



Search for boosted low-mass resonances decaying into hadrons produced in association with a photon in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Many extensions of the Standard Model, including those with dark matter particles, propose new mediator particles that decay into hadrons. This paper presents a search for such low mass narrow resonances decaying into hadrons using 140 fb^{-1} of proton–proton collision data recorded with the ATLAS detector at a centre-of-mass energy of 13 TeV. The resonances are searched for in the invariant mass spectrum of large-radius jets with two-pronged substructure that are recoiling against an energetic photon from initial state radiation, which is used as a trigger to circumvent limitations on the maximum data recording rate. This technique enables the search for boosted hadronically decaying resonances in the mass range 20–100 GeV hitherto unprobed by the ATLAS Collaboration. The observed data are found to agree with Standard Model predictions and 95% confidence level upper limits are set on the coupling of a hypothetical new spin-1 Z' resonance with Standard Model quarks as a function of the assumed Z' -boson mass in the range between 20 and 200 GeV.

1 Introduction

Many extensions of the Standard Model (SM) predict new mediator particles that couple to SM particles. A particular class of spin-1 mediators are referred to as Z' . These Z' mediators appear in dark matter models [1, 2] among many others [3–9]. The minimal requirement for a Z' resonance to be produced in the s -channel at the LHC is a $Z'q\bar{q}$ coupling, which in turn predicts resonances decaying into hadronic but not necessarily leptonic final states. The first searches for hadronically decaying resonances at hadron colliders were carried out at the SPS by the UA1 [10, 11] and UA2 [12, 13] Collaborations. The invariant mass reach was extended by the CDF [14] and D0 [15] Collaborations at the Tevatron, and by the ATLAS [16–18] and CMS [19, 20] Collaborations at the LHC. However, with the increase of the centre-of-mass energy and instantaneous luminosity, the sensitivity to light hadronically decaying resonances with small production cross sections is significantly hampered by the high QCD multijet production cross section, which results in an event rate many orders of magnitude above the data recording bandwidth of the experiment. This limitation has been partially addressed by performing searches using online reconstruction algorithms run at the trigger level [21, 22]. Another technique is to use initial-state radiation (ISR) [23] to avoid reliance on single-jet triggers with transverse momentum (p_T) thresholds of around 0.5 TeV, which has been extensively used at the LHC [24–28].

This paper presents a search for hadronically decaying resonances in the challenging invariant mass range between 20 and 100 GeV that was hitherto unexplored by the ATLAS Collaboration. The search uses 140 fb^{-1} of pp collisions recorded by the ATLAS detector between 2015 and 2018 at a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$. The bandwidth and QCD background limitations are overcome by using a single-photon trigger with a transverse momentum threshold of $p_T > 140 \text{ GeV}$. The search strategy selects ISR photons from the $q\bar{q} \rightarrow Z' \rightarrow q\bar{q}$ process, resulting in a final state with hadronic activity from the $Z' \rightarrow q\bar{q}$ decay recoiling against an energetic photon in the plane perpendicular to the beamline. The leading-order Feynman diagram for the $q\bar{q} \rightarrow \gamma + Z' \rightarrow \gamma + q\bar{q}$ process is shown in Figure 1(a).

The Lorentz boost of the Z' boson brings an increased collimation of the $Z' \rightarrow q\bar{q}$ decay products with decreasing $m_{Z'}$, resulting in a very dense and experimentally challenging jet topology for $m_{Z'} \lesssim 50 \text{ GeV}$. This challenge is overcome by using the track-assisted reclustered (TAR) jet reconstruction technique [29] that combines information from the tracker and the calorimeters, and was first employed in Ref. [30]. The decay products of the Z' resonance are reconstructed as a single large-radius jet. The signal is searched for as a resonance in the spectrum of the invariant mass of the large-radius jet (m_J) over the background expected from SM processes.

The dominant backgrounds are non-resonant in m_J and arise from QCD multijet production in association with either a photon (see Figure 1(b)) or a jet misidentified as a photon. In both cases, QCD jets can pass the selection for a boosted massive Z' resonance decaying into a pair of quarks due to rare fluctuations in parton showering and hadronisation folded with detector response. Both background sources are estimated from data using signal-depleted control regions (CR) after validating the methodology with Monte Carlo (MC) simulations. Resonant backgrounds arise from SM production of $\gamma+V$ ($V = W, Z$), with $V \rightarrow q\bar{q}$ (see Figure 1(c)). Another resonant background arises from SM top-antitop-quark ($t\bar{t}$) production or associated production of a top-quark and a W boson (tW), where one of the two W bosons in the event decays into a quark pair and the other W boson decays into an electron and a neutrino, with the former being misidentified as a photon. All resonant backgrounds are estimated using MC simulations. The correct modelling of the m_J distribution in resonant processes is verified in a dedicated CR enriched in $t\bar{t}$ events. The results are interpreted within the framework of a dark matter model with a Z' mediator in the mass range between 20 and 200 GeV that decays into a pair of quarks [1, 2]. The lower limit of the search

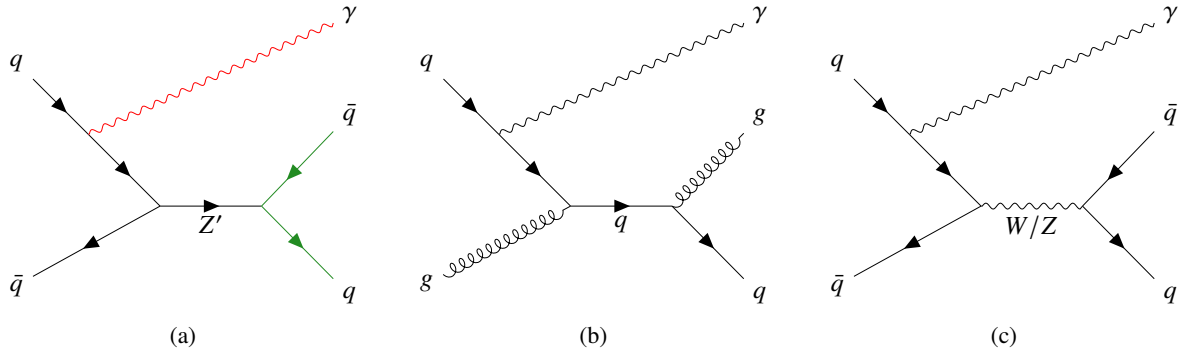


Figure 1: Representative leading-order Feynman diagrams for (a) the $q\bar{q} \rightarrow \gamma + Z' \rightarrow \gamma + q\bar{q}$ process, (b) the non-resonant background from multijet production in association with a photon, and (c) the dominant resonant background from $\gamma + V$, where $V \rightarrow q\bar{q}$ and $V = W, Z$.

range is chosen to avoid the non-trivial effects on the acceptance of the search, while the upper limit is in the region where other searches by the ATLAS Collaboration dominate the sensitivity [16–18, 21, 24, 25, 31].

2 ATLAS detector

The ATLAS experiment [32] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical 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 silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID-2 [33] detector, which is located close to the beampipe. A two-level trigger system is used to select events [34]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. A software suite [35] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

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. Polar 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 $\eta = -\ln \tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_z c}{E-p_z c} \right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$.

3 Data and simulated event samples

This analysis is performed using data from proton–proton (pp) collisions at $\sqrt{s} = 13$ TeV at the LHC, collected during 2015–2018 with the ATLAS detector. The total integrated luminosity of this data sample is 140 fb^{-1} [36], obtained using the LUCID-2 detector for the primary luminosity measurements. Data in this analysis are required to satisfy standard quality requirements [37].

SM background processes and the Z' signal are simulated using MC event generators. A detailed simulation of the ATLAS detector [38] based on the GEANT4 [39] package is used to simulate the detector response for all MC event samples. Contributions from additional pp interactions (pile-up) are simulated with the PYTHIA 8.186 [40] event generator using the NNPDF2.3LO parton distribution function (PDF) set [41] and corrected to match the spectrum of the average number of pp collisions per bunch-crossing in the data. Parton shower simulations with PYTHIA use the A14 set of tuned parameters [42] with the NNPDF2.3LO PDF set [41] and EvtGen [43] is used to model the decays of heavy-flavour hadrons. All simulations using the SHERPA event generator employ its internal parton shower model.

Prompt single-photon production was simulated with SHERPA 2.2.1 [44]. The parton-level process was generated at leading order (LO) in QCD for up to three additional partons, using the CT10NLO PDF set [45], and matched to the parton shower using the MEPS@LO prescription [46]. Photons from the matrix elements were required to be isolated according to a smooth-cone hadronic isolation criterion [47] with $\delta_0 = 0.3$, $\epsilon_\gamma = 0.025$ and $n = 2$. Multijet production was simulated using PYTHIA 8.230 [48, 49] with the NNPDF2.3LO PDF set with LO matrix elements for dijet production matched to the parton shower. The renormalisation and factorisation scales were set to the geometric mean of the squared transverse masses of the two outgoing particles in the matrix element. The $\gamma+V$ processes were simulated with SHERPA 2.2.11 using the NNPDF3.0NNLO PDF set [50]. The perturbative calculations for $\gamma+V$ were performed at next-to-leading order (NLO) in QCD for up to one additional parton and LO for up to three additional partons, and matched to the parton shower [51, 52] using the MEPS@NLO prescription. The matrix elements use the narrow-width approximation for the V bosons. Backgrounds from $t\bar{t}$ and single-top-quark production were generated at NLO in QCD with POWHEG BOX v2 [53–56] using the NNPDF3.0NLO PDF set [50] and interfaced to PYTHIA 8.230 for parton showering and hadronisation. The diagram removal scheme [57] was used to remove interference and overlap between tW and $t\bar{t}$ production. The $t\bar{t}$ samples are normalized using calculations at NNLO in QCD including next-to-next-to-leading logarithmic corrections for soft-gluon radiation [58–64]. The single-top-quark processes are normalized to cross sections at NLO in QCD from HATHOR v2.1 [65, 66]. The backgrounds from QCD V +jets production that are relevant for the top-quark control region defined in Section 5 were simulated with MADGRAPH5_AMC@NLO 2.2.2 [67], using LO-accurate matrix elements with up to four final-state partons. The matrix-element calculation employed the NNPDF3.0NLO set of PDFs, and was interfaced to PYTHIA 8.186. The overlap between matrix element and parton shower emissions was removed using the CKKW-L merging procedure [68, 69]. The V +jets samples were normalised to a next-to-next-to-leading-order prediction in QCD [70].

The signal model [1, 71, 72] features a vector resonance Z' with the $Z'q\bar{q}$ coupling g_q set to 0.2 (with $q = u, d, s, c, b$), which results in a Z' width well below the detector resolution. The signal was simulated generating $\gamma + Z'$ events at LO in QCD with MADGRAPH5_AMC@NLO v2.9.2 using the NNPDF3.0NLO PDF set and interfaced to PYTHIA 8.244. The rates for all decay modes except $Z' \rightarrow q\bar{q}$ were set to 0, and the interference between the Z' and the SM Z boson was neglected [1, 2]. The translation of the results to other g_q values is done following Ref. [73]. The mass of the hypothesised Z' resonance ranged between 20 GeV and 200 GeV.

4 Event reconstruction

At least one pp collision vertex, reconstructed from at least two ID tracks, is required in the event [74]. The vertex whose associated tracks give the highest sum of squared transverse momentum is designated the primary vertex (PV). The ID tracks must have at least seven hits and satisfy $p_T > 0.5$ GeV and $|\eta| < 2.5$ requirements [75, 76]. Their transverse and longitudinal impact parameters relative to the PV must satisfy $|d_0| < 2$ mm and $|z_0 \sin(\theta)| < 3$ mm, respectively.

Photon candidates are reconstructed from three-dimensional topological clusters of energy deposits (topoclusters) in the electromagnetic calorimeter [77]. The contamination from neutral hadrons is reduced using the energy deposition profile in the first two calorimeter layers. ‘Tight’ criteria as defined in Ref. [78] are applied for photon identification and isolation. Photons are required to have $p_T > 10$ GeV and to fall within $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$, thus avoiding the transition region between the barrel and endcap calorimeters.

Jets are formed with the anti- k_t algorithm [79, 80]. Jets with a radius parameter value of $R = 0.2$ are used in the overall reconstruction of the event. These $R = 0.2$ jets are built from topoclusters in the calorimeter that are corrected using the local cell signal weighting (LCW) method [81]. In addition, jets with $R = 0.4$ are used in the identification of b -hadron decays. These $R = 0.4$ jets are clustered from topoclusters and tracks with a particle flow algorithm that subtracts contributions due to charged particles from topoclusters [82]. A multivariate algorithm is used to identify $R = 0.4$ jets containing b -hadrons (b -tagging) with an average efficiency of 85% [83]. Corrections for pile-up [84] and to the energy scale and resolution [85] are applied to both jet definitions. Jets with $R = 0.2$ ($R = 0.4$) are required to have $p_T > 25$ GeV and $|\eta| < 2.2$ (2.5). $R = 0.4$ jets with $p_T < 60$ GeV and $|\eta| < 2.4$ are identified as originating from the PV using associated tracks [86]. No such procedure is applied to $R = 0.2$ jets since they are only used in association with tracks.

The TAR technique [29] is used to reconstruct the $Z' \rightarrow q\bar{q}$ decay in the challenging boosted low-mass phase space for the first time. This technique improves the resolution of jet substructure observables by combining tracking and calorimeter measurements. The TAR jets are formed from ID tracks and $R = 0.2$ jets as follows. The calibrated $R = 0.2$ jets are reclustered into larger jets with $R = 1.0$ using trimming parameters optimized for ATLAS [87]. ID tracks are associated to the $R = 0.2$ subjets of the reclustered jet. The p_T of each associated track is then rescaled by a common factor so the magnitude of the vector p_T sum of the associated tracks equals the p_T of the $R = 0.2$ jet. These rescaled tracks are used to calculate TAR jet observables, e.g., the jet mass m_J .

Resonance candidate $R = 1.0$ TAR jets are selected to be central ($|\eta| < 2$), have sufficient transverse momentum to balance the ISR photon ($p_{T,J} > 150$ GeV), and be collimated ($2m_J/p_{T,J} < 1$). They must be separated from the highest- p_T photon in the event by $\Delta\phi > \pi/2$, and isolated from any photon with $p_T^\gamma/p_T^J > 0.1$ by $\Delta R \geq 1.2$. TAR jets consisting of fewer than three rescaled tracks are rejected, since the substructure variable D_2 introduced in Section 5 is ill-defined for such jets [88].

Muons are reconstructed by matching a track or track segment found in the muon spectrometer to an ID track. Muons must satisfy the ‘Medium’ requirements in Ref. [89] and have $p_T > 25$ GeV and $|\eta| < 2.5$. Muons must be isolated using the ‘Loose’ criteria in Ref. [89], which limits the total energy observed in tracks and calorimeter deposits near the (extrapolated) muon track.

5 Event selection and analysis strategy

The signal is characterised by hadronic activity from the $Z' \rightarrow q\bar{q}$ decay produced back-to-back in azimuth to an isolated prompt energetic photon, which is used to trigger the event [90]. To ensure the trigger is fully efficient, the transverse momentum of the leading photon p_T^γ is required to be greater than 150 GeV. At least one TAR jet is required. To reduce the non-resonant background contribution, events are rejected if any $R = 0.2$ jet within $\Delta R \leq 1.2$ of the leading TAR jet (but not reclustered into it) has a p_T greater than p_T^γ . Similarly, events where the leading TAR jet has $\rho \equiv \log(m_J^2/p_{T,J}^2) \leq -5.4$ are rejected to improve the modelling of non-resonant backgrounds at the low end of the m_J spectrum using the data-driven approach, which will be described later in this Section. This selection has a negligible effect on the signal acceptance in the targeted $m_{Z'}$ range.

The internal energy distribution in TAR jets from signal events is consistent with a two-prong $Z' \rightarrow q\bar{q}$ decay, while TAR jets from non-resonant backgrounds are compatible with a one-prong decay. This difference is characterised using the D_2 observable [88], which was found to be powerful at discriminating between one- and two-prong jets [91]. The D_2 variable is defined using ratios of energy correlation functions that explore the substructure of a jet using an angular-weighted sum over the momenta of its constituents. The values of D_2 for two-prong jets are typically smaller than those for one-prong jets. Figure 2(a) shows a comparison of the distribution of the D_2 observable between non-resonant background processes in three mass ranges and the resonant backgrounds.

The D_2 observable is correlated with m_J . To eliminate the shaping of m_J resulting from the D_2 selection, a decorrelated observable [92–96] is defined as

$$D_2^{\text{DDT}}(\rho, p_T) = D_2 - D_2^{13\%}(\rho, p_T), \quad (1)$$

where ‘DDT’ stands for ‘Designed Decorrelated Tagger’. Here, $D_2^{13\%}$ is the 13% quantile, i.e., the value of D_2 that splits the non-resonant background MC sample into two subsamples of 87% and 13%. Hence, a selection of $D_2^{\text{DDT}}(\rho, p_T) < 0$ has a fixed efficiency of 13% in non-resonant background MC samples, irrespective of the mass or p_T of the jet. The quantile value of 13% was chosen by optimising the overall analysis sensitivity following the S/\sqrt{B} metric, where S and B are the expected numbers of signal and background events, respectively, and by minimising the magnitude of the variations in the initial $D_2^{13\%}(\rho, p_T)$ distribution for non-resonant background events.

