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Aaboud, M.; Newman, Paul; ATLAS Collaboration

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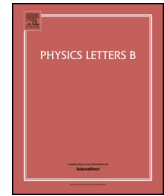
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Search for light resonances decaying to boosted quark pairs and produced in association with a photon or a jet in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration^{*}

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ABSTRACT

This Letter presents a search for new light resonances decaying to pairs of quarks and produced in association with a high- p_T photon or jet. The dataset consists of proton–proton collisions with an integrated luminosity of 36.1 fb^{-1} at a centre-of-mass energy of $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. Resonance candidates are identified as massive large-radius jets with substructure consistent with a particle decaying into a quark pair. The mass spectrum of the candidates is examined for local excesses above background. No evidence of a new resonance is observed in the data, which are used to exclude the production of a lepto-phobic axial-vector Z' boson.

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1. Introduction

Searches for resonance signals in the invariant mass spectrum of hadrons are an essential part of the physics programme at the energy frontier. Many theoretical models predict resonances [1–3] with significant couplings to quarks and gluons, including resonances which also couple to dark-matter particles [4–7]. At the Large Hadron Collider (LHC), the ability to discover or exclude such hadronic resonances has been extended into the TeV range, although no evidence of statistically significant excesses has been seen [8,9].

Sensitivity to light resonances is reduced by the immense background rates that would saturate the trigger and data acquisition systems. The recording of collision data typically requires placing thresholds of several hundred GeV on the transverse momentum (p_T^{min}) of the jet used to trigger the event, which translates to approximate thresholds on mass of $m \approx 2p_T^{\text{min}}$. Consequently, recent searches for dijet resonances at the LHC have poor sensitivity for masses well below 1 TeV. This limitation can be avoided by recording only a summary of the jet information needed for performing a resonance search in the dijet mass spectrum. This strategy is called “data scouting” in CMS [10], “real-time analysis” in LHCb [11] and “trigger-object-level analysis” in ATLAS [12], and has set limits for resonance masses in the range 500–800 GeV [10].

In this Letter, a search using an alternative approach [4,13] is performed, in order to cover even lower resonance masses. The trigger threshold limitations are reduced by examining data where

the light resonance is boosted in the transverse direction¹ via recoil from high transverse momentum (p_T) initial-state radiation (ISR) of a photon or jet. Requiring a hard ISR object in the final state comes at the cost of reduced signal production rates, but allows highly efficient triggering at masses much lower than when triggering directly on the resonance decay products.

The search is performed for resonance masses from 100 GeV to 220 GeV, a range in which the resonance is boosted and its decay products are collimated, such that the resonance mass can be calculated from the mass of a large-radius jet. The dominant background processes are multijet production in the jet channel and photons produced in association with jets in the photon channel, both characterised by non-resonant jets initiated predominantly by single gluons or light-flavour quarks. The Z' signal models considered decay to quark–antiquark pairs. This difference in the dominant jet production mechanism between the signal and the leading backgrounds means that, in the boosted regime considered in this Letter, the use of jet substructure methods strongly suppresses the background, making it a crucial component for the search sensitivity. In addition, current datasets are the largest collected, allowing the sensitivity to rare processes to be extended beyond that of earlier studies.

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

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

Recently, CMS reported results of applying a similar technique [14,15] to exclude a light Z' boson with Standard Model (SM) coupling values (g_q) exceeding 0.1 to 0.25 in the mass range 50–300 GeV. With respect to those results, this Letter also exploits the channel with the ISR photon.

2. ATLAS detector

The ATLAS experiment [16] at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry with layers of tracking, calorimeter, and muon detectors over nearly the entire solid angle around the proton-proton (pp) collision point. The inner detector (ID) consists of a high-granularity silicon pixel detector, including an insertable B-layer [17], and a silicon microstrip tracker, together providing precision tracking in the pseudorapidity range $|\eta| < 2.5$. Complementary, a transition radiation tracker provides tracking and electron identification information for $|\eta| < 2.0$. The ID is surrounded by a 2 T superconducting solenoid. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity, covering the region $|\eta| < 3.2$. A hadron (steel/scintillator-tile) calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with copper/LAr calorimeters ($1.7 < |\eta| < 3.2$) and LAr calorimeters with copper and tungsten absorbers, providing EM and hadronic energy measurements covering the region $|\eta| \leq 4.9$. The muon spectrometer consists of precision tracking chambers covering the region $|\eta| \leq 2.7$. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to 100 kHz. This hardware trigger [18] is followed by a software-based trigger that reduces the rate of recorded events to 1 kHz.

3. Data and simulation samples

The data were collected in pp collisions at $\sqrt{s} = 13$ TeV during 2015 and 2016. Collision events are recorded with two triggers. The first selects events with at least one photon candidate that has an online transverse energy $E_T > 140$ GeV and passes the “loose” identification requirements based on the shower shapes in the EM and hadronic calorimeters [18]. The photon trigger reaches its maximum efficiency for $E_T > 155$ GeV. The second trigger selects events with at least one jet candidate with online $E_T > 380$ GeV formed from clusters of energy deposits in the calorimeters [19] by the anti- k_t algorithm [20,21] with radius parameter $R = 0.4$, implemented in the FastJet package [22]. The jet trigger reaches its maximum efficiency for $p_T > 420$ GeV. Only data satisfying beam, detector and data-quality criteria are considered [23]. The data used correspond to an integrated luminosity of 36.1 fb^{-1} .

Samples of simulated events are used to characterise the hypothetical resonances as well as to study the kinematic distributions of background processes. These samples are not used to estimate the background contributions, except when validating the data-driven background estimate (described in Section 5).

Background samples were simulated using the SHERPA 2.1.1 event generator [24]. Processes containing a photon with associated jets were generated in several bins of photon p_T . The matrix elements were calculated at leading order (LO) with up to three partons for photon $p_T < 70$ GeV or four partons for higher photon p_T . Multijet background samples were generated at LO in several bins of leading-jet p_T . Samples of W +jets, Z +jets, $W+\gamma$ and $Z+\gamma$ events with hadronic decays of the vector-bosons were simulated in bins of W/Z -boson p_T . Matrix elements were calculated at LO with up to four partons for the W/Z +jets samples and up

to three partons for $W/Z+\gamma$ samples. The cross sections were corrected at next-to-leading order (NLO) using K -factors derived from corresponding samples with leptonic vector-boson decays generated at NLO using SHERPA 2.1.1 [24], with matrix elements calculated for up to two partons at NLO and four partons at LO using Comix [25] and OpenLoops [26]. All the above LO background samples were merged with the SHERPA parton shower [27] using the ME+PS@LO prescription [28]. The CT10 set of parton distribution functions (PDFs) [29] were used in conjunction with the dedicated parton shower tuning developed by the SHERPA authors. For the NLO leptonic vector-boson samples utilised to calculate K -factors, the ME+PS@NLO prescription [28] and the CT10NLO PDF set are used.

As a benchmark signal, samples with a Z' resonance with only hadronic couplings were generated as in Refs. [30–32]. This Z' has axial-vector couplings to quarks. The coupling of the Z' to quarks, g_q , is set to be universal in quark flavour and equal to 0.5. The corresponding total width $\Gamma_{Z'}$ is negligible compared to the experimental resolution, which is about 10% of the boson mass. A set of samples was generated with $m_{Z'}$ between 100 and 220 GeV, in 30 GeV steps. A linear and parameterised interpolation was performed in 10 GeV steps in between the generated mass points. The samples were produced with $g_q = 0.5$, using the MADGRAPH_AMC@NLO generator [33] with the NNPDF2.3 LO PDF [34] and the A14 set of tuned parameters (tune) [35]. Parton showers were produced in PYTHIA 8.186 [36]. Interference of this benchmark model with the Standard Model Z boson is assumed to be negligible. For efficient population of the kinematic phase space, a photon (jet) with $p_T \geq 100$ GeV (350 GeV) was required in the generation phase.

The response of the detector to particles was modelled with a full ATLAS detector simulation [37] based on GEANT4 [38]. All simulated events were overlaid with additional pp interactions (pile-up) simulated with the soft strong-interaction processes of PYTHIA 8.186 [36] using the A2 tune [39] and the MSTW2008LO PDF set [40]. The simulated events were reconstructed in the same way as the data, and were reweighted such that the distribution of the expected number of pp interactions per bunch crossing matches that seen in data.

4. Event reconstruction and selection

Events are required to have a reconstructed primary vertex, defined as a vertex with at least two reconstructed tracks with $p_T > 400$ MeV each and with the largest sum of track p_T^2 .

Photons are reconstructed from clusters of energy deposits in the electromagnetic calorimeter. The photon energy scale is corrected using events with $Z \rightarrow e^+e^-$ decays in data [41]. Identification requirements are applied to reduce the contamination from π^0 or other neutral hadrons decaying into photons. The photon identification is based on the profile of the energy deposits in the first and second layers of the electromagnetic calorimeter. Photons used in the event selection must satisfy the “tight” identification and isolation criteria defined in Ref. [42], and must have $|\eta| < 2.37$, excluding the EM calorimeter’s barrel/end-cap transition region of $1.37 < |\eta| < 1.52$. The efficiency of the photon selection is roughly 95% for photons with $E_T > 150$ GeV.

Two non-exclusive categories of jet candidates are built from clusters of energy deposits in the calorimeters [19] and are distinguished by the radius parameter used in the anti- k_t algorithm. Jets with a radius parameter $R = 1.0$ are referred to as *large-R* jets, denoted by J and required to have $|\eta| < 2.0$, whereas jets with a radius parameter $R = 0.4$ are referred to as *narrow* jets, denoted as j and are required to have $|\eta| < 2.4$. To mitigate the effects of pile-up and soft radiation, the large- R jets are trimmed [43].

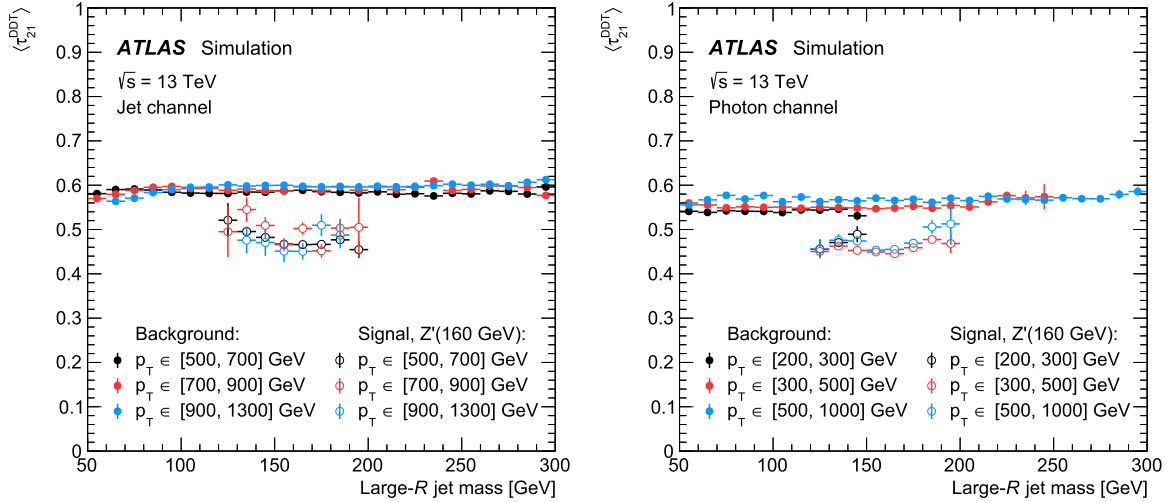


Fig. 1. Mean value of τ_{21}^{DDT} as a function of the large- R jet mass, for various ranges of large- R jet transverse momentum, for cases where the ISR object is a jet (left) and a photon (right).

Trimming takes the original constituents of the jet and reclusters them using the k_t algorithm [44] with a smaller radius parameter, R_{subject} , to produce a collection of subjects. These subjects are discarded if they carry less than a specific fraction (f_{cut}) of the original jet p_T . The trimming parameters optimised for this search are $R_{\text{subject}} = 0.2$ and $f_{\text{cut}} = 5\%$ [45]. Large- R jets are calibrated following the procedure described in Ref. [46].

The energies of selected narrow jets are corrected for contributions from pile-up interactions [47]. A correction used to calibrate jet energy measurements to the scale of the constituent particles of the jet [48] is then applied. Narrow jets with $25 \text{ GeV} < p_T < 60 \text{ GeV}$ are required to originate from the primary vertex as determined by a jet vertex tagger [47] that relies on tracks associated with the jets.

Quality requirements are applied to photon candidates to identify those arising from instrumental problems or non-collision background [49], and events containing such candidates are rejected. In addition, quality requirements are applied to remove events containing jets misreconstructed from detector noise or out-of-time energy deposits in the calorimeter from cosmic rays or other non-collision sources [50].

The production cross sections of the signal models considered in this search are many orders of magnitude lower than the background cross sections. In order to enhance the sensitivity to the signal, jet substructure techniques are used to identify the expected two-body quark-pair signal-like events within a single large- R jet. One of the commonly used jet substructure variables is τ_{21} [51], defined as the ratio τ_2/τ_1 . The variable τ_N is a measure of how consistent a given jet's constituents are with being fully aligned along N or more axes; thus τ_{21} is a useful discriminant for differentiating between a two-particle jet from the decay of a boosted resonance and a single-particle jet. However, τ_{21} is correlated with the reconstructed large- R jet mass m_J . Any selection requirement on τ_{21} leads to a selection of jets from the leading background processes with efficiency strongly dependent on the jet mass, and modifies the final jet mass distribution in a way that makes it difficult to model using a simple functional approach, effectively increasing the systematic uncertainties and weakening the overall sensitivity. To avoid this, the designed decorrelated tagger (DDT) method [14,52,53] is used to decorrelate τ_{21} from the reconstructed jet mass. The variable ρ^{DDT} is defined as

$$\rho^{\text{DDT}} \equiv \log \left(\frac{m_J^2}{p_T^J \times \mu} \right),$$

where $\mu \equiv 1 \text{ GeV}$ is an arbitrary scale parameter. For $\rho^{\text{DDT}} \gtrsim 1$, there is a linear relationship between ρ^{DDT} and the mean value of τ_{21} . ρ^{DDT} is a purely kinematic jet variable, which allows the definition of τ_{21}^{DDT} [52,53], a linearly corrected version of τ_{21} , which has mean values that are independent of the mass of the jet, as seen in Fig. 1 for various ranges of large- R p_T^J .

Selected events are required to have at least one large- R jet, the resonance candidate, and at least one narrow jet or photon with azimuthal angular separation of at least $\Delta\phi = \pi/2$ from the resonance candidate. The ISR jet is the leading narrow jet with $p_T^j > 420 \text{ GeV}$, while the ISR photon is the leading photon with $p_T^\gamma > 155 \text{ GeV}$.

In the signal region (SR), the large- R jet must satisfy $p_T^J > 200 \text{ GeV}$ in the photon channel and $p_T^J > 450 \text{ GeV}$ in the jet channel. Those thresholds are defined due to the minimum $p_T^J > 200 \text{ GeV}$ for which large- R jets uncertainties have been derived (photon channel) and to select events with p_T^J close to the recoil jet p_T^j , as expected for signal (jet channel). In addition, it is required that $p_T^J > 2 \times m_J$ to ensure sufficient collimation of the quark pairs from signal resonances so as to avoid edge effects of using a fixed-cone jet algorithm, $\tau_{21}^{\text{DDT}} < 0.50$ to suppress backgrounds and $\rho^{\text{DDT}} > 1.5$. The τ_{21}^{DDT} requirement was chosen by maximising the expected signal significance. The ρ^{DDT} constraint ensures that the τ_{21}^{DDT} variable is linear relative to ρ^{DDT} . If multiple jets satisfy these requirements, the jet with the lower τ_{21}^{DDT} from the two leading large- R jets is selected.

5. Background estimation and systematic uncertainties

The dominant backgrounds in the jet and photon channels are due to multi-jet production and inclusive γ production, respectively. The inclusive γ background is dominated by γ +jets and also includes multi-jet processes being misidentified with the same topology. In both channels, there is a sub-leading contribution from production of a jet or photon in association with a hadronically decaying electroweak gauge boson, V , where V represents a W or Z boson.

In the dominant backgrounds, the boosted phase space relevant to this search is not well described by Monte Carlo programs. Therefore, a data-driven technique is used to model the expected background in the signal region via a transfer-factor method which extrapolates from a control region (CR), defined by inverting the jet substructure requirement to $\tau_{21}^{\text{DDT}} > 0.50$.

The multi-jet and inclusive γ background estimates are constructed in bins of candidate resonance mass. In each bin, the estimate is calculated as $(N_{\text{CR}} - N_V)$ multiplied by the transfer factor, where N_{CR} is the number of events in the CR and N_V is the expected contribution from production with an associated vector boson estimated from simulated samples, typically around 1%. The transfer factor (TF) is the expected ratio of events which pass the τ_{21}^{DDT} requirement to events which fail, measured using data with $m_J < (0.8 \times m_{Z'})$ or $m_J > (1.2 \times m_{Z'})$, to avoid potential contamination from a signal near $m_{Z'}$. The TF is parameterised in terms of two kinematic quantities, $\log(p_T^J/\mu)$ and ρ^{DDT} ; it is implemented as a two-dimensional histogram, smoothed and interpolated into the signal region using a Gaussian process (GP) regression [54] using a squared exponential or ‘‘Gaussian kernel’’ with a characteristic length scale $\ell \propto 1/\sigma$ for a Gaussian width σ . The length scale ℓ_d along each dimension d of the TF histogram in $(\rho^{\text{DDT}}, \log(p_T/\mu))$ is a free parameter, determined by maximising the marginal likelihood given by [55]:

$$\log L(\mathbf{y} | \mathbf{x}, \{\ell_d\}) = -\frac{n}{2} \log \left[\mathbf{y}^\top R_{\{\ell_d\}}(\mathbf{x}, \mathbf{x}) \mathbf{y} \right] - \frac{1}{2} \log |R_{\{\ell_d\}}(\mathbf{x}, \mathbf{x})|$$

where \mathbf{x} and \mathbf{y} are the measured TF histogram bins with values scaled to have zero mean and unit variance, n is the number of data points, and $R_{\{\ell_d\}}(\mathbf{x}, \mathbf{x})$ is the correlation matrix of the TF measurements induced by the Gaussian kernel with length scales $\{\ell_d\}$. The TF values are regularised by the statistical uncertainties on the measurements according to Ref. [55]. The first term quantifies the fit to the measurements, while the second term penalises model complexity (short length scales) [54].

