

Search for resonances in the mass distribution of jet pairs with one or two jets identified as b -jets in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector



The ATLAS Collaboration *

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ABSTRACT

Searches for high-mass resonances in the dijet invariant mass spectrum with one or two jets identified as b -jets are performed using an integrated luminosity of 3.2 fb^{-1} of proton–proton collisions with a centre-of-mass energy of $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. No evidence of anomalous phenomena is observed in the data, which are used to exclude, at 95% credibility level, excited b^* quarks with masses from 1.1 TeV to 2.1 TeV and leptophobic Z' bosons with masses from 1.1 TeV to 1.5 TeV. Contributions of a Gaussian signal shape with effective cross sections ranging from approximately 0.4 to 0.001 pb are also excluded in the mass range 1.5–5.0 TeV.

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1. Introduction

Many extensions to the Standard Model (SM) predict the existence of new massive particles that couple to quarks or gluons. If produced in proton–proton (pp) collisions at the Large Hadron Collider (LHC), these new beyond-the-SM (BSM) particles could decay into quarks (q) or gluons (g), creating resonant excesses in the two-jet (dijet) invariant mass distributions [1–6]. If the new particle couples to the b -quark and decays into $b\bar{b}$, bq or $b\bar{g}$ pairs, a dedicated search for dijet resonances with one or both jets identified as originating from a b -quark (“ b -jet”) could greatly increase the signal sensitivity.

Prior resonance searches in dijet events containing b -jets were performed by the CDF [7] and CMS [8,9] experiments, probing the mass ranges 200–750 GeV and 1–4 TeV respectively. Excited heavy-flavour quarks have been investigated in alternative decay modes as well [10]. No BSM phenomena have been observed yet. The increase in centre-of-mass energy of the pp collisions at the LHC from $\sqrt{s} = 7$ and 8 TeV to 13 TeV provides a new energy regime in which to search for such a heavy resonance. This is particularly true for heavy states coupling to b -quarks from the proton sea, when compared to states produced by valence quarks. The parton luminosity to create a 2 TeV object increases by an additional factor of 2–3 for $b\bar{b}$ and $b\bar{g}$ over $q\bar{q}$ and qg pairs, when increasing the centre-of-mass energy from 8 TeV to 13 TeV. The total production rate for dijet BSM signals can become large enough

to allow a good signal sensitivity even with a relatively small data sample. In this paper the search for a new narrow resonance decaying to b -quarks with the ATLAS detector, using 3.2 fb^{-1} integrated luminosity of proton–proton collisions at $\sqrt{s} = 13$ TeV, is reported. The mass range 1.1–5.0 TeV is probed.

The results are interpreted in the context of two benchmark processes shown in Fig. 1: an excited heavy-flavour quark b^* and a new gauge boson Z' . Excited quarks are a consequence of quark compositeness models that were proposed to explain the generational structure and mass hierarchy of quarks [11,12]. The Z' boson arises in many extensions to the SM with an additional $U(1)$ group. Two Z' models are considered, one with SM-like fermion couplings in the Sequential Standard Model (SSM) and a leptophobic Z' model [13,14]. All benchmark model decays are expected to result in a narrow resonance superimposed on a smoothly falling dijet invariant mass distribution. This search divides the events into samples with one or two jets identified as b -jets to enhance the signal sensitivity to the benchmark models $b^* \rightarrow b\bar{g}$ and $Z' \rightarrow b\bar{b}$. In addition, the results are interpreted in the context of possible Gaussian-shaped signal contributions to the dijet invariant mass spectra where one or both jets are identified as b -jets. The results, presented in terms of the cross section times acceptance times branching ratio ($\sigma \times A \times \text{BR}$), are quoted for contributions with widths of up to 15% of the resonance mass.

2. The ATLAS detector

The ATLAS experiment [15] at the LHC is a multi-purpose particle detector with a forward–backward symmetric cylindrical

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

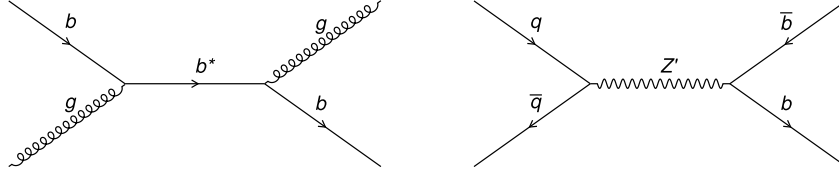


Fig. 1. Leading-order Feynman diagrams for the two processes considered: $gb \rightarrow b^* \rightarrow bg$ and $q\bar{q} \rightarrow Z' \rightarrow b\bar{b}$.

geometry and a near 4π coverage in solid angle.¹ It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of, in ascending order of radius from the beam-line, silicon pixel, silicon microstrip, and transition radiation tracking detectors. The pixel detectors are crucial for b -jet identification. For the second LHC data-taking period, a new inner pixel layer, the Insertable B-Layer (IBL) [16,17], was added at a mean sensor radius of 3.2 cm from the beam-line. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A hadron (steel/scintillator-tile) calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the input rate from the nominal LHC collision rate to an acceptance rate of 100 kHz. This is followed by a software-based trigger that reduces the rate of events recorded to 1 kHz.

3. Data and simulated event samples

The data used in this analysis were collected by the ATLAS detector in pp collisions at the LHC with a centre-of-mass energy of 13 TeV during 2015. Events were recorded using a jet-based trigger requiring at least one jet with a transverse momentum p_T of at least 360 GeV. The full dataset corresponds to an integrated luminosity of 3.2 fb^{-1} with an associated uncertainty of 5% after applying quality criteria to the data. The measurement of the integrated luminosity is derived, following a methodology similar to that detailed in Ref. [18], from a calibration of the luminosity scale using a pair of x - y beam-separation scans.

Monte Carlo (MC) simulated event samples are used to model the expected signals and study the composition of SM background processes. The QCD dijet process is simulated with PYTHIA8 [19] using the A14 tuned parameter set [20] for the modelling of the parton shower, hadronization and underlying event. The leading-order (LO) parton distribution function (PDF) set NNPDF2.3 [21] is used for the generation of events. The renormalization and factorization scales are set to the average transverse momentum p_T of the two leading jets. The EVTGEN decay package [22] is used for bottom and charm hadron decays.

The three signal samples are generated with PYTHIA8 using the A14 set of tuned parameters and the NNPDF2.3 PDF set. For the b^* model, the compositeness scale is set to the excited-quark mass

and 85% of decays are to bg . The remaining decay modes are to a SM gauge boson (Z boson, W boson or photon) and a b -quark. In the SSM Z' model, the Z' boson has the same couplings to SM fermions as the SM Z boson and the bottom quark decay branching ratio $\text{BR}(Z' \rightarrow b\bar{b})$ is 13.8%. The leptophobic Z' model differs by having vanishing couplings to leptons. The corresponding value of $\text{BR}(Z' \rightarrow b\bar{b})$ is 18.9%. For both, only decays to b -quark pairs are simulated. The intrinsic decay width is $\Gamma \sim 0.6\%$ of the resonance mass for the b^* model and $\Gamma \sim 3\%$ of the mass for the SSM Z' boson.

The generated samples are processed with the ATLAS detector simulation [23], which is based on the GEANT4 package [24]. To account for additional pp interactions from the same or close-by bunch crossings, a number of minimum-bias interactions generated using PYTHIA8 and the MSTW2008LO PDF [25] set are superimposed onto the hard scattering events. The MC samples are re-weighted to match the collisions per bunch crossing observed in the data.

4. Event reconstruction and selection

Jets are reconstructed from noise-suppressed topological clusters [26] of energy deposited in the calorimeters using the anti- k_t algorithm [27] with a radius parameter of 0.4. Jet energies and directions are corrected by the jet calibrations derived from $\sqrt{s} = 13 \text{ TeV}$ simulation, and pp collision data taken at $\sqrt{s} = 8 \text{ TeV}$ and $\sqrt{s} = 13 \text{ TeV}$, as described in Ref. [28]. Jets are required to have $p_T > 50 \text{ GeV}$. Events where any of the three leading jets with $p_T > 50 \text{ GeV}$ is compatible with non-collision background or calorimeter noise are removed. Events are preselected in the same way as in the dijet analysis of Ref. [5], requiring that the p_T of the leading jet is greater than 440 GeV to ensure full trigger efficiency. An additional requirement is placed on the jet pseudorapidity, $|\eta| < 2.4$, to ensure tracker coverage for b -jet identification. The analysis is performed in an unbiased dijet mass range of $m_{jj} > 1.1 \text{ TeV}$. To reduce the background from QCD multijet processes and enhance s -channel processes, the rapidity difference $y^* = (y_1 - y_2)/2$ between the two leading jets is required to be $|y^*| < 0.6$. Here y_1 and y_2 are the rapidities of the leading and sub-leading jet respectively.

To identify jets originating from b -hadrons (b -tagging) a multivariate algorithm that combines information about the impact parameters of inner detector tracks associated with the jet, the presence of displaced secondary vertices, and the reconstructed flight paths of b - and c -hadrons associated with the jet [29,30] is employed. The b -tagging working point with 85% efficiency, as determined when integrating over all jets in a simulated sample of $t\bar{t}$ events, is chosen because it gives the highest signal sensitivity. As the average jet energies in this analysis are larger than in $t\bar{t}$ events and the b -tagging efficiency drops with jet p_T , the per-jet efficiencies are below 85% and are roughly 50% for jets with a p_T of 1 TeV.

The b -jet identification algorithm is applied to the two leading jets, and events are categorized as inclusive, single b -tagged “1b” or double b -tagged “2b”, in order to enhance the sensitivity of dif-

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

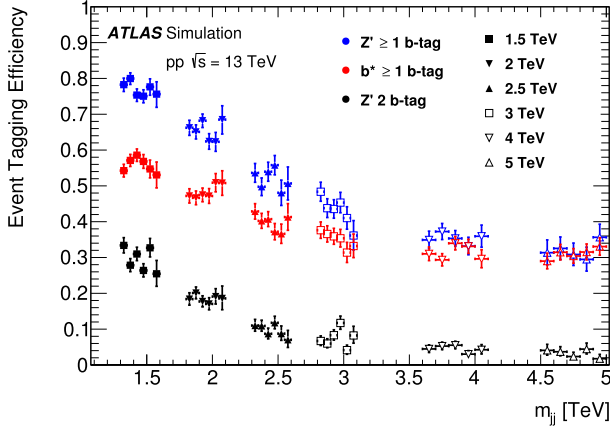


Fig. 2. The per-event b -tagging efficiencies after the event selection as a function of the reconstructed invariant mass for simulated samples with six different b^* and Z' resonance masses.

ferent signal compositions. The “1b” category is defined inclusively, including events from the “2b” category.

The per-event b -tagging efficiencies as functions of the reconstructed invariant mass are shown in Fig. 2. Efficiencies are for benchmark models with different b^* and Z' resonance masses, after the event selection is applied. The tagging efficiency for Z' events in the inclusive “1b” category is higher than for b^* events because this process has more b -quarks in the final state. At high mass, the gluon from the decay of the b^* has a higher probability to produce a $b\bar{b}$ -pair, which causes the event tagging efficiency to be comparable for the Z' and b^* . The tagging efficiency in the “2b” category is about 2.5 times lower at low mass and a factor 10 lower at high mass compared to the inclusive “1b” category for the same Z' events. The average light-flavour jet rejection factor for jets passing the kinematic selection is approximately 30 for jet transverse momenta up to ~ 1 TeV.

Correction factors are applied to the simulated event samples to compensate for differences between data and simulation in b -tagging efficiencies and mis-identification rates. These corrections were derived from comparisons of samples of b -quark-enriched events in data and simulation [31]. The average combined signal acceptance and efficiency is around 20% for the b^* benchmark in the “1b” category and drops with increasing mass from 9% at 1.5 TeV to 2% at 5.0 TeV for the Z' signals for the “2b” category.

5. Dijet mass spectrum

The dijet mass spectrum is predominantly composed of jets arising from QCD interactions. Fig. 3 shows the comparison between data and PYTHIA8 multijet MC simulation. The simulated distributions are normalized to the number of events observed in the data in each category separately. The bin widths are chosen to approximate the m_{jj} resolution as derived from simulated QCD processes, which range from 3% at 1.0 TeV to 2% at 5.0 TeV. Good agreement between the shapes of the PYTHIA8 multijet predictions and the data is found. The inclusive distribution, not restricted in the inner tracking detector acceptance, was analysed in Ref. [5].

The dijet background estimation does not rely on the simulation as it is obtained directly from a fit to the m_{jj} distribution. The following parameterization ansatz is adopted to fit the distribution in the m_{jj} range from 1.1 TeV up to the last data point of the inclusive, “1b” and “2b” mass distributions separately,

$$f(z) = p_1(1 - z)^{p_2} z^{p_3}, \quad (1)$$

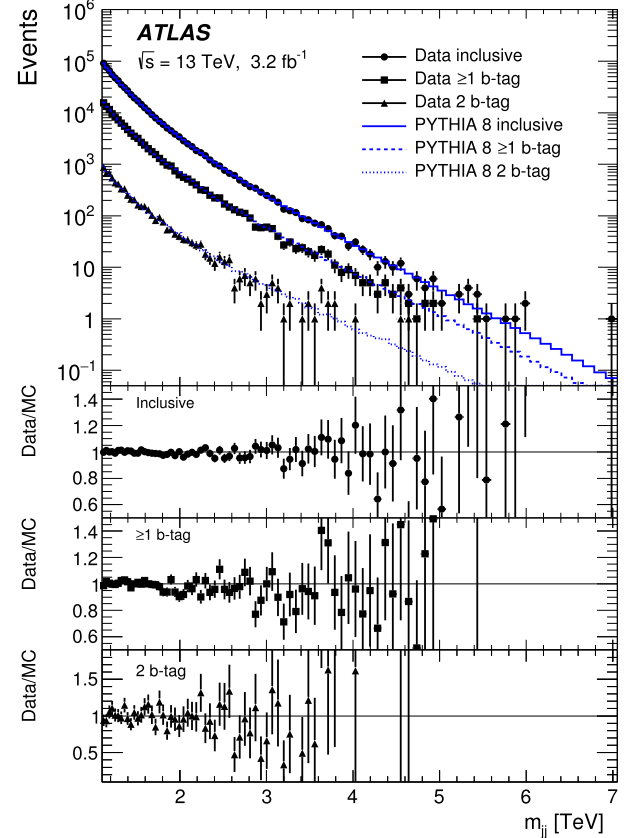


Fig. 3. The invariant mass distribution of the inclusive dijet (dots), “1b” (squares) and “2b” (triangles) categories in data. The inclusive distribution is similar to Ref. [5], but an additional requirement is placed on the jet pseudorapidity, $|\eta| < 2.4$. The MC distributions are normalized to the data in the three categories separately: a solid line for inclusive dijets, a dashed line for “1b” and a small dashed line for “2b” categories. The lower panels show the ratio between data and MC simulation for all three categories.

where p_i are free parameters and $z = m_{jj}/\sqrt{s}$. This ansatz was used in previous searches [5] and is found to provide a satisfactory fit to leading-order PYTHIA8 multijet MC simulation at $\sqrt{s} = 13$ TeV. Employing Wilks’ theorem [32], a log-likelihood statistic is used to confirm that no additional parameters are needed to model these distributions for a data set as large as the one used for this analysis.

The results of the fits are shown in Fig. 4. The fits of this ansatz to the data without considering systematic uncertainties return p -values of 0.73, 0.90 and 0.66 for the inclusive, “1b” and “2b” categories respectively. The p -value was calculated as a goodness-of-fit measure using a χ^2 test statistic determined from pseudo-experiments.

The lower panels of Fig. 4 show the significances of bin-by-bin differences between the data and the fit. These equivalent Gaussian significances are calculated from the Poisson probability, considering only statistical uncertainties.

