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G. Aad, L. Alio, M. Barbero, C. P. Bee, C. Bertella, N. Bousson, J. C.
Clémens, Y. Coadou, F. Djama, F. Etienne, et al.

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Search for new phenomena in photon + jet events collected in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector



ATLAS Collaboration *

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ABSTRACT

This Letter describes a model-independent search for the production of new resonances in photon + jet (γ + jet) events using 20 fb^{-1} of proton–proton LHC data recorded with the ATLAS detector at a centre-of-mass energy of $\sqrt{s} = 8$ TeV. The γ + jet mass distribution is compared to a background model fit from data; no significant deviation from the background-only hypothesis is found. Limits are set at 95% credibility level on generic Gaussian-shaped signals and two benchmark phenomena beyond the Standard Model: non-thermal quantum black holes and excited quarks. Non-thermal quantum black holes are excluded below masses of 4.6 TeV and excited quarks are excluded below masses of 3.5 TeV.

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1. Introduction

Several exotic production mechanisms have been proposed that produce massive photon + jet (γ + jet) final states. They include non-thermal quantum black holes (QBHs) [1–3], excited quarks [4–6], quarks [7–9], Regge excitations of string theory [10–12], and topological pions [13]. Of the past searches [14–18], the only LHC search for this signature was done using proton–proton (pp) collision data obtained at a centre-of-mass energy of $\sqrt{s} = 7$ TeV with the ATLAS detector. It found no evidence of new physics and placed upper limits on the visible signal cross-section in the range 1.5–100 fb and excluded excited-quark masses up to 2.46 TeV at the 95% credibility level (CL) [18]. The present Letter describes a model-independent search for s -channel γ + jet production, improved over the earlier search. It presents the first limits on QBHs decaying to the γ + jet final state and places new limits both on excited quarks and on generic Gaussian-shaped sources which describe other narrow resonant signals such as topological pions. Sensitivity to such signals has been improved compared to the previous search through a combination of an order-of-magnitude larger data sample (20.3 fb^{-1}), a higher centre-of-mass energy ($\sqrt{s} = 8$ TeV), reduced background uncertainties, and improved selection criteria at high invariant mass.

The Standard Model (SM) of particle physics lacks a mechanism whereby pp collisions produce resonances that subsequently decay to a γ + jet final state. Direct γ + jet production can occur at tree level via Compton scattering of a quark and a gluon,

or through quark–antiquark annihilation. The former process accounts for most of the direct γ + jet production. Events with a high transverse momentum photon and one or more jets can also arise from radiation off final-state quarks, or from dijet or multi-jet processes, where secondary photons, referred to as fragmentation photons, are produced during fragmentation of the hard-scattered quarks or gluons [19–22]. The γ + jet invariant mass ($m_{\gamma j}$) distribution resulting from this mixture of processes is smooth and rapidly falling, and is therefore well suited to revealing high-mass resonances decaying to γ + jet.

The $m_{\gamma j}$ distribution is used to search for a peak over the SM background, estimated by fitting a smoothly falling function to the $m_{\gamma j}$ distribution in the region $m_{\gamma j} > 426$ GeV. In the absence of a signal, Bayes' theorem is used to set limits on Gaussian-shaped signals and on two benchmark models: QBHs and excited quarks.

Models with extra dimensions, such as the Arkani-Hamed–Dimopoulos–Dvali (ADD) model [23,24], solve the mass hierarchy problem of the SM by lowering the fundamental scale of quantum gravity (M_D) to a few TeV. Consequently, the LHC could produce quantum black holes with masses at or above M_D [25,26]. QBHs produced near M_D would evaporate faster than they thermalize, decaying into a few particles rather than high-multiplicity final states [2,3]. Regardless of the number of extra dimensions n , such a signal would appear as a local excess over the steeply falling $m_{\gamma j}$ distribution near the threshold mass (M_{th}) and would fall exponentially at higher masses. Searches performed by the CMS Collaboration for QBHs with high-multiplicity energetic final states yielded limits in the range of 4.3–6.2 TeV, for $n = 1$ –6 and different model assumptions [27]. This Letter assumes $M_{\text{th}} = M_D$ and $n = 6$, where the cross-section times branching fraction for QBH production and decay to γ + jet final states at $M_{\text{th}} = 1, 3$ and 5 TeV is 200, 0.3 and 6×10^{-5} pb, respectively [3]. For decays to dijet final

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

states at these same threshold masses, the rates are larger by factors of 11, 39 and 125.

Excited-quark (q^*) states, which the ATLAS and CMS experiments have also sought in dijet final states [28–30], could be produced via the fusion of a gluon with a quark. The model is defined by one parameter, the excited-quark mass m_{q^*} , with the compositeness scale set to m_{q^*} . Only gauge interactions are considered with the SU(3), SU(2), and U(1) coupling multipliers fixed to $f_s = f = f' = 1$ [5]. This results in branching fractions for $q^* \rightarrow qg$ and $q^* \rightarrow q\gamma$ of 0.85 (0.85) and 0.02 (0.005), respectively, for $q = u$ ($q = d$). The leading-order cross-sections times branching fractions combining all flavours of excited quarks for $m_{q^*} = 1, 3$ and 5 TeV are 4, 2×10^{-3} and 3×10^{-6} pb, respectively.

Factorization and renormalization scale uncertainties are not used for either signal type, for comparison with earlier analyses [18,28,29].

2. Signal and background simulation samples

To cross-check the data-driven background estimates, the SM prompt photon processes are simulated with PYTHIA 8.165 [31] and SHERPA 1.4.0 [32]. The PYTHIA and SHERPA prompt photon samples use CTEQ6L1 [33] and CT10 [34] leading-order and next-to-leading-order parton distribution functions (PDFs), respectively. The simulated samples of QBHs are obtained from the QBH 1.05 generator [35] followed by parton showering using PYTHIA 8.165. The simulated q^* signal samples are generated with the excited-quark model in PYTHIA 8.165. Both signal generators use the MSTW2008LO [36] leading-order PDF set with the AU2 underlying-event tune [37]. Additional inelastic pp interactions, termed pileup, are included in the event simulation by overlaying simulated minimum bias events with an average of 20 interactions per bunch crossing. All the above Monte Carlo (MC) simulated samples are produced using the ATLAS full GEANT4 [38] detector simulation [39]. Supplementary studies of the background shape are also performed with the next-to-leading-order JETPHOX 1.3.0 generator [19–21] at parton level using CT10 PDFs.

3. The ATLAS detector

A detailed description of the detector is available in Ref. [40], and the event selection is similar to that described in Ref. [18]. Photons are detected by a lead–liquid–argon sampling electromagnetic calorimeter (EMC). The EMC has a pre-sampler layer and three additional, differently segmented, layers; only the first two are used in photon identification. Upstream of the EMC, the inner detector allows an accurate reconstruction of tracks from the primary pp collision point and also from secondary vertices, permitting an efficient reconstruction of photon conversions in the inner detector. For $|\eta| < 1.37$ ¹ an iron–scintillator tile calorimeter behind the EMC provides hadronic coverage. The endcap and forward regions, $1.5 < |\eta| < 4.9$, are instrumented with liquid–argon calorimeters for both the electromagnetic and hadronic measurements. Events for this analysis were collected with a trigger requiring at least one photon candidate with transverse momentum (p_T)

above 120 GeV [41]. The integrated luminosity of the data sample² is $(20.3 \pm 0.6) \text{ fb}^{-1}$.

4. Event selection

Each event is required to contain a primary vertex with at least two tracks each with $p_T > 400$ MeV. If more than one vertex is found, the primary vertex is defined as the one with the highest scalar summed p_T^2 of associated tracks.

Jets are reconstructed from clusters of calorimeter cells [43], using the anti- k_t clustering algorithm [44] with radius parameter $R = 0.6$. The effects on jet energies due to multiple pp collisions in the same or in neighbouring bunch crossings are accounted for by a jet-area-based correction [45,46]. Jet energies are calibrated to the hadronic energy scale using corrections from MC simulation and the combination of several in situ techniques applied to data [47]. Events are discarded if the leading (highest- p_T) jet is affected by noise or hardware problems in the detector, or is identified as arising from non-collision backgrounds. Only jets with $|\eta_j| < 2.8$ are considered further.

Photon candidates are reconstructed from clusters in the electromagnetic calorimeter and tracking information provided by the inner detector. Inner detector tracking information is used to reject electrons and to recover photons converted to e^+e^- pairs [48]. Photon candidates satisfy standard ATLAS selection criteria that are designed to reject backgrounds from hadrons [49]. The photon candidates must meet η -dependent requirements on hadronic leakage and shower shapes in the first two sampling layers of the electromagnetic calorimeter. Energy calibrations are applied to photon candidates to account for energy loss upstream of the electromagnetic calorimeter and for both lateral and longitudinal shower leakage. The simulation is corrected for differences between data and MC events for each photon shower shape variable. Events are discarded if the leading photon is reconstructed using calorimeter cells affected by noise bursts or transient hardware problems.

These photon identification criteria reduce instrumental backgrounds to a negligible level, but some background from fragmentation photons and hadronic jets remains. This background is further reduced by requirements on nearby calorimeter activity. Energy deposited in the calorimeter near the photon candidate, E_T^{isol} , must be no larger than $0.011 p_T^2 + 3.65$ GeV, a criterion that provides constant efficiency for all pileup conditions and over the entire p_T range explored. This transverse isolation energy is calculated by summing the energy as measured in electromagnetic and hadronic calorimeter cells inside a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ centred on the photon cluster, but excluding the energy of the photon cluster itself, and is corrected on an event-by-event basis for the ambient energy density due to pileup and the underlying event, as well as energy leakage from the photon cluster into the cone. Additionally, the photon is required to have angular separation of $\Delta R(\gamma, \text{jet}) > 1.0$ between the leading photon and all other jets with $p_T > 30$ GeV, with the exception of a required photon-matched jet. Such photon-matched jets arise from the fact that photon energy deposits in the calorimeter are also reconstructed as jets. To further suppress background from fragmentation photons, where the angular separation between the photon and the corresponding photon-matched jet can be large, the leading photon candidate is required to have exactly one reconstructed jet with $\Delta R(\gamma, \text{jet}) < 0.1$. This photon-matched jet is not considered in any other selection criteria, including those related to photon isolation.

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

² The systematic uncertainty on the luminosity is derived, following the same methodology as that detailed in Ref. [42], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

Events containing at least one photon candidate and at least one jet candidate, each with $p_T > 125$ GeV, are selected for final analysis. The photon trigger is fully efficient for these events. In the events where more than one photon or jet is found, the highest- p_T candidates are selected to constitute the photon and jet pair to compute $m_{\gamma j}$.

The sensitivity of the search is improved by requirements on photon and jet pseudorapidities. Dijet production rates increase with jet absolute pseudorapidity whereas rates for an s -channel signal would diminish. Photons are required to be in the barrel calorimeter, $|\eta_\gamma| < 1.37$, and the distance between the photon and jet, $\Delta\eta = |\eta_\gamma - \eta_j|$, must be less than 1.6. The latter requirement was chosen by optimizing the expected significance of signals, using the $\Delta\eta$ distribution found in QBH and excited-quark signal simulations, with respect to the SM background as predicted by the PYTHIA prompt photon simulation.

The acceptance of the event selection is about 60%. It is calculated using parton-level quantities by imposing the kinematic selection criteria (photon/jet $|\eta|$, photon/jet p_T , $\Delta\eta$, ΔR). All other selections, which in general correspond to event and object quality criteria, were used to calculate the efficiency based on the events included in the acceptance. The efficiency falls from 83% to 72% for masses from 1 TeV to 6 TeV for QBH signals and from 85% to 80% for excited-quark signals over the same mass range. There are 285 356 events in the data sample after all event selections. The highest $m_{\gamma j}$ value observed is 2.57 TeV.

5. Background estimation

The combined SM and instrumental background to the search is determined by fitting the $m_{\gamma j}$ distribution to the four-parameter ansatz function [50],

$$f(x \equiv m_{\gamma j}/\sqrt{s}) = p_1(1-x)^{p_2}x^{-(p_3+p_4 \ln x)}. \quad (1)$$

The functional form has been tested with PYTHIA and SHERPA prompt photon simulations and next-to-leading-order JETPHOX predictions with comparable sample size. Two additional control samples in the data are also defined to further validate the functional form. The first control sample is defined by reversing two of the photon identification criteria, ΔE and E_{ratio} [49], that compare the lateral shower shapes of single photons in the first layer of the calorimeter to those of jets with high electromagnetic energy fraction and low particle multiplicity, typical for meson decays. This sample has a similar $m_{\gamma j}$ shape to the dominant background, SM $\gamma + \text{jet}$ events. The second control sample is defined by reversing the photon isolation criterion, E_T^{isol} . This control sample is enriched in the second largest background, dijet events in which a jet has passed the photon identification cuts.

Fig. 1 shows the resulting distribution of the $\gamma + \text{jet}$ invariant mass. The bin widths are chosen to be twice the mass resolution at the centre of each bin. The relative resolution is about 4% of $m_{\gamma j}$ at 1 TeV, improving to about 3% at 2 TeV. The fit result is also shown in Fig. 1. The bottom panel of the figure shows the statistical significance of the difference between data and the fit in each bin [51]. The fit quality is quantified using a negative log-likelihood test statistic. The probability of the fit quality to be at least as good as the observed fit (p -value) is 74%, indicating that the data are consistent with the functional form.

6. Results

6.1. Search results

The search region is defined to be $m_{\gamma j} > 426$ GeV, which is the lower edge of the first bin for which biases due to kinematic and

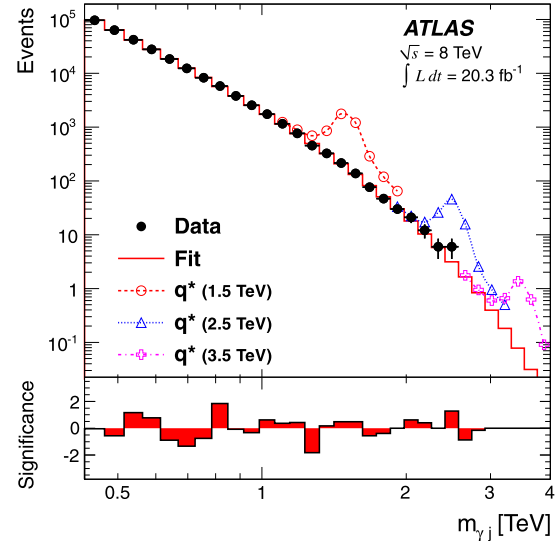


Fig. 1. Invariant mass of the $\gamma + \text{jet}$ pair for events passing the final selections. The bin widths are chosen to be twice the mass resolution at the centre of each bin. Overlaid is the fitted background function integrated over each bin (solid line), with three examples of q^* signals, as described in the text. For better visibility the q^* signals are only drawn for $m_{\gamma j}$ within $\pm 25\%$ of the nominal signal mass. The bottom panel shows the statistical significance of the difference between data and background in each bin.

trigger threshold effects are negligible. The $\gamma + \text{jet}$ search is sensitive to new resonances in the region between 426 GeV and 1 TeV, where the statistics of dijet searches are limited by the higher hadronic trigger thresholds. The BUMPHUNTER algorithm [52] is used to search for statistical evidence of a resonance. The algorithm operates on the binned $m_{\gamma j}$ distribution, comparing the background estimate with the data in mass intervals of varying numbers of adjacent bins across the entire distribution. For each interval in the scan, it computes the significance of any excess found. The significance of the outcome is evaluated using the ensemble of possible outcomes in any part of the distribution under the background-only hypothesis, obtained by repeating the analysis on pseudodata drawn from the background function. The algorithm identifies the two-bin interval 785–916 GeV as the single most discrepant interval. Before including systematic uncertainties, the p -value is 61%, including the trials factor, or “look-elsewhere” effect. Thus, the excess is not significant and the data are consistent with a smoothly falling background.

6.2. Limit results

In the absence of any signal, three types of $\gamma + \text{jet}$ signals are explored: a generic Gaussian-shaped signal with an arbitrary production cross-section, resulting from resonances with varying intrinsic widths convolved with the detector resolution; the QBH model; and the excited-quark model. For each signal mass considered, the fit to the observed mass distribution is repeated with the sum of the four-parameter background function (Eq. (1)) and a signal template with a normalization determined during the fit. Bayesian limits at the 95% CL are computed as described in Ref. [28] using a prior probability density that is constant for positive values of the signal production cross-section and zero for unphysical, negative values.

