PROCEEDINGS OF SCIENCE

J/ψ Production in Ultra-Peripheral Collisions at STAR

William Schmidke, for the STAR Collaboration*
Brookhaven National Laboratory
E-mail: schmidke@bnl.gov

In 2010 and 2011, the STAR Collaboration collected a large sample of triggers for ultra-peripheral *AuAu* collisions. We present measurements from this sample of J/ψ production in association with neutrons from photonuclear breakup. Preliminary results for the cross section as a function of rapidity and p_T are presented; the dominant component at low p_T demonstrates the coherent production of J/ψ off the entire Au nucleus, and a significant component at higher p_T indicates incoherent production off individual nucleons within the nucleus.

Future RHIC runs with polarized protons will provide the opportunity to measure J/ψ production in ultra-peripheral *pp* and *pAu* collisions. The STAR Roman Pot system will allow measurement of the final state protons. A non-zero transverse asymmetry of the produced J/ψs would be the first measure of the generalized parton distribution E^g for gluons, which is connected with the orbital angular momentum of gluons in the nucleon. Estimates of the event rates for planned and considered future RHIC runs are presented.

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*Speaker.

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1. J/ψ production in ultra-peripheral collisions with heavy ions

1.1 Introduction

Heavy ion collisions provide the opportunity to measure high energy photoproduction on nuclear targets. The nuclei may pass each other at impact parameters large enough that no hadronic interaction occurs, referred to as ultra-peripheral collisions (UPC). The large atomic number provides a high flux of Weizsäcker-Williams photons proportional to Z^2; a photon emitted by one nucleus may undergo photoproduction on the other target nucleus. Through Vector Meson Dominance, the most common hadronic process is photoproduction of vector mesons, preserving the quantum numbers of the photon. Of special interest is the production of charmonium J/ψ mesons. The charm quark pair is produced through the photon-gluon fusion process. Thus, photoproduction of J/ψ mesons is sensitive to the gluon content of the target nuclei. J/ψ production in UPCs at RHIC has previously been reported by the PHENIX collaboration [1].

Photoproduction can occur coherently off the entire target nucleus. In this case the large size of the nucleus results in low transverse momentum, p_T, of the produced vector mesons. Alternatively, photoproduction may occur off individual nucleons within the nucleus. The small nucleon size results in higher p_T of the vector mesons produced in such incoherent reactions.

Because of the very large photon fluxes, two nuclei can exchange multiple photons. The additional photons may induce Coulomb excitation in one or both nuclei, resulting in final state neutrons along the beam trajectory. Approximately 10% of UPC interactions result in neutrons emitted by both nuclei. The presence of such high energy neutrons provides the possibility of using them for triggering of the otherwise relatively low activity UPC events.

A comprehensive model of UPC interactions is provided by the STARlight generator [2, 3]. It is capable of modeling coherent and incoherent vector meson photoproduction. It also provides estimates of Coulomb excitation of the nuclei.

1.2 STAR detector and data set

STAR detects charged particles with pseudorapidity $|\eta| < 1.5$ in a large Time Projection Chamber (TPC) in a 0.5 T solenoidal magnetic field. The TPC is surrounded by a Time-Of-Flight (TOF) system and a barrel electromagnetic calorimeter (BEMC). Two Zero Degree Calorimeters (ZDCs) $\pm$18m downstream from the interaction point detect neutrons from nuclear breakup, and two Beam-Beam Counters (BBCs) detect charged particles with $2 < \eta < 5$. The TOF, BEMC, ZDCs, and BEMCs all provide fast signals available for triggering. Luminosity was monitored with coincidences in the ZDCs. This was calibrated with vernier scans of the colliding beams, with a systematic uncertainty of 10%.

The data presented here were collected during 2010 and 2011, when RHIC collided gold beams with 100 GeV per nucleon. The trigger required 2-6 hits in the TOF system, providing low multiplicity events. Signals in both ZDCs consistent with 1-4 beam energy neutrons ensured real beam crossing events, with the upper limit rejecting hadronic gold-gold collisions. Hadronic interactions were also rejected by requiring no hits in the BBCs. The total luminosity accumulated with this trigger was 1.9 nb^{-1}.

Offline, tracks were required to have sufficient hits in the TPC to be well measured. The tracks were also required to extrapolate to a hit in the TOF system to ensure the track was from the triggered beam crossing. Pairs of such tracks were required to form a vertex with only possibly one additional track, ensuring low multiplicity. The vertex was also required to be near the center of the STAR detector. Pairs with a rapidity close to zero were rejected to suppress cosmic rays. The pairs so selected include a sample of the decays $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$.

