Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Recent results on vector meson production in UPC at STAR

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GDR QCD workshop, Orsay, 2023

Recent STAR results

- **Exclusive J/ψ and ψ(2s) photoproduction and Entanglement-Enabled Spin Interference**
  - Ashik Ikbal Sheikh, QM 2023
- **Observation of strong nuclear suppression in exclusive J/ψ photoproduction in Au+Au UPCs at RHIC**
  - Kong Tu, DIS 2023
- **Probing nuclear structure with ρ^0 mesons**
  - Au and U: STAR Collaboration, Sci. Adv. 9, eabq3903 (2023)
  - Ru and Zr: Jie Zhao, ATHIC 2023

Exclusive J/ψ and ψ(2s) photoproduction in Au+Au 200 GeV

The STAR detector

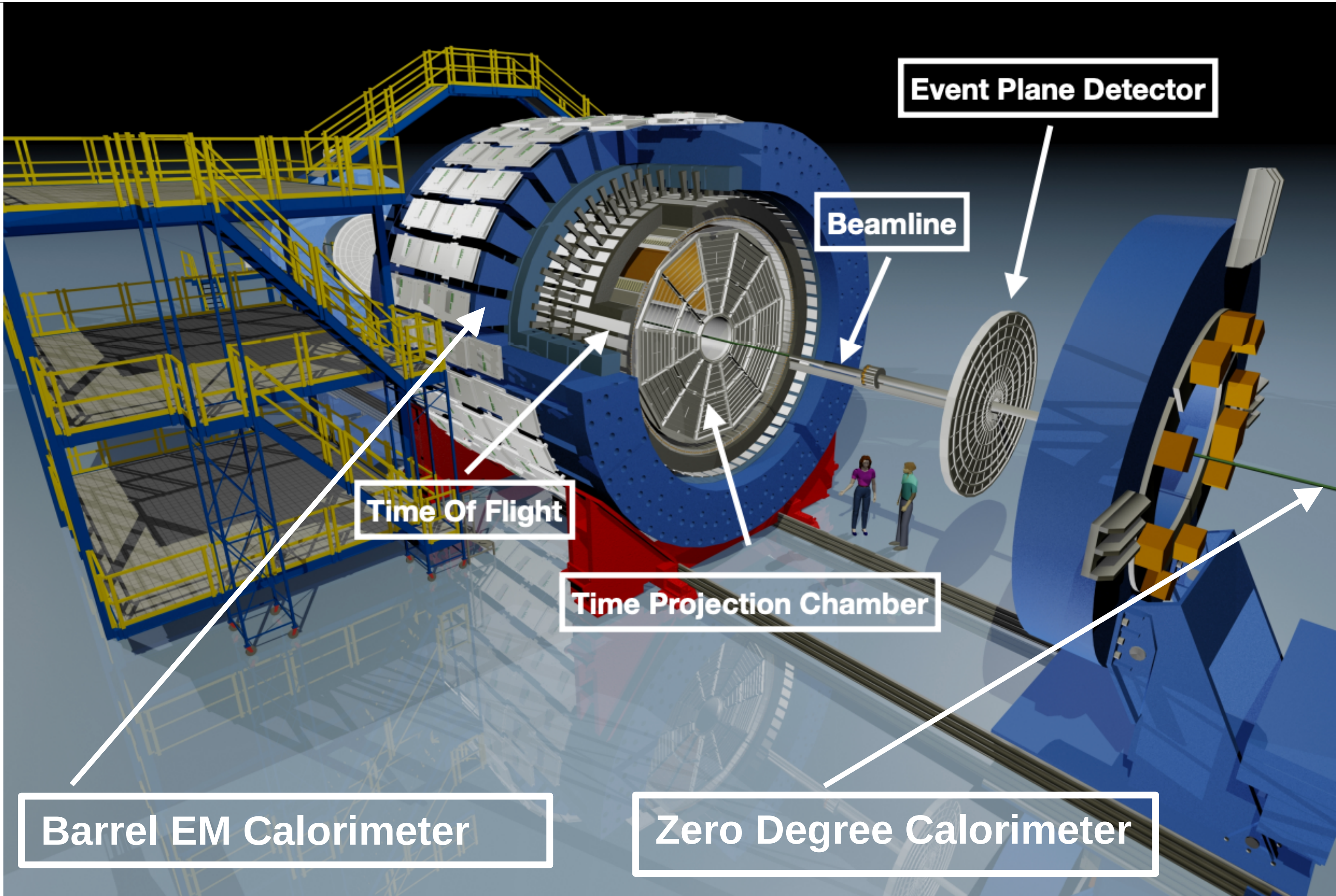
TPC $|y|<1$

BEMC $|y|<1$

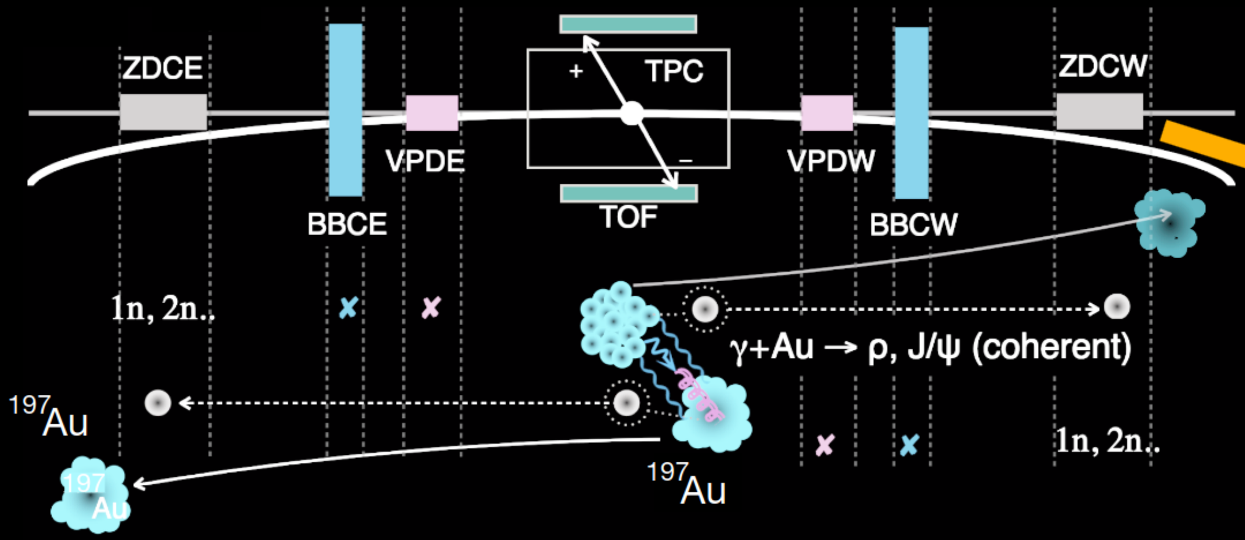
ToF $|y|<0.9$

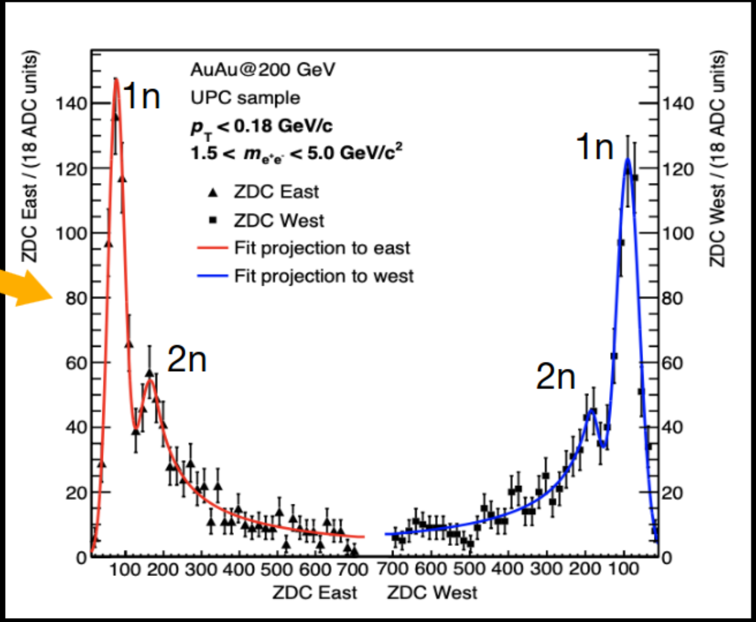
ZDC $|\eta| > 6.6$

(± 18 m from $z = 0$)



