Measurements of J/ψ photoproduction in Ultra-Peripheral Collisions at RHIC

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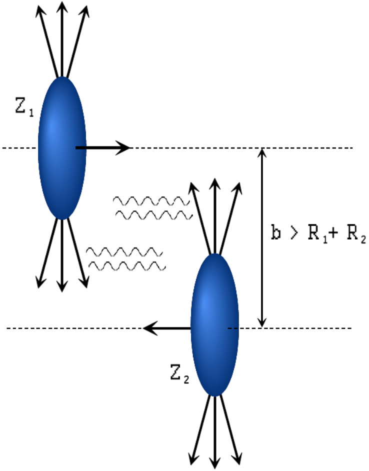
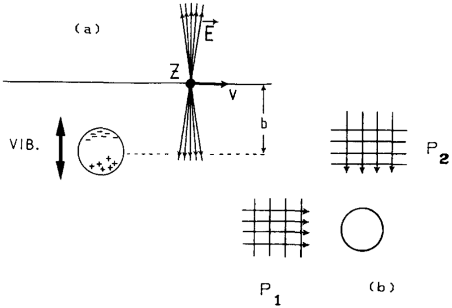
Ultra-peripheral heavy-ion collisions



- In a ultra-peripheral collision (UPC), impact parameter is typically greater than the sum of the nuclear radii
- Electromagnetic field of protons and ions is described as a beam of quasi-real photons
- Photon beam intensity is proportional to Z^2
- Photoproduction processes occur in γp and γA interactions
- QED processes take place in $\gamma\gamma$ interactions

The RHIC is used as a photon-nucleus or a photon-proton collider

Field of virtual photons by the Weizsäcker-Williams concept



Electromagnetic field of a relativistic charge creates the flux of equivalent photons which hit the target

- Lorentz contraction to the perpendicular direction, energy spectrum by Fourier transform:

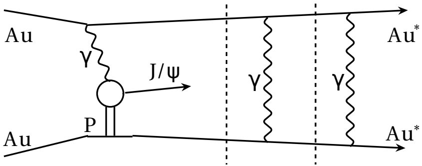
$$I(\omega, b) = \frac{1}{4\pi} |\boldsymbol{E}(\omega) \times \boldsymbol{B}(\omega)|$$

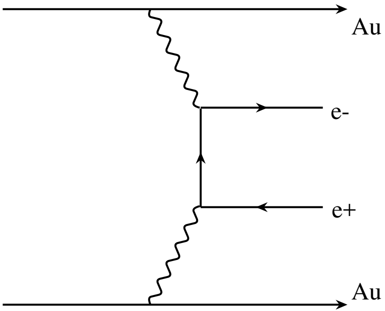
- Putting in field of uniformly moving charge, we have flux of photons per unit of area:

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

- 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

Physics processes studied in ultra-peripheral collisions



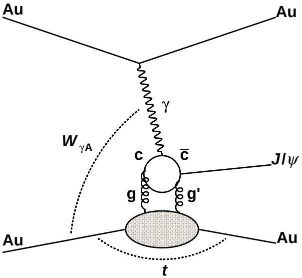


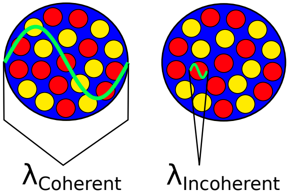
- Equivalent photons of the field can induce photon-nucleus and photon-photon interactions
- Large impact parameters are necessary to suppress short-range hadronic interactions
- Vector mesons and e^+e^- pairs are the only produced particles
- Nuclei typically leave intact, but may be excited by electromagnetic field to emit neutrons

Experimental signatures of a UPC event are just two tracks and forward neutron(s) in an otherwise empty detector

Photoproduction of heavy vector mesons

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





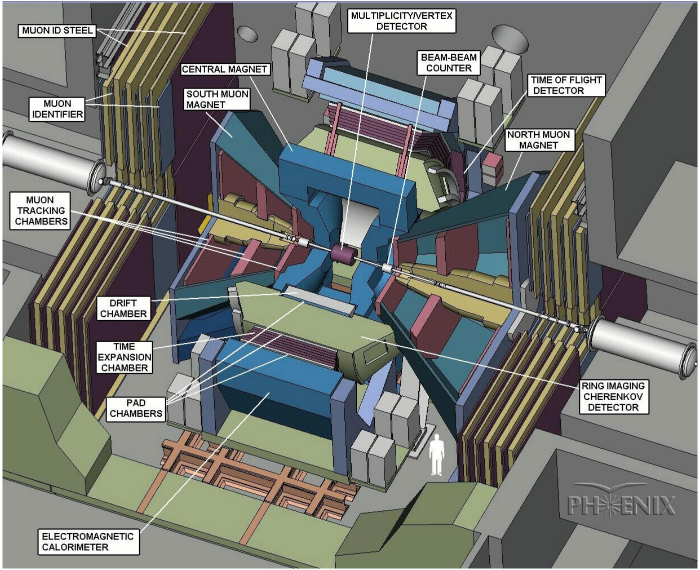
- Photon coupling may be coherent or incoherent
- Momentum fraction of probed gluons is $x = (M_{J/\psi}/W_{\gamma A})^2$

