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Photon-induced J/ψ production and polarization effects in isobar collisions at STAR

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Abstract. Photon-induced J/ψ production in heavy-ion collisions offers a unique probe of the nuclear gluon structure and initial geometry. We present differential cross-section measurements of coherent J/ψ photoproduction in Ru+Ru and Zr+Zr ultra-peripheral collisions at $\sqrt{s_{NN}}$ = 200 GeV. The linear polarization of photons in these processes has been suggested to carry information about the nuclear size and the initial collision geometry. In ultra-peripheral collisions, we observe a clear modulation in the J/ψ decay angular distribution, consistent with expectations from spin interference associated with photon polarization. In non-central collisions, the decay electrons exhibit a pronounced azimuthal anisotropy with respect to the event plane, serving as direct evidence for measuring the photon polarization direction. This novel observation opens new opportunities for mapping the initial state in heavy-ion collisions.

1 Introduction

Relativistic heavy-ion collisions generate extremely strong electromagnetic fields, which can be equivalently treated as a flux of quasi-real photons [1, 2]. These photons may interact with the other nucleus to produce vector mesons such as the J/ψ through photonuclear interactions, a process known as photoproduction. In ultra-peripheral collisions (UPCs), where the nuclei do not physically overlap, the absence of hadronic interactions allows photoproduction to dominate. This makes UPCs an ideal environment for studying photon-induced processes, providing a clean probe of the gluonic structure of nuclei, particularly at small Bjorken-x.

Beyond cross-section measurements, the linear polarization of quasi-real photons provides new opportunities to probe spatial features in both ultra-peripheral and non-central collisions. Since the polarization vector is aligned with the impact parameter, photoproduction becomes sensitive not only to the geometry and size of the nucleus, but also to the initial geometry of the collision, even when the nuclei partially overlap. These sensitivities lead to angular modulations in vector meson decays, including the spin-interference effects and correlations with the event plane.

In these proceedings, new measurements from Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV collected by the STAR experiment are presented. These include the measurement of the coherent J/ψ photoproduction cross section in UPCs, as well as the study of decay

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angular correlations via the azimuthal angle between the J/ψ momentum and the lepton momentum difference, which is sensitive to spin-interference effects. Additionally, the azimuthal anisotropy of decay electrons with respect to the event plane is investigated in hadronic collisions.

2 Analysis and Results

The results are based on Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV recorded by the STAR experiment in 2018. Coherent J/ψ photoproduction is studied in ultra-peripheral collisions, selected by a dedicated trigger that requires low multiplicity in the mid-rapidity Time-of-Flight (TOF) detector, back-to-back energy clusters in the Barrel Electromagnetic Calorimeter (BEMC), and vetoes from the Beam-Beam Counters (BBC, $3.3 < |\eta| < 5.0$). This UPC trigger configuration yields an integrated luminosity of 5.2 nb^{-1} for the combined isobar dataset. In addition, approximately 4 billion minimum-bias events were recorded over the 0–80% centrality range, allowing analysis of J/ψ polarization with respect to the event plane. J/ψ mesons are reconstructed via the e^+e^- decay channel using tracking and particle identification provided by the Time Projection Chamber (TPC), TOF, and BEMC subsystems.

2.1 Measurement of Coherent J/ψ Cross Sections in UPCs

The differential cross section $d\sigma/dy$ of coherent J/ψ photoproduction is measured in ultra-peripheral Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV. The J/ψ yield is extracted from a simultaneous fit to the invariant mass and transverse momentum distributions, using MC templates for coherent, incoherent, and QED components, each passed through full detector simulation and reconstruction [4, 8].

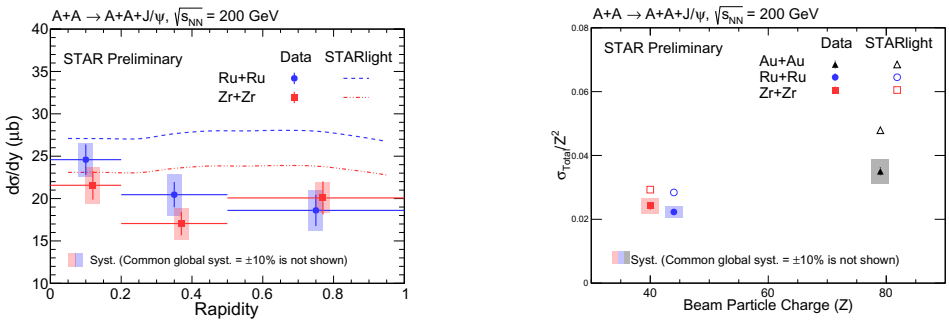

Figure 1. Left: coherent J/ψ photoproduction cross section $d\sigma/dy$ in Ru+Ru and Zr+Zr UPCs at $\sqrt{s_{NN}}$ = 200 GeV. Right: total cross sections integrated over $|y| < 1$ and scaled by $1/Z^2$ to reduce the photon flux dependence. Data are compared with STARlight [5] and Au+Au results [6].

The left panel of Fig. 1 displays the fully corrected differential cross sections $d\sigma/dy$ as a function of rapidity. The measured values for both Ru+Ru and Zr+Zr lie consistently below STARlight predictions. The right panel shows the total cross sections integrated over $|y| < 1$, and scaled by $1/Z^2$ to reduce the photon flux dependence. After scaling, the data remain lower than STARlight predictions across Ru, Zr, and Au [6], without a clear indication of system-size dependence with current uncertainties. These results provide new input for studying the system-size dependence of nuclear gluon distribution at small Bjorken-x.