The final $D_2^{13\%}(\rho, p_T)$ map is obtained by smoothing its initial distribution by convolution with a two-dimensional Gaussian kernel [97]. The parameters of the smoothing procedure like the binning of the initial $D_2^{13\%}(\rho, p_T)$ distribution and the kernel widths in ρ and p_T dimensions are optimised by minimising the Jensen-Shannon distance [98–100] between the m_J distributions for non-resonant background MC samples before and after the $D_2^{\text{DDT}}(\rho, p_T) < 0$ selection. In addition to D_2 , six other jet substructure observables capable of discriminating between one- and two-prong jets [91], including τ_{21} used in a similar previous ATLAS search [24], were explored following the procedure above. The D_2 variable was chosen since it minimises the shaping of the m_J distribution following the Jensen-Shannon distance metric.

Figure 2(b) shows the final $D_2^{13\%}(\rho, p_T)$ map after smoothing. In the following, the ‘tagged’ sample enriched in signal and two-prong resonant backgrounds is defined by the criterion $D_2^{\text{DDT}} < 0$, while the complementary ‘anti-tagged’ sample is enriched in non-resonant backgrounds.

Ideally, the shape of the m_J distribution of non-resonant background should be identical in the tagged and anti-tagged samples. In practice, the accuracy is limited by statistical and theoretical uncertainties on

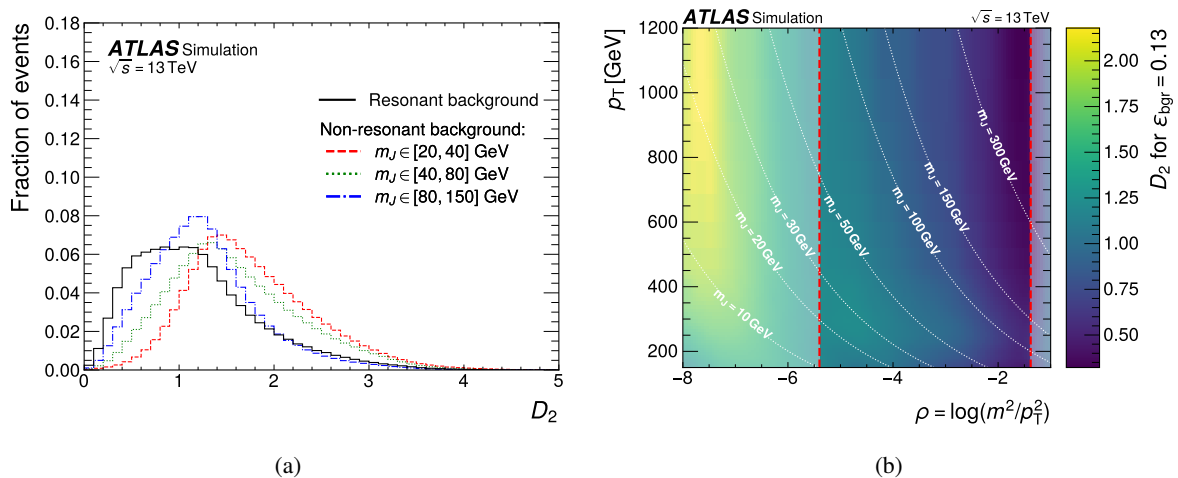


Figure 2: (a) Distribution of the D_2 observable [88] in MC simulations of non-resonant background processes in three different mass ranges (broken lines) compared to the resonant backgrounds (solid line). (b) The 13% quantile of the D_2 observable in the simulated non-resonant background sample. The contours of constant m_J are indicated by white dashed lines. White-shaded areas separated by vertical broken lines indicate the phase space that the $\rho < -5.4$ and $2m_J/p_{T,J} > 1$ selections reject.

the modelling of non-resonant backgrounds in MC simulations. Hence, this background distribution is estimated using data. This is done by modifying the non-resonant background contribution taken from the anti-tagged region in data by an m_J -dependent correction $\kappa_{D_2^{\text{DDT}}}(m_J)$ that is applied to the initial D_2^{DDT} efficiency of 13% as determined in simulations. Typically, the $\kappa_{D_2^{\text{DDT}}}(m_J)$ provides a percent-level correction to the nominal tagging efficiency. In order to reduce the impact of statistical fluctuations, $\kappa_{D_2^{\text{DDT}}}$ is parameterized in m_J by a Bernstein polynomial [101] of order five. In addition to providing an orthonormal basis, Bernstein polynomials bestow the advantage of strictly positive coefficients that are easily interpretable. The order of the Bernstein polynomial was optimised using pseudoexperiments requiring that a spurious signal bias be smaller than one-third of the statistical uncertainty, and considering the χ^2 probability, and the goodness-of-fit in data. The six Bernstein coefficients of $\kappa_{D_2^{\text{DDT}}}$ are determined in the simultaneous fit to data described in Section 6.

The data sample is further split into the central and forward regions defined by $|\eta_\gamma| \leq 1.3$ and $|\eta_\gamma| > 1.3$, respectively. Together with the split into tagged and anti-tagged categories, this defines four analysis regions in total: ‘central tagged’, ‘forward tagged’, ‘central anti-tagged’, and ‘forward anti-tagged’, where the former two are enriched in resonant processes due to the $D_2^{\text{DDT}} < 0$ selection. The central tagged analysis region is then defined as the signal region (SR), since signal tends to be more central for such quark-induced processes with energetic ISR photons. The other three analysis regions are referred to as control regions (CR).

To minimize biases due to a potential signal contamination in the forward tagged CR and other CRs, a single $\kappa_{D_2^{\text{DDT}}}(m_J)$ correction is determined and applied in all four regions in a simultaneous fit procedure discussed in Section 6. In all CRs, the signal contamination never exceeds three permille. Hence, the signal significance, defined as S/\sqrt{B} in the m_J region around the $m_{Z'}$ candidate mass, is at least two times smaller in the CRs compared to the SR, at the level of sensitivity of this analysis. A systematic uncertainty on the assumption that $\kappa_{D_2^{\text{DDT}}}(m_J)$ is identical in the central and forward regions is estimated as described

in Section 6.

The resonant background processes ($\gamma+V$, tW and $t\bar{t}$) and the signal are modelled using MC simulations. The efficiency of the D_2^{DDT} selection in MC simulations is calibrated using $W \rightarrow q\bar{q}'$ decays. This is done using a dedicated top CR (denoted ‘top CR’), which targets the semi-muonic decay of $t\bar{t}$ pairs and hence requires a single energetic muon trigger and exactly one isolated muon with $p_T \geq 30$ GeV. At least three $R = 0.4$ jets must be present, of which at least two should be b -tagged. At least one b -tagged jet must fall within $\Delta R < 1.5$ from the muon to select for collimated $t \rightarrow bW$ decays. Furthermore, at least one TAR jet passing all SR selections except for D_2^{DDT} must be present. TAR jets must be separated by $\Delta R \geq 1.05$ from muons and by $\Delta R \geq 1.45$ from b -tagged jets.

The fiducial on-shell $W \rightarrow qq'$ production rate is extracted in the top CR using a parametrised fit to the W -boson candidate mass spectrum, where the contribution from W bosons is captured by a Gaussian distribution, while the background is described by a second order polynomial. The efficiency of the D_2^{DDT} selection $\varepsilon_{D_2^{\text{DDT}}}^{\text{res}}$ for resonant W -boson production is then determined as the ratio of the fiducial on-shell W -boson production rates after and before applying the $D_2^{\text{DDT}} < 0$ requirement. The ratio

$$\mathcal{R}_{D_2^{\text{DDT}}} = \frac{\varepsilon_{D_2^{\text{DDT},\text{data}}}^{\text{res}}}{\varepsilon_{D_2^{\text{DDT},\text{MC}}}^{\text{res}}}$$

is then used to calibrate the tagging efficiency in MC simulations of resonant processes. The calibration factor is measured to be $\mathcal{R}_{D_2^{\text{DDT}}} = 0.971 \pm 0.026$. Its value and the corresponding uncertainty is propagated to the signal extraction fit described in Section 6.

6 Statistical analysis and systematic uncertainties

The resonant $Z' \rightarrow q\bar{q}$ signal is extracted via a simultaneous maximum-likelihood fit [102, 103] to the binned m_J distributions in the SR and the three CR categories, but not the top CR. This fit considers signal and resonant background predictions from MC simulations scaled to their theoretical cross sections and calibrated for the D_2^{DDT} selection efficiency determined in the top CR. The width of the bins in m_J is chosen as about one-third of the experimental resolution on $m_{Z'}$ while keeping the statistical uncertainties per bin approximately constant. The expected yields v_i for the Poisson probability density in a given m_J bin i are given as

$$v_{\text{SR},i}(\mu, \theta) = \mu \cdot v_{\text{SR},\text{sig},i}(\theta) + \sum_{\text{res. bkg.}} v_{\text{SR},\text{bkg},i}(\theta) + \frac{13\%}{1 - 13\%} \kappa_{D_2^{\text{DDT},i}} \cdot v_{\text{central},i} \quad (2)$$

for the SR and

$$v_{\text{caCR},i}(\mu, \theta) = \mu \cdot v_{\text{caCR},\text{sig},i}(\theta) + \sum_{\text{res. bkg.}} v_{\text{caCR},\text{bkg},i}(\theta) + v_{\text{central},i} \quad (3)$$

in the central anti-tagged CR labelled as ‘caCR’. Here, μ is the signal strength, i.e. a factor multiplying the expected signal yields, θ is the vector of nuisance parameters representing systematic uncertainties and the $\mathcal{R}_{D_2^{\text{DDT}}}$ calibration, ‘sig’ labels the signal and ‘res. bkg’ the resonant background processes. The values $v_{\text{central},i}$ approximate the yield of the non-resonant background in the central anti-tagged CR. The relevant difference between Eqs. (2) and (3) is the transfer factor $\frac{13\%}{1 - 13\%} \kappa_{D_2^{\text{DDT},i}}$ that considers the non-resonant background tagging efficiency in data. The probability densities in the forward tagged and anti-tagged

CRs are defined in analogy to Eqs. (2) and (3), respectively, using the same $\frac{13\%}{1-13\%} \kappa_{D_2^{\text{DDT}},i}$ transfer factor. Hence, the non-resonant background contribution is simultaneously fit in the SR and the three CRs through a common set of the Bernstein coefficients for the $\kappa_{D_2^{\text{DDT}}}(m_J)$ correction.

The uncertainty in the non-resonant background estimate represents the dominant systematic uncertainty in this analysis, contributing between 80% and 90% of the total systematic uncertainty, depending on the $m_{Z'}$ hypothesis. This uncertainty estimate considers three different sources, which are described below.

First, a systematic uncertainty on the assumption that $\kappa_{D_2^{\text{DDT}}}(m_J)$ is identical in the central and forward regions is explicitly considered in the simultaneous maximum-likelihood fit procedure through Eqs. (2) and (3) and their counterparts for the forward CRs. Since the central and forward regions use the same $\kappa_{D_2^{\text{DDT}}}$ correction factor and hence the same Bernstein coefficients, any tensions between the data in the tagged central and forward regions and the estimates obtained from the corresponding untagged regions will result in an increased uncertainty in the fitting procedure. This source of systematic uncertainty explicitly accounts for statistical limitations due to a finite number of data and MC events, and contributes more than 90% of the uncertainty on the non-resonant background estimate.

Second, a systematic uncertainty accounting for a potential spurious signal bias as a function of m_J is considered. This bias is evaluated through a multiplicative nuisance parameter on the signal yield in fits to pseudoexperiments derived from Asimov data. The corresponding uncertainty is below one percent of the uncertainty on the non-resonant background estimate.

Third, a systematic uncertainty related to the extrapolation between the forward and central regions is evaluated. This uncertainty accounts for localised fluctuations in tagged region data on scales that are comparable to the m_J resolution. This uncertainty is derived from the net difference between observed data and the pre-fit background prediction. If this net difference is larger than \sqrt{B} in a given m_J bin, a systematic uncertainty is added to this bin. Only the tagged forward control region is used to determine the net difference in order to minimise any impact from signal that may potentially be present. This systematic uncertainty is applied in the central and forward regions, per m_J bin and it is taken as uncorrelated across bins. It contributes a few percent of the uncertainty in the non-resonant background estimate.

The systematic uncertainties related to MC simulations are parameterized as nuisance parameters with Gaussian or log-normal prior probabilities, are profiled and used to constrain the template shapes and the normalisations varied in the fit. The leading sources of systematic uncertainty related to MC simulations originate from the theoretical modelling of signal events. Among those uncertainties are: the choice of the factorisation and renormalisation scales, the choice of PDFs, and the uncertainty on the strong coupling constant α_s . Sub-leading sources of systematic uncertainties that affect both signal and background events modelled using MC simulations are related to the energy scale and resolution of $R = 0.2$ and $R = 0.4$ jets [85]. Other, typically negligible sources of systematic uncertainty are related to the identification and reconstruction of photons [77], the finite number of MC events, and the measured integrated luminosity [36]. Overall, this search is limited by statistical uncertainties in the data, which typically range between 20% and 50% of the theoretical cross section for the $Z' \rightarrow q\bar{q}$ process, depending on $m_{Z'}$.

7 Results

The distributions of m_J in the SR and the central anti-tagged CR and are shown in Figure 3 after the fit to data under the background-only hypothesis. The statistical weight of the anti-tagged CRs is significantly higher than that of the tagged regions since they have seven times the yield. Hence, the excursion of the data points from the background prediction relative to the total statistical plus systematic uncertainty in the

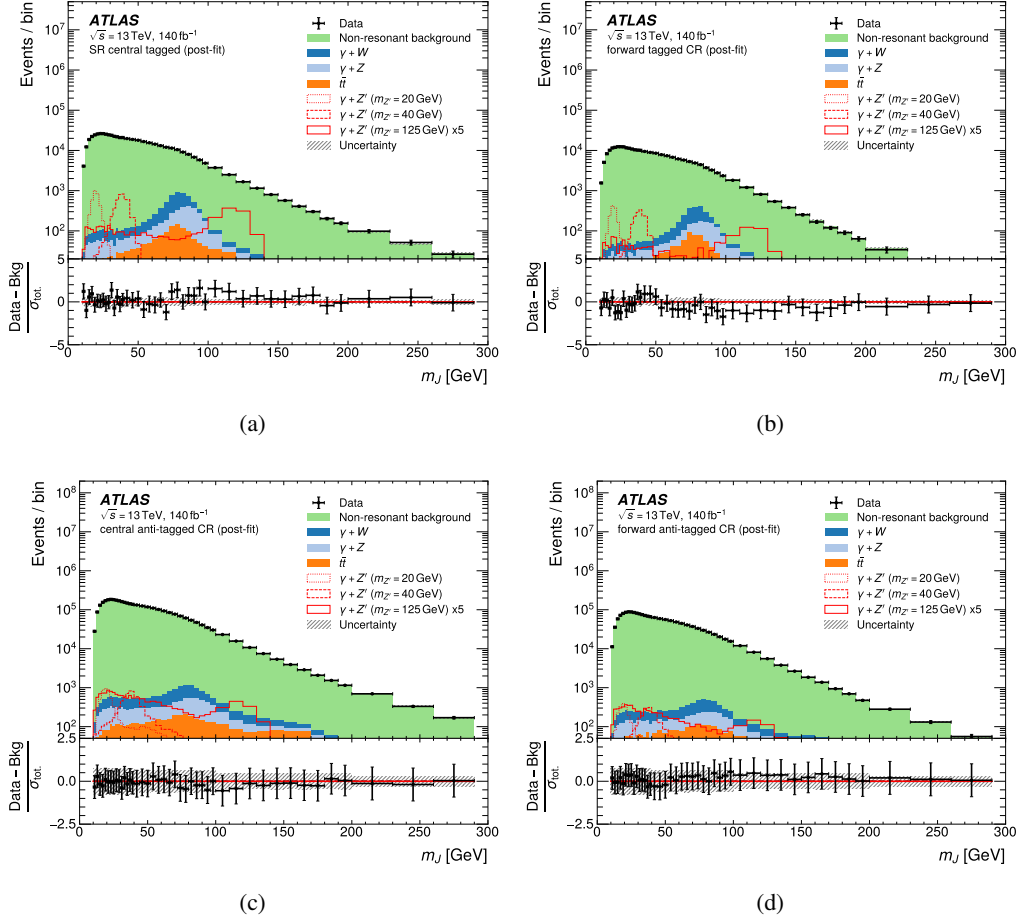


Figure 3: Invariant mass m_J of the resonance candidates in the (a) SR, i.e., central tagged region, (b) forward tagged CR, (c) central anti-tagged CR, and (d) forward anti-tagged CR, after the fit to data under the background-only hypothesis. The total systematic uncertainty is shown as the hatched band. Three representative $\gamma+Z$ signal distributions are overlaid as red lines. The signal is shown for $g_q = 0.2$ with production cross sections of 309 fb, 143 fb, and 34.2 fb for $m_{Z'} = 20, 50,$ and 125 GeV, respectively.

anti-tagged CRs is much smaller than in the tagged regions. For the same reason, the relative contribution of the systematic uncertainty, shown as a hatched band, appears larger in the anti-tagged CRs due to the smaller total uncertainty compared to the tagged regions. Figure 4 shows the corresponding $\kappa_{D_2^{\text{DDT}}}(m_J)$ correction after the fit to data under the background-only hypothesis alongside observed ratios of tagged over anti-tagged events in the central and forward regions. No significant deviation from SM predictions is observed.

