

Ultra-Peripheral Collisions in STAR

Jaroslav Adam
For the STAR Collaboration

Creighton University, Omaha

Creighton
UNIVERSITY

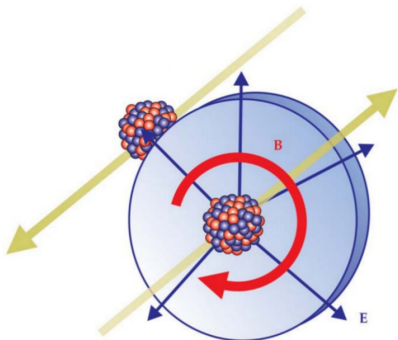
College of Arts and Sciences



Hilton Waikoloa Village

Fifth Joint Meeting of the DNP and the JPS

Ultra-peripheral heavy-ion collisions

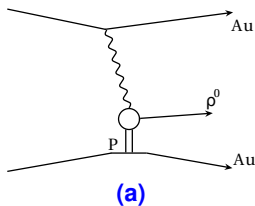


Physics Today **70**, 10, 40 (2017)

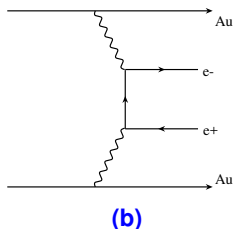
- An **ultra-peripheral collision (UPC)** is a collision at impact parameter greater than the sum of the nuclear radii
- Electromagnetic field of protons and ions behaves like a beam of quasi-real photons
- Photon beam intensity is proportional to Z^2
- Photoproduction in γp and γA interactions
- QED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

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

Physics processes studied in ultra-peripheral collisions



- UPCs are mediated by electromagnetic forces and photon-Pomeron interactions
- We can study photon-nucleus (a) and photon-photon (b) interactions

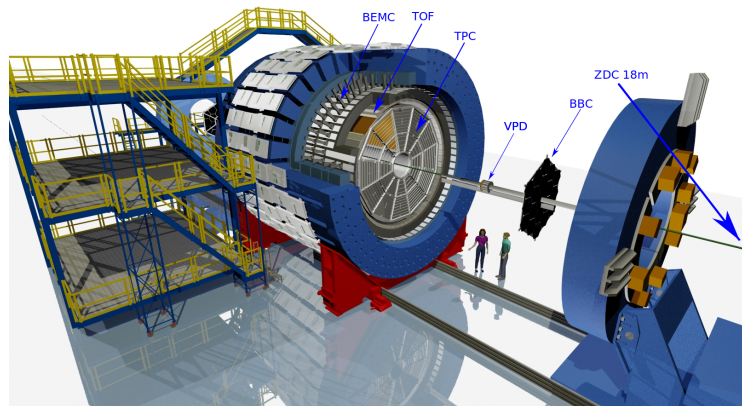


- Vector mesons are detected by their decays to $\pi^+\pi^-$ or e^+e^- pairs
- Nuclei typically leave intact, but may be excited by electromagnetic field to emit neutrons

Vector mesons in (a) and e^+e^- pairs in (b) are the only produced particles

The STAR experiment

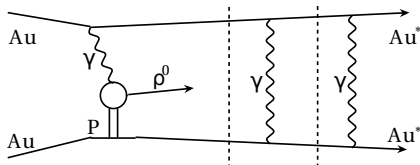
- Central tracking and particle identification, forward counters and neutron detection



- 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, $|\eta| > 6.6$

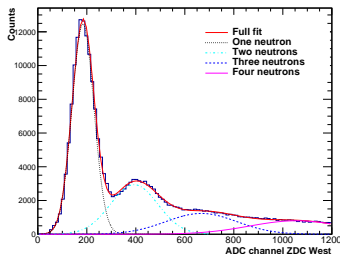
Very forward neutron emission

- Nuclear excitation is mostly independent of the photoproduction process
- Excited nuclei emit very forward neutrons



The neutrons are a convenient way to tag UPC events at the trigger level

- Neutrons from nuclear breakup are detected in ZDCs
- Peak structures for a given number of neutrons
- Fit by Gaussians for 1 – 4 neutrons