UPC events with STAR detector

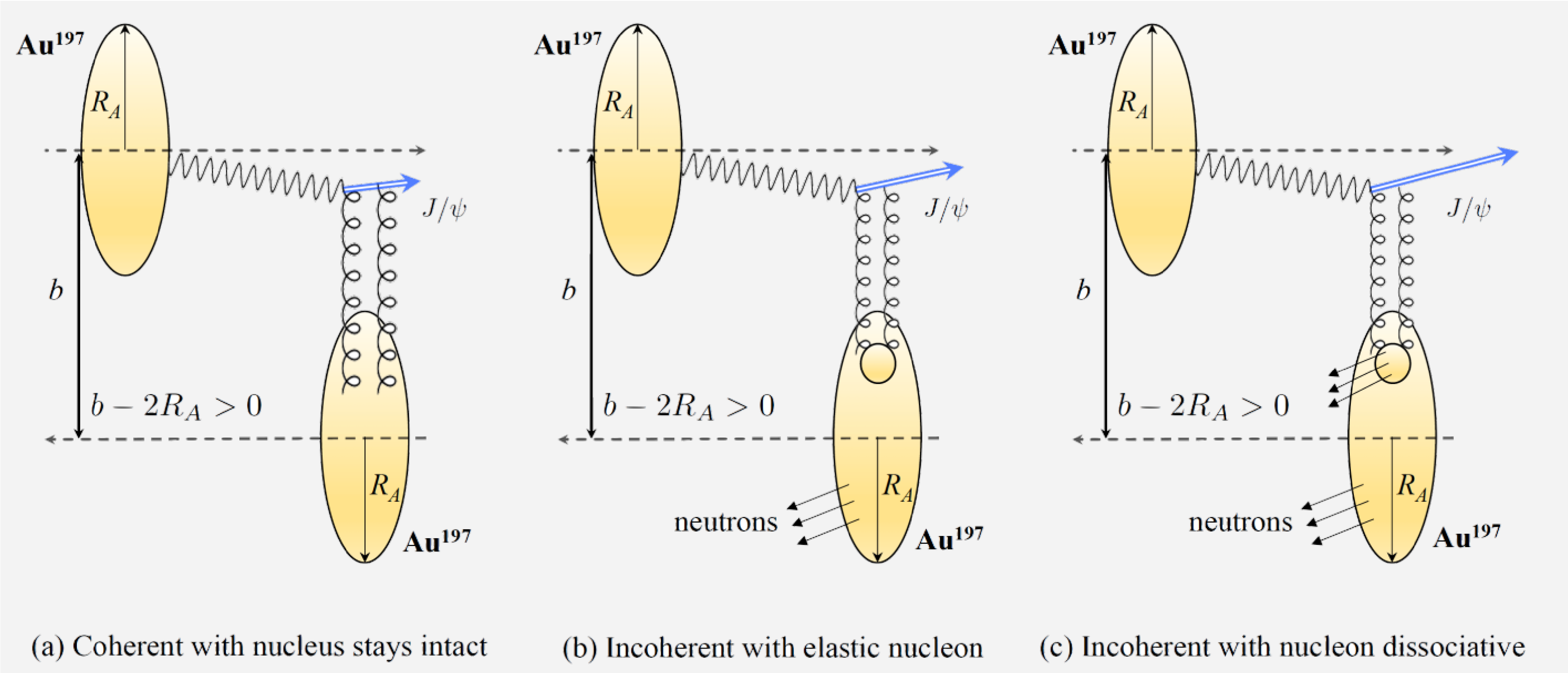




- Both nuclei get excited and emit neutrons in beam direction
- Neutron(s) detected in ZDCs
- ZDC signals show peak structure for neutrons =>Way to trigger UPC events

- Two tracks of opposite charges in TPC
- No activity in both BBCs => Diffractive events (η-gap)

