


Dijet azimuthal correlations and conditional yields in pp and $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector

M. Aaboud *et al.**
(ATLAS Collaboration)

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This paper presents a measurement of forward-forward and forward-central dijet azimuthal angular correlations and conditional yields in proton-proton (pp) and proton-lead ($p + \text{Pb}$) collisions as a probe of the nuclear gluon density in regions where the fraction of the average momentum per nucleon carried by the parton entering the hard scattering is low. In these regions, gluon saturation can modify the rapidly increasing parton distribution function of the gluon. The analysis utilizes 25 pb^{-1} of pp data and $360 \mu\text{b}^{-1}$ of $p + \text{Pb}$ data, both at $\sqrt{s_{NN}} = 5.02$ TeV, collected in 2015 and 2016, respectively, with the ATLAS detector at the Large Hadron Collider. The measurement is performed in the center-of-mass frame of the nucleon-nucleon system in the rapidity range between -4.0 and 4.0 using the two highest transverse-momentum jets in each event, with the highest transverse-momentum jet restricted to the forward rapidity range. No significant broadening of azimuthal angular correlations is observed for forward-forward or forward-central dijets in $p + \text{Pb}$ compared to pp collisions. For forward-forward jet pairs in the proton-going direction, the ratio of conditional yields in $p + \text{Pb}$ collisions to those in pp collisions is suppressed by approximately 20%, with no significant dependence on the transverse momentum of the dijet system. No modification of conditional yields is observed for forward-central dijets.

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I. INTRODUCTION

Studies of particle collisions at accelerators have contributed significantly to an improved understanding of the strong interaction in quantum chromodynamics (QCD) and to the knowledge of the parton distribution functions (PDFs) of the proton. Global QCD analyses of structure functions in deep-inelastic lepton-nucleon scattering at HERA, as well as jet and hadron cross sections at the Large Hadron Collider (LHC), Tevatron, and Relativistic Heavy Ion Collider (RHIC) were performed in a wide kinematic range, providing several new sets of PDFs with the highest degree of precision reached so far [1–4]. These analyses constrain quark and gluon contributions over a wide range of the Bjorken variable x : The longitudinal-momentum fraction of a nucleon carried by its constituent partons. From these measurements, the gluon distribution in the proton is found to rise rapidly for decreasing x . Unitarity requires that the first moment of the gluon-momentum distribution remains finite. Therefore, the steep rise at low x must change at some x value; this phenomenon is known as *saturation* [5].

The search for the onset of saturation was a major scientific goal with deuteron-gold and gold-gold collisions at RHIC

[6–8], where the sensitivity to saturation effects was increased due to the enhancement of the nuclear gluon density in the Lorentz-contracted nucleus [9]. These measurements were able to probe the parton longitudinal-momentum fraction of the nucleon in the nucleus down to $x_A \sim 10^{-3}$. Currently, the gluon nuclear PDFs have large uncertainties at low x_A [10,11], and additional data in this region would help to further constrain them. A midrapidity measurement of jet-production rates at RHIC found no significant modification in deuteron-gold collisions compared to proton-proton (pp) collisions [12]. Recent analyses at the LHC have been performed in the proton-going direction of proton-lead ($p + \text{Pb}$) collisions and at higher center-of-mass energies, allowing a lower value of x_A to be probed for the lead nucleus. The ALICE measurements of cross sections for charged-jet production and dijet azimuthal angular correlations at midrapidity did not find significant modifications in $p + \text{Pb}$ collisions compared to pp collisions [13,14]. The ATLAS and CMS analyses of inclusive jet production also did not find significant evidence of nuclear modification [15,16]. Another approach to probe gluon saturation in nuclear gluon densities was proposed in the framework of the color glass condensate (CGC) model [17] by studying the modifications of dijet azimuthal angular distributions in pp and $p + \text{Pb}$ collisions at forward rapidities at x_A down to 10^{-5} [18]. For back-to-back dijets, the gluon field in the lead nucleus is probed at low momentum where saturation effects are expected to be large [19,20].

In this paper, a measurement of azimuthal correlations between leading and subleading jets in pp and $p + \text{Pb}$

*Full author list given at the end of the article.

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collisions at $\sqrt{s_{NN}} = 5.02$ TeV is presented. The measurement is performed in intervals of the jet center-of-mass rapidity¹ $y^* = y - \Delta y$, where y is the jet rapidity in the laboratory frame, and Δy is the rapidity shift of the center-of-mass frame relative to the laboratory frame. This shift results from the different energy of the proton-beam with respect to the Pb beam in $p + \text{Pb}$ collisions. The leading jet has the highest transverse momentum ($p_{T,1}$) in the event and is required to be in the forward proton-going direction; otherwise, the event is not considered. The subleading jet has the second-highest transverse momentum ($p_{T,2}$) in the event and its rapidity range is not restricted. The center-of-mass rapidities of the leading and subleading jets are y_1^* and y_2^* , respectively. This measurement of dijets can probe the x_A range between 10^{-4} and 10^{-3} in the lead nucleus. The azimuthal angular correlation distributions C_{12} , which are normalized to the number of forward ($2.7 < y_1^* < 4.0$) leading jets N_1 in a given $p_{T,1}$ interval, are defined as:

$$C_{12}(p_{T,1}, p_{T,2}, y_1^*, y_2^*) = \frac{1}{N_1} \frac{dN_{12}}{d\Delta\phi},$$

where N_{12} is the number of dijets and $\Delta\phi$ is the azimuthal angle between the leading and subleading jets. The C_{12} distributions are fitted and their widths W_{12} defined by the root-mean-square of the fit function: $W_{12}(p_{T,1}, p_{T,2}, y_1^*, y_2^*) = \text{RMS}(C_{12})$.

In addition to dijet azimuthal angular distributions, the dijet conditional yields I_{12} are measured and defined as:

$$I_{12}(p_{T,1}, p_{T,2}, y_1^*, y_2^*) = \frac{1}{N_1} \frac{d^4 N_{12}}{dy_1^* dy_2^* dp_{T,1} dp_{T,2}}.$$

The azimuthal angular correlations and conditional yields evaluated in $p + \text{Pb}$ and pp collisions are compared and the ratios in W_{12} and I_{12} between the two systems are calculated as:

$$\rho_W^{\text{pPb}}(p_{T,1}, p_{T,2}, y_1^*, y_2^*) = \frac{W_{12}^{\text{pPb}}}{W_{12}^{\text{pp}}},$$

$$\rho_I^{\text{pPb}}(p_{T,1}, p_{T,2}, y_1^*, y_2^*) = \frac{I_{12}^{\text{pPb}}}{I_{12}^{\text{pp}}}.$$

To define a phase space that better suits next-to-leading-order calculations, a minimum $\Delta p_T = p_{T,1} - p_{T,2}$ is required for the dijets [21–23]. However, techniques such as Sudakov resummation [24] can take into account the absence of Δp_T

requirements. Also, comparisons with fixed-order calculations and soft-gluon resummation, which involve transverse-momentum-dependent PDFs, instead of collinear PDFs, are better suited to scenarios not placing any minimum Δp_T requirement on the dijets. The results of the measurement are therefore presented both without any requirement on Δp_T and with a requirement of $\Delta p_T > 3$ GeV.

II. EXPERIMENTAL SETUP

The measurements presented here are performed using the ATLAS calorimeter, trigger, and data acquisition systems [25]. The calorimeter system consists of a sampling lead/liquid argon (LAr) electromagnetic calorimeter covering $|\eta| < 3.2$, a steel/scintillator sampling hadronic calorimeter covering $|\eta| < 1.7$, a LAr hadronic calorimeter covering $1.5 < |\eta| < 3.2$, and two LAr forward calorimeters (FCal) covering $3.2 < |\eta| < 4.9$. The electromagnetic calorimeters are segmented longitudinally in shower depth into three layers plus an additional presampler layer and have a granularity that varies with the layer and pseudorapidity and which is also much finer than that of the hadronic calorimeter. The hadronic calorimeter has three longitudinal sampling layers and comprises the tile barrel and extended barrel hadronic calorimeters covering $|\eta| < 1.7$, and the hadronic endcap calorimeter (HEC) covering $1.5 < |\eta| < 3.2$. The minimum-bias trigger scintillators detect particles over $2.1 < |\eta| < 3.9$ using two azimuthally segmented counters placed at $z = \pm 3.6$ m. There are 12 measurements per counter. Each counter provides measurements of both the pulse heights and the arrival times of energy deposits from each segment.

A two-level trigger system was used to select the pp and $p + \text{Pb}$ collisions. The first level is the level-1 (L1) hardware-based trigger implemented with custom electronics. The second level is the software-based high-level trigger (HLT). Jet events were selected by the HLT with input from the L1 jet and transverse-energy triggers in pp collisions and minimum-bias trigger in $p + \text{Pb}$ collisions. The two L1 transverse-energy triggers used in pp collisions required the total transverse energy measured in the calorimeters to be greater than 5 and 10 GeV, respectively. The L1 jet trigger used in pp collisions required a jet to exceed transverse-energy thresholds ranging from 12 to 20 GeV. The L1 minimum-bias trigger selected $p + \text{Pb}$ events with at least one hit in the minimum-bias trigger scintillator counters on each side of the IP. The HLT jet trigger employed a jet reconstruction algorithm similar to that applied in the offline analysis and selected events containing jets that exceeded a transverse-energy threshold of 15 GeV in $p + \text{Pb}$ collisions and thresholds ranging from 25 to 85 GeV in pp collisions. In both the pp and $p + \text{Pb}$ collisions, the highest-threshold jet trigger sampled the full delivered luminosity, and jet triggers with lower thresholds were prescaled² and sampled a fraction of delivered luminosity. Both the forward

¹ATLAS 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 upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. For the $p + \text{Pb}$ collisions, the incident Pb beam traveled in the $+z$ direction. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ with $\Delta\eta$ and $\Delta\phi$ defined as the differences between two directions in pseudorapidity and azimuth. Rapidity is defined in terms of energy and momentum of a particle or jet as $y = (1/2) \ln[(E + p_z)/(E - p_z)]$.

²The prescale indicates which fraction of events that passed the trigger selection was selected for recording by the data acquisition system.

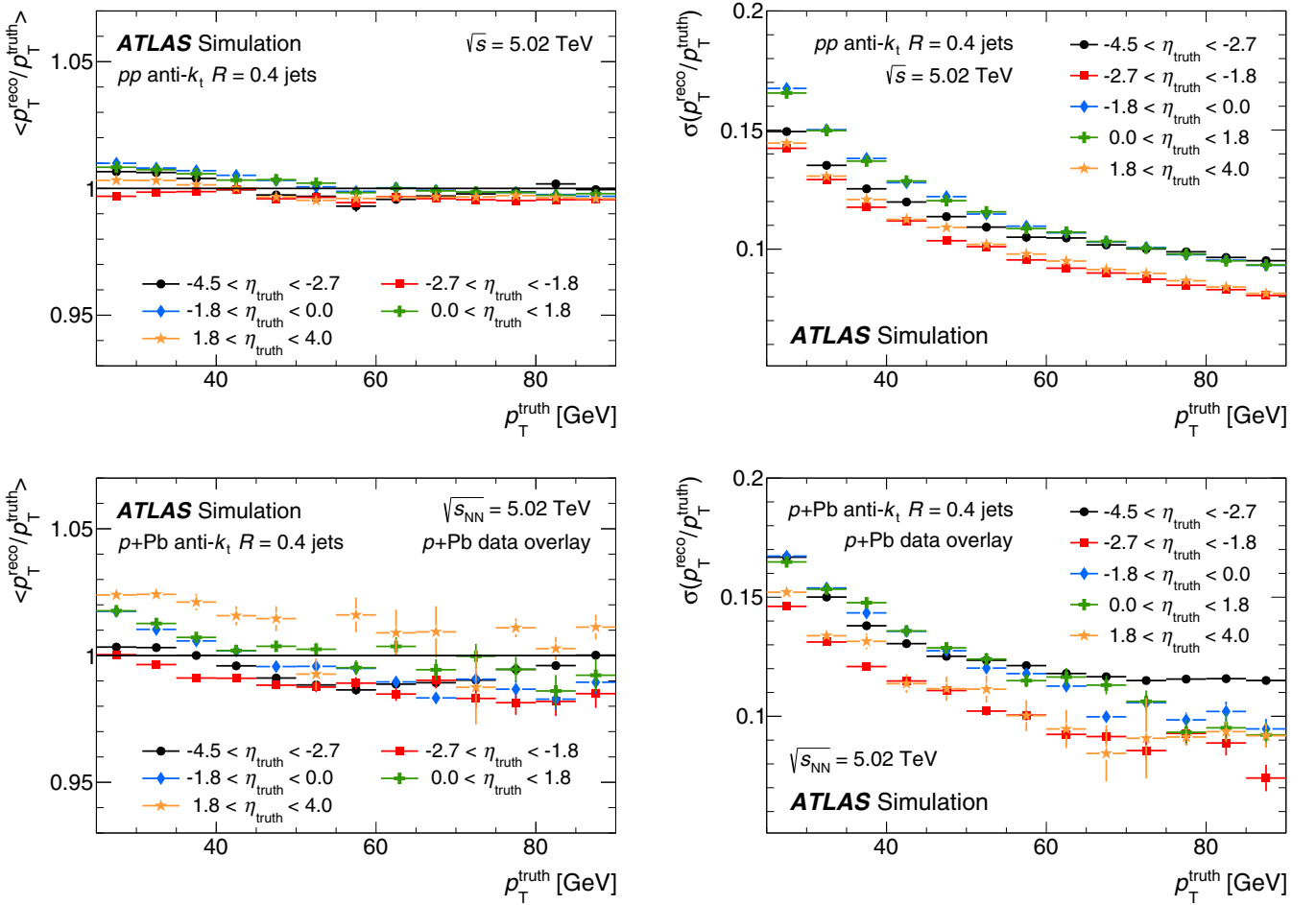


FIG. 1. (Left) Jet energy scale and (right) jet energy resolution evaluated in (top) pp and (bottom) $p + \text{Pb}$ MC samples in different generator-level jet pseudorapidity intervals and shown as a function of the generator-level jet transverse momentum p_T^{truth} .

($3.2 < |\eta| < 4.9$) and central ($|\eta| < 3.2$) jet triggers are used in this measurement.

III. DATA SETS AND EVENT SELECTION

A total of 25 pb^{-1} of $\sqrt{s} = 5.02\text{-TeV}$ pp data from 2015 with two equal-energy proton beams is used. During pp data taking, the average number of interactions per bunch crossing varied from 0.6 to 1.3.

TABLE I. The transverse-momentum intervals ($p_{T,1}$, $p_{T,2}$) of the leading and subleading jets and the center-of-mass rapidity intervals (y_2^*) of the subleading jet. In all cases the center-of-mass rapidity interval of the leading jet is $2.7 < y_1^* < 4.0$.

Bins in $p_{T,1}$ (GeV)	Bins in $p_{T,2}$ (GeV)	Bins in y_2^*
$28 < p_{T,1} < 35$	$28 < p_{T,2} < 35$	$2.7 < y_2^* < 4.0$
$35 < p_{T,1} < 45$	$35 < p_{T,2} < 45$	$1.8 < y_2^* < 2.7$
$45 < p_{T,1} < 90$	$45 < p_{T,2} < 90$	$0.0 < y_2^* < 1.8$
		$-1.8 < y_2^* < 0.0$
		$-4.0 < y_2^* < -1.8$

The $p + \text{Pb}$ data used in this analysis were recorded in 2016 with the LHC configured with a 4-TeV proton-beam and a 1.57-TeV-per-nucleon Pb beam, producing collisions with $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ and $\Delta y = 0.465$. The polar angle θ was π for the proton-beam and zero for the Pb beam. However, in order to be consistent with previous measurements [15,26], the proton-going direction is defined to have positive rapidity in this measurement. The total $p + \text{Pb}$ integrated luminosity is $360 \mu\text{b}^{-1}$. During the $p + \text{Pb}$ data taking the average number of $p + \text{Pb}$ interactions per bunch crossing was 0.03. In $p + \text{Pb}$ and pp collisions, events are required to have a reconstructed vertex. Only events taken during stable beam conditions and satisfying detector and data-quality requirements are considered.

The performance of ATLAS in measuring azimuthal angular correlations and conditional yields in both the pp and $p + \text{Pb}$ data samples was evaluated with a 5.02-TeV pp Monte Carlo (MC) sample simulated using PYTHIA8.212 [27]. Hard-scattering pp events generated with the A14 [28] set of tuned parameters and the NNPDF23LO PDF set [29] were used. The detector response was simulated using GEANT4 [30,31]. The pp MC samples used for this analysis contain approximately 12 million events. Corresponding $p + \text{Pb}$ MC samples were obtained by overlaying signal from pp

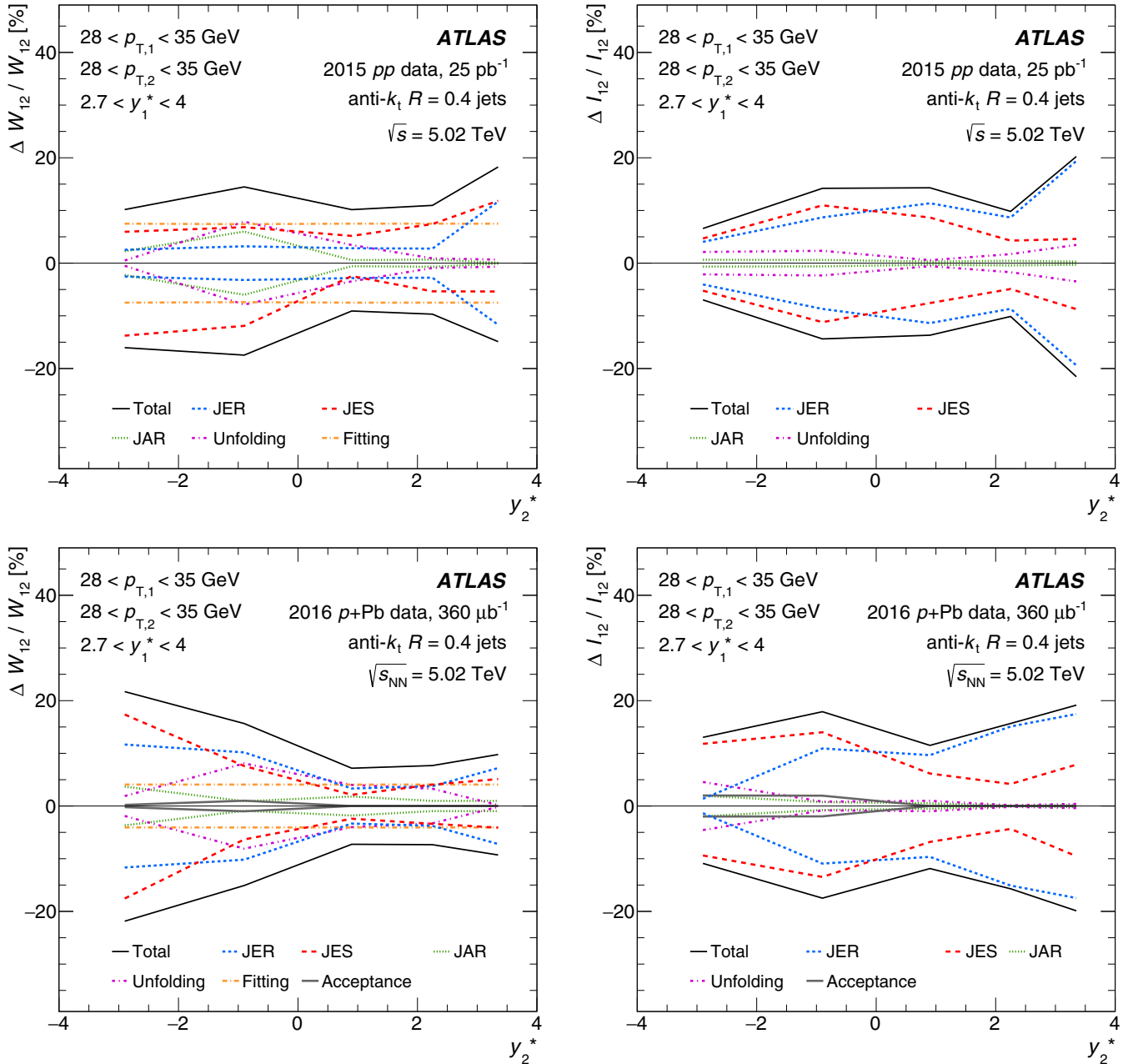


FIG. 2. Relative systematic uncertainties of values of (left) W_{12} and (right) I_{12} in (top) pp and (bottom) $p + \text{Pb}$ collisions. The uncertainty associated with the disabled HEC region is labeled as the “Acceptance” uncertainty. Uncertainty values are presented for the center of the bin and with no Δp_T requirement.

