Physics of ultra-peripheral collisions

from the perspective of STAR experiment

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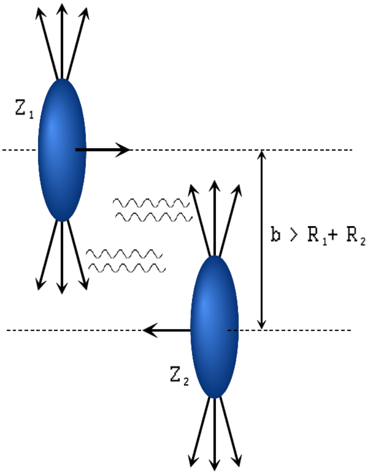
3. Česko-slovenský ALICE workshop

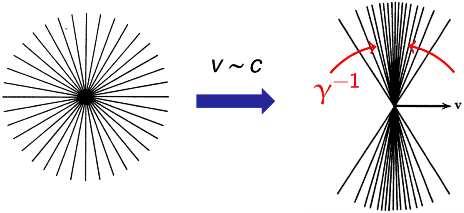
Ultra-peripheral heavy-ion collisions



- 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
- Photoproduction in γp and γA interactions
- Diffraction in pp or AA processes
- QED processes in $\gamma\gamma$ interactions

Hadron collider is turned to a photon-hadron or photon-photon 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:

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

- 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 charge squared, Z^2

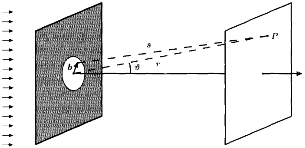
Origin of diffraction in hadronic collisions in analogy with optics

Optics

- Electromagnetic wave as solution to Helmholtz equation

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

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



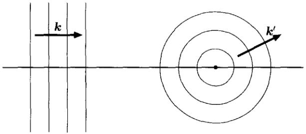
- Every point in a hole of radius, R, is a source of spherical wave
- Diffraction in light intensity at a distance, D, when $kR^2/D \ll 1$

Ion or proton collisions

- Wave function as solution to Schröedinger equation

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

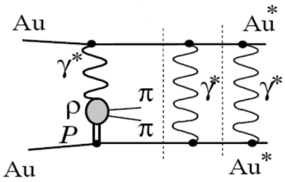
- Scattering is described as an outgoing spherical wave



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

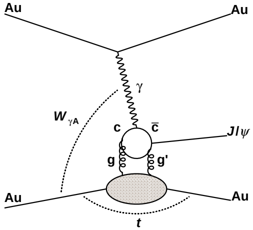
Physics processes studied in ultra-peripheral collisions

Light vector mesons



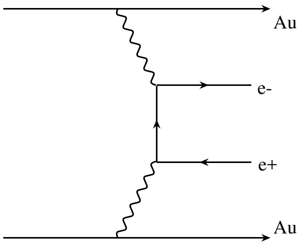
- Photon-pomeron coupling to target nucleus
- ρ^0 is the only produced particle

Heavy vector mesons



- Perturbative QCD, coupling via a gluon pair
- J/ψ is the only produced particle

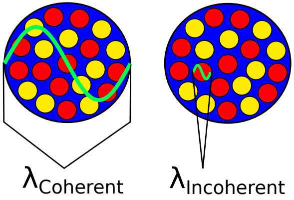
Two-photon pair production

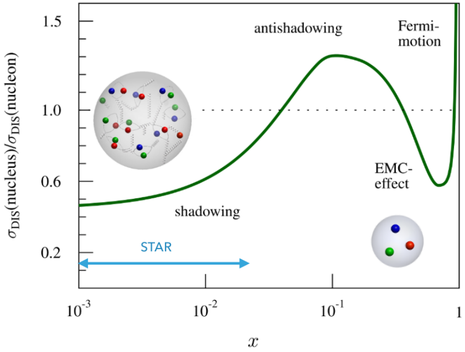


- QED in $\gamma\gamma \to e^+e^-$

Nuclei typically leave intact, but may be excited by electromagnetic field to emit neutrons

