E_{EM}). The trigger also requires no tracks with $p_T > 1$ GeV in the region 0.2×0.2 ($\Delta\eta \times \Delta\phi$) around the jet axis. The third level of the trigger uses the slower but more accurate anti- k_r algorithm [23] with $R = 0.4$ to reconstruct the jet and requires the jet to have a minimum of 35 GeV of transverse energy.

The probability (ε_{π_ν}) for a single π_ν to fire the trigger in simulated events is shown in Fig. 1, for the (a) barrel and (b) endcap region of the calorimeter in several different signal samples. The average probability for the low (high) scalar boson masses is about 20% (55%) for π_ν decays occurring at radii between 2.0 m and 3.5 m in the barrel, and about 6% (30%) for π_ν decays with $|z|$ between 4.0 m and 5.5 m in the endcaps. The turn-on takes place before the inner edge of the HCal as the $\log_{10}(E_H/E_{EM})$ cut allows for a small amount of energy in the ECal. The probability decreases towards the outer region of the HCal where too much of the energy escapes the HCal to pass the jet E_T requirement. The efficiency is lower in the endcaps because events tend to not satisfy the isolation criteria due to the increased occupancy from extra collision events in the same bunch crossing as a hard-scatter interaction (pile-up).

Events also contain a reconstructed primary vertex with at least three tracks with $p_T > 1$ GeV. Events are rejected if any re-

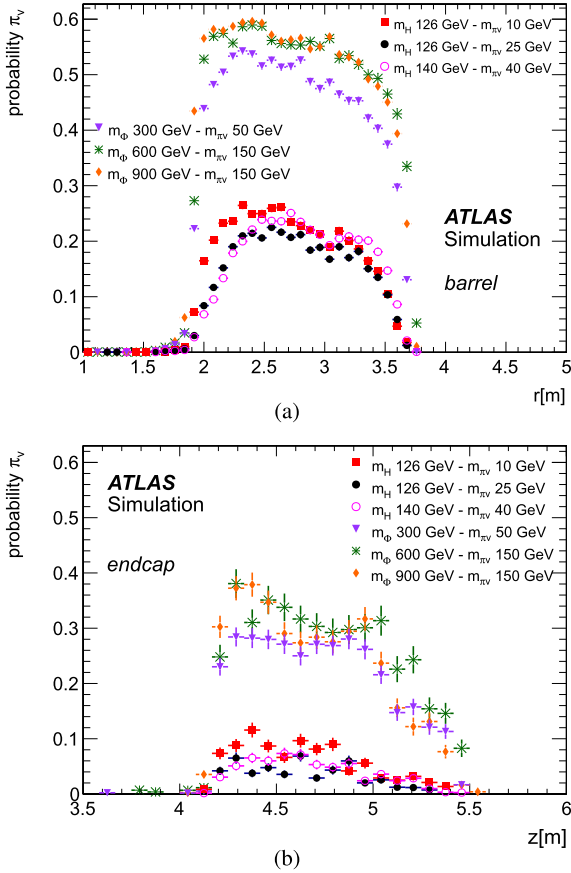


Fig. 1. The probability (ϵ_{π_ν}) for a single π_ν to pass the trigger as a function of the π_ν (a) radial decay length in the barrel and (b) the z position of the decay vertex in the endcaps for several Φ and π_ν masses.

constructed jets show evidence of being caused by a beam-halo interaction [21]. A missing transverse momentum requirement, $E_T^{\text{miss}} < 50$ GeV, is applied to reject non-collision events, such as cosmic rays or beam-halo interactions.

In the offline selection, jets are reconstructed with an anti- k_t algorithm with $R = 0.4$, starting from calorimeter energy clusters calibrated using the local cluster weighting method [24]. Jets are then calibrated using an energy- and η -dependent simulation-based calibration scheme. Jets are rejected if they do not satisfy the standard ATLAS good-jet criteria with the exception of requirements that reject jets with small electromagnetic energy fraction (EMF) [25]. At least one jet must have fired the CalRatio trigger. The jet matching the trigger must pass an $E_T > 60$ GeV requirement while a second jet must satisfy an $E_T > 40$ GeV requirement. If more than one jet fired the CalRatio trigger then only the leading jet is required to have $E_T > 60$ GeV.

Individually, all jets must satisfy $|\eta| < 2.5$, have $\log_{10}(E_H/E_{EM}) > 1.2$, and have no good tracks in the ID with $p_T > 1$ GeV in a region $\Delta R < 0.2^2$ centred on the jet axis. A good track must have at least two hits in the pixel detector and a total of at least nine hits in the pixel and SCT detectors. Fig. 2(a) compares the distribution of the number of good tracks associated with each jet in the multi-jet sample (described in the next section) with that in jets resulting from simulated π_ν decays in the HCAL or ID. Fig. 2(b) makes the same comparison for the distribution of

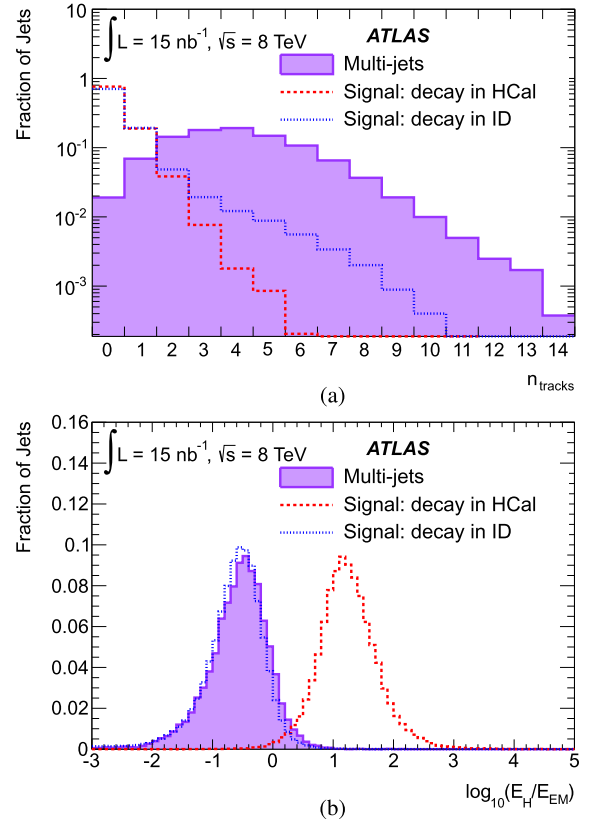


Fig. 2. Distribution of (a) the number of good tracks (n_{tracks}) with $p_T > 1$ GeV and $\Delta R < 0.2$ around the jet axis and (b) the distribution of jet $\log_{10}(E_H/E_{EM})$ with jet $|\eta| < 2.5$, $p_T > 40$ GeV. The dashed histogram is for π_ν jets decaying in the hadronic calorimeter, and the dotted histogram is for π_ν jets decaying in the ID. Both are from the $m_H = 126$ GeV, $m_{\pi_\nu} = 10$ GeV sample. The filled histogram is the multi-jet data sample used to evaluate the multi-jet contribution to the background. Events are required to satisfy $E_T^{\text{miss}} < 50$ GeV.

$\log_{10}(E_H/E_{EM})$ of each jet. The multi-jet data was gathered using a prescaled, single-jet trigger with a 15 GeV requirement.

Jets caused by cosmic rays and beam-halo interactions are often out-of-time. The jet timing is calculated by making an energy-weighted average of the timing for each cell in the jet. Each cell is defined to have a time of 0 ns if its energy is recorded at a time consistent with the arrival of a $\beta = 1$ particle from the IP. The timing of each jet is required to satisfy $-1 < t < 5$ ns. This cut will impact the efficiency for low β π_ν . Due to the requirement of a high- E_T jet in this analysis the β -distribution is peaked near 1 for low mass Φ samples. For the high mass Φ samples the difference between m_Φ and m_{π_ν} results in a large boost for the π_ν at the generated lifetimes. As a result, the inefficiency introduced by the timing cut is at worst 1.5% for the considered samples.

The analysis requires that exactly two jets satisfy these requirements. The second jet requirement significantly reduces the SM multi-jet background contribution. Table 3 lists the final number of expected events in each signal MC sample. The final number of events selected in data is 24.

5. Background estimation

The largest contribution to the expected background comes from SM multi-jet events. Cosmic-ray interactions contribute at a much lower level, and beam-halo interactions make a negligible contribution.

To estimate the multi-jet background contribution, a multi-jet data sample is used to derive the probability that a jet passes the

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

trigger and analysis selection. To obtain a raw background prediction, these jet probabilities are applied to a data sample that represents the multi-jet background before application of jet-level analysis selection. A correction to account for two-jet correlations is applied to this raw prediction to yield the final multi-jet background estimate.

The multi-jet data sample contains events that pass single-jet triggers with an E_T threshold of 15 GeV or higher. These triggers were prescaled in 2012 and their effective luminosities range between 14.8 nb^{-1} and 454.1 nb^{-1} . The dataset is representative of the full 20.3 fb^{-1} of data collected in 2012 and contains events from throughout the data collection period. The events are required to pass the analysis E_T^{miss} requirement and have at least two back-to-back ($\Delta\phi > 2.0$) jets with $E_T > 40 \text{ GeV}$ and $-2.5 < \eta < 2.5$. One jet is required to satisfy the modified ATLAS good-jet criteria used by the analysis. The second is used to measure two probabilities: one, called P , for a jet to pass the trigger and the $E_T > 60 \text{ GeV}$ jet requirement and the other, called Q , for a jet to satisfy the requirement $E_T > 40 \text{ GeV}$. For both P and Q the jet must also pass the $\log_{10}(E_H/E_{EM})$, track isolation, and all other analysis jet selection requirements including the modified ATLAS good-jet criteria. The probabilities are determined as a function of jet E_T and η . The jet E_T and η dependence is calculated independently because the sample is not large. A systematic uncertainty to account for any potential correlation is included in the analysis. To calculate this systematic uncertainty the change in the mean E_T as a function of η and the change in the mean η as a function of E_T is measured in the multi-jet data sample. The maximum variation is 2% for both E_T and η . The E_T or η of each jet are systematically shifted by this amount as P and Q are recalculated. The new P and Q distributions are used to estimate the multi-jet background as described below, and the maximum variation in the result (6%) is used as the systematic uncertainty.

Binned fits of the probabilities as a function of E_T are made to a Landau function and an exponential function for P and Q , respectively. The E_T requirement is ignored when fitting to allow the curve to best match the distribution's shape. The fit errors are propagated through to the systematic in the multi-jet background. The η dependence is strongly correlated with the distribution of material in the calorimeters and cannot be well described by any simple functional form. Thus the probability is obtained directly from the distribution. The $P(E_T)$ parameterisation is additionally split into leading jet and sub-leading jet samples because the probability is different for the two types of jets. This effect is also present for Q ; however, it is accounted for by the correction for jet correlations discussed below. Plots of $P(E_T)$ and $Q(E_T)$ are shown in Fig. 3. The peak present in $P(E_T)$ is the result of the trigger turn-on for the full trigger chain. The trigger jets are dominated by leading jets, and so dominated by the leading jet P .

The probability P is verified using the CalRatio-triggered data. The CalRatio-triggered events are required to pass the same event selection used to derive the single-jet probabilities as well as the requirements for calculating P . The CalRatio-triggered data contains 501 387 events that fired the unprescaled CalRatio trigger and passed the required selection, and the single-jet probabilities predict $513\,000 \pm 94\,000$ (statistical error only) events.

To calculate the raw multi-jet background prediction the probabilities P and Q are applied to jets in events selected by the 15 GeV single-jet trigger. These single-jet probabilities are combined into an event probability using a combinatoric calculation that requires at least one jet in the event to fire the trigger and exactly two jets to pass all the jet selection criteria. The event probability is scaled to account for single-jet trigger prescales, yielding a weight for each event. The sum of all weights in the data sample yields a raw background prediction of 13.2 ± 2.9 (statistical \oplus sys-

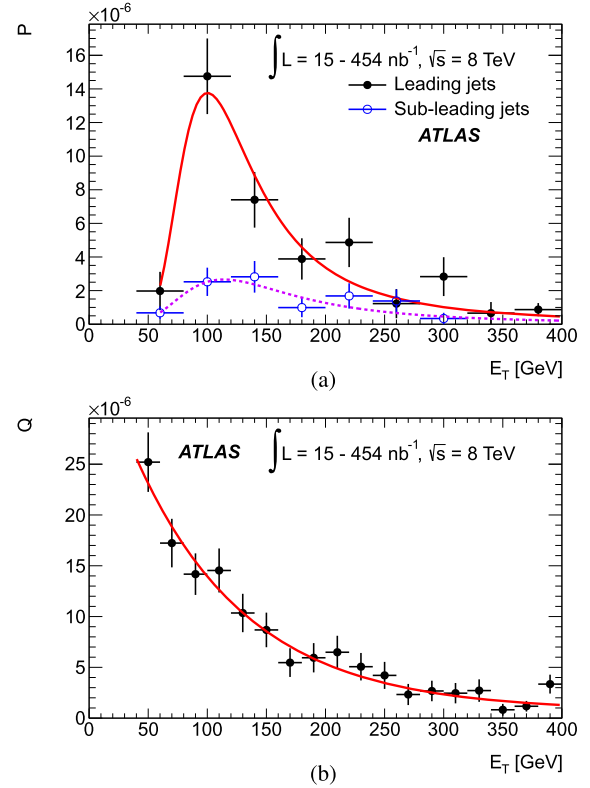


Fig. 3. The probability, P , that a jet from the multi-jet data sample passes the trigger and all jet requirements including the $E_T > 60 \text{ GeV}$ requirement is shown in (a). A Landau function is fitted to the leading and sub-leading jet distributions separately (solid and dashed lines). The probability, Q , to pass all jet requirements including the $E_T > 40 \text{ GeV}$ requirement as a function of jet E_T is shown in (b). An exponential function is fitted to the distribution (solid line). The E_T requirement is ignored when fitting to allow the curve to best match the shape of the data, but is used explicitly when P and Q are applied to a jet. The multi-jet data was gathered using a range of prescaled, single-jet triggers.

tematic error) events. The uncertainty is dominated by the small number of jets firing the CalRatio trigger in multi-jet events.

In multi-jet events the $\log_{10}(E_H/E_{EM})$ and track isolation values of one jet are correlated with those of the second jet. If an event contains one jet of high $\log_{10}(E_H/E_{EM})$, the second jet is more likely to have high $\log_{10}(E_H/E_{EM})$ as well. Likewise, if one jet has no tracks associated with it, the other is more likely to have no associated tracks as well. The single-jet probabilities above ignore this correlation because each is calculated independently of the $\log_{10}(E_H/E_{EM})$ and n_{track} of other jets in the event. As a result, Q is lower than if it were calculated only in events with an accompanying low n_{track} , high $\log_{10}(E_H/E_{EM})$ jet.

A scale factor to account for the correlation is calculated from the multi-jet data sample and the CalRatio-triggered data sample by examining numbers of events in regions in the $\log_{10}(E_H/E_{EM})$ and number-of-tracks (n_{track}) plane that are outside the signal region ($\log_{10}(E_H/E_{EM}) > 1.2$ and $n_{\text{track}} = 0$). The $\log_{10}(E_H/E_{EM})$ binning is chosen such that binning is uniform in EMF.³ A range from 0 to 7 was used for n_{track} . The regions outside the signal region are expected to have very little signal contamination.

In each region the ratio of the number of events observed in the CalRatio-triggered data to the raw prediction is calculated. Two series of ratios are calculated, one as a function of $\log_{10}(E_H/E_{EM})$ and one as a function of n_{track} . To determine the trend in the ra-

³ $\log_{10}(E_H/E_{EM}) = \log_{10}((1 - \text{EMF})/\text{EMF})$.

tio as a function of $\log_{10}(E_H/E_{EM})$ the n_{track} requirement is held constant: a jet is required to have 5 or 6 tracks. The ratio is then determined for several non-overlapping ranges of $\log_{10}(E_H/E_{EM})$. The same procedure is used for n_{track} by requiring jets to have $0.55 < \text{EMF} < 0.65$. Because the ratio is taken with respect to the observed data, this ratio will correct for any normalisation errors in P or Q .

Both sets of ratios are fitted to allow extrapolation into the signal region. The product of the two ratios in the signal region yields a scale factor to correct for the correlation between jets. A systematic error is added to account for the assumption that the two ratios are uncorrelated. The calculated scale factor is 1.8 ± 0.5 . The uncertainty on the scale factor is due to the limited sample size.

To verify the procedure eight other bins on the $\log_{10}(E_H/E_{EM})$ and n_{track} plane were chosen and the full background prediction method was applied. Because signal contamination is negligible outside of the signal region, the predicted number of events can be directly compared to the number of events in the same $\log_{10}(E_H/E_{EM})-n_{\text{track}}$ region in the CalRatio-triggered data. In all cases the prediction is consistent with data to within one standard deviation.

The final multi-jet prediction is 23.2 ± 8.0 (statistical \oplus systematic error) events in the signal region. The uncertainty is dominated by the statistical uncertainty, which is in turn dominated by the small number of jets matching the CalRatio trigger in the multi-jet data sample. The systematic contribution comes from the correlation between E_T and η as well as from the inclusion of a requirement on $\Delta\phi$ (not used in the signal selection) in the determination of P and Q .

Particles from a cosmic-ray shower may pass through and deposit energy in the calorimeter without passing through the ID. These energy deposits can be reconstructed as trackless jets. The overall contribution to the expected background is reduced by the jet-timing and E_T^{miss} requirements.

The cosmic-ray background was studied using a trigger similar to the CalRatio trigger, but active only during an empty crossing. Each proton beam is divided up into buckets, most of which are filled with protons. An empty crossing occurs when an empty bucket in each beam coincides in the centre of the detector, and five buckets on either side in each beam are also empty. Data gathered from these empty crossings are used to study backgrounds that are not beam related.