MC simulation with minimum-bias data events from $p + \text{Pb}$ collisions. These simulated 5.02-TeV pp events used in the overlay procedure were generated with the same set of tuned parameters as for the pp MC sample but with a rapidity shift equivalent to that in the $p + \text{Pb}$ collisions. The simulated hits are combined with those from the data event and used as input to the jet reconstruction. Additionally, a HERWIG++ [32] MC simulation of approximately 5.6 million 5.02-TeV pp events was used for performance studies. The $p + \text{Pb}$ MC samples are weighted at the event level to reproduce the FCal E_T distribution in the $p + \text{Pb}$ data.

IV. JET SELECTION AND RECONSTRUCTION

Jets in pp and $p + \text{Pb}$ collisions are reconstructed using the techniques described in Refs. [15,33], which are briefly summarized here. The jet reconstruction is first run in the four-momentum recombination mode on $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ calorimeter towers with the anti- k_r algorithm [34] with radius parameter $R = 0.4$. Energies in the towers are obtained by summing the energies of calorimeter cells at the electromagnetic energy scale within the tower boundaries. Then an iterative procedure is used to estimate the layer- and η -dependent underlying event (UE) transverse-energy

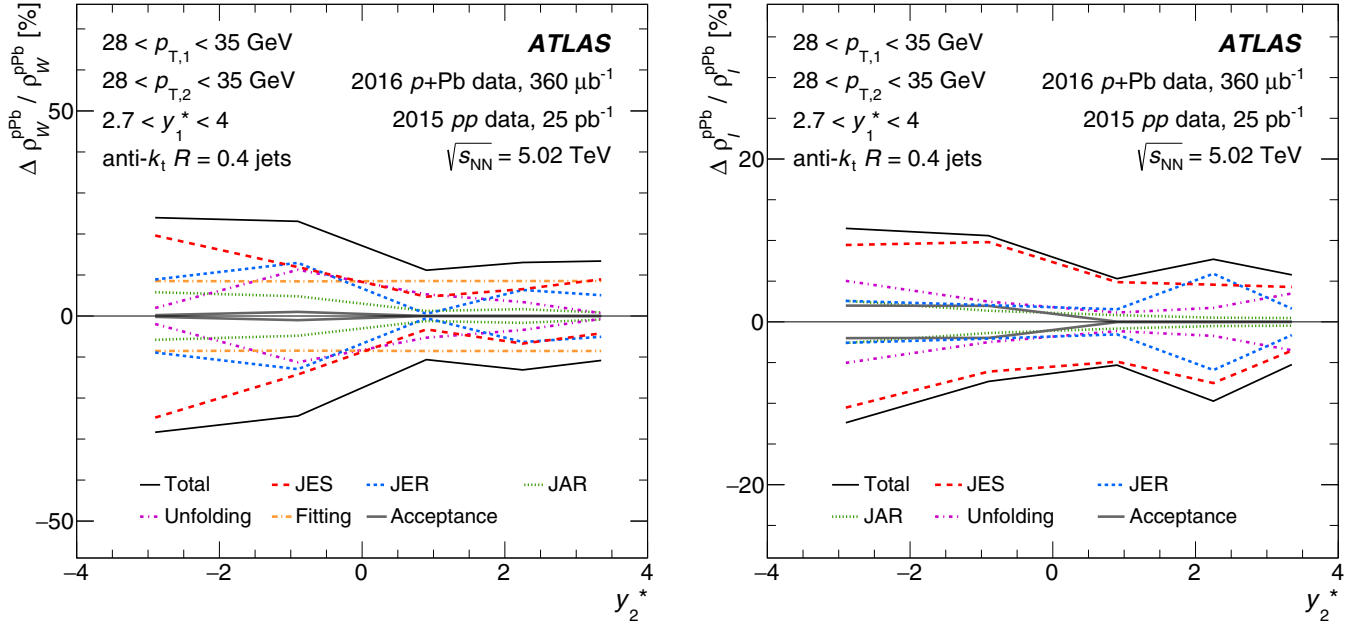


FIG. 3. Relative systematic uncertainties of values of (left) ρ_W^{pPb} and (right) ρ_l^{pPb} . The uncertainty associated with the disabled HEC region is labeled as the “Acceptance” uncertainty. Uncertainty values are presented for the center of the bin and with no Δp_T requirement.

density, while excluding the regions populated by jets. The UE transverse energy is subtracted from each calorimeter tower and the four-momentum of the jet is updated accordingly. Then a jet η - and p_T -dependent correction factor derived from the simulation samples is applied to correct for the calorimeter response. An additional correction based on *in situ* studies of the transverse-momentum balance of jets recoiling against photons, Z bosons, and jets in other regions of the calorimeter is applied [35,36].

Jets are selected in the transverse-momentum range $28 < p_T < 90$ GeV and the center-of-mass rapidity range $|y^*| < 4.0$. These selections guarantee the largest symmetric overlap between the two colliding systems for which most forward jets can be reconstructed using the FCal with full coverage for $R = 0.4$ jets. All reconstructed jets are required to have a $p_T > 28$ GeV such that the jet trigger efficiency is greater than 99%. As a result, no trigger efficiency correction is applied. During the $p + \text{Pb}$ data taking, part of the HEC was disabled in the pseudorapidity and azimuthal intervals $1.3 < \eta < 3.2$ and $-\pi < \phi < -\pi/2$. Reconstructed dijets where the subleading jet area overlaps with the disabled HEC region are excluded from the analysis in $p + \text{Pb}$ data and MC samples.

The MC samples are used to evaluate the jet reconstruction performance and to correct the measured distributions for detector effects. This is done independently for pp and $p + \text{Pb}$ collisions. In the MC samples, the generator-level jets are reconstructed from stable particles³ excluding muons and neutrinos, with the anti- k_t algorithm with radius parameter $R = 0.4$. Using the pseudorapidity and azimuthal angles η_{truth} ,

³Stable particles are defined as particles with a mean lifetime $\tau > 0.3 \times 10^{-10}$ s.

ϕ_{truth} , η_{reco} , and ϕ_{reco} of the generated and reconstructed jets, respectively, generator-level jets are matched to reconstructed jets by requiring $\Delta R < 0.2$.

The efficiency for reconstructing jets in pp and $p + \text{Pb}$ collisions is evaluated using the PYTHIA8 MC samples by determining the probability of finding a reconstructed jet associated with a generator-level jet. The jet reconstruction efficiency is greater than 99% for jets with $p_T > 30$ GeV and decreases to 95% at a jet $p_T = 28$ GeV. The jet reconstruction efficiency exhibits a small variation with rapidity.

The jet energy reconstruction performance is characterized using the ratios of transverse momenta of reconstructed jets to generated jets, p_T^{reco} and p_T^{truth} , respectively, to determine the relevant jet energy scale (JES) and jet energy resolution (JER) corresponding to the mean and width of the jet response ($p_T^{\text{reco}}/p_T^{\text{truth}}$). The values of JES and JER are shown in Fig. 1 as a function of p_T^{truth} , in intervals of generated jet pseudorapidity η_{truth} , for pp and $p + \text{Pb}$ MC samples. The JES shows a very small dependence on η_{truth} , with a maximum deviation of $\pm 3\%$ from unity. Jet angular reconstruction performance has been studied in terms of mean angular differences between the reconstructed and generator-level jet direction in pseudorapidity and azimuthal angle, $\langle \Delta \eta \rangle$ and $\langle \Delta \phi \rangle$, and their resolutions, $\sigma(\Delta \eta)$ and $\sigma(\Delta \phi)$. The mean angular differences are consistent with zero, and the jet angular resolutions (JAR) decrease from approximately 17% to 10% as a function of p_T^{truth} for both the pp and $p + \text{Pb}$ MC samples.

V. ANALYSIS PROCEDURE

The two-highest p_T jets in each event are used to measure the azimuthal angular correlation distributions, which are evaluated as a function of $\Delta \phi$ relative to the leading jet in the center-of-mass rapidity interval $2.7 < y_1^* < 4.0$, and in

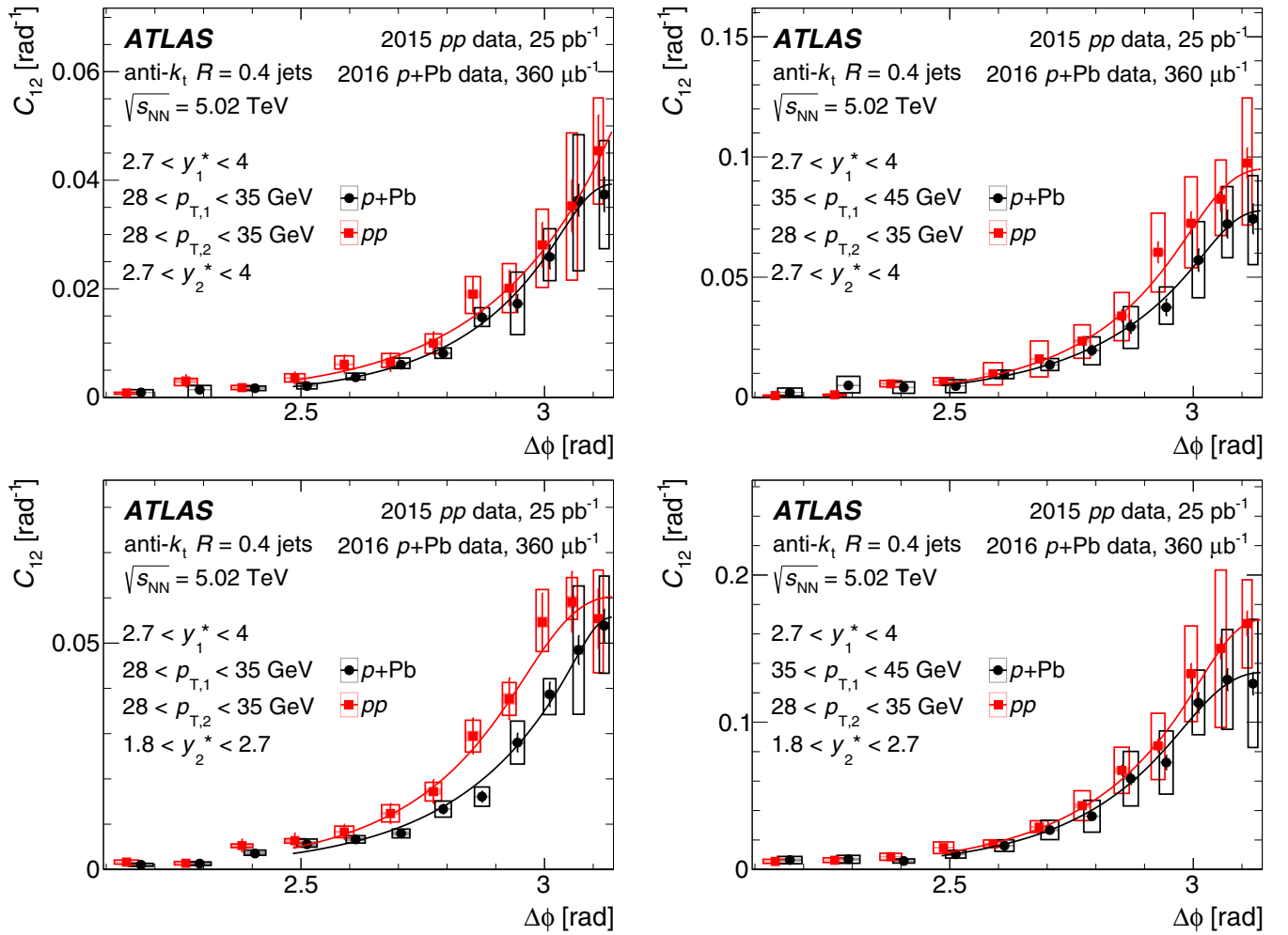


FIG. 4. Unfolded C_{12} distributions in (red squares) pp and (black circles) $p + \text{Pb}$ collisions for different selections of $p_{T,1}$, $p_{T,2}$, y_1^* , and y_2^* as a function of $\Delta\phi$. The lines represent values of the fit function. The data points are shifted horizontally for visibility and do not reflect an actual shift in $\Delta\phi$. The vertical size of the open boxes represents systematic uncertainties and error bars indicate statistical uncertainties. The horizontal size of the open boxes does not represent the width of the bins. Results are shown with no Δp_T requirement, where $\Delta p_T = p_{T,1} - p_{T,2}$.

different intervals of y_2^* , $p_{T,1}$, and $p_{T,2}$. Table I lists the transverse momenta and center-of-mass rapidity intervals used in the measurement. The C_{12} distributions are then fitted to extract their widths.

The effects of migration due to the jet energy and angular resolutions as well as the jet reconstruction efficiency affecting the leading-jet p_T spectra and C_{12} distributions in pp and $p + \text{Pb}$ collisions are corrected for by using a bin-by-bin unfolding procedure. For each of the affected distributions, correction factors that are applied to data are derived from the ratio between two corresponding MC distributions; one evaluated using generator-level jets and the other evaluated using jets reconstructed after the detector simulation. To account for the jets excluded due to the disabled HEC region in $p + \text{Pb}$ data and MC samples, an acceptance correction is applied using the same procedure because generator-level jets are not excluded from the affected region. Thus, the correction factors used in the unfolding account for the missing jets at reconstruction level. The bin-by-bin unfolding procedure is

sensitive to differences in the shapes of distributions between the data and the MC samples. Thus, the jet p_T and C_{12} distributions in the MC reconstructed samples are reweighted to match the shapes in the data. Weights are derived by evaluating the data-to-MC ratios of the reconstructed distributions. The reweighting is done in two steps: (1) weights are evaluated for the jet p_T spectra; (2) when deriving weights for the C_{12} distributions, the dependence of the ratio between data and MC on the jet p_T spectra is removed by applying the weights evaluated in the previous step. The final weight is the product of the two weights. Jet weights of the jet p_T spectra are within 10% of unity for pp and $p + \text{Pb}$ collisions, and the $\Delta\phi$ weights are within 15% of unity near the peak of the C_{12} distributions, where the effect of reweighting is largest.

The unfolded jet p_T and $dN_{12}/d\Delta\phi$ distributions are used to evaluate the C_{12} distributions both in pp and in $p + \text{Pb}$ collisions. The C_{12} distributions are then fitted as a function of $\Delta\Phi = \Delta\phi - \pi$ by a symmetric exponential distribution

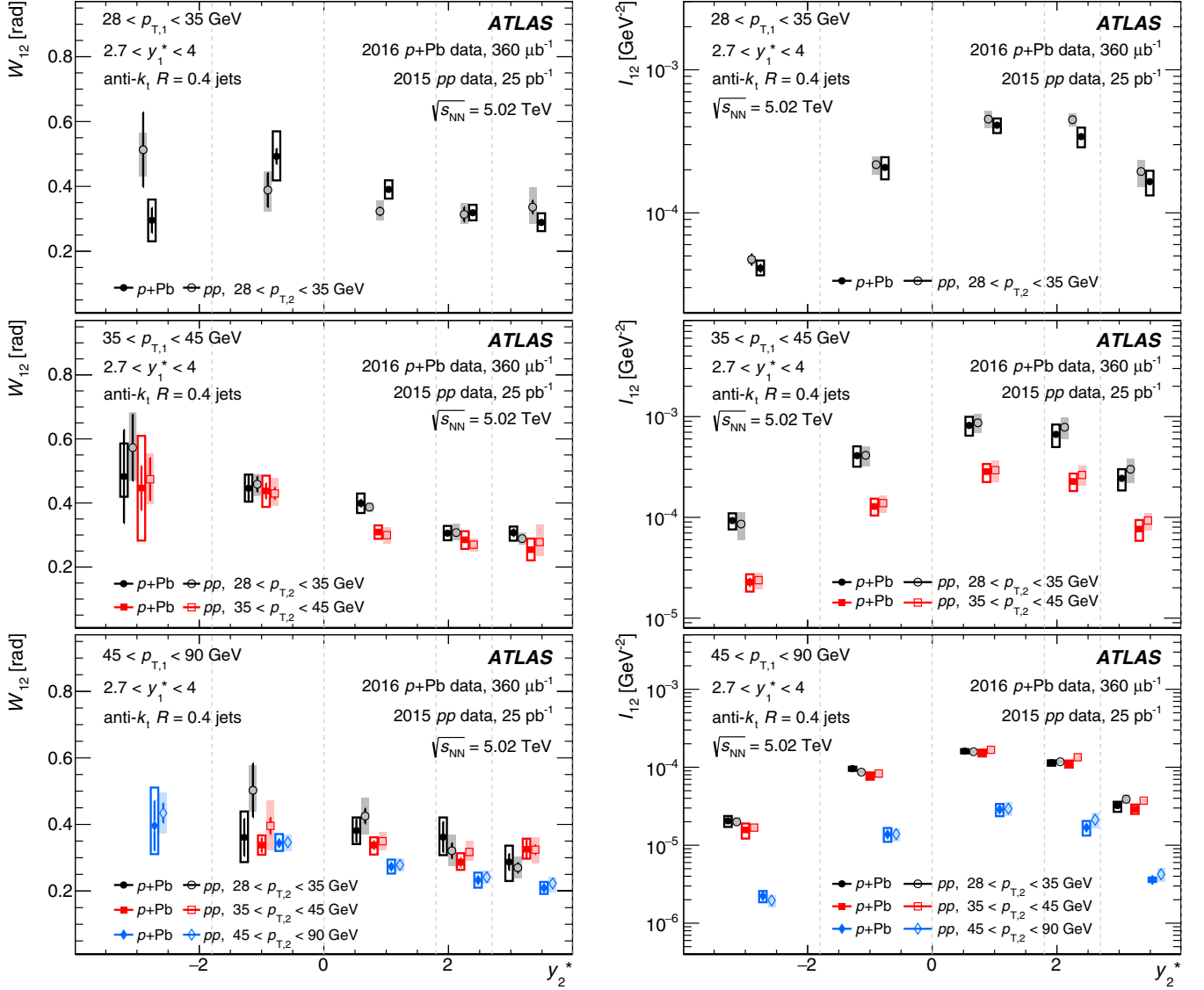


FIG. 5. Comparison of (left) W_{12} and (right) I_{12} values in pp (open symbols) and $p + Pb$ (closed symbols) collisions for different selections of $p_{T,1}$ and $p_{T,2}$ as a function of y_2^* . The y_2^* intervals are separated by dotted vertical lines. The data points are shifted horizontally for visibility, and do not reflect an actual shift in rapidity. The vertical size of the shaded and open boxes represents systematic uncertainties for pp and $p + Pb$, respectively, and the error bars indicate statistical uncertainties. The horizontal size of the shaded and open boxes does not represent the width of the bins. Some points are not presented due to large statistical uncertainties. Results are shown with no Δp_T requirement, where $\Delta p_T = p_{T,1} - p_{T,2}$.

convolved with a Gaussian function:

$$C_{12}(\Delta\phi) = \int_{-\infty}^{\infty} d\delta \frac{e^{-\delta^2/2\sigma^2}}{\sqrt{8\pi\sigma^2\tau^2}} e^{-|\Delta\phi - \delta|/\tau},$$

where τ is the parameter of the exponential component and σ is the width of the Gaussian distribution. All parameters are required to be positive. The resulting fit function is

$$C_{12}(\Delta\phi) = A \frac{e^{\sigma^2/2\tau^2}}{2\tau} \left(\frac{1}{2} e^{\Delta\phi/\tau} \text{Erfc} \left[\frac{1}{\sqrt{2}} \left(\frac{\Delta\phi}{\sigma} + \frac{\sigma}{\tau} \right) \right] + e^{-\Delta\phi/\tau} \left\{ 1 - \frac{1}{2} \text{Erfc} \left[\frac{1}{\sqrt{2}} \left(\frac{\Delta\phi}{\sigma} - \frac{\sigma}{\tau} \right) \right] \right\} \right),$$

where A is a normalization factor. The width W_{12} is chosen to be represented by the analytic root-mean-square of the τ and σ parameters resulting from the fit, $W_{12} = \text{RMS}(C_{12}) = \sqrt{2\tau^2 + \sigma^2}$. The fitting procedure is performed in the range $2.5 < \Delta\phi < \pi$. The convolution of the Gaussian and symmetric exponential functions is found to better describe the data around the peak of the C_{12} distributions than a pure exponential function.

