Editors' Suggestion

Probing Gluon Fluctuations in Nuclei with the First Energy-Dependent Measurement of Incoherent J/ψ Photoproduction in Ultraperipheral PbPb Collisions

V. Chekhovsky *et al.*[*]
(CMS Collaboration)

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Incoherent J/ψ photoproduction in heavy ion ultraperipheral collisions (UPCs) provides a sensitive probe of localized, fluctuating gluonic structures within heavy nuclei. This Letter reports the first measurement of the photon-nucleon center-of-mass energy ($W_{\gamma\mathrm{N}}$) dependence of this process in PbPb UPCs at a nucleon-nucleon center-of-mass energy of 5.02 TeV, using 1.52 nb^{-1} of data recorded by the CMS experiment. The measurement covers a wide $W_{\gamma\mathrm{N}}$ range of ≈40–400 GeV, probing gluons carrying a fraction x of nucleon momentum down to an unexplored regime of 6.5×10^{-5}. Compared to baseline predictions neglecting nuclear effects, the measured cross sections exhibit significantly greater suppression at lower x. Additionally, the ratio of incoherent to coherent photoproduction is found to be constant across the probed $W_{\gamma\mathrm{N}}$ and x range, disfavoring the establishment of the black disk limit. This Letter provides critical insights into the x-dependent evolution of fluctuating gluonic structures within nuclei and calls for further advancements in theoretical models incorporating nuclear shadowing and gluon saturation.

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Understanding the spatial and momentum structure of nuclei at the most fundamental level is a central goal of quantum chromodynamics (QCD), the theory of the strong interaction. The structure of nucleons and nuclei becomes increasingly dominated by gluons [1,2] when probed at higher energies or smaller values of the momentum fraction x carried by partons [3]. Gluon densities grow rapidly at small x, and different physical mechanisms can modify this growth. One such effect is "nuclear shadowing," which arises from the coherent interaction of a probing photon with multiple nucleons in the nucleus, leading to a suppression of the effective gluon distribution [2]. When gluon densities become extremely high at small x, a new phenomenon named "gluon saturation" is expected to occur because of nonlinear interactions among gluons themselves [4,5]. While both phenomena reduce gluon densities at small x, they reflect distinct underlying physics.

In ultraperipheral collisions (UPCs) [6], where relativistic heavy ions interact at impact parameters exceeding the sum of their nuclear radii, strong interactions are highly suppressed. In these collisions, a quasireal photon emitted by an ion can interact with the other ion and induce the diffractive production of a vector meson. Notably, the diffractive photoproduction of heavy vector mesons, e.g., J/ψ, is highly sensitive to the gluon distribution within the target nucleus, offering a powerful probe of the nuclear gluonic structure. This production can occur through coherent or incoherent processes. In coherent photoproduction the photon interacts with the entire nucleus, which remains intact and in its ground state, providing insight into the average nuclear gluon density [7,8]. In contrast, incoherent photoproduction involves interactions between the photon and localized gluonic hotspots, often leading to nuclear excitation or breakup, revealing event-by-event fluctuations in the spatial configuration of the nuclear gluon field [9–11]. These fluctuations are particularly relevant at small x and may be connected to the initial-state geometry of heavy ion collisions and the emergence of collective phenomena in small system collisions [10,12,13].

Ultraperipheral collisions have been extensively used to study coherent and incoherent vector meson photoproduction across a wide range of collision energies, nuclear systems, and rapidities [14–24]. These measurements have demonstrated strong nuclear modifications to the cross sections, providing key tests of models of gluon distributions in nuclei. Recent breakthrough studies by the CMS [25] and ALICE [26] Collaborations have provided the first measurements of the dependence of coherent J/ψ photoproduction on the photon-nucleon center-of-mass energy ($W_{\gamma\mathrm{N}}$). The results reveal significantly greater nuclear suppression at higher $W_{\gamma\mathrm{N}}$ (lower x) compared to the impulse approximation (IA) [27–29], which neglects nuclear effects and treats the nucleus as a collection of free nucleons. However, models incorporating gluon saturation or nuclear shadowing fail to fully describe the data.

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[*] Full author list given at the end of the Letter.

The "black disk limit" phenomenon [2,30] may offer a qualitative interpretation [25]. This limit hypothesizes that the nucleus becomes a uniform, complete absorber of incoming photons at small x, maximizing the coherent photoproduction cross section while strongly suppressing or eliminating incoherent photoproduction. Measurements of the energy dependence of incoherent J/ψ photoproduction, particularly at the high-energy limit, provide a direct test of this phenomenon. However, such measurements remain scarce [9,31], primarily due to challenges in distinguishing low- and high-energy photon contributions, as detailed in later sections. These limitations have hindered studies of fluctuating gluon evolution dynamics within nuclei, especially at small x, for decades. Furthermore, comparing incoherent and coherent channels reduces theoretical uncertainties in the J/ψ wave function, photon flux, nuclear density, nuclear form factor, nucleon parton distribution functions, and the J/ψ formation cross section from single γ-nucleon scattering [28,29,32]. This enables stringent tests of models incorporating subnucleonic fluctuations, nuclear shadowing, and nonlinear QCD effects [2,10,33–35].

This Letter presents the first measurement of the energy dependence of incoherent J/ψ photoproduction in lead-lead (PbPb) UPCs at a nucleon-nucleon center-of-mass energy $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with an integrated luminosity of $1.52\ \mathrm{nb}^{-1}$. The results span an energy range of $40 < W_{\gamma\mathrm{N}} < 400$ GeV, probing x values as low as 6.5×10^{-5}. By quantifying the suppression relative to baseline calculations using the IA and studying the ratio of incoherent to coherent production, these measurements offer new constraints on the evolution of spatial structure and fluctuations of gluon fields in nuclei at small x. The data and uncertainties, along with the covariance matrix reflecting correlations among data points, are available at HEPData [36].

The CMS apparatus [37] is a multipurpose, nearly hermetic detector, designed to trigger on and identify electrons, muons, photons, and hadrons [38–42]. A global "particle-flow" algorithm [43] reconstructs all particles in an event. It integrates information from an all-silicon tracker, a crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter operating inside a 3.8 T superconducting solenoid, and muon detectors within the flux-return yoke. Forward calorimeters [44], made of steel and quartz fibers, extend the pseudorapidity (η) coverage provided by the barrel and end-cap detectors. Two zero-degree calorimeters (ZDCs) [45], made of quartz fibers and plates embedded in tungsten absorbers, are used to detect forward neutrons.

The dimuon decay channel is utilized to reconstruct J/ψ candidates. Events are selected using a hardware-based trigger system requiring at least one muon candidate coincident with a PbPb bunch crossing, without a p_{T} threshold [39]. Events with energy deposits above the noise threshold in either forward calorimeter are vetoed at the trigger level. Offline, a primary interaction vertex is required within 20 cm along the beam axis from the center of the nominal interaction region and 2 cm from the beam axis in the transverse plane, formed from at least two tracks. To suppress hadronic interactions, forward calorimeter energy deposits must not exceed 7.3 and 7.6 GeV on the positive and negative rapidity sides, respectively [46]. Events must contain exactly two oppositely charged muons with an invariant mass of $2.6 < m_{\mu^+\mu^-} < 4.2$ GeV and no extra tracks within $|\eta| < 2.4$. Both muons must meet the "soft muon" criteria [47], combining tracker and muon detector information, and at least one must match the trigger. Backgrounds, including same-sign dimuon pairs, are negligible after these selections.