The analysis selection, with the exception of the jet-timing requirement and the good-vertex requirement, are applied to all events triggered in empty crossings. The $-1 < t < 5$ ns timing requirement is removed to retain more events to give a more accurate determination of the background. A simple scaling can be used to predict the expected cosmic-ray event rate within the timing window because the arrival time of cosmic-ray muons is uniformly distributed. It is found that about 5% of cosmic-ray events firing the trigger and containing two jets are events where both jets satisfy the $-1 < t < 5$ ns requirement.

Two additional corrections are applied to determine the final background prediction due to cosmic-ray events. The first accounts for the different live-times of the triggers. The number of empty crossings is 2.9 times smaller than the number used to collect the full data of 20.3 fb^{-1} . The second correction weights each event to account for soft tracks due to pile-up and underlying-event effects that would have caused the jet to fail the track isolation requirement had it occurred in a collision environment. To determine the weights a trigger that selects random collision events is used to determine the probability as a function of η that a track with $p_T > 1$ GeV is present in a $\Delta R < 0.2$ cone anywhere in the detector as a function of η . This probability is applied to each jet in each event to determine an event weight. The event weights range

from 0.55 to 0.63. Combining all the corrections results in a predicted number of cosmic-ray events of 0.3 ± 0.2 (statistical error).

Another possible background contribution comes from a beam-halo muon that undergoes bremsstrahlung in the HCal. Two selection criteria reduce this type of background. A jet-timing requirement is imposed because most of the jets produced by beam-halo interactions are not coincident in time with jets from pp interactions. In addition, events are rejected when track segments in the endcap muon chambers, from the entering beam-halo muon, align in ϕ with a jet. These two requirements reduce the background considerably with no discernible effect on the signal.

Unpaired isolated crossings, i.e. crossings where only protons from a single beam are present and at least three buckets on either side of the empty beam's bucket are also empty, can be used to study beam-halo events. To estimate this background, artificial events are created by sampling two jets from a collection of jets passing both a CalRatio trigger active only during unpaired isolated crossings and the leading jet requirements from unpaired isolated crossings. All possible pairs of jets are used and the $E_T^{\text{miss}} < 50$ GeV requirement is applied to each constructed event. The number of jets passing the jet analysis selection and the fraction of constructed events satisfying the E_T^{miss} requirement are combined to estimate the background. This method, which also accounts for cosmic-ray muon contamination, predicts 0.07 ± 0.07 events. The large uncertainty is due primarily to the small number of jets passing all required cuts.

Backgrounds from combinations of these non-beam interactions, i.e. a beam-halo jet plus a multi-jet, or a beam-halo jet plus a jet due to a cosmic-ray muon, were found to be negligible.

6. Systematic uncertainties

Table 2 presents a summary of systematic uncertainties associated with the signal sample. The overall uncertainty, taken as the sum in quadrature of all positive and negative contributions respectively, is listed in the last column. The MC signal samples' statistical uncertainty is shown in Table 3 and it is accounted for in the statistical analysis. The overall normalisation uncertainty of the integrated luminosity is 2.8% obtained following the same methodology as that detailed in Ref. [26] from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012. The uncertainties on the Higgs boson production cross-sections at $\sqrt{s} = 8$ TeV, which are equal to the uncertainties on the Φ production cross-sections, are about 10% [18].

The uncertainty on the signal MC samples due to parton distribution functions (PDF) is calculated by reweighting each event using three different PDF sets (MSTW2008nlo68cl [17], CT10 [27], and NNPDF2.3 [28]) and their associated error sets. The RMS change in acceptance for the error sets of each PDF is calculated and combined with the difference in acceptances for each of the three PDFs.

Pile-up primarily affects the acceptance by adding extra tracks and degrading the track isolation of a jet. All MC samples are reweighted to reproduce the observed distribution of the number of interactions per bunch crossing in the data. To determine if pile-up is simulated properly in the MC samples, a direct comparison of data and MC multi-jet samples is performed. The jet E_T , EMF, η , ϕ , associated tracks and timing distributions as a function of the mean number of pile-up interactions are compared in data and MC simulation. A 10% systematic uncertainty is assigned to the acceptance covers all the observed differences.

The jet energy scale (JES) uncertainty is evaluated as a function of the jet EMF and η , following the same strategy used in the *in situ* jet energy intercalibration [24]. The JES is rederived for low

EMF jets for this analysis. The relative jet calorimeter response is studied by balancing the transverse momenta of dijets. The systematic uncertainty is obtained by comparing the p_T -balance in data to the p_T -balance in MC samples. This difference is used to calculate a difference in the JES in data and MC simulation and is propagated to the signal MC samples to get a systematic uncertainty on the acceptance. This study also provides a useful performance comparison between data and MC jets that resemble signal jets.

The E_T^{miss} uncertainty accounts for variations in missing transverse momentum scale and resolution [29]. The timing systematic accounts for mismodeling of jet timing between MC and data. Both of these uncertainties were determined by smearing the associated cut to determine the impact on the acceptance.

The simulation of the trigger is verified by comparing the performance of the trigger in data with the performance in MC simulation on the same multi-jet sample used to evaluate the multi-jet background. Each trigger requirement is studied individually: the jet E_T , the $\log_{10}(E_H/E_{EM})$, and the track isolation. Each requirement is adjusted to make the performance match in data and MC events, and the resulting differences in acceptance from the nominal acceptance, for each requirement, are added in quadrature to determine the systematic uncertainty.

The simulation of initial state radiation (ISR) cannot be directly verified because it is difficult to uniquely identify ISR jets in data [30]. An incorrect ISR rate in the simulation impacts the acceptance by altering the number of jets in the event and by altering the boost of the Φ boson. Each of these is studied independently. The ISR jet population is altered event by event so that the number of ISR jets is halved or doubled (jets in MC samples are labelled as containing ISR if they contain a gluon with $p_T > 2$ GeV). The population of π_ν jets is not altered by this process, but an added ISR jet may overlap with one of the π_ν jets. The effect of a boost caused by an ISR jet is studied by exploiting the correlation between the π_ν jet E_T and the Φ boost. From Ref. [30], the Φ p_T spectrum has an uncertainty of 5%, which directly correlates with a 5% uncertainty in the π_ν jet energy. To calculate the systematic uncertainty associated with the boost, the p_T of ISR jets is conservatively varied by 5% and the change in acceptance is observed.

The changes in acceptance from both sources of ISR uncertainty are taken as correlated systematic errors and added to get the total systematic for ISR simulation.

An incorrect simulation of final state radiation (FSR) has a negligible effect on the analysis' acceptance. FSR can occur in a prompt or displaced jet. But even if displaced, the extra jet cannot degrade track isolation or deposit extra energy in the ECal if the π_ν has decayed in the HCal.

7. Results and exclusion limits

The global acceptance of the selected event topology in the signal MC samples is a function of m_Φ , m_{π_ν} and the proper decay length of the π_ν . At a proper decay length of 1.5 m the acceptance ranges from 0.07% to 0.61%. The main efficiency loss is due to the low probability that both π_ν decay inside the calorimeter. High mass samples suffer further efficiency loss due to the E_T^{miss} requirement. Table 3 lists the expected number of events from all signal MC samples and the background expectation in 20.3 fb^{-1} . The $m_H = 126$ GeV mass samples use the SM Higgs boson cross-sections of $\sigma_{\text{SM}} = 19.0$ pb for the gluon fusion process: other production modes are ignored. The number of events observed in data, 24, is also shown for comparison. No excess of events is observed since the expected background is 23.5 ± 8.0 . The CL_s method [31] is used to derive an upper limit on the

Table 2

Summary of systematic uncertainties for the Φ and Higgs boson production cross-section, jet energy scale, trigger, missing transverse momentum, and the requirement on jet timing as a percentage of the signal yield. Systematic errors that have common values across samples are not listed (pile-up at 10%, ISR at $+2.9\%$, and PDF at 2.1%). The last column reports the total systematic uncertainty (including the luminosity and common systematic errors).

Sample m_H, m_{π_ν} [GeV]	H σ [%]	JES [%]	Trigger [%]	E_T^{miss} [%]	Time Cut [%]	Total [%]
126, 10	+10.4 -10.4	+2.2 -2.7	± 1.1	+5.5 -2.4	+1.6 -6.6	+16.4 -16.7
126, 25	+10.4 -10.4	+1.5 -1.6	± 1.3	+3.1 -1.8	+0.8 -3.3	+15.6 -15.5
126, 40	+10.4 -10.4	+2.6 -6.2	± 1.1	+7.7 -4.6	+1.9 -5.9	+18.2 -16.9
Sample m_Φ, m_{π_ν} [GeV]	Φ σ [%]	JES [%]	Trigger [%]	E_T^{miss} [%]	Time Cut [%]	Total [%]
100, 10	+11.1 -10.6	+2.3 -4.0	± 0.1	+4.6 -3.4	+2.7 -9.5	+16.7 -18.5
100, 25	+11.1 -10.6	+5.5 -3.7	± 1.2	+3.4 -2.5	+1.7 -0.7	+17.0 -15.8
140, 10	+10.1 -10.3	+0.6 -1.1	± 0.5	+4.0 -5.6	+1.9 -6.6	+15.6 -17.2
140, 20	+10.1 -10.3	+1.2 -1.6	± 1.0	+4.0 -3.9	+0.4 -5.0	+15.5 -16.2
140, 40	+10.1 -10.3	+1.3 -1.6	± 1.5	+6.3 -4.6	+1.8 -2.4	+16.5 -15.8
300, 50	+9.6 -10.0	+0.1 -0.3	± 0.3	+9.0 -7.4	+0.5 -3.0	+13.9 -13.3
600, 50	+11.2 -10.1	+0.0 -0.1	± 0.2	+11.7 -11.3	+2.2 -4.4	+17.0 -16.2
600, 150	+11.2 -10.1	+0.2 -0.2	± 0.3	+11.5 -10.2	+2.7 -5.3	+17.5 -15.1
900, 50	+12.8 -11.5	+0.0 -0.1	± 0.1	+12.6 -9.7	+1.0 -3.7	+18.5 -15.9
900, 150	+12.8 -11.5	+0.2 -0.3	± 0.2	+11.8 -10.9	+0.9 -2.5	+18.1 -16.3

$\sigma(\Phi) \times \text{BR}(\Phi \rightarrow \pi_\nu \pi_\nu)$. A profile likelihood ratio is used as the test statistic and a frequentist calculator is used to generate toy data. The likelihood includes a Poisson probability term describing the total number of observed events. Systematic uncertainties are incorporated as nuisance parameters through their effect on the mean of the Poisson functions and through convolution with their assumed Gaussian distributions. The number of expected events in signal MC samples, together with the estimate of expected background, the observed collision events and all the systematic uncertainties are provided as input for computing the CL_s value, which represents the probability for the given observation to be compatible with the signal + background hypothesis.

The acceptance is a function of the Φ mass, the π_ν mass and π_ν proper decay length. To extrapolate to the number of expected events at different proper decay lengths, a large sample of π_ν decays is generated in a range from 0 to 50 m and an efficiency map as a function of π_ν boost is used to determine the efficiency at each decay length. The resulting efficiencies are then converted into the final number of expected events shown in Fig. 4. Finally, Figs. 5 and 6 show the observed limit distribution for the three 126 GeV Higgs samples and for the other Φ samples respectively. The derived 95% confidence level (CL) excluded ranges of proper decay length are listed in Table 4 for the $m_H = 126$ GeV samples, under the alternative assumptions of a 30% BR or a 10% BR for $H \rightarrow \pi_\nu \pi_\nu$.

8. Summary and conclusions

A search for the decay of a scalar boson in the mass range from 100 GeV to 900 GeV, including a search for an exotic decay of the Higgs boson, to a pair of long-lived neutral particles decaying in the ATLAS hadronic calorimeter has been presented. The analysis is based on 20.3 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV collected in 2012 by the ATLAS experiment at the LHC.

Table 3

Summary of expected number of signal events, expected background present in the data sample, and the observed number of events in 20.3 fb^{-1} . The global acceptance is also given. The error on the signal samples is statistical only, the error on the expected background is statistical \oplus systematic. All results are normalised for a proper decay length of the π_ν of 1.5 m. A 100% branching ratio for $\Phi_{\text{HS}} \rightarrow \pi_\nu \pi_\nu$ is assumed.

Sample (m_H, m_{π_ν} [GeV])	Expected yields	Global acceptance (%)
126, 10	536 ± 23	0.139 ± 0.006
126, 25	941 ± 44	0.244 ± 0.011
126, 40	365 ± 31	0.095 ± 0.008

Sample (m_H, m_{π_ν} [GeV])	Expected yields	Global acceptance (%)
100, 10	440 ± 29	0.073 ± 0.005
100, 25	424 ± 37	0.070 ± 0.006
140, 10	525 ± 20	0.168 ± 0.006
140, 20	900 ± 37	0.287 ± 0.012
140, 40	641 ± 30	0.205 ± 0.010
300, 50	444 ± 11	0.609 ± 0.015
600, 50	35 ± 1	0.330 ± 0.010
600, 150	41 ± 2	0.386 ± 0.015
900, 50	3.5 ± 0.1	0.304 ± 0.011
900, 150	4.6 ± 0.2	0.397 ± 0.016

Background	Expected events
SM Multi-jets	23.2 ± 8.0
Cosmic rays	0.3 ± 0.2
Total Expected Background	23.5 ± 8.0
Data	24

Table 4

Ranges of π_ν proper decay lengths excluded at 95% CL assuming a 30% and a 10% BR for a $m_H = 126 \text{ GeV}$.

MC sample m_H, m_{π_ν} [GeV]	Excluded range 30% BR $H \rightarrow \pi_\nu \pi_\nu$ [m]	Excluded range 10% BR $H \rightarrow \pi_\nu \pi_\nu$ [m]
126, 10	0.10–6.08	0.14–3.13
126, 25	0.30–14.99	0.41–7.57
126, 40	0.68–18.50	1.03–8.32

No significant excess of events is observed over the background estimate. Limits are set on the π_ν proper decay lengths for different scalar boson and π_ν mass combinations. For a SM Higgs decaying to π_ν proper decay lengths between 0.10 m and 18.50 m assuming a 30% BR are ruled out, and between 0.14 m and 8.32 m assuming a BR of 10%. Results for low mass Φ (100 GeV and 140 GeV) and high mass Φ (300 GeV, 600 GeV, and 900 GeV) have also been presented as a function of proper decay length.

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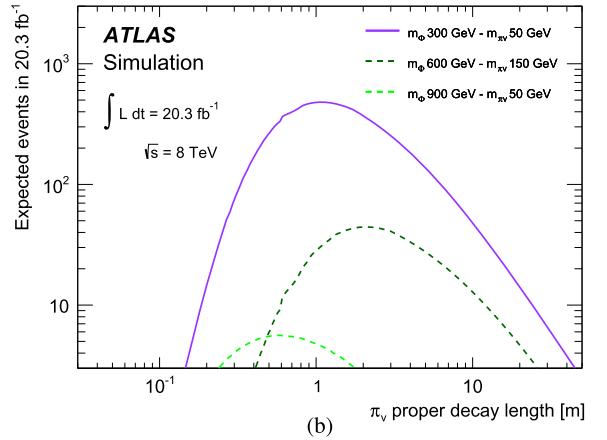
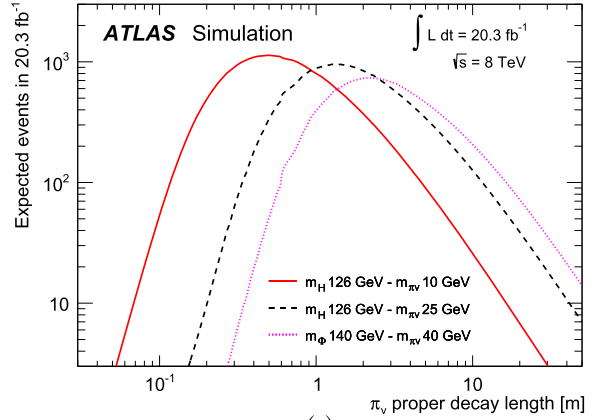


Fig. 4. Number of events expected to pass the analysis selection in 20.3 fb^{-1} as a function of the π_ν proper decay length for (a) three low-mass datasets and (b) three high-mass datasets. 100% branching ratios for $\Phi_{\text{HS}} \rightarrow \pi_\nu \pi_\nu$ are assumed.

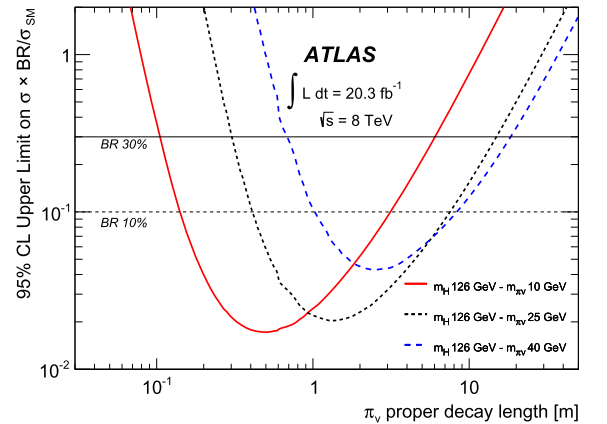


Fig. 5. Observed 95% CL limits on $\sigma / \sigma_{\text{SM}}$ for $m_H = 126 \text{ GeV}$ as a function of the π_ν proper decay length: the solid line is for $m_{\pi_\nu} = 10 \text{ GeV}$, the short-dashed line is for $m_{\pi_\nu} = 25 \text{ GeV}$, the long-dashed line is for $m_{\pi_\nu} = 40 \text{ GeV}$. The σ_{SM} is taken to be 19.0 pb. The horizontal solid line corresponds to BR = 30% and the horizontal dashed line to BR = 10%.

