J/ψ production in Ultra-Peripheral Collisions at STAR

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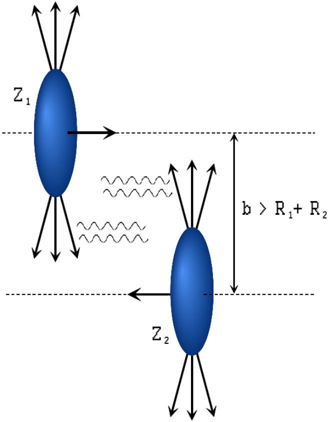
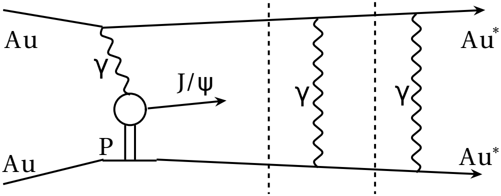
Ultra-peripheral heavy-ion collisions



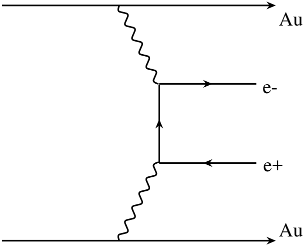
- An ultra-peripheral collision (UPC) is a collision at impact parameter greater than the sum of the nuclear radii
- Electromagnetic field of protons and ions behaves like a beam of quasi-real photons
- Photon beam intensity is proportional to Z^2
- Photoproduction in γp and γA interactions
- QED processes in $\gamma\gamma$ interactions

New STAR results on coherent J/ψ photoproduction in Au+Au UPC at 200 GeV

Physics processes studied in ultra-peripheral collisions



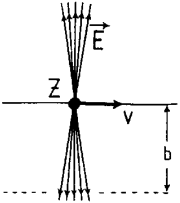
(a)



(b)

- Lorentz-contracted field in UPC is described as a flux of quasi-real photons
- We can study photon-nucleus (a) and photon-photon (b) interactions
- Vector mesons and e^+e^- pairs are the only produced particles
- Nuclei typically leave intact, but may be excited by electromagnetic field to emit neutrons
- The STAR data for the coherent J/ψ production were taken with the requirement for both nuclei to emit at least one neutron (XnXn)

Virtual photon flux by Weizsäcker-Williams concept



- Perpendicular Lorentz contraction, energy spectrum by Fourier transform:

$$I(\omega, b) = \frac{1}{4\pi} |\boldsymbol{E}(\omega) \times \boldsymbol{B}(\omega)|$$

- With the field of uniformly moving charge, flux of photons per unit of area is

$$N(\omega, b) = \frac{Z_1^2 \alpha_{\text{em}} \omega^2}{\pi^2 \gamma_L^2 v^2} \left[K_1^2(x) + \frac{1}{\gamma_L^2} K_0^2(x) \right]$$

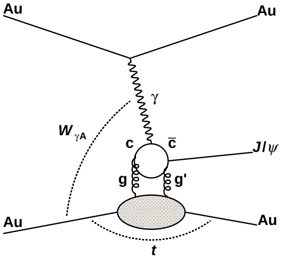
- Modified Bessel function $K_1^2(x)$ of argument $x = \omega b / \gamma_L v$ gives leading contribution of transversal photons in ultra-relativistic limit

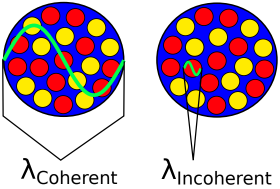
Intensity of the photons is proportional to the squared charge, Z^2

Bertulani, Baur, Phys.Rept. **163** (1988) 299

Photoproduction of heavy vector mesons

- Can be described by perturbative QCD as two-gluon exchange





- Photon coupling may be coherent or incoherent

- Cross section is proportional to the square of gluon distribution, $g_A(x, Q^2)$, at the scale of, $Q^2 = M^2_{J/\psi}/4$:

$$\left.\frac{\mathrm{d}\sigma(\gamma A \to J/\psi A)}{\mathrm{d}t}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha_{\mathrm{em}} M^5_{J/\psi}} 16\pi^3 \left[x g_A(x, Q^2)\right]^2$$