1.3 Results: J/ψ production in heavy ion UPCs

The left of Fig. 1 shows a scatter plot of p_T versus m_{ee} of opposite sign pairs. The mass m_{ee} is used as a proxy for the muon decay channel and is within 10 MeV/c^2 of the correctly reconstructed pair mass. The prominent feature is a cluster of points at low p_T near $m_{ee} = M_{J/\psi}$ = 3.1 GeV/c^2; these are coherently produced J/ψs. There is also a band at this mass extending to higher p_T; these are incoherently produced J/ψs. Finally, there is a band at low p_T extending to lower masses. These are dominantly lepton pairs produced through a two-photon QED process in UPCs.

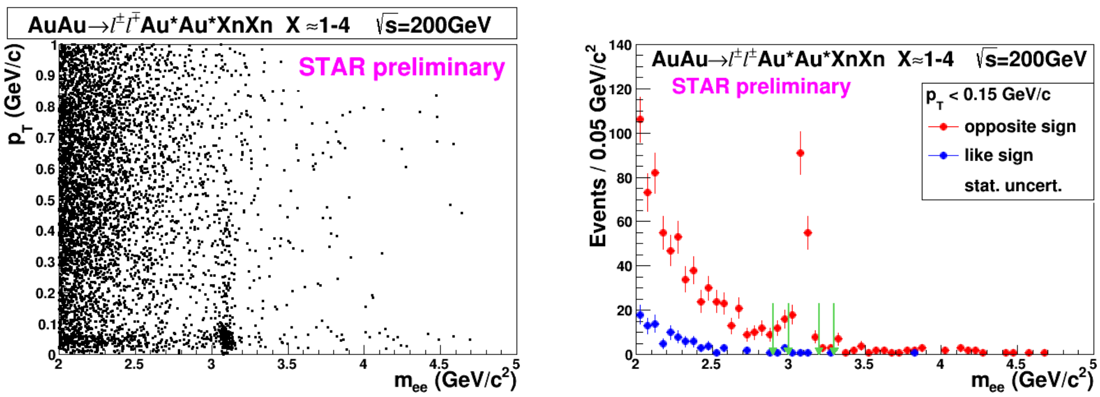

Figure 1: Left: Scatter plot of p_T versus m_{ee} for opposite sign pairs. Right: m_{ee} distribution for $p_T < 0.15$ GeV/c for opposite sign (red) and like sign (blue) pairs.

The right of Fig. 1 shows the m_{ee} distribution for opposite sign and like sign pairs for the coherent region $p_T < 0.15$ GeV/c. The opposite sign distribution shows a clear peak at the J/ψ mass. The same sign distribution is taken as a sample of combinatoric background and is subtracted for further measurements. This still leaves a continuum distribution under the J/ψ peak. The green arrows on the plot show peak and side band regions of m_{ee}. For further measurements side band distributions are subtracted from peak distributions, leaving the measurement of J/ψ distributions. The total sample after subtractions consists of approximately 200 J/ψ events. Cross sections are determined from event counts using a sample of coherent J/ψ generated with STARlight to determine acceptance corrections.

The left of Fig. 2 shows the measured rapidity y distribution of J/ψ production for the coherent region $p_T < 0.15$ GeV/c. Since equal energy beams are collided, the distribution $d\sigma/dy$ must be symmetric under $y \to -y$. To enhance statistical significance, events with $y < 0$ are binned as $|y| > 0$ and total event counts are halved. The measured cross section is consistent with a slight falloff across the range $0 < y < 1$ as expected from STARlight. However, after correcting for Coulomb excitation and the limited neutron spectrum accepted by the trigger [4], the model prediction is a factor of $\sim 2\frac{1}{2}$ higher than the measured cross section.