The transfer factor is parametrised by $(\log(p_T^J/\mu), \rho^{\text{DDT}})$ because τ_{21}^{DDT} is decorrelated from ρ^{DDT} , making the transform factor maximally uniform along this variable. In addition, including $\log(p_T^J/\mu)$ in the parametrisation renders the dependence on the jet mass explicit, allowing for the construction of mass-dependent signal region windows. The TF assume values between 0.6 and 1.3 across the $(\log(p_T^J/\mu), \rho^{\text{DDT}})$ parameter space, in the jet channel, while the TF is between 0.5 and 0.9 in the photon channel. The difference in the TF distributions is due to the choice of the common $\tau_{21}^{\text{DDT}} > 0.5$ cut, which has comparable but not identical background acceptances in simulation for the two channels, while the spread in the range is due to discrepancies between data and simulation as well as the residual correlation between τ_{21}^{DDT} and the jet kinematic parameters.

Residual contamination from signal events which leak into the control region is accounted for in the statistical analysis as follows: the background estimate and its uncertainty are validated by constructing an interpolation using data with $m_J < (0.7 \times m_{Z'})$ or $m_J > (1.3 \times m_{Z'})$, which is then compared to the data observed in a validation region (VR) in which $m_J \in [0.7, 0.8]m_{Z'}$ or $m_J \in [1.2, 1.3]m_{Z'}$. If the difference between the data and the background estimate in the VR is larger than the derived uncertainty, the uncertainty is inflated by a scale factor, without changing the nominal value of the background estimate. This can happen when the background estimate in the VR is derived from a control region with fewer events, and is therefore more sensitive to statistical fluctuations. For the ISR jet channel, the scale factor in the background uncertainty is found to be consistent with 1, while for

the ISR γ channel the scale factor ranges from 1 to 2 across the values of $m_{Z'}$. This difference between channels comes from the number of events in data: the ISR jet channel has 10 times more events than the ISR γ channel.

As a cross-check, the TF method is applied to a candidate mass range near the W and Z boson masses: the signal region’s mass range is set as a $\pm 20\%$ window around 85 GeV ([68, 102] GeV), and the validation region as a $\pm 30\%$ window around the same mass, but with the SR removed ([59.5, 68] GeV and [102, 110.5] GeV). Fig. 2 shows distributions of the large- R jet mass for data and the resulting background estimate. The latter is found to agree with the data within uncertainties. The SM prediction for W and Z production is scaled with the NLO cross section using NLO K -factors, as described in Section 3. The cross sections used are 40.6 pb (18.6 pb) for the $W(Z)$ +jets processes in the ISR jet channel, and 1.52 pb (0.983 pb) for $W(Z)$ + γ processes in the ISR γ channel. These cross sections are taken from the phase space of $p_T(W, Z) > 280$ (140) GeV for the jet (photon) channels, as motivated by the analysis kinematic selections. The best-fit signal strength relative to the SM prediction for W and Z production, $\hat{\mu} = \sigma/\sigma_{W/Z}$, is $\hat{\mu} = 0.93 \pm 0.03$ (stat) ± 0.24 (syst) in the ISR jet channel and $\hat{\mu} = 1.07 \pm 0.13$ (stat) ± 0.35 (syst) in the ISR γ channel, consistent with the SM predictions. This result shows that the TF method works well.

The largest systematic uncertainty is due to the estimate of the dominant background using the TF method. The Gaussian process regression provides a natural measure of the uncertainty in the interpolation, since it yields a mean function value across $(\log(p_T^J/\mu), \rho^{\text{DDT}})$ and a covariance function $\text{cov}(x, x')$ relating the TF measurements at different $(\log(p_T/\mu), \rho^{\text{DDT}})$. A 68% confidence level uncertainty band, within which the true transfer factor is expected to lie [54], can be obtained as $\sqrt{\text{cov}(x, x)}$. This uncertainty band, conditioned on the measurement of the ratio of numbers of events in the signal and control regions ($N_{\text{SR}}/N_{\text{CR}}$), is used as the systematic uncertainty on the transfer factor fit. This uncertainty is tuned using the validation region defined above. The final uncertainty is approximately 1% of the total multi-jet or inclusive photon background estimate.

The uncertainty in the integrated luminosity is 2.1%; it is derived following a methodology similar to that detailed in Ref. [56]. Additional systematic uncertainties stem from the use of simulated samples for the vector boson associated backgrounds as well as the hypothetical signals. The largest sources of systematic uncertainty in each channel arise from uncertainties in the calibration and resolution of the large- R jet energy and mass, as well as the modelling of τ_{21}^{DDT} [57]; individually these uncertainties range up to 10% relative to the signal, but together these uncertainties are less than 1% of the background estimate in the signal region. Additionally, smaller systematic uncertainties are due to the uncertainty in the parton distribution functions and integrated luminosity.

6. Results

The observed distributions of the large- R jet mass are compared with the background estimates in Fig. 3 and Fig. 4 for two representative Z' mass values for the ISR jet and ISR γ channels, respectively. The slope in the data and background distributions changes for a large- R jet mass around 225 GeV (100 GeV) for Fig. 3 (Fig. 4), due to the boosted topology requirement, $p_T^J > 2 \times m_J$. The beginning of this effect is determined by the p_T^J requirements of 450 GeV and 200 GeV for the ISR jet and ISR γ channels, respectively. The observed distributions of the large- R jet mass are well reproduced by the estimated background contributions.

A binned likelihood function $\mathcal{L}(\mu, \theta)$, constructed as a product of Poisson probability terms over all bins of the contributions of

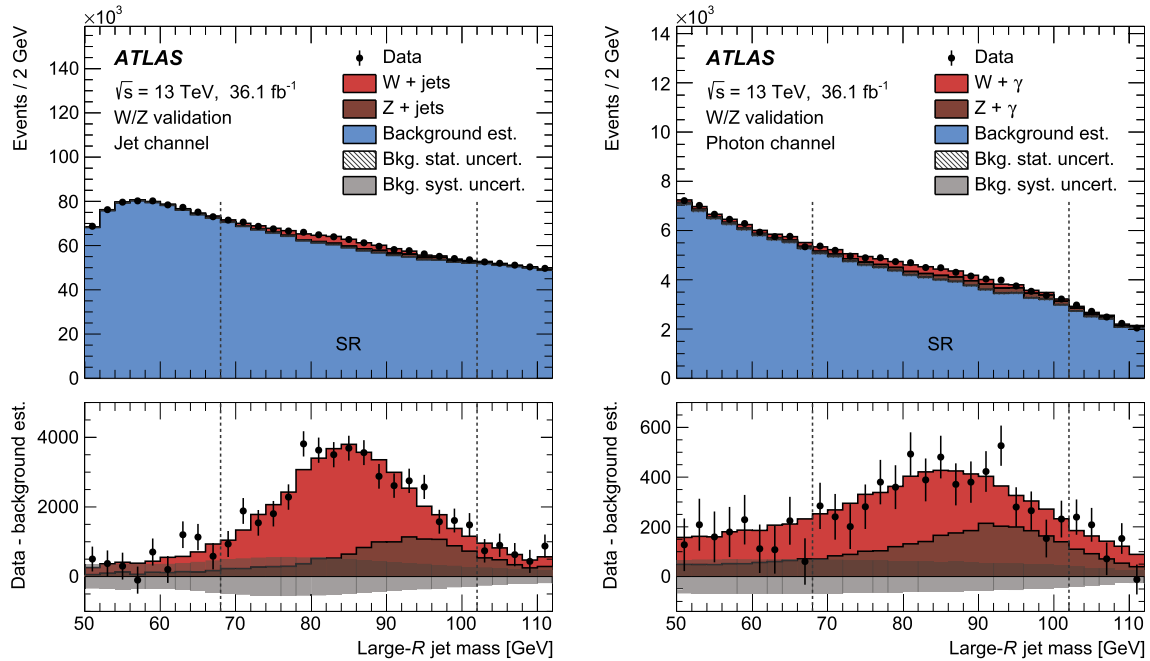


Fig. 2. Top: distribution of large- R jet mass near the W and Z boson masses, as a validation of background estimate using the transfer factor described in the text. The vertical dashed lines indicate the signal region (SR) surrounding the target W and Z boson masses. Bottom: residual between data and the estimated background. The distributions are shown for both the (left) jet and (right) photon channels. The contributions from the W and Z backgrounds have been scaled by their best-fit values, as described in the text. In the top panel, the statistical uncertainty is too small to be visible; in the bottom panel it is incorporated into the error bars on the data.

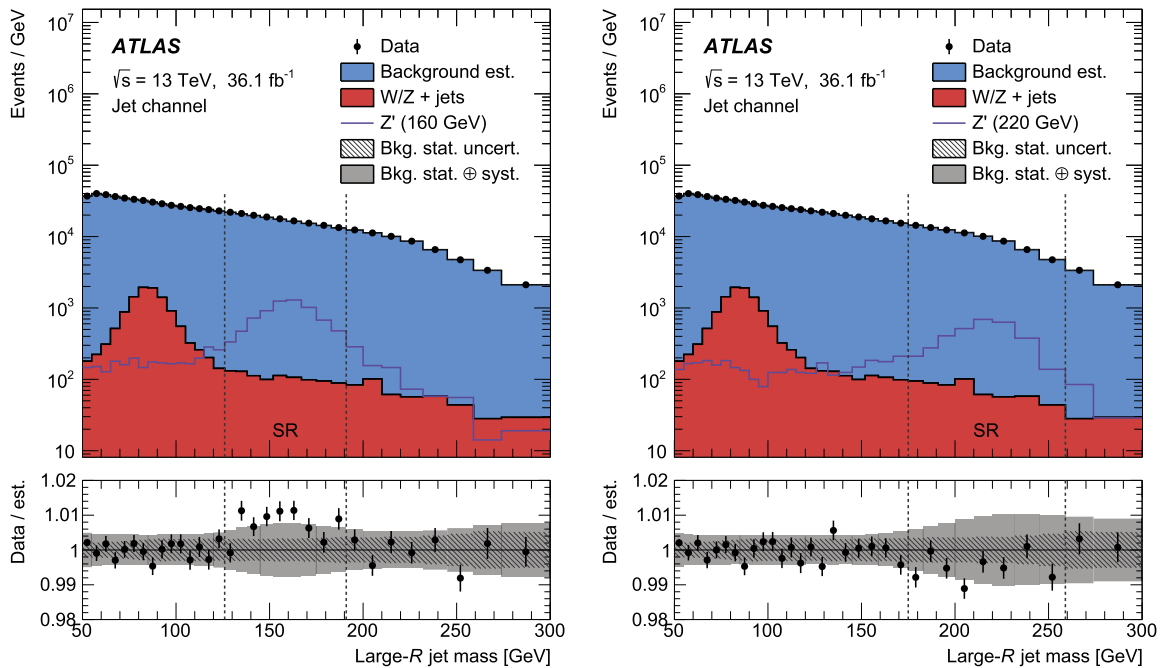


Fig. 3. Top: distribution of large- R jet mass in the jet channel for $m_{Z'} = 160$ GeV (left) and 220 GeV (right). The vertical dashed lines indicate the signal region (SR) surrounding the target Z' mass. The signal is generated with $g_q = 0.5$. Bottom: ratio of data to the estimated background. The background estimate is different for each signal mass hypothesis; more details are given in the text.

the background and of a hypothetical signal of strength μ relative to the benchmark model, is used to set limits. The likelihood function is also dependant on θ , a set of nuisance parameters with Gaussian prior distributions encoding the effects of the systematic uncertainties in background and signal predictions. The fit to the large- R jet mass distribution is performed in each mass-dependent signal region in both the ISR jet and γ channels. The potential sig-

nal contamination in the control region used to define the TF is accounted for by scaling the best-fit signal strength by the ratio of expected signal events passing the τ_{21}^{DDT} selection to the expected number of TF-weighted signal events included in the background estimation, as determined in simulation. Typical values for this scale factor are 0.7 for the ISR jet channel and 0.6 for the ISR γ channel.

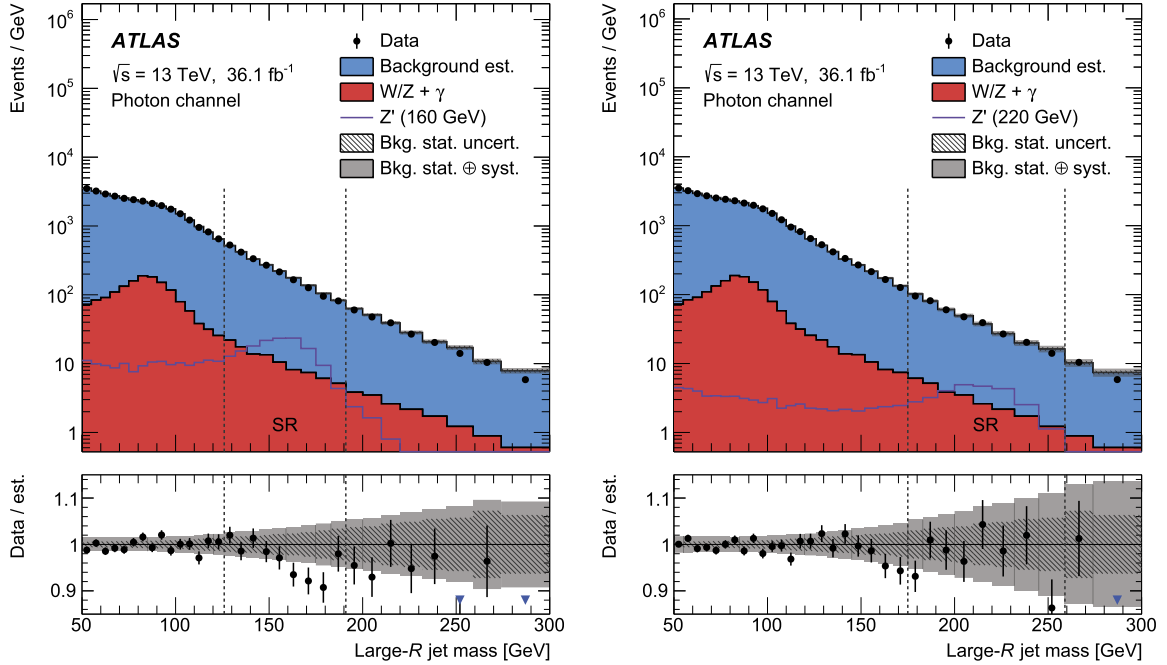


Fig. 4. Top: distribution of large- R jet mass in the photon channel for $m_{Z'} = 160$ GeV (left) and 220 GeV (right). The vertical dashed lines indicate the signal region (SR) surrounding the target Z' mass. The signal is generated with $g_q = 0.5$. Bottom: ratio of data to the estimated background. The background estimate is different for each signal mass hypothesis; more details are given in the text. The blue triangles indicate bins where the ratio is nonzero and outside the vertical range of the plot.

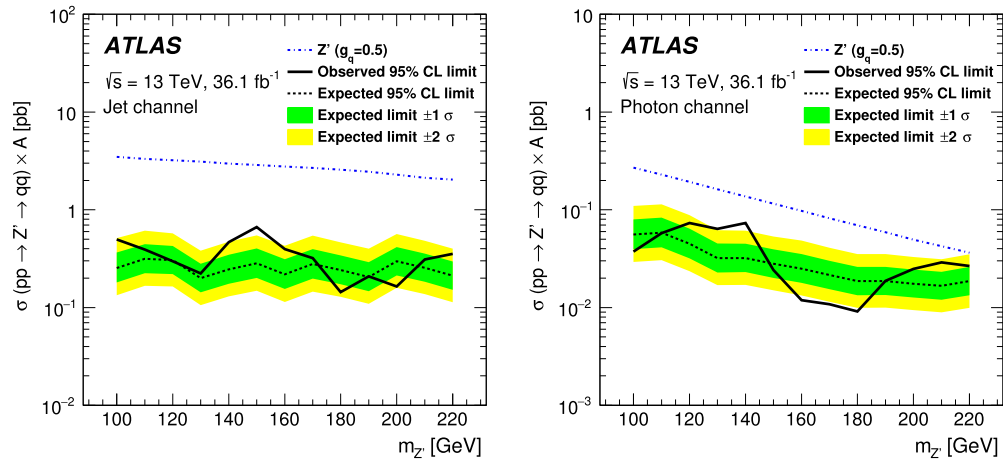


Fig. 5. Observed and expected limits at 95% confidence level on the lepto-phobic axial-vector Z' [30–32] production cross section (σ) times kinematic acceptance (A , see text for details) in the ISR jet channel (left) and the ISR γ channel (right).

The largest excess is observed in the ISR jet signal region centred at 150 GeV. Performing a signal-plus-background fit with a Z' model assumption, the local significance in this region is found to be 2.5σ , corresponding to a global significance of 1.1σ , where the look-elsewhere effect [58] is calculated with respect to the entire mass window examined. The largest positive deviation from the expected background in the ISR γ channel is seen in the signal region centred at 140 GeV, with local (global) significance of 2.2σ (0.8σ).

Upper limits are derived at 95% confidence level on the Z' production cross section times acceptance as a function of the Z' mass between 100 and 220 GeV using profile-likelihood-ratio tests [59] with the CL_s method [60], shown in Fig. 5.

The acceptance accounts for all selection criteria except for the requirement on τ_{21}^{DDT} ; it can vary significantly for various theoretical models, yet can be well estimated without detailed detector

simulation. For the Z' signal model considered in this paper, acceptance values vary from 0.10% to 0.06% in the ISR jet channel and from 4.0% to 1.0% in the ISR γ channel, in the mass range between 100 and 220 GeV. The efficiency of the τ_{21}^{DDT} requirement is less model dependent but more dependent on accurate modelling of the τ_{21}^{DDT} variable in simulated samples. The acceptance times efficiency varies between 0.07%–0.04% (2.6%–0.5%) for the ISR jet (ISR γ) channel over the 100–220 GeV mass interval.

The observed and expected limits on the coupling g_q are shown in Fig. 6, for the combination of the ISR jet and ISR γ channels. The narrow width approximation is valid for the g_q range tested. In the combination, the nuisance parameters corresponding to luminosity and large- R jet energy scale and resolution uncertainties are fully correlated between channels, while the background uncertainties are uncorrelated. The largest deviation is for the 140 GeV signal hypothesis, corresponding to 2.4σ local and 1.2σ global sig-

Table 1

The source of each of the largest uncertainties and their relative impact in the expected signal, quantified by the uncertainty in the best-fit signal strength ($\Delta\mu$) over the best-fit signal strength (μ), for hypothesised signal production of Z' with $m_{Z'} = 100$ GeV, $m_{Z'} = 160$ GeV and $m_{Z'} = 220$ GeV.