The raw number of J/ψ signal events contains contributions from several physics processes: incoherent (with or without nucleon dissociation) and coherent direct J/ψ production from photon-nucleus interactions, and also J/ψ coming from the decay of directly photoproduced $\psi(2S)$, referred to as "feed-down." The incoherent component is extracted by fitting the dimuon invariant mass and p_{T} distributions after correcting for acceptance (A) and efficiency (ϵ) effects in each rapidity bin. The fitting procedures are similar to those of Refs. [19,20,25] (more details are available in the End Matter). The values of $(A\epsilon)_{J/\psi}$, are estimated using a simulated sample of incoherent $J/\psi \to \mu^+\mu^-$ events generated with the STARlight (v3.13) event generator [48]. These events are processed with the full CMS detector response simulation using GEANT4 [49]. Additional corrections determined using a tag-and-probe technique [47,50] are applied to account for any data-to-simulation discrepancies.

The differential cross section for incoherent J/ψ photoproduction is given by

$$\frac{\mathrm{d}\sigma^{\mathrm{incoh}}_{J/\psi}}{\mathrm{d}y} = \frac{N^{\mathrm{incoh}}_{J/\psi}}{(A\epsilon)_{J/\psi}\mathcal{B}_{J/\psi\to\mu^+\mu^-}\mathcal{L}_{\mathrm{int}}\Delta y}. \qquad (1)$$

Here, $N^{\mathrm{incoh}}_{J/\psi}/(A\epsilon)_{J/\psi}$ is the yield of J/ψ produced via incoherent processes, corrected for acceptance and efficiency. The branching fraction $\mathcal{B}_{J/\psi\to\mu^+\mu^-} = (5.961 \pm 0.033)\%$ is taken from Ref. [51], $\mathcal{L}_{\mathrm{int}}$ is the total integrated luminosity [52], and Δy is the rapidity bin width.

In PbPb UPCs, a J/ψ produced at rapidity y can result from two photon energies, $\omega_1 = (M_{J/\psi}/2)e^{-y}$ and $\omega_2 = (M_{J/\psi}/2)e^{+y}$, corresponding to photon emissions from opposite nuclei [25]. This ambiguity affects x and $W_{\gamma\mathrm{N}}$, calculated as $x = (M_{J/\psi}/\sqrt{s_{\mathrm{NN}}})e^{\pm y}$ and $W_{\gamma\mathrm{N}} = \sqrt{\sqrt{s_{\mathrm{NN}}}M_{J/\psi}e^{\mp y}}$. The total cross section at rapidity y combines contributions from both photon energies [7,53]:

$$\frac{\mathrm{d}\sigma_{\mathrm{PbPb}\to\mathrm{PbPb}'J/\psi}(y)}{\mathrm{d}y} = n_\gamma(\omega_1)\sigma_{\gamma\mathrm{Pb}\to J/\psi\mathrm{Pb}'}(\omega_1) + n_\gamma(\omega_2)\sigma_{\gamma\mathrm{Pb}\to J/\psi\mathrm{Pb}'}(\omega_2), \qquad (2)$$

where n_γ is the photon flux, and $\sigma_{\gamma\mathrm{Pb}\to J/\psi\mathrm{Pb}'}$ is the cross section for J/ψ production.

To resolve the "two-way ambiguity," neutron tagging is used based on ZDC energy deposits to classify events as 0n (no neutrons) or Xn (one or more neutrons) [25,46]. Events without neutron multiplicity selection are labeled as An. Combining the classifications from both ZDC sides yields three event categories, denoted 0n0n, 0nXn, and XnXn, that are used for cross section measurements. Neutron peaks in the ZDC energy distributions are fitted with a multi-Gaussian function, achieving purities above 99.6% for Xn neutron signals. Neutrons can be emitted from both electromagnetic dissociation (EMD) or incoherent photoproduction processes. The large EMD cross section (∼200 b) [54] leads to concurrent neutron emission from other PbPb interactions in the same bunch crossing, which can migrate the neutron multiplicity class to a higher one. Such EMD pileup effects are corrected using the zero-bias triggered data (requiring only that two beams cross each other), where the migration probability is directly determined by the probability of observing each neutron multiplicity class [46].

In incoherent J/ψ photoproduction, neutrons primarily align with the outgoing direction of the target nucleus [7,53]. In 0nXn events, J/ψ with the same or opposite sign rapidity as the detected neutrons correspond to contributions from ω_1 and ω_2, respectively. Calculating the associated photon flux is challenging without a robust understanding of incoherent photoproduction itself. However, the photon flux can be extracted using EMD-induced neutron events [48]. To facilitate photon flux determination, the 0n0n and 0nXn events are combined into a single event class, denoted as 0 nAn*, under the assumption that the ω_1 and ω_2 fractions for 0n0n events are similar to those in 0nXn events. An alternative assumption, where 0n0n events only contribute to ω_1, is used as an extreme limit to estimate systematic uncertainties.

The incoherent J/ψ production cross section per γPb interaction is calculated as

$$\sigma_{\gamma\mathrm{Pb}\to J/\psi\mathrm{Pb}'}(\omega) = \frac{\mathrm{d}\sigma^{\mathrm{0nAn}^*}_{\mathrm{PbPb}\to\mathrm{PbPb}'J/\psi}(y)}{\mathrm{d}y} / n_\gamma^{\mathrm{0nAn}^*}(\omega), \quad (3)$$

where $n_\gamma^{\mathrm{0nAn}^*}(\omega)$ is the total photon flux associated with events having no neutrons on one side of the ZDC. This flux can be determined using EMD-induced contributions:

$$n_\gamma^{\mathrm{0nAn}^*}(\omega) = n_\gamma^{\mathrm{0n0n(EMD)}}(\omega) + \frac{1}{2} n_\gamma^{\mathrm{0nXn(EMD)}}(\omega), \quad (4)$$

where $n_\gamma^{\mathrm{0n0n(EMD)}}$ and $n_\gamma^{\mathrm{0nXn(EMD)}}$ represent the photon fluxes for 0n0n and 0nXn EMD events, respectively. These flux components are derived from equivalent photon approximation models implemented in STARlight [48]. The factor of 1/2 accounts for the equal probability of EMD-induced neutrons being emitted in the same or opposite direction as incoherent-induced neutrons, with the latter case contributing to the XnXn classification instead. Alternatively, given a 0.85 probability of an incoherent process with forward neutrons [7], Eq. (4) can be updated by replacing 1/2 with 0.575 (= 1 − 0.85/2). Here, 0.575 represents the fraction of EMD-induced 0nXn events retained in 0 nAn* events. These two approaches differ by approximately 1% and 3.7%–4.7% for the $n_\gamma^{\mathrm{0nAn}^*}$ values at low and high $W_{\gamma\mathrm{N}}$, respectively. These differences are incorporated into the systematic uncertainties of the cross-section measurements.