- Momentum fraction of probed gluons is $x = (M_{J/\psi}/W_{\gamma\mathrm{A}})^2$

Coherent cross section is sensitive to nuclear effects to gluon density at low-x

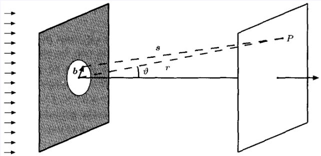
Diffraction origin in hadronic collisions in analogy with optics

Optics

- Electromagnetic wave as solution to Helmholtz equation

$$(\nabla^2 + k^2)U = 0$$

- Wave number $k = 2\pi/\lambda$



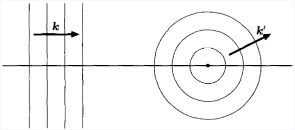
- Every point in a hole of radius, R, is a source of spherical wave
- Diffraction in light intensity at a distance, D, when $kR^2/D \ll 1$

High energy physics

- Wave function as solution to Schröedinger equation

$$-\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r}) + V(\mathbf{r})\psi(\mathbf{r}) = E\psi(\mathbf{r})$$

- Scattering is described as an outgoing spherical wave



- Typically $R \sim 1$ fm, $D \gtrsim 1$ cm and $k \sim \sqrt{s} \sim 200$ GeV
- Optical condition is satisfied

Glauber approach to coherent J/ψ cross section

- Based on the experimental $\gamma p \to J/\psi p$ cross section and nuclear thickness function, $T_A(\vec{r})$, as an input to the Glauber formula:

$$\sigma_{\rm tot}(J/\psi A) = \int {\rm d}^2\vec{r} \left(1 - {\rm e}^{-\sigma_{\rm tot}(J/\psi p) T_A(\vec{r})}\right)$$

- Implemented in STARLIGHT, Klein *et al.*, Comput.Phys.Commun. 212 (2017) 258-268

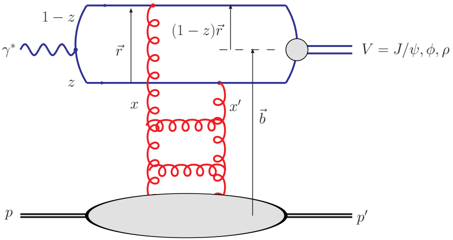
- Coherent photon-nucleus cross section is then found by the vector meson dominance and Woods-Saxon nuclear profile

- Cross section in nucleus-nucleus UPC is obtained by convoluting with photon flux, $N_\gamma(k)$:

$$\sigma(AA \to J/\psi A) = 2 \int {\rm d}k \frac{{\rm d}N_\gamma(k)}{{\rm d}k} \sigma(\gamma A \to J/\psi)$$

- Factor of two in front of the integral accounts for possibility of both nuclei to be a photon source or a target

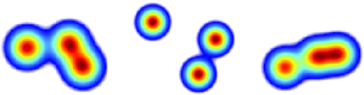
Dipole model for coherent J/ψ photoproduction

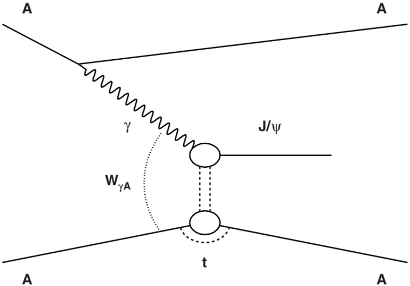


- Allows one to non-linear QCD phenomena via the Color-Glass Condensate
- Used in the model by Mäntysaari, Schenke, Phys.Lett. B772 (2017) 832-838
- Photon fluctuates to quark-antiquark dipole with transverse separation, $\vec{r}$
- The dipole scatters off the nucleus
- Vector meson is formed out of the dipole

