

Probing small Bjorken- x nuclear gluonic structure via coherent J/ψ photoproduction in ultraperipheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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Abstract

Quasi-real photons exchanged in relativistic heavy ion interactions are powerful probes of the gluonic structure of nuclei. The first measurement of the coherent J/ψ photoproduction cross section in ultraperipheral lead-lead collisions is presented over a wide range of photon-nucleus center-of-mass energies per nucleon ($W_{\gamma N}^{\text{Pb}}$). Results are obtained using data at the nucleon-nucleon center-of-mass energy of 5.02 TeV collected by the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of 1.52 nb^{-1} . The cross section is observed to rise rapidly at low $W_{\gamma N}^{\text{Pb}}$, and plateau above $W_{\gamma N}^{\text{Pb}} \approx 40 \text{ GeV}$, up to 400 GeV, center a new regime of small Bjorken- x ($\approx 6 \times 10^{-5}$) gluons being probed in a heavy nucleus. The observed energy dependence is not predicted by current quantum chromodynamic models.

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The electromagnetic fields surrounding relativistic heavy ions are highly Lorentz contracted and can be effectively treated as linearly polarized quasi-real photons [1, 2]. These photons are powerful and clean probes of the gluonic structure of nuclei [3]. At high energy colliders, when two heavy ions pass each other at an impact parameter greater than twice the nuclear radius, it is referred to as an “ultraperipheral collision” or UPC. In UPCs, a projectile photon from one ion can fluctuate into a virtual quark-antiquark pair and interact with the other target ion via gluon exchanges before turning exclusively into a vector meson (VM) final state [4–17]. If the photon interacts with the nucleus as a whole, the process is known as a coherent interaction, while the incoherent process involves interactions of photons with the nuclear constituents of the target nucleus. At energies accessible at the CERN LHC, studies of VM photoproduction in UPCs open the possibility of probing the poorly known nuclear gluonic structure and dynamics in the low Bjorken- x region ($10^{-5} < x < 10^{-2}$). For instance, the increasingly large gluon density at small x may ultimately reach the unitarity limit, leading to the saturation of the gluon density [18, 19] and thus to a saturation of the observed VM cross section. It has also been suggested that the black-disk limit (BDL) [20–25] of strong absorption may be reached at high energies, where the gluon density itself may not have saturated, but the scattering probability by multiple gluons becomes large enough that the cross section may also saturate at the geometric limit of the nucleus.

The photoproduction of heavy-flavor VMs is of particular interest since it can be studied in the perturbative quantum chromodynamic (QCD) framework with a large energy scale defined by the quark mass. In the leading-order QCD contribution, which is sketched in Fig. 1, the coherent J/ψ photoproduction cross section is proportional to the square of the gluon density function. In photon-proton interactions, the J/ψ production cross section has been extensively measured and is observed to significantly increase with the photon-proton center-of-mass energy [7, 26–30]. This is a consequence of the rapidly rising gluon density in the proton at small x [23, 31]. For photons scattering off heavy-nuclear targets, while significant nuclear suppression effects have been observed [11–17, 32], the underlying mechanism remains poorly understood. Little is known regarding the behavior of the interaction towards the high energy limit, which probes gluons at small x (i.e., $x < 10^{-4}$). The major limitation is the experimental difficulty in distinguishing the photon-emitter nucleus and the target nucleus in a symmetric collision system [33]. For VM photoproduction off nuclei at a given rapidity, there is always a mixture of low and high energy photon contributions, as shown by the opposing sides of Fig. 1. This two-way ambiguity limits the measurements at LHC energies to below 125 GeV in the photon-nucleus center-of-mass energy per nucleon ($W_{\gamma N}^A$).

A novel approach for resolving this two-way ambiguity has been proposed in Refs. [33, 34]. By controlling the UPC impact parameter using forward-emitted neutron multiplicities from the electromagnetic dissociation (EMD) of ions, the relative contributions of low and high energy photons to the measured J/ψ cross section can be separated without ambiguity. The energy exchange in an EMD process is of the order of 10 MeV, which is six orders of magnitude lower than the beam energy.

The results presented in this Letter use PbPb UPCs at a nucleon-nucleon center-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV, which were collected by the CMS experiment at the LHC in 2018. The data correspond to an integrated luminosity of 1.52 nb^{-1} . By applying the aforementioned forward neutron tagging technique, this Letter reports the cross section measurement of the coherent J/ψ photoproduction off Pb nuclei over a broad energy range of $40 < W_{\gamma N}^{\text{Pb}} < 400$ GeV, which includes previously unexplored small- x regions (i.e., $x < 10^{-4}$). Tabulated results are provided in the HEPData record for this analysis [35].