GIF, I-CORE and Benozziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the

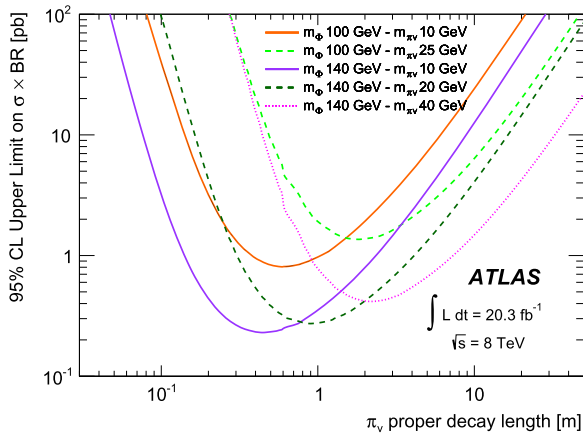
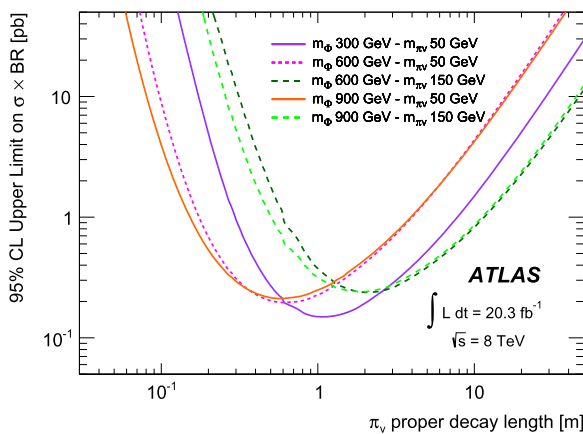
(a) Observed 95% CL limits for $m_\phi = 100$ and 140 GeV.(b) Observed 95% CL limits for $m_\phi = 300, 600,$ and 900 GeV.

Fig. 6. Observed 95% CL limits on $\sigma \times BR$ [pb] for (a) low and (b) high-mass ϕ samples.

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G. Aad⁸⁴, B. Abbott¹¹², J. Abdallah¹⁵², S. Abdel Khalek¹¹⁶, O. Abdinov¹¹, R. Aben¹⁰⁶, B. Abi¹¹³, M. Abolins⁸⁹, O.S. AbouZeid¹⁵⁹, H. Abramowicz¹⁵⁴, H. Abreu¹⁵³, R. Abreu³⁰, Y. Abulaiti^{147a,147b}, B.S. Acharya^{165a,165b,a}, L. Adamczyk^{38a}, D.L. Adams²⁵, J. Adelman¹⁷⁷, S. Adomeit⁹⁹, T. Adye¹³⁰, T. Agatonovic-Jovin^{13a}, J.A. Aguilar-Saavedra^{125a,125f}, M. Agustoni¹⁷, S.P. Ahlen²², F. Ahmadov^{64,b}, G. Aielli^{134a,134b}, H. Akerstedt^{147a,147b}, T.P.A. Åkesson⁸⁰, G. Akimoto¹⁵⁶, A.V. Akimov⁹⁵, G.L. Alberghi^{20a,20b}, J. Albert¹⁷⁰, S. Albrand⁵⁵, M.J. Alconada Verzini⁷⁰, M. Aleksa³⁰, I.N. Aleksandrov⁶⁴, C. Alexa^{26a}, G. Alexander¹⁵⁴, G. Alexandre⁴⁹, T. Alexopoulos¹⁰, M. Alhroob^{165a,165c}, G. Alimonti^{90a}, L. Alio⁸⁴, J. Alison³¹, B.M.M. Allbrooke¹⁸, L.J. Allison⁷¹, P.P. Allport⁷³, A. Aloisio^{103a,103b}, A. Alonso³⁶, F. Alonso⁷⁰, C. Alpigiani⁷⁵, A. Altheimer³⁵, B. Alvarez Gonzalez⁸⁹, M.G. Alviggi^{103a,103b}, K. Amako⁶⁵, Y. Amaral Coutinho^{24a}, C. Amelung²³, D. Amidei⁸⁸, S.P. Amor Dos Santos^{125a,125c}, A. Amorim^{125a,125b}, S. Amoroso⁴⁸, N. Amram¹⁵⁴, G. Amundsen²³, C. Anastopoulos¹⁴⁰, L.S. Ancu⁴⁹, N. Andari³⁰, T. Andeen³⁵, C.F. Anders^{58b}, G. Anders³⁰, K.J. Anderson³¹, A. Andreazza^{90a,90b}, V. Andrei^{58a}, X.S. Anduaga⁷⁰, S. Angelidakis⁹, I. Angelozzi¹⁰⁶, P. Anger⁴⁴, A. Angerami³⁵, F. Anghinolfi³⁰, A.V. Anisenkov^{108,c}, N. Anjos¹², A. Annovi⁴⁷, A. Antonaki⁹, M. Antonelli⁴⁷, A. Antonov⁹⁷, J. Antos^{145b},

F. Anulli ^{133a}, M. Aoki ⁶⁵, L. Aperio Bella ¹⁸, R. Apolle ^{119,d}, G. Arabidze ⁸⁹, I. Aracena ¹⁴⁴, Y. Arai ⁶⁵, J.P. Araque ^{125a}, A.T.H. Arce ⁴⁵, J-F. Arguin ⁹⁴, S. Argyropoulos ⁴², M. Arik ^{19a}, A.J. Armbruster ³⁰, O. Arnaez ³⁰, V. Arnal ⁸¹, H. Arnold ⁴⁸, M. Arratia ²⁸, O. Arslan ²¹, A. Artamonov ⁹⁶, G. Artoni ²³, S. Asai ¹⁵⁶, N. Asbah ⁴², A. Ashkenazi ¹⁵⁴, B. Āsman ^{147a,147b}, L. Asquith ⁶, K. Assamagan ²⁵, R. Astalos ^{145a}, M. Atkinson ¹⁶⁶, N.B. Atlay ¹⁴², B. Auerbach ⁶, K. Augsten ¹²⁷, M. Aurousseau ^{146b}, G. Avolio ³⁰, G. Azuelos ^{94,e}, Y. Azuma ¹⁵⁶, M.A. Baak ³⁰, A.E. Baas ^{58a}, C. Bacci ^{135a,135b}, H. Bachacou ¹³⁷, K. Bachas ¹⁵⁵, M. Backes ³⁰, M. Backhaus ³⁰, J. Backus Mayes ¹⁴⁴, E. Badescu ^{26a}, P. Bagiacci ^{133a,133b}, P. Bagnaia ^{133a,133b}, Y. Bai ^{33a}, T. Bain ³⁵, J.T. Baines ¹³⁰, O.K. Baker ¹⁷⁷, P. Balek ¹²⁸, F. Balli ¹³⁷, E. Banas ³⁹, Sw. Banerjee ¹⁷⁴, A.A.E. Bannoura ¹⁷⁶, V. Bansal ¹⁷⁰, H.S. Bansil ¹⁸, L. Barak ¹⁷³, S.P. Baranov ⁹⁵, E.L. Barberio ⁸⁷, D. Barberis ^{50a,50b}, M. Barbero ⁸⁴, T. Barillari ¹⁰⁰, M. Barisonzi ¹⁷⁶, T. Barklow ¹⁴⁴, N. Barlow ²⁸, B.M. Barnett ¹³⁰, R.M. Barnett ¹⁵, Z. Barnovska ⁵, A. Baroncelli ^{135a}, G. Barone ⁴⁹, A.J. Barr ¹¹⁹, F. Barreiro ⁸¹, J. Barreiro Guimarães da Costa ⁵⁷, R. Bartoldus ¹⁴⁴, A.E. Barton ⁷¹, P. Bartos ^{145a}, V. Bartsch ¹⁵⁰, A. Bassalat ¹¹⁶, A. Basye ¹⁶⁶, R.L. Bates ⁵³, J.R. Batley ²⁸, M. Battaglia ¹³⁸, M. Battistin ³⁰, F. Bauer ¹³⁷, H.S. Bawa ^{144,f}, M.D. Beattie ⁷¹, T. Beau ⁷⁹, P.H. Beauchemin ¹⁶², R. Beccherle ^{123a,123b}, P. Bechtel ²¹, H.P. Beck ¹⁷, K. Becker ¹⁷⁶, S. Becker ⁹⁹, M. Beckingham ¹⁷¹, C. Becot ¹¹⁶, A.J. Beddall ^{19c}, A. Beddall ^{19c}, S. Bedikian ¹⁷⁷, V.A. Bednyakov ⁶⁴, C.P. Bee ¹⁴⁹, L.J. Beemster ¹⁰⁶, T.A. Beermann ¹⁷⁶, M. Begel ²⁵, K. Behr ¹¹⁹, C. Belanger-Champagne ⁸⁶, P.J. Bell ⁴⁹, W.H. Bell ⁴⁹, G. Bella ¹⁵⁴, L. Bellagamba ^{20a}, A. Bellerive ²⁹, M. Bellomo ⁸⁵, K. Belotskiy ⁹⁷, O. Beltramello ³⁰, O. Benary ¹⁵⁴, D. Benchekroun ^{136a}, K. Bendtz ^{147a,147b}, N. Benekos ¹⁶⁶, Y. Benhammou ¹⁵⁴, E. Benhar Noccioli ⁴⁹, J.A. Benitez Garcia ^{160b}, D.P. Benjamin ⁴⁵, J.R. Bensinger ²³, K. Benslama ¹³¹, S. Bentvelsen ¹⁰⁶, D. Berge ¹⁰⁶, E. Bergeaas Kuutmann ¹⁶⁷, N. Berger ⁵, F. Berghaus ¹⁷⁰, J. Beringer ¹⁵, C. Bernard ²², P. Bernat ⁷⁷, C. Bernius ⁷⁸, F.U. Bernlochner ¹⁷⁰, T. Berry ⁷⁶, P. Berta ¹²⁸, C. Bertella ⁸⁴, G. Bertoli ^{147a,147b}, F. Bertolucci ^{123a,123b}, C. Bertsche ¹¹², D. Bertsche ¹¹², M.I. Besana ^{90a}, G.J. Besjes ¹⁰⁵, O. Bessidskaia Bylund ^{147a,147b}, M. Bessner ⁴², N. Besson ¹³⁷, C. Betancourt ⁴⁸, S. Bethke ¹⁰⁰, W. Bhimji ⁴⁶, R.M. Bianchi ¹²⁴, L. Bianchini ²³, M. Bianco ³⁰, O. Biebel ⁹⁹, S.P. Bieniek ⁷⁷, K. Bierwagen ⁵⁴, J. Biesiada ¹⁵, M. Biglietti ^{135a}, J. Bilbao De Mendizabal ⁴⁹, H. Bilokon ⁴⁷, M. Bindi ⁵⁴, S. Binet ¹¹⁶, A. Bingul ^{19c}, C. Bini ^{133a,133b}, C.W. Black ¹⁵¹, J.E. Black ¹⁴⁴, K.M. Black ²², D. Blackburn ¹³⁹, R.E. Blair ⁶, J.-B. Blanchard ¹³⁷, T. Blazek ^{145a}, I. Bloch ⁴², C. Blocker ²³, W. Blum ^{82,*}, U. Blumenschein ⁵⁴, G.J. Bobbink ¹⁰⁶, V.S. Bobrovnikov ^{108,c}, S.S. Bocchetta ⁸⁰, A. Bocci ⁴⁵, C. Bock ⁹⁹, C.R. Boddy ¹¹⁹, M. Boehler ⁴⁸, T.T. Boek ¹⁷⁶, J.A. Bogaerts ³⁰, A.G. Bogdanchikov ¹⁰⁸, A. Bogouch ^{91,*}, C. Bohm ^{147a}, J. Bohm ¹²⁶, V. Boisvert ⁷⁶, T. Bold ^{38a}, V. Boldea ^{26a}, A.S. Boldyrev ⁹⁸, M. Bomben ⁷⁹, M. Bona ⁷⁵, M. Boonekamp ¹³⁷, A. Borisov ¹²⁹, G. Borissov ⁷¹, M. Borri ⁸³, S. Borroni ⁴², J. Bortfeldt ⁹⁹, V. Bortolotto ^{135a,135b}, K. Bos ¹⁰⁶, D. Boscherini ^{20a}, M. Bosman ¹², H. Boterenbrood ¹⁰⁶, J. Boudreau ¹²⁴, J. Bouffard ², E.V. Bouhova-Thacker ⁷¹, D. Boumediene ³⁴, C. Bourdarios ¹¹⁶, N. Bousson ¹¹³, S. Boutouil ^{136d}, A. Boveia ³¹, J. Boyd ³⁰, I.R. Boyko ⁶⁴, I. Bozic ^{13a}, J. Bracinik ¹⁸, A. Brandt ⁸, G. Brandt ¹⁵, O. Brandt ^{58a}, U. Bratzler ¹⁵⁷, B. Brau ⁸⁵, J.E. Brau ¹¹⁵, H.M. Braun ^{176,*}, S.F. Brazzale ^{165a,165c}, B. Brelier ¹⁵⁹, K. Brendlinger ¹²¹, A.J. Brennan ⁸⁷, R. Brenner ¹⁶⁷, S. Bressler ¹⁷³, K. Bristow ^{146c}, T.M. Bristow ⁴⁶, D. Britton ⁵³, F.M. Brochu ²⁸, I. Brock ²¹, R. Brock ⁸⁹, C. Bromberg ⁸⁹, J. Bronner ¹⁰⁰, G. Brooijmans ³⁵, T. Brooks ⁷⁶, W.K. Brooks ^{32b}, J. Brosamer ¹⁵, E. Brost ¹¹⁵, J. Brown ⁵⁵, P.A. Bruckman de Renstrom ³⁹, D. Bruncko ^{145b}, R. Bruneliere ⁴⁸, S. Brunet ⁶⁰, A. Bruni ^{20a}, G. Bruni ^{20a}, M. Bruschi ^{20a}, L. Bryngemark ⁸⁰, T. Buanes ¹⁴, Q. Buat ¹⁴³, F. Bucci ⁴⁹, P. Buchholz ¹⁴², R.M. Buckingham ¹¹⁹, A.G. Buckley ⁵³, S.I. Buda ^{26a}, I.A. Budagov ⁶⁴, F. Buehrer ⁴⁸, L. Bugge ¹¹⁸, M.K. Bugge ¹¹⁸, O. Bulekov ⁹⁷, A.C. Bundock ⁷³, H. Burckhart ³⁰, S. Burdin ⁷³, B. Burghgrave ¹⁰⁷, S. Burke ¹³⁰, I. Burmeister ⁴³, E. Busato ³⁴, D. B scher ⁴⁸, V. B scher ⁸², P. Bussey ⁵³, C.P. Buszello ¹⁶⁷, B. Butler ⁵⁷, J.M. Butler ²², A.I. Butt ³, C.M. Buttar ⁵³, J.M. Butterworth ⁷⁷, P. Butti ¹⁰⁶, W. Buttinger ²⁸, A. Buzatu ⁵³, M. Byszewski ¹⁰, S. Cabrera Urb n ¹⁶⁸, D. Caforio ^{20a,20b}, O. Cakir ^{4a}, P. Calafiura ¹⁵, A. Calandri ¹³⁷, G. Calderini ⁷⁹, P. Calfayan ⁹⁹, R. Calkins ¹⁰⁷, L.P. Caloba ^{24a}, D. Calvet ³⁴, S. Calvet ³⁴, R. Camacho Toro ⁴⁹, S. Camarda ⁴², D. Cameron ¹¹⁸, L.M. Caminada ¹⁵, R. Caminal Armadans ¹², S. Campana ³⁰, M. Campanelli ⁷⁷, A. Campoverde ¹⁴⁹, V. Canale ^{103a,103b}, A. Canepa ^{160a}, M. Cano Bret ⁷⁵, J. Cantero ⁸¹, R. Cantrill ^{125a}, T. Cao ⁴⁰, M.D.M. Capeans Garrido ³⁰, I. Caprini ^{26a}, M. Caprini ^{26a}, M. Capua ^{37a,37b}, R. Caputo ⁸², R. Cardarelli ^{134a}, T. Carli ³⁰, G. Carlino ^{103a}, L. Carminati ^{90a,90b}, S. Caron ¹⁰⁵, E. Carquin ^{32a}, G.D. Carrillo-Montoya ^{146c}, J.R. Carter ²⁸, J. Carvalho ^{125a,125c}, D. Casadei ⁷⁷, M.P. Casado ¹², M. Casolino ¹², E. Castaneda-Miranda ^{146b},