Drawing is from Phys.Rev. D74 (2006) 074016

Coherent photoproduction in hot spot model

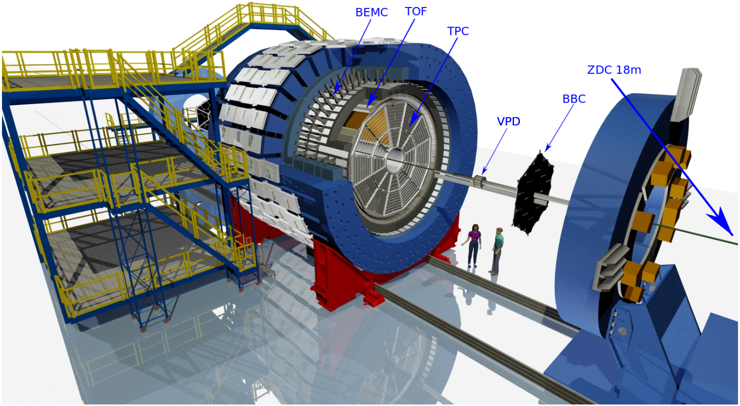




- Also based on dipole approach to photon-nucleus scattering
- Individual nucleons consist of Gaussian hot spots
- Used in the model by Cepila, Contreras, Krelina, Phys.Rev. C97 (2018) no.2, 024901
- Number of hot spots increases with decreasing x
- Diffractive cross section in t is related to transverse distribution of target

The STAR experiment

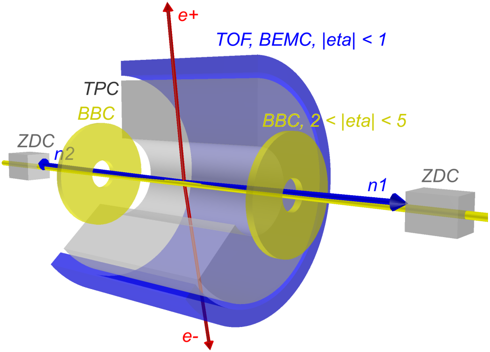
- Central tracking and particle identification, forward counters and neutron detection



- Time Projection Chamber: tracking and identification in $|\eta| < 1$
- Time-Of-Flight: multiplicity trigger, identification and pile-up track removal
- Barrel ElectroMagnetic Calorimeter: topology trigger and pile-up track removal
- Beam-Beam Counters: scintillator counters in $2.1 < |\eta| < 5.2$, forward veto
- Zero Degree Calorimeters: detection of very forward neutrons, $|\eta| > 6.6$

Trigger and data selection for coherent J/ψ production in UPC

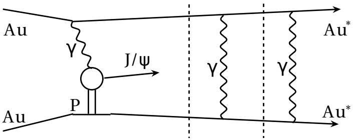
Just two tracks from a low-p_T vector meson, forward neutrons, and nothing else



- Rapidity acceptance for J/ψ is $|y| < 1$
- Trigger requirements assume two tracks and neutrons in ZDCs
- Back-to-back hits in BEMC
- Limited activity in TOF
- Showers in both ZDCs
  - Energy deposition within 1/4 to 4 beam-energy neutrons
  - Full efficiency to a single neutron
- Veto from both BBCs

Detectors are not in scale in the illustration

Very forward neutron emission



- Excited nuclei emit neutrons in a forward direction
- ZDC signal shows peak structures for one neutron, two or more neutrons
- The neutrons are a convenient way to tag UPC events at the trigger level

