Probing a new regime of ultra-dense gluonic matter using high-energy photons with the CMS experiment

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Abstract. In ultraperipheral collisions (UPCs) involving relativistic heavy ions, the production of heavy-flavor coherent vector mesons through photon-nuclear interactions is a key focus due to its direct sensitivity to the nuclear gluon density. Experimental measurements, however, face a two-way ambiguity as the collision involves two lead ions which can act as both a photon-emitter projectile and a target. This ambiguity hinders the separation of contributions from high and low-energy photon-nucleus interactions, restricting our ability to probe the extremely small-x regime where nonlinear QCD effects are anticipated. This writeup unveils the measurement of coherent heavy quarkonium photoproduction, addressing the two-way ambiguity by employing a forward neutron tagging technique in UPC PbPb collisions at 5.02 TeV. Overall these studies focus on the dominance of gluons in nuclear matter probed at higher energies.

1 Introduction

The electromagnetic fields surrounding relativistic heavy ions are highly Lorentz contracted and can be effectively treated as linearly polarized quasireal photons at a first approximation [2, 3]. These photons are powerful probes of the gluonic structure of nuclei [4]. Ultraperipheral collisions (UPCs) occur when two relativistic heavy ions pass each other at large impact parameters, reducing the probability of having the hadronic interactions. Cases like photon photon or photon nucleus interaction occurs in such collisions. Notably, vector meson photoproduction occurs when a photon from one nucleus fluctuates into a quark-antiquark pair, which then scatters off the other nucleus, emerging as a real meson. This phenomenon has been studied at high-energy facilities like the RHIC and LHC.

At energies accessible at the CERN LHC these studies can lead towards probing the poorly known nuclear gluonic structure and dynamics in the low Bjorken-x region. There is a possibility that at a point the increasing gluon density would reach saturation, along with the saturation of Vector meson cross section at the geometric limit of the nucleus. Another possibility can be nucleus target becoming totally absorptive to incoming photons leading to a "Black Disk Limit", where the internal structure of nucleus vanishes [1].

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, 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 significantly increases with the photon-proton center-of-mass energy because of the rising gluon density at small x [1, 5].

For symmetric collision system, where either of the ions can be the photon emitter or target, the complications are even more increased. To solve this two-way ambiguity, we control the UPC impact parameter and thus the relative contributions of low and high energy photons to the measured J/ψ cross section can be separated [1].

2 Analysis Technique

The results shown in this writeup use Pb-Pb 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}. The CMS detector has a highly sophisticated tracking system which captures particle trajectories with high precision. For muon detection, detectors containing 2 million cathode strip chamber wires are placed at the outer edges which detects the ionization trail left by muons. Additionally, the Zero Degree Calorimeters (ZDCs) made from tungsten embedded quartz fibers, detect neutrons produced during ultraperipheral collisions and helps us the identify the centrality in UPCs.

Events are selected using a hardware-based trigger system that requires at least one muon candidate with no explicit selection on its transverse momentum (p_T), coincident with a Pb-Pb bunch crossing [6]. At the trigger level, events with an energy deposit above the noise threshold in either of the forward calorimeters are vetoed. For the off-line analysis, events must 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 detector center. To suppress hadronic collisions, using empty bunch-crossing events only the forward calorimeters having their largest energy deposits below 7.3 and 7.6 GeV in the positive and negative rapidity sides, respectively are selected. [1]

Additionally, both the muon needs to be "soft muons" [7], lying in the range $|\eta| < 2.4$. The dimuon pair (ψ or J/ψ candidates) lies in mass region $2.6 < m_{\mu^+\mu^-} < 4.2$ GeV and rapidity region $1.6 < |y| < 2.4$. For each muon pair, at least one of the muon candidates must match the triggered muon [1].

3 Results

Based on the neutron peaks observed in the total ZDC energy distribution, events are classified with number of nuetrons fallen in ZDCs, 0n0n, 0nXn or XnXn. The relative fractions of J/ψ candidates in 0n0n, 0nXn, and XnXn classes are determined to be 73, 21, and 6% corrected from the corresponding raw fractions of 65, 28, and 7%, respectively [1].

Because of the symmetry of the Pb-Pb collision system,a J/ψ meson measured at rapidity y can result from two possible photon energies: $\omega_1 = (M_{J/\psi}/2 \text{ exp(-y)})$ and $\omega_2 = (M_{J/\psi}/2 \text{ exp(+y)})$. The measured differential cross section at a rapidity y for a neutron multiplicity class, injn (=0n0n, 0nXn, XnXn), of UPC events is the sum of both photon energy contributions [8]:

$$\frac{d\sigma^{injn}_{J/\psi}(y)}{dy} = n^{injn}_{\gamma A}(\omega_1)\,\sigma_{J/\psi}(\omega_1) + n^{injn}_{\gamma A}(\omega_2)\,\sigma_{J/\psi}(\omega_2), \quad (1)$$

The measured coherent J/ψ photoproduction differential cross sections over the rapidity range 1.6 < |y| < 2.4 are reported in Fig. 1 (left) in three neutron multiplicity classes. The results with no neutron selection are given in the right plot of Fig. 1 [1].

The x of the associated parton and $W^{Pb}_{\gamma N}$ with a photon of energy ω_1 can be found using $x = (M_{J/\psi}/\sqrt{s_{NN}})\exp(+y)$ and $W^{Pb}_{\gamma N} = \sqrt{\sqrt{s_{NN}} M_{J/\psi}\exp(-y)}$. The corresponding values for a photon of energy ω_2 are obtained by changing the sign of y in each expression [1].