Uncertainty source	$\Delta\mu/\mu$ [%]		
	$m_{Z'} = 100$ GeV	$m_{Z'} = 160$ GeV	$m_{Z'} = 220$ GeV
Transfer factor	86	90	88
Large- R jet calib. and modelling	19	25	17
W/Z normalisation	43	$\ll 1$	$\ll 1$
Signal PDF	$\ll 1$	$\ll 1$	1
Luminosity	2	$\ll 1$	$\ll 1$
Total systematic uncertainty	91	93	91
Statistical uncertainty	9	10	11

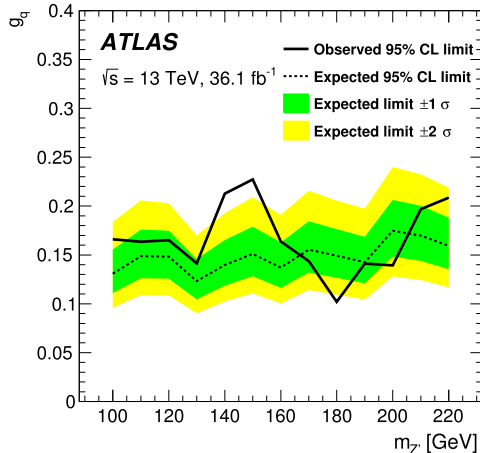


Fig. 6. Observed and expected limits at 95% confidence level on the coupling (g_q) from the lepto-phobic axial-vector Z' model [30–32], for the combination of the ISR jet and ISR γ channels.

nificances. The observed upper limits on the coupling g_q in the 100–220 GeV Z' mass range are competitive but slightly underperform the latest results reported by the CMS experiment [15], partially due to differences in the effect of jet trimming versus soft-drop grooming on relevant large- R jet observables such as jet mass.

The effects of systematic uncertainties are studied for hypothesised signals using the signal-strength parameter μ . The relative uncertainties in the best-fit μ value from the leading sources of systematic uncertainty are shown in Table 1 for $m_{Z'} = 100$, 160 and 220 GeV. The TF systematic uncertainty has the largest impact on the sensitivity, accounting for 86%, 90% and 88% of the total impact for the 100, 160 and 220 GeV signal hypothesis, respectively. The TF uncertainty is larger for the jet channel, due to its smaller length scale of the Gaussian process. For the Z' 160 GeV hypothesis, it accounts for 87% of the impact in the signal strength in the ISR jet channel and 61% in the ISR γ channel. The second biggest impact is due to uncertainties associated with large- R jets. Ref. [57] details the derivation procedure and the breakdown of those uncertainties. The data's statistical uncertainty accounts for about 10% of the total impact at all mass points considered. It is larger in the ISR γ channel than in the ISR jet channel due to the order of magnitude difference in the number of events; this accounts for 21% of the impact in the former and 9% in the latter for $m_{Z'} = 160$ GeV.

7. Conclusion

In summary, a search for new light resonances decaying into pairs of quarks and produced in association with a high- p_T photon

or jet is presented. The search is based on 36.1 fb^{-1} of 13 TeV pp collisions recorded by the ATLAS detector at the LHC. Resonance candidates are identified as massive large-radius jets with substructure consistent with a quark pair. The mass spectrum of the candidates is examined for local excesses above a data-derived estimate of a smoothly falling background. No evidence of anomalous phenomena is observed in the data, and limits are presented on the cross section and couplings of a leptophobic axial-vector Z' benchmark model. Upper limits at 95% confidence level on production cross sections times acceptance are 0.50 pb (0.04 pb) for a 100 GeV signal hypothesis, and 0.35 pb (0.03 pb) for a 220 GeV signal hypothesis in the ISR jet (ISR γ) channels. The observed upper limits on the coupling g_q are 0.17 for $m_{Z'} = 100$ GeV and 0.21 for $m_{Z'} = 220$ GeV, when combining ISR jet and ISR γ channels.

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The ATLAS Collaboration

M. Aaboud^{34d}, G. Aad⁹⁹, B. Abbott¹²⁴, O. Abdinov^{13,*}, B. Abeloos¹²⁸, S.H. Abidi¹⁶⁵, O.S. AbouZeid¹⁴³, N.L. Abraham¹⁵³, H. Abramowicz¹⁵⁹, H. Abreu¹⁵⁸, R. Abreu¹²⁷, Y. Abulaiti^{43a,43b}, B.S. Acharya^{64a,64b,o}, S. Adachi¹⁶¹, L. Adamczyk^{81a}, J. Adelman¹¹⁹, M. Adersberger¹¹², T. Adye¹⁴¹, A.A. Affolder¹⁴³, Y. Afik¹⁵⁸, C. Agheorghiesei^{27c}, J.A. Aguilar-Saavedra^{136f,136a}, F. Ahmadov^{77,ag}, G. Aielli^{71a,71b}, S. Akatsuka⁸³, H. Akerstedt^{43a,43b}, T.P.A. Åkesson⁹⁴, E. Akilli⁵², A.V. Akimov¹⁰⁸, G.L. Alberghi^{23b,23a}, J. Albert¹⁷⁴, P. Albicocco⁴⁹, M.J. Alconada Verzini⁸⁶, S. Alderweireldt¹¹⁷, M. Aleksa³⁵, I.N. Aleksandrov⁷⁷, C. Alexa^{27b}, G. Alexander¹⁵⁹, T. Alexopoulos¹⁰, M. Alhroob¹²⁴, B. Ali¹³⁸, G. Alimonti^{66a}, J. Alison³⁶, S.P. Alkire³⁸, B.M.M. Allbrooke¹⁵³, B.W. Allen¹²⁷, P.P. Allport²¹, A. Aloisio^{67a,67b}, A. Alonso³⁹, F. Alonso⁸⁶, C. Alpigiani¹⁴⁵, A.A. Alshehri⁵⁵, M.I. Alstath⁹⁹, B. Alvarez Gonzalez³⁵, D. Álvarez Piqueras¹⁷², M.G. Alviggi^{67a,67b}, B.T. 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Baas^{59a}, M.J. Baca²¹, H. Bachacou¹⁴², K. Bachas^{65a,65b}, M. Backes¹³¹, P. Bagnaia^{70a,70b}, M. Bahmani⁸², H. Bahrasemani¹⁴⁹, J.T. Baines¹⁴¹, M. Bajic³⁹, O.K. Baker¹⁸¹, P.J. Bakker¹¹⁸, E.M. Baldin^{120b,120a}, P. Balek¹⁷⁸, F. Balli¹⁴², W.K. Balunas¹³³, E. Banas⁸², A. Bandyopadhyay²⁴, S. Banerjee^{179,k}, A.A.E. Bannoura¹⁸⁰, L. Barak¹⁵⁹, E.L. Barberio¹⁰², D. Barberis^{53b,53a}, M. Barbero⁹⁹, T. Barillari¹¹³, M-S. Barisits⁷⁴, J. Barkeloo¹²⁷, T. Barklow¹⁵⁰, N. Barlow³¹, S.L. Barnes^{58c}, B.M. Barnett¹⁴¹, R.M. Barnett¹⁸, Z. Barnovska-Blenessy^{58a}, A. Baroncelli^{72a}, G. Barone²⁶, A.J. Barr¹³¹, L. Barranco Navarro¹⁷², F. Barreiro⁹⁶, J. Barreiro Guimarães da Costa^{15a}, R. Bartoldus¹⁵⁰, A.E. Barton⁸⁷, P. Bartos^{28a}, A. Basalae¹³⁴, A. Bassalat¹²⁸, R.L. Bates⁵⁵, S.J. Batista¹⁶⁵, J.R. Batley³¹, M. Battaglia¹⁴³, M. Bauge^{70a,70b}, F. Bauer¹⁴², K.T. Bauer¹⁶⁹, H.S. Bawa^{150,m}, J.B. Beacham¹²², M.D. Beattie⁸⁷, T. Beau¹³², P.H. Beauchemin¹⁶⁸, P. Bechtel²⁴, H.C. Beck⁵¹, H.P. Beck^{20,s}, K. Becker¹³¹, M. Becker⁹⁷, C. Becot¹²¹, A. Beddall^{12d}, A.J. Beddall^{12a}, V.A. Bednyakov⁷⁷, M. Bedognetti¹¹⁸, C.P. Bee¹⁵², T.A. Beermann³⁵, M. Begalli^{78b}, M. Beger²⁹, J.K. Behr⁴⁴, A.S. Bell⁹², G. Bella¹⁵⁹, L. Bellagamba^{23b}, A. Bellerive³³, M. Bellomo¹⁵⁸, K. Belotskiy¹¹⁰, O. Beltramello³⁵, N.L. Belyaev¹¹⁰, O. Benary^{159,*}, D. Benchekroun^{34a}, M. Bender¹¹², N. Benekos¹⁰, Y. Benhammou¹⁵⁹, E. Benhar Noccioli¹⁸¹, J. Benitez⁷⁵, D.P. Benjamin⁴⁷, M. Benoit⁵², J.R. Bensinger²⁶, S. Bentvelsen¹¹⁸, L. Beresford¹³¹, M. Beretta⁴⁹, D. Berge¹¹⁸, E. Bergeaas Kuutmann¹⁷⁰, N. Berger⁵, L.J. Bergsten²⁶, J. Beringer¹⁸, S. Berlendis⁵⁶, N.R. Bernard¹⁰⁰, G. Bernardi¹³², C. Bernius¹⁵⁰, F.U. Bernlochner²⁴, T. Berry⁹¹, P. Berta⁹⁷, C. Bertella^{15a}, G. Bertoli^{43a,43b}, I.A. Bertram⁸⁷, C. Bertsche⁴⁴, G.J. Besjes³⁹, O. Bessidskaia Bylund^{43a,43b}, M. Bessner⁴⁴, N. Besson¹⁴², A. Bethani⁹⁸, S. Bethke¹¹³, A. Betti²⁴, A.J. Bevan⁹⁰, J. Beyer¹¹³, R.M. Bianchi¹³⁵, O. Biebel¹¹², D. Biedermann¹⁹, R. Bielski⁹⁸, K. Bierwagen⁹⁷, N.V. Biesuz^{69a,69b}, M. Biglietti^{72a}, T.R.V. Billoud¹⁰⁷, H. Bilokon⁴⁹, M. Bindi⁵¹, A. Bingul^{12d}, C. Bini^{70a,70b}, S. Biondi^{23b,23a}, T. Bisanz⁵¹, C. Bittrich⁴⁶, D.M. Bjergaard⁴⁷, J.E. Black¹⁵⁰, K.M. Black²⁵, R.E. Blair⁶, T. Blazek^{28a}, I. Bloch⁴⁴, C. Blocker²⁶, A. Blue⁵⁵, U. Blumenschein⁹⁰, Dr. Blunier^{144a}, G.J. Bobbink¹¹⁸, V.S. Bobrovnikov^{120b,120a}, S.S. Bocchetta⁹⁴, A. Bocci⁴⁷, C. Bock¹¹², M. Boehler⁵⁰, D. Boerner¹⁸⁰, D. Bogavac¹¹², A.G. Bogdanchikov^{120b,120a}, C. Bohm^{43a}, V. Boisvert⁹¹, P. Bokan^{170,51}, T. Bold^{81a}, A.S. Boldyrev¹¹¹, A.E. Bolz^{59b}, M. Bomben¹³², M. Bona⁹⁰, J.S. Bonilla¹²⁷, M. Boonekamp¹⁴², A. Borisov¹⁴⁰, G. Borissov⁸⁷, J. Bortfeldt³⁵, D. Bortoletto¹³¹, V. Bortolotto^{61a,61b,61c}, D. Boscherini^{23b}, M. Bosman¹⁴, J.D. Bossio Sola³⁰, J. Boudreau¹³⁵, E.V. Bouhova-Thacker⁸⁷, D. Boumediene³⁷, C. Bourdarios¹²⁸, S.K. Boutle⁵⁵, A. Boveia¹²², J. Boyd³⁵, I.R. Boyko⁷⁷, A.J. Bozson⁹¹, J. Bracinik²¹, A. Brandt⁸, G. Brandt⁵¹, O. Brandt^{59a}, F. Braren⁴⁴, U. Bratzler¹⁶², B. Brau¹⁰⁰, J.E. Brau¹²⁷, W.D. Breaden Madden⁵⁵, K. Brendlinger⁴⁴, A.J. Brennan¹⁰², L. Brenner¹¹⁸, R. Brenner¹⁷⁰, S. Bressler¹⁷⁸, D.L. Briglin²¹, T.M. Bristow⁴⁸, D. Britton⁵⁵, D. Britzger⁴⁴, I. Brock²⁴, R. Brock¹⁰⁴, G. Brooijmans³⁸, T. Brooks⁹¹, W.K. Brooks^{144b}, E. Brost¹¹⁹, J.H. Broughton²¹,

P.A. Bruckman de Renstrom ⁸², D. Bruncko ^{28b}, A. Bruni ^{23b}, G. Bruni ^{23b}, L.S. Bruni ¹¹⁸, S. Bruno ^{71a,71b}, B.H. Brunt ³¹, M. Bruschi ^{23b}, N. Brusino ¹³⁵, P. Bryant ³⁶, L. Bryngemark ⁴⁴, T. Buanes ¹⁷, Q. Buat ¹⁴⁹, P. Buchholz ¹⁴⁸, A.G. Buckley ⁵⁵, I.A. Budagov ⁷⁷, F. Buehrer ⁵⁰, M.K. Bugge ¹³⁰, O. Bulekov ¹¹⁰, D. Bullock ⁸, T.J. Burch ¹¹⁹, S. Burdin ⁸⁸, C.D. Burgard ¹¹⁸, A.M. Burger ⁵, B. Burghgrave ¹¹⁹, K. Burka ⁸², S. Burke ¹⁴¹, I. Burmeister ⁴⁵, J.T.P. Burr ¹³¹, D. Büscher ⁵⁰, V. Büscher ⁹⁷, P. Bussey ⁵⁵, J.M. Butler ²⁵, C.M. Buttar ⁵⁵, J.M. Butterworth ⁹², P. Butti ³⁵, W. Buttinger ²⁹, A. Buzatu ¹⁵⁵, A.R. Buzykaev ^{120b,120a}, S. Cabrera Urbán ¹⁷², D. Caforio ¹³⁸, H. Cai ¹⁷¹, V.M.M. Cairo ^{40b,40a}, O. Cakir ^{4a}, N. Calace ⁵², P. Calafiura ¹⁸, A. Calandri ⁹⁹, G. Calderini ¹³², P. Calfayan ⁶³, G. Callea ^{40b,40a}, L.P. Caloba ^{78b}, S. Calvente Lopez ⁹⁶, D. Calvet ³⁷, S. Calvet ³⁷, T.P. Calvet ⁹⁹, R. Camacho Toro ³⁶, S. Camarda ³⁵, P. Camarri ^{71a,71b}, D. Cameron ¹³⁰, R. Caminal Armadans ¹⁷¹, C. Camincher ⁵⁶, S. Campana ³⁵, M. Campanelli ⁹², A. Camplani ^{66a,66b}, A. Campoverde ¹⁴⁸, V. Canale ^{67a,67b}, M. Cano Bret ^{58c}, J. Cantero ¹²⁵, T. Cao ¹⁵⁹, M.D.M. Capeans Garrido ³⁵, I. Caprini ^{27b}, M. Caprini ^{27b}, M. Capua ^{40b,40a}, R.M. Carbone ³⁸, R. Cardarelli ^{71a}, F.C. Cardillo ⁵⁰, I. Carli ¹³⁹, T. Carli ³⁵, G. Carlino ^{67a}, B.T. Carlson ¹³⁵, L. Carminati ^{66a,66b}, R.M.D. Carney ^{43a,43b}, S. Caron ¹¹⁷, E. Carquin ^{144b}, S. Carrá ^{66a,66b}, G.D. Carrillo-Montoya ³⁵, D. Casadei ²¹, M.P. Casado ^{14,g}, A.F. Casha ¹⁶⁵, M. Casolino ¹⁴, D.W. Casper ¹⁶⁹, R. Castelijin ¹¹⁸, V. Castillo Gimenez ¹⁷², N.F. Castro ^{136a}, A. Catinaccio ³⁵, J.R. Catmore ¹³⁰, A. Cattai ³⁵, J. Caudron ²⁴, V. Cavaliere ¹⁷¹, E. Cavallaro ¹⁴, D. Cavalli ^{66a}, M. Cavalli-Sforza ¹⁴, V. Cavasinni ^{69a,69b}, E. Celebi ^{12b}, F. Ceradini ^{72a,72b}, L. Cerda Alberich ¹⁷², A.S. Cerqueira ^{78a}, A. Cerri ¹⁵³, L. Cerrito ^{71a,71b}, F. Cerutti ¹⁸, A. Cervelli ^{23b,23a}, S.A. Cetin ^{12b}, A. Chafaq ^{34a}, D. Chakraborty ¹¹⁹, S.K. Chan ⁵⁷, W.S. Chan ¹¹⁸, Y.L. Chan ^{61a}, P. Chang ¹⁷¹, J.D. Chapman ³¹, D.G. Charlton ²¹, C.C. Chau ³³, C.A. Chavez Barajas ¹⁵³, S. Che ¹²², S. Cheatham ^{64a,64c}, A. Chegwidden ¹⁰⁴, S. Chekanov ⁶, S.V. Chekulaev ^{166a}, G.A. Chelkov ^{77,at}, M.A. Chelstowska ³⁵, C. Chen ^{58a}, C.H. Chen ⁷⁶, H. Chen ²⁹, J. Chen ^{58a}, S. Chen ¹⁶¹, S.J. Chen ^{15c}, X. Chen ^{15b,as}, Y. Chen ⁸⁰, H.C. Cheng ¹⁰³, H.J. Cheng ^{15d}, A. Cheplakov ⁷⁷, E. Cheremushkina ¹⁴⁰, R. Cherkaoui El Moursli ^{34e}, E. Cheu ⁷, K. Cheung ⁶², L. Chevalier ¹⁴², V. Chiarella ⁴⁹, G. Chiarelli ^{69a}, G. Chiodini ^{65a}, A.S. Chisholm ³⁵, A. Chitan ^{27b}, Y.H. Chiu ¹⁷⁴, M.V. Chizhov ⁷⁷, K. Choi ⁶³, A.R. Chomont ³⁷, S. Chouridou ¹⁶⁰, Y.S. Chow ^{61a}, V. Christodoulou ⁹², M.C. Chu ^{61a}, J. Chudoba ¹³⁷, A.J. Chuinard ¹⁰¹, J.J. Chwastowski ⁸², L. Chytka ¹²⁶, A.K. Ciftci ^{4a}, D. Cinca ⁴⁵, V. Cindro ⁸⁹, I.A. Cioară ²⁴, A. Ciocio ¹⁸, F. Ciotto ^{67a,67b}, Z.H. Citron ¹⁷⁸, M. Citterio ^{66a}, M. Ciubancan ^{27b}, A. Clark ⁵², M.R. Clark ³⁸, P.J. Clark ⁴⁸, R.N. Clarke ¹⁸, C. Clement ^{43a,43b}, Y. Coadou ⁹⁹, M. Cobal ^{64a,64c}, A. Coccaro ⁵², J. Cochran ⁷⁶, L. Colasurdo ¹¹⁷, B. Cole ³⁸, A.P. Colijn ¹¹⁸, J. Collot ⁵⁶, T. Colombo ¹⁶⁹, P. Conde Muiño ^{136a,136b}, E. Coniavitis ⁵⁰, S.H. Connell ^{32b}, I.A. Connelly ⁹⁸, S. Constantinescu ^{27b}, G. Conti ³⁵, F. Conventi ^{67a,av}, M. Cooke ¹⁸, A.M. Cooper-Sarkar ¹³¹, F. Cormier ¹⁷³, K.J.R. Cormier ¹⁶⁵, M. Corradi ^{70a,70b}, E.E. Corrigan ⁹⁴, F. Corriveau ^{101,ae}, A. Cortes-Gonzalez ³⁵, G. Costa ^{66a}, M.J. Costa ¹⁷², D. Costanzo ¹⁴⁶, G. Cottin ³¹, G. Cowan ⁹¹, B.E. Cox ⁹⁸, K. Cranmer ¹²¹, S.J. Crawley ⁵⁵, R.A. Creager ¹³³, G. Cree ³³, S. Crépe-Renaudin ⁵⁶, F. Crescioli ¹³², W.A. Cribbs ^{43a,43b}, M. Cristinziani ²⁴, V. Croft ¹²¹, G. Crosetti ^{40b,40a}, A. Cueto ⁹⁶, T. Cuhadar Donszelmann ¹⁴⁶, A.R. Cukierman ¹⁵⁰, J. Cummings ¹⁸¹, M. Curatolo ⁴⁹, J. Cúth ⁹⁷, S. Czekierda ⁸², P. Czodrowski ³⁵, M.J. Da Cunha Sargedas De Sousa ^{136a,136b}, C. Da Via ⁹⁸, W. Dabrowski ^{81a}, T. Dado ^{28a,y}, T. Dai ¹⁰³, O. Dale ¹⁷, F. Dallaire ¹⁰⁷, C. Dallapiccola ¹⁰⁰, M. Dam ³⁹, G. D'amen ^{23b,23a}, J.R. Dandoy ¹³³, M.F. Daneri ³⁰, N.P. Dang ^{179,k}, N.D. Dann ⁹⁸, M. Danninger ¹⁷³, M. Dano Hoffmann ¹⁴², V. Dao ¹⁵², G. Darbo ^{53b}, S. Darmora ⁸, J. Dassoulas ³, A. Dattagupta ¹²⁷, T. Daubney ⁴⁴, S. D'Auria ⁵⁵, W. Davey ²⁴, C. David ⁴⁴, T. Davidek ¹³⁹, D.R. Davis ⁴⁷, P. Davison ⁹², E. Dawe ¹⁰², I. Dawson ¹⁴⁶, K. De ⁸, R. De Asmundis ^{67a}, A. De Benedetti ¹²⁴, S. De Castro ^{23b,23a}, S. De Cecco ¹³², N. De Groot ¹¹⁷, P. de Jong ¹¹⁸, H. De la Torre ¹⁰⁴, F. De Lorenzi ⁷⁶, A. De Maria ^{51,u}, D. De Pedis ^{70a}, A. De Salvo ^{70a}, U. De Sanctis ^{71a,71b}, A. De Santo ¹⁵³, K. De Vasconcelos Corga ⁹⁹, J.B. De Vivie De Regie ¹²⁸, R. Debbe ²⁹, C. Debenedetti ¹⁴³, D.V. Dedovich ⁷⁷, N. Dehghanian ³, I. Deigaard ¹¹⁸, M. Del Gaudio ^{40b,40a}, J. Del Peso ⁹⁶, D. Delgove ¹²⁸, F. Deliot ¹⁴², C.M. Delitzsch ⁷, M. Della Pietra ^{67a,67b}, D. Della Volpe ⁵², A. Dell'Acqua ³⁵, L. Dell'Asta ²⁵, M. Dell'Orso ^{69a,69b}, M. Delmastro ⁵, C. Delporte ¹²⁸, P.A. Delsart ⁵⁶, D.A. DeMarco ¹⁶⁵, S. Demers ¹⁸¹, M. Demichev ⁷⁷, A. Demilly ¹³², S.P. Denisov ¹⁴⁰, D. Denysiuk ¹⁴², L. D'Eramo ¹³², D. Derendarz ⁸², J.E. Derkaoui ^{34d}, F. Derue ¹³², P. Dervan ⁸⁸, K. Desch ²⁴, C. Deterre ⁴⁴, K. Dette ¹⁶⁵, M.R. Devesa ³⁰, P.O. Deviveiros ³⁵, A. Dewhurst ¹⁴¹, S. Dhaliwal ²⁶, F.A. Di Bello ⁵², A. Di Ciaccio ^{71a,71b}, L. Di Ciaccio ⁵, W.K. Di Clemente ¹³³, C. Di Donato ^{67a,67b}, A. Di Girolamo ³⁵, B. Di Girolamo ³⁵, B. Di Micco ^{72a,72b}, R. Di Nardo ³⁵, K.F. Di Petrillo ⁵⁷, A. Di Simone ⁵⁰, R. Di Sipio ¹⁶⁵, D. Di Valentino ³³, C. Diaconu ⁹⁹,