In absence of a significant excess, the results are interpreted in Figure 5 as exclusion limits at 95% confidence level (CL) on the g_q coupling strength with the CL_s formalism [104] using a profile likelihood ratio [105] as test statistic. In the range $m_{Z'} < 100$ GeV, hitherto unprobed by ATLAS, g_q couplings as small as 0.1 are excluded.

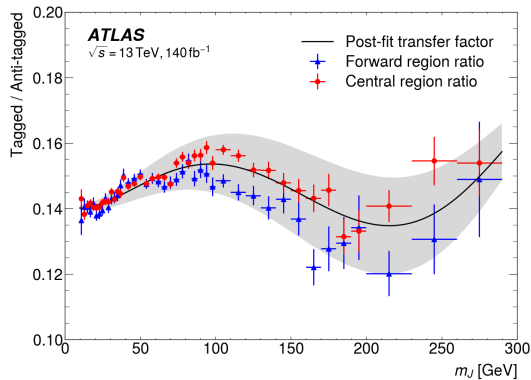


Figure 4: The distribution of the transfer factor $\frac{13\%}{1-13\%} \mathcal{K}_{D_2^{\text{DDT}}}(m_J)$ after the fit to data under the background-only hypothesis. The corresponding uncertainty band is shown as a shaded area. Also shown are the observed ratios of tagged over anti-tagged events in the central (red circles) and forward (blue triangles) regions, where the prior expected contributions from resonant backgrounds have been subtracted and the uncertainties are purely statistical.

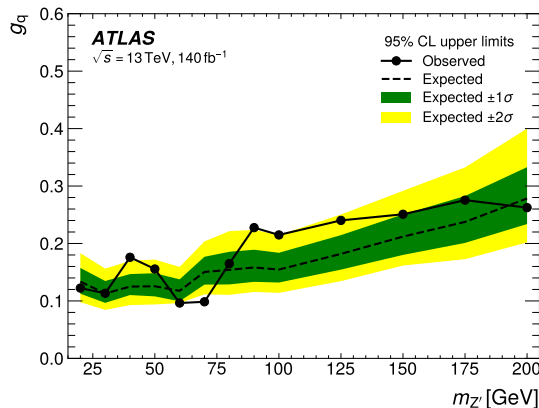


Figure 5: Observed (expected) upper exclusion limits at 95% CL on the coupling strength g_q of a new vector Z' particle decaying to a $q\bar{q}$ pair for the LHC DM WG benchmark signal model from Refs. [1, 71, 72] where decay rates for all decay modes except $Z' \rightarrow q\bar{q}$ are set to 0, and the interference between the Z' and the SM Z boson is neglected. The expected $\pm 1\sigma$ ($\pm 2\sigma$) interval around the expected limit is shown as the filled green (yellow) band.

8 Conclusion

This paper presents a search for light hadronically decaying resonances using 140 fb^{-1} of pp collision data at $\sqrt{s} = 13 \text{ TeV}$ recorded by the ATLAS detector at the LHC. To avoid bandwidth limitations, events are triggered using energetic photons radiated from the initial state, and a search for resonances is performed on the invariant mass of the recoiling hadronic system. A track-assisted reclustered jet reconstruction method that combines information from the tracker and the calorimeters is used to reconstruct these boosted hadronically decaying resonances. A data-driven method is used to estimate the non-resonant background from the Standard Model production of a photon in association with jets and QCD multijet production with a jet misidentified as a photon. These techniques allow a search for new hadronically decaying resonances with invariant masses from 20 to 100 GeV for the first time in ATLAS. No evidence for new resonances is found. The results are interpreted within the framework of a dark matter model with a Z' mediator, i.e., the

$q\bar{q} \rightarrow \gamma + Z' \rightarrow \gamma + q\bar{q}$ process, and probe previously uncharted parameter space for the $Z'q\bar{q}$ coupling g_q for masses $20 < m_{Z'} < 200$ GeV, excluding g_q couplings down to 0.1.

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The ATLAS Collaboration

G. Aad ¹⁰⁴, E. Aakvaag ¹⁷, B. Abbott ¹²³, S. Abdelhameed ^{119a}, K. Abeling ⁵⁶, N.J. Abicht ⁵⁰, S.H. Abidi ³⁰, M. Aboeela ⁴⁵, A. Aboulhorma ^{36e}, H. Abramowicz ¹⁵⁴, H. Abreu ¹⁵³, Y. Abulaiti ¹²⁰, B.S. Acharya ^{70a,70b,1}, A. Ackermann ^{64a}, C. Adam Bourdarios ⁴, L. Adamczyk ^{87a}, S.V. Addepalli ²⁷, M.J. Addison ¹⁰³, J. Adelman ¹¹⁸, A. Adiguzel ^{22c}, T. Adye ¹³⁷, A.A. Affolder ¹³⁹, Y. Afik ⁴⁰, M.N. Agaras ¹³, J. Agarwala ^{74a,74b}, A. Aggarwal ¹⁰², C. Agheorghiesei ^{28c}, F. Ahmadov ^{39,x}, W.S. Ahmed ¹⁰⁶, S. Ahuja ⁹⁷, X. Ai ^{63e}, G. Aielli ^{77a,77b}, A. Aikot ¹⁶⁶, M. Ait Tamlhat ^{36e}, B. Aitbenkikh ^{36a}, M. Akbiyik ¹⁰², T.P.A. Åkesson ¹⁰⁰, A.V. Akimov ³⁸, D. Akiyama ¹⁷¹, N.N. Akolkar ²⁵, S. Aktas ^{22a}, K. Al Houry ⁴², G.L. Alberghi ^{24b}, J. Albert ¹⁶⁸, P. Albicocco ⁵⁴, G.L. Albouy ⁶¹, S. Alderweireldt ⁵³, Z.L. Alegria ¹²⁴, M. Aleksa ³⁷, I.N. Aleksandrov ³⁹, C. Alexa ^{28b}, T. Alexopoulos ¹⁰, F. Alfonsi ^{24b}, M. Algren ⁵⁷, M. Alhroob ¹⁷⁰, B. Ali ¹³⁵, H.M.J. Ali ⁹³, S. Ali ³², S.W. Alibocus ⁹⁴, M. Aliev ^{34c}, G. Alimonti ^{72a}, W. Alkahi ⁵⁶, C. Allaire ⁶⁷, B.M.M. Allbrooke ¹⁴⁹, J.F. Allen ⁵³, C.A. Allendes Flores ^{140f}, P.P. Allport ²¹, A. Aloisio ^{73a,73b}, F. Alonso ⁹², C. Alpigiani ¹⁴¹, Z.M.K. Alsolami ⁹³, M. Alvarez Estevez ¹⁰¹, A. Alvarez Fernandez ¹⁰², M. Alves Cardoso ⁵⁷, M.G. Alvigi ^{73a,73b}, M. Aly ¹⁰³, Y. Amaral Coutinho ^{84b}, A. Ambler ¹⁰⁶, C. Amelung ³⁷, M. Amerl ¹⁰³, C.G. Ames ¹¹¹, D. Amidei ¹⁰⁸, K.J. Amirie ¹⁵⁸, S.P. Amor Dos Santos ^{133a}, K.R. Amos ¹⁶⁶, D. Amperiadou ¹⁵⁵, S. An ⁸⁵, V. Ananiev ¹²⁸, C. Anastopoulos ¹⁴², T. Andeen ¹¹, J.K. Anders ³⁷, A.C. Anderson ⁶⁰, S.Y. Andreato ^{48a,48b}, A. Andreatza ^{72a,72b}, S. Angelidakis ⁹, A. Angerami ⁴², A.V. Anisenkov ³⁸, A. Annovi ^{75a}, C. Antel ⁵⁷, E. Antipov ¹⁴⁸, M. Antonelli ⁵⁴, F. Anulli ^{76a}, M. Aoki ⁸⁵, T. Aoki ¹⁵⁶, M.A. Aparo ¹⁴⁹, L. Aperio Bella ⁴⁹, C. Appelt ¹⁹, A. Apyan ²⁷, S.J. Arbiol Val ⁸⁸, C. Arcangeletti ⁵⁴, A.T.H. Arce ⁵², J-F. Arguin ¹¹⁰, S. Argyropoulos ⁵⁵, J.-H. Arling ⁴⁹, O. Arnaez ⁴, H. Arnold ¹⁴⁸, G. Artoni ^{76a,76b}, H. Asada ¹¹³, K. Asai ¹²¹, S. Asai ¹⁵⁶, N.A. Asbah ³⁷, K. Assamagan ³⁰, R. Astalos ^{29a}, K.S.V. Astrand ¹⁰⁰, S. Atashi ¹⁶², R.J. Atkin ^{34a}, M. Atkinson ¹⁶⁵, H. Atmani ^{36f}, P.A. Atmasiddha ¹³¹, K. Augsten ¹³⁵, S. Auricchio ^{73a,73b}, A.D. Auriol ²¹, V.A. Austrup ¹⁰³, G. Avolio ³⁷, K. Axiotis ⁵⁷, G. Azuelos ^{110,ac}, D. Babal ^{29b}, H. Bachacou ¹³⁸, K. Bachas ^{155,p}, A. Bachiu ³⁵, F. Backman ^{48a,48b}, A. Badea ⁴⁰, T.M. Baer ¹⁰⁸, P. Bagnaia ^{76a,76b}, M. Bahmani ¹⁹, D. Bahner ⁵⁵, K. Bai ¹²⁶, J.T. Baines ¹³⁷, L. Baines ⁹⁶, O.K. Baker ¹⁷⁵, E. Bakos ¹⁶, D. Bakshi Gupta ⁸, L.E. Balabram Filho ^{84b}, V. Balakrishnan ¹²³, R. Balasubramanian ¹¹⁷, E.M. Baldin ³⁸, P. Balek ^{87a}, E. Ballabene ^{24b,24a}, F. Balli ¹³⁸, L.M. Baltes ^{64a}, W.K. Balunas ³³, J. Balz ¹⁰², I. Bamwidhi ^{119b}, E. Banas ⁸⁸, M. Bandieramonte ¹³², A. Bandyopadhyay ²⁵, S. Bansal ²⁵, L. Barak ¹⁵⁴, M. Barakat ⁴⁹, E.L. Barberio ¹⁰⁷, D. Barberis ^{58b,58a}, M. Barbero ¹⁰⁴, M.Z. Barel ¹¹⁷, T. Barillari ¹¹², M-S. Barisits ³⁷, T. Barklow ¹⁴⁶, P. Baron ¹²⁵, D.A. Baron Moreno ¹⁰³, A. Baroncelli ^{63a}, A.J. Barr ¹²⁹, J.D. Barr ⁹⁸, F. Barreiro ¹⁰¹, J. Barreiro Guimarães da Costa ¹⁴, U. Barron ¹⁵⁴, M.G. Barros Teixeira ^{133a}, S. Barsov ³⁸, F. Bartels ^{64a}, R. Bartoldus ¹⁴⁶, A.E. Barton ⁹³, P. Bartos ^{29a}, A. Basan ¹⁰², M. Baselga ⁵⁰, A. Bassalat ^{67,b}, M.J. Basso ^{159a}, S. Bataju ⁴⁵, R. Bate ¹⁶⁷, R.L. Bates ⁶⁰, S. Batlamous ¹⁰¹, B. Batool ¹⁴⁴, M. Battaglia ¹³⁹, D. Battulga ¹⁹, M. Bauce ^{76a,76b}, M. Bauer ⁸⁰, P. Bauer ²⁵, L.T. Bazzano Hurrell ³¹, J.B. Beacham ⁵², T. Beau ¹³⁰, J.Y. Beaucamp ⁹², P.H. Beauchemin ¹⁶¹, P. Bechtel ²⁵, H.P. Beck ^{20,o}, K. Becker ¹⁷⁰, A.J. Beddall ⁸³, V.A. Bednyakov ³⁹, C.P. Bee ¹⁴⁸, L.J. Beemster ¹⁶, T.A. Beermann ³⁷, M. Begalli ^{84d}, M. Biegel ³⁰, A. Behera ¹⁴⁸, J.K. Behr ⁴⁹, J.F. Beirer ³⁷, F. Beisiegel ²⁵, M. Belfkir ^{119b}, G. Bella ¹⁵⁴, L. Bellagamba ^{24b}, A. Bellerive ³⁵, P. Bellos ²¹, K. Beloborodov ³⁸, D. Benckekroun ^{36a}, F. Bendebba ^{36a}, Y. Benhammou ¹⁵⁴,