A. Castelli ¹⁰⁶, V. Castillo Gimenez ¹⁶⁸, N.F. Castro ^{125a}, P. Catastini ⁵⁷, A. Catinaccio ³⁰, J.R. Catmore ¹¹⁸,
 A. Cattai ³⁰, G. Cattani ^{134a,134b}, J. Caudron ⁸², V. Cavaliere ¹⁶⁶, D. Cavalli ^{90a}, M. Cavalli-Sforza ¹²,
 V. Cavasinni ^{123a,123b}, F. Ceradini ^{135a,135b}, B.C. Cerio ⁴⁵, K. Cerny ¹²⁸, A.S. Cerqueira ^{24b}, A. Cerri ¹⁵⁰,
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 I. Chalupkova ¹²⁸, P. Chang ¹⁶⁶, B. Chapleau ⁸⁶, J.D. Chapman ²⁸, D. Charfeddine ¹¹⁶, D.G. Charlton ¹⁸,
 C.C. Chau ¹⁵⁹, C.A. Chavez Barajas ¹⁵⁰, S. Cheatham ⁸⁶, A. Chegwidden ⁸⁹, S. Chekanov ⁶,
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 J. Chudoba ¹²⁶, J.J. Chwastowski ³⁹, L. Chytka ¹¹⁴, G. Ciapetti ^{133a,133b}, A.K. Ciftci ^{4a}, R. Ciftci ^{4a}, D. Cinca ⁵³,
 V. Cindro ⁷⁴, A. Ciocio ¹⁵, P. Cirkovic ^{13b}, Z.H. Citron ¹⁷³, M. Citterio ^{90a}, M. Ciubancan ^{26a}, A. Clark ⁴⁹,
 P.J. Clark ⁴⁶, R.N. Clarke ¹⁵, W. Cleland ¹²⁴, J.C. Clemens ⁸⁴, C. Clement ^{147a,147b}, Y. Coadou ⁸⁴,
 M. Cobal ^{165a,165c}, A. Coccaro ¹³⁹, J. Cochran ⁶³, L. Coffey ²³, J.G. Cogan ¹⁴⁴, J. Coggeshall ¹⁶⁶, B. Cole ³⁵,
 S. Cole ¹⁰⁷, A.P. Colijn ¹⁰⁶, J. Collot ⁵⁵, T. Colombo ^{58c}, G. Colon ⁸⁵, G. Compostella ¹⁰⁰,
 P. Conde Muiño ^{125a,125b}, E. Coniavitis ⁴⁸, M.C. Conidi ¹², S.H. Connell ^{146b}, I.A. Connelly ⁷⁶,
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 M. Corradi ^{20a}, F. Corriveau ^{86.j}, A. Corso-Radu ¹⁶⁴, A. Cortes-Gonzalez ¹², G. Cortiana ¹⁰⁰, G. Costa ^{90a},
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 M. Curatolo ⁴⁷, C. Cuthbert ¹⁵¹, H. Czirr ¹⁴², P. Czodrowski ³, Z. Czynzula ¹⁷⁷, S. D'Auria ⁵³, M. D'Onofrio ⁷³,
 M.J. Da Cunha Sargedas De Sousa ^{125a,125b}, C. Da Via ⁸³, W. Dabrowski ^{38a}, A. Dafinca ¹¹⁹, T. Dai ⁸⁸,
 O. Dale ¹⁴, F. Dallaire ⁹⁴, C. Dallapiccola ⁸⁵, M. Dam ³⁶, A.C. Daniells ¹⁸, M. Dano Hoffmann ¹³⁷, V. Dao ⁴⁸,
 G. Darbo ^{50a}, S. Darmora ⁸, J. Dassoulas ⁴², A. Dattagupta ⁶⁰, W. Davey ²¹, C. David ¹⁷⁰, T. Davidek ¹²⁸,
 E. Davies ^{119.d}, M. Davies ¹⁵⁴, O. Davignon ⁷⁹, A.R. Davison ⁷⁷, P. Davison ⁷⁷, Y. Davygora ^{58a}, E. Dawe ¹⁴³,
 I. Dawson ¹⁴⁰, R.K. Daya-Ishmukhametova ⁸⁵, K. De ⁸, R. de Asmundis ^{103a}, S. De Castro ^{20a,20b},
 S. De Cecco ⁷⁹, N. De Groot ¹⁰⁵, P. de Jong ¹⁰⁶, H. De la Torre ⁸¹, F. De Lorenzi ⁶³, L. De Nooij ¹⁰⁶,
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 W.J. Dearnaley ⁷¹, R. Debbe ²⁵, C. Debenedetti ¹³⁸, B. Dechenaux ⁵⁵, D.V. Dedovich ⁶⁴, I. Deigaard ¹⁰⁶,
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 P.A. Delsart ⁵⁵, C. Deluca ¹⁰⁶, S. Demers ¹⁷⁷, M. Demichev ⁶⁴, A. Demilly ⁷⁹, S.P. Denisov ¹²⁹,
 D. Derendarz ³⁹, J.E. Derkaoui ^{136d}, F. Derue ⁷⁹, P. Dervan ⁷³, K. Desch ²¹, C. Deterre ⁴², P.O. Deviveiros ¹⁰⁶,
 A. Dewhurst ¹³⁰, S. Dhaliwal ¹⁰⁶, A. Di Ciaccio ^{134a,134b}, L. Di Ciaccio ⁵, A. Di Domenico ^{133a,133b},
 C. Di Donato ^{103a,103b}, A. Di Girolamo ³⁰, B. Di Girolamo ³⁰, A. Di Mattia ¹⁵³, B. Di Micco ^{135a,135b},
 R. Di Nardo ⁴⁷, A. Di Simone ⁴⁸, R. Di Sipio ^{20a,20b}, D. Di Valentino ²⁹, F.A. Dias ⁴⁶, M.A. Diaz ^{32a},
 E.B. Diehl ⁸⁸, J. Dietrich ⁴², T.A. Dietzsch ^{58a}, S. Diglio ⁸⁴, A. Dimitrievska ^{13a}, J. Dingfelder ²¹,
 C. Dionisi ^{133a,133b}, P. Dita ^{26a}, S. Dita ^{26a}, F. Dittus ³⁰, F. Djama ⁸⁴, T. Djobava ^{51b}, J.I. Djuvsland ^{58a},
 M.A.B. do Vale ^{24c}, A. Do Valle Wemans ^{125a,125g}, D. Dobos ³⁰, C. Doglioni ⁴⁹, T. Doherty ⁵³, T. Dohmae ¹⁵⁶,
 J. Dolejsi ¹²⁸, Z. Dolezal ¹²⁸, B.A. Dolgoshein ^{97,*}, M. Donadelli ^{24d}, S. Donati ^{123a,123b}, P. Dondero ^{120a,120b},
 J. Donini ³⁴, J. Dopke ¹³⁰, A. Doria ^{103a}, M.T. Dova ⁷⁰, A.T. Doyle ⁵³, M. Dris ¹⁰, J. Dubbert ⁸⁸, S. Dube ¹⁵,
 E. Dubreuil ³⁴, E. Duchovni ¹⁷³, G. Duckeck ⁹⁹, O.A. Ducu ^{26a}, D. Duda ¹⁷⁶, A. Dudarev ³⁰, F. Dudziak ⁶³,
 L. Duflot ¹¹⁶, L. Duguid ⁷⁶, M. Dührssen ³⁰, M. Dunford ^{58a}, H. Duran Yildiz ^{4a}, M. Düren ⁵²,
 A. Durglishvili ^{51b}, M. Dwuznik ^{38a}, M. Dyndal ^{38a}, J. Ebke ⁹⁹, W. Edson ², N.C. Edwards ⁴⁶, W. Ehrenfeld ²¹,
 T. Eifert ¹⁴⁴, G. Eigen ¹⁴, K. Einsweiler ¹⁵, T. Ekelof ¹⁶⁷, M. El Kacimi ^{136c}, M. Ellert ¹⁶⁷, S. Elles ⁵,
 F. Ellinghaus ⁸², N. Ellis ³⁰, J. Elmsheuser ⁹⁹, M. Elsing ³⁰, D. Emelianov ¹³⁰, Y. Enari ¹⁵⁶, O.C. Endner ⁸²,
 M. Endo ¹¹⁷, R. Engelmann ¹⁴⁹, J. Erdmann ¹⁷⁷, A. Ereditato ¹⁷, D. Eriksson ^{147a}, G. Ernis ¹⁷⁶, J. Ernst ²,
 M. Ernst ²⁵, J. Ernwein ¹³⁷, D. Errede ¹⁶⁶, S. Errede ¹⁶⁶, E. Ertel ⁸², M. Escalier ¹¹⁶, H. Esch ⁴³, C. Escobar ¹²⁴,
 B. Esposito ⁴⁷, A.I. Etienvre ¹³⁷, E. Etzion ¹⁵⁴, H. Evans ⁶⁰, A. Ezhilov ¹²², L. Fabbri ^{20a,20b}, G. Facini ³¹,

R.M. Fakhruddinov¹²⁹, S. Falciano^{133a}, R.J. Falla⁷⁷, J. Faltova¹²⁸, Y. Fang^{33a}, M. Fanti^{90a,90b}, A. Farbin⁸, A. Farilla^{135a}, T. Farooque¹², S. Farrell¹⁵, S.M. Farrington¹⁷¹, P. Farthouat³⁰, F. Fassi^{136e}, P. Fassnacht³⁰, D. Fassouliotis⁹, A. Favareto^{50a,50b}, L. Fayard¹¹⁶, P. Federic^{145a}, O.L. Fedin^{122,k}, W. Fedorko¹⁶⁹, M. Fehling-Kaschek⁴⁸, S. Feigl³⁰, L. Feligioni⁸⁴, C. Feng^{33d}, E.J. Feng⁶, H. Feng⁸⁸, A.B. Fenyuk¹²⁹, S. Fernandez Perez³⁰, S. Ferrag⁵³, J. Ferrando⁵³, A. Ferrari¹⁶⁷, P. Ferrari¹⁰⁶, R. Ferrari^{120a}, D.E. Ferreira de Lima⁵³, A. Ferrer¹⁶⁸, D. Ferrere⁴⁹, C. Ferretti⁸⁸, A. Ferretto Parodi^{50a,50b}, M. Fiascaris³¹, F. Fiedler⁸², A. Filipčič⁷⁴, M. Filipuzzi⁴², F. Filthaut¹⁰⁵, M. Fincke-Keeler¹⁷⁰, K.D. Finelli¹⁵¹, M.C.N. Fiolhais^{125a,125c}, L. Fiorini¹⁶⁸, A. Firan⁴⁰, A. Fischer², J. Fischer¹⁷⁶, W.C. Fisher⁸⁹, E.A. Fitzgerald²³, M. Flechl⁴⁸, I. Fleck¹⁴², P. Fleischmann⁸⁸, S. Fleischmann¹⁷⁶, G.T. Fletcher¹⁴⁰, G. Fletcher⁷⁵, T. Flick¹⁷⁶, A. Floderus⁸⁰, L.R. Flores Castillo^{174,l}, A.C. Florez Bustos^{160b}, M.J. Flowerdew¹⁰⁰, A. Formica¹³⁷, A. Forti⁸³, D. Fortin^{160a}, D. Fournier¹¹⁶, H. Fox⁷¹, S. Fracchia¹², P. Francavilla⁷⁹, M. Franchini^{20a,20b}, S. Franchino³⁰, D. Francis³⁰, L. Franconi¹¹⁸, M. Franklin⁵⁷, S. Franz⁶¹, M. Fraternali^{120a,120b}, S.T. French²⁸, C. Friedrich⁴², F. Friedrich⁴⁴, D. Froidevaux³⁰, J.A. Frost²⁸, C. Fukunaga¹⁵⁷, E. Fullana Torregrosa⁸², B.G. Fulson¹⁴⁴, J. Fuster¹⁶⁸, C. Gabaldon⁵⁵, O. Gabizon¹⁷⁶, A. Gabrielli^{20a,20b}, A. Gabrielli^{133a,133b}, S. Gadatsch¹⁰⁶, S. Gadomski⁴⁹, G. Gagliardi^{50a,50b}, P. Gagnon⁶⁰, C. Galea¹⁰⁵, B. Galhardo^{125a,125c}, E.J. Gallas¹¹⁹, V. Gallo¹⁷, B.J. Gallop¹³⁰, P. Gallus¹²⁷, G. Galster³⁶, K.K. Gan¹¹⁰, J. Gao^{33b,h}, Y.S. Gao^{144,f}, F.M. Garay Walls⁴⁶, F. Garberon¹⁷⁷, C. García¹⁶⁸, J.E. García Navarro¹⁶⁸, M. Garcia-Sciveres¹⁵, R.W. Gardner³¹, N. Garelli¹⁴⁴, V. Garonne³⁰, C. Gatti⁴⁷, G. Gaudio^{120a}, B. Gaur¹⁴², L. Gauthier⁹⁴, P. Gauzzi^{133a,133b}, I.L. Gavrilenko⁹⁵, C. Gay¹⁶⁹, G. Gaycken²¹, E.N. Gazis¹⁰, P. Ge^{33d}, Z. Gecse¹⁶⁹, C.N.P. Gee¹³⁰, D.A.A. Geerts¹⁰⁶, Ch. Geich-Gimbel²¹, K. Gellerstedt^{147a,147b}, C. Gemme^{50a}, A. Gemmell⁵³, M.H. Genest⁵⁵, S. Gentile^{133a,133b}, M. George⁵⁴, S. George⁷⁶, D. Gerbaudo¹⁶⁴, A. Gershon¹⁵⁴, H. Ghazlane^{136b}, N. Ghodbane³⁴, B. Giacobbe^{20a}, S. Giagu^{133a,133b}, V. Giangiobbe¹², P. Giannetti^{123a,123b}, F. Gianotti³⁰, B. Gibbard²⁵, S.M. Gibson⁷⁶, M. Gilchriese¹⁵, T.P.S. Gillam²⁸, D. Gillberg³⁰, G. Gilles³⁴, D.M. Gingrich^{3,e}, N. Giokaris⁹, M.P. Giordani^{165a,165c}, R. Giordano^{103a,103b}, F.M. Giorgi^{20a}, F.M. Giorgi¹⁶, P.F. Giraud¹³⁷, D. Giugni^{90a}, C. Giuliani⁴⁸, M. Giulini^{58b}, B.K. Gjelsten¹¹⁸, S. Gkaitatzis¹⁵⁵, I. Gkialas^{155,m}, L.K. Gladilin⁹⁸, C. Glasman⁸¹, J. Glatzer³⁰, P.C.F. Glaysher⁴⁶, A. Glazov⁴², G.L. Glonti⁶⁴, M. Goblirsch-Kolb¹⁰⁰, J.R. Goddard⁷⁵, J. Godlewski³⁰, C. Goeringer⁸², S. Goldfarb⁸⁸, T. Golling¹⁷⁷, D. Golubkov¹²⁹, A. Gomes^{125a,125b,125d}, L.S. Gomez Fajardo⁴², R. Gonçalves^{125a}, J. Goncalves Pinto Firmino Da Costa¹³⁷, L. Gonella²¹, S. González de la Hoz¹⁶⁸, G. Gonzalez Parra¹², S. Gonzalez-Sevilla⁴⁹, L. Goossens³⁰, P.A. Gorbounov⁹⁶, H.A. Gordon²⁵, I. Gorelov¹⁰⁴, B. Gorini³⁰, E. Gorini^{72a,72b}, A. Gorišek⁷⁴, E. Gornicki³⁹, A.T. Goshaw⁶, C. Gössling⁴³, M.I. Gostkin⁶⁴, M. Gouighri^{136a}, D. Goujdami^{136c}, M.P. Goulette⁴⁹, A.G. Goussiou¹³⁹, C. Goy⁵, S. Gozpinar²³, H.M.X. Grabas¹³⁷, L. Graber⁵⁴, I. Grabowska-Bold^{38a}, P. Grafström^{20a,20b}, K.-J. Grahn⁴², J. Gramling⁴⁹, E. Gramstad¹¹⁸, S. Grancagnolo¹⁶, V. Grassi¹⁴⁹, V. Gratchev¹²², H.M. Gray³⁰, E. Graziani^{135a}, O.G. Grebenyuk¹²², Z.D. Greenwood^{78,n}, K. Gregersen⁷⁷, I.M. Gregor⁴², P. Grenier¹⁴⁴, J. Griffiths⁸, A.A. Grillo¹³⁸, K. Grimm⁷¹, S. Grinstein^{12,o}, Ph. Gris³⁴, Y.V. Grishkevich⁹⁸, J.-F. Grivaz¹¹⁶, J.P. Grohs⁴⁴, A. Grohsjean⁴², E. Gross¹⁷³, J. Grosse-Knetter⁵⁴, G.C. Grossi^{134a,134b}, J. Groth-Jensen¹⁷³, Z.J. Grout¹⁵⁰, L. Guan^{33b}, J. Guenther¹²⁷, F. Guescini⁴⁹, D. Guest¹⁷⁷, O. Gueta¹⁵⁴, C. Guicheney³⁴, E. Guido^{50a,50b}, T. Guillemin¹¹⁶, S. Guindon², U. Gul⁵³, C. Gumpert⁴⁴, J. Guo³⁵, S. Gupta¹¹⁹, P. Gutierrez¹¹², N.G. Gutierrez Ortiz⁵³, C. Gutsche⁷⁷, N. Guttman¹⁵⁴, C. Guyot¹³⁷, C. Gwenlan¹¹⁹, C.B. Gwilliam⁷³, A. Haas¹⁰⁹, C. Haber¹⁵, H.K. Hadavand⁸, N. Haddad^{136e}, P. Haefner²¹, S. Hageböck²¹, Z. Hajduk³⁹, H. Hakobyan¹⁷⁸, M. Haleem⁴², D. Hall¹¹⁹, G. Halladjian⁸⁹, K. Hamacher¹⁷⁶, P. Hamal¹¹⁴, K. Hamano¹⁷⁰, M. Hamer⁵⁴, A. Hamilton^{146a}, S. Hamilton¹⁶², G.N. Hamity^{146c}, P.G. Hamnett⁴², L. Han^{33b}, K. Hanagaki¹¹⁷, K. Hanawa¹⁵⁶, M. Hance¹⁵, P. Hanke^{58a}, R. Hanna¹³⁷, J.B. Hansen³⁶, J.D. Hansen³⁶, P.H. Hansen³⁶, K. Hara¹⁶¹, A.S. Hard¹⁷⁴, T. Harenberg¹⁷⁶, F. Hariri¹¹⁶, S. Harkusha⁹¹, D. Harper⁸⁸, R.D. Harrington⁴⁶, O.M. Harris¹³⁹, P.F. Harrison¹⁷¹, F. Hartjes¹⁰⁶, M. Hasegawa⁶⁶, S. Hasegawa¹⁰², Y. Hasegawa¹⁴¹, A. Hasib¹¹², S. Hassani¹³⁷, S. Haug¹⁷, M. Hauschild³⁰, R. Hauser⁸⁹, M. Havranek¹²⁶, C.M. Hawkes¹⁸, R.J. Hawking³⁰, A.D. Hawkins⁸⁰, T. Hayashi¹⁶¹, D. Hayden⁸⁹, C.P. Hays¹¹⁹, H.S. Hayward⁷³, S.J. Haywood¹³⁰, S.J. Head¹⁸, T. Heck⁸², V. Hedberg⁸⁰, L. Heelan⁸, S. Heim¹²¹, T. Heim¹⁷⁶, B. Heinemann¹⁵, L. Heinrich¹⁰⁹, J. Hejbal¹²⁶, L. Helary²², C. Heller⁹⁹, M. Heller³⁰, S. Hellman^{147a,147b}, D. Hellmich²¹, C. Hensens³⁰, J. Henderson¹¹⁹, R.C.W. Henderson⁷¹, Y. Heng¹⁷⁴,

