Photoproduction in UPCs at RHIC

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The strongest EM-fields in heavy ion collisions

- In heavy ion collisions,
  \[ E_{\text{max}} = 10^{18} \, \text{V/m} , \quad B_{\text{max}} \sim 10^{14} - 10^{18} \, \text{T} \]
  
  \[ \Rightarrow \text{Strongest EM-field in the universe, but transient} \]

- EM-field treated in terms of quasi-real photons
  \[ W_{\gamma,\text{max}} \sim \gamma \hbar c/R ; \]
  \[ W_{\gamma,\text{max}} \sim 3 \, \text{GeV (RHIC)} \]
  \[ W_{\gamma,\text{max}} \sim 80 \, \text{GeV (LHC)} \]

\[ \Rightarrow \text{EM-fields are quantized as photons} \]
Heavy Ions miss each other: Ultra-peripheral Collisions (UPCs)

Collisions where nuclei do NOT collide

No hadronic collisions happen

Ions interact through photon-ion and photon-photon collisions

=> Called Ultra-peripheral collisions (UPCs)
Photoproduction of Vector Mesons (VM) in UPC

\[
\text{Au} + \gamma \rightarrow \bar{q}q \rightarrow \text{VM (J/\psi, } \rho^0, \ldots)\]

\[
\text{Au} + \gamma \rightarrow \text{VM (J/\psi, } \rho^0, \ldots) \rightarrow \text{Au*} \]

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UPC VM: Powerful probe of parton densities inside nuclei

- Probes parton density & fluctuations inside nuclei—constraints for A+A initial state
- Modification of parton densities in heavy nuclei

=> VMs help to probe parton density inside nuclei before EIC era
UPC events with STAR detector

- Neutron(s) detected in ZDCs
- ZDC signals show peak structure for neutrons
- No activity in both BBCs => Diffractive events (η-gap)

=> Method to trigger UPC events

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\( \text{J}/\psi \) measurements in 200 GeV Au+Au UPCs

\[ \text{Au+Au} \rightarrow e^+e^-+e^+e^-+e^+e^-+ \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \]

\( \left| y_{ee} \right| < 1.0 \)

\( p_{T,ee} < 0.15 \text{ GeV}/c \)

\( \chi^2/\text{NDF} = 75.5/52 \)

- Data, all \( n \)
- coh J/\psi
- inc J/\psi
- inc J/\psi N diss
- coh \( \psi(2S) \)
- coh \( \psi(2S) \rightarrow J/\psi + X \)
- QED 2\( \gamma \)
- MC sum

\( m_{ee} \) distribution

\( \text{p}_{T} \) distribution

\( |y_{ee}| < 1.0 \)

\( 3.0 < m_{ee} < 3.2 \)

\( \chi^2/\text{NDF} = 41.4/28 \)

=> Coherent and incoherent contributions can be disentangled via the combined fit of mass and \( p_T \).
Rapidity dependence $J/\psi$ production cross-section

- Measured for coherent and incoherent contributions for different neutron emission in ZDCs
- Systematic unc. in incoherent to coherent cross-section ratio are largely cancelled
- Sensitive to the nuclear structure and deformation

=> Important to constrain theoretical models related to nuclear geometry

STAR, arXiv:2311.13637

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Incoherent production compared with H1 data with free proton

Strong nuclear suppression (~49%) seen (Mäntysaari et. al, Phys. Rev. Lett. 117 (2016) 5, 052301)

Models found H1 data supports sub-nucleonic fluctuations (Mäntysaari et. al, Phys. Rev. D 106 (2022) 7, 074019)

STAR data shows the bound nucleon has similar shape as the free proton — similar sub-nucleonic fluctuations in heavy nuclei

=> Strong nuclear suppression and sub-nucleonic fluctuations in Au nucleus

STAR, arXiv:2311.13632

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VM spin interference: A novel quantum phenomenon for high resolution gluon imaging
Polarized Photons from colliding nuclei

Transverse view of Lorentz contracted nuclei

=> Photons in UPC are linearly polarized

Experimental access to photon polarization demonstrated by STAR, measuring the Breit-Wheeler process, $\gamma\gamma \rightarrow e^+e^-$

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UPC vector meson spin and decay daughters are correlated

Polarization of photon → Inherited by VM

Decay VM → $d_1d_2$ daughters preferentially emitted (L+S conservation)

=> The cos(2φ) modulation in VM momentum distribution w.r.t photon polarization direction
Measuring the modulation over a large no. of events

Photon polarization correlated with Impact parameter —> random from one event to the next

=> Event average washes out the cos(2φ) modulation w.r.t photon polarization direction
Two independent paths of VM production

\[ \text{PATH - 1} \]

\[ \text{PATH - 2} \]