Systematic uncertainties affecting the limits on production of new signals are evaluated. The signal yield is subject to systematic uncertainties on the integrated luminosity (2.8%), photon isolation efficiency (1.2%), trigger efficiency (0.5%), and photon identification efficiencies (1.5%). The last of these includes extrapolation to

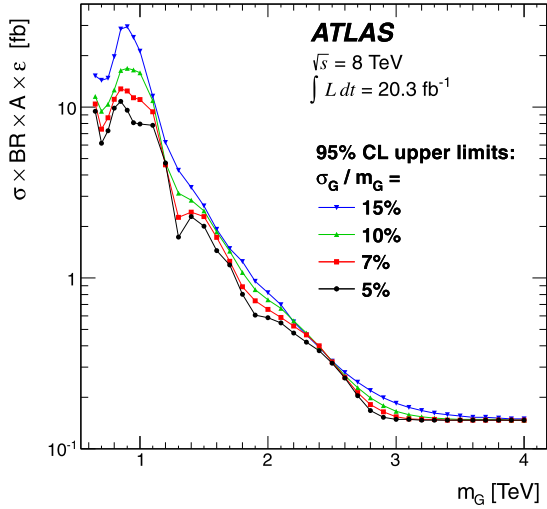


Fig. 2. The 95% CL upper limits on $\sigma \times BR \times A \times \epsilon$ for a hypothetical signal with a Gaussian-shaped $m_{\gamma j}$ distribution as a function of the signal mass m_G for four values of the relative width σ_G/m_G .

high p_T (0.1%) and pileup effects (0.1%). Uncertainties on the jet and photon energy scale contribute 1.0–1.5% and 0.3%, respectively, through their effects on the shape and yield of the signal distribution. The sizes of the systematic uncertainties are similar for the q^* and QBH signals. These systematic uncertainties are treated as marginalized nuisance parameters in the limit calculation. Systematic uncertainties on the value and shape of the signal acceptance due to the PDF uncertainties were examined and found to be negligible. To account for the statistical uncertainties on the background fit parameters, the background function is repeatedly fit to pseudodata for which the content of each bin is drawn from Poisson distributions. The mean of the Poisson distribution for a given bin corresponds to the number of entries actually observed in that bin in the data. The variations in the fit predictions for a given bin, 1% of the background at 1 TeV to about 20% of the background at 3 TeV, are taken as indicative of the systematic uncertainty. This bin-by-bin uncertainty is treated in the limit as fully correlated, using a single nuisance parameter that scales the entire background distribution. Several other fit functions from Ref. [50] were tested, and a negligible systematic uncertainty was found.

Fig. 2 shows the model-independent limits on the visible cross-section, defined as the product of the cross-section (σ) times branching fraction (BR) times acceptance (A) times efficiency (ϵ), of a potential signal as a function of the mass of each signal template, and includes the systematic uncertainties discussed above. The signal line shape is modelled as a Gaussian distribution, with one of four relative widths: $\sigma_G/m_G = 5\%$, 7% , 10% , and 15% , where σ_G (m_G) is the width (mean mass) of the Gaussian. The differences between the limits for different widths are driven by the increased sensitivity to local fluctuations for the narrower signals. Beyond the highest-mass event recorded, 2.57 TeV, the limits begin to converge due to the absence of observed events. At 1 TeV and 4 TeV the limits are 8 fb and 0.1 fb, respectively, for $\sigma_G/m_G = 5\%$. At 3 TeV, the new limit improves the earlier ATLAS result in this channel by an order of magnitude.

The limit on the visible cross-section in the QBH model is shown in Fig. 3 as a function of M_{th} . The observed (expected) lower limit on the QBH mass threshold is found to be 4.6 (4.6) TeV, at 95% CL. The uncertainty on the QBH theoretical cross-section arising from PDF uncertainties moves the uppermost excluded mass by 0.2%.

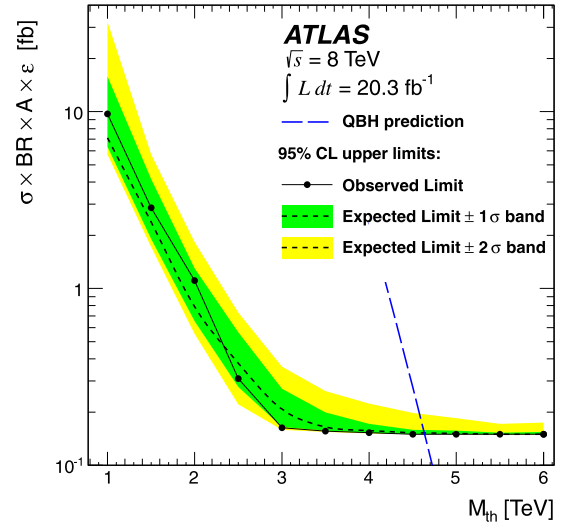


Fig. 3. The 95% CL upper limits on $\sigma \times BR \times A \times \epsilon$ for QBHs decaying to a photon and a jet, as a function of the threshold mass M_{th} , assuming $M_D = M_{th}$ and $n = 6$. The limits take into account statistical and systematic uncertainties. Points along the solid black line indicate the mass of the signal where the limit is computed. The black short dashed line is the central value of the expected limit. Also shown are the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands indicating the underlying distribution of possible limit outcomes under the background-only hypothesis. The predicted visible cross-section for QBHs is shown as the long dashed line.

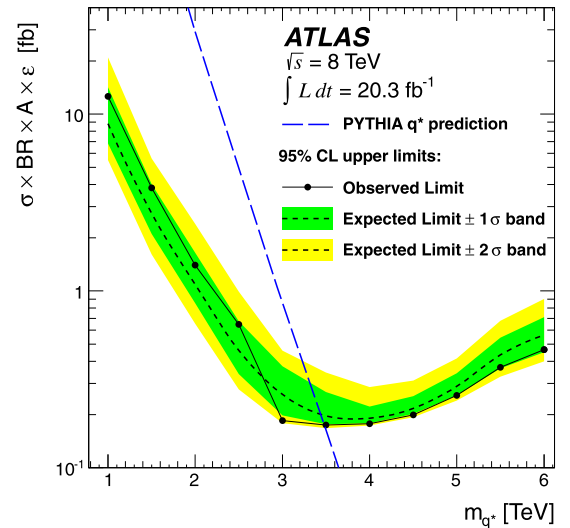


Fig. 4. The 95% CL upper limits on $\sigma \times BR \times A \times \epsilon$ for excited quarks decaying to a photon and a jet, as a function of the signal mass m_{q^*} . The limits take into account statistical and systematic uncertainties. Points along the solid black line indicate the mass of the signal where the limit is computed. The black short dashed line is the central value of the expected limit. Also shown are the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands indicating the underlying distribution of possible limit outcomes under the background-only hypothesis. The long dashed line shows the predicted visible cross-section for excited-quark production from PYTHIA.

The limit on the visible cross-section in the excited-quark model as a function of the q^* mass, assumed to be the same for u^* and d^* , is shown in Fig. 4. The rise in the expected and observed limits at high m_{q^*} is due to the increased fraction of off-shell production of the q^* , which alters the signal distribution to lower masses with a wider peak. The observed (expected) lower limit on the excited-quark mass is found to be 3.5 (3.4) TeV, at 95% CL. With a much lower branching fraction than the dijet channel but also smaller backgrounds, this result improves on the present exclusion limits in the dijet final state: 3.32 TeV from CMS with

5 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$ [30], and 2.83 TeV from ATLAS with 4.8 fb^{-1} [28] of data at $\sqrt{s} = 7 \text{ TeV}$. The uncertainty on the q^* theoretical cross-section arising from PDF uncertainties moves the uppermost excluded mass by 0.9%.

7. Conclusions

In conclusion, the $\gamma + \text{jet}$ mass distribution measured in 20.3 fb^{-1} of pp collision data, collected at $\sqrt{s} = 8 \text{ TeV}$ by the ATLAS experiment at the LHC, is well described by the background model and no evidence for new phenomena is found. Limits at 95% CL using Bayesian statistics are presented for signal processes yielding a Gaussian line shape, non-thermal quantum black holes, and excited quarks. The limits on Gaussian-shaped resonances exclude 4 TeV resonances with visible cross-sections near 0.1 fb. Non-thermal quantum black hole and excited-quark models with a $\gamma + \text{jet}$ final state are excluded for masses up to 4.6 TeV and 3.5 TeV, respectively. The limits reported here on the production of new resonances in the $\gamma + \text{jet}$ final state are the most stringent limits set to date in this channel.

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G. Aad⁴⁸, T. Abajyan²¹, B. Abbott¹¹², J. Abdallah¹², S. Abdel Khalek¹¹⁶, O. Abdinov¹¹, R. Aben¹⁰⁶, B. Abi¹¹³, M. Abolins⁸⁹, O.S. AbouZeid¹⁵⁹, H. Abramowicz¹⁵⁴, H. Abreu¹³⁷, Y. Abulaiti^{147a,147b}, B.S. Acharya^{165a,165b,a}, L. Adamczyk^{38a}, D.L. Adams²⁵, T.N. Addy⁵⁶, J. Adelman¹⁷⁷, S. Adomeit⁹⁹, T. Adye¹³⁰, S. Aefsky²³, T. Agatonovic-Jovin^{13b}, J.A. Aguilar-Saavedra^{125b,b}, M. Agustoni¹⁷, S.P. Ahlen²², A. Ahmad¹⁴⁹, M. Ahsan⁴¹, G. Aielli^{134a,134b}, T.P.A. Åkesson⁸⁰, G. Akimoto¹⁵⁶, A.V. Akimov⁹⁵, M.A. Alam⁷⁶, J. Albert¹⁷⁰, S. Albrand⁵⁵, M.J. Alconada Verzini⁷⁰, M. Aleksa³⁰, I.N. Aleksandrov⁶⁴, F. Alessandria^{90a}, C. Alexa^{26a}, G. Alexander¹⁵⁴, G. Alexandre⁴⁹, T. Alexopoulos¹⁰, M. Alhroob^{165a,165c}, M. Aliev¹⁶, G. Alimonti^{90a}, L. Alio⁸⁴, J. Alison³¹, B.M.M. Allbrooke¹⁸, L.J. Allison⁷¹, P.P. Allport⁷³, S.E. Allwood-Spiers⁵³, J. Almond⁸³, A. Aloisio^{103a,103b}, R. Alon¹⁷³, A. Alonso³⁶, F. Alonso⁷⁰, A. Altheimer³⁵, B. Alvarez Gonzalez⁸⁹, M.G. Alviggi^{103a,103b}, K. Amako⁶⁵, Y. Amaral Coutinho^{24a}, C. Amelung²³, V.V. Ammosov^{129,*}, S.P. Amor Dos Santos^{125a}, A. Amorim^{125a,c}, S. Amoroso⁴⁸, N. Amram¹⁵⁴, C. Anastopoulos³⁰, L.S. Ancu¹⁷, N. Andari³⁰, T. Andeen³⁵, C.F. Anders^{58b}, G. Anders^{58a}, K.J. Anderson³¹, A. Andreazza^{90a,90b}, V. Andrei^{58a}, X.S. Anduaga⁷⁰, S. Angelidakis⁹, P. Anger⁴⁴, A. Angerami³⁵, F. Anghinolfi³⁰, A.V. Anisenkov¹⁰⁸, N. Anjos^{125a}, A. Annovi⁴⁷, A. Antonaki⁹, M. Antonelli⁴⁷, A. Antonov⁹⁷, J. Antos^{145b}, F. Anulli^{133a}, M. Aoki¹⁰², L. Aperio Bella¹⁸, R. Apolle^{119,d}, G. Arabidze⁸⁹, I. Aracena¹⁴⁴, Y. Arai⁶⁵, A.T.H. Arce⁴⁵, S. Arfaoui¹⁴⁹, J.-F. Arguin⁹⁴, S. Argyropoulos⁴², E. Arik^{19a,*}, M. Arik^{19a}, A.J. Armbruster⁸⁸, O. Arnaez⁸², V. Arnal⁸¹, O. Arslan²¹, A. Artamonov⁹⁶, G. Artoni^{133a,133b}, S. Asai¹⁵⁶, N. Asbah⁹⁴, S. Ask²⁸, B. Åsman^{147a,147b}, L. Asquith⁶, K. Assamagan²⁵, R. Astalos^{145a}, A. Astbury¹⁷⁰, M. Atkinson¹⁶⁶, N.B. Atlay¹⁴², B. Auerbach⁶, E. Auge¹¹⁶, K. Augsten¹²⁷, M. Aurousseau^{146b}, G. Avolio³⁰, D. Axen¹⁶⁹, G. Azuelos^{94,e}, Y. Azuma¹⁵⁶, M.A. Baak³⁰, C. Bacci^{135a,135b}, A.M. Bach¹⁵, H. Bachacou¹³⁷, K. Bachas¹⁵⁵, M. Backes³⁰, M. Backhaus²¹, J. Backus Mayes¹⁴⁴, E. Badescu^{26a}, P. Bagiacchi^{133a,133b}, P. Bagnaia^{133a,133b}, Y. Bai^{33a}, D.C. Bailey¹⁵⁹, T. Bain³⁵, J.T. Baines¹³⁰, O.K. Baker¹⁷⁷, S. Baker⁷⁷, P. Balek¹²⁸, F. Balli¹³⁷, E. Banas³⁹, Sw. Banerjee¹⁷⁴, D. Banfi³⁰, A. Bangert¹⁵¹, V. Bansal¹⁷⁰, H.S. Bansil¹⁸, L. Barak¹⁷³, S.P. Baranov⁹⁵, T. Barber⁴⁸, E.L. Barberio⁸⁷, D. Barberis^{50a,50b}, M. Barbero⁸⁴, D.Y. Bardin⁶⁴, T. Barillari¹⁰⁰, M. Barisonzi¹⁷⁶, T. Barklow¹⁴⁴, N. Barlow²⁸, B.M. Barnett¹³⁰, R.M. Barnett¹⁵, A. Baroncelli^{135a}, G. Barone⁴⁹, A.J. Barr¹¹⁹, F. Barreiro⁸¹, J. Barreiro Guimarães da Costa⁵⁷, R. Bartoldus¹⁴⁴, A.E. Barton⁷¹, V. Bartsch¹⁵⁰, A. Bassalat¹¹⁶, A. Basye¹⁶⁶, R.L. Bates⁵³, L. Batkova^{145a}, J.R. Batley²⁸, M. Battistin³⁰, F. Bauer¹³⁷, H.S. Bawa^{144,f}, S. Beale⁹⁹, T. Beau⁷⁹, P.H. Beauchemin¹⁶², R. Beccherle^{50a}, P. Bechtel²¹, H.P. Beck¹⁷, K. Becker¹⁷⁶, S. Becker⁹⁹, M. Beckingham¹³⁹, K.H. Becks¹⁷⁶, A.J. Beddall^{19c}, A. Beddall^{19c}, S. Bedikian¹⁷⁷, V.A. Bednyakov⁶⁴, C.P. Bee⁸⁴, L.J. Beemster¹⁰⁶, T.A. Beermann¹⁷⁶, M. Begel²⁵, C. Belanger-Champagne⁸⁶, P.J. Bell⁴⁹, W.H. Bell⁴⁹, G. Bella¹⁵⁴, L. Bellagamba^{20a}, A. Bellerive²⁹, M. Bellomo³⁰, A. Belloni⁵⁷, O.L. Beloborodova^{108,g}, K. Belotskiy⁹⁷, O. Beltramello³⁰, O. Benary¹⁵⁴, D. Benchekroun^{136a}, K. Bendtz^{147a,147b}, N. Benekos¹⁶⁶, Y. Benhammou¹⁵⁴, E. Benhar Noccioli⁴⁹, J.A. Benitez Garcia^{160b}, D.P. Benjamin⁴⁵, J.R. Bensinger²³, K. Benslama¹³¹, S. Bentvelsen¹⁰⁶, D. Berge³⁰, E. Bergeas Kuutmann¹⁶, N. Berger⁵, F. Berghaus¹⁷⁰, E. Berglund¹⁰⁶, J. Beringer¹⁵, C. Bernard²², P. Bernat⁷⁷, R. Bernhard⁴⁸, C. Bernius⁷⁸, F.U. Bernlochner¹⁷⁰, T. Berry⁷⁶, C. Bertella⁸⁴, F. Bertolucci^{123a,123b}, M.I. Besana^{90a}, G.J. Besjes¹⁰⁵, O. Bessidskaia^{147a,147b}, N. Besson¹³⁷, S. Bethke¹⁰⁰, W. Bhimji⁴⁶, R.M. Bianchi¹²⁴, L. Bianchini²³, M. Bianco³⁰, O. Biebel⁹⁹, S.P. Bieniek⁷⁷, K. Bierwagen⁵⁴, J. Biesiada¹⁵, M. Biglietti^{135a}, J. Bilbao De Mendizabal⁴⁹, H. Bilokon⁴⁷, M. Bindi^{20a,20b}, S. Binet¹¹⁶, A. Bingul^{19c}, C. Bini^{133a,133b}, B. Bittner¹⁰⁰, C.W. Black¹⁵¹, J.E. Black¹⁴⁴, K.M. Black²², D. Blackburn¹³⁹, R.E. Blair⁶, J.-B. Blanchard¹³⁷, T. Blazek^{145a}, I. Bloch⁴², C. Blocker²³, J. Blocki³⁹, W. Blum^{82,*}, U. Blumenschein⁵⁴, G.J. Bobbink¹⁰⁶, V.S. Bobrovnikov¹⁰⁸, S.S. Bocchetta⁸⁰, A. Bocci⁴⁵, C.R. Boddy¹¹⁹, M. Boehler⁴⁸, J. Boek¹⁷⁶, T.T. Boek¹⁷⁶, N. Boelaert³⁶, J.A. Bogaerts³⁰, A.G. Bogdanchikov¹⁰⁸, A. Bogouch^{91,*}, C. Bohm^{147a}, J. Bohm¹²⁶, V. Boisvert⁷⁶, T. Bold^{38a}, V. Boldea^{26a}, N.M. Bolnet¹³⁷, M. Bomben⁷⁹, M. Bona⁷⁵, M. Boonekamp¹³⁷, S. Bordini⁷⁹, C. Borer¹⁷, A. Borisov¹²⁹, G. Borissov⁷¹, M. Borri⁸³, S. Borroni⁴², J. Bortfeldt⁹⁹, V. Bortolotto^{135a,135b}, K. Bos¹⁰⁶, D. Boscherini^{20a}, M. Bosman¹², H. Boterenbrood¹⁰⁶, J. Bouchami⁹⁴, J. Boudreau¹²⁴, E.V. Bouhova-Thacker⁷¹, D. Boumediene³⁴, C. Bourdarios¹¹⁶, N. Bousson⁸⁴, S. Boutouil^{136d}, A. Boveia³¹, J. Boyd³⁰, I.R. Boyko⁶⁴, I. Bozovic-Jelisavcic^{13b}, J. Bracinik¹⁸, P. Branchini^{135a}, A. Brandt⁸, G. Brandt¹⁵, O. Brandt⁵⁴, U. Bratzler¹⁵⁷, B. Brau⁸⁵, J.E. Brau¹¹⁵, H.M. Braun^{176,*}, S.F. Brazzale^{165a,165c}, B. Brelief¹⁵⁹, J. Bremer³⁰,