K.C. Benkendorfer ⁶², L. Beresford ⁴⁹, M. Beretta ⁵⁴, E. Bergeaas Kuutmann ¹⁶⁴, N. Berger ⁴,
 B. Bergmann ¹³⁵, J. Beringer ^{18a}, G. Bernardi ⁵, C. Bernius ¹⁴⁶, F.U. Bernlochner ²⁵,
 F. Bernon ^{37,104}, A. Berrocal Guardia ¹³, T. Berry ⁹⁷, P. Berta ¹³⁶, A. Berthold ⁵¹, S. Bethke ¹¹²,
 A. Betti ^{76a,76b}, A.J. Bevan ⁹⁶, N.K. Bhalla ⁵⁵, S. Bhatta ¹⁴⁸, D.S. Bhattacharya ¹⁶⁹,
 P. Bhattarai ¹⁴⁶, K.D. Bhide ⁵⁵, V.S. Bhopatkar ¹²⁴, R.M. Bianchi ¹³², G. Bianco ^{24b,24a},
 O. Biebel ¹¹¹, R. Bielski ¹²⁶, M. Biglietti ^{78a}, C.S. Billingsley ⁴⁵, M. Bindi ⁵⁶, A. Bingul ^{22b},
 C. Bini ^{76a,76b}, G.A. Bird ³³, M. Birman ¹⁷², M. Biros ¹³⁶, S. Biryukov ¹⁴⁹, T. Bisanz ⁵⁰,
 E. Bisceglie ^{44b,44a}, J.P. Biswal ¹³⁷, D. Biswas ¹⁴⁴, I. Bloch ⁴⁹, A. Blue ⁶⁰, U. Blumenschein ⁹⁶,
 J. Blumenthal ¹⁰², V.S. Bobrovnikov ³⁸, M. Boehler ⁵⁵, B. Boehm ¹⁶⁹, D. Bogavac ³⁷,
 A.G. Bogdanchikov ³⁸, L.S. Boggia ¹³⁰, C. Bohm ^{48a}, V. Boisvert ⁹⁷, P. Bokan ³⁷, T. Bold ^{87a},
 M. Bomben ⁵, M. Bona ⁹⁶, M. Boonekamp ¹³⁸, C.D. Booth ⁹⁷, A.G. Borbély ⁶⁰,
 I.S. Bordulev ³⁸, G. Borissov ⁹³, D. Bortoletto ¹²⁹, D. Boscherini ^{24b}, M. Bosman ¹³,
 J.D. Bossio Sola ³⁷, K. Bouaouda ^{36a}, N. Bouchhar ¹⁶⁶, L. Boudet ⁴, J. Boudreau ¹³²,
 E.V. Bouhova-Thacker ⁹³, D. Boumediene ⁴¹, R. Bouquet ^{58b,58a}, A. Boveia ¹²², J. Boyd ³⁷,
 D. Boye ³⁰, I.R. Boyko ³⁹, L. Bozianu ⁵⁷, J. Bracinik ²¹, N. Brahimi ⁴, G. Brandt ¹⁷⁴,
 O. Brandt ³³, F. Braren ⁴⁹, B. Brau ¹⁰⁵, J.E. Brau ¹²⁶, R. Brenner ¹⁷², L. Brenner ¹¹⁷,
 R. Brenner ¹⁶⁴, S. Bressler ¹⁷², G. Brianti ^{79a,79b}, D. Britton ⁶⁰, D. Britzger ¹¹², I. Brock ²⁵,
 G. Brooijmans ⁴², E.M. Brooks ^{159b}, E. Brost ³⁰, L.M. Brown ¹⁶⁸, L.E. Bruce ⁶²,
 T.L. Bruckler ¹²⁹, P.A. Bruckman de Renstrom ⁸⁸, B. Brüers ⁴⁹, A. Bruni ^{24b}, G. Bruni ^{24b},
 M. Bruschi ^{24b}, N. Bruscinò ^{76a,76b}, T. Buanes ¹⁷, Q. Buat ¹⁴¹, D. Buchin ¹¹², A.G. Buckley ⁶⁰,
 O. Bulekov ³⁸, B.A. Bullard ¹⁴⁶, S. Burdin ⁹⁴, C.D. Burgard ⁵⁰, A.M. Burger ³⁷,
 B. Burghgrave ⁸, O. Burlayenko ⁵⁵, J. Burleson ¹⁶⁵, J.T.P. Burr ³³, J.C. Burzynski ¹⁴⁵,
 E.L. Busch ⁴², V. Büscher ¹⁰², P.J. Bussey ⁶⁰, J.M. Butler ²⁶, C.M. Buttar ⁶⁰,
 J.M. Butterworth ⁹⁸, W. Buttinger ¹³⁷, C.J. Buxo Vazquez ¹⁰⁹, A.R. Buzykaev ³⁸,
 S. Cabrera Urbán ¹⁶⁶, L. Cadamuro ⁶⁷, D. Caforio ⁵⁹, H. Cai ¹³², Y. Cai ^{14,114c}, Y. Cai ^{114a},
 V.M.M. Cairo ³⁷, O. Cakir ^{3a}, N. Calace ³⁷, P. Calafiura ^{18a}, G. Calderini ¹³⁰, P. Calfayan ⁶⁹,
 G. Callea ⁶⁰, L.P. Caloba ^{84b}, D. Calvet ⁴¹, S. Calvet ⁴¹, M. Calvetti ^{75a,75b}, R. Camacho Toro ¹³⁰,
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 D. Cameron ³⁷, C. Camincher ¹⁶⁸, M. Campanelli ⁹⁸, A. Camplani ⁴³, V. Canale ^{73a,73b},
 A.C. Canbay ^{3a}, E. Canonero ⁹⁷, J. Cantero ¹⁶⁶, Y. Cao ¹⁶⁵, F. Capocasa ²⁷, M. Capua ^{44b,44a},
 A. Carbone ^{72a,72b}, R. Cardarelli ^{77a}, J.C.J. Cardenas ⁸, G. Carducci ^{44b,44a}, T. Carli ³⁷,
 G. Carlino ^{73a}, J.I. Carlotto ¹³, B.T. Carlson ^{132,q}, E.M. Carlson ^{168,159a}, J. Carmignani ⁹⁴,
 L. Carminati ^{72a,72b}, A. Carnelli ¹³⁸, M. Carnesale ^{76a,76b}, S. Caron ¹¹⁶, E. Carquin ^{140f},
 S. Carrá ^{72a}, G. Carratta ^{24b,24a}, A.M. Carroll ¹²⁶, T.M. Carter ⁵³, M.P. Casado ^{13,i},
 M. Caspar ⁴⁹, F.L. Castillo ⁴, L. Castillo Garcia ¹³, V. Castillo Gimenez ¹⁶⁶, N.F. Castro ^{133a,133e},
 A. Catinaccio ³⁷, J.R. Catmore ¹²⁸, T. Cavaliere ⁴, V. Cavaliere ³⁰, N. Cavalli ^{24b,24a},
 L.J. Caviedes Betancourt ^{23b}, Y.C. Cekmecelioglu ⁴⁹, E. Celebi ⁸³, S. Cella ³⁷, F. Celli ¹²⁹,
 M.S. Centonze ^{71a,71b}, V. Cepaitis ⁵⁷, K. Cerny ¹²⁵, A.S. Cerqueira ^{84a}, A. Cerri ¹⁴⁹,
 L. Cerrito ^{77a,77b}, F. Cerutti ^{18a}, B. Cervato ¹⁴⁴, A. Cervelli ^{24b}, G. Cesarini ⁵⁴, S.A. Cetin ⁸³,
 D. Chakraborty ¹¹⁸, J. Chan ^{18a}, W.Y. Chan ¹⁵⁶, J.D. Chapman ³³, E. Chapon ¹³⁸,
 B. Chargeishvili ^{152b}, D.G. Charlton ²¹, M. Chatterjee ²⁰, C. Chauhan ¹³⁶, Y. Che ^{114a},
 S. Chekanov ⁶, S.V. Chekulaev ^{159a}, G.A. Chelkov ^{39,a}, A. Chen ¹⁰⁸, B. Chen ¹⁵⁴, B. Chen ¹⁶⁸,
 H. Chen ^{114a}, H. Chen ³⁰, J. Chen ^{63c}, J. Chen ¹⁴⁵, M. Chen ¹²⁹, S. Chen ¹⁵⁶, S.J. Chen ^{114a},
 X. Chen ^{63c}, X. Chen ^{15,ab}, Y. Chen ^{63a}, C.L. Cheng ¹⁷³, H.C. Cheng ^{65a}, S. Cheong ¹⁴⁶,
 A. Cheplakov ³⁹, E. Cheremushkina ⁴⁹, E. Cherepanova ¹¹⁷, R. Cherkaoui El Moursli ^{36e},
 E. Cheu ⁷, K. Cheung ⁶⁶, L. Chevalier ¹³⁸, V. Chiarella ⁵⁴, G. Chiarelli ^{75a}, N. Chiedde ¹⁰⁴,
 G. Chiodini ^{71a}, A.S. Chisholm ²¹, A. Chitan ^{28b}, M. Chitishvili ¹⁶⁶, M.V. Chizhov ³⁹,

K. Choi ¹¹, Y. Chou ¹⁴¹, E.Y.S. Chow ¹¹⁶, K.L. Chu ¹⁷², M.C. Chu ^{65a}, X. Chu ^{14,114c},
 Z. Chubinidze ⁵⁴, J. Chudoba ¹³⁴, J.J. Chwastowski ⁸⁸, D. Cieri ¹¹², K.M. Ciesla ^{87a},
 V. Cindro ⁹⁵, A. Ciocio ^{18a}, F. Cirotto ^{73a,73b}, Z.H. Citron ¹⁷², M. Citterio ^{72a}, D.A. Ciubotaru ^{28b},
 A. Clark ⁵⁷, P.J. Clark ⁵³, N. Clarke Hall ⁹⁸, C. Clarry ¹⁵⁸, J.M. Clavijo Columbie ⁴⁹,
 S.E. Clawson ⁴⁹, C. Clement ^{48a,48b}, Y. Coadou ¹⁰⁴, M. Cobal ^{70a,70c}, A. Coccaro ^{58b},
 R.F. Coelho Barrue ^{133a}, R. Coelho Lopes De Sa ¹⁰⁵, S. Coelli ^{72a}, B. Cole ⁴², J. Collot ⁶¹,
 P. Conde Muiño ^{133a,133g}, M.P. Connell ^{34c}, S.H. Connell ^{34c}, E.I. Conroy ¹²⁹, F. Conventi ^{73a,ad},
 H.G. Cooke ²¹, A.M. Cooper-Sarkar ¹²⁹, F.A. Corchia ^{24b,24a}, A. Cordeiro Oudot Choi ¹³⁰,
 L.D. Corpe ⁴¹, M. Corradi ^{76a,76b}, F. Corriveau ^{106,w}, A. Cortes-Gonzalez ¹⁹, M.J. Costa ¹⁶⁶,
 F. Costanza ⁴, D. Costanzo ¹⁴², B.M. Cote ¹²², J. Couthures ⁴, G. Cowan ⁹⁷, K. Cranmer ¹⁷³,
 D. Cremonini ^{24b,24a}, S. Crépe-Renaudin ⁶¹, F. Crescioli ¹³⁰, M. Cristinziani ¹⁴⁴,
 M. Cristoforetti ^{79a,79b}, V. Croft ¹¹⁷, J.E. Crosby ¹²⁴, G. Crosetti ^{44b,44a}, A. Cueto ¹⁰¹, H. Cui ⁹⁸,
 Z. Cui ⁷, W.R. Cunningham ⁶⁰, F. Curcio ¹⁶⁶, J.R. Curran ⁵³, P. Czodrowski ³⁷,
 M.J. Da Cunha Sargedas De Sousa ^{58b,58a}, J.V. Da Fonseca Pinto ^{84b}, C. Da Via ¹⁰³,
 W. Dabrowski ^{87a}, T. Dado ³⁷, S. Dahbi ¹⁵¹, T. Dai ¹⁰⁸, D. Dal Santo ²⁰, C. Dallapiccola ¹⁰⁵,
 M. Dam ⁴³, G. D'amen ³⁰, V. D'Amico ¹¹¹, J. Damp ¹⁰², J.R. Dandoy ³⁵, D. Dannheim ³⁷,
 M. Danninger ¹⁴⁵, V. Dao ¹⁴⁸, G. Darbo ^{58b}, S.J. Das ^{30,ae}, F. Dattola ⁴⁹, S. D'Auria ^{72a,72b},
 A. D'avanzo ^{73a,73b}, C. David ^{34a}, T. Davidek ¹³⁶, I. Dawson ⁹⁶, H.A. Day-hall ¹³⁵, K. De ⁸,
 R. De Asmundis ^{73a}, N. De Biase ⁴⁹, S. De Castro ^{24b,24a}, N. De Groot ¹¹⁶, P. de Jong ¹¹⁷,
 H. De la Torre ¹¹⁸, A. De Maria ^{114a}, A. De Salvo ^{76a}, U. De Sanctis ^{77a,77b}, F. De Santis ^{71a,71b},
 A. De Santo ¹⁴⁹, J.B. De Vivie De Regie ⁶¹, J. Debevc ⁹⁵, D.V. Dedovich ³⁹, J. Degens ⁹⁴,
 A.M. Deiana ⁴⁵, F. Del Corso ^{24b,24a}, J. Del Peso ¹⁰¹, L. Delagrangé ¹³⁰, F. Deliot ¹³⁸,
 C.M. Delitzsch ⁵⁰, M. Della Pietra ^{73a,73b}, D. Della Volpe ⁵⁷, A. Dell'Acqua ³⁷,
 L. Dell'Asta ^{72a,72b}, M. Delmastro ⁴, P.A. Delsart ⁶¹, S. Demers ¹⁷⁵, M. Demichev ³⁹,
 S.P. Denisov ³⁸, L. D'Eramo ⁴¹, D. Derendarz ⁸⁸, F. Derue ¹³⁰, P. Dervan ⁹⁴, K. Desch ²⁵,
 C. Deutsch ²⁵, F.A. Di Bello ^{58b,58a}, A. Di Ciaccio ^{77a,77b}, L. Di Ciaccio ⁴,
 A. Di Domenico ^{76a,76b}, C. Di Donato ^{73a,73b}, A. Di Girolamo ³⁷, G. Di Gregorio ³⁷,
 A. Di Luca ^{79a,79b}, B. Di Micco ^{78a,78b}, R. Di Nardo ^{78a,78b}, K.F. Di Petrillo ⁴⁰,
 M. Diamantopoulou ³⁵, F.A. Dias ¹¹⁷, T. Dias Do Vale ¹⁴⁵, M.A. Diaz ^{140a,140b},
 F.G. Diaz Capriles ²⁵, A.R. Didenko ³⁹, M. Didenko ¹⁶⁶, E.B. Diehl ¹⁰⁸, S. Díez Cornell ⁴⁹,
 C. Diez Pardos ¹⁴⁴, C. Dimitriadi ¹⁶⁴, A. Dimitrievska ²¹, J. Dingfelder ²⁵, T. Dingley ¹²⁹,
 I-M. Dinu ^{28b}, S.J. Dittmeier ^{64b}, F. Dittus ³⁷, M. Divisek ¹³⁶, F. Djama ¹⁰⁴, T. Djobava ^{152b},
 C. Doglioni ^{103,100}, A. Dohnalova ^{29a}, J. Dolejsi ¹³⁶, Z. Dolezal ¹³⁶, K. Domijan ^{87a},
 K.M. Dona ⁴⁰, M. Donadelli ^{84d}, B. Dong ¹⁰⁹, J. Donini ⁴¹, A. D'Onofrio ^{73a,73b},
 M. D'Onofrio ⁹⁴, J. Dopke ¹³⁷, A. Doria ^{73a}, N. Dos Santos Fernandes ^{133a}, P. Dougan ¹⁰³,
 M.T. Dova ⁹², A.T. Doyle ⁶⁰, M.A. Dragnet ¹²⁹, E. Dreyer ¹⁷², I. Drivas-koulouris ¹⁰,
 M. Drnevich ¹²⁰, M. Drozdova ⁵⁷, D. Du ^{63a}, T.A. du Pree ¹¹⁷, F. Dubinin ³⁸, M. Dubovsky ^{29a},
 E. Duchovni ¹⁷², G. Duckeck ¹¹¹, O.A. Ducu ^{28b}, D. Duda ⁵³, A. Dudarev ³⁷, E.R. Duden ²⁷,
 M. D'uffizi ¹⁰³, L. Duflost ⁶⁷, M. Dührssen ³⁷, I. Duminica ^{28g}, A.E. Dumitriu ^{28b},
 M. Dunford ^{64a}, S. Dungs ⁵⁰, K. Dunne ^{48a,48b}, A. Duperrin ¹⁰⁴, H. Duran Yildiz ^{3a},
 M. Düren ⁵⁹, A. Durglishvili ^{152b}, B.L. Dwyer ¹¹⁸, G.I. Dyckes ^{18a}, M. Dyndal ^{87a},
 B.S. Dziedzic ³⁷, Z.O. Earnshaw ¹⁴⁹, G.H. Eberwein ¹²⁹, B. Eckerova ^{29a}, S. Eggebrecht ⁵⁶,
 E. Egidio Purcino De Souza ^{84e}, L.F. Ehrke ⁵⁷, G. Eigen ¹⁷, K. Einsweiler ^{18a}, T. Ekelof ¹⁶⁴,
 P.A. Ekman ¹⁰⁰, S. El Farkh ^{36b}, Y. El Ghazali ^{63a}, H. El Jarrari ³⁷, A. El Moussaouy ^{36a},
 V. Ellajosyula ¹⁶⁴, M. Ellert ¹⁶⁴, F. Ellinghaus ¹⁷⁴, N. Ellis ³⁷, J. Elmsheuser ³⁰, M. Elsayy ^{119a},
 M. Elsing ³⁷, D. Emelianov ¹³⁷, Y. Enari ⁸⁵, I. Ene ^{18a}, S. Epari ¹³, P.A. Erland ⁸⁸,
 D. Ernani Martins Neto ⁸⁸, M. Errenst ¹⁷⁴, M. Escalier ⁶⁷, C. Escobar ¹⁶⁶, E. Etzion ¹⁵⁴,

