Entanglement-Enabled Spin Interference in Exclusive J/ψ Photoproduction through Ultra-Peripheral Collisions at STAR

Ashik Ikbal Sheikh (for the STAR Collaboration)[1,*]

[1]Department of Physics, Kent State University, Kent, OH 44242, USA

Abstract. In ultra-peripheral collisions (UPC), exclusive vector meson photoproduction, such as ρ^0 and J/ψ, serves as a sensitive probe for studying the gluon structure in heavy nuclei. The linear polarization of the photons involved in these processes help to image the nucleus through the so-called entanglement-enabled spin interference in vector meson photoproductions. The photoproduced J/ψ has longer lifetime (2160 fm/c) and non-localized wave function which provides unique opportunity to study the entanglement between the photon and the Pomeron phases emitted from each nucleus. We present the first measurement of the interference pattern for the photoproduced J/ψ in Au+Au UPC at $\sqrt{s_{\rm NN}}$ = 200 GeV with the STAR experiment.

1 Introduction

The ultra-peripheral heavy-ion collisions (UPCs) are special type of collisions where the colliding nuclei pass each other with a nucleus-nucleus impact parameter (b) large enough to avoid nuclear contacts [1, 2]. However, the interactions can still occur through the exchange of quasi-real photons or gluons from the colliding nuclei. The photons do not interact directly with gluons because they do not carry color, interactions occur when the photon undergoes a temporary fluctuation into a quark-antiquark pair that, in turn, interacts with the gluons inside the nucleus. This process produces a vector meson (ρ, ϕ, J/ψ, etc.) which has the same intrinsic quantum numbers as the incoming photon. Since the interactions occur primarily via gluons, the produced vector meson is sensitive to the gluon distribution of the colliding nuclei [3] and hence provides a unique opportunity to probe the gluonic structure of nuclear matter.

Recent measurements from the Solenoidal Tracker at RHIC (STAR) experiment [4] exhibit that the quasi-real photons participating in UPC processes are linearly polarized in the transverse plane, and the polarization direction is aligned radially with the emitting source. During the vector meson production, the polarization direction of the spin-1 photon is transferred directly to the produced vector meson. When the produced vector meson decays, the spin of the system is transferred into the orbital angular momentum of the daughters, leading their momenta being preferentially aligned with the parent spin direction. This results in an azimuthal $\cos(2\phi)$ modulation in the momentum distribution with respect to the polarization direction, where ϕ is the angle between momenta of the vector meson and one of the decay

*e-mail: ashikhep@gmail.com/asheikh2@kent.edu

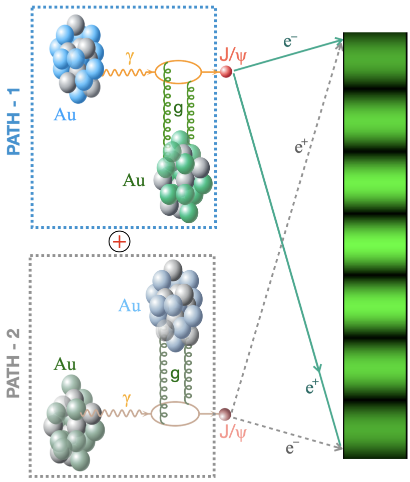

Figure 1. Photon-Pomeron emission ambiguity leads to two possible paths for J/ψ vector meson production in UPC. Amplitudes from both the paths interfere and exhibit interference like pattern.

daughters as defined in the next section (Sec. 2). Since the polarization direction is oriented approximately with the nucleus-nucleus impact parameter, it is random from one event to another, and hence the $\cos(2\phi)$ modulation vanishes when averaged over a large number of events. In UPC vector meson production, there exists ambiguity regarding the assignment of the photon-contributing and gluon-contributing nuclei. A reasonably good approximation is to consider that the vector meson production occurs in either of the two nuclei. This scenario bears resemblance to a two-source interferometer, albeit with the unstable particles. Both the amplitudes from the two nuclei contribute in the vector meson production as shown in the cartoon (Fig. 1). In other words, the interference between the two contributing amplitudes happens which makes the $\cos(2\phi)$ modulation between the momentum and polarization of the produced vector meson observable [5]. This $\cos(2\phi)$ pattern provides a novel way for nuclear tomography and 3D imaging of relativistic nuclei as established in STAR [6] recently.