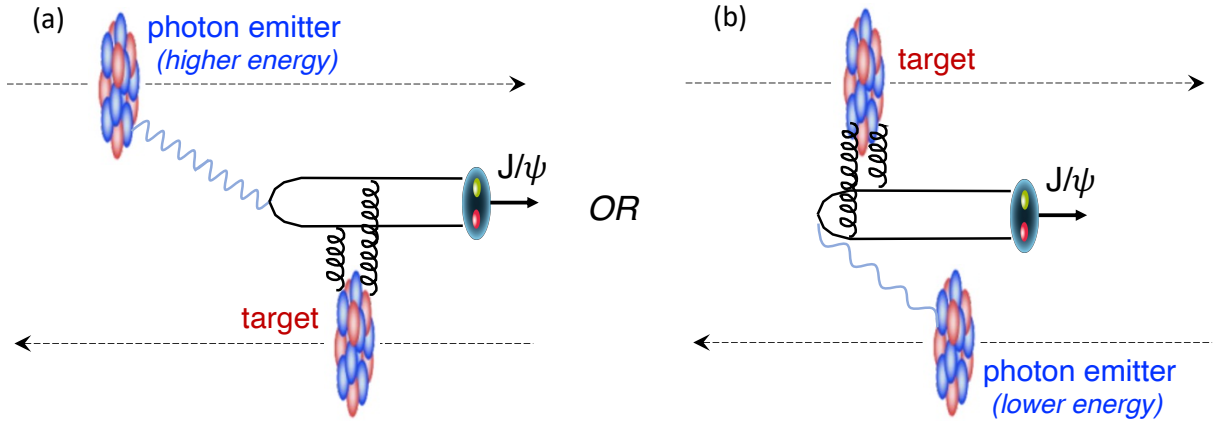


Figure 1: A pictorial representation of the J/ψ photoproduction process in PbPb at leading-order QCD, showing the origin of the two-way ambiguity. The blue wavy and black helical lines represent emitted photons and gluons, respectively.

The CMS apparatus [36] is a multipurpose, nearly hermetic detector, designed to trigger on [37, 38] and identify electrons, muons, photons, and hadrons [39–41]. A global “particle-flow” algorithm [42] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. Forward calorimeters [43], made of steel and quartz-fibres, extend the pseudorapidity coverage provided by the barrel and endcap detectors. Two zero-degree calorimeters (ZDCs) [44], made of quartz fibers and plates embedded in tungsten absorbers, are used to detect neutrons from nuclear dissociation events.

Events are selected using a hardware-based trigger system that requires at least one muon candidate with no explicit selection on its minimum transverse momentum (p_T), coincident with a PbPb bunch crossing [38]. At the trigger level, events with an energy deposit above the noise threshold in either of the two forward calorimeters are vetoed. For the offline analysis, events are required to have a primary interaction vertex, formed by using two or more tracks coming from the collision, that is within 20 cm along the beam axis and at a radius less than 2 cm in the transverse plane from the CMS detector center. To suppress hadronic PbPb collisions, the largest energy deposits in the forward calorimeters are required to be below 7.3 and 7.6 GeV in the positive and negative rapidity sides, respectively. These energy requirements are determined from empty bunch-crossing events [45], providing a purity of nearly 100% with negligible efficiency loss. In addition, events must contain exactly two muon candidates and no additional tracks in the range $|\eta| < 2.4$.

To select high-quality muons, both muons are required to be “soft muons”, as defined in Ref. [46], based on the combined information of the tracker and muon detector systems. Pairs of muons of opposite signs with an invariant mass in the range $2.6 < m_{\mu^+\mu^-} < 4.2$ GeV are taken as J/ψ and $\psi(2S)$ meson candidates. To reconstruct J/ψ mesons at low p_T , the dimuon rapidity must satisfy $1.6 < |y| < 2.4$ for both muons to reach the muon detector systems. For each muon pair, at least one of the muon candidates is required to be matched to the triggered muon. Combinatorial backgrounds are estimated using same-sign muon pairs, and found to be negligible after the event and muon requirements.

The detector reconstruction efficiency is estimated using a Monte Carlo (MC) sample of coher-

ent $J/\psi \rightarrow \mu^+\mu^-$ events generated with the STARLIGHT (v3.13) event generator [47]. These simulated events are further processed with the full CMS detector response simulation using GEANT4 [48].

The raw signal yields of J/ψ and $\psi(2S)$ mesons, $N_{J/\psi}$ and $N_{\psi(2S)}$, are extracted by fitting the dimuon invariant mass distribution for a given rapidity bin with two Crystal Ball (CB) functions [49] to describe the J/ψ and $\psi(2S)$ resonances, and a third-order polynomial function to parametrize the underlying background from quantum electrodynamic processes ($\gamma\gamma \rightarrow \mu^+\mu^-$) (see Appendix A). The raw number of J/ψ signal events contains contributions from several physics processes: coherent and incoherent (with or without nucleon dissociation) J/ψ production from direct photon-nucleus interactions, and also J/ψ mesons coming from the decay of coherent and incoherent $\psi(2S)$ production, referred to as “feed-down”. Coherent and incoherent productions each have a distinct characteristic p_T spectra, so their individual contributions can be disentangled using a template fit to the measured J/ψ p_T distribution, as done in Refs. [13, 15]. The feed-down contribution is estimated directly by measuring the $\psi(2S)$ signal yield from the fit to the dimuon invariant mass distributions. Details on the coherent J/ψ yield ($N_{J/\psi}^{\text{coh}}$) extraction for each rapidity bin, including corrections for the incoherent production and feed-down contribution, are provided in Appendix A.

The final corrected coherent J/ψ production differential cross section is determined using

$$\frac{d\sigma_{J/\psi}^{\text{coh}}}{dy} = \frac{N_{J/\psi}^{\text{coh}}}{\epsilon_{J/\psi} \mathcal{B}_{J/\psi \rightarrow \mu\mu} \mathcal{L}_{\text{int}} \epsilon_{\text{evtsel}} \Delta y'} \quad (1)$$

where the event selection efficiency of $\epsilon_{\text{evtsel}} = 94.2\%$ and the J/ψ reconstruction efficiency $\epsilon_{J/\psi}$, ranging from 2.6 to 11.9% for $1.6 < |y| < 2.4$, are evaluated using simulated samples. Additional corrections determined using the tag-and-probe technique [46, 50] are applied to account for any data-to-simulation discrepancy. The world-average value for the J/ψ dimuon branching fraction [51] $\mathcal{B}_{J/\psi \rightarrow \mu^+\mu^-}$ is used. The quantity \mathcal{L}_{int} is the total integrated luminosity of the data sample [52], and Δy is the rapidity binning used in the measurement.