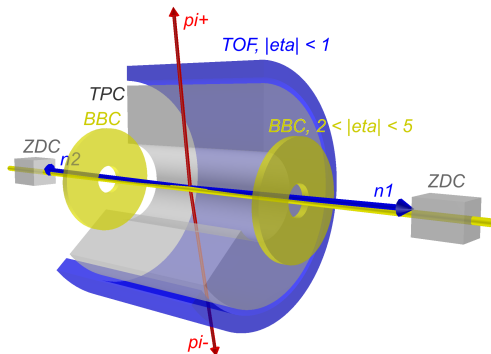


STAR, Phys.Rev. C **96**, 054904 (2017)

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

Trigger and data selection for UPC processes

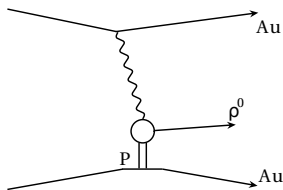
Just two tracks from a vector meson decay, forward neutrons, and nothing else



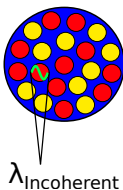
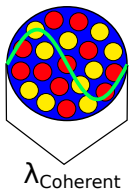
- Trigger requirements assume two tracks and neutrons in ZDCs
- Activity in TOF as $2 \leq n_{\text{hits}} \leq 6$
- Showers in both ZDCs
 - ▶ Energy deposition within 1/4 to 4 beam-energy neutrons
 - ▶ Full efficiency to a single neutron
- Veto from both BBCs

Detectors are not in scale in the illustration

Light vector mesons

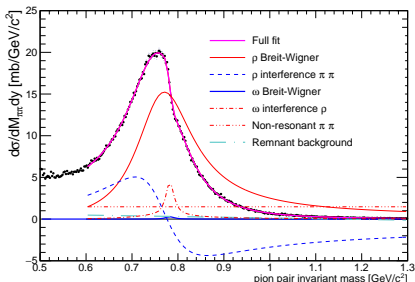


- Test for photon-pomeron coupling
- Soft-Pomeron model for $\gamma p \rightarrow \rho^0 p$
- Probe to model of Fock states of the photon



- Photon-nucleus coupling may be coherent or incoherent

Diffractive coherent production is a probe to nuclear effects

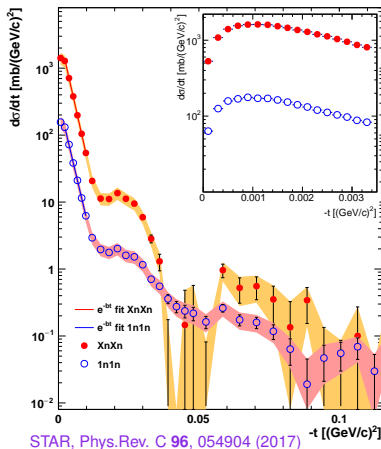


STAR, Phys.Rev. C 96, 054904 (2017)

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

Diffraction in ρ^0 photoproduction

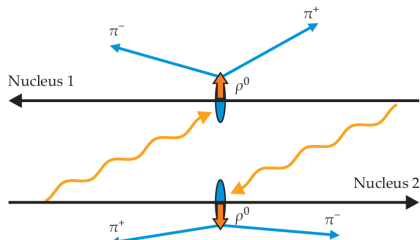
- ρ^0 photoproduction cross section
- $-t$ is momentum transfer to target nucleus
- Diffractive dips at $-t = 0.018$ and 0.043 GeV^{-2}
- Two cases of nuclear breakup:
 - ▶ $1n1n$: just one neutron at (+) and (-) rapidities
 - ▶ $XnXn$: one or more neutrons at (+) and (-) rapidities
- Exponential slope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



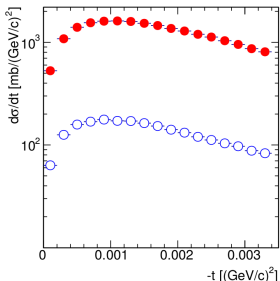
Similarity in exponential parts implies no evidence for increase of nuclear size with photon energy

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)