STAR has measured a large and prominent $\cos(2\phi)$ modulation for ρ^0 and confirmed that the observed interference is a result of an overlap of two wave functions at a distance an order of magnitude larger than the ρ^0 travel distance within its lifetime [6]. The ρ^0 being a short-lived particle, the interference may occur at the daughter pions level which is an example of quantum interference between nonidentical particles. Since ρ^0 and the daughter pions are bosons, it is impossible to comment accurately on the level of interference by looking at the sign of the interference. The J/ψ has several advantages over ρ^0 in order to understand this novel phenomenon [7]. The J/ψ has longer lifespan than ρ^0 and its decay daughters are fermions. So, the J/ψ has the potential to shed light on the level of interference. Apart from that, being heavier, J/ψ can probe the parton distribution function at smaller length scale. In these proceedings, we present the measurements of the spin interference effect in coherent J/ψ photoproduction at $\sqrt{s_N N}$ = 200 GeV Au+Au collisions in STAR which can uniquely probe the gluonic matter and the entanglement of the photon-gluon phases in a nucleus.

2 Data analysis

We analyzed data sets from Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, collected with STAR detector. The main sub-detectors used are: Time Projection Chamber (TPC) ($|\eta| < 1$) , Time-of-Flight (TOF) ($|\eta| < 0.9$), Barrel Electromagnetic Calorimeter (BEMC) ($|\eta| < 1$), Beam Beam Counters (BBCs) ($2.2 < |\eta| < 5$) and Zero Degree Calorimeters (ZDCs) ($|\eta| > 6.3$). To trigger the UPC events, we require forward neutron showers in both ZDCs, limited activities

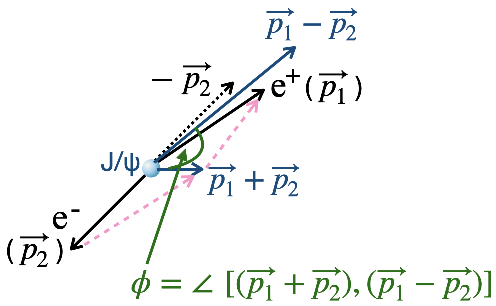

Figure 2. The ϕ observable in transverse plane sensitive to the photon polarization interference effects. This is a simple decay topology of low p_T J/ψ where the decay daughters with momenta $\vec{p}_1$ and $\vec{p}_2$ are emitted almost back-to-back. This ensures $|\vec{p}_1 + \vec{p}_2| << |\vec{p}_1 - \vec{p}_2|$.

in TOF, and no signal in the BBCs. We also require the BEMC to veto any additional non-UPC activity. Tracking and particle identification is provided by the TPC at mid rapidity, $|\eta| < 1$. The analysis aims to select events with exclusive $J/\psi \to e^+e^-$ production which requires to have only two tracks from J/ψ decay in a single event. Assuming very low p_T J/ψ, the tracks are oriented in a back-to-back topology, leaving hits in opposite sextants of BEMC.

The observable (ϕ) sensitive to the photon polarization interference effects is constructed from the selected e^+e^- pairs using [8]:

$$cos\phi = \frac{(\vec{p}_1 + \vec{p}_2).(\vec{p}_1 - \vec{p}_2)}{|\vec{p}_1 + \vec{p}_2||\vec{p}_1 - \vec{p}_2|} \tag{1}$$

where $\vec{p}_1$ and $\vec{p}_2$ are the momentum vectors of the daughter electrons in the plane transverse to the beam direction. When the daughter electrons are almost back-to-back as shown in Fig. 2, i.e., $|\vec{p}_1 + \vec{p}_2| << |\vec{p}_1 - \vec{p}_2|$, the ϕ angle in Eq. 1 is equivalent to the angle between the parent and one of its daughters momentum. The measured ϕ observable of e^+e^- pairs in the J/ψ mass window (2.95 - 3.2 GeV/c^2) are fitted with, $f(\phi) = 1 + a_2 cos(2\phi)$, where a_2 is the modulation parameter, obtained from the fit. The measured raw a_2 is corrected for Bremsstrahlung process and the detector effects using STARLight+GEANT simulation. We also correct the a_2 for continuum $\gamma\gamma \to e^+e^-$ background using: $a_2^{measured} = f \times a_2^{bkg} + (1-f) \times a_2^{sig}$, with $f = \frac{N_{bkg}}{N_{sig}+N_{bkg}}$ being the relative yield, obtained from the invariant mass distribution of e^+e^- pairs. The a_2^{bkg} is estimated from background data.