Figure: Spectrum of Analog-to-Digital counts from ZDCs

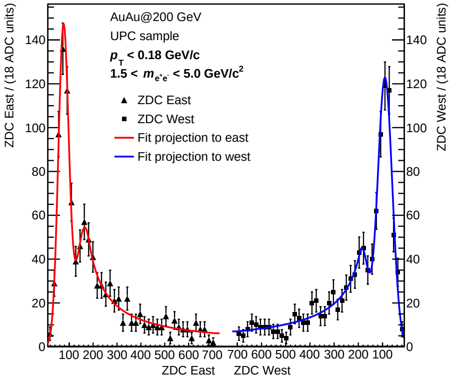
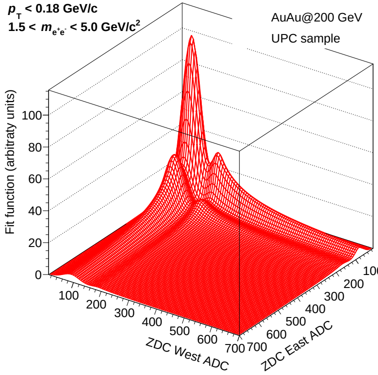
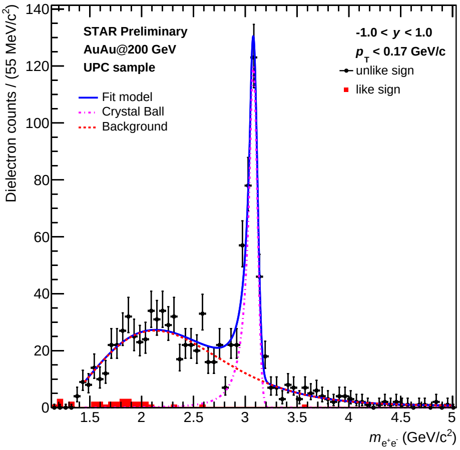


Figure: Two-dimensional fit by a sum of Gaussian and Crystal Ball functions



Invariant mass of selected candidates



- Signal of J/ψ and continuum from $\gamma\gamma \to e^+e^-$
- Minimal like-sign background
- Fit by Crystal Ball for J/ψ and empiric formula for $\gamma\gamma \to e^+e^-$
- Parametrization for $\gamma\gamma \to e^+e^-$ is:

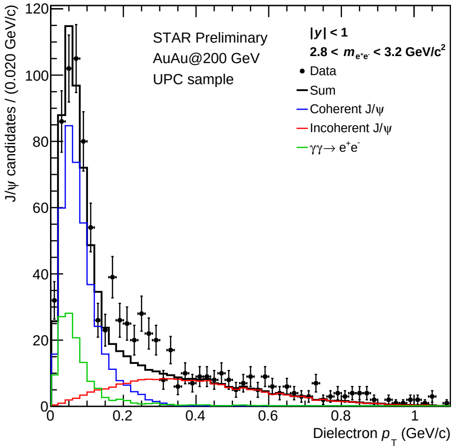
$$f_{\gamma\gamma \to e^+e^-} = (m - c_1)e^{\lambda(m-c_1)^2 + c_2 m^3}$$

- The parametrization is effective convolution of $\gamma\gamma \to e^+e^-$ cross section and detector effects

Mass fit is used to account for $\gamma\gamma \to e^+e^-$ contribution in J/ψ signal

Transverse momentum of J/ψ candidates

- Dielectrons within J/ψ mass peak
- Individual components by MC templates:
  - Coherent J/ψ
  - Incoherent J/ψ
  - $\gamma\gamma \to e^+e^-$
- MC templates are provided by STARLIGHT
- Contribution of $\gamma\gamma \to e^+e^-$ is normalized using fit to the invariant mass distribution
- Illustrative normalization for coherent and incoherent components