K. Brendlinger¹²¹, R. Brenner¹⁶⁷, S. Bressler¹⁷³, T.M. Bristow⁴⁶, D. Britton⁵³, F.M. Brochu²⁸, I. Brock²¹,
 R. Brock⁸⁹, F. Broggi^{90a}, C. Bromberg⁸⁹, J. Bronner¹⁰⁰, G. Brooijmans³⁵, T. Brooks⁷⁶, W.K. Brooks^{32b},
 E. Brost¹¹⁵, G. Brown⁸³, J. Brown⁵⁵, P.A. Bruckman de Renstrom³⁹, D. Bruncko^{145b}, R. Bruneliere⁴⁸,
 S. Brunet⁶⁰, A. Bruni^{20a}, G. Bruni^{20a}, M. Bruschi^{20a}, L. Bryngemark⁸⁰, T. Buanes¹⁴, Q. Buat⁵⁵, F. Bucci⁴⁹,
 J. Buchanan¹¹⁹, P. Buchholz¹⁴², R.M. Buckingham¹¹⁹, A.G. Buckley⁴⁶, S.I. Buda^{26a}, I.A. Budagov⁶⁴,
 B. Budick¹⁰⁹, F. Buehrer⁴⁸, L. Bugge¹¹⁸, O. Bulekov⁹⁷, A.C. Bundock⁷³, M. Bunse⁴³, H. Burckhart³⁰,
 S. Burdin⁷³, T. Burgess¹⁴, S. Burke¹³⁰, E. Busato³⁴, V. Büscher⁸², P. Bussey⁵³, C.P. Buszello¹⁶⁷,
 B. Butler⁵⁷, J.M. Butler²², C.M. Buttar⁵³, J.M. Butterworth⁷⁷, W. Buttinger²⁸, A. Buzatu⁵³,
 M. Byszewski¹⁰, S. Cabrera Urbán¹⁶⁸, D. Caforio^{20a,20b}, O. Cakir^{4a}, P. Calafiura¹⁵, G. Calderini⁷⁹,
 P. Calfayan⁹⁹, R. Calkins¹⁰⁷, L.P. Caloba^{24a}, R. Caloi^{133a,133b}, D. Calvet³⁴, S. Calvet³⁴, R. Camacho Toro⁴⁹,
 P. Camarri^{134a,134b}, D. Cameron¹¹⁸, L.M. Caminada¹⁵, R. Caminal Armadans¹², S. Campana³⁰,
 M. Campanelli⁷⁷, V. Canale^{103a,103b}, F. Canelli³¹, A. Canepa^{160a}, J. Cantero⁸¹, R. Cantrill⁷⁶, T. Cao⁴⁰,
 M.D.M. Capeans Garrido³⁰, I. Caprini^{26a}, M. Caprini^{26a}, D. Capriotti¹⁰⁰, M. Capua^{37a,37b}, R. Caputo⁸²,
 R. Cardarelli^{134a}, T. Carli³⁰, G. Carlino^{103a}, L. Carminati^{90a,90b}, S. Caron¹⁰⁵, E. Carquin^{32b},
 G.D. Carrillo-Montoya^{146c}, A.A. Carter⁷⁵, J.R. Carter²⁸, J. Carvalho^{125a,h}, D. Casadei⁷⁷, M.P. Casado¹²,
 C. Caso^{50a,50b,*}, E. Castaneda-Miranda^{146b}, A. Castelli¹⁰⁶, V. Castillo Gimenez¹⁶⁸, N.F. Castro^{125a},
 G. Cataldi^{72a}, P. Catastini⁵⁷, A. Catinaccio³⁰, J.R. Catmore³⁰, A. Cattai³⁰, G. Cattani^{134a,134b},
 S. Caughron⁸⁹, V. Cavaliere¹⁶⁶, D. Cavalli^{90a}, M. Cavalli-Sforza¹², V. Cavasinni^{123a,123b},
 F. Ceradini^{135a,135b}, B. Cerio⁴⁵, A.S. Cerqueira^{24b}, A. Cerri¹⁵, L. Cerrito⁷⁵, F. Cerutti¹⁵, A. Cervelli¹⁷,
 S.A. Cetin^{19b}, A. Chafaq^{136a}, D. Chakraborty¹⁰⁷, I. Chalupkova¹²⁸, K. Chan³, P. Chang¹⁶⁶, B. Chapleau⁸⁶,
 J.D. Chapman²⁸, J.W. Chapman⁸⁸, D.G. Charlton¹⁸, V. Chavda⁸³, C.A. Chavez Barajas³⁰, S. Cheatham⁸⁶,
 S. Chekanov⁶, S.V. Chekulaev^{160a}, G.A. Chelkov⁶⁴, M.A. Chelstowska⁸⁸, C. Chen⁶³, H. Chen²⁵,
 S. Chen^{33c}, X. Chen¹⁷⁴, Y. Chen³⁵, Y. Cheng³¹, A. Cheplakov⁶⁴, R. Cherkaoui El Moursli^{136e},
 V. Chernyatin^{25,*}, E. Cheu⁷, L. Chevalier¹³⁷, V. Chiarella⁴⁷, G. Chiefari^{103a,103b}, J.T. Childers³⁰,
 A. Chilingarov⁷¹, G. Chiodini^{72a}, A.S. Chisholm¹⁸, R.T. Chislett⁷⁷, A. Chitan^{26a}, M.V. Chizhov⁶⁴,
 G. Choudalakis³¹, S. Chouridou⁹, B.K.B. Chow⁹⁹, I.A. Christidi⁷⁷, A. Christov⁴⁸, D. Chromek-Burckhart³⁰,
 M.L. Chu¹⁵², J. Chudoba¹²⁶, G. Ciapetti^{133a,133b}, A.K. Ciftci^{4a}, R. Ciftci^{4a}, D. Cinca⁶², V. Cindro⁷⁴,
 A. Ciochio¹⁵, M. Cirilli⁸⁸, P. Cirkovic^{13b}, Z.H. Citron¹⁷³, M. Citterio^{90a}, M. Ciubancan^{26a}, A. Clark⁴⁹,
 P.J. Clark⁴⁶, R.N. Clarke¹⁵, J.C. Clemens⁸⁴, B. Clement⁵⁵, C. Clement^{147a,147b}, Y. Coadou⁸⁴,
 M. Cobal^{165a,165c}, A. Coccaro¹³⁹, J. Cochran⁶³, S. Coelli^{90a}, L. Coffey²³, J.G. Cogan¹⁴⁴, J. Coggeshall¹⁶⁶,
 J. Colas⁵, B. Cole³⁵, S. Cole¹⁰⁷, A.P. Colijn¹⁰⁶, C. Collins-Tooth⁵³, J. Collot⁵⁵, T. Colombo^{58c}, G. Colon⁸⁵,
 G. Compostella¹⁰⁰, P. Conde Muiño^{125a}, E. Coniavitis¹⁶⁷, M.C. Conidi¹², S.M. Consonni^{90a,90b},
 V. Consorti⁴⁸, S. Constantinescu^{26a}, C. Conta^{120a,120b}, G. Conti⁵⁷, F. Conventi^{103a,i}, M. Cooke¹⁵,
 B.D. Cooper⁷⁷, A.M. Cooper-Sarkar¹¹⁹, N.J. Cooper-Smith⁷⁶, K. Copic¹⁵, T. Cornelissen¹⁷⁶, M. Corradi^{20a},
 F. Corriveau^{86,j}, A. Corso-Radu¹⁶⁴, A. Cortes-Gonzalez¹², G. Cortiana¹⁰⁰, G. Costa^{90a}, M.J. Costa¹⁶⁸,
 D. Costanzo¹⁴⁰, D. Côté⁸, G. Cottin^{32a}, L. Courneyea¹⁷⁰, G. Cowan⁷⁶, B.E. Cox⁸³, K. Cranmer¹⁰⁹,
 S. Crépe-Renaudin⁵⁵, F. Crescioli⁷⁹, M. Cristinziani²¹, G. Crosetti^{37a,37b}, C.-M. Cuciuc^{26a},
 C. Cuenca Almenar¹⁷⁷, T. Cuhadar Donszelmann¹⁴⁰, J. Cummings¹⁷⁷, M. Curatolo⁴⁷, C. Cuthbert¹⁵¹,
 H. Czirr¹⁴², P. Czodrowski⁴⁴, Z. Czyczula¹⁷⁷, S. D'Auria⁵³, M. D'Onofrio⁷³, A. D'Orazio^{133a,133b},
 M.J. Da Cunha Sargedas De Sousa^{125a}, C. Da Via⁸³, W. Dabrowski^{38a}, A. Dafinca¹¹⁹, T. Dai⁸⁸,
 F. Dallaire⁹⁴, C. Dallapiccola⁸⁵, M. Dam³⁶, D.S. Damiani¹³⁸, A.C. Daniells¹⁸, V. Dao¹⁰⁵, G. Darbo^{50a},
 G.L. Darlea^{26c}, S. Darmora⁸, J.A. Dassoulas⁴², W. Davey²¹, C. David¹⁷⁰, T. Davidek¹²⁸, E. Davies^{119,d},
 M. Davies⁹⁴, O. Davignon⁷⁹, A.R. Davison⁷⁷, Y. Davygora^{58a}, E. Dawe¹⁴³, I. Dawson¹⁴⁰,
 R.K. Daya-Ishmukhametova²³, K. De⁸, R. de Asmundis^{103a}, S. De Castro^{20a,20b}, S. De Cecco⁷⁹,
 J. de Graat⁹⁹, N. De Groot¹⁰⁵, P. de Jong¹⁰⁶, C. De La Taille¹¹⁶, H. De la Torre⁸¹, F. De Lorenzi⁶³,
 L. De Nooij¹⁰⁶, D. De Pedis^{133a}, A. De Salvo^{133a}, U. De Sanctis^{165a,165c}, A. De Santo¹⁵⁰,
 J.B. De Vivie De Regie¹¹⁶, G. De Zorzi^{133a,133b}, W.J. Dearnaley⁷¹, R. Debbe²⁵, C. Debenedetti⁴⁶,
 B. Dechenaux⁵⁵, D.V. Dedovich⁶⁴, J. Degenhardt¹²¹, J. Del Peso⁸¹, T. Del Prete^{123a,123b}, T. Delemontex⁵⁵,
 M. Deliyergiyev⁷⁴, A. Dell'Acqua³⁰, L. Dell'Asta²², M. Della Pietra^{103a,i}, D. della Volpe^{103a,103b},
 M. Delmastro⁵, P.A. Delsart⁵⁵, C. Deluca¹⁰⁶, S. Demers¹⁷⁷, M. Demichev⁶⁴, A. Demilly⁷⁹,
 B. Demirköz^{12,k}, S.P. Denisov¹²⁹, D. Derendarz³⁹, J.E. Derkaoui^{136d}, F. Derue⁷⁹, P. Dervan⁷³, K. Desch²¹,
 P.O. Deviveiros¹⁰⁶, A. Dewhurst¹³⁰, B. DeWilde¹⁴⁹, S. Dhaliwal¹⁰⁶, R. Dhullipudi^{78,l},

