Ultra-Peripheral Collisions in STAR

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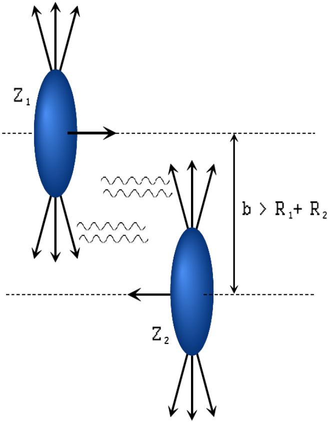
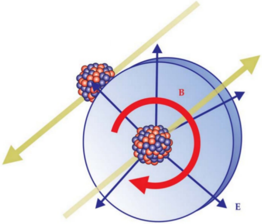
Ultra-peripheral heavy-ion collisions



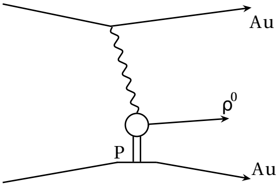
- Heavy ions are accelerated to relativistic energies
- Impact parameter is larger than the sum of nuclear radii
- Electromagnetic field of protons and ions behaves like a beam of quasi-real photons
- Photon beam intensity is proportional to Z^2
- Photoproduction in γp and γA interactions
- QED processes in $\gamma\gamma$ interactions

RHIC works as a photon-hadron and photon-photon collider

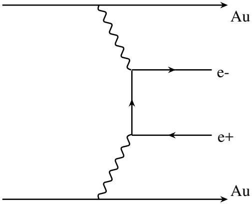
Physics processes studied in ultra-peripheral collisions



(a)



(b)

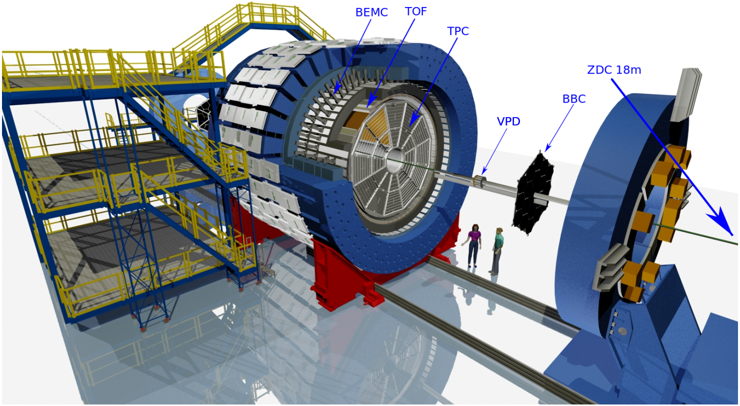


(c)

- An ultra-peripheral collision (UPC) **(a)** creates a Lorentz-contracted field
- We can study photon-nucleus **(b)** and photon-photon **(c)** interactions
- Vector mesons in **(b)** and e^+e^- pairs in **(c)** are the only produced particles
- Vector mesons are detected by their decays to $\pi^+\pi^-$ or e^+e^- pairs
- Nuclei typically leave intact, but may be excited by electromagnetic field to emit neutrons
- Neutrons can be detected in forward neutron detectors

The STAR experiment

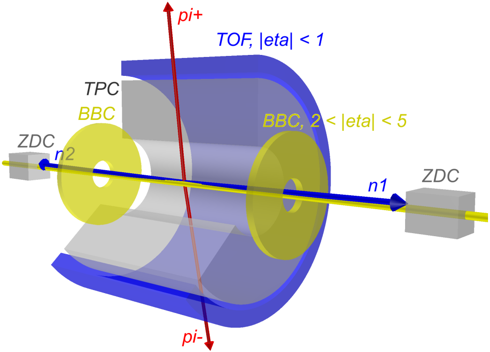
- Central tracking and particle identification, forward counters and neutron detection



- 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 UPC processes

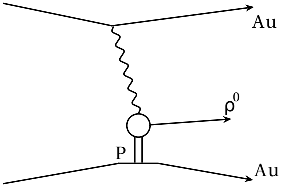
Just two tracks from a vector meson decay, forward neutrons, and nothing else

