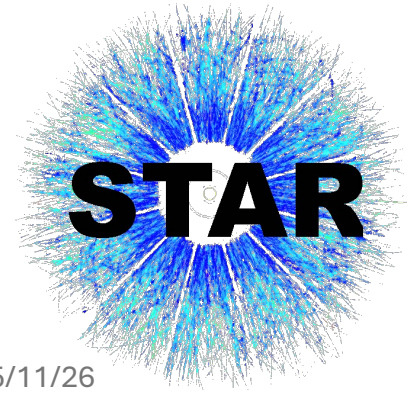
Supported in Part By
U.S. DEPARTMENT OF ENERGY
Office of Science

Measurements of Vector Mesons in Ultra-Peripheral Collisions at STAR

Xihe Han

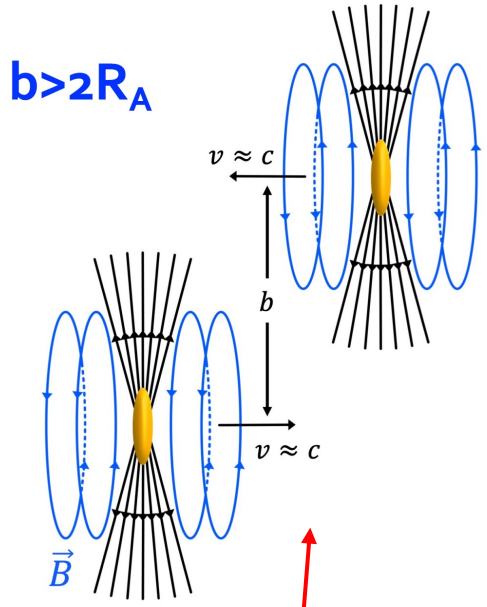
The Ohio State University

2026 RHIC/AGS User's Meeting

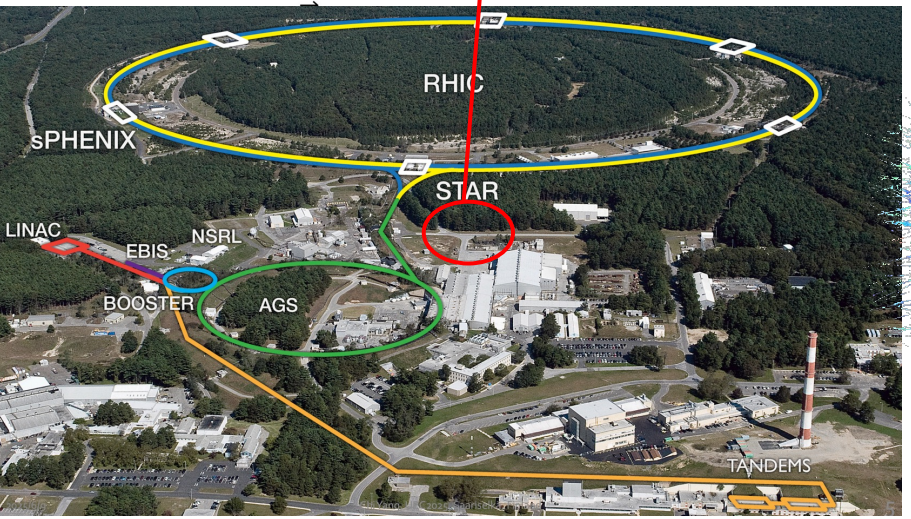


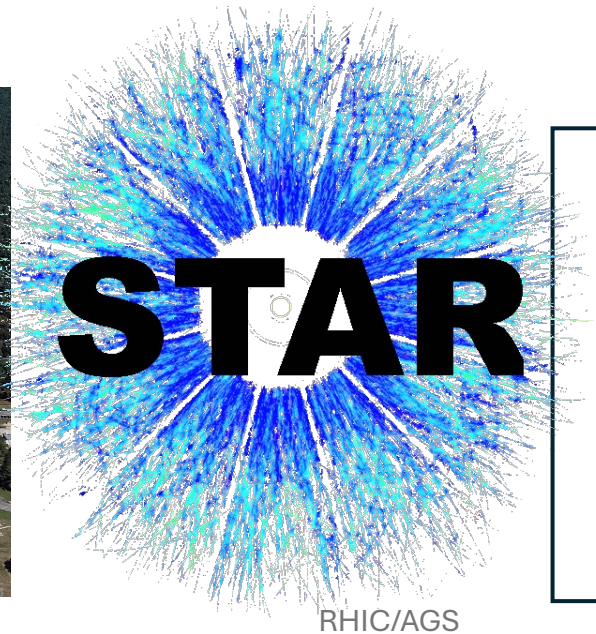
Sincerely apologize in advance for any omissions or misinterpretations ☹

Basics on Ultra-Peripheral Collisions (UPCs)



- **No** hadronic overlap
- **Long-range electromagnetic interactions dominate.**



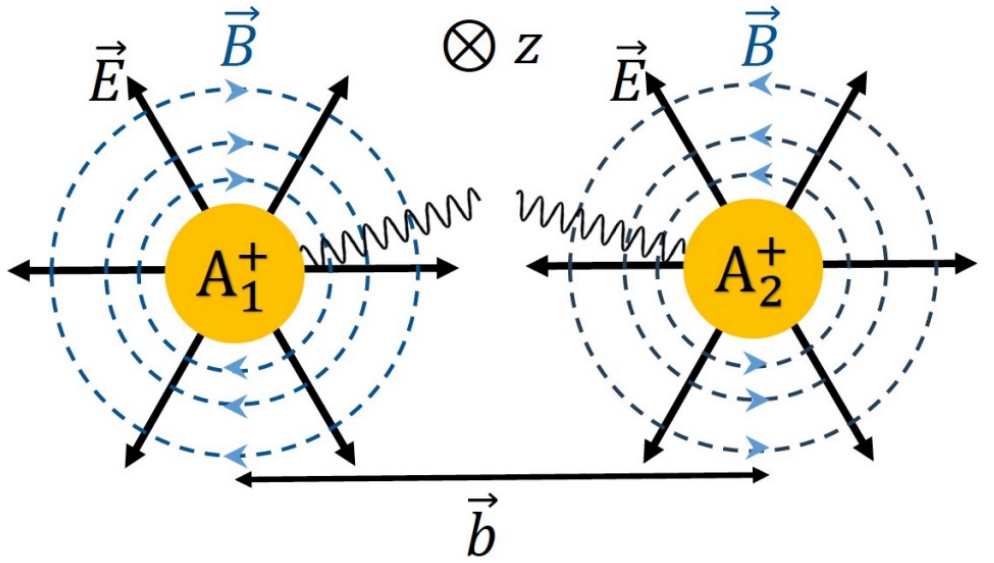


No hadronic overlap ≠ no physics.

Heavy Ions as Sources of (Quasi) Real Photons

- V. Weizsacker, E.J. Williams- Equivalent Photon Approximation

$$N(k,b) = \frac{Z^2\alpha}{\pi^2}\frac{k}{(\hbar c)^2}\frac{1}{\gamma^2}\left[K_1^2(x) + \frac{1}{\gamma^2}K_0^2(x)\right]$$



A highly Lorentz-boosted EM Field: Flux of quasi-real photons

Virtuality $Q^2 \sim \left(\frac{\hbar}{R_A}\right)^2 \sim 30\text{MeV}$

Mostly transversely polarized

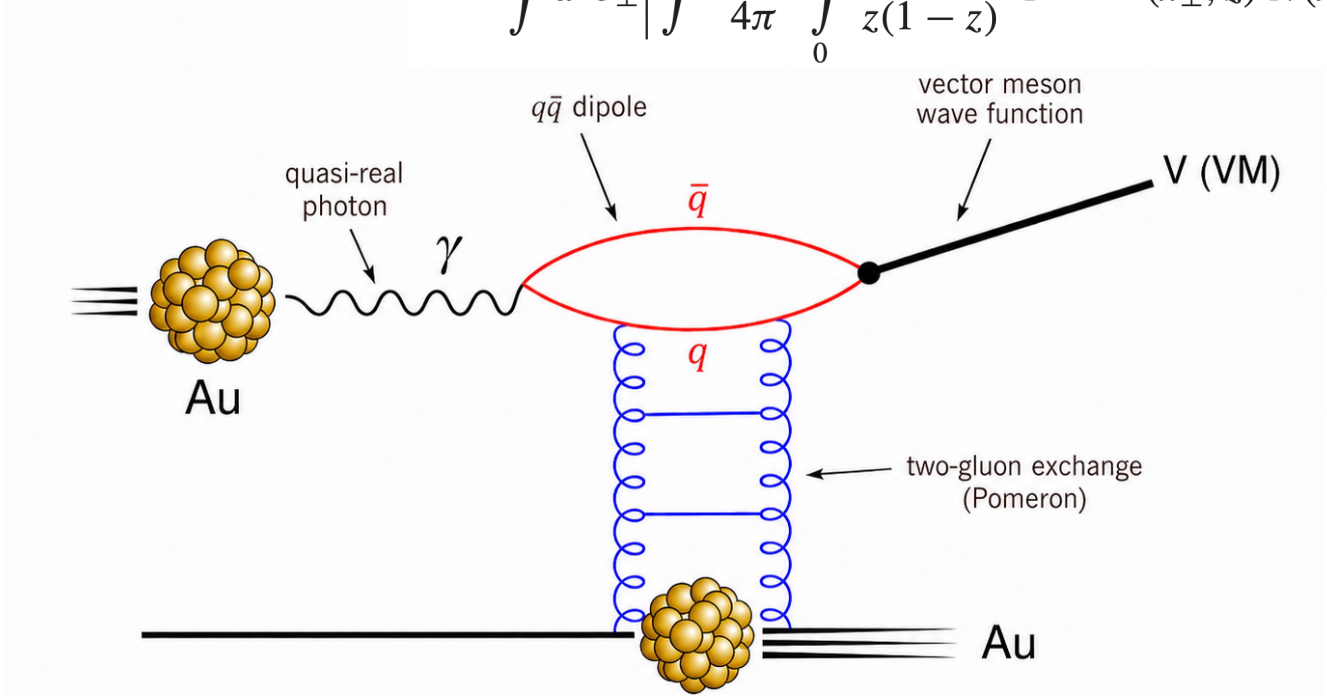
$\omega_{\max} \sim \frac{\gamma\hbar c}{R_A} \sim 3.0\text{GeV}$ -> an excellent source of quasi-real photons.

How photons interact via the strong force

$$\sigma^{\gamma^*+A\rightarrow V+A}$$

$$\sigma_{AA\rightarrow VA} \sim \text{Photon Flux} \cdot \sigma_{\gamma A\rightarrow VA}$$

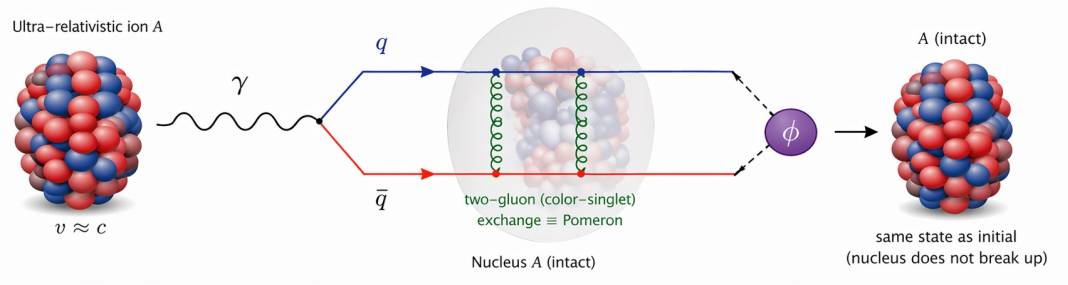
$$= \int d^2b_\perp \left| \int \frac{d^2x_\perp}{4\pi} \int_0^1 \frac{dz}{z(1-z)} \Psi^{\gamma^*\rightarrow q\bar{q}}(\vec{x}_\perp, z)\, N(\vec{x}_\perp, \vec{b}_\perp, Y) \Psi^V(\vec{x}_\perp, z)^* \right|^2 .$$



Exclusive Vector Meson Production in UPCs

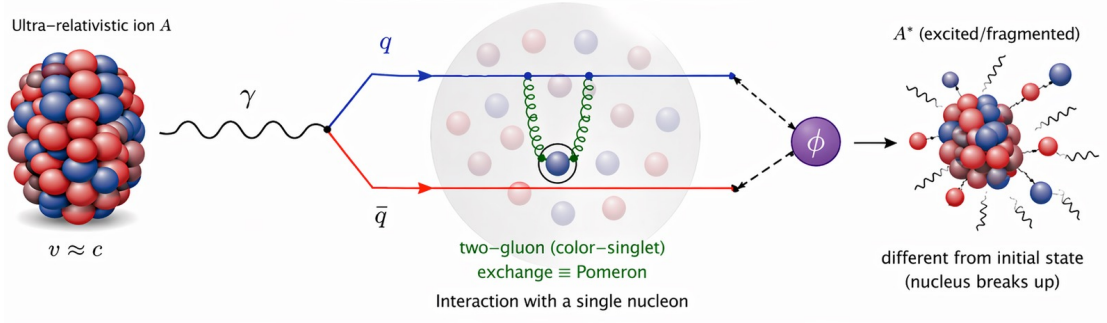
- $\gamma A \rightarrow VA$ process:
  1. A quasi-real photon from the Lorentz-contracted EM field fluctuates into a $q\bar{q}$ pair.
  2. This neutral color dipole interacts with the nucleus via a colorless 2-gluon exchange (Pomeron).
  3. The exclusive interaction produces a vector meson: $\rho^0, \phi, J/\psi \ldots$
  4. We detect the decay products of the vector meson.