VI. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties originate from the JES, JER, JAR, the fitting procedure, acceptance correction, and unfolding procedure. For each source of systematic uncertainty, the

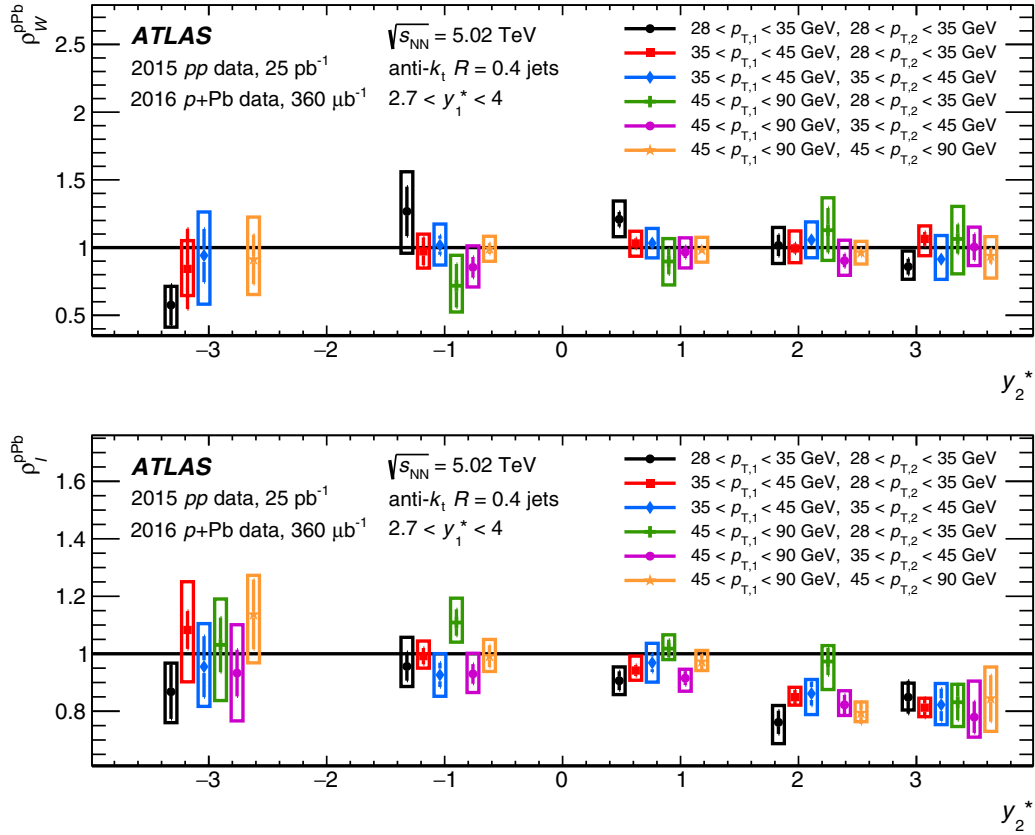


FIG. 6. Ratios (top) ρ_W^{pPb} of W_{12} and (bottom) ρ_I^{pPb} of I_{12} values between $p + \text{Pb}$ collisions and pp collisions for different selections of $p_{T,1}$ and $p_{T,2}$ as a function of y_2^* . The data points are shifted horizontally for visibility and do not reflect an actual shift in rapidity. The vertical size of the open boxes represents systematic uncertainties and the error bars indicate statistical uncertainties. The horizontal size of the open boxes does not represent the width of the bins. Some points are not presented due to large statistical uncertainties. Results are shown with no Δp_T requirement, where $\Delta p_T = p_{T,1} - p_{T,2}$.

values of W_{12} and I_{12} and the ratios ρ_W^{pPb} and ρ_I^{pPb} in $p + \text{Pb}$ and pp collisions are re-evaluated. The absolute difference between the varied and nominal values is used as an estimate of the uncertainty.

The systematic uncertainty due to the JES is determined from *in situ* studies of the calorimeter response [33,35–37], and studies of a relative energy-scale difference between the heavy-ion jet reconstruction procedure [37] and the procedure used in 13-TeV pp collisions [38]. The JES uncertainty depends on the jet p_T and jet η and is applied as a modification to the reconstructed jet p_T and varied separately by ± 1 standard deviation. The bin-by-bin correction factors are recomputed accordingly and the data are unfolded with them. The resulting uncertainty from the JES is typically less than 15% for the values of both W_{12} and I_{12} . An additional source of systematic uncertainty for the JES in $p + \text{Pb}$ collisions originates from differences between detector response and its simulation compared to pp collisions. These differences are about 1%, and their resulting systematic uncertainties are added to the total JES systematic uncertainty in quadrature.

The uncertainty due to the JER is evaluated by repeating the unfolding procedure with modified bin-by-bin correction factors, where an additional contribution is added to the resolution of the simulated jet p_T using a Gaussian smearing

procedure [38]. The smearing factor is evaluated with an *in situ* technique developed for 13 TeV pp data involving studies of dijet transverse-momentum balance [39]. An additional uncertainty is included to account for differences between the heavy-ion jet reconstruction and that used in the analyses of 13-TeV pp data. The resulting uncertainty is symmetrized. The size of the uncertainty due to the JER for the values of I_{12} is as large as 30% and is typically below 10% for the values of W_{12} .

The systematic uncertainty from the JAR originates in differences in the angular resolution between the data and MC samples. The uncertainty is derived as the difference between the angular resolutions evaluated using the two different MC generators, HERWIG++ and PYTHIA8. Distributions are unfolded with modified bin-by-bin correction factors where the reconstructed jet η and ϕ are smeared to reflect an up to $\sim 5\%$ uncertainty of the JAR. The size of the resulting uncertainty on W_{12} and I_{12} is typically below 6%.

A systematic uncertainty related to a possible dependence of the result on the fit range is considered. This systematic uncertainty is present only for the values of W_{12} and ρ_W^{pPb} . The uncertainty is evaluated by modifying the fit interval from the default of $2.5 < \Delta\phi < \pi$ to a fit range of $2.1 < \Delta\phi < \pi$. In different ranges of $p_{T,1}$ and $p_{T,2}$, the resulting uncertainties

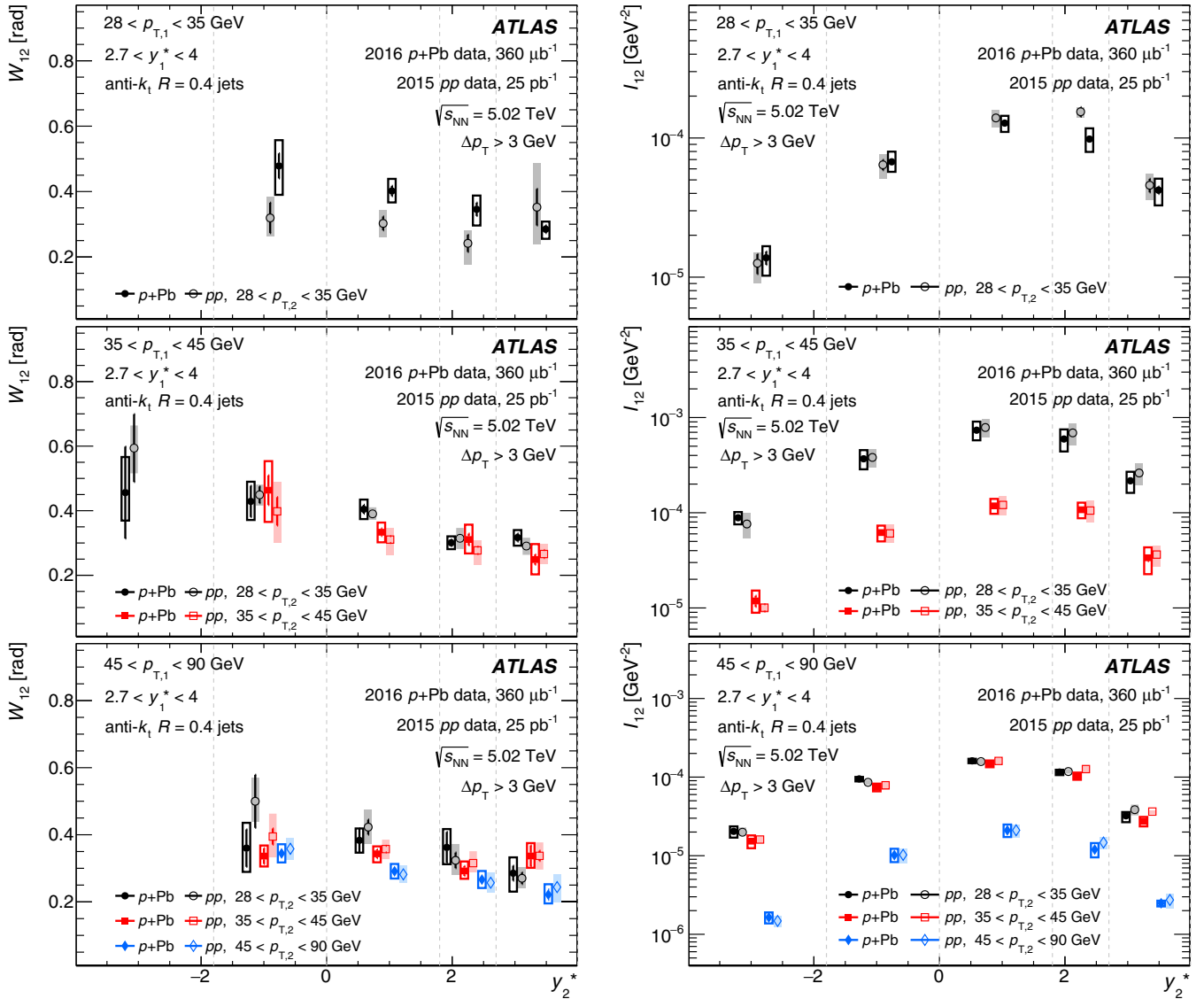


FIG. 7. Comparison of (left) W_{12} and (right) I_{12} values in pp (open symbols) and $p + Pb$ (closed symbols) collisions for different selections of $p_{T,1}$ and $p_{T,2}$ as a function of y_2^* . The y_2^* intervals are separated by dotted vertical lines. The data points are shifted horizontally for visibility and do not reflect an actual shift in rapidity. The vertical size of the shaded and open boxes represents systematic uncertainties for pp and $p + Pb$, respectively, and the error bars indicate statistical uncertainties. The horizontal size of the shaded and open boxes does not represent the width of the bins. Some data points in the rapidity interval of $-4.0 < y_2^* < 1.8$ are not presented due to large statistical uncertainties. Results are shown with the requirement of $\Delta p_T > 3$ GeV, where $\Delta p_T = p_{T,1} - p_{T,2}$.

are fitted to a constant function over the range $|y^*| < 4.0$. The systematic uncertainty is smoothed by a fit in order to minimize the impact of the statistical fluctuations. The size of the resulting uncertainty of W_{12} is less than 7%.

The systematic uncertainty from the bin-by-bin unfolding procedure is associated with differences in the shapes of distributions between the data and MC samples. To achieve better correspondence with the data, the simulated values are reweighted to match the shapes in the data. The entire change in the unfolded values induced by the use of reweighted bin-by-bin correction factors is taken as the systematic uncertainty, which is below 5% for C_{12} and I_{12} .

The systematic uncertainty associated with the acceptance correction for the disabled part of the HEC during $p + Pb$ data

taking is evaluated by increasing the size of the excluded region by 0.1 in azimuth and pseudorapidity, which corresponds to the size of the calorimeter towers. The resulting uncertainty is symmetrized to account for no reduction in the size of the excluded region due to the simultaneous overlap of the jet area with the regions covered by the enabled and disabled HEC. The uncertainty only affects the rapidity region $-4.0 < y_2^* < -1.4$. The resulting uncertainty of W_{12} is negligible. The yields I_{12} have an uncertainty of up to 10%.

For these measurements, the systematic uncertainties in the values of W_{12} and I_{12} are presented in Fig. 2. The systematic uncertainties from each source are assumed to be uncorrelated and are thus combined in quadrature to obtain the total systematic uncertainty.

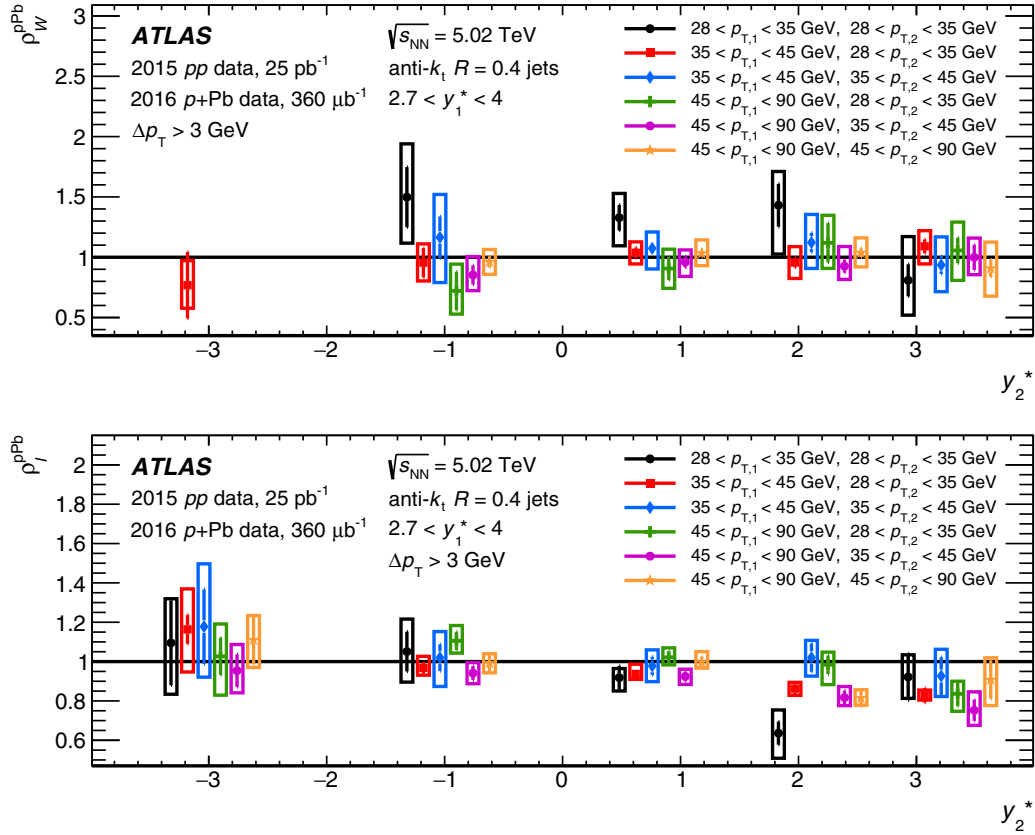


FIG. 8. Ratios (top) ρ_W^{pPb} of W_{12} and (bottom) ρ_I^{pPb} of I_{12} values between $p + \text{Pb}$ collisions and pp collisions for different selections of $p_{T,1}$ and $p_{T,2}$ as a function of y_2^* . The data points are shifted horizontally for visibility and do not reflect an actual shift in rapidity. The vertical size of the open boxes represents systematic uncertainties and the error bars indicate statistical uncertainties. The horizontal size of the open boxes does not represent the width of the bin. Some data points in the rapidity interval of $-4.0 < y_2^* < 1.8$ are not presented due to large statistical uncertainties. Results are shown with the requirement of $\Delta p_T > 3 \text{ GeV}$, where $\Delta p_T = p_{T,1} - p_{T,2}$.

In evaluating the $p + \text{Pb}$ to pp ratios, the correlations between the various systematic uncertainties are considered. The uncertainties associated with unfolding, fitting, the acceptance correction, and the additional JES uncertainties associated with the differences between the detector response and its simulations in $p + \text{Pb}$ collisions compared to pp collisions are taken to be uncorrelated between the two collision systems and are added in quadrature. All other uncertainties associated with the JES, JER, and JAR are taken to be correlated. To account for correlations, the ratios are reevaluated by applying variations to both collision systems simultaneously. The resulting variations of the ratios from their central values are used as the correlated systematic uncertainty from a given source. Examples of systematic uncertainties for the values of ρ_W^{pPb} and ρ_I^{pPb} are presented in Fig. 3, where the systematic uncertainty from the JES (up to 20%) is dominant.

VII. RESULTS

This section presents values of W_{12} and I_{12} and the ratios ρ_W^{pPb} and ρ_I^{pPb} in $p + \text{Pb}$ and pp collisions. Examples of unfolded C_{12} distributions in different intervals of $p_{T,1}$ and $p_{T,2}$ evaluated in pp and $p + \text{Pb}$ collisions are shown in Fig. 4 together with the fit results. The C_{12} distributions have a characteristic peak at $\Delta\phi = \pi$.

The results of measurements of W_{12} in $p + \text{Pb}$ and pp collisions for different ranges of $p_{T,1}$ and $p_{T,2}$ as a function of y_2^* are presented in left panels of Fig. 5. The value of W_{12} decreases with decreasing rapidity separation ($|y_1^* - y_2^*|$) between the leading and subleading jets in both the pp and $p + \text{Pb}$ collisions. The value of W_{12} increases with imbalance in p_T between the leading and subleading jets. The results of the measurement of conditional yields I_{12} in $p + \text{Pb}$ and pp collisions are shown in the right panels of Fig. 5. Initially, the value of I_{12} increases with decreasing separation in rapidity between the two jets, reaching a maximum for subleading jets in the interval $0.0 < y_2^* < 1.8$ and then decreases for smaller rapidity separations between the two jets. This is attributed to the decrease of the dijet cross section at large rapidity being faster than that of the inclusive jet cross section. The distributions of I_{12} have similar shapes in pp and $p + \text{Pb}$ collisions for all $p_{T,1}$ and $p_{T,2}$ combinations.

The ratios ρ_W^{pPb} between $p + \text{Pb}$ collisions and pp collisions for different ranges of $p_{T,1}$ and $p_{T,2}$ as a function of y_2^* are consistent with unity and are presented in the top panel of Fig. 6. The ratios ρ_I^{pPb} between $p + \text{Pb}$ collisions and pp collisions in the same bins of rapidity and transverse momentum are shown in the bottom panel of Fig. 6. The uncertainty of this ratio is dominated by systematic uncertainties, which

are correlated in jet p_T and y^* . The ratios ρ_l^{pPb} are consistent with unity for subleading jets in the lead-going direction and for central-forward dijets. The ratio of conditional yields of jet pairs when both the leading and subleading jets are in the proton-going direction is suppressed by approximately 20% in $p + \text{Pb}$ collisions compared to pp collisions, with no significant dependence on jet p_T . In the most forward-forward configuration, with both jets in the lowest jet- p_T interval $28 < p_{T,1}, p_{T,2} < 35$ GeV, the x_A range probed is between 10^{-4} and 10^{-3} . The suppression indicates a reduction in the nuclear gluon density per nucleon relative to the unbound nucleon in a region where nuclear shadowing and saturation are predicted [20].

Results for the values of W_{12} and I_{12} from pp collisions and $p + \text{Pb}$ collisions with the requirement of $\Delta p_T > 3$ GeV are shown in Fig. 7. The ratios of the two W_{12} and I_{12} values, ρ_W^{pPb} and ρ_I^{pPb} , are shown in Fig. 8. The values of W_{12} and ρ_W^{pPb} are observed to be unaffected by the Δp_T requirement. The conditional yields I_{12} are smaller than the results with no Δp_T requirement, while the conditional yield ratios ρ_I^{pPb} are unaffected by the Δp_T requirement.

VIII. SUMMARY

This paper presents measurements of dijet azimuthal angular correlations and the conditional yields of leading and subleading jets in pp and $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data, recorded by the ATLAS experiment at the Large Hadron Collider, correspond to 25 pb^{-1} and $360 \mu\text{b}^{-1}$ of pp and $p + \text{Pb}$ collisions, respectively. The measurement utilizes pairs of $R = 0.4$ anti- k_t jets in the transverse-momentum range $28 < p_T < 90$ GeV and center-of-mass rapidity range $-4.0 < y^* < 4.0$. The shapes of the azimuthal angular correlation functions for forward-forward and forward-central dijets and conditional yields are sensitive to possible effects of gluon saturation at low x_A . Dijets with a large separation in rapidity and where both jets have small transverse-momentum probe an approximate x_A range between 10^{-4} and 10^{-3} .

