



Letter

Characterization of nuclear breakup as a function of hard-scattering kinematics using dijets measured by ATLAS in $p + \text{Pb}$ collisions

The ATLAS Collaboration¹

ARTICLE INFO

Editor: Dr. M. Doser

Keywords:

Dijet
Heavy ion collisions
Event geometry estimators
Color fluctuations
Nuclear breakup

ABSTRACT

This Letter analyzes the sensitivity of event geometry estimators to the initial-state kinematics of hard scattering in proton–lead collisions. This analysis uses dijets as a proxy for the parton–parton scattering configuration, correlating it with event geometry estimators, namely the energy deposited in the Zero-Degree Calorimeter and the transverse energy recorded in the Forward Calorimeter in the Pb-going direction. The analysis uses data recorded by the ATLAS detector at the Large Hadron Collider with a nucleon–nucleon center-of-mass energy of 8.16 TeV, corresponding to an integrated luminosity of 56 nb^{−1}. The jets are measured within the pseudorapidity interval $-2.8 < \eta < 4.5$, where positive η values correspond to the direction of the proton beam. Results are presented as a function of the Bjorken- x of the parton originating from the proton, x_p . Both event geometry estimators are found to be dependent on x_p , with the energy deposited in the Zero-Degree Calorimeter about six times less sensitive to x_p compared with the transverse energy deposited in the Forward Calorimeter.

1. Introduction

The study of hard processes in proton–lead ($p + \text{Pb}$) collisions at the Large Hadron Collider (LHC) [1] has contributed to a richer understanding of nuclear matter, both in the hot, dense medium produced in nucleus–nucleus collisions and in the cold nuclear environment [2,3].

The modification of parton distribution functions in the nuclear environment (nPDFs) [4,5] has been studied through measurements across multiple channels by experiments at the LHC [6–13] and at the Relativistic Heavy Ion Collider (RHIC) [14–17]. One important reason to study the modification of PDFs within nuclei is to understand the production rates of hard probes, like jets and heavy vector bosons, in deep inelastic scattering on nuclei and proton–ion ($p + \text{A}$) collisions.

Hard process rates have also been studied as a function of $p + \text{Pb}$ collision centrality, defined using “global” event-level variables sensitive to the collision geometry, such as forward transverse energy or the number of forward neutrons. Both of these variables are expected to be sensitive to the overall collision geometry, particularly the number of binary collisions (N_{coll}) experienced by the projectile proton [18]. This assumption was validated by ATLAS in a Z boson measurement [7], where the inclusive Z yields were found to be approximately proportional to N_{coll} . Centrality was defined by the event activity, which is the transverse energy measured in the Forward Calorimeter (FCal) facing the nuclear debris [19].

However, such linearity in different centrality selections was *not* observed for jets. ATLAS observed an event activity bias in the first mea-

surement of inclusive jet production in $p + \text{Pb}$ collisions at 5.02 TeV [20]. The analysis reported a significant suppression of the jet production normalized to N_{coll} in central events compared with peripheral events, with centrality defined using the event activity. The suppression was found to be a function of the jet kinematics. More specifically, the central-to-peripheral ratio (R_{CP}) was found to be a function of the jet energy. Similar observations were made at RHIC by PHENIX [21] and, more recently, by STAR [22]. These results were interpreted as evidence that protons in a configuration containing a parton with a large partonic momentum fraction (Bjorken- x), when interacting with a nuclear target, have a significantly smaller than average cross-section and size [23], a manifestation of color fluctuation (CF) effects [24–26]. CFs in QCD refer to variations in the transverse area occupied by color fields, which become spatially compact when a single parton carries a large fraction of the hadron’s momentum [27]. By causing the proton to interact with fewer nucleons in the nucleus, the CF effects were found to induce a bias on the event activity and, therefore, on the forward transverse energy used to define the centrality. This bias depends on the kinematics of the jets, suggesting that fluctuations in the initial state can weaken the correlation between impact parameter and centrality. More recently, ATLAS probed this effect in greater detail by analyzing the centrality dependence of dijet production in $p + \text{Pb}$ data collected at 8.16 TeV [28]. By leveraging dijets to reconstruct the event-level initial-state kinematics, this analysis directly showed a correlation between the event activity bias and the Bjorken- x of the proton, x_p , consistent with the CF interpretation proposed in ref. [23].

Contact: atlas.publications@cern.ch.

¹ Authors are listed at the end of this paper.

In comparison, the linear scaling of Z boson production with N_{coll} was validated in a kinematic region characterized by a proton configuration with $x_p < 0.1$, away from where CF effects are most visible [7]. Furthermore, the Z boson R_{CP} measured as a function of rapidity shows hints of a correlation with x_p in specific higher-rapidity selections, where a significant fraction of the Z bosons also sample large- x_p configurations.

The event activity bias, identified in jets, poses significant challenges in identifying jet quenching signatures in small systems like $p + A$. Events with identical impact parameter but different proton configurations can end up in different centrality classes. Since any jet quenching signal in $p + \text{Pb}$ collisions is small and the event activity bias can be larger, this ambiguity complicates the interpretation of event activity selected $p + \text{Pb}$ measurements. Thus, it becomes a topic of great interest to extract the centrality dependence of hard process rates using observables that are less sensitive to initial-state effects [29]. One alternative approach is to select different centrality classes in $p + A$ events based on the number of spectator neutrons measured at $|\eta| \gtrsim 8$ with a Zero-Degree Calorimeter (ZDC) instrumented in the nucleus-going direction [30,31]. ZDCs have been used as a way to select central events in searches for energy loss signatures, with the measurements in refs. [32,33] motivated by the argument that this classification is less biased than the event activity-based selection method.

A measurement of forward neutron production in $p + \text{Pb}$, published by ALICE [34], reported the energy accumulated in the neutron ZDC as a function of the estimated number of binary collisions. The results, self-normalized to the average in minimum bias (MB) events in $p + \text{Pb}$ collisions, found the energy in the Pb-going neutron ZDC to monotonically increase with the number of binary collisions, showing a correlation between these two quantities. Despite this, the dynamics of the nuclear breakup in $p + \text{Pb}$ collisions are still not well understood in many aspects, and are poorly modeled by event generators, especially in the presence of a hard scattering.

Recently, the authors of ref. [35] argued that CF effects may also be relevant in the nuclear breakup process in ultra-peripheral collisions (UPCs) characterized by a resolved photon exchange, linking the number of nucleons wounded by interactions with a vector meson with the nuclear breakup dynamics. Such effects, related to the number of interacting nucleons, can also improve the understanding of ZDC energy measured in $e + A$ collisions at the future Electron-Ion Collider, where it was proposed as a possible centrality tag [36] to map out the impact parameter dependence on nPDFs. A similar model, using a proton instead of a vector meson in the scattering with the nucleus, can be used for the nuclear breakup in $p + \text{Pb}$ interactions.

Given the importance of CF effects on centrality-dependent measurements of hard-scattering rates in $p + \text{Pb}$ collisions, it is of great interest to study the correlation between the kinematics of the hard-scattered partons, the neutron energy at very forward rapidity after nuclear breakup, and the forward calorimeter event activity in these events. This inverts the typical approach by directly measuring the quantities used for centrality estimates as a function of jet kinematics, providing the first quantitative investigation of global observables in the presence of CF effects.

This Letter presents the first characterization of very forward energy in dijet events in $p + \text{Pb}$ collisions at LHC energies, using 56 nb⁻¹ of $p + \text{Pb}$ data collected by ATLAS during 2016 at a nucleon–nucleon center-of-mass energy ($\sqrt{s_{\text{NN}}}$) of 8.16 TeV. The energy deposited in the ZDC ($E_{\text{ZDC}}^{\text{Pb}}$) and the transverse energy (E_{T}) recorded in the FCal ($\text{FCal} \Sigma E_{\text{T}}^{\text{Pb}}$), both measured on the Pb-going side, are reported as a function of x_p . The normalized $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal} \Sigma E_{\text{T}}^{\text{Pb}}$ distributions and the means of these distributions, $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ and $\langle \text{FCal} \Sigma E_{\text{T}}^{\text{Pb}} \rangle$, are analyzed to characterize the evolution of forward energy production in response to changes in the proton configuration. The correlation between $\text{FCal} \Sigma E_{\text{T}}^{\text{Pb}}$ and $E_{\text{ZDC}}^{\text{Pb}}$ is also investigated to provide insights about the underlying physics linking event activity and nuclear breakup dynamics in $p + \text{Pb}$ collisions.

Following ref. [28], dijets are defined using the two highest transverse momentum¹ jets in a given collision, measured over a wide range of transverse momentum, p_{T} , and center-of-mass (CM) rapidity, y^{CM} , to access a broad x_p phase space. The value of x_p is estimated from the final-state kinematics of the two highest p_{T} jets in each event by using

$$x_p = \frac{p_{\text{T},1} e^{y_1^{\text{CM}}} + p_{\text{T},2} e^{y_2^{\text{CM}}}}{\sqrt{s_{\text{NN}}}}, \quad (1)$$

where $p_{\text{T},1}$ ($p_{\text{T},2}$) and y_1^{CM} (y_2^{CM}) denote the transverse momentum and the rapidity of the leading (sub-leading) jet. At leading order in a perturbative approach, Eq. (1) is the Bjorken- x of the scattered parton in the proton [37]. Direct estimates of the parton level kinematics through jet observables have been done in dijet measurements at the LHC [38] and RHIC [39]. In simulations, the x_p estimate based on final-state jet kinematics was found to be, on average, 6–8% lower than the true parton-level value in the phase space covered by the analysis. The relative resolution of this estimate, $\sigma_{x_p^{\text{reco}}/x_p^{\text{PYTHIA}}}$, is around 10% for the lowest x_p events, decreasing to 4% with increasing x_p .

In this analysis, x_p is unfolded for experimental effects due to the finite precision of jet reconstruction, and reported at the generator level. $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal} \Sigma E_{\text{T}}^{\text{Pb}}$ are not unfolded for experimental effects, as was done when used for centrality selections in previous analyses [20,28,33].

These results present a novel approach to study geometry in proton–nucleus collisions and provide new insights into the role of partonic proton configurations and color fluctuations in the dynamics characterizing these reactions.

2. ATLAS detector

The measurement presented in this Letter is performed using the ATLAS inner detector, calorimeter, ZDC, trigger, and data acquisition systems [30].

The inner detector measures charged particles within the pseudorapidity interval $|\eta| < 2.5$ using a combination of silicon pixel detectors, silicon microstrip detectors (SCT), and a straw-tube transition radiation tracker (TRT), all immersed in a 2 T axial magnetic field. Each of the three detectors is composed of a barrel and two symmetric endcap sections. The pixel detector barrel section is composed of four layers including the insertable B-layer [40,41], and each endcap consists of three disks placed symmetrically on each side of the interaction region. The SCT barrel section contains four layers of modules with sensors on both sides, and each endcap consists of nine layers of double-sided modules with radial strips. The TRT contains layers of staggered straws interleaved with the transition radiation material. Candidate collision vertices are reconstructed using inner detector tracks. The vertex with the highest track Σp_{T}^2 is defined as the primary vertex.

The calorimeter system consists of a sampling liquid-argon (LAr) electromagnetic (EM) calorimeter covering $|\eta| < 3.2$, a steel-scintillator sampling hadronic calorimeter covering $|\eta| < 1.7$, LAr hadronic calorimeters covering $1.5 < |\eta| < 3.2$, and two LAr FCals covering $3.2 < |\eta| < 4.9$. The EM calorimeters are segmented longitudinally in shower depth into three layers with an additional presampler layer covering

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the center 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 proportional to the rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$ in the relativistic limit. In the analysis the pseudorapidity sign is determined by the nuclear species, protons travel towards positive rapidities, while ions travel towards negative rapidities. The rapidity in the proton–nucleon center-of-mass frame is shifted by +0.465 units compared with the ATLAS frame. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

$|\eta| < 1.8$. The hadronic calorimeters have three sampling layers longitudinal in shower depth for $|\eta| < 1.7$ and four sampling layers for $1.5 < |\eta| < 3.2$. During the 2016 $p + \text{Pb}$ data taking, a sector of the hadronic endcap calorimeter (HEC), corresponding to $-3.2 < \eta < -1.5$ and $-\pi < \phi < -\pi/2$ was disabled. The FCal is composed of calorimeter towers segmented with fine granularity in $\Delta x \times \Delta y$, corresponding approximately to $\Delta\eta \times \Delta\phi = 0.15 \times 0.15 (0.3 \times 0.3)$ at $\eta = 3.5 (4.5)$ [42]. The EM energy scale is used to measure the energy in each tower ($E_{\text{tower}}^{\text{EM}}$). The EM scale properly corrects the energy deposited by photons and electrons, but does not include any compensation to correct for the differences between EM and hadronic showers, as is standard for FCal measurements that are used as geometry estimators in $p + \text{Pb}$ [20,28,33] and $\text{Pb} + \text{Pb}$ [43] measurements.

The ATLAS ZDC consists of two detectors located in absorbers ± 140 m from the ATLAS interaction point. Each detector is a sampling calorimeter made up of four modules each with a material budget of 1.14 hadronic interaction lengths. The modules are made of layers of tungsten plates with quartz rods interspersed between them. They measure forward-going neutral particles with $|\eta| > 8.3$, primarily neutrons from nuclear breakup, which carry the original per-nucleon beam energy up to an additional smearing from nuclear Fermi momentum, and very forward neutral particles produced in the interaction.

To have sufficient experimental resolution to reconstruct a single neutron peak while simultaneously measuring calorimeter deposits from 80 or more neutrons from in-time pileup², the ZDC requires a large dynamic range from its front-end electronics. Experimentally, this is accomplished by configuring the ZDC with a dual gain readout system, where a high-gain analog-to-digital converter (ADC) samples with enough granularity to precisely measure relatively smaller energy deposits, while a low-gain module ensures that the ZDC does not saturate in events with sizable contamination from in-time pileup. This dual-gain readout is combined at the reconstruction level to give a single measurement of $E_{\text{ZDC}}^{\text{Pb}}$. In addition, having a reference for each signal allows for a data-driven correction of ADC non-linear behavior, applied at the level of the reconstruction.

ATLAS uses a two-level trigger system. The first-level trigger (Level 1) is hardware-based and implemented with custom electronics. It is followed by the software-based high-level trigger (HLT) [44]. An extensive software suite [45] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3. Data selection and Monte Carlo simulations

For the 2016 $p + \text{Pb}$ run at $\sqrt{s_{\text{NN}}} = 8.16$ TeV, the LHC beam energy configuration was asymmetric between the protons (6.5 TeV), and the Pb nuclei (2.56 TeV/nucleon), resulting in a rapidity shift of the center of mass by 0.465 units toward the p -going direction. The data were collected over two running periods characterized by interchanging species between beam directions. In the first period of the data-taking, when Pb ions circulated clockwise in the LHC, a total integrated luminosity of 56 nb^{-1} was collected. The data analyzed in this Letter are comprised solely of the first data-taking period, referred to as the $p + \text{Pb}$ orientation. The second data-taking period is omitted since the presence of a detector from the LHCf experiment [46] precludes a precise measurement of the spectator neutron energy. The positive η direction used in the analysis is defined by the proton-going direction.

The data used satisfy detector and data-quality requirements, and contain at least one reconstructed vertex and two reconstructed jets. A set of fully efficient central and forward single-jet triggers [44], characterized by different p_{T} thresholds, was chosen to provide full p_{T} coverage over the phase space of this analysis.

Jets are formed from calorimeter towers and are reconstructed using the anti- k_t algorithm [47,48] with E-scheme recombination and $R = 0.4$, as was done in previous ATLAS jet measurements in $p + \text{Pb}$ [28,33]. This analysis considers events where the two highest p_{T} jets have reconstructed $p_{\text{T},1} > 40$ GeV, $p_{\text{T},2} > 30$ GeV and $-2.8 < \eta_1, \eta_2 < 4.5$, respectively. Sub-leading jets have a lower p_{T} threshold to allow for some momentum imbalance in the reconstructed dijet at low $p_{\text{T,Avg}}$. The asymmetric η requirement is imposed to avoid jets biasing the centrality determination in the Pb-going FCal. Events with either the leading or the sub-leading jet reconstructed in the acceptance of the disabled HEC region are discarded in both data and Monte Carlo (MC) simulations. To define a rejection criterion for the analysis, the disabled region is increased by an additional 0.4 margin in both pseudorapidity and azimuthal angle, as done in previous jet analyses using these datasets [28,33,49]. In this way, jets with constituents affected by the disabled HEC are not considered and an efficiency correction is applied (see Section 4).

Centrality is defined using FCal $\Sigma E_{\text{T}}^{\text{Pb}}$ [28,50,51]. To reject contamination from UPC events, the centrality range 0–90% is considered. The contribution of UPC jet production in these events was studied by applying an additional selection based on the rapidity gap [52] and is found to be negligible. In-time pileup events are rejected by requiring that no non-primary vertices have more than six associated tracks.³ This removes approximately 12% of events from the sample. All these selections are consistent with the $p + \text{Pb}$ analysis presented in ref. [28].

The ZDC ADCs sample their own baseline before every event. This baseline is sensitive to the long tails of preceding $p + \text{Pb}$ interactions with significant ZDC activity. By rejecting events with baseline values elevated relative to an acceptable range taken from a dedicated zero pileup sample, events with an out-of-time⁴ pileup contribution that can affect measurements in the FCal are excluded. This requirement removes approximately 8% of events, after the nominal pileup cut and the centrality selection. This requirement is agnostic to the kinematic properties of the considered event, as it only depends on the process in a previous event.

MC simulations are used to evaluate the performance of the detector and analysis procedure, and to correct the measured distributions for detector effects. The detector response in all MC samples is simulated using GEANT4 [45,53]. The disabled HEC sector is replicated in the simulation. The $p + \text{Pb}$ MC sample makes use of dijet events from 8.16 TeV pp collisions, including the boost in rapidity relative to the lab frame that is in the data, simulated by PYTHIA8 [54] with the A14 set of tuned parameters [55] and the NNPDF2.3LO parton distribution functions [56]. Events from the PYTHIA8 dijet sample are overlaid with events from a dedicated $p + \text{Pb}$ data sample collected using MB triggers. The overlay procedure combines the PYTHIA8 and data events during the digitization step of simulation. The FCal $\Sigma E_{\text{T}}^{\text{Pb}}$ from the PYTHIA8 event is mostly insensitive to the x_p estimated from the dijet kinematics [38]. An event-by-event reweighting procedure is applied to the MC overlay sample, such that the resulting FCal $\Sigma E_{\text{T}}^{\text{Pb}}$ distribution better matches that of the dijet data sample.

4. Analysis

The value of FCal $\Sigma E_{\text{T}}^{\text{Pb}}$ is defined by a sum over the projection of each $E_{\text{tower}}^{\text{EM}}$ into the transverse plane, for the towers in the pseudorapidity hemisphere facing the Pb ion beam. This definition of FCal $\Sigma E_{\text{T}}^{\text{Pb}}$ is

³ The average interactions per bunch crossing, $\bar{\mu}$, varied throughout the $p + \text{Pb}$ data-taking. A majority of the sampled luminosity had a modest pileup profile $0.1 < \bar{\mu} < 0.3$. Low pileup samples $\bar{\mu} < 0.01$ were taken to study the impact of pileup on the data.

⁴ Out-of-time pileup refers to events preceded by another $p + \text{Pb}$ collision where a detector measures signals originating from the preceding event in the sampling window of the current event.

² In-time pileup refer to events containing multiple simultaneous $p + \text{Pb}$ collisions.

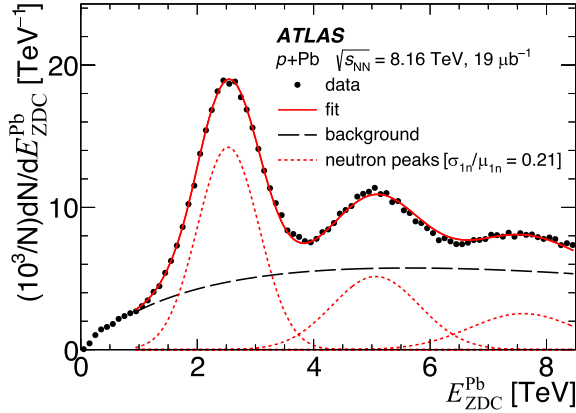


Fig. 1. Low energy region of the calibrated ZDC spectrum for events triggered using the proton-going ZDC. The fit result is shown by the solid line. All the fit components are displayed using dashed lines.

consistent with the characterization of centrality used in previous ATLAS $p + \text{Pb}$ analyses, for example in refs. [28,57].