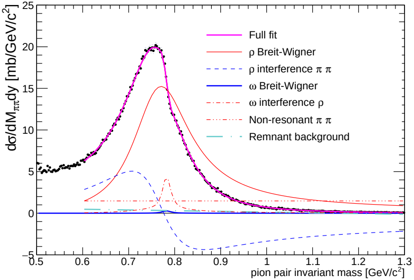


- Trigger requirements assume two tracks and neutrons in ZDCs
- Activity in TOF as $2 \leq n_{\mathrm{hits}} \leq 6$
- Showers in both ZDCs
  - Energy deposition within 1/4 to 4 beam-energy neutrons
  - Full efficiency to a single neutron
- Veto from both BBCs

Detectors are not in scale in the illustration

Light vector mesons





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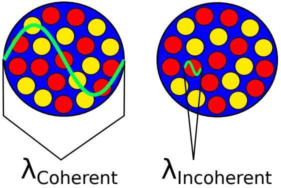
- Test for photon-pomeron coupling
- Soft-Pomeron model for $\gamma p \to \rho^0 p$
- Probe to model of Fock states of the photon

- Large sample of UPC $\pi^+\pi^-$ events
- Fit to mass by combination of ρ^0, ω^0 and direct $\pi^+\pi^-$ pairs



- Photon-nucleus coupling may be coherent or incoherent

> Diffractive coherent production is sensitive to nuclear effects

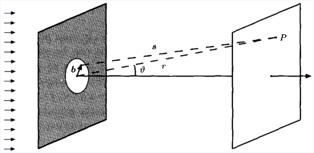
Diffraction origin in hadronic collisions in analogy with optics

Optics

- Electromagnetic wave as solution to Helmholtz equation:

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

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



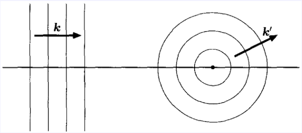
- Every point in hole of radius R is source of spherical wave
- Diffraction in light intensity at distance D when $kR^2/D \ll 1$

High energy physics

- Wave function as solution to Schröedinger equation

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

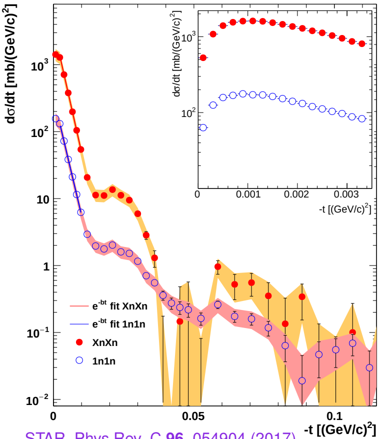
- Scattering is described as outgoing spherical wave



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

Diffraction in ρ^0 photoproduction

- ρ^0 photoproduction cross section
- $-t$ is momentum transfer to target nucleus
- Diffractive dips at $-t = 0.018$ and 0.043 GeV^{-2}
- Two cases of nuclear breakup:
  - 1n1n: just one neutron at (+) and (-) rapidities
  - XnXn: one or more neutrons at (+) and (-) rapidities
- Exponential slope in $\mathrm{d}\sigma/\mathrm{d}t$ is consistent with LHC (JHEP 1509, 095 (2015))



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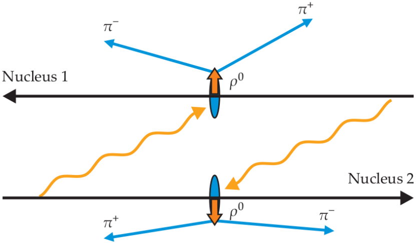
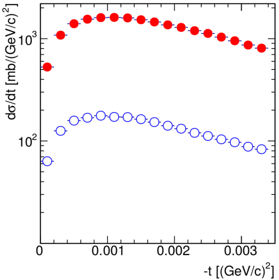
> Similarity in exponential parts implies no evidence for increase of nuclear size with photon energy