Coherent Production



- Interaction with the entire nucleus
- Target stays intact
- Small momentum transfer
- Sharp peak at $|t| \approx \left|\frac{\hbar}{R_A}\right|^2$

Incoherent Production

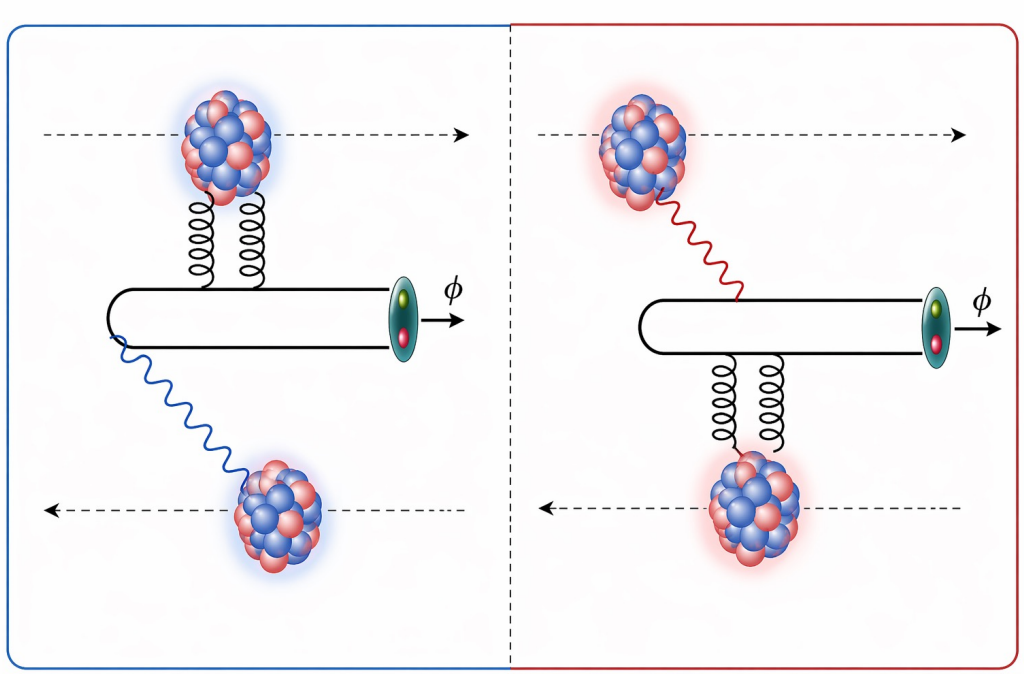


- Only one or a few nucleons participate
- Target is excited or breaks up
- Large momentum transfer
- Broad distribution in $|t|$

Emission ambiguity in UPCs

- When identical beams collide, there is an ambiguity about which nucleus emitted the photon, leading to **quantum interference**.
- The ambiguity exists for both coherent and incoherent processes.

Low energy photon
High energy target
$k = \frac{M_V}{2} e^{-y}, x = \frac{M_V}{\sqrt{s}} e^{+y}$

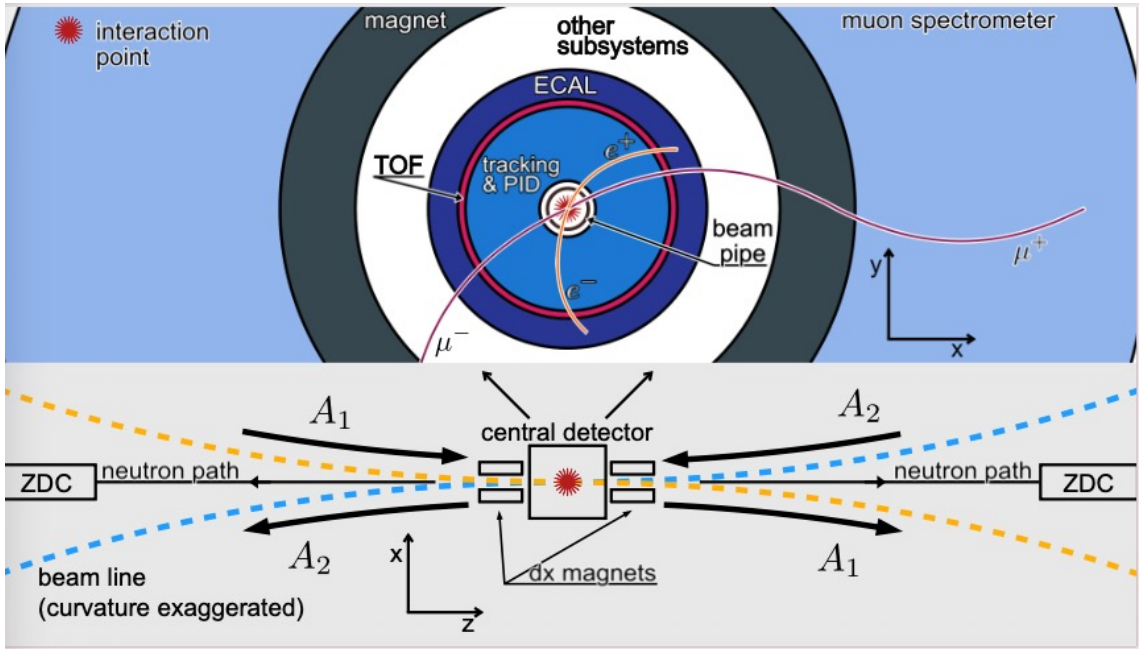


High energy photon
Low energy target
$k = \frac{M_V}{2} e^{+y}, x = \frac{M_V}{\sqrt{s}} e^{-y}$

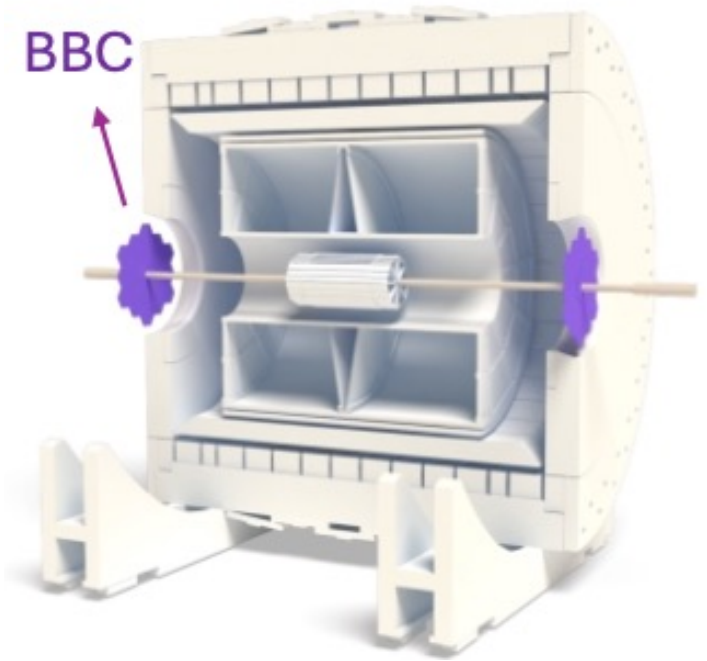
$$\frac{d\sigma_{AA\to AAV}}{dy} = k\frac{dN}{dk}(k_1)\sigma_{\gamma A\to VA}(k_1) + k\frac{dN}{dk}(k_2)\sigma_{\gamma A\to VA}(k_2)$$

The STAR Detector and UPCs

UPC exclusive production signatures:
Minimal hadronic activity
Forward rapidity gap



Cross-sectional and longitudinal view of the STAR detector



Longitudinal view highlighting BBC

ZDC(Zero Degree Calorimeter): Detects forward neutrons from **Coulomb dissociation**, allowing classification of nuclear breakup and triggering on UPC events.

BBC (Beam-Beam Counter): helps veto hadronic interactions by **requiring no forward charged activity.**

Early Measurements

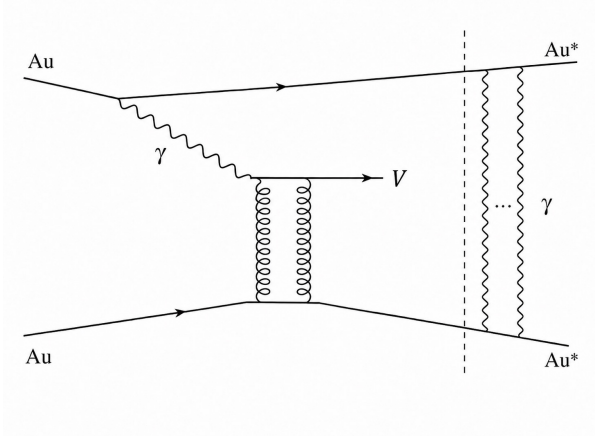
Early Measurement – Coherent ρ^0 Photoproduction

STAR, Phys. Rev. Lett. **89** (2002) 272302.

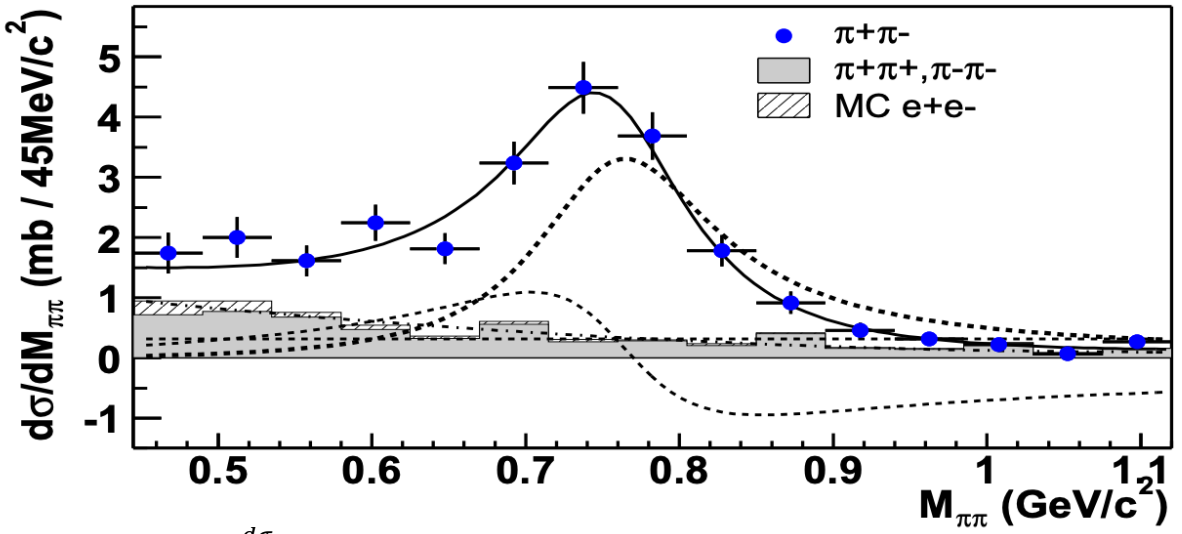
- Year 2000
- Au+Au at $\sqrt{s_{NN}} = 130\text{GeV}$
- Half Field
- "topological Trigger" + ZDCMB (59 inv mb)

Foundational STAR UPC vector meson paper

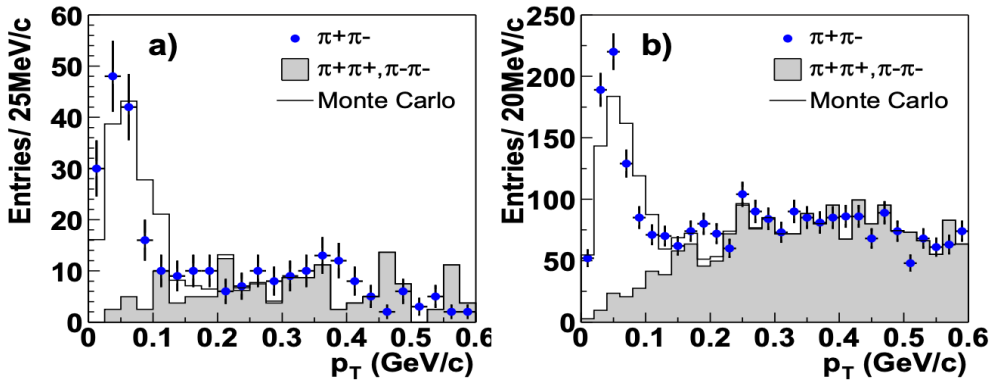
Established UPC events can be studied by triggering on **mutual Coulomb excitation.**



Separated measurements into **different neutron emission classes (0n0n, 0nXn, XnXn…)**



First UPC $\frac{d\sigma_{\rho^0}}{dM_{\pi\pi}}$ measurement with pair $p_T < 150$ MeV/c in ZDCMB data at STAR



p_T spectra demonstrating coherent peak by (a) topological trigger and (b) ZDCMB

Two-source Interference in UPC Photoproduction

STAR, *Phys. Rev. Lett.* **102** (2009) 112301.
Au+Au at $\sqrt{s_{NN}} = 200$ Gev.

Recall: Two source ambiguity as **quantum interference**

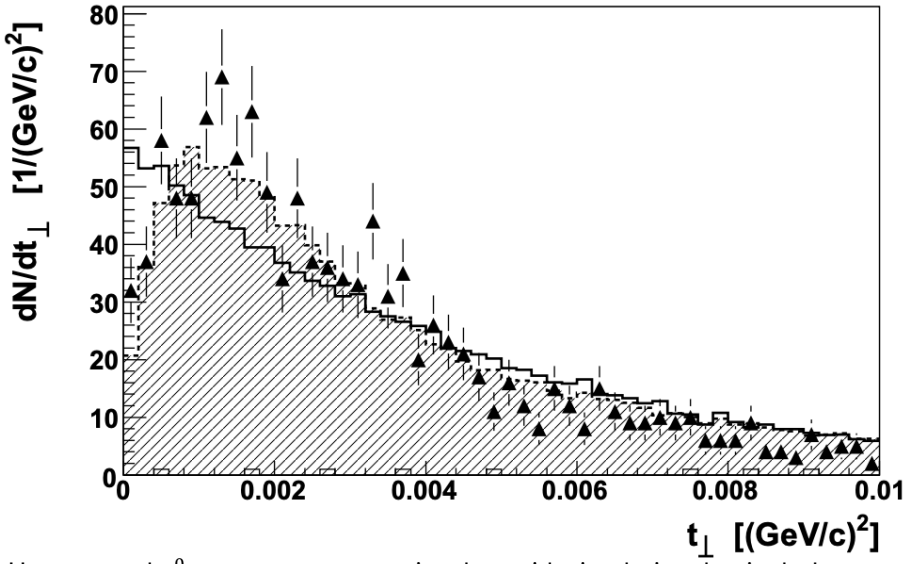
For vector mesons, $J^{PC} = 1^{--}$

Exchanging role of two nuclei – parity transformation.