Photoproduction of vector mesons





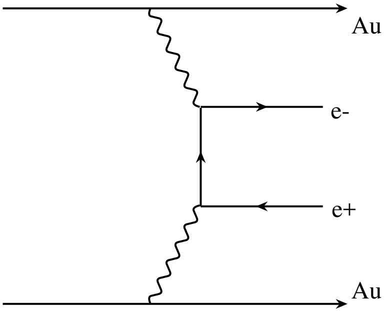
- Photon coupling is coherent (to entire nucleus) or incoherent (to a single nucleon)

- Light vector mesons probe Fock states of the photon and soft-Pomeron approach to the process
- Cross section of heavy meson photoproduction is sensitive to gluon density

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

Two-photon pair production, $\gamma\gamma \to e^{+}e^{-}$

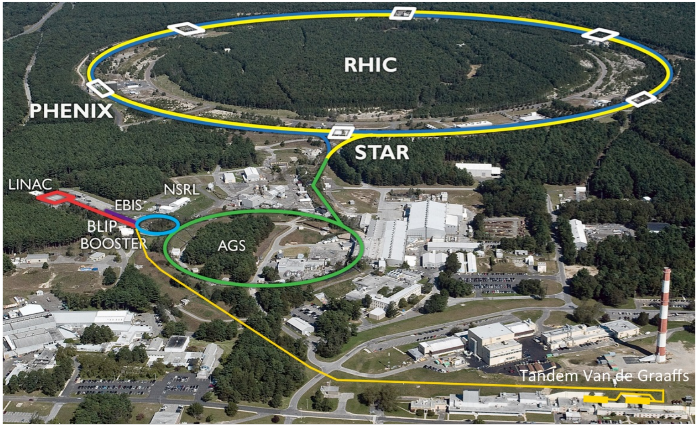
- Probe to fundamental QED and cross check to vector meson results
- Calculations factorize photon flux emitted by nuclei and $\gamma\gamma \to e^{+}e^{-}$ process itself
- Similar factorization is used also for vector meson models
- Mechanism for neutron emission is the same as with vector mesons



Experimental realization of energy to matter conversion

RHIC collider

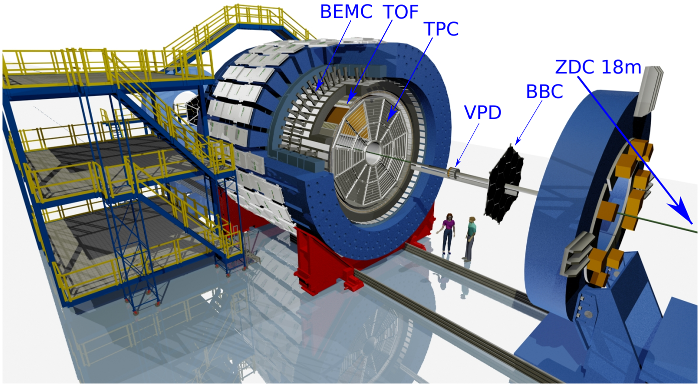
- Relativistic Heavy Ion Collider
- Located at Brookhaven National Laboratory (BNL), Long Island
- Nuclei up to Au, polarized protons
- Various beam energies up to $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV, 510 GeV for pp



Two more years to go, then conversion to Electron Ion Collider (EIC)

The STAR experiment at RHIC (Solenoidal Tracker At RHIC)

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

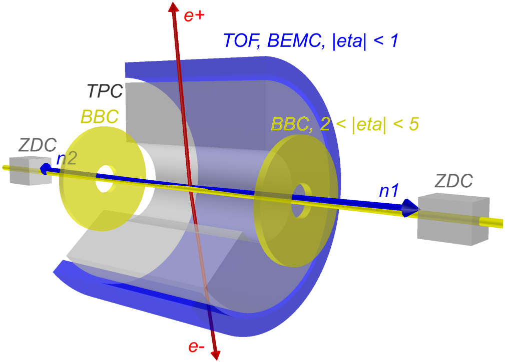


- Time Projection Chamber: tracking and identification in $|\eta| < 1$
- Time-Of-Flight: multiplicity trigger, particle identification and pile-up track removal
- Barrel ElectroMagnetic Calorimeter: topology trigger and pile-up track removal
- Beam-Beam Counters: scintillator counters in $2.1 < |\eta|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