=> The paths are indistinguishable

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Photon source ambiguity: Interference among amplitudes of two possible paths

Interference makes the modulation observable in experiment

=> Two indistinguishable paths may interfere and make the cos(2\(\phi\)) modulation observable

Best analogy: Double slit experiment in Optics
Observation of interference for $\rho^0 \rightarrow \pi^+\pi^-$ at STAR

STAR, Sci. Adv. 9, eabq3903 (2023)

Observed the interference for coherent $\rho^0$ photoproduction in UPCs

Measured in 3 different collision systems: Au+Au, U+U, p+Au $\rightarrow$ Sensitive to nuclear shape/size
The $p_T$ dependence of interference for $\rho^0 \rightarrow \pi^+ \pi^-$ at STAR

Clear $p_T$ dependence of interference observed

Interference gets weak at higher $p_T$ — Incoherent processes take over

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Impact of spin interference on $|t|$ distribution studied in different $\phi$ bins

Improved measurement of mass radii using spin interference effect

$R (Au) = 6.53 \pm 0.06 \text{ fm}; \quad R (U) = 7.29 \pm 0.08 \text{ fm}$
Spin interference with $J/\psi \rightarrow e^+e^-$

$J/\psi \rightarrow e^+e^-$

Boson  Fermions

Mass: 0.7 GeV/c$^2$  
Lifetime: 1.3 fm/c

Mass: 3.1 GeV/c$^2$  
Lifetime: 2160 fm/c

Measured sign of the interference tells us the level of interference

$J/\psi$ heavier than $\rho^0$ and $J/\psi$ has much longer lifetime

$J/\psi$ decay length much longer than typical distance b/w two colliding nuclei in UPCs

$\rightarrow$ Probes finer structure and captures high quality images of the gluon distributions

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Observed spin interference for $J/\psi \rightarrow e^+e^-$

Interference cos(2\(\phi\)) pattern

Observed spin interference for $J/\psi \rightarrow e^+e^-$

Observable for $J/\psi$ spin interference

Interference signal fitted with: $1 + a_2 \cos(2\phi)$

$a_2$ is the measure of the modulation

$p_T < 200$ MeV/c

$2.95 < m_{e^+e^-} < 3.2$ GeV/c^2

STAR Preliminary

$|f(\phi)| = 1 + a_2 \cos(2\phi)$

$a_2 = 0.102 \pm 0.027 \pm 0.029$

Data

Fit

$\pm 1\sigma$

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Corrections of interference signal due to $2\gamma$ background

- The $\gamma + \gamma \rightarrow e^+ + e^-$ has also the $J/\Psi$ interference like pattern due to detector effect.

- We correct for the $2\gamma$ process with: $a_2 = f \times a^{bkg}_2 + (1-f) \times a^{sig}_2$, with $f = \frac{N_{bkg}}{N_{sig} + N_{bkg}}$

=> Background correction is done to extract true modulation signal.

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We considered the Bremsstrahlung process and $J/\Psi \rightarrow e^+ + e^- + \gamma$, using the STARLight+Geant simulations.

Bremsstrahlung correction performed for true modulation signal.
**Signal for J/ψ Spin interference**

- Measured and corrected signal for $J/\Psi$ spin interference:
  
  $$a_2 = 0.102 \pm 0.027 \pm 0.029$$

- Measurement has $\sim 3\sigma$ significance above zero

- Compared with STARLight and theory calculations

- STARLight has no spin interference physics — consistent with zero

- Theory (Diffractive+Interference) predicts negative modulation

=> Observed spin interference signal $\sim 10\%$ in the measured kinematic range

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**Graphical Representation**

![Graph showing measured and corrected signal for J/ψ spin interference.](image)
The $p_T$-dependent interference of J/$\psi$

- Interference signal shows strong $p_T$ dependence and rises toward positive.
- STARLight predicts zero.
- Diffractive+interference calculations are negative at low and high $p_T$.
- Diffractive+interference with additional soft $\gamma$ radiation predicts negative at low $p_T$ and rises towards positive value at higher $p_T$.

$\Rightarrow$ Modulation strength in data positively increases with $p_T$ in the measured kinematics.

Diff+Int+Rad predictions: Brandenburg et. al, Phys. Rev. D 106, 074008 (2022)

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Summary and take home

- Measured the coherent and incoherent J/ψ production in Au+Au UPCs
- STAR observed the spin interference of the photoproduced ρ⁰ and J/ψ
- Measured interference signal increases with $p_T$
- Measurements are sensitive to nuclear geometry and useful to constrain the theoretical models
- RHIC, LHC and future EIC experiments can provide further insights into these
Backup
Main central barrel detectors for UPC measurements: TPC, TOF, BEMC

Forward detectors: BBC or EPD, ZDC