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(ALICE Collaboration) Abelev, B.; ...; Antičić, Tome; ...; Gotovac, Sven; ...; Mudnić, Eugen; ...; Planinić, Mirko; ...; ...

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Exclusive J/ψ Photoproduction off Protons in Ultraperipheral p -Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

B. Abelev *et al.**

(ALICE Collaboration)

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We present the first measurement at the LHC of exclusive J/ψ photoproduction off protons, in ultraperipheral proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Events are selected with a dimuon pair produced either in the rapidity interval, in the laboratory frame, $2.5 < y < 4$ (p -Pb) or $-3.6 < y < -2.6$ (Pb- p), and no other particles observed in the ALICE acceptance. The measured cross sections $\sigma(\gamma + p \rightarrow J/\psi + p)$ are $33.2 \pm 2.2(\text{stat}) \pm 3.2(\text{syst}) \pm 0.7(\text{theor})$ nb in p -Pb and $284 \pm 36(\text{stat})_{-32}^{+27}(\text{syst}) \pm 26(\text{theor})$ nb in Pb- p collisions. We measure this process up to about 700 GeV in the γp center of mass, which is a factor of two larger than the highest energy studied at HERA. The data are consistent with a power law dependence of the J/ψ photoproduction cross section in γp energies from about 20 to 700 GeV, or equivalently, from Bjorken x scaling variable between $\sim 2 \times 10^{-2}$ and $\sim 2 \times 10^{-5}$, thus indicating no significant change in the gluon density behavior of the proton between HERA and LHC energies.

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Exclusive J/ψ photoproduction off protons is defined by a reaction in which the J/ψ is produced from a γp interaction, where the proton emerges intact: $\gamma + p \rightarrow J/\psi + p$. This process allows a detailed study of the gluon distribution in the proton, since its cross section is expected to scale as the square of the gluon probability density function (PDF), according to leading order QCD calculations [1]. The mass of the charm quark provides an energy scale large enough to allow perturbative QCD calculations, albeit with some theoretical uncertainties [2]. This process provides a powerful tool to search for gluon saturation [3,4], which is the most straightforward mechanism to slow down the growth of the PDF for gluons carrying a small fraction of the momentum of hadrons (Bjorken x scaling variable). Finding evidence of gluon saturation has become a central task for present experiments and for future projects [5,6] that aim to study quantum chromodynamics (QCD).

Both ZEUS and H1 Collaborations measured the exclusive J/ψ photoproduction off protons at γp center-of-mass energies ranging from 20 to 305 GeV [7–9]. This process has also been studied in pp [10], $p\bar{p}$ [11], and heavy-ion collisions [12–14].

In this Letter we present the first measurement of exclusive J/ψ photoproduction in collisions of protons with Pb nuclei at center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV. The J/ψ is produced by the interaction

of a photon with either a proton or a nuclear target, where the photon is emitted from one of the two colliding particles. Although both $\gamma + p \rightarrow J/\psi + p$ and $\gamma + \text{Pb} \rightarrow J/\psi + \text{Pb}$ can occur, the Pb electric charge makes photon emission from the ion to be strongly enhanced with respect to that from the proton [15,16].

The main ALICE detector used in this analysis is the single-arm muon spectrometer [17], covering the pseudorapidity interval $-4.0 < \eta < -2.5$. The beam directions of the LHC were reversed in order to measure both forward and backward rapidity. Thus, J/ψ s are reconstructed in the $2.5 < y < 4.0$ (p -Pb) and $-3.6 < y < -2.6$ (Pb- p) rapidity intervals, where y is measured in the laboratory frame with respect to the proton beam direction. (The ALICE detector acceptance is given in the laboratory pseudorapidity η . The convention in ALICE is that the muon spectrometer is located at $\eta < 0$. In contrast, the laboratory rapidity y will change sign according to the proton beam direction, from which it takes its orientation. In p -Pb, for example, the proton goes in the $\eta < 0$ direction, and $y > 0$.) The γp center-of-mass energy $W_{\gamma p}$ is determined by the J/ψ rapidity: $W_{\gamma p}^2 = 2E_p M_{J/\psi} \exp(-y)$, where $M_{J/\psi}$ is the J/ψ mass, y is the J/ψ rapidity, and E_p is the proton energy ($E_p = 4$ TeV in the lab frame), while the Bjorken x scaling variable is given by $x = (M_{J/\psi}/W_{\gamma p})^2$. We study $21 < W_{\gamma p} < 45$ GeV for $y > 0$ and $577 < W_{\gamma p} < 952$ GeV for $y < 0$, thereby exceeding the $W_{\gamma p}$ range of HERA.

The muon spectrometer consists of a ten interaction length absorber, followed by five tracking stations, each made of two planes of cathode pad chambers, with the third station placed inside a dipole magnet with a 3 T · m integrated magnetic field. The muon trigger system,

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downstream of the tracking chambers, consists of four planes of resistive plate chambers placed behind a 7.2 interaction length iron wall. The single muon trigger threshold for the data used in this analysis was set to transverse momentum $p_T = 0.5$ GeV/c. Other detectors used in this analysis are the silicon pixel detector (SPD), VZERO, and zero degree calorimeters (ZDCs) [17]. The central region $|\eta| < 1.4$ is covered by the SPD consisting of two cylindrical layers of silicon pixels. The pseudorapidity interval $2.8 < \eta < 5.1$ is covered by VZERO-A and $-3.7 < \eta < -1.7$ by VZERO-C. These detectors are scintillator tile arrays with a time resolution better than 1 ns, allowing us to distinguish between beam-beam and beam-gas interactions. The two ZDCs are located at ± 112.5 m from the interaction point, and are used to detect neutrons and protons emitted in the very forward region.

The trigger for the p -Pb configuration required two oppositely charged tracks in the muon spectrometer, and a veto on VZERO-A beam-beam interactions. In the Pb- p configuration, the trigger purity was improved with respect to the p -Pb by suppressing beam-induced backgrounds. This was achieved by requiring at least one hit in the VZERO-C beam-beam trigger and a veto on the VZERO-A beam-gas trigger. The integrated luminosity L was corrected for the probability that exclusivity requirements could be spoiled by multiple interactions in the same bunch crossing. This pile-up correction is on average 5%, giving $L = 3.9 \text{ nb}^{-1} \pm 3.7\%$ (syst) for p -Pb and $L = 4.5 \text{ nb}^{-1} \pm 3.4\%$ (syst) for Pb- p data [18].

Events with exactly two reconstructed tracks in the muon spectrometer were selected off-line. The muon tracks had to fulfill the requirements on the radial coordinate of the track at the end of the absorber and on the extrapolation to the nominal vertex, as described in Refs. [12,19]. Both track pseudorapidities were required to be within the chosen range $-4.0 < \eta_{\text{track}} < -2.5$ for p -Pb and $-3.7 < \eta_{\text{track}} < -2.5$ for Pb- p . Track segments in the tracking chambers must be matched with corresponding segments in the trigger chambers. The dimuon rapidity was in the range $2.5 < y < 4.0$ for p -Pb and $-3.6 < y < -2.6$ for Pb- p . The chosen range in Pb- p ensured that the muon tracks are in the overlap of the muon spectrometer and VZERO-C geometrical acceptance, as VZERO-C was part of the trigger in Pb- p . A cut on VZERO timing was imposed off-line to be compatible with crossing beams. In order to reduce contamination from nonexclusive J/ψ s that come mainly from proton dissociation, only events with no midrapidity tracklets (track segments formed by two hits at each SPD layer) were kept. For the same reasons, events with neutron or proton activity in any of the ZDCs were rejected.