Selection criteria for UPC events

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

- Rapidity acceptance for J/ψ or ρ^0 is $|y| < 1$

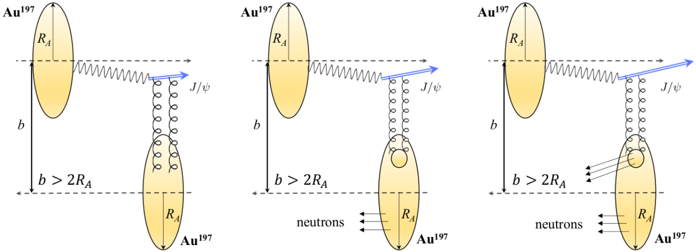


Detectors are not in scale in the illustration

- Dedicated trigger for limited activity and topology in TOF or BEMC
- Showers in both ZDCs
  - Energy deposition to be consistent with selected breakup case
  - Full efficiency to a single neutron
- Veto from both BBCs against any other hadron activity

News on J/ψ and $\gamma\gamma \to e^+e^-$ UPCs in AuAu

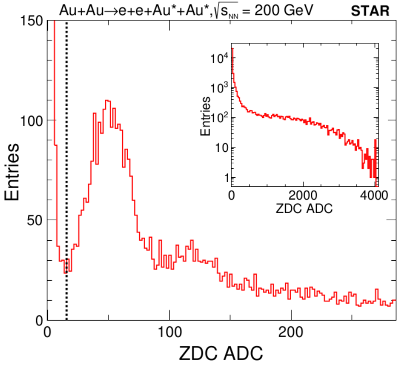
- Recent PRL and PRC submissions, arXiv:2311.13637 and arXiv:2311.13632
- Coherent and incoherent J/ψ photoproduction and $\gamma\gamma \to e^+e^-$ cross section

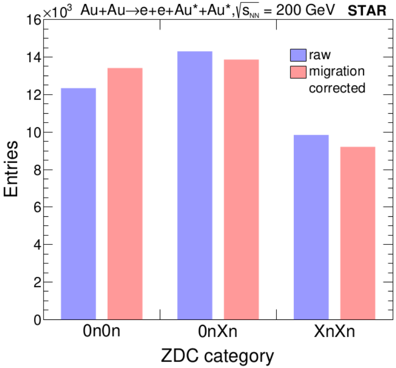


Use of forward neutrons to determine photon-nucleus center-of-mass energy

Neutron tagging by ZDCs

- Single-neutron at 50 ADC, full range up to ∼80 neutrons
- Separation between no activity and at least one neutron (dashed line)
- Classes for neutron emission corrected for migrations:





0n0n

No signal in ZDCs

0nXn

One ZDC has signal, the other is empty

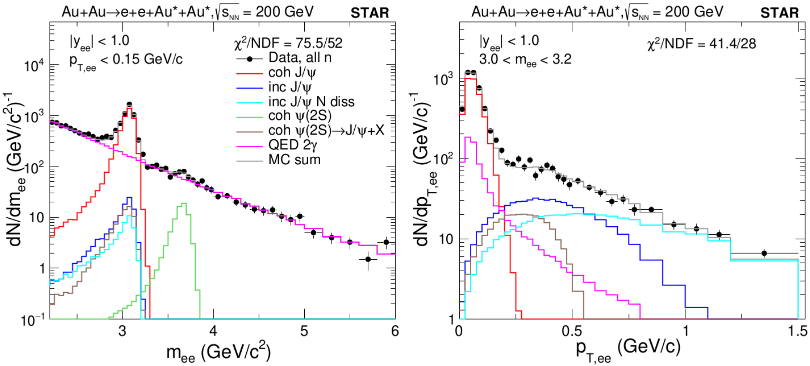
XnXn

Both ZDCs have signal

- Additional class *all n* as a sum of all, 0n0n, 0nXn and XnXn (meaning no requirement on ZDC)

Mass and p_T of selected dielectron candidates

- Coherent enriched sample below p_T = 0.15 GeV
- No requirement on ZDC (*all n*)
- Fit by MC templates folded by complete detector simulation