Coherent J/ψ photoproduction cross sections are reported in classes of the forward-neutron multiplicity, which is determined by the energies deposited in the ZDCs, as done in Ref. [45]. Based on the neutron peaks observed in the total ZDC energy distribution, events are classified as having no neutrons (0n) or with at least one neutron (Xn, $X \geq 1$) in each ZDC. The purities of 0n and Xn classes are estimated using a multi-Gaussian function fit to the ZDC energy distribution, and are found to be better than 99.6% [45]. A total of three neutron multiplicity event classes are formed by combining the classifications of each ZDC side, labeled as 0n0n, 0nXn, and XnXn. Results without neutron multiplicity selection, labeled as AnAn, are also reported for comparison and complementarity with previous measurements. Except for the AnAn case, a correction is made for the effect of having an additional EMD in the event. This correction is obtained by evaluating the migration probability among neutron multiplicity classes, following the approach of Ref. [45]. An average change of +11, -30, and -29% in the raw J/ψ yields is estimated for the 0n0n, 0nXn, and XnXn event classes, respectively.

Because of the symmetry of the PbPb collision system, a J/ψ meson measured at rapidity y can result from two possible photon energies: $\omega_1 = (M_{J/\psi}/2) \exp(-y)$ and $\omega_2 = (M_{J/\psi}/2) \exp(+y)$. The x of the associated parton and $W_{\gamma N}^{\text{Pb}}$ with a photon of energy ω_1 can be found using $x = (M_{J/\psi}/\sqrt{s_{\text{NN}}}) \exp(+y)$ and $W_{\gamma N}^{\text{Pb}} = \sqrt{\sqrt{s_{\text{NN}}} M_{J/\psi} \exp(-y)}$. The corresponding values for a photon of energy ω_2 are obtained by changing the sign of y in each expression.

The measured differential cross section at a given rapidity y for a given neutron multiplicity

class, $injn$ ($= 0n0n, 0nXn, XnXn$), of UPC events is the sum of both photon energy contributions [33, 34]:

$$\frac{d\sigma_{J/\psi}^{injn}(y)}{dy} = n_{\gamma A}^{injn}(\omega_1) \sigma_{J/\psi}(\omega_1) + n_{\gamma A}^{injn}(\omega_2) \sigma_{J/\psi}(\omega_2), \quad (2)$$

where it should be kept in mind that ω_1 and ω_2 are themselves functions of y . Here, $n_{\gamma A}(\omega) = \omega dN_{\gamma A}(\omega)/d\omega$ is the photon flux and $\sigma_{J/\psi}(\omega)$ is the coherent J/ψ photoproduction cross section for a single γ -ion interaction, averaged over the given y range. The photon flux from a relativistic ion is determined with high precision using the equivalent approximation model as implemented with the STARLIGHT event generator [47]. The flux strongly depends on the ion-impact parameter; the high energy photon flux is enhanced relative to that of low energy photons at smaller impact parameters and for higher neutron multiplicities. Therefore, after simultaneously measuring the J/ψ differential coherent cross section as a function of rapidity (i.e., the left-hand side of Eq. (2)) and computing the photon fluxes in each of the three neutron classes, a combined χ^2 fit is performed to extract the differential cross sections for low and high energies, $\sigma_{J/\psi}(\omega_1)$ and $\sigma_{J/\psi}(\omega_2)$.

Systematic uncertainties are evaluated by taking the maximum variation from the nominal result for a given source. The uncertainties are estimated to be 1.5% in the integrated luminosity [52, 53], and 0.55% in $\mathcal{B}_{J/\psi \rightarrow \mu^+\mu^-}$ [51]. Uncertainties in the tag-and-probe corrections are determined to be 3–8% from low to high $W_{\gamma N}^{Pb}$ values. The choice of the forward calorimeter threshold energy in rejecting hadronic contamination leads to 1–4% uncertainties found by modifying the limits and noting the change in the results. For the systematic uncertainty in the raw signal yield extraction, different functional forms for modeling the shapes of the signal and background are studied, including: (i) a sum of CB and Gaussian functions for the J/ψ signal shape; (ii) a second-order polynomial for the dimuon continuum background; (iii) fixing the CB shape parameters to the values determined from MC signal distributions; (iv) varying the range of the dimuon invariant mass distribution used in the fit; (v) changing the dimuon continuum p_T shape to the one determined from side-band mass regions. The results vary by less than 8% when these changes are made. The uncertainty in the neutron migration correction is estimated to be less than 2% by comparing to an alternative approach following Ref. [54], using the observed rate of single- and double-sided neutron emissions per bunch crossing. Individual sources of experimental uncertainties are added in quadrature to obtain the total systematic uncertainty of 6–12%. Theoretical uncertainties in the photon flux calculation are separately evaluated to be 3–16% by varying the Pb nuclei radius ($R = 6.67 \pm 0.03$ fm), the nuclear skin thickness ($a = 0.56 \pm 0.03$ fm) [55], and the EMD cross section [56] within the experimental uncertainties, where uncertainties at low and high $W_{\gamma N}^{Pb}$ are found to be strongly anticorrelated. Correlations between uncertainties are evaluated as a function of $W_{\gamma N}^{Pb}$ and included in the covariance matrix [35] of the fit.

The resulting measured coherent J/ψ photoproduction differential cross sections over the rapidity range $1.6 < |y| < 2.4$ are reported in Fig. 2 (left) in three neutron multiplicity classes. The results with no neutron selection are given in the right plot of Fig. 2. The measurements are performed as a function of $|y|$, but are shown at negative y values, following the ALICE convention [13, 15]. Predictions from several theoretical calculations are also shown in both plots for comparison. The leading twist approximation (LTA) [34] is a perturbative QCD calculation that takes into account nuclear shadowing effects from multi-nucleon interference. Both weak (WS) and strong (SS) shadowing scenarios are shown [34]. The color dipole (CD) models, with different model parameters (BGK, BGW, IIM), assume quark-antiquark dipole scattering from the nuclear targets [57].