Motivation



Kong Tu, DIS 2023

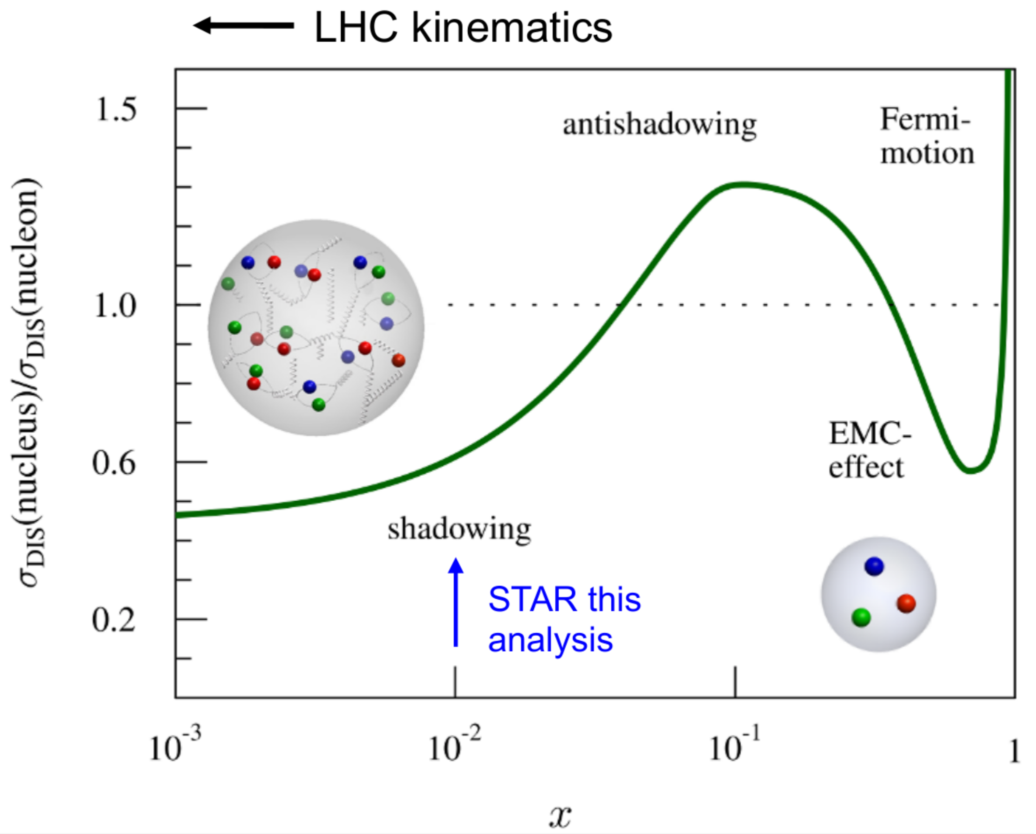
Motivation

Coherent

Probing the nuclear parton distribution functions at x ~ 0.01 – 0.05

Incoherent

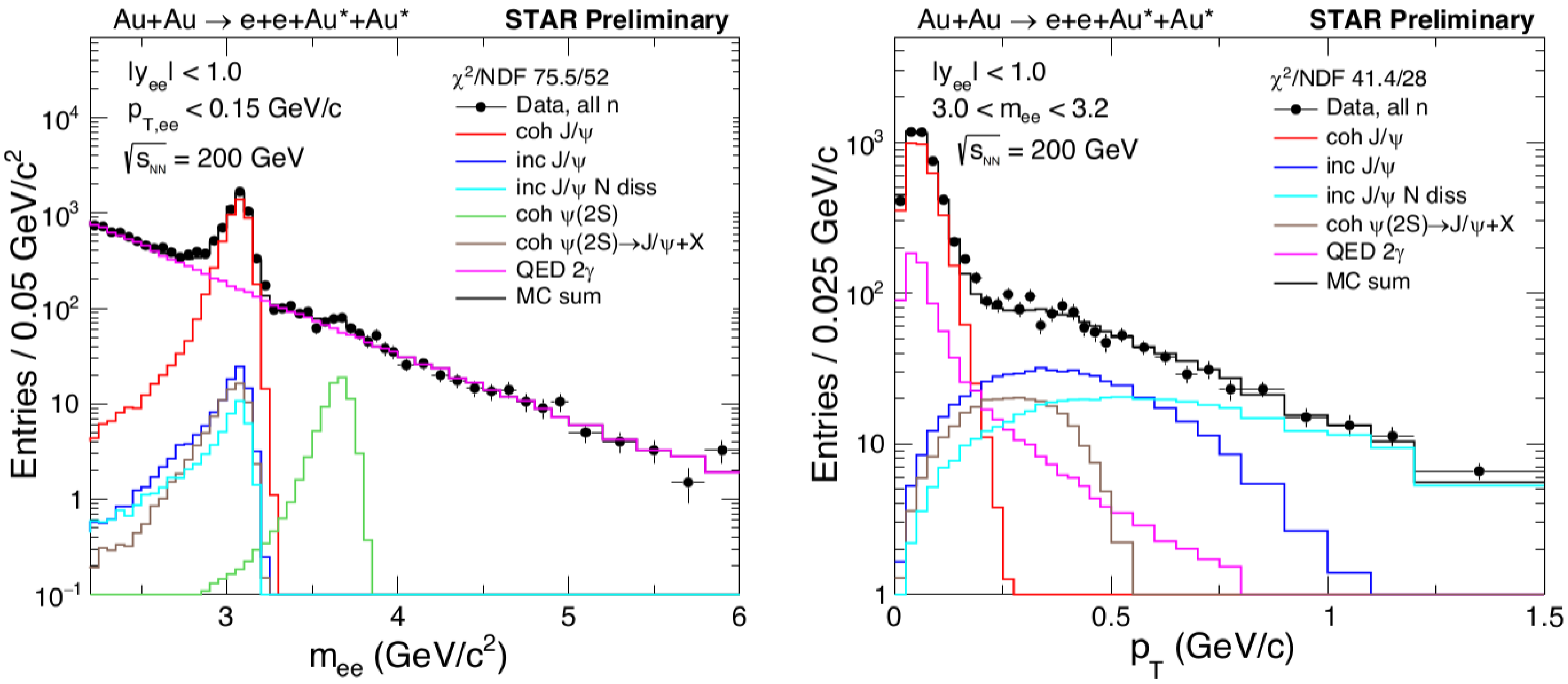