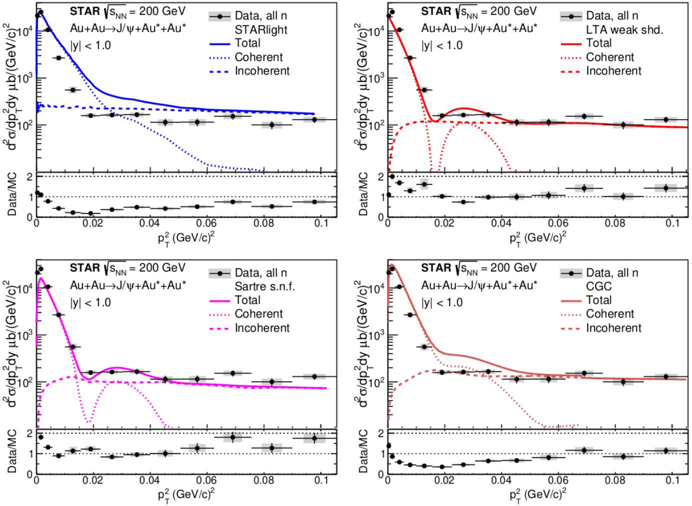
- The templates include: coherent J/ψ and $\psi(2S)$, incoherent J/ψ w/o dissociation, feed-down from $\psi(2S) \to J/\psi$+X and QED $\gamma\gamma \to e^+e^-$

Fit results are used to extract signal of individual processes

J/ψ photoproduction cross section in $-t$ ($\approx p_T^2$)

- Mid-rapidity $|y| < 1$, average $W_{\gamma\mathrm{N}}$ = 25 GeV
- Momentum transfer squared at target nucleus is related to p_T of the J/ψ as $-t \approx p_T^2$
- Better agreement with data is found for Sartre and LTA calculations in data/MC ratios

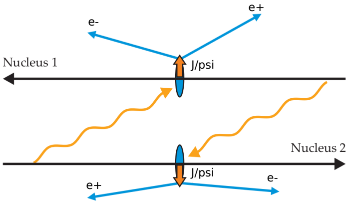
> Coherent peak at low p_T^2, incoherent photoproduction at larger p_T^2 (decreasing exponential)



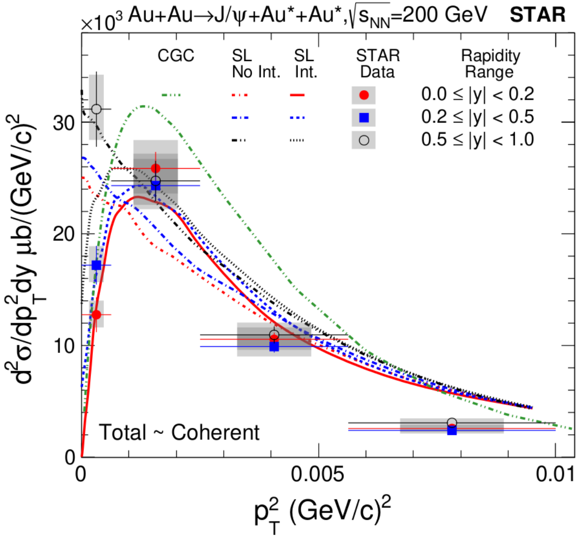
Additional 10% luminosity uncertainty is not shown

arXiv:2311.13632

Interference in J/ψ photoproduction



- Region of the lowest $p_T^2 < 0.01$ GeV^2, almost all production is coherent
- Bins in rapidity, *all n* neutron category
- Suppression by more than 0.5 in the lowest p_T^2 bin