M. Diamond¹⁶⁵, F.A. Dias³⁹, M.A. Diaz^{144a}, J. Dickinson¹⁸, E.B. Diehl¹⁰³, J. Dietrich¹⁹, S. Díez Cornell⁴⁴, A. Dimitrievska¹⁶, J. Dingfelder²⁴, P. Dita^{27b}, S. Dita^{27b}, F. Dittus³⁵, F. Djama⁹⁹, T. Djobava^{157b}, J.I. Djuvsland^{59a}, M.A.B. Do Vale^{78c}, M. Dobre^{27b}, D. Dodsworth²⁶, C. Doglioni⁹⁴, J. Dolejsi¹³⁹, Z. Dolezal¹³⁹, M. Donadelli^{78d}, S. Donati^{69a,69b}, J. Donini³⁷, M. D'Onofrio⁸⁸, J. Dopke¹⁴¹, A. Doria^{67a}, M.T. Dova⁸⁶, A.T. Doyle⁵⁵, E. Drechsler⁵¹, M. Dris¹⁰, Y. Du^{58b}, J. Duarte-Campderros¹⁵⁹, F. Dubinin¹⁰⁸, A. Dubreuil⁵², E. Duchovni¹⁷⁸, G. Duckeck¹¹², A. Ducourthial¹³², O.A. Ducu^{107,x}, D. Duda¹¹⁸, A. Dudarev³⁵, A.C. Dudder⁹⁷, E.M. Duffield¹⁸, L. Duflot¹²⁸, M. Dührssen³⁵, C. Dülsen¹⁸⁰, M. Dumancic¹⁷⁸, A.E. Dumitriu^{27b,e}, A.K. Duncan⁵⁵, M. Dunford^{59a}, A. Duperrin⁹⁹, H. Duran Yildiz^{4a}, M. Düren⁵⁴, A. Durglishvili^{157b}, D. Duschinger⁴⁶, B. Dutta⁴⁴, D. Duvnjak¹, M. Dyndal⁴⁴, B.S. Dziedzic⁸², C. Eckardt⁴⁴, K.M. Ecker¹¹³, R.C. Edgar¹⁰³, T. Eifert³⁵, G. Eigen¹⁷, K. Einsweiler¹⁸, T. Ekelof¹⁷⁰, M. El Kacimi^{34c}, R. El Kosseifi⁹⁹, V. Ellajosyula⁹⁹, M. Ellert¹⁷⁰, S. Elles⁵, F. Ellinghaus¹⁸⁰, A.A. Elliot¹⁷⁴, N. Ellis³⁵, J. Elmsheuser²⁹, M. Elsing³⁵, D. Emelianov¹⁴¹, Y. Enari¹⁶¹, J.S. Ennis¹⁷⁶, M.B. Epland⁴⁷, J. Erdmann⁴⁵, A. Ereditato²⁰, M. Ernst²⁹, S. Errede¹⁷¹, M. Escalier¹²⁸, C. Escobar¹⁷², B. Esposito⁴⁹, O. Estrada Pastor¹⁷², A.I. Etiennevire¹⁴², E. Etzion¹⁵⁹, H. Evans⁶³, A. Ezhilov¹³⁴, M. Ezzi^{34e}, F. Fabbri^{23b,23a}, L. Fabbri^{23b,23a}, V. Fabiani¹¹⁷, G. Facini⁹², R.M. Fakhruddinov¹⁴⁰, S. Falciano^{70a}, R.J. Falla⁹², J. Faltova³⁵, Y. Fang^{15a}, M. Fanti^{66a,66b}, A. Farbin⁸, A. Farilla^{72a}, E.M. Farina^{68a,68b}, T. Farooque¹⁰⁴, S. Farrell¹⁸, S.M. Farrington¹⁷⁶, P. Farthouat³⁵, F. Fassi^{34e}, P. Fassnacht³⁵, D. Fassouliotis⁹, M. Faucci Giannelli⁴⁸, A. Favareto^{53b,53a}, W.J. Fawcett¹³¹, L. Fayard¹²⁸, O.L. Fedin^{134,q}, W. Fedorko¹⁷³, S. Feigl¹³⁰, L. Felgioni⁹⁹, C. Feng^{58b}, E.J. Feng³⁵, M. Feng⁴⁷, M.J. Fenton⁵⁵, A.B. Fenyuk¹⁴⁰, L. Feremenga⁸, P. Fernandez Martinez¹⁷², J. Ferrando⁴⁴, A. Ferrari¹⁷⁰, P. Ferrari¹¹⁸, R. Ferrari^{68a}, D.E. Ferreira de Lima^{59b}, A. Ferrer¹⁷², D. Ferrere⁵², C. Ferretti¹⁰³, F. Fiedler⁹⁷, M. Filipuzzi⁴⁴, A. Filipčič⁸⁹, F. Filthaut¹¹⁷, M. Fincke-Keeler¹⁷⁴, K.D. Finelli²⁵, M.C.N. Fiolhais^{136a,136c,b}, L. Fiorini¹⁷², A. Fischer², C. Fischer¹⁴, J. Fischer¹⁸⁰, W.C. Fisher¹⁰⁴, N. Flaschel⁴⁴, I. Fleck¹⁴⁸, P. Fleischmann¹⁰³, R.R.M. Fletcher¹³³, T. Flick¹⁸⁰, B.M. Flierl¹¹², L.R. Flores Castillo^{61a}, M.J. Flowerdew¹¹³, N. Fomin¹⁷, G.T. Forcolin⁹⁸, A. Formica¹⁴², F.A. Förster¹⁴, A.C. Forti⁹⁸, A.G. Foster²¹, D. Fournier¹²⁸, H. Fox⁸⁷, S. Fracchia¹⁴⁶, P. Francavilla^{69a,69b}, M. Franchini^{23b,23a}, S. Franchino^{59a}, D. Francis³⁵, L. Franconi¹³⁰, M. Franklin⁵⁷, M. Frate¹⁶⁹, M. Fraternali^{68a,68b}, D. Freeborn⁹², S.M. Fressard-Batraneanu³⁵, B. Freund¹⁰⁷, W.S. Freund^{78b}, D. Froidevaux³⁵, J.A. Frost¹³¹, C. Fukunaga¹⁶², T. Fusayasu¹¹⁴, J. Fuster¹⁷², O. Gabizon¹⁵⁸, A. Gabrielli^{23b,23a}, A. Gabrielli¹⁸, G.P. Gach^{81a}, S. Gadatsch³⁵, S. Gadomski⁵², G. Gagliardi^{53b,53a}, L.G. Gagnon¹⁰⁷, C. Galea¹¹⁷, B. Galhardo^{136a,136c}, E.J. Gallas¹³¹, B.J. Gallop¹⁴¹, P. Gallus¹³⁸, G. Galster³⁹, K.K. Gan¹²², S. Ganguly³⁷, Y. Gao⁸⁸, Y.S. Gao^{150,m}, C. García¹⁷², J.E. García Navarro¹⁷², J.A. García Pascual^{15a}, M. Garcia-Sciveres¹⁸, R.W. Gardner³⁶, N. Garelli¹⁵⁰, V. Garonne¹³⁰, A. Gascon Bravo⁴⁴, K. Gasnikova⁴⁴, C. Gatti⁴⁹, A. Gaudiello^{53b,53a}, G. Gaudio^{68a}, I.L. Gavrilenko¹⁰⁸, C. Gay¹⁷³, G. Gaycken²⁴, E.N. Gazis¹⁰, C.N.P. Gee¹⁴¹, J. Geisen⁵¹, M. Geisen⁹⁷, M.P. Geisler^{59a}, K. Gellerstedt^{43a,43b}, C. Gemme^{53b}, M.H. Genest⁵⁶, C. Geng¹⁰³, S. Gentile^{70a,70b}, C. Gentsos¹⁶⁰, S. George⁹¹, D. Gerbaudo¹⁴, G. Gessner⁴⁵, S. Ghasemi¹⁴⁸, M. Ghneimat²⁴, B. Giacobbe^{23b}, S. Giagu^{70a,70b}, N. Giangiacomi^{23b,23a}, P. Giannetti^{69a}, S.M. Gibson⁹¹, M. Gignac¹⁷³, M. Gilchriese¹⁸, D. Gillberg³³, G. Gilles¹⁸⁰, D.M. Gingrich^{3,au}, M.P. Giordani^{64a,64c}, F.M. Giorgi^{23b}, P.F. Giraud¹⁴², P. Giromini⁵⁷, G. Giugliarelli^{64a,64c}, D. Giugni^{66a}, F. Giuli¹³¹, C. Giuliani¹¹³, M. Giulini^{59b}, B.K. Gjelsten¹³⁰, S. Gkaitatzis¹⁶⁰, I. Gkialas^{9,j}, E.L. Gkougkousis¹⁴, P. Gkoutoumis¹⁰, L.K. Gladilin¹¹¹, C. Glasman⁹⁶, J. Glatzer¹⁴, P.C.F. Glaysher⁴⁴, A. Glazov⁴⁴, M. Goblirsch-Kolb²⁶, J. Godlewski⁸², S. Goldfarb¹⁰², T. Golling⁵², D. Golubkov¹⁴⁰, A. Gomes^{136a,136b,136d}, R. Goncalves Gama^{78b}, J. Goncalves Pinto Firmino Da Costa¹⁴², R. Gonçalves^{136a}, G. Gonella⁵⁰, L. Gonella²¹, A. Gongadze⁷⁷, F. Gonnella²¹, J.L. Gonski⁵⁷, S. González de la Hoz¹⁷², S. Gonzalez-Sevilla⁵², L. Goossens³⁵, P.A. Gorbounov¹⁰⁹, H.A. Gordon²⁹, B. Gorini³⁵, E. Gorini^{65a,65b}, A. Gorišek⁸⁹, A.T. Goshaw⁴⁷, C. Gössling⁴⁵, M.I. Gostkin⁷⁷, C.A. Gottardo²⁴, C.R. Goudet¹²⁸, D. Goujdami^{34c}, A.G. Goussiou¹⁴⁵, N. Govender^{32b,c}, C. Goy⁵, E. Gozani¹⁵⁸, I. Grabowska-Bold^{81a}, P.O.J. Gradin¹⁷⁰, E.C. Graham⁸⁸, J. Gramling¹⁶⁹, E. Gramstad¹³⁰, S. Grancagnolo¹⁹, V. Gratchev¹³⁴, P.M. Gravila^{27f}, C. Gray⁵⁵, H.M. Gray¹⁸, Z.D. Greenwood^{93,aj}, C. Grefe²⁴, K. Gregersen⁹², I.M. Gregor⁴⁴, P. Grenier¹⁵⁰, K. Grevtsov⁵, J. Griffiths⁸, A.A. Grillo¹⁴³, K. Grimm⁸⁷, S. Grinstein^{14,z}, Ph. Gris³⁷, J.-F. Grivaz¹²⁸, S. Groh⁹⁷, E. Gross¹⁷⁸, J. Grosse-Knetter⁵¹, G.C. Grossi⁹³, Z.J. Grout⁹², A. Grummer¹¹⁶, L. Guan¹⁰³, W. Guan¹⁷⁹, J. Guenther³⁵, F. Guescini^{166a}, D. Guest¹⁶⁹, O. Gueta¹⁵⁹, B. Gui¹²², E. Guido^{53b,53a}, T. Guillemin⁵,