A. Di Ciaccio ^{134a,134b}, L. Di Ciaccio ⁵, C. Di Donato ^{103a,103b}, A. Di Girolamo ³⁰, B. Di Girolamo ³⁰,
 S. Di Luise ^{135a,135b}, A. Di Mattia ¹⁵³, B. Di Micco ^{135a,135b}, R. Di Nardo ⁴⁷, A. Di Simone ⁴⁸,
 R. Di Sipio ^{20a,20b}, M.A. Diaz ^{32a}, E.B. Diehl ⁸⁸, J. Dietrich ⁴², T.A. Dietzsch ^{58a}, S. Diglio ⁸⁷,
 K. Dindar Yagci ⁴⁰, J. Dingfelder ²¹, F. Dinut ^{26a}, C. Dionisi ^{133a,133b}, P. Dita ^{26a}, S. Dita ^{26a}, F. Dittus ³⁰,
 F. Djama ⁸⁴, T. Djobava ^{51b}, M.A.B. do Vale ^{24c}, A. Do Valle Wemans ^{125a,m}, T.K.O. Doan ⁵, D. Dobos ³⁰,
 E. Dobson ⁷⁷, J. Dodd ³⁵, C. Doglioni ⁴⁹, T. Doherty ⁵³, T. Dohmae ¹⁵⁶, Y. Doi ^{65,*}, J. Dolejsi ¹²⁸,
 Z. Dolezal ¹²⁸, B.A. Dolgoshein ^{97,*}, M. Donadelli ^{24d}, J. Donini ³⁴, J. Dopke ³⁰, A. Doria ^{103a},
 A. Dos Anjos ¹⁷⁴, A. Dotti ^{123a,123b}, M.T. Dova ⁷⁰, A.T. Doyle ⁵³, M. Dris ¹⁰, J. Dubbert ⁸⁸, S. Dube ¹⁵,
 E. Dubreuil ³⁴, E. Duchovni ¹⁷³, G. Duckeck ⁹⁹, D. Duda ¹⁷⁶, A. Dudarev ³⁰, F. Dudziak ⁶³, L. Duflot ¹¹⁶,
 M.-A. Dufour ⁸⁶, L. Duguid ⁷⁶, M. Dührssen ³⁰, M. Dunford ^{58a}, H. Duran Yildiz ^{4a}, M. Düren ⁵²,
 M. Dwuznik ^{38a}, J. Ebke ⁹⁹, W. Edson ², C.A. Edwards ⁷⁶, N.C. Edwards ⁴⁶, W. Ehrenfeld ²¹, T. Eifert ¹⁴⁴,
 G. Eigen ¹⁴, K. Einsweiler ¹⁵, E. Eisenhandler ⁷⁵, T. Ekelof ¹⁶⁷, M. El Kacimi ^{136c}, M. Ellert ¹⁶⁷, S. Elles ⁵,
 F. Ellinghaus ⁸², K. Ellis ⁷⁵, N. Ellis ³⁰, J. Elmsheuser ⁹⁹, M. Elsing ³⁰, D. Emelianov ¹³⁰, Y. Enari ¹⁵⁶,
 O.C. Endner ⁸², R. Engelmann ¹⁴⁹, A. Engl ⁹⁹, J. Erdmann ¹⁷⁷, A. Ereditato ¹⁷, D. Eriksson ^{147a}, G. Ernis ¹⁷⁶,
 J. Ernst ², M. Ernst ²⁵, J. Ernwein ¹³⁷, D. Errede ¹⁶⁶, S. Errede ¹⁶⁶, E. Ertel ⁸², M. Escalier ¹¹⁶, H. Esch ⁴³,
 C. Escobar ¹²⁴, X. Espinal Curull ¹², B. Esposito ⁴⁷, F. Etienne ⁸⁴, A.I. Etievre ¹³⁷, E. Etzion ¹⁵⁴,
 D. Evangelakou ⁵⁴, H. Evans ⁶⁰, L. Fabbri ^{20a,20b}, C. Fabre ³⁰, G. Facini ³⁰, R.M. Fakhruddinov ¹²⁹,
 S. Falciano ^{133a}, Y. Fang ^{33a}, M. Fanti ^{90a,90b}, A. Farbin ⁸, A. Farilla ^{135a}, T. Farooque ¹⁵⁹, S. Farrell ¹⁶⁴,
 S.M. Farrington ¹⁷¹, P. Farthouat ³⁰, F. Fassi ¹⁶⁸, P. Fassnacht ³⁰, D. Fassouliotis ⁹, B. Fatholahzadeh ¹⁵⁹,
 A. Favareto ^{90a,90b}, L. Fayard ¹¹⁶, P. Federic ^{145a}, O.L. Fedin ¹²², W. Fedorko ¹⁶⁹, M. Fehling-Kaschek ⁴⁸,
 L. Felgioni ⁸⁴, C. Feng ^{33d}, E.J. Feng ⁶, H. Feng ⁸⁸, A.B. Fenyuk ¹²⁹, J. Ferencei ^{145b}, W. Fernando ⁶,
 S. Ferrag ⁵³, J. Ferrando ⁵³, V. Ferrara ⁴², A. Ferrari ¹⁶⁷, P. Ferrari ¹⁰⁶, R. Ferrari ^{120a},
 D.E. Ferreira de Lima ⁵³, A. Ferrer ¹⁶⁸, D. Ferrere ⁴⁹, C. Ferretti ⁸⁸, A. Ferretto Parodi ^{50a,50b}, M. Fiascaris ³¹,
 F. Fiedler ⁸², A. Filipčič ⁷⁴, M. Filipuzzi ⁴², F. Filthaut ¹⁰⁵, M. Fincke-Keeler ¹⁷⁰, K.D. Finelli ⁴⁵,
 M.C.N. Fiolhais ^{125a,h}, L. Fiorini ¹⁶⁸, A. Firan ⁴⁰, J. Fischer ¹⁷⁶, M.J. Fisher ¹¹⁰, E.A. Fitzgerald ²³, M. Flechl ⁴⁸,
 I. Fleck ¹⁴², P. Fleischmann ¹⁷⁵, S. Fleischmann ¹⁷⁶, G.T. Fletcher ¹⁴⁰, G. Fletcher ⁷⁵, T. Flick ¹⁷⁶,
 A. Floderus ⁸⁰, L.R. Flores Castillo ¹⁷⁴, A.C. Florez Bustos ^{160b}, M.J. Flowerdew ¹⁰⁰, T. Fonseca Martin ¹⁷,
 A. Formica ¹³⁷, A. Forti ⁸³, D. Fortin ^{160a}, D. Fournier ¹¹⁶, H. Fox ⁷¹, P. Francavilla ¹², M. Franchini ^{20a,20b},
 S. Franchino ³⁰, D. Francis ³⁰, M. Franklin ⁵⁷, S. Franz ⁶¹, M. Fraternali ^{120a,120b}, S. Fratina ¹²¹, S.T. French ²⁸,
 C. Friedrich ⁴², F. Friedrich ⁴⁴, D. Froidevaux ³⁰, J.A. Frost ²⁸, C. Fukunaga ¹⁵⁷, E. Fullana Torregrosa ¹²⁸,
 B.G. Fulsom ¹⁴⁴, J. Fuster ¹⁶⁸, C. Gabaldon ⁵⁵, O. Gabizon ¹⁷³, A. Gabrielli ^{20a,20b}, A. Gabrielli ^{133a,133b},
 S. Gadatsch ¹⁰⁶, T. Gadfort ²⁵, S. Gadomski ⁴⁹, G. Gagliardi ^{50a,50b}, P. Gagnon ⁶⁰, C. Galea ⁹⁹,
 B. Galhardo ^{125a}, E.J. Gallas ¹¹⁹, V. Gallo ¹⁷, B.J. Gallop ¹³⁰, P. Gallus ¹²⁷, G. Galster ³⁶, K.K. Gan ¹¹⁰,
 R.P. Gandrajula ⁶², Y.S. Gao ^{144,f}, F.M. Garay Walls ⁴⁶, F. Garbersson ¹⁷⁷, C. García ¹⁶⁸, J.E. García Navarro ¹⁶⁸,
 M. Garcia-Sciveres ¹⁵, R.W. Gardner ³¹, N. Garelli ¹⁴⁴, V. Garonne ³⁰, C. Gatti ⁴⁷, G. Gaudio ^{120a}, B. Gaur ¹⁴²,
 L. Gauthier ⁹⁴, P. Gauzzi ^{133a,133b}, I.L. Gavrilenko ⁹⁵, C. Gay ¹⁶⁹, G. Gaycken ²¹, E.N. Gazis ¹⁰, P. Ge ^{33d,n},
 Z. Gece ¹⁶⁹, C.N.P. Gee ¹³⁰, D.A.A. Geerts ¹⁰⁶, Ch. Geich-Gimbel ²¹, K. Gellerstedt ^{147a,147b}, C. Gemme ^{50a},
 A. Gemmell ⁵³, M.H. Genest ⁵⁵, S. Gentile ^{133a,133b}, M. George ⁵⁴, S. George ⁷⁶, D. Gerbaudo ¹⁶⁴,
 A. Gershon ¹⁵⁴, H. Ghazlane ^{136b}, N. Ghodbane ³⁴, B. Giacobbe ^{20a}, S. Giagu ^{133a,133b}, V. Giangiobbe ¹²,
 P. Giannetti ^{123a,123b}, F. Gianotti ³⁰, B. Gibbard ²⁵, S.M. Gibson ⁷⁶, M. Gilchriese ¹⁵, T.P.S. Gillam ²⁸,
 D. Gillberg ³⁰, A.R. Gillman ¹³⁰, D.M. Gingrich ^{3,e}, N. Giokaris ⁹, M.P. Giordani ^{165a,165c},
 R. Giordano ^{103a,103b}, F.M. Giorgi ¹⁶, P. Giovannini ¹⁰⁰, P.F. Giraud ¹³⁷, D. Giugni ^{90a}, C. Giuliani ⁴⁸,
 M. Giunta ⁹⁴, B.K. Gjelsten ¹¹⁸, I. Gkialas ^{155,o}, L.K. Gladilin ⁹⁸, C. Glasman ⁸¹, J. Glatzer ²¹, A. Glazov ⁴²,
 G.L. Glonti ⁶⁴, M. Goblirsch-Kolb ¹⁰⁰, J.R. Goddard ⁷⁵, J. Godfrey ¹⁴³, J. Godlewski ³⁰, M. Goebel ⁴²,
 C. Goeringer ⁸², S. Goldfarb ⁸⁸, T. Golling ¹⁷⁷, D. Golubkov ¹²⁹, A. Gomes ^{125a,c}, L.S. Gomez Fajardo ⁴²,
 R. Gonçalves ⁷⁶, J. Goncalves Pinto Firmino Da Costa ⁴², L. Gonella ²¹, S. González de la Hoz ¹⁶⁸,
 G. Gonzalez Parra ¹², M.L. Gonzalez Silva ²⁷, S. Gonzalez-Sevilla ⁴⁹, J.J. Goodson ¹⁴⁹, L. Goossens ³⁰,
 P.A. Gorbounov ⁹⁶, H.A. Gordon ²⁵, I. Gorelov ¹⁰⁴, G. Gorfine ¹⁷⁶, B. Gorini ³⁰, E. Gorini ^{72a,72b},
 A. Gorišek ⁷⁴, E. Gornicki ³⁹, A.T. Goshaw ⁶, C. Gössling ⁴³, M.I. Gostkin ⁶⁴, I. Gough Eschrich ¹⁶⁴,
 M. Gouighri ^{136a}, D. Goujdami ^{136c}, M.P. Goulette ⁴⁹, A.G. Goussiou ¹³⁹, C. Goy ⁵, S. Gozpinar ²³,
 H.M.X. Grabas ¹³⁷, L. Graber ⁵⁴, I. Grabowska-Bold ^{38a}, P. Grafström ^{20a,20b}, K.-J. Grahn ⁴², E. Gramstad ¹¹⁸,
 F. Grancagnolo ^{72a}, S. Grancagnolo ¹⁶, V. Grassi ¹⁴⁹, V. Gratchev ¹²², H.M. Gray ³⁰, J.A. Gray ¹⁴⁹,

E. Graziani ^{135a}, O.G. Grebenyuk ¹²², Z.D. Greenwood ^{78,l}, K. Gregersen ³⁶, I.M. Gregor ⁴², P. Grenier ¹⁴⁴,
 J. Griffiths ⁸, N. Grigalashvili ⁶⁴, A.A. Grillo ¹³⁸, K. Grimm ⁷¹, S. Grinstein ^{12,p}, Ph. Gris ³⁴,
 Y.V. Grishkevich ⁹⁸, J.-F. Grivaz ¹¹⁶, J.P. Grohs ⁴⁴, A. Grohsjean ⁴², E. Gross ¹⁷³, J. Grosse-Knetter ⁵⁴,
 J. Groth-Jensen ¹⁷³, K. Grybel ¹⁴², F. Guescini ⁴⁹, D. Guest ¹⁷⁷, O. Gueta ¹⁵⁴, C. Guicheney ³⁴,
 E. Guido ^{50a,50b}, T. Guillemin ¹¹⁶, S. Guindon ², U. Gul ⁵³, J. Gunther ¹²⁷, J. Guo ³⁵, S. Gupta ¹¹⁹,
 P. Gutierrez ¹¹², N.G. Gutierrez Ortiz ⁵³, N. Guttman ¹⁵⁴, O. Gutzwiller ¹⁷⁴, C. Guyot ¹³⁷, C. Gwenlan ¹¹⁹,
 C.B. Gwilliam ⁷³, A. Haas ¹⁰⁹, C. Haber ¹⁵, H.K. Hadavand ⁸, P. Haefner ²¹, S. Hageboeck ²¹, Z. Hajduk ³⁹,
 H. Hakobyan ¹⁷⁸, D. Hall ¹¹⁹, G. Halladjian ⁶², K. Hamacher ¹⁷⁶, P. Hamal ¹¹⁴, K. Hamano ⁸⁷, M. Hamer ⁵⁴,
 A. Hamilton ^{146a,q}, S. Hamilton ¹⁶², L. Han ^{33b}, K. Hanagaki ¹¹⁷, K. Hanawa ¹⁵⁶, M. Hance ¹⁵, C. Handel ⁸²,
 P. Hanke ^{58a}, J.R. Hansen ³⁶, J.B. Hansen ³⁶, J.D. Hansen ³⁶, P.H. Hansen ³⁶, P. Hansson ¹⁴⁴, K. Hara ¹⁶¹,
 A.S. Hard ¹⁷⁴, T. Harenberg ¹⁷⁶, S. Harkusha ⁹¹, D. Harper ⁸⁸, R.D. Harrington ⁴⁶, O.M. Harris ¹³⁹,
 J. Hartert ⁴⁸, F. Hartjes ¹⁰⁶, A. Harvey ⁵⁶, S. Hasegawa ¹⁰², Y. Hasegawa ¹⁴¹, S. Hassani ¹³⁷, S. Haug ¹⁷,
 M. Hauschild ³⁰, R. Hauser ⁸⁹, M. Havranek ²¹, C.M. Hawkes ¹⁸, R.J. Hawking ³⁰, A.D. Hawkins ⁸⁰,
 T. Hayashi ¹⁶¹, D. Hayden ⁸⁹, C.P. Hays ¹¹⁹, H.S. Hayward ⁷³, S.J. Haywood ¹³⁰, S.J. Head ¹⁸, T. Heck ⁸²,
 V. Hedberg ⁸⁰, L. Heelan ⁸, S. Heim ¹²¹, B. Heinemann ¹⁵, S. Heisterkamp ³⁶, J. Hejbal ¹²⁶, L. Helary ²²,
 C. Heller ⁹⁹, M. Heller ³⁰, S. Hellman ^{147a,147b}, D. Hellmich ²¹, C. Helsens ³⁰, J. Henderson ¹¹⁹,
 R.C.W. Henderson ⁷¹, A. Henrichs ¹⁷⁷, A.M. Henriques Correia ³⁰, S. Henrot-Versille ¹¹⁶, C. Hensel ⁵⁴,
 G.H. Herbert ¹⁶, C.M. Hernandez ⁸, Y. Hernández Jiménez ¹⁶⁸, R. Herrberg-Schubert ¹⁶, G. Herten ⁴⁸,
 R. Hertenberger ⁹⁹, L. Hervas ³⁰, G.G. Hesketh ⁷⁷, N.P. Hessey ¹⁰⁶, R. Hickling ⁷⁵, E. Higón-Rodríguez ¹⁶⁸,
 J.C. Hill ²⁸, K.H. Hiller ⁴², S. Hillert ²¹, S.J. Hillier ¹⁸, I. Hinchliffe ¹⁵, E. Hines ¹²¹, M. Hirose ¹¹⁷,
 D. Hirschbuehl ¹⁷⁶, J. Hobbs ¹⁴⁹, N. Hod ¹⁰⁶, M.C. Hodgkinson ¹⁴⁰, P. Hodgson ¹⁴⁰, A. Hoecker ³⁰,
 M.R. Hoferkamp ¹⁰⁴, J. Hoffman ⁴⁰, D. Hoffmann ⁸⁴, J.I. Hofmann ^{58a}, M. Hohlfeld ⁸², S.O. Holmgren ^{147a},
 J.L. Holzbauer ⁸⁹, T.M. Hong ¹²¹, L. Hooft van Huysduynen ¹⁰⁹, J.-Y. Hostachy ⁵⁵, S. Hou ¹⁵²,
 A. Hoummada ^{136a}, J. Howard ¹¹⁹, J. Howarth ⁸³, M. Hrabovsky ¹¹⁴, I. Hristova ¹⁶, J. Hrivnac ¹¹⁶,
 T. Hryn'ova ⁵, P.J. Hsu ⁸², S.-C. Hsu ¹³⁹, D. Hu ³⁵, X. Hu ²⁵, Y. Huang ^{33a}, Z. Hubacek ³⁰, F. Hubaut ⁸⁴,
 F. Huegging ²¹, A. Huettmann ⁴², T.B. Huffman ¹¹⁹, E.W. Hughes ³⁵, G. Hughes ⁷¹, M. Huhtinen ³⁰,
 T.A. Hülsing ⁸², M. Hurwitz ¹⁵, N. Huseynov ^{64,r}, J. Huston ⁸⁹, J. Huth ⁵⁷, G. Iacobucci ⁴⁹, G. Iakovidis ¹⁰,
 I. Ibragimov ¹⁴², L. Iconomidou-Fayard ¹¹⁶, J. Idarraga ¹¹⁶, P. Iengo ^{103a}, O. Igonkina ¹⁰⁶, Y. Ikegami ⁶⁵,
 K. Ikematsu ¹⁴², M. Ikeno ⁶⁵, D. Iliadis ¹⁵⁵, N. Ilic ¹⁵⁹, Y. Inamaru ⁶⁶, T. Ince ¹⁰⁰, P. Ioannou ⁹, M. Iodice ^{135a},
 K. Iordanidou ⁹, V. Ippolito ^{133a,133b}, A. Irlles Quiles ¹⁶⁸, C. Isaksson ¹⁶⁷, M. Ishino ⁶⁷, M. Ishitsuka ¹⁵⁸,
 R. Ishmukhametov ¹¹⁰, C. Issever ¹¹⁹, S. Istin ^{19a}, A.V. Ivashin ¹²⁹, W. Iwanski ³⁹, H. Iwasaki ⁶⁵, J.M. Izen ⁴¹,
 V. Izzo ^{103a}, B. Jackson ¹²¹, J.N. Jackson ⁷³, M. Jackson ⁷³, P. Jackson ¹, M.R. Jaekel ³⁰, V. Jain ², K. Jakobs ⁴⁸,
 S. Jakobsen ³⁶, T. Jakoubek ¹²⁶, J. Jakubek ¹²⁷, D.O. Jamin ¹⁵², D.K. Jana ¹¹², E. Jansen ⁷⁷, H. Jansen ³⁰,
 J. Janssen ²¹, M. Janus ¹⁷¹, R.C. Jared ¹⁷⁴, G. Jarlskog ⁸⁰, L. Jeanty ⁵⁷, G.-Y. Jeng ¹⁵¹, I. Jen-La Plante ³¹,
 D. Jennens ⁸⁷, P. Jenni ^{48,s}, J. Jentsch ⁴³, C. Jeske ¹⁷¹, S. Jézéquel ⁵, M.K. Jha ^{20a}, H. Ji ¹⁷⁴, W. Ji ⁸², J. Jia ¹⁴⁹,
 Y. Jiang ^{33b}, M. Jimenez Belenguer ⁴², S. Jin ^{33a}, O. Jinnouchi ¹⁵⁸, M.D. Joergensen ³⁶, D. Joffe ⁴⁰,
 K.E. Johansson ^{147a}, P. Johansson ¹⁴⁰, S. Johnert ⁴², K.A. Johns ⁷, K. Jon-And ^{147a,147b}, G. Jones ¹⁷¹,
 R.W.L. Jones ⁷¹, T.J. Jones ⁷³, P.M. Jorge ^{125a}, K.D. Joshi ⁸³, J. Jovicevic ¹⁴⁸, X. Ju ¹⁷⁴, C.A. Jung ⁴³,
 R.M. Jungst ³⁰, P. Jussel ⁶¹, A. Juste Rozas ^{12,p}, M. Kaci ¹⁶⁸, A. Kaczmarska ³⁹, P. Kadlecik ³⁶, M. Kado ¹¹⁶,
 H. Kagan ¹¹⁰, M. Kagan ¹⁴⁴, E. Kajomovitz ¹⁵³, S. Kalinin ¹⁷⁶, S. Kama ⁴⁰, N. Kanaya ¹⁵⁶, M. Kaneda ³⁰,
 S. Kaneti ²⁸, T. Kanno ¹⁵⁸, V.A. Kantserov ⁹⁷, J. Kanzaki ⁶⁵, B. Kaplan ¹⁰⁹, A. Kapliy ³¹, D. Kar ⁵³,
 K. Karakostas ¹⁰, N. Karastathis ¹⁰, M. Karnevskiy ⁸², S.N. Karpov ⁶⁴, V. Kartvelishvili ⁷¹,
 A.N. Karyukhin ¹²⁹, L. Kashif ¹⁷⁴, G. Kasieczka ^{58b}, R.D. Kass ¹¹⁰, A. Kastanas ¹⁴, Y. Kataoka ¹⁵⁶, A. Katre ⁴⁹,
 J. Katzy ⁴², V. Kaushik ⁷, K. Kawagoe ⁶⁹, T. Kawamoto ¹⁵⁶, G. Kawamura ⁵⁴, S. Kazama ¹⁵⁶, V.F. Kazanin ¹⁰⁸,
 M.Y. Kazarinov ⁶⁴, R. Keeler ¹⁷⁰, P.T. Keener ¹²¹, R. Kehoe ⁴⁰, M. Keil ⁵⁴, J.S. Keller ¹³⁹, H. Keoshkerian ⁵,
 O. Kepka ¹²⁶, B.P. Kerševan ⁷⁴, S. Kersten ¹⁷⁶, K. Kessoku ¹⁵⁶, J. Keung ¹⁵⁹, R.A. Keyes ⁸⁶, F. Khalil-zada ¹¹,
 H. Khandanyan ^{147a,147b}, A. Khanov ¹¹³, D. Kharchenko ⁶⁴, A. Khodinov ⁹⁷, A. Khomich ^{58a}, T.J. Khoo ²⁸,
 G. Khoraiuli ²¹, A. Khoroshilov ¹⁷⁶, V. Khovanskiy ⁹⁶, E. Khramov ⁶⁴, J. Khubua ^{51b}, H. Kim ^{147a,147b},
 S.H. Kim ¹⁶¹, N. Kimura ¹⁷², O. Kind ¹⁶, B.T. King ⁷³, M. King ⁶⁶, R.S.B. King ¹¹⁹, S.B. King ¹⁶⁹, J. Kirk ¹³⁰,
 A.E. Kiryunin ¹⁰⁰, T. Kishimoto ⁶⁶, D. Kisielewska ^{38a}, T. Kitamura ⁶⁶, T. Kittelmann ¹²⁴, K. Kiuchi ¹⁶¹,
 E. Kladiva ^{145b}, M. Klein ⁷³, U. Klein ⁷³, K. Kleinknecht ⁸², M. Klemetti ⁸⁶, P. Klimek ^{147a,147b},
 A. Klimentov ²⁵, R. Klingenberg ⁴³, J.A. Klinger ⁸³, E.B. Klinkby ³⁶, T. Klioutchnikova ³⁰, P.F. Klok ¹⁰⁵,