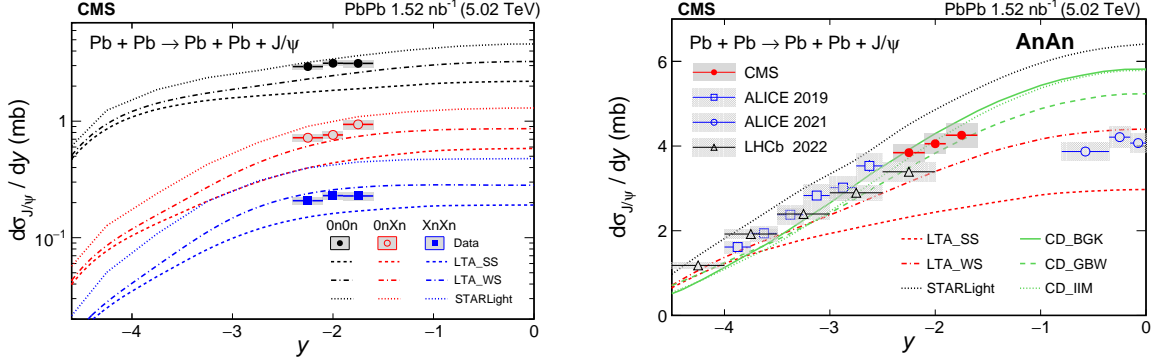


Figure 2: The differential coherent J/ψ photoproduction cross section as a function of rapidity, in different neutron multiplicity classes (left): 0n0n, 0nXn and XnXn; (right): AnAn. The small vertical bars and shaded boxes represent the statistical and systematic uncertainties, respectively. The horizontal bars show the bin widths. Theoretical predictions from LTA weak/strong shadowing [34], color dipole models (CD_BGK, CD_BGW, and CD_IIM) [57], and STARLIGHT [47] are shown by the curves. The right plot also displays the results from the ALICE [13, 15] and LHCb [17] experiments.

For the case of no neutron selection (AnAn), the data follow the trend of the forward-rapidity measurements from ALICE [13] over a new y region. None of the models describe the combined results over the full rapidity range. The color dipole models agree with the measurements in the forward-rapidity region, but fail to describe the data at $y \approx 0$. In each neutron multiplicity class, the LTA predictions tend to be lower than the CMS results, particularly for the strong shadowing scenario. These comparisons indicate that there are key ingredients missing from the theoretical understanding of high energy photon-nucleus scattering processes.

To gain further insight, the total measured J/ψ coherent photoproduction cross section as a function of $W_{\gamma N}^{\text{Pb}}$ up to ≈ 400 GeV is shown in Fig. 3, after decomposing the two-way ambiguity. Because the contributions of high energy photons are negligible at very forward rapidity (less than 5% for $-4.5 < y < -3.5$) [33, 34], and the fact that $y \approx 0$, $\omega_1 \approx \omega_2 \approx M_{J/\psi}/2$, the total cross section at lower $W_{\gamma N}^{\text{Pb}}$ values can be approximated using ALICE and LHCb measurements. These results are also shown in Fig. 3. The experimental and theoretical (from the photon flux) uncertainties are displayed separately in Fig. 3. Predictions from the LTA and CD models, as well as the gluon saturation models bBK [58], IPsat [59], and GG [60]), are compared to the experimental measurements. The naive prediction from the impulse approximation (IA) model [33] is also shown, providing a reference assuming the absence of any nuclear effects except for coherence.

The measured total cross section has an unexpected energy dependence, rising by more than a factor of 4 as $W_{\gamma N}^{\text{Pb}}$ goes from $W_{\gamma N}^{\text{Pb}} \approx 15$ to 40 GeV. This is consistent with the expectation of a fast-growing gluon density at low x (e.g., from the IA model). However, this trend vanishes for $W_{\gamma N}^{\text{Pb}} > 40$ GeV, and instead the total cross section begins a slow linear rise with a slope of $(3.0 \pm 0.4 \text{ (stat)} \pm 1.4 \text{ (syst)}) \times 10^{-5}$ mb/GeV up to $W_{\gamma N}^{\text{Pb}} \approx 400$ GeV. Considering the experimental uncertainties across the measured $W_{\gamma N}^{\text{Pb}}$ range, none of the theoretical models are consistent with the measurements, with the CD-BGK model having the best p -value of 1.6×10^{-8} . This result could imply the onset of novel physics mechanisms in the coherent J/ψ photoproduction process starting at $W_{\gamma N}^{\text{Pb}} \approx 40$ GeV, for example, the saturation of the gluon density in the Pb nucleus at the corresponding x value. This picture may be less straightforward due to higher-order perturbative QCD corrections (e.g., quark-antiquark exchange) as suggested in