S. Guindon³⁵, U. Gul⁵⁵, C. Gumpert³⁵, J. Guo^{58c}, W. Guo¹⁰³, Y. Guo^{58a,t}, R. Gupta⁴¹, S. Gurbuz^{12c}, G. Gustavino¹²⁴, B.J. Gutelman¹⁵⁸, P. Gutierrez¹²⁴, N.G. Gutierrez Ortiz⁹², C. Gutsche⁹², C. Guyot¹⁴², M.P. Guzik^{81a}, C. Gwenlan¹³¹, C.B. Gwilliam⁸⁸, A. Haas¹²¹, C. Haber¹⁸, H.K. Hadavand⁸, N. Haddad^{34e}, A. Hadeef⁹⁹, S. Hageböck²⁴, M. Hagihara¹⁶⁷, H. Hakobyan^{182,*}, M. Haleem⁴⁴, J. Haley¹²⁵, G. Halladjian¹⁰⁴, G.D. Hallewell⁹⁹, K. Hamacher¹⁸⁰, P. Hamal¹²⁶, K. Hamano¹⁷⁴, A. Hamilton^{32a}, G.N. Hamity¹⁴⁶, P.G. Hamnett⁴⁴, K. Han^{58a,ai}, L. Han^{58a}, S. Han^{15d}, K. Hanagaki^{79,w}, K. Hanawa¹⁶¹, M. Hance¹⁴³, D.M. Handl¹¹², B. Haney¹³³, R. Hankache¹³², P. Hanke^{59a}, J.B. Hansen³⁹, J.D. Hansen³⁹, M.C. Hansen²⁴, P.H. Hansen³⁹, K. Hara¹⁶⁷, A.S. Hard¹⁷⁹, T. Harenberg¹⁸⁰, F. Hariri¹²⁸, S. Harkusha¹⁰⁵, P.F. Harrison¹⁷⁶, N.M. Hartmann¹¹², Y. Hasegawa¹⁴⁷, A. Hasib⁴⁸, S. Hassani¹⁴², S. Haug²⁰, R. Hauser¹⁰⁴, L. Hauswald⁴⁶, L.B. Havener³⁸, M. Havranek¹³⁸, C.M. Hawkes²¹, R.J. Hawkins³⁵, D. Hayden¹⁰⁴, C.P. Hays¹³¹, J.M. Hays⁹⁰, H.S. Hayward⁸⁸, S.J. Haywood¹⁴¹, T. Heck⁹⁷, V. Hedberg⁹⁴, L. Heelan⁸, S. Heer²⁴, K.K. Heidegger⁵⁰, S. Heim⁴⁴, T. Heim¹⁸, B. Heinemann^{44,ap}, J.J. Heinrich¹¹², L. Heinrich¹²¹, C. Heinz⁵⁴, J. Hejbal¹³⁷, L. Helary³⁵, A. Held¹⁷³, S. Hellman^{43a,43b}, C. Helsen³⁵, R.C.W. Henderson⁸⁷, Y. Heng¹⁷⁹, S. Henkelmann¹⁷³, A.M. Henriques Correia³⁵, S. Henrot-Versille¹²⁸, G.H. Herbert¹⁹, H. Herde²⁶, V. Herget¹⁷⁵, Y. Hernández Jiménez^{32c}, H. Herr⁹⁷, G. Herten⁵⁰, R. Hertenberger¹¹², L. Hervas³⁵, T.C. Herwig¹³³, G.G. Hesketh⁹², N.P. Hessey^{166a}, J.W. Hetherly⁴¹, S. Higashino⁷⁹, E. Higón-Rodríguez¹⁷², K. Hildebrand³⁶, E. Hill¹⁷⁴, J.C. Hill³¹, K.H. Hiller⁴⁴, S.J. Hillier²¹, M. Hils⁴⁶, I. Hinchliffe¹⁸, M. Hirose⁵⁰, D. Hirschbuehl¹⁸⁰, B. Hiti⁸⁹, O. Hladik¹³⁷, D.R. Hlaluku^{32c}, X. Hoad⁴⁸, J. Hobbs¹⁵², N. Hod^{166a}, M.C. Hodgkinson¹⁴⁶, P. Hodgson¹⁴⁶, A. Hoecker³⁵, M.R. Hoferkamp¹¹⁶, F. Hoenig¹¹², D. Hohn²⁴, T.R. Holmes³⁶, M. Holzbock¹¹², M. Homann⁴⁵, S. Honda¹⁶⁷, T. Honda⁷⁹, T.M. Hong¹³⁵, B.H. Hooberman¹⁷¹, W.H. Hopkins¹²⁷, Y. Horii¹¹⁵, A.J. Horton¹⁴⁹, J-Y. Hostachy⁵⁶, A. Hostiuc¹⁴⁵, S. Hou¹⁵⁵, A. Hoummada^{34a}, J. Howarth⁹⁸, J. Hoya⁸⁶, M. Hrabovsky¹²⁶, J. Hrdinka³⁵, I. Hristova¹⁹, J. Hrivnac¹²⁸, A. Hrynevich¹⁰⁶, T. Hryn'ova⁵, P.J. Hsu⁶², S.-C. Hsu¹⁴⁵, Q. Hu²⁹, S. Hu^{58c}, Y. Huang^{15a}, Z. Hubacek¹³⁸, F. Hubaut⁹⁹, F. Huegging²⁴, T.B. Huffman¹³¹, E.W. Hughes³⁸, M. Huhtinen³⁵, R.F.H. Hunter³³, P. Huo¹⁵², N. Huseynov^{77,ag}, J. Huston¹⁰⁴, J. Huth⁵⁷, R. Hyneman¹⁰³, G. Iacobucci⁵², G. Iakovidis²⁹, I. Ibragimov¹⁴⁸, L. Iconomidou-Fayard¹²⁸, Z. Idrissi^{34e}, P. Iengo³⁵, O. Igonkina^{118,ac}, T. Iizawa¹⁷⁷, Y. Ikegami⁷⁹, M. Ikeno⁷⁹, Y. Ilchenko¹¹, D. Iliadis¹⁶⁰, N. Ilic¹⁵⁰, F. Iltzsche⁴⁶, G. Introzzi^{68a,68b}, P. Ioannou^{9,*}, M. Iodice^{72a}, K. Iordanidou³⁸, V. Ippolito⁵⁷, M.F. Isacson¹⁷⁰, N. Ishijima¹²⁹, M. Ishino¹⁶¹, M. Ishitsuka¹⁶³, C. Issever¹³¹, S. Istin^{12c,an}, F. Ito¹⁶⁷, J.M. Iturbe Ponce^{61a}, R. Iuppa^{73a,73b}, H. Iwasaki⁷⁹, J.M. Izen⁴², V. Izzo^{67a}, S. Jabbar³, P. Jackson¹, R.M. Jacobs²⁴, V. Jain², G. Jäkel¹⁸⁰, K.B. Jakobi⁹⁷, K. Jakobs⁵⁰, S. Jakobsen⁷⁴, T. Jakoubek¹³⁷, D.O. Jamin¹²⁵, D.K. Jana⁹³, R. Jansky⁵², J. Janssen²⁴, M. Janus⁵¹, P.A. Janus^{81a}, G. Jarlskog⁹⁴, N. Javadov^{77,ag}, T. Javůrek⁵⁰, M. Javurkova⁵⁰, F. Jeanneau¹⁴², L. Jeanty¹⁸, J. Jejelava^{157a,ah}, A. Jelinskas¹⁷⁶, P. Jenni^{50,d}, C. Jeske¹⁷⁶, S. Jézéquel⁵, H. Ji¹⁷⁹, J. Jia¹⁵², H. Jiang⁷⁶, Y. Jiang^{58a}, Z. Jiang^{150,r}, S. Jiggins⁹², J. Jimenez Pena¹⁷², S. Jin^{15c}, A. Jinaru^{27b}, O. Jinnouchi¹⁶³, H. Jivan^{32c}, P. Johansson¹⁴⁶, K.A. Johns⁷, C.A. Johnson⁶³, W.J. Johnson¹⁴⁵, K. Jon-And^{43a,43b}, R.W.L. Jones⁸⁷, S.D. Jones¹⁵³, S. Jones⁷, T.J. Jones⁸⁸, J. Jongmanns^{59a}, P.M. Jorge^{136a,136b}, J. Jovicevic^{166a}, X. Ju¹⁷⁹, A. Juste Rozas^{14,z}, A. Kaczmarska⁸², M. Kado¹²⁸, H. Kagan¹²², M. Kagan¹⁵⁰, S.J. Kahn⁹⁹, T. Kaji¹⁷⁷, E. Kajomovitz¹⁵⁸, C.W. Kalderon⁹⁴, A. Kaluza⁹⁷, S. Kama⁴¹, A. Kamenshchikov¹⁴⁰, N. Kanaya¹⁶¹, L. Kanjir⁸⁹, V.A. Kantserov¹¹⁰, J. Kanzaki⁷⁹, B. Kaplan¹²¹, L.S. Kaplan¹⁷⁹, D. Kar^{32c}, K. Karakostas¹⁰, N. Karastathis¹⁰, M.J. Kareem^{166b}, E. Karentzos¹⁰, S.N. Karpov⁷⁷, Z.M. Karpova⁷⁷, V. Kartvelishvili⁸⁷, A.N. Karyukhin¹⁴⁰, K. Kasahara¹⁶⁷, L. Kashif¹⁷⁹, R.D. Kass¹²², A. Kastanas¹⁵¹, Y. Kataoka¹⁶¹, C. Kato¹⁶¹, A. Katre⁵², J. Katzy⁴⁴, K. Kawade⁸⁰, K. Kawagoe⁸⁵, T. Kawamoto¹⁶¹, G. Kawamura⁵¹, E.F. Kay⁸⁸, V.F. Kazanin^{120b,120a}, R. Keeler¹⁷⁴, R. Kehoe⁴¹, J.S. Keller³³, E. Kellermann⁹⁴, J.J. Kempster⁹¹, J. Kendrick²¹, H. Keoshkerian¹⁶⁵, O. Kepka¹³⁷, S. Kersten¹⁸⁰, B.P. Kerševan⁸⁹, R.A. Keyes¹⁰¹, M. Khader¹⁷¹, F. Khalil-Zada¹³, A. Khanov¹²⁵, A.G. Kharlamov^{120b,120a}, T. Kharlamova^{120b,120a}, A. Khodinov¹⁶⁴, T.J. Khoo⁵², V. Khovanskiy^{109,*}, E. Khramov⁷⁷, J. Khubua^{157b}, S. Kido⁸⁰, C.R. Kilby⁹¹, H.Y. Kim⁸, S.H. Kim¹⁶⁷, Y.K. Kim³⁶, N. Kimura^{64a,64c}, O.M. Kind¹⁹, B.T. King⁸⁸, D. Kirchmeier⁴⁶, J. Kirk¹⁴¹, A.E. Kiryunin¹¹³, T. Kishimoto¹⁶¹, D. Kisielewska^{81a}, V. Kitali⁴⁴, O. Kivernyk⁵, E. Kladiva^{28b}, T. Klapdor-Kleingrothaus⁵⁰, M.H. Klein¹⁰³, M. Klein⁸⁸, U. Klein⁸⁸, K. Kleinknecht⁹⁷, P. Klimek¹¹⁹, A. Klimentov²⁹, R. Klingenberg^{45,*}, T. Klingl²⁴, T. Klioutchnikova³⁵, F.F. Klitzner¹¹², P. Kluit¹¹⁸, S. Kluth¹¹³, E. Kneringer⁷⁴, E.B.F.G. Knoops⁹⁹, A. Knue¹¹³, A. Kobayashi¹⁶¹, D. Kobayashi⁸⁵,

T. Kobayashi¹⁶¹, M. Kobel⁴⁶, M. Kocian¹⁵⁰, P. Kodys¹³⁹, T. Koffas³³, E. Koffeman¹¹⁸, M.K. Köhler¹⁷⁸, N.M. Köhler¹¹³, T. Koi¹⁵⁰, M. Kolb^{59b}, I. Koletsou⁵, T. Kondo⁷⁹, N. Kondrashova^{58c}, K. Köneke⁵⁰, A.C. König¹¹⁷, T. Kono^{79,ao}, R. Konoplich^{121,ak}, N. Konstantinidis⁹², B. Konya⁹⁴, R. Kopeliansky⁶³, S. Koperny^{81a}, K. Korcyl⁸², K. Kordas¹⁶⁰, A. Korn⁹², I. Korolkov¹⁴, E.V. Korolkova¹⁴⁶, O. Kortner¹¹³, S. Kortner¹¹³, T. Kosek¹³⁹, V.V. Kostyukhin²⁴, A. Kotwal⁴⁷, A. Koulouris¹⁰, A. Kourkouveli-Charalampidi^{68a,68b}, C. Kourkouvelis⁹, E. Kourlitis¹⁴⁶, V. Kouskoura²⁹, A.B. Kowalewska⁸², R. Kowalewski¹⁷⁴, T.Z. Kowalski^{81a}, C. Kozakai¹⁶¹, W. Kozanecki¹⁴², A.S. Kozhin¹⁴⁰, V.A. Kramarenko¹¹¹, G. Kramberger⁸⁹, D. Krasnopevtsev¹¹⁰, M.W. Krasny¹³², A. Krasznahorkay³⁵, D. Krauss¹¹³, J.A. Kremer^{81a}, J. Kretzschmar⁸⁸, K. Kreutzfeldt⁵⁴, P. Krieger¹⁶⁵, K. Krizka¹⁸, K. Kroeninger⁴⁵, H. Kroha¹¹³, J. Kroll¹³⁷, J. Kroll¹³³, J. Kroseberg²⁴, J. Krstic¹⁶, U. Kruchonak⁷⁷, H. Krüger²⁴, N. Krumnack⁷⁶, M.C. Kruse⁴⁷, T. Kubota¹⁰², H. Kucuk⁹², S. Kuday^{4b}, J.T. Kuechler¹⁸⁰, S. Kuehn³⁵, A. Kugel^{59a}, F. Kuger¹⁷⁵, T. Kuhl⁴⁴, V. Kukhtin⁷⁷, R. Kukla⁹⁹, Y. Kulchitsky¹⁰⁵, S. Kuleshov^{144b}, Y.P. Kulinich¹⁷¹, M. Kuna¹¹, T. Kunigo⁸³, A. Kupco¹³⁷, T. Kupfer⁴⁵, O. Kuprash¹⁵⁹, H. Kurashige⁸⁰, L.L. Kurchaninov^{166a}, Y.A. Kurochkin¹⁰⁵, M.G. Kurth^{15d}, E.S. Kuwertz¹⁷⁴, M. Kuze¹⁶³, J. Kvita¹²⁶, T. Kwan¹⁷⁴, D. Kyriazopoulos¹⁴⁶, A. La Rosa¹¹³, J.L. La Rosa Navarro^{78d}, L. La Rotonda^{40b,40a}, F. La Ruffa^{40b,40a}, C. Lacasta¹⁷², F. Lacava^{70a,70b}, J. Lacey⁴⁴, D.P.J. Lack⁹⁸, H. Lacker¹⁹, D. Lacour¹³², E. Ladygin⁷⁷, R. Lafaye⁵, B. Laforge¹³², S. Lai⁵¹, S. Lammers⁶³, W. Lampl⁷, E. Lançon²⁹, U. Landgraf⁵⁰, M.P.J. Landon⁹⁰, M.C. Lanfermann⁵², V.S. Lang⁴⁴, J.C. Lange¹⁴, R.J. Langenberg³⁵, A.J. Lankford¹⁶⁹, F. Lanni²⁹, K. Lantsch²⁴, A. Lanza^{68a}, A. Lapertosa^{53b,53a}, S. Laplace¹³², J.F. Laporte¹⁴², T. Lari^{66a}, F. Lasagni Manghi^{23b,23a}, M. Lassnig³⁵, T.S. Lau^{61a}, P. Laurelli⁴⁹, W. Lavrijsen¹⁸, A.T. Law¹⁴³, P. Laycock⁸⁸, T. Lazovich⁵⁷, M. Lazzaroni^{66a,66b}, B. Le¹⁰², O. Le Dortz¹³², E. Le Guirriec⁹⁹, E.P. Le Quilleuc¹⁴², M. LeBlanc⁷, T. LeCompte⁶, F. Ledroit-Guillon⁵⁶, C.A. Lee²⁹, G.R. Lee^{144a}, L. Lee⁵⁷, S.C. Lee¹⁵⁵, B. Lefebvre¹⁰¹, G. Lefebvre¹³², M. Lefebvre¹⁷⁴, F. Legger¹¹², C. Leggett¹⁸, G. Lehmann Miotto³⁵, X. Lei⁷, W.A. Leight⁴⁴, M.A.L. Leite^{78d}, R. Leitner¹³⁹, D. Lellouch¹⁷⁸, B. Lemmer⁵¹, K.J.C. Leney⁹², T. Lenz²⁴, B. Lenzi³⁵, R. Leone⁷, S. Leone^{69a}, C. Leonidopoulos⁴⁸, G. Lerner¹⁵³, C. Leroy¹⁰⁷, R. Les¹⁶⁵, A.A.J. Lesage¹⁴², C.G. Lester³¹, M. Levchenko¹³⁴, J. Levêque⁵, D. Levin¹⁰³, L.J. Levinson¹⁷⁸, M. Levy²¹, D. Lewis⁹⁰, B. Li^{58a,t}, C-Q. Li^{58a}, H. Li¹⁵², L. Li^{58c}, Q. Li^{15d}, Q.Y. Li^{58a}, S. Li⁴⁷, X. Li^{58c}, Y. Li¹⁴⁸, Z. Liang^{15a}, B. Liberti^{71a}, A. Liblong¹⁶⁵, K. Lie^{61c}, W. Liebig¹⁷, A. Limosani¹⁵⁴, C.Y. Lin³¹, K. Lin¹⁰⁴, S.C. Lin¹⁵⁶, T.H. Lin⁹⁷, R.A. Linck⁶³, B.E. Lindquist¹⁵², A.L. Lioni⁵², E. Lipeles¹³³, A. Lipniacka¹⁷, M. Lisovsky^{59b}, T.M. Liss^{171,ar}, A. Lister¹⁷³, A.M. Litke¹⁴³, B. Liu⁷⁶, H.B. Liu²⁹, H. Liu¹⁰³, J.B. Liu^{58a}, J.K.K. Liu¹³¹, J. Liu^{58b}, K. Liu⁹⁹, L. Liu¹⁷¹, M. Liu^{58a}, Y.L. Liu^{58a}, Y.W. Liu^{58a}, M. Livan^{68a,68b}, A. Lleres⁵⁶, J. Llorente Merino^{15a}, S.L. Lloyd⁹⁰, C.Y. Lo^{61b}, F. Lo Sterzo⁴¹, E.M. Lobodzinska⁴⁴, P. Loch⁷, F.K. Loebinger⁹⁸, A. Loesle⁵⁰, K.M. Loew²⁶, T. Lohse¹⁹, K. Lohwasser¹⁴⁶, M. Lokajicek¹³⁷, B.A. Long²⁵, J.D. Long¹⁷¹, R.E. Long⁸⁷, L. Longo^{65a,65b}, K.A. Looper¹²², J.A. Lopez^{144b}, I. Lopez Paz¹⁴, A. Lopez Solis¹³², J. Lorenz¹¹², N. Lorenzo Martinez⁵, M. Losada²², P.J. Lösel¹¹², X. Lou^{15a}, A. Lounis¹²⁸, J. Love⁶, P.A. Love⁸⁷, H. Lu^{61a}, N. Lu¹⁰³, Y.J. Lu⁶², H.J. Lubatti¹⁴⁵, C. Luci^{70a,70b}, A. Lucotte⁵⁶, C. Luedtke⁵⁰, F. Luehring⁶³, W. Lukas⁷⁴, L. Luminari^{70a}, B. Lund-Jensen¹⁵¹, M.S. Lutz¹⁰⁰, P.M. Luzi¹³², D. Lynn²⁹, R. Lysak¹³⁷, E. Lytken⁹⁴, F. Lyu^{15a}, V. Lyubushkin⁷⁷, H. Ma²⁹, L.L. Ma^{58b}, Y. Ma^{58b}, G. Maccarrone⁴⁹, A. Macchiolo¹¹³, C.M. Macdonald¹⁴⁶, J. Machado Miguens^{133,136b}, D. Madaffari¹⁷², R. Madar³⁷, W.F. Mader⁴⁶, A. Madsen⁴⁴, N. Madysa⁴⁶, J. Maeda⁸⁰, S. Maeland¹⁷, T. Maeno²⁹, A.S. Maevskiy¹¹¹, V. Magerl⁵⁰, C. Maiani¹²⁸, C. Maidantchik^{78b}, T. Maier¹¹², A. Maio^{136a,136b,136d}, O. Majersky^{28a}, S. Majewski¹²⁷, Y. Makida⁷⁹, N. Makovec¹²⁸, B. Malaescu¹³², Pa. Malecki⁸², V.P. Maleev¹³⁴, F. Malek⁵⁶, U. Mallik⁷⁵, D. Malon⁶, C. Malone³¹, S. Maltezos¹⁰, S. Malyukov³⁵, J. Mamuzic¹⁷², G. Mancini⁴⁹, I. Mandić⁸⁹, J. Maneira^{136a,136b}, L. Manhaes de Andrade Filho^{78a}, J. Manjarres Ramos⁴⁶, K.H. Mankinen⁹⁴, A. Mann¹¹², A. Manousos³⁵, B. Mansoulie¹⁴², J.D. Mansour^{15a}, R. Mantifel¹⁰¹, M. Mantoani⁵¹, S. Manzoni^{66a,66b}, L. Mapelli³⁵, G. Marceca³⁰, L. March⁵², L. Marchese¹³¹, G. Marchiori¹³², M. Marcisovsky¹³⁷, C.A. Marin Tobon³⁵, M. Marjanovic³⁷, D.E. Marley¹⁰³, F. Marroquim^{78b}, S.P. Marsden⁹⁸, Z. Marshall¹⁸, M.U.F. Martensson¹⁷⁰, S. Marti-Garcia¹⁷², C.B. Martin¹²², T.A. Martin¹⁷⁶, V.J. Martin⁴⁸, B. Martin dit Latour¹⁷, M. Martinez^{14,z}, V.I. Martinez Outschoorn¹⁷¹, S. Martin-Haugh¹⁴¹, V.S. Martoiu^{27b}, A.C. Martyniuk⁹², A. Marzin³⁵, L. Masetti⁹⁷, T. Mashimo¹⁶¹, R. Mashinistov¹⁰⁸, J. Masik⁹⁸, A.L. Maslennikov^{120b,120a}, L.H. Mason¹⁰², L. Massa^{71a,71b}, P. Mastrandrea⁵, A. Mastroberardino^{40b,40a}, T. Masubuchi¹⁶¹, P. Mättig¹⁸⁰, J. Maurer^{27b}