The statistical significance of any localized excess in the dijet mass distribution is quantified using the BUMPHUNTER algorithm [33]. The algorithm compares the binned m_{jj} distribution of the data to the fitted background estimate, considering contiguous mass intervals in all possible locations, from a width of two bins to one-half of the distribution. For each interval in the scan, it computes the significance of any excess found. The algorithm identifies the intervals 1493–1614 GeV in the “1b” and 3596–3827 GeV in the “2b” sample, indicated by the two vertical lines in Fig. 4, as the most discrepant intervals. The statistical significance of these

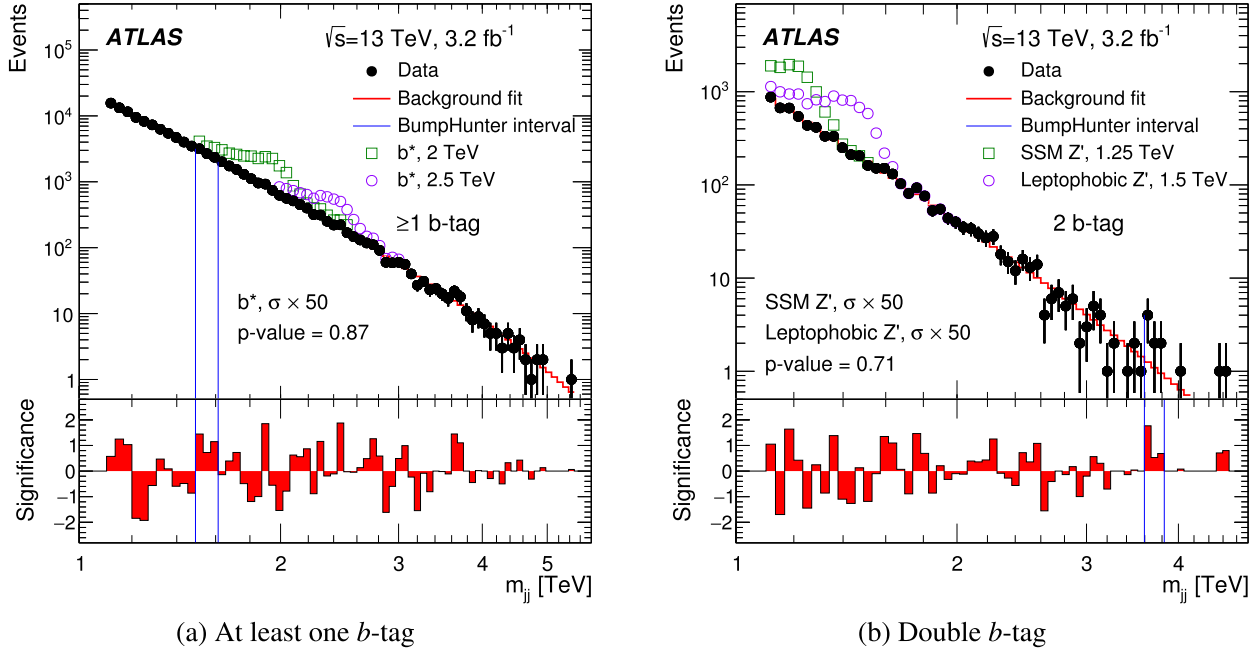


Fig. 4. Dijet mass spectra overlaid with the fits to the background function together with the results from BumpHunter and benchmark signals scaled by a factor of 50. The most discrepant region is indicated by the two blue lines. The lower panels show the significances per bin of the data with respect to the background fit, in terms of the number of standard deviations, considering only the statistical fluctuations. The distributions are shown for the (a) “1b” and (b) “2b” categories. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

outcomes is evaluated using the ensemble of Poisson outcomes across all intervals scanned, by applying the algorithm to many pseudo-data samples drawn randomly from the background fit. Without including systematic uncertainties, the probability that fluctuations of the background model would produce excesses at least as significant as those observed in the data, anywhere in the distribution, is greater than 60% in the “1b” and “2b” categories. Thus, there is no evidence of localized contributions to the mass distribution from BSM phenomena.

6. Systematic uncertainties

Uncertainties in the parameters of the fitted background function Eq. (1) are evaluated by fitting the ansatz to pseudo-data drawn via Poisson fluctuations around the fitted background model. The uncertainty in the prediction in each m_{jj} bin is taken to be the root mean square of the function value for 10000 generated pseudo-experiments. To estimate an uncertainty due to the choice of background parameterization, one additional degree of freedom, $z^{p_4 \log(z)}$, is appended as a multiplicative factor to the nominal ansatz (Eq. (1)), and the difference between the estimated parameters from the two fits is taken as an uncertainty.

The uncertainty in the jet energy scale is estimated using various methods in 8 TeV data, corrected to the new centre-of-mass energy by taking the difference between the 8 TeV and 13 TeV runs into account using MC simulation [28]. The jet energy scale uncertainty used in this analysis relies on a set of three nuisance parameters [34]. For untagged jets it is within the range 1–5% for jet transverse momenta greater than 200 GeV.

The relative additional uncertainty in the energy scale of b -tagged jets is estimated using the MC samples and verified with data following the method described in Ref. [35]. The ratio r_{trk} of the sum of track transverse momenta inside the jet to the total jet transverse momentum measured in the calorimeter is used for this estimate. The double ratio of r_{trk} from data and simulation is formed and compared for inclusive jets and b -jets. The estimated

relative additional uncertainty for jets with $200 < p_T < 800$ GeV is found to be less than 2.6%, and this value is subsequently used in the higher p_T regions. This relative uncertainty is applied in addition to the nominal jet energy scale uncertainty. The maximum uncertainty for b -tagged jets is estimated to be 6% and is conservatively applied to all p_T regions.

The uncertainty in the jet energy resolution is estimated using the same method as the untagged jet energy scale uncertainty and relies on an additional Gaussian smearing of the reconstructed jet energies in MC simulation. For jets with $p_T > 50$ GeV, the uncertainty is less than 2%.

The uncertainty introduced by the application of the b -tagging algorithm is the largest systematic uncertainty in the analysis. The uncertainty in the measured tagging efficiency of b -jets is estimated by studying $t\bar{t}$ events in 13 TeV data for jet p_T up to 200 GeV [31]. The uncertainties in the measured rate of mistagging c -jets and light-flavour jets are estimated in 8 TeV data. The uncertainties are extrapolated to 13 TeV, taking into account the addition of the new IBL system as well as reconstruction and tagging improvements. An additional term is included to extrapolate the measured uncertainties to the high- p_T region of interest. This term is calculated from simulated events by considering variations on the quantities affecting the b -tagging performance such as the impact parameter resolution, percentage of poorly measured tracks, description of the detector material, and track multiplicity per jet. The dominant effect on the uncertainty when extrapolating at high- p_T is related to the different tagging efficiency when smearing the tracks impact parameters based on the resolution measured in data and simulation. The difference in the impact parameter resolution is due to effects from alignment, dead modules and additional material not properly modelled in the simulation. The impact of the b -tagging efficiency uncertainty increases with jet p_T and reaches 50% above 2 TeV.

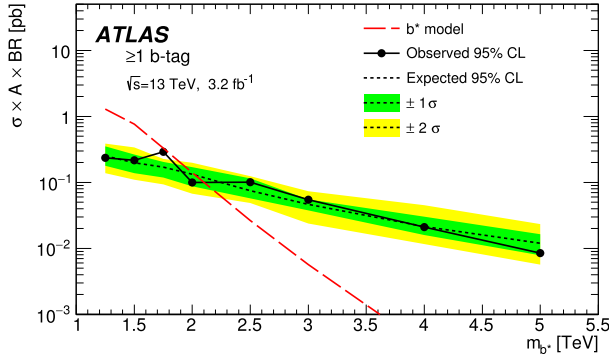


Fig. 5. Observed (filled circles) and expected (dotted line) 95% credibility-level upper limits on the cross section σ times acceptance A times branching ratio BR , including kinematic acceptance and b -tagging efficiencies, for the b^* model. The dashed line shows the cross section calculated from theory. The plot shows the case with a single b -tag.

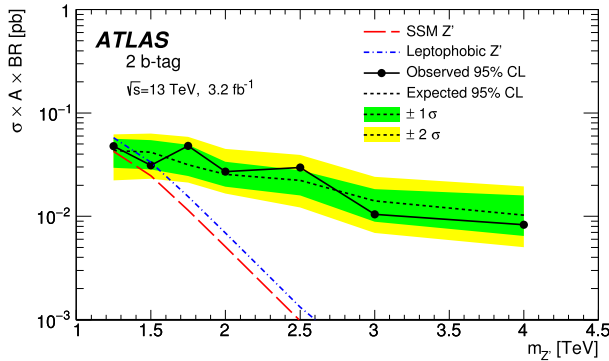


Fig. 6. Observed (filled circles) and expected (dotted line) 95% credibility-level upper limits on the cross section σ times the acceptance A times branching ratio BR , including kinematic acceptance and b -tagging efficiencies, for the $Z' \rightarrow b\bar{b}$ models. The dashed lines show the cross section calculated from theory. The plot shows the case with double b -tag.

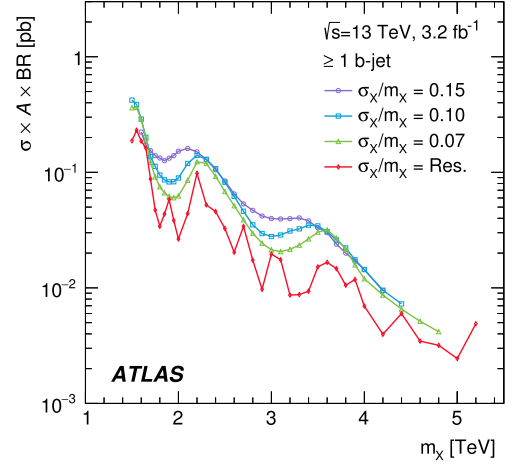
7. Results

Due to the absence of a signal, 95% credibility-level upper limits are set on the cross section for new processes that would produce a contribution to the dijet mass distribution with b -tagging. The signal shapes are taken as provided by $b^* \rightarrow b\bar{g}$ and $Z' \rightarrow b\bar{b}$ production processes.

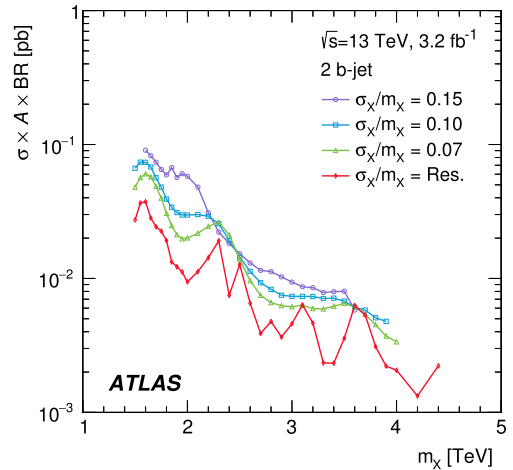
The limits on b^* and Z' cross sections are shown in Figs. 5 and 6. The limits were obtained using a Bayesian method [36]. The Bayesian credible intervals were calculated using a posterior probability density from the likelihood function for the observed mass spectrum obtained by a fit to the background (Eq. (1)), while the signal shape was derived from MC simulations. The limit is interpolated between discrete values of the mass to create a continuous curve. The systematic uncertainties associated with the uncertainty in the integrated luminosity, jet energy scale, jet energy resolution, b -tagging and alternative fit functions are all included in the limit-setting.

Fig. 5 shows that the b^* model, with the decay to $g + b(\bar{b})$, is excluded for b^* masses from 1.1 TeV up to 2.1 TeV at leading-order in QCD. Fig. 6 shows that the leptophobic $Z' \rightarrow b\bar{b}$ model with SM-like couplings to quarks is excluded up to 1.5 TeV at leading-order in QCD. The present data are not sufficient to provide an exclusion limit for the SSM Z' model.

As shown in Fig. 7, narrow resonance contributions of various widths with visible cross sections $\sigma \times A \times BR$ ranging from approximately 0.4 to 0.001 pb are excluded in the mass range 1.5–5.0 TeV. These limits should be used when long low-mass



(a) At least one b -tag



(b) Double b -tag

Fig. 7. The 95% credibility-level upper limits on the cross section σ times the acceptance A times branching ratio BR , including kinematic acceptance and b -tagging efficiencies, for resonances exhibiting a generic Gaussian shape. The circles, squares and triangles correspond to the cases where the width of the Gaussian signal is 15%, 10% or 7% of the signal mass. The figure also shows as a red line the case where the width is given by the dijet mass resolution, which is as low as 2% at 5.0 TeV. The plots show the limits obtained, applying (a) at least one b -tag and (b) double b -tag. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

off-shell tails from PDFs and non-perturbative effects on the narrow resonance signal shape can be safely truncated or neglected and, after applying the selection described in Section 4, the reconstructed mass distribution approximates a Gaussian distribution. For a detailed description of how to use these limits, see the instructions in Ref. [37]. To estimate the b -tagging efficiency, invariant-mass-dependent correction factors as given in Fig. 2 can be used.

8. Summary

A search for new resonances decaying to jets with a single or double b -tag in pp collisions with the ATLAS detector at the LHC is presented. The dataset corresponds to an integrated luminosity of 3.2 fb^{-1} collected at $\sqrt{s} = 13 \text{ TeV}$ in 2015. The studies use the dijet invariant mass m_{jj} in the range of 1.1–5.0 TeV with b -tagging applied to the leading and sub-leading jets and categorize the events according to their b -jet multiplicity.

The background from jets initiated by b -quarks is well described by the leading-order parton-shower models. The dijet back-

ground is also well described by the analytic fit function with three parameters which is used in the light-flavour dijet analysis [5].

No evidence of a significant excess of events is found compared to the expectations of the Standard Model. The largest observed local excess is less than 2σ for both the single and double b -tag channels.

The expected contribution from the b^* model is excluded in the mass range 1.1–2.1 TeV at leading-order in QCD using the single b -jet channel. The results can not exclude contributions from the SSM $Z' \rightarrow b\bar{b}$ model in the mass range 1.1–5.0 TeV in the double b -jet channel. For the leptophobic Z' model with SM-like couplings to quarks, the mass range 1.1–1.5 TeV is excluded at leading-order in QCD in this channel.

This analysis excludes generic high-mass particles decaying to two jets, where one or two jets originate from b -quarks, with visible cross sections ranging from 0.4 to 0.001 pb in the mass range 1.1–5.0 TeV. The exclusion limits are applicable for resonances exhibiting a Gaussian shape and width similar to the b^* or Z' models. The limits were calculated assuming that the width of the Gaussian signal is 15%, 10% or 7% of its mass.