In a typical $p + \text{Pb}$ event involving a hard scattering, most of the energy deposited into the Pb-going ZDC originates from spectator neutrons evaporating off the struck nucleus. A peaked structure appears in the low-energy region of the ZDC spectrum due to the detector's response to a small number of neutrons, which can be clearly distinguished. An example of the ZDC energy spectrum and peak fitting result is displayed in Fig. 1. The first peak in this structure represents the ZDC response to the energy of a single spectator neutron. The absolute energy response of the ZDC modules is calibrated by a Lagrangian optimization procedure that sets the mean of the single neutron peak equal to the nominal per nucleon beam energy and adjusts calibration factors in each layer to minimize the width of the single neutron peak. The calibration procedure is repeated throughout the run to account for intra-run changes in the detector response. Following calibration, a simultaneous fit is performed to the first three neutron peaks, as well as a background term. Background sources include neutral pions, photons, and beam-beam backgrounds. The functional form of the background term is chosen to facilitate fit convergence in the 1–3 neutron range. On physical grounds this contribution should vanish at zero energy and at large energies. These fits are used to validate the energy scale set by the calibration. The fit procedure is applied on a per-run basis, to account for changes in the detector response during data-taking.

The width of the single neutron peak originates from two separate sources. First, the ZDC is a sampling calorimeter that has a finite experimental resolution. Second, the contribution from nuclear Fermi momentum smears the neutron energy away from the nominal per-nucleon beam energy. The use of a Gaussian distribution to model the calorimeter response to a single neutron is motivated by the assumption that the modification from the convolution of these two sources is roughly symmetric. Below 1 TeV, the detector is primarily observing a mix of low-energy photons and beam backgrounds, with a negligible fraction from single neutrons. The ZDC amplitude reconstruction procedure also requires pulse heights well above detector noise that limit its precision below 1 TeV. Therefore, below that threshold, the measured energy is treated as zero, i.e., compatible with zero neutrons showering in the ZDC.

A residual pileup subtraction is applied to the $E_{\text{ZDC}}^{\text{Pb}}$ distribution, to remove in-time pileup contributions from interactions that are not rejected by the vertex requirement, and that are characterized by no significant pileup energy deposit in the FCal. This procedure removes approximately 0.19% of the events from the sample.

The jet reconstruction performance for this data sample was scrutinized in detail in a previous analysis, see ref. [28] for all the relevant details.

To correct for detector effects and bin migration, dijet events are unfolded in x_p using a two-dimensional Bayesian procedure [58], implemented within the RooUnfold package [59] and validated by closure tests. The value of x_p at particle level is estimated with Eq. (1) using the leading and sub-leading particle-level jets. $\text{FCal} \Sigma E_{\text{T}}^{\text{Pb}}$ and $E_{\text{ZDC}}^{\text{Pb}}$ are individually propagated through the unfolding procedure with fully diagonal migration matrices, preserving the event-level correlation between the hard-scattering kinematics and each of the calorimetric energies. An efficiency correction is included in the unfolding to account for reconstructed jets that migrate out of the measurement phase space at the detector-level due to energy resolution effects, as well as to the disabled HEC region.

Each response matrix is reweighted at the event level by the ratio of reconstructed data to reconstructed simulation, as a function of x_p , such that the simulated spectrum better matches the shape of the data. The statistical uncertainties in the resulting $\text{FCal} \Sigma E_{\text{T}}^{\text{Pb}}$ and the $E_{\text{ZDC}}^{\text{Pb}}$ distributions, binned as a function of x_p , are evaluated using a bootstrapping method [60].

5. Systematic uncertainties

This measurement unfolds experimental effects in the dijet measurements to access x_p at the particle level. This approach is subject to systematic uncertainties associated with the jet energy scale (JES) and jet energy resolution (JER), the unfolding procedure, and an uncertainty due to a sector of the HEC being disabled for the running period. Measurements of $E_{\text{ZDC}}^{\text{Pb}}$ and $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ have additional uncertainties applied to the energy scale of the ZDC. Since the ZDC energies are not unfolded, these uncertainties are evaluated at the reconstructed level. Other sources of systematic uncertainty, such as those related to the removal of the residual pileup in the ZDC, were found to be negligible. For each source of systematic uncertainty, except for the uncertainties in the disabled HEC sector and the ZDC energy scale, the entire analysis is repeated by changing the response matrix according to the systematic variation. The difference between the nominal measurement and that obtained with the systematic variation is taken as the systematic uncertainty.

The treatment of the uncertainties related to the determination of x_p via jets, namely the uncertainties in the JES, JER, and HEC exclusion, is identical to the procedure outlined in ref. [28] and the discussion of these uncertainties is minimized in this Letter. The JES and JER correspond to the mean and variance of the $p_{\text{T}}^{\text{reco}}/p_{\text{T}}^{\text{gen}}$ distributions, where $p_{\text{T}}^{\text{gen}}$ denotes the transverse momentum of the matched generator-level jet in simulation. The HEC exclusion uncertainty evaluates the sensitivity to increasing the exclusion region by 0.1 in both azimuth and pseudorapidity, and repeating the analysis procedure.

The systematic uncertainty in the unfolding procedure is related to the sensitivity to the choice of the prior distribution, i.e., the response matrix reweighting described in Section 4. To determine the sensitivity of the results to the reweighting procedure, a new set of response matrices was generated without reweighting at the event level, and the full analysis procedure was repeated.

An uncertainty associated with the ZDC energy stability is assigned to quantify the run-by-run variations in the single neutron peak position extracted from fits like the one shown in Fig. 1. The residual between the nominal per-nucleon beam energy (2.56 TeV) and the extracted peak position, after allowing for 1σ deviations from the stability, is taken as an uncertainty in the ZDC energy scale. This approach was chosen to avoid overestimating the uncertainties assigned to the ZDC measurements. This residual is intrinsically linked to the finite time-resolution of the calibration procedure described in Section 4. A systematic uncertainty is also assigned to the ZDC non-linear correction mentioned in Section 2. This uncertainty is determined by calculating the difference

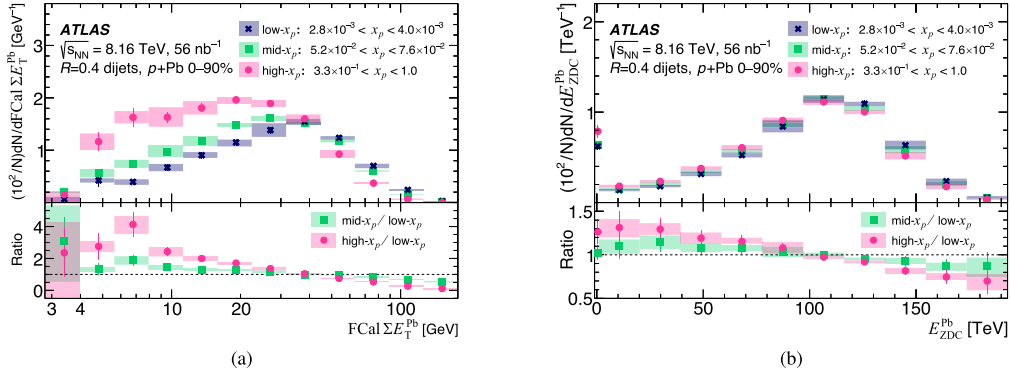


Fig. 2. (a) FCal ΣE_T^{Pb} and (b) $E_{\text{ZDC}}^{\text{Pb}}$ distributions plotted for low-, middle-, and high- x_p selections. These distributions are normalized to display the change of shape with x_p . The bottom panel displays the ratio of the middle- and high- x_p selection over the low- x_p selection. In sub-figure (b) the energy below the ZDC detection threshold (e.g., formally assigned as zero by ZDC reconstruction) is reported in a dedicated bin. Please note that results in each bin are divided by the bin width. This is relevant in sub-figure (b) comparing the zero energy bin to the rest of the distribution. Vertical error bars represent the statistical uncertainty, and the shaded areas represent the systematic uncertainty. The width of the shaded area indicates the bin width.

between $E_{\text{ZDC}}^{\text{Pb}}$ with and without the non-linear correction applied, across the whole spectrum of $E_{\text{ZDC}}^{\text{Pb}}$ values. Akin to the previous ZDC uncertainties, an additional systematic uncertainty is assigned to the stability of this correction and any residual scale variation.

The stability of the FCal in measuring $\text{FCal } \Sigma E_T^{\text{Pb}}$ across the run was scrutinized and the associated uncertainty is found to be negligible compared with other systematic uncertainties assigned.

The variations for each systematic uncertainty were then added in quadrature to produce the total systematic uncertainties in each data point.

The $E_{\text{ZDC}}^{\text{Pb}}$ total systematic uncertainties are dominated by the ZDC energy stability term, which is within 7% for most bins considered. The uncertainty grows towards high $E_{\text{ZDC}}^{\text{Pb}}$ values and at the edges of the x_p measurement range, where it reaches up to 30%.

The total systematic uncertainties in the $\text{FCal } \Sigma E_T^{\text{Pb}}$ distributions in various x_p bins is dominated by contributions from the JES, JER, and unfolding prior components. It is within 10% for most bins, increasing at high and low $\text{FCal } \Sigma E_T^{\text{Pb}}$ values and at the edges of the x_p measurement range, where it gets up to 20%.

The total systematic uncertainties in the distributions of $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ and $\langle \text{FCal } \Sigma E_T^{\text{Pb}} \rangle$ are below 2% in all the x_p bins except for the lowest, where it reaches 3%. When ratios are constructed, the JES, JER, HEC, and ZDC uncertainties are treated as fully correlated between measurement interval, while the prior uncertainty is treated as uncorrelated.

6. Results

Normalized distributions of $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal } \Sigma E_T^{\text{Pb}}$ in dijet events are presented in intervals of x_p , estimated by using Eq. (1), chosen to allow a direct comparison with the results of ref. [28]. The highest and lowest bins are wider to accrue more statistics.

Fig. 2(a) shows a comparison of $\text{FCal } \Sigma E_T^{\text{Pb}}$ distributions in well-separated intervals of x_p . The lower panel of Fig. 2(a) shows the ratio of the middle- and high- x_p $\text{FCal } \Sigma E_T^{\text{Pb}}$ distributions to that in low- x_p dijet events. These ratios show that, relative to a lower- x_p selection, higher- x_p events have a $\text{FCal } \Sigma E_T^{\text{Pb}}$ distribution that is significantly different and shifted towards lower energies. This observation represents the first direct confirmation of the event activity bias first observed by ATLAS in jet measurements [20,28].

The distributions of $E_{\text{ZDC}}^{\text{Pb}}$ are presented, in the same fashion as Fig. 2(a), in Fig. 2(b). The lower panel of Fig. 2(b) shows the ratio of the middle- and high- x_p $E_{\text{ZDC}}^{\text{Pb}}$ distributions to that in low- x_p dijet events. The ratio reveals a significant difference between the $E_{\text{ZDC}}^{\text{Pb}}$ distribution in high- x_p and low- x_p events, where the high- x_p distribution has a higher

fraction of events with fewer forward neutrons. This conclusion for the ZDC is qualitatively similar to, but substantially weaker than, the event activity bias in the FCal observed in Fig. 2(a).

The first bin in all the $E_{\text{ZDC}}^{\text{Pb}}$ distributions of Fig. 2(b) is set to 0–1 TeV, to isolate events that are compatible with zero neutrons in the detector. The fraction of events in these bins is smaller than 1%. These distributions are normalized to the bin width, introducing the visual jump between the first bin and the rest of the distribution. Furthermore, in ref. [61], ALICE observes a small fraction of hadronic Pb + Pb collisions with neutron topologies consistent with zero neutrons in one ZDC side. Extending this to the $p + \text{Pb}$ case, one might expect a small fraction of hadronic events to also be characterized by zero breakup neutrons.

These observations of shifting distributions, for both $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal } \Sigma E_T^{\text{Pb}}$, are consistent with a reduction in the number of interactions between the proton projectile and the nucleons in the nucleus with increasing x_p . The relative magnitude of the shift in the distribution of calorimeter energies is significantly larger in the $\text{FCal } \Sigma E_T^{\text{Pb}}$ case compared with the $E_{\text{ZDC}}^{\text{Pb}}$ case.

To better understand the correlations between x_p and the energy (transverse energy) detected in the ZDC (FCal), the mean values of the distributions are presented as a function of x_p in Fig. 3. Both curves exhibit a decrease as a function of x_p , more pronounced in the region $x_p \gtrsim 0.02$, corresponding to the onset of effects attributed to small proton size configurations in ref. [28]. The energy accumulated in the Pb-going side of the ZDC decreases by up to $\sim 5\%$ in this region, while a decrease of up to 40% is observed for the FCal. The observed decrease of $\sim 5\%$ in the $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ corresponds to, on average, an energy detected in the ZDC corresponding to two fewer beam-energy neutrons. Such a trend is qualitatively compatible with a reduced number of interactions for small proton configurations resulting in a smaller number of breakup neutrons, as suggested in ref. [35].

Fig. 4 shows the comparison between the rates of the x_p -dependent decrease between $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal } \Sigma E_T^{\text{Pb}}$, both normalized to their maximum values. The lower panel shows the ratio of the relative change in $\langle \text{FCal } \Sigma E_T^{\text{Pb}} \rangle$ over the relative change in $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ as a function of x_p . The ratio remains approximately constant, as shown by the fit in the Figure. For x_p bins $\lesssim 0.02$, the systematic uncertainty in the ratio becomes large despite cancellations from correlated sources of uncertainty, as even small deviations in $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ in this region where $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ is close to its maximal value can have a large effect on the ratio denominator. However, the ratio remains consistent with the constant fit within the large systematic uncertainties. This result shows that, in $p + \text{Pb}$ collisions, the energy deposited in the ZDC is about six times less sensitive to the hard process kinematics than the transverse energy at FCal rapidities.

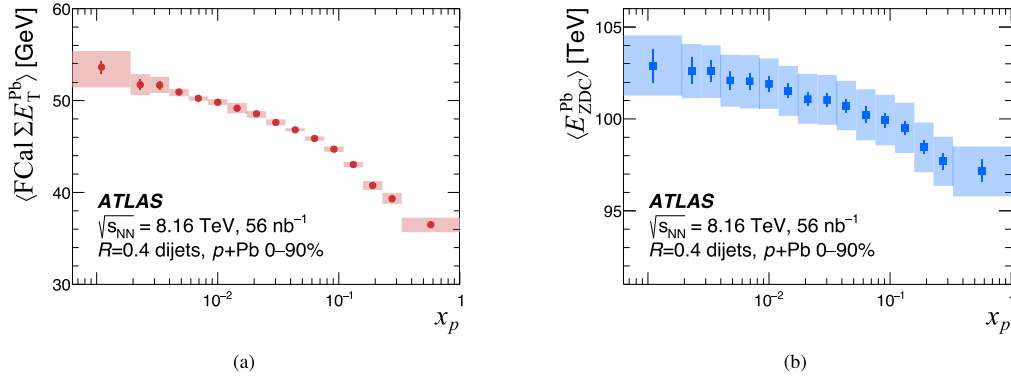


Fig. 3. (a) $\langle \text{FCal} \Sigma E_T^{\text{Pb}} \rangle$ and (b) $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ both as a function of x_p . Vertical error bars represent the statistical uncertainty, and the shaded areas represent the systematic uncertainty. The width of the shaded area indicates the bin width.

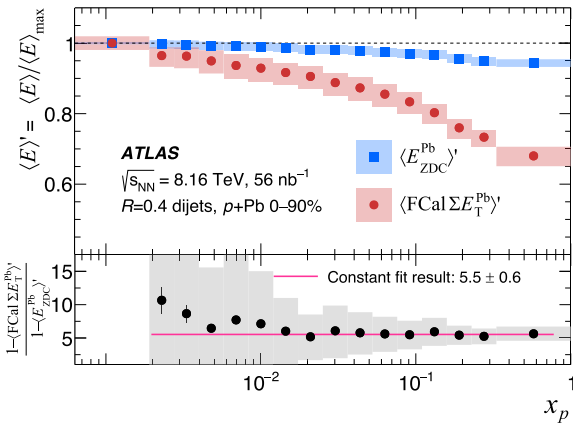


Fig. 4. $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$ as a function of x_p (square) compared with $\langle \text{FCal} \Sigma E_T^{\text{Pb}} \rangle$ as a function of x_p (circle). Both plots are normalized to their maximum value, to display both quantities on the same scale. The bottom panel shows the ratio of the relative change in $\langle \text{FCal} \Sigma E_T^{\text{Pb}} \rangle$ over the relative change in $\langle E_{\text{ZDC}}^{\text{Pb}} \rangle$, fit to a constant function (solid line). Shaded areas represent the systematic uncertainty. The width of the shaded area indicates the bin width. The statistical error on the $\langle E \rangle_{\text{max}}$ is included in the systematic band as it is correlated bin-to-bin in x_p for all bins except for the lowest x_p bin. The vertical error bars represent the uncorrelated statistical uncertainty.

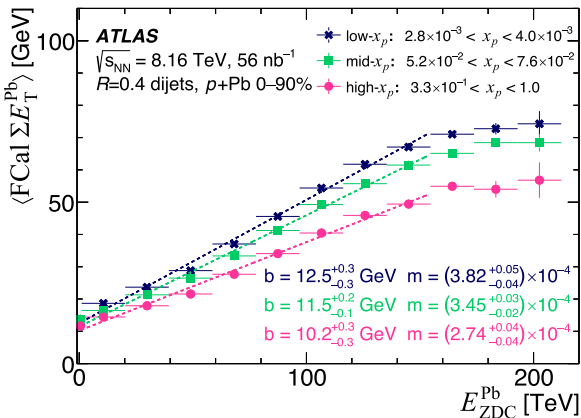


Fig. 5. $\langle \text{FCal} \Sigma E_T^{\text{Pb}} \rangle$ plotted as a function of $E_{\text{ZDC}}^{\text{Pb}}$ for three selections of x_p : a low, middle, and high selection. The data in each bin are fit to a linear form ($f(x) = m \cdot x + b$) to approximately describe the correlation between the two energies. Fit parameters (and fit uncertainties) are reported on the figure. The values of x_p are measured at the reconstructed level.

The correlation between the transverse energy produced by the interactions of the participants and the energy deposited by the spectator neutrons in the ZDC in x_p selections, measured at the reconstructed level, is also studied. The Pearson correlation coefficient between $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal} \Sigma E_T^{\text{Pb}}$, calculated for events in each x_p bin, decreases by 3% from the high- x_p to low- x_p . This finding suggests that, in a smaller proton configuration, the forward transverse energy produced by the interactions of the participants is slightly less correlated with the number of spectator neutrons at very forward rapidities.

To further study the evolution of the correlation between $\text{FCal} \Sigma E_T^{\text{Pb}}$ and $E_{\text{ZDC}}^{\text{Pb}}$ with x_p , Fig. 5 reports $\langle \text{FCal} \Sigma E_T^{\text{Pb}} \rangle$ as a function of $E_{\text{ZDC}}^{\text{Pb}}$ for three different x_p selections. A relationship of $\langle \text{FCal} \Sigma E_T^{\text{Pb}} \rangle$ as a function of $E_{\text{ZDC}}^{\text{Pb}}$ consistent with a linear dependence is observed in the range of 0–150 TeV in $E_{\text{ZDC}}^{\text{Pb}}$ for all the x_p bins. In Fig. 5, each distribution is fit to a linear function over that domain to approximately capture the underlying relation between the energies measured in the two calorimeters. The data above 150 TeV, corresponding to ~ 60 neutrons, are not considered in the fit since visible deviations from the linear trend start to appear. This behavior is likely due to fluctuations in the nuclear breakup occurring in events characterized by the highest (most central) event activity (collision geometry). The dependence of the linear fit's slope and intercept on the fit range was studied by systematically varying the upper limit of the fit range to cover ± 1 bin in $E_{\text{ZDC}}^{\text{Pb}}$ relative to the nominal choice of 150 TeV. The slope of the linear correlation between $\langle \text{FCal} \Sigma E_T^{\text{Pb}} \rangle$ and $E_{\text{ZDC}}^{\text{Pb}}$ decreases progressively moving from low to high- x_p values, an observation consistent with the x_p dependence of the Pearson correlation coefficient. Both these quantities are useful metrics for describing how the relationship between $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal} \Sigma E_T^{\text{Pb}}$ changes with x_p . However, a change in the number of neutrons does not directly imply a change in the transverse energy produced by the interactions of the participants at forward rapidity; they change as they both are correlated with the $p+\text{Pb}$ collision geometry.