B. Maček⁸⁹, S.J. Maxfield⁸⁸, D.A. Maximov^{120b,120a}, R. Mazini¹⁵⁵, I. Maznas¹⁶⁰, S.M. Mazza^{66a,66b}, N.C. Mc Fadden¹¹⁶, G. Mc Goldrick¹⁶⁵, S.P. Mc Kee¹⁰³, A. McCarn¹⁰³, R.L. McCarthy¹⁵², T.G. McCarthy¹¹³, L.I. McClymont⁹², E.F. McDonald¹⁰², J.A. Mcfayden³⁵, G. Mchedlidze⁵¹, S.J. McMahon¹⁴¹, P.C. McNamara¹⁰², C.J. McNicol¹⁷⁶, R.A. McPherson^{174,ae}, S. Meehan¹⁴⁵, T.M. Megy⁵⁰, S. Mehlhase¹¹², A. Mehta⁸⁸, T. Meideck⁵⁶, B. Meirose⁴², D. Melini^{172,h}, B.R. Mellado Garcia^{32c}, J.D. Mellenthin⁵¹, M. Melo^{28a}, F. Meloni²⁰, A. Melzer²⁴, S.B. Menary⁹⁸, L. Meng⁸⁸, X.T. Meng¹⁰³, A. Mengarelli^{23b,23a}, S. Menke¹¹³, E. Meoni^{40b,40a}, S. Mergelmeyer¹⁹, C. Merlassino²⁰, P. Mermod⁵², L. Merola^{67a,67b}, C. Meroni^{66a}, F.S. Merritt³⁶, A. Messina^{70a,70b}, J. Metcalfe⁶, A.S. Mete¹⁶⁹, C. Meyer¹³³, J. Meyer¹¹⁸, J-P. Meyer¹⁴², H. Meyer Zu Theenhausen^{59a}, F. Miano¹⁵³, R.P. Middleton¹⁴¹, S. Miglioranzi^{53b,53a}, L. Mijović⁴⁸, G. Mikenberg¹⁷⁸, M. Mikesikova¹³⁷, M. Mikuž⁸⁹, M. Milesi¹⁰², A. Milic¹⁶⁵, D.A. Millar⁹⁰, D.W. Miller³⁶, C. Mills⁴⁸, A. Milov¹⁷⁸, D.A. Milstead^{43a,43b}, A.A. Minaenko¹⁴⁰, Y. Minami¹⁶¹, I.A. Minashvili^{157b}, A.I. Mincer¹²¹, B. Mindur^{81a}, M. Mineev⁷⁷, Y. Minegishi¹⁶¹, Y. Ming¹⁷⁹, L.M. Mir¹⁴, A. Mirto^{65a,65b}, K.P. Mistry¹³³, T. Mitani¹⁷⁷, J. Mitrevski¹¹², V.A. Mitsou¹⁷², A. Miucci²⁰, P.S. Miyagawa¹⁴⁶, A. Mizukami⁷⁹, J.U. Mjörnmark⁹⁴, T. Mkrtchyan¹⁸², M. Mlynarikova¹³⁹, T. Moa^{43a,43b}, K. Mochizuki¹⁰⁷, P. Mogg⁵⁰, S. Mohapatra³⁸, S. Molander^{43a,43b}, R. Moles-Valls²⁴, M.C. Mondragon¹⁰⁴, K. Mönig⁴⁴, J. Monk³⁹, E. Monnier⁹⁹, A. Montalbano¹⁵², J. Montejo Berlingen³⁵, F. Monticelli⁸⁶, S. Monzani^{66a}, R.W. Moore³, N. Morange¹²⁸, D. Moreno²², M. Moreno Llácer³⁵, P. Morettini^{53b}, M. Morgenstern¹¹⁸, S. Morgenstern³⁵, D. Mori¹⁴⁹, T. Mori¹⁶¹, M. Morii⁵⁷, M. Morinaga¹⁷⁷, V. Morisbak¹³⁰, A.K. Morley³⁵, G. Mornacchi³⁵, J.D. Morris⁹⁰, L. Morvaj¹⁵², P. Moschovakos¹⁰, M. Mosidze^{157b}, H.J. Moss¹⁴⁶, J. Moss^{150,n}, K. Motohashi¹⁶³, R. Mount¹⁵⁰, E. Mountricha²⁹, E.J.W. Moyse¹⁰⁰, S. Muanza⁹⁹, F. Mueller¹¹³, J. Mueller¹³⁵, R.S.P. Mueller¹¹², D. Muenstermann⁸⁷, P. Mullen⁵⁵, G.A. Mullier²⁰, F.J. Munoz Sanchez⁹⁸, W.J. Murray^{176,141}, H. Musheghyan³⁵, M. Muškinja⁸⁹, C. Mwewa^{32a}, A.G. Myagkov^{140,al}, M. Myska¹³⁸, B.P. Nachman¹⁸, O. Nackenhorst⁵², K. Nagai¹³¹, R. Nagai^{79,ao}, K. Nagano⁷⁹, Y. Nagasaka⁶⁰, K. Nagata¹⁶⁷, M. Nagel⁵⁰, E. Nagy⁹⁹, A.M. Nairz³⁵, Y. Nakahama¹¹⁵, K. Nakamura⁷⁹, T. Nakamura¹⁶¹, I. Nakano¹²³, R.F. Naranjo Garcia⁴⁴, R. Narayan¹¹, D.I. Narrias Villar^{59a}, I. Naryshkin¹³⁴, T. Naumann⁴⁴, G. Navarro²², R. Nayyar⁷, H.A. Neal¹⁰³, P.Y. Nechaeva¹⁰⁸, T.J. Neep¹⁴², A. Negri^{68a,68b}, M. Negrini^{23b}, S. Nektarijevic¹¹⁷, C. Nellist⁵¹, A. Nelson¹⁶⁹, M.E. Nelson¹³¹, S. Nemecek¹³⁷, P. Nemethy¹²¹, M. Nessi^{35,f}, M.S. Neubauer¹⁷¹, M. Neumann¹⁸⁰, P.R. Newman²¹, T.Y. Ng^{61c}, Y.S. Ng¹⁹, T. Nguyen Manh¹⁰⁷, R.B. Nickerson¹³¹, R. Nicolaidou¹⁴², J. Nielsen¹⁴³, N. Nikiporou¹¹, V. Nikolaenko^{140,al}, I. Nikolic-Audit¹³², K. Nikolopoulos²¹, P. Nilsson²⁹, Y. Ninomiya⁷⁹, A. Nisati^{70a}, N. Nishu^{58c}, R. Nisius¹¹³, I. Nitsche⁴⁵, T. Nitta¹⁷⁷, T. Nobe¹⁶¹, Y. Noguchi⁸³, M. Nomachi¹²⁹, I. Nomidis³³, M.A. Nomura²⁹, T. Nooney⁹⁰, M. Nordberg³⁵, N. Norjoharuddeen¹³¹, O. Novgorodova⁴⁶, M. Nozaki⁷⁹, L. Nozka¹²⁶, K. Ntekas¹⁶⁹, E. Nurse⁹², F. Nuti¹⁰², F.G. Oakham^{33,au}, H. Oberlack¹¹³, T. Obermann²⁴, J. Ocariz¹³², A. Ochi⁸⁰, I. Ochoa³⁸, J.P. Ochoa-Ricoux^{144a}, K. O'Connor²⁶, S. Oda⁸⁵, S. Odaka⁷⁹, A. Oh⁹⁸, S.H. Oh⁴⁷, C.C. Ohm¹⁵¹, H. Ohman¹⁷⁰, H. Oide^{53b,53a}, H. Okawa¹⁶⁷, Y. Okumura¹⁶¹, T. Okuyama⁷⁹, A. Olariu^{27b}, L.F. Oleiro Seabra^{136a}, S.A. Olivares Pino^{144a}, D. Oliveira Damazio²⁹, M.J.R. Olsson³⁶, A. Olszewski⁸², J. Olszowska⁸², D.C. O'Neil¹⁴⁹, A. Onofre^{136a,136e}, K. Onogi¹¹⁵, P.U.E. Onyisi¹¹, H. Oppen¹³⁰, M.J. Oreglia³⁶, Y. Oren¹⁵⁹, D. Orestano^{72a,72b}, E.C. Orgill⁹⁸, N. Orlando^{61b}, A.A. O'Rourke⁴⁴, R.S. Orr¹⁶⁵, B. Osculati^{53b,53a,*}, V. O'Shea⁵⁵, R. Ospanov^{58a}, G. Otero y Garzon³⁰, H. Otono⁸⁵, M. Ouchrif^{34d}, F. Ould-Saada¹³⁰, A. Ouraou¹⁴², K.P. Oussoren¹¹⁸, Q. Ouyang^{15a}, M. Owen⁵⁵, R.E. Owen²¹, V.E. Ozcan^{12c}, N. Ozturk⁸, K. Pachal¹⁴⁹, A. Pacheco Pages¹⁴, L. Pacheco Rodriguez¹⁴², C. Padilla Aranda¹⁴, S. Pagan Griso¹⁸, M. Paganini¹⁸¹, F. Paige²⁹, G. Palacino⁶³, S. Palazzo^{40b,40a}, S. Palestini³⁵, M. Palka^{81b}, D. Pallin³⁷, E.St. Panagiotopoulou¹⁰, I. Panagoulas¹⁰, C.E. Pandini⁵², J.G. Panduro Vazquez⁹¹, P. Pani³⁵, S. Panitkin²⁹, D. Pantea^{27b}, L. Paolozzi⁵², T.D. Papadopoulou¹⁰, K. Papageorgiou^{9,j}, A. Paramonov⁶, D. Paredes Hernandez¹⁸¹, A.J. Parker⁸⁷, K.A. Parker⁴⁴, M.A. Parker³¹, F. Parodi^{53b,53a}, J.A. Parsons³⁸, U. Parzefall⁵⁰, V.R. Pascuzzi¹⁶⁵, J.M.P. Pasner¹⁴³, E. Pasqualucci^{70a}, S. Passaggio^{53b}, F. Pastore⁹¹, S. Patariaia⁹⁷, J.R. Pater⁹⁸, T. Pauly³⁵, B. Pearson¹¹³, S. Pedraza Lopez¹⁷², R. Pedro^{136a,136b}, S.V. Peleganchuk^{120b,120a}, O. Penc¹³⁷, C. Peng^{15d}, H. Peng^{58a}, J. Penwell⁶³, B.S. Peralva^{78a}, M.M. Perego¹⁴², D.V. Perepelitsa²⁹, F. Peri¹⁹, L. Perini^{66a,66b}, H. Pernegger³⁵, S. Perrella^{67a,67b}, R. Peschke⁴⁴, V.D. Peshekhonov^{77,*}, K. Peters⁴⁴, R.F.Y. Peters⁹⁸, B.A. Petersen³⁵, T.C. Petersen³⁹, E. Petit⁵⁶, A. Petridis¹, C. Petridou¹⁶⁰, P. Petroff¹²⁸, E. Petrolo^{70a},