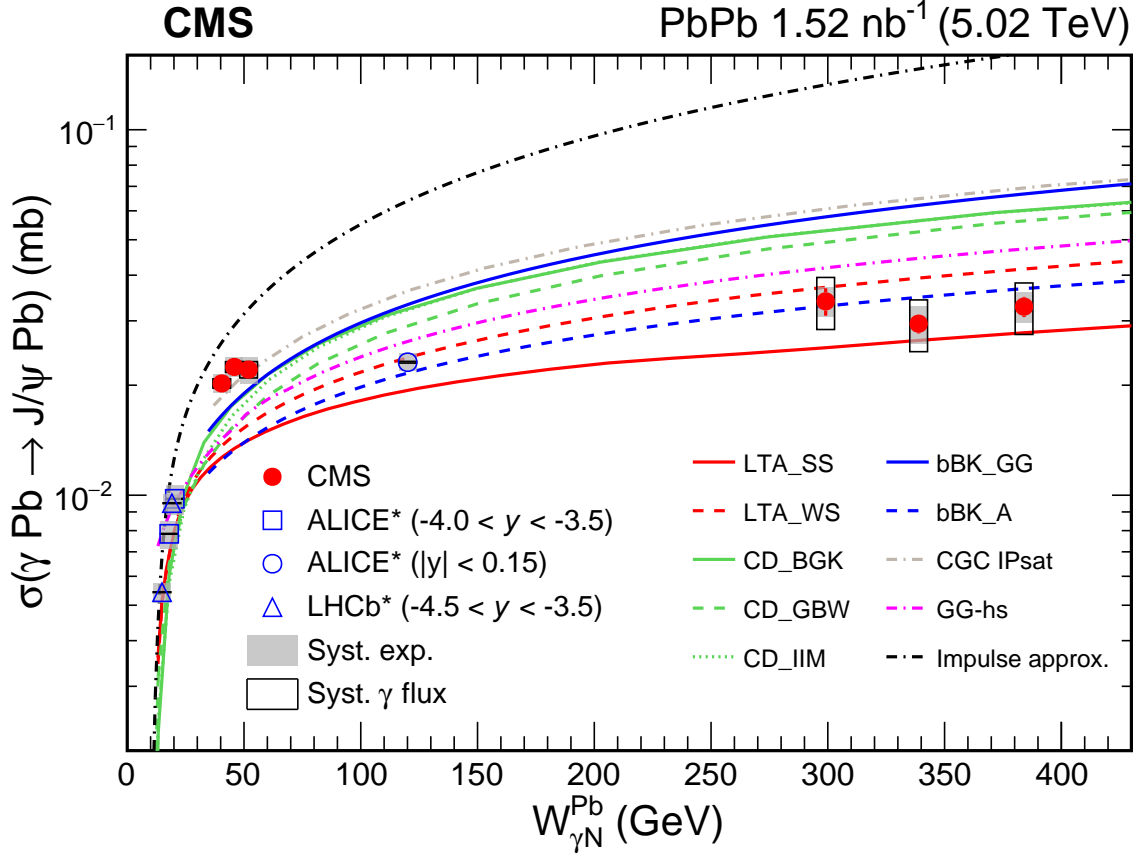


Figure 3: The total coherent J/ψ photoproduction cross section as a function of $W_{\gamma N}^{\text{Pb}}$ from the CMS measurement in PbPb UPCs at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Approximated results (implied by the asterisk) from the ALICE [13, 15] and LHCb [17] experiments are displayed for specific rapidity regions, where the two-way ambiguity effect is expected to be negligible. The $W_{\gamma N}^{\text{Pb}}$ values used correspond to the center of each experiment's rapidity range. The vertical bars and the shaded and open boxes represent the statistical, experimental, and theoretical (photon flux) uncertainties, respectively. The predictions from various theoretical calculations [33, 34, 57–60] are shown by the curves.

Refs. [61, 62]. On the other hand, the observed behavior is also expected when approaching the BDL, where major part of the target Pb nucleus becomes completely absorptive to projectile photons because of the large scattering probability in the presence of dense gluons at small x [21]. In this scenario, the photon-nucleus cross section approaches the the unitarity limit allowed by the geometric size of the nucleus. The slow rise in the measured cross section from about 40 to 400 GeV would then be due to periphery of the nucleus not becoming fully “black.”

To quantify the nuclear effects on the observed gluon density function in a Pb nucleus, a nuclear gluon suppression factor, $R_g^{\text{Pb}}(x, \mu^2 = 2.4 \text{ GeV}^2)$ as a function of x and with $\mu = M_{J/\psi}/2$, where μ is the energy scale, is defined as the square root of the ratio of the measured coherent J/ψ photoproduction cross section σ^{Meas} to the IA prediction σ^{IA} , $R_g^{\text{Pb}} = \sqrt{\sigma^{\text{Meas}}/\sigma^{\text{IA}}}$ [63]. The extracted R_g^{Pb} values are shown in Fig. 4 as a function of x . The suppression in the relatively high- x (low $W_{\gamma N}^{\text{Pb}}$) region of $x > 5 \times 10^{-3}$ is moderate, approximately 0.8–0.9. Moving toward smaller x values, R_g^{Pb} starts dropping rapidly to 0.4–0.5 for $x \approx 6 \times 10^{-5}$. Similar to the cross section measurement, no theoretical model predicts the observed values and x dependence of R_g^{Pb} over the wide x range reported. If the BDL of strong absorption is reached for $x < 5 \times 10^{-3}$,

corresponding to $W_{\gamma N}^{\text{Pb}} > 40 \text{ GeV}$, the direct connection between the measured cross section and the single gluon density function, as in the weak absorption limit, no longer holds. Instead, the cross section will reach the unitarity limit while the gluon density can continue increasing. Therefore, new theoretical approaches are needed to understand the structure and dynamics of the strong force for a heavy nucleus in this new domain of extreme gluon density.