G. Evans [ID133a](#), H. Evans [ID69](#), L.S. Evans [ID97](#), A. Ezhilov [ID38](#), S. Ezzarqtouni [ID36a](#), F. Fabbri [ID24b,24a](#), L. Fabbri [ID24b,24a](#), G. Facini [ID98](#), V. Fadeyev [ID139](#), R.M. Fakhrutdinov [ID38](#), D. Fakoudis [ID102](#), S. Falciano [ID76a](#), L.F. Falda Ulhoa Coelho [ID37](#), F. Fallavollita [ID112](#), G. Falsetti [ID44b,44a](#), J. Faltova [ID136](#), C. Fan [ID165](#), Y. Fan [ID14](#), Y. Fang [ID14,114c](#), M. Fanti [ID72a,72b](#), M. Faraj [ID70a,70b](#), Z. Farazpay [ID99](#), A. Farbin [ID8](#), A. Farilla [ID78a](#), T. Farooque [ID109](#), S.M. Farrington [ID53](#), F. Fassi [ID36e](#), D. Fassouliotis [ID9](#), M. Faucci Giannelli [ID77a,77b](#), W.J. Fawcett [ID33](#), L. Fayard [ID67](#), P. Federic [ID136](#), P. Federicova [ID134](#), O.L. Fedin [ID38,a](#), M. Feickert [ID173](#), L. Feligioni [ID104](#), D.E. Fellers [ID126](#), C. Feng [ID63b](#), Z. Feng [ID117](#), M.J. Fenton [ID162](#), L. Ferencz [ID49](#), R.A.M. Ferguson [ID93](#), S.I. Fernandez Luengo [ID140f](#), P. Fernandez Martinez [ID13](#), M.J.V. Fernoux [ID104](#), J. Ferrando [ID93](#), A. Ferrari [ID164](#), P. Ferrari [ID117,116](#), R. Ferrari [ID74a](#), D. Ferrere [ID57](#), C. Ferretti [ID108](#), D. Fiacco [ID76a,76b](#), F. Fiedler [ID102](#), P. Fiedler [ID135](#), A. Filipčič [ID95](#), E.K. Filmer [ID1](#), F. Filthaut [ID116](#), M.C.N. Fiolhais [ID133a,133c,c](#), L. Fiorini [ID166](#), W.C. Fisher [ID109](#), T. Fitschen [ID103](#), P.M. Fitzhugh [ID138](#), I. Fleck [ID144](#), P. Fleischmann [ID108](#), T. Flick [ID174](#), M. Flores [ID34d,z](#), L.R. Flores Castillo [ID65a](#), L. Flores Sanz De Acedo [ID37](#), F.M. Follega [ID79a,79b](#), N. Fomin [ID33](#), J.H. Foo [ID158](#), A. Formica [ID138](#), A.C. Forti [ID103](#), E. Fortin [ID37](#), A.W. Fortman [ID18a](#), M.G. Foti [ID18a](#), L. Fountas [ID9,j](#), D. Fournier [ID67](#), H. Fox [ID93](#), P. Francavilla [ID75a,75b](#), S. Francescato [ID62](#), S. Franchellucci [ID57](#), M. Franchini [ID24b,24a](#), S. Franchino [ID64a](#), D. Francis [ID37](#), L. Franco [ID116](#), V. Franco Lima [ID37](#), L. Franconi [ID49](#), M. Franklin [ID62](#), G. Frattari [ID27](#), Y.Y. Frid [ID154](#), J. Friend [ID60](#), N. Fritzsche [ID37](#), A. Froch [ID55](#), D. Froidevaux [ID37](#), J.A. Frost [ID129](#), Y. Fu [ID63a](#), S. Fuenzalida Garrido [ID140f](#), M. Fujimoto [ID104](#), K.Y. Fung [ID65a](#), E. Furtado De Simas Filho [ID84e](#), M. Furukawa [ID156](#), J. Fuster [ID166](#), A. Gaa [ID56](#), A. Gabrielli [ID24b,24a](#), A. Gabrielli [ID158](#), P. Gadow [ID37](#), G. Gagliardi [ID58b,58a](#), L.G. Gagnon [ID18a](#), S. Gaid [ID163](#), S. Galantzan [ID154](#), J. Gallagher [ID1](#), E.J. Gallas [ID129](#), B.J. Gallop [ID137](#), K.K. Gan [ID122](#), S. Ganguly [ID156](#), Y. Gao [ID53](#), F.M. Garay Walls [ID140a,140b](#), B. Garcia [ID30](#), C. García [ID166](#), A. Garcia Alonso [ID117](#), A.G. Garcia Caffaro [ID175](#), J.E. García Navarro [ID166](#), M. Garcia-Sciveres [ID18a](#), G.L. Gardner [ID131](#), R.W. Gardner [ID40](#), N. Garelli [ID161](#), D. Garg [ID81](#), R.B. Garg [ID146](#), J.M. Gargan [ID53](#), C.A. Garner [ID158](#), C.M. Garvey [ID34a](#), V.K. Gassmann [ID161](#), G. Gaudio [ID74a](#), V. Gautam [ID13](#), P. Gauzzi [ID76a,76b](#), J. Gavranovic [ID95](#), I.L. Gavrilenko [ID38](#), A. Gavrilyuk [ID38](#), C. Gay [ID167](#), G. Gaycken [ID126](#), E.N. Gazis [ID10](#), A.A. Geanta [ID28b](#), C.M. Gee [ID139](#), A. Gekow [ID122](#), C. Gemme [ID58b](#), M.H. Genest [ID61](#), A.D. Gentry [ID115](#), S. George [ID97](#), W.F. George [ID21](#), T. Geralis [ID47](#), P. Gessinger-Befurt [ID37](#), M.E. Geyik [ID174](#), M. Ghani [ID170](#), K. Ghorbanian [ID96](#), A. Ghosal [ID144](#), A. Ghosh [ID162](#), A. Ghosh [ID7](#), B. Giacobbe [ID24b](#), S. Giagu [ID76a,76b](#), T. Giani [ID117](#), A. Giannini [ID63a](#), S.M. Gibson [ID97](#), M. Gignac [ID139](#), D.T. Gil [ID87b](#), A.K. Gilbert [ID87a](#), B.J. Gilbert [ID42](#), D. Gillberg [ID35](#), G. Gilles [ID117](#), L. Ginabat [ID130](#), D.M. Gingrich [ID2,ac](#), M.P. Giordani [ID70a,70c](#), P.F. Giraud [ID138](#), G. Giugliarelli [ID70a,70c](#), D. Giugni [ID72a](#), F. Giuli [ID37](#), I. Gkialas [ID9,j](#), L.K. Gladilin [ID38](#), C. Glasman [ID101](#), G.R. Gledhill [ID126](#), G. Glemža [ID49](#), M. Glisic [ID126](#), I. Gnesi [ID44b,e](#), Y. Go [ID30](#), M. Goblirsch-Kolb [ID37](#), B. Gocke [ID50](#), D. Godin [ID110](#), B. Gokturk [ID22a](#), S. Goldfarb [ID107](#), T. Golling [ID57](#), M.G.D. Gololo [ID34g](#), D. Golubkov [ID38](#), J.P. Gombas [ID109](#), A. Gomes [ID133a,133b](#), G. Gomes Da Silva [ID144](#), A.J. Gomez Delegido [ID166](#), R. Gonçalves [ID133a](#), L. Gonella [ID21](#), A. Gongadze [ID152c](#), F. Gonnella [ID21](#), J.L. Gonski [ID146](#), R.Y. González Andana [ID53](#), S. González de la Hoz [ID166](#), R. Gonzalez Lopez [ID94](#), C. Gonzalez Renteria [ID18a](#), M.V. Gonzalez Rodrigues [ID49](#), R. Gonzalez Suarez [ID164](#), S. Gonzalez-Sevilla [ID57](#), L. Goossens [ID37](#), B. Gorini [ID37](#), E. Gorini [ID71a,71b](#), A. Gorišek [ID95](#), T.C. Gosart [ID131](#), A.T. Goshaw [ID52](#), M.I. Gostkin [ID39](#), S. Goswami [ID124](#), C.A. Gottardo [ID37](#), S.A. Gotz [ID111](#), M. Gouighri [ID36b](#), V. Goumarre [ID49](#), A.G. Goussiou [ID141](#), N. Govender [ID34c](#), R.P. Grabarczyk [ID129](#), I. Grabowska-Bold [ID87a](#), K. Graham [ID35](#), E. Gramstad [ID128](#), S. Grancagnolo [ID71a,71b](#), C.M. Grant [ID1,138](#), P.M. Gravila [ID28f](#), F.G. Gravili [ID71a,71b](#), H.M. Gray [ID18a](#), M. Greco [ID71a,71b](#), M.J. Green [ID1](#), C. Grefe [ID25](#), A.S. Grefsrud [ID17](#), I.M. Gregor [ID49](#), K.T. Greif [ID162](#), P. Grenier [ID146](#), S.G. Grewe [ID112](#), A.A. Grillo [ID139](#), K. Grimm [ID32](#), S. Grinstein [ID13,s](#), J.-F. Grivaz [ID67](#), E. Gross [ID172](#), J. Grosse-Knetter [ID56](#), L. Guan [ID108](#), J.G.R. Guerrero Rojas [ID166](#), G. Guerrieri [ID37](#),

R. Gugel ¹⁰², J.A.M. Guhit ¹⁰⁸, A. Guida ¹⁹, E. Guilloton ¹⁷⁰, S. Guindon ³⁷, F. Guo ^{14,114c}, J. Guo ^{63c}, L. Guo ⁴⁹, Y. Guo ¹⁰⁸, R. Gupta ¹³², S. Gurbuz ²⁵, S.S. Gurdasani ⁵⁵, G. Gustavino ^{76a,76b}, P. Gutierrez ¹²³, L.F. Gutierrez Zagazeta ¹³¹, M. Gutsche ⁵¹, C. Gutschow ⁹⁸, C. Gwenlan ¹²⁹, C.B. Gwilliam ⁹⁴, E.S. Haaland ¹²⁸, A. Haas ¹²⁰, M. Habedank ⁴⁹, C. Haber ^{18a}, H.K. Hadavand ⁸, A. Hadeef ⁵¹, S. Hadzic ¹¹², A.I. Hagan ⁹³, J.J. Hahn ¹⁴⁴, E.H. Haines ⁹⁸, M. Haleem ¹⁶⁹, J. Haley ¹²⁴, J.J. Hall ¹⁴², G.D. Hallewell ¹⁰⁴, L. Halser ²⁰, K. Hamano ¹⁶⁸, M. Hamer ²⁵, G.N. Hamity ⁵³, E.J. Hampshire ⁹⁷, J. Han ^{63b}, K. Han ^{63a}, L. Han ^{114a}, L. Han ^{63a}, S. Han ^{18a}, Y.F. Han ¹⁵⁸, K. Hanagaki ⁸⁵, M. Hance ¹³⁹, D.A. Hangal ⁴², H. Hanif ¹⁴⁵, M.D. Hank ¹³¹, J.B. Hansen ⁴³, P.H. Hansen ⁴³, D. Harada ⁵⁷, T. Harenberg ¹⁷⁴, S. Harkusha ³⁸, M.L. Harris ¹⁰⁵, Y.T. Harris ²⁵, J. Harrison ¹³, N.M. Harrison ¹²², P.F. Harrison ¹⁷⁰, N.M. Hartman ¹¹², N.M. Hartmann ¹¹¹, R.Z. Hasan ^{97,137}, Y. Hasegawa ¹⁴³, F. Haslbeck ¹²⁹, S. Hassan ¹⁷, R. Hauser ¹⁰⁹, C.M. Hawkes ²¹, R.J. Hawkings ³⁷, Y. Hayashi ¹⁵⁶, D. Hayden ¹⁰⁹, C. Hayes ¹⁰⁸, R.L. Hayes ¹¹⁷, C.P. Hays ¹²⁹, J.M. Hays ⁹⁶, H.S. Hayward ⁹⁴, F. He ^{63a}, M. He ^{14,114c}, Y. He ⁴⁹, Y. He ⁹⁸, N.B. Heatley ⁹⁶, V. Hedberg ¹⁰⁰, A.L. Heggelund ¹²⁸, N.D. Hehir ^{96,*}, C. Heidegger ⁵⁵, K.K. Heidegger ⁵⁵, J. Heilman ³⁵, S. Heim ⁴⁹, T. Heim ^{18a}, J.G. Heinlein ¹³¹, J.J. Heinrich ¹²⁶, L. Heinrich ^{112,aa}, J. Hejbal ¹³⁴, A. Held ¹⁷³, S. Hellesund ¹⁷, C.M. Helling ¹⁶⁷, S. Hellman ^{48a,48b}, R.C.W. Henderson ⁹³, L. Henkelmann ³³, A.M. Henriques Correia ³⁷, H. Herde ¹⁰⁰, Y. Hernández Jiménez ¹⁴⁸, L.M. Herrmann ²⁵, T. Herrmann ⁵¹, G. Herten ⁵⁵, R. Hertenberger ¹¹¹, L. Hervas ³⁷, M.E. Hesping ¹⁰², N.P. Hessey ^{159a}, M. Hidaoui ^{36b}, N. Hidic ¹³⁶, E. Hill ¹⁵⁸, S.J. Hillier ²¹, J.R. Hinds ¹⁰⁹, F. Hinterkeuser ²⁵, M. Hirose ¹²⁷, S. Hirose ¹⁶⁰, D. Hirschbuehl ¹⁷⁴, T.G. Hitchings ¹⁰³, B. Hiti ⁹⁵, J. Hobbs ¹⁴⁸, R. Hobincu ^{28e}, N. Hod ¹⁷², M.C. Hodgkinson ¹⁴², B.H. Hodgkinson ¹²⁹, A. Hoecker ³⁷, D.D. Hofer ¹⁰⁸, J. Hofer ⁴⁹, T. Holm ²⁵, M. Holzbock ³⁷, L.B.A.H. Hommels ³³, B.P. Honan ¹⁰³, J.J. Hong ⁶⁹, J. Hong ^{63c}, T.M. Hong ¹³², B.H. Hooberman ¹⁶⁵, W.H. Hopkins ⁶, M.C. Hoppesch ¹⁶⁵, Y. Horii ¹¹³, S. Hou ¹⁵¹, A.S. Howard ⁹⁵, J. Howarth ⁶⁰, J. Hoya ⁶, M. Hrabovsky ¹²⁵, A. Hrynevich ⁴⁹, T. Hryn'ova ⁴, P.J. Hsu ⁶⁶, S.-C. Hsu ¹⁴¹, T. Hsu ⁶⁷, M. Hu ^{18a}, Q. Hu ^{63a}, S. Huang ^{65b}, X. Huang ^{14,114c}, Y. Huang ¹⁴², Y. Huang ¹⁰², Y. Huang ¹⁴, Z. Huang ¹⁰³, Z. Hubacek ¹³⁵, M. Huebner ²⁵, F. Huegging ²⁵, T.B. Huffman ¹²⁹, C.A. Hugli ⁴⁹, M. Huhtinen ³⁷, S.K. Huiberts ¹⁷, R. Hulsken ¹⁰⁶, N. Huseynov ^{12,g}, J. Huston ¹⁰⁹, J. Huth ⁶², R. Hyneman ¹⁴⁶, G. Iacobucci ⁵⁷, G. Iakovidis ³⁰, L. Iconomidou-Fayard ⁶⁷, J.P. Iddon ³⁷, P. Iengo ^{73a,73b}, R. Iguchi ¹⁵⁶, Y. Iiyama ¹⁵⁶, T. Iizawa ¹²⁹, Y. Ikegami ⁸⁵, N. Ilic ¹⁵⁸, H. Imam ^{84c}, M. Ince Lezki ⁵⁷, T. Ingebretsen Carlson ^{48a,48b}, J.M. Inglis ⁹⁶, G. Introzzi ^{74a,74b}, M. Iodice ^{78a}, V. Ippolito ^{76a,76b}, R.K. Irwin ⁹⁴, M. Ishino ¹⁵⁶, W. Islam ¹⁷³, C. Issever ^{19,49}, S. Istin ^{22a,ag}, H. Ito ¹⁷¹, R. Iuppa ^{79a,79b}, A. Ivina ¹⁷², J.M. Izen ⁴⁶, V. Izzo ^{73a}, P. Jacka ¹³⁴, P. Jackson ¹, C.S. Jagfeld ¹¹¹, G. Jain ^{159a}, P. Jain ⁴⁹, K. Jakobs ⁵⁵, T. Jakoubek ¹⁷², J. Jamieson ⁶⁰, W. Jang ¹⁵⁶, M. Javurkova ¹⁰⁵, P. Jawahar ¹⁰³, L. Jeanty ¹²⁶, J. Jejelava ^{152a,y}, P. Jenni ^{55,f}, C.E. Jessiman ³⁵, C. Jia ^{63b}, J. Jia ¹⁴⁸, X. Jia ^{14,114c}, Z. Jia ^{114a}, C. Jiang ⁵³, S. Jiggins ⁴⁹, J. Jimenez Pena ¹³, S. Jin ^{114a}, A. Jinaru ^{28b}, O. Jinnouchi ¹⁵⁷, P. Johansson ¹⁴², K.A. Johns ⁷, J.W. Johnson ¹³⁹, D.M. Jones ¹⁴⁹, E. Jones ⁴⁹, K.S. Jones ⁸, P. Jones ³³, R.W.L. Jones ⁹³, T.J. Jones ⁹⁴, H.L. Joos ^{56,37}, R. Joshi ¹²², J. Jovicevic ¹⁶, X. Ju ^{18a}, J.J. Junggeburth ¹⁰⁵, T. Junkermann ^{64a}, A. Juste Rozas ^{13,s}, M.K. Juzek ⁸⁸, S. Kabana ^{140e}, A. Kaczmaraska ⁸⁸, M. Kado ¹¹², H. Kagan ¹²², M. Kagan ¹⁴⁶, A. Kahn ¹³¹, C. Kahra ¹⁰², T. Kaji ¹⁵⁶, E. Kajomovitz ¹⁵³, N. Kakati ¹⁷², I. Kalaitzidou ⁵⁵, C.W. Kalderon ³⁰, N.J. Kang ¹³⁹, D. Kar ^{34g}, K. Karava ¹²⁹, M.J. Kareem ^{159b}, E. Karentzos ⁵⁵, O. Karkout ¹¹⁷, S.N. Karpov ³⁹, Z.M. Karpova ³⁹, V. Kartvelishvili ⁹³, A.N. Karyukhin ³⁸, E. Kasimi ¹⁵⁵, J. Katzy ⁴⁹, S. Kaur ³⁵, K. Kawade ¹⁴³, M.P. Kawale ¹²³, C. Kawamoto ⁸⁹, T. Kawamoto ^{63a}, E.F. Kay ³⁷,