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

$$\left.\frac{d\sigma(\gamma A \to J/\psi A)}{dt}\right|_{t=0} \propto \left[x g_A(x, Q^2)\right]^2$$

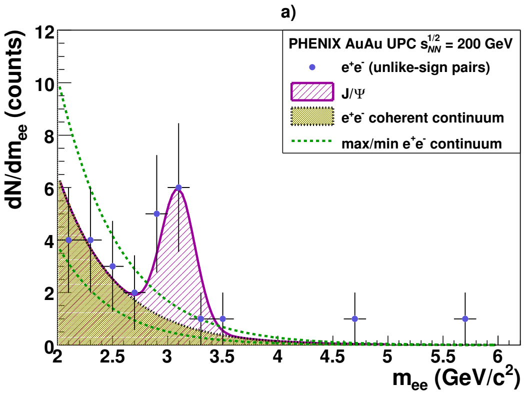
Coherent cross section is sensitive to nuclear effects of gluon density at low-x

The PHENIX experiment at RHIC



- The first data on J/ψ in UPCs at a hadron collider taken in 2004
- Measured as $J/\psi \rightarrow e^{+}e^{-}$
- Central tracking in Drift Chamber
- Identification in Cerenkov Detector and Electromagnetic Calorimeter
- Neutron detection in very forward Zero-degree Calorimeters
- Veto to non-UPC activity in Beam-beam Counters

Photoproduction of J/ψ at PHENIX, Au+Au UPC at 200 GeV



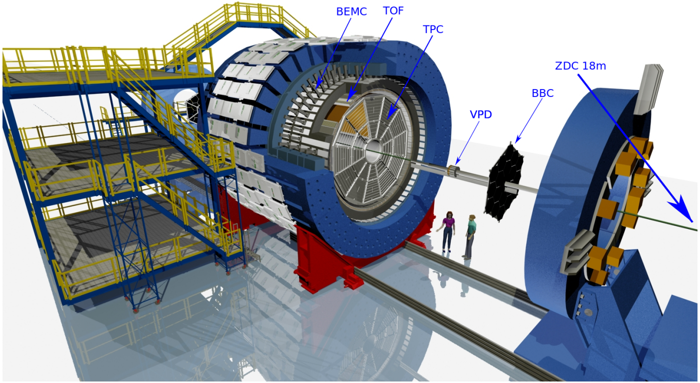
- Pairs of e^+e^- with at least one very forward neutron, and no other activity
- Clear separation between the J/ψ and two-photon $\gamma\gamma \to e^+e^-$
- Limited statistics to distinguish coherent and incoherent mechanism
- Opening for electromagnetic studies at hadron colliders

The first measurement of exclusive J/ψ photoproduction and e^+e^- pairs at a hadron collider

Phys.Lett. B679 (2009) 321-329

The STAR experiment

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

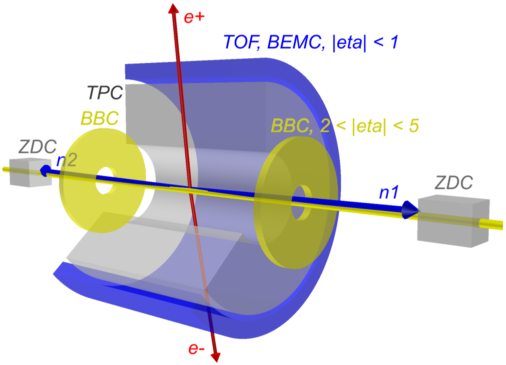


- Time Projection Chamber: tracking and identification in $|\eta| < 1$
- Time-Of-Flight: multiplicity trigger, identification and pile-up track removal
- Barrel ElectroMagnetic Calorimeter: topology trigger and pile-up track removal
- Beam-Beam Counters: scintillator counters in $2.1 < |\eta| < 5.2$,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