E.-E. Kluge^{58a}, P. Kluit¹⁰⁶, S. Kluth¹⁰⁰, E. Kneringer⁶¹, E.B.F.G. Knoops⁸⁴, A. Knue⁵⁴, B.R. Ko⁴⁵,
 T. Kobayashi¹⁵⁶, M. Kobel⁴⁴, M. Kocian¹⁴⁴, P. Kodys¹²⁸, S. Koenig⁸², P. Koevesarki²¹, T. Koffas²⁹,
 E. Koffeman¹⁰⁶, L.A. Kogan¹¹⁹, S. Kohlmann¹⁷⁶, F. Kohn⁵⁴, Z. Kohout¹²⁷, T. Kohriki⁶⁵, T. Koi¹⁴⁴,
 H. Kolanoski¹⁶, I. Koletsou^{90a}, J. Koll⁸⁹, A.A. Komar^{95,*}, Y. Komori¹⁵⁶, T. Kondo⁶⁵, K. Köneke⁴⁸,
 A.C. König¹⁰⁵, T. Kono^{42,t}, R. Konoplich^{109,u}, N. Konstantinidis⁷⁷, R. Kopeliansky¹⁵³, S. Koperny^{38a},
 L. Köpke⁸², A.K. Kopp⁴⁸, K. Korcyl³⁹, K. Kordas¹⁵⁵, A. Korn⁴⁶, A.A. Korol¹⁰⁸, I. Korolkov¹²,
 E.V. Korolkova¹⁴⁰, V.A. Korotkov¹²⁹, O. Kortner¹⁰⁰, S. Kortner¹⁰⁰, V.V. Kostyukhin²¹, S. Kotov¹⁰⁰,
 V.M. Kotov⁶⁴, A. Kotwal⁴⁵, C. Kourkoumelis⁹, V. Kouskoura¹⁵⁵, A. Koutsman^{160a}, R. Kowalewski¹⁷⁰,
 T.Z. Kowalski^{38a}, W. Kozanecki¹³⁷, A.S. Kozhin¹²⁹, V. Kral¹²⁷, V.A. Kramarenko⁹⁸, G. Kramberger⁷⁴,
 M.W. Krasny⁷⁹, A. Krasznahorkay¹⁰⁹, J.K. Kraus²¹, A. Kravchenko²⁵, S. Kreiss¹⁰⁹, J. Kretzschmar⁷³,
 K. Kreutzfeldt⁵², N. Krieger⁵⁴, P. Krieger¹⁵⁹, K. Kroeninger⁵⁴, H. Kroha¹⁰⁰, J. Kroll¹²¹, J. Kroseberg²¹,
 J. Krstic^{13a}, U. Kruchonak⁶⁴, H. Krüger²¹, T. Kruker¹⁷, N. Krumnack⁶³, Z.V. Krumshteyn⁶⁴, A. Kruse¹⁷⁴,
 M.K. Kruse⁴⁵, M. Kruskal²², T. Kubota⁸⁷, S. Kuday^{4a}, S. Kuehn⁴⁸, A. Kugel^{58c}, T. Kuhl⁴², V. Kukhtin⁶⁴,
 Y. Kulchitsky⁹¹, S. Kuleshov^{32b}, M. Kuna⁷⁹, J. Kunkle¹²¹, A. Kupco¹²⁶, H. Kurashige⁶⁶, M. Kurata¹⁶¹,
 Y.A. Kurochkin⁹¹, R. Kurumida⁶⁶, V. Kus¹²⁶, E.S. Kuwertz¹⁴⁸, M. Kuze¹⁵⁸, J. Kvita¹⁴³, R. Kwee¹⁶,
 A. La Rosa⁴⁹, L. La Rotonda^{37a,37b}, L. Labarga⁸¹, S. Lablak^{136a}, C. Lacasta¹⁶⁸, F. Lacava^{133a,133b},
 J. Lacey²⁹, H. Lacker¹⁶, D. Lacour⁷⁹, V.R. Lacuesta¹⁶⁸, E. Ladygin⁶⁴, R. Lafaye⁵, B. Laforge⁷⁹,
 T. Lagouri¹⁷⁷, S. Lai⁴⁸, H. Laier^{58a}, E. Laisne⁵⁵, L. Lambourne⁷⁷, C.L. Lampen⁷, W. Lampl⁷, E. Lançon¹³⁷,
 U. Landgraf⁴⁸, M.P.J. Landon⁷⁵, V.S. Lang^{58a}, C. Lange⁴², A.J. Lankford¹⁶⁴, F. Lanni²⁵, K. Lantzsck³⁰,
 A. Lanza^{120a}, S. Laplace⁷⁹, C. Lapoire²¹, J.F. Laporte¹³⁷, T. Lari^{90a}, A. Larner¹¹⁹, M. Lassnig³⁰,
 P. Laurelli⁴⁷, V. Lavorini^{37a,37b}, W. Lavrijsen¹⁵, P. Laycock⁷³, B.T. Le⁵⁵, O. Le Dortz⁷⁹, E. Le Guirriec⁸⁴,
 E. Le Menedeu¹², T. LeCompte⁶, F. Ledroit-Guillon⁵⁵, C.A. Lee¹⁵², H. Lee¹⁰⁶, J.S.H. Lee¹¹⁷, S.C. Lee¹⁵²,
 L. Lee¹⁷⁷, G. Lefebvre⁷⁹, M. Lefebvre¹⁷⁰, M. Legendre¹³⁷, F. Legger⁹⁹, C. Leggett¹⁵, A. Lehan⁷³,
 M. Lehmacher²¹, G. Lehmann Miotto³⁰, A.G. Leister¹⁷⁷, M.A.L. Leite^{24d}, R. Leitner¹²⁸, D. Lellouch¹⁷³,
 B. Lemmer⁵⁴, V. Lendermann^{58a}, K.J.C. Leney^{146c}, T. Lenz¹⁰⁶, G. Lenzen¹⁷⁶, B. Lenzi³⁰, R. Leone⁷,
 K. Leonhardt⁴⁴, S. Leontsinis¹⁰, C. Leroy⁹⁴, J.-R. Lessard¹⁷⁰, C.G. Lester²⁸, C.M. Lester¹²¹, J. Levêque⁵,
 D. Levin⁸⁸, L.J. Levinson¹⁷³, A. Lewis¹¹⁹, G.H. Lewis¹⁰⁹, A.M. Leyko²¹, M. Leyton¹⁶, B. Li^{33b,v}, B. Li⁸⁴,
 H. Li¹⁴⁹, H.L. Li³¹, S. Li⁴⁵, X. Li⁸⁸, Z. Liang^{119,w}, H. Liao³⁴, B. Liberti^{134a}, P. Lichard³⁰, K. Lie¹⁶⁶,
 J. Liebal²¹, W. Liebig¹⁴, C. Limbach²¹, A. Limosani⁸⁷, M. Limper⁶², S.C. Lin^{152,x}, F. Linde¹⁰⁶,
 B.E. Lindquist¹⁴⁹, J.T. Linnemann⁸⁹, E. Lipeles¹²¹, A. Lipniacka¹⁴, M. Lisovyi⁴², T.M. Liss¹⁶⁶,
 D. Lissauer²⁵, A. Lister¹⁶⁹, A.M. Litke¹³⁸, B. Liu¹⁵², D. Liu¹⁵², J.B. Liu^{33b}, K. Liu^{33b,y}, L. Liu⁸⁸, M. Liu⁴⁵,
 M. Liu^{33b}, Y. Liu^{33b}, M. Livan^{120a,120b}, S.S.A. Livermore¹¹⁹, A. Lleres⁵⁵, J. Llorente Merino⁸¹,
 S.L. Lloyd⁷⁵, F. Lo Sterzo^{133a,133b}, E. Lobodzinska⁴², P. Loch⁷, W.S. Lockman¹³⁸, T. Loddenkoetter²¹,
 F.K. Loebinger⁸³, A.E. Loeschall-Jensen³⁶, A. Loginov¹⁷⁷, C.W. Loh¹⁶⁹, T. Lohse¹⁶, K. Lohwasser⁴⁸,
 M. Lokajicek¹²⁶, V.P. Lombardo⁵, R.E. Long⁷¹, L. Lopes^{125a}, D. Lopez Mateos⁵⁷, B. Lopez Paredes¹⁴⁰,
 J. Lorenz⁹⁹, N. Lorenzo Martinez¹¹⁶, M. Losada¹⁶³, P. Loscutoff¹⁵, M.J. Losty^{160a,*}, X. Lou⁴¹,
 A. Lounis¹¹⁶, J. Love⁶, P.A. Love⁷¹, A.J. Lowe^{144,f}, F. Lu^{33a}, H.J. Lubatti¹³⁹, C. Luci^{133a,133b}, A. Lucotte⁵⁵,
 D. Ludwig⁴², I. Ludwig⁴⁸, J. Ludwig⁴⁸, F. Luehring⁶⁰, W. Lukas⁶¹, L. Luminari^{133a}, E. Lund¹¹⁸,
 J. Lundberg^{147a,147b}, O. Lundberg^{147a,147b}, B. Lund-Jensen¹⁴⁸, M. Lungwitz⁸², D. Lynn²⁵, R. Lysak¹²⁶,
 E. Lytken⁸⁰, H. Ma²⁵, L.L. Ma^{33d}, G. Maccarrone⁴⁷, A. Macchiolo¹⁰⁰, B. Maček⁷⁴,
 J. Machado Miguens^{125a}, D. Macina³⁰, R. Mackeprang³⁶, R. Madar⁴⁸, R.J. Madaras¹⁵, H.J. Maddocks⁷¹,
 W.F. Mader⁴⁴, A. Madsen¹⁶⁷, M. Maeno⁸, T. Maeno²⁵, L. Magnoni¹⁶⁴, E. Magradze⁵⁴, K. Mahboubi⁴⁸,
 J. Mahlstedt¹⁰⁶, S. Mahmoud⁷³, G. Mahout¹⁸, C. Maiani¹³⁷, C. Maidantchik^{24a}, A. Maio^{125a,c},
 S. Majewski¹¹⁵, Y. Makida⁶⁵, N. Makovec¹¹⁶, P. Mal^{137,z}, B. Malaescu⁷⁹, Pa. Malecki³⁹, V.P. Maleev¹²²,
 F. Malek⁵⁵, U. Mallik⁶², D. Malon⁶, C. Malone¹⁴⁴, S. Maltezos¹⁰, V.M. Malyshev¹⁰⁸, S. Malyukov³⁰,
 J. Mamuzic^{13b}, L. Mandelli^{90a}, I. Mandić⁷⁴, R. Mandrysch⁶², J. Maneira^{125a}, A. Manfredini¹⁰⁰,
 L. Manhaes de Andrade Filho^{24b}, J.A. Manjarres Ramos¹³⁷, A. Mann⁹⁹, P.M. Manning¹³⁸,
 A. Manousakis-Katsikakis⁹, B. Mansoulie¹³⁷, R. Mantifel⁸⁶, L. Mapelli³⁰, L. March¹⁶⁸, J.F. Marchand²⁹,
 F. Marchese^{134a,134b}, G. Marchiori⁷⁹, M. Marcisovsky¹²⁶, C.P. Marino¹⁷⁰, C.N. Marques^{125a},
 F. Marroquim^{24a}, Z. Marshall¹⁵, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁸, B. Martin³⁰, B. Martin⁸⁹, J.P. Martin⁹⁴,
 T.A. Martin¹⁷¹, V.J. Martin⁴⁶, B. Martin dit Latour⁴⁹, H. Martinez¹³⁷, M. Martinez^{12,p},
 S. Martin-Haugh¹⁵⁰, A.C. Martyniuk¹⁷⁰, M. Marx¹³⁹, F. Marzano^{133a}, A. Marzin¹¹², L. Masetti⁸²,