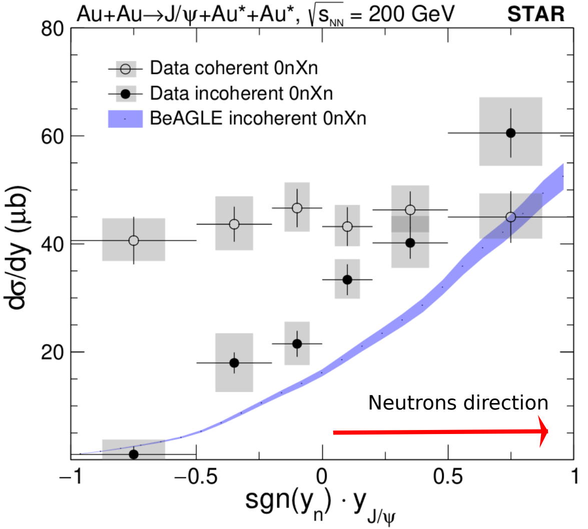
> Interference due to the symmetry of Au+Au collisions

arXiv:2311.13632, drawing adapted from Phys.Today 70 (2017) 10, 40-47

Coherent and incoherent 0nXn neutron class

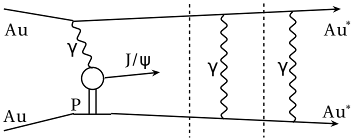
- Neutron emission in one side, no ZDC hit in the other (0nXn class)
- Positive rapidity *y* is defined along the direction of produced neutron(s)
- No effect of neutron direction to coherent process (independent Coulomb nuclear excitation)

Increase in incoherent production in the neutron direction (nuclear breakup directly in incoherent process)



arXiv:2311.13632

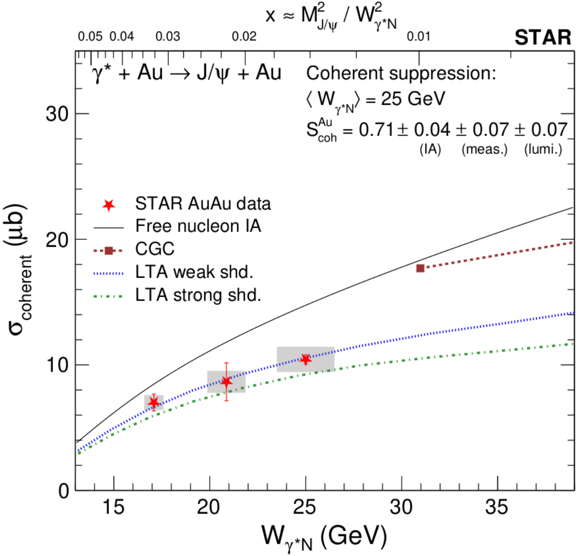
Coherent J/ψ photoproduction vs. photon-nucleus CM energy $W_{\gamma N}$



- Values for σ_{coherent} are obtained after solving photon source-target ambiguity by making use of the forward neutrons (0n0n, 0nXn, XnXn)

- LTA with weak shadowing describes the data

Significant suppression w.r.t. the Impulse Approximation (IA) is observed

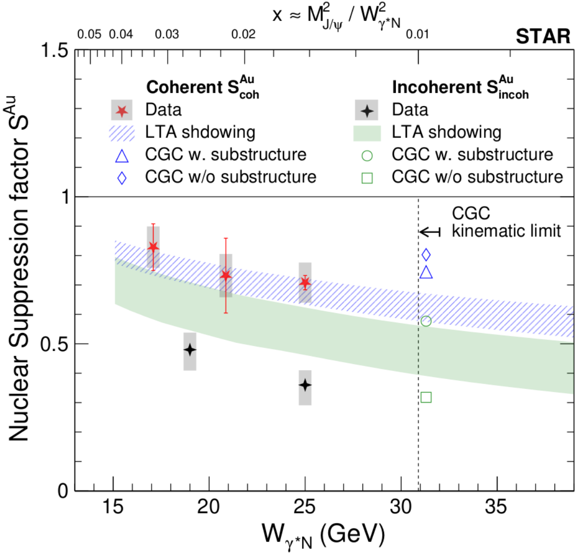


arXiv:2311.13632

Nuclear suppression factor

- Coherent suppression $S_{\text{coh}}^{\text{Au}}$ is determined relative to the IA
- Incoherent suppression $S_{\text{incoh}}^{\text{Au}}$ is a ratio of *all n* cross section to HERA parametrization for free protons
- Bands for LTA model span between weak and strong shadowing
- CGC is shown at its kinematic limit for $x > 0.01$