Systematic uncertainties are evaluated by taking the maximum deviation from the nominal result for each source. The uncertainty in the integrated luminosity is 1.7% [55,56], and the uncertainty in $\mathcal{B}_{J/\psi\to\mu^+\mu^-}$ is 0.55% [51]. Fit-related uncertainties in signal yield extraction are evaluated by varying the signal and background models, as follows: (i) using a sum of Crystal Ball [57] and Gaussian functions for the J/ψ and $\psi(2S)$ signals; (ii) fixing the Crystal Ball parameters to values determined from Monte Carlo simulations; (iii) using a fourth-order polynomial for the quantum electrodynamics (QED) background; (iv) adjusting the dimuon invariant mass range in the fit and sideband mass region for the QED background p_T template; (v) varying the coherent-process-dominated p_T region to be $p_\mathrm{T} < 0.3$ GeV; (vi) varying the Pb nuclear radius by 1 fm for the coherent J/ψ p_T template simulation as suggested in Ref. [25]; (vii) allowing free parameters for the p_T distributions of incoherent J/ψ and $\psi(2S)$ with nucleon dissociation. They contribute a total of 6%–13%, depending on $W_{\gamma\mathrm{N}}$. Tag-and-probe corrections introduce uncertainties of 3%–7%, while the choice of forward calorimeter threshold leads to a 4%–8% uncertainty. The uncertainty in the neutron multiplicity migration correction is 0.1%–0.2%, determined by comparing an alternative approach [58] with the observed neutron emission rates. The uncertainties from fractions at low and high ω in 0n0n events are 1%–7% depending on the $W_{\gamma\mathrm{N}}$ values. Individual sources of experimental uncertainties are added in quadrature to obtain the total systematic uncertainty of 10%–18%. Uncertainties stemming from photon flux calculations are below 3%, reflecting variations due to uncertainties in the Pb nuclear radius, nuclear skin thickness [59], and the EMD cross section [60].

The measured total differential incoherent J/ψ photoproduction cross sections are reported in Fig. 1 (left) in three rapidity bins within $1.6 < |y| < 2.4$. Results resolving the two-way ambiguity are shown versus signed y in Fig. 1 (right). Values at $-y$ and $+y$ reflect J/ψ and neutrons with same or opposite rapidity signs, respectively. The significant asymmetry between $-y$ and $+y$ confirms a strong correlation between the incoherent J/ψ and neutrons. The higher values at $-y$ compared to $+y$ primarily result from the larger number of low energy photons.

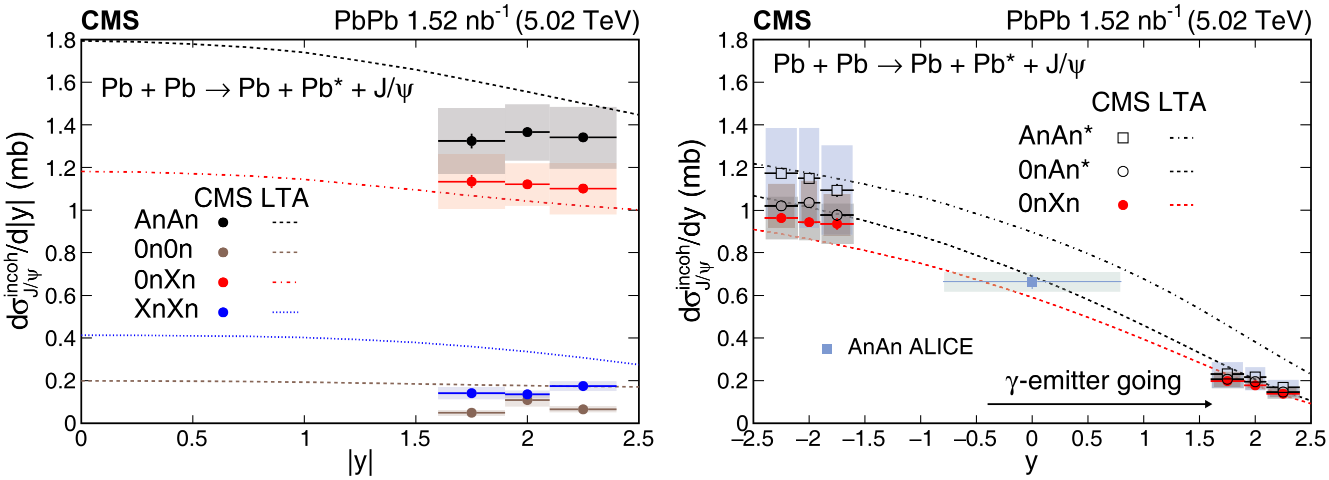

FIG. 1. The total differential incoherent J/ψ photoproduction cross section versus $|y|$ (left) and y (right). The right panel shows the results after disentangling the directional correlation between the produced J/ψ and emitted forward neutrons. The small vertical bars and shaded boxes represent the statistical and systematic uncertainties, respectively. The horizontal bars show the bin widths. Theoretical predictions from the LTA [28,29] are shown by curves.

The 0 nAn* (AnAn*) categories are the sums of the 0nXn and 0n0n (0nXn, 0n0n, and XnXn) categories. The ALICE data [9], although measured within $0.2 < p_T < 1.0$ GeV, are in good agreement with the rapidity distribution of CMS AnAn* data. A model focusing on leading-twist contributions, which includes weak nuclear shadowing effects from multinucleon interference during the scattering process within the perturbative QCD framework (referred to as LTA [28,29]), cannot describe the data in different neutron categories simultaneously, especially in the positive y region.

Following Eq. (3), the total incoherent J/ψ photoproduction cross section (0 nAn*) is corrected by the photon flux values to obtain the cross section per γPb interaction. The results are shown as a function of $W_{\gamma N}$ in Fig. 2. Results are compared with several theoretical models: IA and LTA [28,29], and CGC [61,62]. The CGC model is based on the color glass condensate (CGC) framework, an effective theory that describes the high-gluon density regime of QCD [5]. The CGC calculations use an impact-parameter dependent saturation formalism [63] and offer predictions in two scenarios: with and without additional nucleon substructure fluctuations [61,62], labeled CGC-SF and CGC-noSF, respectively. The experimental data are significantly lower than the IA prediction for $40 < W_{\gamma N} < 400$ GeV, indicating strong nuclear modification of incoherent J/ψ photoproduction in γPb interactions. The LTA model describes the CMS data for $W_{\gamma N} < 60$ GeV, but seems to systematically overestimate the data at higher $W_{\gamma N}$. While the CGC-noSF model describes the ALICE and CMS data for $W_{\gamma N} > 90$ GeV, it underestimates the CMS data for $W_{\gamma N} < 60$ GeV. The CGC-SF model systematically overestimates the data.

To quantify the impact of nuclear modifications on incoherent J/ψ photoproduction, a nuclear suppression factor, $S^{J/\psi}$, is defined as a ratio of measured cross section to the IA prediction in Ref. [28,29]. The extracted $S^{J/\psi}$ values are plotted as a function of x in Fig. 3. The suppression in the region of $x > 3 \times 10^{-3}$ is approximately 0.4–0.5. The $S^{J/\psi}$ value drops rapidly to around 0.25 at $x \approx 10^{-3}$ before plateauing at a value of around 0.14–0.18

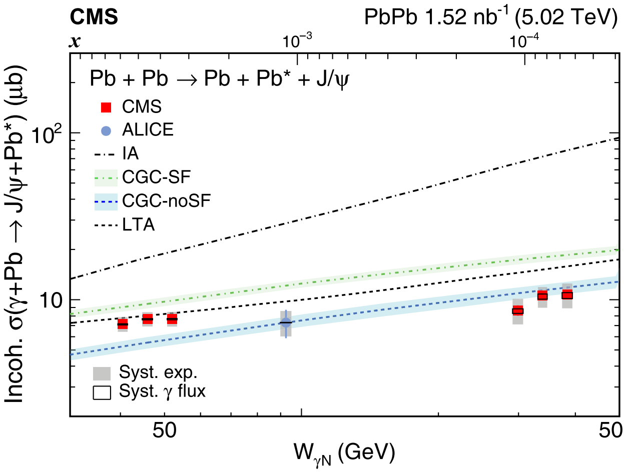

FIG. 2. The incoherent J/ψ photoproduction cross section per γPb interaction as a function of $W_{\gamma N}$ (lower axis) or x (upper axis) from the CMS measurement. The ALICE data ($|y| < 0.9$) measured at $\sqrt{s_{NN}} = 2.76$ TeV [18] is also displayed. The small vertical bars, shaded, and open boxes represent the statistical, experimental, and theoretical (photon flux) uncertainties, respectively. Theoretical predictions from IA and LTA [28,29], and CGC [61,62] models are shown by the curves, where the shaded bands are the theoretical uncertainties.