Search for possible sub-nucleonic density fluctuations (“hot spots”)



Kong Tu, DIS 2023

J/ψ and ψ(2s) in 200 GeV Au+Au UPCs

Kong Tu, DIS 2023

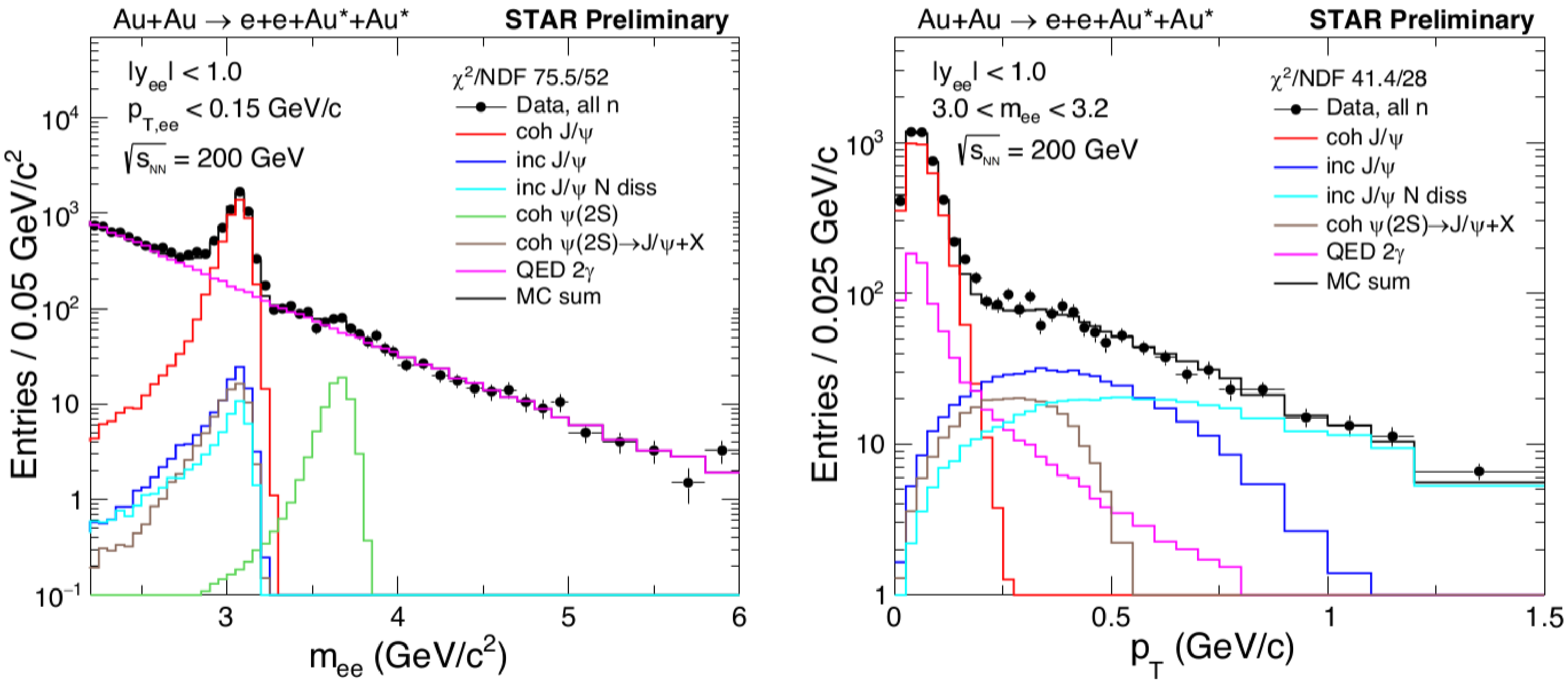


Coherent/incoherent separation:combined template fit (using H1 ep data and STARlight)