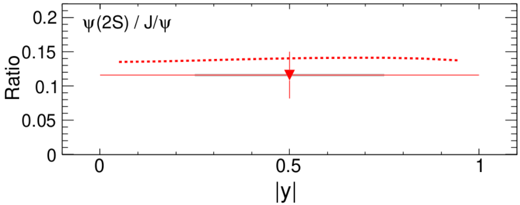
Stronger incoherent suppression is found than in the coherent case

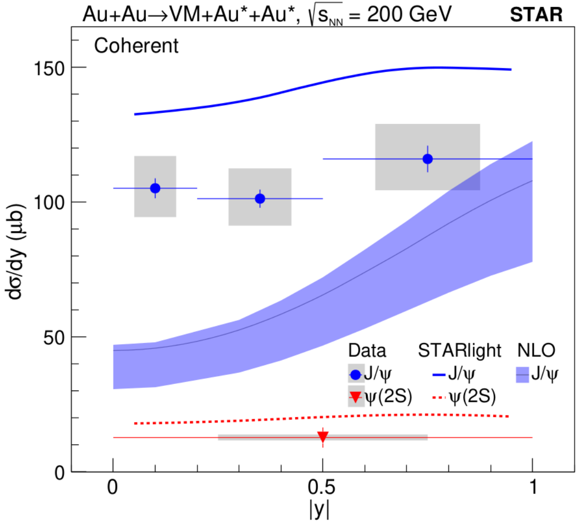


arXiv:2311.13637

Coherent $\psi(2S)$ photoproduction vs. rapidity

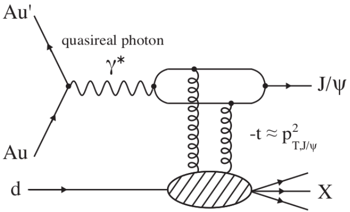
- Coherent $\psi(2S)$ and J/ψ cross section in bins of $|y|$ and their ratio
- Case of *all n* neutron category
- The ratio is correctly predicted by STARlight

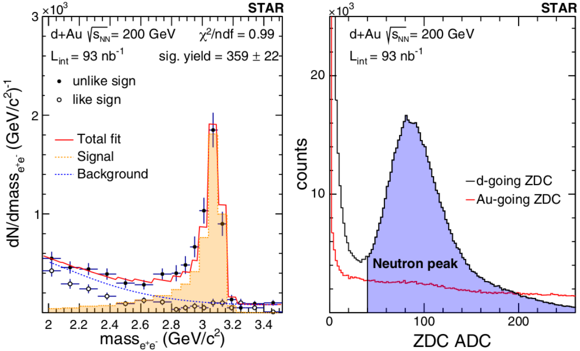




arXiv:2311.13632

J/ψ photoproduction off deuterons





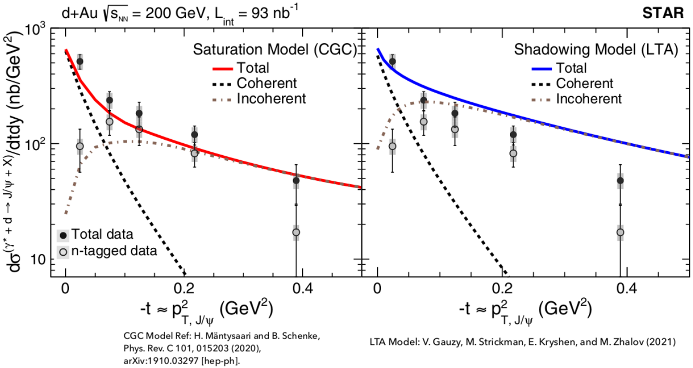
- Measured in d-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
- Au is more likely the photon source due to Z^2 proportionality in the flux

Coherent and incoherent cross section on deuterons with neutron tagging

Phys.Rev.Lett. 128 (2022) 12, 122303

Cross section of J/ψ photoproduction in d-Au UPC

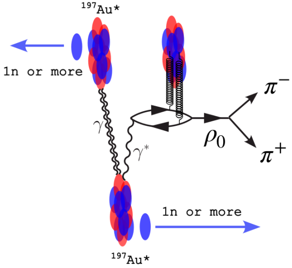
- Results vs. momentum transfer squared at the deuteron $-t$
- Direct incoherent measurement with neutron tagging (neutron in the direction of deuteron)