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M. Aaboud^{136d}, G. Aad⁸⁷, B. Abbott¹¹⁴, J. Abdallah⁶⁵, O. Abdinov¹², B. Abeloos¹¹⁸, R. Aben¹⁰⁸, O.S. AbouZeid¹³⁸, N.L. Abraham¹⁵⁰, H. Abramowicz¹⁵⁴, H. Abreu¹⁵³, R. Abreu¹¹⁷, Y. Abulaiti^{147a,147b}, B.S. Acharya^{164a,164b,a}, L. Adamczyk^{40a}, D.L. Adams²⁷, J. Adelman¹⁰⁹, S. Adomeit¹⁰¹, T. Adye¹³², A.A. Affolder⁷⁶, T. Agatonovic-Jovin¹⁴, J. Agricola⁵⁶, J.A. Aguilar-Saavedra^{127a,127f}, S.P. Ahlen²⁴, F. Ahmadov^{67,b}, G. Aielli^{134a,134b}, H. Akerstedt^{147a,147b}, T.P.A. Åkesson⁸³, A.V. Akimov⁹⁷, G.L. Alberghi^{22a,22b}, J. Albert¹⁶⁹, S. Albrand⁵⁷, M.J. Alconada Verzini⁷³, M. Aleksa³², I.N. Aleksandrov⁶⁷, C. Alexa^{28b}, G. Alexander¹⁵⁴, T. Alexopoulos¹⁰, M. Alhroob¹¹⁴, M. Aliev^{75a,75b}, G. Alimonti^{93a}, J. Alison³³, S.P. Alkire³⁷, B.M.M. Allbrooke¹⁵⁰, B.W. Allen¹¹⁷, P.P. Allport¹⁹, A. Aloisio^{105a,105b}, A. Alonso³⁸, F. Alonso⁷³, C. Alpigiani¹³⁹, M. Alstaty⁸⁷, B. Alvarez Gonzalez³², D. Álvarez Piqueras¹⁶⁷, M.G. Alviggi^{105a,105b}, B.T. Amadio¹⁶, K. Amako⁶⁸, Y. Amaral Coutinho^{26a}, C. Amelung²⁵, D. Amidei⁹¹, S.P. Amor Dos Santos^{127a,127c}, A. Amorim^{127a,127b}, S. Amoroso³², G. Amundsen²⁵, C. Anastopoulos¹⁴⁰, L.S. Ancu⁵¹, N. Andari¹⁰⁹, T. Andeen¹¹, C.F. Anders^{60b}, G. Anders³², J.K. Anders⁷⁶, K.J. Anderson³³, A. Andreazza^{93a,93b}, V. Andrei^{60a}, S. Angelidakis⁹, I. Angelozzi¹⁰⁸, P. Anger⁴⁶, A. Angerami³⁷, F. Anghinolfi³², A.V. Anisenkov^{110,c}, N. Anjos¹³, A. Annovi^{125a,125b}, M. Antonelli⁴⁹, A. Antonov⁹⁹, F. Anulli^{133a}, M. Aoki⁶⁸, L. Aperio Bella¹⁹, G. Arabidze⁹², Y. Arai⁶⁸, J.P. Araque^{127a}, A.T.H. Arce⁴⁷, F.A. Arduh⁷³, J-F. Arguin⁹⁶, S. Argyropoulos⁶⁵, M. Arik^{20a}, A.J. Armbruster¹⁴⁴, L.J. Armitage⁷⁸, O. Arnaez³², H. Arnold⁵⁰, M. Arratia³⁰, O. Arslan²³, A. Artamonov⁹⁸, G. Artoni¹²¹, S. Artz⁸⁵, S. Asai¹⁵⁶, N. Asbah⁴⁴, A. Ashkenazi¹⁵⁴, B. Åsman^{147a,147b}, L. Asquith¹⁵⁰, K. Assamagan²⁷, R. Astalos^{145a}, M. Atkinson¹⁶⁶, N.B. Atlay¹⁴², K. Augsten¹²⁹, G. Avolio³², B. Axen¹⁶, M.K. Ayoub¹¹⁸, G. Azuelos^{96,d}, M.A. Baak³², A.E. Baas^{60a}, M.J. Baca¹⁹, H. Bachacou¹³⁷, K. Bachas^{75a,75b}, M. Backes³², M. Backhaus³², P. Bagiacchi^{133a,133b}, P. Bagnaia^{133a,133b}, Y. Bai^{35a}, J.T. Baines¹³², O.K. Baker¹⁷⁶, E.M. Baldin^{110,c}, P. Balek¹³⁰, T. Balestri¹⁴⁹, F. Balli¹³⁷, W.K. Balunas¹²³, E. Banas⁴¹, Sw. Banerjee^{173,e}, A.A.E. Bannoura¹⁷⁵, L. Barak³², E.L. Barberio⁹⁰, D. Barberis^{52a,52b}, M. Barbero⁸⁷, T. Barillari¹⁰², M. Barisonzi^{164a,164b}, T. Barklow¹⁴⁴, N. Barlow³⁰, S.L. Barnes⁸⁶, B.M. Barnett¹³², R.M. Barnett¹⁶, Z. Barnovska⁵, A. Baroncelli^{135a}, G. Barone²⁵, A.J. Barr¹²¹, L. Barranco Navarro¹⁶⁷, F. Barreiro⁸⁴, J. Barreiro Guimarães da Costa^{35a}, R. Bartoldus¹⁴⁴, A.E. Barton⁷⁴, P. Bartos^{145a}, A. Basalae¹²⁴, A. Bassalat¹¹⁸, R.L. Bates⁵⁵, S.J. Batista¹⁵⁹, J.R. Batley³⁰, M. Battaglia¹³⁸, M. Baue^{133a,133b}, F. Bauer¹³⁷, H.S. Bawa^{144,f}, J.B. Beacham¹¹², M.D. Beattie⁷⁴, T. Beau⁸², P.H. Beauchemin¹⁶², P. Bechtel²³, H.P. Beck^{18,g}, K. Becker¹²¹, M. Becker⁸⁵, M. Beckingham¹⁷⁰, C. Becot¹¹¹, A.J. Beddall^{20e}, A. Beddall^{20b}, V.A. Bednyakov⁶⁷, M. Bedognetti¹⁰⁸, C.P. Bee¹⁴⁹, L.J. Beemster¹⁰⁸, T.A. Beermann³², M. Begel²⁷, J.K. Behr⁴⁴, C. Belanger-Champagne⁸⁹, A.S. Bell⁸⁰, G. Bella¹⁵⁴, L. Bellagamba^{22a}, A. Bellerive³¹, M. Bellomo⁸⁸, K. Belotskiy⁹⁹, O. Beltramello³², N.L. Belyaev⁹⁹, O. Benary¹⁵⁴, D. Bencheikroun^{136a}, M. Bender¹⁰¹, K. Bendtz^{147a,147b}, N. Benekos¹⁰, Y. Benhammou¹⁵⁴, E. Benhar Nocchioli¹⁷⁶, J. Benitez⁶⁵, D.P. Benjamin⁴⁷, J.R. Bensinger²⁵, S. Bentvelsen¹⁰⁸, L. Beresford¹²¹, M. Beretta⁴⁹, D. Berge¹⁰⁸, E. Bergeaas Kuutmann¹⁶⁵, N. Berger⁵, J. Beringer¹⁶, S. Berlendis⁵⁷, N.R. Bernard⁸⁸, C. Bernius¹¹¹, F.U. Bernlochner²³, T. Berry⁷⁹, P. Berta¹³⁰, C. Bertella⁸⁵, G. Bertoli^{147a,147b}, F. Bertolucci^{125a,125b}, I.A. Bertram⁷⁴, C. Bertsche⁴⁴, D. Bertsche¹¹⁴, G.J. Besjes³⁸, O. Bessidskaia Bylund^{147a,147b}, M. Bessner⁴⁴, N. Besson¹³⁷, C. Betancourt⁵⁰, S. Bethke¹⁰², A.J. Bevan⁷⁸, W. Bhimji¹⁶, R.M. Bianchi¹²⁶, L. Bianchini²⁵, M. Bianco³², O. Biebel¹⁰¹, D. Biedermann¹⁷, R. Bielski⁸⁶, N.V. Biesuz^{125a,125b}, M. Biglietti^{135a}, J. Bilbao De Mendizabal⁵¹, H. Bilokon⁴⁹, M. Bindi⁵⁶, S. Binet¹¹⁸, A. Bingul^{20b}, C. Bini^{133a,133b}, S. Biondi^{22a,22b}, D.M. Bjergaard⁴⁷, C.W. Black¹⁵¹, J.E. Black¹⁴⁴, K.M. Black²⁴, D. Blackburn¹³⁹, R.E. Blair⁶, J.-B. Blanchard¹³⁷, J.E. Blanco⁷⁹, T. Blazek^{145a}, I. Bloch⁴⁴, C. Blocker²⁵, W. Blum^{85,*}, U. Blumenschein⁵⁶, S. Blunier^{34a}, G.J. Bobbink¹⁰⁸, V.S. Bobrovnikov^{110,c}, S.S. Bocchetta⁸³, A. Bocci⁴⁷, C. Bock¹⁰¹, M. Boehler⁵⁰, D. Boerner¹⁷⁵, J.A. Bogaerts³², D. Bogavac¹⁴, A.G. Bogdanchikov¹¹⁰, C. Böhm^{147a}, V. Boisvert⁷⁹, P. Bokan¹⁴, T. Bold^{40a}, A.S. Boldyrev^{164a,164c}, M. Bomben⁸², M. Bona⁷⁸,

M. Boonekamp¹³⁷, A. Borisov¹³¹, G. Borissov⁷⁴, J. Bortfeldt¹⁰¹, D. Bortoletto¹²¹, V. Bortolotto^{62a,62b,62c}, K. Bos¹⁰⁸, D. Boscherini^{22a}, M. Bosman¹³, J.D. Bossio Sola²⁹, J. Boudreau¹²⁶, J. Bouffard², E.V. Bouhova-Thacker⁷⁴, D. Boumediene³⁶, C. Bourdarios¹¹⁸, S.K. Boutle⁵⁵, A. Boveia³², J. Boyd³², I.R. Boyko⁶⁷, J. Bracinik¹⁹, A. Brandt⁸, G. Brandt⁵⁶, O. Brandt^{60a}, U. Bratzler¹⁵⁷, B. Brau⁸⁸, J.E. Brau¹¹⁷, H.M. Braun^{175,*}, W.D. Breaden Madden⁵⁵, K. Brendlinger¹²³, A.J. Brennan⁹⁰, L. Brenner¹⁰⁸, R. Brenner¹⁶⁵, S. Bressler¹⁷², T.M. Bristow⁴⁸, D. Britton⁵⁵, D. Britzger⁴⁴, F.M. Brochu³⁰, I. Brock²³, R. Brock⁹², G. Brooijmans³⁷, T. Brooks⁷⁹, W.K. Brooks^{34b}, J. Brosamer¹⁶, E. Brost¹¹⁷, J.H. Broughton¹⁹, P.A. Bruckman de Renstrom⁴¹, D. Bruncko^{145b}, R. Bruneliere⁵⁰, A. Bruni^{22a}, G. Bruni^{22a}, L.S. Bruni¹⁰⁸, B.H. Brunt³⁰, M. Bruschi^{22a}, N. Bruscino²³, P. Bryant³³, L. Bryngemark⁸³, T. Buanes¹⁵, Q. Buat¹⁴³, P. Buchholz¹⁴², A.G. Buckley⁵⁵, I.A. Budagov⁶⁷, F. Buehrer⁵⁰, M.K. Bugge¹²⁰, O. Bulekov⁹⁹, D. Bullock⁸, H. Burckhart³², S. Burdin⁷⁶, C.D. Burgard⁵⁰, B. Burghgrave¹⁰⁹, K. Burka⁴¹, S. Burke¹³², I. Burmeister⁴⁵, E. Busato³⁶, D. Büscher⁵⁰, V. Büscher⁸⁵, P. Bussey⁵⁵, J.M. Butler²⁴, C.M. Buttar⁵⁵, J.M. Butterworth⁸⁰, P. Butti¹⁰⁸, W. Buttinger²⁷, A. Buzatu⁵⁵, A.R. Buzykaev^{110,c}, S. Cabrera Urbán¹⁶⁷, D. Caforio¹²⁹, V.M. Cairo^{39a,39b}, O. Cakir^{4a}, N. Calace⁵¹, P. Calafiura¹⁶, A. Calandri⁸⁷, G. Calderini⁸², P. Calfayan¹⁰¹, L.P. Caloba^{26a}, D. Calvet³⁶, S. Calvet³⁶, T.P. Calvet⁸⁷, R. Camacho Toro³³, S. Camarda³², P. Camarri^{134a,134b}, D. Cameron¹²⁰, R. Caminal Armadans¹⁶⁶, C. Camincher⁵⁷, S. Campana³², M. Campanelli⁸⁰, A. Camplani^{93a,93b}, A. Campoverde¹⁴², V. Canale^{105a,105b}, A. Canepa^{160a}, M. Cano Bret^{35e}, J. Cantero¹¹⁵, R. Cantrill^{127a}, T. Cao⁴², M.D.M. Capeans Garrido³², I. Caprini^{28b}, M. Caprini^{28b}, M. Capua^{39a,39b}, R. Caputo⁸⁵, R.M. Carbone³⁷, R. Cardarelli^{134a}, F. Cardillo⁵⁰, T. Carli³², G. Carlino^{105a}, L. Carminati^{93a,93b}, S. Caron¹⁰⁷, E. Carquin^{34b}, G.D. Carrillo-Montoya³², J.R. Carter³⁰, J. Carvalho^{127a,127c}, D. Casadei¹⁹, M.P. Casado^{13,h}, M. Casolino¹³, D.W. Casper¹⁶³, E. Castaneda-Miranda^{146a}, R. Castelijns¹⁰⁸, A. Castelli¹⁰⁸, V. Castillo Gimenez¹⁶⁷, N.F. Castro^{127a,i}, A. Catinaccio³², J.R. Catmore¹²⁰, A. Cattai³², J. Caudron⁸⁵, V. Cavaliere¹⁶⁶, E. Cavallaro¹³, D. Cavalli^{93a}, M. Cavalli-Sforza¹³, V. Cavasinni^{125a,125b}, F. Ceradini^{135a,135b}, L. Cerda Alberich¹⁶⁷, B.C. Cerio⁴⁷, A.S. Cerqueira^{26b}, A. Cerri¹⁵⁰, L. Cerrito⁷⁸, F. Cerutti¹⁶, M. Cerv³², A. Cervelli¹⁸, S.A. Cetin^{20d}, A. Chafaq^{136a}, D. Chakraborty¹⁰⁹, I. Chalupkova¹³⁰, S.K. Chan⁵⁹, Y.L. Chan^{62a}, P. Chang¹⁶⁶, J.D. Chapman³⁰, D.G. Charlton¹⁹, A. Chatterjee⁵¹, C.C. Chau¹⁵⁹, C.A. Chavez Barajas¹⁵⁰, S. Che¹¹², S. Cheatham⁷⁴, A. Chegwidan⁹², S. Chekanov⁶, S.V. Chekulaev^{160a}, G.A. Chelkov^{67,j}, M.A. Chelstowska⁹¹, C. Chen⁶⁶, H. Chen²⁷, K. Chen¹⁴⁹, S. Chen^{35c}, S. Chen¹⁵⁶, X. Chen^{35f}, Y. Chen⁶⁹, H.C. Cheng⁹¹, H.J. Cheng^{35a}, Y. Cheng³³, A. Cheplakov⁶⁷, E. Cheremushkina¹³¹, R. Cherkouli El Moursli^{136e}, V. Chernyatin^{27,*}, E. Cheu⁷, L. Chevalier¹³⁷, V. Chiarella⁴⁹, G. Chiarelli^{125a,125b}, G. Chiodini^{75a}, A.S. Chisholm¹⁹, A. Chitan^{28b}, M.V. Chizhov⁶⁷, K. Choi⁶³, A.R. Chomont³⁶, S. Chouridou⁹, B.K.B. Chow¹⁰¹, V. Christodoulou⁸⁰, D. Chromek-Burckhart³², J. Chudoba¹²⁸, A.J. Chuinard⁸⁹, J.J. Chwastowski⁴¹, L. Chytka¹¹⁶, G. Ciapetti^{133a,133b}, A.K. Ciftci^{4a}, D. Cinca⁵⁵, V. Cindro⁷⁷, I.A. Cioara²³, A. Ciochio¹⁶, F. Ciotto^{105a,105b}, Z.H. Citron¹⁷², M. Citterio^{93a}, M. Ciubancan^{28b}, A. Clark⁵¹, B.L. Clark⁵⁹, M.R. Clark³⁷, P.J. Clark⁴⁸, R.N. Clarke¹⁶, C. Clement^{147a,147b}, Y. Coadou⁸⁷, M. Cobal^{164a,164c}, A. Coccaro⁵¹, J. Cochran⁶⁶, L. Coffey²⁵, L. Colasurdo¹⁰⁷, B. Cole³⁷, A.P. Colijn¹⁰⁸, J. Collot⁵⁷, T. Colombo³², G. Compostella¹⁰², P. Conde Muñio^{127a,127b}, E. Coniavitis⁵⁰, S.H. Connell^{146b}, I.A. Connelly⁷⁹, V. Consorti⁵⁰, S. Constantinescu^{28b}, G. Conti³², F. Conventi^{105a,k}, M. Cooke¹⁶, B.D. Cooper⁸⁰, A.M. Cooper-Sarkar¹²¹, K.J.R. Cormier¹⁵⁹, T. Cornelissen¹⁷⁵, M. Corradi^{133a,133b}, F. Corriveau^{89,l}, A. Corso-Radu¹⁶³, A. Cortes-Gonzalez¹³, G. Cortiana¹⁰², G. Costa^{93a}, M.J. Costa¹⁶⁷, D. Costanzo¹⁴⁰, G. Cottin³⁰, G. Cowan⁷⁹, B.E. Cox⁸⁶, K. Cranmer¹¹¹, S.J. Crawley⁵⁵, G. Cree³¹, S. Crépé-Renaudin⁵⁷, F. Crescioli⁸², W.A. Cribbs^{147a,147b}, M. Crispin Ortuzar¹²¹, M. Cristinziani²³, V. Croft¹⁰⁷, G. Crosetti^{39a,39b}, T. Cuhadar Donszelmann¹⁴⁰, J. Cummings¹⁷⁶, M. Curatolo⁴⁹, J. Cúth⁸⁵, C. Cuthbert¹⁵¹, H. Czirr¹⁴², P. Czodrowski³, G. D'amen^{22a,22b}, S. D'Auria⁵⁵, M. D'Onofrio⁷⁶, M.J. Da Cunha Sargedass De Sousa^{127a,127b}, C. Da Via⁸⁶, W. Dabrowski^{40a}, T. Dado^{145a}, T. Dai⁹¹, O. Dale¹⁵, F. Dallaire⁹⁶, C. Dallapiccola⁸⁸, M. Dam³⁸, J.R. Dandoy³³, N.P. Dang⁵⁰, A.C. Daniells¹⁹, N.S. Dann⁸⁶, M. Danninger¹⁶⁸, M. Dano Hoffmann¹³⁷, V. Dao⁵⁰, G. Darbo^{52a}, S. Darmora⁸, J. Dassoulas³, A. Dattagupta⁶³, W. Davey²³, C. David¹⁶⁹, T. Davidek¹³⁰, M. Davies¹⁵⁴, P. Davison⁸⁰, E. Dawe⁹⁰, I. Dawson¹⁴⁰, R.K. Daya-Ishmukhametova⁸⁸, K. De⁸, R. de Asmundis^{105a}, A. De Benedetti¹¹⁴, S. De Castro^{22a,22b}, S. De Cecco⁸², N. De Groot¹⁰⁷, P. de Jong¹⁰⁸, H. De la Torre⁸⁴, F. De Lorenzi⁶⁶, A. De Maria⁵⁶, D. De Pedis^{133a}, A. De Salvo^{133a}, U. De Sanctis¹⁵⁰, A. De Santo¹⁵⁰,