C. Hengler⁴², A. Henrichs¹⁷⁷, A.M. Henriques Correia³⁰, S. Henrot-Versille¹¹⁶, G.H. Herbert¹⁶, Y. Hernández Jiménez¹⁶⁸, R. Herrberg-Schubert¹⁶, G. Herten⁴⁸, R. Hertenberger⁹⁹, L. Hervas³⁰, G.G. Hesketh⁷⁷, N.P. Hessey¹⁰⁶, R. Hickling⁷⁵, E. Higón-Rodríguez¹⁶⁸, E. Hill¹⁷⁰, J.C. Hill²⁸, K.H. Hiller⁴², S. Hillert²¹, S.J. Hillier¹⁸, I. Hinchliffe¹⁵, E. Hines¹²¹, M. Hirose¹⁵⁸, D. Hirschbuehl¹⁷⁶, J. Hobbs¹⁴⁹, N. Hod¹⁰⁶, M.C. Hodgkinson¹⁴⁰, P. Hodgson¹⁴⁰, A. Hoecker³⁰, M.R. Hoferkamp¹⁰⁴, F. Hoenic⁹⁹, J. Hoffman⁴⁰, D. Hoffmann⁸⁴, M. Hohlfeld⁸², T.R. Holmes¹⁵, T.M. Hong¹²¹, L. Hooft van Huysduynen¹⁰⁹, W.H. Hopkins¹¹⁵, Y. Horii¹⁰², J.-Y. Hostachy⁵⁵, S. Hou¹⁵², A. Hoummada^{136a}, J. Howard¹¹⁹, J. Howarth⁴², M. Hrabovsky¹¹⁴, I. Hristova¹⁶, J. Hrivnac¹¹⁶, T. Hryn'ova⁵, C. Hsu^{146c}, P.J. Hsu⁸², S.-C. Hsu¹³⁹, D. Hu³⁵, X. Hu⁸⁸, Y. Huang⁴², Z. Hubacek³⁰, F. Hubaut⁸⁴, F. Huegging²¹, T.B. Huffman¹¹⁹, E.W. Hughes³⁵, G. Hughes⁷¹, M. Huhtinen³⁰, T.A. Hülsing⁸², M. Hurwitz¹⁵, N. Huseynov^{64,b}, J. Huston⁸⁹, J. Huth⁵⁷, G. Iacobucci⁴⁹, G. Iakovidis¹⁰, I. Ibragimov¹⁴², L. Iconomidou-Fayard¹¹⁶, E. Ideal¹⁷⁷, Z. Idrissi^{136e}, P. Iengo^{103a}, O. Igonkina¹⁰⁶, T. Iizawa¹⁷², Y. Ikegami⁶⁵, K. Ikematsu¹⁴², M. Ikeno⁶⁵, Y. Ilchenko^{31,p}, D. Iliadis¹⁵⁵, N. Ilic¹⁵⁹, Y. Inamaru⁶⁶, T. Ince¹⁰⁰, P. Ioannou⁹, M. Iodice^{135a}, K. Iordanidou⁹, V. Ippolito⁵⁷, A. Irles Quiles¹⁶⁸, C. Isaksson¹⁶⁷, M. Ishino⁶⁷, M. Ishitsuka¹⁵⁸, R. Ishmukhametov¹¹⁰, C. Issever¹¹⁹, S. Istin^{19a}, J.M. Iturbe Ponce⁸³, R. Iuppa^{134a,134b}, J. Ivarsson⁸⁰, W. Iwanski³⁹, H. Iwasaki⁶⁵, J.M. Izen⁴¹, V. Izzo^{103a}, B. Jackson¹²¹, M. Jackson⁷³, P. Jackson¹, M.R. Jaekel³⁰, V. Jain², K. Jakobs⁴⁸, S. Jakobsen³⁰, T. Jakoubek¹²⁶, J. Jakubek¹²⁷, D.O. Jamin¹⁵², D.K. Jana⁷⁸, E. Jansen⁷⁷, H. Jansen³⁰, J. Janssen²¹, M. Janus¹⁷¹, G. Jarlskog⁸⁰, N. Javadov^{64,b}, T. Javůrek⁴⁸, L. Jeanty¹⁵, J. Jejelava^{51a,q}, G.-Y. Jeng¹⁵¹, D. Jennens⁸⁷, P. Jenni^{48,r}, J. Jentsch⁴³, C. Jeske¹⁷¹, S. Jézéquel⁵, H. Ji¹⁷⁴, J. Jia¹⁴⁹, Y. Jiang^{33b}, M. Jimenez Belenguer⁴², S. Jin^{33a}, A. Jinaru^{26a}, O. Jinnouchi¹⁵⁸, M.D. Joergensen³⁶, K.E. Johansson^{147a,147b}, P. Johansson¹⁴⁰, K.A. Johns⁷, K. Jon-And^{147a,147b}, G. Jones¹⁷¹, R.W.L. Jones⁷¹, T.J. Jones⁷³, J. Jongmanns^{58a}, P.M. Jorge^{125a,125b}, K.D. Joshi⁸³, J. Jovicevic¹⁴⁸, X. Ju¹⁷⁴, C.A. Jung⁴³, R.M. Jungst³⁰, P. Jussel⁶¹, A. Juste Rozas^{12,o}, M. Kaci¹⁶⁸, A. Kaczmarska³⁹, M. Kado¹¹⁶, H. Kagan¹¹⁰, M. Kagan¹⁴⁴, E. Kajomovitz⁴⁵, C.W. Kalderon¹¹⁹, S. Kama⁴⁰, A. Kamenshchikov¹²⁹, N. Kanaya¹⁵⁶, M. Kaneda³⁰, S. Kaneti²⁸, V.A. Kantserov⁹⁷, J. Kanzaki⁶⁵, B. Kaplan¹⁰⁹, A. Kapliy³¹, D. Kar⁵³, K. Karakostas¹⁰, N. Karastathis¹⁰, M.J. Kareem⁵⁴, M. Karnevskiy⁸², S.N. Karpov⁶⁴, Z.M. Karpova⁶⁴, K. Karthik¹⁰⁹, V. Kartvelishvili⁷¹, A.N. Karyukhin¹²⁹, L. Kashif¹⁷⁴, G. Kasieczka^{58b}, R.D. Kass¹¹⁰, A. Kastanas¹⁴, Y. Kataoka¹⁵⁶, A. Katre⁴⁹, J. Katzy⁴², V. Kaushik⁷, K. Kawagoe⁶⁹, T. Kawamoto¹⁵⁶, G. Kawamura⁵⁴, S. Kazama¹⁵⁶, V.F. Kazanin¹⁰⁸, M.Y. Kazarinov⁶⁴, R. Keeler¹⁷⁰, R. Kehoe⁴⁰, M. Keil⁵⁴, J.S. Keller⁴², J.J. Kempster⁷⁶, H. Keoshkerian⁵, O. Kepka¹²⁶, B.P. Kerševan⁷⁴, S. Kersten¹⁷⁶, K. Kessoku¹⁵⁶, J. Keung¹⁵⁹, F. Khalil-zada¹¹, H. Khandanyan^{147a,147b}, A. Khanov¹¹³, A. Khodinov⁹⁷, A. Khomich^{58a}, T.J. Khoo²⁸, G. Khoriauli²¹, A. Khoroshilov¹⁷⁶, V. Khovanskiy⁹⁶, E. Khramov⁶⁴, J. Khubua^{51b}, H.Y. Kim⁸, H. Kim^{147a,147b}, S.H. Kim¹⁶¹, N. Kimura¹⁷², O. Kind¹⁶, B.T. King⁷³, M. King¹⁶⁸, R.S.B. King¹¹⁹, S.B. King¹⁶⁹, J. Kirk¹³⁰, A.E. Kiryunin¹⁰⁰, T. Kishimoto⁶⁶, D. Kisielewska^{38a}, F. Kiss⁴⁸, T. Kittelmann¹²⁴, K. Kiuchi¹⁶¹, E. Kladiva^{145b}, M. Klein⁷³, U. Klein⁷³, K. Kleinknecht⁸², P. Klimek^{147a,147b}, A. Klimentov²⁵, R. Klingenberg⁴³, J.A. Klinger⁸³, T. Klioutchnikova³⁰, P.F. Klok¹⁰⁵, E.-E. Kluge^{58a}, P. Kluit¹⁰⁶, S. Kluth¹⁰⁰, E. Kneringer⁶¹, E.B.F.G. Knoops⁸⁴, A. Knue⁵³, D. Kobayashi¹⁵⁸, T. Kobayashi¹⁵⁶, M. Kobel⁴⁴, M. Kocian¹⁴⁴, P. Kodys¹²⁸, P. Koevesarki²¹, T. Koffas²⁹, E. Koffeman¹⁰⁶, L.A. Kogan¹¹⁹, S. Kohlmann¹⁷⁶, Z. Kohout¹²⁷, T. Kohriki⁶⁵, T. Koi¹⁴⁴, H. Kolanoski¹⁶, I. Koletsou⁵, J. Koll⁸⁹, A.A. Komar^{95,*}, Y. Komori¹⁵⁶, T. Kondo⁶⁵, N. Kondrashova⁴², K. Köneke⁴⁸, A.C. König¹⁰⁵, S. König⁸², T. Kono^{65,s}, R. Konoplich^{109,t}, N. Konstantinidis⁷⁷, R. Kopeliansky¹⁵³, S. Koperny^{38a}, L. Köpke⁸², A.K. Kopp⁴⁸, K. Korcyl³⁹, K. Kordas¹⁵⁵, A. Korn⁷⁷, A.A. Korol^{108,c}, I. Korolkov¹², E.V. Korolkova¹⁴⁰, V.A. Korotkov¹²⁹, O. Kortner¹⁰⁰, S. Kortner¹⁰⁰, V.V. Kostyukhin²¹, V.M. Kotov⁶⁴, A. Kotwal⁴⁵, C. Kourkoumelis⁹, V. Kouskoura¹⁵⁵, A. Koutsman^{160a}, R. Kowalewski¹⁷⁰, T.Z. Kowalski^{38a}, W. Kozanecki¹³⁷, A.S. Kozhin¹²⁹, V. Kral¹²⁷, V.A. Kramarenko⁹⁸, G. Kramberger⁷⁴, D. Krasnopevtsev⁹⁷, M.W. Krasny⁷⁹, A. Krasznahorkay³⁰, J.K. Kraus²¹, A. Kravchenko²⁵, S. Kreiss¹⁰⁹, M. Kretz^{58c}, J. Kretzschmar⁷³, K. Kreutzfeldt⁵², P. Krieger¹⁵⁹, K. Kroeninger⁵⁴, H. Kroha¹⁰⁰, J. Kroll¹²¹, J. Kroseberg²¹, J. Krstic^{13a}, U. Kruchonak⁶⁴, H. Krüger²¹, T. Kruker¹⁷, N. Krumnack⁶³, Z.V. Krumshteyn⁶⁴, A. Kruse¹⁷⁴, M.C. Kruse⁴⁵, M. Kruskal²², T. Kubota⁸⁷, H. Kucuk⁷⁷, S. Kuday^{4a}, S. Kuehn⁴⁸, A. Kugel^{58c}, A. Kuhl¹³⁸, T. Kuhl⁴², V. Kukhtin⁶⁴, Y. Kulchitsky⁹¹, S. Kuleshov^{32b}, M. Kuna^{133a,133b}, J. Kunkle¹²¹, A. Kupco¹²⁶, H. Kurashige⁶⁶, Y.A. Kurochkin⁹¹, R. Kurumida⁶⁶, V. Kus¹²⁶, E.S. Kuwertz¹⁴⁸, M. Kuze¹⁵⁸, J. Kvita¹¹⁴, A. La Rosa⁴⁹, L. La Rotonda^{37a,37b}, C. Lacasta¹⁶⁸, F. Lacava^{133a,133b}, J. Lacey²⁹, H. Lacker¹⁶, D. Lacour⁷⁹,