Quantum interference in UPC

- Each nucleus can be photon emitter or a target
- Photoproduction amplitudes add in destructive interference
- Interference has effects to very low $-t$



Physics Today **70**, 10, 40 (2017)



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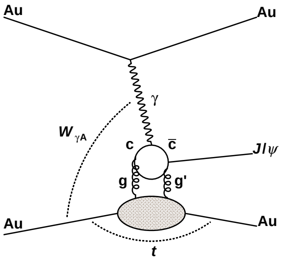
- Experimentally evident as a downturn at $-t$ close to zero
- Impact parameter is 20 - 40 fm
- ρ^0 can travel about 1.5 fm before decaying to $\pi^+\pi^-$

Collapse of ρ^0 wave function must occur much later than $\rho^0 \to \pi^+\pi^-$ decay

Photoproduction of heavy vector mesons

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



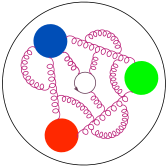
- Cross section is sensitive to nuclear gluon distribution $g_A(x, Q^2)$ at the scale $Q^2 = M^2_{J/\psi}/4$:

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

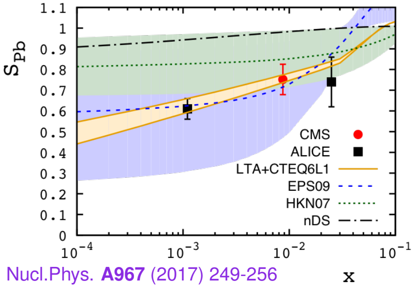
- Momentum fraction of probed gluons is $x = (M_{J/\psi}/W_{\gamma\mathrm{A}})^2$

Gluons in nuclei

- Hadrons are viewed as quarks bound together by gluons



- Gluons can interact with each other
- Density in nuclei is not same as in nucleons alone



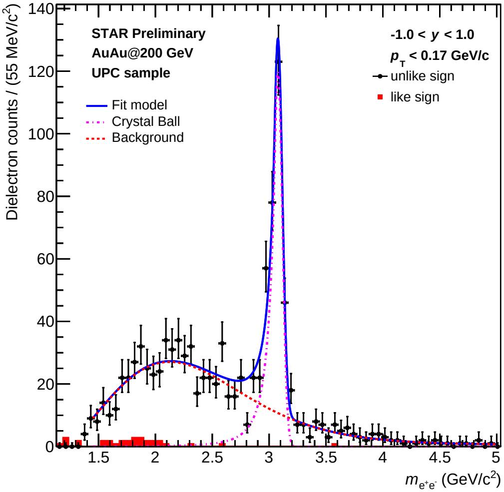
Nucl.Phys. **A967** (2017) 249-256

- We observe nuclear gluon shadowing at small-x: partial depletion of nuclear (w.r.t. nucleon) gluon density
- Quantified via suppression factor S_{A} as ratio of experimental $\gamma\mathrm{A}$ cross section to calculation with no nuclear effects:

$$S_{\mathrm{A}} = \left[\frac{\sigma_{\gamma\mathrm{A}}^{\mathrm{exp}}}{\sigma_{\gamma\mathrm{A}}^{\mathrm{IA}}} \right]^{1/2}$$

- STAR data on UPC J/ψ will come at $x \approx 0.015$

Data for J/ψ sample



- Data sample of e^+e^- pairs in Au+Au UPC
- Trigger by back-to-back topology in BEMC
- Crystal Ball function for J/ψ
- Main background is from $\gamma\gamma \to e^+e^-$
- Background is parametrized as:

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

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

Very clean signal, minimal hadronic background represented by like-sign events

Summary and outlook

- High statistics sample of $\rho^0 \to \pi^+\pi^-$ allowed a series of measurements
- Diffraction pattern is present in cross section t-dependence
- Quantum interference at very low t

- Coherent J/ψ photoproduction is a probe of nuclear gluon shadowing
- Clean signal with minimal hadronic background

- Analysis of J/ψ and $\gamma\gamma \to e^+e^-$ in progress
- Prospects for jets in UPC and other final states