J.B. De Vivie De Regie¹¹⁸, W.J. Dearnaley⁷⁴, R. Debbe²⁷, C. Debenedetti¹³⁸, D.V. Dedovich⁶⁷, N. Dehghanian³, I. Deigaard¹⁰⁸, M. Del Gaudio^{39a,39b}, J. Del Peso⁸⁴, T. Del Prete^{125a,125b}, D. Delgove¹¹⁸, F. Deliot¹³⁷, C.M. Delitzsch⁵¹, M. Deliyergiyev⁷⁷, A. Dell'Acqua³², L. Dell'Asta²⁴, M. Dell'Orso^{125a,125b}, M. Della Pietra^{105a,k}, D. della Volpe⁵¹, M. Delmastro⁵, P.A. Delsart⁵⁷, C. Deluca¹⁰⁸, D.A. DeMarco¹⁵⁹, S. Demers¹⁷⁶, M. Demichev⁶⁷, A. Demilly⁸², S.P. Denisov¹³¹, D. Denysiuk¹³⁷, D. Derendarz⁴¹, J.E. Derkaoui^{136d}, F. Derue⁸², P. Dervan⁷⁶, K. Desch²³, C. Deterre⁴⁴, K. Dette⁴⁵, P.O. Deviveiros³², A. Dewhurst¹³², S. Dhaliwal²⁵, A. Di Ciaccio^{134a,134b}, L. Di Ciaccio⁵, W.K. Di Clemente¹²³, C. Di Donato^{133a,133b}, A. Di Girolamo³², B. Di Girolamo³², B. Di Micco^{135a,135b}, R. Di Nardo³², A. Di Simone⁵⁰, R. Di Sipio¹⁵⁹, D. Di Valentino³¹, C. Diaconu⁸⁷, M. Diamond¹⁵⁹, F.A. Dias⁴⁸, M.A. Diaz^{34a}, E.B. Diehl⁹¹, J. Dietrich¹⁷, S. Diglio⁸⁷, A. Dimitrievska¹⁴, J. Dingfelder²³, P. Dita^{28b}, S. Dita^{28b}, F. Dittus³², F. Djama⁸⁷, T. Djobava^{53b}, J.I. Djuvsland^{60a}, M.A.B. do Vale^{26c}, D. Dobos³², M. Dobre^{28b}, C. Doglioni⁸³, T. Dohmae¹⁵⁶, J. Dolejsi¹³⁰, Z. Dolezal¹³⁰, B.A. Dolgoshein^{99,*}, M. Donadelli^{26d}, S. Donati^{125a,125b}, P. Dondero^{122a,122b}, J. Donini³⁶, J. Dopke¹³², A. Doria^{105a}, M.T. Dova⁷³, A.T. Doyle⁵⁵, E. Drechsler⁵⁶, M. Dris¹⁰, Y. Du^{35d}, J. Duarte-Campderros¹⁵⁴, E. Duchovni¹⁷², G. Duckeck¹⁰¹, O.A. Ducu^{96,m}, D. Duda¹⁰⁸, A. Dudarev³², E.M. Duffield¹⁶, L. Dufлот¹¹⁸, L. Duguid⁷⁹, M. Dührssen³², M. Dumancic¹⁷², M. Dunford^{60a}, H. Duran Yildiz^{4a}, M. Düren⁵⁴, A. Durglishvili^{53b}, D. Duschinger⁴⁶, B. Dutta⁴⁴, M. Dyndal^{40a}, C. Eckardt⁴⁴, K.M. Ecker¹⁰², R.C. Edgar⁹¹, N.C. Edwards⁴⁸, T. Eifert³², G. Eigen¹⁵, K. Einsweiler¹⁶, T. Ekelof¹⁶⁵, M. El Kacimi^{136c}, V. Ellajosyula⁸⁷, M. Ellert¹⁶⁵, S. Elles⁵, F. Ellinghaus¹⁷⁵, A.A. Elliot¹⁶⁹, N. Ellis³², J. Elmsheuser²⁷, M. Elsing³², D. Emelianov¹³², Y. Enari¹⁵⁶, O.C. Endner⁸⁵, M. Endo¹¹⁹, J.S. Ennis¹⁷⁰, J. Erdmann⁴⁵, A. Ereditato¹⁸, G. Ernis¹⁷⁵, J. Ernst², M. Ernst²⁷, S. Errede¹⁶⁶, E. Ertel⁸⁵, M. Escalier¹¹⁸, H. Esch⁴⁵, C. Escobar¹²⁶, B. Esposito⁴⁹, A.I. Etienne¹³⁷, E. Etzion¹⁵⁴, H. Evans⁶³, A. Ezhilov¹²⁴, F. Fabbri^{22a,22b}, L. Fabbri^{22a,22b}, G. Facini³³, R.M. Fakhrutdinov¹³¹, S. Falciano^{133a}, R.J. Falla⁸⁰, J. Faltova¹³⁰, Y. Fang^{35a}, M. Fanti^{93a,93b}, A. Farbin⁸, A. Farilla^{135a}, C. Farina¹²⁶, T. Farooque¹³, S. Farrell¹⁶, S.M. Farrington¹⁷⁰, P. Farthouat³², F. Fassi^{136e}, P. Fassnacht³², D. Fassouliotis⁹, M. Fauci Giannelli⁷⁹, A. Favareto^{52a,52b}, W.J. Fawcett¹²¹, L. Fayard¹¹⁸, O.L. Fedin^{124,n}, W. Fedorko¹⁶⁸, S. Feigl¹²⁰, L. Feligioni⁸⁷, C. Feng^{35d}, E.J. Feng³², H. Feng⁹¹, A.B. Fenyuk¹³¹, L. Feremenga⁸, P. Fernandez Martinez¹⁶⁷, S. Fernandez Perez¹³, J. Ferrando⁵⁵, A. Ferrari¹⁶⁵, P. Ferrari¹⁰⁸, R. Ferrari^{122a}, D.E. Ferreira de Lima^{60b}, A. Ferrer¹⁶⁷, D. Ferrere⁵¹, C. Ferretti⁹¹, A. Ferretto Parodi^{52a,52b}, F. Fiedler⁸⁵, A. Filipčič⁷⁷, M. Filipuzzi⁴⁴, F. Filthaut¹⁰⁷, M. Fincke-Keeler¹⁶⁹, K.D. Finelli¹⁵¹, M.C.N. Fiolhais^{127a,127c}, L. Fiorini¹⁶⁷, A. Firan⁴², A. Fischer², C. Fischer¹³, J. Fischer¹⁷⁵, W.C. Fisher⁹², N. Flaschel⁴⁴, I. Fleck¹⁴², P. Fleischmann⁹¹, G.T. Fletcher¹⁴⁰, R.R.M. Fletcher¹²³, T. Flick¹⁷⁵, A. Floderus⁸³, L.R. Flores Castillo^{62a}, M.J. Flowerdew¹⁰², G.T. Forcolin⁸⁶, A. Formica¹³⁷, A. Forti⁸⁶, A.G. Foster¹⁹, D. Fournier¹¹⁸, H. Fox⁷⁴, S. Fracchia¹³, P. Francavilla⁸², M. Franchini^{22a,22b}, D. Francis³², L. Franconi¹²⁰, M. Franklin⁵⁹, M. Frate¹⁶³, M. Fraternali^{122a,122b}, D. Freeborn⁸⁰, S.M. Fressard-Batraneanu³², F. Friedrich⁴⁶, D. Froidevaux³², J.A. Frost¹²¹, C. Fukunaga¹⁵⁷, E. Fullana Torregrosa⁸⁵, T. Fusayasu¹⁰³, J. Fuster¹⁶⁷, C. Gabaldon⁵⁷, O. Gabizon¹⁷⁵, A. Gabrielli^{22a,22b}, A. Gabrielli¹⁶, G.P. Gach^{40a}, S. Gadatsch³², S. Gadomski⁵¹, G. Gagliardi^{52a,52b}, L.G. Gagnon⁹⁶, P. Gagnon⁶³, C. Galea¹⁰⁷, B. Galhardo^{127a,127c}, E.J. Gallas¹²¹, B.J. Gallop¹³², P. Gallus¹²⁹, G. Galster³⁸, K.K. Gan¹¹², J. Gao^{35b,87}, Y. Gao⁴⁸, Y.S. Gao^{144,f}, F.M. Garay Walls⁴⁸, C. García¹⁶⁷, J.E. García Navarro¹⁶⁷, M. Garcia-Sciveres¹⁶, R.W. Gardner³³, N. Garelli¹⁴⁴, V. Garonne¹²⁰, A. Gascon Bravo⁴⁴, C. Gatti⁴⁹, A. Gaudiello^{52a,52b}, G. Gaudio^{122a}, B. Gaur¹⁴², L. Gauthier⁹⁶, I.L. Gavrilenko⁹⁷, C. Gay¹⁶⁸, G. Gaycken²³, E.N. Gazis¹⁰, Z. Gece¹⁶⁸, C.N.P. Gee¹³², Ch. Geich-Gimbel²³, M. Geisen⁸⁵, M.P. Geisler^{60a}, C. Gemme^{52a}, M.H. Genest⁵⁷, C. Geng^{35b,o}, S. Gentile^{133a,133b}, S. George⁷⁹, D. Gerbaudo¹³, A. Gershon¹⁵⁴, S. Ghasemi¹⁴², H. Ghazlane^{136b}, M. Ghneimat²³, B. Giacobbe^{22a}, S. Giagu^{133a,133b}, P. Giannetti^{125a,125b}, B. Gibbard²⁷, S.M. Gibson⁷⁹, M. Gignac¹⁶⁸, M. Gilchriese¹⁶, T.P.S. Gillam³⁰, D. Gillberg³¹, G. Gilles¹⁷⁵, D.M. Gingrich^{3,d}, N. Giokaris⁹, M.P. Giordani^{164a,164c}, F.M. Giorgi^{22a}, F.M. Giorgi¹⁷, P.F. Giraud¹³⁷, P. Giromini⁵⁹, D. Giugni^{93a}, F. Giuli¹²¹, C. Giuliani¹⁰², M. Giulini^{60b}, B.K. Gjølsten¹²⁰, S. Gkaitatzis¹⁵⁵, I. Gkialas¹⁵⁵, E.L. Gkoukousis¹¹⁸, L.K. Gladilin¹⁰⁰, C. Glasman⁸⁴, J. Glatzer³², P.C.F. Glaysher⁴⁸, A. Glazov⁴⁴, M. Goblirsch-Kolb¹⁰², J. Godlewski⁴¹, S. Goldfarb⁹¹, T. Golling⁵¹, D. Golubkov¹³¹, A. Gomes^{127a,127b,127d}, R. Gonçalo^{127a}, J. Goncalves Pinto Firmino Da Costa¹³⁷, L. Gonella¹⁹, A. Gongadze⁶⁷, S. González de la Hoz¹⁶⁷, G. Gonzalez Parra¹³, S. Gonzalez-Sevilla⁵¹, L. Goossens³², P.A. Gorbounov⁹⁸, H.A. Gordon²⁷,

I. Gorelov¹⁰⁶, B. Gorini³², E. Gorini^{75a,75b}, A. Gorišek⁷⁷, E. Gornicki⁴¹, A.T. Goshaw⁴⁷, C. Gössling⁴⁵, M.I. Gostkin⁶⁷, C.R. Goudet¹¹⁸, D. Goujdami^{136c}, A.G. Goussiou¹³⁹, N. Govender^{146b}, E. Gozani¹⁵³, L. Graber⁵⁶, I. Grabowska-Bold^{40a}, P.O.J. Gradin⁵⁷, P. Grafström^{22a,22b}, J. Gramling⁵¹, E. Gramstad¹²⁰, S. Grancagnolo¹⁷, V. Gratchev¹²⁴, P.M. Gravila^{28e}, H.M. Gray³², E. Graziani^{135a}, Z.D. Greenwood^{81,p}, C. Grefe²³, K. Gregersen⁸⁰, I.M. Gregor⁴⁴, P. Grenier¹⁴⁴, K. Grevtsov⁵, J. Griffiths⁸, A.A. Grillo¹³⁸, K. Grimm⁷⁴, S. Grinstein^{13,q}, Ph. Gris³⁶, J.-F. Grivaz¹¹⁸, S. Groh⁸⁵, J.P. Grohs⁴⁶, E. Gross¹⁷², J. Grosse-Knetter⁵⁶, G.C. Grossi⁸¹, Z.J. Grout¹⁵⁰, L. Guan⁹¹, W. Guan¹⁷³, J. Guenther¹²⁹, F. Guescini⁵¹, D. Guest¹⁶³, O. Gueta¹⁵⁴, E. Guido^{52a,52b}, T. Guillemin⁵, S. Guindon², U. Gul⁵⁵, C. Gumpert³², J. Guo^{35e}, Y. Guo^{35b,o}, S. Gupta¹²¹, G. Gustavino^{133a,133b}, P. Gutierrez¹¹⁴, N.G. Gutierrez Ortiz⁸⁰, C. Gutsche⁴⁶, C. Guyot¹³⁷, C. Gwenlan¹²¹, C.B. Gwilliam⁷⁶, A. Haas¹¹¹, C. Haber¹⁶, H.K. Hadavand⁸, N. Haddad^{136e}, A. Hadeef⁸⁷, P. Haefner²³, S. Hageböck²³, Z. Hajduk⁴¹, H. Hakobyan^{177,*}, M. Haleem⁴⁴, J. Haley¹¹⁵, G. Halladjian⁹², G.D. Hallewell⁸⁷, K. Hamacher¹⁷⁵, P. Hamal¹¹⁶, K. Hamano¹⁶⁹, A. Hamilton^{146a}, G.N. Hamity¹⁴⁰, P.G. Hamnett⁴⁴, L. Han^{35b}, K. Hanagaki^{68,r}, K. Hanawa¹⁵⁶, M. Hance¹³⁸, B. Haney¹²³, P. Hanke^{60a}, R. Hanna¹³⁷, J.B. Hansen³⁸, J.D. Hansen³⁸, M.C. Hansen²³, P.H. Hansen³⁸, K. Hara¹⁶¹, A.S. Hard¹⁷³, T. Harenberg¹⁷⁵, F. Hariri¹¹⁸, S. Harkusha⁹⁴, R.D. Harrington⁴⁸, P.F. Harrison¹⁷⁰, F. Hartjes¹⁰⁸, N.M. Hartmann¹⁰¹, M. Hasegawa⁶⁹, Y. Hasegawa¹⁴¹, A. Hasib¹¹⁴, S. Hassani¹³⁷, S. Haug¹⁸, R. Hauser⁹², L. Hauswald⁴⁶, M. Havranek¹²⁸, C.M. Hawkes¹⁹, R.J. Hawkes³², D. Hayden⁹², C.P. Hays¹²¹, J.M. Hays⁷⁸, H.S. Hayward⁷⁶, S.J. Haywood¹³², S.J. Head¹⁹, T. Heck⁸⁵, V. Hedberg⁸³, L. Heelan⁸, S. Heim¹²³, T. Heim¹⁶, B. Heinemann¹⁶, J.J. Heinrich¹⁰¹, L. Heinrich¹¹¹, C. Heinz⁵⁴, J. Hejbal¹²⁸, L. Helary²⁴, S. Hellman^{147a,147b}, C. Helsens³², J. Henderson¹²¹, R.C.W. Henderson⁷⁴, Y. Heng¹⁷³, S. Henkelmann¹⁶⁸, A.M. Henriques Correia³², S. Henrot-Versille¹¹⁸, G.H. Herbert¹⁷, Y. Hernández Jiménez¹⁶⁷, G. Herten⁵⁰, R. Hertenberger¹⁰¹, L. Hervas³², G.G. Hesketh⁸⁰, N.P. Hessey¹⁰⁸, J.W. Hetherly⁴², R. Hickling⁷⁸, E. Higón-Rodríguez¹⁶⁷, E. Hill¹⁶⁹, J.C. Hill³⁰, K.H. Hiller⁴⁴, S.J. Hillier¹⁹, I. Hinchliffe¹⁶, E. Hines¹²³, R.R. Hinman¹⁶, M. Hirose¹⁵⁸, D. Hirschbuehl¹⁷⁵, J. Hobbs¹⁴⁹, N. Hod^{160a}, M.C. Hodgkinson¹⁴⁰, P. Hodgson¹⁴⁰, A. Hoecker³², M.R. Hoferkamp¹⁰⁶, F. Hoenig¹⁰¹, D. Hohn²³, T.R. Holmes¹⁶, M. Homann⁴⁵, T.M. Hong¹²⁶, B.H. Hooberman¹⁶⁶, W.H. Hopkins¹¹⁷, Y. Horii¹⁰⁴, A.J. Horton¹⁴³, J.-Y. Hostachy⁵⁷, S. Hou¹⁵², A. Hoummada^{136a}, J. Howarth⁴⁴, M. Hrabovsky¹¹⁶, I. Hristova¹⁷, J. Hrivnac¹¹⁸, T. Hryn'ova⁵, A. Hrynevich⁹⁵, C. Hsu^{146c}, P.J. Hsu^{152,s}, S.-C. Hsu¹³⁹, D. Hu³⁷, Q. Hu^{35b}, Y. Huang⁴⁴, Z. Hubacek¹²⁹, F. Hubaut⁸⁷, F. Huegging²³, T.B. Huffman¹²¹, E.W. Hughes³⁷, G. Hughes⁷⁴, M. Huhtinen³², T.A. Hülsing⁸⁵, P. Huo¹⁴⁹, N. Huseynov^{67,b}, J. Huston⁹², J. Huth⁵⁹, G. Iacobucci⁵¹, G. Iakovidis²⁷, I. Ibragimov¹⁴², L. Iconomidou-Fayard¹¹⁸, E. Ideal¹⁷⁶, Z. Idrissi^{136e}, P. Iengo³², O. Igonkina¹⁰⁸, T. Iizawa¹⁷¹, Y. Ikegami⁶⁸, M. Ikeno⁶⁸, Y. Ilchenko^{11,t}, D. Iliadis¹⁵⁵, N. Ilic¹⁴⁴, T. Ince¹⁰², G. Introzzi^{122a,122b}, P. Ioannou^{9,*}, M. Iodice^{135a}, K. Iordanidou³⁷, V. Ippolito⁵⁹, M. Ishino⁷⁰, M. Ishitsuka¹⁵⁸, R. Ishmukhametov¹¹², C. Issever¹²¹, S. Istin^{20a}, F. Ito¹⁶¹, J.M. Iturbe Ponce⁸⁶, R. Iuppa^{134a,134b}, W. Iwanski⁴¹, H. Iwasaki⁶⁸, J.M. Izen⁴³, V. Izzo^{105a}, S. Jabbar³, B. Jackson¹²³, M. Jackson⁷⁶, P. Jackson¹, V. Jain², K.B. Jakobi⁸⁵, K. Jakobs⁵⁰, S. Jakobsen³², T. Jakoubek¹²⁸, D.O. Jamin¹¹⁵, D.K. Jana⁸¹, E. Jansen⁸⁰, R. Jansky⁶⁴, J. Janssen²³, M. Janus⁵⁶, G. Jarlskog⁸³, N. Javadov^{67,b}, T. Javůrek⁵⁰, F. Jeanneau¹³⁷, L. Jeanty¹⁶, J. Jejelava^{53a,u}, G.-Y. Jeng¹⁵¹, D. Jennens⁹⁰, P. Jenni^{50,v}, J. Jentzsch⁴⁵, C. Jeske¹⁷⁰, S. Jézéquel⁵, H. Ji¹⁷³, J. Jia¹⁴⁹, H. Jiang⁶⁶, Y. Jiang^{35b}, S. Jiggins⁸⁰, J. Jimenez Pena¹⁶⁷, S. Jin^{35a}, A. Jinaru^{28b}, O. Jinnouchi¹⁵⁸, P. Johansson¹⁴⁰, K.A. Johns⁷, W.J. Johnson¹³⁹, K. Jon-And^{147a,147b}, G. Jones¹⁷⁰, R.W.L. Jones⁷⁴, S. Jones⁷, T.J. Jones⁷⁶, J. Jongmanns^{60a}, P.M. Jorge^{127a,127b}, J. Jovicevic^{160a}, X. Ju¹⁷³, A. Juste Rozas^{13,q}, M.K. Köhler¹⁷², A. Kaczmarska⁴¹, M. Kado¹¹⁸, H. Kagan¹¹², M. Kagan¹⁴⁴, S.J. Kahn⁸⁷, E. Kajomovitz⁴⁷, C.W. Kalderon¹²¹, A. Kaluza⁸⁵, S. Kama⁴², A. Kamenshchikov¹³¹, N. Kanaya¹⁵⁶, S. Kaneti³⁰, L. Kanjir⁷⁷, V.A. Kantserov⁹⁹, J. Kanzaki⁶⁸, B. Kaplan¹¹¹, L.S. Kaplan¹⁷³, A. Kapliy³³, D. Kar^{146c}, K. Karakostas¹⁰, A. Karamaoun³, N. Karastathis¹⁰, M.J. Kareem⁵⁶, E. Karentzos¹⁰, M. Karnevskiy⁸⁵, S.N. Karpov⁶⁷, Z.M. Karpova⁶⁷, K. Karthik¹¹¹, V. Kartvelishvili⁷⁴, A.N. Karyukhin¹³¹, K. Kasahara¹⁶¹, L. Kashif¹⁷³, R.D. Kass¹¹², A. Kastanas¹⁵, Y. Kataoka¹⁵⁶, C. Kato¹⁵⁶, A. Katre⁵¹, J. Katzy⁴⁴, K. Kawagoe⁷², T. Kawamoto¹⁵⁶, G. Kawamura⁵⁶, S. Kazama¹⁵⁶, V.F. Kazanin^{110,c}, R. Keeler¹⁶⁹, R. Kehoe⁴², J.S. Keller⁴⁴, J.J. Kempster⁷⁹, K. Kentaro¹⁰⁴, H. Keoshkerian¹⁵⁹, O. Kepka¹²⁸, B.P. Kerševan⁷⁷, S. Kersten¹⁷⁵, R.A. Keyes⁸⁹, F. Khalil-zada¹², A. Khanov¹¹⁵, A.G. Kharlamov^{110,c}, T.J. Khoo⁵¹, V. Khovanskii⁹⁸, E. Khramov⁶⁷, J. Khubua^{53b,w}, S. Kido⁶⁹, H.Y. Kim⁸, S.H. Kim¹⁶¹, Y.K. Kim³³, N. Kimura¹⁵⁵, O.M. Kind¹⁷, B.T. King⁷⁶, M. King¹⁶⁷,