V.R. Lacuesta¹⁶⁸, E. Ladygin⁶⁴, R. Lafaye⁵, B. Laforge⁷⁹, T. Lagouri¹⁷⁷, S. Lai⁴⁸, H. Laier^{58a},
L. Lambourne⁷⁷, S. Lammers⁶⁰, C.L. Lampen⁷, W. Lampl⁷, E. Lançon¹³⁷, U. Landgraf⁴⁸, M.P.J. Landon⁷⁵,
V.S. Lang^{58a}, A.J. Lankford¹⁶⁴, F. Lanni²⁵, K. Lantzsch³⁰, S. Laplace⁷⁹, C. Lapoire²¹, J.F. Laporte¹³⁷,
T. Lari^{90a}, F. Lasagni Manghi^{20a,20b}, M. Lassnig³⁰, P. Laurelli⁴⁷, W. Lavrijsen¹⁵, A.T. Law¹³⁸, P. Laycock⁷³,
O. Le Dortz⁷⁹, E. Le Guirriec⁸⁴, E. Le Menedeu¹², T. LeCompte⁶, F. Ledroit-Guillon⁵⁵, C.A. Lee¹⁵²,
H. Lee¹⁰⁶, J.S.H. Lee¹¹⁷, S.C. Lee¹⁵², L. Lee¹, G. Lefebvre⁷⁹, M. Lefebvre¹⁷⁰, F. Legger⁹⁹, C. Leggett¹⁵,
A. Lehan⁷³, M. Lehmacher²¹, G. Lehmann Miotto³⁰, X. Lei⁷, W.A. Leight²⁹, A. Leisos¹⁵⁵, A.G. Leister¹⁷⁷,
M.A.L. Leite^{24d}, R. Leitner¹²⁸, D. Lellouch¹⁷³, B. Lemmer⁵⁴, K.J.C. Leney⁷⁷, T. Lenz²¹, G. Lenzen¹⁷⁶,
B. Lenzi³⁰, R. Leone⁷, S. Leone^{123a,123b}, C. Leonidopoulos⁴⁶, S. Leontsinis¹⁰, C. Leroy⁹⁴, C.G. Lester²⁸,
C.M. Lester¹²¹, M. Levchenko¹²², J. Levêque⁵, D. Levin⁸⁸, L.J. Levinson¹⁷³, M. Levy¹⁸, A. Lewis¹¹⁹,
G.H. Lewis¹⁰⁹, A.M. Leyko²¹, M. Leyton⁴¹, B. Li^{33b,u}, B. Li⁸⁴, H. Li¹⁴⁹, H.L. Li³¹, L. Li⁴⁵, L. Li^{33e}, S. Li⁴⁵,
Y. Li^{33c,v}, Z. Liang¹³⁸, H. Liao³⁴, B. Liberti^{134a}, P. Lichard³⁰, K. Lie¹⁶⁶, J. Liebal²¹, W. Liebig¹⁴,
C. Limbach²¹, A. Limosani⁸⁷, S.C. Lin^{152,w}, T.H. Lin⁸², F. Linde¹⁰⁶, B.E. Lindquist¹⁴⁹, J.T. Linnemann⁸⁹,
E. Lipeles¹²¹, A. Lipniacka¹⁴, M. Lisovyi⁴², T.M. Liss¹⁶⁶, D. Lissauer²⁵, A. Lister¹⁶⁹, A.M. Litke¹³⁸,
B. Liu¹⁵², D. Liu¹⁵², J.B. Liu^{33b}, K. Liu^{33b,x}, L. Liu⁸⁸, M. Liu⁴⁵, M. Liu^{33b}, Y. Liu^{33b}, M. Livan^{120a,120b},
S.S.A. Livermore¹¹⁹, A. Lleres⁵⁵, J. Llorente Merino⁸¹, S.L. Lloyd⁷⁵, F. Lo Sterzo¹⁵², E. Lobodzinska⁴²,
P. Loch⁷, W.S. Lockman¹³⁸, F.K. Loebinger⁸³, A.E. Loevschall-Jensen³⁶, A. Loginov¹⁷⁷, T. Lohse¹⁶,
K. Lohwasser⁴², M. Lokajicek¹²⁶, V.P. Lombardo⁵, B.A. Long²², J.D. Long⁸⁸, R.E. Long⁷¹, L. Lopes^{125a},
D. Lopez Mateos⁵⁷, B. Lopez Paredes¹⁴⁰, I. Lopez Paz¹², J. Lorenz⁹⁹, N. Lorenzo Martinez⁶⁰,
M. Losada¹⁶³, P. Loscutoff¹⁵, X. Lou⁴¹, A. Lounis¹¹⁶, J. Love⁶, P.A. Love⁷¹, A.J. Lowe^{144,f}, F. Lu^{33a},
N. Lu⁸⁸, H.J. Lubatti¹³⁹, C. Luci^{133a,133b}, A. Lucotte⁵⁵, F. Luehring⁶⁰, W. Lukas⁶¹, L. Luminari^{133a},
O. Lundberg^{147a,147b}, B. Lund-Jensen¹⁴⁸, M. Lungwitz⁸², D. Lynn²⁵, R. Lysak¹²⁶, E. Lytken⁸⁰, H. Ma²⁵,
L.L. Ma^{33d}, G. Maccarrone⁴⁷, A. Macchiolo¹⁰⁰, J. Machado Miguens^{125a,125b}, D. Macina³⁰,
D. Madaffari⁸⁴, R. Madar⁴⁸, H.J. Maddocks⁷¹, W.F. Mader⁴⁴, A. Madsen¹⁶⁷, M. Maeno⁸, T. Maeno²⁵,
A. Maevskiy⁹⁸, E. Magradze⁵⁴, K. Mahboubi⁴⁸, J. Mahlstedt¹⁰⁶, S. Mahmoud⁷³, C. Maiani¹³⁷,
C. Maidantchik^{24a}, A.A. Maier¹⁰⁰, A. Maio^{125a,125b,125d}, S. Majewski¹¹⁵, Y. Makida⁶⁵, N. Makovec¹¹⁶,
P. Mal^{137,y}, B. Malaescu⁷⁹, Pa. Malecki³⁹, V.P. Maleev¹²², F. Malek⁵⁵, U. Mallik⁶², D. Malon⁶,
C. Malone¹⁴⁴, S. Maltezos¹⁰, V.M. Malyshev¹⁰⁸, S. Malyukov³⁰, J. Mamuzic^{13b}, B. Mandelli³⁰,
L. Mandelli^{90a}, I. Mandić⁷⁴, R. Mandrysch⁶², J. Maneira^{125a,125b}, A. Manfredini¹⁰⁰,
L. Manhaes de Andrade Filho^{24b}, J.A. Manjarres Ramos^{160b}, A. Mann⁹⁹, P.M. Manning¹³⁸,
A. Manousakis-Katsikakis⁹, B. Mansoulie¹³⁷, R. Mantifel⁸⁶, L. Mapelli³⁰, L. March^{146c}, J.F. Marchand²⁹,
G. Marchiori⁷⁹, M. Marcisovsky¹²⁶, C.P. Marino¹⁷⁰, M. Marjanovic^{13a}, C.N. Marques^{125a},
F. Marroquim^{24a}, S.P. Marsden⁸³, Z. Marshall¹⁵, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁸, B. Martin³⁰,
B. Martin⁸⁹, T.A. Martin¹⁷¹, V.J. Martin⁴⁶, B. Martin dit Latour¹⁴, H. Martinez¹³⁷, M. Martinez^{12,o},
S. Martin-Haugh¹³⁰, A.C. Martyniuk⁷⁷, M. Marx¹³⁹, F. Marzano^{133a}, A. Marzin³⁰, L. Masetti⁸²,
T. Mashimo¹⁵⁶, R. Mashinistov⁹⁵, J. Masik⁸³, A.L. Maslennikov^{108,c}, I. Massa^{20a,20b}, L. Massa^{20a,20b},
N. Massol⁵, P. Mastrandrea¹⁴⁹, A. Mastroberardino^{37a,37b}, T. Masubuchi¹⁵⁶, P. Mättig¹⁷⁶, J. Mattmann⁸²,
J. Maurer^{26a}, S.J. Maxfield⁷³, D.A. Maximov^{108,c}, R. Mazini¹⁵², L. Mazzaferro^{134a,134b}, G. Mc Goldrick¹⁵⁹,
S.P. Mc Kee⁸⁸, A. McCarn⁸⁸, R.L. McCarthy¹⁴⁹, T.G. McCarthy²⁹, N.A. McCubbin¹³⁰, K.W. McFarlane^{56,*},
J.A. MCFayden⁷⁷, G. Mchedlidze⁵⁴, S.J. McMahon¹³⁰, R.A. McPherson^{170,j}, J. Mechnich¹⁰⁶,
M. Medinnis⁴², S. Meehan³¹, S. Mehlhase⁹⁹, A. Mehta⁷³, K. Meier^{58a}, C. Meineck⁹⁹, B. Meirose⁸⁰,
C. Melachrinos³¹, B.R. Mellado Garcia^{146c}, F. Meloni¹⁷, A. Mengarelli^{20a,20b}, S. Menke¹⁰⁰, E. Meoni¹⁶²,
K.M. Mercurio⁵⁷, S. Mergelmeyer²¹, N. Meric¹³⁷, P. Mermod⁴⁹, L. Merola^{103a,103b}, C. Meroni^{90a},
F.S. Merritt³¹, H. Merritt¹¹⁰, A. Messina^{30,z}, J. Metcalfe²⁵, A.S. Mete¹⁶⁴, C. Meyer⁸², C. Meyer¹²¹,
J-P. Meyer¹³⁷, J. Meyer³⁰, R.P. Middleton¹³⁰, S. Migas⁷³, L. Mijović²¹, G. Mikenberg¹⁷³,
M. Mikestikova¹²⁶, M. Mikuž⁷⁴, A. Milic³⁰, D.W. Miller³¹, C. Mills⁴⁶, A. Milov¹⁷³, D.A. Milstead^{147a,147b},
D. Milstein¹⁷³, A.A. Minaenko¹²⁹, Y. Minami¹⁵⁶, I.A. Minashvili⁶⁴, A.I. Mincer¹⁰⁹, B. Mindur^{38a},
M. Mineev⁶⁴, Y. Ming¹⁷⁴, L.M. Mir¹², G. Mirabelli^{133a}, T. Mitani¹⁷², J. Mitrevski⁹⁹, V.A. Mitsou¹⁶⁸,
S. Mitsui⁶⁵, A. Miucci⁴⁹, P.S. Miyagawa¹⁴⁰, J.U. Mjörnmark⁸⁰, T. Moa^{147a,147b}, K. Mochizuki⁸⁴,
S. Mohapatra³⁵, W. Mohr⁴⁸, S. Molander^{147a,147b}, R. Moles-Valls¹⁶⁸, K. Mönig⁴², C. Monini⁵⁵,
J. Monk³⁶, E. Monnier⁸⁴, J. Montejo Berlingen¹², F. Monticelli⁷⁰, S. Monzani^{133a,133b}, R.W. Moore³,
N. Morange⁶², D. Moreno⁸², M. Moreno Llácer⁵⁴, P. Morettini^{50a}, M. Morgenstern⁴⁴, M. Morii⁵⁷,

S. Moritz⁸², A.K. Morley¹⁴⁸, G. Mornacchi³⁰, J.D. Morris⁷⁵, L. Morvaj¹⁰², H.G. Moser¹⁰⁰, M. Mosidze^{51b}, J. Moss¹¹⁰, K. Motohashi¹⁵⁸, R. Mount¹⁴⁴, E. Mountricha²⁵, S.V. Mouraviev^{95,*}, E.J.W. Moyse⁸⁵, S. Muanza⁸⁴, R.D. Mudd¹⁸, F. Mueller^{58a}, J. Mueller¹²⁴, K. Mueller²¹, T. Mueller²⁸, T. Mueller⁸², D. Muenstermann⁴⁹, Y. Munwes¹⁵⁴, J.A. Murillo Quijada¹⁸, W.J. Murray^{171,130}, H. Musheghyan⁵⁴, E. Musto¹⁵³, A.G. Myagkov^{129,aa}, M. Myska¹²⁷, O. Nackenhorst⁵⁴, J. Nadal⁵⁴, K. Nagai⁶¹, R. Nagai¹⁵⁸, Y. Nagai⁸⁴, K. Nagano⁶⁵, A. Nagarkar¹¹⁰, Y. Nagasaka⁵⁹, M. Nagel¹⁰⁰, A.M. Nairz³⁰, Y. Nakahama³⁰, K. Nakamura⁶⁵, T. Nakamura¹⁵⁶, I. Nakano¹¹¹, H. Namasivayam⁴¹, G. Nanava²¹, R. Narayan^{58b}, T. Nattermann²¹, T. Naumann⁴², G. Navarro¹⁶³, R. Nayyar⁷, H.A. Neal⁸⁸, P.Yu. Nechaeva⁹⁵, T.J. Neep⁸³, P.D. Nef¹⁴⁴, A. Negri^{120a,120b}, G. Negri³⁰, M. Negrini^{20a}, S. Nektarijevic⁴⁹, C. Nellist¹¹⁶, A. Nelson¹⁶⁴, T.K. Nelson¹⁴⁴, S. Nemecek¹²⁶, P. Nemethy¹⁰⁹, A.A. Nepomuceno^{24a}, M. Nessi^{30,ab}, M.S. Neubauer¹⁶⁶, M. Neumann¹⁷⁶, R.M. Neves¹⁰⁹, P. Nevski²⁵, P.R. Newman¹⁸, D.H. Nguyen⁶, R.B. Nickerson¹¹⁹, R. Nicolaidou¹³⁷, B. Nicquevert³⁰, J. Nielsen¹³⁸, N. Nikiforou³⁵, A. Nikiforov¹⁶, V. Nikolaenko^{129,aa}, I. Nikolic-Audit⁷⁹, K. Nikolics⁴⁹, K. Nikolopoulos¹⁸, P. Nilsson⁸, Y. Ninomiya¹⁵⁶, A. Nisati^{133a}, R. Nisius¹⁰⁰, T. Nobe¹⁵⁸, L. Nodulman⁶, M. Nomachi¹¹⁷, I. Nomidis²⁹, S. Norberg¹¹², M. Nordberg³⁰, O. Novgorodova⁴⁴, S. Nowak¹⁰⁰, M. Nozaki⁶⁵, L. Nozka¹¹⁴, K. Ntekas¹⁰, G. Nunes Hanninger⁸⁷, T. Nunnemann⁹⁹, E. Nurse⁷⁷, F. Nuti⁸⁷, B.J. O'Brien⁴⁶, F. O'grady⁷, D.C. O'Neil¹⁴³, V. O'Shea⁵³, F.G. Oakham^{29,e}, H. Oberlack¹⁰⁰, T. Obermann²¹, J. Ocariz⁷⁹, A. Ochi⁶⁶, M.I. Ochoa⁷⁷, S. Oda⁶⁹, S. Odaka⁶⁵, H. Ogren⁶⁰, A. Oh⁸³, S.H. Oh⁴⁵, C.C. Ohm¹⁵, H. Ohman¹⁶⁷, W. Okamura¹¹⁷, H. Okawa²⁵, Y. Okumura³¹, T. Okuyama¹⁵⁶, A. Olariu^{26a}, A.G. Olchevski⁶⁴, S.A. Olivares Pino⁴⁶, D. Oliveira Damazio²⁵, E. Oliver Garcia¹⁶⁸, A. Olszewski³⁹, J. Olszowska³⁹, A. Onofre^{125a,125e}, P.U.E. Onyisi^{31,p}, C.J. Oram^{160a}, M.J. Oreglia³¹, Y. Oren¹⁵⁴, D. Orestano^{135a,135b}, N. Orlando^{72a,72b}, C. Oropeza Barrera⁵³, R.S. Orr¹⁵⁹, B. Osculati^{50a,50b}, R. Ospanov¹²¹, G. Otero y Garzon²⁷, H. Otono⁶⁹, M. Ouchrif^{136d}, E.A. Ouellette¹⁷⁰, F. Ould-Saada¹¹⁸, A. Ouraou¹³⁷, K.P. Oussoren¹⁰⁶, Q. Ouyang^{33a}, A. Ovcharova¹⁵, M. Owen⁸³, V.E. Ozcan^{19a}, N. Ozturk⁸, K. Pachal¹¹⁹, A. Pacheco Pages¹², C. Padilla Aranda¹², M. Pagáčová⁴⁸, S. Pagan Griso¹⁵, E. Paganis¹⁴⁰, C. Pahl¹⁰⁰, F. Paige²⁵, P. Pais⁸⁵, K. Pajchel¹¹⁸, G. Palacino^{160b}, S. Palestini³⁰, M. Palka^{38b}, D. Pallin³⁴, A. Palma^{125a,125b}, J.D. Palmer¹⁸, Y.B. Pan¹⁷⁴, E. Panagiotopoulou¹⁰, J.G. Panduro Vazquez⁷⁶, P. Pani¹⁰⁶, N. Panikashvili⁸⁸, S. Panitkin²⁵, D. Pantea^{26a}, L. Paolozzi^{134a,134b}, Th.D. Papadopoulou¹⁰, K. Papageorgiou^{155,m}, A. Paramonov⁶, D. Paredes Hernandez¹⁵⁵, M.A. Parker²⁸, F. Parodi^{50a,50b}, J.A. Parsons³⁵, U. Parzefall⁴⁸, E. Pasqualucci^{133a}, S. Passaggio^{50a}, A. Passeri^{135a}, F. Pastore^{135a,135b,*}, Fr. Pastore⁷⁶, G. Pásztor²⁹, S. Patariaia¹⁷⁶, N.D. Patel¹⁵¹, J.R. Pater⁸³, S. Patricelli^{103a,103b}, T. Pauly³⁰, J. Pearce¹⁷⁰, L.E. Pedersen³⁶, M. Pedersen¹¹⁸, S. Pedraza Lopez¹⁶⁸, R. Pedro^{125a,125b}, S.V. Peleganchuk¹⁰⁸, D. Pelikan¹⁶⁷, H. Peng^{33b}, B. Penning³¹, J. Penwell⁶⁰, D.V. Perepelitsa²⁵, E. Perez Codina^{160a}, M.T. Pérez García-Estañ¹⁶⁸, V. Perez Reale³⁵, L. Perini^{90a,90b}, H. Pernegger³⁰, S. Perrella^{103a,103b}, R. Perrino^{72a}, R. Peschke⁴², V.D. Peshekhonov⁶⁴, K. Peters³⁰, R.F.Y. Peters⁸³, B.A. Petersen³⁰, T.C. Petersen³⁶, E. Petit⁴², A. Petridis^{147a,147b}, C. Petridou¹⁵⁵, E. Petrolo^{133a}, F. Petrucci^{135a,135b}, N.E. Pettersson¹⁵⁸, R. Pezoa^{32b}, P.W. Phillips¹³⁰, G. Piacquadio¹⁴⁴, E. Pianori¹⁷¹, A. Picazio⁴⁹, E. Piccaro⁷⁵, M. Piccinini^{20a,20b}, R. Piegaia²⁷, D.T. Pignotti¹¹⁰, J.E. Pilcher³¹, A.D. Pilkington⁷⁷, J. Pina^{125a,125b,125d}, M. Pinamonti^{165a,165c,ac}, A. Pinder¹¹⁹, J.L. Pinfold³, A. Pingel³⁶, B. Pinto^{125a}, S. Pires⁷⁹, M. Pitt¹⁷³, C. Pizio^{90a,90b}, L. Plazak^{145a}, M.-A. Pleier²⁵, V. Pleskot¹²⁸, E. Plotnikova⁶⁴, P. Plucinski^{147a,147b}, S. Poddar^{58a}, F. Podlyski³⁴, R. Poettgen⁸², L. Poggioli¹¹⁶, D. Pohl²¹, M. Pohl⁴⁹, G. Polesello^{120a}, A. Policicchio^{37a,37b}, R. Polifka¹⁵⁹, A. Polini^{20a}, C.S. Pollard⁴⁵, V. Polychronakos²⁵, K. Pommès³⁰, L. Pontecorvo^{133a}, B.G. Pope⁸⁹, G.A. Popeneciu^{26b}, D.S. Popovic^{13a}, A. Poppleton³⁰, X. Portell Bueso¹², S. Pospisil¹²⁷, K. Potamianos¹⁵, I.N. Potrap⁶⁴, C.J. Potter¹⁵⁰, C.T. Potter¹¹⁵, G. Poulard³⁰, J. Poveda⁶⁰, V. Pozdnyakov⁶⁴, P. Pralavorio⁸⁴, A. Pranko¹⁵, S. Prasad³⁰, R. Pravahan⁸, S. Prell⁶³, D. Price⁸³, J. Price⁷³, L.E. Price⁶, D. Prieur¹²⁴, M. Primavera^{72a}, M. Proissl⁴⁶, K. Prokofiev⁴⁷, F. Prokoshin^{32b}, E. Protopapadaki¹³⁷, S. Protopopescu²⁵, J. Proudfoot⁶, M. Przybycien^{38a}, H. Przysiezniak⁵, E. Ptacek¹¹⁵, D. Puddu^{135a,135b}, E. Pueschel⁸⁵, D. Puldon¹⁴⁹, M. Purohit^{25,ad}, P. Puzo¹¹⁶, J. Qian⁸⁸, G. Qin⁵³, Y. Qin⁸³, A. Quadt⁵⁴, D.R. Quarrie¹⁵, W.B. Quayle^{165a,165b}, M. Queitsch-Maitland⁸³, D. Quilty⁵³, A. Qureshi^{160b}, V. Radeka²⁵, V. Radescu⁴², S.K. Radhakrishnan¹⁴⁹, P. Radloff¹¹⁵, P. Rados⁸⁷, F. Ragusa^{90a,90b}, G. Rahal¹⁷⁹, S. Rajagopalan²⁵, M. Rammensee³⁰, A.S. Randle-Conde⁴⁰, C. Rangel-Smith¹⁶⁷, K. Rao¹⁶⁴, F. Rauscher⁹⁹, T.C. Rave⁴⁸, T. Ravenscroft⁵³, M. Raymond³⁰, A.L. Read¹¹⁸, N.P. Readoff⁷³,