7. Conclusion

This Letter presents the characterization of the dependence of two event geometry estimators, used in the analysis of hard-scatterings in $p+\text{Pb}$ collisions, on the initial-state kinematics. The transverse energy deposited in the ATLAS Forward Calorimeter and the forward energy recorded by the Zero-Degree Calorimeter in $p+\text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV are analyzed as a function of the estimated Bjorken- x of the proton, x_p , accessed through dijet events detected using the ATLAS calorimeter. Both $E_{\text{ZDC}}^{\text{Pb}}$ and $\text{FCal} \Sigma E_T^{\text{Pb}}$ are shown to be sensitive to x_p , especially in the region $x_p \gtrsim 0.02$, where previous ATLAS results from the same data [28] have shown strong evidence of event activity biases that can be interpreted in terms of color fluctuation effects related to

the proton configuration at the moment of the hard-scattering [23]. The average $E_{\text{ZDC}}^{\text{Pb}}$ shows variations corresponding to two beam-energy neutrons between the high- and low- x_p selections considered in the analysis. Still, compared with the transverse energy in the Pb-going FCal, the energy deposited in the Pb-going ZDC is found to be about six times more robust against variations in the event kinematics for measurements of hard process rate modifications.

Further studies on the correlation between the two geometry estimators as a function of x_p are also reported. This analysis exposes a linear, x_p -dependent, relation between FCal $\Sigma E_{\text{T}}^{\text{Pb}}$ and $E_{\text{ZDC}}^{\text{Pb}}$. These results can be used to inform the simultaneous modeling of event activity and nuclear breakup in $p + \text{Pb}$ collisions characterized by the presence of a hard-scattering.

The results presented in this Letter qualitatively support models that connect color fluctuations with neutrons evaporated in the nuclear breakup [35,62]. Access to the underlying physics linking hard-scatterings and nuclear breakup will also aid the understanding of nuclear evaporation in processes characterized by resolved photon exchange, such as dijet production in UPCs at the LHC and $e + A$ collisions at the future Electron-Ion Collider.

Data availability

The public release of data supporting the findings of this article will follow the CERN Open Data Policy. The values of relevant plots and tables associated with this article are stored in HEPData.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank CERN for the very successful operation of the LHC and its injectors, as well as the support staff at CERN and at our institutions worldwide without whom ATLAS could not be operated efficiently. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in ref. [63].

We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRG and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMFT, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ICHEP and Academy of Sciences and Humanities, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW, Poland; FCT, Portugal; MNE/IFA, Romania; MSTDI, Serbia; MSSR, Slovakia; ARIS and MVZI, Slovenia; DSI/NRF, South Africa; MICIU/AEI, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; NSTC, Taipei; TENMAK, Türkiye; STFC/UKRI, United Kingdom; DOE and NSF, United States of America.

Individual groups and members have received support from BCKDF, CANARIE, CRC and DRAC, Canada; CERN-CZ, FORTE and PRIMUS, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex

and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA and AGAUR programs from Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom; Eric and Wendy Schmidt Fund for Strategic Innovation, United States of America.

In addition, individual members wish to acknowledge support from Armenia: Yerevan Physics Institute (FAPERJ); CERN: European Organization for Nuclear Research (CERN DOCT); Chile: Agencia Nacional de Investigación y Desarrollo (ANID FONDECYT reg. 1230987, FONDECYT 1230812, FONDECYT 1240864, Fondecyt 3240661, Fondecyt Regular 1240721); China: Chinese Ministry of Science and Technology (MOST-2023YFA1605700, MOST-2023YFA1609300), National Natural Science Foundation of China (NSFC - 12175119, NSFC 12275265); Czech Republic: Czech Science Foundation (GACR - 24-11373S), Ministry of Education Youth and Sports (ERC-CZ-LL2327, FORTE CZ.02.01.01/00/22_008/0004632), PRIMUS Research Programme (PRIMUS/21/SCI/017); EU: H2020 European Research Council (ERC - 101002463); European Union: European Research Council (BARD No. 101116429, ERC - 948254, ERC 101089007), European Regional Development Fund (HE COFUND GA No.101081355, ERDF), Horizon 2020 Framework Programme (MUCCA - CHIST-ERA-19-XAI-00), European Union, Future Artificial Intelligence Research (FAIR-NextGenerationEU PE00000013), Horizon 2020 (EuroHPC - EHPC-DEV-2024D11-051), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU), Marie Skłodowska-Curie Actions (ERC Horizon-2020, GA 956086, GAP-101168829); France: Agence Nationale de la Recherche (ANR-21-CE31-0013, ANR-21-CE31-0022, ANR-22-EDIR-0002, ANR-24-CE31-0504-01); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG - 469666862, DFG - CR 312/5-2); China: Research Grants Council (GRF); Italy: Istituto Nazionale di Fisica Nucleare (ICSC, NextGenerationEU), Ministero dell'Università e della Ricerca (NextGenEU 153D23001490006 M4C2.1.1, NextGenEU 153D23000820006 M4C2.1.1, NextGenEU 153D23001490006 M4C2.1.1, SOE2024_0000023); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI JP22H01227, JSPS KAKENHI JP22H04944, JSPS KAKENHI JP22KK0227, JSPS KAKENHI JP23KK0245, JSPS KAKENHI JP24K23939); Norway: Research Council of Norway (RCN-314472); Poland: Ministry of Science and Higher Education (IDUB AGH, POB8, D4 no 9722), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS 2023/51/B/ST2/02507, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, UMO-2022/47/O/ST2/00148, UMO-2023/49/B/ST2/04085, UMO-2023/51/B/ST2/00920, UMO-2024/53/N/ST2/00869); Portugal: Foundation for Science and Technology (FCT); Spain: Agència de Gestió d'Ajuts Universitaris i de Recerca. (AGAUR - 2023 BP 00141), Generalitat Valenciana (ASFAE/2022/008), Ministry of Science and Innovation (MCIN & NextGenEU PCI2022-135018-2, MICIN & FEDER PID2021-125273NB, RYC2019-028510-I, RYC2020-030254-I, RYC2021-031273-I, RYC2022-038164-I), Ministerio de Ciencia, Innovación y Universidades/Agencia Estatal de Investigación (PID2022-142604OB-C22); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS 22:2312), Swedish Research Council (Swedish Research Council 2023-04654, VR 2021-03651, VR 2022-03845, VR 2022-04683, VR 2023-03403, VR 2024-05451), Knut and Alice Wallenberg Foundation (KAW 2018.0458, KAW 2022.0358, KAW 2023.0366); Switzerland: Swiss National Science Foundation (SNSF - PCEFP2_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust RPG-2020-004), Royal Society (NIF-R1-231091); United States of America: U.S. Department of Energy (ECA DE-AC02-76SF00515), Neubauer Family Foundation.

The ATLAS Collaboration

G. Aad¹⁵², E. Aakvaag¹⁸, B. Abbott¹⁷⁴, S. Abdelhameed¹⁶⁹, K. Abeling⁸², N.J. Abicht⁷⁶, S.H. Abidi⁴³, M. Aboelela⁷¹, A. Aboulhorma⁶⁰, H. Abramowicz²²⁴, Y. Abulaiti¹⁷¹, B.S. Acharya^{XIV,100,101}, A. Ackermann⁹¹, C. Adam Bourdarios⁵, L. Adamczyk¹³⁴, S.V. Addepalli²¹⁴, M.J. Addison¹⁵¹, J. Adelman¹⁶⁸, A. Adiguzel²⁶, T. Adye¹⁹⁴, A.A. Affolder¹⁹⁶, Y. Afik⁶⁵, M.N. Agaras¹⁴, A. Aggarwal¹⁵⁰, C. Agheorghiesei³⁶, F. Ahmadov^{XXXI,64}, S. Ahuja¹⁴⁵, X. Ai²⁰⁷, G. Aielli^{115,116}, A. Aikot²³⁷, M. Ait Tamlihat⁶⁰, B. Aitbenchikh⁵⁶, M. Akbiyik¹⁵⁰, T.P.A. Åkesson¹⁴⁸, A.V. Akimov²¹⁶, D. Akiyama²⁴², N.N. Akolkar³¹, S. Aktas²⁴, G.L. Alberghi³⁰, J. Albert²³⁹, P. Albicocco⁸⁰, G.L. Albouy⁸⁸, S. Alderweireldt⁷⁹, Z.L. Alegria¹⁷⁵, M. Aleksa⁶², I.N. Aleksandrov⁶⁴, C. Alexa³⁵, T. Alexopoulos¹¹, F. Alfonsi³⁰, M. Algren⁸³, M. Alhroob²⁴¹, B. Ali¹⁹², H.M.J. Ali^{XXIV,141}, S. Ali⁴⁵, S.W. Alibocus¹⁴², M. Aliev⁴⁹, G. Alimonti¹⁰⁵, W. Alkakh⁸², C. Allaire⁹⁷, B.M.M. Allbrooke²¹⁷, J.S. Allen¹⁵¹, J.F. Allen⁷⁹, P.P. Allport²³, A. Aloisio^{107,108}, F. Alonso¹⁴⁰, C. Alpigiani²⁰⁵, Z.M.K. Alsolami¹⁴¹, A. Alvarez Fernandez¹⁵⁰, M. Alves Cardoso⁸³, M.G. Alviggi^{107,108}, M. Aly¹⁵¹, Y. Amaral Coutinho¹²⁶, A. Ambler¹⁵⁴, C. Amelung⁶², M. Ameri¹⁵¹, C.G. Ames¹⁵⁹, T. Amezza¹⁸¹, D. Amidei¹⁵⁶, B. Amini⁸¹, K. Amirie²²⁸, A. Amirkhanov⁶⁴, S.P. Amor Dos Santos¹⁸⁴, K.R. Amos²³⁷, D. Amperiadou²²⁵, S. An¹³⁰, C. Anastopoulos²¹⁰, T. Andeen¹², J.K. Anders¹⁴², A.C. Anderson⁸⁷, A. Andreazza^{105,106}, S. Angelidakis¹⁰, A. Angerami⁶⁷, A.V. Anisenkov⁶⁴, A. Annovi¹¹¹, C. Antel⁶², E. Antipov²¹⁶, M. Antonelli⁸⁰, F. Anulli¹¹³, M. Aoki¹³⁰, T. Aoki²²⁶, M.A. Aparo²¹⁷, L. Aperio Bella⁷⁵, M. Apicella⁴⁴, C. Appelt²²⁴, A. Apyan³³, S.J. Arbiol Val¹³⁶, C. Arcangeletti⁸⁰, A.T.H. Arce⁷⁸, J-F. Arguin¹⁵⁸, S. Argyropoulos²²⁵, J.-H. Arling⁷⁵, O. Arnaez⁵, H. Arnold²¹⁶, G. Artoni^{113,114}, H. Asada¹⁶¹, K. Asai¹⁷², S. Asai²²⁶, S. Asatryan²⁴⁷, N.A. Asbah⁶², R.A. Ashby Pickering²⁴¹, A.M. Aslam¹⁴⁵, K. Assamagan⁴³, R. Astalos⁴¹, K.S.V. Astrand¹⁴⁸, S. Atashi²³³, R.J. Atkin⁴⁷, H. Atmani⁶¹, P.A. Atlasiddha¹⁸², K. Augsten¹⁹², A.D. Auriol⁶⁶, V.A. Austrup¹⁵¹, G. Avolio⁶², K. Axiotis⁸³, G. Azuelos^{XXXV,158}, A. Azzam¹⁴, D. Babal⁴², H. Bachacou¹⁹⁵, K. Bachas^{XVIII,225}, A. Bachi⁵⁵, E. Bachmann⁷⁷, M.J. Backes⁹¹, A. Badea⁶⁵, T.M. Baer¹⁵⁶, P. Bagnaia^{113,114}, M. Bahmani²¹, D. Bahner⁸¹, K. Bai¹⁷⁷, J.T. Baines¹⁹⁴, L. Baines¹⁴⁴, O.K. Baker²⁴⁶, E. Bakos¹⁷, D. Bakshi Gupta⁹, L.E. Balabram Filho¹²⁶, V. Balakrishnan¹⁷⁴, R. Balasubramanian⁵, E.M. Baldin⁶³, P. Balek¹³⁴, E. Ballabene^{30,29}, F. Balli¹⁹⁵, L.M. Baltes⁹¹, W.K. Balunas⁴⁶, J. Balz¹⁵⁰, I. Bamwidhi¹⁷⁰, E. Banas¹³⁶, M. Bandieramonte¹⁸³, A. Bandyopadhyay³¹, S. Bansal³¹, L. Barak²²⁴, M. Barakat⁷⁵, E.L. Barberio¹⁵⁵, D. Barberis²⁰, M. Barbero¹⁵², M.Z. Barel¹⁶⁷, T. Barillari¹⁶⁰, M-S. Barisits⁶², T. Barklow²¹⁴, P. Baron¹⁹³, D.A. Baron Moreno¹⁵¹, A. Baronecchi⁹⁰, A.J. Barr¹⁸⁰, J.D. Barr¹⁴⁶, F. Barreiro¹⁴⁹, J. Barreiro Guimarães da Costa¹⁵, M.G. Barros Teixeira¹⁸⁴, S. Barsov⁶³, F. Bartels⁹¹, R. Bartoldus²¹⁴, A.E. Barton¹⁴¹, P. Bartos⁴¹, A. Basan¹⁵⁰, M. Baselga⁷⁶, S. Bashiri¹³⁶, A. Bassalat^{II,97}, M.J. Basso²²⁹, S. Bataju⁷¹, R. Bate²³⁸, R.L. Bates⁸⁷, S. Batlamous¹⁴⁹, M. Battaglia¹⁹⁶, D. Battulga²¹, M. Bauce^{113,114}, M. Bauer¹²¹, P. Bauer³¹, L.T. Bayer⁷⁵, L.T. Bazzano Hurrell⁴⁴, J.B. Beacham¹⁶⁰, T. Beau¹⁸¹, J.Y. Beaupre¹⁴⁰, P.H. Beauchemin²³², P. Bechtel³¹, H.P. Beck^{XVII,22}, K. Becker²⁴¹, A.J. Beddall¹²⁴, V.A. Bednyakov⁶⁴, C.P. Bee²¹⁶, L.J. Beemster¹⁷, M. Begalli¹²⁸, M. Begel⁴³, J.K. Behr⁷⁵, J.F. Beirer⁶², F. Beisiegel³¹, M. Belfkir¹⁷⁰, G. Bella²²⁴, L. Bellagamba³⁰, A. Bellerive⁵⁵, C.D. Bellgraph⁹⁹, P. Bellos²³, K. Beloborodov⁶³, D. Benchebkroun⁵⁶, F. Bendebba⁵⁶, Y. Benhammou²²⁴, K.C. Benkendorfer⁸⁹, L. Beresford⁷⁵, M. Beretta⁸⁰, E. Bergeas Kuutmann²³⁵, N. Berger⁵, B. Bergmann¹⁹², J. Beringer¹⁹, G. Bernardi⁶, C. Bernius²¹⁴, F.U. Bernlochner³¹, F. Bernon⁶², A. Berrocal Guardia¹⁴, T. Berry¹⁴⁵, P. Berta¹⁹³, A. Berthold⁷⁷, A. Berti¹⁸⁴, R. Bertrand¹⁵², S. Bethke¹⁶⁰, A. Bett^{113,114}, A.J. Bevan¹⁴⁴, L. Bezio⁸³, N.K. Bhalla⁸¹, S.

Bharthuar¹⁶⁰, S. Bhatta²¹⁶, P. Bhattacharj²¹⁴, Z.M. Bhatti¹⁷¹, K.D. Bhide⁸¹, V.S. Bhopatkar¹⁷⁵, R.M. Bianchi¹⁸³, G. Bianco^{30,29}, O. Biebel¹⁵⁹, M. Biglietti¹¹⁷, C.S. Billingsley⁷¹, Y. Bimgdi⁶¹, M. Bindi⁸², A. Bingham²⁴⁵, A. Bingul²⁵, C. Bini^{113,114}, G.A. Bird⁴⁶, M. Birman²⁴³, M. Biros¹⁹³, S. Biryukov²¹⁷, T. Bisanz⁷⁶, E. Bisceglie^{30,29}, J.P. Biswal¹⁹⁴, D. Biswas²¹², I. Bloch⁷⁵, A. Blue⁸⁷, U. Blumenschein¹⁴⁴, J. Blumenthal¹⁵⁰, V.S. Bobrovnikov⁶⁴, L. Boccardo^{85,84}, M. Boehler⁸¹, B. Boehm²⁴⁰, D. Bogavac¹⁴, A.G. Bogdanchikov⁶³, L.S. Boggia¹⁸¹, V. Boisvert¹⁴⁵, K. Bogan⁶², T. Bold¹³⁴, M. Bomben⁶, M. Bona¹⁴⁴, M. Boonekamp¹⁹⁵, A.G. Borbély⁸⁷, I.S. Bordulev⁶³, G. Borissov¹⁴¹, D. Bortoletto¹⁸⁰, D. Boscherini³⁰, M. Bosman¹⁴, K. Bouaouda⁵⁶, N. Bouchhar²³⁷, L. Boudet⁵, J. Boudreau¹⁸³, E.V. Bouhova-Thacker¹⁴¹, D. Boumedienne⁶⁶, R. Bouquet^{85,84}, A. Boveia¹⁷³, J. Boyd⁶², D. Boye⁴³, I.R. Boyko⁶⁴, L. Bozianu⁸³, J. Bracinik²³, N. Brahimi⁵, G. Brandt²⁴⁵, O. Brandt⁴⁶, B. Brau¹⁵³, J.E. Brau¹⁷⁷, R. Brenner²⁴³, L. Brenner¹⁶⁷, R. Brenner²³⁵, S. Bressler²⁴³, G. Brianti^{119,120}, D. Britton⁸⁷, D. Britzger¹⁶⁰, I. Brock³¹, R. Brock¹⁵⁷, G. Brooijmans⁶⁷, A.J. Brooks⁹⁹, E.M. Brooks²³⁰, E. Brost⁴³, L.M. Brown^{239,229}, L.E. Bruce⁸⁹, T.L. Bruckler¹⁸⁰, P.A. Bruckman de Renstrom¹³⁶, B. Brüers⁷⁵, A. Bruni³⁰, G. Bruni³⁰, D. Brunner^{73,74}, M. Bruschi³⁰, N. Bruscino^{113,114}, T. Buanes¹⁸, Q. Buat²⁰⁵, D. Buchin¹⁶⁰, A.G. Buckley⁸⁷, O. Bulekov¹²⁴, B.A. Bullard²¹⁴, S. Burdin¹⁴², C.D. Burgard⁷⁶, A.M. Burger¹³⁹, B. Burghgrave⁹, O. Burlayenko⁸¹, J. Burleson²³⁶, J.C. Burzynski²¹³, E.L. Busch⁶⁷, V. Büscher¹⁵⁰, P.J. Bussey⁸⁷, J.M. Butler³², C.M. Buttar⁸⁷, J.M. Butterworth¹⁴⁶, W. Buttinger¹⁹⁴, C.J. Buxo Vazquez¹⁵⁷, A.R. Buzykaev⁶⁴, S. Cabrera Urbán²³⁷, L. Cadamuro⁹⁷, D. Caforio⁸⁶, H. Cai¹⁸³, Y. Cai^{30,164,29}, Y. Cai¹⁶², V.M.M. Cairo⁶², O. Cakir³, N. Calace⁶², P. Calafiura¹⁹, G. Calderini¹⁸¹, P. Calfayan⁵⁵, G. Callea⁸⁷, L.P. Caloba¹²⁶, D. Calvet⁶⁶, S. Calvet⁶⁶, R. Camacho Toro¹⁸¹, S. Camarda⁶², D. Camarero Munoz³³, P. Camarri^{115,116}, C. Camincher²³⁹, M. Campanelli¹⁴⁶, A. Camplani⁶⁸, V. Canale^{107,108}, A.C. Canbay³, E. Canonero¹⁴⁵, J. Cantero²³⁷, Y. Cao²³⁶, F. Capocasa³³, M. Capua^{70,69}, A. Carbone^{105,106}, R. Cardarelli¹¹⁵, J.C.J. Cardenas⁹, M.P. Cardiff³³, G. Carducci^{70,69}, T. Carl⁶², G. Carlino¹⁰⁷, J.I. Carlotto¹⁴, B.T. Carlson^{XIX,183}, E.M. Carlson²³⁹, J. Carmignani¹⁴², L. Carminati^{105,106}, A. Carnelli⁵, M. Carnesale⁶², S. Caron¹⁶⁶, E. Carquin²⁰³, I.B. Carr¹⁵⁵, S. Carrá^{109,110}, G. Carratta^{30,29}, A.M. Carroll¹⁷⁷, M.P. Casado^{IX,14}, P. Casolaro^{107,108}, M. Caspar⁷⁵, F.L. Castillo⁵, L. Castillo Garcia¹⁴, V. Castillo Gimenez²³⁷, N.F. Castro^{184,188}, A. Catinaccio⁶², J.R. Catmore¹⁷⁹, T. Cavaliere⁵, V. Cavaliere⁴³, L.J. Cavedes Betancourt²⁸, E. Celebi¹²⁴, S. Cella⁶², V. Cepaitis⁸³, K. Cerny¹⁷⁶, A.S. Cerqueira¹²⁵, A. Cerri^{XXXIX,111}, L. Cerrito^{115,116}, F. Cerutti¹⁹, B. Cervato^{105,106}, A. Cervelli³⁰, G. Cesarini⁸⁰, S.A. Cetin¹²⁴, P.M. Chabrilat¹⁸¹, R. Chakkappai⁹⁷, S. Chakraborty²⁴¹, J. Chan¹⁹, W.Y. Chan²²⁶, J.D. Chapman⁴⁶, E. Chapon¹⁹⁵, B. Chargeishvili²²¹, D.G. Charlton²³, C. Chauhan¹⁹³, Y. Che¹⁶², S. Chekanov⁷, S.V. Chekulaev²²⁹, G.A. Chelkov^{I,64}, B. Chen²²⁴, B. Chen²³⁹, H. Chen¹⁶², H. Chen⁴³, J. Chen²⁰⁸, J. Chen²¹³, M. Chen¹⁸⁰, S. Chen¹³⁷, S.J. Chen¹⁶², X. Chen²⁰⁸, X. Chen^{XXXIV,16}, Z. Chen⁹⁰, C.L. Cheng²⁴⁴, H.C. Cheng⁹³, S. Cheong²¹⁴, A. Cheplakov⁶⁴, E. Cherepanova¹⁶⁷, R. Cherkasov¹⁶⁷, Moursli⁶⁰, E. Cheu⁸, K. Cheung⁹⁶, L. Chevalier¹⁹⁵, V. Chiereella⁸⁰, G. Chiarelli¹¹¹, G. Chiodini¹⁰³, A.S. Chisholm²³, A. Chitan³⁵, M. Chitishvili²³⁷, M.V. Chizhov^{XX,64}, K. Choi¹², Y. Chou²⁰⁵, E.Y.S. Chow¹⁶⁶, K.L. Chu²⁴³, M.C. Chu⁹³, X. Chu^{15,164}, Z. Chubinidze⁸⁰, J. Chudoba¹⁹¹, J.J. Chwastowski¹³⁶, D. Cieri¹⁶⁰, K.M. Ciesla¹³⁴, V. Cindro¹⁴³, A. Ciocio¹⁹, F. Ciotto^{107,108}, Z.H. Citron²⁴³, M. Citterio¹⁰⁵, D.A. Ciubotaru³⁵, A. Clark⁸³, P.J. Clark⁷⁹, N. Clarke Hall¹⁴⁶, C. Clarry²²⁸, S.E. Clawson⁷⁵, C. Clement^{73,74}, Y. Coadou¹⁵², M. Cobl^{100,102}, A. Coccaro⁸⁵, R.F. Coelho Barrue¹⁸⁴, R. Coelho Lopes De Sa¹⁵³, S. Coelli¹⁰⁵, L. S. Colangeli²²⁸, B. Cole⁶⁷, P. Collado Soto¹⁴⁹, J. Collot⁸⁸, M.R. Coluccia¹⁰³, P. Conde Muino^{184,190}, M.P. Connell⁴⁹, S.H. Connell⁴⁹, E.I. Conroy¹⁸⁰, M.