The dimuon invariant mass spectra ($M_{\mu^+\mu^-}$) after these selections are shown in Fig. 1. The J/ψ peak is clearly visible in both data sets, and is well described by a Crystal Ball parametrization [20], which yields masses and widths in agreement with the Monte Carlo simulations. The

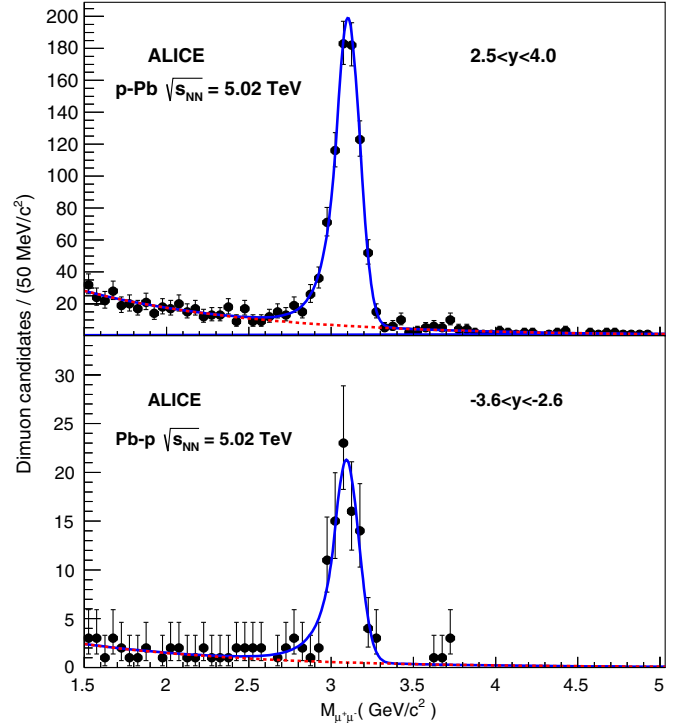


FIG. 1 (color online). Invariant mass distribution for events with two oppositely charged muons, for both forward (top panel) and backward (bottom panel) dimuon rapidity samples.

dimuon continuum is well described by an exponential as expected from two-photon production of continuum pairs ($\gamma\gamma \rightarrow \mu^+\mu^-$) [12,13].

The extracted number of J/ψ s obtained from the invariant mass fit includes a mix of exclusive and non-exclusive J/ψ candidates. A different p_T distribution is expected from exclusive and nonexclusive J/ψ events [9]. For this reason, the number of exclusive J/ψ s can be determined from the dimuon p_T distributions shown in Fig. 2. The bulk of dimuon events having $p_T < 1$ GeV/c is mainly due to exclusive J/ψ production, while the tail extending up to higher p_T on the top panel (p -Pb) comes from nonexclusive interactions. Exclusive J/ψ coming from γp interactions and $\gamma\gamma$ contribute to both p_T spectra. In addition, for p -Pb, a background, coming from non-exclusive J/ψ s and nonexclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ events was taken into account, while for the Pb- p sample a contribution from coherent J/ψ in γPb interactions was considered. The latter process was neglected in p -Pb as it amounts to less than 2% [16]. If modifications to the nuclear gluon distribution, also known as nuclear shadowing, are considered, this contribution would be even smaller. Here, an additional 50% reduction is expected [13] from shadowing effects. The p_T shapes for the J/ψ in γp , $\gamma\gamma \rightarrow \mu^+\mu^-$, and coherent J/ψ in γPb components (Monte Carlo templates) were obtained using STARLIGHT [21,22] events folded with the detector response simulation. For p -Pb, these templates were fitted to the data leaving the normalization free for

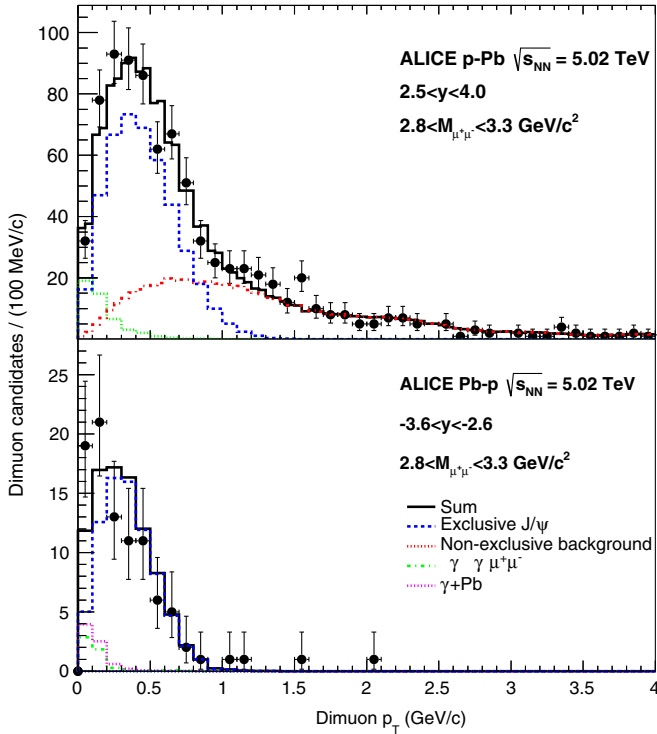


FIG. 2 (color online). Transverse momentum distribution for events with two oppositely charged muons, for both forward (top panel) and backward (bottom panel) dimuon rapidity samples.

J/ψ in γp and the nonexclusive background. The $\gamma\gamma \rightarrow \mu^+\mu^-$ component was constrained from the invariant mass fit shown in Fig. 1 [12]. The nonexclusive contributions were subtracted using this fitting procedure, giving $N_{J/\psi}$.

The p_T distribution of nonexclusive J/ψ candidates and the nonexclusive dimuon continuum were obtained from data, using the same event selection as above, but requiring events to have more than two hits in the VZERO-C counters. At HERA the ratio of the nonexclusive J/ψ production cross section to the exclusive one was found to decrease with $W_{\gamma p}$ [9]. Extrapolating, this means a factor 2 smaller nonexclusive J/ψ contribution in the Pb- p sample. We note that for this sample dissociation products went towards the VZERO-A counter, which was used as a veto at trigger level, providing an explanation on the negligible nonexclusive contribution observed.

The number of exclusive J/ψ coming from γp interactions ($N_{J/\psi}^{\text{exc}}$) was obtained as $N_{J/\psi}^{\text{exc}} = N_{J/\psi} / (1 + f_D)$, where f_D is the fraction of J/ψ mesons coming from the decay of $\psi(2S)$. Following the procedure described in Refs. [12,13], we obtained $f_D = 7.9_{-1.9}^{+2.4}\%$ (syst) in p -Pb and $f_D = 11_{-2.8}^{+3.6}\%$ (syst) in Pb- p . The contribution of exclusive χ_c states was neglected, as these are expected to be strongly suppressed in proton-nucleus collisions [23,24]. The resulting yield is $N_{J/\psi}^{\text{exc}}(p\text{-Pb}) = 414 \pm 28(\text{stat}) \pm 27(\text{syst})$.

$N_{J/\psi}^{\text{exc}}$ in the Pb- p sample was obtained by event counting, and then subtracting the $\gamma\gamma$ and the γPb components as well as the feed-down from $\psi(2S)$ decays. Based on our recent

coherent J/ψ results in γPb [12], taking into account the difference in the center-of-mass energy, we estimated that 7 ± 2 (stat) events are expected in this sample. We obtained $N_{J/\psi}^{\text{exc}}(\text{Pb-}p) = 71 \pm 9(\text{stat})_{-5}^{+2}(\text{syst})$. A compatible number for $N_{J/\psi}^{\text{exc}}$ was found studying the J/ψ p_T (see Fig. 2 bottom panel). The exclusive J/ψ template was obtained by changing the exponential slope of the p_T^2 spectrum in STARLIGHT from its default value of 4.0 to 6.7 $(\text{GeV}/c)^{-2}$. This value agrees with an extrapolation of the $W_{\gamma p}$ dependence of the p_T^2 slope seen by H1 [9].

The product of the detector acceptance and efficiency $A \times \epsilon$ for J/ψ was calculated using STARLIGHT and ranges from 11% to 31% for the rapidity intervals corresponding to the measurements given in Table II. The systematic uncertainties on the measurement of the J/ψ cross section are listed in Table I. The cross section corresponding to exclusive J/ψ photoproduction off protons was obtained using $(d\sigma/dy) = (N_{J/\psi}^{\text{exc}}) / (A \times \epsilon) \times \text{BR} \times L \times \Delta y$, where BR is the branching ratio and Δy is the rapidity interval. We obtained $(d\sigma/dy) = 6.42 \pm 0.43(\text{stat}) \pm 0.61(\text{syst}) \mu\text{b}$ for p -Pb and $(d\sigma/dy) = 2.46 \pm 0.31(\text{stat})_{-0.28}^{+0.24}(\text{syst}) \mu\text{b}$ for Pb- p collisions (see Table II).

We measured the cross section for the exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ process at invariant mass $1.5 < M_{\mu^+\mu^-} < 2.5 \text{ GeV}/c^2$ and in the rapidity range $2.5 < y < 4.0$, using the same technique as for the J/ψ to remove the non-exclusive background, obtaining $\sigma(\gamma\gamma \rightarrow \mu^+\mu^-) = 1.76 \pm 0.12(\text{stat}) \pm 0.16(\text{syst}) \mu\text{b}$ for this kinematic range. The STARLIGHT prediction for this standard QED process is $1.8 \mu\text{b}$, which is in good agreement with this measurement. This provides an additional indication that the nonexclusive background subtraction is under control.