The widths of the azimuthal correlation functions are found to be smaller for pairs of jets with higher $p_{T,1}, p_{T,2}$, but larger for large rapidity interval between the jets. No significant broadening of azimuthal angular correlations is observed for forward-forward and forward-central dijets in $p + \text{Pb}$ compared to pp collisions. The measurement of conditional yields of forward-forward dijets in $p + \text{Pb}$ collisions compared to pp collisions shows a suppression of approximately 20%, with no

significant dependence on jet p_T . The observed suppression can be interpreted in terms of the nuclear gluon density in a low- x region where it is not well known. It may therefore be used to constrain possible nuclear effects including saturation.

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Barberio,¹⁰² D. Barberis,^{53b,53a} M. Barbero,⁹⁹ T. Barillari,¹¹³ M.-S. Barisits,³⁵ J. Barkeloo,¹²⁸ T. Barklow,¹⁵⁰ R. Barnea,¹⁵⁷ S. L. Barnes,^{58c} B. M. Barnett,¹⁴¹ R. M. Barnett,¹⁸ Z. Barnovska-Blenessy,^{58a} A. Baroncelli,^{58a} G. Barone,²⁹ A. J. Barr,¹³² L. Barranco Navarro,¹⁷¹ F. Barreiro,⁹⁶ J. Barreiro Guimarães da Costa,^{15a} R. Bartoldus,¹⁵⁰ A. E. Barton,⁸⁷ P. Bartos,^{28a} A. Basalaeu,⁴⁴ A. Bassalat,^{129,az} R. L. Bates,⁵⁵ S. J. Batista,¹⁶⁴ S. Batlamous,^{34e} J. R. Batley,³¹ M. Battaglia,¹⁴³ M. Bauce,^{70a,70b} F. Bauer,¹⁴² K. T. Bauer,¹⁶⁸ H. S. Bawa,^{150,t} J. B. Beacham,¹²³ T. Beau,¹³³ P. H. Beauchemin,¹⁶⁷ P. Bechtel,²⁴ H. C. Beck,⁵¹ H. P. Beck,^{20,h} K. Becker,⁵⁰ M. Becker,⁹⁷ C. Becot,⁴⁴ A. Beddall,^{12d} A. J. Beddall,^{12a} V. A. Bednyakov,⁷⁷ M. Bedognetti,¹¹⁸ C. P. Bee,¹⁵² T. A. Beermann,⁷⁴ M. Begalli,^{78b} M. Begel,²⁹ A. Behera,¹⁵² J. K. Behr,⁴⁴ F. Beisiegel,²⁴ A. S. Bell,⁹² G. Bella,¹⁵⁸ L. Bellagamba,^{23b} A. Bellerive,³³ M. Bellomo,¹⁵⁷ P. Bellos,⁹ K. Beloborodov,^{120b,120a} K. Belotskiy,¹¹⁰ N. L. Belyaev,¹¹⁰ O. Benary,^{158,a} D. Benckekroun,^{34a} N. Benekos,¹⁰ Y. Benhammou,¹⁵⁸ E. Benhar Noccioli,¹⁸⁰ D. P. Benjamin,⁶ M. Benoit,⁵² J. R. Bensinger,²⁶ S. Bentvelsen,¹¹⁸ L. Beresford,¹³² M. Beretta,⁴⁹ D. Berge,⁴⁴ E. Bergeaas Kuutmann,¹⁶⁹ N. Berger,⁵ B. Bergman,¹³⁹ L. J. Bergsten,²⁶ J. Beringer,¹⁸ S. Berlindis,⁷ N. R. Bernard,¹⁰⁰ G. Bernardi,¹³³ C. Bernius,¹⁵⁰ F. U. Bernlochner,²⁴ T. Berry,⁹¹ P. Berta,⁹⁷ C. Bertella,^{15a} G. Bertoli,^{43a,43b} I. A. Bertram,⁸⁷ G. J. Besjes,³⁹ O. Bessidskaia Bylund,¹⁷⁹ N. Besson,¹⁴² A. Bethani,⁹⁸ S. Bethke,¹¹³ A. Betti,²⁴ A. J. Bevan,⁹⁰ J. Beyer,¹¹³ R. Bi,¹³⁶ R. M. Bianchi,¹³⁶ O. Biebel,¹¹² D. Biedermann,¹⁹ R. Bielski,³⁵ K. Bierwagen,⁹⁷ N. V. Biesuz,^{69a,69b} M. Biglietti,^{72a} T. R. V. Billoud,¹⁰⁷ M. Bindi,⁵¹ A. Bingul,^{12d} C. Bini,^{70a,70b} S. Biondi,^{23b,23a} M. Birman,¹⁷⁷ T. Bisanz,⁵¹ J. P. Biswal,¹⁵⁸ A. Bitadze,⁹⁸ C. Bittrich,⁴⁶ D. M. Bjergaard,⁴⁷ J. E. Black,¹⁵⁰ K. M. Black,²⁵ T. Blazek,^{28a} I. Bloch,⁴⁴ C. Blocker,²⁶ A. Blue,⁵⁵ U. Blumenschein,⁹⁰ Dr. Blunier,^{144a} G. J. Bobbink,¹¹⁸ V. S. Bobrovnikov,^{120b,120a} S. S. Bocchetta,⁹⁴ A. Bocchi,⁴⁷ D. Boerner,⁴⁴ D. Bogavac,¹¹² A. G. Bogdanchikov,^{120b,120a} C. Bohm,^{43a} V. Boisvert,⁹¹ P. Bokan,^{51,169} T. Bold,^{81a} A. S. Boldyrev,¹¹¹ A. E. Bolz,^{59b} M. Bomben,¹³³ M. Bona,⁹⁰ J. S. Bonilla,¹²⁸ M. Boonekamp,¹⁴² H. M. Borecka-Bielska,⁸⁸ A. Borisov,¹²¹ G. Borissov,⁸⁷ J. Bortfeldt,³⁵ D. Bortoletto,¹³² V. Bortolotto,^{71a,71b} D. Boscherini,^{23b} M. Bosman,¹⁴ J. D. Bossio Sola,³⁰ K. Bouaouda,^{34a} J. Boudreau,¹³⁶ E. V. Bouhova-Thacker,⁸⁷ D. Boumediene,³⁷ C. Bourdarios,¹²⁹ S. K. Boutle,⁵⁵ A. Boveia,¹²³ J. Boyd,³⁵ D. Boye,^{32b,i} I. R. Boyko,⁷⁷ A. J. Bozson,⁹¹ J. Bracinič,²¹ N. Brahimi,⁹⁹ G. Brandt,¹⁷⁹ O. Brandt,^{59a} F. Braren,⁴⁴ U. Bratzler,¹⁶¹ B. Brau,¹⁰⁰ J. E. Brau,¹²⁸ W. D. Breaden Madden,⁵⁵ K. Brendlinger,⁴⁴ L. Brenner,⁴⁴ R. Brenner,¹⁶⁹ S. Bressler,¹⁷⁷ B. Brickwedde,⁹⁷ D. L. Briglin,²¹ D. Britton,⁵⁵ D. Britzger,¹¹³ I. Brock,²⁴ R. Brock,¹⁰⁴ G. Brooijmans,³⁸ T. Brooks,⁹¹ W. K. Brooks,^{144b} E. Brost,¹¹⁹ J. H. Broughton,²¹ P. A. Bruckman de Renstrom,⁸² D. Bruncko,^{28b} A. Bruni,^{23b} G. Bruni,^{23b} L. S. Bruni,¹¹⁸ S. Bruno,^{71a,71b} B. H. Brunt,³¹ M. Bruschi,^{23b} N. Bruscinò,¹³⁶ P. Bryant,³⁶ L. Bryngemark,⁹⁴ T. Buanes,¹⁷ Q. Buat,³⁵ P. Buchholz,¹⁴⁸ A. G. Buckley,⁵⁵ I. A. Budagov,⁷⁷ M. K. Bugge,¹³¹ F. Bühner,⁵⁰ O. Bulekov,¹¹⁰ T. J. Burch,¹¹⁹ S. Burdini,⁸⁸ C. D. Burgard,¹¹⁸ A. M. Burger,⁵ B. Burghgrave,⁸ K. Burka,⁸² I. Burmeister,⁴⁵ J. T. P. Burr,¹³² V. Büscher,⁹⁷ E. Buschmann,⁵¹ P. Bussey,⁵⁵ J. M. Butler,²⁵ C. M. Buttar,⁵⁵ J. M. Butterworth,⁹² P. Butti,³⁵ W. Buttinger,³⁵ A. Buzatu,¹⁵⁵ A. R. Buzykaev,^{120b,120a} G. Cabras,^{23b,23a} S. Cabrera Urbán,¹⁷¹ D. Caforio,¹³⁹ H. Cai,¹⁷⁰ V. M. M. Cairo,² O. Cakir,^{4a} N. Calace,³⁵ P. Calafiura,¹⁸ A. Calandri,⁹⁹ G. Calderini,¹³³ P. Calfayan,⁶³ G. Callea,⁵⁵ L. P. Caloba,^{78b} S. Calvente Lopez,⁹⁶ D. Calvet,³⁷ S. Calvet,³⁷ T. P. Calvet,¹⁵² M. Calvetti,^{69a,69b} R. Camacho Toro,¹³³ S. Camarda,³⁵ D. Camarero Munoz,⁹⁶ P. Camarri,^{71a,71b} D. Cameron,¹³¹ R. Caminal Armadans,¹⁰⁰ C. Camincher,³⁵ S. Campana,³⁵ M. Campanelli,⁹² A. Camplani,³⁹ A. Campoverde,¹⁴⁸ V. Canale,^{67a,67b} M. Cano Bret,^{58c} J. Cantero,¹²⁶ T. Cao,¹⁵⁸ Y. Cao,¹⁷⁰ M. D. M. Capeans Garrido,³⁵ M. Capua,^{40b,40a} R. M. Carbone,³⁸ R. Cardarelli,^{71a} F. C. Cardillo,¹⁴⁶ I. Carli,¹⁴⁰ T. Carli,³⁵ G. Carlino,^{67a} B. T. Carlson,¹³⁶ L. Carminati,^{66a,66b} R. M. D. Carney,^{43a,43b} S. Caron,¹¹⁷ E. Carquin,^{144b} S. Carrá,^{66a,66b} J. W. S. Carter,¹⁶⁴ M. P. Casado,^{14,j} A. F. Casha,¹⁶⁴ D. W. Casper,¹⁶⁸ R. Castelijn,¹¹⁸ F. L. Castillo,¹⁷¹ V. Castillo Gimenez,¹⁷¹ N. F. Castro,^{137a,137e} A. Catinaccio,³⁵ J. R. Catmore,¹³¹ A. Cattai,³⁵ J. Caudron,²⁴ V. Cavaliere,²⁹ E. Cavallaro,¹⁴ D. Cavalli,^{66a} M. Cavalli-Sforza,¹⁴ V. Cavasinni,^{69a,69b} E. Celebi,^{12b} L. Cerda Alberich,¹⁷¹ A. S. Cerqueira,^{78a} A. Cerri,¹⁵³ L. Cerrito,^{71a,71b} F. 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- J. Chen,^{58a} J. Chen,³⁸ S. Chen,¹³⁴ S. J. Chen,^{15c} X. Chen,^{15b,1} Y. Chen,⁸⁰ Y-H. Chen,⁴⁴ H. C. Cheng,^{61a} H. J. Cheng,^{15d,ba}
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 C. Di Donato,^{67a,67b} A. Di Girolamo,³⁵ G. Di Gregorio,^{69a,69b} B. Di Micco,^{72a,72b} R. Di Nardo,¹⁰⁰ K. F. Di Petrillo,⁵⁷
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 E. Drechsler,¹⁴⁹ E. Dreyer,¹⁴⁹ T. Dreyer,⁵¹ Y. Du,^{58b} F. Dubinin,¹⁰⁸ M. Dubovsky,^{28a} A. Dubreuil,⁵² E. Duchovni,¹⁷⁷
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 M. Elsing,³⁵ D. Emeliyanov,¹⁴¹ A. Emerman,³⁸ Y. Enari,¹⁶⁰ J. S. Ennis,¹⁷⁵ M. B. Epland,⁴⁷ J. Erdmann,⁴⁵ A. Ereditato,²⁰
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 S. Falciano,^{70a} P. J. Falke,⁵ S. Falke,⁵ J. Faltova,¹⁴⁰ Y. Fang,^{15a} M. Fanti,^{66a,66b} A. Farbin,⁸ A. Farilla,^{72a} E. M. Farina,^{68a,68b}
 T. Faroouque,¹⁰⁴ S. Farrell,¹⁸ S. M. Farrington,¹⁷⁵ P. Farthouat,³⁵ F. Fassi,^{34e} P. Fassnacht,³⁵ D. Fassouliotis,⁹
 M. Faucci Giannelli,⁴⁸ W. J. Fawcett,³¹ L. Fayard,¹²⁹ O. L. Fedin,^{135,r} W. Fedorko,¹⁷² M. Feickert,⁴¹ S. Feigl,¹³¹ L. Felgioni,⁹⁹
 C. Feng,^{58b} E. J. Feng,³⁵ M. Feng,⁴⁷ M. J. Fenton,⁵⁵ A. B. Fenyuk,¹²¹ J. Ferrando,⁴⁴ A. Ferrari,¹⁶⁹ P. Ferrari,¹¹⁸ R. Ferrari,^{68a}
 D. E. Ferreira de Lima,^{59b} A. Ferrer,¹⁷¹ D. Ferrere,⁵² C. Ferretti,¹⁰³ F. Fiedler,⁹⁷ A. Filipčić,⁸⁹ F. Filthaut,¹¹⁷ K. D. Finelli,²⁵
 M. C. N. Fiolhais,^{137a,137c,s} L. Fiorini,¹⁷¹ C. Fischer,¹⁴ W. C. Fisher,¹⁰⁴ I. Fleck,¹⁴⁸ P. Fleischmann,¹⁰³ R. R. M. Fletcher,¹³⁴
 T. Flick,¹⁷⁹ B. M. Flierl,¹¹² L. M. Flores,¹³⁴ L. R. Flores Castillo,^{61a} F. M. Follega,^{73a,73b} N. Fomin,¹⁷ G. T. Forcolin,^{73a,73b}
 A. Formica,¹⁴² F. A. Förster,¹⁴ A. C. Forti,⁹⁸ A. G. Foster,²¹ D. Fournier,¹²⁹ H. Fox,⁸⁷ S. Fracchia,¹⁴⁶ P. Francavilla,^{69a,69b}
 M. Franchini,^{23b,23a} S. Franchino,^{59a} D. Francis,³⁵ L. Franconi,¹⁴³ M. Franklin,⁵⁷ M. Frate,¹⁶⁸ A. N. Fray,⁹⁰ D. Freeborn,⁹²
 B. Freund,¹⁰⁷ W. S. Freund,^{78b} E. M. Freundlich,⁴⁵ D. C. Frizzell,¹²⁵ D. Froidevaux,³⁵ J. A. Frost,¹³² C. Fukunaga,¹⁶¹
 E. Fullana Torregrosa,¹⁷¹ E. Fumagalli,^{53b,53a} T. Fusayasu,¹¹⁴ J. Fuster,¹⁷¹ A. Gabrielli,^{23b,23a} A. Gabrielli,¹⁸ G. P. Gach,^{81a}
 S. Gadatsch,⁵² P. Gadow,¹¹³ G. Gagliardi,^{53b,53a} L. G. Gagnon,¹⁰⁷ C. Galea,^{27b} B. Galhardo,^{137a,137c} E. J. Gallas,¹³²
 B. J. Gallop,¹⁴¹ P. Gallus,¹³⁹ G. Galster,³⁹ R. Gamboa Goni,⁹⁰ K. K. Gan,¹²³ S. Ganguly,¹⁷⁷ J. Gao,^{58a} Y. Gao,⁸⁸ Y. S. Gao,^{150a,t}
 C. García,¹⁷¹ J. E. García Navarro,¹⁷¹ J. A. García Pascual,^{15a} C. Garcia-Argos,⁵⁰ M. Garcia-Sciveres,¹⁸ R. W. Gardner,³⁶
 N. Garelli,¹⁵⁰ S. Gargiulo,⁵⁰ V. Garonne,¹³¹ A. Gaudiello,^{53b,53a} G. Gaudio,^{68a} I. L. Gavrilenko,¹⁰⁸ A. Gavriluk,¹⁰⁹ C. Gay,¹⁷²
 G. Gaycken,²⁴ E. N. Gazis,¹⁰ C. N. P. Gee,¹⁴¹ J. Geisen,⁵¹ M. Geisen,⁹⁷ M. P. Geisler,^{59a} C. Gemme,^{53b} M. H. Genest,⁵⁶
 C. Geng,¹⁰³ S. Gentile,^{70a,70b} S. George,⁹¹ D. Gerbaudo,¹⁴ G. Gessner,⁴⁵ S. Ghasemi,¹⁴⁸ M. Ghasemi Bostanabad,¹⁷³
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 M. Gignac,¹⁴³ D. Gillberg,³³ G. Gilles,¹⁷⁹ D. M. Gingrich,^{3,f} M. P. Giordani,^{64a,64c} F. M. Giorgi,^{23b} P. F. Giraud,¹⁴²
 G. Giugliarelli,^{64a,64c} D. Giugni,^{66a} F. Giuli,¹³² M. Giulini,^{59b} S. Gkaitatzis,¹⁵⁹ I. Gkialas,^{9,u} E. L. Gkoukousis,¹⁴
 P. Gkoutoumis,¹⁰ L. K. Gladilin,¹¹¹ C. Glasman,⁹⁶ J. Glatzer,¹⁴ P. C. F. Glaysher,⁴⁴ A. Glazov,⁴⁴ M. Goblirsch-Kolb,²⁶