Contreras Cossio¹², F. Conventi^{XXXVI,107}, A.M. Cooper-Sarkar¹⁸⁰, L. Corazzina^{113,114}, F. A. Corchia^{30,29}, A. Cordeiro Oudot Choi²⁰⁵, L.D. Corpe⁶⁶, M. Corradi^{113,114}, F. Corriveau^{XXIX,154}, A. Cortes-Gonzalez²²⁶, M.J. Costa²³⁷, F. Costanza⁵, D. Costanzo²¹⁰, B.M. Cote¹⁷³, J. Couthures⁵, G. Cowan¹⁴⁵, K. Cranmer²⁴⁴, L. Cremer⁷⁶, D. Cremonini^{30,29}, S. Crépé-Renaudin⁸⁸, F. Crescioli¹⁸¹, T. Cresta^{109,110}, M. Cristinziani²¹², M. Cristoforetti^{119,120}, V. Croft¹⁶⁷, J.E. Crosby¹⁷⁵, G. Crosetti^{70,69}, A. Cueto¹⁴⁹, H. Cui¹⁴⁶, Z. Cui⁸, W.R. Cunningham⁸⁷, F. Curcio²³⁷, J. R. Curran⁷⁹, M.J. Da Cunha Sargedas De Sousa^{85,84}, J.V. Da Fonseca Pinto¹²⁶, C. Da Via¹⁵¹, W. Dabrowski¹³⁴, T. Dado⁶², S. Dabhi²¹⁹, T. Dai¹⁵⁶, D. Dal Santo²², C. Dallapiccola¹⁵³, M. Dam⁶⁸, G. D'amen⁴³, V. D'Amico¹⁵⁹, J. Damp¹⁵⁰, J.R. Dandoy⁵⁵, D. Dannheim⁶², G. D'anniballe^{111,112}, M. Danninger²¹³, V. Dao²¹⁶, G. Darbo⁸⁵, S.J. Das⁴³, F. Dattola⁷⁵, S. D'Auria^{105,106}, A. D'Avanzo^{107,108}, T. Davidek¹⁹³, J. Davidson²⁴¹, I. Dawson¹⁴⁴, K. De⁹, C. De Almeida Rossi²²⁸, R. De Asmundis¹⁰⁷, N. De Biase⁷⁵, S. De Castro^{30,29}, N. De Groot¹⁶⁶, P. De Jong¹⁶⁷, H. De la Torre¹⁶⁸, A. De Maria¹⁶², A. De Salvo¹¹³, U. De Sanctis^{115,116}, F. De Santis^{103,104}, A. De Santo²¹⁷, J.B. De Vivie De Regie⁸⁸, J. Debevc¹⁴³, D.V. Dedovich⁶⁴, J. Degens¹⁴², A.M. Deiana⁷¹, J. Del Peso¹⁴⁹, L. Delagrangé¹⁸¹, F. Deliot¹⁹⁵, C.M. Delitzsch⁷⁶, M. Della Pietra^{107,108}, D. Della Volpe⁸³, A. Dell'Acqua⁶², L. Dell'Asta^{105,106}, M. Delmastro⁵, C.C. Delogu¹⁵⁰, P.A. Delsart²⁴⁶, S. Demers²⁴⁶, M. Demichev⁶⁴, S.P. Denisov⁶³, H. Denizli^{XIII,24}, L. D'Eramo⁶⁶, D. Derendarz¹³⁶, F. Derue¹⁸¹, P. Dervan^{XLII,142}, A. M. Desai¹, K. Desch³¹, F.A. Di Bello^{85,84}, A. Di Ciaccio^{115,116}, L. Di Ciaccio⁵, A. Di Domenico^{113,114}, C. Di Donato^{107,108}, A. Di Girolamo⁶², G. Di Gregorio⁶², A. Di Luca^{119,120}, B. Di Micco^{117,118}, R. Di Nardo^{117,118}, K.F. Di Petrillo⁶⁵, M. Diamantopoulou⁵⁵, F.A. Dias¹⁶⁷, M.A. Diaz^{197,198}, A. R. Didenko⁶⁴, M. Didenko²³⁷, S.D. Diefenbacher¹⁹, E.B. Diehl¹⁵⁶, S. Díez Cornell⁷⁵, C. Diez Pardos²¹², C. Dimitriadis²¹⁵, A. Dimitrievska²³, A. Dimri²¹⁶, J. Dingfelder³¹, T. Dingley¹⁸⁰, I.M. Dinu³⁵, S.J. Dittmeier⁹², F. Dittus⁶², M. Divisek¹⁹³, B. Dixit¹⁴², F. Djama¹⁵², T. Djobava²²¹, C. Doglioni^{151,148}, A. Dohnalova⁴¹, Z. Dolezal¹⁹³, K. Domijan¹³⁴, K.M. Dona⁶⁵, M. Donadelli¹²⁸, B. Dong¹⁵⁷, J. Donini⁶⁶, A. D'Onofrio^{107,108}, M. D'Onofrio¹⁴², J. Dopke¹⁹⁴, A. Doria¹⁰⁷, N. Dos Santos Fernandes¹⁸⁴, P. Dougan¹⁵¹, M.T. Dova¹⁴⁰, A.T. Doyle⁸⁷, M.A. Dragnet¹⁸⁰, M.P. Drescher⁸², E. Dreyer²⁴³, I. Drivas-koulouris¹¹, M. Drnevich¹⁷¹, M. Drozdova⁸³, D. Du⁹⁰, T.A. du Pree¹⁶⁷, Z. Duan¹⁶², M. Dubau⁵, F. Dubinin⁶⁴, M. Dubovsky⁴¹, E. Duchovni²⁴³, G. Duckeck¹⁵⁹, P. K. Duckett¹⁴⁶, O.A. Ducu³⁵, D. Duda⁷⁹, A. Dudarev⁶², E. R. Duden³³, M. D'uffizi¹⁵¹, L. Duflo⁹⁷, M. Dührssen⁶², I. Duminica⁴⁰, A.E. Dumitriu³⁵, M. Dunford⁹¹, S. Dungs⁷⁶, K. Dunne^{73,74}, A. Duperrin¹⁵², H. Duran Yildiz³, M. Düren⁸⁶, A. Durglishvili²²¹, D. Duvnjak⁵⁵, G.I. Dyckes¹⁹, M. Dyndal¹³⁴, B.S. Dziedzic⁶², Z.O. Earnshaw²¹⁷, G.H. Eberwein¹⁸⁰, B. Eckerova⁴¹, S. Eggebrecht⁸², E. Egidio Purcino De Souza¹²⁹, G. Eigen¹⁸, K. Einsweiler¹⁹, T. Ekelof²³⁵, P.A. Ekman¹⁴⁸, S. El Farkh⁵⁷, Y. El Ghazali⁹⁰, H. El Jarrari⁶², A. El Moussaouy⁵⁶, V. Ellajosyula²³⁵, M. Ellert²³⁵, F. Ellinghaus²⁴⁵, T.A. Elliot¹⁴⁵, N. Ellis⁶², J. Elmsheuser⁴³, M. Elsayy¹⁶⁹, M. Elsing⁶², D. Emelianov¹⁹⁴, Y. Enari¹³⁰, I. Ene¹⁹, S. Epari¹⁵⁸, D. Ernani Martins Neto¹³⁶, F. Ernst⁶², M. Errenst²⁴⁵, M. Escalier⁹⁷, C. Escobar²³⁷, E. Etzion²²⁴, G. Evans^{184,185}, H. Evans⁹⁹, L.S. Evans¹⁴⁵, A. Ezhilov⁶³, S. Ezzarqtouni⁵⁶, F. Fabbri^{30,29}, L. Fabbri^{30,29}, G. Facini¹⁴⁶, V. Fadeyev¹⁹⁶, R.M. Fakhrutdinov⁶³, D. Fakoudis¹⁵⁰, S. Falciano¹¹³, L.F. Falda Ulhoa Coelho¹⁸⁴, F. Fallavollita¹⁶⁰, G. Falsetti^{70,69}, J. Faltova¹⁹³, C. Fan²³⁶, K. Y. Fan⁹⁴, Y. Fan¹⁵, Y. Fang^{15,164}, M. Fanti^{105,106}, M. Faraj^{100,101}, Z. Farazpay¹⁴⁷, A. Farbin⁹, A. Farilla¹¹⁷, T. Farooque¹⁵⁷, J. N. Farr²⁴⁶, S.M. Farrington^{194,79}, F. Fassi⁶⁰, D. Fassouliotis¹⁰, L. Fayard⁹⁷, P. Federic¹⁹³, P. Federicova¹⁹¹, O.L. Fedin¹⁶³, M. Feickert²⁴⁴, L. Feligioni¹⁵², D.E. Fellers¹⁹, C. Feng²⁰⁶, Z. Feng¹⁶⁷, M.J. Fenton²³³, L. Ferencz⁷⁵, B. Fernandez

Barbadillo¹⁴¹, P. Fernandez Martinez⁹⁸, M.J.V. Fernoux¹⁵², J. Ferrando¹⁴¹, A. Ferrari²³⁵, P. Ferrari^{167,166}, R. Ferrari¹⁰⁹, D. Ferrere⁸³, C. Ferretti¹⁵⁶, M. P. Fewell¹, D. Fiacco^{113,114}, F. Fiedler¹⁵⁰, P. Fiedler¹⁹², S. Filimonov⁶⁴, M.S. Filip^{XXI,35}, A. Filipčić¹⁴³, E.K. Filmer²²⁹, F. Filthaut¹⁶⁶, M.C.N. Fiolhais^{III,184,186}, L. Fiorini²³⁷, W.C. Fisher¹⁵⁷, T. Fitschen¹⁵¹, P. M. Fitzhugh¹⁹⁵, I. Fleck²¹², P. Fleischmann¹⁵⁶, T. Flick²⁴⁵, M. Flores^{XXXIII,50}, L.R. Flores Castillo⁹³, L. Flores Sanz De Acedo⁶², F.M. Follega^{119,120}, N. Fomin⁴⁶, J.H. Foo²²⁸, A. Formica¹⁹⁵, A.C. Forti¹⁵¹, E. Fortin⁶², A.W. Fortman¹⁹, L. Foster¹⁹, L. Fountas^{X,10}, D. Fournier⁹⁷, H. Fox¹⁴¹, P. Francavilla^{111,112}, S. Francescato⁸⁹, S. Franchellucci⁸³, M. Franchini^{30,29}, S. Franchino⁹¹, D. Francis⁶², L. Franco¹⁶⁶, V. Franco Lima⁶², L. Franconi⁷⁵, M. Franklin⁸⁹, G. Frattari³³, Y.Y. Frid²²⁴, J. Friend⁸⁷, N. Fritzsche⁶², A. Froch⁸³, D. Froidevaux⁶², J.A. Frost¹⁸⁰, Y. Fu¹⁵⁷, S. Fuenzalida Garrido²⁰³, M. Fujimoto¹⁵², K. Y. Fung⁹³, E. Furtado De Simas Filho¹²⁹, M. Furukawa²²⁶, J. Fuster²³⁷, A. Gaa⁸², A. Gabrielli^{30,29}, A. Gabrielli²²⁸, P. Gadow⁶², G. Gagliardi^{85,84}, L.G. Gagnon¹⁹, S. Gaid¹³², S. Galantzan²²⁴, J. Gallagher¹, E.J. Gallas¹⁸⁰, A.L. Gallen²³⁵, B.J. Gallop¹⁹⁴, K.K. Gan¹⁷³, S. Ganguly²²⁶, Y. Gao⁷⁹, A. Garabaglu²⁰⁵, F.M. Garay Walls^{197,198}, C. García²³⁷, A. Garcia Alonso¹⁶⁷, A.G. Garcia Caffaro²⁴⁶, J.E. García Navarro²³⁷, M. A. Garcia Ruiz²⁸, M. Garcia-Sciveres¹⁹, G.L. Gardner¹⁸², R.W. Gardner⁶⁵, N. Garelli²³², R.B. Garg²¹⁴, J.M. Gargan⁷⁹, C.A. Garner²²⁸, C.M. Garvey⁴⁷, V. K. Gassmann²³², G. Gaudio¹⁰⁹, V. Gautam¹⁴, P. Gauzzi^{113,114}, J. Gavranovic¹⁴³, I.L. Gavrilenko¹⁸⁴, A. Gavriluk⁶³, C. Gay²³⁸, G. Gaycken¹⁷⁷, E.N. Gazis¹¹, A. Gekow¹⁷³, C. Gemme⁸⁵, M.H. Genest⁸⁸, A. D. Gentry¹⁶⁵, S. George¹⁴⁵, T. Gerasis⁷², A. A. Gerwin¹⁷⁴, P. Gessinger-Befurt⁶², M.E. Geyik²⁴⁵, M. Ghani²⁴¹, K. Ghorbanian¹⁴⁴, A. Ghosal²¹², A. Ghosh²³³, A. Ghosh⁸, B. Giacobbe³⁰, S. Giagu^{113,114}, T. Giani¹⁶⁷, A. Giannini⁹⁰, S.M. Gibson¹⁴⁵, M. Gignac¹⁹⁶, D.T. Gil¹³⁵, A.K. Gilbert¹³⁴, B.J. Gilbert⁶⁷, D. Gillberg⁵⁵, G. Gilles¹⁶⁷, D.M. Gingrich^{XXXV,2}, M.P. Giordani^{100,102}, P.F. Giraud¹⁹⁵, G. Giugliarelli^{100,102}, D. Giugni¹⁰⁵, F. Giuli^{115,116}, I. Gkialas^{X,10}, L.K. Gladilin⁶³, C. Glasman¹⁴⁹, M. Glazewska²², R. M. Gleason²³³, G. Glemža⁷⁵, M. Glisic¹⁷⁷, I. Gnesi⁷⁰, Y. Go⁴³, M. Goblirsch-Kolb⁶², B. Gocke⁷⁶, D. Godin¹⁵⁸, B. Gokturk²⁴, S. Goldfarb¹⁵⁵, T. Golling⁸³, M.G.D. Gololo⁴⁹, D. Golubkov⁶³, J.P. Gombas¹⁵⁷, A. Gomes^{184,185}, G. Gomes Da Silva²¹², A.J. Gomez Delegido²³⁷, R. Gonçalo¹⁸⁴, L. Gonella²³, A. Gongadze²²², F. Gonnella²³, J.L. Gonski²¹⁴, R.Y. González Andana⁷⁹, S. González de la Hoz²³⁷, M. V. Gonzalez Rodrigues⁷⁵, R. Gonzalez Suarez²³⁵, S. Gonzalez-Sevilla⁸³, L. Goossens⁶², B. Gorini⁶², E. Gorini^{103,104}, A. Gorišek¹⁴³, T.C. Gosart¹⁸², A.T. Goshaw⁷⁸, M.I. Gostkin⁶⁴, S. Goswami¹⁷⁵, C.A. Gottardo⁶², S. A. Gotz¹⁵⁹, M. Gough⁵⁷, A.G. Goussiou²⁰⁵, N. Govender⁴⁹, R. P. Grabarczyk¹⁸⁰, I. Grabowska-Bold¹³⁴, K. Graham⁵⁵, E. Gramstad¹⁷⁹, S. Grancagnolo^{103,104}, C.M. Grant¹, P.M. Gravila³⁹, F.G. Gravili^{103,104}, H.M. Gray¹⁹, M. Greco¹⁶⁰, M. J. Green¹, C. Grefe³¹, A. S. Grefsrud¹⁸, I.M. Gregor⁷⁵, K.T. Greif²³³, P. Grenier²¹⁴, S.G. Grewe¹⁶⁰, A.A. Grillo¹⁹⁶, K. Grimm⁴⁵, S. Grinstein^{XXV,14}, J.-F. Grivaz⁹⁷, E. Gross²⁴³, J. Grosse-Knetter⁸², L. Guan¹⁵⁶, G. Guerrieri⁶², R. Guevara¹⁷⁹, R. Gugel¹⁵⁰, J.A.M. Guhit¹⁵⁶, A. Guida²¹, E. Guillon²⁴¹, S. Guindon⁶², F. Guo^{15,164}, J. Guo²⁰⁸, L. Guo⁷⁵, L. Guo^{XXIII,163}, Y. Guo¹⁵⁶, A. Gupta⁷⁶, R. Gupta¹⁸³, S. Gupta³³, S. Gurbuz³¹, S.S. Gurdasani⁷⁵, G. Gustavino^{113,114}, P. Gutierrez¹⁷⁴, L.F. Gutierrez Zagazeta¹⁸², M. Gutsche⁷⁷, C. Gutsche¹⁴⁶, C. Gwenlan¹⁸⁰, C.B. Gwilliam¹⁴², E.S. Haaland¹⁷⁹, A. Haas¹⁷¹, M. Habedank⁸⁷, C. Haber¹⁹, H.K. Hadavand⁹, A. Haddad⁶⁶, A. Hade⁷⁷, A.I. Hagan¹⁴¹, J. J. Hahn²¹², E.H. Haines¹⁴⁶, M. Haleem²⁴⁰, J. Haley¹⁷⁵, G.D. Hallerwell¹⁵², L. Halser²², K. Hamano²³⁹, H. Hamdaoui²³⁵, M. Hamer³¹, S. E. D. Hammoud⁹⁷, E.J. Hampshire¹⁴⁵, J. Han²⁰⁶, L. Han¹⁶², L. Han⁹⁰, S. Han¹⁵, K. Hanagaki¹³⁰, M. Hance¹⁹⁶, D.A. Hangal⁶⁷, H. Hanif²¹³, M.D. Hank¹⁸², J.B. Hansen⁶⁸, P.H. Hansen⁶⁸, D. Harada⁸³, T. Harenberg²⁴⁵, S. Harkusha²⁴⁷, M.L.