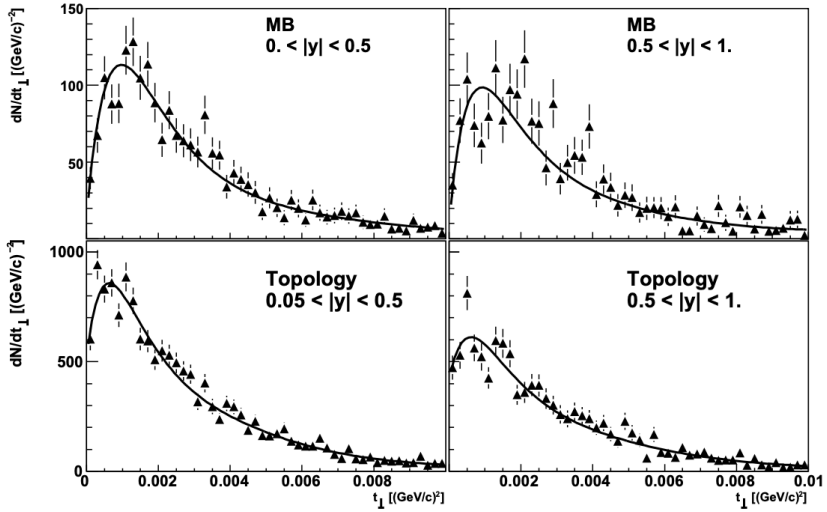
$$A_{tot} = A_1 - A_2 e^{ip_T \cdot b}$$

At midrapidity where $|A_1| \sim |A_2|$, and low $|t| = p_t^2$: **Suppression**

From cross section to quantum interference, confirmed.



Uncorrected ρ^0 t spectrum comparing data with simulation that includes quantum interference (dashed line) and simulation without interference (black line).



Corrected ρ^0 t spectrum in mid rapidity (left) and higher rapidity (right) regions

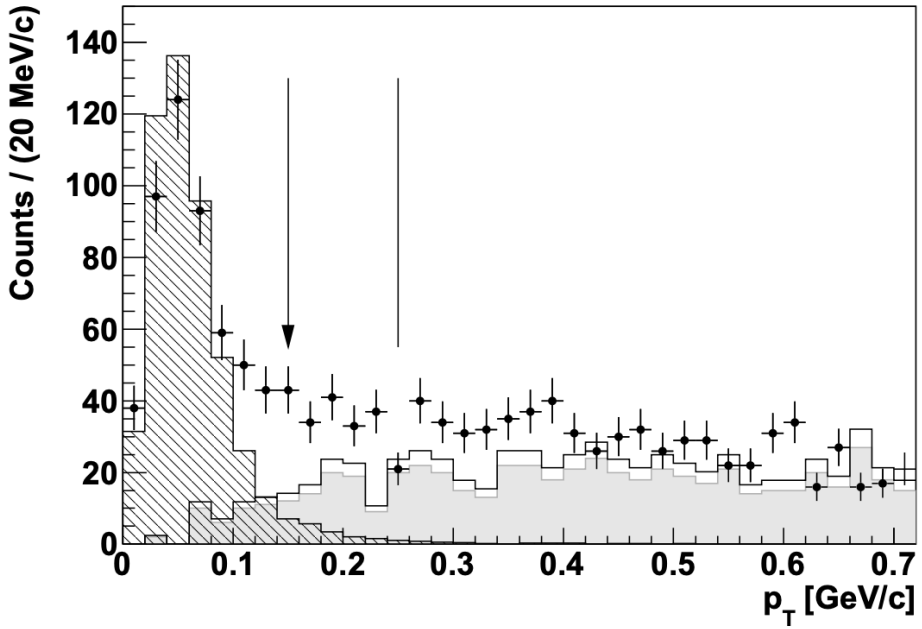
Excited ρ in UPC Photoproduction via Four-Pion

STAR, Phys. Rev. C **81** (2010) 044901.

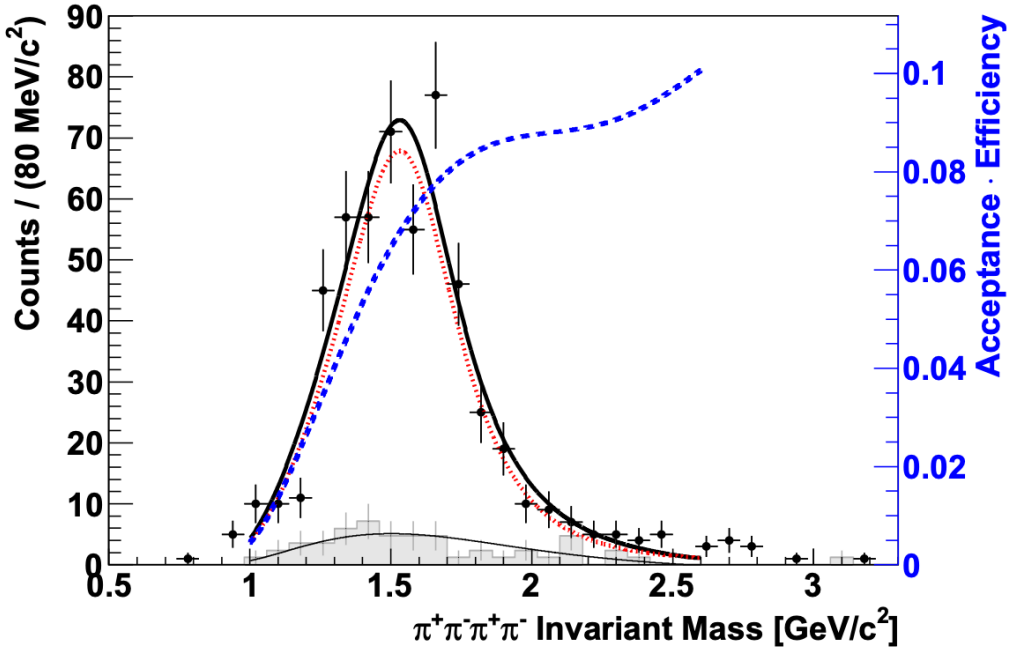
2007, Au+Au at $\sqrt{s_{NN}} = 200$ GeV

Extends the STAR UPC program beyond the ground-state ρ^0 and into excited light-vector phenomenology through coherent four-pion photoproduction.

The PDG currently lists two excited ρ^0 states, the $\rho^0(1450)$ and the $\rho^0(1700)$, which are seen in various production modes and decay channels including two- and four-pion final states [4]. The nature of these states is still an open question, because their decay patterns do not match quark model predictions [5]. Little data exist on



Coherent low p_T peak in four-pion channel



Invariant-mass Distribution in coherent four-pion channel

More ρ^0 UPC Photoproduction Measurements

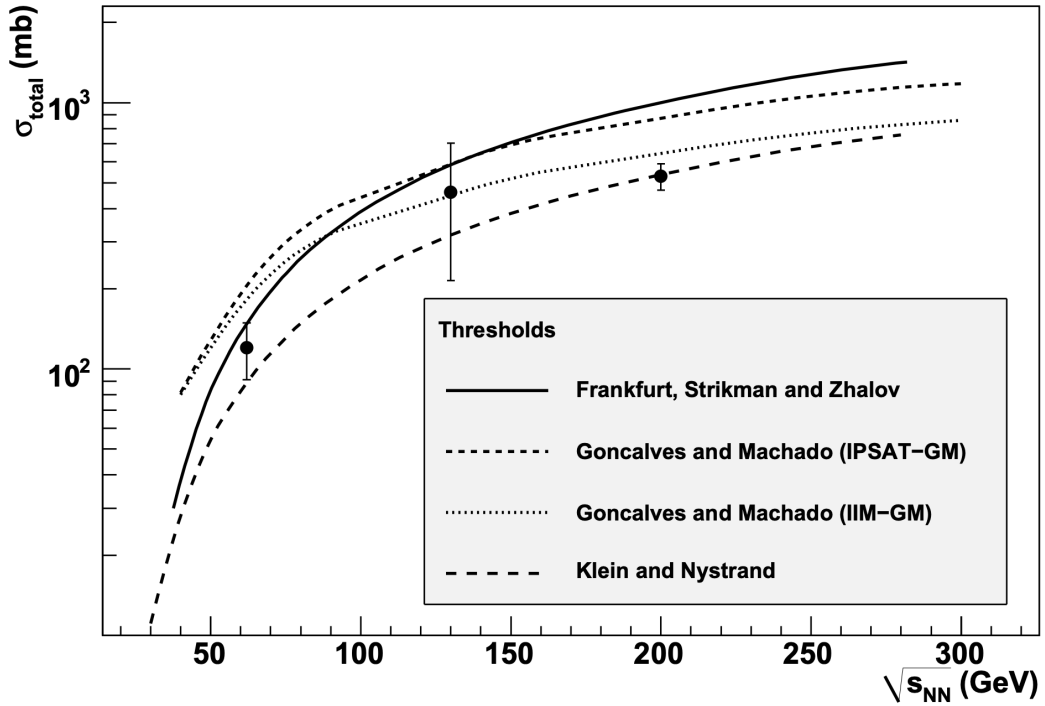
STAR, *Phys. Rev. C* **85** (2012) 014910. Au+Au at $\sqrt{s_{NN}} = 62.4$ GeV

Parameter	STAR at $\sqrt{s_{NN}} = 62.4$ GeV coherent ($\lvert y_{\rho^0}\rvert < 1$)	STAR at $\sqrt{s_{NN}} = 62.4$ GeV coherent (full rapidity)	STAR at $\sqrt{s_{NN}} = 130$ GeV [11] coherent (full rapidity)	STAR at $\sqrt{s_{NN}} = 200$ GeV [10] coherent (full rapidity)
$\sigma^{\rho^0}_{XnXn}$ (mb)	$6.2 \pm 0.9 \pm 0.8$	$10.5 \pm 1.5 \pm 1.6$	$28.3 \pm 2.0 \pm 6.3$	$31.9 \pm 1.5 \pm 4.5$
$\sigma^{\rho^0}_{0nXn}$ (mb)	$16.7 \pm 2.7 \pm 2.$	$31.8 \pm 5.2 \pm 3.9$	$95 \pm 60 \pm 25$	$105 \pm 5 \pm 15$
$\sigma^{\rho^0}_{0n0n}$ (mb)	$28.5 \pm 5.2 \pm 4.8$	$78 \pm 14 \pm 13$	$370 \pm 170 \pm 80$	$391 \pm 18 \pm 55$
$\sigma^{\rho^0}_{total}$ (mb)	$51.5 \pm 5.9 \pm 5.3$	$120 \pm 15 \pm 22$	$460 \pm 220 \pm 110$	$530 \pm 19 \pm 57$

Provides the crucial lower-energy anchor point for STAR light-meson UPC physics.

The 62.4 GeV result constrains how fast the coherent ρ^0 cross section rises with collision energy.

The increase is weaker than in many theory predictions.



The Precision Era

2017 ρ^0 Measurement

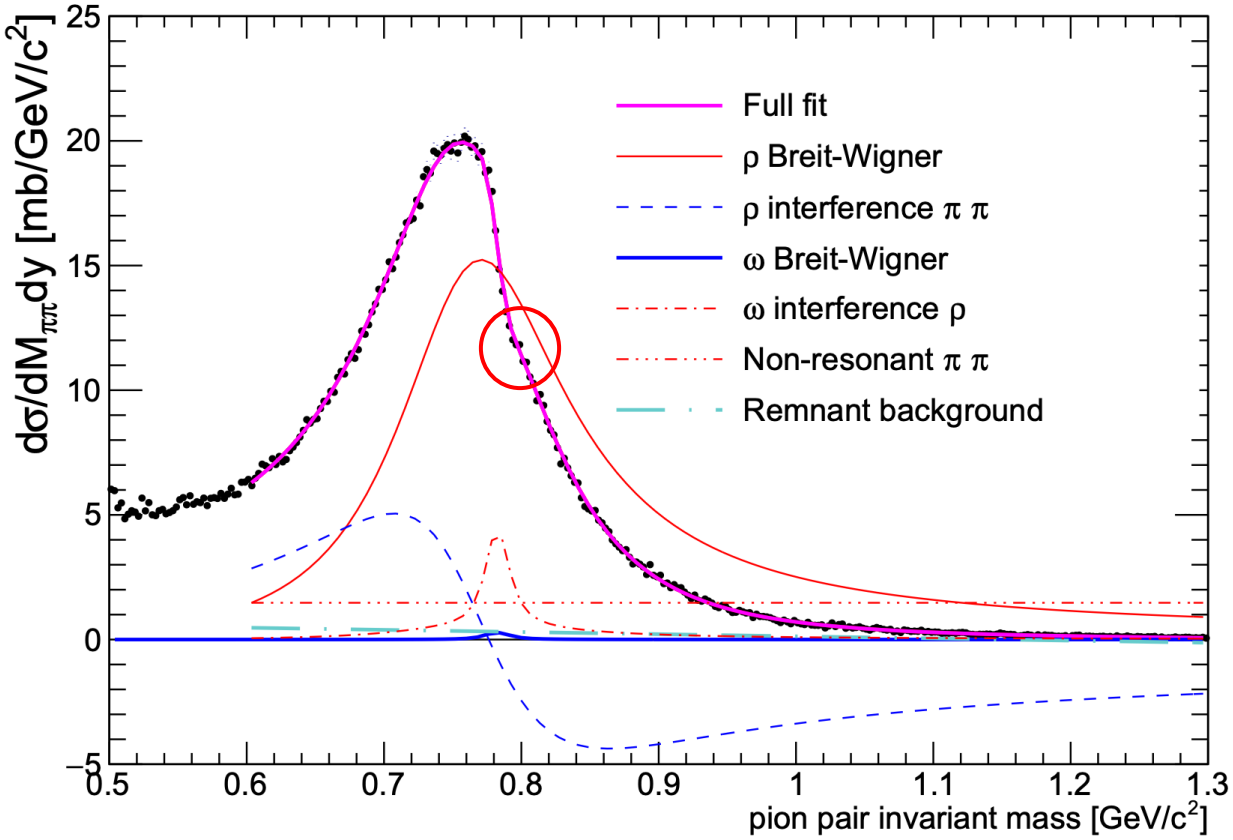
STAR, Phys. Rev. C **96** (2017) 054904

Run 10, 1100 μb^{-1}, Au+Au at $\sqrt{s_{NN}} = 200$ GeV, **Modern UPC trigger**

$$\frac{d\sigma}{dM_{\pi^+\pi^-}} \propto \left| A_\rho \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + iM_\rho\Gamma_\rho} + B_{\pi\pi} + C_\omega e^{i\phi_\omega} \frac{\sqrt{M_{\pi\pi} M_\omega \Gamma_{\omega\to\pi\pi}}}{M_{\pi\pi}^2 - M_\omega^2 + iM_\omega\Gamma_\omega} \right|^2 + f_p$$

First observation/extraction of the ω meson in UPCs.