Data selection for coherent J/ψ in UPC at STAR

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

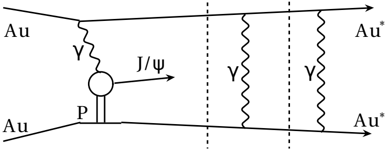
- Rapidity acceptance for J/ψ is $|y| < 1$
- Trigger requirements assume two tracks and at least one neutron in each ZDC



PoS DIS2019 (2019) 042

- 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

Very forward neutron emission



- Excited nuclei emit neutrons in a forward direction

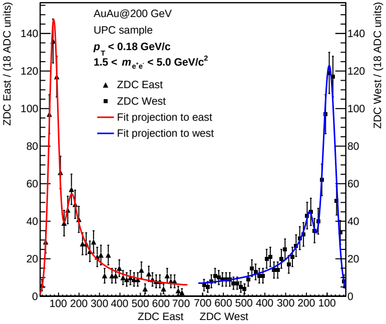


Figure: Spectrum of Analog-to-Digital counts from ZDCs

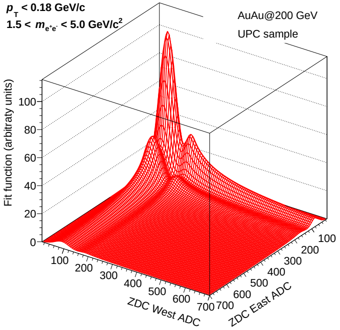
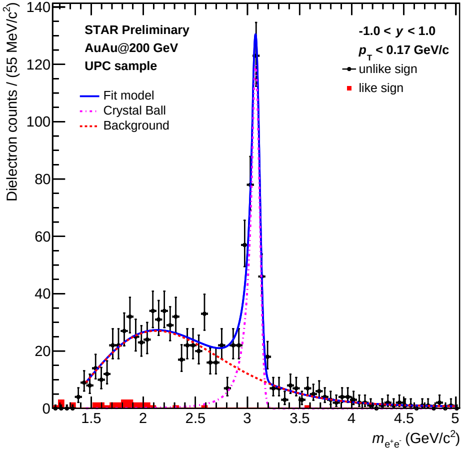


Figure: Two-dimensional fit by a sum of Gaussian and Crystal Ball functions

- 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

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:

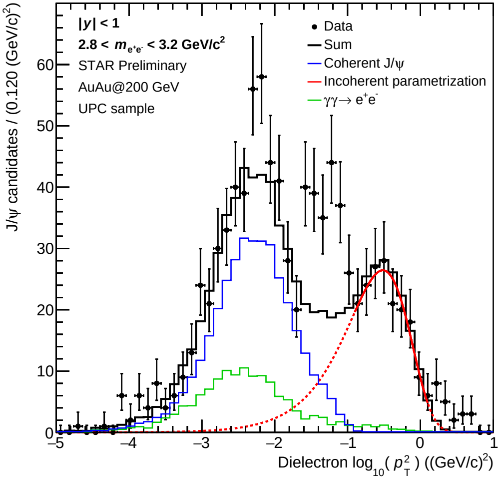
$$f_{\gamma\gamma \to e^+e^-} = (m - c_1)e^{\lambda(m-c_1)^2 + c_2 m^3}$$

- 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



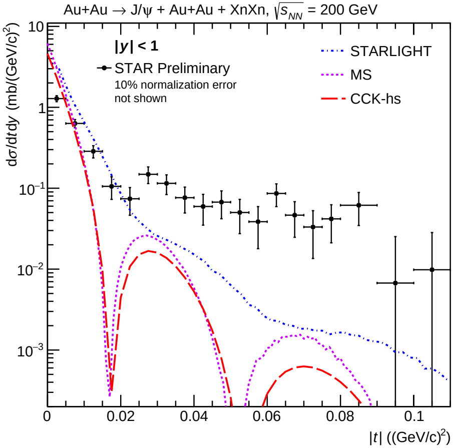
Fit to $\log_{10}(p_T^2)$ is used to account for incoherent background in coherent signal

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 $\gamma\gamma \to e^+e^-$ 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 $J/\psi \to e^+e^-$ (PDG)
- $\mathcal{L}$ = luminosity of data sample
- $\Delta|t|$ = size of bin in $|t|$
- Δy = size of bin in rapidity (= 2 for $|y| < 1$)

