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Probing nuclear structure at the Electron-Ion Collider and in ultra-peripheral nuclear collisions

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Abstract. Within the Color Glass Condensate framework, we demonstrate that exclusive vector meson production at high energy is sensitive to the geometric deformation of the target nucleus and subnucleon scale fluctuations. Deformation of the nucleus enhances the incoherent cross section in the small $|t|$ region. Subnucleon scale fluctuations increase the incoherent cross section in the large $|t|$ region. In ultra-peripheral collisions (UPCs), larger deformation leads to a wider distribution of the minimal impact parameter B_{min} required to produce a UPC. This, together with larger incoherent cross sections for larger deformation, results in smaller extracted radii. Our results demonstrate great potential for future studies of nuclear structure in UPCs and electron-ion collisions.

1 Introduction

Understanding the geometric structure of nuclei is of fundamental interest. Exclusive vector meson (e.g. J/ψ) production in electron-ion collisions is a clean and powerful process to probe nuclei at small longitudinal momentum fraction x for several reasons. First, a large rapidity gap allows for the clean identification of an exclusive vector meson production process. Further, its cross section is approximately proportional to the squared gluon distribution [1] (at leading order), providing increased sensitivity over inclusive processes. Finally, only in such exclusive scattering is it possible to determine the total momentum transfer to the target hadron or nucleus, which is the Fourier conjugate to the impact parameter and provides access to the target geometry.

Before facilities like the Electron-Ion Collider (EIC), LHeC/FCC-he, and EicC [2–4] are realized, ultra-peripheral collisions (UPCs) of heavy ions offer a great opportunity to explore nuclear structure with beams of quasi-real photons [5, 6]. In UPCs, the photon-nucleus ($\gamma + A$) interactions involving photons emitted from one of the colliding nuclei are dominant. Recently, STAR collaboration have revealed significant $\cos(2\Delta\Phi)$ modulations in exclusive ρ meson photoproduction in UPCs [7] with $\Delta\Phi$ the angle between the produced ρ

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meson transverse momentum \mathbf{q}_\perp and its decay product pions' relative transverse momentum. This modulation originates from the fact that both nuclei can act as photon sources and as such there are two production channels whose interference need to be taken into account. STAR also extracts the strong-interaction nuclear radii of ^{197}Au and ^{238}U .

In this work, we perform calculations of exclusive vector meson production in electron + uranium collisions and ultra-peripheral U+U collisions with different deformation parameters within the Color Glass Condensate (CGC) framework [8–10].

2 Model

The exclusive production of a vector meson, $\gamma^* + p/A \rightarrow V + p/A$, provides insight into the small- x structure of the target nuclei. The coherent cross section, corresponding to the events where the target remains intact, is obtained by averaging the amplitude over the target color charge configurations before squaring. The incoherent vector meson production, for which the final state of the target is different from its initial state, has the form of a variance,

$$\frac{d\sigma_{\text{Coh.}}^{\gamma^*+A \rightarrow V+A}}{d|t|} = \frac{1}{16\pi} |\langle \mathcal{A} \rangle_\Omega|^2, \quad \frac{d\sigma_{\text{Incoh.}}^{\gamma^*+A \rightarrow V+A}}{d|t|} = \frac{1}{16\pi} \left[\langle |\mathcal{A}|^2 \rangle_\Omega - |\langle \mathcal{A} \rangle_\Omega|^2 \right]. \quad (1)$$

Here $\langle \dots \rangle_\Omega$ correspond to an average over the target configurations Ω . The scattering amplitude for exclusive vector meson production in the dipole picture is

$$\mathcal{A} = 2i \int d^2\mathbf{r}_\perp d^2\mathbf{b}_\perp \frac{dz}{4\pi} e^{-i[\mathbf{b}_\perp - (1/2-z)\mathbf{r}_\perp] \cdot \Delta_\perp} \times [\Psi_V^* \Psi_\gamma](Q^2, \mathbf{r}_\perp, z) N_\Omega(\mathbf{r}_\perp, \mathbf{b}_\perp, x_\mathbb{P}). \quad (2)$$

Here, \mathbf{r}_\perp is the transverse size of the $q\bar{q}$ dipole, \mathbf{b}_\perp is the impact parameter measured relative to the target center, and Q^2 is the photon virtuality. The fraction of the large photon plus-momentum carried by the quark is given by z , $x_\mathbb{P}$ is the fraction of the target longitudinal momentum transferred to the meson in the frame where the target has a large momentum, and Δ_\perp is the transverse momentum transfer, with $-t \approx \Delta_\perp^2$. The $\gamma^* \rightarrow q\bar{q}$ splitting is described by the virtual photon light front wave function Ψ_γ . The Ψ_V is the vector meson wave function, for which we use the Boosted Gaussian parametrization from [11].

In UPCs, there are two indistinguishable contributions to vector meson production. Either of the colliding nuclei can act as a source of linearly polarized photons and the other being the target. We take into account the quantum mechanical interference of these two processes. We also implement the non-zero transverse momentum of the incoming photons, which significantly impacts the transverse momentum spectra of the produced vector mesons [12]. This effect is particularly important near the diffractive minima of the coherent cross-section.