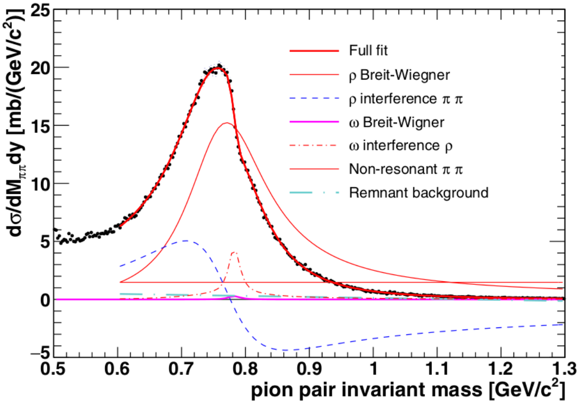


Sensitive to deuteron gluon distribution and breakup process, baseline for EIC

Phys.Rev.Lett. 128 (2022) 12, 122303

ρ^0 photoproduction in AuAu UPC





- High statistics $\pi^+\pi^-$ events (1100 μb^{-1}) at $\sqrt{s_{NN}} = 200$ GeV
- Individual components are separated in mass fit

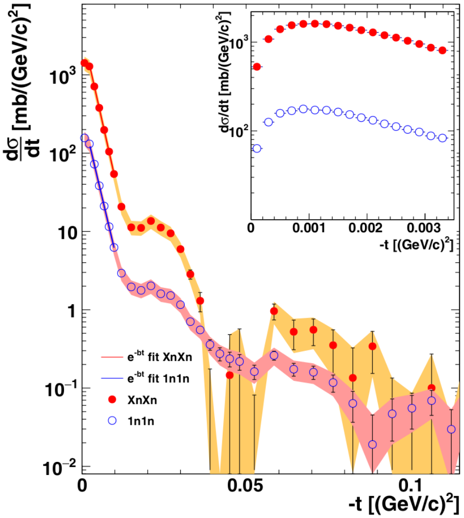
Clean sample of ρ^0 photoproduction events

Phys.Rev.C 96 (2017) 5, 054904

Results on ρ^0 photoproduction in AuAu UPC

- Cross section as a function of squared momentum transfer at target nucleus $-t = p_T^2$
- Single-neutron and more-neutron categories
- Interference between source and target nuclei at very low $-t$
- Diffractive minima consistent with Au size

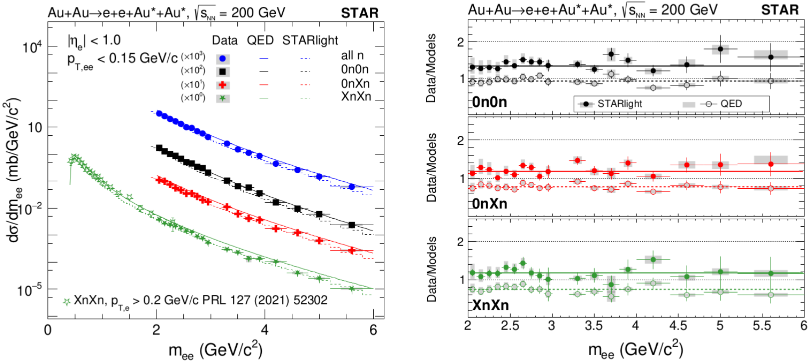
Observation of the minima indicates the onset of black disk regime



Phys.Rev.C 96 (2017) 5, 054904

Cross section of $\gamma\gamma \rightarrow e^+e^-$ pair production in AuAu UPC

- Cross section as a function of dielectron mass
- Individual neutron emission categories
- New data up to m_{ee} of 6 GeV, addition to previous results at lower masses



Models are consistent with data in all neutron categories, confirming relation between photon flux and neutron emission in mutual Coulomb excitation

arXiv:2311.13632

Summary

UPCs are a clean probe to diffraction phenomena, mechanisms of gluon shadowing and saturation, and fundamental QED

More STAR data to come (some of):

- J/ψ in pp UPC with protons detected in Roman Pots
- Combined samples for J/ψ in AuAu, question of diffractive dips in t dependence
- Strangeness in UPC events