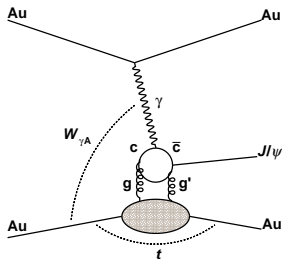
STAR, Phys.Rev. C 96, 054904 (2017)

- 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 $\rho^0 \rightarrow \pi^+\pi^-$ decay

Photoproduction of heavy vector mesons

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



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

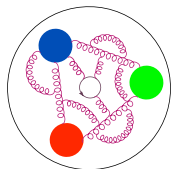
$$\left. \frac{d\sigma(\gamma A \rightarrow J/\psi A)}{dt} \right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha_{em} M_{J/\psi}^5} 16\pi^3 \left[x g_A(x, Q^2) \right]^2$$

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

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

Gluons in nuclei

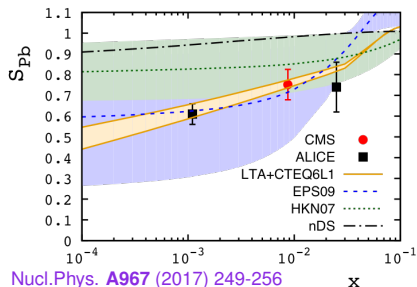
- Gluons can interact with each other



- Density in nuclei is not same as in nucleons alone

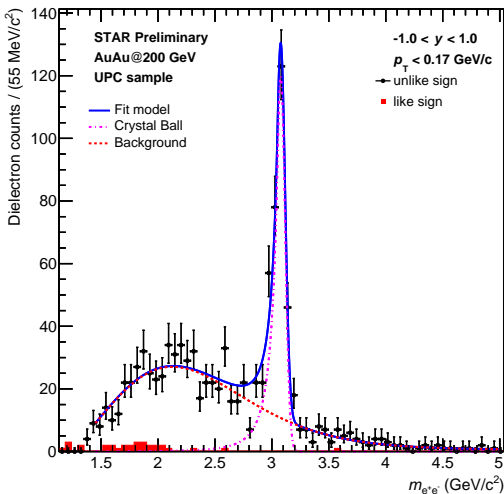
- We observe nuclear gluon shadowing at small- x : partial depletion of nuclear (w.r.t. nucleon) gluon density
- Suppression factor S_A : ratio of experimental γA cross section to calculation without nuclear effects:

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



STAR data on coherent J/ψ in UPC will come at $x \approx 0.015$, onset of shadowing

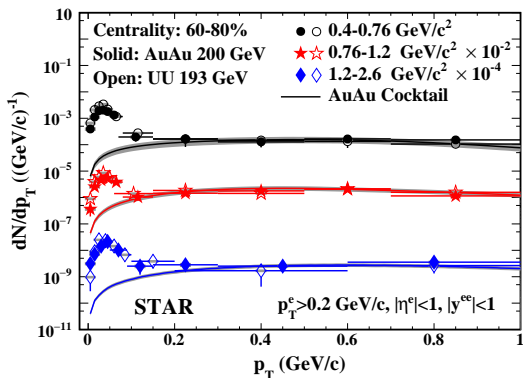
Data for J/ψ sample



- 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 $\gamma\gamma \rightarrow e^+e^-$
- Background is parametrized as:
$$f_{\text{bkg}} = (m - c_1)e^{\lambda(m - c_1)^2 + c_2 m^3}$$
- Parametrization is effective convolution of $\gamma\gamma \rightarrow e^+e^-$ cross section and detector effects

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

Electromagnetic processes in peripheral collisions



STAR, Phys.Rev.Lett. 121, 132301 (2018)

- Data on e^+e^- pairs in peripheral Au+Au and U+U collisions
- Yield enhanced at low p_T , contradictory to hadronic expectation
- Shape of the excess is consistent with e^+e^- from photoproduction

Novel probe to electromagnetic fields of the nuclei

Summary and outlook

- High statistics sample of $\rho^0 \rightarrow \pi^+\pi^-$ 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

- UPC-like events are also present in peripheral hadronic collisions

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