Momentum transfer **$t \approx p_T^2$**

J/ψ and ψ(2s) in 200 GeV Au+Au UPCs

Kong Tu, DIS 2023



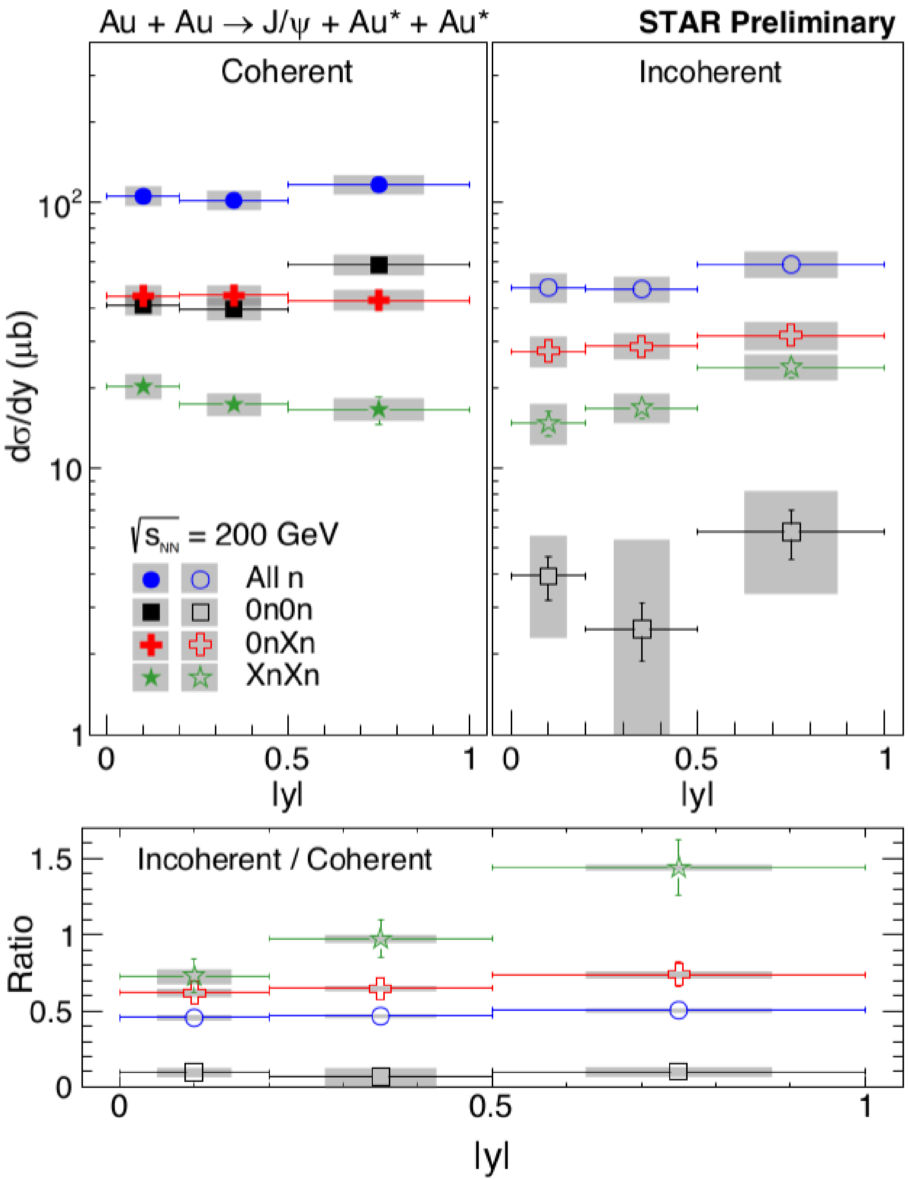
Coherent/incoherent separation:combined template fit (using H1 ep data and STARlight)

Low momentum transfer (p_T^2) dominated by coherent photoproduction

First measurement of J/ψ photoproduction vs rapidity at RHIC

Incoherent/coherent ratio sensitive to nuclear structure and nuclear deformation at small x

See W. Zhao, INT 2023



- 0n0n: no neutron on either side
- 0nXn: >=1 neutron on one side
- XnXn: >=1 neutron on both sides