Simultaneous fit of ρ^0, ω, and nonresonant/direct $\pi^+\pi^-$ production.



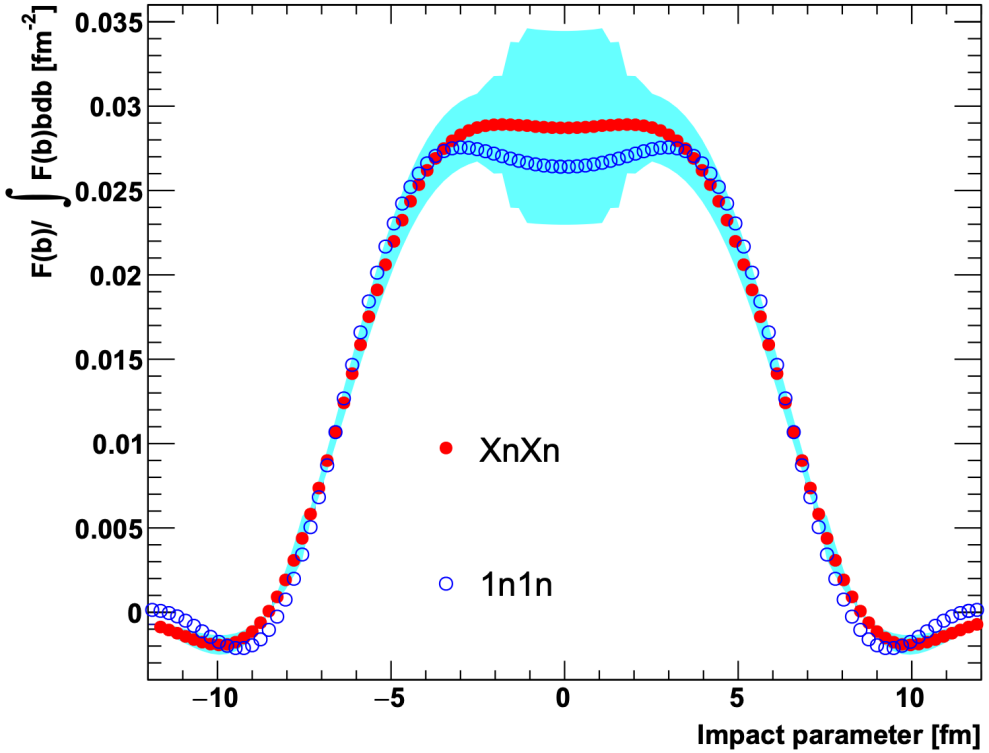
2017 ρ^0 Measurement - Tomography

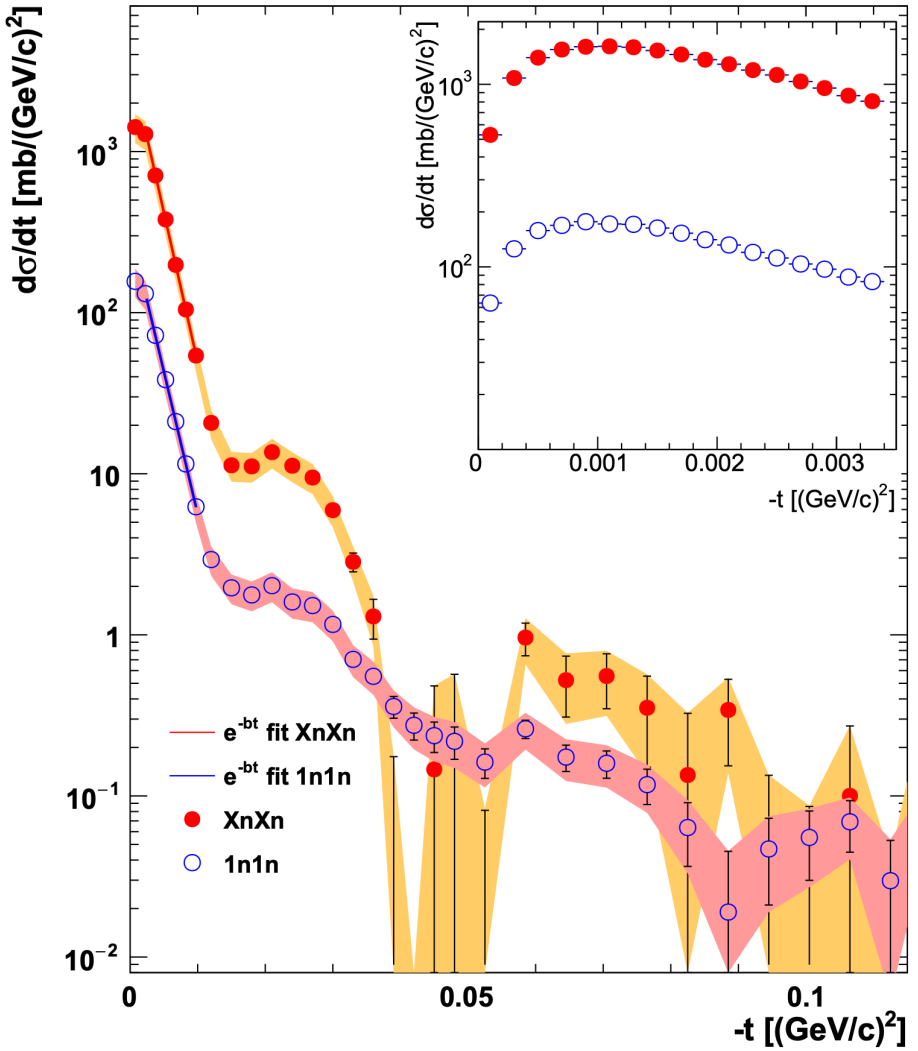
STAR, Phys. Rev. C **96** (2017) 054904

Run 10, 1100 μb^{-1}, Au+Au at $\sqrt{s_{NN}} = 200$ GeV, Modern UPC trigger

Demonstrated coherent diffractive peaks with two minima
The positions of the diffractive minima encode information about the transverse nuclear profile.

$F(b)$



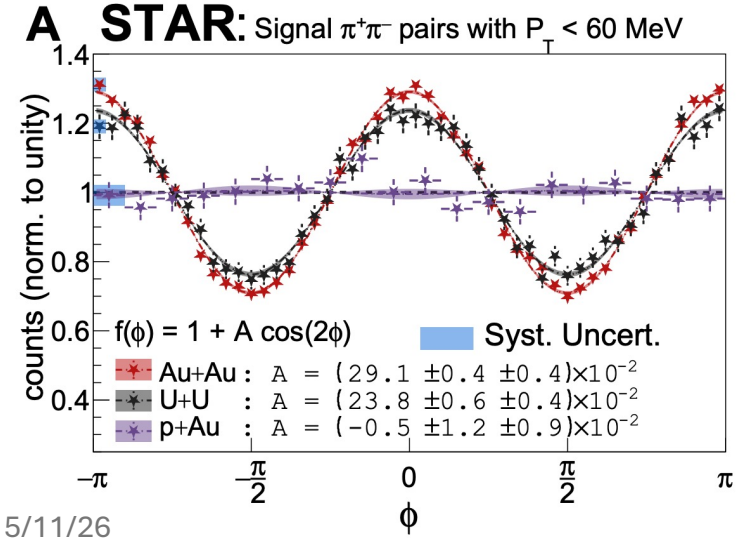


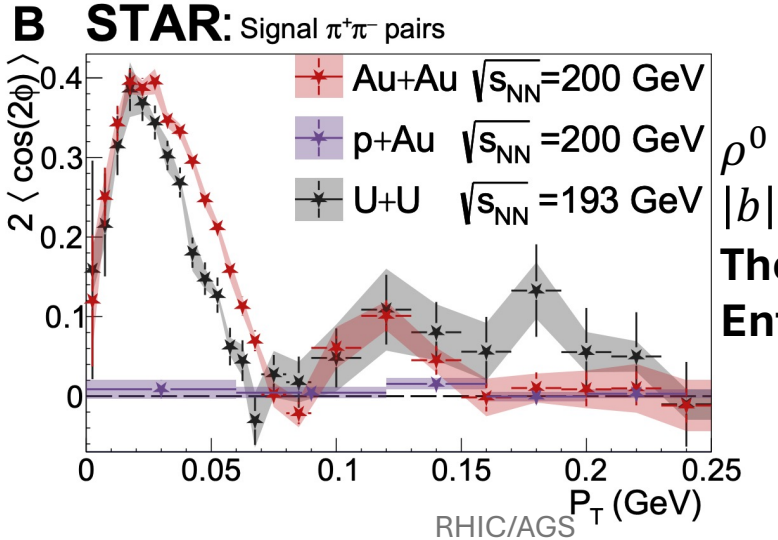
Shows coherent diffraction of ρ^0 off of an object as big as Au nuclei.

Tomography of Ultra-relativistic Nuclei with Polarized Photon-gluon Collisions

STAR, Sci. Adv. 9, abq3903 (2023)

- The initial photons are **linearly polarized in the transverse plane.**
- The decayed pion pair must therefore carry the angular information as orbital angular momentum:
  - $M_{\rho\to\pi\pi} \sim \epsilon_\rho \cdot q \ \rightarrow |M|^2 \sim \cos^2(\phi) \sim 1 + \cos(2\phi)$
- But the initial polarization axis is random event-by-event.
  - **In the lab frame**, the modulation would average away.
- Two-way emission ambiguity gives an interference term involving $P_T \cdot b$**, which makes** $\boldsymbol{P_T}$ statistically correlated with the hidden initial polarization. $\cos\phi = (\vec{p_{T1}} + \vec{p_{T2}}) \cdot (\vec{p_{T1}} - \vec{p_{T2}}) / (|\vec{p_{T1}} + \vec{p_{T2}}| \times |\vec{p_{T1}} - \vec{p_{T2}}|)$





ρ^0 decay time: ~ 1fm

$|b| \sim 10 - 20$ fm

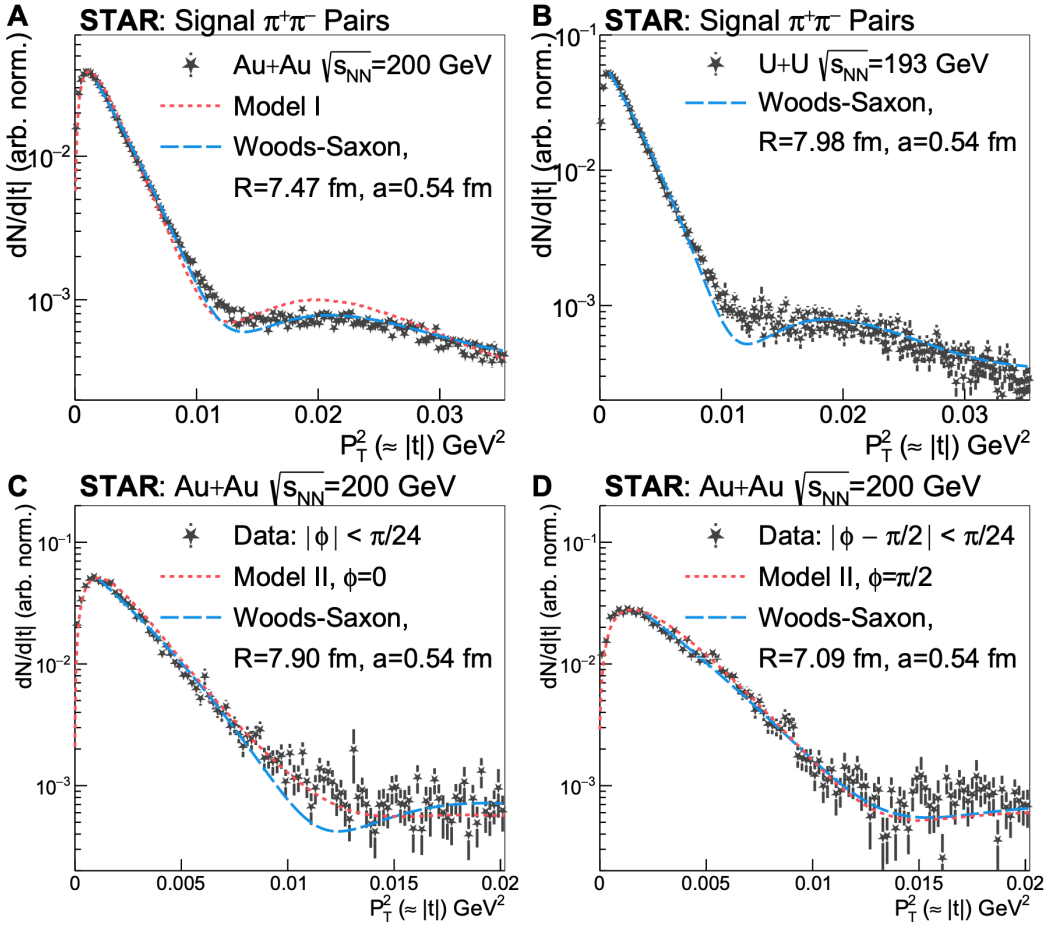
The final pion pair kept the interference pattern!

Entanglement Enabled Intensity Interferometry

Tomography of Ultra-relativistic Nuclei with Polarized Photon-gluon Collisions

STAR, Sci. Adv. 9, abq3903 (2023)

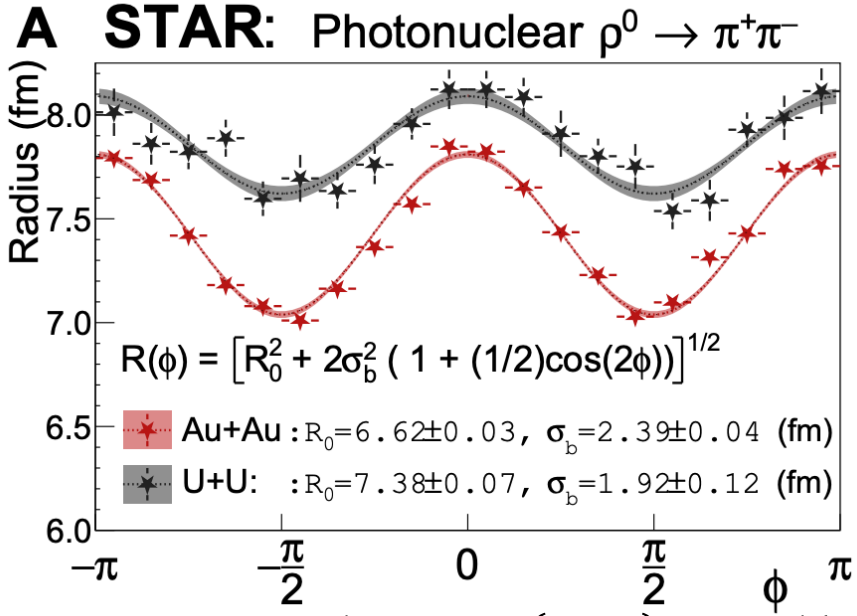
- Recall: Tomography thorough coherent t distribution



Fit the $|t|$ distribution with Woods Saxon FF.