T. Mashimo ¹⁵⁶, R. Mashinistov ⁹⁵, J. Masik ⁸³, A.L. Maslennikov ¹⁰⁸, I. Massa ^{20a,20b}, N. Massol ⁵,
 P. Mastrandrea ¹⁴⁹, A. Mastroberardino ^{37a,37b}, T. Masubuchi ¹⁵⁶, H. Matsunaga ¹⁵⁶, T. Matsushita ⁶⁶,
 P. Mättig ¹⁷⁶, S. Mättig ⁴², J. Mattmann ⁸², C. Mattravers ^{119,d}, J. Maurer ⁸⁴, S.J. Maxfield ⁷³,
 D.A. Maximov ^{108,g}, R. Mazini ¹⁵², L. Mazzaferro ^{134a,134b}, M. Mazzanti ^{90a}, S.P. Mc Kee ⁸⁸, A. McCarn ¹⁶⁶,
 R.L. McCarthy ¹⁴⁹, T.G. McCarthy ²⁹, N.A. McCubbin ¹³⁰, K.W. McFarlane ^{56,*}, J.A. Mcfayden ¹⁴⁰,
 G. Mchedlidze ^{51b}, T. Mclaughlan ¹⁸, S.J. McMahon ¹³⁰, R.A. McPherson ^{170,j}, A. Meade ⁸⁵, J. Mechnich ¹⁰⁶,
 M. Mechtel ¹⁷⁶, M. Medinnis ⁴², S. Meehan ³¹, R. Meera-Lebbai ¹¹², S. Mehlhase ³⁶, A. Mehta ⁷³,
 K. Meier ^{58a}, C. Meineck ⁹⁹, B. Meirose ⁸⁰, C. Melachrinou ³¹, B.R. Mellado Garcia ^{146c}, F. Meloni ^{90a,90b},
 L. Mendoza Navas ¹⁶³, A. Mengarelli ^{20a,20b}, S. Menke ¹⁰⁰, E. Meoni ¹⁶², K.M. Mercurio ⁵⁷,
 S. Mergelmeyer ²¹, N. Meric ¹³⁷, P. Mermod ⁴⁹, L. Merola ^{103a,103b}, C. Meroni ^{90a}, F.S. Merritt ³¹,
 H. Merritt ¹¹⁰, A. Messina ^{30,aa}, J. Metcalfe ²⁵, A.S. Mete ¹⁶⁴, C. Meyer ⁸², C. Meyer ³¹, J.-P. Meyer ¹³⁷,
 J. Meyer ³⁰, J. Meyer ⁵⁴, S. Michal ³⁰, R.P. Middleton ¹³⁰, S. Migas ⁷³, L. Mijović ¹³⁷, G. Mikenberg ¹⁷³,
 M. Mikestikova ¹²⁶, M. Mikuž ⁷⁴, D.W. Miller ³¹, W.J. Mills ¹⁶⁹, C. Mills ⁵⁷, A. Milov ¹⁷³,
 D.A. Milstead ^{147a,147b}, D. Milstein ¹⁷³, A.A. Minaenko ¹²⁹, M. Miñano Moya ¹⁶⁸, I.A. Minashvili ⁶⁴,
 A.I. Mincer ¹⁰⁹, B. Mindur ^{38a}, M. Mineev ⁶⁴, Y. Ming ¹⁷⁴, L.M. Mir ¹², G. Mirabelli ^{133a}, T. Mitani ¹⁷²,
 J. Mitrevski ¹³⁸, V.A. Mitsou ¹⁶⁸, S. Mitsui ⁶⁵, P.S. Miyagawa ¹⁴⁰, J.U. Mjörnmark ⁸⁰, T. Moa ^{147a,147b},
 V. Moeller ²⁸, S. Mohapatra ¹⁴⁹, W. Mohr ⁴⁸, S. Molander ^{147a,147b}, R. Moles-Valls ¹⁶⁸, A. Molfetas ³⁰,
 K. Mönig ⁴², C. Monini ⁵⁵, J. Monk ³⁶, E. Monnier ⁸⁴, J. Montejo Berlingen ¹², F. Monticelli ⁷⁰,
 S. Monzani ^{20a,20b}, R.W. Moore ³, C. Mora Herrera ⁴⁹, A. Moraes ⁵³, N. Morange ⁶², J. Morel ⁵⁴,
 D. Moreno ⁸², M. Moreno Llácer ¹⁶⁸, P. Morettini ^{50a}, M. Morgenstern ⁴⁴, M. Morii ⁵⁷, S. Moritz ⁸²,
 A.K. Morley ¹⁴⁸, G. Mornacchi ³⁰, J.D. Morris ⁷⁵, L. Morvaj ¹⁰², H.G. Moser ¹⁰⁰, M. Mosidze ^{51b}, J. Moss ¹¹⁰,
 R. Mount ¹⁴⁴, E. Mountricha ^{10,ab}, S.V. Mouraviev ^{95,*}, E.J.W. Moyse ⁸⁵, R.D. Mudd ¹⁸, F. Mueller ^{58a},
 J. Mueller ¹²⁴, K. Mueller ²¹, T. Mueller ²⁸, T. Mueller ⁸², D. Muenstermann ⁴⁹, Y. Munwes ¹⁵⁴,
 J.A. Murillo Quijada ¹⁸, W.J. Murray ¹³⁰, I. Mussche ¹⁰⁶, E. Musto ¹⁵³, A.G. Myagkov ^{129,ac}, M. Myska ¹²⁶,
 O. Nackenhorst ⁵⁴, J. Nadal ¹², K. Nagai ⁶¹, R. Nagai ¹⁵⁸, Y. Nagai ⁸⁴, K. Nagano ⁶⁵, A. Nagarkar ¹¹⁰,
 Y. Nagasaka ⁵⁹, M. Nagel ¹⁰⁰, A.M. Nairz ³⁰, Y. Nakahama ³⁰, K. Nakamura ⁶⁵, T. Nakamura ¹⁵⁶,
 I. Nakano ¹¹¹, H. Namasivayam ⁴¹, G. Nanava ²¹, A. Napier ¹⁶², R. Narayan ^{58b}, M. Nash ^{77,d},
 T. Nattermann ²¹, T. Naumann ⁴², G. Navarro ¹⁶³, H.A. Neal ⁸⁸, P.Yu. Nechaeva ⁹⁵, T.J. Neep ⁸³,
 A. Negri ^{120a,120b}, G. Negri ³⁰, M. Negrini ^{20a}, S. Nektarijevic ⁴⁹, A. Nelson ¹⁶⁴, T.K. Nelson ¹⁴⁴,
 S. Nemecek ¹²⁶, P. Nemethy ¹⁰⁹, A.A. Nepomuceno ^{24a}, M. Nessi ^{30,ad}, M.S. Neubauer ¹⁶⁶, M. Neumann ¹⁷⁶,
 A. Neusiedl ⁸², R.M. Neves ¹⁰⁹, P. Nevski ²⁵, F.M. Newcomer ¹²¹, P.R. Newman ¹⁸, D.H. Nguyen ⁶,
 V. Nguyen Thi Hong ¹³⁷, R.B. Nickerson ¹¹⁹, R. Nicolaidou ¹³⁷, B. Nicquevert ³⁰, J. Nielsen ¹³⁸,
 N. Nikiforou ³⁵, A. Nikiforov ¹⁶, V. Nikolaenko ^{129,ac}, I. Nikolic-Audit ⁷⁹, K. Nikolics ⁴⁹, K. Nikolopoulos ¹⁸,
 P. Nilsson ⁸, Y. Ninomiya ¹⁵⁶, A. Nisati ^{133a}, R. Nisius ¹⁰⁰, T. Nobe ¹⁵⁸, L. Nodulman ⁶, M. Nomachi ¹¹⁷,
 I. Nomidis ¹⁵⁵, S. Norberg ¹¹², M. Nordberg ³⁰, J. Novakova ¹²⁸, M. Nozaki ⁶⁵, L. Nozka ¹¹⁴, K. Ntekas ¹⁰,
 A.-E. Nuncio-Quiroz ²¹, G. Nunes Hanninger ⁸⁷, T. Nunnemann ⁹⁹, E. Nurse ⁷⁷, B.J. O'Brien ⁴⁶, F. O'grady ⁷,
 D.C. O'Neil ¹⁴³, V. O'Shea ⁵³, L.B. Oakes ⁹⁹, F.G. Oakham ^{29,e}, H. Oberlack ¹⁰⁰, J. Ocariz ⁷⁹, A. Ochi ⁶⁶,
 M.I. Ochoa ⁷⁷, S. Oda ⁶⁹, S. Odaka ⁶⁵, J. Odier ⁸⁴, H. Ogren ⁶⁰, A. Oh ⁸³, S.H. Oh ⁴⁵, C.C. Ohm ³⁰,
 T. Ohshima ¹⁰², W. Okamura ¹¹⁷, H. Okawa ²⁵, Y. Okumura ³¹, T. Okuyama ¹⁵⁶, A. Olariu ^{26a},
 A.G. Olchevski ⁶⁴, S.A. Olivares Pino ⁴⁶, M. Oliveira ^{125a,h}, D. Oliveira Damazio ²⁵, E. Oliver Garcia ¹⁶⁸,
 D. Olivito ¹²¹, A. Olszewski ³⁹, J. Olszowska ³⁹, A. Onofre ^{125a,ae}, P.U.E. Onyisi ^{31,af}, C.J. Oram ^{160a},
 M.J. Oreglia ³¹, Y. Oren ¹⁵⁴, D. Orestano ^{135a,135b}, N. Orlando ^{72a,72b}, C. Oropeza Barrera ⁵³, R.S. Orr ¹⁵⁹,
 B. Osculati ^{50a,50b}, R. Ospanov ¹²¹, G. Otero y Garzon ²⁷, H. Otono ⁶⁹, J.P. Ottersbach ¹⁰⁶, M. Ouchrif ^{136d},
 E.A. Ouellette ¹⁷⁰, F. Ould-Saada ¹¹⁸, A. Ouraou ¹³⁷, K.P. Oussoren ¹⁰⁶, Q. Ouyang ^{33a}, A. Ovcharova ¹⁵,
 M. Owen ⁸³, S. Owen ¹⁴⁰, V.E. Ozcan ^{19a}, N. Ozturk ⁸, K. Pachal ¹¹⁹, A. Pacheco Pages ¹²,
 C. Padilla Aranda ¹², S. Pagan Griso ¹⁵, E. Paganis ¹⁴⁰, C. Pahl ¹⁰⁰, F. Paige ²⁵, P. Pais ⁸⁵, K. Pajchel ¹¹⁸,
 G. Palacino ^{160b}, C.P. Paleari ⁷, S. Palestini ³⁰, D. Pallin ³⁴, A. Palma ^{125a}, J.D. Palmer ¹⁸, Y.B. Pan ¹⁷⁴,
 E. Panagiotopoulou ¹⁰, J.G. Panduro Vazquez ⁷⁶, P. Pani ¹⁰⁶, N. Panikashvili ⁸⁸, S. Panitkin ²⁵, D. Pantea ^{26a},
 A. Papadelis ^{147a}, Th.D. Papadopoulou ¹⁰, K. Papageorgiou ^{155,o}, A. Paramonov ⁶, D. Paredes Hernandez ³⁴,
 M.A. Parker ²⁸, F. Parodi ^{50a,50b}, J.A. Parsons ³⁵, U. Parzefall ⁴⁸, S. Pashapour ⁵⁴, E. Pasqualucci ^{133a},
 S. Passaggio ^{50a}, A. Passeri ^{135a}, F. Pastore ^{135a,135b,*}, Fr. Pastore ⁷⁶, G. Pásztor ^{49,ag}, S. Pataraiia ¹⁷⁶,
 N.D. Patel ¹⁵¹, J.R. Pater ⁸³, S. Patricelli ^{103a,103b}, T. Pauly ³⁰, J. Pearce ¹⁷⁰, M. Pedersen ¹¹⁸,

S. Pedraza Lopez¹⁶⁸, M.I. Pedraza Morales¹⁷⁴, S.V. Peleganchuk¹⁰⁸, D. Pelikan¹⁶⁷, H. Peng^{33b}, B. Penning³¹, A. Penson³⁵, J. Penwell⁶⁰, D.V. Perepelitsa³⁵, T. Perez Cavalcanti⁴², E. Perez Codina^{160a}, M.T. Pérez García-Estañ¹⁶⁸, V. Perez Reale³⁵, L. Perini^{90a,90b}, H. Pernegger³⁰, R. Perrino^{72a}, V.D. Peshekhonov⁶⁴, K. Peters³⁰, R.F.Y. Peters^{54.ah}, B.A. Petersen³⁰, J. Petersen³⁰, T.C. Petersen³⁶, E. Petit⁵, A. Petridis^{147a,147b}, C. Petridou¹⁵⁵, E. Petrolo^{133a}, F. Petrucci^{135a,135b}, M. Petteni¹⁴³, R. Pezoa^{32b}, P.W. Phillips¹³⁰, G. Piacquadio¹⁴⁴, E. Pianori¹⁷¹, A. Picazio⁴⁹, E. Piccaro⁷⁵, M. Piccinini^{20a,20b}, S.M. Piec⁴², R. Piegaiia²⁷, D.T. Pignotti¹¹⁰, J.E. Pilcher³¹, A.D. Pilkington⁷⁷, J. Pina^{125a,c}, M. Pinamonti^{165a,165c.ai}, A. Pinder¹¹⁹, J.L. Pinfold³, A. Pingel³⁶, B. Pinto^{125a}, C. Pizio^{90a,90b}, M.-A. Pleier²⁵, V. Pleskot¹²⁸, E. Plotnikova⁶⁴, P. Plucinski^{147a,147b}, S. Poddar^{58a}, F. Podlyski³⁴, R. Poettgen⁸², L. Poggioli¹¹⁶, D. Pohl²¹, M. Pohl⁴⁹, G. Polesello^{120a}, A. Policicchio^{37a,37b}, R. Polifka¹⁵⁹, A. Polini^{20a}, C.S. Pollard⁴⁵, V. Polychronakos²⁵, D. Pomeroy²³, K. Pommès³⁰, L. Pontecorvo^{133a}, B.G. Pope⁸⁹, G.A. Popeneciu^{26b}, D.S. Popovic^{13a}, A. Poppleton³⁰, X. Portell Bueso¹², G.E. Pospelov¹⁰⁰, S. Pospisil¹²⁷, I.N. Potrap⁶⁴, C.J. Potter¹⁵⁰, C.T. Potter¹¹⁵, G. Poulard³⁰, J. Poveda⁶⁰, V. Pozdnyakov⁶⁴, R. Prabhu⁷⁷, P. Pralavorio⁸⁴, A. Pranko¹⁵, S. Prasad³⁰, R. Pravahan²⁵, S. Prell⁶³, D. Price⁶⁰, J. Price⁷³, L.E. Price⁶, D. Prieur¹²⁴, M. Primavera^{72a}, M. Proissl⁴⁶, K. Prokofiev¹⁰⁹, F. Prokoshin^{32b}, E. Protopapadaki¹³⁷, S. Protopopescu²⁵, J. Proudfoot⁶, X. Prudent⁴⁴, M. Przybycien^{38a}, H. Przysiezniak⁵, S. Psoroulas²¹, E. Ptacek¹¹⁵, E. Pueschel⁸⁵, D. Puldon¹⁴⁹, M. Purohit^{25.aj}, P. Puzo¹¹⁶, Y. Pylypchenko⁶², J. Qian⁸⁸, A. Quadt⁵⁴, D.R. Quarrie¹⁵, W.B. Quayle^{146c}, D. Quilty⁵³, V. Radeka²⁵, V. Radescu⁴², P. Radloff¹¹⁵, F. Ragusa^{90a,90b}, G. Rahal¹⁷⁹, S. Rajagopalan²⁵, M. Rammensee⁴⁸, M. Rammes¹⁴², A.S. Randle-Conde⁴⁰, C. Rangel-Smith⁷⁹, K. Rao¹⁶⁴, F. Rauscher⁹⁹, T.C. Rave⁴⁸, T. Ravenscroft⁵³, M. Raymond³⁰, A.L. Read¹¹⁸, D.M. Rebuzzi^{120a,120b}, A. Redelbach¹⁷⁵, G. Redlinger²⁵, R. Reece¹²¹, K. Reeves⁴¹, A. Reinsch¹¹⁵, I. Reisinger⁴³, M. Relich¹⁶⁴, C. Rembser³⁰, Z.L. Ren¹⁵², A. Renaud¹¹⁶, M. Rescigno^{133a}, S. Resconi^{90a}, B. Resende¹³⁷, P. Reznicek⁹⁹, R. Rezvani⁹⁴, R. Richter¹⁰⁰, E. Richter-Was^{38b}, M. Ridel⁷⁹, P. Rieck¹⁶, M. Rijssenbeek¹⁴⁹, A. Rimoldi^{120a,120b}, L. Rinaldi^{20a}, R.R. Rios⁴⁰, E. Ritsch⁶¹, I. Riu¹², G. Rivoltella^{90a,90b}, F. Rizatdinova¹¹³, E. Rizvi⁷⁵, S.H. Robertson^{86.j}, A. Robichaud-Veronneau¹¹⁹, D. Robinson²⁸, J.E.M. Robinson⁸³, A. Robson⁵³, J.G. Rocha de Lima¹⁰⁷, C. Roda^{123a,123b}, D. Roda Dos Santos¹²⁶, L. Rodrigues³⁰, A. Roe⁵⁴, S. Roe³⁰, O. Røhne¹¹⁸, S. Rolli¹⁶², A. Romaniouk⁹⁷, M. Romano^{20a,20b}, G. Romeo²⁷, E. Romero Adam¹⁶⁸, N. Rompotis¹³⁹, L. Roos⁷⁹, E. Ros¹⁶⁸, S. Rosati^{133a}, K. Rosbach⁴⁹, A. Rose¹⁵⁰, M. Rose⁷⁶, P.L. Rosendahl¹⁴, O. Rosenthal¹⁴², V. Rossetti¹², E. Rossi^{133a,133b}, L.P. Rossi^{50a}, R. Rosten¹³⁹, M. Rotaru^{26a}, I. Roth¹⁷³, J. Rothberg¹³⁹, D. Rousseau¹¹⁶, C.R. Royon¹³⁷, A. Rozanov⁸⁴, Y. Rozen¹⁵³, X. Ruan^{146c}, F. Rubbo¹², I. Rubinskiy⁴², N. Ruckstuhl¹⁰⁶, V.I. Rud⁹⁸, C. Rudolph⁴⁴, M.S. Rudolph¹⁵⁹, F. Rühr⁷, A. Ruiz-Martinez⁶³, L. Rummyantsev⁶⁴, Z. Rurikova⁴⁸, N.A. Rusakovich⁶⁴, A. Ruschke⁹⁹, J.P. Rutherford⁷, N. Ruthmann⁴⁸, P. Ruzicka¹²⁶, Y.F. Ryabov¹²², M. Rybar¹²⁸, G. Rybkin¹¹⁶, N.C. Ryder¹¹⁹, A.F. Saavedra¹⁵¹, A. Saddique³, I. Sadeh¹⁵⁴, H.F.-W. Sadrozinski¹³⁸, R. Sadykov⁶⁴, F. Safai Tehrani^{133a}, H. Sakamoto¹⁵⁶, G. Salamanna⁷⁵, A. Salamon^{134a}, M. Saleem¹¹², D. Salek³⁰, D. Salihagic¹⁰⁰, A. Salnikov¹⁴⁴, J. Salt¹⁶⁸, B.M. Salvachua Ferrando⁶, D. Salvatore^{37a,37b}, F. Salvatore¹⁵⁰, A. Salvucci¹⁰⁵, A. Salzburger³⁰, D. Sampsonidis¹⁵⁵, A. Sanchez^{103a,103b}, J. Sánchez¹⁶⁸, V. Sanchez Martinez¹⁶⁸, H. Sandaker¹⁴, H.G. Sander⁸², M.P. Sanders⁹⁹, M. Sandhoff¹⁷⁶, T. Sandoval²⁸, C. Sandoval¹⁶³, R. Sandstroem¹⁰⁰, D.P.C. Sankey¹³⁰, A. Sansoni⁴⁷, C. Santoni³⁴, R. Santonico^{134a,134b}, H. Santos^{125a}, I. Santoyo Castillo¹⁵⁰, K. Sapp¹²⁴, A. Saproinov⁶⁴, J.G. Saraiva^{125a}, T. Sarangi¹⁷⁴, E. Sarkisyan-Grinbaum⁸, B. Sarrazin²¹, F. Sarri^{123a,123b}, G. Sartisohn¹⁷⁶, O. Sasaki⁶⁵, Y. Sasaki¹⁵⁶, N. Sasao⁶⁷, I. Satsounkevitch⁹¹, G. Sauvage^{5.*}, E. Sauvan⁵, J.B. Sauvan¹¹⁶, P. Savard^{159.e}, V. Savinov¹²⁴, D.O. Savu³⁰, C. Sawyer¹¹⁹, L. Sawyer^{78.l}, D.H. Saxon⁵³, J. Saxon¹²¹, C. Sbarra^{20a}, A. Sbrizzi³, T. Scanlon³⁰, D.A. Scannicchio¹⁶⁴, M. Scarcella¹⁵¹, J. Schaarschmidt¹¹⁶, P. Schacht¹⁰⁰, D. Schaefer¹²¹, A. Schaelicke⁴⁶, S. Schaepe²¹, S. Schaezel^{58b}, U. Schäfer⁸², A.C. Schaffer¹¹⁶, D. Schaile⁹⁹, R.D. Schamberger¹⁴⁹, V. Scharf^{58a}, V.A. Schegelsky¹²², D. Scheirich⁸⁸, M. Schernau¹⁶⁴, M.I. Scherzer³⁵, C. Schiavi^{50a,50b}, J. Schieck⁹⁹, C. Schillo⁴⁸, M. Schioppa^{37a,37b}, S. Schlenker³⁰, E. Schmidt⁴⁸, K. Schmieden³⁰, C. Schmitt⁸², C. Schmitt⁹⁹, S. Schmitt^{58b}, B. Schneider¹⁷, Y.J. Schnellbach⁷³, U. Schnoor⁴⁴, L. Schoeffel¹³⁷, A. Schoening^{58b}, A.L.S. Schorlemmer⁵⁴, M. Schott⁸², D. Schouten^{160a}, J. Schovancova¹²⁶, M. Schram⁸⁶, C. Schroeder⁸², N. Schroer^{58c}, N. Schuh⁸², M.J. Schultens²¹, H.-C. Schultz-Coulon^{58a}, H. Schulz¹⁶, M. Schumacher⁴⁸, B.A. Schumm¹³⁸, Ph. Schune¹³⁷, A. Schwartzman¹⁴⁴, Ph. Schwegler¹⁰⁰,