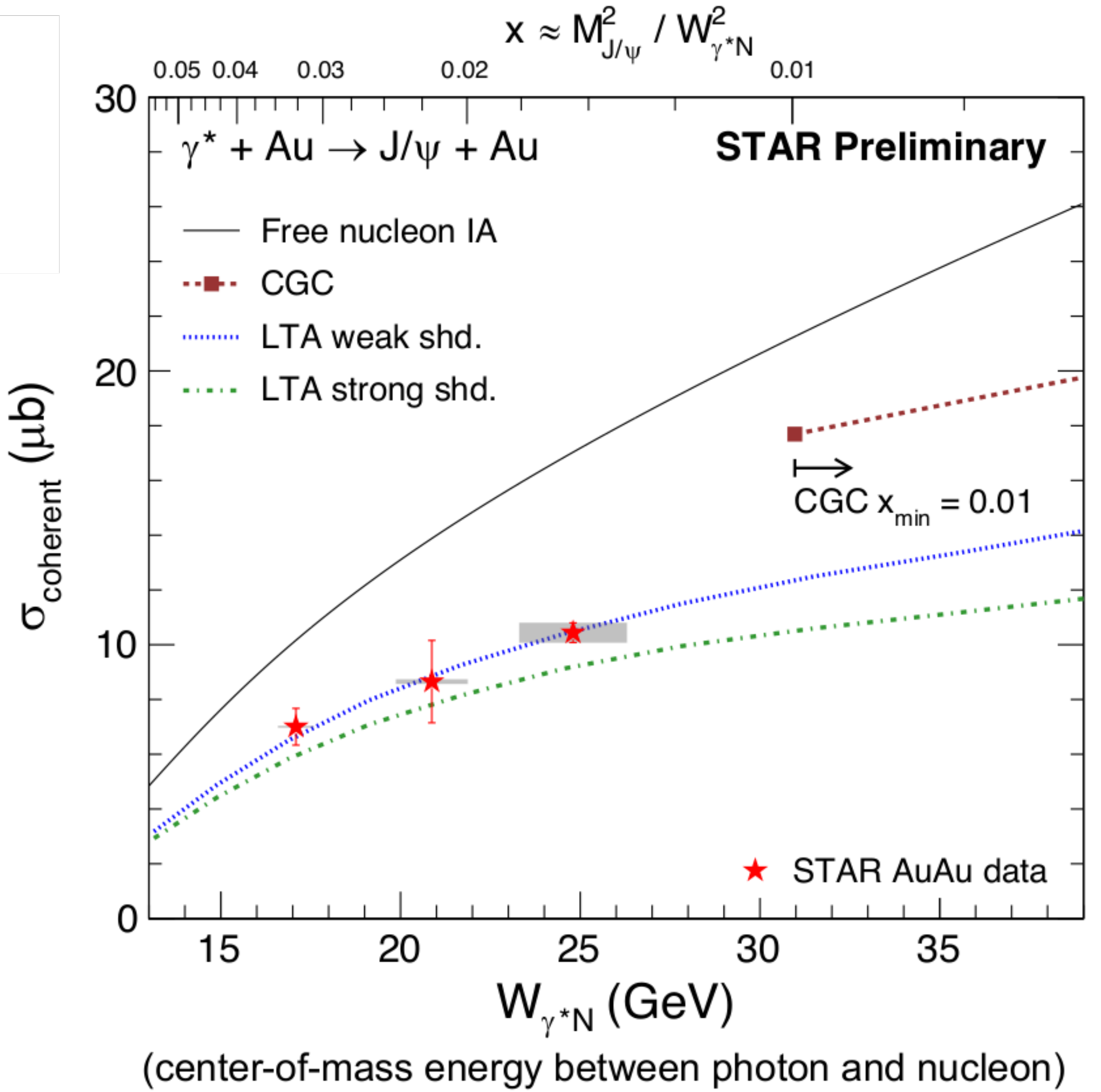
Kong Tu, DIS 2023

Coherent J/ψ photoproduction

Shadowing model with Leading Twist Approximation describes the data very well.

The suppression factor **Data/Impulse Approximation (free nucleon) ~ 60%**

Results with r**esolved two-source ambiguity** (which Au nucleus provides the photon)