- S. Goldfarb,¹⁰² T. Golling,⁵² D. Golubkov,¹²¹ A. Gomes,^{137a,137b} R. Goncalves Gama,⁵¹ R. Gonçalo,^{137a} G. Gonella,⁵⁰ L. Gonella,²¹ A. Gongadze,⁷⁷ F. Gonnella,²¹ J. L. Gonski,⁵⁷ S. González de la Hoz,¹⁷¹ S. Gonzalez-Sevilla,⁵² L. Goossens,³⁵ P. A. Gorbounov,¹⁰⁹ H. A. Gordon,²⁹ B. Gorini,³⁵ E. Gorini,^{65a,65b} A. Gorišek,⁸⁹ A. T. Goshaw,⁴⁷ C. Gössling,⁴⁵ M. I. Gostkin,⁷⁷ C. A. Gottardo,²⁴ C. R. Goudet,¹²⁹ D. Goujdami,^{34c} A. G. Goussiou,¹⁴⁵ N. Govender,^{32b,v} C. Goy,⁵ E. Gozani,¹⁵⁷ I. Grabowska-Bold,^{81a} P. O. J. Gradin,¹⁶⁹ E. C. Graham,⁸⁸ J. Gramling,¹⁶⁸ E. Gramstad,¹³¹ S. Grancagnolo,¹⁹ M. Grandi,¹⁵³ V. Gratchev,¹³⁵ P. M. Gravila,^{27f} F. G. Gravili,^{65a,65b} C. Gray,⁵⁵ H. M. Gray,¹⁸ C. Grefe,²⁴ K. Gregersen,⁹⁴ I. M. Gregor,⁴⁴ P. Grenier,¹⁵⁰ K. Grevtsov,⁴⁴ N. A. Grieser,¹²⁵ J. Griffiths,⁸ A. A. Grillo,¹⁴³ K. Grimm,^{150a,w} S. Grinstein,^{14,x} J.-F. Grivaz,¹²⁹ S. Groh,⁹⁷ E. Gross,¹⁷⁷ M. Grosse Perdekamp,¹⁷⁰ J. Grosse-Knetter,⁵¹ Z. J. Grout,⁹² C. Grud,¹⁰³ A. Grummer,¹¹⁶ L. Guan,¹⁰³ W. Guan,¹⁷⁸ J. Guenther,³⁵ A. Guerguichon,¹²⁹ F. Guescini,^{165a} D. Guest,¹⁶⁸ R. Gugel,⁵⁰ B. Gui,¹²³ T. Guillemin,⁵ S. Guindon,³⁵ U. Gul,⁵⁵ J. Guo,^{58c} W. Guo,¹⁰³ Y. Guo,^{58a,y} Z. Guo,⁹⁹ R. Gupta,⁴⁴ S. Gurbuz,^{12c} G. Gustavino,¹²⁵ P. Gutierrez,¹²⁵ C. Gutsche,⁹² C. Guyot,¹⁴² M. P. Guzik,^{81a} C. Gwenlan,¹³² C. B. Gwilliam,⁸⁸ A. Haas,¹²² C. Haber,¹⁸ H. K. Hadavand,⁸ N. Haddad,^{34e} A. Hadeif,^{58a} S. Hageböck,³⁵ M. Hagihara,¹⁶⁶ M. Haleem,¹⁷⁴ J. Haley,¹²⁶ G. Halladjian,¹⁰⁴ G. D. Hallewell,⁹⁹ K. Hamacher,¹⁷⁹ P. Hamal,¹²⁷ K. Hamano,¹⁷³ H. Hamdaoui,^{34e} G. N. Hamity,¹⁴⁶ K. Han,^{58a,z} L. Han,^{58a} S. Han,^{15d,ba} K. Hanagaki,^{79,aa} M. Hance,¹⁴³ D. M. Handl,¹¹² B. Haney,¹³⁴ R. Hankache,¹³³ P. Hanke,^{59a} E. Hansen,⁹⁴ J. B. Hansen,³⁹ J. D. Hansen,³⁹ M. C. Hansen,²⁴ P. H. Hansen,³⁹ E. C. Hanson,⁹⁸ K. Hara,¹⁶⁶ A. S. Hard,¹⁷⁸ T. Harenberg,¹⁷⁹ S. Harkusha,¹⁰⁵ P. F. Harrison,¹⁷⁵ N. M. Hartmann,¹¹² Y. Hasegawa,¹⁴⁷ A. Hasib,⁴⁸ S. Hassani,¹⁴² S. Haug,²⁰ R. Hauser,¹⁰⁴ L. Hauswald,⁴⁶ L. B. Havener,³⁸ M. Havranek,¹³⁹ C. M. Hawkes,²¹ R. J. Hawkings,³⁵ D. Hayden,¹⁰⁴ C. Hayes,¹⁵² C. P. Hays,¹³² J. M. Hays,⁹⁰ H. S. Hayward,⁸⁸ S. J. Haywood,¹⁴¹ F. He,^{58a} M. P. Heath,⁴⁸ V. Hedberg,⁹⁴ L. Heelan,⁸ S. Heer,²⁴ K. K. Heidegger,⁵⁰ J. Heilman,³³ S. Heim,⁴⁴ T. Heim,¹⁸ B. Heinemann,^{44,ab} J. J. Heinrich,¹¹² L. Heinrich,¹²² C. Heinz,⁵⁴ J. Hejbal,¹³⁸ L. Helary,^{59b} A. Held,¹⁷² S. Hellesund,¹³¹ C. M. Helling,¹⁴³ S. Hellman,^{43a,43b} C. Helsen,³⁵ R. C. W. Henderson,⁸⁷ Y. Heng,¹⁷⁸ S. Henkelmann,¹⁷² A. M. Henriques Correia,³⁵ G. H. Herbert,¹⁹ H. Herde,²⁶ V. Herget,¹⁷⁴ Y. Hernández Jiménez,^{32c} H. Herr,⁹⁷ M. G. Herrmann,¹¹² T. Herrmann,⁴⁶ G. Herten,⁵⁰ R. Hertenberger,¹¹² L. Hervas,³⁵ T. C. Herwig,¹³⁴ G. G. Hesketh,⁹² N. P. Hessey,^{165a} A. Higashida,¹⁶⁰ S. Higashino,⁷⁹ E. Higón-Rodríguez,¹⁷¹ K. Hildebrand,³⁶ E. Hill,¹⁷³ J. C. Hill,³¹ K. K. Hill,²⁹ K. H. Hiller,⁴⁴ S. J. Hillier,²¹ M. Hils,⁴⁶ I. Hinchliffe,¹⁸ F. Hinterkeuser,²⁴ M. Hirose,¹³⁰ D. Hirschbuehl,¹⁷⁹ B. Hiti,⁸⁹ O. Hladik,¹³⁸ D. R. Hlaluku,^{32c} X. Hoad,⁴⁸ J. Hobbs,¹⁵² N. Hod,¹⁷⁷ M. C. Hodgkinson,¹⁴⁶ A. Hoecker,³⁵ F. Hoenig,¹¹² D. Hohn,⁵⁰ D. Hohov,¹²⁹ T. R. Holmes,³⁶ M. Holzbock,¹¹² M. Homann,⁴⁵ L. B. A. H. Hommels,³¹ S. Honda,¹⁶⁶ T. Honda,⁷⁹ T. M. Hong,¹³⁶ A. Hönle,¹¹³ B. H. Hooberman,¹⁷⁰ W. H. Hopkins,¹²⁸ Y. Horii,¹¹⁵ P. Horn,⁴⁶ A. J. Horton,¹⁴⁹ L. A. Horyn,³⁶ J.-Y. Hostachy,⁵⁶ A. Hostiuc,¹⁴⁵ S. Hou,¹⁵⁵ A. Hoummada,^{34a} J. Howarth,⁹⁸ J. Hoya,⁸⁶ M. Hrabovsky,¹²⁷ J. Hrdinka,³⁵ I. Hristova,¹⁹ J. Hrivnac,¹²⁹ A. Hrynevich,¹⁰⁶ T. Hryn'ova,⁵ P. J. Hsu,⁶² S.-C. Hsu,¹⁴⁵ Q. Hu,²⁹ S. Hu,^{58c} Y. Huang,^{15a} Z. Hubacek,¹³⁹ F. Hubaut,⁹⁹ M. Huebner,²⁴ F. Huettinger,²⁴ T. B. Huffman,¹³² M. Huhtinen,³⁵ R. F. H. Hunter,³³ P. Huo,¹⁵² A. M. Hupe,³³ N. Huseynov,^{77,e} J. Huston,¹⁰⁴ J. Huth,⁵⁷ R. Hyneman,¹⁰³ G. Iacobucci,⁵² G. Iakovidis,²⁹ I. Ibragimov,¹⁴⁸ L. Iconomidou-Fayard,¹²⁹ Z. Idrissi,^{34e} P. Iengo,³⁵ R. Ignazzi,³⁹ O. Igonkina,^{118,a,ac} R. Iguchi,¹⁶⁰ T. Iizawa,⁵² Y. Ikegami,⁷⁹ M. Ikeno,⁷⁹ D. Iliadis,¹⁵⁹ N. Ilic,¹¹⁷ F. Iltzsche,⁴⁶ G. Introzzi,^{68a,68b} M. Iodice,^{72a} K. Iordanidou,³⁸ V. Ippolito,^{70a,70b} M. F. Isacson,¹⁶⁹ N. Ishijima,¹³⁰ M. Ishino,¹⁶⁰ M. Ishitsuka,¹⁶² W. Islam,¹²⁶ C. Issever,¹³² S. Istin,¹⁵⁷ F. Ito,¹⁶⁶ J. M. Iturbe Ponce,^{61a} R. Iuppa,^{73a,73b} A. Ivina,¹⁷⁷ H. Iwasaki,⁷⁹ J. M. Izen,⁴² V. Izzo,^{67a} P. Jacka,¹³⁸ P. Jackson,¹ R. M. Jacobs,²⁴ V. Jain,² G. Jäkel,¹⁷⁹ K. B. Jakobi,⁹⁷ K. Jakobs,⁵⁰ S. Jakobsen,⁷⁴ T. Jakoubek,¹³⁸ D. O. Jamin,¹²⁶ R. Jansky,⁵² J. Janssen,²⁴ M. Janus,⁵¹ P. A. Janus,^{81a} G. Jarlskog,⁹⁴ N. Javadov,^{77,e} T. Javůrek,³⁵ M. Javurkova,⁵⁰ F. Jeanneau,¹⁴² L. Jeanty,¹²⁸ J. Jejelava,^{156a,ad} A. Jelinskas,¹⁷⁵ P. Jenni,^{50,ae} J. Jeong,⁴⁴ N. Jeong,⁴⁴ S. Jézéquel,⁵ H. Ji,¹⁷⁸ J. Jia,¹⁵² H. Jiang,⁷⁶ Y. Jiang,^{58a} Z. Jiang,^{150,af} S. Jiggins,⁵⁰ F. A. Jimenez Morales,³⁷ J. Jimenez Pena,¹⁷¹ S. Jin,^{15c} A. Jinaru,^{27b} O. Jinnouchi,¹⁶² H. Jivan,^{32c} P. Johansson,¹⁴⁶ K. A. Johns,⁷ C. A. Johnson,⁶³ K. Jon-And,^{43a,43b} R. W. L. Jones,⁸⁷ S. D. Jones,¹⁵³ S. Jones,⁷ T. J. Jones,⁸⁸ J. Jongmanns,^{59a} P. M. Jorge,^{137a,137b} J. Jovicevic,^{165a} X. Ju,¹⁸ J. J. Junggeburth,¹¹³ A. Juste Rozas,^{14,x} A. Kaczmarska,⁸² M. Kado,¹²⁹ H. Kagan,¹²³ M. Kagan,¹⁵⁰ T. Kaji,¹⁷⁶ E. Kajomovitz,¹⁵⁷ C. W. Kalderon,⁹⁴ A. Kaluza,⁹⁷ A. Kamenshchikov,¹²¹ L. Kanjir,⁸⁹ Y. Kano,¹⁶⁰ V. A. Kantserov,¹¹⁰ J. Kanzaki,⁷⁹ L. S. Kaplan,¹⁷⁸ D. Kar,^{32c} M. J. Kareem,^{165b} E. Karentzos,¹⁰ S. N. Karpov,⁷⁷ Z. M. Karpova,⁷⁷ V. Kartvelishvili,⁸⁷ A. N. Karyukhin,¹²¹ L. Kashif,¹⁷⁸ R. D. Kass,¹²³ A. Kastanas,^{43a,43b} Y. Kataoka,¹⁶⁰ C. Kato,^{58d,58c} J. Katzy,⁴⁴ K. Kawade,⁸⁰ K. Kawagoe,⁸⁵ T. Kawaguchi,¹¹⁵ T. Kawamoto,¹⁶⁰ G. Kawamura,⁵¹ E. F. Kay,⁸⁸ V. F. Kazanin,^{120b,120a} R. Keeler,¹⁷³ R. Kehoe,⁴¹ J. S. Keller,³³ E. Kellermann,⁹⁴ J. J. Kempster,²¹ J. Kendrick,²¹ O. Kepka,¹³⁸ S. Kersten,¹⁷⁹ B. P. Kerševan,⁸⁹ S. Ketabchi Haghighat,¹⁶⁴ R. A. Keyes,¹⁰¹ M. Khader,¹⁷⁰ F. Khalil-Zada,¹³ A. Khanov,¹²⁶ A. G. Kharlamov,^{120b,120a} T. Kharlamova,^{120b,120a} E. E. Khoda,¹⁷² A. Khodinov,¹⁶³ T. J. Khoo,⁵² E. Khranov,⁷⁷ J. Khubua,^{156b} S. Kido,⁸⁰ M. Kiehn,⁵² C. R. Kilby,⁹¹ Y. K. Kim,³⁶ N. Kimura,^{64a,64c} O. M. Kind,¹⁹ B. T. King,^{88,a} D. Kirchmeier,⁴⁶ J. Kirk,¹⁴¹ A. E. Kiryunin,¹¹³ T. Kishimoto,¹⁶⁰ V. Kitali,⁴⁴ O. Kivernyk,⁵ E. Kladiva,^{28b,a} T. Klapdor-Kleingrothaus,⁵⁰ M. H. Klein,¹⁰³ M. Klein,⁸⁸ U. Klein,⁸⁸ K. Kleinknecht,⁹⁷ P. Klimek,¹¹⁹ A. Klimentov,²⁹ T. Klingl,²⁴ T. Klioutchnikova,³⁵ F. F. Klitzner,¹¹² P. Kluit,¹¹⁸ S. Kluth,¹¹³ E. Kneringer,⁷⁴ E. B. F. G. Knoops,⁹⁹ A. Knue,⁵⁰ D. Kobayashi,⁸⁵ T. Kobayashi,¹⁶⁰ M. Kobel,⁴⁶ M. Kocian,¹⁵⁰ P. Kodys,¹⁴⁰ P. T. Koenig,²⁴ T. Koffas,³³ N. M. Köhler,¹¹³ T. Koi,¹⁵⁰ M. Kolb,^{59b} I. Koletsou,⁵ T. Kondo,⁷⁹ N. Kondrashova,^{58c} K. Köneke,⁵⁰ A. C. König,¹¹⁷ T. Kono,⁷⁹ R. Konoplich,^{122,ag} V. Konstantinides,⁹² N. Konstantinidis,⁹² B. Konya,⁹⁴ R. Kopeliansky,⁶³ S. Koperny,^{81a} K. Korcyl,⁸² K. Kordas,¹⁵⁹ G. Koren,¹⁵⁸ A. Korn,⁹² I. Korolkov,¹⁴ E. V. Korolkova,¹⁴⁶ N. Korotkova,¹¹¹ O. Kortner,¹¹³ S. Kortner,¹¹³ T. Kosek,¹⁴⁰ V. V. Kostyukhin,²⁴ A. Kotwal,⁴⁷ A. Koulouris,¹⁰ A. Kourkoumeli-Charalampidi,^{68a,68b} C. Kourkoumelis,⁹ E. Kourlitis,¹⁴⁶ V. Kouskoura,²⁹ A. B. Kowalewska,⁸² R. Kowalewski,¹⁷³ C. Kozakai,¹⁶⁰ W. Kozanecki,¹⁴²