The cross section $(d\sigma/dy)(p + \text{Pb} \rightarrow p + \text{Pb} + J/\psi)$ is related to the photon-proton cross section, $\sigma(\gamma + p \rightarrow J/\psi + p) \equiv \sigma(W_{\gamma p})$, through the photon flux, dn/dk :

TABLE I. Summary of the contributions to the systematic uncertainty for the integrated J/ψ cross section measurement for the full rapidity interval.

Source	p -Pb	Pb- p
Signal extraction	6%	+0.0% -6.0%
Luminosity [18]	3.3%	3.0%
Tracking efficiency [19]	4%	6%
Muon trigger efficiency [19]	2.8%	3.2%
Matching	1%	1%
VZERO-C efficiency	...	3.5%
Total uncorrelated	8.5%	+8.3% -10.2%
Luminosity [18]	1.6%	1.6%
Branching ratio [25]	1%	1%
VZERO-A veto efficiency	+2.0% -0.0%	+2.0% -0.0%
Feed-down	-2.2% +1.8%	+2.6% -3.1%
J/ψ acceptance	3%	3%
Total	$\pm 9.6\%$	+9.6% -11.3%

TABLE II. Differential cross sections for exclusive J/ψ photoproduction off protons in ultraperipheral p -Pb and Pb- p collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The corresponding J/ψ photoproduction cross sections in bins of $W_{\gamma p}$ are also presented.

Rapidity	$(d\sigma/dy)(\mu b)$	$k(dn/dk)$	$W_{\gamma p}$ (GeV)	$\langle W_{\gamma p} \rangle$ (GeV)	$\sigma(\gamma + p \rightarrow J/\psi + p)(nb)$
$2.5 < y < 4.0$	$6.42 \pm 0.43(\text{stat}) \pm 0.61(\text{syst})$	193.3	(21,45)	32.3	$33.2 \pm 2.2(\text{stat}) \pm 3.2(\text{syst}) \pm 0.7(\text{theor})$
$3.5 < y < 4.0$	$5.77 \pm 0.76(\text{stat}) \pm 0.58(\text{syst})$	208.9	(21,27)	24.1	$27.6 \pm 3.6(\text{stat}) \pm 2.8(\text{syst}) \pm 0.6(\text{theor})$
$3.0 < y < 3.5$	$6.71 \pm 0.60(\text{stat}) \pm 0.55(\text{syst})$	193.3	(27,35)	30.9	$34.7 \pm 3.1(\text{stat}) \pm 2.9(\text{syst}) \pm 0.7(\text{theor})$
$2.5 < y < 3.0$	$6.83 \pm 1.0(\text{stat}) \pm 0.75(\text{syst})$	177.6	(35,45)	39.6	$38.5 \pm 5.6(\text{stat}) \pm 4.2(\text{syst}) \pm 0.8(\text{theor})$
$-3.6 < y < -2.6$	$2.46 \pm 0.31(\text{stat})^{+0.24}_{-0.28}(\text{syst})$	8.66	(577,952)	706	$284 \pm 36(\text{stat})^{+27}_{-32}(\text{syst}) \pm 26(\text{theor})$

$$\frac{d\sigma}{dy}(p + \text{Pb} \rightarrow p + \text{Pb} + J/\psi) = k \frac{dn}{dk} \sigma(\gamma + p \rightarrow J/\psi + p).$$

Here, k is the photon energy, which is determined by the J/ψ mass and rapidity, $k = (1/2)M_{J/\psi} \exp(-y)$. The average photon flux values for the different rapidity intervals were calculated using STARLIGHT and are listed in Table II. The $\langle W_{\gamma p} \rangle$ is calculated by weighting with the product of the photon spectrum and the cross section $\sigma(\gamma p)$ from STARLIGHT. The photon spectrum is calculated in impact parameter space requiring that there should be no hadronic interaction. The uncertainty in this approach is estimated by increasing or decreasing the Pb radius with ± 0.5 fm, corresponding to the nuclear skin thickness and is of the same order as the upper limit for the difference between the proton and neutron radius of Pb when calculating the hadronic interaction probability. This gives an uncertainty of 9% in the photon flux for the high energy data point and 2% at low energy (see Table II). The uncertainty is larger for the high photon energies since here one is dominated by small impact parameters and thus more sensitive to the rejection of hadronic interactions with impact parameters near the Pb radius.

Figure 3 shows the ALICE measurements for $\sigma(W_{\gamma p})$. Comparisons to previous measurements and to different theoretical models are also shown. As mentioned earlier,

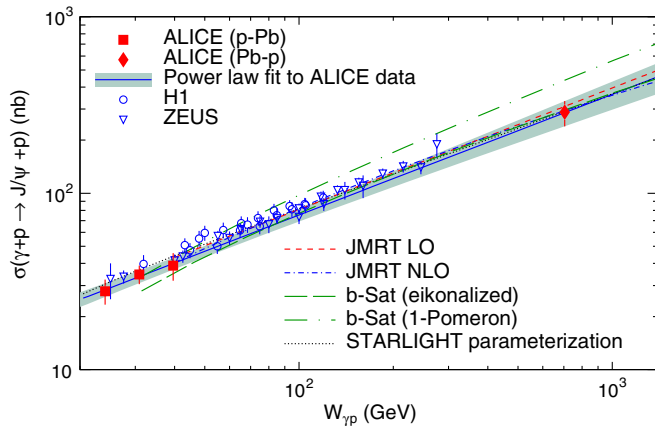


FIG. 3 (color online). Exclusive J/ψ photoproduction cross section off protons measured by ALICE and compared to HERA data. Comparisons to STARLIGHT, JMRT, and the b-SAT models are shown. The power law fit to ALICE data is also shown.

$\sigma(W_{\gamma p})$ is proportional to the square of the gluon PDF of the proton [1]. For HERA energies, the gluon distribution at the low Bjorken x scaling variable is well described by a power law in x [26], which implies the cross section $\sigma(W_{\gamma p})$ will also follow a power law. A deviation from such a trend in the measured cross section as x decreases, or equivalently, as $W_{\gamma p}$ increases, could indicate a change in the evolution of the gluon density function, as expected at the onset of saturation.

Both the ZEUS and H1 Collaborations [7–9] fitted their data using a power law $\sigma \sim W_{\gamma p}^\delta$, obtaining $\delta = 0.69 \pm 0.02(\text{stat}) \pm 0.03(\text{syst})$, and $\delta = 0.67 \pm 0.03(\text{stat} + \text{syst})$, respectively. Because of the large HERA statistics, a simultaneous fit of H1, ZEUS, ALICE low energy points data gives power-law fit parameters almost identical to those obtained from HERA alone. A fit to ALICE data alone gives $\delta = 0.68 \pm 0.06(\text{stat} + \text{syst})$, only uncorrelated systematic errors were considered here. Thus, no deviation from a power law is observed up to about 700 GeV.

Two calculations are available from the JMRT group [27]: the first one referred to as LO is based on a power law description of the process, while the second model is labeled as NLO, and includes contributions which mimic effects expected from the dominant NLO corrections. Because both JMRT models have been fitted to the same data, the resulting energy dependences are very similar. Our data support their extracted gluon distribution up to $x \sim 2 \times 10^{-5}$. The STARLIGHT parameterization is based on a power law fit using only fixed-target and HERA data, giving $\delta = 0.65 \pm 0.02$. Figure 3 also shows predictions from the b-SAT eikonalized model [28] which uses the color glass condensate approach [29] to incorporate saturation, constraining it to HERA data alone. The results from the models mentioned above are within one sigma of our measurement. The b-SAT 1-Pomeron prediction taken from Ref. [5] also agrees with the ALICE low energy data points, but it is about 4 sigmas above our measurement at the highest energy.