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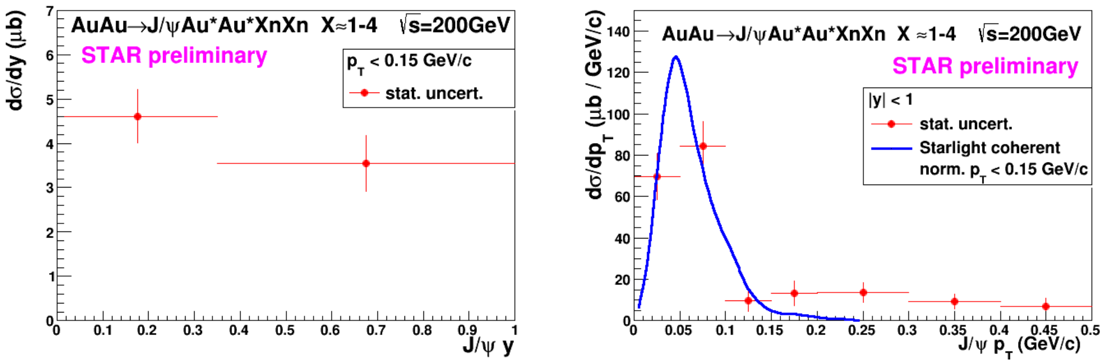


Figure 2: Left: Rapidity y distribution of J/ψ production for $p_T < 0.15$. Right: Transverse momentum p_T distribution of J/ψ production for $|y| < 1$. The blue curve is the prediction of STARlight coherent production, normalized to the data for $p_T < 0.15$ GeV/c. There is a 10% scale uncertainty on the cross sections from the luminosity measurement.

The right of Fig. 2 shows the measured transverse momentum p_T distribution of J/ψ production for the STAR acceptance region $|y| < 1$. It exhibits a peak for $p_T < 0.1$ GeV/c, a lower tail at higher p_T and is consistent with zero for $p_T > 0.5$ GeV/c (not shown). The plot also shows the STARlight expectation for coherent J/ψ production normalized to the data for $p_T < 0.15$ GeV/c; it is consistent with the observed peak at low p_T. The tail at $p_T > 0.15$ GeV/c is a clear signal of incoherent J/ψ production, and comprises approximately 30% of the total J/ψ cross section.

2. J/ψ production in ultra-peripheral collisions with polarized protons

2.1 Generalized Parton Distributions

Generalized Parton Distributions (GPDs) provide a theoretical framework for addressing fundamental questions about proton structure. GPDs are correlated parton momentum and helicity distributions in transverse spatial dimensions, and describe the quark and gluon orbital angular momentum contributions to the proton spin. They are characterized for each quark flavor q and gluons g by distributions $H^{q,g}$ with conserved nucleon helicity and $E^{q,g}$ with flipped nucleon helicity; the $E^{q,g}$ quantify the orbital angular momentum of the partons.

GPDs are measured through exclusive reactions, with the quantum numbers of the final state determining the combination of q and g accessed by the process. Again through the photon-gluon process J/ψ production is sensitive to the gluon GPDs H^g and E^g. In scattering with transversely polarized protons, an azimuthal asymmetry of the cross section A_{UT} can be measured. The asymmetry is calculable within the GPD framework and is proportional to the helicity-flip GPDs, $A_{UT} \propto E^{q,g}$. Measurement of such an asymmetry for J/ψ production thus provides a measure of the gluon orbital angular momentum contribution to the proton spin.

2.2 E^g with STAR at RHIC

GPDs are ideally studied in lepton-proton collisions, where measurement of the final state lepton and proton controls the kinematics of the reaction. Such measurements are a significant part of the program at a future Electron Ion Collider (EIC) [5]. Before an EIC is realized, RHIC, with its capability to collide transversely polarized protons, has the unique opportunity to measure A_{UT} with J/ψ production in UPCs. In this case a Weizsäcker-Williams photon from the opposing beam particle undergoes photoproduction off the polarized proton target; azimuthal asymmetries of produced J/ψs with respect to the proton spin may then be measured.

The results presented in Section 1 demonstrate the capability of STAR for measurement of J/ψs in UPC. Subsequent to the RHIC run periods presented there, a trigger optimized for J/ψ detection has been implemented. The trigger requires electromagnetic energy deposits in back-to-back sextants of the BEMC. The BEMC based trigger is cleaner than the TOF based trigger for the older data sets; this allowed the neutron requirement in the trigger to be removed. Without the mutual Coulomb excitation requirement, the cross section measured is larger by an order of magnitude, providing a significant boost in statistics.

Recently STAR has also installed a Roman Pot (RP) system for measurement of final state forward protons. The RPs are placed approximately 16 m downstream on each side of the STAR interaction point. Silicon strip detectors installed in the Roman Pots are moved to within 2.5 cm of the proton beam (8 sigma of the beam size). Final state protons with nearly full beam energy are measured in the four-momentum-squared t range of $0.03 < |t| < 0.3$ (GeV/c)^2 for 100 GeV beam energy and $0.19 < |t| < 1.9$ (GeV/c)^2 for 250 GeV beam energy.