Harris¹⁵³, Y.T. Harris³¹, J. Harrison¹⁴, N.M. Harrison¹⁷³, P.F. Harrison²⁴¹, M. L. E. Hart¹⁴⁶, N.M. Hartman¹⁶⁰, N.M. Hartmann¹⁵⁹, R. Z. Hasan^{145,194}, Y. Hasegawa²¹¹, F. Haslbeck¹⁸⁰, S. Hassan¹⁸, R. Hauser¹⁵⁷, M. Haviernik¹⁹³, C.M. Hawkes²³, R.J. Hawkes⁶², Y. Hayashi²²⁶, D. Hayden¹⁵⁷, C. Hayes¹⁵⁶, R.L. Hayes¹⁶⁷, C.P. Hays¹⁸⁰, J.M. Hays¹⁴⁴, H.S. Hayward¹⁴², M. He^{15,164}, Y. He⁷⁵, Y. He¹⁴⁶, N.B. Heatley¹⁴⁴, V. Hedberg¹⁴⁸, C. Heidegger⁸¹, K.K. Heidegger⁸¹, J. Heilman⁵⁵, S. Heim⁷⁵, T. Heim¹⁹, J.G. Heinlein¹⁸², J.J. Heinrich¹⁷⁷, L. Heinrich¹⁶⁰, J. Hejbal¹⁹¹, M. Helbig⁷⁷, A. Held²⁴⁴, S. Hellesund¹⁸, C.M. Helling²³⁸, S. Hellman^{73,74}, A.M. Henriques Correia⁶², H. Herde¹⁴⁸, Y. Hernández Jiménez²¹⁶, L.M. Herrmann³¹, T. Herrmann⁷⁷, G. Herten⁸¹, R. Hertenberger¹⁵⁹, L. Hervas⁶², M.E. Hespings¹⁵⁰, N.P. Hessey²²⁹, J. Hessler¹⁶⁰, M. Hidaoui⁵⁷, N. Hidic¹⁹³, E. Hill²²⁸, T. S. Hillersoy¹⁸, S.J. Hillier²³, J.R. Hinds¹⁵⁷, F. Hinterkeuser³¹, M. Hirose¹⁷⁸, S. Hirose²³¹, D. Hirschbuehl²⁴⁵, T.G. Hitchings¹⁵¹, B. Hiti¹⁴³, J. Hobbs²¹⁶, R. Hobincu³⁸, N. Hod²⁴³, A.M. Hodges²³⁶, M.C. Hodgkinson²¹⁰, B.H. Hodgkinson¹⁸⁰, A. Hoecker⁶², D. D. Hofer¹⁵⁶, J. Hofer²³⁷, M. Holzbock⁶², L.B.A.H. Hommels⁴⁶, V. Homsak¹⁸⁰, B.P. Honan¹⁵¹, J. J. Hong⁹⁹, T.M. Hong¹⁸³, B.H. Hooberman²³⁶, W.H. Hopkins⁷, M. C. Hoppesch²³⁶, Y. Hori¹⁶¹, M. E. Horstmann¹⁶⁰, S. Hou²¹⁹, M. R. Housenga²³⁶, A.S. Howard¹⁴³, J. Howarth⁸⁷, J. Hoya⁷, M. Hrabovsky¹⁷⁶, T. Hryn'ova⁵, P.J. Hsu⁹⁶, S.-C. Hsu²⁰⁵, T. Hsu⁹⁷, M. Hu¹⁹, Q. Hu⁹⁰, S. Huang⁴⁶, X. Huang^{15,164}, Y. Huang¹⁹³, Y. Huang¹⁶³, Y. Huang¹⁵⁰, Y. Huang¹⁵, Z. Huang⁹⁷, Z. Hubacek¹⁹², M. Huebner³¹, F. Huegging³¹, T.B. Huffman¹⁸⁰, M. Hufnagel Maranha De Faria¹²⁵, C. A. Hugli⁷⁵, M. Huhtinen⁶², S.K. Huiberts¹⁸, R. Hulsken¹⁵⁴, C. E. Hultquist¹⁹, D.L. Humphreys¹⁵³, N. Huseynov^{VII,13}, J. Huston¹⁵⁷, J. Huth⁸⁹, R. Hyneman⁸, G. Iacobucci⁸³, G. Iakovidis⁴³, L. Iconomidou-Fayard⁹⁷, J. P. Iddon⁶², P. Iengo^{107,108}, R. Iguchi²²⁶, Y. Iiyama²²⁶, T. Iizawa²²⁶, Y. Ikegami¹³⁰, D. Iliadis²²⁵, N. Ilic²²⁸, H. Imam⁵⁶, G. Inacio Goncalves¹²⁸, S. A. Infante Cabanas¹⁹⁹, T. Ingebretsen Carlson^{73,74}, J. M. Inglis¹⁴⁴, G. Introzzi^{109,110}, M. Iodice¹¹⁷, V. Ippolito^{113,114}, R. K. Irwin¹⁴², M. Ishino²²⁶, W. Islam²⁴⁴, C. Issever²¹, S. Istin^{XLI,24}, K. Itabashi¹³⁰, H. Ito²⁴², R. Iuppa^{119,120}, A. Ivina²⁴³, V. Izzo¹⁰⁷, P. Jacka¹⁹², P. Jackson¹, P. Jain⁷⁵, K. Jakobs⁸¹, T. Jakoubek²⁴³, J. Jamieson⁸⁷, W. Jang²²⁶, S. Jankovych¹⁹³, M. Javurkova¹⁵³, P. Jawahar¹⁵¹, L. Jeanty¹⁷⁷, J. Jejelava^{XXXII,220}, P. Jenni^{VI,81}, C.E. Jessiman⁵⁵, C. Jia²⁰⁶, H. Jia²³⁸, J. Jia²¹⁶, X. Jia^{15,164}, Z. Jia¹⁶², C. Jiang⁷⁹, Q. Jiang⁹⁴, S. Jiggins⁷⁵, M. Jimenez Ortega²³⁷, J. Jimenez Pena¹⁴, S. Jin¹⁶², A. Jinaru³⁵, O. Jinnouchi²⁰⁴, P. Johansson²¹⁰, K.A. Johns⁸, J.W. Johnson¹⁹⁶, F. A. Jolly⁷⁵, D.M. Jones²¹⁷, E. Jones⁷⁵, K.S. Jones⁹, P. Jones⁴⁶, R.W.L. Jones¹⁴¹, T.J. Jones¹⁴², H.L. Joos^{82,62}, R. Joshi¹⁷³, J. Jovicevic¹⁷, X. Ju¹⁹, J.J. Junggeburth⁶², T. Junkermann⁹¹, A. Juste Rozas^{XXV,14}, M.K. Juzek¹³⁶, S. Kabana²⁰², A. Kaczmarzka¹³⁶, M. Kado¹⁶⁰, H. Kagan¹⁷³, M. Kagan²¹⁴, A. Kahn¹⁸², C. Kahra¹⁵⁰, T. Kaji²²⁶, E. Kajomovitz²²³, N. Kakati²⁴³, N. Kakoty¹⁴, I. Kalaitzidou⁸¹, S. Kandel⁹, N. Kanellos¹¹, N.J. Kang¹⁹⁶, D. Kar^{XLII,54}, K. Karava¹⁸⁰, E. Karentzos³¹, O. Karkout¹⁶⁷, S.N. Karpov⁶⁴, Z.M. Karpova⁶⁴, V. Kartvelishvili¹⁴¹, A.N. Karyukhin⁶³, E. Kasimi²²⁵, J. Katzy⁷⁵, S. Kaur⁵⁵, K. Kawade²¹¹, M.P. Kawale¹⁷⁴, C. Kawamoto¹³⁷, T. Kawamoto⁹⁰, E.F. Kay⁶², F.I. Kaya²³², S. Kazakov¹⁵⁷, V.F. Kazanin⁶³, J.M. Keaveney⁴⁷, R. Keeler²³⁹, G.V. Kehris⁸⁹, J.S. Keller⁵⁵, J.J. Kempster²¹⁷, O. Kepka¹⁹¹, J. Kerr²³⁰, B.P. Kerridge¹⁹⁴, B.P. Kerševan¹⁴³, L. Keszeghova⁴¹, R. A. Khan¹⁸³, A. Khanov¹⁷⁵, A.G. Kharlamov⁶³, T. Kharlamova⁶³, E.E. Khoda²⁰⁵, M. Kholodenko¹⁸⁴, T.J. Khoo²¹, G. Khoraiuli²⁴⁰, Y. Khoulaki⁵⁶, J. Khubua^{XLII,221}, Y.A.R. Khwaira¹⁸¹, B. Kibirige⁵⁴, D. Kim⁷, D.W. Kim^{73,74}, Y.K. Kim⁶⁵, N. Kimura¹⁴⁶, M.K. Kingston⁸², A. Kirchhoff⁸², C. Kirfel³¹, F. Kirfel³¹, J. Kirk¹⁹⁴, A.E. Kiryunin¹⁶⁰, S. Kita²³¹, O. Kivernyk³¹, M. Klassen²³², C. Klein⁵⁵, L. Klein²⁴⁰, M.H. Klein⁷¹, S.B. Klein⁸³, U. Klein¹⁴², A. Klimentov⁴³, T. Klioutchnikova⁶², P. Kluit¹⁶⁷, S. Kluth¹⁶⁰, E. Kneringer¹²¹, T.M. Knight²²⁸, A. Knue⁷⁶, M. Kobel⁷⁷, D. Kobylanski²⁴³, S.F. Koch¹⁸⁰, M. Kocian²¹⁴, P. Kodys¹⁹³, D.M. Koeck¹⁷⁷, T. Koffas⁵⁵, O. Kolay⁷⁷, I. Koletsos⁵, T. Komarek¹³⁶, K. Köneke⁸², A.X.Y. Kong¹, T. Kono¹⁷², N. Konstantinidis¹⁴⁶, P. Kontaxakis⁸³, B. Konya¹⁴⁸, R. Kopeliansky⁶⁷, S. Koperny¹³⁴, K. Korcyl¹³⁶, K. Kordas^{IV,225}, A. Korn¹⁴⁶, S. Korn⁸², I. Korolkov¹⁴, N. Korotkova⁶³, B. Kortman¹⁶⁷, O. Kortner¹⁶⁰, S. Kortner¹⁶⁰, W.H. Kostecka¹⁶⁸, M. Kostov⁴¹, V.V. Kostyukhin²¹², A. Kotsokechagia⁶², A. Kotwal¹⁷⁸, A. Koulouris⁶², A. Kourkoulis^{109,110}, C. Kourkoulis¹⁰, E. Kourlitis¹⁶⁰, O. Kovanda¹⁷⁷, R. Kowalewski²³⁹, W. Kozanecki¹⁷⁷, A.S. Kozhin⁶³, V.A. Kramarenko⁶³, G. Kramberger¹⁴³, P. Kramer³¹, M.W. Krasny¹⁸¹, A. Krasznahorkay¹⁵³, A. C. Kraus¹⁶⁸, J.W. Kraus²⁴⁵, J.A. Kremer⁷⁵, N. B. Krengel²¹², T. Kresse⁷⁷, L. Kretschmann²⁴⁵, J. Kretschmar¹⁴², P. Krieger²²⁸, K. Krizka²³, K. Kroeninger⁷⁶, H. Kroha¹⁶⁰, J. Kroll¹⁹¹, J. Kroll¹⁸², K.S. Krowpman¹⁵⁷, U. Kruchonak⁶⁴, H. Krüger³¹, N. Krumnack¹²³, M.C. Kruse⁷⁸, O. Kuchinskia⁶⁴, S. Kuday³, S. Kuehn⁶², R. Kuesters⁸¹, T. Kuhl⁷⁵, V. Kukhtin⁶⁴, Y. Kulchitsky⁶⁴, S. Kuleshov^{200,198}, J. Kull¹, E. V. Kumar¹⁵⁹, M. Kumar⁵⁴, N. Kumari⁷⁵, P. Kumari²³⁰, A. Kupco¹⁹¹, T. Kupfer⁷⁶, A. Kupich⁶³, O. Kuprash⁸¹, H. Kurashige¹³³, L.L. Kurchaninov²²⁹, O. Kurdysh⁵, Y.A. Kurochkin⁶³, A. Kurova⁶³, M. Kuze²⁰⁴, A.K. Kvam¹⁵³, J. Kvita¹⁷⁶, N.G. Kyriacou¹⁵⁶, C. Lacasta²³⁷, F. Lacava^{113,114}, H. Lacker²¹, D. Lacour¹⁸¹, N.N. Lad¹⁴⁶, E. Ladygin⁶⁴, A. Lafarge⁶⁶, B. Laforge¹⁸¹, T. Lagouri²⁴⁶, F.Z. Lahbabi⁵⁶, S. Lai⁸², J.E. Lambert²³⁹, S. Lammers⁹⁹, W. Lamp⁸, C. Lampoudis^{IV,225}, G. Lamprinouidis¹⁵⁰, A.N. Lancaster¹⁶⁸, E. Lançon⁴³, U. Landgraf⁸¹, M.P.J. Landon¹⁴⁴, V.S. Lang⁸¹, O. K. B. Langrekken¹⁷⁹, A.J. Lankford²³³, F. Lanni⁶², K. Lantzsch³¹, A. Lanza¹⁰⁹, M. Lanzac Berrocal²³⁷, J.F. Laporte¹⁹⁵, T. Lari¹⁰⁵, D. Larsen¹⁸, L. Larson¹², F. Lasagni Manghi³⁰, M. Lassnig⁶², S.D. Lawlor²¹⁰, R. Lazaridou²⁴¹, M. Lazzaroni^{105,106}, H. D. M. Le¹⁵⁷, E.M. Le Boulicaut²⁴⁶, L.T. Le Pottier¹⁹, B. Leban^{30,29}, F. Ledroit-Guillon⁸⁸, T.F. Lee²³⁰, L.L. Leeuw⁴⁹, M. Lefebvre²³⁹, C. Leggett¹⁹, G. Lehmann Miotto⁶², M. Leigh⁸³, W.A. Leight¹⁵³, W. Leinonen¹⁶⁶, A. Leisos^{XXII,225}, M.A.L. Leite¹²⁷, C.E. Leitgeb²¹, R. Leitner¹⁹³, K.J.C. Leney⁷¹, T. Lenz³¹, S. Leone¹¹¹, C. Leonidopoulos⁷⁹, A. Leopold²¹⁵, J. LePage-Bourbonnais⁵⁵, R. Les¹⁵⁷, C.G. Lester⁴⁶, M. Levchenko⁶³, J. Levêque⁵, L.J. Levinson²⁴³, G. Levring^{30,29}, M.P. Lewicki¹³⁶, C. Lewis²⁰⁵, D.J. Lewis⁵, L. Lewitt²¹⁰, A. Li⁴³, B. Li²⁰⁶, C. Li¹⁵⁶, C.-Q. Li¹⁶⁰, H. Li²⁰⁶, H. Li¹⁵¹, H. Li¹⁶, H. Li⁹⁰, H. Li²⁰⁶, J. Li²⁰⁸, K. Li¹⁵, L. Li²⁰⁸, R. Li²⁴⁶, S. Li^{15,164}, S. Li^{209,208}, T. Li⁶, X. Li¹⁵⁴, Z. Li²²⁶, Z. Li^{15,164}, Z. Li⁹⁰, S. Liang^{15,164}, Z. Liang¹⁵, M. Liberatore¹⁹⁵, B. Liberti¹¹⁵, K. Lie⁹⁵, J. Lieber Marin¹²⁹, H. Lien⁹⁹, H. Lin¹⁵⁶, S. F. Lin²¹⁶, L. Linden¹⁵⁹, R.E. Lindley⁸, J.H. Lindon⁶², J. Ling⁸⁹, E. Lipeles¹⁸², A. Lipniacka¹⁸, A. Lister²³⁸, J.D. Little⁹⁹, B. Liu¹⁵, B.X. Liu¹⁶³, D. Liu^{209,208}, D. Liu¹⁹⁶, E. H. L. Liu²³, J.K.K. Liu¹⁷¹, K. Liu²⁰⁹, K. Liu^{209,208}, M. Liu⁹⁰, M.Y. Liu⁹⁰, P. Liu¹⁵, Q. Liu^{209,205,208}, X. Liu⁹⁰, X. Liu²⁰⁶, Y. Liu^{163,164}, Y.L. Liu²⁰⁶, Y.W. Liu⁹⁰, Z. Liu^{XII,97}, S.L. Lloyd¹⁴⁴, E.M. Lobodzinska⁷⁵, P. Loch⁸, E. Lodhi²²⁸, T. Lohse²¹, K. Lohwasser²¹⁰, E. Loiacono⁷⁵, J. D. Lomas²³, J.D. Long⁶⁷, I. Longarini²³³, R. Longo²³⁶, A. Lopez Solis¹⁴, N.A. Lopez-canelas⁸, N. Lorenzo Martinez⁵, A.M. Lory¹⁵⁹, M. Losada¹⁶⁹, G. Löschcke Centeno²¹⁷, X. Lou^{73,74}, X. Lou^{15,164}, A. Lounis⁹⁷, P.A. Love¹⁴¹, M. Lu⁹⁷, S. Lu¹⁸², Y.J. Lu²¹⁹, H.J. Lubatti²⁰⁵, C. Luci^{113,114}, F.L. Lucio Alves¹⁶², F. Luehring⁹⁹, B. S. Lunday¹⁸², O. Lundberg²¹⁵, J. Lunde⁶², N.A. Luongo⁷, M.S. Lutz⁶², A.B. Lux³², D. Lynn⁴³, R. Lysak¹⁹¹, V. Lysenko¹⁹², E. Lytken¹⁴⁸, V. Lyubushkin⁶⁴, T. Lyubushkina⁶⁴, M.M. Lyukova²¹⁶, H. Ma⁴³, K. Ma⁹⁰, L.L. Ma²⁰⁶, W. Ma⁹⁰, Y. Ma¹⁷⁵, J.C. MacDonald¹⁵⁰, P.C. Machado De Abreu Farias¹²⁹, R. Madar⁶⁶, T. Madula¹⁴⁶, J. Maeda¹³³, T. Maeno⁴³, P.T. Mafa^{XI,49}, H. Maguire²¹⁰, M. Maheshwari⁴⁶, V. Maiboroda⁹⁷, A. Maio^{184,185,187}, K. Maj¹³⁴, O. Majersky⁷⁵, S. Majewski¹⁷⁷, R. Makhmanazarov⁶³, N. Makovec⁹⁷,