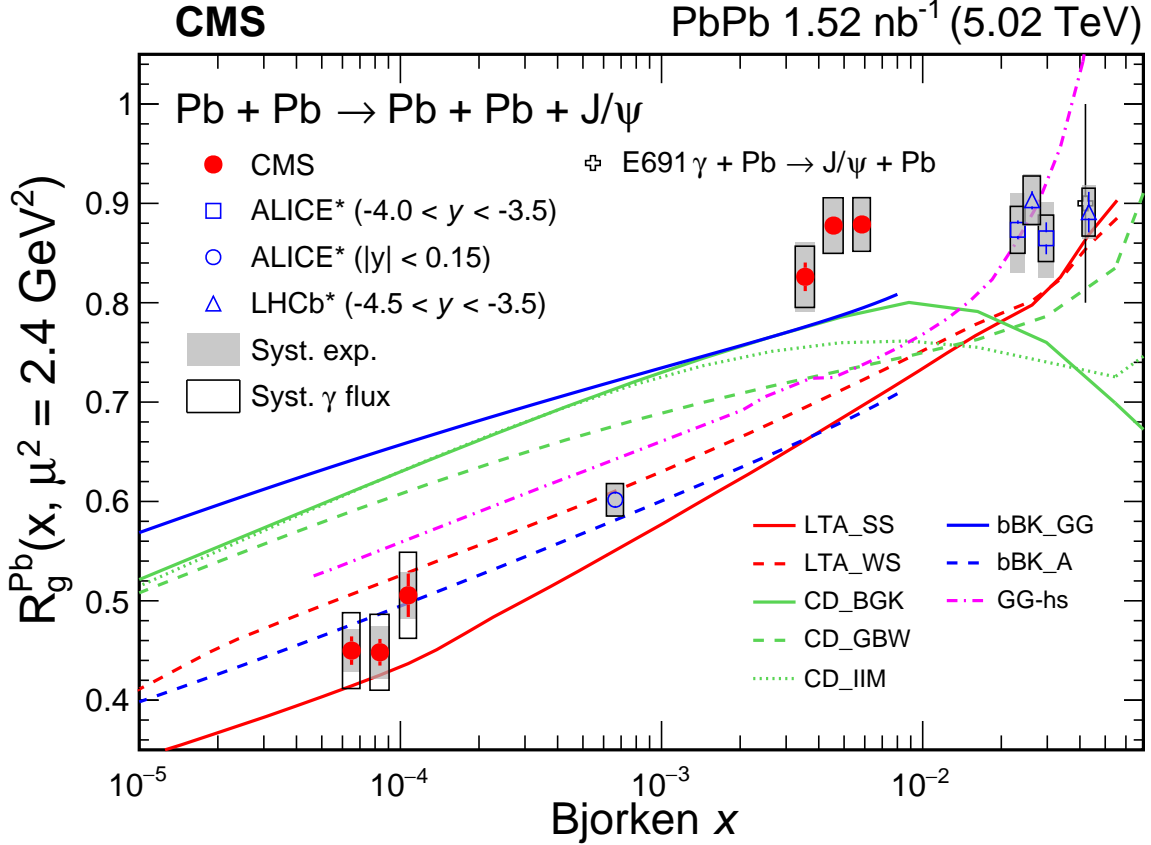


Figure 4: The nuclear gluon suppression factor R_g^{Pb} as a function of Bjorken x extracted from the CMS measurement of the coherent J/ψ photoproduction in PbPb UPCs at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$. Approximated results (implied by the asterisk) from the ALICE [13, 15] and LHCb [17] experiments are displayed for specific rapidity regions, where the two-way ambiguity effect is expected to be negligible. A measurement of J/ψ photoproduction from the E691 experiment [64, 65] is also given. The x values are evaluated at the centers of their corresponding rapidity ranges. The vertical bars and shaded and open boxes represent the statistical, experimental systematic, and theoretical systematic uncertainties, respectively. The latter is due to the uncertainties in the photon flux and the IA. Predictions from various theoretical calculations [34, 57, 58, 60] are shown by the curves.

In summary, the first measurement of the coherent J/ψ photoproduction cross section off lead nuclei, as a function of the photon-nuclear center-of-mass energy per nucleon ($W_{\gamma N}^{\text{Pb}}$) has been presented over a broad energy range. In a coherent process, the J/ψ is produced by the photon interacting with the nucleus as a whole. Results are obtained with ultraperipheral PbPb collision data by applying the forward neutron tagging technique. The cross section is observed to rise rapidly at low $W_{\gamma N}^{\text{Pb}}$ but appears to plateau above $W_{\gamma N}^{\text{Pb}} \approx 40 \text{ GeV}$, up to 400 GeV , where a new regime of gluon momentum fraction (Bjorken $x \approx 6 \times 10^{-5}$) in a heavy nucleus is probed. This observed trend is not predicted by current theoretical models. This can be interpreted

either as the first direct evidence for the saturation of nuclear gluonic density or that the scattering cross section is near the black-disk limit.

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A Method of coherent J/ψ yield extraction

To extract the J/ψ yield from coherent photoproduction, a two-step analysis is performed by fitting first the dimuon invariant mass distribution at $p_T < 0.2$ GeV, and then the dimuon p_T distribution within the mass window of $2.95 < m_{\mu^+\mu^-} < 3.25$ GeV.