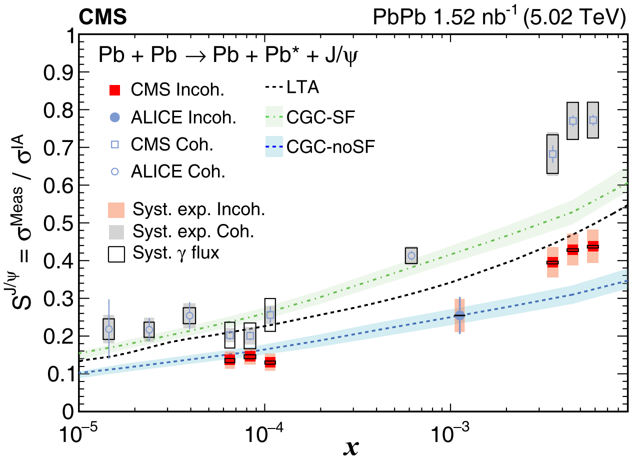

FIG. 3. The nuclear suppression factor $S^{J/\psi}$ of incoherent (from this Letter and ALICE [18]) and coherent (from CMS [25] and ALICE [26]) J/ψ photoproduction as a function of x. The vertical bars and shaded and open boxes represent the statistical, experimental systematic, and theoretical systematic uncertainties, respectively. The prediction (incoherent) from the LTA [28,29] and CGC [61,62] models are shown by curves, where the shaded bands are the theoretical uncertainties.

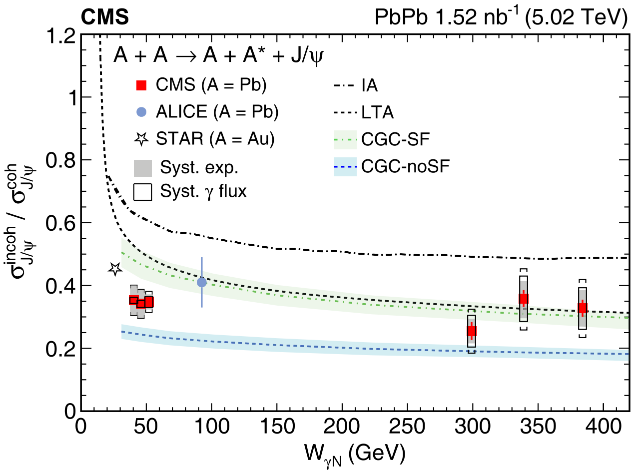

FIG. 4. The ratio between incoherent and coherent J/ψ photoproduction cross section as a function of $W_{\gamma N}$. The midrapidity data from the STAR [31] and ALICE [18] experiments are also displayed. The vertical bars, the shaded boxes, open boxes, and brackets of the CMS data represent the statistical, experimental, theoretical (photon flux), and total uncertainties, respectively. The vertical bar ALICE data represent the total uncertainties. The STAR error bars are invisible due to the assumption of substantial cancellation of systematic uncertainties. Theoretical predictions from the IA [27,29], LTA [28,29], and CGC [61,62] models are shown by curves, where the shaded bands are the theoretical uncertainties.

for $x < 10^{-4}$. The $S^{J/\psi}$ of incoherent production is generally lower than that of coherent production for $x > 10^{-4}$. (Note that the nuclear gluon suppression factor of coherent J/ψ photoproduction reported in Refs. [25,26] is defined by $R_g^{\rm Pb} = \sqrt{S^{J/\psi}}$). However, at lower x, their $S^{J/\psi}$ values become more comparable, suggesting that nuclear suppression effects become insensitive to whether the process is coherent or incoherent at sufficiently small x. Both LTA and CGC models fail to describe the observed $S^{J/\psi}$ distribution over the probed x region.

Figure 4 shows the ratio of measured incoherent to coherent J/ψ cross sections, derived using the coherent results from Ref. [25]. The data are significantly lower than the IA prediction [27,29], suggesting that the incoherent photoproduction is more strongly suppressed than the coherent photoproduction, likely due to underlying nuclear effects. At $W_{\gamma N} < 60$ GeV, the LTA [28,29] predicts a steeply rising trend toward lower energies, which is not supported by the data. This is despite the fact that the LTA model can successfully describe the incoherent J/ψ cross section in this energy range, as shown in Fig. 2. Although the CGC-SF prediction does not describe separately the coherent and incoherent cross sections well, it qualitatively captures the overall trend of their ratio across the entire $W_{\gamma N}$ range. In contrast, the CGC-noSF model significantly underestimates the data. In the higher $W_{\gamma N}$ region, both the LTA and CGC-SF models describe the data. For the $W_{\gamma N}$ range probed, the CMS measured ratios stay around a constant value which agrees with previous measurements performed by the STAR [31] and ALICE [18] experiments. The nearly flat ratio suggests that the recent results of slowly increasing coherent J/ψ photoproduction cross section versus $W_{\gamma N}$ [25,26] should not be attributed to the aforementioned black disk limit [30]. If it were, the ratio would decrease at higher $W_{\gamma N}$, as the nuclear inner structure becomes invisible.

In summary, this Letter presents the first energy-dependent measurements of incoherent J/ψ photoproduction in ultraperipheral lead-lead collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV. The data covers a photon-nucleon energy range of 40–400 GeV, probing gluons x values between 5.9×10^{-3} and 6.5×10^{-5}. Compared to baseline predictions without nuclear effects, incoherent J/ψ photoproduction cross sections exhibit greater suppression at lower x, and this suppression is more pronounced than that of coherent J/ψ production. The observed constant ratio between incoherent and coherent photoproduction cross sections suggests suppression mechanisms disfavoring simple black disk limit scenarios at small x. A model that includes gluon field fluctuations at the subnucleon level does not fully describe the incoherent and coherent cross sections, but captures the general trend of their ratio across the $W_{\gamma N}$ range. This Letter offers important new insights into the evolution of fluctuating gluon fields within nuclei across a wide x range, indicating the need for advancements in current theoretical models. These measurements also provide valuable input for the planning of future facilities, such as the EIC [64] and

LHeC [65], where photoproduction processes will be of great interest.

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I. Data availability—Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy [66].