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Martinovicova¹⁹³, V.S. Martoiu³⁵, A.C. Martyniuk¹⁴⁶, A. Marzin⁶², D. Mascione^{119,120}, L. Masetti¹⁵⁰, J. Masik¹⁵¹, A.L. Maslennikov⁶⁴, S.L. Mason⁶⁷, P. Massarotti^{107,108}, P. Mastrandrea^{111,112}, A. Mastroberardino^{70,69}, T. Masubuchi¹⁷⁸, T.T. Mathew¹⁷⁷, J. Matousek¹⁹³, D.M. Mattern⁷⁶, J. Maurer³⁵, T. Maurin⁸⁷, A.J. Maury⁹⁷, B. Maček¹⁴³, C. Mavungu Tsava¹⁵², D.A. Maximov⁶³, A. E. May¹⁵¹, E. Mayer⁶⁶, R. Mazini⁵⁴, I. Maznas¹⁶⁸, S.M. Mazza¹⁹⁶, E. Mazzeo⁶², J.P. Mc Gowan²³⁹, S.P. Mc Kee¹⁵⁶, C.A. Mc Lean⁷, C.C. McCracken²³⁸, E.F. McDonald¹⁵⁵, A.E. McDougall¹⁶⁷, L. F. Mcelhinney¹⁴¹, J.A. Mcfayden²¹⁷, R.P. McGovern¹⁸², R.P. Mckenzie⁵⁴, T.C. Mclachlan⁷⁵, D.J. Mclaughlin¹⁴⁶, S.J. McMahon¹⁹⁴, C.M. Mcpartland¹⁴², R.A. McPherson^{XXIX,239}, S. Mehlhase¹⁵⁹, A. Mehta¹⁴², D. Melini²³⁷, B.R. Mellado Garcia⁵⁴, A.H. Melo⁸², F. Meloni⁷⁵, A.M. Mendes Jacques Da Costa¹⁵¹, L. Meng¹⁴¹, S. Menke¹⁶⁰, M. Mentink⁶², E. Meoni^{70,69}, G. Mercado¹⁶⁸, S. Merianos²²⁵, C. Merlassino^{100,102}, C. Meroni^{105,106}, J. Metcalfe⁷, A.S. Mete⁷, E. Meuser¹⁵⁰, C. Meyer⁹⁹, J.P. Meyer¹⁹⁵, Y. Miao¹⁶², R.P. Middleton¹⁹⁴, M. Mihovilovic⁹⁷, L. Mijović⁷⁹, G. Mikenberg²⁴³, M. Mikestikova¹⁹¹, M. Mikuž¹⁴³, H. Mildner¹⁵⁰, A. Milic⁶², D.W. Miller⁶⁵, E. H. Miller²¹⁴, L.S. Miller⁵⁵, A. Milov²⁴³, D.A. Milstead^{73,74}, T. Min¹⁶², A.A. Minaenko⁶³, I.A. Minashvili²²¹, A.I. Mincer¹⁷¹, B. Mindur¹³⁴, M. Mineev⁶⁴, Y. Mino¹³⁷, L.M. Mir¹⁴, M. Miralles Lopez⁸⁷, M. Mironova¹⁹, M. Missio¹⁶⁶, A. Mitra²⁴¹, V.A. Mitsou²³⁷, Y. Mitsumori¹⁶¹, O. Miu²²⁸, P.S. Miyagawa¹⁴⁴, T. Mkrtchyan⁹¹, M. Mlinarevic¹⁴⁶, M. Mlynarikova⁶², S. Mobius²², M. H. Mohamed Farook¹⁶⁵, S. Mohapatra⁶⁷, M.F. Mohd Soberi⁷⁹, S. Mohiuddin¹⁷⁵, G. Mokgatitswane⁵⁴, L. Moleri²⁴³, U. Molinatti¹⁸⁰, L.G. Mollier²², B. Mondal¹⁹¹, S. Mondal¹⁹², K. Mönig⁷⁵, E. Monnier¹⁵², L. Monsonis Romero²³⁷, J. Montejo Berlingen¹⁴, A. Montella^{73,74}, M. Montella¹⁷³, F. Montereali^{117,118}, F. Monticelli¹⁴⁰, S. Monzani^{100,102}, A. Moranco Tarda⁶⁸, N. Morange⁹⁷, A.L. Moreira De Carvalho⁷⁵, M. Moreno Llacer²³⁷, C. Moreno Martinez⁸³, J.M. Moreno Perez²⁸, P. Morettini⁸⁵, S. Morgenstern⁶², M. Morii⁸⁹, M. Morinaga²²⁶, M. Moritsu¹³⁸, F. Morodei^{113,114}, P. Moschovakos⁶², B. Moser⁸¹, M. Mosidze²²¹, T. Moskalets⁷¹, P. Moskvitina¹⁶⁶, J. Moss⁴⁵, P. Moszkowicz¹³⁴, A. Moussa⁵⁹, Y. Moyal²⁴³, H. Moyano Gomez¹⁴, E.J.W. Moyse¹⁵³, O. Mtintsilana⁵⁴, S. Muanza¹⁵², M. Mucha³¹, J. Mueller¹⁸³, G.A. Mullier²³⁵, A.J. Mullin⁴⁶, J.J. Mullin⁷⁸, A.C. Mullins⁷¹, A.E. Mulski⁸⁹, D.P. Mungo²²⁸, D. Munoz Perez²³⁷, F.J. Munoz Sanchez¹⁵¹, W.J. Murray^{241,194}, M. Muškinja¹⁴³, C. Mwewa⁷⁵, A.G. Myagkov^{1,63}, A.J. Myers⁹, G. Myers¹⁵⁶, M. Myska¹⁹², B.P. Nachman¹⁹, K. Nagai¹⁸⁰, K. Nagano¹³⁰, R. Nagasaka²²⁶, J.L. Nagle^{XXXVIII,43}, E. Nagy¹⁵², A.M. Nairz⁶², Y. Nakahama¹³⁰, K. Nakamura¹³⁰, K. Nakkalil⁶, A. Nandi⁹², H. Nanjo¹⁷⁸, E.A. Narayanan⁷⁰, Y. Narukawa²²⁶, I. Naryshkin⁶³, L. Nasella^{105,106}, S. Nasri¹⁷, C. Nass³¹, G. Navarro²⁷, J. Navarro-Gonzalez³⁵, A. Nayaz²¹, P.Y. Nechaeva⁶³, S. Nechaeva^{30,29}, F. Nechansky¹⁹¹, L. Nedic¹⁸⁰, T.J. Neep²³, A. Negri^{109,110}, M. Negri³⁰, C. Nellist¹⁶⁷, C. Nelson¹⁵⁴, K. Nelson¹⁵⁶, S. Nemecek¹⁹¹, M. Nessi^{VIII,62}, M.S. Neubauer²³⁶, J. Newell¹⁴², P.R. Newman²³, Y.W.Y. Ng²³⁶, B. Ngair¹⁶⁹, H.D.N. Nguyen¹⁵⁸, J.D. Nichols¹⁷⁴, R.B. Nickerson¹⁸⁰, R. Nicolaïdou¹⁹⁵, J. Nielsen¹⁹⁶, M. Niemeyer⁸², J. Niermann⁶², N. Nikiforou⁶², V. Nikolaenko^{1,63}, I. Nikolic-Audit¹⁸¹, P. Nilsson⁴³, I. Ninca⁷⁵, G. Ninio²²⁴, A. Nisati¹¹³, R. Nisius¹⁶⁰, N. Nitika^{100,102}, J-E. Nitschke⁷⁷, E.K. Nkadimeng⁴⁸, T. Nobe²²⁶, T. Nommensen²¹⁸, M.B. Norfolk²¹⁰, B.J. Norman⁵⁵, M. Noury⁵⁶, J. Novak¹⁴³, T. Novak¹⁴³, R. Novotny¹⁹², L. Nozka¹⁷⁶, K. Ntekas²³³, N.M.J. Nunes De Moura Junior¹²⁶, J. Ocariz¹⁸¹, A. Ochi¹³³, I. Ochoa¹⁸⁴, S. Oerdek⁷⁵, J.T. Offermann⁶⁵, A. Ogrodnik¹⁹³, A. Oh¹⁵¹, C.C. Ohm²¹⁵, H. Oide¹³⁰, M.L. Ojeda⁶², Y. Okumura²²⁶, L.F. Oleiro Seabra¹⁸⁴, I. Oleksiyuk⁸³, G. Oliveira Correa¹⁴, D. Oliveira Damazio⁴³, J.L. Oliver²³³, R. Omar⁹⁹, Ö.O. Öncel⁸¹, A.P. O'Neill²², A. Onofre^{V,184,188}, P.U.E. Onyisi¹², M.J. Oreglia⁶⁵, D. Orestano^{117,118}, R. Orlandini^{117,118}, R.S. Orr²²⁸, L.M. Osojnak⁶², Y. Osumi¹⁶¹, G. Otero y Garzón⁴⁴, H. Otono¹³⁸, M. Ouchrif⁵⁹, F. Ould-Saada¹⁷⁹, T. Ovsianikova²⁰⁵, M. Owen⁸⁷, R.E. Owen¹⁹⁴, V.E. Ozcan²⁴, F. Ozturk¹³⁶, N. Ozturk⁹, S. Ozturk¹²⁴, H.A. Pacey¹⁸⁰, K. Pachal²²⁹, A. Pacheco Pages¹⁴, C. Padilla Aranda¹⁴, G. Padovano^{113,114}, S. Pagan Griso¹⁹, G. Palacino⁹⁹, A. Palazzo^{103,104}, J. Pampel³¹, J. Pan²⁴⁶, T. Pan⁹³, D.K. Panchal¹², C.E. Pandini⁸⁸, J.G. Panduro Vazquez¹⁹⁴, H.D. Pandya¹, H. Pang¹⁹⁵, P. Pani⁷⁵, G. Panizzo^{100,102}, L. Panwar¹⁸¹, L. Paolozzi⁸³, S. Parajuli²³⁶, A. Paramonov⁷, C. Paraskevopoulos⁸⁰, D. Paredes Hernandez⁹⁴, A. Pareti^{109,110}, K.R. Park⁶⁷, T.H. Park¹⁶⁰, F. Parodi^{85,84}, J.A. Parsons⁶⁷, U. Parzefall⁸¹, B. Pascual Dias⁶⁶, L. Pascual Dominguez¹⁴⁹, E. Pasqualucci¹¹³, S. Passaggio⁸⁵, F. Pastore¹⁴⁵, P. Patel¹³⁶, U.M. Patel⁷⁸, J.R. Pater¹⁵¹, T. Pauly⁶², F. Pauwels¹⁹³, C.I. Pazos²³², M. Pedersen¹⁷⁹, R. Pedro¹⁸⁴, S.V. Peleganchuk⁶³, O. Penc¹⁹¹, E.A. Pender⁷⁹, S. Peng¹⁶, G. D. Penn²⁴⁶, K.E. Penski¹⁵⁹, M. Penzin⁶³, B.S. Peralva¹²⁸, A.P. Pereira Peixoto²⁰⁵, L. Pereira Sanchez²¹⁴, D.V. Perepelitsa^{XXXVIII,43}, G. Perera¹⁵³, E. Perez Codina⁶², M. Perganti¹¹, H. Pernegger⁶², S. Perrella^{113,114}, O. Perrin⁶⁶, K. Peters⁷⁵, R.F.Y. Peters¹⁵¹, B.A. Petersen⁶², T.C. Petersen⁶⁸, E. Petit¹⁵², V. Petousis¹⁹², A. R. Petri^{105,106}, C. Petridou^{IV,225}, T. Petru¹⁹³, A. Petrukhin²¹², M. Pettee¹⁹, A. Petukhov¹²⁴, K. Petukhova⁶², R. Pezoa²⁰³, L. Pezzotti^{30,29}, G. Pezzullo²⁴⁶, L. Pfaffenbichler⁶², A. J. Pfleger⁶², T.M. Pham²⁴⁴, T. Pham¹⁵⁵, P.W. Phillips¹⁹⁴, G. Piacquadio²¹⁶, E. Pianori¹⁹, F. Piazza¹⁷⁷, R. Piegaia⁴⁴, D. Pietreanu³⁵, A.D. Pilkington¹⁵¹, M. Pinamonti^{100,102}, J.L. Pinfold², B.C. Pinheiro Pereira¹⁸⁴, J. Pinol Bel¹⁴, A. E. Pinto Pinoargote¹⁸¹, L. Pintucci^{100,102}, K. M. Piper²¹⁷, A. Pirttikoski⁸³, D.A. Pizzi⁵⁵, L. Pizzimento⁹⁴, A. Plebani⁴⁶, M.-A. Pleier⁴³, V. Pleskot¹⁹³, E. Plotnikova⁶⁴, G. Poddar¹⁴⁴, R. Poettgen¹⁴⁸, L. Poggioni¹⁸¹, S. Polacek¹⁹³, G. Polesello¹⁰⁹, A. Poley²¹³, A. Polini³⁰, C.S. Pollard²⁴¹, Z.B. Pollock¹⁷³, E. Pompa Pacchi¹⁷⁴, N. I. Pond¹⁴⁶, D. Ponomarenko⁹⁹, L. Pontecorvo⁶², S. Popa³⁴, G.A. Popeneciu³⁷, A. Poreba⁶², D.M. Portillo Quintero²²⁹, S. Pospisil¹⁹², M. A. Postill²¹⁰, P. Postolache³⁶, K. Potamianos²⁴¹, P.A. Potepa¹³⁴, I.N. Potrap⁶⁴, C.J. Potter⁴⁶, H. Potti²¹⁸, J. Poveda²³⁷, M.E. Pozo Astigarraga⁶², R. Pozzi⁶², A. Prades Ibanez^{115,116}, J. Pretel²³⁹, D. Price¹⁵¹, M. Primavera¹⁰³, L. Primomo^{100,102}, M.A. Principe Martin¹⁴⁹, R. Privara¹⁷⁶, T. Procter¹³⁵, M.L. Proffitt²⁰⁵, N. Proklova¹⁸², K. Prokofiev⁹⁵, G. Proto¹⁶⁰, J. Proudfoot⁷, M. Przybycien¹³⁴, W.W. Przygoda¹³⁵, A. Psallidas⁷², J.E. Puddefoot²¹⁰, D. Pudza⁸⁰, D. Pyatiizbyantseva¹⁶⁶, J. Qian¹⁵⁶, R. Qian¹⁵⁷, D. Qichen¹⁵¹, Y. Qin¹⁴, T. Qiu⁷⁹, A. Quadt⁸², M. Queitsch-Maitland¹⁵¹, G. Quetant⁸³, R.P. Quinn²³⁸, G. Rabanal Bolanos⁸⁹, D. Rafanoharana¹⁶⁰, F. Raffaeli^{115,116}, F. Ragusa^{105,106}, J.L. Rainbolt⁶⁵, J.A. Raine⁸³, S. Rajagopalan⁴³, E. Ramakoti⁶⁴, L. Rambelli^{85,84}, I.A. Ramirez-Berend⁵⁵, K. Ran^{75,164}, D. S. Rankin¹⁸², N.P. Rapheeha⁵⁴, H. Rasheed³⁵, D.F. Rassloff⁹¹, A. Rastogi¹⁹, S. Rave¹⁵⁰, S. Ravera^{85,84}, B. Ravina⁶², I. Ravinovich²⁴³, M. Raymond⁶², A.L. Read¹⁷⁹, N.P. Readioff²¹⁰, D.M. Rebuffi^{109,110}, A. S. Reed¹⁶⁰, K. Reeves³³,