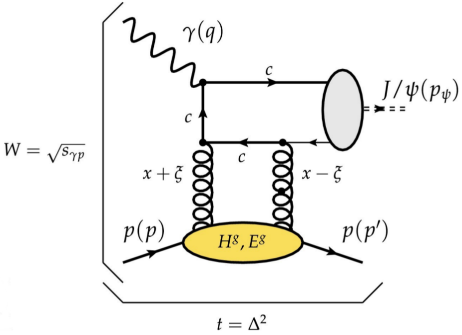
Coherent J/ψ cross section as a function of t



- **STARLIGHT:** Klein, Nystrand, CPC 212 (2017) 258-268
  - Vector meson dominance and Glauber approach
  - Includes effects of photon p_T
- **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 MS and CCK models
- Slope below first diffractive minimum is consistent with STARLIGHT

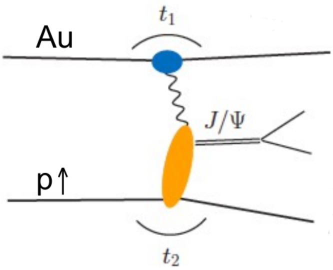
Photoproduction of J/ψ on polarized protons

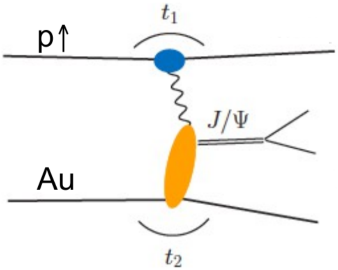


- A tool to measure Generalized Parton Distributions (GPDs)
- The GPDs are quark momentum and helicity distributions in transverse space
- Provides 3D imaging of proton
- The observable is angular modulation to J/ψ photoproduction cross section
- Amount of modulation is given by GPDs, Phys.Lett. B793 (2019) 33-40

Proof of principle obtained in p↑Au STAR data taken in 2015

UPC processes in p↑+Au



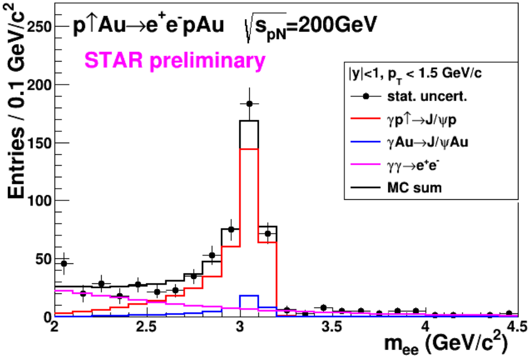


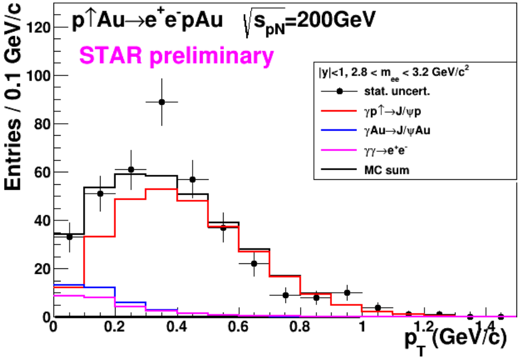
- Photoproduction on p↑ target
- Large photon flux from Au ions

- Photoproduction on Au target
- No asymmetry on unpolarized target

Photoproduction on polarized protons is dominant over γAu and $\gamma\gamma \to e^+e^-$

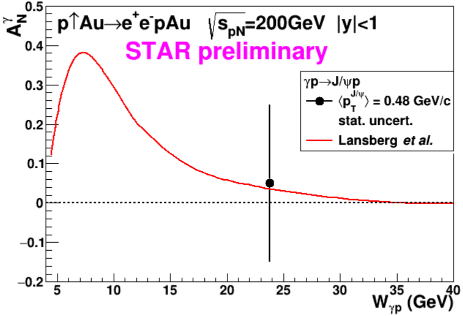
UPC data on p↑+Au





- Mass and p_T of selected J/ψ candidates
- Fit by components of γp, γAu and $\gamma\gamma \to e^+e^-$
- p_T in [0.2, 1.5] GeV considered for angular asymmetry, purity over 90%

Results on J/psi A-gamma-N in p↑+Au UPC



- Observed angular asymmetry $A_N^\gamma = 0.05 \pm 0.20$ at $W_{\gamma p} = 23.8$ GeV
- Result provides no discrimination about the prediction, but is a proof of principle
- More statistics at lower photon-proton energies is needed to test the models

Very first measurement is understood as a proof of principle

Summary

- Collisions of light are now a well established experimental tool
- A large variety of processes for future measurements and colliders

Figure: Collision of light