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End Matter

Method of incoherent J/ψ signal yield extraction—The reconstructed dimuon candidates can originate from several sources: coherent and incoherent J/ψ photoproduction; J/ψ coming from the decay of coherent and incoherent photoproduced $\psi(2S)$ (referred to as "feed-down"); and the dimuon QED continuum resulting from the $\gamma\gamma \to \mu^+\mu^-$ process. To extract the incoherent J/ψ photoproduction contribution, a two-step analysis is performed by first fitting the uncorrected dimuon invariant mass distribution in the coherent-process-dominated kinematic region of $p_T < 0.2$ GeV, and then fitting the corrected dimuon p_T spectrum within the J/ψ mass window of $2.95 < m_{\mu^+\mu^-} < 3.25$ GeV. In the first step, two Crystal Ball functions are used to describe the J/ψ and $\psi(2S)$ signals, while a third-order polynomial function parametrizes the QED background ($\gamma\gamma \to \mu^+\mu^-$), following the fitting method described in Ref. [25]. The contributions from the QED and feed-down processes are determined in this step. In the second step, by taking advantage of the different p_T spectra between coherent and incoherent J/ψ photoproduction, in addition to constraints on the contributions from the QED continuum and the feed-down, the incoherent J/ψ photoproduction yield is calculated using fitting techniques similar to those of Refs. [19,20,25,26].

Considering the long tail of the QED continuum in the high-p_T region, which may arise from high-order $\gamma\gamma$ processes or semicoherent processes as discussed in Refs. [46,67,68], the p_T shape from the sideband region of the J/ψ mass peak is used. While the p_T spectrum in the sideband is an averaged p_T shape of the lower-mass sideband ($2.75 < m_{\mu^+\mu^-} < 2.90$ GeV) and higher-mass sideband ($3.30 < m_{\mu^+\mu^-} < 3.35$ GeV), the lower or higher sideband alone is used for estimating the systematic uncertainties. Previous studies [19,20,25,26] neglected the contribution of J/ψ from direct incoherent photoproduced $\psi(2S)$ decays with nucleon dissociation. In this study, we obtained the p_T template for this contribution by assuming that the direct incoherent photoproduced $\psi(2S)$ has the same p_T^2 slope as measured by the H1 experiment at HERA [69]. The p_T shape of direct incoherent photoproduced J/ψ with nucleon dissociation is modeled using an empirical function, employed by the H1 [70], ALICE [19,20,26], and CMS [25] experiments: $\mathrm{d}N/\mathrm{d}p_T \approx p_T[1 + (b_{\mathrm{pd}}/n_{\mathrm{pd}})p_T^2]^{-n_{\mathrm{pd}}}$. The two fit parameters, b_{pd} and n_{pd}, are fixed to the values obtained by the H1 experiment [70] as default, but are treated as free parameters in the fit for systematic uncertainty estimation. Normalizations of coherent and incoherent $\psi(2S)$ feed-down to J/ψ are constrained to those of the prompt coherent and incoherent J/ψ photoproduction components according to the cross section ratios of $\psi(2S)$ to J/ψ extracted from the fit to the invariant mass distributions within the coherent-process-dominant p_T (< 0.2 GeV) region, following Eqs. (A2)–(A4) in Ref. [25]. The primary fitting procedures are consistent with the well-established methods in Refs. [19,20,26]. Since the incoherent J/ψ has a broad p_T distribution, directly extracting the total uncorrected yield from the raw p_T distribution and then correcting it by its reconstruction efficiency would require calculating the p_T-integrated efficiency. This would depend on the input p_T shape. To mitigate the uncertainty regarding the p_T-integrated efficiency arising from the input p_T shape, a p_T-dependent efficiency is applied on the uncorrected p_T spectra. Subsequently, a fit of these corrected p_T spectra allows the direct extraction of the corrected total incoherent J/ψ yield $N^{\mathrm{incoh}}_{J/\psi}/(A\epsilon)_{J/\psi}$.

Figure 5 shows examples of the corrected dimuon p_T spectrum for dimuon candidates having an invariant mass in the J/ψ mass window. The cases where J/ψ candidates and neutrons have the same or opposite rapidity signs are denoted as "J/ψ-Xn(Same)" and "J/ψ-Xn(Opposite)."

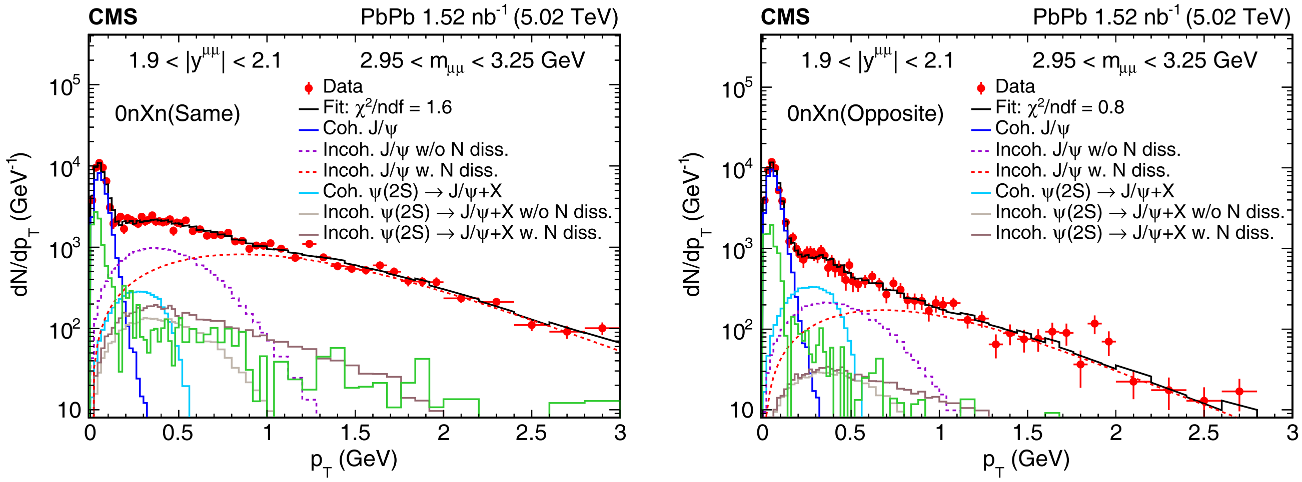

FIG. 5. The corrected transverse momentum spectra of $\mu^+\mu^-$ pairs with a dimuon invariant mass in the J/ψ mass window of $(2.95 < m_{\mu^+\mu^-} < 3.25\ \mathrm{GeV})$ in “0nXn(Same)” (left) and “0nXn(Opposite)” (right) events. The results of the fit are shown by the various curves. The vertical bars on the data points represent the statistical uncertainty.

The magnitudes of coherent contributions in the two panels are similar, whereas the incoherent contribution in the left panel is significantly higher than that in the right panel. This behavior confirms the theoretical expectations [7,53] that the emitted neutrons in coherent J/ψ production events are primarily caused by additional soft-photon exchange between the two nuclei, resulting in no correlation between the neutron direction and the J/ψ rapidity. In contrast, the neutrons emitted from incoherent J/ψ production exhibit a strong correlation between the neutron directions and the J/ψ rapidity, as these neutrons are mainly induced by the incoherent interaction process itself. Similar findings are also reported in a recent STAR measurement [71].