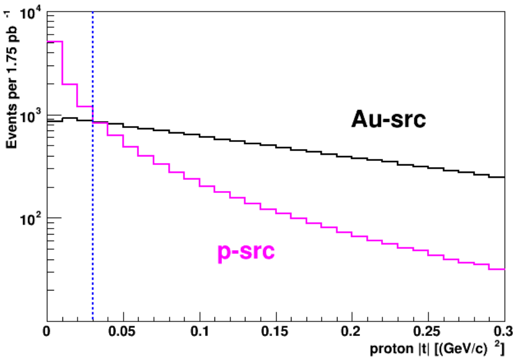
The BEMC based trigger for UPC J/ψ production and RP system have both been used in recent RHIC runs and have demonstrated excellent performance. A trigger based on a coincidence of the BEMC trigger and a hit in one of the RPs can provide a sample of UPC J/ψs for a measurement of E^g.

2.3 Future RHIC runs

A measurement of E^g is part of the program for future RHIC runs [6]. At present RHIC is scheduled to have a polarized proton-proton run with 250 GeV beam energies in 2017; the expected total luminosity is 400 pb^{-1}. For the trigger described in the previous section, the detected proton may come from either the proton that was the source of the photon, or the proton that was the photon target. The former case has proton $-t$ mostly below the RP acceptance, so the tagged proton is dominantly the target proton in the final state. The event generator SARTRE [7], based on the bSat color dipole model, has been used to estimate event rates. Cuts were applied to select events where the final state proton was measured in the RP system and the J/ψ was measured in the central STAR detector. The 2017 run with this trigger is expected to produce approximately 11k UPC J/ψs, sufficient for a first measurement of E^g.

Also under consideration, for early in the next decade, is a gold+polarized proton run with 100 GeV per nucleon beam energies; the expected total luminosity is 1.75 pb^{-1}. Although this is much smaller than the 2017 run, the UPC cross section is enhanced by the high Z^2 of the gold nuclei. For such asymmetric collisions there are two processes. The gold nucleus may be the source of the photon, scattering off the polarized proton, which may result in an asymmetry A_{UT} of J/ψ production. Alternatively, the proton may be the source of the photon, scattering off the unpolarized gold nucleus, with no asymmetry for J/ψ production.

For this run only the proton beam will be instrumented with RPs. The left side of Fig. 3 shows the $|t|$ distribution of measured final state protons expected from the SARTRE prediction. Shown



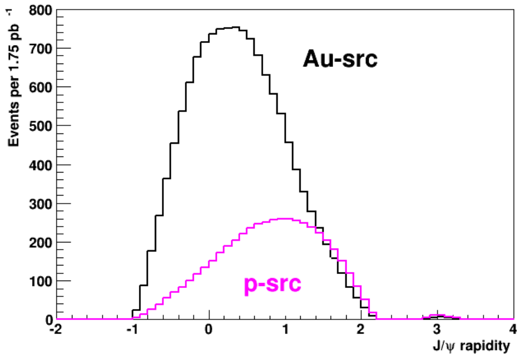


Figure 3: Predictions of SARTRE for a gold+polarized proton run with 100 GeV/nucleon beams. The process where the gold is the photon source is shown with black curves; where the proton is the photon source are magenta curves. Left: Four-momentum-squared $|t|$ of the final state proton. The blue line show the lower end of the RP acceptance; the upper end is the right edge of the plot range. Right: Rapidity y distribution of the produced J/ψs.

are the two processes; for the case where the proton was the source of the photon, most of the protons are below the $|t|$ acceptance of the RPs. Also, the fraction of the two processes may be adjusted by selecting different $|t|$ ranges. The right side of Fig. 3 shows the rapidity distribution of the produced J/ψs for the two processes. The distribution for the proton source case is peaked in the proton beam direction. Again, the fraction of the two processes may be adjusted by selecting different rapidity ranges. In total, this run is expected to produce approximately 13k UPC J/ψs where the polarized proton was the photon target, with a background of 5k where the proton was the photon source. Along with the ability to adjust the signal and background fractions by varying proton $|t|$ and J/ψ rapidity, this data sample will provide a good measurement of E^g before an EIC is realized later in the next decade.

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