M. Petrov¹³¹, F. Petrucci^{72a,72b}, N.E. Pettersson¹⁰⁰, A. Peyaud¹⁴², R. Pezoa^{144b}, F.H. Phillips¹⁰⁴, P.W. Phillips¹⁴¹, G. Piacquadio¹⁵², E. Pianori¹⁷⁶, A. Picazio¹⁰⁰, M.A. Pickering¹³¹, R. Piegaia³⁰, J.E. Pilcher³⁶, A.D. Pilkington⁹⁸, M. Pinamonti^{71a,71b}, J.L. Pinfold³, H. Pirumov⁴⁴, M. Pitt¹⁷⁸, L. Plazak^{28a}, M-A. Pleier²⁹, V. Pleskot⁹⁷, E. Plotnikova⁷⁷, D. Pluth⁷⁶, P. Podberezko^{120b,120a}, R. Poettgen⁹⁴, R. Poggi^{68a,68b}, L. Poggioli¹²⁸, I. Pogrebnyak¹⁰⁴, D. Pohl²⁴, I. Pokharel⁵¹, G. Polesello^{68a}, A. Poley⁴⁴, A. Policicchio^{40b,40a}, R. Polifka³⁵, A. Polini^{23b}, C.S. Pollard⁵⁵, V. Polychronakos²⁹, K. Pommès³⁵, D. Ponomarenko¹¹⁰, L. Pontecorvo^{70a}, G.A. Popeneciu^{27d}, D.M. Portillo Quintero¹³², S. Pospisil¹³⁸, K. Potamianos⁴⁴, I.N. Potrap⁷⁷, C.J. Potter³¹, H. Potti¹¹, T. Poulsen⁹⁴, J. Poveda³⁵, M.E. Pozo Astigarraga³⁵, P. Pralavorio⁹⁹, A. Pranko¹⁸, S. Prell⁷⁶, D. Price⁹⁸, M. Primavera^{65a}, S. Prince¹⁰¹, N. Proklova¹¹⁰, K. Prokofiev^{61c}, F. Prokoshin^{144b}, S. Protopopescu²⁹, J. Proudfoot⁶, M. Przybycien^{81a}, A. Puri¹⁷¹, P. Puzo¹²⁸, J. Qian¹⁰³, Y. Qin⁹⁸, A. Quadt⁵¹, M. Queitsch-Maitland⁴⁴, D. Quilty⁵⁵, S. Raddum¹³⁰, V. Radeka²⁹, V. Radescu¹³¹, S.K. Radhakrishnan¹⁵², P. Radloff¹²⁷, P. Rados¹⁰², F. Ragusa^{66a,66b}, G. Rahal⁹⁵, J.A. Raine⁹⁸, S. Rajagopalan²⁹, C. Rangel-Smith¹⁷⁰, T. Rashid¹²⁸, S. Raspopov⁵, M.G. Ratti^{66a,66b}, D.M. Rauch⁴⁴, F. Rauscher¹¹², S. Rave⁹⁷, I. Ravinovich¹⁷⁸, J.H. Rawling⁹⁸, M. Raymond³⁵, A.L. Read¹³⁰, N.P. Readoff⁵⁶, M. Reale^{65a,65b}, D.M. Rebuzzi^{68a,68b}, A. Redelbach¹⁷⁵, G. Redlinger²⁹, R. Reece¹⁴³, R.G. Reed^{32c}, K. Reeves⁴², L. Rehnisch¹⁹, J. Reichert¹³³, A. Reiss⁹⁷, C. Rembser³⁵, H. Ren^{15d}, M. Rescigno^{70a}, S. Resconi^{66a}, E.D. Resseguie¹³³, S. Rettie¹⁷³, E. Reynolds²¹, O.L. Rezanova^{120b,120a}, P. Reznicek¹³⁹, R. Rezvani¹⁰⁷, R. Richter¹¹³, S. Richter⁹², E. Richter-Was^{81b}, O. Ricken²⁴, M. Ridel¹³², P. Rieck¹¹³, C.J. Riegel¹⁸⁰, J. Rieger⁵¹, O. Rifki¹²⁴, M. Rijssenbeek¹⁵², A. Rimoldi^{68a,68b}, M. Rimoldi²⁰, L. Rinaldi^{23b}, G. Ripellino¹⁵¹, B. Ristic³⁵, E. Ritsch³⁵, I. Riu¹⁴, F. Rizatdinova¹²⁵, E. Rizvi⁹⁰, C. Rizzi¹⁴, R.T. Roberts⁹⁸, S.H. Robertson^{101,ae}, A. Robichaud-Veronneau¹⁰¹, D. Robinson³¹, J.E.M. Robinson⁴⁴, A. Robson⁵⁵, E. Rocco⁹⁷, C. Roda^{69a,69b}, Y. Rodina^{99,aa}, S. Rodriguez Bosca¹⁷², A. Rodriguez Perez¹⁴, D. Rodriguez Rodriguez¹⁷², S. Roe³⁵, C.S. Rogan⁵⁷, O. Röhne¹³⁰, J. Roloff⁵⁷, A. Romaniouk¹¹⁰, M. Romano^{23b,23a}, S.M. Romano Saez³⁷, E. Romero Adam¹⁷², N. Rompotis⁸⁸, M. Ronzani⁵⁰, L. Roos¹³², S. Rosati^{70a}, K. Rosbach⁵⁰, P. Rose¹⁴³, N-A. Rosien⁵¹, E. Rossi^{67a,67b}, L.P. Rossi^{53b}, J.H.N. Rosten³¹, R. Rosten¹⁴⁵, M. Rotaru^{27b}, J. Rothberg¹⁴⁵, D. Rousseau¹²⁸, D. Roy^{32c}, A. Rozanov⁹⁹, Y. Rozen¹⁵⁸, X. Ruan^{32c}, F. Rubbo¹⁵⁰, F. Rühr⁵⁰, A. Ruiz-Martinez³³, Z. Rurikova⁵⁰, N.A. Rusakovich⁷⁷, H.L. Russell¹⁰¹, J.P. Rutherford⁷, N. Ruthmann³⁵, E.M. Rüttinger^{44,1}, Y.F. Ryabov¹³⁴, M. Rybar¹⁷¹, G. Rybkin¹²⁸, S. Ryu⁶, A. Ryzhov¹⁴⁰, G.F. Rzehorz⁵¹, A.F. Saavedra¹⁵⁴, G. Sabato¹¹⁸, S. Sacerdoti³⁰, H.F-W. Sadrozinski¹⁴³, R. Sadykov⁷⁷, F. Safai Tehrani^{70a}, P. Saha¹¹⁹, M. Sahinsoy^{59a}, M. Saimpert⁴⁴, M. Saito¹⁶¹, T. Saito¹⁶¹, H. Sakamoto¹⁶¹, Y. Sakurai¹⁷⁷, G. Salamanna^{72a,72b}, J.E. Salazar Loyola^{144b}, D. Salek¹¹⁸, P.H. Sales De Bruin¹⁷⁰, D. Salihagic¹¹³, A. Salnikov¹⁵⁰, J. Salt¹⁷², D. Salvatore^{40b,40a}, F. Salvatore¹⁵³, A. Salvucci^{61a,61b,61c}, A. Salzburger³⁵, D. Sammel⁵⁰, D. Sampsonidis¹⁶⁰, D. Sampsonidou¹⁶⁰, J. Sánchez¹⁷², A. Sanchez Pineda^{64a,64c}, H. Sandaker¹³⁰, R.L. Sandbach⁹⁰, C.O. Sander⁴⁴, M. Sandhoff¹⁸⁰, C. Sandoval²², D.P.C. Sankey¹⁴¹, M. Sannino^{53b,53a}, Y. Sano¹¹⁵, A. Sansoni⁴⁹, C. Santoni³⁷, H. Santos^{136a}, I. Santoyo Castillo¹⁵³, A. Saponov⁷⁷, J.G. Saraiva^{136a,136d}, O. Sasaki⁷⁹, K. Sato¹⁶⁷, E. Sauvan⁵, G. Savage⁹¹, P. Savard^{165,au}, N. Savic¹¹³, C. Sawyer¹⁴¹, L. Sawyer^{93,aj}, C. Sbarra^{23b}, A. Sbrizzi^{23b,23a}, T. Scanlon⁹², D.A. Scannicchio¹⁶⁹, J. Schaarschmidt¹⁴⁵, P. Schacht¹¹³, B.M. Schachtner¹¹², D. Schaefer³⁶, L. Schaefer¹³³, J. Schaeffer⁹⁷, S. Schaepe³⁵, S. Schaezel^{59b}, U. Schäfer⁹⁷, A.C. Schaffer¹²⁸, D. Schaile¹¹², R.D. Schamberger¹⁵², V.A. Schegelsky¹³⁴, D. Scheirich¹³⁹, F. Schenck¹⁹, M. Schernau¹⁶⁹, C. Schiavi^{53b,53a}, S. Schier¹⁴³, L.K. Schildgen²⁴, C. Schillo⁵⁰, M. Schioppa^{40b,40a}, S. Schlenker³⁵, K.R. Schmidt-Sommerfeld¹¹³, K. Schmieden³⁵, C. Schmitt⁹⁷, S. Schmitt⁴⁴, S. Schmitz⁹⁷, U. Schnoor⁵⁰, L. Schoeffel¹⁴², A. Schoening^{59b}, B.D. Schoenrock¹⁰⁴, E. Schopf²⁴, M. Schott⁹⁷, J.F.P. Schouwenberg¹¹⁷, J. Schovancova³⁵, S. Schramm⁵², N. Schuh⁹⁷, A. Schulte⁹⁷, M.J. Schultens²⁴, H-C. Schultz-Coulon^{59a}, M. Schumacher⁵⁰, B.A. Schumm¹⁴³, Ph. Schune¹⁴², A. Schwartzman¹⁵⁰, T.A. Schwarz¹⁰³, H. Schweiger⁹⁸, Ph. Schwemling¹⁴², R. Schwienhorst¹⁰⁴, A. Sciandra²⁴, G. Sciolla²⁶, M. Scornajenghi^{40b,40a}, F. Scuri^{69a}, F. Scutti¹⁰², J. Searcy¹⁰³, P. Seema²⁴, S.C. Seidel¹¹⁶, A. Seiden¹⁴³, J.M. Seixas^{78b}, G. Sekhniaidze^{67a}, K. Sekhon¹⁰³, S.J. Sekula⁴¹, N. Semprini-Cesari^{23b,23a}, S. Senkin³⁷, C. Serfon¹³⁰, L. Serin¹²⁸, L. Serkin^{64a,64b}, M. Sessa^{72a,72b}, R. Seuster¹⁷⁴, H. Severini¹²⁴, F. Sforza¹⁶⁸, A. Sfyrly⁵², E. Shabalina⁵¹, N.W. Shaikh^{43a,43b}, L.Y. Shan^{15a}, R. Shang¹⁷¹, J.T. Shank²⁵, M. Shapiro¹⁸, P.B. Shatalov¹⁰⁹, K. Shaw^{64a,64b}, S.M. Shaw⁹⁸, A. Shcherbakova^{43a,43b}, C.Y. Shehu¹⁵³, Y. Shen¹²⁴,

N. Sherafati ³³, A.D. Sherman ²⁵, P. Sherwood ⁹², L. Shi ^{155,aq}, S. Shimizu ⁸⁰, C.O. Shimmin ¹⁸¹,
 M. Shimojima ¹¹⁴, I.P.J. Shipsey ¹³¹, S. Shirabe ⁸⁵, M. Shiyakova ⁷⁷, J. Shlomi ¹⁷⁸, A. Shmeleva ¹⁰⁸,
 D. Shoaleh Saadi ¹⁰⁷, M.J. Shochet ³⁶, S. Shojaii ¹⁰², D.R. Shope ¹²⁴, S. Shrestha ¹²², E. Shulga ¹¹⁰,
 M.A. Shupe ⁷, P. Sicho ¹³⁷, A.M. Sickles ¹⁷¹, P.E. Sidebo ¹⁵¹, E. Sideras Haddad ^{32c}, O. Sidiropoulou ¹⁷⁵,
 A. Sidoti ^{23b,23a}, F. Siegert ⁴⁶, Dj. Sijacki ¹⁶, J. Silva ^{136a,136d}, M. Silva Jr. ¹⁷⁹, S.B. Silverstein ^{43a}, V. Simak ¹³⁸,
 L. Simic ⁷⁷, S. Simion ¹²⁸, E. Simioni ⁹⁷, B. Simmons ⁹², M. Simon ⁹⁷, P. Sinervo ¹⁶⁵, N.B. Sinev ¹²⁷,
 M. Sioli ^{23b,23a}, G. Siragusa ¹⁷⁵, I. Siral ¹⁰³, S.Yu. Sivoklokov ¹¹¹, J. Sjölin ^{43a,43b}, M.B. Skinner ⁸⁷,
 P. Skubic ¹²⁴, M. Slater ²¹, T. Slavicek ¹³⁸, M. Slawinska ⁸², K. Sliwa ¹⁶⁸, R. Slovak ¹³⁹, V. Smakhtin ¹⁷⁸,
 B.H. Smart ⁵, J. Smiesko ^{28a}, N. Smirnov ¹¹⁰, S.Yu. Smirnov ¹¹⁰, Y. Smirnov ¹¹⁰, L.N. Smirnova ¹¹¹,
 O. Smirnova ⁹⁴, J.W. Smith ⁵¹, M.N.K. Smith ³⁸, R.W. Smith ³⁸, M. Smizanska ⁸⁷, K. Smolek ¹³⁸,
 A.A. Snesarev ¹⁰⁸, I.M. Snyder ¹²⁷, S. Snyder ²⁹, R. Sobie ^{174,ae}, F. Socher ⁴⁶, A. Soffer ¹⁵⁹, A. Søgaard ⁴⁸,
 D.A. Soh ¹⁵⁵, G. Sokhrannyi ⁸⁹, C.A. Solans Sanchez ³⁵, M. Solar ¹³⁸, E.Yu. Soldatov ¹¹⁰, U. Soldevila ¹⁷²,
 A.A. Solodkov ¹⁴⁰, A. Soloshenko ⁷⁷, O.V. Solovyanov ¹⁴⁰, V. Solovyev ¹³⁴, P. Sommer ¹⁴⁶, H. Son ¹⁶⁸,
 A. Sopczak ¹³⁸, D. Sosa ^{59b}, C.L. Sotiropoulou ^{69a,69b}, S. Sottocornola ^{68a,68b}, R. Soualah ^{64a,64c,i},
 A.M. Soukharev ^{120b,120a}, D. South ⁴⁴, B.C. Sowden ⁹¹, S. Spagnolo ^{65a,65b}, M. Spalla ^{69a,69b},
 M. Spangenberg ¹⁷⁶, F. Spanò ⁹¹, D. Sperlich ¹⁹, F. Spettel ¹¹³, T.M. Spieker ^{59a}, R. Spighi ^{23b}, G. Spigo ³⁵,
 L.A. Spiller ¹⁰², M. Spousta ¹³⁹, R.D. St. Denis ^{55,*}, A. Stabile ^{66a,66b}, R. Stamen ^{59a}, S. Stamm ¹⁹,
 E. Stanecka ⁸², R.W. Stanek ⁶, C. Stanescu ^{72a}, M.M. Stanitzki ⁴⁴, B. Stapf ¹¹⁸, S. Stapnes ¹³⁰,
 E.A. Starchenko ¹⁴⁰, G.H. Stark ³⁶, J. Stark ⁵⁶, S.H. Stark ³⁹, P. Staroba ¹³⁷, P. Starovoitov ^{59a}, S. Stärz ³⁵,
 R. Staszewski ⁸², M. Stegler ⁴⁴, P. Steinberg ²⁹, B. Stelzer ¹⁴⁹, H.J. Stelzer ³⁵, O. Stelzer-Chilton ^{166a},
 H. Stenzel ⁵⁴, T.J. Stevenson ⁹⁰, G.A. Stewart ⁵⁵, M.C. Stockton ¹²⁷, M. Stoebe ¹⁰¹, G. Stoica ^{27b}, P. Stolte ⁵¹,
 S. Stonjek ¹¹³, A.R. Stradling ⁸, A. Straessner ⁴⁶, M.E. Stramaglia ²⁰, J. Strandberg ¹⁵¹, S. Strandberg ^{43a,43b},
 M. Strauss ¹²⁴, P. Strizenec ^{28b}, R. Ströhmer ¹⁷⁵, D.M. Strom ¹²⁷, R. Stroynowski ⁴¹, A. Strubig ⁴⁸,
 S.A. Stucci ²⁹, B. Stugu ¹⁷, N.A. Styles ⁴⁴, D. Su ¹⁵⁰, J. Su ¹³⁵, S. Suchek ^{59a}, Y. Sugaya ¹²⁹, M. Suk ¹³⁸,
 V.V. Sulim ¹⁰⁸, D.M.S. Sultan ^{73a,73b}, S. Sultansoy ^{4c}, T. Sumida ⁸³, S. Sun ⁵⁷, X. Sun ³, K. Suruliz ¹⁵³,
 C.J.E. Suster ¹⁵⁴, M.R. Sutton ¹⁵³, S. Suzuki ⁷⁹, M. Svatos ¹³⁷, M. Swiatlowski ³⁶, S.P. Swift ², I. Sykora ^{28a},
 T. Sykora ¹³⁹, D. Ta ⁵⁰, K. Tackmann ^{44,ab}, J. Taenzer ¹⁵⁹, A. Taffard ¹⁶⁹, R. Tafirout ^{166a}, E. Tahirovic ⁹⁰,
 N. Taiblum ¹⁵⁹, H. Takai ²⁹, R. Takashima ⁸⁴, E.H. Takasugi ¹¹³, K. Takeda ⁸⁰, T. Takeshita ¹⁴⁷, Y. Takubo ⁷⁹,
 M. Talby ⁹⁹, A.A. Talyshev ^{120b,120a}, J. Tanaka ¹⁶¹, M. Tanaka ¹⁶³, R. Tanaka ¹²⁸, R. Tanioka ⁸⁰,
 B.B. Tannenwald ¹²², S. Tapia Araya ^{144b}, S. Tapprogge ⁹⁷, S. Tarem ¹⁵⁸, G.F. Tartarelli ^{66a}, P. Tas ¹³⁹,
 M. Tasevsky ¹³⁷, T. Tashiro ⁸³, E. Tassi ^{40b,40a}, A. Tavares Delgado ^{136a,136b}, Y. Tayalati ^{34e}, A.C. Taylor ¹¹⁶,
 A.J. Taylor ⁴⁸, G.N. Taylor ¹⁰², P.T.E. Taylor ¹⁰², W. Taylor ^{166b}, P. Teixeira-Dias ⁹¹, D. Temple ¹⁴⁹,
 H. Ten Kate ³⁵, P.K. Teng ¹⁵⁵, J.J. Teoh ¹²⁹, F. Tepel ¹⁸⁰, S. Terada ⁷⁹, K. Terashi ¹⁶¹, J. Terron ⁹⁶, S. Terzo ¹⁴,
 M. Testa ⁴⁹, R.J. Teuscher ^{165,ae}, S.J. Thais ¹⁸¹, T. Theveneaux-Pelzer ⁹⁹, F. Thiele ³⁹, J.P. Thomas ²¹,
 J. Thomas-Wilsker ⁹¹, A.S. Thompson ⁵⁵, P.D. Thompson ²¹, L.A. Thomsen ¹⁸¹, E. Thomson ¹³³, Y. Tian ³⁸,
 M.J. Tibbetts ¹⁸, R.E. Ticse Torres ⁵¹, V.O. Tikhomirov ^{108,am}, Yu.A. Tikhonov ^{120b,120a}, S. Timoshenko ¹¹⁰,
 P. Tipton ¹⁸¹, S. Tisserant ⁹⁹, K. Todome ¹⁶³, S. Todorova-Nova ⁵, S. Todt ⁴⁶, J. Tojo ⁸⁵, S. Tokár ^{28a},
 K. Tokushuku ⁷⁹, E. Tolley ¹²², L. Tomlinson ⁹⁸, M. Tomoto ¹¹⁵, L. Tompkins ^{150,r}, K. Toms ¹¹⁶, B. Tong ⁵⁷,
 P. Tornambe ⁵⁰, E. Torrence ¹²⁷, H. Torres ⁴⁶, E. Torró Pastor ¹⁴⁵, J. Toth ^{99,ad}, F. Touchard ⁹⁹, D.R. Tovey ¹⁴⁶,
 C.J. Treado ¹²¹, T. Trefzger ¹⁷⁵, F. Tresoldi ¹⁵³, A. Tricoli ²⁹, I.M. Trigger ^{166a}, S. Trincaz-Duvold ¹³²,
 M.F. Tripiana ¹⁴, W. Trischuk ¹⁶⁵, B. Trocme ⁵⁶, A. Trofymov ⁴⁴, C. Troncon ^{66a}, M. Trovatelli ¹⁷⁴,
 L. Truong ^{32b}, M. Trzebinski ⁸², A. Trzupek ⁸², K.W. Tsang ^{61a}, J.C.-L. Tseng ¹³¹, P.V. Tsiarehka ¹⁰⁵,
 N. Tsirintanis ⁹, S. Tsiskaridze ¹⁴, V. Tsiskaridze ⁵⁰, E.G. Tskhadadze ^{157a}, I.I. Tsukerman ¹⁰⁹, V. Tsulaia ¹⁸,
 S. Tsuno ⁷⁹, D. Tsybychev ¹⁵², Y. Tu ^{61b}, A. Tudorache ^{27b}, V. Tudorache ^{27b}, T.T. Tulbure ^{27a}, A.N. Tuna ⁵⁷,
 S. Turchikhin ⁷⁷, D. Turgeman ¹⁷⁸, I. Turk Cakir ^{4b,v}, R. Turra ^{66a}, P.M. Tuts ³⁸, G. Uccielli ^{23b,23a}, I. Ueda ⁷⁹,
 M. Ughetto ^{43a,43b}, F. Ukegawa ¹⁶⁷, G. Unal ³⁵, A. Undrus ²⁹, G. Unel ¹⁶⁹, F.C. Ungaro ¹⁰², Y. Unno ⁷⁹,
 K. Uno ¹⁶¹, J. Urban ^{28b}, P. Urquijo ¹⁰², P. Urrejola ⁹⁷, G. Usai ⁸, J. Usui ⁷⁹, L. Vacavant ⁹⁹, V. Vacek ¹³⁸,
 B. Vachon ¹⁰¹, K.O.H. Vadla ¹³⁰, A. Vaidya ⁹², C. Valderanis ¹¹², E. Valdes Santurio ^{43a,43b}, M. Valente ⁵²,
 S. Valentinetti ^{23b,23a}, A. Valero ¹⁷², L. Valéry ¹⁴, A. Vallier ⁵, J.A. Valls Ferrer ¹⁷²,
 W. Van Den Wollenberg ¹¹⁸, H. Van der Graaf ¹¹⁸, P. Van Gemmeren ⁶, J. Van Nieuwkoop ¹⁴⁹,
 I. Van Vulpen ¹¹⁸, M.C. van Woerden ¹¹⁸, M. Vanadia ^{71a,71b}, W. Vandelli ³⁵, A. Vaniachine ¹⁶⁴,
 P. Vankov ¹¹⁸, G. Vardanyan ¹⁸², R. Vari ^{70a}, E.W. Varnes ⁷, C. Varni ^{53b,53a}, T. Varol ⁴¹, D. Varouchas ¹²⁸,