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K. Coldham,[175] P. Das,[175] G. Dezoort,[175] P. Elmer,[175] P. Fackeldey,[175] A. Frankenthal,[175] B. Greenberg,[175] N. Haubrich,[175] K. Kennedy,[175] G. Kopp,[175] S. Kwan,[175] D. Lange,[175] A. Loeliger,[175] D. Marlow,[175] I. Ojalvo,[175] J. Olsen,[175] F. Simpson,[175] D. Stickland,[175] C. Tully,[175] L. H. Vage,[175] S. Malik,[176] R. Sharma,[176] A. S. Bakshi,[177] S. Chandra,[177] R. Chawla,[177] A. Gu,[177] L. Gutay,[177] M. Jones,[177] A. W. Jung,[177] A. M. Koshy,[177] M. Liu,[177] G. Negro,[177] N. Neumeister,[177] G. Paspalaki,[177] S. Piperov,[177] J. F. Schulte,[177] A. K. Virdi,[177] F. Wang,[177] A. Wildridge,[177] W. Xie,[177] Y. Yao,[177] J. Dolen,[178] N. Parashar,[178] A. Pathak,[178] D. Acosta,[179] A. Agrawal,[179] T. Carnahan,[179] K. M. Ecklund,[179] P. J. Fernández Manteca,[179] S. Freed,[179] P. Gardner,[179] F. J. M. Geurts,[179] X. Huang,[179] I. Krommydas,[179] W. Li,[179] J. Lin,[179] O. Miguel Colin,[179] B. P. Padley,[179] R. Redjimi,[179] J. Rotter,[179] E. Yigitbasi,[179] Y. Zhang,[179] A. Bodek,[180] P. de Barbaro,[180] R. Demina,[180] J. L. Dulemba,[180] A. Garcia-Bellido,[180] O. Hindrichs,[180] A. Khukhunaishvili,[180] N. Parmar,[180] P. Parygin,[180,p] R. Taus,[180] B. Chiarito,[181] J. P. Chou,[181] S. V. Clark,[181] D. Gadkari,[181] Y. Gershtein,[181] E. Halkiadakis,[181] M. Heindl,[181] C. Houghton,[181] D. Jaroslawski,[181] S. Konstantinou,[181] I. Laflotte,[181] A. Lath,[181] R. Montalvo,[181] K. Nash,[181] J. Reichert,[181] P. Saha,[181] S. Salur,[181] S. Schnetzer,[181] S. Somalwar,[181] R. Stone,[181] S. A. Thayil,[181] S. Thomas,[181] J. Vora,[181] D. Ally,[182] A. G. Delannoy,[182] S. Fiorendi,[182] S. Higginbotham,[182] T. Holmes,[182] A. R. Kanuganti,[182] N. Karunarathna,[182] L. Lee,[182] E. Nibigira,[182] S. Spanier,[182] D. Aebi,[183] M. Ahmad,[183] T. Akhter,[183] K. Androsov,[183,iii] O. Bouhali,[183,nnnn] R. Eusebi,[183] J. Gilmore,[183] T. Huang,[183] T. Kamon,[183,oooo] H. Kim,[183] S. Luo,[183] R. Mueller,[183] D. Overton,[183] A. Safonov,[183] N. Akchurin,[184] J. Damgov,[184] Y. Feng,[184] N. Gogate,[184] Y. Kazhykarim,[184] K. Lamichhane,[184] S. W. Lee,[184] C. Madrid,[184] A. Mankel,[184] T. Peltola,[184] I. Volobouev,[184] E. Appelt,[185] Y. Chen,[185] S. Greene,[185] A. Gurrola,[185] W. Johns,[185] R. Kunnawalkam Elayavalli,[185] A. Melo,[185] D. Rathjens,[185] F. Romeo,[185] P. Sheldon,[185] S. Tuo,[185] J. Velkovska,[185] J. Viinikainen,[185] B. Cardwell,[186] H. Chung,[186] B. Cox,[186] J. Hakala,[186] R. Hirosky,[186] A. Ledovskoy,[186] C. Mantilla,[186] C. Neu,[186] C. Ramón Álvarez,[186] S. Bhattacharya,[187] P. E. Karchin,[187] A. Aravind,[188] S. Banerjee,[188] K. Black,[188] T. Bose,[188] E. Chavez,[188] S. Dasu,[188] P. Everaerts,[188] C. Galloni,[188] H. He,[188] M. Herndon,[188] A. Herve,[188] C. K. Koraka,[188] A. Lanaro,[188] R. Loveless,[188] J. Madhusudanan Sreekala,[188] A. Mallampalli,[188] A. Mohammadi,[188] S. Mondal,[188] G. Parida,[188] L. Pétré,[188] D. Pinna,[188] A. Savin,[188] V. Shang,[188] V. Sharma,[188] W. H. Smith,[188] D. Teague,[188] H. F. Tsoi,[188] W. Vetens,[188] A. Warden,[188] S. Afanasiev,[189] V. Alexakhin,[189] D. Budkouski,[189] I. Golutvin,[189,a] I. Gorbunov,[189] V. Karjavine,[189] O. Kodolova,[189,pppp,p] V. Korenkov,[189] A. Lanev,[189] A. Malakhov,[189] V. Matveev,[189,p] A. Nikitenko,[189,qqqq,pppp] V. Palichik,[189] V. Perelygin,[189] M. Savina,[189] V. Shalaev,[189] S. Shmatov,[189] S. Shulha,[189] V. Smirnov,[189] O. Teryaev,[189] N. Voytishin,[189] B. S. Yuldashev,[189,a,rrrr] A. Zarubin,[189] I. Zhizhin,[189] G. Gavrilov,[189] V. Golovtcov,[189] Y. Ivanov,[189] V. Kim,[189,p] V. Murzin,[189] V. Oreshkin,[189] D. Sosnov,[189] V. Sulimov,[189] L. Uvarov,[189] A. Vorobyev,[189,a] Yu. Andreev,[189] A. Dermenev,[189] S. Gninenko,[189] N. Golubev,[189] A. Karneyeu,[189] D. Kirpichnikov,[189] M. Kirsanov,[189] N. Krasnikov,[189] I. Tlisova,[189] A. Toropin,[189] T. Aushev,[189] K. Ivanov,[189] V. Gavrilov,[189] N. Lychkovskaya,[189] V. Popov,[189] A. Zhokin,[189] R. Chistov,[189,p] M. Danilov,[189,p] S. Polikarpov,[189,p] V. Andreev,[189] M. Azarkin,[189] M. Kirakosyan,[189] A. Terkulov,[189] E. Boos,[189] A. Ershov,[189] A. Gribushin,[189] L. Khein,[189] V. Korotkikh,[189] O. Lukina,[189] S. Petrushanko,[189] V. Savrin,[189] A. Snigirev,[189] I. Vardanyan,[189] V. Blinov,[189,p] T. Dimova,[189,p] A. Kozyrev,[189,p] O. Radchenko,[189,p] Y. Skovpen,[189,p] V. Kachanov,[189] S. Slabospitskii,[189] A. Uzunian,[189] A. Babaev,[189] V. Borshch,[189] and D. Druzhkin[189]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Vienna, Austria*
[3]*Universiteit Antwerpen, Antwerpen, Belgium*
[4]*Vrije Universiteit Brussel, Brussel, Belgium*
[5]*Université Libre de Bruxelles, Bruxelles, Belgium*
[6]*Ghent University, Ghent, Belgium*
[7]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[8]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*