$\frac{d\sigma}{dt} \sim A|F(t)|^2$, extract radius and neutron skin depth.

Two source ambiguity interfere with a phase involving $\cos(P_T \cdot b)$ **alters the $|t|$ distribution beyond very low $|t|$ region.** At $\phi = 90^o$, interference effect is minimized. One can fit $\frac{dN}{d|t|}$ in ϕ slices and account for ρ^0 probe size



Result: $R_{Au} = 6.53 \pm 0.03(\text{stat.}) \pm 0.05(\text{syst})$ fm

Spin Interference in J/ψ

STAR, arXiv:2512.02865. Submitted to Phys. Rev. Lett

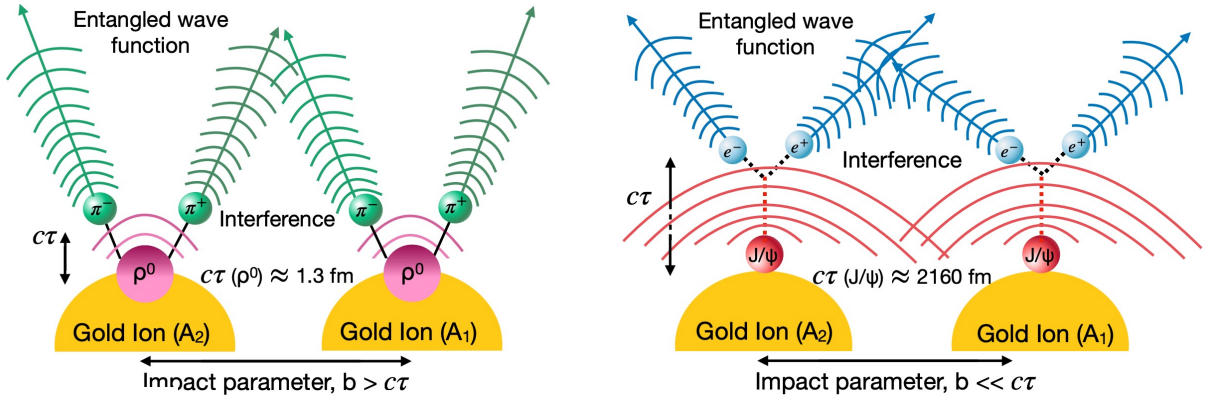
Au+Au, Ru+Ru, Zr+Zr, $\sqrt{s_{NN}} = 200$ GeV

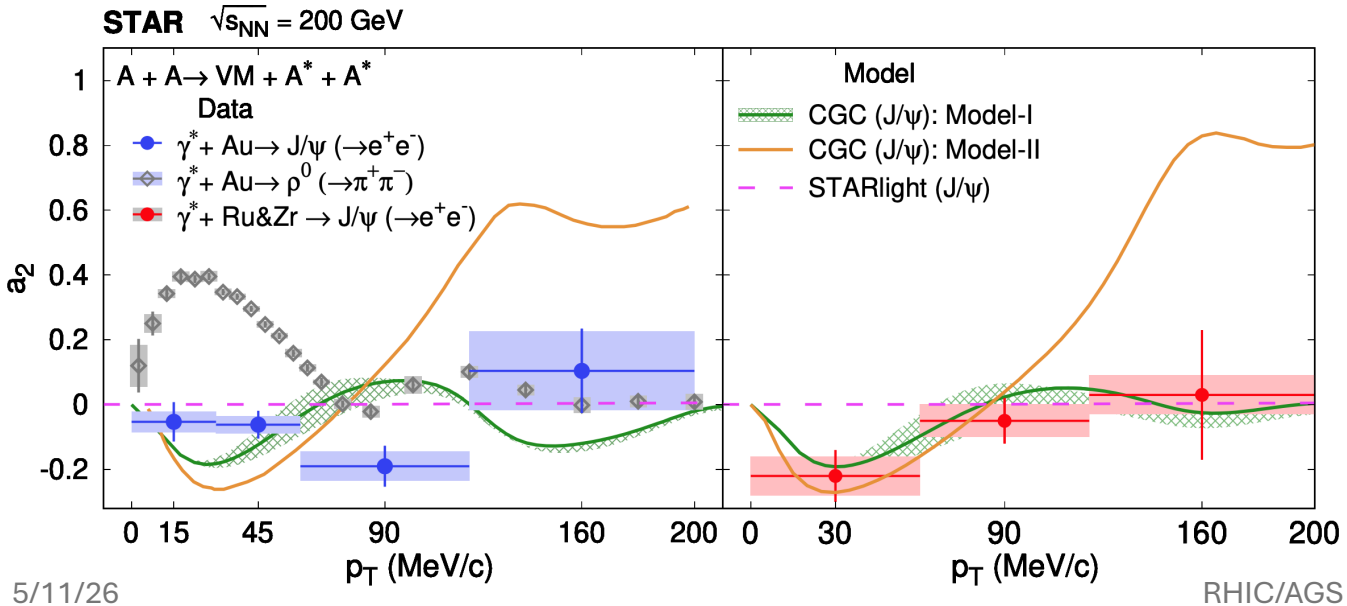
Evidence that the spin structure of the **final-state daughters.**

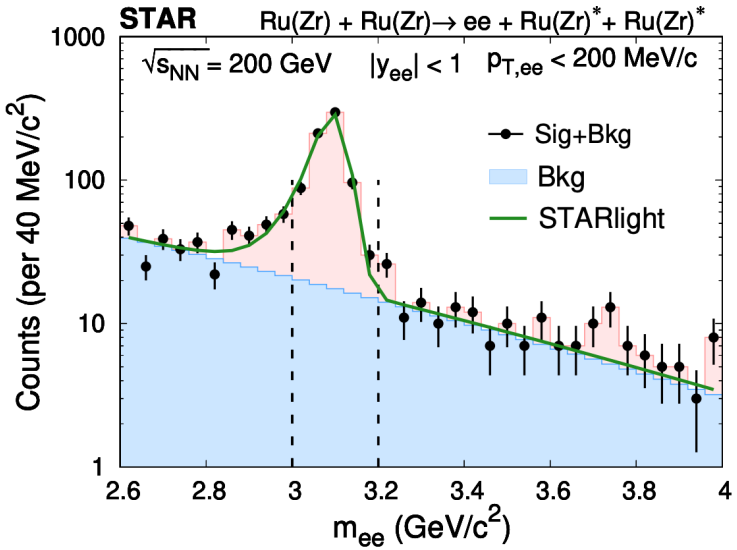
The long lifetime allows the quantum state to evolve and interfere well beyond the nuclear volume.

Compared with ρ^0, J/ψ has:

1. Longer life-time
2. **Fermion** decay products



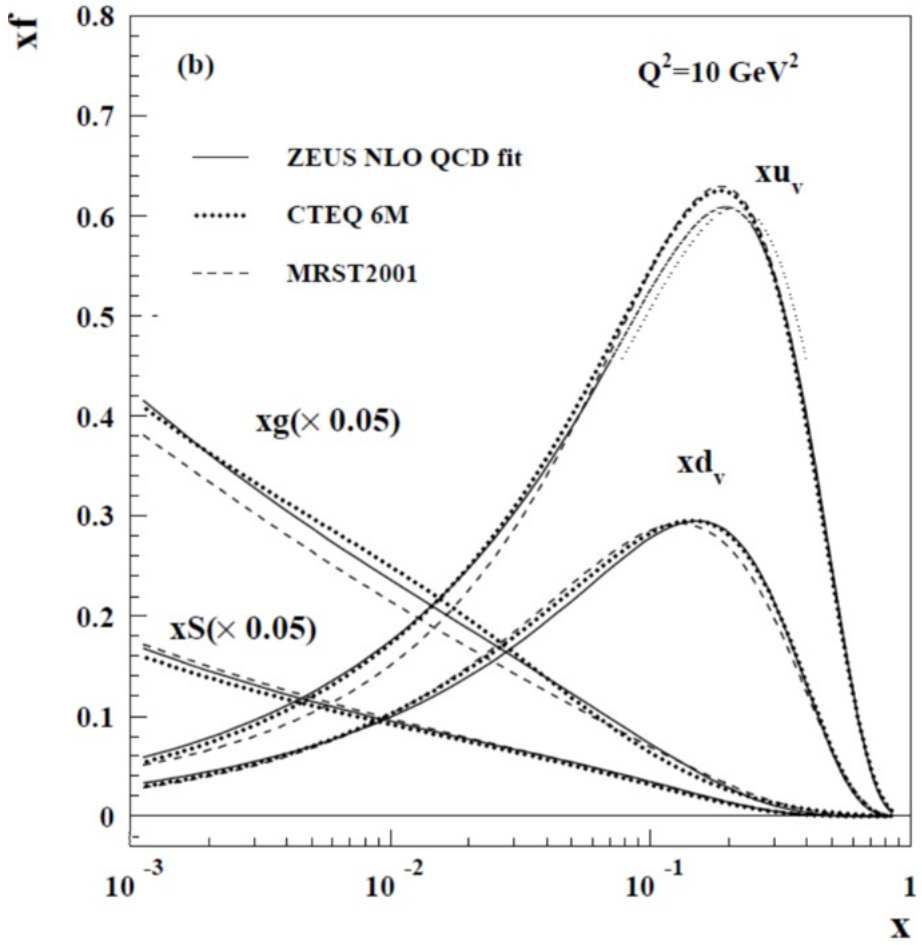


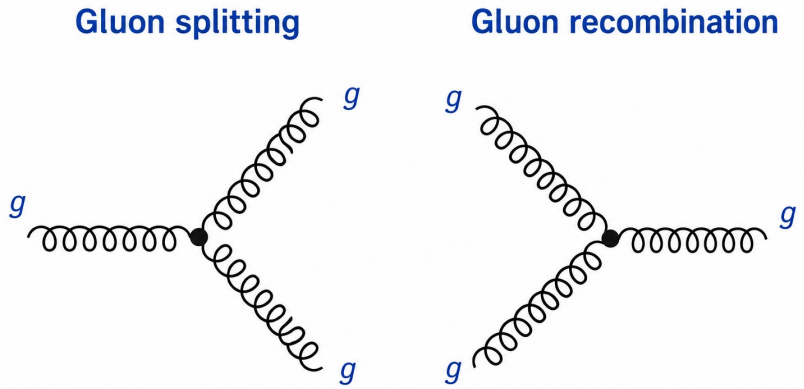


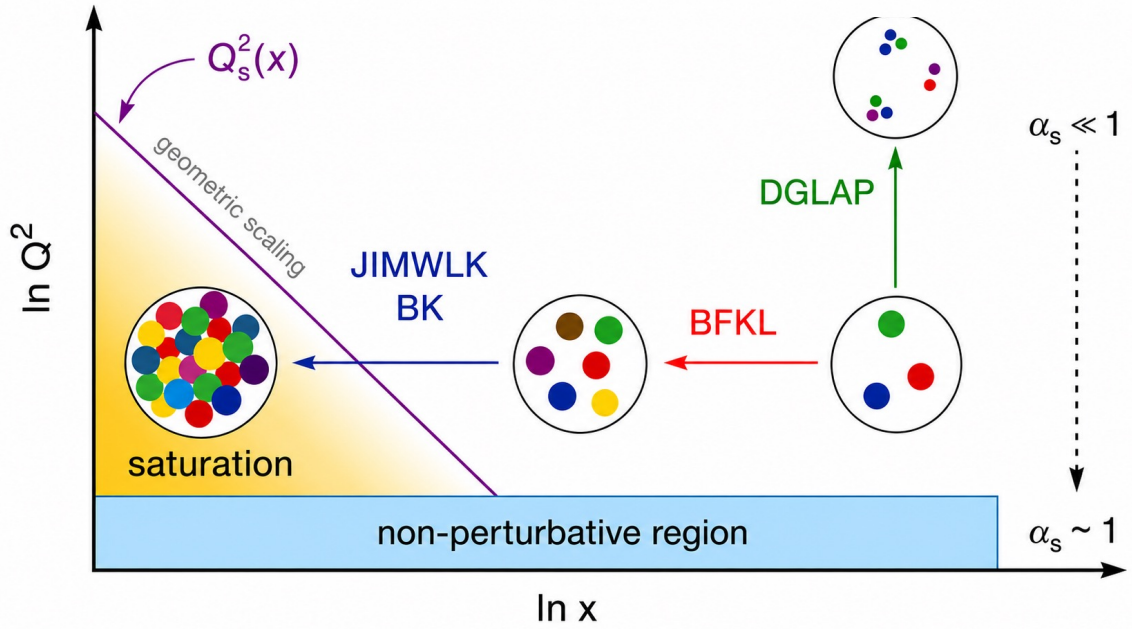
Connecting to EIC Physics

UPCs as Probes of Gluon Structure

- Shadowing: The nucleus has fewer effective gluons than A free nucleons.
- Saturation: Gluon field becomes so dense that nonlinear recombination matters.