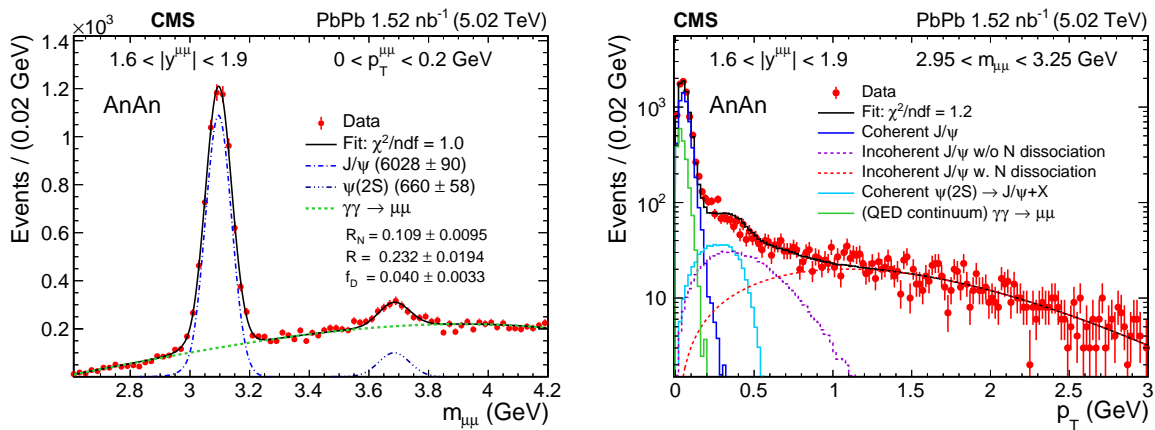


Figure 5: The invariant mass distribution of $\mu^+\mu^-$ pairs with dimuon $p_T < 0.2$ GeV from the signal events with no neutron multiplicity selection (AnAn) (left). The results of the fit are shown by the various curves, and the corresponding values of the χ^2 / degrees of freedom (ndf) and the fitted number of J/ψ and $\psi(2S)$ events are given. The values of the factors R_N , R , and f_D , defined below, are also shown. The transverse momentum distribution of $\mu^+\mu^-$ events with a dimuon invariant mass in the J/ψ mass window of ($2.95 < m_{\mu^+\mu^-} < 3.25$ GeV) (right). Again, the results of the fit are shown by the various curves. In both plots, the vertical bars on the data points give the statistical uncertainty.

An example of an invariant mass distribution for the reconstructed dimuon pairs is shown for events with a dimuon $p_T < 0.2$ GeV and no neutron multiplicity selection in Fig. 5 (left). The parameters of the CB functions left free in the fit include the pole mass $\mu_{J/\psi}$ and width $\Gamma_{J/\psi}$ of the J/ψ . The analogous parameters for the $\psi(2S)$ are constrained by demanding $\mu_{\psi(2S)} = \mu_{J/\psi} M_{\psi(2S)} / M_{J/\psi}$ and $\Gamma_{\psi(2S)} = \Gamma_{J/\psi} M_{\psi(2S)} / M_{J/\psi}$, respectively, where $M_{J/\psi}$ and $M_{\psi(2S)}$ are the world-average mass values [51]. The results of the fit are shown by the various curves, with the J/ψ and $\psi(2S)$ signals being clearly visible. The raw yields of J/ψ and $\psi(2S)$ events, $N_{J/\psi}$ and $N_{\psi(2S)}$, are given in the figure.

Figure 5 (right) shows an example of the $\mu^+\mu^-$ p_T spectrum for events with a dimuon invariant mass in the J/ψ mass window ($2.95 < m_{\mu^+\mu^-} < 3.25$ GeV). Because the different physics

processes involved have distinct shapes, their individual contributions can be measured via template fits. The template p_T spectra for coherent J/ψ production, feed-down J/ψ from coherently photoproduced $\psi(2S)$ decays, incoherent J/ψ production without nucleon dissociation, and the dimuon continuum from quantum electrodynamic processes ($\gamma\gamma \rightarrow \mu^+\mu^-$) are obtained from simulated events with the STARLIGHT event generator [47] and the GEANT4 [48] simulation of the CMS detector. The predicted slope of the p_T distribution for coherently photoproduced J/ψ particles from STARLIGHT is adjusted by varying the nuclear radius parameter to best describe the data p_T distribution.

To describe incoherent J/ψ p_T spectra with nucleon dissociation, an empirical function employed by the H1 [28] and ALICE [13, 15] experiments is used: $dN/dp_T \approx p_T [1 + (b_{\text{pd}}/n_{\text{pd}})p_T^2]^{-n_{\text{pd}}}$, where b_{pd} and n_{pd} are fit parameters. Normalizations of the coherent J/ψ , incoherent J/ψ without nucleon dissociation, and incoherent J/ψ with nucleon dissociation components are free parameters in the fit. The normalization of the dimuon continuum is fixed to the value determined from the invariant mass fitting, as shown in Fig. 5 (left). Normalizations of coherent and incoherent $\psi(2S)$ feed-down to J/ψ are constrained to those of the prompt coherent and incoherent J/ψ components according to the feed-down fractions (f_D) extracted from $\psi(2S)$ yields in the invariant mass distribution, as described below. The entire procedure is repeated for each neutron multiplicity class.

The measured p_T spectrum in the range $0.2 < p_T < 0.5$ GeV is not well described by the fit, as was also seen in previous ALICE studies [13, 15]. This discrepancy is not unexpected since the STARLIGHT event generator does not precisely describe all the physics processes involved. To estimate the systematic uncertainty due to this effect, the p_T upper limit is changed to $p_T < 0.3$ GeV and the extraction of the coherent cross section is repeated, leading to an uncertainty of less than 2%.

The final raw coherent J/ψ yield, $N_{J/\psi}^{\text{coh}}$, is evaluated by:

$$N_{J/\psi}^{\text{coh}} = \frac{N_{J/\psi}}{1 + f_I + f_D}, \quad (3)$$

where f_I and f_D are the fractional contamination of incoherent processes and coherent $\psi(2S)$ feed-down, respectively. The incoherent contamination, f_I , is obtained by fitting the p_T distribution and calculating the fraction of incoherent J/ψ events in the $p_T < 0.2$ GeV region. The feed-down contamination, f_D , is estimated based on the ratio of the number of $\psi(2S)$ to J/ψ events, $R_N = N_{\psi(2S)}/N_{J/\psi}$, found from the fit to the dimuon invariant mass distribution. This parameter can be expressed as

$$R_N = \frac{\sigma_{\psi(2S)} \mathcal{B}_{\psi(2S) \rightarrow \mu\mu} \epsilon_{\psi(2S)}}{(\sigma_{J/\psi} \epsilon_{J/\psi} + \sigma_{\psi(2S)} \mathcal{B}_{\psi(2S) \rightarrow J/\psi} \epsilon_{\psi(2S) \rightarrow J/\psi}) \mathcal{B}_{J/\psi \rightarrow \mu\mu}}. \quad (4)$$

The symbols ϵ and \mathcal{B} represent the two reconstruction efficiencies and decay branching fractions, respectively.