- A. S. Kozhin,¹²¹ V. A. Kramarenko,¹¹¹ G. Kramberger,⁸⁹ D. Krasnopevtsev,^{58a} M. W. Krasny,¹³³ A. Krasznahorkay,³⁵ D. Krauss,¹¹³ J. A. Kremer,^{81a} J. Kretschmar,⁸⁸ P. Krieger,¹⁶⁴ K. Krizka,¹⁸ K. Kroeninger,⁴⁵ H. Kroha,¹¹³ J. Kroll,¹³⁸ J. Kroll,¹³⁴ J. Krstic,¹⁶ U. Kruchonak,⁷⁷ H. Krüger,²⁴ N. Krumnack,⁷⁶ M. C. Kruse,⁴⁷ T. Kubota,¹⁰² S. Kудay,^{4b} J. T. Kuechler,⁴⁴ S. Kuehn,³⁵ A. Kugel,^{59a} T. Kuhl,⁴⁴ V. Kukhtin,⁷⁷ R. Kukla,⁹⁹ Y. Kulchitsky,^{105,ah} S. Kuleshov,^{144b} Y. P. Kulnich,¹⁷⁰ M. Kuna,⁵⁶ T. Kunigo,⁸³ A. Kupco,¹³⁸ T. Kupfer,⁴⁵ O. Kuprash,⁵⁰ H. Kurashige,⁸⁰ L. L. Kurchaninov,^{165a} Y. A. Kurochkin,¹⁰⁵ A. Kurova,¹¹⁰ M. G. Kurth,^{15d,ba} E. S. Kuwertz,³⁵ M. Kuze,¹⁶² J. Kvita,¹²⁷ T. Kwan,¹⁰¹ A. La Rosa,¹¹³ J. L. La Rosa Navarro,^{78d} L. La Rotonda,^{40b,40a} F. La Ruffa,^{40b,40a} C. Lacasta,¹⁷¹ F. Lacava,^{70a,70b} J. Lacey,⁴⁴ D. P. J. Lack,⁹⁸ H. Lacker,¹⁹ D. Lacour,¹³³ E. Ladygin,⁷⁷ R. Lafaye,⁵ B. Laforge,¹³³ T. Lagouri,^{32c} S. Lai,⁵¹ S. Lammers,⁶³ W. Lampl,⁷ E. Lançon,²⁹ U. Landgraf,⁵⁰ M. P. J. Landon,⁹⁰ M. C. Lanfermann,⁵² V. S. Lang,⁴⁴ J. C. Lange,⁵¹ R. J. Langenberg,³⁵ A. J. Lankford,¹⁶⁸ F. Lanni,²⁹ K. Lantzsich,²⁴ A. Lanza,^{68a} A. Lapertosa,^{53b,53a} S. Laplace,¹³³ J. F. Laporte,¹⁴² T. Lari,^{66a} F. Lasagni Manghi,^{23b,23a} M. Lassnig,³⁵ T. S. Lau,^{61a} A. Laudrain,¹²⁹ A. Laurier,³³ M. Lavorgna,^{67a,67b} M. Lazzaroni,^{66a,66b} B. Le,¹⁰² O. Le Dortz,¹³³ E. Le Guirriec,⁹⁹ E. P. Le Quilleuc,¹⁴² M. LeBlanc,⁷ T. LeCompte,⁶ F. Ledroit-Guillon,⁵⁶ C. A. Lee,²⁹ G. R. Lee,^{144a} L. Lee,⁵⁷ S. C. Lee,¹⁵⁵ S. J. Lee,³³ B. Lefebvre,¹⁰¹ M. Lefebvre,¹⁷³ F. Legger,¹¹² C. Leggett,¹⁸ K. Lehmann,¹⁴⁹ N. Lehmann,¹⁷⁹ G. Lehmann Miotto,³⁵ W. A. Leight,⁴⁴ A. Leisos,^{159,ai} M. A. L. Leite,^{78d} R. Leitner,¹⁴⁰ D. Lellouch,^{177,a} K. J. C. Leney,⁹² T. Lenz,²⁴ B. Lenzi,³⁵ R. Leone,⁷ S. Leone,^{69a} C. Leonidopoulos,⁴⁸ A. Leopold,¹³³ G. Lerner,¹⁵³ C. Leroy,¹⁰⁷ R. Les,¹⁶⁴ A. A. J. Lesage,¹⁴² C. G. Lester,³¹ M. Levchenko,¹³⁵ J. Levêque,⁵ D. Levin,¹⁰³ L. J. Levinson,¹⁷⁷ B. Li,^{15b} B. Li,¹⁰³ C-Q. Li,^{58a,aj} H. Li,^{58a} H. Li,^{58b} K. Li,¹⁵⁰ L. Li,^{58c} M. Li,^{15a} Q. Li,^{15d,ba} Q. Y. Li,^{58a} S. Li,^{58d,58c} X. Li,^{58c} Y. Li,⁴⁴ Z. Liang,^{15a} B. Liberti,^{71a} A. Liblong,¹⁶⁴ K. Lie,^{61c} S. Liem,¹¹⁸ A. Limosani,¹⁵⁴ C. Y. Lin,³¹ K. Lin,¹⁰⁴ T. H. Lin,⁹⁷ R. A. Linck,⁶³ J. H. Lindon,²¹ A. L. Lioni,⁵² E. Lipeles,¹³⁴ A. Lipniacka,¹⁷ M. Lisovyi,^{59b} T. M. Liss,^{170,ak} A. Lister,¹⁷² A. M. Litke,¹⁴³ J. D. Little,⁸ B. Liu,⁷⁶ B. L. Liu,⁶ H. B. Liu,²⁹ H. Liu,¹⁰³ J. B. Liu,^{58a} J. K. K. Liu,¹³² K. Liu,¹³³ M. Liu,^{58a} P. Liu,¹⁸ Y. Liu,^{15d,ba} Y. L. Liu,^{58a} Y. W. Liu,^{58a} M. Livan,^{68a,68b} A. Lleres,⁵⁶ J. Llorente Merino,^{15a} S. L. Lloyd,⁹⁰ C. Y. Lo,^{61b} F. Lo Sterzo,⁴¹ E. M. Lobodzinska,⁴⁴ P. Loch,⁷ T. Lohse,¹⁹ K. Lohwasser,¹⁴⁶ M. Lokajicek,¹³⁸ J. D. Long,¹⁷⁰ R. E. Long,⁸⁷ L. Longo,^{65a,65b} K. A. Looper,¹²³ J. A. Lopez,^{144b} I. Lopez Paz,⁹⁸ A. Lopez Solis,¹⁴⁶ J. Lorenz,¹¹² N. Lorenzo Martinez,⁵ M. Losada,²² P. J. Lösel,¹¹² A. Lösle,⁵⁰ X. Lou,⁴⁴ X. Lou,^{15a} A. Lounis,¹²⁹ J. Love,⁶ P. A. Love,⁸⁷ J. J. Lozano Bahilo,¹⁷¹ H. Lu,^{61a} M. Lu,^{58a} Y. J. Lu,⁶² H. J. Lubatti,¹⁴⁵ C. Luci,^{70a,70b} A. Lucotte,⁵⁶ C. Luedtke,⁵⁰ F. Luehring,⁶³ I. Luise,¹³³ L. Luminari,^{70a} B. Lund-Jensen,¹⁵¹ M. S. Lutz,¹⁰⁰ P. M. Luzzi,¹³³ D. Lynn,²⁹ R. Lysak,¹³⁸ E. Lytken,⁹⁴ F. Lyu,^{15a} V. Lyubushkin,⁷⁷ T. Lyubushkina,⁷⁷ H. Ma,²⁹ L. L. Ma,^{58b} Y. Ma,^{58b} G. Maccarrone,⁴⁹ A. Macchiolo,¹¹³ C. M. Macdonald,¹⁴⁶ J. Machado Miguens,^{134,137b} D. Madaffari,¹⁷¹ R. Madar,³⁷ W. F. Mader,⁴⁶ N. Madysa,⁴⁶ J. Maeda,⁸⁰ K. Maekawa,¹⁶⁰ S. Maeland,¹⁷ T. Maeno,²⁹ M. Maerker,⁴⁶ A. S. Maeviskiy,¹¹¹ V. Magerl,⁵⁰ D. J. Mahon,³⁸ C. Maidantchik,^{78b} T. Maier,¹¹² A. Maio,^{137a,137b,137d} O. Majersky,^{28a} S. Majewski,¹²⁸ Y. Makida,⁷⁹ N. Makovec,¹²⁹ B. Malaescu,¹³³ Pa. Malecki,⁸² V. P. Maleev,¹³⁵ F. Malek,⁵⁶ U. Mallik,⁷⁵ D. Malon,⁶ C. Malone,³¹ S. Maltezos,¹⁰ S. Malyukov,³⁵ J. Mamuzic,¹⁷¹ G. Mancini,⁴⁹ I. Mandić,⁸⁹ L. Manhaes de Andrade Filho,^{78a} I. M. Maniatis,¹⁵⁹ J. Manjarres Ramos,⁴⁶ K. H. Mankinen,⁹⁴ A. Mann,¹¹² A. Manousos,⁷⁴ B. Mansoulie,¹⁴² S. Manzoni,¹¹⁸ A. Marantis,¹⁵⁹ G. Marceca,³⁰ L. Marchese,¹³² G. Marchiori,¹³³ M. Marcisovsky,¹³⁸ C. Marcon,⁹⁴ C. A. Marin Tobon,³⁵ M. Marjanovic,³⁷ F. Marroquim,^{78b} Z. Marshall,¹⁸ M. U. F. Martensson,¹⁶⁹ S. Marti-Garcia,¹⁷¹ C. B. Martin,¹²³ T. A. Martin,¹⁷⁵ V. J. Martin,⁴⁸ B. Martin dit Latour,¹⁷ M. Martinez,^{14,x} V. I. Martinez Outschoorn,¹⁰⁰ S. Martin-Haugh,¹⁴¹ V. S. Martoiu,^{27b} A. C. Martyniuk,⁹² A. Marzin,³⁵ L. Masetti,⁹⁷ T. Mashimo,¹⁶⁰ R. Mashinistov,¹⁰⁸ J. Masik,⁹⁸ A. L. Maslennikov,^{120b,120a} L. H. Mason,¹⁰² L. Massa,^{71a,71b} P. Massarotti,^{67a,67b} P. Mastrandrea,^{69a,69b} A. Mastroberardino,^{40b,40a} T. Masubuchi,¹⁶⁰ P. Mättig,²⁴ J. Maurer,^{27b} B. Maček,⁸⁹ S. J. Maxfield,⁸⁸ D. A. Maximov,^{120b,120a} R. Mazini,¹⁵⁵ I. Maznas,¹⁵⁹ S. M. Mazza,¹⁴³ S. P. Mc Kee,¹⁰³ A. McCarn Deiana,⁴¹ T. G. McCarthy,¹¹³ L. I. McClymont,⁹² W. P. McCormack,¹⁸ E. F. McDonald,¹⁰² J. A. McFayden,³⁵ G. Mchedlidze,⁵¹ M. A. McKay,⁴¹ K. D. McLean,¹⁷³ S. J. McMahon,¹⁴¹ P. C. McNamara,¹⁰² C. J. McNicol,¹⁷⁵ R. A. McPherson,^{173,o} J. E. Mdhuli,^{32c} Z. A. Meadows,¹⁰⁰ S. Meehan,¹⁴⁵ T. M. Megy,⁵⁰ S. Mehlhase,¹¹² A. Mehta,⁸⁸ T. Meideck,⁵⁶ B. Meirose,⁴² D. Melini,^{171,al} B. R. Mellado Garcia,^{32c} J. D. Mellenthin,⁵¹ M. Melo,^{28a} F. Meloni,⁴⁴ A. Melzer,²⁴ S. B. Menary,⁹⁸ E. D. Mendes Gouveia,^{137a} L. Meng,³⁵ X. T. Meng,¹⁰³ S. Menke,¹¹³ E. Meoni,^{40b,40a} S. Mergelmeyer,¹⁹ S. A. M. Merkt,¹³⁶ C. Merlassino,²⁰ P. Mermod,⁵² L. Merola,^{67a,67b} C. Meroni,^{66a} A. Messina,^{70a,70b} J. Metcalfe,⁶ A. S. Mete,¹⁶⁸ C. Meyer,⁶³ J. Meyer,¹⁵⁷ J-P. Meyer,¹⁴² H. Meyer Zu Theenhausen,^{59a} F. Miano,¹⁵³ R. P. Middleton,¹⁴¹ L. Mijović,⁴⁸ G. Mikenberg,¹⁷⁷ M. Mikestikova,¹³⁸ M. Mikuž,⁸⁹ M. Milesi,¹⁰² A. Milic,¹⁶⁴ D. A. Millar,⁹⁰ D. W. Miller,³⁶ A. Milov,¹⁷⁷ D. A. Milstead,^{43a,43b} R. A. Mina,^{150,af} A. A. Minaenko,¹²¹ M. Miñano Moya,¹⁷¹ I. A. Minashvili,^{156b} A. I. Mincer,¹²² B. Mindur,^{81a} M. Mineev,⁷⁷ Y. Minegishi,¹⁶⁰ Y. Ming,¹⁷⁸ L. M. Mir,¹⁴ A. Mirto,^{65a,65b} K. P. Mistry,¹³⁴ T. Mitani,¹⁷⁶ J. Mitrevski,¹¹² V. A. Mitsou,¹⁷¹ M. Mittal,^{58c} A. Miucci,²⁰ P. S. Miyagawa,¹⁴⁶ A. Mizukami,⁷⁹ J. U. Mjörnmark,⁹⁴ T. Mkrtychyan,¹⁸¹ M. Mlynarikova,¹⁴⁰ T. Moa,^{43a,43b} K. Mochizuki,¹⁰⁷ P. Mogg,⁵⁰ S. Mohapatra,³⁸ R. Moles-Valls,²⁴ M. C. Mondragon,¹⁰⁴ K. Mönig,⁴⁴ J. Monk,³⁹ E. Monnier,⁹⁹ A. Montalbano,¹⁴⁹ J. Montejo Berlingen,³⁵ F. Monticelli,⁸⁶ S. Monzani,^{66a} N. Morange,¹²⁹ D. Moreno,²² M. Moreno Llácer,³⁵ P. Morettini,^{53b} M. Morgenstern,¹¹⁸ S. Morgenstern,⁴⁶ D. Mori,¹⁴⁹ M. Morii,⁵⁷ M. Morinaga,¹⁷⁶ V. Morisbak,¹³¹ A. K. Morley,³⁵ G. Mornacchi,³⁵ A. P. Morris,⁹² L. Morvaj,¹⁵² P. Moschovakos,¹⁰ M. Mosidze,^{156b} H. J. Moss,¹⁴⁶ J. Moss,^{150a,am} K. Motohashi,¹⁶² E. Mountricha,³⁵ E. J. W. Moyse,¹⁰⁰ S. Muanza,⁹⁹ F. Mueller,¹¹³ J. Mueller,¹³⁶ R. S. P. Mueller,¹¹² D. Muenstermann,⁸⁷ G. A. Mullier,⁹⁴ F. J. Munoz Sanchez,⁹⁸ P. Murin,^{28b} W. J. Murray,^{175,141} A. Murrone,^{66a,66b} M. Muškinja,⁸⁹ C. Mwewa,^{32a} A. G. Myagkov,^{121,an} J. Myers,¹²⁸ M. Myska,¹³⁹ B. P. Nachman,¹⁸ O. Nackenhurst,⁴⁵ K. Nagai,¹³² K. Nagano,⁷⁹ Y. Nagasaka,⁶⁰ M. Nagel,⁵⁰ E. Nagy,⁹⁹ A. M. Nairz,³⁵ Y. Nakahama,¹¹⁵

- K. Nakamura,⁷⁹ T. Nakamura,¹⁶⁰ I. Nakano,¹²⁴ H. Nanjo,¹³⁰ F. Napolitano,^{59a} R. F. Naranjo Garcia,⁴⁴ R. Narayan,¹¹
D. I. Narrias Villar,^{59a} I. Naryshkin,¹³⁵ T. Naumann,⁴⁴ G. Navarro,²² H. A. Neal,^{103,a} P. Y. Nechaeva,¹⁰⁸ F. Nechansky,⁴⁴
T. J. Neep,¹⁴² A. Negri,^{68a,68b} M. Negrini,^{23b} S. Nektarijevic,¹¹⁷ C. Nellist,⁵¹ M. E. Nelson,¹³² S. Nemecek,¹³⁸ P. Nemethy,¹²²
M. Nessi,^{35,ao} M. S. Neubauer,¹⁷⁰ M. Neumann,¹⁷⁹ P. R. Newman,²¹ T. Y. Ng,^{61c} Y. S. Ng,¹⁹ Y. W. Y. Ng,¹⁶⁸
H. D. N. Nguyen,⁹⁹ T. Nguyen Manh,¹⁰⁷ E. Nibigira,³⁷ R. B. Nickerson,¹³² R. Nicolaidou,¹⁴² D. S. Nielsen,³⁹ J. Nielsen,¹⁴³
N. Nikiforou,¹¹ V. Nikolaenko,^{121,an} I. Nikolic-Audit,¹³³ K. Nikolopoulos,²¹ P. Nilsson,²⁹ H. R. Nindhito,⁵² Y. Ninomiya,⁷⁹
A. Nisati,^{70a} N. Nishu,^{58c} R. Nisius,¹¹³ I. Nitsche,⁴⁵ T. Nitta,¹⁷⁶ T. Nobe,¹⁶⁰ Y. Noguchi,⁸³ M. Nomachi,¹³⁰ I. Nomidis,¹³³
M. A. Nomura,²⁹ M. Nordberg,³⁵ N. Norjoharuddeen,¹³² T. Novak,⁸⁹ O. Novgorodova,⁴⁶ R. Novotny,¹³⁹ L. Nozka,¹²⁷
K. Ntekas,¹⁶⁸ E. Nurse,⁹² F. Nuti,¹⁰² F. G. Oakham,^{33,f} H. Oberlack,¹¹³ J. Ocariz,¹³³ A. Ochi,⁸⁰ I. Ochoa,³⁸
J. P. Ochoa-Ricoux,^{144a} K. O'Connor,²⁶ S. Oda,⁸⁵ S. Odaka,⁷⁹ S. Oerdek,⁵¹ A. Ogrodnik,^{81a} A. Oh,⁹⁸ S. H. Oh,⁴⁷ C. C. Ohm,¹⁵¹
H. Oide,^{53b,53a} M. L. Ojeda,¹⁶⁴ H. Okawa,¹⁶⁶ Y. Okazaki,⁸³ Y. Okumura,¹⁶⁰ T. Okuyama,⁷⁹ A. Olariu,^{27b} L. F. Oleiro Seabra,^{137a}
S. A. Olivares Pino,^{144a} D. Oliveira Damazio,²⁹ J. L. Oliver,¹ M. J. R. Olsson,³⁶ A. Olszewski,⁸² J. Olszowska,⁸²
D. C. O'Neil,¹⁴⁹ A. Onofre,^{137a,137e} K. Onogi,¹¹⁵ P. U. E. Onyisi,¹¹ H. Oppen,¹³¹ M. J. Oreglia,³⁶ G. E. Orellana,⁸⁶ Y. Oren,¹⁵⁸
D. Orestano,^{72a,72b} N. Orlando,¹⁴ A. A. O'Rourke,⁴⁴ R. S. Orr,¹⁶⁴ B. Osculati,^{53b,53a,a} V. O'Shea,⁵⁵ R. Ospanov,^{58a}
G. Otero y Garzon,³⁰ H. Otono,⁸⁵ M. Ouchrif,^{34d} F. Ould-Saada,¹³¹ A. Ouraou,¹⁴² Q. Ouyang,^{15a} M. Owen,⁵⁵ R. E. Owen,²¹
V. E. Ozcan,^{12c} N. Ozturk,⁸ J. Pacalt,¹²⁷ H. A. Pacey,³¹ K. Pachal,¹⁴⁹ A. Pacheco Pages,¹⁴ L. Pacheco Rodriguez,¹⁴²
C. Padilla Aranda,¹⁴ S. Pagan Griso,¹⁸ M. Paganini,¹⁸⁰ G. Palacino,⁶³ S. Palazzo,⁴⁸ S. Palestini,³⁵ M. Palka,^{81b} D. Pallin,³⁷
I. Panagoulas,¹⁰ C. E. Pandini,³⁵ J. G. Panduro Vazquez,⁹¹ P. Pani,⁴⁴ G. Panizzo,^{64a,64c} L. Paolozzi,⁵² K. Papageorgiou,^{9,u}
A. Paramonov,⁶ D. Paredes Hernandez,^{61b} S. R. Paredes Saenz,¹³² B. Parida,¹⁶³ T. H. Park,¹⁶⁴ A. J. Parker,⁸⁷ M. A. Parker,³¹
F. Parodi,^{53b,53a} E. W. P. Parrish,¹¹⁹ J. A. Parsons,³⁸ U. Parzefall,⁵⁰ V. R. Pascuzzi,¹⁶⁴ J. M. P. Pasner,¹⁴³ E. Pasqualucci,^{70a}
S. Passaggio,^{53b} F. Pastore,⁹¹ P. Pasuwan,^{43a,43b} S. Patariaia,⁹⁷ J. R. Pater,⁹⁸ A. Pathak,^{178,g} T. Pauly,³⁵ B. Pearson,¹¹³
M. Pedersen,¹³¹ L. Pedraza Diaz,¹¹⁷ R. Pedro,^{137a,137b} S. V. Peleganchuk,^{120b,120a} O. Penc,¹³⁸ C. Peng,^{15a} H. Peng,^{58a}
B. S. Peralva,^{78a} M. M. Perego,¹²⁹ A. P. Pereira Peixoto,^{137a} D. V. Perepelitsa,²⁹ F. Peri,¹⁹ L. Perini,^{66a,66b} H. Pernegger,³⁵
S. Perrella,^{67a,67b} V. D. Peshekhonov,^{77,a} K. Peters,⁴⁴ R. F. Y. Peters,⁹⁸ B. A. Petersen,³⁵ T. C. Petersen,³⁹ E. Petit,⁵⁶
A. Petridis,¹ C. Petridou,¹⁵⁹ P. Petroff,¹²⁹ M. Petrov,¹³² F. Petrucci,^{72a,72b} M. Pettee,¹⁸⁰ N. E. Pettersson,¹⁰⁰ A. Peyaud,¹⁴²
R. Pezoa,^{144b} T. Pham,¹⁰² F. H. Phillips,¹⁰⁴ P. W. Phillips,¹⁴¹ M. W. Phipps,¹⁷⁰ G. Piacquadio,¹⁵² E. Pianori,¹⁸ A. Picazio,¹⁰⁰
R. H. Pickles,⁹⁸ R. Piegala,³⁰ J. E. Pilcher,³⁶ A. D. Pilkington,⁹⁸ M. Pinamonti,^{71a,71b} J. L. Pinfeld,³ M. Pitt,¹⁷⁷
L. Pizzimento,^{71a,71b} M.-A. Pleier,²⁹ V. Pleskot,¹⁴⁰ E. Plotnikova,⁷⁷ D. Pluth,⁷⁶ P. Podberezko,^{120b,120a} R. Poettgen,⁹⁴
R. Poggi,⁵² L. Poggioli,¹²⁹ I. Pogrebnyak,¹⁰⁴ D. Pohl,²⁴ I. Pokharel,⁵¹ G. Polesello,^{68a} A. Poley,¹⁸ A. Policicchio,^{70a,70b}
R. Polifka,³⁵ A. Polini,^{23b} C. S. Pollard,⁴⁴ V. Polychronakos,²⁹ D. Ponomarenko,¹¹⁰ L. Pontecorvo,³⁵ G. A. Popeneciu,^{27d}
D. M. Portillo Quintero,¹³³ S. Pospisil,¹³⁹ K. Potamianos,⁴⁴ I. N. Potrap,⁷⁷ C. J. Potter,³¹ H. Potti,¹¹ T. Poulsen,⁹⁴ J. Poveda,³⁵
T. D. Powell,¹⁴⁶ M. E. Pozo Astigarraga,³⁵ P. Pralavorio,⁹⁹ S. Prell,⁷⁶ D. Price,⁹⁸ M. Primavera,^{65a} S. Prince,¹⁰¹
M. L. Proffitt,¹⁴⁵ N. Proklova,¹¹⁰ K. Prokofiev,^{61c} F. Prokoshin,^{144b} S. Protopopescu,²⁹ J. Proudfoot,⁶ M. Przybycien,^{81a}
A. Puri,¹⁷⁰ P. Puzo,¹²⁹ J. Qian,¹⁰³ Y. Qin,⁹⁸ A. Quadt,⁵¹ M. Queitsch-Maitland,⁴⁴ A. Qureshi,¹ P. Rados,¹⁰² F. Ragusa,^{66a,66b}
G. Rahal,⁹⁵ J. A. Raine,⁵² S. Rajagopalan,²⁹ A. Ramirez Morales,⁹⁰ K. Ran,^{15d,ba} T. Rashid,¹²⁹ S. Raspopov,⁵ M. G. Ratti,^{66a,66b}
D. M. Rauch,⁴⁴ F. Rauscher,¹¹² S. Rave,⁹⁷ B. Ravina,¹⁴⁶ I. Ravinovich,¹⁷⁷ J. H. Rawling,⁹⁸ M. Raymond,³⁵ A. L. Read,¹³¹
N. P. Readioff,⁵⁶ M. Reale,^{65a,65b} D. M. Rebuffi,^{68a,68b} A. Redelbach,¹⁷⁴ G. Redlinger,²⁹ R. G. Reed,^{32c} K. Reeves,⁴²
L. Rehnisch,¹⁹ J. Reichert,¹³⁴ D. Reikher,¹⁵⁸ A. Reiss,⁹⁷ A. Rej,¹⁴⁸ C. Rembser,³⁵ H. Ren,^{15a} M. Rescigno,^{70a} S. Resconi,^{66a}
E. D. Resseguie,¹³⁴ S. Rettie,¹⁷² E. Reynolds,²¹ O. L. Rezanova,^{120b,120a} P. Rezneck,¹⁴⁰ E. Ricci,^{73a,73b} R. Richter,¹¹³
S. Richter,⁴⁴ E. Richter-Was,^{81b} O. Ricken,²⁴ M. Ridel,¹³³ P. Rieck,¹¹³ C. J. Riegel,¹⁷⁹ O. Rifki,⁴⁴ M. Rijssenbeek,¹⁵²
A. Rimoldi,^{68a,68b} M. Rimoldi,²⁰ L. Rinaldi,^{23b} G. Ripellino,¹⁵¹ B. Ristić,⁸⁷ E. Ritsch,³⁵ I. Riu,¹⁴ J. C. Rivera Vergara,^{144a}
F. Rizatdinova,¹²⁶ E. Rizvi,⁹⁰ C. Rizzi,¹⁴ R. T. Roberts,⁹⁸ S. H. Robertson,^{101,o} D. Robinson,³¹ J. E. M. Robinson,⁴⁴
A. Robson,⁵⁵ E. Rocco,⁹⁷ C. Roda,^{69a,69b} Y. Rodina,⁹⁹ S. Rodriguez Bosca,¹⁷¹ A. Rodriguez Perez,¹⁴
D. Rodriguez Rodriguez,¹⁷¹ A. M. Rodríguez Vera,^{165b} S. Roe,³⁵ O. Røhne,¹³¹ R. Røhrig,¹¹³ C. P. A. Roland,⁶³ J. Roloff,⁵⁷
A. Romaniouk,¹¹⁰ M. Romano,^{23b,23a} N. Rompotis,⁸⁸ M. Ronzani,¹²² L. Roos,¹³³ S. Rosati,^{70a} K. Rosbach,⁵⁰ N.-A. Rosien,⁵¹
B. J. Rosser,¹³⁴ E. Rossi,⁴⁴ E. Rossi,^{72a,72b} E. Rossi,^{67a,67b} L. P. Rossi,^{53b} L. Rossini,^{66a,66b} J. H. N. Rosten,³¹ R. Rosten,¹⁴
M. Rotaru,^{27b} J. Rothberg,¹⁴⁵ D. Rousseau,¹²⁹ D. Roy,^{32c} A. Rozano,⁹⁹ Y. Rozen,¹⁵⁷ X. Ruan,^{32c} F. Rubbo,¹⁵⁰ F. Rühr,⁵⁰
A. Ruiz-Martinez,¹⁷¹ Z. Rurikova,⁵⁰ N. A. Rusakovich,⁷⁷ H. L. Russell,¹⁰¹ J. P. Rutherford,⁷ E. M. Rüttinger,^{44,ap}
Y. F. Ryabov,¹³⁵ M. Rybar,³⁸ G. Rybkin,¹²⁹ S. Ryu,⁶ A. Ryzhov,¹²¹ G. F. Rzehorz,⁵¹ P. Sabatini,⁵¹ G. Sabato,¹¹⁸ S. Sacerdoti,¹²⁹
H. F.-W. Sadrozinski,¹⁴³ R. Sadykov,⁷⁷ F. Safai Tehrani,^{70a} P. Saha,¹¹⁹ M. Sahinsoy,^{59a} A. Sahu,¹⁷⁹ M. Saimpert,⁴⁴ M. Saito,¹⁶⁰
T. Saito,¹⁶⁰ H. Sakamoto,¹⁶⁰ A. Sakharov,^{122,ag} D. Salamani,⁵² G. Salamanna,^{72a,72b} J. E. Salazar Loyola,^{144b} P. H. Sales De
Bruin,¹⁶⁹ D. Salihagic,^{113,a} A. Salnikov,¹⁵⁰ J. Salt,¹⁷¹ D. Salvatore,^{40b,40a} F. Salvatore,¹⁵³ A. Salvucci,^{61a,61b,61c} A. Salzburger,³⁵
J. Samarati,³⁵ D. Sammel,⁵⁰ D. Sampsonidis,¹⁵⁹ D. Sampsonidou,¹⁵⁹ J. Sánchez,¹⁷¹ A. Sanchez Pineda,^{64a,64c} H. Sandaker,¹³¹
C. O. Sander,⁴⁴ M. Sandhoff,¹⁷⁹ C. Sandoval,²² D. P. C. Sankey,¹⁴¹ M. Sannino,^{53b,53a} Y. Sano,¹¹⁵ A. Sansoni,⁴⁹ C. Santoni,³⁷
H. Santos,^{137a} A. Santra,¹⁷¹ A. Saponov,⁷⁷ J. G. Saraiva,^{137a,137d} O. Sasaki,⁷⁹ K. Sato,¹⁶⁶ E. Sauvan,⁵ P. Savard,^{164,f}
N. Savic,¹¹³ R. Sawada,¹⁶⁰ C. Sawyer,¹⁴¹ L. Sawyer,^{93,aq} C. Sbarra,^{23b} A. Sbrizzi,^{23a} T. Scanlon,⁹² J. Schaarschmidt,¹⁴⁵
P. Schacht,¹¹³ B. M. Schachtner,¹¹² D. Schaefer,³⁶ L. Schaefer,¹³⁴ J. Schaeffer,⁹⁷ S. Schaepe,³⁵ U. Schäfer,⁹⁷ A. C. Schaffer,¹²⁹
D. Schaile,¹¹² R. D. Schamberger,¹⁵² N. Scharmberg,⁹⁸ V. A. Schegelsky,¹³⁵ D. Scheirich,¹⁴⁰ F. Schenck,¹⁹ M. Schernau,¹⁶⁸