LHCb recently published results for $\sigma(W_{\gamma p})$ based on exclusive J/ψ production in pp collisions [10]. Their analysis, using data from a symmetric system, suffers from the intrinsic impossibility of identifying the photon emitter and the photon target. Since the nonexclusive background, as mentioned above, depends on $W_{\gamma p}$, this feeds into the uncertainty in the subtraction of these processes, making

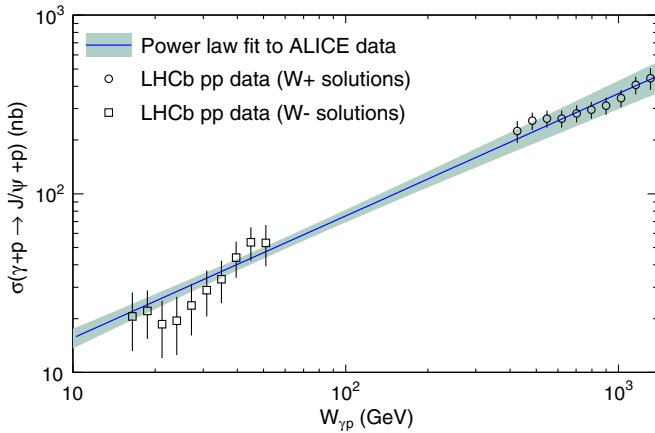


FIG. 4 (color online). The power law fit to ALICE data is compared to LHCb solutions.

the extraction of the underlying $\sigma(W_{\gamma p})$ strongly model dependent. Moreover, in contrast with p -Pb collisions, there is a large uncertainty in the hadronic survival probability in pp collisions, as well as an unknown contribution from production through Odderon-Pomeron fusion [11,23]. For each $d\sigma/dy$ measurement, they reported a $W+$ and a $W-$ solution. These coupled solutions are shown in Fig. 4, together with the power law fit to ALICE measurements. Despite these ambiguities and assumptions the LHCb solutions turned out to be compatible with the power law dependence extracted from our data.

In summary, we have made the first measurement of exclusive J/ψ photoproduction off protons in p -Pb collisions at the LHC. Our data are compatible with a power law dependence of $\sigma(W_{\gamma p})$ up to about 700 GeV in $W_{\gamma p}$, corresponding to $x \sim 2 \times 10^{-5}$. A natural explanation is that no change in the behavior of the gluon PDF in the proton is observed between HERA and LHC energies.

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B. Abelev,⁷¹ J. Adam,³⁷ D. Adamová,⁷⁹ M. M. Aggarwal,⁸³ G. Aglieri Rinella,³⁴ M. Agnello,^{107,90} A. Agostinelli,²⁶ N. Agrawal,⁴⁴ Z. Ahammed,¹²⁶ N. Ahmad,¹⁸ I. Ahmed,¹⁵ S. U. Ahn,⁶⁴ S. A. Ahn,⁶⁴ I. Aimo,^{107,90} S. Aiola,¹³¹ M. Ajaz,¹⁵ A. Akindinov,⁵⁴ S. N. Alam,¹²⁶ D. Aleksandrov,⁹⁶ B. Alessandro,¹⁰⁷ D. Alexandre,⁹⁸ A. Alici,^{12,101} A. Alkin,³ J. Alme,³⁵ T. Alt,³⁹ S. Altinpinar,¹⁷ I. Altsybeev,¹²⁵ C. Alves Garcia Prado,¹¹⁵ C. Andrei,⁷⁴ A. Andronic,⁹³ V. Anguelov,⁸⁹ J. Anielski,⁵⁰ T. Antičić,⁹⁴ F. Antinori,¹⁰⁴ P. Antonioli,¹⁰¹ L. Aphecetche,¹⁰⁹ H. Appelshäuser,⁴⁹ S. Arcelli,²⁶ N. Armesto,¹⁶ R. Arnaldi,¹⁰⁷ T. Aronsson,¹³¹ I. C. Arsene,^{93,21} M. Arslanok,⁴⁹ A. Augustinus,³⁴ R. Averbeck,⁹³ T. C. Awes,⁸⁰ M. D. Azmi,^{18,85} M. Bach,³⁹ A. Badalà,¹⁰³ Y. W. Baek,^{40,66} S. Bagnasco,¹⁰⁷ R. Bailhache,⁴⁹ R. Bala,⁸⁶ A. Baldissieri,¹⁴ F. Baltasar Dos Santos Pedrosa,³⁴ R. C. Baral,⁵⁷ R. Barbera,²⁷ F. Barile,³¹ G. G. Barnaföldi,¹³⁰ L. S. Barnby,⁹⁸ V. Barret,⁶⁶ J. Bartke,¹¹² M. Basile,²⁶ N. Bastid,⁶⁶ S. Basu,¹²⁶ B. Bathen,⁵⁰ G. Batigne,¹⁰⁹ A. Batista Camejo,⁶⁶ B. Batyunya,⁶² P. C. Batzing,²¹ C. Baumann,⁴⁹ I. G. Bearden,⁷⁶ H. Beck,⁴⁹ C. Bedda,⁹⁰ N. K. Behera,⁴⁴ I. Belikov,⁵¹ F. Bellini,²⁶ R. Bellwied,¹¹⁷ E. Belmont-Moreno,⁶⁰ R. Belmont III,¹²⁹ V. Belyaev,⁷² G. Bencedi,¹³⁰ S. Beole,²⁵ I. Berceanu,⁷⁴ A. Bercuci,⁷⁴ Y. Berdnikov,^{81,b} D. Berenyi,¹³⁰ M. E. Berger,⁸⁸ R. A. Bertens,⁵³ D. Berzano,²⁵ L. Betev,³⁴ A. Bhasin,⁸⁶ I. R. Bhat,⁸⁶ A. K. Bhati,⁸³ B. Bhattacharjee,⁴¹ J. Bhom,¹²² L. Bianchi,²⁵ N. Bianchi,⁶⁸ C. Bianchin,⁵³ J. Bielčik,³⁷ J. Bielčíková,⁷⁹ A. Bilandzic,⁷⁶ S. Bjelogrić,⁵³ F. Blanco,¹⁰ D. Blau,⁹⁶ C. Blume,⁴⁹ F. Bock,^{70,89} A. Bogdanov,⁷² H. Bøggild,⁷⁶ M. Bogolyubsky,¹⁰⁸ F. V. Böhmer,⁸⁸ L. Boldizsár,¹³⁰ M. Bombara,³⁸ J. Book,⁴⁹ H. Borel,¹⁴ A. Borissov,^{129,92} F. Bossú,⁶¹ M. Botje,⁷⁷ E. Botta,²⁵ S. Böttger,⁴⁸ P. Braun-Munzinger,⁹³ M. Bregant,¹¹⁵ T. Breitner,⁴⁸ T. A. Broker,⁴⁹ T. A. Browning,⁹¹ M. Broz,³⁷ E. Bruna,¹⁰⁷ G. E. Bruno,³¹ D. Budnikov,⁹⁵ H. Buesching,⁴⁹ S. Bufalino,¹⁰⁷ P. Buncic,³⁴ O. Busch,⁸⁹ Z. Buthelezi,⁶¹ D. Caffarri,^{34,28} X. Cai,⁷ H. Caines,¹³¹ L. Calero Diaz,⁶⁸ A. Caliva,⁵³ E. Calvo Villar,⁹⁹ P. Camerini,²⁴ F. Carena,³⁴ W. Carena,³⁴ J. Castillo Castellanos,¹⁴ E. A. R. Casula,²³ V. Catanescu,⁷⁴ C. Cavicchioli,³⁴ C. Ceballos Sanchez,⁹ J. Cepila,³⁷ P. Cerello,¹⁰⁷ B. Chang,¹¹⁸ S. Chapeland,³⁴ J. L. Charvet,¹⁴ S. Chattopadhyay,¹²⁶ S. Chattopadhyay,⁹⁷ V. Chelnokov,³ M. Cherney,⁸² C. Cheshkov,¹²⁴ B. Cheynis,¹²⁴ V. Chibante Barroso,³⁴ D. D. Chinellato,^{116,117} P. Chochula,³⁴ M. Chojnacki,⁷⁶ S. Choudhury,¹²⁶ P. Christakoglou,⁷⁷ C. H. Christensen,⁷⁶ P. Christiansen,³² T. Chujo,¹²² S. U. Chung,⁹² C. Cicalo,¹⁰² L. Cifarelli,^{26,12} F. Cindolo,¹⁰¹ J. Cleymans,⁸⁵ F. Colamaria,³¹ D. Colella,³¹ A. Collu,²³ M. Colocci,²⁶ G. Conesa Balbastre,⁶⁷ Z. Conesa del Valle,⁴⁷ M. E. Connors,¹³¹ J. G. Contreras,^{11,37} T. M. Cormier,^{80,129} Y. Corrales Morales,²⁵ P. Cortese,³⁰ I. Cortés Maldonado,² M. R. Cosentino,¹¹⁵ F. Costa,³⁴ P. Crochet,⁶⁶ R. Cruz Albino,¹¹ E. Cuautle,⁵⁹ L. Cunqueiro,^{68,34} A. Dainese,¹⁰⁴ R. Dang,⁷ A. Danu,⁵⁸ D. Das,⁹⁷ I. Das,⁴⁷ K. Das,⁹⁷ S. Das,⁴ A. Dash,¹¹⁶ S. Dash,⁴⁴ S. De,¹²⁶ H. Delagrange,^{109,a} A. Deloff,⁷³ E. Dénes,¹³⁰ G. D'Erasmus,³¹ A. De Caro,^{29,12} G. de Cataldo,¹⁰⁰ J. de Cuveland,³⁹ A. De Falco,²³ D. De Gruttola,^{29,12} N. De Marco,¹⁰⁷ S. De Pasquale,²⁹ R. de Rooij,⁵³