[9]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[10]*Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil*
[11]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
[12]*University of Sofia, Sofia, Bulgaria*
[13]*Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile*
[14]*Beihang University, Beijing, China*
[15]*Department of Physics, Tsinghua University, Beijing, China*
[16]*Institute of High Energy Physics, Beijing, China*
[17]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[18]*Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China*
[19]*Sun Yat-Sen University, Guangzhou, China*
[20]*University of Science and Technology of China, Hefei, China*
[21]*Nanjing Normal University, Nanjing, China*
[22]*Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China*
[23]*Zhejiang University, Hangzhou, Zhejiang, China*
[24]*Universidad de Los Andes, Bogota, Colombia*
[25]*Universidad de Antioquia, Medellin, Colombia*
[26]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
[27]*University of Split, Faculty of Science, Split, Croatia*
[28]*Institute Rudjer Boskovic, Zagreb, Croatia*
[29]*University of Cyprus, Nicosia, Cyprus*
[30]*Charles University, Prague, Czech Republic*
[31]*Escuela Politecnica Nacional, Quito, Ecuador*
[32]*Universidad San Francisco de Quito, Quito, Ecuador*
[33]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
[34]*Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt*
[35]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[36]*Department of Physics, University of Helsinki, Helsinki, Finland*
[37]*Helsinki Institute of Physics, Helsinki, Finland*
[38]*Lappeenranta-Lahti University of Technology, Lappeenranta, Finland*
[39]*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[40]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
[41]*Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*
[42]*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*
[43]*Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France*
[44]*Georgian Technical University, Tbilisi, Georgia*
[45]*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
[46]*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[47]*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
[48]*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[49]*University of Hamburg, Hamburg, Germany*
[50]*Karlsruher Institut fuer Technologie, Karlsruhe, Germany*
[51]*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
[52]*National and Kapodistrian University of Athens, Athens, Greece*
[53]*National Technical University of Athens, Athens, Greece*
[54]*University of Ioánnina, Ioánnina, Greece*
[55]*HUN-REN Wigner Research Centre for Physics, Budapest, Hungary*
[56]*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
[57]*Faculty of Informatics, University of Debrecen, Debrecen, Hungary*
[58]*HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary*
[59]*Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary*
[60]*Panjab University, Chandigarh, India*
[61]*University of Delhi, Delhi, India*
[62]*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
[63]*Indian Institute of Technology Madras, Madras, India*
[64]*Tata Institute of Fundamental Research-A, Mumbai, India*
[65]*Tata Institute of Fundamental Research-B, Mumbai, India*

[66]*National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India*
[67]*Indian Institute of Science Education and Research (IISER), Pune, India*
[68]*Isfahan University of Technology, Isfahan, Iran*
[69]*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
[70]*University College Dublin, Dublin, Ireland*
[71a]*INFN Sezione di Bari, Bari, Italy*
[71b]*Università di Bari, Bari, Italy*
[71c]*Politecnico di Bari, Bari, Italy*
[72a]*INFN Sezione di Bologna, Bologna, Italy*
[72b]*Università di Bologna, Bologna, Italy*
[73a]*INFN Sezione di Catania, Catania, Italy*
[73b]*Università di Catania, Catania, Italy*
[74a]*INFN Sezione di Firenze, Firenze, Italy*
[74b]*Università di Firenze, Firenze, Italy*
[75]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[76a]*INFN Sezione di Genova, Genova, Italy*
[76b]*Università di Genova, Genova, Italy*
[77a]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[77b]*Università di Milano-Bicocca, Milano, Italy*
[78a]*INFN Sezione di Napoli, Napoli, Italy*
[78b]*Università di Napoli 'Federico II', Napoli, Italy*
[78c]*Università della Basilicata, Potenza, Italy*
[78d]*Scuola Superiore Meridionale (SSM), Napoli, Italy*
[79a]*INFN Sezione di Padova, Padova, Italy*
[79b]*Università di Padova, Padova, Italy*
[79c]*Università di Trento, Trento, Italy*
[80a]*INFN Sezione di Pavia, Pavia, Italy*
[80b]*Università di Pavia, Pavia, Italy*
[81a]*INFN Sezione di Perugia, Perugia, Italy*
[81b]*Università di Perugia, Perugia, Italy*
[82a]*INFN Sezione di Pisa, Pisa, Italy*
[82b]*Università di Pisa, Pisa, Italy*
[82c]*Scuola Normale Superiore di Pisa, Pisa, Italy*
[82d]*Università di Siena, Siena, Italy*
[83a]*INFN Sezione di Roma, Roma, Italy*
[83b]*Sapienza Università di Roma, Roma, Italy*
[84a]*INFN Sezione di Torino, Torino, Italy*
[84b]*Università di Torino, Torino, Italy*
[84c]*Università del Piemonte Orientale, Novara, Italy*
[85a]*INFN Sezione di Trieste, Trieste, Italy*
[85b]*Università di Trieste, Trieste, Italy*
[86]*Kyungpook National University, Daegu, Korea*
[87]*Department of Mathematics and Physics - GWNU, Gangneung, Korea*
[88]*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
[89]*Hanyang University, Seoul, Korea*
[90]*Korea University, Seoul, Korea*
[91]*Kyung Hee University, Department of Physics, Seoul, Korea*
[92]*Sejong University, Seoul, Korea*
[93]*Seoul National University, Seoul, Korea*
[94]*University of Seoul, Seoul, Korea*
[95]*Yonsei University, Department of Physics, Seoul, Korea*
[96]*Sungkyunkwan University, Suwon, Korea*
[97]*College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait*
[98]*Kuwait University - College of Science - Department of Physics, Safat, Kuwait*
[99]*Riga Technical University, Riga, Latvia*
[100]*University of Latvia (LU), Riga, Latvia*
[101]*Vilnius University, Vilnius, Lithuania*
[102]*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
[103]*Universidad de Sonora (UNISON), Hermosillo, Mexico*
[104]*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*

[105]*Universidad Iberoamericana, Mexico City, Mexico*
[106]*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
[107]*University of Montenegro, Podgorica, Montenegro*
[108]*University of Canterbury, Christchurch, New Zealand*
[109]*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
[110]*AGH University of Krakow, Krakow, Poland*
[111]*National Centre for Nuclear Research, Swierk, Poland*
[112]*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[113]*Warsaw University of Technology, Warsaw, Poland*
[114]*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
[115]*Faculty of Physics, University of Belgrade, Belgrade, Serbia*
[116]*VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
[117]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[118]*Universidad Autónoma de Madrid, Madrid, Spain*
[119]*Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*
[120]*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
[121]*University of Colombo, Colombo, Sri Lanka*
[122]*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
[123]*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[124]*PSI Center for Neutron and Muon Sciences, Villigen, Switzerland*
[125]*ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
[126]*Universität Zürich, Zurich, Switzerland*
[127]*National Central University, Chung-Li, Taiwan*
[128]*National Taiwan University (NTU), Taipei, Taiwan*
[129]*High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand*
[130]*Tunis El Manar University, Tunis, Tunisia*
[131]*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
[132]*Middle East Technical University, Physics Department, Ankara, Turkey*
[133]*Bogazici University, Istanbul, Turkey*
[134]*Istanbul Technical University, Istanbul, Turkey*
[135]*Istanbul University, Istanbul, Turkey*
[136]*Yildiz Technical University, Istanbul, Turkey*
[137]*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine*
[138]*National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine*
[139]*University of Bristol, Bristol, United Kingdom*
[140]*Rutherford Appleton Laboratory, Didcot, United Kingdom*
[141]*Imperial College, London, United Kingdom*
[142]*Brunel University, Uxbridge, United Kingdom*
[143]*Baylor University, Waco, Texas, USA*
[144]*Catholic University of America, Washington, DC, USA*
[145]*The University of Alabama, Tuscaloosa, Alabama, USA*
[146]*Boston University, Boston, Massachusetts, USA*
[147]*Brown University, Providence, Rhode Island, USA*
[148]*University of California, Davis, Davis, California, USA*
[149]*University of California, Los Angeles, California, USA*
[150]*University of California, Riverside, Riverside, California, USA*
[151]*University of California, San Diego, La Jolla, California, USA*
[152]*University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA*
[153]*California Institute of Technology, Pasadena, California, USA*
[154]*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
[155]*University of Colorado Boulder, Boulder, Colorado, USA*
[156]*Cornell University, Ithaca, New York, USA*
[157]*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[158]*University of Florida, Gainesville, Florida, USA*
[159]*Florida State University, Tallahassee, Florida, USA*
[160]*Florida Institute of Technology, Melbourne, Florida, USA*
[161]*University of Illinois Chicago, Chicago, Illinois, USA*
[162]*The University of Iowa, Iowa City, Iowa, USA*
[163]*Johns Hopkins University, Baltimore, Maryland, USA*
[164]*The University of Kansas, Lawrence, Kansas, USA*