J.A. Reidelsturz²⁴⁵, D. Reikher¹⁷⁷, A. Rej⁷⁶, C. Rembser⁶², H. Ren⁹⁰, M. Renda³⁵, F. Renner⁷⁵, A.G. Rennie⁸⁷, A.L. Rescia⁷⁵, S. Resconi¹⁰⁵, M. Ressegotti⁸⁵, S. Rettie⁶², W.F. Rettie⁵⁵, M. M. Revering⁴⁶, E. Reynolds¹⁹, O.L. Rezanova⁶⁴, P. Reznicek¹⁹³, H. Riani⁵⁹, N. Ribaric⁷⁸, E. Ricci^{119,120}, R. Richter¹⁶⁰, S. Richter^{73,74}, E. Richter-Was¹³⁵, M. Ridel¹⁸¹, S. Ridouani⁵⁹, P. Rieck¹⁷¹, P. Riedler⁶², E.M. Riefel^{73,74}, J. O. Rieger¹⁶⁷, M. Rijssenbeek²¹⁶, M. Rimoldi⁶², L. Rinaldi^{30,29}, P. Rincke^{235,82}, G. Ripellino²³⁵, I. Riu¹⁴, J.C. Rivera Vergara²³⁹, F. Rizatdinova¹⁷⁵, E. Rizvi¹⁴⁴, B.R. Roberts¹⁹, S.S. Roberts¹⁹⁶, D. Robinson⁴⁶, M. Robles Manzano¹⁵⁰, A. Robson⁸⁷, A. Rocchi^{115,116}, C. Roda^{111,112}, S. Rodriguez Bosca⁶², Y. Rodriguez Garcia²⁷, A.M. Rodríguez Vera¹⁶⁸, S. Roe⁶², J.T. Roemer⁶², O. Röhne¹⁷⁹, R.A. Rojas⁶², C.P.A. Roland¹⁸¹, A. Romaniouk¹²¹, E. Romano^{109,110}, M. Romano³⁰, A.C. Romero Hernandez²³⁶, N. Rompotis¹⁴², L. Roos¹⁸¹, S. Rosati¹¹³, B.J. Rosser⁶⁵, E. Rossi¹⁸⁰, E. Rossi^{107,108}, L.P. Rossi⁸⁹, L. Rossini⁸¹, R. Rosten¹⁷³, M. Rotaru³⁵, R. Roth⁶², B. Rottler⁸¹, D. Rousseau⁹⁷, D. Rouso⁷⁵, S. Roy-Garand²²⁸, A. Rozanov¹⁵², Z. M. A. Rozario⁸⁷, Y. Rozen²²³, A. Rubio Jimenez²³⁷, V.H. Ruelas Rivera²¹, T.A. Ruggeri¹, A. Ruggiero¹⁸⁰, A. Ruiz-Martinez²³⁷, A. Rummler⁶², Z. Rurikova⁸¹, N.A. Rusakovich⁶⁴, H.L. Russell²³⁹, G. Russo^{113,114}, J.P. Rutherford⁸, S. Rutherford Colmenares⁴⁶, M. Rybar¹⁹³, P. Rybczynski¹³⁴, A. Ryzhov⁷¹, J.A. Sabater Iglesias⁸³, H.F.W. Sadrozinski¹⁹⁶, F. Safai Tehrani¹¹³, S. Saha¹, M. Sahinsoy¹²⁴, B. Sahoo²⁴³, A. Saibel²³⁷, B. T. Saifuddin¹⁷⁴, M. Saimpert¹⁹⁵, G.T. Saito¹²⁷, M. Saito²²⁶, T. Saito²²⁶, A. Sala^{105,106}, A. Salnikov²¹⁴, J. Salt²³⁷, A. Salvador Salas²²⁴, F. Salvatore²¹⁷, A. Salzburger⁶², D. Sammel⁸¹, E. Sampson¹⁴¹, D. Sampsonidis^{14,225}, D. Sampsonidou¹⁷⁷, J. Sánchez²³⁷, V. Sanchez Sebastian²³⁷, H. Sandaker¹⁷⁹, C.O. Sander⁷⁵, J.A. Sandesara²⁴⁴, M. Sandhoff²⁴⁵, C. Sandoval²⁸, L. Sanfilippo⁹¹, D.P.C. Sankey¹⁹⁴, T. Sano¹³⁷, A. Sansoni⁸⁰, M. Santana Queiroz²⁰, L. Santi⁶², C. Santoni⁶⁶, H. Santos^{184,185}, A. Santra²⁴³, E. Sanzani^{30,29}, K.A. Saoucha¹³², J.G. Saraiva^{184,187}, J. Sardain⁸, O. Sasaki¹³⁰, K. Sato²³¹, C. Sauer⁶², E. Sauvan⁵, P. Savard^{XXXV,228}, R. Sawada²²⁶, C. Sawyer¹⁹⁴, L. Sawyer¹⁴⁷, C. Sbarra³⁰, A. Sbrizzi^{30,29}, T. Scanlon¹⁴⁶, J. Schaarschmidt²⁰⁵, U. Schäfer¹⁵⁰, A.C. Schaffer^{97,71}, D. Schaile¹⁵⁹, R.D. Schamberger²¹⁶, C. Scharf²¹, M.M. Schefer²², V.A. Schegelsky⁶³, D. Scheirich¹⁹³, M. Schernau²⁰², C. Scheulen⁸³, C. Schiavi^{85,84}, M. Schioppa^{70,69}, B. Schlag²¹⁴, S. Schlenker⁶², J. Schmeing²⁴⁵, E. Schmidt¹⁶⁰, M. A. Schmidt²⁴⁵, K. Schmieden¹⁵⁰, C. Schmitt¹⁵⁰, N. Schmitt¹⁵⁰, S. Schmitt⁷⁵, N.A. Schneider¹⁵⁹, L. Schoeffel¹⁹⁵, A. Schoening⁹², P.G. Scholer⁵⁵, E. Schopf²¹², M. Schott³¹, S. Schramm⁸³, T. Schroer⁸³, H-C. Schultz-Coulon⁹¹, M. Schumacher⁸¹, B.A. Schumm¹⁹⁶, Ph. Schune¹⁹⁵, H.R. Schwartz¹⁹⁶, A. Schwartzman²¹⁴, T.A. Schwarz¹⁵⁶, Ph. Schwemling¹⁹⁵, R. Schwienhorst¹⁵⁷, F.G. Sciacca²², A. Sciandra⁴³, G. Sciolla³³, F. Scuri¹¹¹, C.D. Sebastiani⁶², K. Sedlaczek¹⁶⁸, S.C. Seidel¹⁶⁵, A. Seiden¹⁹⁶, B.D. Seidlitz⁶⁷, C. Seitz⁷⁵, J.M. Seixas¹²⁶, G. Sekhniaidze¹⁰⁷, L. Selem⁸⁸, N. Semprini-Cesari^{30,29}, A. Semushin²⁴⁷, D. Sengupta⁸³, V. Senthilkumar²³⁷, L. Serin⁹⁷, M. Sessa^{107,108}, H. Severini¹⁷⁴, F. Sforza^{85,84}, A. Sfyrila⁸³, Q. Sha¹⁵, E. Shabalina⁸², H. Shaddix¹⁶⁸, A.H. Shah⁴⁶, R. Shaheen²¹⁵, J.D. Shahinian¹⁸², M. Shamim⁶², L.Y. Shan¹⁵, M. Shapiro¹⁹, A. Sharma⁶², A.S. Sharma²³⁸, P. Sharma⁴³, P.B. Shatalov⁶³, K. Shaw²¹⁷, S.M. Shaw¹⁵¹, Q. Shen¹⁵, D.J. Sheppard²¹³, P. Sherwood¹⁴⁶, L. Shi¹⁴⁶, X. Shi¹⁵, S. Shimizu¹³⁰, C.O. Shimm²⁴⁶, I.P.J. Shipsey^{XLII,180}, S. Shirabe¹³⁸, M. Shiyakova^{XXVII,64}, M.J. Shochet⁶⁵, D.R. Shope¹⁷⁹, B. Shrestha¹⁷⁴, S. Shrestha^{XL,173}, I. Shreyber⁶⁴, M.J. Shroff²³⁹, P. Sicho¹⁹¹, A.M. Sickles²³⁶, E. Sideras Haddad^{54,234}, A. C. Sidley¹⁶⁷, A. Sidoti³⁰, F. Siegert⁷⁷, Dj. Sijacki¹⁷, F. Sili¹⁴⁰, J.M. Silva⁷⁹, I. Silva Ferreira¹²⁶, M.V. Silva Oliveira⁴³, S.B. Silverstein⁷³, S. Simion⁹⁷, R. Simoniello⁶², E.L. Simpson¹⁵¹, H. Simpson²¹⁷, L.R. Simpson⁷, S. Simsek¹²⁴, S. Sindhu⁸², P. Sinervo²²⁸, S. N. Singh³³, S. Singh⁴³, S. Sinha⁷⁵, S. Sinha¹⁵¹, M. Sioli^{30,29}, K. Sioulas¹⁰, I. Siral⁶², E. Sitnikova⁷⁵, J. Sjölin^{73,74}, A. Skar⁸², E. Skorda²³, P. Skubic¹⁷⁴, M. Slawinska¹³⁶, I. Slazyk¹⁸, I. Sliuser¹⁷⁹, V. Smakhtin²⁴³, B.H. Smart¹⁹⁴, S.Yu. Smirnov¹⁹⁸, Y. Smirnov¹²⁴, L.N. Smirnova¹⁶³, O. Smirnova¹⁴⁸, A.C. Smith⁶⁷, D.R. Smith²³³, J.L. Smith¹⁵¹, M. B. Smith⁵⁵, R. Smith²¹⁴, H. Smitmanns¹⁵⁰, M. Smizanska¹⁴¹, K. Smolek¹⁹², P. Smolyanskiy¹⁹², A.A. Snesev⁶⁴, H.L. Snoek¹⁶⁷, S. Snyder⁴³, R. Sobie^{XXIX,239}, A. Soffer²²⁴, C.A. Solans Sanchez⁶², E.Yu. Soldatov⁶⁴, U. Soldevila²³⁷, A.A. Solodkov⁵⁴, S. Solomon³³, A. Soloshenko⁶⁴, K. Solovieva⁸¹, O.V. Solovyanov⁶⁶, P. Sommer⁷⁷, A. Sonay¹⁴, A. Sopczak¹⁹², A.L. Sopio⁷⁹, F. Sopkova⁴², J. D. Sorensen¹⁶⁵, I.R. Sotarriva Alvarez²⁰⁴, V. Sothilingam⁹¹, O. J. Soto Sandoval^{199,198}, S. Sottocornola⁹⁹, R. Soualah¹³¹, Z. Soumami⁶⁰, D. South⁷⁵, N. Soybelman²⁴³, S. Spagnolo^{103,104}, M. Spalla¹⁶⁰, D. Sperlich⁸¹, B. Spisso^{107,108}, D.P. Spiteri⁸⁷, L. Splendore¹⁵², M. Spousta¹⁹³, E.J. Staats⁵⁵, R. Stamen⁹¹, E. Stanecka¹³⁶, W. Stanek-Maslouska⁷⁵, M.V. Stange⁷⁷, B. Stanislaus¹⁹, M.M. Stanitzki⁷⁵, B. Stapf⁶⁷, E.A. Starchenko⁶³, G.H. Stark¹⁹⁶, J. Stark¹³⁹, P. Staroba¹⁹¹, P. Starovoitov¹³², R. Staszewski¹³⁶, G. Stavropoulos⁷², A. Steff⁶², P. Steinberg⁴³, B. Stelzer^{213,229}, H.J. Stelzer¹⁸³, O. Stelzer²²⁹, H. Stenzel⁸⁶, T.J. Stevenson²¹⁷, G.A. Stewart⁶², J.R. Stewart¹⁷⁵, M.C. Stockton⁶², G. Stoicea³⁵, M. Stolarski¹⁸⁴, S. Stonjek¹⁶⁰, A. Straessner⁷⁷, J. Strandberg²¹⁵, S. Strandberg^{73,74}, M. Stratmann²⁴⁵, M. Strauss¹⁷⁴, T. Streblner¹⁵², P. Strizenc⁴², R. Ströhmer²⁴⁰, D.M. Strom¹⁷⁷, R. Stroynowski⁷¹, A. Strubig^{73,74}, S.A. Stucci⁴³, B. Stugu¹⁸, J. Stupak¹⁷⁴, N.A. Styles⁷⁵, D. Su²¹⁴, S. Su⁹⁰, X. Su⁹⁰, D. Suchy⁴¹, K. Sugizaki¹⁸², V.V. Sulini⁶³, M.J. Sullivan¹⁴², D.M.S. Sultan¹⁸⁰, L. Sultanaliyeva⁶³, S. Sultansoy⁴, S. Sun²⁴⁴, W. Sun¹⁵, O. Sunneborn Gudnadottir²³⁵, N. Sur¹⁴⁸, M.R. Sutton²¹⁷, H. Suzuki²³¹, M. Svatos¹⁹¹, P. N. Swallow⁴⁶, M. Swiatkowski²²⁹, T. Swirski²⁴⁰, A. Swoboda⁶², I. Sykora⁴¹, M. Sykora¹⁹³, T. Sykora¹⁹³, D. Ta¹⁵⁰, K. Tackmann^{XXVI,75}, A. Taffard²³³, R. Tafirout²²⁹, Y. Takubo¹³⁰, M. Talby¹⁵², A.A. Talyshev⁶³, K.C. Tam⁹⁴, N.M. Tami²²⁴, A. Tanaka²²⁶, J. Tanaka²²⁶, R. Tanaka⁹⁷, M. Tanasini²¹⁶, Z. Tao²³⁸, S. Tapia Araya²⁰³, S. Tapprogge¹⁵⁰, A. Tarek Abouelfadl Mohamed¹⁵⁷, S. Tarem²²³, K. Tariq¹⁵, G. Tarna⁶², G.F. Tartarelli¹⁰⁵, M. J. Tartarin¹³⁹, P. Tas¹⁹³, M. Tasevsky¹⁹¹, E. Tassi^{70,69}, A.C. Tate²³⁶, G. Tateno²²⁶, Y. Tayalati^{XXVIII,60}, G.N. Taylor¹⁵⁵, W. Taylor²³⁰, A.S. Tegetmeier¹³⁹, P. Teixeira-Dias¹⁴⁵, J.J. Teoh²²⁸, K. Terashi²²⁶, J. Terron¹⁴⁹, S. Terzo¹⁴, M. Testa⁸⁰, R.J. Teuscher^{XXIX,228}, A. Thaler¹²¹, O. Theiner⁸³, T. Theveneaux-Pelzer¹⁵², D.W. Thomas¹⁴⁵, J.P. Thomas²³, E.A. Thompson¹⁹, P.D. Thompson²³, E. Thomson¹⁸², R. E. Thornberry⁷¹, C. Tian⁹⁰, Y. Tian⁸³, V. Tikhomirov¹²⁴, Yu.A. Tikhonov⁶⁴, S. Timoshenko⁶³, D. Timoshyn¹⁹³, E.X.L. Ting¹, P. Tipton²⁴⁶, A. Tishelman-Charny⁴³, K. Todome²⁰⁴, S. Todorova-Nova¹⁹³, L. Toffolin^{100,102}, M. Togawa¹³⁰, J. Tojo¹³⁸, S. Tokár⁴¹, O. Toldaiev⁹⁹, G. Tolkachev¹⁵², M. Tomoto^{130,161}, L. Tompkins^{XV,214}, E. Torrence¹⁷⁷, H. Torres¹³⁹, E. Torró Pastor²³⁷, M. Toscani⁴⁴, C. Toscirri⁶⁵, M. Tost¹², D.R. Tovey²¹⁰, T. Trefzger²⁴⁰, P.M. Tricarico¹⁴, A. Tricoli⁴³, I.M. Trigger²²⁹, S. Trincas-Duvold¹⁸¹, D.A. Trischuk³³, A. Tropina⁶⁴, L. Truong⁴⁹, M. Trzebinski¹³⁶, A. Trzupek¹³⁶, F. Tsai²¹⁶, M. Tsai¹⁵⁶, A. Tsiamis²²⁵, P.V. Tsiarashka⁶⁴, S. Tsigaridas²²⁹, A. Tsigaridis^{XXII,225}, V. Tsiskaridze²²⁰, E.G. Tskhadadze²²⁰, M. Tsopoulou²²⁵, Y. Tsujikawa¹³⁷, I.I. Tsukerman⁶³, V. Tsulaia¹⁹, S. Tsuno¹³⁰, K. Tsurii¹⁷², D. Tsybychev²¹⁶, Y. Tu⁹⁴, A. Tudorache³⁵, V. Tudorache³⁵, S. B. Tuncay¹⁸⁰, S. Turchikhin^{85,84}, I. Turk Cakir³, R. Turra¹⁰⁵, T. Turtuvshin^{XXX,64}, P.M. Tuts⁶⁷, S. Tzamarias^{IV,225}, E. Tzovara¹⁵⁰, Y. Uematsu¹³⁰, F. Ukegawa²³¹, P.A. Ulloa Poblete^{199,198}, E.N. Umaka⁴³, G. Una⁶², A. Undrus⁴³, G. Unel²³³, J. Urban⁴², P. Urrejola¹⁹⁷, G. Usai⁹, R. Ushioda²²⁷, M. Usman¹⁵⁸, F. Ustuner⁷⁹, Z. Uysal¹²⁴, V. Vacek¹⁹², B. Vachon¹⁵⁴, T. Vafeiadis⁶², A. Vaitkus¹⁴⁶, C. Valderanis¹⁵⁹, E. Valdes Santurio^{73,74}, M. Valente⁶², S. Valentini^{30,29}, A. Valero²³⁷, E. Valiente Moreno²³⁷, A. Vallier¹³⁹, J.A. Valls Ferrer²³⁷, D. R. Van

Arneman¹⁶⁷, T.R. Van Daalen²⁰⁵, A. Van Der Graaf⁷⁶, H. Z. Van Der Schyf⁵⁴, P. Van Gemmeren⁷, M. Van Rijnbach⁶², S. Van Stroud¹⁴⁶, I. Van Vulpén¹⁶⁷, P. Vana¹⁹³, M. Vanadia^{115,116}, U. M. Vande Voorde²¹⁵, W. Vandelli⁶², E.R. Vandewall¹⁷⁵, D. Vannicola²²⁴, L. Vannoli⁸⁰, R. Vari¹¹³, M. Varma²⁴⁶, E.W. Varnes⁸, C. Varni¹⁶⁸, D. Varouchas⁹⁷, L. Varriale²³⁷, K.E. Varvell²¹⁸, M.E. Vasile³⁵, L. Vaslin¹³⁰, M. D. Vassilev²¹⁴, A. Vasyukov⁶⁴, L. M. Vaughan¹⁷⁵, R. Vavricka¹⁹³, T. Vazquez Schroeder¹⁴, J. Veatch⁴⁵, V. Vecchio¹⁵¹, M.J. Veen¹⁵³, I. Veliscek⁴³, I. Velkovska¹⁴³, L.M. Veloce²²⁸, F. Veloso^{184,186}, S. Veneziano¹¹³, A. Ventura^{103,104}, A. Verbitskiy¹⁶⁰, M. Verducci^{111,112}, C. Vergis¹⁴⁴, M. Verissimo De Araujo¹²⁶, W. Verkerke¹⁶⁷, J.C. Vermeulen¹⁶⁷, C. Vernieri²¹⁴, M. Vessella²³³, M.C. Vetterli^{XXXV,213}, A. Vgenopoulos¹⁵⁰, N. Viaux Maira²⁰³, T. Vickey²¹⁰, O.E. Vickey Boeriu²¹⁰, G.H.A. Viehhauser¹⁸⁰, L. Viganò⁹², M. Vigi¹⁶⁰, M. Villa^{30,29}, M. Villaplana Perez²³⁷, E.M. Villhauer⁶⁵, E. Vilucchi⁸⁰, M. Vincent²³⁷, M.G. Vinciter⁵⁵, A. Visibile¹⁶⁷, C. Vittori⁶², I. Vivarelli^{30,29}, E. Voevodina¹⁶⁰, F. Vogel¹⁵⁹, J.C. Voigt⁷⁷, P. Vokac¹⁹², Yu. Volkotrub¹³⁵, E. Von Toerne³¹, B. Vormwald⁶², K. Vorobev⁷⁸, M. Vos²³⁷, K. Voss²¹², M. Vozak⁶², L. Vozdecky¹⁷⁴, N. Vranjes¹⁷, M. Vranjes Milosavljevic¹⁷, M. Vreeswijk¹⁶⁷, N.K. Vu^{209,208}, R. Vuillermet⁶², O. Vujinovic¹⁵⁰, I. Vukotic⁶⁵, I. K. Vyas⁵⁵, J.F. Wack⁴⁶, S. Wada²³¹, C. Wagner²¹⁴, J.M. Wagner¹⁹, W. Wagner²⁴⁵, S. Wahdan²⁴⁵, H. Wahlberg¹⁴⁰, C. H. Waits¹⁷⁴, J. Walder¹⁹⁴, R. Walker¹⁵⁹, K. Walkingshaw Pass⁸⁷, W. Walkowiak²¹², A. Wall¹⁸², E.J. Wallin¹⁴⁸, T. Wamorkar¹⁹, A. Wang⁹⁰, A.Z. Wang¹⁹⁶, C. Wang¹⁵⁰, C. Wang¹², H. Wang¹⁹, J. Wang⁹⁵, P. Wang¹⁵¹, P. Wang¹⁴⁶, R. Wang⁸⁹, R. Wang⁷, S.M. Wang²¹⁹, S. Wang¹⁵, T. Wang⁹⁰, T. Wang⁹⁰, W.T. Wang¹²², W. Wang¹⁵, X. Wang²³⁶, X. Wang²⁰⁸, X. Wang⁷⁵, Y. Wang¹⁶², Y. Wang⁹⁰, Z. Wang¹⁵⁶, Z. Wang²⁰⁹, Z. Wang¹⁵⁶, C. Wanotayaroj¹³⁰, A. Warburton¹⁵⁴, A.L. Warnerbring²¹², N. Warrack⁸⁷, S. Waterhouse¹⁴⁵, A.T. Watson²³, H. Watson⁷⁹, M.F. Watson²³, E. Watton⁸⁷, G. Watts²⁰⁵, B.M. Waugh¹⁴⁶, J. M. Webb⁸¹, C. Weber⁴³, H. A. Weber²¹, M.S. Weber²², S.M. Weber⁹¹, C. Wei⁹⁰, Y. Wei⁸¹, A.R. Weidberg¹⁸⁰, E.J. Weik¹⁷¹, J. Weingarten⁷⁶, C. Weiser⁸¹, C.J. Wells⁷⁵, T. Wenaus⁴³, B. Wendland⁷⁶, T. Wengler⁶², N.S. Wenke¹⁶⁰, N. Wermes³¹, M. Wessels⁹¹, A.M. Wharton¹⁴¹, A.S. White⁸⁹, A. White⁹, M.J. White¹, D. Whiteson²³³, L. Wickremasinghe¹⁷⁸, W. Wiedenmann²⁴⁴, M. Wielders¹⁹⁴, R. Wierda²¹⁵, C. Wigglesworth⁶⁸, H.G. Wilkens⁶², J. J. H. Wilkinson⁴⁶, D.M. Williams⁶⁷, H.H. Williams¹⁸², S. Williams⁴⁶, S. Willoc¹⁵³, B.J. Wilson¹⁵¹, D.J. Wilson¹⁵¹, P.J. Windischhofer⁶⁵, F.I. Winkel⁴⁴, F. Winklmeier¹⁷⁷, B.T. Winter⁸¹, M. Wittgen²¹⁴, M. Wobisch¹⁴⁷, T. Wojtkowski⁸⁸, Z. Wolffs¹⁶⁷, J. Wollrath⁶², M.W. Wolter¹³⁶, H. Wolters^{184,186}, M.C. Wong¹⁹⁶, E.L. Woodward⁶⁷, S.D. Worm⁷⁵, B.K. Wosiek¹³⁶, K.W. Woźniak¹³⁶, S. Wozniowski⁸², K. Wraight⁸⁷, C. Wu²²⁸, C. Wu²³, J. Wu²²⁶, M. Wu¹⁶³, M. Wu¹⁶⁶, S.L. Wu²⁴⁴, S. Wu¹⁵, X. Wu⁹⁰, Y. Wu⁹⁰, Z. Wu⁵, J. Wuerzinger¹⁶⁰, T.R. Wyatt¹⁵¹, B.M. Wynne⁷⁹, S. Xella⁶⁸, L. Xia¹⁶², M. Xia¹⁶, M. Xie⁹⁰, A. Xiong¹⁷⁷, J. Xiong¹⁹, D. Xu¹⁵, H. Xu⁹⁰, L. Xu⁹⁰, R. Xu¹⁸², T. Xu¹⁵⁶, Y. Xu²⁰⁵, Z. Xu⁷⁹, R. Xue¹⁸³, B. Yabsley²¹⁸, S. Yacoub⁴⁷, Y. Yamaguchi¹³⁰, E. Yamashita²²⁶, H. Yamauchi²³¹, T. Yamazaki¹⁹, Y. Yamazaki¹³³, S. Yan⁸⁷, Z. Yan¹⁵³, H.J. Yang^{208,209}, H.T. Yang⁹⁰, S. Yang⁹⁰, T. Yang⁹⁵, X. Yang⁶², X. Yang¹⁵, Y. Yang²²⁶, Y. Yang⁹⁰, W-M. Yao¹⁹, C. L. Yardley²¹⁷, J. Ye¹⁵, S. Ye⁴³, X. Ye⁹⁰, Y. Yeh¹⁴⁶, I. Yeletsikh⁶⁴, B. Yeo²⁰, M.R. Yexley¹⁴⁶, T. P. Yildirim¹⁸⁰, K. Yorita²⁴², C.J.S. Young⁶², C. Young²¹⁴, N.D. Young¹⁷⁷, Y. Yu⁹⁰, J. Yuan^{XXXVII,15,164}, M. Yuan¹⁵⁶, R. Yuan^{209,208}, L. Yue¹⁴⁶, M. Zaazoua⁹⁰, B. Zabinski¹³⁶, I. Zahir⁵⁶, A. Zaio^{85,84}, Z.K. Zak¹³⁶, T. Zakareishvili²³⁷, S. Zambito⁸³, J.A. Zamora Saa²⁰⁰, J. Zang²²⁶, R. Zanzottera^{105,106}, O. Zaplatilek¹⁹², C. Zeitnitz²⁴⁵, H. Zeng¹⁵, J.C. Zeng²³⁶, D.T. Zenger Jr³³, O. Zenin⁶³, T. Ženiš⁴¹, S. Zenz¹⁴⁴, D. Zerwas⁹⁷, M. Zhai^{15,164}, D.F. Zhang²¹⁰, G. Zhang¹⁵, J. Zhang²⁰⁶, J. Zhang⁷, K. Zhang^{15,164}, L. Zhang⁹⁰, L. Zhang¹⁶², P. Zhang^{15,164}, R. Zhang¹⁶², S. Zhang¹³⁹, T. Zhang²²⁶, Y. Zhang²⁰⁵,