Ph. Schwemling¹³⁷, R. Schwienhorst⁸⁹, J. Schwindling¹³⁷, T. Schwindt²¹, M. Schwoerer⁵, F.G. Sciacca¹⁷, E. Scifo¹¹⁶, G. Sciolla²³, W.G. Scott¹³⁰, F. Scutti²¹, J. Searcy⁸⁸, G. Sedov⁴², E. Sedykh¹²², S.C. Seidel¹⁰⁴, A. Seiden¹³⁸, F. Seifert⁴⁴, J.M. Seixas^{24a}, G. Sekhniaidze^{103a}, S.J. Sekula⁴⁰, K.E. Selbach⁴⁶, D.M. Seliverstov¹²², G. Sellers⁷³, M. Seman^{145b}, N. Semprini-Cesari^{20a,20b}, C. Serfon³⁰, L. Serin¹¹⁶, L. Serkin⁵⁴, T. Serre⁸⁴, R. Seuster^{160a}, H. Severini¹¹², F. Sforza¹⁰⁰, A. Sfyrla³⁰, E. Shabalina⁵⁴, M. Shamim¹¹⁵, L.Y. Shan^{33a}, J.T. Shank²², Q.T. Shao⁸⁷, M. Shapiro¹⁵, P.B. Shatalov⁹⁶, K. Shaw^{165a,165c}, P. Sherwood⁷⁷, S. Shimizu⁶⁶, M. Shimojima¹⁰¹, T. Shin⁵⁶, M. Shiyakova⁶⁴, A. Shmeleva⁹⁵, M.J. Shochet³¹, D. Short¹¹⁹, S. Shrestha⁶³, E. Shulga⁹⁷, M.A. Shupe⁷, S. Shushkevich⁴², P. Sicho¹²⁶, D. Sidorov¹¹³, A. Sidoti^{133a}, F. Siegert⁴⁸, Dj. Sijacki^{13a}, O. Silbert¹⁷³, J. Silva^{125a}, Y. Silver¹⁵⁴, D. Silverstein¹⁴⁴, S.B. Silverstein^{147a}, V. Simak¹²⁷, O. Simard⁵, Lj. Simic^{13a}, S. Simion¹¹⁶, E. Simioni⁸², B. Simmons⁷⁷, R. Simoniello^{90a,90b}, M. Simonyan³⁶, P. Sinervo¹⁵⁹, N.B. Sinev¹¹⁵, V. Sipica¹⁴², G. Siragusa¹⁷⁵, A. Sircar⁷⁸, A.N. Sisakyan^{64,*}, S.Yu. Sivoklov⁹⁸, J. Sjölin^{147a,147b}, T.B. Sjrursen¹⁴, L.A. Skinnari¹⁵, H.P. Skottowe⁵⁷, K.Yu. Skovpen¹⁰⁸, P. Skubic¹¹², M. Slater¹⁸, T. Slavicek¹²⁷, K. Sliwa¹⁶², V. Smakhtin¹⁷³, B.H. Smart⁴⁶, L. Smestad¹¹⁸, S.Yu. Smirnov⁹⁷, Y. Smirnov⁹⁷, L.N. Smirnova^{98,ak}, O. Smirnova⁸⁰, K.M. Smith⁵³, M. Smizanska⁷¹, K. Smolek¹²⁷, A.A. Snesarev⁹⁵, G. Snidero⁷⁵, J. Snow¹¹², S. Snyder²⁵, R. Sobie^{170,j}, J. Sodomka¹²⁷, A. Soffer¹⁵⁴, D.A. Soh^{152,w}, C.A. Solans³⁰, M. Solar¹²⁷, J. Solc¹²⁷, E.Yu. Soldatov⁹⁷, U. Soldevila¹⁶⁸, E. Solfaroli Camillocci^{133a,133b}, A.A. Solodkov¹²⁹, O.V. Solovyanov¹²⁹, V. Solovyev¹²², N. Soni¹, A. Sood¹⁵, V. Sopko¹²⁷, B. Sopko¹²⁷, M. Sosebee⁸, R. Soualah^{165a,165c}, P. Soueid⁹⁴, A.M. Soukharev¹⁰⁸, D. South⁴², S. Spagnolo^{72a,72b}, F. Spanò⁷⁶, W.R. Spearman⁵⁷, R. Spighi^{20a}, G. Spigo³⁰, M. Spousta^{128,al}, T. Spreitzer¹⁵⁹, B. Spurlock⁸, R.D. St. Denis⁵³, J. Stahlman¹²¹, R. Stamen^{58a}, E. Stanecka³⁹, R.W. Stanek⁶, C. Stanescu^{135a}, M. Stanescu-Bellu⁴², M.M. Stanitzki⁴², S. Stapnes¹¹⁸, E.A. Starchenko¹²⁹, J. Stark⁵⁵, P. Staroba¹²⁶, P. Starovoitov⁴², R. Staszewski³⁹, A. Staude⁹⁹, P. Stavina^{145a,*}, G. Steele⁵³, P. Steinbach⁴⁴, P. Steinberg²⁵, I. Stekl¹²⁷, B. Stelzer¹⁴³, H.J. Stelzer⁸⁹, O. Stelzer-Chilton^{160a}, H. Stenzel⁵², S. Stern¹⁰⁰, G.A. Stewart³⁰, J.A. Stillings²¹, M.C. Stockton⁸⁶, M. Stoebe⁸⁶, K. Stoerig⁴⁸, G. Stoicea^{26a}, S. Stonjek¹⁰⁰, A.R. Stradling⁸, A. Straessner⁴⁴, J. Strandberg¹⁴⁸, S. Strandberg^{147a,147b}, A. Strandlie¹¹⁸, E. Strauss¹⁴⁴, M. Strauss¹¹², P. Strizenec^{145b}, R. Ströhmer¹⁷⁵, D.M. Strom¹¹⁵, R. Stroynowski⁴⁰, B. Stugu¹⁴, I. Stumer^{25,*}, J. Stupak¹⁴⁹, P. Sturm¹⁷⁶, N.A. Styles⁴², D. Su¹⁴⁴, H.S. Subramania³, R. Subramaniam⁷⁸, A. Succurro¹², Y. Sugaya¹¹⁷, C. Suhr¹⁰⁷, M. Suk¹²⁷, V.V. Sulin⁹⁵, S. Sultansoy^{4c}, T. Sumida⁶⁷, X. Sun⁵⁵, J.E. Sundermann⁴⁸, K. Suruliz¹⁴⁰, G. Susinno^{37a,37b}, M.R. Sutton¹⁵⁰, Y. Suzuki⁶⁵, M. Svatos¹²⁶, S. Swedish¹⁶⁹, M. Swiatlowski¹⁴⁴, I. Sykora^{145a}, T. Sykora¹²⁸, D. Ta¹⁰⁶, K. Tackmann⁴², A. Taffard¹⁶⁴, R. Tafirout^{160a}, N. Taiblum¹⁵⁴, Y. Takahashi¹⁰², H. Takai²⁵, R. Takashima⁶⁸, H. Takeda⁶⁶, T. Takeshita¹⁴¹, Y. Takubo⁶⁵, M. Talby⁸⁴, A.A. Talyshv^{108,g}, J.Y.C. Tam¹⁷⁵, M.C. Tamsett^{78,am}, K.G. Tan⁸⁷, J. Tanaka¹⁵⁶, R. Tanaka¹¹⁶, S. Tanaka¹³², S. Tanaka⁶⁵, A.J. Tanasijczuk¹⁴³, K. Tani⁶⁶, N. Tannoury⁸⁴, S. Tapprogge⁸², S. Tarem¹⁵³, F. Tarrade²⁹, G.F. Tartarelli^{90a}, P. Tas¹²⁸, M. Tasevsky¹²⁶, T. Tashiro⁶⁷, E. Tassi^{37a,37b}, A. Tavares Delgado^{125a}, Y. Tayalati^{136d}, C. Taylor⁷⁷, F.E. Taylor⁹³, G.N. Taylor⁸⁷, W. Taylor^{160b}, M. Teinturier¹¹⁶, F.A. Teischinger³⁰, M. Teixeira Dias Castanheira⁷⁵, P. Teixeira-Dias⁷⁶, K.K. Temming⁴⁸, H. Ten Kate³⁰, P.K. Teng¹⁵², S. Terada⁶⁵, K. Terashi¹⁵⁶, J. Terron⁸¹, M. Testa⁴⁷, R.J. Teuscher^{159,j}, J. Therhaag²¹, T. Theveneaux-Pelzer³⁴, S. Thoma⁴⁸, J.P. Thomas¹⁸, E.N. Thompson³⁵, P.D. Thompson¹⁸, P.D. Thompson¹⁵⁹, A.S. Thompson⁵³, L.A. Thomsen³⁶, E. Thomson¹²¹, M. Thomson²⁸, W.M. Thong⁸⁷, R.P. Thun^{88,*}, F. Tian³⁵, M.J. Tibbetts¹⁵, T. Tic¹²⁶, V.O. Tikhomirov⁹⁵, Yu.A. Tikhonov^{108,g}, S. Timoshenko⁹⁷, E. Tiouchichine⁸⁴, P. Tipton¹⁷⁷, S. Tisserant⁸⁴, T. Todorov⁵, S. Todorova-Nova¹²⁸, B. Toggerson¹⁶⁴, J. Tojo⁶⁹, S. Tokár^{145a}, K. Tokushuku⁶⁵, K. Tollefson⁸⁹, L. Tomlinson⁸³, M. Tomoto¹⁰², L. Tompkins³¹, K. Toms¹⁰⁴, A. Tonoyan¹⁴, C. Topfel¹⁷, N.D. Topilin⁶⁴, E. Torrence¹¹⁵, H. Torres⁷⁹, E. Torró Pastor¹⁶⁸, J. Toth^{84,ag}, F. Touchard⁸⁴, D.R. Tovey¹⁴⁰, H.L. Tran¹¹⁶, T. Trefzger¹⁷⁵, L. Tremblet³⁰, A. Tricoli³⁰, I.M. Trigger^{160a}, S. Trincaz-Duvoid⁷⁹, M.F. Tripiana⁷⁰, N. Triplett²⁵, W. Trischuk¹⁵⁹, B. Trocmé⁵⁵, C. Troncon^{90a}, M. Trottier-McDonald¹⁴³, M. Trovatelli^{135a,135b}, P. True⁸⁹, M. Trzebinski³⁹, A. Trzupek³⁹, C. Tsarouchas³⁰, J.C-L. Tseng¹¹⁹, P.V. Tsiareshka⁹¹, D. Tsionou¹³⁷, G. Tsipolitis¹⁰, S. Tsiskaridze¹², V. Tsiskaridze⁴⁸, E.G. Tskhadadze^{51a}, I.I. Tsukerman⁹⁶, V. Tsulaia¹⁵, J.-W. Tsung²¹, S. Tsuno⁶⁵, D. Tsybychev¹⁴⁹, A. Tua¹⁴⁰, A. Tudorache^{26a}, V. Tudorache^{26a}, J.M. Tuggle³¹, A.N. Tuna¹²¹, S. Turchikhin^{98,ak}, D. Turecek¹²⁷, I. Turk Cakir^{4d}, R. Turra^{90a,90b}, P.M. Tuts³⁵, A. Tykhonov⁷⁴, M. Tylmad^{147a,147b}, M. Tyndel¹³⁰, K. Uchida²¹, I. Ueda¹⁵⁶, R. Ueno²⁹, M. Ughetto⁸⁴, M. Ugland¹⁴,