S.B. King¹⁶⁸, J. Kirk¹³², A.E. Kiryunin¹⁰², T. Kishimoto⁶⁹, D. Kisielewska^{40a}, F. Kiss⁵⁰, K. Kiuchi¹⁶¹, O. Kivernyk¹³⁷, E. Kladiva^{145b}, M.H. Klein³⁷, M. Klein⁷⁶, U. Klein⁷⁶, K. Kleinknecht⁸⁵, P. Klimek^{147a,147b}, A. Klimentov²⁷, R. Klingenberg⁴⁵, J.A. Klinger¹⁴⁰, T. Klioutchnikova³², E.-E. Kluge^{60a}, P. Kluit¹⁰⁸, S. Kluth¹⁰², J. Knapik⁴¹, E. Kneringer⁶⁴, E.B.F.G. Knoop⁸⁷, A. Knue⁵⁵, A. Kobayashi¹⁵⁶, D. Kobayashi¹⁵⁸, T. Kobayashi¹⁵⁶, M. Kobel⁴⁶, M. Kocian¹⁴⁴, P. Kodys¹³⁰, T. Koffas³¹, E. Koffeman¹⁰⁸, T. Koi¹⁴⁴, H. Kolanoski¹⁷, M. Kolb^{60b}, I. Koletsou⁵, A.A. Komar^{97,*}, Y. Komori¹⁵⁶, T. Kondo⁶⁸, N. Kondrashova⁴⁴, K. Köneke⁵⁰, A.C. König¹⁰⁷, T. Kono^{68,x}, R. Konoplich^{111,y}, N. Konstantinidis⁸⁰, R. Kopeliansky⁶³, S. Koperny^{40a}, L. Köpke⁸⁵, A.K. Kopp⁵⁰, K. Korcyl⁴¹, K. Kordas¹⁵⁵, A. Korn⁸⁰, A.A. Korol^{110,c}, I. Korolkov¹³, E.V. Korolkova¹⁴⁰, O. Kortner¹⁰², S. Kortner¹⁰², T. Kosek¹³⁰, V.V. Kostyukhin²³, A. Kotwal⁴⁷, A. Kourkumeli-Charalampidi¹⁵⁵, C. Kourkumelis⁹, V. Kouskoura²⁷, A.B. Kowalewska⁴¹, R. Kowalewski¹⁶⁹, T.Z. Kowalski^{40a}, C. Kozakai¹⁵⁶, W. Kozanecki¹³⁷, A.S. Kozhin¹³¹, V.A. Kramarenko¹⁰⁰, G. Kramberger⁷⁷, D. Krasnopevtsev⁹⁹, M.W. Krasny⁸², A. Krasznahorkay³², J.K. Kraus²³, A. Kravchenko²⁷, M. Kretz^{60c}, J. Kretzschmar⁷⁶, K. Kreutzfeldt⁵⁴, P. Krieger¹⁵⁹, K. Krizka³³, K. Kroeninger⁴⁵, H. Kroha¹⁰², J. Kroll¹²³, J. Kroseberg²³, J. Krstic¹⁴, U. Kruchonak⁶⁷, H. Krüger²³, N. Krumnack⁶⁶, A. Kruse¹⁷³, M.C. Kruse⁴⁷, M. Kruskal²⁴, T. Kubota⁹⁰, H. Kucuk⁸⁰, S. Kuday^{4b}, J.T. Kuechler¹⁷⁵, S. Kuehn⁵⁰, A. Kugel^{60c}, F. Kuger¹⁷⁴, A. Kuhl¹³⁸, T. Kuhl⁴⁴, V. Kukhtin⁶⁷, R. Kukla¹³⁷, Y. Kulchitsky⁹⁴, S. Kuleshov^{34b}, M. Kuna^{133a,133b}, T. Kunigo⁷⁰, A. Kupco¹²⁸, H. Kurashige⁶⁹, Y.A. Kurochkin⁹⁴, V. Kus¹²⁸, E.S. Kuwertz¹⁶⁹, M. Kuze¹⁵⁸, J. Kvita¹¹⁶, T. Kwan¹⁶⁹, D. Kyriazopoulos¹⁴⁰, A. La Rosa¹⁰², J.L. La Rosa Navarro^{26d}, L. La Rotonda^{39a,39b}, C. Lacasta¹⁶⁷, F. Lacava^{133a,133b}, J. Lacey³¹, H. Lacker¹⁷, D. Lacour⁸², V.R. Lacuesta¹⁶⁷, E. Ladygin⁶⁷, R. Lafaye⁵, B. Laforge⁸², T. Lagouri¹⁷⁶, S. Lai⁵⁶, S. Lammers⁶³, W. Lampl⁷, E. Lançon¹³⁷, U. Landgraf⁵⁰, M.P.J. Landon⁷⁸, V.S. Lang^{60a}, J.C. Lange¹³, A.J. Lankford¹⁶³, F. Lanni²⁷, K. Lantzsche²³, A. Lanza^{122a}, S. Laplace⁸², C. Lapoire³², J.F. Laporte¹³⁷, T. Lari^{93a}, F. Lasagni Manghi^{22a,22b}, M. Lassnig³², P. Laurelli⁴⁹, W. Lavrijsen¹⁶, A.T. Law¹³⁸, P. Laycock⁷⁶, T. Lazovich⁵⁹, M. Lazzaroni^{93a,93b}, B. Le⁹⁰, O. Le Dortz⁸², E. Le Guirriec⁸⁷, E.P. Le Quilleuc¹³⁷, M. LeBlanc¹⁶⁹, T. LeCompte⁶, F. Ledroit-Guillon⁵⁷, C.A. Lee²⁷, S.C. Lee¹⁵², L. Lee¹, G. Lefebvre⁸², M. Lefebvre¹⁶⁹, F. Legger¹⁰¹, C. Leggett¹⁶, A. Lehan⁷⁶, G. Lehmann Miotto³², X. Lei⁷, W.A. Leight³¹, A. Leisos^{155,z}, A.G. Leister¹⁷⁶, M.A.L. Leite^{26d}, R. Leitner¹³⁰, D. Lellouch¹⁷², B. Lemmer⁵⁶, K.J.C. Leney⁸⁰, T. Lenz²³, B. Lenzi³², R. Leone⁷, S. Leone^{125a,125b}, C. Leonidopoulos⁴⁸, S. Leontsinis¹⁰, G. Lerner¹⁵⁰, C. Leroy⁹⁶, A.A.J. Lesage¹³⁷, C.G. Lester³⁰, M. Levchenko¹²⁴, J. Levêque⁵, D. Levin⁹¹, L.J. Levinson¹⁷², M. Levy¹⁹, D. Lewis⁷⁸, A.M. Leyko²³, M. Leyton⁴³, B. Li^{35b,o}, H. Li¹⁴⁹, H.L. Li³³, L. Li⁴⁷, L. Li^{35e}, Q. Li^{35a}, S. Li⁴⁷, X. Li⁸⁶, Y. Li¹⁴², Z. Liang^{35a}, B. Liberti^{134a}, A. Liblong¹⁵⁹, P. Lichard³², K. Lie¹⁶⁶, J. Liebal²³, W. Liebig¹⁵, A. Limosani¹⁵¹, S.C. Lin^{152,aa}, T.H. Lin⁸⁵, B.E. Lindquist¹⁴⁹, A.E. Lioni⁵¹, E. Lipeles¹²³, A. Lipniacka¹⁵, M. Lisovsky^{60b}, T.M. Liss¹⁶⁶, A. Lister¹⁶⁸, A.M. Litke¹³⁸, B. Liu^{152,ab}, D. Liu¹⁵², H. Liu⁹¹, H. Liu²⁷, J. Liu⁸⁷, J.B. Liu^{35b}, K. Liu⁸⁷, L. Liu¹⁶⁶, M. Liu⁴⁷, M. Liu^{35b}, Y.L. Liu^{35b}, Y. Liu^{35b}, M. Livan^{122a,122b}, A. Lleres⁵⁷, J. Llorente Merino^{35a}, S.L. Lloyd⁷⁸, F. Lo Sterzo¹⁵², E. Lobodzinska⁴⁴, P. Loch⁷, W.S. Lockman¹³⁸, F.K. Loebinger⁸⁶, A.E. Loevschall-Jensen³⁸, K.M. Loew²⁵, A. Loginov¹⁷⁶, T. Lohse¹⁷, K. Lohwasser⁴⁴, M. Lokajicek¹²⁸, B.A. Long²⁴, J.D. Long¹⁶⁶, R.E. Long⁷⁴, L. Longo^{75a,75b}, K.A. Looper¹¹², L. Lopes^{127a}, D. Lopez Mateos⁵⁹, B. Lopez Paredes¹⁴⁰, I. Lopez Paz¹³, A. Lopez Solis⁸², J. Lorenz¹⁰¹, N. Lorenzo Martinez⁶³, M. Losada²¹, P.J. Lösel¹⁰¹, X. Lou^{35a}, A. Lounis¹¹⁸, J. Love⁶, P.A. Love⁷⁴, H. Lu^{62a}, N. Lu⁹¹, H.J. Lubatti¹³⁹, C. Luci^{133a,133b}, A. Lucotte⁵⁷, C. Luedtke⁵⁰, F. Luehring⁶³, W. Lukas⁶⁴, L. Luminari^{133a}, O. Lundberg^{147a,147b}, B. Lund-Jensen¹⁴⁸, P.M. Luzi⁸², D. Lynn²⁷, R. Lysak¹²⁸, E. Lytken⁸³, V. Lyubushkin⁶⁷, H. Ma²⁷, L.L. Ma^{35d}, Y. Ma^{35d}, G. Maccarrone⁴⁹, A. Macchiolo¹⁰², C.M. Macdonald¹⁴⁰, B. Maček⁷⁷, J. Machado Miguens^{123,127b}, D. Madaffari⁸⁷, R. Madar³⁶, H.J. Maddocks¹⁶⁵, W.F. Mader⁴⁶, A. Madsen⁴⁴, J. Maeda⁶⁹, S. Maeland¹⁵, T. Maeno²⁷, A. Maevskiy¹⁰⁰, E. Magradze⁵⁶, J. Mahlstedt¹⁰⁸, C. Maiani¹¹⁸, C. Maidantchik^{26a}, A.A. Maier¹⁰², T. Maier¹⁰¹, A. Maio^{127a,127b,127d}, S. Majewski¹¹⁷, Y. Makida⁶⁸, N. Makovec¹¹⁸, B. Malaescu⁸², Pa. Malecki⁴¹, V.P. Maleev¹²⁴, F. Malek⁵⁷, U. Mallik⁶⁵, D. Malon⁶, C. Malone¹⁴⁴, S. Maltezos¹⁰, V.M. Malyshev¹¹⁰, S. Malyukov³², J. Mamuzic¹⁶⁷, G. Mancini⁴⁹, B. Mandelli³², L. Mandelli^{93a}, I. Mandić⁷⁷, J. Maneira^{127a,127b}, L. Manhaes de Andrade Filho^{26b}, J. Manjarres Ramos^{160b}, A. Mann¹⁰¹, A. Manousos³², B. Mansoulie¹³⁷, J.D. Mansour^{35a}, R. Mantifel⁸⁹, M. Mantoani⁵⁶, S. Manzoni^{93a,93b}, L. Mapelli³², G. Marceca²⁹, L. March⁵¹, G. Marchiori⁸², M. Marcisovsky¹²⁸, M. Marjanovic¹⁴, D.E. Marley⁹¹, F. Marroquim^{26a}, S.P. Marsden⁸⁶, Z. Marshall¹⁶, S. Marti-Garcia¹⁶⁷, B. Martin⁹²,