Y. Zhang¹⁴⁶, Y. Zhang⁹⁰, Y. Zhang¹⁶², Z. Zhang²⁰⁶, Z. Zhang⁹⁷, H. Zhao²⁰⁵, T. Zhao²⁰⁶, Y. Zhao⁵⁵, Z. Zhao⁹⁰, Z. Zhao⁹⁰, A. Zhemchugov⁶⁴, J. Zheng¹⁶², K. Zheng²³⁶, X. Zheng⁹⁰, Z. Zheng²¹⁴, D. Zhong²³⁶, B. Zhou¹⁵⁶, H. Zhou⁸, N. Zhou²⁰⁸, Y. Zhou¹⁶, Y. Zhou¹⁶², Y. Zhou⁸, C.G. Zhu²⁰⁶, J. Zhu¹⁵⁶, X. Zhu²⁰⁹, Y. Zhu²⁰⁸, Y. Zhu⁹⁰, X. Zhuang¹⁵, K. Zhukov⁹⁹, N.I. Zimine⁶⁴, J. Zinsser⁹², M. Ziolkowski²¹², L. Živković¹⁷, A. Zoccoli^{30,29}, K. Zoch⁸⁹, A. Zografos⁶², T.G. Zorbas²¹⁰, O. Zormpa⁷², L. Zwalinski⁶²

Affiliation Notes

^I Also at Affiliated with an institute formerly covered by a cooperation agreement with CERN

^{II} Also at An-Najah National University, Nablus, Palestine

^{III} Also at Borough of Manhattan Community College, City University of New York, New York NY, United States of America

^{IV} Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece

^V Also at Centre of Physics of the Universities of Minho and Porto (CF-UM-UP), Portugal

^{VI} Also at CERN, Geneva, Switzerland

^{VII} Also at CMD-AC UNEC Research Center, Azerbaijan State University of Economics (UNEC), Azerbaijan

^{VIII} Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland

^{IX} Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

^X Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece

^{XI} Also at Department of Mathematical Sciences, University of South Africa, Johannesburg, South Africa

^{XII} Also at Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China

^{XIII} Also at Department of Physics, Bolu Abant İzzet Baysal University, Bolu, Türkiye

^{XIV} Also at Department of Physics, King's College London, London, United Kingdom

^{XV} Also at Department of Physics, Stanford University, Stanford CA, United States of America

^{XVI} Also at Department of Physics, Stellenbosch University, South Africa

^{XVII} Also at Department of Physics, University of Fribourg, Fribourg, Switzerland

^{XVIII} Also at Department of Physics, University of Thessaly, Greece

^{XIX} Also at Department of Physics, Westmont College, Santa Barbara, United States of America

^{XX} Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia, Bulgaria

^{XXI} Also at Faculty of Physics, University of Bucharest, Romania

^{XXII} Also at Hellenic Open University, Patras, Greece

^{XXIII} Also at Henan University, China

^{XXIV} Also at Imam Mohammad Ibn Saud Islamic University, Saudi Arabia

^{XXV} Also at Institut Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain

^{XXVI} Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

^{XXVII} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria

^{XXVIII} Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco

^{XXIX} Also at Institute of Particle Physics (IPP), Canada

^{XXX} Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia

^{XXXI} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

- XXXII Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
 XXXIII Also at National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines
 XXXIV Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China
 XXXV Also at TRIUMF, Vancouver BC, Canada
 XXXVI Also at Università di Napoli Parthenope, Napoli, Italy
 XXXVII Also at University of Chinese Academy of Sciences (UCAS), Beijing, China
 XXXVIII Also at University of Colorado Boulder, Department of Physics, Colorado, United States of America
 XXXIX Also at University of Siena, Italy
 XL Also at Washington College, Chestertown, MD, United States of America
 XLI Also at Yeditepe University, Physics Department, Istanbul, Türkiye
 XLII Deceased

Collaboration Institutes

- ¹ Department of Physics, University of Adelaide, Adelaide, Australia
² Department of Physics, University of Alberta, Edmonton, AB, Canada
³ Department of Physics, Ankara University, Ankara, Türkiye
⁴ Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye
⁵ LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
⁶ APC, Université Paris Cité, CNRS/IN2P3, Paris, France
⁷ High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA
⁸ Department of Physics, University of Arizona, Tucson, AZ, USA
⁹ Department of Physics, University of Texas at Arlington, Arlington, TX, USA
¹⁰ Physics Department, National and Kapodistrian University of Athens, Athens, Greece
¹¹ Physics Department, National Technical University of Athens, Zografou, Greece
¹² Department of Physics, University of Texas at Austin, Austin, TX, USA
¹³ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
¹⁴ Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
¹⁵ Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
¹⁶ Physics Department, Tsinghua University, Beijing, China
¹⁷ Institute of Physics, University of Belgrade, Belgrade, Serbia
¹⁸ Department for Physics and Technology, University of Bergen, Bergen, Norway
¹⁹ Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
²⁰ University of California, Berkeley, CA, USA
²¹ Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
²² Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
²³ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
²⁴ Department of Physics, Bogazici University, Istanbul, Türkiye
²⁵ Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye
²⁶ Department of Physics, Istanbul University, Istanbul, Türkiye
²⁷ Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia
²⁸ Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia
²⁹ Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy
³⁰ INFN Sezione di Bologna, Italy
³¹ Physikalisches Institut, Universität Bonn, Bonn, Germany
³² Department of Physics, Boston University, Boston, MA, USA
³³ Department of Physics, Brandeis University, Waltham, MA, USA
³⁴ Transilvania University of Brasov, Brasov, Romania
³⁵ Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
³⁶ Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
³⁷ Physics Department, National Institute for Research and Development of Isotopic and Molecular Technologies, Cluj-Napoca, Romania
³⁸ National University of Science and Technology Politehnica, Bucharest, Romania
³⁹ West University in Timisoara, Timisoara, Romania
⁴⁰ Faculty of Physics, University of Bucharest, Bucharest, Romania
⁴¹ Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
⁴² Department of Subnuclear Physics, Institute of Experimental Physics, Slovak Academy of Sciences, Kosice, Slovak Republic
⁴³ Physics Department, Brookhaven National Laboratory, Upton, NY, USA
⁴⁴ Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina
⁴⁵ California State University, CA, USA
⁴⁶ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
⁴⁷ Department of Physics, University of Cape Town, Cape Town, South Africa
⁴⁸ iThemba Labs, Western Cape, South Africa
⁴⁹ Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
⁵⁰ National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines
⁵¹ Department of Physics, Stellenbosch University, Matieland, South Africa
⁵² Department of Physics, University of South Africa, Pretoria, South Africa
⁵³ University of Zululand, KwaDlangezwa, South Africa
⁵⁴ School of Physics, University of the Witwatersrand, Johannesburg, South Africa
⁵⁵ Department of Physics, Carleton University, Ottawa, ON, Canada
⁵⁶ Faculté des Sciences Ain Chock, Université Hassan II de Casablanca, Morocco
⁵⁷ Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco
⁵⁸ Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
⁵⁹ Faculté des Sciences, LPMR, Université Mohamed Premier, Oujda, Morocco
⁶⁰ Faculté des sciences, Université Mohammed V, Rabat, Morocco
⁶¹ Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco
⁶² CERN, Geneva, Switzerland
⁶³ Affiliated with an institute formerly covered by a cooperation agreement with CERN
⁶⁴ Affiliated with an international laboratory covered by a cooperation agreement with CERN
⁶⁵ Enrico Fermi Institute, University of Chicago, Chicago, IL, USA
⁶⁶ LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
⁶⁷ Nevis Laboratory, Columbia University, Irvington, NY, USA
⁶⁸ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
⁶⁹ Dipartimento di Fisica, Università della Calabria, Rende, Italy
⁷⁰ INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
⁷¹ Physics Department, Southern Methodist University, Dallas, TX, USA

- ⁷² National Centre for Scientific Research Demokritos, Agia Paraskevi, Greece
- ⁷³ Department of Physics, Stockholm University, Sweden
- ⁷⁴ Oskar Klein Centre, Stockholm, Sweden
- ⁷⁵ Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
- ⁷⁶ Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
- ⁷⁷ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁷⁸ Department of Physics, Duke University, Durham, NC, USA
- ⁷⁹ SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁸⁰ INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- ⁸¹ Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
- ⁸² II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
- ⁸³ Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
- ⁸⁴ Dipartimento di Fisica, Università di Genova, Genova, Italy
- ⁸⁵ INFN Sezione di Genova, Italy
- ⁸⁶ II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁸⁷ SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁸⁸ LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
- ⁸⁹ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, USA
- ⁹⁰ Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
- ⁹¹ Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ⁹² Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ⁹³ Department of Physics, Chinese University of Hong Kong, Shatin Hong Kong, N.T, China
- ⁹⁴ Department of Physics, University of Hong Kong, Hong Kong, China
- ⁹⁵ Department of Physics, Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon Hong Kong, China
- ⁹⁶ Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
- ⁹⁷ IJCLab, Université Paris-Saclay, CNRS/IN2P3, Orsay, 91405, France
- ⁹⁸ Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain
- ⁹⁹ Department of Physics, Indiana University, Bloomington, IN, USA
- ¹⁰⁰ INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
- ¹⁰¹ ICTP, Trieste, Italy
- ¹⁰² Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
- ¹⁰³ INFN Sezione di Lecce, Italy
- ¹⁰⁴ Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ¹⁰⁵ INFN Sezione di Milano, Italy
- ¹⁰⁶ Dipartimento di Fisica, Università di Milano, Milano, Italy
- ¹⁰⁷ INFN Sezione di Napoli, Italy
- ¹⁰⁸ Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ¹⁰⁹ INFN Sezione di Pavia, Italy
- ¹¹⁰ Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹¹¹ INFN Sezione di Pisa, Italy
- ¹¹² Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹¹³ INFN Sezione di Roma, Italy
- ¹¹⁴ Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- ¹¹⁵ INFN Sezione di Roma Tor Vergata, Italy
- ¹¹⁶ Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ¹¹⁷ INFN Sezione di Roma Tre, Italy
- ¹¹⁸ Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- ¹¹⁹ INFN-TIFPA, Italy
- ¹²⁰ Università degli Studi di Trento, Trento, Italy
- ¹²¹ Department of Astro and Particle Physics, Universität Innsbruck, Innsbruck, Austria
- ¹²² University of Iowa, Iowa City, IA, USA
- ¹²³ Department of Physics and Astronomy, Iowa State University, Ames, IA, USA
- ¹²⁴ Istinye University, Sariyer, Istanbul, Türkiye
- ¹²⁵ Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
- ¹²⁶ COPPE/EE/IF, Universidade Federal do Rio, De Janeiro Rio de Janeiro, Brazil
- ¹²⁷ Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
- ¹²⁸ Rio de Janeiro State University, Rio de Janeiro, Brazil
- ¹²⁹ Federal University of Bahia, Bahia, Brazil
- ¹³⁰ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ¹³¹ Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates
- ¹³² University of Sharjah, Sharjah, United Arab Emirates
- ¹³³ Graduate School of Science, Kobe University, Kobe, Japan
- ¹³⁴ Faculty of Physics and Applied Computer Science, AGH University of Krakow, Krakow, Poland
- ¹³⁵ Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- ¹³⁶ Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- ¹³⁷ Faculty of Science, Kyoto University, Kyoto, Japan
- ¹³⁸ Research Center for Advanced Particle Physics, Department of Physics, Kyushu University, Fukuoka, Japan
- ¹³⁹ L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France
- ¹⁴⁰ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ¹⁴¹ Physics Department, Lancaster University, Lancaster, United Kingdom
- ¹⁴² Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ¹⁴³ Department of Experimental Particle Physics, Department of Physics, Jožef Stefan Institute, University of Ljubljana, Ljubljana, Slovenia
- ¹⁴⁴ Department of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ¹⁴⁵ Department of Physics, Royal Holloway University of London, Egham, United Kingdom
- ¹⁴⁶ Department of Physics and Astronomy, University College London, London, United Kingdom
- ¹⁴⁷ Louisiana Tech University, Ruston, LA, USA
- ¹⁴⁸ Fysiska institutionen, Lunds universitet, Lund, Sweden
- ¹⁴⁹ Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
- ¹⁵⁰ Institut für Physik, Universität Mainz, Mainz, Germany
- ¹⁵¹ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ¹⁵² CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
- ¹⁵³ Department of Physics, University of Massachusetts, Amherst, MA, USA
- ¹⁵⁴ Department of Physics, McGill University, Montreal, QC, Canada
- ¹⁵⁵ School of Physics, University of Melbourne, Victoria, Australia
- ¹⁵⁶ Department of Physics, University of Michigan, Ann Arbor, MI, USA
- ¹⁵⁷ Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA

- ¹⁵⁸ Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- ¹⁵⁹ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁶⁰ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁶¹ Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁶² Department of Physics, Nanjing University, Nanjing, China
- ¹⁶³ School of Science, Shenzhen Campus of Sun Yat-sen University, China
- ¹⁶⁴ University of Chinese Academy of Science (UCAS), Beijing, China
- ¹⁶⁵ Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA
- ¹⁶⁶ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands
- ¹⁶⁷ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁶⁸ Department of Physics, Northern Illinois University, DeKalb, IL, USA
- ¹⁶⁹ New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
- ¹⁷⁰ United Arab Emirates University, Al Ain, United Arab Emirates
- ¹⁷¹ Department of Physics, New York University, New York, NY, USA
- ¹⁷² Ochanomizu University, Bunkyo-ku, Otsuka Tokyo, Japan
- ¹⁷³ Ohio State University, Columbus, OH, USA
- ¹⁷⁴ Department of Physics and Astronomy, Homer L. Dodge, University of Oklahoma, Norman, OK, USA
- ¹⁷⁵ Department of Physics, Oklahoma State University, Stillwater, OK, USA
- ¹⁷⁶ Joint Laboratory of Optics, Palacký University, Olomouc, Czech Republic
- ¹⁷⁷ Institute for Fundamental Science, University of Oregon, Eugene, OR, USA
- ¹⁷⁸ Graduate School of Science, University of Osaka, Osaka, Japan
- ¹⁷⁹ Department of Physics, University of Oslo, Oslo, Norway
- ¹⁸⁰ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹⁸¹ LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France
- ¹⁸² Department of Physics, University of Pennsylvania, Philadelphia, PA, USA
- ¹⁸³ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, USA
- ¹⁸⁴ Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
- ¹⁸⁵ Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
- ¹⁸⁶ Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
- ¹⁸⁷ Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
- ¹⁸⁸ Departamento de Física, Escola de Ciências, Universidade do Minho, Braga, Portugal
- ¹⁸⁹ Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain, Spain
- ¹⁹⁰ Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
- ¹⁹¹ Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic
- ¹⁹² Czech Technical University, Prague Prague, Czech Republic
- ¹⁹³ Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
- ¹⁹⁴ Particle Physics Department, Rutherford Appleton Laboratory Didcot, United Kingdom
- ¹⁹⁵ IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ¹⁹⁶ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, USA
- ¹⁹⁷ Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
- ¹⁹⁸ Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile
- ¹⁹⁹ Departamento de Física, Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, Universidad de La Serena, Chile
- ²⁰⁰ Department of Physics, Universidad Andres Bello, Santiago, Chile
- ²⁰¹ Universidad San Sebastian, Recoleta, Chile
- ²⁰² Instituto de Alta Investigación Universidad de Tarapacá, Arica, Chile
- ²⁰³ Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ²⁰⁴ Department of Physics, Institute of Science, Tokyo, Japan
- ²⁰⁵ Department of Physics, University of Washington, Seattle, WA, USA
- ²⁰⁶ Institute of Frontier and Interdisciplinary Science and Key, Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
- ²⁰⁷ School of Physics, Zhengzhou University, China
- ²⁰⁸ School of Physics and Astronomy, State Key Laboratory of Dark Matter Physics, Key Laboratory for Particle Astrophysics and Cosmology (MOE), Shanghai Jiao Tong University, SKLPPC, Shanghai, China
- ²⁰⁹ State Key Laboratory of Dark Matter Physics, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai, China
- ²¹⁰ Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ²¹¹ Department of Physics, Shinshu University, Nagano, Japan
- ²¹² Department Physik, Universität Siegen, Siegen, Germany
- ²¹³ Department of Physics, Simon Fraser University, Burnaby, BC, Canada
- ²¹⁴ SLAC National Accelerator Laboratory, Stanford, CA, USA
- ²¹⁵ Department of Physics, Royal Institute of Technology, Stockholm, Sweden
- ²¹⁶ Departments of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA
- ²¹⁷ Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- ²¹⁸ School of Physics, University of Sydney, Sydney, Australia
- ²¹⁹ Institute of Physics, Academia Sinica, Taipei, Taiwan
- ²²⁰ E. Andronikashvili Institute of Physics, Iv. Javakhishvili, Tbilisi State University, Tbilisi, Georgia
- ²²¹ High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ²²² University of Georgia, Tbilisi, Georgia
- ²²³ Department of Physics, Israel Institute of Technology, Technion Haifa, Israel
- ²²⁴ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- ²²⁵ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- ²²⁶ International Center for Elementary Particle Physics, Department of Physics, University of Tokyo, Tokyo, Japan
- ²²⁷ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- ²²⁸ Department of Physics, University of Toronto, Toronto, ON, Canada
- ²²⁹ TRIUMF, Vancouver, BC, Canada
- ²³⁰ Department of Physics and Astronomy, York University, Toronto, ON, Canada
- ²³¹ Division of Physics and Tomonaga Center, Faculty of Pure and Applied Sciences, the History of the Universe, University of Tsukuba, Tsukuba, Japan
- ²³² Department of Physics and Astronomy, Tufts University, Medford, MA, USA
- ²³³ Department of Physics and Astronomy, University of California Irvine, Irvine, CA, USA
- ²³⁴ University of West Attica, Athens, Greece
- ²³⁵ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- ²³⁶ Department of Physics, University of Illinois, Urbana, IL, USA

- ²³⁷ Centro Mixto, Instituto de Física Corpuscular (IFIC), Universidad de Valencia - CSIC, Valencia, Spain
- ²³⁸ Department of Physics, University of British Columbia, Vancouver, BC, Canada
- ²³⁹ Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
- ²⁴⁰ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
- ²⁴¹ Department of Physics, University of Warwick, Coventry, United Kingdom
- ²⁴² Waseda University, Tokyo, Japan
- ²⁴³ Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel
- ²⁴⁴ Department of Physics, University of Wisconsin, Madison, WI, USA
- ²⁴⁵ Fachgruppe Physik, Fakultät für Mathematik und Naturwissenschaften, Bergische Universität Wuppertal, Wuppertal, Germany
- ²⁴⁶ Department of Physics, Yale University, New Haven, CT, USA
- ²⁴⁷ Yerevan Physics Institute, Yerevan, Armenia

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