M. A. Diaz Corchero,¹⁰ T. Dietel,^{50,85} P. Dillenseger,⁴⁹ R. Divià,³⁴ D. Di Bari,³¹ S. Di Liberto,¹⁰⁵ A. Di Mauro,³⁴ P. Di Nezza,⁶⁸ Ø. Djuvsland,¹⁷ A. Dobrin,⁵³ T. Dobrowolski,⁷³ D. Domenicis Gimenez,¹¹⁵ B. Dönigus,⁴⁹ O. Dordic,²¹ S. Dørheim,⁸⁸ A. K. Dubey,¹²⁶ A. Dubla,⁵³ L. Ducroux,¹²⁴ P. Dupieux,⁶⁶ A. K. Dutta Majumdar,⁹⁷ T. E. Hilden,⁴² R. J. Ehlers,¹³¹ D. Elia,¹⁰⁰ H. Engel,⁴⁸ B. Erasmus,^{34,109} H. A. Erdal,³⁵ D. Eschweiler,³⁹ B. Espagnon,⁴⁷ M. Esposito,³⁴ M. Estienne,¹⁰⁹ S. Esumi,¹²² D. Evans,⁹⁸ S. Evdokimov,¹⁰⁸ D. Fabris,¹⁰⁴ J. Faivre,⁶⁷ D. Falchieri,²⁶ A. Fantoni,⁶⁸ M. Fasel,^{89,70} D. Fehlker,¹⁷ L. Feldkamp,⁵⁰ D. Felea,⁵⁸ A. Feliciello,¹⁰⁷ G. Feofilov,¹²⁵ J. Ferencei,⁷⁹ A. Fernández Téllez,² E. G. Ferreira,¹⁶ A. Ferretti,²⁵ A. Festanti,²⁸ J. Figiel,¹¹² M. A. S. Figueredo,¹¹⁹ S. Filchagin,⁹⁵ D. Finogeev,⁵² F. M. Fionda,³¹ E. M. Fiore,³¹ E. Floratos,⁸⁴ M. Floris,³⁴ S. Foertsch,⁶¹ P. Foka,⁹³ S. Fokin,⁹⁶ E. Fragiaco,¹⁰⁶ A. Francescon,^{34,28} U. Frankenfeld,⁹³ U. Fuchs,³⁴ C. Furget,⁶⁷ A. Furs,⁵² M. Fusco Girard,²⁹ J. J. Gaardhøje,⁷⁶ M. Gagliardi,²⁵ A. M. Gago,⁹⁹ M. Gallio,²⁵ D. R. Gangadharan,^{19,70} P. Ganoti,^{80,84} C. Gao,⁷ C. Garabatos,⁹³ E. Garcia-Solis,¹³ C. Gargiulo,³⁴ I. Garishvili,⁷¹ J. Gerhard,³⁹ M. Germain,¹⁰⁹ A. Gheata,³⁴ M. Gheata,^{34,58} B. Ghidini,³¹ P. Ghosh,¹²⁶ S. K. Ghosh,⁴ P. Gianotti,⁶⁸ P. Giubellino,³⁴ E. Gladysz-Dziadus,¹¹² P. Glässel,⁸⁹ A. Gomez Ramirez,⁴⁸ P. González-Zamora,¹⁰ S. Gorbunov,³⁹ L. Görlich,¹¹² S. Gotovac,¹¹¹ L. K. Graczykowski,¹²⁸ A. Grelli,⁵³ A. Grigoras,³⁴ C. Grigoras,³⁴ V. Grigoriev,⁷² A. Grigoryan,¹ S. Grigoryan,⁶² B. Grinyov,³ N. Grion,¹⁰⁶ J. F. Grosse-Oetringhaus,³⁴ J.-Y. Grossiord,¹²⁴ R. Grosso,³⁴ F. Guber,⁵² R. Guernane,⁶⁷ B. Guerzoni,²⁶ M. Guilbaud,¹²⁴ K. Gulbrandsen,⁷⁶ H. Gulkanyan,¹ M. Gumbo,⁸⁵ T. Gunji,¹²¹ A. Gupta,⁸⁶ R. Gupta,⁸⁶ K. H. Khan,¹⁵ R. Haake,⁵⁰ Ø. Haaland,¹⁷ C. Hadjidakis,⁴⁷ M. Haiduc,⁵⁸ H. Hamagaki,¹²¹ G. Hamar,¹³⁰ L. D. Hanratty,⁹⁸ A. Hansen,⁷⁶ J. W. Harris,¹³¹ H. Hartmann,³⁹ A. Harton,¹³ D. Hatzifotiadou,¹⁰¹ S. Hayashi,¹²¹ S. T. Heckel,⁴⁹ M. Heide,⁵⁰ H. Helstrup,³⁵ A. Hergehelegiu,⁷⁴ G. Herrera Corral,¹¹ B. A. Hess,³³ K. F. Hetland,³⁵ B. Hippolyte,⁵¹ J. Hladky,⁵⁶ P. Hristov,³⁴ M. Huang,¹⁷ T. J. Humanic,¹⁹ N. Hussain,⁴¹ D. Hutter,³⁹ D. S. Hwang,²⁰ R. Ilkaev,⁹⁵ I. Ilkiv,⁷³ M. Inaba,¹²² G. M. Innocenti,²⁵ C. Ionita,³⁴ M. Ippolitov,⁹⁶ M. Irfan,¹⁸ M. Ivanov,⁹³ V. Ivanov,⁸¹ A. Jacholkowski,²⁷ P. M. Jacobs,⁷⁰ C. Jahnke,¹¹⁵ H. J. Jang,⁶⁴ M. A. Janik,¹²⁸ P. H. S. Y. Jayarathna,¹¹⁷ C. Jena,²⁸ S. Jena,¹¹⁷ R. T. Jimenez Bustamante,⁵⁹ P. G. Jones,⁹⁸ H. Jung,⁴⁰ A. Jusko,⁹⁸ V. Kadyshevskiy,⁶² S. Kalcher,³⁹ P. Kalinak,⁵⁵ A. Kalweit,³⁴ J. Kamin,⁴⁹ J. H. Kang,¹³² V. Kaplin,⁷² S. Kar,¹²⁶ A. Karasu Uysal,⁶⁵ O. Karavichev,⁵² T. Karavicheva,⁵² E. Karpechev,⁵² U. Keschull,⁴⁸ R. Keidel,¹³³ D. L. D. Keijdener,⁵³ M. Keil SVN,³⁴ M. M. Khan,^{18,c} P. Khan,⁹⁷ S. A. Khan,¹²⁶ A. Khanzadeev,⁸¹ Y. Kharlov,¹⁰⁸ B. Kileng,³⁵ B. Kim,¹³² D. W. Kim,^{64,40} D. J. Kim,¹¹⁸ J. S. Kim,⁴⁰ M. Kim,⁴⁰ M. Kim,¹³² S. Kim,²⁰ T. Kim,¹³² S. Kirsch,³⁹ I. Kisel,³⁹ S. Kiselev,⁵⁴ A. Kisiel,¹²⁸ G. Kiss,¹³⁰ J. L. Klay,⁶ J. Klein,⁸⁹ C. Klein-Bösing,⁵⁰ A. Kluge,³⁴ M. L. Knichel,⁹³ A. G. Knospe,¹¹³ C. Kobdaj,^{110,34} M. Kofarago,³⁴ M. K. Köhler,⁹³ T. Kollegger,³⁹ A. Kolojvari,¹²⁵ V. Kondratiev,¹²⁵ N. Kondratyeva,⁷² A. Konevskikh,⁵² V. Kovalenko,¹²⁵ M. Kowalski,¹¹² S. Kox,⁶⁷ G. Koyithatta Meethalevedu,⁴⁴ J. Kral,¹¹⁸ I. Králik,⁵⁵ A. Kravčáková,³⁸ M. Krelina,³⁷ M. Kretz,³⁹ M. Krivda,^{98,55} F. Krizek,⁷⁹ E. Kryshen,³⁴ M. Krzewicki,^{93,39} V. Kučera,⁷⁹ Y. Kucheriaev,^{96,a} T. Kugathasan,³⁴ C. Kuhn,⁵¹ P. G. Kuijer,⁷⁷ I. Kulakov,⁴⁹ J. Kumar,⁴⁴ P. Kurashvili,⁷³ A. Kurepin,⁵² A. B. Kurepin,⁵² A. Kuryakin,⁹⁵ S. Kuschpil,⁷⁹ M. J. Kweon,^{46,89} Y. Kwon,¹³² P. Ladron de Guevara,⁵⁹ C. Lagana Fernandes,¹¹⁵ I. Lakomov,⁴⁷ R. Langoy,¹²⁷ C. Lara,⁴⁸ A. Lardeux,¹⁰⁹ A. Lattuca,²⁵ S. L. La Pointe,^{53,107} P. La Rocca,²⁷ R. Lea,²⁴ L. Leardini,⁸⁹ G. R. Lee,⁹⁸ I. Legrand,³⁴ J. Lehnert,⁴⁹ R. C. Lemmon,⁷⁸ V. Lenti,¹⁰⁰ E. Leogrande,⁵³ M. Leoncino,²⁵ I. León Monzón,¹¹⁴ P. Lévai,¹³⁰ S. Li,^{7,66} J. Lien,¹²⁷ R. Lietava,⁹⁸ S. Lindal,²¹ V. Lindenstruth,³⁹ C. Lippmann,⁹³ M. A. Lisa,¹⁹ H. M. Ljunggren,³² D. F. Lodato,⁵³ P. I. Loenne,¹⁷ V. R. Loggins,¹²⁹ V. Loginov,⁷² D. Lohner,⁸⁹ C. Loizides,⁷⁰ X. Lopez,⁶⁶ E. López Torres,⁹ X.-G. Lu,⁸⁹ P. Luettig,⁴⁹ M. Lunardon,²⁸ G. Luparello,^{53,24} R. Ma,¹³¹ A. Maevskaya,⁵² M. Mager,³⁴ D. P. Mahapatra,⁵⁷ S. M. Mahmood,²¹ A. Maire,^{51,89} R. D. Majka,¹³¹ M. Malaev,⁸¹ I. Maldonado Cervantes,⁵⁹ L. Malinina,^{62,d} D. Mal'Kevich,⁵⁴ P. Malzacher,⁹³ A. Mamonov,⁹⁵ L. Manceau,¹⁰⁷ V. Manko,⁹⁶ F. Manso,⁶⁶ V. Manzari,¹⁰⁰ M. Marchisone,^{66,25} J. Mareš,⁵⁶ G. V. Margagliotti,²⁴ A. Margotti,¹⁰¹ A. Marín,⁹³ C. Markert,¹¹³ M. Marquard,⁴⁹ I. Martashvili,¹²⁰ N. A. Martin,⁹³ P. Martinengo,³⁴ M. I. Martínez,² G. Martínez García,¹⁰⁹ J. Martin Blanco,¹⁰⁹ Y. Martynov,³ A. Mas,¹⁰⁹ S. Masciocchi,⁹³ M. Maserà,²⁵ A. Masoni,¹⁰² L. Massacrier,¹⁰⁹ A. Mastroserio,³¹ A. Matyja,¹¹² C. Mayer,¹¹² J. Mazer,¹²⁰ M. A. Mazzoni,¹⁰⁵ F. Meddi,²² A. Menchaca-Rocha,⁶⁰ E. Meninno,²⁹ J. Mercado Pérez,⁸⁹ M. Meres,³⁶ Y. Miake,¹²² K. Mikhaylov,^{54,62} L. Milano,³⁴ J. Milosevic,^{21,e} A. Mischke,⁵³ A. N. Mishra,⁴⁵ D. Miśkowiec,⁹³ J. Mitra,¹²⁶ C. M. Mitu,⁵⁸ J. Mlynarz,¹²⁹ N. Mohammadi,⁵³ B. Mohanty,^{75,126} L. Molnar,⁵¹ L. Montaña Zetina,¹¹ E. Montes,¹⁰ M. Morando,²⁸ D. A. Moreira De Godoy,^{115,109} S. Moretto,²⁸ A. Morreale,¹⁰⁹ A. Morsch,³⁴ V. Muccifora,⁶⁸ E. Mudnic,¹¹¹ D. Mühlheim,⁵⁰ S. Muhuri,¹²⁶ M. Mukherjee,¹²⁶ H. Müller,³⁴ M. G. Munhoz,¹¹⁵ S. Murray,⁸⁵ L. Musa,³⁴ J. Musinsky,⁵⁵ B. K. Nandi,⁴⁴ R. Nania,¹⁰¹ E. Nappi,¹⁰⁰ C. Natrass,¹²⁰ K. Nayak,⁷⁵ T. K. Nayak,¹²⁶ S. Nazarenko,⁹⁵ A. Nedosekin,⁵⁴ M. Nicassio,⁹³ M. Niculescu,^{34,58} B. S. Nielsen,⁷⁶ S. Nikolaev,⁹⁶ S. Nikulin,⁹⁶ V. Nikulin,⁸¹ B. S. Nilsen,⁸² F. Noferini,^{12,101}