T.A. Martin¹⁷⁰, V.J. Martin⁴⁸, B. Martin dit Latour¹⁵, M. Martinez^{13,q}, S. Martin-Haugh¹³², V.S. Martoiu^{28b}, A.C. Martyniuk⁸⁰, M. Marx¹³⁹, A. Marzin³², L. Masetti⁸⁵, T. Mashimo¹⁵⁶, R. Mashinistov⁹⁷, J. Masik⁸⁶, A.L. Maslennikov^{110,c}, I. Massa^{22a,22b}, L. Massa^{22a,22b}, P. Mastrandrea⁵, A. Mastroberardino^{39a,39b}, T. Masubuchi¹⁵⁶, P. Mättig¹⁷⁵, J. Mattmann⁸⁵, J. Maurer^{28b}, S.J. Maxfield⁷⁶, D.A. Maximov^{110,c}, R. Mazini¹⁵², S.M. Mazza^{93a,93b}, N.C. Mc Fadden¹⁰⁶, G. Mc Goldrick¹⁵⁹, S.P. Mc Kee⁹¹, A. McCarn⁹¹, R.L. McCarthy¹⁴⁹, T.G. McCarthy¹⁰², L.I. McClymont⁸⁰, E.F. McDonald⁹⁰, K.W. McFarlane^{58,*}, J.A. Mcfayden⁸⁰, G. Mchedlidze⁵⁶, S.J. McMahon¹³², R.A. McPherson^{169,l}, M. Medinnis⁴⁴, S. Meehan¹³⁹, S. Mehlhase¹⁰¹, A. Mehta⁷⁶, K. Meier^{60a}, C. Meineck¹⁰¹, B. Meirose⁴³, D. Melini¹⁶⁷, B.R. Mellado Garcia^{146c}, M. Melo^{145a}, F. Meloni¹⁸, A. Mengarelli^{22a,22b}, S. Menke¹⁰², E. Meoni¹⁶², S. Mergelmeyer¹⁷, P. Mermod⁵¹, L. Merola^{105a,105b}, C. Meroni^{93a}, F.S. Merritt³³, A. Messina^{133a,133b}, J. Metcalfe⁶, A.S. Mete¹⁶³, C. Meyer⁸⁵, C. Meyer¹²³, J-P. Meyer¹³⁷, J. Meyer¹⁰⁸, H. Meyer Zu Theenhausen^{60a}, F. Miano¹⁵⁰, R.P. Middleton¹³², S. Miglioranza^{52a,52b}, L. Mijović²³, G. Mikenberg¹⁷², M. Mikestikova¹²⁸, M. Mikuž⁷⁷, M. Milesi⁹⁰, A. Milic⁶⁴, D.W. Miller³³, C. Mills⁴⁸, A. Milov¹⁷², D.A. Milstead^{147a,147b}, A.A. Minaenko¹³¹, Y. Minami¹⁵⁶, I.A. Minashvili⁶⁷, A.I. Mincer¹¹¹, B. Mindur^{40a}, M. Mineev⁶⁷, Y. Ming¹⁷³, L.M. Mir¹³, K.P. Mistry¹²³, T. Mitani¹⁷¹, J. Mitrevski¹⁰¹, V.A. Mitsou¹⁶⁷, A. Miucci⁵¹, P.S. Miyagawa¹⁴⁰, J.U. Mjörnmark⁸³, T. Moa^{147a,147b}, K. Mochizuki⁹⁶, S. Mohapatra³⁷, S. Molander^{147a,147b}, R. Moles-Valls²³, R. Monden⁷⁰, M.C. Mondragon⁹², K. Mönig⁴⁴, J. Monk³⁸, E. Monnier⁸⁷, A. Montalbano¹⁴⁹, J. Montejo Berlingen³², F. Monticelli⁷³, S. Monzani^{93a,93b}, R.W. Moore³, N. Morange¹¹⁸, D. Moreno²¹, M. Moreno Llácer⁵⁶, P. Morettini^{52a}, D. Mori¹⁴³, T. Mori¹⁵⁶, M. Morii⁵⁹, M. Morinaga¹⁵⁶, V. Morisbak¹²⁰, S. Moritz⁸⁵, A.K. Morley¹⁵¹, G. Mornacchi³², J.D. Morris⁷⁸, S.S. Mortensen³⁸, L. Morvaj¹⁴⁹, M. Mosidze^{53b}, J. Moss¹⁴⁴, K. Motohashi¹⁵⁸, R. Mount¹⁴⁴, E. Mountricha²⁷, S.V. Mouraviev^{97,*}, E.J.W. Moyse⁸⁸, S. Muanza⁸⁷, R.D. Mudd¹⁹, F. Mueller¹⁰², J. Mueller¹²⁶, R.S.P. Mueller¹⁰¹, T. Mueller³⁰, D. Muenstermann⁷⁴, P. Mullen⁵⁵, G.A. Mullier¹⁸, F.J. Munoz Sanchez⁸⁶, J.A. Murillo Quijada¹⁹, W.J. Murray^{170,132}, H. Musheghyan⁵⁶, M. Muskinja⁷⁷, A.G. Myagkov^{131,ac}, M. Myska¹²⁹, B.P. Nachman¹⁴⁴, O. Nackenhorst⁵¹, K. Nagai¹²¹, R. Nagai^{68,x}, K. Nagano⁶⁸, Y. Nagasaka⁶¹, K. Nagata¹⁶¹, M. Nagel⁵⁰, E. Nagy⁸⁷, A.M. Nairz³², Y. Nakahama³², K. Nakamura⁶⁸, T. Nakamura¹⁵⁶, I. Nakano¹¹³, H. Namasivayam⁴³, R.F. Naranjo Garcia⁴⁴, R. Narayan¹¹, D.I. Narrias Villar^{60a}, I. Naryshkin¹²⁴, T. Naumann⁴⁴, G. Navarro²¹, R. Nayyar⁷, H.A. Neal⁹¹, P.Yu. Nechaeva⁹⁷, T.J. Neep⁸⁶, P.D. Nef¹⁴⁴, A. Negri^{122a,122b}, M. Negrini^{22a}, S. Nektarijevic¹⁰⁷, C. Nellist¹¹⁸, A. Nelson¹⁶³, S. Nemecek¹²⁸, P. Nemethy¹¹¹, A.A. Nepomuceno^{26a}, M. Nessi^{32,ad}, M.S. Neubauer¹⁶⁶, M. Neumann¹⁷⁵, R.M. Neves¹¹¹, P. Nevski²⁷, P.R. Newman¹⁹, D.H. Nguyen⁶, T. Nguyen Manh⁹⁶, R.B. Nickerson¹²¹, R. Nicolaidou¹³⁷, J. Nielsen¹³⁸, A. Nikiforov¹⁷, V. Nikolaenko^{131,ac}, I. Nikolic-Audit⁸², K. Nikolopoulos¹⁹, J.K. Nilsen¹²⁰, P. Nilsson²⁷, Y. Ninomiya¹⁵⁶, A. Nisati^{133a}, R. Nisius¹⁰², T. Nobe¹⁵⁶, L. Nodulman⁶, M. Nomachi¹¹⁹, I. Nomidis³¹, T. Nooney⁷⁸, S. Norberg¹¹⁴, M. Nordberg³², N. Norjoharuddeen¹²¹, O. Novgorodova⁴⁶, S. Nowak¹⁰², M. Nozaki⁶⁸, L. Nozka¹¹⁶, K. Ntekas¹⁰, E. Nurse⁸⁰, F. Nuti⁹⁰, F. O'grady⁷, D.C. O'Neil¹⁴³, A.A. O'Rourke⁴⁴, V. O'Shea⁵⁵, F.G. Oakham^{31,d}, H. Oberlack¹⁰², T. Obermann²³, J. Ocariz⁸², A. Ochi⁶⁹, I. Ochoa³⁷, J.P. Ochoa-Ricoux^{34a}, S. Oda⁷², S. Odaka⁶⁸, H. Ogren⁶³, A. Oh⁸⁶, S.H. Oh⁴⁷, C.C. Ohm¹⁶, H. Ohman¹⁶⁵, H. Oide³², H. Okawa¹⁶¹, Y. Okumura³³, T. Okuyama⁶⁸, A. Olariu^{28b}, L.F. Oleiro Seabra^{127a}, S.A. Olivares Pino⁴⁸, D. Oliveira Damazio²⁷, A. Olszewski⁴¹, J. Olszowska⁴¹, A. Onofre^{127a,127e}, K. Onogi¹⁰⁴, P.U.E. Onyisi^{11,t}, M.J. Oreglia³³, Y. Oren¹⁵⁴, D. Orestano^{135a,135b}, N. Orlando^{62b}, R.S. Orr¹⁵⁹, B. Osculati^{52a,52b}, R. Ospanov⁸⁶, G. Otero y Garzon²⁹, H. Otono⁷², M. Ouchrif^{136d}, F. Ould-Saada¹²⁰, A. Ouraou¹³⁷, K.P. Oussoren¹⁰⁸, Q. Ouyang^{35a}, M. Owen⁵⁵, R.E. Owen¹⁹, V.E. Ozcan^{20a}, N. Ozturk⁸, K. Pachal¹⁴³, A. Pacheco Pages¹³, C. Padilla Aranda¹³, M. Pagáčová⁵⁰, S. Pagan Griso¹⁶, F. Paige²⁷, P. Pais⁸⁸, K. Pajchel¹²⁰, G. Palacino^{160b}, S. Palestini³², M. Palka^{40b}, D. Pallin³⁶, A. Palma^{127a,127b}, E. St. Panagiotopoulou¹⁰, C.E. Pandini⁸², J.G. Panduro Vazquez⁷⁹, P. Pani^{147a,147b}, S. Panitkin²⁷, D. Pantea^{28b}, L. Paolozzi⁵¹, Th.D. Papadopoulou¹⁰, K. Papageorgiou¹⁵⁵, A. Paramonov⁶, D. Paredes Hernandez¹⁷⁶, A.J. Parker⁷⁴, M.A. Parker³⁰, K.A. Parker¹⁴⁰, F. Parodi^{52a,52b}, J.A. Parsons³⁷, U. Parzefall⁵⁰, V.R. Pascuzzi¹⁵⁹, E. Pasqualucci^{133a}, S. Passaggio^{52a}, Fr. Pastore⁷⁹, G. Pásztor^{31,ae}, S. Patariaia¹⁷⁵, J.R. Pater⁸⁶, T. Pauly³², J. Pearce¹⁶⁹, B. Pearson¹¹⁴, L.E. Pedersen³⁸, M. Pedersen¹²⁰, S. Pedraza Lopez¹⁶⁷, R. Pedro^{127a,127b}, S.V. Peleganchuk^{110,c}, D. Pelikan¹⁶⁵, O. Penc¹²⁸, C. Peng^{35a}, H. Peng^{35b}, J. Penwell⁶³, B.S. Peralva^{26b}, M.M. Perego¹³⁷, D.V. Perepelitsa²⁷, E. Perez Codina^{160a},

L. Perini^{93a,93b}, H. Pernegger³², S. Perrella^{105a,105b}, R. Peschke⁴⁴, V.D. Peshekhonov⁶⁷, K. Peters⁴⁴, R.F.Y. Peters⁸⁶, B.A. Petersen³², T.C. Petersen³⁸, E. Petit⁵⁷, A. Petridis¹, C. Petridou¹⁵⁵, P. Petroff¹¹⁸, E. Petrolo^{133a}, M. Petrov¹²¹, F. Petrucci^{135a,135b}, N.E. Pettersson⁸⁸, A. Peyaud¹³⁷, R. Pezoa^{34b}, P.W. Phillips¹³², G. Piacquadio¹⁴⁴, E. Pianori¹⁷⁰, A. Picazio⁸⁸, E. Piccaro⁷⁸, M. Piccinini^{22a,22b}, M.A. Pickering¹²¹, R. Piegai²⁹, J.E. Pilcher³³, A.D. Pilkington⁸⁶, A.W.J. Pin⁸⁶, M. Pinamonti^{164a,164c,af}, J.L. Pinfold³, A. Pingel³⁸, S. Pires⁸², H. Pirumov⁴⁴, M. Pitt¹⁷², L. Plazak^{145a}, M.-A. Pleier²⁷, V. Pleskot⁸⁵, E. Plotnikova⁶⁷, P. Plucinski⁹², D. Pluth⁶⁶, R. Poettgen^{147a,147b}, L. Poggioli¹¹⁸, D. Pohl²³, G. Polesello^{122a}, A. Poley⁴⁴, A. Policicchio^{39a,39b}, R. Polifka¹⁵⁹, A. Polini^{22a}, C.S. Pollard⁵⁵, V. Polychronakos²⁷, K. Pommès³², L. Pontecorvo^{133a}, B.G. Pope⁹², G.A. Popeneciu^{28c}, D.S. Popovic¹⁴, A. Poppleton³², S. Pospisil¹²⁹, K. Potamianos¹⁶, I.N. Potrap⁶⁷, C.J. Potter³⁰, C.T. Potter¹¹⁷, G. Poulard³², J. Poveda³², V. Pozdnyakov⁶⁷, M.E. Pozo Astigarraga³², P. Pralavorio⁸⁷, A. Pranko¹⁶, S. Prell⁶⁶, D. Price⁸⁶, L.E. Price⁶, M. Primavera^{75a}, S. Prince⁸⁹, M. Proissl⁴⁸, K. Prokofiev^{62c}, F. Prokoshin^{34b}, S. Protopopescu²⁷, J. Proudfoot⁶, M. Przybycien^{40a}, D. Puddu^{135a,135b}, M. Purohit^{27,ag}, P. Puzo¹¹⁸, J. Qian⁹¹, G. Qin⁵⁵, Y. Qin⁸⁶, A. Quadt⁵⁶, W.B. Quayle^{164a,164b}, M. Queitsch-Maitland⁸⁶, D. Quilty⁵⁵, S. Raddum¹²⁰, V. Radeka²⁷, V. Radescu^{60b}, S.K. Radhakrishnan¹⁴⁹, P. Radloff¹¹⁷, P. Rados⁹⁰, F. Ragusa^{93a,93b}, G. Rahal¹⁷⁸, J.A. Raine⁸⁶, S. Rajagopalan²⁷, M. Rammensee³², C. Rangel-Smith¹⁶⁵, M.G. Ratti^{93a,93b}, F. Rauscher¹⁰¹, S. Rave⁸⁵, T. Ravenscroft⁵⁵, I. Ravinovich¹⁷², M. Raymond³², A.L. Read¹²⁰, N.P. Readioff⁷⁶, M. Reale^{75a,75b}, D.M. Rebuzzi^{122a,122b}, A. Redelbach¹⁷⁴, G. Redlinger²⁷, R. Reece¹³⁸, K. Reeves⁴³, L. Rehnisch¹⁷, J. Reichert¹²³, H. Reisin²⁹, C. Rembser³², H. Ren^{35a}, M. Rescigno^{133a}, S. Resconi^{93a}, O.L. Rezanova^{110,c}, P. Reznicek¹³⁰, R. Rezvani⁹⁶, R. Richter¹⁰², S. Richter⁸⁰, E. Richter-Was^{40b}, O. Ricken²³, M. Ridel⁸², P. Rieck¹⁷, C.J. Riegel¹⁷⁵, J. Rieger⁵⁶, O. Rifki¹¹⁴, M. Rijssenbeek¹⁴⁹, A. Rimoldi^{122a,122b}, M. Rimoldi¹⁸, L. Rinaldi^{22a}, B. Ristić⁵¹, E. Ritsch³², I. Riu¹³, F. Rizatdinova¹¹⁵, E. Rizvi⁷⁸, C. Rizzi¹³, S.H. Robertson^{89,l}, A. Robichaud-Veronneau⁸⁹, D. Robinson³⁰, J.E.M. Robinson⁴⁴, A. Robson⁵⁵, C. Roda^{125a,125b}, Y. Rodina⁸⁷, A. Rodriguez Perez¹³, D. Rodriguez Rodriguez¹⁶⁷, S. Roe³², C.S. Rogan⁵⁹, O. Røhne¹²⁰, A. Romaniouk⁹⁹, M. Romano^{22a,22b}, S.M. Romano Saez³⁶, E. Romero Adam¹⁶⁷, N. Rompotis¹³⁹, M. Ronzani⁵⁰, L. Roos⁸², E. Ros¹⁶⁷, S. Rosati^{133a}, K. Rosbach⁵⁰, P. Rose¹³⁸, O. Rosenthal¹⁴², N.-A. Rosien⁵⁶, V. Rossetti^{147a,147b}, E. Rossi^{105a,105b}, L.P. Rossi^{52a}, J.H.N. Rosten³⁰, R. Rosten¹³⁹, M. Rotaru^{28b}, I. Roth¹⁷², J. Rothberg¹³⁹, D. Rousseau¹¹⁸, C.R. Royon¹³⁷, A. Rozanov⁸⁷, Y. Rozen¹⁵³, X. Ruan^{146c}, F. Rubbo¹⁴⁴, M.S. Rudolph¹⁵⁹, F. Rühr⁵⁰, A. Ruiz-Martinez³¹, Z. Rurikova⁵⁰, N.A. Rusakovich⁶⁷, A. Ruschke¹⁰¹, H.L. Russell¹³⁹, J.P. Rutherford⁷, N. Ruthmann³², Y.F. Ryabov¹²⁴, M. Rybar¹⁶⁶, G. Rybkin¹¹⁸, S. Ryu⁶, A. Ryzhov¹³¹, G.F. Rzehorz⁵⁶, A.F. Saavedra¹⁵¹, G. Sabato¹⁰⁸, S. Sacerdoti²⁹, H.F.-W. Sadrozinski¹³⁸, R. Sadykov⁶⁷, F. Safai Tehrani^{133a}, P. Saha¹⁰⁹, M. Sahinsoy^{60a}, M. Saimpert¹³⁷, T. Saito¹⁵⁶, H. Sakamoto¹⁵⁶, Y. Sakurai¹⁷¹, G. Salamanna^{135a,135b}, A. Salamon^{134a,134b}, J.E. Salazar Loyola^{34b}, D. Salek¹⁰⁸, P.H. Sales De Bruin¹³⁹, D. Salihagic¹⁰², A. Salnikov¹⁴⁴, J. Salt¹⁶⁷, D. Salvatore^{39a,39b}, F. Salvatore¹⁵⁰, A. Salvucci^{62a}, A. Salzburger³², D. Sammel⁵⁰, D. Sampsonidis¹⁵⁵, A. Sanchez^{105a,105b}, J. Sánchez¹⁶⁷, V. Sanchez Martinez¹⁶⁷, H. Sandaker¹²⁰, R.L. Sandbach⁷⁸, H.G. Sander⁸⁵, M. Sandhoff¹⁷⁵, C. Sandoval²¹, R. Sandstroem¹⁰², D.P.C. Sankey¹³², M. Sannino^{52a,52b}, A. Sansoni⁴⁹, C. Santoni³⁶, R. Santonico^{134a,134b}, H. Santos^{127a}, I. Santoyo Castillo¹⁵⁰, K. Sapp¹²⁶, A. Sapronov⁶⁷, J.G. Saraiva^{127a,127d}, B. Sarrazin²³, O. Sasaki⁶⁸, Y. Sasaki¹⁵⁶, K. Sato¹⁶¹, G. Sauvage^{5,*}, E. Sauvan⁵, G. Savage⁷⁹, P. Savard^{159,d}, C. Sawyer¹³², L. Sawyer^{81,p}, J. Saxon³³, C. Sbarra^{22a}, A. Sbrizzi^{22a,22b}, T. Scanlon⁸⁰, D.A. Scannicchio¹⁶³, M. Scarcella¹⁵¹, V. Scarfone^{39a,39b}, J. Schaarschmidt¹⁷², P. Schacht¹⁰², B.M. Schachtner¹⁰¹, D. Schaefer³², R. Schaefer⁴⁴, J. Schaeffer⁸⁵, S. Schaepe²³, S. Schaetzel^{60b}, U. Schäfer⁸⁵, A.C. Schaffer¹¹⁸, D. Schaile¹⁰¹, R.D. Schamberger¹⁴⁹, V. Scharf^{60a}, V.A. Schegelsky¹²⁴, D. Scheirich¹³⁰, M. Schernau¹⁶³, C. Schiavi^{52a,52b}, S. Schier¹³⁸, C. Schillo⁵⁰, M. Schioppa^{39a,39b}, S. Schlenker³², K.R. Schmidt-Sommerfeld¹⁰², K. Schmieden³², C. Schmitt⁸⁵, S. Schmitt⁴⁴, S. Schmitz⁸⁵, B. Schneider^{160a}, U. Schnoor⁵⁰, L. Schoeffel¹³⁷, A. Schoening^{60b}, B.D. Schoenrock⁹², E. Schopf²³, M. Schott⁸⁵, J. Schovancova⁸, S. Schramm⁵¹, M. Schreyer¹⁷⁴, N. Schuh⁸⁵, M.J. Schultens²³, H.-C. Schultz-Coulon^{60a}, H. Schulz¹⁷, M. Schumacher⁵⁰, B.A. Schumm¹³⁸, Ph. Schune¹³⁷, A. Schwartzman¹⁴⁴, T.A. Schwarz⁹¹, Ph. Schwegler¹⁰², H. Schweiger⁸⁶, Ph. Schwemling¹³⁷, R. Schwienhorst⁹², J. Schwindling¹³⁷, T. Schwindt²³, G. Sciolla²⁵, F. Scuri^{125a,125b}, F. Scutti⁹⁰, J. Searcy⁹¹, P. Seema²³, S.C. Seidel¹⁰⁶, A. Seiden¹³⁸, F. Seifert¹²⁹, J.M. Seixas^{26a}, G. Sekhniaidze^{105a}, K. Sekhon⁹¹, S.J. Sekula⁴²,