3 Results

Figure 1 shows the effects of quadrupole (β_2) deformation and of subnucleonic structure fluctuations on the incoherent $\gamma + \text{U} \rightarrow \text{J}/\psi + \text{U}^{(*)}$ cross sections. As the quadrupole deformation increases, there is a noticeable rise in the incoherent cross section, particularly at small $|t| < 0.02 \text{ GeV}^2$. This enhancement can be attributed to the random orientations of the deformed nucleus in the laboratory frame, leading to larger density fluctuations of configurations projected onto the transverse plane. Consequently, larger event-by-event fluctuations in scattering amplitude occur. Similar effects are reported for octupole (β_3) and hexadecapole (β_4) deformations in [9]. Comparing the dashed black line, representing the case without subnucleonic fluctuations, to the red line with subnucleonic fluctuations, a distinct trend emerges

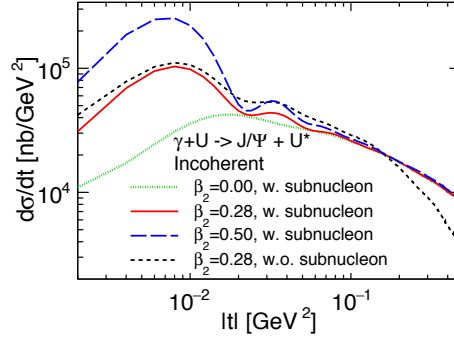


Figure 1. (Color online) The incoherent J/ψ photoproduction cross sections at $x_p = 1.7 \times 10^{-3}$ in e+U collisions for different β_2 values and with or without subnucleonic structure fluctuations.

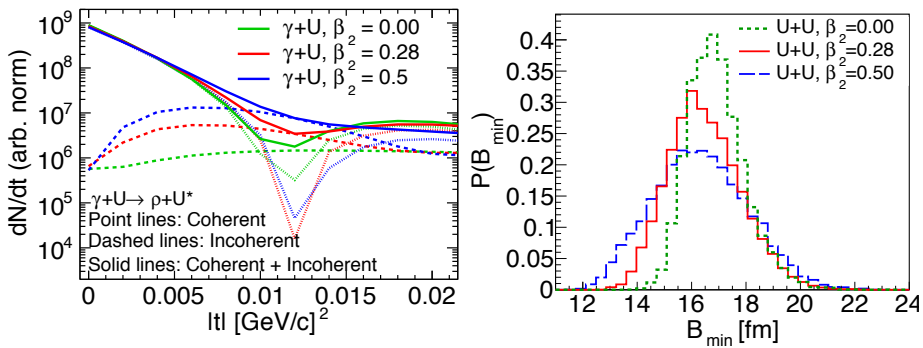


Figure 2. (Color online) Left panel: The coherent, incoherent, and total ρ photoproduction cross sections in e+U collisions for different β_2 values. Right panel: The distributions of minimal impact parameters B_{\min} for UPCs between the two uranium nuclei at 193 GeV for different β_2 values.

at $|t| > 0.25 \text{ GeV}^2$. The faster drop in the black line demonstrates that subnucleonic fluctuations alter the slope and magnitude of the incoherent cross section at large $|t|$. The figure shows the potential of such a measurement for imaging nuclear properties, ranging from deformations to subnucleonic fluctuations across orders of magnitude in momentum transfer.

The nuclear deformation was found to play a significant role in imaging the nucleus' averaged radius in e+A collisions and UPCs [10]. The left panel of Figure 2 shows the cross sections for ρ production in $\gamma + U \rightarrow \rho + U^*$ at $Q^2 = 0.0 \text{ GeV}^2$ processes, with varying β_2 values. The increase in the degree of deformation leads to an enhancement of the incoherent cross section. This enhancement produces a flatter total $dN/d|t|$ distribution. Since only the total cross section is accessible experimentally, we extract the uranium radius by fitting the total $dN/d|t|$. It is found that the slope of the total cross section is flatter for U with a large deformation, which would result in a smaller extracted radius. The right panel of Figure 2 shows the minimal impact parameters B_{\min} distributions for UPCs between the two uranium nuclei for different β_2 values. Larger β_2 values lead to wider B_{\min} distributions. Configurations that allow for small B_{\min} , with greater interference and larger photon transverse momentum, result in flatter spectra and enter with a larger weight. These two effects result in the larger effective radii R for smaller deformations of the nucleus. For details, please refer to [10].

4 Conclusions

We have demonstrated that nuclear deformations can significantly modify the incoherent vector meson production cross section $e+A$ collisions. Nuclear deformations and subnucleonic fluctuations on different length scales exhibit distinct effects in different momentum transfer regions. This result suggests that future EIC experiments can disentangle fluctuations at multiple length scales. A larger deformation leads to smaller extracted radii because of the increased incoherent contribution and, in UPCs, because of how the deformation affects the minimal impact parameter B_{\min} distribution. This study offers alternative methods to access nuclear properties. Combining traditional nuclear structure experiments, electron-ion, and ultra-peripheral collisions could provide unprecedented insights in the future.

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