F.I. Kaya ¹⁶¹, S. Kazakos ¹⁰⁹, V.F. Kazanin ³⁸, Y. Ke ¹⁴⁸, J.M. Keaveney ^{34a}, R. Keeler ¹⁶⁸,
 G.V. Kehris ⁶², J.S. Keller ³⁵, A.S. Kelly ⁹⁸, J.J. Kempster ¹⁴⁹, P.D. Kennedy ¹⁰², O. Kepka ¹³⁴,
 B.P. Kerridge ¹³⁷, S. Kersten ¹⁷⁴, B.P. Kerševan ⁹⁵, L. Keszeghova ^{29a}, S. Kitabchi Haghighat ¹⁵⁸,
 R.A. Khan ¹³², A. Khanov ¹²⁴, A.G. Kharlamov ³⁸, T. Kharlamova ³⁸, E.E. Khoda ¹⁴¹,
 M. Kholodenko ^{133a}, T.J. Khoo ¹⁹, G. Khoriauli ¹⁶⁹, J. Khubua ^{152b}, Y.A.R. Khwaira ¹³⁰,
 B. Kibirige ^{34g}, D. Kim ⁶, D.W. Kim ^{48a,48b}, Y.K. Kim ⁴⁰, N. Kimura ⁹⁸, M.K. Kingston ⁵⁶,
 A. Kirchhoff ⁵⁶, C. Kirfel ²⁵, F. Kirfel ²⁵, J. Kirk ¹³⁷, A.E. Kiryunin ¹¹², C. Kitsaki ¹⁰,
 O. Kivernyk ²⁵, M. Klassen ¹⁶¹, C. Klein ³⁵, L. Klein ¹⁶⁹, M.H. Klein ⁴⁵, S.B. Klein ⁵⁷,
 U. Klein ⁹⁴, P. Klimek ³⁷, A. Klimentov ³⁰, T. Klioutchnikova ³⁷, P. Kluit ¹¹⁷, S. Kluth ¹¹²,
 E. Kneringer ⁸⁰, T.M. Knight ¹⁵⁸, A. Knue ⁵⁰, D. Kobylanski ¹⁷², S.F. Koch ¹²⁹,
 M. Kocian ¹⁴⁶, P. Kodyš ¹³⁶, D.M. Koeck ¹²⁶, P.T. Koenig ²⁵, T. Koffas ³⁵, O. Kolay ⁵¹,
 I. Koletsou ⁴, T. Komarek ⁸⁸, K. Köneke ⁵⁵, A.X.Y. Kong ¹, T. Kono ¹²¹, N. Konstantinidis ⁹⁸,
 P. Kontaxakis ⁵⁷, B. Konya ¹⁰⁰, R. Kopeliansky ⁴², S. Koperny ^{87a}, K. Korcyl ⁸⁸,
 K. Kordas ^{155,d}, A. Korn ⁹⁸, S. Korn ⁵⁶, I. Korolkov ¹³, N. Korotkova ³⁸, B. Kortman ¹¹⁷,
 O. Kortner ¹¹², S. Kortner ¹¹², W.H. Kostecka ¹¹⁸, V.V. Kostyukhin ¹⁴⁴, A. Kotsokechagia ¹³⁸,
 A. Kotwal ⁵², A. Koulouris ³⁷, A. Kourkoumeli-Charalampidi ^{74a,74b}, C. Kourkoumelis ⁹,
 E. Kourlitis ^{112,aa}, O. Kovanda ¹²⁶, R. Kowalewski ¹⁶⁸, W. Kozanecki ¹³⁸, A.S. Kozhin ³⁸,
 V.A. Kramarenko ³⁸, G. Kramberger ⁹⁵, P. Kramer ¹⁰², M.W. Krasny ¹³⁰, A. Krasznahorkay ³⁷,
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










































































































































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E.J.W. Moyse ¹⁰⁵, O. Mtintsilana ^{34g}, S. Muanza ¹⁰⁴, J. Mueller ¹³², D. Muenstermann ⁹³,
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 A.G. Myagkov ^{38,a}, A.J. Myers ⁸, G. Myers ¹⁰⁸, M. Myska ¹³⁵, B.P. Nachman ^{18a},
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 J. Navarro-Gonzalez ¹⁶⁶, R. Nayak ¹⁵⁴, A. Nayaz ¹⁹, P.Y. Nechaeva ³⁸, S. Nechaeva ^{24b,24a},
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 E.K. Nkadimeng ^{34g}, T. Nobe ¹⁵⁶, T. Nommensen ¹⁵⁰, M.B. Norfolk ¹⁴², B.J. Norman ³⁵,
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 S.A. Olivares Pino ^{140d}, G. Oliveira Correa ¹³, D. Oliveira Damazio ³⁰, J.L. Oliver ¹⁶²,
 Ö.O. Öncel ⁵⁵, A.P. O'Neill ²⁰, A. Onofre ^{133a,133e}, P.U.E. Onyisi ¹¹, M.J. Oreglia ⁴⁰,
 G.E. Orellana ⁹², D. Orestano ^{78a,78b}, N. Orlando ¹³, R.S. Orr ¹⁵⁸, L.M. Osojnak ¹³¹,
 R. Ospanov ^{63a}, G. Otero y Garzon ³¹, H. Otono ⁹⁰, P.S. Ott ^{64a}, G.J. Ottino ^{18a}, M. Ouchrif ^{36d},
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 J. Pinol Bel ¹³, A.E. Pinto Pinoargote ^{138,138}, L. Pintucci ^{70a,70c}, K.M. Piper ¹⁴⁹, A. Pirttikoski ⁵⁷,
 D.A. Pizzi ³⁵, L. Pizzimento ^{65b}, A. Pizzini ¹¹⁷, M.-A. Pleier ³⁰, V. Pleskot ¹³⁶, E. Plotnikova ³⁹,
 G. Poddar ⁹⁶, R. Poettgen ¹⁰⁰, L. Poggioli ¹³⁰, I. Pokharel ⁵⁶, S. Polacek ¹³⁶, G. Polesello ^{74a},
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 N.I. Pond ⁹⁸, D. Ponomarenko ¹¹⁶, L. Pontecorvo ³⁷, S. Popa ^{28a}, G.A. Popeneciu ^{28d},
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K. Potamianos ^{id170}, P.A. Potepa ^{id87a}, I.N. Potrap ^{id39}, C.J. Potter ^{id33}, H. Potti ^{id150}, J. Poveda ^{id166},
 M.E. Pozo Astigarraga ^{id37}, A. Prades Ibanez ^{id77a,77b}, J. Pretel ^{id168}, D. Price ^{id103}, M. Primavera ^{id71a},
 L. Primomo ^{id70a,70c}, M.A. Principe Martin ^{id101}, R. Privara ^{id125}, T. Procter ^{id60}, M.L. Proffitt ^{id141},
 N. Proklova ^{id131}, K. Prokofiev ^{id65c}, G. Proto ^{id112}, J. Proudfoot ^{id6}, M. Przybycien ^{id87a},
 W.W. Przygoda ^{id87b}, A. Psallidas ^{id47}, J.E. Puddefoot ^{id142}, D. Pudzha ^{id55}, D. Pyatiizbyantseva ^{id38},
 J. Qian ^{id108}, D. Qichen ^{id103}, Y. Qin ^{id13}, T. Qiu ^{id53}, A. Quadt ^{id56}, M. Queitsch-Maitland ^{id103},
 G. Quetant ^{id57}, R.P. Quinn ^{id167}, G. Rabanal Bolanos ^{id62}, D. Rafanoharana ^{id55}, F. Raffaelli ^{id77a,77b},
 F. Ragusa ^{id72a,72b}, J.L. Rainbolt ^{id40}, J.A. Raine ^{id57}, S. Rajagopalan ^{id30}, E. Ramakoti ^{id38},
 L. Rambelli ^{id58b,58a}, I.A. Ramirez-Berend ^{id35}, K. Ran ^{id49,114c}, D.S. Rankin ^{id131}, N.P. Rapheeha ^{id34g},
 H. Rasheed ^{id28b}, V. Raskina ^{id130}, D.F. Rassloff ^{id64a}, A. Rastogi ^{id18a}, S. Rave ^{id102}, S. Ravera ^{id58b,58a},
 B. Ravina ^{id56}, I. Ravinovich ^{id172}, M. Raymond ^{id37}, A.L. Read ^{id128}, N.P. Readioff ^{id142},
 D.M. Rebuzzi ^{id74a,74b}, G. Redlinger ^{id30}, A.S. Reed ^{id112}, K. Reeves ^{id27}, J.A. Reidelsturz ^{id174},
 D. Reikher ^{id126}, A. Rej ^{id50}, C. Rembser ^{id37}, M. Renda ^{id28b}, F. Renner ^{id49}, A.G. Rennie ^{id162},
 A.L. Rescia ^{id49}, S. Resconi ^{id72a}, M. Ressegotti ^{id58b,58a}, S. Rettie ^{id37}, J.G. Reyes Rivera ^{id109},
 E. Reynolds ^{id18a}, O.L. Rezanova ^{id38}, P. Reznicek ^{id136}, H. Riani ^{id36d}, N. Ribaric ^{id93}, E. Ricci ^{id79a,79b},
 R. Richter ^{id112}, S. Richter ^{id48a,48b}, E. Richter-Was ^{id87b}, M. Ridel ^{id130}, S. Ridouani ^{id36d}, P. Rieck ^{id120},
 P. Riedler ^{id37}, E.M. Riefel ^{id48a,48b}, J.O. Rieger ^{id117}, M. Rijssenbeek ^{id148}, M. Rimoldi ^{id37},
 L. Rinaldi ^{id24b,24a}, T.T. Rinn ^{id30}, M.P. Rinnagel ^{id111}, G. Ripellino ^{id164}, I. Riu ^{id13},
 J.C. Rivera Vergara ^{id168}, F. Rizatdinova ^{id124}, E. Rizvi ^{id96}, B.R. Roberts ^{id18a}, S.S. Roberts ^{id139},
 S.H. Robertson ^{id106,w}, D. Robinson ^{id33}, M. Robles Manzano ^{id102}, A. Robson ^{id60}, A. Rocchi ^{id77a,77b},
 C. Roda ^{id75a,75b}, S. Rodriguez Bosca ^{id37}, Y. Rodriguez Garcia ^{id23a}, A. Rodriguez Rodriguez ^{id55},
 A.M. Rodríguez Vera ^{id118}, S. Roe ^{id37}, J.T. Roemer ^{id37}, A.R. Roepe-Gier ^{id139}, O. Røhne ^{id128},
 R.A. Rojas ^{id105}, C.P.A. Roland ^{id130}, J. Roloff ^{id30}, A. Romaniouk ^{id38}, E. Romano ^{id74a,74b},
 M. Romano ^{id24b}, A.C. Romero Hernandez ^{id165}, N. Rompotis ^{id94}, L. Roos ^{id130}, S. Rosati ^{id76a},
 B.J. Rosser ^{id40}, E. Rossi ^{id129}, E. Rossi ^{id73a,73b}, L.P. Rossi ^{id62}, L. Rossini ^{id55}, R. Rosten ^{id122},
 M. Rotaru ^{id28b}, B. Rottler ^{id55}, C. Rougier ^{id91}, D. Rousseau ^{id67}, D. Rousso ^{id49}, A. Roy ^{id165},
 S. Roy-Garand ^{id158}, A. Rozanov ^{id104}, Z.M.A. Rozario ^{id60}, Y. Rozen ^{id153}, A. Rubio Jimenez ^{id166},
 A.J. Ruby ^{id94}, V.H. Ruelas Rivera ^{id19}, T.A. Ruggeri ^{id1}, A. Ruggiero ^{id129}, A. Ruiz-Martinez ^{id166},
 A. Rummler ^{id37}, Z. Rurikova ^{id55}, N.A. Rusakovich ^{id39}, H.L. Russell ^{id168}, G. Russo ^{id76a,76b},
 J.P. Rutherford ^{id7}, S. Rutherford Colmenares ^{id33}, M. Rybar ^{id136}, E.B. Rye ^{id128}, A. Ryzhov ^{id45},
 J.A. Sabater Iglesias ^{id57}, H.F.W. Sadrozinski ^{id139}, F. Safai Tehrani ^{id76a}, B. Safarzadeh Samani ^{id137},
 S. Saha ^{id1}, M. Sahinsoy ^{id83}, A. Saibel ^{id166}, M. Saimpert ^{id138}, M. Saito ^{id156}, T. Saito ^{id156},
 A. Sala ^{id72a,72b}, D. Salamani ^{id37}, A. Salnikov ^{id146}, J. Salt ^{id166}, A. Salvador Salas ^{id154},
 D. Salvatore ^{id44b,44a}, F. Salvatore ^{id149}, A. Salzburger ^{id37}, D. Sammel ^{id55}, E. Sampson ^{id93},
 D. Sampsonidis ^{id155,d}, D. Sampsonidou ^{id126}, J. Sánchez ^{id166}, V. Sanchez Sebastian ^{id166},
 H. Sandaker ^{id128}, C.O. Sander ^{id49}, J.A. Sandesara ^{id105}, M. Sandhoff ^{id174}, C. Sandoval ^{id23b},
 L. Sanfilippo ^{id64a}, D.P.C. Sankey ^{id137}, T. Sano ^{id89}, A. Sansoni ^{id54}, L. Santi ^{id37,76b}, C. Santoni ^{id41},
 H. Santos ^{id133a,133b}, A. Santra ^{id172}, E. Sanzani ^{id24b,24a}, K.A. Saoucha ^{id163}, J.G. Saraiva ^{id133a,133d},
 J. Sardain ^{id7}, O. Sasaki ^{id85}, K. Sato ^{id160}, C. Sauer ^{id64b}, E. Sauvan ^{id4}, P. Savard ^{id158,ac}, R. Sawada ^{id156},
 C. Sawyer ^{id137}, L. Sawyer ^{id99}, C. Sbarra ^{id24b}, A. Sbrizzi ^{id24b,24a}, T. Scanlon ^{id98},
 J. Schaarschmidt ^{id141}, U. Schäfer ^{id102}, A.C. Schaffer ^{id67,45}, D. Schaile ^{id111}, R.D. Schamberger ^{id148},
 C. Scharf ^{id19}, M.M. Schefer ^{id20}, V.A. Schegelsky ^{id38}, D. Scheirich ^{id136}, M. Schernau ^{id162},
 C. Scheulen ^{id56}, C. Schiavi ^{id58b,58a}, M. Schioppa ^{id44b,44a}, B. Schlag ^{id146,m}, K.E. Schleicher ^{id55},
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 M. Schott ^{id25}, J. Schovancova ^{id37}, S. Schramm ^{id57}, T. Schroer ^{id57}, H-C. Schultz-Coulon ^{id64a},
 M. Schumacher ^{id55}, B.A. Schumm ^{id139}, Ph. Schune ^{id138}, A.J. Schuy ^{id141}, H.R. Schwartz ^{id139},