D.M. Rebuffi ^{120a,120b}, A. Redelbach ¹⁷⁵, G. Redlinger ²⁵, R. Reece ¹³⁸, K. Reeves ⁴¹, L. Rehnisch ¹⁶,
 H. Reisin ²⁷, M. Relich ¹⁶⁴, C. Rembser ³⁰, H. Ren ^{33a}, Z.L. Ren ¹⁵², A. Renaud ¹¹⁶, M. Rescigno ^{133a},
 S. Resconi ^{90a}, O.L. Rezanova ^{108,c}, P. Reznicek ¹²⁸, R. Rezvani ⁹⁴, R. Richter ¹⁰⁰, M. Ridel ⁷⁹, P. Rieck ¹⁶,
 J. Rieger ⁵⁴, M. Rijssenbeek ¹⁴⁹, A. Rimoldi ^{120a,120b}, L. Rinaldi ^{20a}, E. Ritsch ⁶¹, I. Riu ¹², F. Rizatdinova ¹¹³,
 E. Rizvi ⁷⁵, S.H. Robertson ^{86,j}, A. Robichaud-Veronneau ⁸⁶, D. Robinson ²⁸, J.E.M. Robinson ⁸³,
 A. Robson ⁵³, C. Roda ^{123a,123b}, L. Rodrigues ³⁰, S. Roe ³⁰, O. Røhne ¹¹⁸, S. Rolli ¹⁶², A. Romaniouk ⁹⁷,
 M. Romano ^{20a,20b}, E. Romero Adam ¹⁶⁸, N. Rompotis ¹³⁹, M. Ronzani ⁴⁸, L. Roos ⁷⁹, E. Ros ¹⁶⁸,
 S. Rosati ^{133a}, K. Rosbach ⁴⁹, M. Rose ⁷⁶, P. Rose ¹³⁸, P.L. Rosendahl ¹⁴, O. Rosenthal ¹⁴², V. Rossetti ^{147a,147b},
 E. Rossi ^{103a,103b}, L.P. Rossi ^{50a}, R. Rosten ¹³⁹, M. Rotaru ^{26a}, I. Roth ¹⁷³, J. Rothberg ¹³⁹, D. Rousseau ¹¹⁶,
 C.R. Royon ¹³⁷, A. Rozanov ⁸⁴, Y. Rozen ¹⁵³, X. Ruan ^{146c}, F. Rubbo ¹², I. Rubinskiy ⁴², V.I. Rud ⁹⁸,
 C. Rudolph ⁴⁴, M.S. Rudolph ¹⁵⁹, F. Rühr ⁴⁸, A. Ruiz-Martinez ³⁰, Z. Rurikova ⁴⁸, N.A. Rusakovich ⁶⁴,
 A. Ruschke ⁹⁹, J.P. Rutherford ⁷, N. Ruthmann ⁴⁸, Y.F. Ryabov ¹²², M. Rybar ¹²⁸, G. Rybkin ¹¹⁶,
 N.C. Ryder ¹¹⁹, A.F. Saavedra ¹⁵¹, G. Sabato ¹⁰⁶, S. Sacerdoti ²⁷, A. Saddique ³, I. Sadeh ¹⁵⁴,
 H.F.-W. Sadrozinski ¹³⁸, R. Sadykov ⁶⁴, F. Safai Tehrani ^{133a}, H. Sakamoto ¹⁵⁶, Y. Sakurai ¹⁷²,
 G. Salamanna ^{135a,135b}, A. Salamon ^{134a}, M. Saleem ¹¹², D. Salek ¹⁰⁶, P.H. Sales De Bruin ¹³⁹,
 D. Salihagic ¹⁰⁰, A. Salnikov ¹⁴⁴, J. Salt ¹⁶⁸, D. Salvatore ^{37a,37b}, F. Salvatore ¹⁵⁰, A. Salvucci ¹⁰⁵,
 A. Salzburger ³⁰, D. Sampsonidis ¹⁵⁵, A. Sanchez ^{103a,103b}, J. Sánchez ¹⁶⁸, V. Sanchez Martinez ¹⁶⁸,
 H. Sandaker ¹⁴, R.L. Sandbach ⁷⁵, H.G. Sander ⁸², M.P. Sanders ⁹⁹, M. Sandhoff ¹⁷⁶, T. Sandoval ²⁸,
 C. Sandoval ¹⁶³, R. Sandstroem ¹⁰⁰, D.P.C. Sankey ¹³⁰, A. Sansoni ⁴⁷, C. Santoni ³⁴, R. Santonico ^{134a,134b},
 H. Santos ^{125a}, I. Santoyo Castillo ¹⁵⁰, K. Sapp ¹²⁴, A. Sapronov ⁶⁴, J.G. Saraiva ^{125a,125d}, B. Sarrazin ²¹,
 G. Sartisohn ¹⁷⁶, O. Sasaki ⁶⁵, Y. Sasaki ¹⁵⁶, G. Sauvage ^{5,*}, E. Sauvan ⁵, P. Savard ^{159,e}, D.O. Savu ³⁰,
 C. Sawyer ¹¹⁹, L. Sawyer ^{78,n}, D.H. Saxon ⁵³, J. Saxon ¹²¹, C. Sbarra ^{20a}, A. Sbrizzi ^{20a,20b}, T. Scanlon ⁷⁷,
 D.A. Scannicchio ¹⁶⁴, M. Scarcella ¹⁵¹, V. Scarfone ^{37a,37b}, J. Schaarschmidt ¹⁷³, P. Schacht ¹⁰⁰,
 D. Schaefer ³⁰, R. Schaefer ⁴², S. Schaepe ²¹, S. Schaetzel ^{58b}, U. Schäfer ⁸², A.C. Schaffer ¹¹⁶, D. Schaile ⁹⁹,
 R.D. Schamberger ¹⁴⁹, V. Scharf ^{58a}, V.A. Schegelsky ¹²², D. Scheirich ¹²⁸, M. Schernau ¹⁶⁴, M.I. Scherzer ³⁵,
 C. Schiavi ^{50a,50b}, J. Schieck ⁹⁹, C. Schillo ⁴⁸, M. Schioppa ^{37a,37b}, S. Schlenker ³⁰, E. Schmidt ⁴⁸,
 K. Schmieden ³⁰, C. Schmitt ⁸², S. Schmitt ^{58b}, B. Schneider ¹⁷, Y.J. Schnellbach ⁷³, U. Schnoor ⁴⁴,
 L. Schoeffel ¹³⁷, A. Schoening ^{58b}, B.D. Schoenrock ⁸⁹, A.L.S. Schorlemmer ⁵⁴, M. Schott ⁸², D. Schouten ^{160a},
 J. Schovancova ²⁵, S. Schramm ¹⁵⁹, M. Schreyer ¹⁷⁵, C. Schroeder ⁸², N. Schuh ⁸², M.J. Schultens ²¹,
 H.-C. Schultz-Coulon ^{58a}, H. Schulz ¹⁶, M. Schumacher ⁴⁸, B.A. Schumm ¹³⁸, Ph. Schune ¹³⁷,
 C. Schwanenberger ⁸³, A. Schwartzman ¹⁴⁴, T.A. Schwarz ⁸⁸, Ph. Schwegler ¹⁰⁰, Ph. Schwemling ¹³⁷,
 R. Schwienhorst ⁸⁹, J. Schwindling ¹³⁷, T. Schwindt ²¹, M. Schwoerer ⁵, F.G. Sciacca ¹⁷, E. Scifo ¹¹⁶,
 G. Sciolla ²³, W.G. Scott ¹³⁰, F. Scuri ^{123a,123b}, F. Scutti ²¹, J. Searcy ⁸⁸, G. Sedov ⁴², E. Sedykh ¹²²,
 S.C. Seidel ¹⁰⁴, A. Seiden ¹³⁸, F. Seifert ¹²⁷, J.M. Seixas ^{24a}, G. Sekhniaidze ^{103a}, S.J. Sekula ⁴⁰, K.E. Selbach ⁴⁶,
 D.M. Seliverstov ^{122,*}, G. Sellers ⁷³, N. Semprini-Cesari ^{20a,20b}, C. Serfon ³⁰, L. Serin ¹¹⁶, L. Serkin ⁵⁴,
 T. Serre ⁸⁴, R. Seuster ^{160a}, H. Severini ¹¹², T. Sfiligoj ⁷⁴, F. Sforza ¹⁰⁰, A. Sfyrla ³⁰, E. Shabalina ⁵⁴,
 M. Shamim ¹¹⁵, L.Y. Shan ^{33a}, R. Shang ¹⁶⁶, J.T. Shank ²², M. Shapiro ¹⁵, P.B. Shatalov ⁹⁶, K. Shaw ^{165a,165b},
 C.Y. Shehu ¹⁵⁰, P. Sherwood ⁷⁷, L. Shi ^{152,ae}, S. Shimizu ⁶⁶, C.O. Shimmin ¹⁶⁴, M. Shimojima ¹⁰¹,
 M. Shiyakova ⁶⁴, A. Shmeleva ⁹⁵, M.J. Shochet ³¹, D. Short ¹¹⁹, S. Shrestha ⁶³, E. Shulga ⁹⁷, M.A. Shupe ⁷,
 S. Shushkevich ⁴², P. Sicho ¹²⁶, O. Sidiropoulou ¹⁵⁵, D. Sidorov ¹¹³, A. Sidoti ^{133a}, F. Siegert ⁴⁴, Dj. Sijacki ^{13a},
 J. Silva ^{125a,125d}, Y. Silver ¹⁵⁴, D. Silverstein ¹⁴⁴, S.B. Silverstein ^{147a}, V. Simak ¹²⁷, O. Simard ⁵, Lj. Simic ^{13a},
 S. Simion ¹¹⁶, E. Simioni ⁸², B. Simmons ⁷⁷, R. Simoniello ^{90a,90b}, M. Simonyan ³⁶, P. Sinervo ¹⁵⁹,
 N.B. Sinev ¹¹⁵, V. Sipica ¹⁴², G. Siragusa ¹⁷⁵, A. Sircar ⁷⁸, A.N. Sisakyan ^{64,*}, S.Yu. Sivoklokov ⁹⁸,
 J. Sjölin ^{147a,147b}, T.B. Sjursen ¹⁴, H.P. Skottowe ⁵⁷, K.Yu. Skovpen ¹⁰⁸, P. Skubic ¹¹², M. Slater ¹⁸,
 T. Slavicek ¹²⁷, K. Sliwa ¹⁶², V. Smakhtin ¹⁷³, B.H. Smart ⁴⁶, L. Smestad ¹⁴, S.Yu. Smirnov ⁹⁷, Y. Smirnov ⁹⁷,
 L.N. Smirnova ^{98,af}, O. Smirnova ⁸⁰, K.M. Smith ⁵³, M. Smizanska ⁷¹, K. Smolek ¹²⁷, A.A. Snesev ⁹⁵,
 G. Snidero ⁷⁵, S. Snyder ²⁵, R. Sobie ^{170,j}, F. Socher ⁴⁴, A. Soffer ¹⁵⁴, D.A. Soh ^{152,ae}, C.A. Solans ³⁰,
 M. Solar ¹²⁷, J. Solc ¹²⁷, E.Yu. Soldatov ⁹⁷, U. Soldevila ¹⁶⁸, A.A. Solodkov ¹²⁹, A. Soloshenko ⁶⁴,
 O.V. Solovyanov ¹²⁹, V. Solovyev ¹²², P. Sommer ⁴⁸, H.Y. Song ^{33b}, N. Soni ¹, A. Sood ¹⁵, A. Sopczak ¹²⁷,
 B. Sopko ¹²⁷, V. Sopko ¹²⁷, V. Sorin ¹², M. Sosebee ⁸, R. Soualah ^{165a,165c}, P. Soueid ⁹⁴, A.M. Soukharev ^{108,c},
 D. South ⁴², S. Spagnolo ^{72a,72b}, F. Spanò ⁷⁶, W.R. Spearman ⁵⁷, F. Spettel ¹⁰⁰, R. Spighi ^{20a}, G. Spigo ³⁰,
 L.A. Spiller ⁸⁷, M. Spousta ¹²⁸, T. Spreitzer ¹⁵⁹, B. Spurlock ⁸, R.D. St. Denis ^{53,*}, S. Staerz ⁴⁴, J. Stahlman ¹²¹,

R. Stamen^{58a}, S. Stamm¹⁶, E. Stanecka³⁹, R.W. Stanek⁶, C. Stanescu^{135a}, M. Stanescu-Bellu⁴², M.M. Stanitzki⁴², S. Stapnes¹¹⁸, E.A. Starchenko¹²⁹, J. Stark⁵⁵, P. Staroba¹²⁶, P. Starovoitov⁴², R. Staszewski³⁹, P. Stavina^{145a,*}, P. Steinberg²⁵, B. Stelzer¹⁴³, H.J. Stelzer³⁰, O. Stelzer-Chilton^{160a}, H. Stenzel⁵², S. Stern¹⁰⁰, G.A. Stewart⁵³, J.A. Stillings²¹, M.C. Stockton⁸⁶, M. Stoebe⁸⁶, G. Stoicea^{26a}, P. Stolte⁵⁴, S. Stonjek¹⁰⁰, A.R. Stradling⁸, A. Straessner⁴⁴, M.E. Stramaglia¹⁷, J. Strandberg¹⁴⁸, S. Strandberg^{147a,147b}, A. Strandlie¹¹⁸, E. Strauss¹⁴⁴, M. Strauss¹¹², P. Strizenc^{145b}, R. Ströhmer¹⁷⁵, D.M. Strom¹¹⁵, R. Stroynowski⁴⁰, A. Strubig¹⁰⁵, S.A. Stucci¹⁷, B. Stugu¹⁴, N.A. Styles⁴², D. Su¹⁴⁴, J. Su¹²⁴, R. Subramaniam⁷⁸, A. Succurro¹², Y. Sugaya¹¹⁷, C. Suhr¹⁰⁷, M. Suk¹²⁷, V.V. Sulin⁹⁵, S. Sultansoy^{4c}, T. Sumida⁶⁷, S. Sun⁵⁷, X. Sun^{33a}, J.E. Sundermann⁴⁸, K. Suruliz¹⁵⁰, G. Susinno^{37a,37b}, M.R. Sutton¹⁵⁰, Y. Suzuki⁶⁵, M. Svatos¹²⁶, S. Swedish¹⁶⁹, M. Swiatlowski¹⁴⁴, I. Sykora^{145a}, T. Sykora¹²⁸, D. Ta⁸⁹, C. Taccini^{135a,135b}, K. Tackmann⁴², J. Taenzer¹⁵⁹, A. Taffard¹⁶⁴, R. Tafirout^{160a}, N. Taiblum¹⁵⁴, H. Takai²⁵, R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹⁴¹, Y. Takubo⁶⁵, M. Talby⁸⁴, A.A. Talyshev^{108,c}, J.Y.C. Tam¹⁷⁵, K.G. Tan⁸⁷, J. Tanaka¹⁵⁶, R. Tanaka¹¹⁶, S. Tanaka¹³², S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴³, B.B. Tannenwald¹¹⁰, N. Tannoury²¹, S. Tapprogge⁸², S. Tarem¹⁵³, F. Tarrade²⁹, G.F. Tartarelli^{90a}, P. Tas¹²⁸, M. Tasevsky¹²⁶, T. Tashiro⁶⁷, E. Tassi^{37a,37b}, A. Tavares Delgado^{125a,125b}, Y. Tayalati^{136d}, F.E. Taylor⁹³, G.N. Taylor⁸⁷, W. Taylor^{160b}, F.A. Teischinger³⁰, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate³⁰, P.K. Teng¹⁵², J.J. Teoh¹¹⁷, S. Terada⁶⁵, K. Terashi¹⁵⁶, J. Terron⁸¹, S. Terzo¹⁰⁰, M. Testa⁴⁷, R.J. Teuscher^{159,j}, J. Therhaag²¹, T. Theveneaux-Pelzer³⁴, J.P. Thomas¹⁸, J. Thomas-Wilsker⁷⁶, E.N. Thompson³⁵, P.D. Thompson¹⁸, P.D. Thompson¹⁵⁹, R.J. Thompson⁸³, A.S. Thompson⁵³, L.A. Thomsen³⁶, E. Thomson¹²¹, M. Thomson²⁸, W.M. Thong⁸⁷, R.P. Thun^{88,*}, F. Tian³⁵, M.J. Tibbetts¹⁵, V.O. Tikhomirov^{95,ag}, Yu.A. Tikhonov^{108,c}, S. Timoshenko⁹⁷, E. Tiouchichine⁸⁴, P. Tipton¹⁷⁷, S. Tisserant⁸⁴, T. Todorov⁵, S. Todorova-Nova¹²⁸, B. Toggerson⁷, J. Tojo⁶⁹, S. Tokár^{145a}, K. Tokushuku⁶⁵, K. Tollefson⁸⁹, E. Tolley⁵⁷, L. Tomlinson⁸³, M. Tomoto¹⁰², L. Tompkins³¹, K. Toms¹⁰⁴, N.D. Topilin⁶⁴, E. Torrence¹¹⁵, H. Torres¹⁴³, E. Torró Pastor¹⁶⁸, J. Toth^{84,ah}, F. Touchard⁸⁴, D.R. Tovey¹⁴⁰, H.L. Tran¹¹⁶, T. Trefzger¹⁷⁵, L. Tremblet³⁰, A. Tricoli³⁰, I.M. Trigger^{160a}, S. Trincaz-Duvoid⁷⁹, M.F. Tripiana¹², W. Trischuk¹⁵⁹, B. Trocme⁵⁵, C. Troncon^{90a}, M. Trottier-McDonald¹⁵, M. Trovatelli^{135a,135b}, P. True⁸⁹, M. Trzebinski³⁹, A. Trzupek³⁹, C. Tsarouchas³⁰, J.C.-L. Tseng¹¹⁹, P.V. Tsiarehka⁹¹, D. Tsiou¹³⁷, G. Tsipolitis¹⁰, N. Tsirintanis⁹, S. Tsiskaridze¹², V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁶, V. Tsulaia¹⁵, S. Tsuno⁶⁵, D. Tsybychev¹⁴⁹, A. Tudorache^{26a}, V. Tudorache^{26a}, A.N. Tuna¹²¹, S.A. Tuppusti^{20a,20b}, S. Turchikhin^{98,af}, D. Turecek¹²⁷, I. Turk Cakir^{4d}, R. Turra^{90a,90b}, P.M. Tuts³⁵, A. Tykhonov⁴⁹, M. Tylmad^{147a,147b}, M. Tyndel¹³⁰, K. Uchida²¹, I. Ueda¹⁵⁶, R. Ueno²⁹, M. Ughetto⁸⁴, M. Uglund¹⁴, M. Uhlenbrock²¹, F. Ukegawa¹⁶¹, G. Unal³⁰, A. Undrus²⁵, G. Unel¹⁶⁴, F.C. Ungaro⁴⁸, Y. Unno⁶⁵, C. Unverdorben⁹⁹, D. Urbaniec³⁵, P. Urquijo⁸⁷, G. Usai⁸, A. Usanova⁶¹, L. Vacavant⁸⁴, V. Vacek¹²⁷, B. Vachon⁸⁶, N. Valencic¹⁰⁶, S. Valentinetti^{20a,20b}, A. Valero¹⁶⁸, L. Valery³⁴, S. Valkar¹²⁸, E. Valladolid Gallego¹⁶⁸, S. Vallecorsa⁴⁹, J.A. Valls Ferrer¹⁶⁸, W. Van Den Wollenberg¹⁰⁶, P.C. Van Der Deijl¹⁰⁶, R. van der Geer¹⁰⁶, H. van der Graaf¹⁰⁶, R. Van Der Leeuw¹⁰⁶, D. van der Ster³⁰, N. van Eldik³⁰, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴³, I. van Vulpen¹⁰⁶, M.C. van Woerden³⁰, M. Vanadia^{133a,133b}, W. Vandelli³⁰, R. Vanguri¹²¹, A. Vaniachine⁶, P. Vankov⁴², F. Vannucci⁷⁹, G. Vardanyan¹⁷⁸, R. Vari^{133a}, E.W. Varnes⁷, T. Varol⁸⁵, D. Varouchas⁷⁹, A. Vartapetian⁸, K.E. Varvell¹⁵¹, F. Vazeille³⁴, T. Vazquez Schroeder⁵⁴, J. Veatch⁷, F. Veloso^{125a,125c}, T. Velz²¹, S. Veneziano^{133a}, A. Ventura^{72a,72b}, D. Ventura⁸⁵, M. Venturi¹⁷⁰, N. Venturi¹⁵⁹, A. Venturini²³, V. Vercesi^{120a}, M. Verducci^{133a,133b}, W. Verkerke¹⁰⁶, J.C. Vermeulen¹⁰⁶, A. Vest⁴⁴, M.C. Vetterli^{143,e}, O. Viazlo⁸⁰, I. Vichou¹⁶⁶, T. Vickey^{146c,ai}, O.E. Vickey Boeriu^{146c}, G.H.A. Viehhauser¹¹⁹, S. Viel¹⁶⁹, R. Vigne³⁰, M. Villa^{20a,20b}, M. Villaplana Perez^{90a,90b}, E. Vilucchi⁴⁷, M.G. Vincker²⁹, V.B. Vinogradov⁶⁴, J. Virzi¹⁵, I. Vivarelli¹⁵⁰, F. Vives Vaque³, S. Vlachos¹⁰, D. Vladoiu⁹⁹, M. Vlasak¹²⁷, A. Vogel²¹, M. Vogel^{32a}, P. Vokac¹²⁷, G. Volpi^{123a,123b}, M. Volpi⁸⁷, H. von der Schmitt¹⁰⁰, H. von Radziewski⁴⁸, E. von Toerne²¹, V. Vorobel¹²⁸, K. Vorobev⁹⁷, M. Vos¹⁶⁸, R. Voss³⁰, J.H. Vosseveld⁷³, N. Vranjes¹³⁷, M. Vranjes Milosavljevic^{13a}, V. Vrba¹²⁶, M. Vreeswijk¹⁰⁶, T. Vu Anh⁴⁸, R. Vuillermet³⁰, I. Vukotic³¹, Z. Vykydal¹²⁷, P. Wagner²¹, W. Wagner¹⁷⁶, H. Wahlberg⁷⁰, S. Wahrmund⁴⁴, J. Wakabayashi¹⁰², J. Walder⁷¹, R. Walker⁹⁹, W. Walkowiak¹⁴², R. Wall¹⁷⁷, P. Waller⁷³, B. Walsh¹⁷⁷, C. Wang^{152,aj}, C. Wang⁴⁵, F. Wang¹⁷⁴, H. Wang¹⁵, H. Wang⁴⁰, J. Wang⁴², J. Wang^{33a}, K. Wang⁸⁶, R. Wang¹⁰⁴, S.M. Wang¹⁵², T. Wang²¹, X. Wang¹⁷⁷, C. Wanotayaroj¹¹⁵, A. Warburton⁸⁶,