D.M. Seliverstov ^{124,*}, N. Semprini-Cesari ^{22a,22b}, C. Serfon ¹²⁰, L. Serin ¹¹⁸, L. Serkin ^{164a,164b},
M. Sessa ^{135a,135b}, R. Seuster ¹⁶⁹, H. Severini ¹¹⁴, T. Sfiligoi ⁷⁷, F. Sforza ³², A. Sfyrla ⁵¹, E. Shabalina ⁵⁶,
N.W. Shaikh ^{147a,147b}, L.Y. Shan ^{35a}, R. Shang ¹⁶⁶, J.T. Shank ²⁴, M. Shapiro ¹⁶, P.B. Shatalov ⁹⁸,
K. Shaw ^{164a,164b}, S.M. Shaw ⁸⁶, A. Shcherbakova ^{147a,147b}, C.Y. Shehu ¹⁵⁰, P. Sherwood ⁸⁰, L. Shi ^{152,ah},
S. Shimizu ⁶⁹, C.O. Shimmin ¹⁶³, M. Shimojima ¹⁰³, M. Shiyakova ^{67,ai}, A. Shmeleva ⁹⁷, D. Shoaleh Saadi ⁹⁶,
M.J. Shochet ³³, S. Shojaii ^{93a,93b}, S. Shrestha ¹¹², E. Shulga ⁹⁹, M.A. Shupe ⁷, P. Sicho ¹²⁸, A.M. Sickles ¹⁶⁶,
P.E. Sidebo ¹⁴⁸, O. Sidiropoulou ¹⁷⁴, D. Sidorov ¹¹⁵, A. Sidoti ^{22a,22b}, F. Siegert ⁴⁶, Dj. Sijacki ¹⁴,
J. Silva ^{127a,127d}, S.B. Silverstein ^{147a}, V. Simak ¹²⁹, O. Simard ⁵, Lj. Simic ¹⁴, S. Simion ¹¹⁸, E. Simioni ⁸⁵,
B. Simmons ⁸⁰, D. Simon ³⁶, M. Simon ⁸⁵, P. Sinervo ¹⁵⁹, N.B. Sinev ¹¹⁷, M. Sioli ^{22a,22b}, G. Siragusa ¹⁷⁴,
S.Yu. Sivoklokov ¹⁰⁰, J. Sjölin ^{147a,147b}, T.B. Sjursen ¹⁵, M.B. Skinner ⁷⁴, H.P. Skottowe ⁵⁹, P. Skubic ¹¹⁴,
M. Slater ¹⁹, T. Slavicek ¹²⁹, M. Slawinska ¹⁰⁸, K. Sliwa ¹⁶², R. Slovak ¹³⁰, V. Smakhtin ¹⁷², B.H. Smart ⁵,
L. Smestad ¹⁵, J. Smiesko ^{145a}, S.Yu. Smirnov ⁹⁹, Y. Smirnov ⁹⁹, L.N. Smirnova ^{100,aj}, O. Smirnova ⁸³,
M.N.K. Smith ³⁷, R.W. Smith ³⁷, M. Smizanska ⁷⁴, K. Smolek ¹²⁹, A.A. Snesarev ⁹⁷, S. Snyder ²⁷,
R. Sobie ^{169,1}, F. Socher ⁴⁶, A. Soffer ¹⁵⁴, D.A. Soh ¹⁵², G. Sokhrannyi ⁷⁷, C.A. Solans Sanchez ³², M. Solar ¹²⁹,
E.Yu. Soldatov ⁹⁹, U. Soldevila ¹⁶⁷, A.A. Solodkov ¹³¹, A. Soloshenko ⁶⁷, O.V. Solovyanov ¹³¹, V. Solovyeu ¹²⁴,
P. Sommer ⁵⁰, H. Son ¹⁶², H.Y. Song ^{35b,ak}, A. Sood ¹⁶, A. Sopczak ¹²⁹, V. Sopko ¹²⁹, V. Sorin ¹³, D. Sosa ^{60b},
C.L. Sotiropoulou ^{125a,125b}, R. Soualah ^{164a,164c}, A.M. Soukharev ^{110,c}, D. South ⁴⁴, B.C. Sowden ⁷⁹,
S. Spagnolo ^{75a,75b}, M. Spalla ^{125a,125b}, M. Spangenberg ¹⁷⁰, F. Spanò ⁷⁹, D. Sperlich ¹⁷, F. Spettel ¹⁰²,
R. Spighi ^{22a}, G. Spigo ³², L.A. Spiller ⁹⁰, M. Spousta ¹³⁰, R.D. St. Denis ^{55,*}, A. Stabile ^{93a}, R. Stamen ^{60a},
S. Stamm ¹⁷, E. Stanecka ⁴¹, R.W. Stanek ⁶, C. Stanescu ^{135a}, M. Stanescu-Bellu ⁴⁴, M.M. Stanitzki ⁴⁴,
S. Stapnes ¹²⁰, E.A. Starchenko ¹³¹, G.H. Stark ³³, J. Stark ⁵⁷, P. Staroba ¹²⁸, P. Starovoitov ^{60a}, S. Stärz ³²,
R. Staszewski ⁴¹, P. Steinberg ²⁷, B. Stelzer ¹⁴³, H.J. Stelzer ³², O. Stelzer-Chilton ^{160a}, H. Stenzel ⁵⁴,
G.A. Stewart ⁵⁵, J.A. Stillings ²³, M.C. Stockton ⁸⁹, M. Stoebe ⁸⁹, G. Stoica ^{28b}, P. Stolte ⁵⁶, S. Stonjek ¹⁰²,
A.R. Stradling ⁸, A. Straessner ⁴⁶, M.E. Stramaglia ¹⁸, J. Strandberg ¹⁴⁸, S. Strandberg ^{147a,147b},
A. Strandlie ¹²⁰, M. Strauss ¹¹⁴, P. Strizenec ^{145b}, R. Ströhmer ¹⁷⁴, D.M. Strom ¹¹⁷, R. Stroynowski ⁴²,
A. Strubig ¹⁰⁷, S.A. Stucci ¹⁸, B. Stugu ¹⁵, N.A. Styles ⁴⁴, D. Su ¹⁴⁴, J. Su ¹²⁶, R. Subramaniam ⁸¹,
S. Suchek ^{60a}, Y. Sugaya ¹¹⁹, M. Suk ¹²⁹, V.V. Sulin ⁹⁷, S. Sultansoy ^{4c}, T. Sumida ⁷⁰, S. Sun ⁵⁹, X. Sun ^{35a},
J.E. Sundermann ⁵⁰, K. Suruliz ¹⁵⁰, G. Susinno ^{39a,39b}, M.R. Sutton ¹⁵⁰, S. Suzuki ⁶⁸, M. Svatos ¹²⁸,
M. Swiatlowski ³³, I. Sykora ^{145a}, T. Sykora ¹³⁰, D. Ta ⁵⁰, C. Taccini ^{135a,135b}, K. Tackmann ⁴⁴, J. Taenzer ¹⁵⁹,
A. Taffard ¹⁶³, R. Tahirout ^{160a}, N. Taiblum ¹⁵⁴, H. Takai ²⁷, R. Takashima ⁷¹, T. Takeshita ¹⁴¹, Y. Takubo ⁶⁸,
M. Talby ⁸⁷, A.A. Talyshv ^{110,c}, K.G. Tan ⁹⁰, J. Tanaka ¹⁵⁶, R. Tanaka ¹¹⁸, S. Tanaka ⁶⁸, B.B. Tannenwald ¹¹²,
S. Tapia Araya ^{34b}, S. Tapprogge ⁸⁵, S. Tarem ¹⁵³, G.F. Tartarelli ^{93a}, P. Tas ¹³⁰, M. Tasevsky ¹²⁸, T. Tashiro ⁷⁰,
E. Tassi ^{39a,39b}, A. Tavares Delgado ^{127a,127b}, Y. Tayalati ^{136d}, A.C. Taylor ¹⁰⁶, G.N. Taylor ⁹⁰, P.T.E. Taylor ⁹⁰,
W. Taylor ^{160b}, F.A. Teischinger ³², P. Teixeira-Dias ⁷⁹, K.K. Temming ⁵⁰, D. Temple ¹⁴³, H. Ten Kate ³²,
P.K. Teng ¹⁵², J.J. Teoh ¹¹⁹, F. Tepel ¹⁷⁵, S. Terada ⁶⁸, K. Terashi ¹⁵⁶, J. Terron ⁸⁴, S. Terzo ¹⁰², M. Testa ⁴⁹,
R.J. Teuscher ^{159,1}, T. Theveniaux-Pelzer ⁸⁷, J.P. Thomas ¹⁹, J. Thomas-Wilsker ⁷⁹, E.N. Thompson ³⁷,
P.D. Thompson ¹⁹, A.S. Thompson ⁵⁵, L.A. Thomsen ¹⁷⁶, E. Thomson ¹²³, M. Thomson ³⁰, M.J. Tibbetts ¹⁶,
R.E. Ticse Torres ⁸⁷, V.O. Tikhomirov ^{97,al}, Yu.A. Tikhonov ^{110,c}, S. Timoshenko ⁹⁹, P. Tipton ¹⁷⁶,
S. Tisserant ⁸⁷, K. Todome ¹⁵⁸, T. Todorov ^{5,*}, S. Todorova-Nova ¹³⁰, J. Tojo ⁷², S. Tokár ^{145a},
K. Tokushuku ⁶⁸, E. Tolley ⁵⁹, L. Tomlinson ⁸⁶, M. Tomoto ¹⁰⁴, L. Tompkins ^{144,am}, K. Toms ¹⁰⁶, B. Tong ⁵⁹,
E. Torrence ¹¹⁷, H. Torres ¹⁴³, E. Torró Pastor ¹³⁹, J. Toth ^{87,an}, F. Touchard ⁸⁷, D.R. Tovey ¹⁴⁰, T. Trefzger ¹⁷⁴,
A. Tricoli ²⁷, I.M. Trigger ^{160a}, S. Trincaz-Duviois ⁸², M.F. Tripiana ¹³, W. Trischuk ¹⁵⁹, B. Trocmé ⁵⁷,
A. Trofymov ⁴⁴, C. Troncon ^{93a}, M. Trottier-McDonald ¹⁶, M. Trovatelli ¹⁶⁹, L. Truong ^{164a,164c},
M. Trzebinski ⁴¹, A. Trzupek ⁴¹, J.C.-L. Tseng ¹²¹, P.V. Tsiarshka ⁹⁴, G. Tsipolitis ¹⁰, N. Tsirintanis ⁹,
S. Tsiskaridze ¹³, V. Tsiskaridze ⁵⁰, E.G. Tskhadadze ^{53a}, K.M. Tsui ^{62a}, I.I. Tsukerman ⁹⁸, V. Tsulaia ¹⁶,
S. Tsuno ⁶⁸, D. Tsybychev ¹⁴⁹, A. Tudorache ^{28b}, V. Tudorache ^{28b}, A.N. Tuna ⁵⁹, S.A. Tupputi ^{22a,22b},
S. Turchikhin ^{100,aj}, D. Turecek ¹²⁹, D. Turgeman ¹⁷², R. Turra ^{93a,93b}, A.J. Turvey ⁴², P.M. Tuts ³⁷,
M. Tyndel ¹³², G. Ucchielli ^{22a,22b}, I. Ueda ¹⁵⁶, R. Ueno ³¹, M. Ughetto ^{147a,147b}, F. Ukegawa ¹⁶¹, G. Unal ³²,
A. Undrus ²⁷, G. Unel ¹⁶³, F.C. Ungaro ⁹⁰, Y. Unno ⁶⁸, C. Unverdorben ¹⁰¹, J. Urban ^{145b}, P. Urquijo ⁹⁰,
P. Urrejola ⁸⁵, G. Usai ⁸, A. Usanova ⁶⁴, L. Vacavant ⁸⁷, V. Vacek ¹²⁹, B. Vachon ⁸⁹, C. Valderanis ¹⁰¹,
E. Valdes Santurio ^{147a,147b}, N. Valencic ¹⁰⁸, S. Valentini ^{22a,22b}, A. Valero ¹⁶⁷, L. Valery ¹³, S. Valkar ¹³⁰,
S. Vallecorsa ⁵¹, J.A. Valls Ferrer ¹⁶⁷, W. Van Den Wollenberg ¹⁰⁸, P.C. Van Der Deijl ¹⁰⁸,