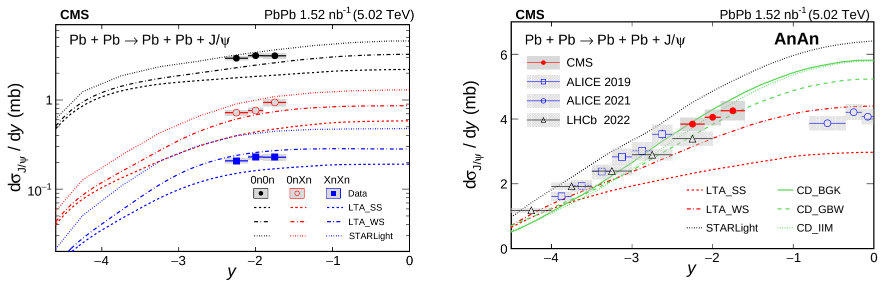

Figure 1. The differential coherent J/ψ photoproduction cross section as a function of rapidity, in different neutron multiplicity classes: 0n0n, 0nXn, and XnXn (left); AnAn (right) [1]

The measured total cross section has an unexpected energy dependence, approximately quadrupling as $W_{\gamma N}^{Pb}$ goes from 15 to 40 GeV, as seen in Fig. 2. This is consistent with the expectation of a fast growing gluon density at low x (e.g., from the IA model, where most of the nuclear effects are neglected, except coherence). However, this trend vanishes for $W_{\gamma N}^{Pb} > 40$ GeV, and instead the total cross section begins a slow linear rise with a slope of $(2.2 \pm 1.9) \times 10^{-5}$ mb/ GeV determined by a fit to CMS data with proper consideration of the covariance matrix of both statistical and systematic uncertainties. Considering the experimental uncertainties across the measured $W_{\gamma N}^{Pb}$ range, none of the theoretical models are consistent with the measurements, although data is close to Impulse Approximation (without nuclear effects) at low W and with the CD-BGK model having the best p value of 1.6×10^{-8}. Here, the photon-nucleus cross section approaches the unitarity limit allowed by the geometric size of the nucleus but the periphery of the nucleus won't become fully black [1].

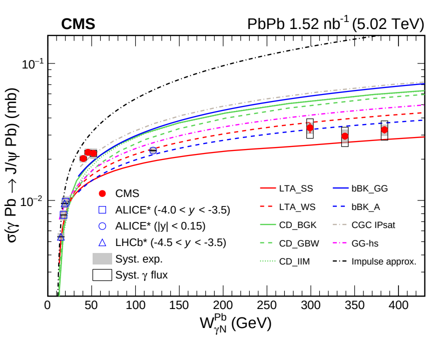

Figure 2. The total coherent J/ψ photoproduction cross section as a function of $W_{\gamma N}^{Pb}$ from the CMS measurement in Pb-Pb UPCs at = 5.02. Approximated results (implied by the asterisk) from the ALICE [9] and LHCb [10] experiments are displayed for specific rapidity regions, where the two-way ambiguity effect is expected to be negligible [1]

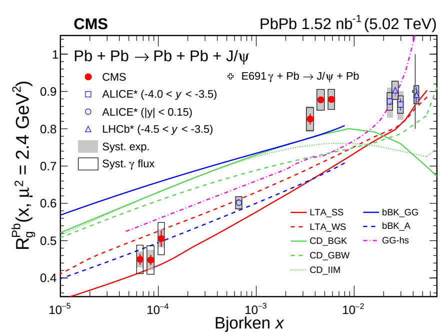

Figure 3. The nuclear gluon suppression factor R_g^{Pb} as a function of Bjorken x extracted from the coherent J/ψ photoproduction in Pb-Pb UPCs. Approximated results (implied by the asterisk) from the ALICE [9] and LHCb [10] experiments are displayed for specific rapidity regions, with negligible two-way ambiguity effect [1]

To quantify the nuclear effects on the observed gluon density function in a Pb nucleus, a nuclear gluon suppression factor, $R_g^{Pb}(x, \mu^2 = 2.4 GeV^2)$ as a function of x and with μ =

$M_{J/\psi}/2$, where μ is the energy scale, is defined as $R_g^{Pb} = \sqrt{\sigma^{\text{Meas}}/\sigma^{\text{IA}}}$, where σ^{Meas} is the measured cross section. The extracted R_g^{Pb} values are shown in Fig.3 as a function of x. The suppression in the relatively high-x (low $W_{\gamma N}^{Pb}$) region of $x > 5 \times 10^{-3}$ is approximately 0.8–0.9. At 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, this is also beyond model expectation in full phase space. At high-x region,a flat trend is observed which quickly decrease towards lower x region [1].

4 Summary

A comprehensive analysis of the coherent J/ψ photoproduction cross section off lead nuclei has been presented, with a focus on its behavior as a function of the photon-nuclear center-of-mass energy per nucleon ($W_{\gamma N}^{Pb}$). Utilizing ultraperipheral Pb-Pb collision data and employing the forward neutron tagging method, the results span a wide range of $W_{\gamma N}^{Pb}$. At lower energies, the cross section shows a steep increase, but it levels off around $W_{\gamma N}^{Pb} \approx 40$ GeV and remains constant up to 400 GeV. This energy range explores a new regime of gluon momentum fraction, with Bjorken $x \approx 6 \times 10^{-5}$, within a heavy nucleus. Interestingly, this behavior is not aligned with predictions from existing theoretical models. It may either indicate the first direct observation of nuclear gluon saturation or suggest that the cross section is approaching the black-disk limit.

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