P. Nomokonov,⁶² G. Nooren,⁵³ J. Norman,¹¹⁹ A. Nyanin,⁹⁶ J. Nystrand,¹⁷ H. Oeschler,⁸⁹ S. Oh,¹³¹ S. K. Oh,^{63,40,f}
A. Okatan,⁶⁵ L. Olah,¹³⁰ J. Oleniacz,¹²⁸ A. C. Oliveira Da Silva,¹¹⁵ J. Onderwaater,⁹³ C. Oppedisano,¹⁰⁷
A. Ortiz Velasquez,^{59,32} A. Oskarsson,³² J. Otwinowski,^{112,93} K. Oyama,⁸⁹ M. Ozdemir,⁴⁹ P. Sahoo,⁴⁵ Y. Pachmayer,⁸⁹
M. Pachr,³⁷ P. Pagano,²⁹ G. Paic̃,⁵⁹ F. Painke,³⁹ C. Pajares,¹⁶ S. K. Pal,¹²⁶ A. Palmeri,¹⁰³ D. Pant,⁴⁴ V. Papikyan,¹
G. S. Pappalardo,¹⁰³ P. Pareek,⁴⁵ W. J. Park,⁹³ S. Parmar,⁸³ A. Passfeld,⁵⁰ D. I. Patalakha,¹⁰⁸ V. Paticchio,¹⁰⁰ B. Paul,⁹⁷
T. Pawlak,¹²⁸ T. Peitzmann,⁵³ H. Pereira Da Costa,¹⁴ E. Pereira De Oliveira Filho,¹¹⁵ D. Peresunko,⁹⁶ C. E. Pérez Lara,⁷⁷
A. Pesci,¹⁰¹ V. Peskov,⁴⁹ Y. Pestov,⁵ V. Petráček,³⁷ M. Petran,³⁷ M. Petris,⁷⁴ M. Petrovici,⁷⁴ C. Petta,²⁷ S. Piano,¹⁰⁶
M. Pikna,³⁶ P. Pillot,¹⁰⁹ O. Pinazza,^{101,34} L. Pinsky,¹¹⁷ D. B. Piyarathna,¹¹⁷ M. Płoskoń,⁷⁰ M. Planinic,^{123,94} J. Pluta,¹²⁸
S. Pochybova,¹³⁰ P. L. M. Podesta-Lerma,¹¹⁴ M. G. Poghosyan,^{82,34} E. H. O. Pohjoisaho,⁴² B. Polichtchouk,¹⁰⁸
N. Poljak,^{94,123} A. Pop,⁷⁴ S. Porteboeuf-Houssais,⁶⁶ J. Porter,⁷⁰ B. Potukuchi,⁸⁶ S. K. Prasad,^{129,4} R. Preghenella,^{101,12}
F. Prino,¹⁰⁷ C. A. Pruneau,¹²⁹ I. Pshenichnov,⁵² G. Puddu,²³ P. Pujahari,¹²⁹ V. Punin,⁹⁵ J. Putschke,¹²⁹ H. Qvigstad,²¹
A. Rachevski,¹⁰⁶ S. Raha,⁴ J. Rak,¹¹⁸ A. Rakotozafindrabe,¹⁴ L. Ramello,³⁰ R. Raniwala,⁸⁷ S. Raniwala,⁸⁷ S. S. Räsänen,⁴²
B. T. Rascanu,⁴⁹ D. Rathee,⁸³ A. W. Rauf,¹⁵ V. Razazi,²³ K. F. Read,¹²⁰ J. S. Real,⁶⁷ K. Redlich,^{73,g} R. J. Reed,^{129,131}
A. Rehman,¹⁷ P. Reichelt,⁴⁹ M. Reicher,⁵³ F. Reidt,^{89,34} R. Renfordt,⁴⁹ A. R. Reolon,⁶⁸ A. Reshetin,⁵² F. Rettig,³⁹
J.-P. Revol,³⁴ K. Reygers,⁸⁹ V. Riabov,⁸¹ R. A. Ricci,⁶⁹ T. Richert,³² M. Richter,²¹ P. Riedler,³⁴ W. Riegler,³⁴ F. Riggi,²⁷
A. Rivetti,¹⁰⁷ E. Rocco,⁵³ M. Rodríguez Cahuantzi,² A. Rodríguez Manso,⁷⁷ K. Røed,²¹ E. Rogochaya,⁶² S. Rohni,⁸⁶
D. Rohr,³⁹ D. Röhrich,¹⁷ R. Romita,^{78,119} F. Ronchetti,⁶⁸ L. Ronflette,¹⁰⁹ P. Rosnet,⁶⁶ A. Rossi,³⁴ F. Roukoutakis,⁸⁴ A. Roy,⁴⁵
C. Roy,⁵¹ P. Roy,⁹⁷ A. J. Rubio Montero,¹⁰ R. Rui,²⁴ R. Russo,²⁵ E. Ryabinkin,⁹⁶ Y. Ryabov,⁸¹ A. Rybicki,¹¹² S. Sadovsky,¹⁰⁸
K. Šafařík,³⁴ B. Sahlmuller,⁴⁹ R. Sahoo,⁴⁵ P. K. Sahu,⁵⁷ J. Saini,¹²⁶ S. Sakai,⁶⁸ C. A. Salgado,¹⁶ J. Salzwedel,¹⁹ S. Sambyal,⁸⁶
V. Samsonov,⁸¹ X. Sanchez Castro,⁵¹ F. J. Sánchez Rodríguez,¹¹⁴ L. Šándor,⁵⁵ A. Sandoval,⁶⁰ M. Sano,¹²² G. Santagati,²⁷
D. Sarkar,¹²⁶ E. Scapparone,¹⁰¹ F. Scarlassara,²⁸ R. P. Scharenberg,⁹¹ C. Schiaua,⁷⁴ R. Schicker,⁸⁹ C. Schmidt,⁹³
H. R. Schmidt,³³ S. Schuchmann,⁴⁹ J. Schukraft,³⁴ M. Schulc,³⁷ T. Schuster,¹³¹ Y. Schutz,^{109,34} K. Schwarz,⁹³ K. Schweda,⁹³
G. Scioli,²⁶ E. Scomparin,¹⁰⁷ R. Scott,¹²⁰ G. Segato,²⁸ J. E. Seger,⁸² Y. Sekiguchi,¹²¹ I. Selyuzhenkov,⁹³ J. Seo,⁹²
E. Serradilla,^{10,60} A. Sevcenco,⁵⁸ A. Shabetai,¹⁰⁹ G. Shabratova,⁶² R. Shahoyan,³⁴ A. Shangaraev,¹⁰⁸ N. Sharma,¹²⁰
S. Sharma,⁸⁶ K. Shigaki,⁴³ K. Shtejer,^{25,9} Y. Sibiriak,⁹⁶ S. Siddhanta,¹⁰² T. Siemiarczuk,⁷³ D. Silvermyr,⁸⁰ C. Silvestre,⁶⁷
G. Simatovic,¹²³ R. Singaraju,¹²⁶ R. Singh,⁸⁶ S. Singha,^{126,75} V. Singhal,¹²⁶ B. C. Sinha,¹²⁶ T. Sinha,⁹⁷ B. Sitar,³⁶ M. Sitta,³⁰
T. B. Skaali,²¹ K. Skjerdal,¹⁷ M. Slupecki,¹¹⁸ N. Smirnov,¹³¹ R. J. M. Snellings,⁵³ C. Sogaard,³² R. Soltz,⁷¹ J. Song,⁹²
M. Song,¹³² F. Soramel,²⁸ S. Sorensen,¹²⁰ M. Spacek,³⁷ E. Spiriti,⁶⁸ I. Sputowska,¹¹² M. Spyropoulou-Stassinaki,⁸⁴
B. K. Srivastava,⁹¹ J. Stachel,⁸⁹ I. Stan,⁵⁸ G. Stefanek,⁷³ M. Steinpreis,¹⁹ E. Stenlund,³² G. Steyn,⁶¹ J. H. Stiller,⁸⁹
D. Stocco,¹⁰⁹ M. Stolpovskiy,¹⁰⁸ P. Strmen,³⁶ A. A. P. Suaide,¹¹⁵ T. Sugitate,⁴³ C. Suire,⁴⁷ M. Suleymanov,¹⁵ R. Sultanov,⁵⁴
M. Šumbera,⁷⁹ T. Susa,⁹⁴ T. J. M. Symons,⁷⁰ A. Szabo,³⁶ A. Szanto de Toledo,¹¹⁵ I. Szarka,³⁶ A. Szczepankiewicz,³⁴
M. Szymanski,¹²⁸ J. Takahashi,¹¹⁶ M. A. Tangaro,³¹ J. D. Tapia Takaki,^{47,h} A. Tarantola Peloni,⁴⁹ A. Tarazona Martinez,³⁴
M. G. Tarczila,⁷⁴ A. Tauro,³⁴ G. Tejeda Muñoz,² A. Telesca,³⁴ C. Terrevoli,²³ J. Thäder,⁹³ D. Thomas,⁵³ R. Tieulent,¹²⁴
A. R. Timmins,¹¹⁷ A. Toia,^{49,104} V. Trubnikov,³ W. H. Trzaska,¹¹⁸ T. Tsuji,¹²¹ A. Tumkin,⁹⁵ R. Turrisi,¹⁰⁴ T. S. Tveter,²¹
K. Ullaland,¹⁷ A. Uras,¹²⁴ G. L. Usai,²³ M. Vajzer,⁷⁹ M. Vala,^{55,62} L. Valencia Palomo,⁶⁶ S. Vallero,^{25,89} P. Vande Vyvre,³⁴
J. Van Der Maarel,⁵³ J. W. Van Hoorne,³⁴ M. van Leeuwen,⁵³ A. Vargas,² M. Vargyas,¹¹⁸ R. Varma,⁴⁴ M. Vasileiou,⁸⁴
A. Vasiliev,⁹⁶ V. Vechernin,¹²⁵ M. Veldhoen,⁵³ A. Velure,¹⁷ M. Venaruzzo,^{24,69} E. Vercellin,²⁵ S. Vergara Limón,² R. Vernet,⁸
M. Verweij,¹²⁹ L. Vickovic,¹¹¹ G. Viesti,²⁸ J. Viinikainen,¹¹⁸ Z. Vilakazi,⁶¹ O. Villalobos Baillie,⁹⁸ A. Vinogradov,⁹⁶
L. Vinogradov,¹²⁵ Y. Vinogradov,⁹⁵ T. Virgili,²⁹ Y. P. Viyogi,¹²⁶ A. Vodopyanov,⁶² M. A. Völkl,⁸⁹ K. Voloshin,⁵⁴
S. A. Voloshin,¹²⁹ G. Volpe,³⁴ B. von Haller,³⁴ I. Vorobyev,¹²⁵ D. Vranic,^{93,34} J. Vrláková,³⁸ B. Vulpescu,⁶⁶ A. Vyushin,⁹⁵
B. Wagner,¹⁷ J. Wagner,⁹³ V. Wagner,³⁷ M. Wang,^{7,109} Y. Wang,⁸⁹ D. Watanabe,¹²² M. Weber,^{34,117} J. P. Wessels,⁵⁰
U. Westerhoff,⁵⁰ J. Wiechula,³³ J. Wikne,²¹ M. Wilde,⁵⁰ G. Wilk,⁷³ J. Wilkinson,⁸⁹ M. C. S. Williams,¹⁰¹ B. Windelband,⁸⁹
M. Winn,⁸⁹ C. G. Yaldo,¹²⁹ Y. Yamaguchi,¹²¹ H. Yang,⁵³ P. Yang,⁷ S. Yang,¹⁷ S. Yano,⁴³ S. Yasnopolskiy,⁹⁶ J. Yi,⁹² Z. Yin,⁷
I.-K. Yoo,⁹² I. Yushmanov,⁹⁶ V. Zaccolo,⁷⁶ C. Zach,³⁷ A. Zaman,¹⁵ C. Zampolli,¹⁰¹ S. Zaporozhets,⁶² A. Zarochentsev,¹²⁵
P. Závada,⁵⁶ N. Zaviyalov,⁹⁵ H. Zbroszczyk,¹²⁸ I. S. Zgura,⁵⁸ M. Zhalov,⁸¹ H. Zhang,⁷ X. Zhang,^{7,70} Y. Zhang,⁷ C. Zhao,²¹
N. Zhigareva,⁵⁴ D. Zhou,⁷ F. Zhou,⁷ Y. Zhou,⁵³ Zhuo Zhou,¹⁷ H. Zhu,⁷ J. Zhu,⁷ X. Zhu,⁷ A. Zichichi,^{12,26} A. Zimmermann,⁸⁹
M. B. Zimmermann,^{50,34} G. Zinovjev,³ Y. Zoccarato,^{1,24} and M. Zyzak⁴⁹