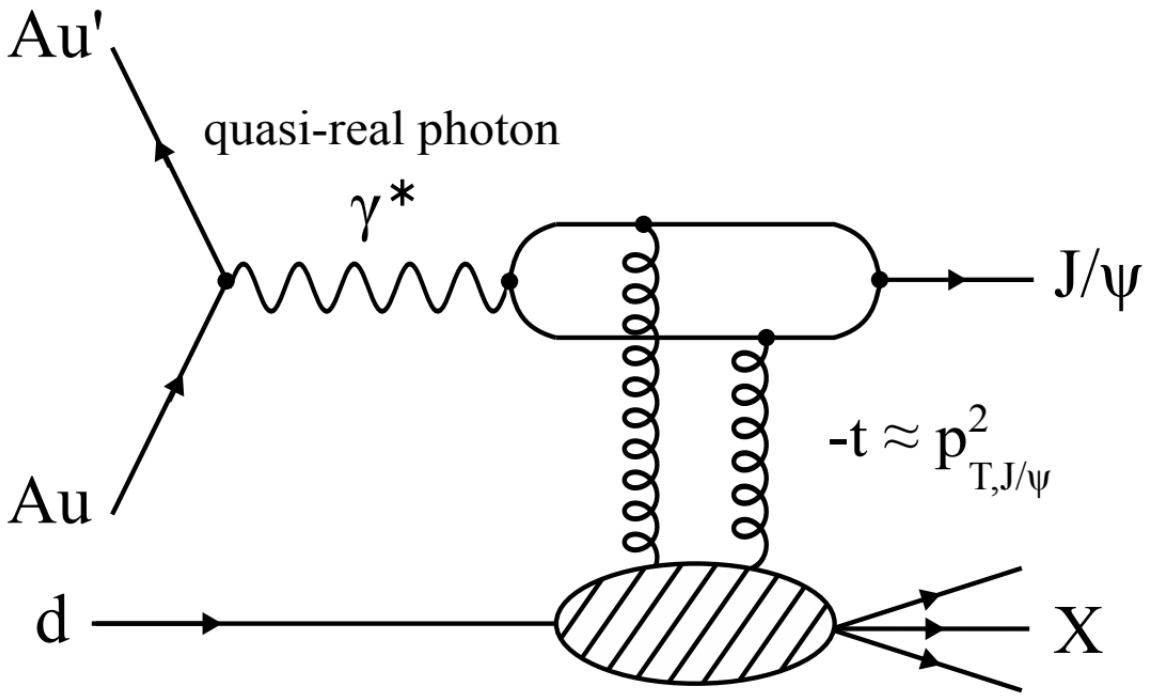






Resolving the Two-Way Ambiguity

- Use an asymmetric collision system.



$$k = \frac{M_{J/\psi}}{2} e^{-y}, W_{\gamma N} = \sqrt{2\sqrt{s}_{NN} k} \sim 25 \text{ GeV}$$

Vary J/ψ rapidity → Changing photon energy

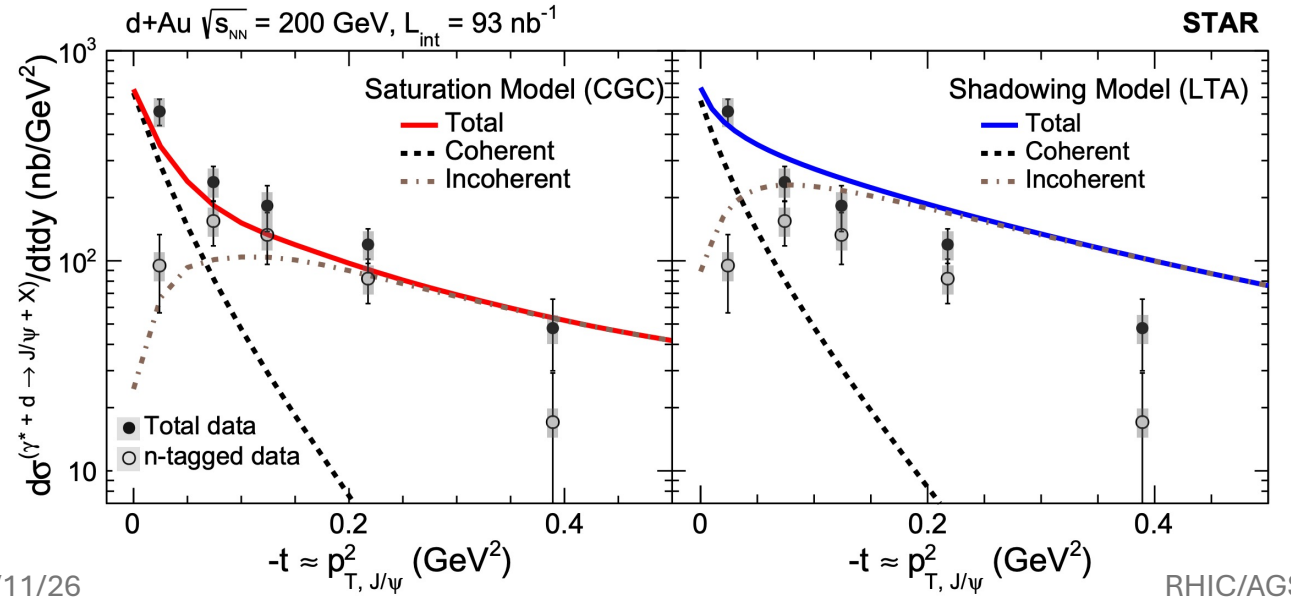
J/ψ Production in d+Au

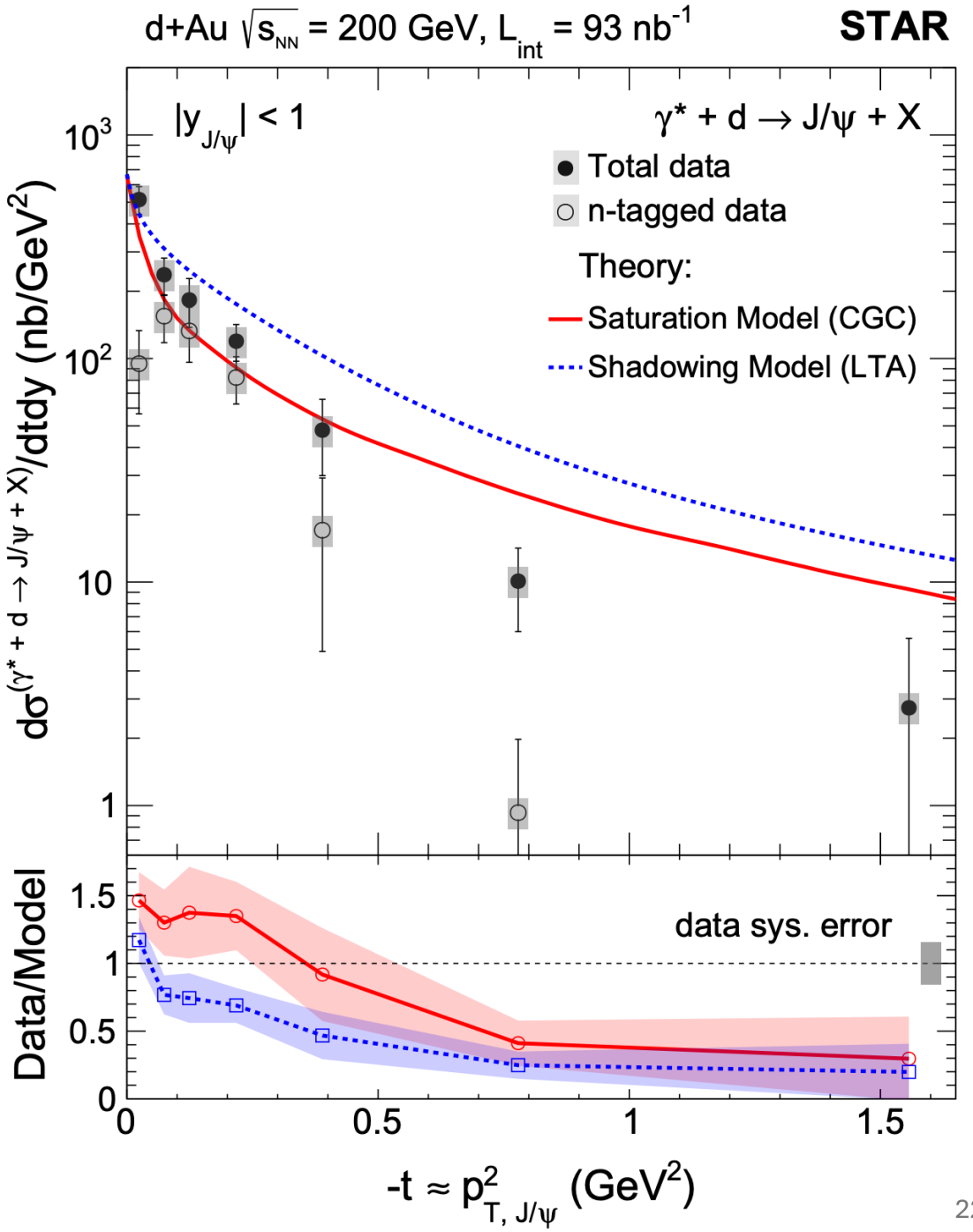
STAR, Phys. Rev. Lett. **128**(2022) 122303.

Run 16 d+Au at $\sqrt{s}$ = 200 GeV

Neutron tagged = incoherent dominant

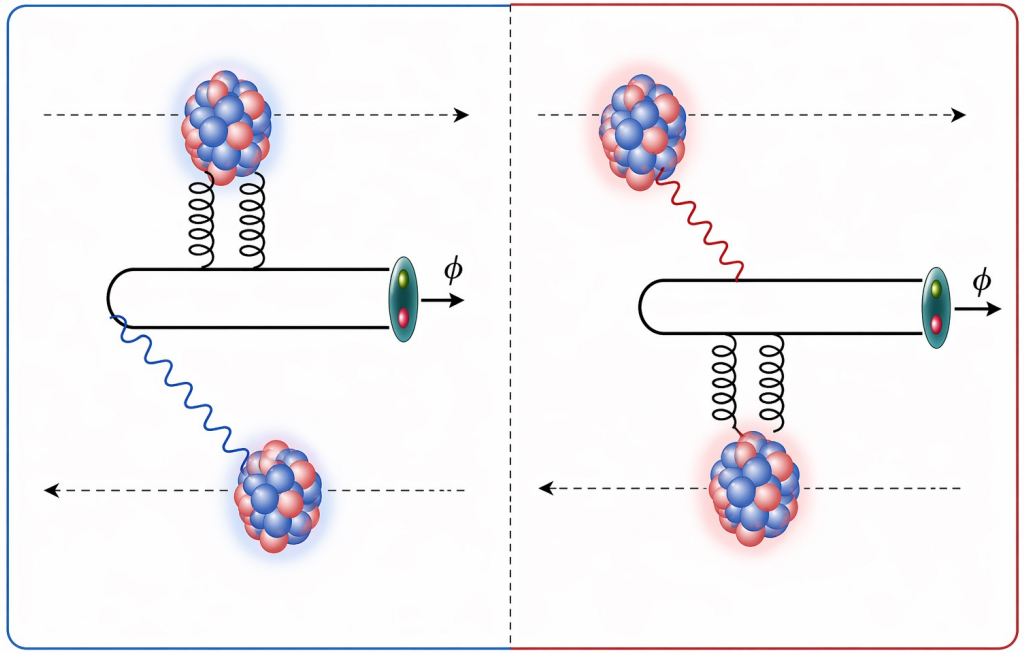
Data can already discriminate among different pictures of deuteron gluon structure, with **saturation-based descriptions giving a better account of the measured distributions than the shadowing model.**

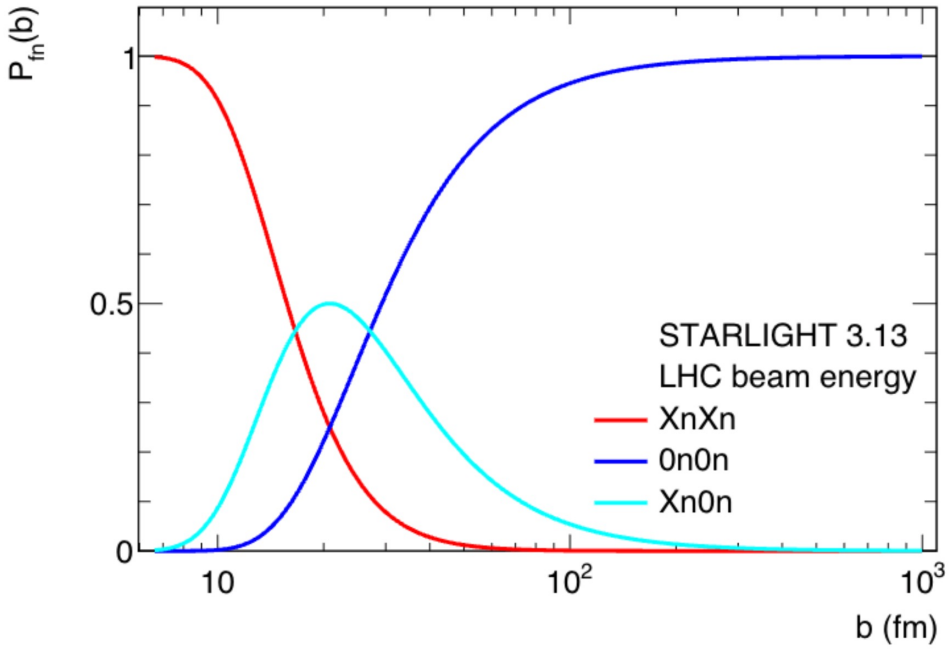




Resolving the Two-Way Ambiguity – cont.

$$\frac{d\sigma_{AA\to AAV}}{dy} = k\frac{dN}{dk}(k_1)\sigma_{\gamma A\to VA}(k_1) + k\frac{dN}{dk}(k_2)\sigma_{\gamma A\to VA}(k_2)$$