- C. Schiavi,^{53b,53a} S. Schier,¹⁴³ L. K. Schildgen,²⁴ Z. M. Schillaci,²⁶ E. J. Schioppa,³⁵ M. Schioppa,^{40b,40a} K. E. Schleicher,⁵⁰ S. Schlenker,³⁵ K. R. Schmidt-Sommerfeld,¹¹³ K. Schmieden,³⁵ C. Schmitt,⁹⁷ S. Schmitt,⁴⁴ S. Schmitz,⁹⁷ J. C. Schmoeckel,⁴⁴ U. Schnoor,⁵⁰ L. Schoeffel,¹⁴² A. Schoening,^{59b} E. Schopf,¹³² M. Schott,⁹⁷ J. F. P. Schouwenberg,¹¹⁷ J. Schovancova,³⁵ S. Schramm,⁵² A. Schulte,⁹⁷ H-C. Schultz-Coulon,^{59a} M. Schumacher,⁵⁰ B. A. Schumm,¹⁴³ Ph. Schune,¹⁴² A. Schwartzman,¹⁵⁰ T. A. Schwarz,¹⁰³ Ph. Schwemling,¹⁴² R. Schwienhorst,¹⁰⁴ A. Sciandra,²⁴ G. Sciolla,²⁶ M. Scornajenghi,^{40b,40a} F. Scuri,^{69a} F. Scutti,¹⁰² L. M. Scyboz,¹¹³ C. D. Sebastiani,^{70a,70b} P. Seema,¹⁹ S. C. Seidel,¹¹⁶ A. Seiden,¹⁴³ T. Seiss,³⁶ J. M. Seixas,^{78b} G. Sekhniaidze,^{67a} K. Sekhon,¹⁰³ S. J. Sekula,⁴¹ N. Semprini-Cesari,^{23b,23a} S. Sen,⁴⁷ S. Senkin,³⁷ C. Serfon,¹³¹ L. Serin,¹²⁹ L. Serkin,^{64a,64b} M. Sessa,^{58a} H. Severini,¹²⁵ F. Sforza,¹⁶⁷ A. Sfyrla,⁵² E. Shabalina,⁵¹ J. D. Shahinian,¹⁴³ N. W. Shaikh,^{43a,43b} D. Shaked Renous,¹⁷⁷ L. Y. Shan,^{15a} R. Shang,¹⁷⁰ J. T. Shank,²⁵ M. Shapiro,¹⁸ A. S. Sharma,¹ A. Sharma,¹³² P. B. Shatalov,¹⁰⁹ K. Shaw,¹⁵³ S. M. Shaw,⁹⁸ A. Shcherbakova,¹³⁵ Y. Shen,¹²⁵ N. Sherafati,³³ A. D. Sherman,²⁵ P. Sherwood,⁹² L. Shi,^{155,ar} S. Shimizu,⁷⁹ C. O. Shimmin,¹⁸⁰ Y. Shimogama,¹⁷⁶ M. Shimojima,¹¹⁴ I. P. J. Shipsey,¹³² S. Shirabe,⁸⁵ M. Shiyakova,^{77,as} J. Shlomi,¹⁷⁷ A. Shmeleva,¹⁰⁸ M. J. Shochet,³⁶ S. Shojaii,¹⁰² D. R. Shope,¹²⁵ S. Shrestha,¹²³ E. Shulga,¹¹⁰ P. Sicho,¹³⁸ A. M. Sickles,¹⁷⁰ P. E. Sidebo,¹⁵¹ E. Sideras Haddad,^{32c} O. Sidiropoulou,³⁵ A. Sidoti,^{23b,23a} F. Siegert,⁴⁶ Dj. Sijacki,¹⁶ J. Silva,^{137a} M. Silva, Jr.,¹⁷⁸ M. V. Silva Oliveira,^{78a} S. B. Silverstein,^{43a} S. Simion,¹²⁹ E. Simioni,⁹⁷ M. Simon,⁹⁷ R. Simoniello,⁹⁷ P. Sinervo,¹⁶⁴ N. B. Sinev,¹²⁸ M. Sioli,^{23b,23a} I. Siral,¹⁰³ S. Yu. Sivoklokov,¹¹¹ J. Sjölin,^{43a,43b} P. Skubic,¹²⁵ M. Slawinska,⁸² K. Sliwa,¹⁶⁷ R. Slovak,¹⁴⁰ V. Smakhtin,¹⁷⁷ B. H. Smart,⁵ J. Smiesko,^{28a} N. Smirnov,¹¹⁰ S. Yu. Smirnov,¹¹⁰ Y. Smirnov,¹¹⁰ L. N. Smirnova,¹¹¹ O. Smirnova,⁹⁴ J. W. Smith,⁵¹ M. Smizanska,⁸⁷ K. Smolek,¹³⁹ A. Smykiewicz,⁸² A. A. Snesarev,¹⁰⁸ I. M. Snyder,¹²⁸ S. Snyder,²⁹ R. Sobie,^{173,o} A. M. Soffa,¹⁶⁸ A. Soffer,¹⁵⁸ A. Søggaard,⁴⁸ F. Sohns,⁵¹ G. Sokhranyi,⁸⁹ C. A. Solans Sanchez,³⁵ E. Yu. Soldatov,¹¹⁰ U. Soldevila,¹⁷¹ A. A. Solodkov,¹²¹ A. Soloshenko,⁷⁷ O. V. Solovyanov,¹²¹ V. Solov'yev,¹³⁵ P. Sommer,¹⁴⁶ H. Son,¹⁶⁷ W. Song,¹⁴¹ W. Y. Song,^{165b} A. Sopczak,¹³⁹ F. Sopkova,^{28b} C. L. Sotiropoulou,^{69a,69b} S. Sottocornola,^{68a,68b} R. Soualah,^{64a,64c,at} A. M. Soukharev,^{120b,120a} D. South,⁴⁴ S. Spagnolo,^{65a,65b} M. Spalla,¹¹³ M. Spangenberg,¹⁷⁵ F. Spanò,⁹¹ D. Sperlich,¹⁹ T. M. Spieker,^{59a} R. Spighi,^{23b} G. Spigo,³⁵ L. A. Spiller,¹⁰² D. P. Spiteri,⁵⁵ M. Spousta,¹⁴⁰ A. Stabile,^{66a,66b} B. L. Stamas,¹¹⁹ R. Stamen,^{59a} S. Stamm,¹⁹ E. Stanecka,⁸² R. W. Staneck,⁶ B. Stanislaus,¹³² M. M. Stanitzki,⁴⁴ B. Stapf,¹¹⁸ E. A. Starchenko,¹²¹ G. H. Stark,¹⁴³ J. Stark,⁵⁶ S. H. Stark,³⁹ P. Staroba,¹³⁸ P. Starovoitov,^{59a} S. Stärz,¹⁰¹ R. Staszewski,⁸² M. Stegler,⁴⁴ P. Steinberg,²⁹ B. Stelzer,¹⁴⁹ H. J. Stelzer,³⁵ O. Stelzer-Chilton,^{165a} H. Stenzel,⁵⁴ T. J. Stevenson,¹⁵³ G. A. Stewart,³⁵ M. C. Stockton,³⁵ G. Stoica,^{27b} P. Stolte,⁵¹ S. Stonjek,¹¹³ A. Straessner,⁴⁶ J. Strandberg,¹⁵¹ S. Strandberg,^{43a,43b} M. Strauss,¹²⁵ P. Strizenec,^{28b} R. Ströhmer,¹⁷⁴ D. M. Strom,¹²⁸ R. Stroynovski,⁴¹ A. Strubig,⁴⁸ S. A. Stucci,²⁹ B. Stugu,¹⁷ J. Stupak,¹²⁵ N. A. Styles,⁴⁴ D. Su,¹⁵⁰ S. Suchek,^{59a} Y. Sugaya,¹³⁰ V. V. Sulim,¹⁰⁸ M. J. Sullivan,⁸⁸ D. M. S. Sultan,⁵² S. Sultansoy,^{4c} T. Sumida,⁸³ S. Sun,¹⁰³ X. Sun,³ K. Suruliz,¹⁵³ C. J. E. Suster,¹⁵⁴ M. R. Sutton,¹⁵³ S. Suzuki,⁷⁹ M. Svatos,¹³⁸ M. Swiatlowski,³⁶ S. P. Swift,² A. Sydorenko,⁹⁷ I. Sykora,^{28a} M. Sykora,¹⁴⁰ T. Sykora,¹⁴⁰ D. Ta,⁹⁷ K. Tackmann,^{44,au} J. Taenzer,¹⁵⁸ A. Taffard,¹⁶⁸ R. Tafirout,^{165a} E. Tahirovic,⁹⁰ N. Taiblum,¹⁵⁸ H. Takai,²⁹ R. Takashima,⁸⁴ K. Takeda,⁸⁰ T. Takeshita,¹⁴⁷ Y. Takubo,⁷⁹ M. Talby,⁹⁹ A. A. Talyshv,^{120b,120a} J. Tanaka,¹⁶⁰ M. Tanaka,¹⁶² R. Tanaka,¹²⁹ B. B. Tannenwald,¹²³ S. Tapia Araya,¹⁷⁰ S. Tapprogge,⁹⁷ A. Tarek Abouelfadl Mohamed,¹³³ S. Tarem,¹⁵⁷ G. Tarna,^{27b,q} G. F. Tartarelli,^{66a} P. Tas,¹⁴⁰ M. Tasevsky,¹³⁸ T. Tashiro,⁸³ E. Tassi,^{40b,40a} A. Tavares Delgado,^{137a,137b} Y. Tayalati,^{34c} A. J. Taylor,⁴⁸ G. N. Taylor,¹⁰² P. T. E. Taylor,¹⁰² W. Taylor,^{165b} A. S. Tee,⁸⁷ R. Teixeira De Lima,¹⁵⁰ P. Teixeira-Dias,⁹¹ H. Ten Kate,³⁵ J. J. Teoh,¹¹⁸ S. Terada,⁷⁹ K. Terashi,¹⁶⁰ J. Terron,⁹⁶ S. Terzo,¹⁴ M. Testa,⁴⁹ R. J. Teuscher,^{164,o} S. J. Thais,¹⁸⁰ T. Thevenaux-Pelzer,⁴⁴ F. Thiele,³⁹ D. W. Thomas,⁹¹ J. P. Thomas,²¹ A. S. Thompson,⁵⁵ P. D. Thompson,²¹ L. A. Thomsen,¹⁸⁰ E. Thomson,¹³⁴ Y. Tian,³⁸ R. E. Ticse Torres,⁵¹ V. O. Tikhomirov,^{108,av} Yu. A. Tikhonov,^{120b,120a} S. Timoshenko,¹¹⁰ P. Tipton,¹⁸⁰ S. Tisserant,⁹⁹ K. Todome,¹⁶² S. Todorova-Nova,⁵ S. Todt,⁴⁶ J. Tojo,⁸⁵ S. Tokár,^{28a} K. Tokushuku,⁷⁹ E. Tolley,¹²³ K. G. Tomiwa,^{32c} M. Tomoto,¹¹⁵ L. Tompkins,^{150,af} K. Toms,¹¹⁶ B. Tong,⁵⁷ P. Tornambe,⁵⁰ E. Torrence,¹²⁸ H. Torres,⁴⁶ E. Torró Pastor,¹⁴⁵ C. Tosciri,¹³² J. Toth,^{99,aw} D. R. Tovey,¹⁴⁶ C. J. Treado,¹²² T. Trefzger,¹⁷⁴ F. Tresoldi,¹⁵³ A. Tricoli,²⁹ I. M. Trigger,^{165a} S. Trincz-Duvoid,¹³³ W. Trischuk,¹⁶⁴ B. Trocmé,⁵⁶ A. Trofymov,¹²⁹ C. Troncon,^{66a} M. Trovatelli,¹⁷³ F. Trovato,¹⁵³ L. Truong,^{32b} M. Trzebinski,⁸² A. Trzupek,⁸² F. Tsai,⁴⁴ J. C.-L. Tseng,¹³² P. V. Tsiarshka,^{105,ah} A. Tsirigotis,¹⁵⁹ N. Tsirintanis,⁹ V. Tsiskaridze,¹⁵² E. G. Tskhadadze,^{156a} I. I. Tsukerman,¹⁰⁹ V. Tsulaia,¹⁸ S. Tsuno,⁷⁹ D. Tsybychev,^{152,163} Y. Tu,^{61b} A. Tudorache,^{27b} V. Tudorache,^{27b} T. T. Tulbure,^{27a} A. N. Tuna,⁵⁷ S. Turchikhin,⁷⁷ D. Turgeman,¹⁷⁷ I. Turk Cakir,^{4b,ax} R. J. Turner,²¹ R. T. Turra,^{66a} P. M. Tuts,³⁸ S. Tzamarias,¹⁵⁹ E. Tzovara,⁹⁷ G. Uccielli,⁴⁵ I. Ueda,⁷⁹ M. Ughetto,^{43a,43b} F. Ukegawa,¹⁶⁶ G. Unal,³⁵ A. Undrus,²⁹ G. Unel,¹⁶⁸ F. C. Ungaro,¹⁰² Y. Unno,⁷⁹ K. Uno,¹⁶⁰ J. Urban,^{28b} P. Urquijo,¹⁰² G. Usai,⁸ J. Usui,⁷⁹ L. Vacavant,⁹⁹ V. Vacek,¹³⁹ B. Vachon,¹⁰¹ K. O. H. Vadla,¹³¹ A. Vaidya,⁹² C. Valderanis,¹¹² E. Valdes Santurio,^{43a,43b} M. Valente,⁵² S. Valentinetti,^{23b,23a} A. Valero,¹⁷¹ L. Valéry,⁴⁴ R. A. Vallance,²¹ A. Vallier,⁵ J. A. Valls Ferrer,¹⁷¹ T. R. Van Daalen,¹⁴ P. Van Gemmeren,⁶ I. Van Vulpen,¹¹⁸ M. Vanadia,^{71a,71b} W. Vandelli,³⁵ A. Vaniachine,¹⁶³ R. Vari,^{70a} E. W. Varnes,⁷ C. Varni,^{53b,53a} T. Varol,⁴¹ D. Varouchas,¹²⁹ K. E. Varvell,¹⁵⁴ G. A. Vasquez,^{144b} J. G. Vasquez,¹⁸⁰ F. Vazeille,³⁷ D. Vazquez Furelos,¹⁴ T. Vazquez Schroeder,³⁵ J. Veatch,⁵¹ V. Vecchio,^{72a,72b} L. M. Veloce,¹⁶⁴ F. Veloso,^{137a,137c} S. Veneziano,^{70a} A. Ventura,^{65a,65b} N. Venturi,³⁵ A. Verbytskyi,¹¹³ V. Vercesi,^{68a} M. Verducci,^{72a,72b} C. M. Vergel Infante,⁷⁶ C. Vergis,²⁴ W. Verkerke,¹¹⁸ A. T. Vermeulen,¹¹⁸ J. C. Vermeulen,¹¹⁸ M. C. Vetterli,^{149,f} N. Viaux Maira,^{144b} M. Vicente Barreto Pinto,⁵² I. Vichou,^{170,a} T. Vickey,¹⁴⁶ O. E. Vickey Boeriu,¹⁴⁶ G. H. A. Viehhauser,¹³² L. Vigani,¹³² M. Villa,^{23b,23a} M. Villaplana Perez,^{66a,66b} E. Vilucchi,⁴⁹ M. G. Vincker,³³ V. B. Vinogradov,⁷⁷ A. Vishwakarma,⁴⁴ C. Vittori,^{23b,23a} I. Vivarelli,¹⁵³ M. Vogel,¹⁷⁹ P. Vokac,¹³⁹ G. Volpi,¹⁴ S. E. von Buddenbrock,^{32c} E. Von Toerne,²⁴ V. Vorobel,¹⁴⁰ K. Vorobev,¹¹⁰ M. Vos,¹⁷¹ J. H. Vossebeld,⁸⁸ N. Vranjes,¹⁶