2.2 Spin Interference Measurement in Isobar UPCs

Azimuthal modulations in ρ^0 photoproduction observed by STAR have been attributed to quantum interference between amplitudes where the meson is coherently produced in either nucleus at spatially distinct locations [7]. Such interference leads to distinctive angular patterns in the decay products, which reflect the linear polarization of the quasi-real photon. Compared to the ρ^0, the J/ψ offers a complementary interference system due to its longer lifetime and fermionic decay channel, providing access to different spatial and quantum interference configurations.

To explore potential spin interference in J/ψ production, the azimuthal correlation observable $A_{2\phi} = \langle \cos 2\Delta\phi \rangle$ is analyzed, where $\Delta\phi = \phi(\vec{p}_{e^+} - \vec{p}_{e^-}) - \phi_{J/\psi}$ denotes the angle between the J/ψ momentum direction and the difference vector of the decay electron momenta.

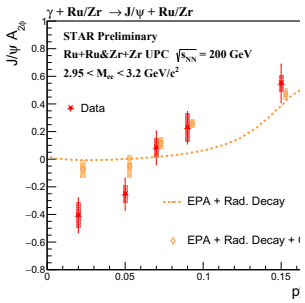

Figure 2. Azimuthal anisotropy parameter $A_{2\phi}$ in Ru+Ru and Zr+Zr UPCs at $\sqrt{s_{NN}} = 200$ GeV. Left: $A_{2\phi}$ as a function of dielectron transverse momentum p_T^{ee}; Right: $A_{2\phi}$ integrated for J/ψ with $p_T < 0.2$ GeV/c.

In Fig. 2, the orange curve shows theoretical input without spin interference [8], and the orange markers, obtained after full detector simulation, serve as the baseline for comparison with the measured data. The red markers show the measured $A_{2\phi}$, plotted in the left panel versus dielectron transverse momentum p_T^{ee}, and in the right panel as the p_T-integrated value for J/ψ with $p_T < 0.2$ GeV/c. At low p_T^{ee}, the data exhibit a negative modulation deviating by 2.4σ from the baseline, suggesting sensitivity to the photon's linear polarization and indicating a possible spin interference effect in coherent J/ψ photoproduction.

2.3 Decay Anisotropy with Respect to the Reaction Plane

While spin interference effects have been observed in vector meson photoproduction in UPCs, direct experimental evidence for the alignment between photon linear polarization and the impact parameter direction is still absent. To address this, the azimuthal decay anisotropy of J/ψ mesons with respect to the event plane $\Psi_{\rm EP}$ is quantified via the second-order Fourier coefficient $A_2 = \langle \cos 2(\phi_e - \Psi_{\rm EP}) \rangle$, where ϕ_e denotes the azimuthal angle of the decay electron in the J/ψ rest frame. This analysis is performed in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} =$ 200 GeV over the 0–80% centrality range, with $\Psi_{\rm EP}$ reconstructed from charged-particle tracks in the TPC.

Fig. 3 shows A_2 versus collision centrality (left) and dielectron transverse momentum (right). A clear negative modulation appears at low $p_T^{ee} < 0.2$ GeV/c (yellow markers), where coherent photoproduction dominates, while the hadronic-dominated region ($0.2 < p_T^{ee} <$ 1.5 GeV/c, blue markers) shows no significant anisotropy. A residual hadronic component at low p_T^{ee} is estimated by fitting the J/ψ p_T spectrum above 0.2 GeV/c with a Tsallis function and extrapolating to low p_T. Assuming $A_2^{\rm hadronic} = 0$, the red markers represent the extracted photon-induced anisotropy $A_2^{\rm photonic}$, calculated as $A_2^{\rm photonic} = A_2^{\rm measured}/(1 - Y_{\rm hadronic}/Y_{\rm total})$, where $Y_{\rm hadronic}$ is the extrapolated hadronic yield and $Y_{\rm total}$ the measured yield in that region.

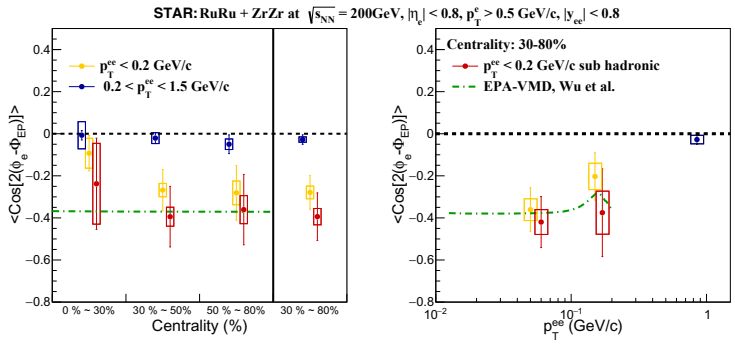

Figure 3. J/ψ decay anisotropy A_2 versus centrality (left) and pair p_T (right) in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV, compared with EPA–VMD model predictions [9].

The extracted value in 30–80% centrality is $A_2^{\text{photonic}} = -0.39 \pm 0.11$ (stat.) $\pm$ 0.04 (sys.), corresponding to a 3.3σ deviation from zero. The result is consistent with EPA–VMD model predictions [9]. This provides the first direct experimental evidence that such photons retain sensitivity to the initial collision geometry, offering a new approach for determining the impact parameter orientation in hadronic interactions.

3 Conclusions

Photon-induced J/ψ production in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV provides new insights into nuclear gluon structure and collision geometry. Coherent cross sections in ultra-peripheral events are found to be below STARlight predictions. Azimuthal modulations in J/ψ decays suggest spin interference effects and reveal photon polarization aligned with the reaction plane in non-UPC events. These results demonstrate that vector meson photoproduction is a sensitive probe of the initial state in heavy-ion collisions.

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