A. Vartapetian⁸, K.E. Varvell¹⁵⁴, G.A. Vasquez^{144b}, J.G. Vasquez¹⁸¹, F. Vazeille³⁷, D. Vazquez Furelos¹⁴, T. Vazquez Schroeder¹⁰¹, J. Veatch⁵¹, V. Veeraraghavan⁷, L.M. Veloce¹⁶⁵, F. Veloso^{136a,136c}, S. Veneziano^{70a}, A. Ventura^{65a,65b}, M. Venturi¹⁷⁴, N. Venturi³⁵, V. Vercesi^{68a}, M. Verducci^{72a,72b}, W. Verkerke¹¹⁸, A.T. Vermeulen¹¹⁸, J.C. Vermeulen¹¹⁸, M.C. Vetterli^{149,au}, N. Viaux Maira^{144b}, O. Viazlo⁹⁴, I. Vichou^{171,*}, T. Vickey¹⁴⁶, O.E. Vickey Boeriu¹⁴⁶, G.H.A. Viehhauser¹³¹, S. Viel¹⁸, L. Vigani¹³¹, M. Villa^{23b,23a}, M. Villaplana Perez^{66a,66b}, E. Vilucchi⁴⁹, M.G. Vincter³³, V.B. Vinogradov⁷⁷, A. Vishwakarma⁴⁴, C. Vittori^{23b,23a}, I. Vivarelli¹⁵³, S. Vlachos¹⁰, M. Vogel¹⁸⁰, P. Vokac¹³⁸, G. Volpi¹⁴, S.E. von Buddenbrock^{32c}, H. von der Schmitt¹¹³, E. Von Toerne²⁴, V. Vorobel¹³⁹, K. Vorobev¹¹⁰, M. Vos¹⁷², R. Voss³⁵, J.H. Vossebeld⁸⁸, N. Vranjes¹⁶, M. Vranjes Milosavljevic¹⁶, V. Vrba¹³⁸, M. Vreeswijk¹¹⁸, T. Šfiligoj⁸⁹, R. Vuillermet³⁵, I. Vukotic³⁶, T. Ženiš^{28a}, L. Živković¹⁶, P. Wagner²⁴, W. Wagner¹⁸⁰, J. Wagner-Kuhr¹¹², H. Wahlberg⁸⁶, S. Wahrenmund⁴⁶, K. Wakamiya⁸⁰, J. Walder⁸⁷, R. Walker¹¹², W. Walkowiak¹⁴⁸, V. Wallangen^{43a,43b}, C. Wang^{15c}, C. Wang^{58b,e}, F. Wang¹⁷⁹, H. Wang¹⁸, H. Wang³, J. Wang¹⁵⁴, J. Wang⁴⁴, Q. Wang¹²⁴, R.-J. Wang¹³², R. Wang⁶, S.M. Wang¹⁵⁵, T. Wang³⁸, W. Wang^{155,p}, W.X. Wang^{58a,af}, Z. Wang^{58c}, C. Wanotayaroj⁴⁴, A. Warburton¹⁰¹, C.P. Ward³¹, D.R. Wardrope⁹², A. Washbrook⁴⁸, P.M. Watkins²¹, A.T. Watson²¹, M.F. Watson²¹, G. Watts¹⁴⁵, S. Watts⁹⁸, B.M. Waugh⁹², A.F. Webb¹¹, S. Webb⁹⁷, M.S. Weber²⁰, S.A. Weber³³, S.M. Weber^{59a}, S.W. Weber¹⁷⁵, J.S. Webster⁶, A.R. Weidberg¹³¹, B. Weinert⁶³, J. Weingarten⁵¹, M. Weirich⁹⁷, C. Weiser⁵⁰, P.S. Wells³⁵, T. Wenaus²⁹, T. Wengler³⁵, S. Wenig³⁵, N. Wermes²⁴, M.D. Werner⁷⁶, P. Werner³⁵, M. Wessels^{59a}, T.D. Weston²⁰, K. Whalen¹²⁷, N.L. Whallon¹⁴⁵, A.M. Wharton⁸⁷, A.S. White¹⁰³, A. White⁸, M.J. White¹, R. White^{144b}, D. Whiteson¹⁶⁹, B.W. Whitmore⁸⁷, F.J. Wickens¹⁴¹, W. Wiedenmann¹⁷⁹, M. Wielers¹⁴¹, C. Wiglesworth³⁹, L.A.M. Wiik-Fuchs⁵⁰, A. Wildauer¹¹³, F. Wilk⁹⁸, H.G. Wilkens³⁵, H.H. Williams¹³³, S. Williams³¹, C. Willis¹⁰⁴, S. Willocq¹⁰⁰, J.A. Wilson²¹, I. Wingerter-Seez⁵, E. Winkels¹⁵³, F. Winklmeier¹²⁷, O.J. Winston¹⁵³, B.T. Winter²⁴, M. Wittgen¹⁵⁰, M. Wobisch⁹³, A. Wolf⁹⁷, T.M.H. Wolf¹¹⁸, R. Wolff⁹⁹, M.W. Wolter⁸², H. Wolters^{136a,136c}, V.W.S. Wong¹⁷³, N.L. Woods¹⁴³, S.D. Worm²¹, B.K. Wosiek⁸², J. Wotschack³⁵, K.W. Woźniak⁸², M. Wu³⁶, S.L. Wu¹⁷⁹, X. Wu⁵², Y. Wu¹⁰³, T.R. Wyatt⁹⁸, B.M. Wynne⁴⁸, S. Xella³⁹, Z. Xi¹⁰³, L. Xia^{15b}, D. Xu^{15a}, L. Xu²⁹, T. Xu¹⁴², W. Xu¹⁰³, B. Yabsley¹⁵⁴, S. Yacoub^{32a}, D. Yamaguchi¹⁶³, Y. Yamaguchi¹⁶³, A. Yamamoto⁷⁹, S. Yamamoto¹⁶¹, T. Yamanaka¹⁶¹, F. Yamane⁸⁰, M. Yamatani¹⁶¹, T. Yamazaki¹⁶¹, Y. Yamazaki⁸⁰, Z. Yan²⁵, H.J. Yang^{58c,58d}, H.T. Yang¹⁸, Y. Yang¹⁵⁵, Z. Yang¹⁷, W.-M. Yao¹⁸, Y.C. Yap⁴⁴, Y. Yasu⁷⁹, E. Yatsenko⁵, K.H. Yau Wong²⁴, J. Ye⁴¹, S. Ye²⁹, I. Yeletsikh⁷⁷, E. Yigitbasi²⁵, E. Yildirim⁹⁷, K. Yorita¹⁷⁷, K. Yoshihara¹³³, C.J.S. Young³⁵, C. Young¹⁵⁰, J. Yu⁸, J. Yu⁷⁶, S.P.Y. Yuen²⁴, I. Yusuff^{31,a}, B. Zabinski⁸², G. Zacharis¹⁰, R. Zaidan¹⁴, A.M. Zaitsev^{140,al}, N. Zakharchuk⁴⁴, J. Zalieckas¹⁷, A. Zaman¹⁵², S. Zambito⁵⁷, D. Zanzi¹⁰², C. Zeitnitz¹⁸⁰, G. Zemaityte¹³¹, A. Zemla^{81a}, J.C. Zeng¹⁷¹, Q. Zeng¹⁵⁰, O. Zenin¹⁴⁰, D. Zerwas¹²⁸, D.F. Zhang^{58b}, D. Zhang¹⁰³, F. Zhang¹⁷⁹, G. Zhang^{58a,af}, H. Zhang¹²⁸, J. Zhang⁶, L. Zhang⁵⁰, L. Zhang^{58a}, M. Zhang¹⁷¹, P. Zhang^{15c}, R. Zhang^{58a,e}, R. Zhang²⁴, X. Zhang^{58b}, Y. Zhang^{15d}, Z. Zhang¹²⁸, X. Zhao⁴¹, Y. Zhao^{58b,128,ai}, Z. Zhao^{58a}, A. Zhemchugov⁷⁷, B. Zhou¹⁰³, C. Zhou¹⁷⁹, L. Zhou⁴¹, M.S. Zhou^{15d}, M. Zhou¹⁵², N. Zhou^{58c}, Y. Zhou⁷, C.G. Zhu^{58b}, H. Zhu^{15a}, J. Zhu¹⁰³, Y. Zhu^{58a}, X. Zhuang^{15a}, K. Zhukov¹⁰⁸, A. Zibell¹⁷⁵, D. Zieminska⁶³, N.I. Zimine⁷⁷, C. Zimmermann⁹⁷, S. Zimmermann⁵⁰, Z. Zinonos¹¹³, M. Zinser⁹⁷, M. Ziolkowski¹⁴⁸, G. Zoernig¹⁷⁹, A. Zoccoli^{23b,23a}, R. Zou³⁶, M. Zur Nedden¹⁹, L. Zwalinski³⁵

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

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

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

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

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

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

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

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

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

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

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

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

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

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

¹⁵ (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Physics Department, Tsinghua University, Beijing; (c) Department of Physics, Nanjing University, Nanjing;

¹⁶ University of Chinese Academy of Science (UCAS), Beijing, China

¹⁷ Institute of Physics, University of Belgrade, Belgrade, Serbia

- ¹⁷ Department for Physics and Technology, University of Bergen, Bergen, Norway
- ¹⁸ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States of America
- ¹⁹ Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
- ²⁰ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ²¹ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ²² Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia
- ²³ (a) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna; (b) INFN Sezione di Bologna, Italy
- ²⁴ Physikalisches Institut, Universität Bonn, Bonn, Germany
- ²⁵ Department of Physics, Boston University, Boston, MA, United States of America
- ²⁶ Department of Physics, Brandeis University, Waltham, MA, United States of America
- ²⁷ (a) Transilvania University of Brasov, Brasov; (b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (e) University Politehnica Bucharest, Bucharest; (f) West University in Timisoara, Timisoara, Romania
- ²⁸ (a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- ²⁹ Physics Department, Brookhaven National Laboratory, Upton, NY, United States of America
- ³⁰ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ³¹ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ³² (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- ³³ Department of Physics, Carleton University, Ottawa, ON, Canada
- ³⁴ (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires (CNESTEN), Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
- ³⁵ CERN, Geneva, Switzerland
- ³⁶ Enrico Fermi Institute, University of Chicago, Chicago, IL, United States of America
- ³⁷ LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
- ³⁸ Nevis Laboratory, Columbia University, Irvington, NY, United States of America
- ³⁹ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ⁴⁰ (a) Dipartimento di Fisica, Università della Calabria, Rende; (b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
- ⁴¹ Physics Department, Southern Methodist University, Dallas, TX, United States of America
- ⁴² Physics Department, University of Texas at Dallas, Richardson, TX, United States of America
- ⁴³ (a) Department of Physics, Stockholm University; (b) Oskar Klein Centre, Stockholm, Sweden
- ⁴⁴ Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
- ⁴⁵ Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁶ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁴⁷ Department of Physics, Duke University, Durham, NC, United States of America
- ⁴⁸ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁹ INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- ⁵⁰ Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
- ⁵¹ II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
- ⁵² Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
- ⁵³ (a) Dipartimento di Fisica, Università di Genova, Genova; (b) INFN Sezione di Genova, Italy
- ⁵⁴ II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵⁵ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁶ LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
- ⁵⁷ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States of America
- ⁵⁸ (a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; (b) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; (c) School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai; (d) Tsung-Dao Lee Institute, Shanghai, China
- ⁵⁹ (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ⁶⁰ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶¹ (a) Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, University of Hong Kong, Hong Kong; (c) Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- ⁶² Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
- ⁶³ Department of Physics, Indiana University, Bloomington, IN, United States of America
- ⁶⁴ (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- ⁶⁵ (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁶⁶ (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁶⁷ (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ⁶⁸ (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ⁶⁹ (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ⁷⁰ (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- ⁷¹ (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ⁷² (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- ⁷³ (a) INFN-TIFPA; (b) Università degli Studi di Trento, Trento, Italy
- ⁷⁴ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁷⁵ University of Iowa, Iowa City, IA, United States of America
- ⁷⁶ Department of Physics and Astronomy, Iowa State University, Ames, IA, United States of America
- ⁷⁷ Joint Institute for Nuclear Research, Dubna, Russia
- ⁷⁸ (a) Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; (b) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (c) Universidade Federal de São João del Rei (UFSJ), São João del Rei; (d) Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
- ⁷⁹ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁸⁰ Graduate School of Science, Kobe University, Kobe, Japan
- ⁸¹ (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- ⁸² Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- ⁸³ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁸⁴ Kyoto University of Education, Kyoto, Japan

- ⁸⁵ Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
- ⁸⁶ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁸⁷ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁸⁸ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁸⁹ Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
- ⁹⁰ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁹¹ Department of Physics, Royal Holloway University of London, Egham, United Kingdom
- ⁹² Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁹³ Louisiana Tech University, Ruston, LA, United States of America
- ⁹⁴ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁹⁵ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- ⁹⁶ Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
- ⁹⁷ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁹⁸ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁹⁹ CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
- ¹⁰⁰ Department of Physics, University of Massachusetts, Amherst, MA, United States of America
- ¹⁰¹ Department of Physics, McGill University, Montreal, QC, Canada
- ¹⁰² School of Physics, University of Melbourne, Victoria, Australia
- ¹⁰³ Department of Physics, University of Michigan, Ann Arbor, MI, United States of America
- ¹⁰⁴ Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States of America
- ¹⁰⁵ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- ¹⁰⁶ Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
- ¹⁰⁷ Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- ¹⁰⁸ P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- ¹⁰⁹ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ¹¹⁰ National Research Nuclear University MEPhI, Moscow, Russia
- ¹¹¹ D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- ¹¹² Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹¹³ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹¹⁴ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹¹⁵ Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹¹⁶ Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States of America
- ¹¹⁷ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹¹⁸ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹¹⁹ Department of Physics, Northern Illinois University, DeKalb, IL, United States of America
- ¹²⁰ ^(a) Budker Institute of Nuclear Physics, SB RAS, Novosibirsk; ^(b) Novosibirsk State University Novosibirsk, Russia
- ¹²¹ Department of Physics, New York University, New York, NY, United States of America
- ¹²² Ohio State University, Columbus, OH, United States of America
- ¹²³ Faculty of Science, Okayama University, Okayama, Japan
- ¹²⁴ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States of America
- ¹²⁵ Department of Physics, Oklahoma State University, Stillwater, OK, United States of America
- ¹²⁶ Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
- ¹²⁷ Center for High Energy Physics, University of Oregon, Eugene, OR, United States of America
- ¹²⁸ LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- ¹²⁹ Graduate School of Science, Osaka University, Osaka, Japan
- ¹³⁰ Department of Physics, University of Oslo, Oslo, Norway
- ¹³¹ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹³² LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
- ¹³³ Department of Physics, University of Pennsylvania, Philadelphia, PA, United States of America
- ¹³⁴ Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg, Russia
- ¹³⁵ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States of America
- ¹³⁶ ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP; ^(b) Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Departamento de Física, Universidade de Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain; ^(g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ¹³⁷ Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
- ¹³⁸ Czech Technical University in Prague, Prague, Czech Republic
- ¹³⁹ Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
- ¹⁴⁰ State Research Center Institute for High Energy Physics, NRC KI, Protvino, Russia
- ¹⁴¹ Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹⁴² IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ¹⁴³ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States of America
- ¹⁴⁴ ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ¹⁴⁵ Department of Physics, University of Washington, Seattle, WA, United States of America
- ¹⁴⁶ Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ¹⁴⁷ Department of Physics, Shinshu University, Nagano, Japan
- ¹⁴⁸ Department Physik, Universität Siegen, Siegen, Germany
- ¹⁴⁹ Department of Physics, Simon Fraser University, Burnaby, BC, Canada
- ¹⁵⁰ SLAC National Accelerator Laboratory, Stanford, CA, United States of America
- ¹⁵¹ Physics Department, Royal Institute of Technology, Stockholm, Sweden
- ¹⁵² Departments of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States of America
- ¹⁵³ Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- ¹⁵⁴ School of Physics, University of Sydney, Sydney, Australia
- ¹⁵⁵ Institute of Physics, Academia Sinica, Taipei, Taiwan
- ¹⁵⁶ Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- ¹⁵⁷ ^(a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ¹⁵⁸ Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
- ¹⁵⁹ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- ¹⁶⁰ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- ¹⁶¹ International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan

- ¹⁶² Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
¹⁶³ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
¹⁶⁴ Tomsk State University, Tomsk, Russia
¹⁶⁵ Department of Physics, University of Toronto, Toronto, ON, Canada
¹⁶⁶ ^(a) TRIUMF, Vancouver, BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
¹⁶⁷ Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
¹⁶⁸ Department of Physics and Astronomy, Tufts University, Medford, MA, United States of America
¹⁶⁹ Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States of America
¹⁷⁰ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
¹⁷¹ Department of Physics, University of Illinois, Urbana, IL, United States of America
¹⁷² Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia, Spain
¹⁷³ Department of Physics, University of British Columbia, Vancouver, BC, Canada
¹⁷⁴ Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
¹⁷⁵ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
¹⁷⁶ Department of Physics, University of Warwick, Coventry, United Kingdom
¹⁷⁷ Waseda University, Tokyo, Japan
¹⁷⁸ Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
¹⁷⁹ Department of Physics, University of Wisconsin, Madison, WI, United States of America
¹⁸⁰ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
¹⁸¹ Department of Physics, Yale University, New Haven, CT, United States of America
¹⁸² Yerevan Physics Institute, Yerevan, Armenia

- ^a Also at Department of Physics, University of Malaya, Kuala Lumpur, Malaysia.
^b Also at Borough of Manhattan Community College, City University of New York, NY, United States of America.
^c Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
^d Also at CERN, Geneva, Switzerland.
^e Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
^f Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
^g Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.
^h Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain.
ⁱ Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.
^j Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
^k Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY, United States of America.
^l Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
^m Also at Department of Physics, California State University, Fresno, CA, United States of America.
ⁿ Also at Department of Physics, California State University, Sacramento, CA, United States of America.
^o Also at Department of Physics, King's College London, London, United Kingdom.
^p Also at Department of Physics, Nanjing University, Nanjing, China.
^q Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
^r Also at Department of Physics, Stanford University, United States of America.
^s Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
^t Also at Department of Physics, University of Michigan, Ann Arbor, MI, United States of America.
^u Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy.
^v Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
^w Also at Graduate School of Science, Osaka University, Osaka, Japan.
^x Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
^y Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany.
^z Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
^{aa} Also at Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain.
^{ab} Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
^{ac} Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
^{ad} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
^{ae} Also at Institute of Particle Physics (IPP), Canada.
^{af} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
^{ag} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
^{ah} Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
^{ai} Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
^{aj} Also at Louisiana Tech University, Ruston, LA, United States of America.
^{ak} Also at Manhattan College, New York, NY, United States of America.
^{al} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
^{am} Also at National Research Nuclear University MEPhI, Moscow, Russia.
^{an} Also at Near East University, Nicosia, North Cyprus, Mersin, Turkey.
^{ao} Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
^{ap} Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
^{aq} Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
^{ar} Also at The City College of New York, New York, NY, United States of America.
^{as} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
^{at} Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
^{au} Also at TRIUMF, Vancouver, BC, Canada.
^{av} Also at Università di Napoli Parthenope, Napoli, Italy.
* Deceased.