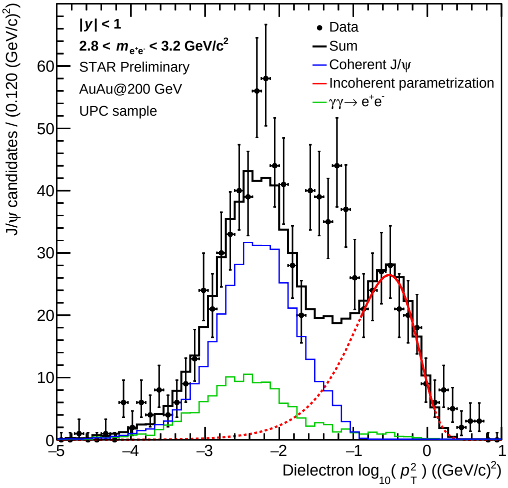
Coherent and incoherent J/ψ have different shapes of p_T spectrum

Fit to transverse momentum in $\log_{10}(p_T^2)$

- Separation of incoherent and coherent components
- Parametrization for incoherent J/ψ:

$$f_{\text{incoherent}} = A \cdot e^{-bp_T^2}$$

- The fit (solid line) is performed over incoherent region
- Contribution of $\gamma\gamma \to e^+e^-$ is normalized from invariant mass fit
- Illustrative normalization for coherent component



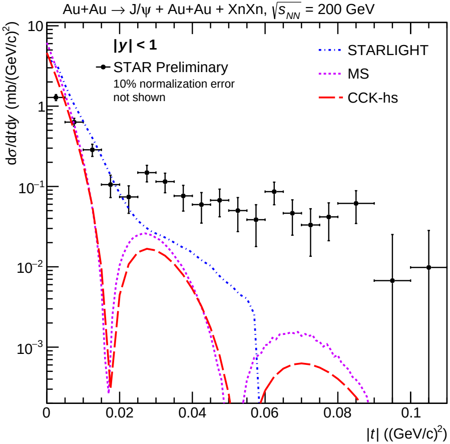
Fit to $\log_{10}(p_T^2)$ is used to account for incoherent background in coherent signal

Calculation of coherent cross section in bins of $|t|$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}|t|\mathrm{d}y} = \frac{N^{coh}_{J/\psi}}{A\times\varepsilon \cdot \mathcal{B} \cdot \mathcal{L}} \cdot \frac{1}{\Delta|t|\Delta y}$$

- $N^{coh}_{J/\psi}$ = yield of coherent J/ψ at a given $|t| = p_T^2$
  - Background from $\gamma\gamma \rightarrow e^+e^-$ is subtracted using invariant mass fit
  - Incoherent background is subtracted from fit to $\log_{10}(p_T^2)$
- $A \times \varepsilon$ = detector acceptance and efficiency
- $\mathcal{B}$ = branching ratio of $J/\psi \rightarrow e^+e^-$ (PDG)
- $\mathcal{L}$ = luminosity of data sample
- $\Delta|t|$ = size of bin in $|t|$
- Δy = size of bin in rapidity (= 2 for $|y| < 1$)

Coherent J/ψ cross section as a function of t



- **STARLIGHT:** Klein, Nystrand, CPC 212 (2017) 258-268
  - Vector meson dominance and Glauber approach
- **MS:** Mäntysaari, Schenke, Phys.Lett. B772 (2017) 832-838
  - Dipole approach with IPsat amplitude
  - Scaled to XnXn using STARLIGHT
- **CCK:** Cepila, Contreras, Krelina, Phys.Rev. C97 (2018) no.2, 024901
  - Hot spot model for nucleons, dipole approach
  - Scaled to XnXn using STARLIGHT

- Diffractive dip around $|t| = 0.02$ GeV^2 is correctly predicted by the dipole MS and CCK models
- Slope below first diffractive minimum is consistent with the Glauber approach in STARLIGHT

Summary

- The first STAR data on coherent J/ψ photoproduction as a function of t
- Trigger by back-to-back topology in the Barrel Electromagnetic Calorimeter
- Requirement for a neutron emission in a forward direction

- Diffractive structure is present in the t-dependence of cross section
- Comparison to the Glauber and dipole models

- Diffractive dip is present in dipole calculations
- The slope of t-dependence is correct in the Glauber model