The ratio of the cross sections of coherent $\psi(2S)$ to coherent J/ψ production, $R = \sigma_{\psi(2S)}/\sigma_{J/\psi}$, can then be expressed in terms of R_N as

$$R = \frac{R_N \mathcal{B}_{J/\psi \rightarrow \mu\mu} \epsilon_{J/\psi}}{\mathcal{B}_{\psi(2S) \rightarrow \mu\mu} \epsilon_{\psi(2S)} - R_N \mathcal{B}_{\psi(2S) \rightarrow J/\psi} \epsilon_{\psi(2S) \rightarrow J/\psi} \mathcal{B}_{J/\psi \rightarrow \mu\mu}}. \quad (5)$$

Finally, the fraction of the coherent J/ψ yield that comes from the feed-down of coherently

photoproduced $\psi(2S)$ is found using the expression

$$f_D = R \frac{\epsilon_{\psi(2S) \rightarrow J/\psi}}{\epsilon_{J/\psi}} \mathcal{B}_{\psi(2S) \rightarrow J/\psi}. \quad (6)$$

The world-average values [51] for the J/ψ and $\psi(2S)$ branching fractions are used in these equations.


The resulting measured values of the incoherent and feed-down fractions and their uncertainties from the fits are given in Table 1 for each of the neutron multiplicity class.

Table 1: The measured values of the incoherent and feed-down fractions (f_I) and (f_D), respectively, and their uncertainties for each of the neutron multiplicity class.




















	0n0n	0nXn	XnXn	AnAn
f_I	0.005 ± 0.001	0.103 ± 0.005	0.090 ± 0.011	0.035 ± 0.003
f_D	0.028 ± 0.005	0.037 ± 0.007	0.050 ± 0.012	0.032 ± 0.004

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






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

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
















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


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







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









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

























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




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











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





















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



































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


























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
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











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








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


A. Bala , S. Banerjee , M. Guchait , S. Karmakar , S. Kumar , G. Majumder ,
K. Mazumdar , S. Mukherjee , A. Thachayath 

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
























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













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





















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










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

























A. Benaglia^a , G. Boldrini^a , F. Brivio^{a,b} , F. Cetorelli^{a,b} , F. De Guio^{a,b} , M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^{a,b} , M.T. Lucchini^{a,b} , M. Malberti^a , S. Malvezzi^a , A. Massironi^a , D. Menasce^a , L. Moroni^a , M. Paganoni^{a,b} , D. Pedrini^a , B.S. Pinolini^a , S. Ragazzi^{a,b} , N. Redaelli^a , T. Tabarelli de Fatis^{a,b} , D. Zuolo^{a,b} 

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







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C. Sciacca^{a,b} 
















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A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , S. Fantinel^a ,
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




























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











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G. Mantovani^{a,b} , V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,52} , A. Piccinelli^{a,b} ,
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








































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



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


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
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



































J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello , J.A. Murillo Quijada , A. Sehrawat , L. Valencia Palomo 

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






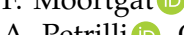


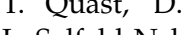

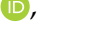


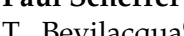


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


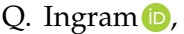

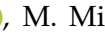
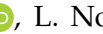


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

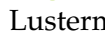


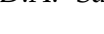

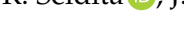
CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , E. Auffray , G. Auzinger , J. Baechler, D. Barney , A. Bermúdez Martínez , M. Bianco , B. Bilin , A.A. Bin Anuar , A. Bocci , E. Brondolin , C. Caillol , T. Camporesi , G. Cerminara , N. Chernyavskaya , S.S. Chhibra , S. Choudhury, M. Cipriani , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , M. Dünser , N. Dupont, F. Fallavollita⁵⁷, A. Florent , L. Forthomme , G. Franzoni , W. Funk , S. Ghosh⁵⁸ , S. Giani, D. Gigi, K. Gill, F. Glege , L. Gouskos , E. Govorkova , M. Haranko , J. Hegeman , V. Innocente , T. James , P. Janot , J. Kaspar , J. Kieseler , N. Kratochwil , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , F. Meijers , S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli, L. Orsini, F. Pantaleo , E. Perez, M. Peruzzi , A. Petrilli , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , M. Pitt , H. Qu , T. Quast, D. Rabady , A. Racz, G. Reales Gutiérrez, M. Rovere , H. Sakulin , J. Salfeld-Nebgen , S. Scarfi, M. Selvaggi , A. Sharma , P. Silva , P. Sphicas⁵⁹ , A.G. Stahl Leiton , A. Steen, S. Summers , K. Tatar , D. Treille , P. Tropea , A. Tsirou, D. Walter , J. Wanczyk⁶⁰ , K.A. Wozniak , W.D. Zeuner












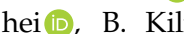

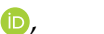






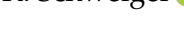


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










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B. Grynyov 


















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


























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












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














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


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
















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




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








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






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





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






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







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







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







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







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

















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





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














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

















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





















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B. Greenberg , N. Haubrich , S. Higginbotham , G. Kopp , S. Kwan , D. Lange ,
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















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G. Paspalaki , S. Piperov , A. Purohit , J.F. Schulte , M. Stojanovic , J. Thieman ,
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










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











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

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















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