(ALICE Collaboration)

- ¹A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
- ²Benemérita Universidad Autónoma de Puebla, Puebla, Mexico
- ³Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine
- ⁴Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
- ⁵Budker Institute for Nuclear Physics, Novosibirsk, Russia
- ⁶California Polytechnic State University, San Luis Obispo, California, USA
- ⁷Central China Normal University, Wuhan, China
- ⁸Centre de Calcul de l'IN2P3, Villeurbanne, France
- ⁹Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
- ¹⁰Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
- ¹¹Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
- ¹²Centro Fermi-Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi," Rome, Italy
- ¹³Chicago State University, Chicago, USA
- ¹⁴Commissariat à l'Energie Atomique, IRFU, Saclay, France
- ¹⁵COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan
- ¹⁶Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
- ¹⁷Department of Physics and Technology, University of Bergen, Bergen, Norway
- ¹⁸Department of Physics, Aligarh Muslim University, Aligarh, India
- ¹⁹Department of Physics, Ohio State University, Columbus, Ohio, USA
- ²⁰Department of Physics, Sejong University, Seoul, South Korea
- ²¹Department of Physics, University of Oslo, Oslo, Norway
- ²²Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN Rome, Italy
- ²³Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
- ²⁴Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
- ²⁵Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
- ²⁶Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
- ²⁷Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
- ²⁸Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
- ²⁹Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
- ³⁰Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy
- ³¹Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
- ³²Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
- ³³Eberhard Karls Universität Tübingen, Tübingen, Germany
- ³⁴European Organization for Nuclear Research (CERN), Geneva, Switzerland
- ³⁵Faculty of Engineering, Bergen University College, Bergen, Norway
- ³⁶Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
- ³⁷Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
- ³⁸Faculty of Science, P. J. Šafárik University, Košice, Slovakia
- ³⁹Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- ⁴⁰Gangneung-Wonju National University, Gangneung, South Korea
- ⁴¹Gauhati University, Department of Physics, Guwahati, India
- ⁴²Helsinki Institute of Physics (HIP), Helsinki, Finland
- ⁴³Hiroshima University, Hiroshima, Japan
- ⁴⁴Indian Institute of Technology Bombay (IIT), Mumbai, India
- ⁴⁵Indian Institute of Technology Indore, Indore (IITI), India
- ⁴⁶Inha University, Incheon, South Korea
- ⁴⁷Institut de Physique Nucléaire d'Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France
- ⁴⁸Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- ⁴⁹Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- ⁵⁰Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
- ⁵¹Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
- ⁵²Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
- ⁵³Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands
- ⁵⁴Institute for Theoretical and Experimental Physics, Moscow, Russia
- ⁵⁵Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
- ⁵⁶Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
- ⁵⁷Institute of Physics, Bhubaneswar, India
- ⁵⁸Institute of Space Science (ISS), Bucharest, Romania

- ⁵⁹*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico*
- ⁶⁰*Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico*
- ⁶¹*iThemba LABS, National Research Foundation, Somerset West, South Africa*
- ⁶²*Joint Institute for Nuclear Research (JINR), Dubna, Russia*
- ⁶³*Konkuk University, Seoul, South Korea*
- ⁶⁴*Korea Institute of Science and Technology Information, Daejeon, South Korea*
- ⁶⁵*KTO Karatay University, Konya, Turkey*
- ⁶⁶*Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS-IN2P3, Clermont-Ferrand, France*
- ⁶⁷*Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France*
- ⁶⁸*Laboratori Nazionali di Frascati, INFN, Frascati, Italy*
- ⁶⁹*Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy*
- ⁷⁰*Lawrence Berkeley National Laboratory, Berkeley, California, USA*
- ⁷¹*Lawrence Livermore National Laboratory, Livermore, California, USA*
- ⁷²*Moscow Engineering Physics Institute, Moscow, Russia*
- ⁷³*National Centre for Nuclear Studies, Warsaw, Poland*
- ⁷⁴*National Institute for Physics and Nuclear Engineering, Bucharest, Romania*
- ⁷⁵*National Institute of Science Education and Research, Bhubaneswar, India*
- ⁷⁶*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
- ⁷⁷*Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands*
- ⁷⁸*Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom*
- ⁷⁹*Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic*
- ⁸⁰*Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA*
- ⁸¹*Petersburg Nuclear Physics Institute, Gatchina, Russia*
- ⁸²*Physics Department, Creighton University, Omaha, Nebraska, USA*
- ⁸³*Physics Department, Panjab University, Chandigarh, India*
- ⁸⁴*Physics Department, University of Athens, Athens, Greece*
- ⁸⁵*Physics Department, University of Cape Town, Cape Town, South Africa*
- ⁸⁶*Physics Department, University of Jammu, Jammu, India*
- ⁸⁷*Physics Department, University of Rajasthan, Jaipur, India*
- ⁸⁸*Physik Department, Technische Universität München, Munich, Germany*
- ⁸⁹*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ⁹⁰*Politecnico di Torino, Turin, Italy*
- ⁹¹*Purdue University, West Lafayette, Indiana, USA*
- ⁹²*Pusan National University, Pusan, South Korea*
- ⁹³*Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany*
- ⁹⁴*Rudjer Bošković Institute, Zagreb, Croatia*
- ⁹⁵*Russian Federal Nuclear Center (VNIIEF), Sarov, Russia*
- ⁹⁶*Russian Research Centre Kurchatov Institute, Moscow, Russia*
- ⁹⁷*Saha Institute of Nuclear Physics, Kolkata, India*
- ⁹⁸*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
- ⁹⁹*Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru*
- ¹⁰⁰*Sezione INFN, Bari, Italy*
- ¹⁰¹*Sezione INFN, Bologna, Italy*
- ¹⁰²*Sezione INFN, Cagliari, Italy*
- ¹⁰³*Sezione INFN, Catania, Italy*
- ¹⁰⁴*Sezione INFN, Padova, Italy*
- ¹⁰⁵*Sezione INFN, Rome, Italy*
- ¹⁰⁶*Sezione INFN, Trieste, Italy*
- ¹⁰⁷*Sezione INFN, Turin, Italy*
- ¹⁰⁸*SSC IHEP of NRC Kurchatov institute, Protvino, Russia*
- ¹⁰⁹*SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France*
- ¹¹⁰*Suranaree University of Technology, Nakhon Ratchasima, Thailand*
- ¹¹¹*Technical University of Split FESB, Split, Croatia*
- ¹¹²*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland*
- ¹¹³*The University of Texas at Austin, Physics Department, Austin, Texas, USA*
- ¹¹⁴*Universidad Autónoma de Sinaloa, Culiacán, Mexico*
- ¹¹⁵*Universidade de São Paulo (USP), São Paulo, Brazil*
- ¹¹⁶*Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil*

- ¹¹⁷*University of Houston, Houston, Texas, USA*
¹¹⁸*University of Jyväskylä, Jyväskylä, Finland*
¹¹⁹*University of Liverpool, Liverpool, United Kingdom*
¹²⁰*University of Tennessee, Knoxville, Tennessee, USA*
¹²¹*University of Tokyo, Tokyo, Japan*
¹²²*University of Tsukuba, Tsukuba, Japan*
¹²³*University of Zagreb, Zagreb, Croatia*
¹²⁴*Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, France*
¹²⁵*V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia*
¹²⁶*Variable Energy Cyclotron Centre, Kolkata, India*
¹²⁷*Vestfold University College, Tonsberg, Norway*
¹²⁸*Warsaw University of Technology, Warsaw, Poland*
¹²⁹*Wayne State University, Detroit, Michigan, USA*
¹³⁰*Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary*
¹³¹*Yale University, New Haven, Connecticut, USA*
¹³²*Yonsei University, Seoul, South Korea*
¹³³*Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany*

^aDeceased.

^bAlso at St. Petersburg State Polytechnical University.

^cAlso at Department of Applied Physics, Aligarh Muslim University, Aligarh, India.

^dAlso at M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia.

^eAlso at University of Belgrade, Faculty of Physics and “Vinča” Institute of Nuclear Sciences, Belgrade, Serbia.

^fPermanent address: Konkuk University, Seoul, Korea.

^gAlso at Institute of Theoretical Physics, University of Wrocław, Wrocław, Poland.

^hAlso at University of Kansas, Lawrence, KS, USA.