A. Schwartzman ¹⁴⁶, T.A. Schwarz ¹⁰⁸, Ph. Schwemling ¹³⁸, R. Schwienhorst ¹⁰⁹,
 F.G. Sciacca ²⁰, A. Sciandra ³⁰, G. Sciolla ²⁷, F. Scuri ^{75a}, C.D. Sebastiani ⁹⁴, K. Sedlaczek ¹¹⁸,
 S.C. Seidel ¹¹⁵, A. Seiden ¹³⁹, B.D. Seidlitz ⁴², C. Seitz ⁴⁹, J.M. Seixas ^{84b}, G. Sekhniaidze ^{73a},
 L. Selem ⁶¹, N. Semprini-Cesari ^{24b,24a}, D. Sengupta ⁵⁷, V. Senthilkumar ¹⁶⁶, L. Serin ⁶⁷,
 M. Sessa ^{77a,77b}, H. Severini ¹²³, F. Sforza ^{58b,58a}, A. Sfyrla ⁵⁷, Q. Sha ¹⁴, E. Shabalina ⁵⁶,
 A.H. Shah ³³, R. Shaheen ¹⁴⁷, J.D. Shahinian ¹³¹, D. Shaked Renous ¹⁷², L.Y. Shan ¹⁴,
 M. Shapiro ^{18a}, A. Sharma ³⁷, A.S. Sharma ¹⁶⁷, P. Sharma ⁸¹, P.B. Shatalov ³⁸, K. Shaw ¹⁴⁹,
 S.M. Shaw ¹⁰³, Q. Shen ^{63c}, D.J. Sheppard ¹⁴⁵, P. Sherwood ⁹⁸, L. Shi ⁹⁸, X. Shi ¹⁴,
 S. Shimizu ⁸⁵, C.O. Shimmin ¹⁷⁵, J.D. Shinner ⁹⁷, I.P.J. Shipsey ¹²⁹, S. Shirabe ⁹⁰,
 M. Shiyakova ^{39,u}, M.J. Shochet ⁴⁰, D.R. Shope ¹²⁸, B. Shrestha ¹²³, S. Shrestha ^{122,af},
 M.J. Shroff ¹⁶⁸, P. Sicho ¹³⁴, A.M. Sickles ¹⁶⁵, E. Sideras Haddad ^{34g}, A.C. Sidley ¹¹⁷,
 A. Sidoti ^{24b}, F. Siegert ⁵¹, Dj. Sijacki ¹⁶, F. Sili ⁹², J.M. Silva ⁵³, I. Silva Ferreira ^{84b},
 M.V. Silva Oliveira ³⁰, S.B. Silverstein ^{48a}, S. Simion ⁶⁷, R. Simoniello ³⁷, E.L. Simpson ¹⁰³,
 H. Simpson ¹⁴⁹, L.R. Simpson ¹⁰⁸, N.D. Simpson ¹⁰⁰, S. Simsek ⁸³, S. Sindhu ⁵⁶, P. Sinervo ¹⁵⁸,
 S. Singh ¹⁵⁸, S. Sinha ⁴⁹, S. Sinha ¹⁰³, M. Sioli ^{24b,24a}, I. Siral ³⁷, E. Sitnikova ⁴⁹,
 J. Sjölin ^{48a,48b}, A. Skaf ⁵⁶, E. Skorda ²¹, P. Skubic ¹²³, M. Slawinska ⁸⁸, V. Smakhtin ¹⁷²,
 B.H. Smart ¹³⁷, S.Yu. Smirnov ³⁸, Y. Smirnov ³⁸, L.N. Smirnova ^{38,a}, O. Smirnova ¹⁰⁰,
 A.C. Smith ⁴², D.R. Smith ¹⁶², E.A. Smith ⁴⁰, J.L. Smith ¹⁰³, R. Smith ¹⁴⁶, M. Smizanska ⁹³,
 K. Smolek ¹³⁵, A.A. Snesarev ³⁸, S.R. Snider ¹⁵⁸, H.L. Snoek ¹¹⁷, S. Snyder ³⁰, R. Sobie ^{168,w},
 A. Soffer ¹⁵⁴, C.A. Solans Sanchez ³⁷, E.Yu. Soldatov ³⁸, U. Soldevila ¹⁶⁶, A.A. Solodkov ³⁸,
 S. Solomon ²⁷, A. Soloshenko ³⁹, K. Solovieva ⁵⁵, O.V. Solovyanov ⁴¹, P. Sommer ⁵¹,
 A. Sonay ¹³, W.Y. Song ^{159b}, A. Sopczak ¹³⁵, A.L. Soppio ⁹⁸, F. Sopkova ^{29b}, J.D. Sorenson ¹¹⁵,
 I.R. Sotarriva Alvarez ¹⁵⁷, V. Sothilingam ^{64a}, O.J. Soto Sandoval ^{140c,140b}, S. Sottocornola ⁶⁹,
 R. Soualah ¹⁶³, Z. Soumami ^{36e}, D. South ⁴⁹, N. Soybelman ¹⁷², S. Spagnolo ^{71a,71b},
 M. Spalla ¹¹², D. Sperlich ⁵⁵, G. Spigo ³⁷, B. Spisso ^{73a,73b}, D.P. Spiteri ⁶⁰, M. Spousta ¹³⁶,
 E.J. Staats ³⁵, R. Stamen ^{64a}, A. Stampeki ²¹, M. Standke ²⁵, E. Stanecka ⁸⁸,
 W. Stanek-Maslouska ⁴⁹, M.V. Stange ⁵¹, B. Stanislaus ^{18a}, M.M. Stanitzki ⁴⁹, B. Stapf ⁴⁹,
 E.A. Starchenko ³⁸, G.H. Stark ¹³⁹, J. Stark ⁹¹, P. Staroba ¹³⁴, P. Starovoitov ^{64a}, S. Stärz ¹⁰⁶,
 R. Staszewski ⁸⁸, G. Stavropoulos ⁴⁷, P. Steinberg ³⁰, B. Stelzer ^{145,159a}, H.J. Stelzer ¹³²,
 O. Stelzer-Chilton ^{159a}, H. Stenzel ⁵⁹, T.J. Stevenson ¹⁴⁹, G.A. Stewart ³⁷, J.R. Stewart ¹²⁴,
 M.C. Stockton ³⁷, G. Stoicea ^{28b}, M. Stolarski ^{133a}, S. Stonjek ¹¹², A. Straessner ⁵¹,
 J. Strandberg ¹⁴⁷, S. Strandberg ^{48a,48b}, M. Stratmann ¹⁷⁴, M. Strauss ¹²³, T. Strebler ¹⁰⁴,
 P. Strizenec ^{29b}, R. Ströhmer ¹⁶⁹, D.M. Strom ¹²⁶, R. Stroynowski ⁴⁵, A. Strubig ^{48a,48b},
 S.A. Stucci ³⁰, B. Stugu ¹⁷, J. Stupak ¹²³, N.A. Styles ⁴⁹, D. Su ¹⁴⁶, S. Su ^{63a}, W. Su ^{63d},
 X. Su ^{63a}, D. Suchy ^{29a}, K. Sugizaki ¹⁵⁶, V.V. Sulin ³⁸, M.J. Sullivan ⁹⁴, D.M.S. Sultan ¹²⁹,
 L. Sultanliyeva ³⁸, S. Sultansoy ^{3b}, T. Sumida ⁸⁹, S. Sun ¹⁷³, O. Sunneborn Gudnadottir ¹⁶⁴,
 N. Sur ¹⁰⁴, M.R. Sutton ¹⁴⁹, H. Suzuki ¹⁶⁰, M. Svatos ¹³⁴, M. Swiatlowski ^{159a}, T. Swirski ¹⁶⁹,
 I. Sykora ^{29a}, M. Sykora ¹³⁶, T. Sykora ¹³⁶, D. Ta ¹⁰², K. Tackmann ^{49,t}, A. Taffard ¹⁶²,
 R. Tafirout ^{159a}, J.S. Tafoya Vargas ⁶⁷, Y. Takubo ⁸⁵, M. Talby ¹⁰⁴, A.A. Talyshev ³⁸,
 K.C. Tam ^{65b}, N.M. Tamir ¹⁵⁴, A. Tanaka ¹⁵⁶, J. Tanaka ¹⁵⁶, R. Tanaka ⁶⁷, M. Tanasini ¹⁴⁸,
 Z. Tao ¹⁶⁷, S. Tapia Araya ^{140f}, S. Tapprogge ¹⁰², A. Tarek Abouelfadl Mohamed ¹⁰⁹,
 S. Tarem ¹⁵³, K. Tariq ¹⁴, G. Tarna ^{28b}, G.F. Tartarelli ^{72a}, M.J. Tartarin ⁹¹, P. Tas ¹³⁶,
 M. Tasevsky ¹³⁴, E. Tassi ^{44b,44a}, A.C. Tate ¹⁶⁵, G. Tateno ¹⁵⁶, Y. Tayalati ^{36e,v}, G.N. Taylor ¹⁰⁷,
 W. Taylor ^{159b}, R. Teixeira De Lima ¹⁴⁶, P. Teixeira-Dias ⁹⁷, J.J. Teoh ¹⁵⁸, K. Terashi ¹⁵⁶,
 J. Terron ¹⁰¹, S. Terzo ¹³, M. Testa ⁵⁴, R.J. Teuscher ^{158,w}, A. Thaler ⁸⁰, O. Theiner ⁵⁷,
 N. Themistokleous ⁵³, T. Thevenaux-Pelzer ¹⁰⁴, O. Thielmann ¹⁷⁴, D.W. Thomas ⁹⁷,
 J.P. Thomas ²¹, E.A. Thompson ^{18a}, P.D. Thompson ²¹, E. Thomson ¹³¹, R.E. Thornberry ⁴⁵,

C. Tian ^{63a}, Y. Tian ⁵⁶, V. Tikhomirov ^{38,a}, Yu.A. Tikhonov ³⁸, S. Timoshenko ³⁸,
 D. Timoshyn ¹³⁶, E.X.L. Ting ¹, P. Tipton ¹⁷⁵, A. Tishelman-Charny ³⁰, S.H. Tlou ^{34g},
 K. Todome ¹⁵⁷, S. Todorova-Nova ¹³⁶, S. Todt ⁵¹, L. Toffolin ^{70a,70c}, M. Togawa ⁸⁵, J. Tojo ⁹⁰,
 S. Tokár ^{29a}, K. Tokushuku ⁸⁵, O. Toldaiev ⁶⁹, M. Tomoto ^{85,113}, L. Tompkins ^{146,m},
 K.W. Topolnicki ^{87b}, E. Torrence ¹²⁶, H. Torres ⁹¹, E. Torró Pastor ¹⁶⁶, M. Toscani ³¹,
 C. Toscirci ⁴⁰, M. Tost ¹¹, D.R. Tovey ¹⁴², I.S. Trandafir ^{28b}, T. Trefzger ¹⁶⁹, A. Tricoli ³⁰,
 I.M. Trigger ^{159a}, S. Trincaz-Duvoid ¹³⁰, D.A. Trischuk ²⁷, B. Trocmé ⁶¹, A. Tropina ³⁹,
 L. Truong ^{34c}, M. Trzebinski ⁸⁸, A. Trzupiek ⁸⁸, F. Tsai ¹⁴⁸, M. Tsai ¹⁰⁸, A. Tsiamis ¹⁵⁵,
 P.V. Tsiareshka ³⁸, S. Tsigaridas ^{159a}, A. Tsirigotis ^{155,r}, V. Tsiskaridze ¹⁵⁸, E.G. Tskhadadze ^{152a},
 M. Tsopoulou ¹⁵⁵, Y. Tsujikawa ⁸⁹, I.I. Tsukerman ³⁸, V. Tsulaia ^{18a}, S. Tsuno ⁸⁵, K. Tsurii ¹²¹,
 D. Tsybychev ¹⁴⁸, Y. Tu ^{65b}, A. Tudorache ^{28b}, V. Tudorache ^{28b}, A.N. Tuna ⁶²,
 S. Turchikhin ^{58b,58a}, I. Turk Cakir ^{3a}, R. Turra ^{72a}, T. Turtuvshin ³⁹, P.M. Tuts ⁴²,
 S. Tzamarias ^{155,d}, E. Tzovara ¹⁰², F. Ukegawa ¹⁶⁰, P.A. Ulloa Poblete ^{140c,140b}, E.N. Umaka ³⁰,
 G. Unal ³⁷, A. Undrus ³⁰, G. Unel ¹⁶², J. Urban ^{29b}, P. Urrejola ^{140a}, G. Usai ⁸,
 R. Ushioda ¹⁵⁷, M. Usman ¹¹⁰, Z. Uysal ⁸³, V. Vacek ¹³⁵, B. Vachon ¹⁰⁶, T. Vafeiadis ³⁷,
 A. Vaitkus ⁹⁸, C. Valderanis ¹¹¹, E. Valdes Santurio ^{48a,48b}, M. Valente ^{159a}, S. Valentinetti ^{24b,24a},
 A. Valero ¹⁶⁶, E. Valiente Moreno ¹⁶⁶, A. Vallier ⁹¹, J.A. Valls Ferrer ¹⁶⁶, D.R. Van Arneeman ¹¹⁷,
 T.R. Van Daalen ¹⁴¹, A. Van Der Graaf ⁵⁰, P. Van Gemmeren ⁶, M. Van Rijnbach ³⁷,
 S. Van Stroud ⁹⁸, I. Van Vulpen ¹¹⁷, P. Vana ¹³⁶, M. Vanadia ^{77a,77b}, W. Vandelli ³⁷,
 E.R. Vandewall ¹²⁴, D. Vannicola ¹⁵⁴, L. Vannoli ⁵⁴, R. Vari ^{76a}, E.W. Varnes ⁷, C. Varni ^{18b},
 T. Varol ¹⁵¹, D. Varouchas ⁶⁷, L. Varriale ¹⁶⁶, K.E. Varvell ¹⁵⁰, M.E. Vasile ^{28b}, L. Vaslin ⁸⁵,
 G.A. Vasquez ¹⁶⁸, A. Vasyukov ³⁹, L.M. Vaughan ¹²⁴, R. Vavricka ¹⁰², T. Vazquez Schroeder ³⁷,
 J. Veatch ³², V. Vecchio ¹⁰³, M.J. Veen ¹⁰⁵, I. Veliscek ³⁰, L.M. Veloce ¹⁵⁸, F. Veloso ^{133a,133c},
 S. Veneziano ^{76a}, A. Ventura ^{71a,71b}, S. Ventura Gonzalez ¹³⁸, A. Verbytskyi ¹¹²,
 M. Verducci ^{75a,75b}, C. Vergis ⁹⁶, M. Verissimo De Araujo ^{84b}, W. Verkerke ¹¹⁷,
 J.C. Vermeulen ¹¹⁷, C. Vernieri ¹⁴⁶, M. Vessella ¹⁰⁵, M.C. Vetterli ^{145,ac}, A. Vgenopoulos ¹⁰²,
 N. Viaux Maira ^{140f}, T. Vickey ¹⁴², O.E. Vickey Boeriu ¹⁴², G.H.A. Viehhauser ¹²⁹, L. Vigani ^{64b},
 M. Vigl ¹¹², M. Villa ^{24b,24a}, M. Villaplana Perez ¹⁶⁶, E.M. Villhauer ⁵³, E. Vilucchi ⁵⁴,
 M.G. Vincter ³⁵, A. Visibile ¹¹⁷, C. Vittori ³⁷, I. Vivarelli ^{24b,24a}, E. Voevodina ¹¹², F. Vogel ¹¹¹,
 J.C. Voigt ⁵¹, P. Vokac ¹³⁵, Yu. Volkotrub ^{87b}, J. Von Ahnen ⁴⁹, E. Von Toerne ²⁵,
 B. Vormwald ³⁷, V. Vorobel ¹³⁶, K. Vorobev ³⁸, M. Vos ¹⁶⁶, K. Voss ¹⁴⁴, M. Vozak ¹¹⁷,
 L. Vozdecky ¹²³, N. Vranjes ¹⁶, M. Vranjes Milosavljevic ¹⁶, M. Vreeswijk ¹¹⁷, N.K. Vu ^{63d,63c},
 R. Vuillermet ³⁷, O. Vujinovic ¹⁰², I. Vukotic ⁴⁰, S. Wada ¹⁶⁰, C. Wagner ¹⁰⁵, J.M. Wagner ^{18a},
 W. Wagner ¹⁷⁴, S. Wahdan ¹⁷⁴, H. Wahlberg ⁹², J. Walder ¹³⁷, R. Walker ¹¹¹, W. Walkowiak ¹⁴⁴,
 A. Wall ¹³¹, E.J. Wallin ¹⁰⁰, T. Wamorkar ⁶, A.Z. Wang ¹³⁹, C. Wang ¹⁰², C. Wang ¹¹,
 H. Wang ^{18a}, J. Wang ^{65c}, P. Wang ⁹⁸, R. Wang ⁶², R. Wang ⁶, S.M. Wang ¹⁵¹, S. Wang ^{63b},
 S. Wang ¹⁴, T. Wang ^{63a}, W.T. Wang ⁸¹, W. Wang ¹⁴, X. Wang ^{114a}, X. Wang ¹⁶⁵,
 X. Wang ^{63c}, Y. Wang ^{63d}, Y. Wang ^{114a}, Y. Wang ^{63a}, Z. Wang ¹⁰⁸, Z. Wang ^{63d,52,63c},
 Z. Wang ¹⁰⁸, A. Warburton ¹⁰⁶, R.J. Ward ²¹, N. Warrack ⁶⁰, S. Waterhouse ⁹⁷, A.T. Watson ²¹,
 H. Watson ⁶⁰, M.F. Watson ²¹, E. Watton ^{60,137}, G. Watts ¹⁴¹, B.M. Waugh ⁹⁸, J.M. Webb ⁵⁵,
 C. Weber ³⁰, H.A. Weber ¹⁹, M.S. Weber ²⁰, S.M. Weber ^{64a}, C. Wei ^{63a}, Y. Wei ⁵⁵,
 A.R. Weidberg ¹²⁹, E.J. Weik ¹²⁰, J. Weingarten ⁵⁰, C. Weiser ⁵⁵, C.J. Wells ⁴⁹, T. Wenaus ³⁰,
 B. Wendland ⁵⁰, T. Wengler ³⁷, N.S. Wenke ¹¹², N. Wermes ²⁵, M. Wessels ^{64a}, A.M. Wharton ⁹³,
 A.S. White ⁶², A. White ⁸, M.J. White ¹, D. Whiteson ¹⁶², L. Wickremasinghe ¹²⁷,
 W. Wiedenmann ¹⁷³, M. Wielers ¹³⁷, C. Wiglesworth ⁴³, D.J. Wilbern ¹²³, H.G. Wilkens ³⁷,
 J.J.H. Wilkinson ³³, D.M. Williams ⁴², H.H. Williams ¹³¹, S. Williams ³³, S. Willocq ¹⁰⁵,
 B.J. Wilson ¹⁰³, P.J. Windischhofer ⁴⁰, F.I. Winkel ³¹, F. Winklmeier ¹²⁶, B.T. Winter ⁵⁵,