[165]*Kansas State University, Manhattan, Kansas, USA*
[166]*University of Maryland, College Park, Maryland, USA*
[167]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[168]*University of Minnesota, Minneapolis, Minnesota, USA*
[169]*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
[170]*State University of New York at Buffalo, Buffalo, New York, USA*
[171]*Northeastern University, Boston, Massachusetts, USA*
[172]*Northwestern University, Evanston, Illinois, USA*
[173]*University of Notre Dame, Notre Dame, Indiana, USA*
[174]*The Ohio State University, Columbus, Ohio, USA*
[175]*Princeton University, Princeton, New Jersey, USA*
[176]*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
[177]*Purdue University, West Lafayette, Indiana, USA*
[178]*Purdue University Northwest, Hammond, Indiana, USA*
[179]*Rice University, Houston, Texas, USA*
[180]*University of Rochester, Rochester, New York, USA*
[181]*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
[182]*University of Tennessee, Knoxville, Tennessee, USA*
[183]*Texas A and M University, College Station, Texas, USA*
[184]*Texas Tech University, Lubbock, Texas, USA*
[185]*Vanderbilt University, Nashville, Tennessee, USA*
[186]*University of Virginia, Charlottesville, Virginia, USA*
[187]*Wayne State University, Detroit, Michigan, USA*
[188]*University of Wisconsin - Madison, Madison, Wisconsin, USA*
[189]*An institute or international laboratory covered by a cooperation agreement with CERN*

[a] Deceased.
[b] Also at Yerevan State University, Yerevan, Armenia.
[c] Also at TU Wien, Vienna, Austria.
[d] Also at Ghent University, Ghent, Belgium.
[e] Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil.
[f] Also at FACAMP—Faculdades de Campinas, Sao Paulo, Brazil.
[g] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[h] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[i] Also at University of Chinese Academy of Sciences, Beijing, China.
[j] Also at China Center of Advanced Science and Technology, Beijing, China.
[k] Also at University of Chinese Academy of Sciences, Beijing, China.
[l] Also at China Spallation Neutron Source, Guangdong, China.
[m] Also at Henan Normal University, Xinxiang, China.
[n] Also at University of Shanghai for Science and Technology, Shanghai, China.
[o] Also at The University of Iowa, Iowa City, Iowa, USA.
[p] Also at Another institute or international laboratory covered by a cooperation agreement with CERN.
[q] Also at Helwan University, Cairo, Egypt.
[r] Also at Suez University, Suez, Egypt.
[s] Also at British University in Egypt, Cairo, Egypt.
[t] Also at Purdue University, West Lafayette, Indiana, USA.
[u] Also at Université de Haute Alsace, Mulhouse, France.
[v] Also at Istinye University, Istanbul, Turkey.
[w] Also at Tbilisi State University, Tbilisi, Georgia.
[x] Also at The University of the State of Amazonas, Manaus, Brazil.
[y] Also at University of Hamburg, Hamburg, Germany.
[z] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[aa] Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[bb] Also at Brandenburg University of Technology, Cottbus, Germany.
[cc] Also at Forschungszentrum Jülich, Juelich, Germany.
[dd] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[ee] Also at HUN-REN ATOMKI—Institute of Nuclear Research, Debrecen, Hungary.
[ff] Also at Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.
[gg] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

[hh] Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.
[ii] Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[jj] Also at Punjab Agricultural University, Ludhiana, India.
[kk] Also at University of Visva-Bharati, Santiniketan, India.
[ll] Also at Indian Institute of Science (IISc), Bangalore, India.
[mm] Also at Amity University Uttar Pradesh, Noida, India.
[nn] Also at IIT Bhubaneswar, Bhubaneswar, India.
[oo] Also at Institute of Physics, Bhubaneswar, India.
[pp] Also at University of Hyderabad, Hyderabad, India.
[qq] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[rr] Also at Isfahan University of Technology, Isfahan, Iran.
[ss] Also at Sharif University of Technology, Tehran, Iran.
[tt] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[uu] Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran.
[vv] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[ww] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[xx] Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[yy] Also at Scuola Superiore Meridionale, Università di Napoli ’Federico II’, Napoli, Italy.
[zz] Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[aaa] Also at Lulea University of Technology, Lulea, Sweden.
[bbb] Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.
[ccc] Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France.
[ddd] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[eee] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[fff] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[ggg] Also at Saegis Campus, Nugegoda, Sri Lanka.
[hhh] Also at National and Kapodistrian University of Athens, Athens, Greece.
[iii] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[jjj] Also at Universität Zürich, Zurich, Switzerland.
[kkk] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[lll] Also at Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[mmm] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[nnn] Also at Konya Technical University, Konya, Turkey.
[ooo] Also at Izmir Bakircay University, Izmir, Turkey.
[ppp] Also at Adiyaman University, Adiyaman, Turkey.
[qqq] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[rrr] Also at Marmara University, Istanbul, Turkey.
[sss] Also at Milli Savunma University, Istanbul, Turkey.
[ttt] Also at Kafkas University, Kars, Turkey.
[uuu] Also at Istanbul Okan University, Istanbul, Turkey.
[vvv] Also at Hacettepe University, Ankara, Turkey.
[www] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[xxx] Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[yyy] Also at Yildiz Technical University, Istanbul, Turkey.
[zzz] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[aaaa] Also at IPPP Durham University, Durham, United Kingdom.
[bbbb] Also at Monash University, Faculty of Science, Clayton, Australia.
[cccc] Also at Università di Torino, Torino, Italy.
[dddd] Also at Bethel University, St. Paul, Minnesota, USA.
[eeee] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[ffff] Also at California Institute of Technology, Pasadena, California, USA.
[gggg] Also at United States Naval Academy, Annapolis, Maryland, USA.
[hhhh] Also at Ain Shams University, Cairo, Egypt.
[iiii] Also at Bingol University, Bingol, Turkey.
[jjjj] Also at Georgian Technical University, Tbilisi, Georgia.
[kkkk] Also at Sinop University, Sinop, Turkey.
[llll] Also at Erciyes University, Kayseri, Turkey.
[mmmm] Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.
[nnnn] Also at Texas A and M University at Qatar, Doha, Qatar.

[oooo] Also at Kyungpook National University, Daegu, Korea.
[pppp] Also at Yerevan Physics Institute, Yerevan, Armenia.
[qqqq] Also at Imperial College, London, United Kingdom.
[rrrr] Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.