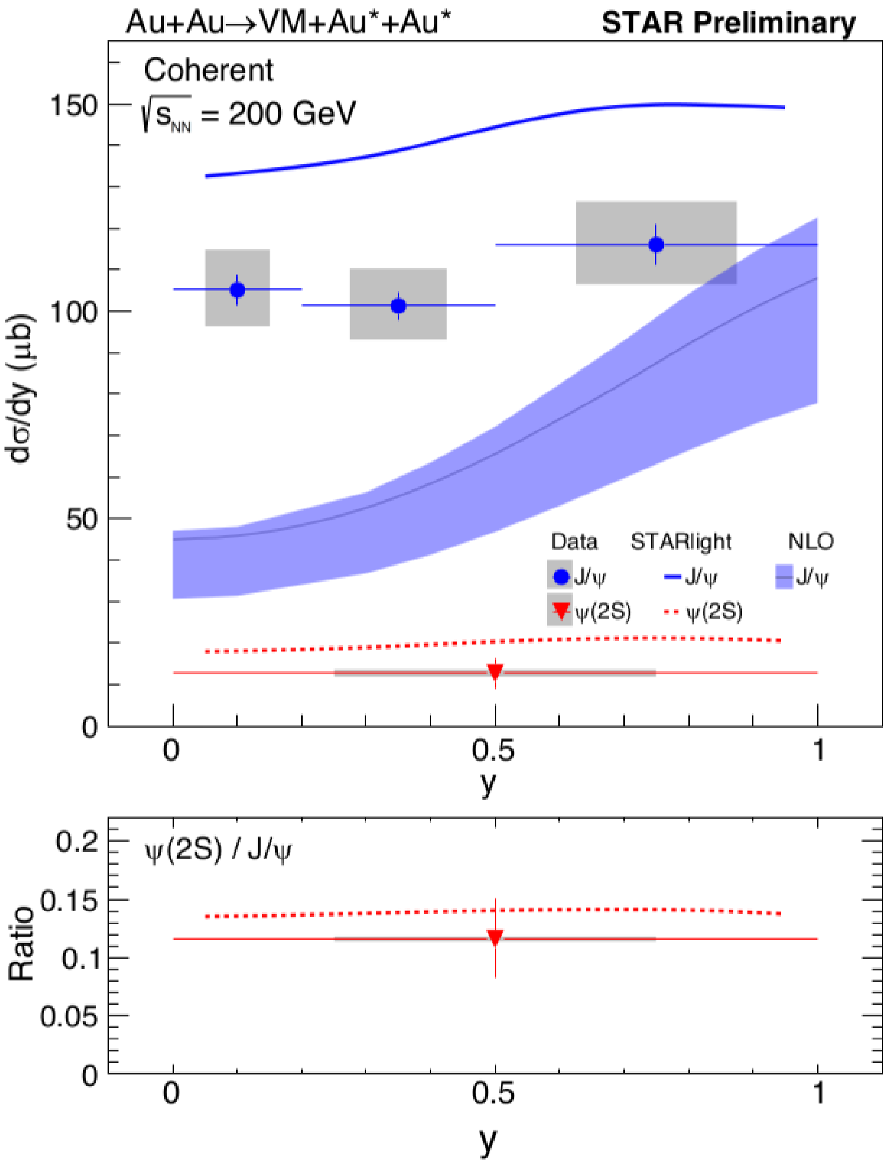


Kong Tu, DIS 2023

Coherent ψ(2s) vs J/ψ photoproduction

Next-to-Leading Order (NLO) pQCD calculation, constrained by the LHC data do not describe the STAR data

EPPS21 + scale at 2.39 GeV.
Only scale uncertainty shown.



Reference to NLO pQCD calculation:
a) arXiv:2210.16048
b) Phys. Rev. C 106 (2022) 3, 035202

Kong Tu, DIS 2023

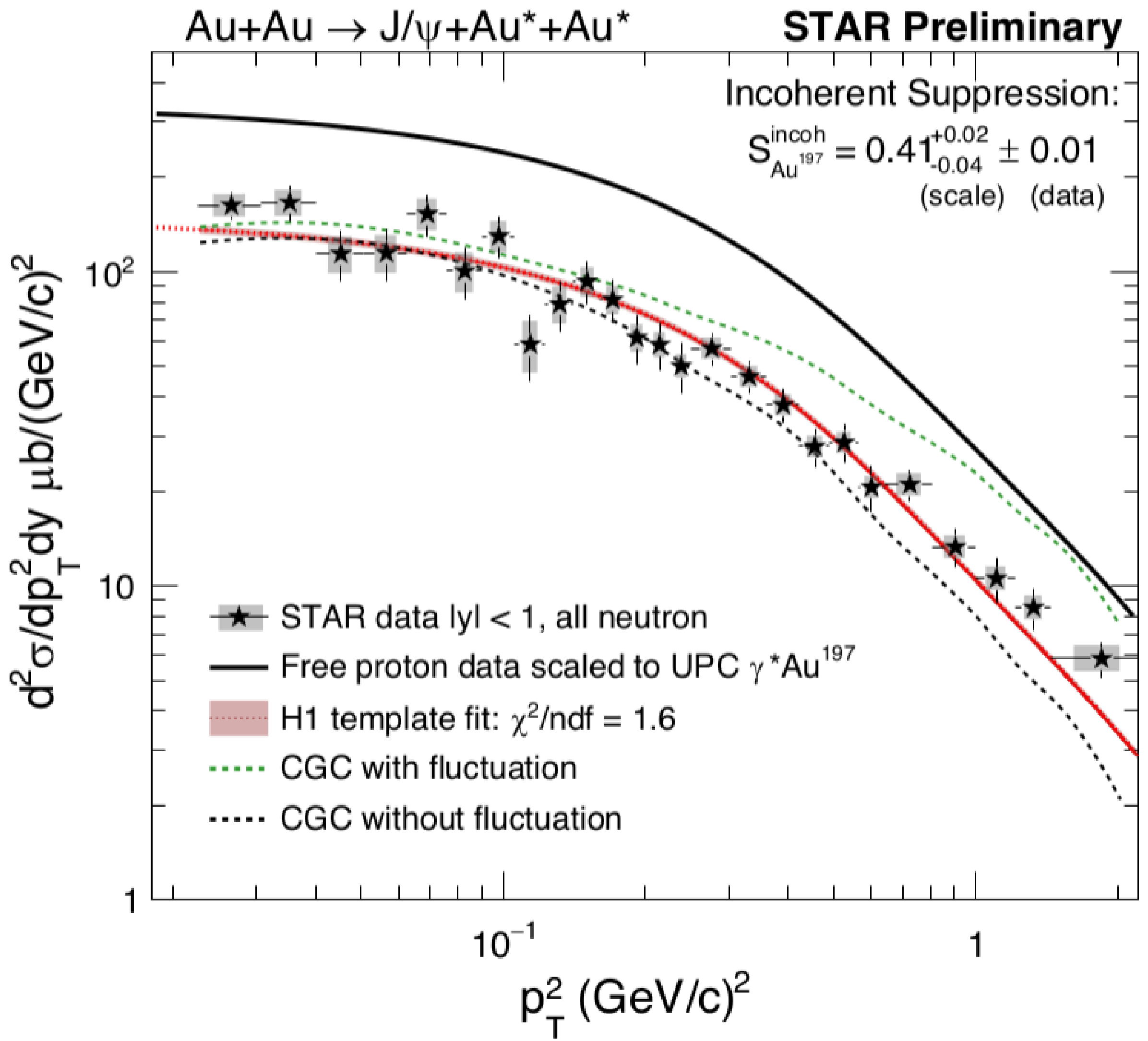
Incoherent J/ψ photoproduction

Compared to the **H1 data with free proton, the suppression factor ~40%** Stronger than that for coherent production