3 Results and discussions

Left panel of Fig. 3 displays the measured and corrected cos(2ϕ) modulation parameter, a_2, as a function of e^+e^- pair invariant mass, m_{ee}, with a pair transverse momentum $p_T < 200$ MeV/c in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The measured spin interference signal in J/ψ mass region, $2.95 < m_{ee} < 3.2$ GeV/c^2, is $a_2 = 0.102 \pm 0.027 \pm 0.029$. The measurements are compared with the STARLight [9] and Diffractive+Interference [10] calculations in the same kinematic range. The STARLight calculations have no interference effect and hence predict the a_2 values consistent with zero. The Diffractive+Interference calculations show negative modulations, opposite trend to the data.

The right panel of Fig. 3 shows corrected a_2, as a function of e^+e^- pair p_T in the J/ψ mass region, $2.95 < m_{ee} < 3.2$ GeV/c^2, in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. We observe a strong p_T dependence which rises towards positive value as p_T increases. The STARLight [9] predicts a null result whereas the Diffractive+Interference [10] calculations

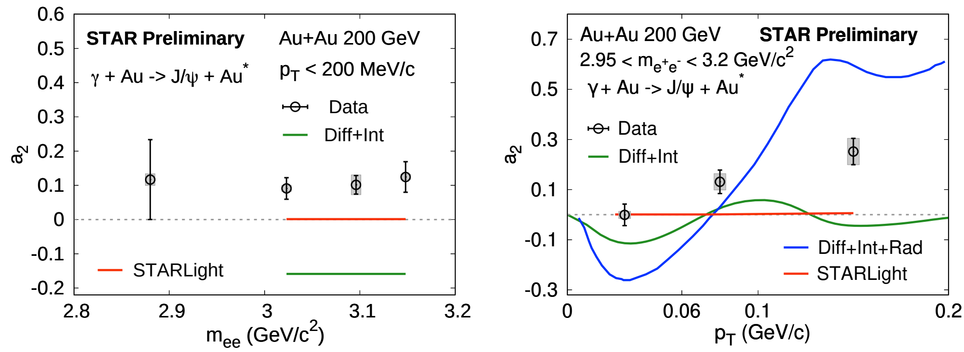

Figure 3. Left panel: The $\cos(2\phi)$ modulation parameter, a_2, as a function of e^+e^- pair invariant mass, m_{ee}, with a pair transverse momentum p_T < 200 MeV/c in Au+Au 200 GeV. The statistical uncertainty on each data point is shown in vertical bars, while the systematic uncertainty shown in the shaded bands. The STARLight [9] and Diff+Int [10] calculations are shown with red and green curves respectively. Right panel: The $\cos(2\phi)$ modulation parameter, a_2, with pair p_T in J/ψ mass region, $2.95 < m_{ee} < 3.2$ GeV/c^2 for Au+Au 200 GeV. The STARLight [9], Diff+Int [10] and Diff+Int+Rad [7] calculations are shown with red, green and blue curves respectively.

are negative in low and high p_T. Nevertheless, the Diffractive+Interference calculations with additional photon radiation [7] predict negative modulation at low p_T with rising trend towards positive value at higher p_T where the calculations are close to the measured data within uncertainty.

4 Summary and conclusions

In summary, we measured the entanglement-enabled spin interference signal for J/ψ in $p_T <$ 200 MeV/c for Au+Au UPCs at $\sqrt{s_{NN}}$ = 200 GeV. The measured signal, $a_2 = 0.102 \pm 0.027 \pm 0.029$, has 3σ significance above zero. The a_2 is observed to have a strong p_T dependence, rises towards positive values as p_T increases. Theoretical calculations considering diffractive and interference effects with additional photon radiation anticipate a negative modulation at low p_T that is transiting towards a positive values at higher p_T, approaching towards the observed data within uncertainty. The significantly improved measurements in future RHIC runs, LHC and future EIC experiments will bring new insight into this novel phenomenon.

References

[1] C. A. Bertulani, S. R. Klein, and J. Nystrand, *Ann.Rev.Nucl.Part.Sci. 55 (2005) 271–310*
[2] A. Baltz et al., *Phys.Rept. 458 (2008) 1–171*
[3] STAR Collaboration, *J. High Energ. Phys. 2020, 178 (2020)*
[4] STAR Collaboration, *Phys. Rev. Lett. 127, 052302 (2021)*
[5] S. Klein and J. Nystrand, *Phys. Rev. Lett. 84, 2330 (2000)*
[6] STAR Collaboration, *Sci. Adv. 9, eabq3903 (2023)*
[7] Brandenburg et al., *Phys. Rev. D 106, 074008 (2022)*
[8] Xing et al., *J. High Energ. Phys. 2020, 064 (2020)*
[9] Klein et al., *Comput.Phys.Commun. 212 (2017) 258-268*
[10] Mäntysaari et al., *Phys.Rev.D 106 (2022) 7, 074019*