J.K. Winter ¹⁰³, M. Wittgen¹⁴⁶, M. Wobisch ⁹⁹, T. Wojtkowski⁶¹, Z. Wolffs ¹¹⁷, J. Wollrath¹⁶², M.W. Wolter ⁸⁸, H. Wolters ^{133a,133c}, M.C. Wong¹³⁹, E.L. Woodward ⁴², S.D. Worm ⁴⁹, B.K. Wosiek ⁸⁸, K.W. Woźniak ⁸⁸, S. Wozniowski ⁵⁶, K. Wraight ⁶⁰, C. Wu ²¹, M. Wu ^{114b}, M. Wu ¹¹⁶, S.L. Wu ¹⁷³, X. Wu ⁵⁷, Y. Wu ^{63a}, Z. Wu ⁴, J. Wuerzinger ^{112,aa}, T.R. Wyatt ¹⁰³, B.M. Wynne ⁵³, S. Xella ⁴³, L. Xia ^{114a}, M. Xia ¹⁵, M. Xie ^{63a}, S. Xin ^{14,114c}, A. Xiong ¹²⁶, J. Xiong ^{18a}, D. Xu ¹⁴, H. Xu ^{63a}, L. Xu ^{63a}, R. Xu ¹³¹, T. Xu ¹⁰⁸, Y. Xu ¹⁵, Z. Xu ⁵³, Z. Xu^{114a}, B. Yabsley ¹⁵⁰, S. Yacoob ^{34a}, Y. Yamaguchi ¹⁵⁷, E. Yamashita ¹⁵⁶, H. Yamauchi ¹⁶⁰, T. Yamazaki ^{18a}, Y. Yamazaki ⁸⁶, J. Yan^{63c}, S. Yan ⁶⁰, Z. Yan ¹⁰⁵, H.J. Yang ^{63c,63d}, H.T. Yang ^{63a}, S. Yang ^{63a}, T. Yang ^{65c}, X. Yang ³⁷, X. Yang ¹⁴, Y. Yang ⁴⁵, Y. Yang^{63a}, Z. Yang ^{63a}, W-M. Yao ^{18a}, H. Ye ^{114a}, H. Ye ⁵⁶, J. Ye ¹⁴, S. Ye ³⁰, X. Ye ^{63a}, Y. Yeh ⁹⁸, I. Yeletsikh ³⁹, B.K. Yeo ^{18b}, M.R. Yexley ⁹⁸, T.P. Yildirim ¹²⁹, P. Yin ⁴², K. Yorita ¹⁷¹, S. Younas ^{28b}, C.J.S. Young ³⁷, C. Young ¹⁴⁶, C. Yu ^{14,114c}, Y. Yu ^{63a}, J. Yuan ^{14,114c}, M. Yuan ¹⁰⁸, R. Yuan ^{63d,63c}, L. Yue ⁹⁸, M. Zaazoua ^{63a}, B. Zabinski ⁸⁸, E. Zaid⁵³, Z.K. Zak ⁸⁸, T. Zakareishvili ¹⁶⁶, S. Zambito ⁵⁷, J.A. Zamora Saa ^{140d,140b}, J. Zang ¹⁵⁶, D. Zanzi ⁵⁵, O. Zaplatilek ¹³⁵, C. Zeitnitz ¹⁷⁴, H. Zeng ¹⁴, J.C. Zeng ¹⁶⁵, D.T. Zenger Jr ²⁷, O. Zenin ³⁸, T. Ženiš ^{29a}, S. Zenz ⁹⁶, S. Zerradi ^{36a}, D. Zerwas ⁶⁷, M. Zhai ^{14,114c}, D.F. Zhang ¹⁴², J. Zhang ^{63b}, J. Zhang ⁶, K. Zhang ^{14,114c}, L. Zhang ^{63a}, L. Zhang ^{114a}, P. Zhang ^{14,114c}, R. Zhang ¹⁷³, S. Zhang ¹⁰⁸, S. Zhang ⁹¹, T. Zhang ¹⁵⁶, X. Zhang ^{63c}, X. Zhang ^{63b}, Y. Zhang ^{63c}, Y. Zhang ⁹⁸, Y. Zhang ^{114a}, Z. Zhang ^{18a}, Z. Zhang ^{63b}, Z. Zhang ⁶⁷, H. Zhao ¹⁴¹, T. Zhao ^{63b}, Y. Zhao ¹³⁹, Z. Zhao ^{63a}, Z. Zhao ^{63a}, A. Zhemchugov ³⁹, J. Zheng ^{114a}, K. Zheng ¹⁶⁵, X. Zheng ^{63a}, Z. Zheng ¹⁴⁶, D. Zhong ¹⁶⁵, B. Zhou ¹⁰⁸, H. Zhou ⁷, N. Zhou ^{63c}, Y. Zhou¹⁵, Y. Zhou ^{114a}, Y. Zhou⁷, C.G. Zhu ^{63b}, J. Zhu ¹⁰⁸, X. Zhu^{63d}, Y. Zhu ^{63c}, Y. Zhu ^{63a}, X. Zhuang ¹⁴, K. Zhukov ⁶⁹, N.I. Zimine ³⁹, J. Zinsser ^{64b}, M. Ziolkowski ¹⁴⁴, L. Živković ¹⁶, A. Zoccoli ^{24b,24a}, K. Zoch ⁶², T.G. Zorbas ¹⁴², O. Zormpa ⁴⁷, W. Zou ⁴², L. Zwalinski ³⁷.

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

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

³(^a)Department of Physics, Ankara University, Ankara; (^b)Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye.

⁴LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.

⁵APC, Université Paris Cité, CNRS/IN2P3, Paris; France.

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

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

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

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

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

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

¹²Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

¹³Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.

¹⁴Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; China.

¹⁵Physics Department, Tsinghua University, Beijing; China.

¹⁶Institute of Physics, University of Belgrade, Belgrade; Serbia.

¹⁷Department for Physics and Technology, University of Bergen, Bergen; Norway.

¹⁸(^a)Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; (^b)University of California, Berkeley CA; United States of America.

- ¹⁹Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
- ²⁰Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
- ²¹School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
- ²²(^a) Department of Physics, Bogazici University, Istanbul; (^b) Department of Physics Engineering, Gaziantep University, Gaziantep; (^c) Department of Physics, Istanbul University, Istanbul; Türkiye.
- ²³(^a) Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; (^b) Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia.
- ²⁴(^a) Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; (^b) INFN Sezione di Bologna; Italy.
- ²⁵Physikalisches Institut, Universität Bonn, Bonn; Germany.
- ²⁶Department of Physics, Boston University, Boston MA; United States of America.
- ²⁷Department of Physics, Brandeis University, Waltham MA; United States of America.
- ²⁸(^a) Transilvania University of Brasov, Brasov; (^b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (^c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (^d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (^e) National University of Science and Technology Politehnica, Bucharest; (^f) West University in Timisoara, Timisoara; (^g) Faculty of Physics, University of Bucharest, Bucharest; Romania.
- ²⁹(^a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (^b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
- ³⁰Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
- ³¹Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina.
- ³²California State University, CA; United States of America.
- ³³Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
- ³⁴(^a) Department of Physics, University of Cape Town, Cape Town; (^b) iThemba Labs, Western Cape; (^c) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; (^d) National Institute of Physics, University of the Philippines Diliman (Philippines); (^e) University of South Africa, Department of Physics, Pretoria; (^f) University of Zululand, KwaDlangezwa; (^g) School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
- ³⁵Department of Physics, Carleton University, Ottawa ON; Canada.
- ³⁶(^a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (^b) Faculté des Sciences, Université Ibn-Tofail, Kénitra; (^c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (^d) LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; (^e) Faculté des sciences, Université Mohammed V, Rabat; (^f) Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
- ³⁷CERN, Geneva; Switzerland.
- ³⁸Affiliated with an institute covered by a cooperation agreement with CERN.
- ³⁹Affiliated with an international laboratory covered by a cooperation agreement with CERN.
- ⁴⁰Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
- ⁴¹LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
- ⁴²Nevis Laboratory, Columbia University, Irvington NY; United States of America.
- ⁴³Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
- ⁴⁴(^a) Dipartimento di Fisica, Università della Calabria, Rende; (^b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
- ⁴⁵Physics Department, Southern Methodist University, Dallas TX; United States of America.

- ⁴⁶Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
- ⁴⁷National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
- ⁴⁸(^a) Department of Physics, Stockholm University; (^b) Oskar Klein Centre, Stockholm; Sweden.
- ⁴⁹Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
- ⁵⁰Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany.
- ⁵¹Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
- ⁵²Department of Physics, Duke University, Durham NC; United States of America.
- ⁵³SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
- ⁵⁴INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
- ⁵⁵Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
- ⁵⁶II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
- ⁵⁷Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ⁵⁸(^a) Dipartimento di Fisica, Università di Genova, Genova; (^b) INFN Sezione di Genova; Italy.
- ⁵⁹II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
- ⁶⁰SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
- ⁶¹LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
- ⁶²Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
- ⁶³(^a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; (^b) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; (^c) School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; (^d) Tsung-Dao Lee Institute, Shanghai; (^e) School of Physics and Microelectronics, Zhengzhou University; China.
- ⁶⁴(^a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (^b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
- ⁶⁵(^a) Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (^b) Department of Physics, University of Hong Kong, Hong Kong; (^c) Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.
- ⁶⁶Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
- ⁶⁷IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
- ⁶⁸Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain.
- ⁶⁹Department of Physics, Indiana University, Bloomington IN; United States of America.
- ⁷⁰(^a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (^b) ICTP, Trieste; (^c) Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.
- ⁷¹(^a) INFN Sezione di Lecce; (^b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
- ⁷²(^a) INFN Sezione di Milano; (^b) Dipartimento di Fisica, Università di Milano, Milano; Italy.
- ⁷³(^a) INFN Sezione di Napoli; (^b) Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
- ⁷⁴(^a) INFN Sezione di Pavia; (^b) Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
- ⁷⁵(^a) INFN Sezione di Pisa; (^b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
- ⁷⁶(^a) INFN Sezione di Roma; (^b) Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
- ⁷⁷(^a) INFN Sezione di Roma Tor Vergata; (^b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
- ⁷⁸(^a) INFN Sezione di Roma Tre; (^b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
- ⁷⁹(^a) INFN-TIFPA; (^b) Università degli Studi di Trento, Trento; Italy.
- ⁸⁰Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.

- ⁸¹University of Iowa, Iowa City IA; United States of America.
- ⁸²Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
- ⁸³Istinye University, Sariyer, Istanbul; Türkiye.
- ⁸⁴(^a)Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;(^b)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;(^c)Instituto de Física, Universidade de São Paulo, São Paulo;(^d)Rio de Janeiro State University, Rio de Janeiro;(^e)Federal University of Bahia, Bahia; Brazil.
- ⁸⁵KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
- ⁸⁶Graduate School of Science, Kobe University, Kobe; Japan.
- ⁸⁷(^a)AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow;(^b)Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
- ⁸⁸Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
- ⁸⁹Faculty of Science, Kyoto University, Kyoto; Japan.
- ⁹⁰Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
- ⁹¹L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
- ⁹²Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
- ⁹³Physics Department, Lancaster University, Lancaster; United Kingdom.
- ⁹⁴Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
- ⁹⁵Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
- ⁹⁶School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
- ⁹⁷Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
- ⁹⁸Department of Physics and Astronomy, University College London, London; United Kingdom.
- ⁹⁹Louisiana Tech University, Ruston LA; United States of America.
- ¹⁰⁰Fysiska institutionen, Lunds universitet, Lund; Sweden.
- ¹⁰¹Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
- ¹⁰²Institut für Physik, Universität Mainz, Mainz; Germany.
- ¹⁰³School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
- ¹⁰⁴CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
- ¹⁰⁵Department of Physics, University of Massachusetts, Amherst MA; United States of America.
- ¹⁰⁶Department of Physics, McGill University, Montreal QC; Canada.
- ¹⁰⁷School of Physics, University of Melbourne, Victoria; Australia.
- ¹⁰⁸Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
- ¹⁰⁹Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
- ¹¹⁰Group of Particle Physics, University of Montreal, Montreal QC; Canada.
- ¹¹¹Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
- ¹¹²Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
- ¹¹³Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
- ¹¹⁴(^a)Department of Physics, Nanjing University, Nanjing;(^b)School of Science, Shenzhen Campus of Sun Yat-sen University;(^c)University of Chinese Academy of Science (UCAS), Beijing; China.
- ¹¹⁵Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
- ¹¹⁶Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.
- ¹¹⁷Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam;

Netherlands.

¹¹⁸Department of Physics, Northern Illinois University, DeKalb IL; United States of America.

¹¹⁹^(a)New York University Abu Dhabi, Abu Dhabi;^(b)United Arab Emirates University, Al Ain; United Arab Emirates.

¹²⁰Department of Physics, New York University, New York NY; United States of America.

¹²¹Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.

¹²²Ohio State University, Columbus OH; United States of America.

¹²³Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.

¹²⁴Department of Physics, Oklahoma State University, Stillwater OK; United States of America.

¹²⁵Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.

¹²⁶Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.

¹²⁷Graduate School of Science, Osaka University, Osaka; Japan.

¹²⁸Department of Physics, University of Oslo, Oslo; Norway.

¹²⁹Department of Physics, Oxford University, Oxford; United Kingdom.

¹³⁰LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.

¹³¹Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.

¹³²Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.

¹³³^(a)Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;^(b)Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;^(c)Departamento de Física, Universidade de Coimbra, Coimbra;^(d)Centro de Física Nuclear da Universidade de Lisboa, Lisboa;^(e)Departamento de Física, Universidade do Minho, Braga;^(f)Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);^(g)Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.

¹³⁴Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.

¹³⁵Czech Technical University in Prague, Prague; Czech Republic.

¹³⁶Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.

¹³⁷Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.

¹³⁸IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.

¹³⁹Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.

¹⁴⁰^(a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;^(b)Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago;^(c)Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena;^(d)Universidad Andres Bello, Department of Physics, Santiago;^(e)Instituto de Alta Investigación, Universidad de Tarapacá, Arica;^(f)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.

¹⁴¹Department of Physics, University of Washington, Seattle WA; United States of America.

¹⁴²Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

¹⁴³Department of Physics, Shinshu University, Nagano; Japan.

¹⁴⁴Department Physik, Universität Siegen, Siegen; Germany.

¹⁴⁵Department of Physics, Simon Fraser University, Burnaby BC; Canada.

¹⁴⁶SLAC National Accelerator Laboratory, Stanford CA; United States of America.

¹⁴⁷Department of Physics, Royal Institute of Technology, Stockholm; Sweden.

¹⁴⁸Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.

- ¹⁴⁹Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
- ¹⁵⁰School of Physics, University of Sydney, Sydney; Australia.
- ¹⁵¹Institute of Physics, Academia Sinica, Taipei; Taiwan.
- ¹⁵²(^a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (^b) High Energy Physics Institute, Tbilisi State University, Tbilisi; (^c) University of Georgia, Tbilisi; Georgia.
- ¹⁵³Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
- ¹⁵⁴Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
- ¹⁵⁵Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
- ¹⁵⁶International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
- ¹⁵⁷Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.
- ¹⁵⁸Department of Physics, University of Toronto, Toronto ON; Canada.
- ¹⁵⁹(^a) TRIUMF, Vancouver BC; (^b) Department of Physics and Astronomy, York University, Toronto ON; Canada.
- ¹⁶⁰Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.
- ¹⁶¹Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
- ¹⁶²Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.
- ¹⁶³University of Sharjah, Sharjah; United Arab Emirates.
- ¹⁶⁴Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
- ¹⁶⁵Department of Physics, University of Illinois, Urbana IL; United States of America.
- ¹⁶⁶Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
- ¹⁶⁷Department of Physics, University of British Columbia, Vancouver BC; Canada.
- ¹⁶⁸Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
- ¹⁶⁹Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
- ¹⁷⁰Department of Physics, University of Warwick, Coventry; United Kingdom.
- ¹⁷¹Waseda University, Tokyo; Japan.
- ¹⁷²Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.
- ¹⁷³Department of Physics, University of Wisconsin, Madison WI; United States of America.
- ¹⁷⁴Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
- ¹⁷⁵Department of Physics, Yale University, New Haven CT; United States of America.
- ^a Also Affiliated with an institute covered by a cooperation agreement with CERN.
- ^b Also at An-Najah National University, Nablus; Palestine.
- ^c Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
- ^d Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
- ^e Also at Centro Studi e Ricerche Enrico Fermi; Italy.
- ^f Also at CERN, Geneva; Switzerland.
- ^g Also at CMD-AC UNEC Research Center, Azerbaijan State University of Economics (UNEC); Azerbaijan.
- ^h Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ⁱ Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
- ^j Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
- ^k Also at Department of Physics, California State University, Sacramento; United States of America.

- ^l Also at Department of Physics, King's College London, London; United Kingdom.
- ^m Also at Department of Physics, Stanford University, Stanford CA; United States of America.
- ⁿ Also at Department of Physics, Stellenbosch University; South Africa.
- ^o Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
- ^p Also at Department of Physics, University of Thessaly; Greece.
- ^q Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
- ^r Also at Hellenic Open University, Patras; Greece.
- ^s Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
- ^t Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
- ^u Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
- ^v Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
- ^w Also at Institute of Particle Physics (IPP); Canada.
- ^x Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- ^y Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
- ^z Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
- ^{aa} Also at Technical University of Munich, Munich; Germany.
- ^{ab} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
- ^{ac} Also at TRIUMF, Vancouver BC; Canada.
- ^{ad} Also at Università di Napoli Parthenope, Napoli; Italy.
- ^{ae} Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
- ^{af} Also at Washington College, Chestertown, MD; United States of America.
- ^{ag} Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
- * Deceased