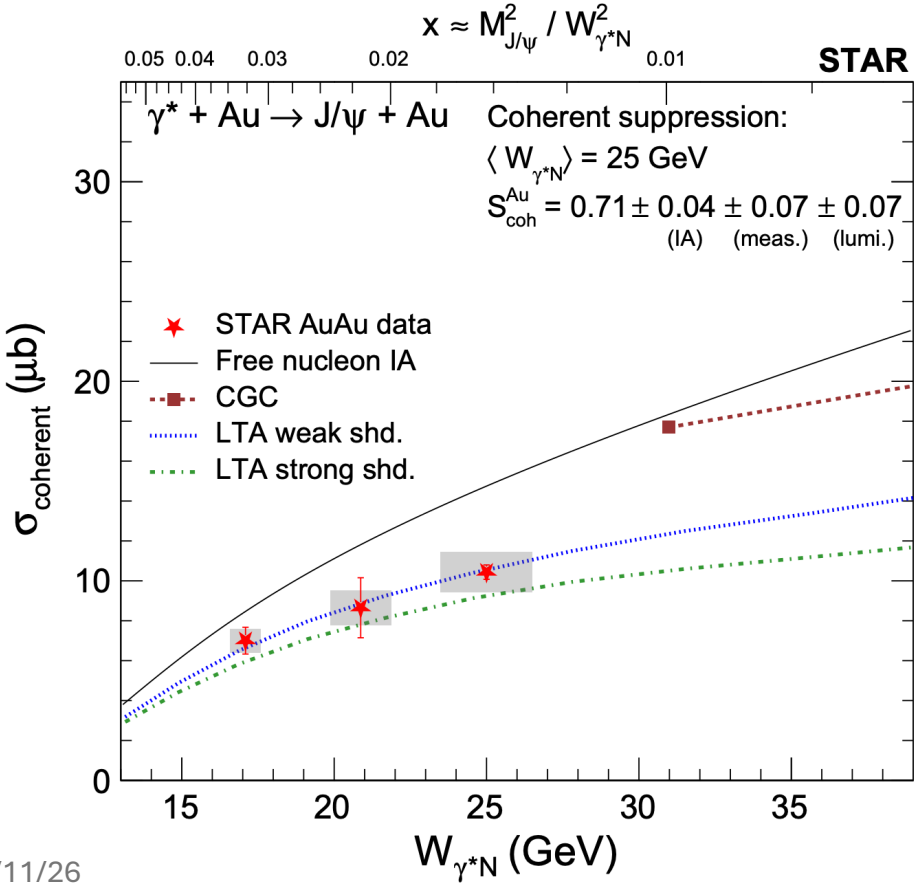


- Photon flux factors are **impact-parameter dependent**.
  - Different impact parameter → photon flux distribution changes, but $\sigma_{\gamma A\to VA}$ does not.
- We can gauge the impact parameter distribution via **different neutron tagging**
  - $\frac{d\sigma}{dy}$ **measurement with different neutron tagging allows us to solve for** $\sigma_{\gamma A\to VA}$

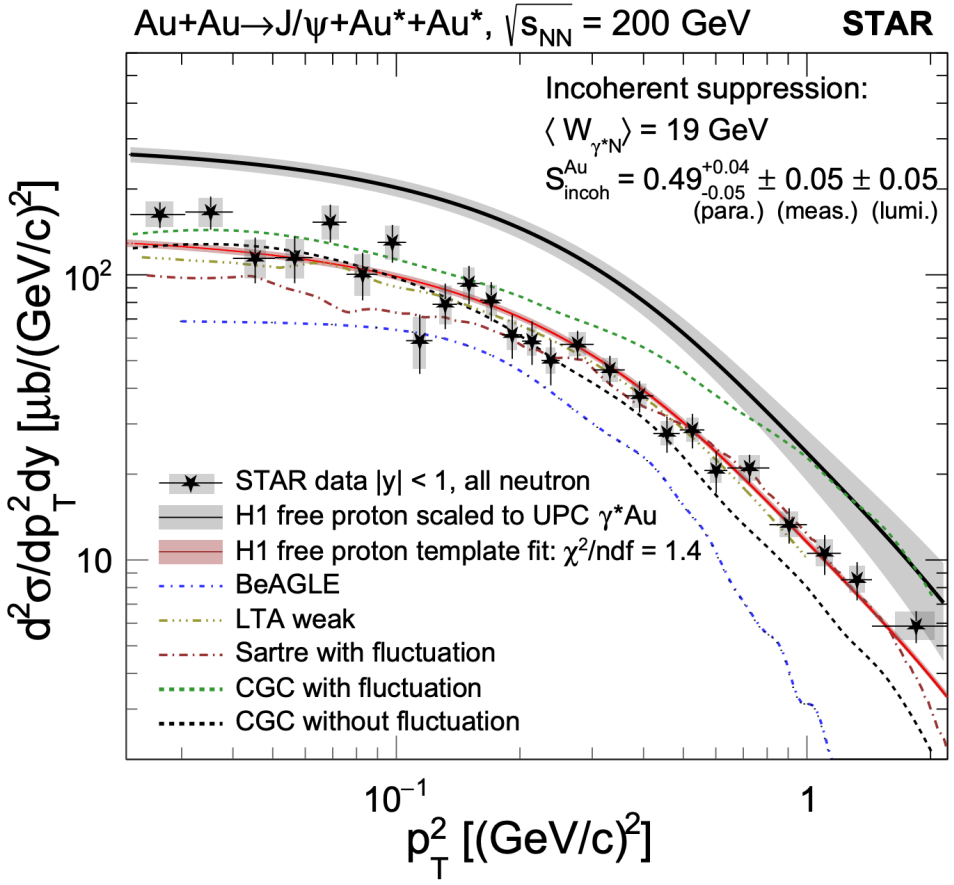
Strong suppression of J/ψ production in Au+Au UPCs

STAR, Phys. Rev. Lett. **133** (2024) 052301 *STAR, Phys. Rev. C* **110** (2024) 014911

Coherent and incoherent J/ψ measurements.
J/ψ coherent measurement with photon energy
$\psi(2S), e^+e^-$ production (not shown here)

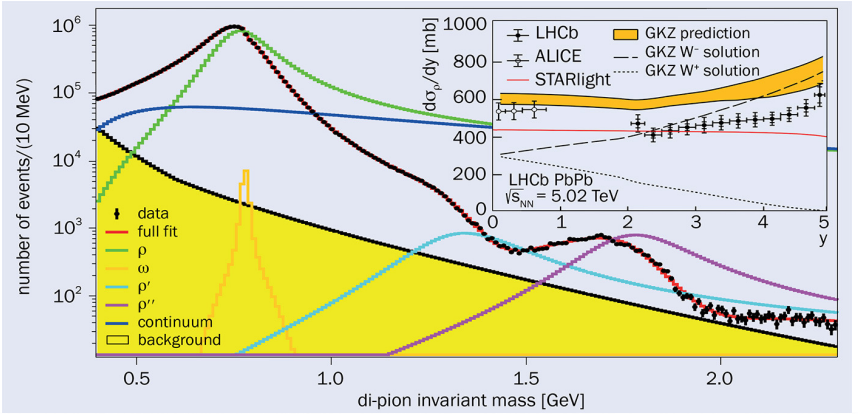


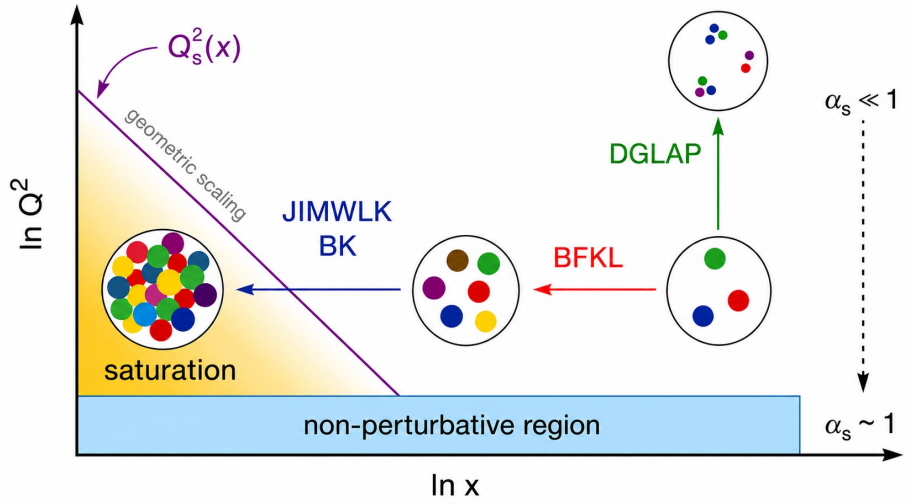
Strong suppression for both coherent and incoherent J/ψ
Coherent J/ψ suppression described well by weak shadowing model.



What's Next?

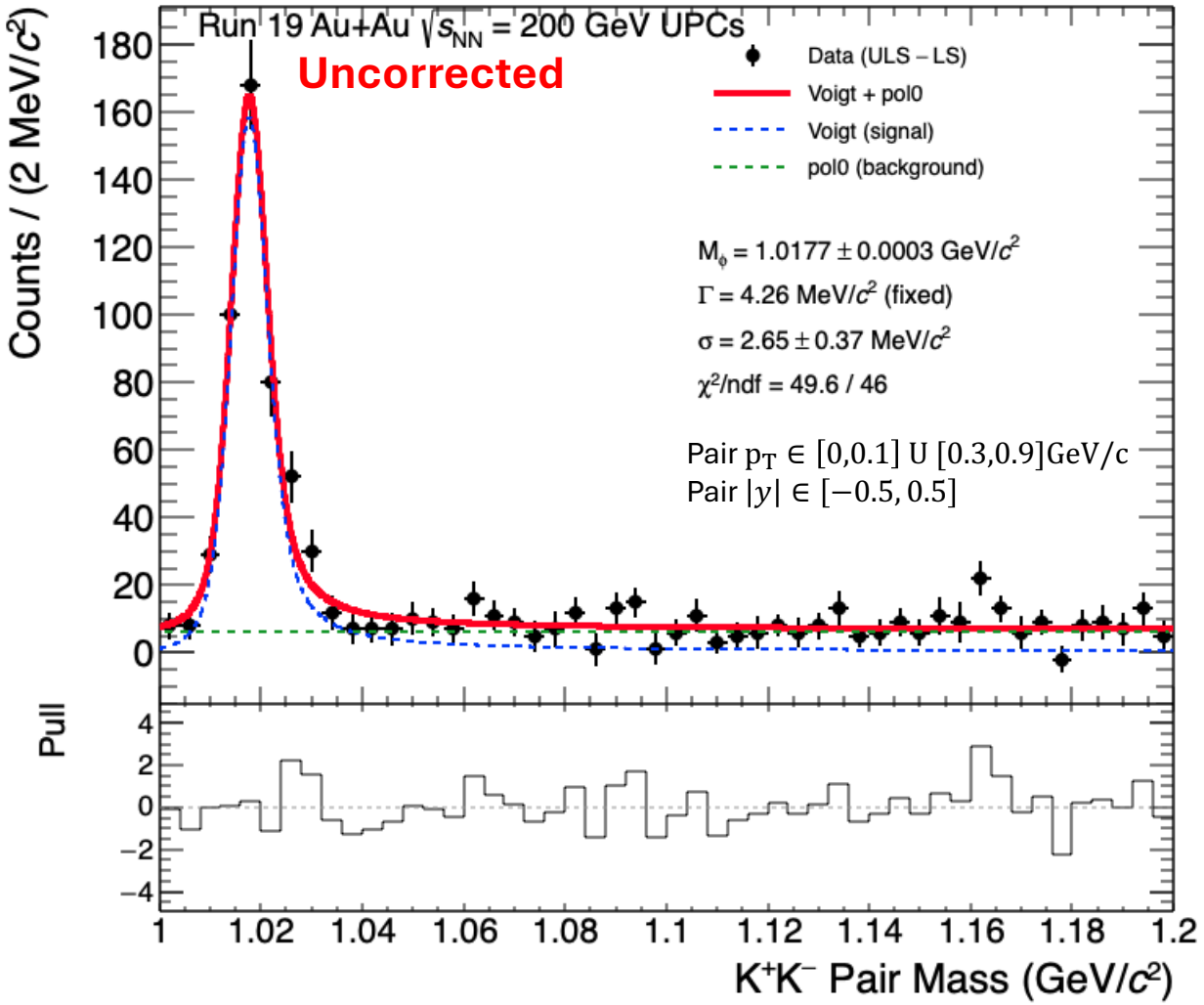
- Full use of EESI to higher $\pi^+\pi^-$ mass spectrum
- **ϕ Measurement – transition region**
  - **More tomography via $|t|$ fitting**
- A-dependence cross section
  - $A^{2/3}$ vs $A^{4/3}$ scaling
- K^+K^- spectrum …
- And so much more!