M. Uhlenbrock²¹, F. Ukegawa¹⁶¹, G. Unal³⁰, A. Undrus²⁵, G. Unel¹⁶⁴, F.C. Ungaro⁴⁸, Y. Unno⁶⁵, D. Urbaniec³⁵, P. Urquijo²¹, G. Usai⁸, A. Usanova⁶¹, L. Vacavant⁸⁴, V. Vacek¹²⁷, B. Vachon⁸⁶, S. Vahsen¹⁵, N. Valencic¹⁰⁶, S. Valentineti^{20a,20b}, A. Valero¹⁶⁸, L. Valery³⁴, S. Valkar¹²⁸, E. Valladolid Gallego¹⁶⁸, S. Vallecorsa⁴⁹, J.A. Valls Ferrer¹⁶⁸, R. Van Berg¹²¹, P.C. Van Der Deijl¹⁰⁶, R. van der Geer¹⁰⁶, H. van der Graaf¹⁰⁶, R. Van Der Leeuw¹⁰⁶, D. van der Ster³⁰, N. van Eldik³⁰, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴³, I. van Vulpen¹⁰⁶, M. Vanadia¹⁰⁰, W. Vandelli³⁰, A. Vaniachine⁶, P. Vankov⁴², F. Vannucci⁷⁹, R. Vari^{133a}, E.W. Varnes⁷, T. Varol⁸⁵, D. Varouchas¹⁵, A. Vartapetian⁸, K.E. Varvell¹⁵¹, V.I. Vassilakopoulos⁵⁶, F. Vazeille³⁴, T. Vazquez Schroeder⁵⁴, J. Veatch⁷, F. Veloso^{125a}, S. Veneziano^{133a}, A. Ventura^{72a,72b}, D. Ventura⁸⁵, M. Venturi⁴⁸, N. Venturi¹⁵⁹, V. Vercesi^{120a}, M. Verducci¹³⁹, W. Verkerke¹⁰⁶, J.C. Vermeulen¹⁰⁶, A. Vest⁴⁴, M.C. Vetterli^{143.e}, I. Vichou¹⁶⁶, T. Vickey^{146c.an}, O.E. Vickey Boeriu^{146c}, G.H.A. Viehhauser¹¹⁹, S. Viel¹⁶⁹, R. Vigne³⁰, M. Villa^{20a,20b}, M. Villaplana Perez¹⁶⁸, E. Vilucchi⁴⁷, M.G. Vincter²⁹, V.B. Vinogradov⁶⁴, J. Virzi¹⁵, O. Vitells¹⁷³, M. Viti⁴², I. Vivarelli⁴⁸, F. Vives Vaque³, S. Vlachos¹⁰, D. Vladoiu⁹⁹, M. Vlasak¹²⁷, A. Vogel²¹, P. Vokac¹²⁷, G. Volpi⁴⁷, M. Volpi⁸⁷, G. Volpini^{90a}, H. von der Schmitt¹⁰⁰, H. von Radziewski⁴⁸, E. von Toerne²¹, V. Vorobel¹²⁸, M. Vos¹⁶⁸, R. Voss³⁰, J.H. Vosseveld⁷³, N. Vranjes¹³⁷, M. Vranjes Milosavljevic¹⁰⁶, V. Vrba¹²⁶, M. Vreeswijk¹⁰⁶, T. Vu Anh⁴⁸, R. Vuillermet³⁰, I. Vukotic³¹, Z. Vykydal¹²⁷, W. Wagner¹⁷⁶, P. Wagner²¹, S. Wahrenmund⁴⁴, J. Wakabayashi¹⁰², S. Walch⁸⁸, J. Walder⁷¹, R. Walker⁹⁹, W. Walkowiak¹⁴², R. Wall¹⁷⁷, P. Waller⁷³, B. Walsh¹⁷⁷, C. Wang⁴⁵, H. Wang¹⁷⁴, H. Wang⁴⁰, J. Wang¹⁵², J. Wang^{33a}, K. Wang⁸⁶, R. Wang¹⁰⁴, S.M. Wang¹⁵², T. Wang²¹, X. Wang¹⁷⁷, A. Warburton⁸⁶, C.P. Ward²⁸, D.R. Wardrope⁷⁷, M. Warsinsky⁴⁸, A. Washbrook⁴⁶, C. Wasicki⁴², I. Watanabe⁶⁶, P.M. Watkins¹⁸, A.T. Watson¹⁸, I.J. Watson¹⁵¹, M.F. Watson¹⁸, G. Watts¹³⁹, S. Watts⁸³, A.T. Waugh¹⁵¹, B.M. Waugh⁷⁷, S. Webb⁸³, M.S. Weber¹⁷, J.S. Webster³¹, A.R. Weidberg¹¹⁹, P. Weigell¹⁰⁰, J. Weingarten⁵⁴, C. Weiser⁴⁸, H. Weits¹⁰⁶, P.S. Wells³⁰, T. Wenaus²⁵, D. Wendland¹⁶, Z. Weng^{152.w}, T. Wengler³⁰, S. Wenig³⁰, N. Wermes²¹, M. Werner⁴⁸, P. Werner³⁰, M. Werth¹⁶⁴, M. Wessels^{58a}, J. Wetter¹⁶², K. Whalen²⁹, A. White⁸, M.J. White⁸⁷, R. White^{32b}, S. White^{123a,123b}, D. Whiteson¹⁶⁴, D. Whittington⁶⁰, D. Wicke¹⁷⁶, F.J. Wickens¹³⁰, W. Wiedenmann¹⁷⁴, M. Wielers^{80.d}, P. Wienemann²¹, C. Wiglesworth³⁶, L.A.M. Wiik-Fuchs²¹, P.A. Wijeratne⁷⁷, A. Wildauer¹⁰⁰, M.A. Wildt^{42.t}, I. Wilhelm¹²⁸, H.G. Wilkens³⁰, J.Z. Will⁹⁹, E. Williams³⁵, H.H. Williams¹²¹, S. Williams²⁸, W. Willis^{35.*}, S. Willocq⁸⁵, J.A. Wilson¹⁸, A. Wilson⁸⁸, I. Wingerter-Seez⁵, S. Winkelmann⁴⁸, F. Winklmeier³⁰, M. Wittgen¹⁴⁴, T. Wittig⁴³, J. Wittkowski⁹⁹, S.J. Wollstadt⁸², M.W. Wolter³⁹, H. Wolters^{125a.h}, W.C. Wong⁴¹, G. Wooden⁸⁸, B.K. Wosiek³⁹, J. Wotschack³⁰, M.J. Woudstra⁸³, K.W. Wozniak³⁹, K. Wraight⁵³, M. Wright⁵³, B. Wrona⁷³, S.L. Wu¹⁷⁴, X. Wu⁴⁹, Y. Wu⁸⁸, E. Wulf³⁵, T.R. Wyatt⁸³, B.M. Wynne⁴⁶, S. Xella³⁶, M. Xiao¹³⁷, C. Xu^{33b.ab}, D. Xu^{33a}, L. Xu^{33b.ao}, B. Yabsley¹⁵¹, S. Yacoob^{146b.ap}, M. Yamada⁶⁵, H. Yamaguchi¹⁵⁶, Y. Yamaguchi¹⁵⁶, A. Yamamoto⁶⁵, K. Yamamoto⁶³, S. Yamamoto¹⁵⁶, T. Yamamura¹⁵⁶, T. Yamanaka¹⁵⁶, K. Yamauchi¹⁰², Y. Yamazaki⁶⁶, Z. Yan²², H. Yang^{33e}, H. Yang¹⁷⁴, U.K. Yang⁸³, Y. Yang¹¹⁰, Z. Yang^{147a,147b}, S. Yanush⁹², L. Yao^{33a}, Y. Yasu⁶⁵, E. Yatsenko⁴², K.H. Yau Wong²¹, J. Ye⁴⁰, S. Ye²⁵, A.L. Yen⁵⁷, E. Yildirim⁴², M. Yilmaz^{4b}, R. Yoosoofmiya¹²⁴, K. Yorita¹⁷², R. Yoshida⁶, K. Yoshihara¹⁵⁶, C. Young¹⁴⁴, C.J.S. Young¹¹⁹, S. Youssef²², D.R. Yu¹⁵, J. Yu⁸, J. Yu¹¹³, L. Yuan⁶⁶, A. Yurkewicz¹⁰⁷, B. Zabinski³⁹, R. Zaidan⁶², A.M. Zaitsev^{129.ac}, S. Zambito²³, L. Zanello^{133a,133b}, D. Zanzi¹⁰⁰, A. Zaytsev²⁵, C. Zeitnitz¹⁷⁶, M. Zeman¹²⁷, A. Zemla³⁹, O. Zenin¹²⁹, T. Ženiš^{145a}, D. Zerwas¹¹⁶, G. Zevi della Porta⁵⁷, D. Zhang⁸⁸, H. Zhang⁸⁹, J. Zhang⁶, L. Zhang¹⁵², X. Zhang^{33d}, Z. Zhang¹¹⁶, Z. Zhao^{33b}, A. Zhemchugov⁶⁴, J. Zhong¹¹⁹, B. Zhou⁸⁸, N. Zhou¹⁶⁴, C.G. Zhu^{33d}, H. Zhu⁴², J. Zhu⁸⁸, Y. Zhu^{33b}, X. Zhuang^{33a}, A. Zibell⁹⁹, D. Zieminska⁶⁰, N.I. Zimin⁶⁴, C. Zimmermann⁸², R. Zimmermann²¹, S. Zimmermann²¹, S. Zimmermann⁴⁸, Z. Zinonos^{123a,123b}, M. Ziolkowski¹⁴², R. Zitoun⁵, L. Živković³⁵, G. Zobernig¹⁷⁴, A. Zoccoli^{20a,20b}, M. zur Nedden¹⁶, G. Zurzolo^{103a,103b}, V. Zutshi¹⁰⁷, L. Zwalinski³⁰

¹ School of Chemistry and Physics, University of Adelaide, Adelaide, Australia

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

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

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

(d) Turkish Atomic Energy Authority, Ankara, Turkey

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

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

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

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

- ⁹ Physics Department, University of Athens, Athens, Greece
- ¹⁰ Physics Department, National Technical University of Athens, Zografou, Greece
- ¹¹ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ¹² Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
- ¹³ ^(a) Institute of Physics, University of Belgrade, Belgrade; ^(b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
- ¹⁴ Department for Physics and Technology, University of Bergen, Bergen, Norway
- ¹⁵ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
- ¹⁶ Department of Physics, Humboldt University, Berlin, Germany
- ¹⁷ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ¹⁸ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ¹⁹ ^(a) Department of Physics, Bogazici University, Istanbul; ^(b) Department of Physics, Dogus University, Istanbul; ^(c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
- ²⁰ ^(a) INFN Sezione di Bologna; ^(b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- ²¹ Physikalisches Institut, University of Bonn, Bonn, Germany
- ²² Department of Physics, Boston University, Boston, MA, United States
- ²³ Department of Physics, Brandeis University, Waltham, MA, United States
- ²⁴ ^(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; ^(c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; ^(d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
- ²⁵ Physics Department, Brookhaven National Laboratory, Upton, NY, United States
- ²⁶ ^(a) National Institute of Physics and Nuclear Engineering, Bucharest; ^(b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; ^(c) University Politehnica Bucharest, Bucharest; ^(d) West University in Timisoara, Timisoara, Romania
- ²⁷ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ²⁸ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ²⁹ Department of Physics, Carleton University, Ottawa, ON, Canada
- ³⁰ CERN, Geneva, Switzerland
- ³¹ Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
- ³² ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ³³ ^(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; ^(b) Department of Modern Physics, University of Science and Technology of China, Anhui; ^(c) Department of Physics, Nanjing University, Jiangsu; ^(d) School of Physics, Shandong University, Shandong; ^(e) Physics Department, Shanghai Jiao Tong University, Shanghai, China
- ³⁴ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- ³⁵ Nevis Laboratory, Columbia University, Irvington, NY, United States
- ³⁶ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ³⁷ ^(a) INFN Gruppo Collegato di Cosenza; ^(b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ³⁸ ^(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; ^(b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- ³⁹ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ⁴⁰ Physics Department, Southern Methodist University, Dallas, TX, United States
- ⁴¹ Physics Department, University of Texas at Dallas, Richardson, TX, United States
- ⁴² DESY, Hamburg and Zeuthen, Germany
- ⁴³ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁴ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁴⁵ Department of Physics, Duke University, Durham, NC, United States
- ⁴⁶ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁷ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁸ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- ⁴⁹ Section de Physique, Université de Genève, Geneva, Switzerland
- ⁵⁰ ^(a) INFN Sezione di Genova; ^(b) Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁵¹ ^(a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵² II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵³ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁴ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁵ Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- ⁵⁶ Department of Physics, Hampton University, Hampton, VA, United States
- ⁵⁷ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
- ⁵⁸ ^(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁵⁹ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶⁰ Department of Physics, Indiana University, Bloomington, IN, United States
- ⁶¹ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶² University of Iowa, Iowa City, IA, United States
- ⁶³ Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
- ⁶⁴ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁵ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁶ Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁷ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁶⁸ Kyoto University of Education, Kyoto, Japan
- ⁶⁹ Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷⁰ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷¹ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷² ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷³ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁴ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁵ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁶ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁷ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁷⁸ Louisiana Tech University, Ruston, LA, United States
- ⁷⁹ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁸⁰ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸¹ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain

- 82 Institut für Physik, Universität Mainz, Mainz, Germany
- 83 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- 84 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- 85 Department of Physics, University of Massachusetts, Amherst, MA, United States
- 86 Department of Physics, McGill University, Montreal, QC, Canada
- 87 School of Physics, University of Melbourne, Victoria, Australia
- 88 Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- 89 Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- 90 ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- 91 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- 92 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- 93 Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
- 94 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- 95 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- 96 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- 97 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- 98 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- 99 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 100 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- 101 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 102 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- 103 ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- 104 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- 105 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- 106 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- 107 Department of Physics, Northern Illinois University, DeKalb, IL, United States
- 108 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- 109 Department of Physics, New York University, New York, NY, United States
- 110 Ohio State University, Columbus, OH, United States
- 111 Faculty of Science, Okayama University, Okayama, Japan
- 112 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
- 113 Department of Physics, Oklahoma State University, Stillwater, OK, United States
- 114 Palacký University, RCPTM, Olomouc, Czech Republic
- 115 Center for High Energy Physics, University of Oregon, Eugene, OR, United States
- 116 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- 117 Graduate School of Science, Osaka University, Osaka, Japan
- 118 Department of Physics, University of Oslo, Oslo, Norway
- 119 Department of Physics, Oxford University, Oxford, United Kingdom
- 120 ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- 121 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
- 122 Petersburg Nuclear Physics Institute, Gatchina, Russia
- 123 ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- 124 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
- 125 ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa, Portugal; ^(b) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
- 126 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- 127 Czech Technical University in Prague, Praha, Czech Republic
- 128 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- 129 State Research Center Institute for High Energy Physics, Protvino, Russia
- 130 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- 131 Physics Department, University of Regina, Regina, SK, Canada
- 132 Ritsumeikan University, Kusatsu, Shiga, Japan
- 133 ^(a) INFN Sezione di Roma I; ^(b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- 134 ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 135 ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- 136 ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies, Université Hassan II, Casablanca; ^(b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; ^(d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; ^(e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
- 137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- 138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
- 139 Department of Physics, University of Washington, Seattle, WA, United States
- 140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- 141 Department of Physics, Shinshu University, Nagano, Japan
- 142 Fachbereich Physik, Universität Siegen, Siegen, Germany
- 143 Department of Physics, Simon Fraser University, Burnaby, BC, Canada
- 144 SLAC National Accelerator Laboratory, Stanford, CA, United States
- 145 ^(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- 146 ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- 147 ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
- 148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
- 149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
- 150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- 151 School of Physics, University of Sydney, Sydney, Australia
- 152 Institute of Physics, Academia Sinica, Taipei, Taiwan
- 153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- 154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- 155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

- ¹⁵⁶ International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- ¹⁵⁷ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- ¹⁵⁸ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- ¹⁵⁹ Department of Physics, University of Toronto, Toronto, ON, Canada
- ¹⁶⁰ ^(a) TRIUMF, Vancouver, BC; ^(b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
- ¹⁶¹ Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- ¹⁶² Department of Physics and Astronomy, Tufts University, Medford, MA, United States
- ¹⁶³ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- ¹⁶⁴ Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
- ¹⁶⁵ ^(a) INFN Gruppo Collegato di Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- ¹⁶⁶ Department of Physics, University of Illinois, Urbana, IL, United States
- ¹⁶⁷ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- ¹⁶⁸ Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- ¹⁶⁹ Department of Physics, University of British Columbia, Vancouver, BC, Canada
- ¹⁷⁰ Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
- ¹⁷¹ Department of Physics, University of Warwick, Coventry, United Kingdom
- ¹⁷² Waseda University, Tokyo, Japan
- ¹⁷³ Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- ¹⁷⁴ Department of Physics, University of Wisconsin, Madison, WI, United States
- ¹⁷⁵ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- ¹⁷⁶ Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- ¹⁷⁷ Department of Physics, Yale University, New Haven, CT, United States
- ¹⁷⁸ Yerevan Physics Institute, Yerevan, Armenia
- ¹⁷⁹ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- ^a Also at Department of Physics, King's College London, London, United Kingdom.
- ^b Also at Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa, Portugal.
- ^c Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
- ^d Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ^e Also at TRIUMF, Vancouver, BC, Canada.
- ^f Also at Department of Physics, California State University, Fresno, CA, United States.
- ^g Also at Novosibirsk State University, Novosibirsk, Russia.
- ^h Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
- ⁱ Also at Università di Napoli Parthenope, Napoli, Italy.
- ^j Also at Institute of Particle Physics (IPP), Canada.
- ^k Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
- ^l Also at Louisiana Tech University, Ruston, LA, United States.
- ^m Also at Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
- ⁿ Also at Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States.
- ^o Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
- ^p Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
- ^q Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
- ^r Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
- ^s Also at CERN, Geneva, Switzerland.
- ^t Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
- ^u Also at Manhattan College, New York, NY, United States.
- ^v Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^w Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
- ^x Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^y Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
- ^z Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.
- ^{aa} Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.
- ^{ab} Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France.
- ^{ac} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- ^{ad} Also at Section de Physique, Université de Genève, Geneva, Switzerland.
- ^{ae} Also at Departamento de Física, Universidade de Minho, Braga, Portugal.
- ^{af} Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.
- ^{ag} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- ^{ah} Also at DESY, Hamburg and Zeuthen, Germany.
- ^{ai} Also at International School for Advanced Studies (SISSA), Trieste, Italy.
- ^{aj} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
- ^{ak} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
- ^{al} Also at Nevis Laboratory, Columbia University, Irvington, NY, United States.
- ^{am} Also at Physics Department, Brookhaven National Laboratory, Upton, NY, United States.
- ^{an} Also at Department of Physics, Oxford University, Oxford, United Kingdom.
- ^{ao} Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
- ^{ap} Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
- * Deceased.