C.P. Ward²⁸, D.R. Wardrope⁷⁷, M. Warsinsky⁴⁸, A. Washbrook⁴⁶, C. Wasicki⁴², P.M. Watkins¹⁸, A.T. Watson¹⁸, I.J. Watson¹⁵¹, M.F. Watson¹⁸, G. Watts¹³⁹, S. Watts⁸³, B.M. Waugh⁷⁷, S. Webb⁸³, M.S. Weber¹⁷, S.W. Weber¹⁷⁵, J.S. Webster³¹, A.R. Weidberg¹¹⁹, P. Weigell¹⁰⁰, B. Weinert⁶⁰, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Weits¹⁰⁶, P.S. Wells³⁰, T. Wenaus²⁵, D. Wendland¹⁶, Z. Weng^{152,ae}, T. Wengler³⁰, S. Wenig³⁰, N. Wermes²¹, M. Werner⁴⁸, P. Werner³⁰, M. Wessels^{58a}, J. Wetter¹⁶², K. Whalen²⁹, A. White⁸, M.J. White¹, R. White^{32b}, S. White^{123a,123b}, D. Whiteson¹⁶⁴, D. Wicke¹⁷⁶, F.J. Wickens¹³⁰, W. Wiedenmann¹⁷⁴, M. Wielers¹³⁰, P. Wienemann²¹, C. Wiglesworth³⁶, L.A.M. Wiik-Fuchs²¹, P.A. Wijeratne⁷⁷, A. Wildauer¹⁰⁰, M.A. Wildt^{42,ak}, H.G. Wilkens³⁰, J.Z. Will⁹⁹, H.H. Williams¹²¹, S. Williams²⁸, C. Willis⁸⁹, S. Willocq⁸⁵, A. Wilson⁸⁸, J.A. Wilson¹⁸, I. Wingerter-Seez⁵, F. Winklmeier¹¹⁵, B.T. Winter²¹, M. Wittgen¹⁴⁴, T. Wittig⁴³, J. Wittkowski⁹⁹, S.J. Wollstadt⁸², M.W. Wolter³⁹, H. Wolters^{125a,125c}, B.K. Wosiek³⁹, J. Wotschack³⁰, M.J. Woudstra⁸³, K.W. Wozniak³⁹, M. Wright⁵³, M. Wu⁵⁵, S.L. Wu¹⁷⁴, X. Wu⁴⁹, Y. Wu⁸⁸, E. Wulf³⁵, T.R. Wyatt⁸³, B.M. Wynne⁴⁶, S. Xella³⁶, M. Xiao¹³⁷, D. Xu^{33a}, L. Xu^{33b,al}, B. Yabsley¹⁵¹, S. Yacoub^{146b,am}, R. Yakabe⁶⁶, M. Yamada⁶⁵, H. Yamaguchi¹⁵⁶, Y. Yamaguchi¹¹⁷, A. Yamamoto⁶⁵, K. Yamamoto⁶³, S. Yamamoto¹⁵⁶, T. Yamamura¹⁵⁶, T. Yamanaka¹⁵⁶, K. Yamauchi¹⁰², Y. Yamazaki⁶⁶, Z. Yan²², H. Yang^{33e}, H. Yang¹⁷⁴, U.K. Yang⁸³, Y. Yang¹¹⁰, S. Yanush⁹², L. Yao^{33a}, W.-M. Yao¹⁵, Y. Yasu⁶⁵, E. Yatsenko⁴², K.H. Yau Wong²¹, J. Ye⁴⁰, S. Ye²⁵, I. Yeletsikh⁶⁴, A.L. Yen⁵⁷, E. Yildirim⁴², M. Yilmaz^{4b}, R. Yoosoofmiya¹²⁴, K. Yorita¹⁷², R. Yoshida⁶, K. Yoshihara¹⁵⁶, C. Young¹⁴⁴, C.J.S. Young³⁰, S. Youssef²², D.R. Yu¹⁵, J. Yu⁸, J.M. Yu⁸⁸, J. Yu¹¹³, L. Yuan⁶⁶, A. Yurkewicz¹⁰⁷, I. Yusuff^{28,an}, B. Zabinski³⁹, R. Zaidan⁶², A.M. Zaitsev^{129,aa}, A. Zaman¹⁴⁹, S. Zambito²³, L. Zanello^{133a,133b}, D. Zanzi⁸⁷, C. Zeitnitz¹⁷⁶, M. Zeman¹²⁷, A. Zemla^{38a}, K. Zengel²³, O. Zenin¹²⁹, T. Ženiš^{145a}, D. Zerwas¹¹⁶, G. Zevi della Porta⁵⁷, D. Zhang⁸⁸, F. Zhang¹⁷⁴, H. Zhang⁸⁹, J. Zhang⁶, L. Zhang¹⁵², X. Zhang^{33d}, Z. Zhang¹¹⁶, Z. Zhao^{33b}, A. Zhemchugov⁶⁴, J. Zhong¹¹⁹, B. Zhou⁸⁸, L. Zhou³⁵, N. Zhou¹⁶⁴, C.G. Zhu^{33d}, H. Zhu^{33a}, J. Zhu⁸⁸, Y. Zhu^{33b}, X. Zhuang^{33a}, K. Zhukov⁹⁵, A. Zibell¹⁷⁵, D. Zieminska⁶⁰, N.I. Zimine⁶⁴, C. Zimmermann⁸², R. Zimmermann²¹, S. Zimmermann²¹, S. Zimmermann⁴⁸, Z. Zinonos⁵⁴, M. Ziolkowski¹⁴², G. Zoernig¹⁷⁴, A. Zoccoli^{20a,20b}, M. zur Nedden¹⁶, G. Zurzolo^{103a,103b}, V. Zutshi¹⁰⁷, L. Zwalinski³⁰

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

² Physics Department, SUNY Albany, Albany, NY, United States

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

⁴ (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Gazi University, Ankara; (c) Division of Physics, TOBB University of Economics and Technology, Ankara;

(d) Turkish Atomic Energy Authority, Ankara, Turkey

⁵ LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States

⁷ Department of Physics, University of Arizona, Tucson, AZ, United States

⁸ Department of Physics, The University of Texas at Arlington, Arlington, TX, United States

⁹ Physics Department, University of Athens, Athens, Greece

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

¹¹ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹² Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

¹³ (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

¹⁴ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁵ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States

¹⁶ Department of Physics, Humboldt University, Berlin, Germany

¹⁷ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁸ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

¹⁹ (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

²⁰ (a) INFN, Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

²¹ Physikalisches Institut, University of Bonn, Bonn, Germany

²² Department of Physics, Boston University, Boston, MA, United States

²³ Department of Physics, Brandeis University, Waltham, MA, United States

²⁴ (a) Universidade Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, 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

²⁵ Physics Department, Brookhaven National Laboratory, Upton, NY, United States

²⁶ (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania

²⁷ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

²⁸ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

²⁹ Department of Physics, Carleton University, Ottawa, ON, Canada

³⁰ CERN, Geneva, Switzerland

³¹ Enrico Fermi Institute, University of Chicago, Chicago, IL, United States

³² (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

³³ (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; (e) Physics Department, Shanghai Jiao Tong University, Shanghai, China

³⁴ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

- ³⁵ Nevis Laboratory, Columbia University, Irvington, NY, United States
- ³⁶ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ³⁷ ^(a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; ^(b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ³⁸ ^(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; ^(b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- ³⁹ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ⁴⁰ Physics Department, Southern Methodist University, Dallas, TX, United States
- ⁴¹ Physics Department, University of Texas at Dallas, Richardson, TX, United States
- ⁴² DESY, Hamburg and Zeuthen, Germany
- ⁴³ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁴ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁴⁵ Department of Physics, Duke University, Durham, NC, United States
- ⁴⁶ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, 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, Iv. Javakishvili 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 Grenoble-Alpes, CNRS/IN2P3, 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 Louisiana Tech University, Ruston, LA, United States
- ⁷⁹ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁸⁰ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸¹ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸² Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸³ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸⁴ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁵ Department of Physics, University of Massachusetts, Amherst, MA, United States
- ⁸⁶ Department of Physics, McGill University, Montreal, QC, Canada
- ⁸⁷ School of Physics, University of Melbourne, Victoria, Australia
- ⁸⁸ Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- ⁸⁹ Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- ⁹⁰ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹¹ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- ⁹² National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- ⁹³ Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
- ⁹⁴ Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- ⁹⁵ P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- ⁹⁶ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁷ National Research Nuclear University MEPhI, Moscow, Russia
- ⁹⁸ D.V. Skobel'syn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- ⁹⁹ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁰⁰ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰¹ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰² Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰³ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ¹⁰⁴ Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- ¹⁰⁵ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁶ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁷ Department of Physics, Northern Illinois University, DeKalb, IL, United States
- ¹⁰⁸ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹⁰⁹ Department of Physics, New York University, New York, NY, United States
- ¹¹⁰ Ohio State University, Columbus, OH, United States
- ¹¹¹ Faculty of Science, Okayama University, Okayama, Japan

- 112 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
 113 Department of Physics, Oklahoma State University, Stillwater, OK, United States
 114 Palacký University, RCPTM, Olomouc, Czech Republic
 115 Center for High Energy Physics, University of Oregon, Eugene, OR, United States
 116 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
 117 Graduate School of Science, Osaka University, Osaka, Japan
 118 Department of Physics, University of Oslo, Oslo, Norway
 119 Department of Physics, Oxford University, Oxford, United Kingdom
 120 ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
 121 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
 122 Petersburg Nuclear Physics Institute, Gatchina, Russia
 123 ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
 124 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
 125 ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; ^(b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Department of Physics, University of Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); ^(g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
 126 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
 127 Czech Technical University in Prague, Praha, Czech Republic
 128 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
 129 State Research Center Institute for High Energy Physics, Protvino, Russia
 130 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
 131 Physics Department, University of Regina, Regina, SK, Canada
 132 Ritsumeikan University, Kusatsu, Shiga, Japan
 133 ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
 134 ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
 135 ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
 136 ^(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
 137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
 138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
 139 Department of Physics, University of Washington, Seattle, WA, United States
 140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
 141 Department of Physics, Shinshu University, Nagano, Japan
 142 Fachbereich Physik, Universität Siegen, Siegen, Germany
 143 Department of Physics, Simon Fraser University, Burnaby, BC, Canada
 144 SLAC National Accelerator Laboratory, Stanford, CA, United States
 145 ^(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
 146 ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
 147 ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
 148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
 149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
 150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
 151 School of Physics, University of Sydney, Sydney, Australia
 152 Institute of Physics, Academia Sinica, Taipei, Taiwan
 153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
 154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
 155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
 156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
 157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
 158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
 159 Department of Physics, University of Toronto, Toronto, ON, Canada
 160 ^(a) TRIUMF, Vancouver, BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
 161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
 162 Department of Physics and Astronomy, Tufts University, Medford, MA, United States
 163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
 164 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
 165 ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
 166 Department of Physics, University of Illinois, Urbana, IL, United States
 167 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
 168 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
 169 Department of Physics, University of British Columbia, Vancouver, BC, Canada
 170 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
 171 Department of Physics, University of Warwick, Coventry, United Kingdom
 172 Waseda University, Tokyo, Japan
 173 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
 174 Department of Physics, University of Wisconsin, Madison, WI, United States
 175 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
 176 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
 177 Department of Physics, Yale University, New Haven, CT, United States
 178 Yerevan Physics Institute, Yerevan, Armenia
 179 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

^a Also at Department of Physics, King’s College London, London, United Kingdom.

^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

- ^c Also at Novosibirsk State University, Novosibirsk, Russia.
- ^d Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ^e Also at TRIUMF, Vancouver, BC, Canada.
- ^f Also at Department of Physics, California State University, Fresno, CA, United States.
- ^g Also at Tomsk State University, Tomsk, Russia.
- ^h Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
- ⁱ Also at Università di Napoli Parthenope, Napoli, Italy.
- ^j Also at Institute of Particle Physics (IPP), Canada.
- ^k Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ^l Also at Chinese University of Hong Kong, China.
- ^m Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
- ⁿ Also at Louisiana Tech University, Ruston, LA, United States.
- ^o Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
- ^p Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.
- ^q Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
- ^r Also at CERN, Geneva, Switzerland.
- ^s Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
- ^t Also at Manhattan College, New York, NY, United States.
- ^u Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^v Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
- ^w Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^x Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
- ^y Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.
- ^z Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.
- ^{aa} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- ^{ab} Also at Section de Physique, Université de Genève, Geneva, Switzerland.
- ^{ac} Also at International School for Advanced Studies (SISSA), Trieste, Italy.
- ^{ad} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
- ^{ae} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
- ^{af} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
- ^{ag} Also at National Research Nuclear University MEPhI, Moscow, Russia.
- ^{ah} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- ^{ai} Also at Department of Physics, Oxford University, Oxford, United Kingdom.
- ^{aj} Also at Department of Physics, Nanjing University, Jiangsu, China.
- ^{ak} Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
- ^{al} Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
- ^{am} Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
- ^{an} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
- * Deceased.