R. van der Geer¹⁰⁸, H. van der Graaf¹⁰⁸, N. van Eldik¹⁵³, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴³, I. van Vulpen¹⁰⁸, M.C. van Woerden³², M. Vanadia^{133a,133b}, W. Vandelli³², R. Vanguri¹²³, A. Vaniachine¹³¹, P. Vankov¹⁰⁸, G. Vardanyan¹⁷⁷, R. Vari^{133a}, E.W. Varnes⁷, T. Varol⁴², D. Varouchas⁸², A. Vartapetian⁸, K.E. Varvell¹⁵¹, J.G. Vasquez¹⁷⁶, F. Vazeille³⁶, T. Vazquez Schroeder⁸⁹, J. Veatch⁵⁶, L.M. Veloce¹⁵⁹, F. Veloso^{127a,127c}, S. Veneziano^{133a}, A. Ventura^{75a,75b}, M. Venturi¹⁶⁹, N. Venturi¹⁵⁹, A. Venturini²⁵, V. Vercesi^{122a}, M. Verducci^{133a,133b}, W. Verkerke¹⁰⁸, J.C. Vermeulen¹⁰⁸, A. Vest^{46,ao}, M.C. Vetterli^{143,d}, O. Viazlo⁸³, I. Vichou¹⁶⁶, T. Vickey¹⁴⁰, O.E. Vickey Boeriu¹⁴⁰, G.H.A. Viehhauser¹²¹, S. Viel¹⁶, L. Vigani¹²¹, R. Vigne⁶⁴, M. Villa^{22a,22b}, M. Villaplana Perez^{93a,93b}, E. Vilucchi⁴⁹, M.G. Vinciter³¹, V.B. Vinogradov⁶⁷, C. Vittori^{22a,22b}, I. Vivarelli¹⁵⁰, S. Vlachos¹⁰, M. Vlasak¹²⁹, M. Vogel¹⁷⁵, P. Vokac¹²⁹, G. Volpi^{125a,125b}, M. Volpi⁹⁰, H. von der Schmitt¹⁰², E. von Toerne²³, V. Vorobel¹³⁰, K. Vorobev⁹⁹, M. Vos¹⁶⁷, R. Voss³², J.H. Vosseveld⁷⁶, N. Vranjes¹⁴, M. Vranjes Milosavljevic¹⁴, V. Vrba¹²⁸, M. Vreeswijk¹⁰⁸, R. Vuillermet³², I. Vukotic³³, Z. Vykydal¹²⁹, P. Wagner²³, W. Wagner¹⁷⁵, H. Wahlberg⁷³, S. Wahrmund⁴⁶, J. Wakabayashi¹⁰⁴, J. Walder⁷⁴, R. Walker¹⁰¹, W. Walkowiak¹⁴², V. Wallangen^{147a,147b}, C. Wang^{35c}, C. Wang^{35d,87}, F. Wang¹⁷³, H. Wang¹⁶, H. Wang⁴², J. Wang⁴⁴, J. Wang¹⁵¹, K. Wang⁸⁹, R. Wang⁶, S.M. Wang¹⁵², T. Wang²³, T. Wang³⁷, W. Wang^{35b}, X. Wang¹⁷⁶, C. Wanotayaroj¹¹⁷, A. Warburton⁸⁹, C.P. Ward³⁰, D.R. Wardrope⁸⁰, A. Washbrook⁴⁸, P.M. Watkins¹⁹, A.T. Watson¹⁹, M.F. Watson¹⁹, G. Watts¹³⁹, S. Watts⁸⁶, B.M. Waugh⁸⁰, S. Webb⁸⁵, M.S. Weber¹⁸, S.W. Weber¹⁷⁴, J.S. Webster⁶, A.R. Weidberg¹²¹, B. Weinert⁶³, J. Weingarten⁵⁶, C. Weiser⁵⁰, H. Weits¹⁰⁸, P.S. Wells³², T. Wenaus²⁷, T. Wengler³², S. Wenig³², N. Wermes²³, M. Werner⁵⁰, P. Werner³², M. Wessels^{60a}, J. Wetter¹⁶², K. Whalen¹¹⁷, N.L. Whallon¹³⁹, A.M. Wharton⁷⁴, A. White⁸, M.J. White¹, R. White^{34b}, D. Whiteson¹⁶³, F.J. Wickens¹³², W. Wiedenmann¹⁷³, M. Wielers¹³², P. Wienemann²³, C. Wiglesworth³⁸, L.A.M. Wiik-Fuchs²³, A. Wildauer¹⁰², F. Wilk⁸⁶, H.G. Wilkens³², H.H. Williams¹²³, S. Williams¹⁰⁸, C. Willis⁹², S. Willocq⁸⁸, J.A. Wilson¹⁹, I. Wingerter-Seez⁵, F. Winklmeier¹¹⁷, O.J. Winston¹⁵⁰, B.T. Winter²³, M. Wittgen¹⁴⁴, J. Wittkowski¹⁰¹, S.J. Wollstadt⁸⁵, M.W. Wolter⁴¹, H. Wolters^{127a,127c}, B.K. Wosiek⁴¹, J. Wotschack³², M.J. Woudstra⁸⁶, K.W. Wozniak⁴¹, M. Wu⁵⁷, M. Wu³³, S.L. Wu¹⁷³, X. Wu⁵¹, Y. Wu⁹¹, T.R. Wyatt⁸⁶, B.M. Wynne⁴⁸, S. Xella³⁸, D. Xu^{35a}, L. Xu²⁷, B. Yabsley¹⁵¹, S. Yacoob^{146a}, R. Yakabe⁶⁹, D. Yamaguchi¹⁵⁸, Y. Yamaguchi¹¹⁹, A. Yamamoto⁶⁸, S. Yamamoto¹⁵⁶, T. Yamanaka¹⁵⁶, K. Yamauchi¹⁰⁴, Y. Yamazaki⁶⁹, Z. Yan²⁴, H. Yang^{35e}, H. Yang¹⁷³, Y. Yang¹⁵², Z. Yang¹⁵, W.-M. Yao¹⁶, Y.C. Yap⁸², Y. Yasu⁶⁸, E. Yatsenko⁵, K.H. Yau Wong²³, J. Ye⁴², S. Ye²⁷, I. Yeletsikh⁶⁷, A.L. Yen⁵⁹, E. Yildirim⁸⁵, K. Yorita¹⁷¹, R. Yoshida⁶, K. Yoshihara¹²³, C. Young¹⁴⁴, C.J.S. Young³², S. Youssef²⁴, D.R. Yu¹⁶, J. Yu⁸, J.M. Yu⁹¹, J. Yu⁶⁶, L. Yuan⁶⁹, S.P.Y. Yuen²³, I. Yusuff^{30,ap}, B. Zabinski⁴¹, R. Zaidan^{35d}, A.M. Zaitsev^{131,ac}, N. Zakharchuk⁴⁴, J. Zalieckas¹⁵, A. Zaman¹⁴⁹, S. Zambito⁵⁹, L. Zanello^{133a,133b}, D. Zanzi⁹⁰, C. Zeitnitz¹⁷⁵, M. Zeman¹²⁹, A. Zemla^{40a}, J.C. Zeng¹⁶⁶, Q. Zeng¹⁴⁴, K. Zengel²⁵, O. Zenin¹³¹, T. Ženiš^{145a}, D. Zerwas¹¹⁸, D. Zhang⁹¹, F. Zhang¹⁷³, G. Zhang^{35b,ak}, H. Zhang^{35c}, J. Zhang⁶, L. Zhang⁵⁰, R. Zhang²³, R. Zhang^{35b,aq}, X. Zhang^{35d}, Z. Zhang¹¹⁸, X. Zhao⁴², Y. Zhao^{35d,118}, Z. Zhao^{35b}, A. Zhemchugov⁶⁷, J. Zhong¹²¹, B. Zhou⁹¹, C. Zhou⁴⁷, L. Zhou³⁷, L. Zhou⁴², M. Zhou¹⁴⁹, N. Zhou^{35f}, C.G. Zhu^{35d}, H. Zhu^{35a}, J. Zhu⁹¹, Y. Zhu^{35b}, X. Zhuang^{35a}, K. Zhukov⁹⁷, A. Zibell¹⁷⁴, D. Zieminska⁶³, N.I. Zimine⁶⁷, C. Zimmermann⁸⁵, S. Zimmermann⁵⁰, Z. Zinonos⁵⁶, M. Zinser⁸⁵, M. Ziolkowski¹⁴², L. Živković¹⁴, G. Zobernig¹⁷³, A. Zoccoli^{22a,22b}, M. zur Nedden¹⁷, G. Zurzolo^{105a,105b}, L. Zwalinski³²

¹ Department of Physics, University of Adelaide, Adelaide, Australia² Physics Department, SUNY Albany, Albany, NY, United States³ Department of Physics, University of Alberta, Edmonton, AB, Canada⁴ (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey⁵ LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France⁶ High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States⁷ Department of Physics, University of Arizona, Tucson, AZ, United States⁸ Department of Physics, The University of Texas at Arlington, Arlington, TX, United States⁹ Physics Department, University of Athens, Athens, Greece¹⁰ Physics Department, National Technical University of Athens, Zografou, Greece¹¹ Department of Physics, The University of Texas at Austin, Austin, TX, United States¹² Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan¹³ Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain¹⁴ Institute of Physics, University of Belgrade, Belgrade, Serbia¹⁵ Department for Physics and Technology, University of Bergen, Bergen, Norway¹⁶ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States¹⁷ Department of Physics, Humboldt University, Berlin, Germany¹⁸ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

- ¹⁹ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ²⁰ ^(a) Department of Physics, Bogazici University, Istanbul; ^(b) Department of Physics Engineering, Gaziantep University, Gaziantep; ^(d) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; ^(e) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
- ²¹ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- ²² ^(a) INFN Sezione di Bologna; ^(b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- ²³ Physikalisches Institut, University of Bonn, Bonn, Germany
- ²⁴ Department of Physics, Boston University, Boston, MA, United States
- ²⁵ Department of Physics, Brandeis University, Waltham, MA, United States
- ²⁶ ^(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; ^(c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; ^(d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- ²⁷ Physics Department, Brookhaven National Laboratory, Upton, NY, United States
- ²⁸ ^(a) Transilvania University of Brasov, Brasov, Romania; ^(b) National Institute of Physics and Nuclear Engineering, Bucharest; ^(c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; ^(d) University Politehnica Bucharest, Bucharest; ^(e) West University in Timisoara, Timisoara, Romania
- ²⁹ Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina
- ³⁰ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ³¹ Department of Physics, Carleton University, Ottawa, ON, Canada
- ³² CERN, Geneva, Switzerland
- ³³ Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
- ³⁴ ^(a) Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago; ^(b) Departamento de Fisica, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ³⁵ ^(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) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai ^{ar}; Physics Department, Tsinghua University, Beijing 100084, China
- ³⁶ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- ³⁷ Nevis Laboratory, Columbia University, Irvington, NY, United States
- ³⁸ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ³⁹ ^(a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; ^(b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ⁴⁰ ^(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
- ⁴¹ Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- ⁴² Physics Department, Southern Methodist University, Dallas, TX, United States
- ⁴³ Physics Department, University of Texas at Dallas, Richardson, TX, United States
- ⁴⁴ DESY, Hamburg and Zeuthen, Germany
- ⁴⁵ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁶ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁴⁷ Department of Physics, Duke University, Durham, NC, United States
- ⁴⁸ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁴⁹ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁵⁰ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- ⁵¹ Section de Physique, Université de Genève, Geneva, Switzerland
- ⁵² ^(a) INFN Sezione di Genova; ^(b) Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁵³ ^(a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵⁴ II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵⁵ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁶ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁷ Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- ⁵⁸ Department of Physics, Hampton University, Hampton, VA, United States
- ⁵⁹ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
- ⁶⁰ ^(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
- ⁶¹ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶² ^(a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; ^(b) Department of Physics, The University of Hong Kong, Hong Kong; ^(c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- ⁶³ Department of Physics, Indiana University, Bloomington, IN, United States
- ⁶⁴ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶⁵ University of Iowa, Iowa City, IA, United States
- ⁶⁶ Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
- ⁶⁷ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁸ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁹ Graduate School of Science, Kobe University, Kobe, Japan
- ⁷⁰ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁷¹ Kyoto University of Education, Kyoto, Japan
- ⁷² Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷³ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷⁴ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷⁵ ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷⁶ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁷ Department of Physics, Jozef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁸ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁹ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁸⁰ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁸¹ Louisiana Tech University, Ruston, LA, United States
- ⁸² Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁸³ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸⁴ Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
- ⁸⁵ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸⁶ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸⁷ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁸ Department of Physics, University of Massachusetts, Amherst, MA, United States
- ⁸⁹ Department of Physics, McGill University, Montreal, QC, Canada

- ⁹⁰ School of Physics, University of Melbourne, Victoria, Australia
- ⁹¹ Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- ⁹² Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- ⁹³ (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹⁴ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- ⁹⁵ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- ⁹⁶ Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- ⁹⁷ P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- ⁹⁸ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁹ National Research Nuclear University MEPhI, Moscow, Russia
- ¹⁰⁰ D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- ¹⁰¹ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁰² Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰³ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰⁴ Graduate School of Science and Kobayashi–Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰⁵ (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ¹⁰⁶ Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- ¹⁰⁷ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁸ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁹ Department of Physics, Northern Illinois University, DeKalb, IL, United States
- ¹¹⁰ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹¹¹ Department of Physics, New York University, New York, NY, United States
- ¹¹² Ohio State University, Columbus, OH, United States
- ¹¹³ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹⁴ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
- ¹¹⁵ Department of Physics, Oklahoma State University, Stillwater, OK, United States
- ¹¹⁶ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁷ Center for High Energy Physics, University of Oregon, Eugene, OR, United States
- ¹¹⁸ LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- ¹¹⁹ Graduate School of Science, Osaka University, Osaka, Japan
- ¹²⁰ Department of Physics, University of Oslo, Oslo, Norway
- ¹²¹ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹²² (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²³ Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
- ¹²⁴ National Research Centre "Kurchatov Institute", B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- ¹²⁵ (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²⁶ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
- ¹²⁷ (a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); (g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ¹²⁸ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- ¹²⁹ Czech Technical University in Prague, Praha, Czech Republic
- ¹³⁰ Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- ¹³¹ State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
- ¹³² Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³³ (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- ¹³⁴ (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ¹³⁵ (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- ¹³⁶ (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; (b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V, 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, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
- ¹⁶² Department of Physics and Astronomy, Tufts University, Medford, MA, United States

- ¹⁶³ Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
¹⁶⁴ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
¹⁶⁵ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
¹⁶⁶ Department of Physics, University of Illinois, Urbana, IL, United States
¹⁶⁷ Instituto de Física Corpuscular (IFIC) and Departamento de Física Atomica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
¹⁶⁸ Department of Physics, University of British Columbia, Vancouver, BC, Canada
¹⁶⁹ Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
¹⁷⁰ Department of Physics, University of Warwick, Coventry, United Kingdom
¹⁷¹ Waseda University, Tokyo, Japan
¹⁷² Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
¹⁷³ Department of Physics, University of Wisconsin, Madison, WI, United States
¹⁷⁴ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
¹⁷⁵ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
¹⁷⁶ Department of Physics, Yale University, New Haven, CT, United States
¹⁷⁷ Yerevan Physics Institute, Yerevan, Armenia
¹⁷⁸ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

- ^a Also at Department of Physics, King's College London, London, United Kingdom.
^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
^c Also at Novosibirsk State University, Novosibirsk, Russia.
^d Also at TRIUMF, Vancouver, BC, Canada.
^e Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States.
^f Also at Department of Physics, California State University, Fresno, CA, United States.
^g Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
^h Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.
ⁱ Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal.
^j Also at Tomsk State University, Tomsk, Russia.
^k Also at Università di Napoli Parthenope, Napoli, Italy.
^l Also at Institute of Particle Physics (IPP), Canada.
^m Also at National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
ⁿ Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
^o Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
^p Also at Louisiana Tech University, Ruston, LA, United States.
^q Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
^r Also at Graduate School of Science, Osaka University, Osaka, Japan.
^s Also at Department of Physics, National Tsing Hua University, Taiwan.
^t Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.
^u Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
^v Also at CERN, Geneva, Switzerland.
^w Also at Georgian Technical University (GTU), Tbilisi, Georgia.
^x Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
^y Also at Manhattan College, New York, NY, United States.
^z Also at Hellenic Open University, Patras, Greece.
^{aa} Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
^{ab} Also at School of Physics, Shandong University, Shandong, China.
^{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 Eotvos Lorand University, Budapest, Hungary.
^{af} Also at International School for Advanced Studies (SISSA), Trieste, Italy.
^{ag} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
^{ah} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
^{ai} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
^{aj} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
^{ak} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
^{al} Also at National Research Nuclear University MEPhI, Moscow, Russia.
^{am} Also at Department of Physics, Stanford University, Stanford, CA, United States.
^{an} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
^{ao} Also at Flensburg University of Applied Sciences, Flensburg, Germany.
^{ap} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
^{aq} Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
^{ar} Also affiliated with PKU-CHEP.
^{*} Deceased.