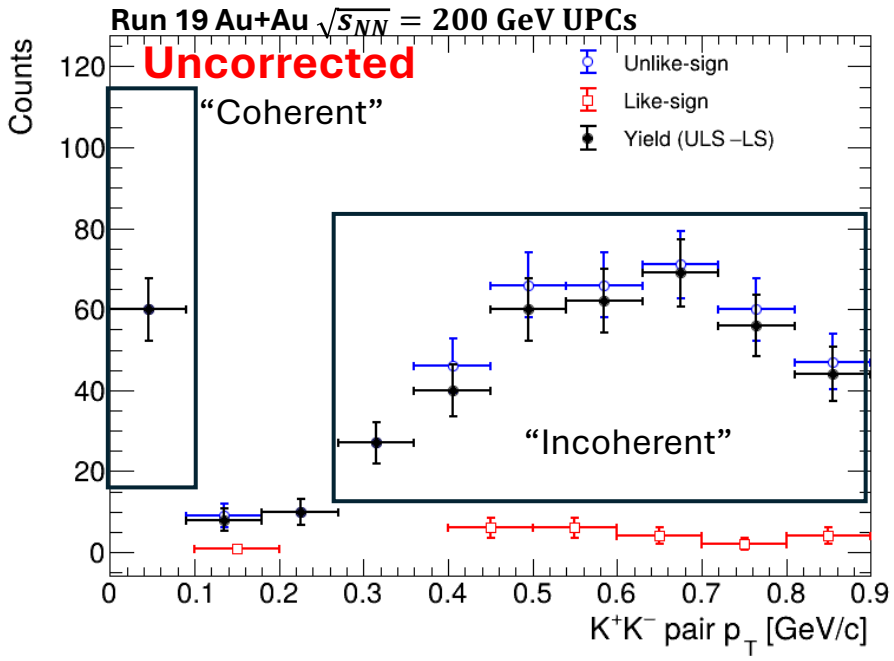
A sneak peak – UPC ϕ

Work in Progress



Run 19 Au+Au at $\sqrt{s_{NN}} = 200$ GeV, **zdcmb**
First dataset with iTPC

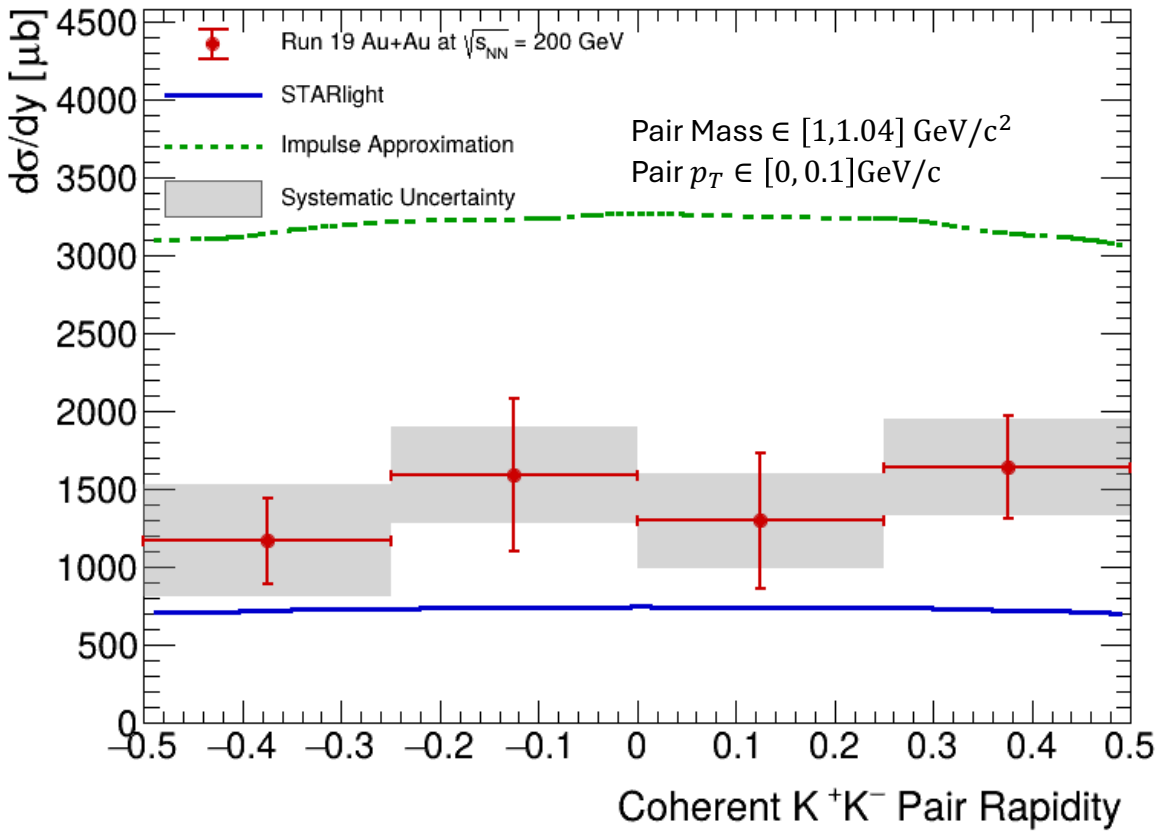
Signal region: $M_{KK} \in [1\ , 1.04]\mathrm{GeV}/c^2$
Coherent Pairs ($p_T < 0.1$ GeV/c) : 61
Incoherent Pairs: 358

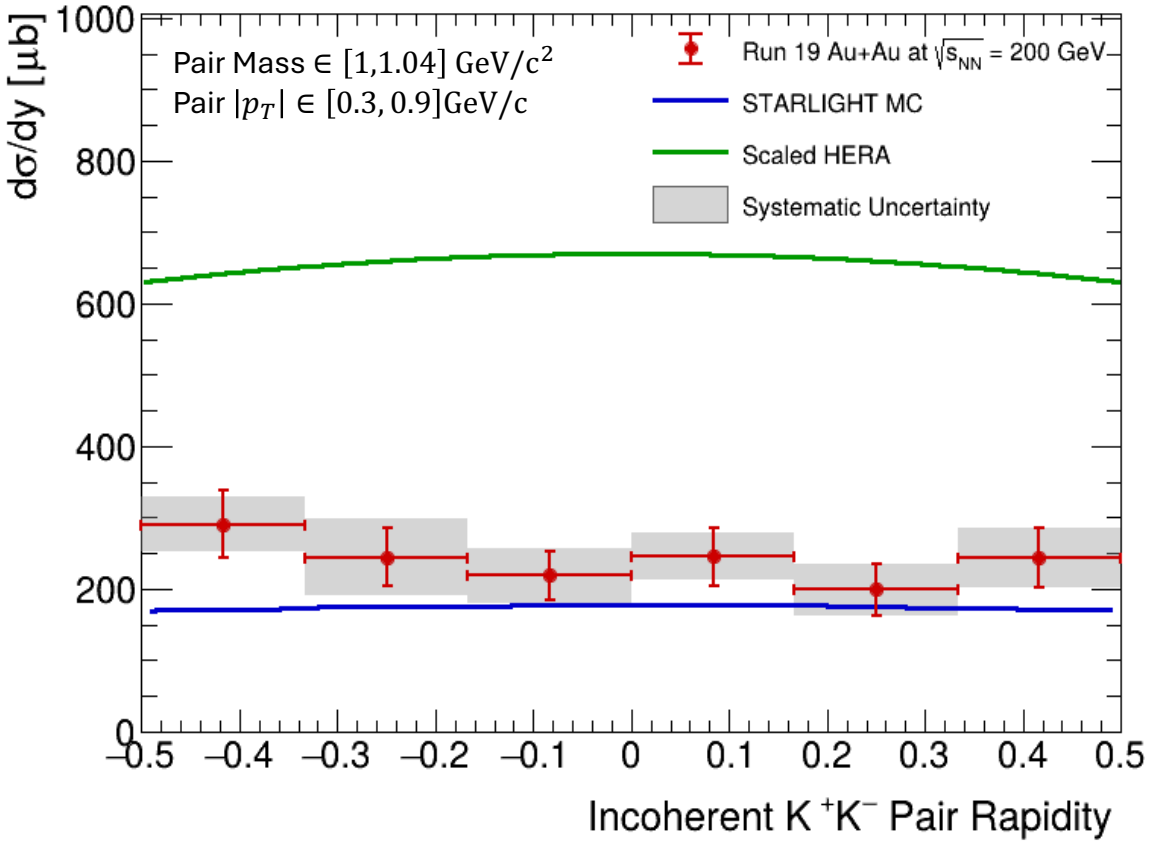


A sneak peak – UPC ϕ

STAR PRELIMINARY 10% Luminosity, 7% Tracking Global Scale Uncertainty Not Shown

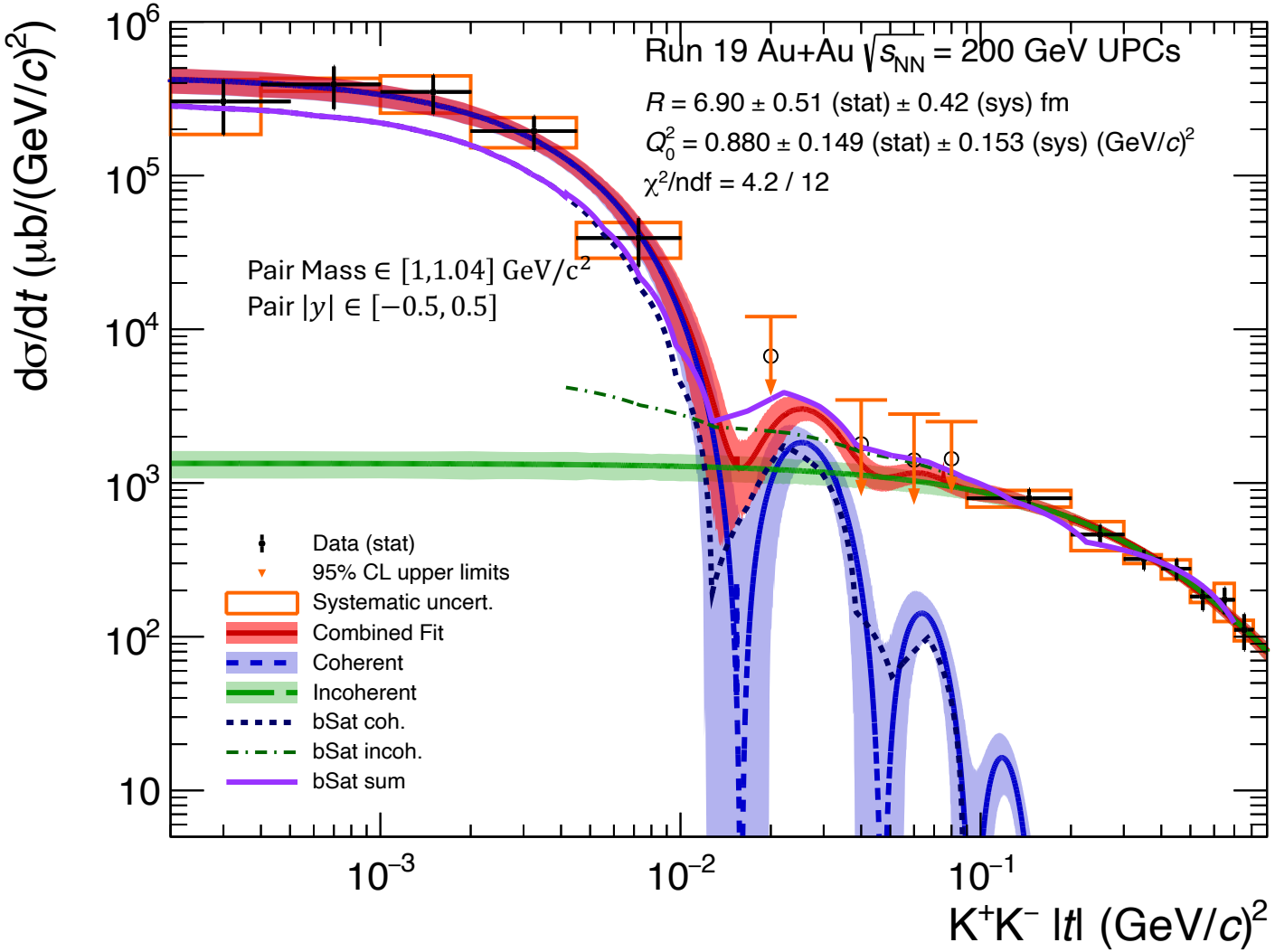
Strong suppression compared with impulse approximation (coherent) and scaled HERA data (incoherent)

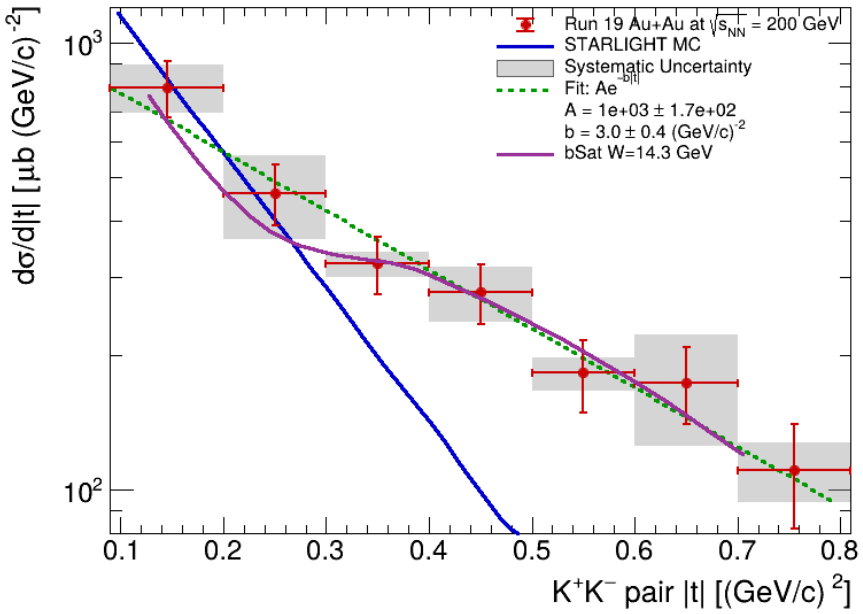


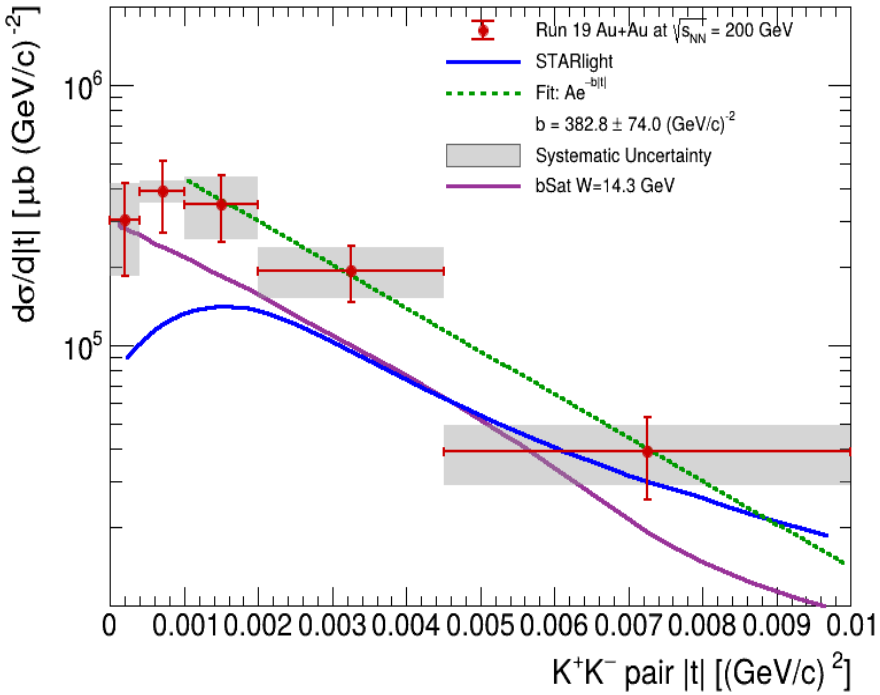


A sneak peak – UPC ϕ

STAR PRELIMINARY 10% Luminosity, 7% Tracking Global Scale Uncertainty Not Shown







Summary

- STAR established UPCs at RHIC as a clean photonuclear laboratory.
- STAR showed that UPCs are sensitive not only to nuclear size, but also to nuclear quantum interference.
- The light-vector-meson program evolved from cross sections to diffraction and nuclear imaging.
- STAR extended UPC physics from soft vector mesons to hard gluon probes.