M. Vranjes Milosavljevic,¹⁶ V. Vrba,¹³⁹ M. Vreeswijk,¹¹⁸ T. Šfiligoj,⁸⁹ R. Vuillermet,³⁵ I. Vukotic,³⁶ T. Ženiš,^{28a} L. Živković,¹⁶ P. Wagner,²⁴ W. Wagner,¹⁷⁹ J. Wagner-Kuhr,¹¹² H. Wahlberg,⁸⁶ S. Wahrenund,⁴⁶ K. Wakamiya,⁸⁰ V. M. Walbrecht,¹¹³ J. Walder,⁸⁷ R. Walker,¹¹² S. D. Walker,⁹¹ W. Walkowiak,¹⁴⁸ V. Wallangen,^{43a,43b} A. M. Wang,⁵⁷ C. Wang,^{58b} F. Wang,¹⁷⁸ H. Wang,¹⁸ H. Wang,³ J. Wang,¹⁵⁴ J. Wang,^{59b} P. Wang,⁴¹ Q. Wang,¹²⁵ R.-J. Wang,¹³³ R. Wang,^{58a} R. Wang,⁶ S. M. Wang,¹⁵⁵ W. T. Wang,^{58a} W. Wang,^{15c,ay} W. X. Wang,^{58a,ay} Y. Wang,^{58a,aj} Z. Wang,^{58c} C. Wanotayaroj,⁴⁴ A. Warburton,¹⁰¹ C. P. Ward,³¹ D. R. Wardrope,⁹² A. Washbrook,⁴⁸ A. T. Watson,²¹ M. F. Watson,²¹ G. Watts,¹⁴⁵ B. M. Waugh,⁹² A. F. Webb,¹¹ S. Webb,⁹⁷ C. Weber,¹⁸⁰ M. S. Weber,²⁰ S. A. Weber,³³ S. M. Weber,^{59a} A. R. Weidberg,¹³² J. Weingarten,⁴⁵ M. Weirich,⁹⁷ C. Weiser,⁵⁰ P. S. Wells,³⁵ T. Wenaus,²⁹ T. Wengler,³⁵ S. Wenig,³⁵ N. Wermes,²⁴ M. D. Werner,⁷⁶ P. Werner,³⁵ M. Wessels,^{59a} T. D. Weston,²⁰ K. Whalen,¹²⁸ N. L. Whallon,¹⁴⁵ A. M. Wharton,⁸⁷ A. S. White,¹⁰³ A. White,⁸ M. J. White,¹ R. White,^{144b} D. Whiteson,¹⁶⁸ B. W. Whitmore,⁸⁷ F. J. Wickens,¹⁴¹ W. Wiedenmann,¹⁷⁸ M. Wielers,¹⁴¹ C. Wiglesworth,³⁹ L. A. M. Wiik-Fuchs,⁵⁰ F. Wilk,⁹⁸ H. G. Wilkens,³⁵ L. J. Wilkins,⁹¹ H. H. Williams,¹³⁴ S. Williams,³¹ C. Willis,¹⁰⁴ S. Willocq,¹⁰⁰ J. A. Wilson,²¹ I. Wingerter-Seez,⁵ E. Winkels,¹⁵³ F. Winklmeier,¹²⁸ O. J. Winston,¹⁵³ B. T. Winter,⁵⁰ M. Wittgen,¹⁵⁰ M. Wobisch,⁹³ A. Wolf,⁹⁷ T. M. H. Wolf,¹¹⁸ R. Wolff,⁹⁹ J. Wollrath,⁵⁰ M. W. Wolter,⁸² H. Wolters,^{137a,137c} V. W. S. Wong,¹⁷² N. L. Woods,¹⁴³ S. D. Worm,²¹ B. K. Wosiek,⁸² K. W. Woźniak,⁸² K. Wraight,⁵⁵ S. L. Wu,¹⁷⁸ X. Wu,⁵² Y. Wu,^{58a} T. R. Wyatt,⁹⁸ B. M. Wynne,⁴⁸ S. Xella,³⁹ Z. Xi,¹⁰³ L. Xia,¹⁷⁵ D. Xu,^{15a} H. Xu,^{58a,q} L. Xu,²⁹ T. Xu,¹⁴² W. Xu,¹⁰³ Z. Xu,¹⁵⁰ B. Yabsley,¹⁵⁴ S. Yacoob,^{32a} K. Yajima,¹³⁰ D. P. Yallup,⁹² D. Yamaguchi,¹⁶² Y. Yamaguchi,¹⁶² A. Yamamoto,⁷⁹ T. Yamanaka,¹⁶⁰ F. Yamane,⁸⁰ M. Yamatani,¹⁶⁰ T. Yamazaki,¹⁶⁰ Y. Yamazaki,⁸⁰ Z. Yan,²⁵ H. J. Yang,^{58c,58d} H. T. Yang,¹⁸ S. Yang,⁷⁵ Y. Yang,¹⁶⁰ Z. Yang,¹⁷ W.-M. Yao,¹⁸ Y. C. Yap,⁴⁴ Y. Yasu,⁷⁹ E. Yatsenko,^{58c,58d} J. Ye,⁴¹ S. Ye,²⁹ I. Yeletsikh,⁷⁷ E. Yigitbasi,²⁵ E. Yildirim,⁹⁷ K. Yorita,¹⁷⁶ K. Yoshihara,¹³⁴ C. J. S. Young,³⁵ C. Young,¹⁵⁰ J. Yu,⁷⁶ X. Yue,^{59a} S. P. Y. Yuen,²⁴ B. Zabinski,⁸² G. Zacharis,¹⁰ E. Zaffaroni,⁵² R. Zaidan,¹⁴ A. M. Zaitsev,^{121,an} T. Zakareishvili,^{156b} N. Zakharchuk,³³ S. Zambito,⁵⁷ D. Zanzi,³⁵ D. R. Zaripovas,⁵⁵ S. V. Zeißner,⁴⁵ C. Zeitnitz,¹⁷⁹ G. Zemaityte,¹³² J. C. Zeng,¹⁷⁰ O. Zenin,¹²¹ D. Zerwas,¹²⁹ M. Zgubič,¹³² D. F. Zhang,^{15b} F. Zhang,¹⁷⁸ G. Zhang,^{58a} G. Zhang,^{15b} H. Zhang,^{15c} J. Zhang,⁶ L. Zhang,^{15c} L. Zhang,^{58a} M. Zhang,¹⁷⁰ R. Zhang,^{58a} R. Zhang,²⁴ X. Zhang,^{58b} Y. Zhang,^{15d,ba} Z. Zhang,¹²⁹ P. Zhao,⁴⁷ Y. Zhao,^{58b} Z. Zhao,^{58a} A. Zhemchugov,⁷⁷ Z. Zheng,¹⁰³ D. Zhong,¹⁷⁰ B. Zhou,¹⁰³ C. Zhou,¹⁷⁸ M. S. Zhou,^{15d,ba} M. Zhou,¹⁵² N. Zhou,^{58c} Y. Zhou,⁷ C. G. Zhu,^{58b} H. L. Zhu,^{58a} H. Zhu,^{15a} J. Zhu,¹⁰³ Y. Zhu,^{58a} X. Zhuang,^{15a} K. Zhukov,¹⁰⁸ V. Zhulanov,^{120b,120a} A. Zibell,¹⁷⁴ D. Zieminska,⁶³ N. I. Zimine,⁷⁷ S. Zimmermann,⁵⁰ Z. Zinonos,¹¹³ M. Ziolkowski,¹⁴⁸ G. Zobernig,¹⁷⁸ A. Zoccoli,^{23b,23a} K. Zoch,⁵¹ T. G. Zorbass,¹⁴⁶ R. Zou,³⁶ and L. Zwalinski³⁵

(ATLAS Collaboration)

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

²Physics Department, SUNY Albany, Albany, New York, USA

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

^{4a}Department of Physics, Ankara University, Ankara, Turkey

^{4b}Istanbul Aydin University, Istanbul, Turkey

^{4c}Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

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

⁶High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA

⁷Department of Physics, University of Arizona, Tucson, Arizona, USA

⁸Department of Physics, University of Texas at Arlington, Arlington, Texas, USA

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

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

¹¹Department of Physics, University of Texas at Austin, Austin, Texas, USA

^{12a}Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey

^{12b}Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey

^{12c}Department of Physics, Bogazici University, Istanbul, Turkey

^{12d}Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

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

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

^{15a}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

^{15b}Physics Department, Tsinghua University, Beijing, China

^{15c}Department of Physics, Nanjing University, Nanjing, China

^{15d}University of Chinese Academy of Science (UCAS), Beijing, China

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

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

¹⁸Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA

¹⁹Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany

²⁰Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

- ²¹*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
- ²²*Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia*
- ^{23a}*INFN Bologna and Università di Bologna, Dipartimento di Fisica, Bologna, Italy*
^{23b}*INFN Sezione di Bologna, Italy*
- ²⁴*Physikalisches Institut, Universität Bonn, Bonn, Germany*
- ²⁵*Department of Physics, Boston University, Boston Massachusetts, USA*
- ²⁶*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
^{27a}*Transilvania University of Brasov, Brasov, Romania*
- ^{27b}*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
^{27c}*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
- ^{27d}*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
^{27e}*University Politehnica Bucharest, Bucharest, Romania*
^{27f}*West University in Timisoara, Timisoara, Romania*
- ^{28a}*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
- ^{28b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
²⁹*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
- ³⁰*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
- ³¹*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
^{32a}*Department of Physics, University of Cape Town, Cape Town, South Africa*
- ^{32b}*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
^{32c}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
³³*Department of Physics, Carleton University, Ottawa, Ontario, Canada*
- ^{34a}*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies, Université Hassan II, Casablanca, Morocco*
^{34b}*Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN), Rabat, Morocco*
^{34c}*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
^{34d}*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
^{34e}*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
- ³⁵*CERN, Geneva, Switzerland*
- ³⁶*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
- ³⁷*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
³⁸*Nevis Laboratory, Columbia University, Irvington, New York, USA*
- ³⁹*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
^{40a}*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
- ^{40b}*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
- ⁴¹*Physics Department, Southern Methodist University, Dallas, Texas, USA*
⁴²*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
^{43a}*Department of Physics, Stockholm University, Sweden*
^{43b}*Oskar Klein Centre, Stockholm, Sweden*
- ⁴⁴*Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
- ⁴⁵*Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
- ⁴⁶*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
⁴⁷*Department of Physics, Duke University, Durham, North Carolina, USA*
- ⁴⁸*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
⁴⁹*INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁵⁰*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
- ⁵¹*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
- ⁵²*Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
^{53a}*Dipartimento di Fisica, Università di Genova, Genova, Italy*
^{53b}*INFN Sezione di Genova, Italy*
- ⁵⁴*II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
- ⁵⁵*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵⁶*LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
- ⁵⁷*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
- ^{58a}*Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China*
- ^{58b}*Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China*
- ^{58c}*School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai, China*
^{58d}*Tsung-Dao Lee Institute, Shanghai, China*

- ^{59a}*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
^{59b}*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ⁶⁰*Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
- ^{61a}*Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China*
^{61b}*Department of Physics, University of Hong Kong, Hong Kong, China*
- ^{61c}*Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
- ⁶²*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
- ⁶³*Department of Physics, Indiana University, Bloomington, Indiana, USA*
- ^{64a}*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
^{64b}*ICTP, Trieste, Italy*
- ^{64c}*Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
^{65a}*INFN Sezione di Lecce, Lecce, Italy*
- ^{65b}*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
^{66a}*INFN Sezione di Milano, Milano, Italy*
- ^{66b}*Dipartimento di Fisica, Università di Milano, Milano, Italy*
^{67a}*INFN Sezione di Napoli, Napoli, Italy*
- ^{67b}*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
^{68a}*INFN Sezione di Pavia, Pavia, Italy*
- ^{68b}*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
^{69a}*INFN Sezione di Pisa, Pisa, Italy*
- ^{69b}*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
^{70a}*INFN Sezione di Roma, Roma, Italy*
- ^{70b}*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
^{71a}*INFN Sezione di Roma Tor Vergata, Roma, Italy*
- ^{71b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
^{72a}*INFN Sezione di Roma Tre, Roma, Italy*
- ^{72b}*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
^{73a}*INFN-TIFPA, Trento, Italy*
^{73b}*Università degli Studi di Trento, Trento, Italy*
- ⁷⁴*Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
⁷⁵*University of Iowa, Iowa City, Iowa, USA*
- ⁷⁶*Department of Physics and Astronomy, Iowa State University, Ames Iowa, USA*
⁷⁷*Joint Institute for Nuclear Research, Dubna, Russia*
- ^{78a}*Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, São Paulo, Brazil*
^{78b}*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, São Paulo, Brazil*
^{78c}*Universidade Federal de São João del Rei (UFSJ), São João del Rei, São Paulo, Brazil*
^{78d}*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
- ⁷⁹*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
⁸⁰*Graduate School of Science, Kobe University, Kobe, Japan*
- ^{81a}*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
^{81b}*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
- ⁸²*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
⁸³*Faculty of Science, Kyoto University, Kyoto, Japan*
⁸⁴*Kyoto University of Education, Kyoto, Japan*
- ⁸⁵*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
- ⁸⁶*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
⁸⁷*Physics Department, Lancaster University, Lancaster, United Kingdom*
- ⁸⁸*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁸⁹*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
⁹⁰*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
⁹¹*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
⁹²*Department of Physics and Astronomy, University College London, London, United Kingdom*
⁹³*Louisiana Tech University, Ruston, Louisiana, USA*
- ⁹⁴*Fysiska institutionen, Lunds universitet, Lund, Sweden*
- ⁹⁵*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*
- ⁹⁶*Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
⁹⁷*Institut für Physik, Universität Mainz, Mainz, Germany*
- ⁹⁸*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*

- ⁹⁹*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
- ¹⁰⁰*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
- ¹⁰¹*Department of Physics, McGill University, Montreal, Quebec, Canada*
- ¹⁰²*School of Physics, University of Melbourne, Victoria, Australia*
- ¹⁰³*Department of Physics, University of Michigan, Ann Arbor, Michigan, USA*
- ¹⁰⁴*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
- ¹⁰⁵*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
- ¹⁰⁶*Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus*
- ¹⁰⁷*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*
- ¹⁰⁸*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
- ¹⁰⁹*Institute for Theoretical and Experimental Physics of the National Research Centre Kurchatov Institute, Moscow, Russia*
- ¹¹⁰*National Research Nuclear University MEPhI, Moscow, Russia*
- ¹¹¹*D.V. Skobel'syn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*
- ¹¹²*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
- ¹¹³*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
- ¹¹⁴*Nagasaki Institute of Applied Science, Nagasaki, Japan*
- ¹¹⁵*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
- ¹¹⁶*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
- ¹¹⁷*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
- ¹¹⁸*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
- ¹¹⁹*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
- ^{120a}*Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia*
- ^{120b}*Novosibirsk State University Novosibirsk, Russia*
- ¹²¹*Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia*
- ¹²²*Department of Physics, New York University, New York, New York, USA*
- ¹²³*Ohio State University, Columbus, Ohio, USA*
- ¹²⁴*Faculty of Science, Okayama University, Okayama, Japan*
- ¹²⁵*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
- ¹²⁶*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
- ¹²⁷*Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic*
- ¹²⁸*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
- ¹²⁹*LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
- ¹³⁰*Graduate School of Science, Osaka University, Osaka, Japan*
- ¹³¹*Department of Physics, University of Oslo, Oslo, Norway*
- ¹³²*Department of Physics, Oxford University, Oxford, United Kingdom*
- ¹³³*LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*
- ¹³⁴*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
- ¹³⁵*Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg, Russia*
- ¹³⁶*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
- ^{137a}*Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Portugal*
- ^{137b}*Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
- ^{137c}*Departamento de Física, Universidade de Coimbra, Coimbra, Portugal*
- ^{137d}*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
- ^{137e}*Departamento de Física, Universidade do Minho, Braga, Portugal*
- ^{137f}*Universidad de Granada, Granada (Spain), Portugal*
- ^{137g}*Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica; Portugal*
- ¹³⁸*Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic*
- ¹³⁹*Czech Technical University in Prague, Prague, Czech Republic*
- ¹⁴⁰*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
- ¹⁴¹*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹⁴²*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- ¹⁴³*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
- ^{144a}*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
- ^{144b}*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- ¹⁴⁵*Department of Physics, University of Washington, Seattle, Washington, USA*
- ¹⁴⁶*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
- ¹⁴⁷*Department of Physics, Shinshu University, Nagano, Japan*
- ¹⁴⁸*Department Physik, Universität Siegen, Siegen, Germany*
- ¹⁴⁹*Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*

- ¹⁵⁰*SLAC National Accelerator Laboratory, Stanford, California, USA*
^{150a}*California State University, California, USA*
- ¹⁵¹*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
- ¹⁵²*Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA*
- ¹⁵³*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
- ¹⁵⁴*School of Physics, University of Sydney, Sydney, Australia*
- ¹⁵⁵*Institute of Physics, Academia Sinica, Taipei, Taiwan*
- ^{156a}*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
^{156b}*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
- ¹⁵⁷*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
- ¹⁵⁸*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
- ¹⁵⁹*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
- ¹⁶⁰*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
- ¹⁶¹*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
¹⁶²*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
¹⁶³*Tomsk State University, Tomsk, Russia*
- ¹⁶⁴*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
^{165a}*TRIUMF, Vancouver British Columbia, Ontario, Canada*
^{165b}*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
- ¹⁶⁶*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
- ¹⁶⁷*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
- ¹⁶⁸*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
- ¹⁶⁹*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
¹⁷⁰*Department of Physics, University of Illinois, Urbana, Illinois, USA*
- ¹⁷¹*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia (CSIC), Valencia, Spain*
- ¹⁷²*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
- ¹⁷³*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
- ¹⁷⁴*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
¹⁷⁵*Department of Physics, University of Warwick, Coventry, United Kingdom*
¹⁷⁶*Waseda University, Tokyo, Japan*
- ¹⁷⁷*Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel*
- ¹⁷⁸*Department of Physics, University of Wisconsin—Madison, Madison, Wisconsin, USA*
- ¹⁷⁹*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
¹⁸⁰*Department of Physics, Yale University, New Haven, Connecticut, USA*
¹⁸¹*Yerevan Physics Institute, Yerevan, Armenia*

^aDeceased.

^bAlso at Department of Physics, King's College London, London, United Kingdom.

^cAlso at Istanbul University, Dept. of Physics, Istanbul, Turkey.

^dAlso at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid, Spain.

^eAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

^fAlso at TRIUMF, Vancouver BC, Canada.

^gAlso at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.

^hAlso at Department of Physics, University of Fribourg, Fribourg, Switzerland.

ⁱAlso at Physics Dept, University of South Africa, Pretoria, South Africa.

^jAlso at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

^kAlso at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

^lAlso at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

^mAlso at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.

ⁿAlso at Università di Napoli Parthenope, Napoli, Italy.

^oAlso at Institute of Particle Physics (IPP), Canada.

^pAlso at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

^qAlso at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.

^rAlso at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

^sAlso at Borough of Manhattan Community College, City University of New York, New York, USA.

^tAlso at Department of Physics, California State University, Fresno, California, USA.

^uAlso at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

^vAlso at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

^wAlso at Department of Physics, California State University, East Bay, USA.

- ^xAlso at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
- ^yAlso at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.
- ^zAlso at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
- ^{aa}Also at Graduate School of Science, Osaka University, Osaka, Japan.
- ^{ab}Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
- ^{ac}Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
- ^{ad}Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
- ^{ae}Also at CERN, Geneva, Switzerland.
- ^{af}Also at Department of Physics, Stanford University, Stanford, California, USA.
- ^{ag}Also at Manhattan College, New York, New York, USA.
- ^{ah}Also at Joint Institute for Nuclear Research, Dubna, Russia.
- ^{ai}Also at Hellenic Open University, Patras, Greece.
- ^{aj}Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France.
- ^{ak}Also at The City College of New York, New York, New York, USA.
- ^{al}Also at Universidad de Granada, Granada (Spain), Spain.
- ^{am}Also at Department of Physics, California State University, Sacramento, California, USA.
- ^{an}Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- ^{ao}Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
- ^{ap}Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
- ^{aq}Also at Louisiana Tech University, Ruston, Louisiana, USA.
- ^{ar}Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
- ^{as}Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
- ^{at}Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.
- ^{au}Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
- ^{av}Also at National Research Nuclear University MEPhI, Moscow, Russia.
- ^{aw}Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- ^{ax}Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
- ^{ay}Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^{az}Physics Department, An-Najah National University, Nablus, Palestine.
- ^{ba}Also at Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China.