The H1 data consistent with models witl sub-nucleonic fluctuation
[Phys. Rev. Lett. 117 (2016) 5, 052301]

STAR data shows the bound nucleon has a similar shape in p_T^2 as the free proton →similar sub-nucleonic fluctuation in heavy nuclei.
[Phys. Rev. D 106 (2022) 7, 074019]

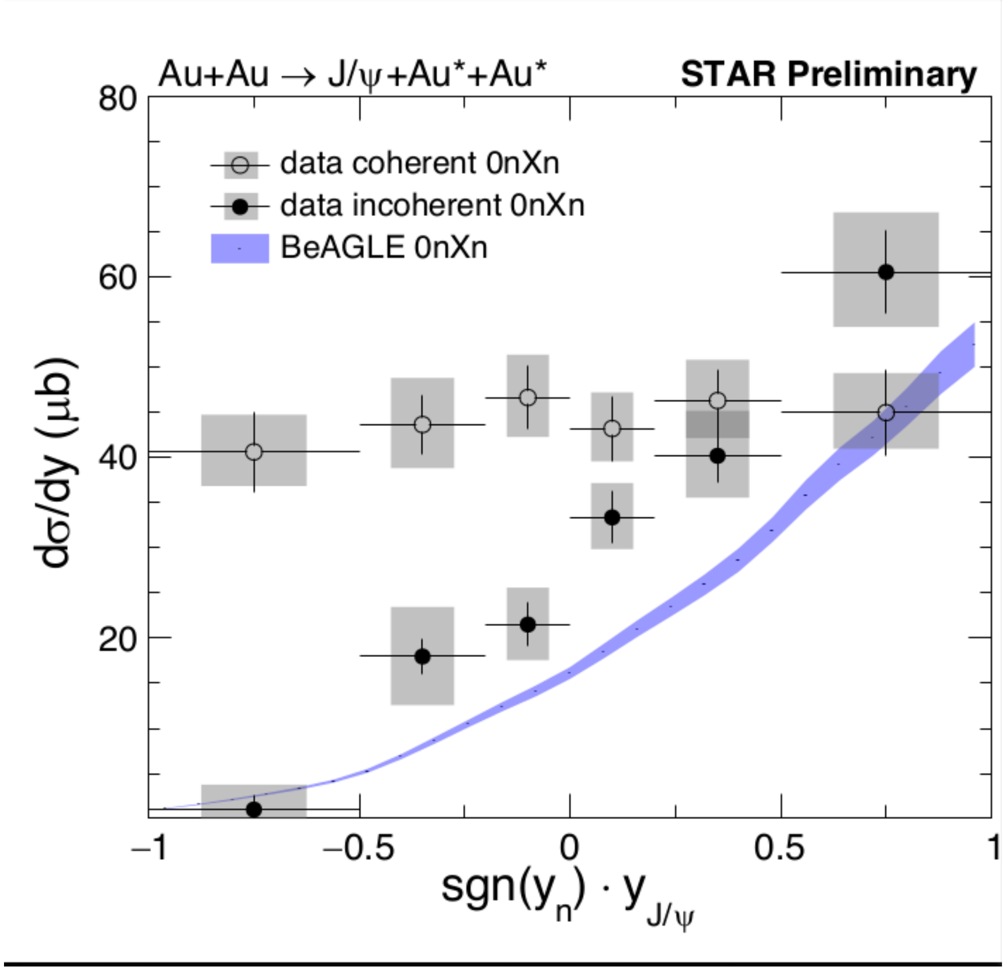
Kong Tu, DIS 2023



Coherent vs incoherent photoproduction

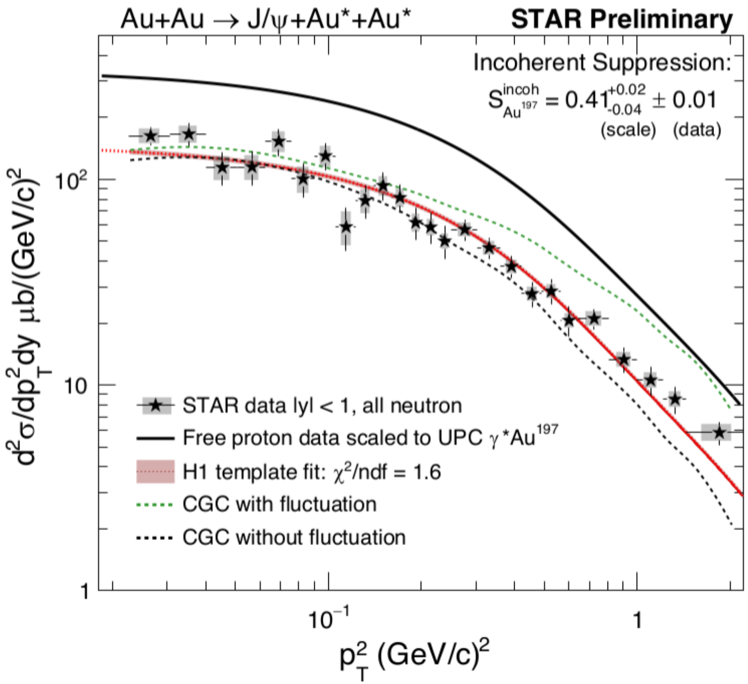
Coherent J/ψ production is independent of neutron emissions

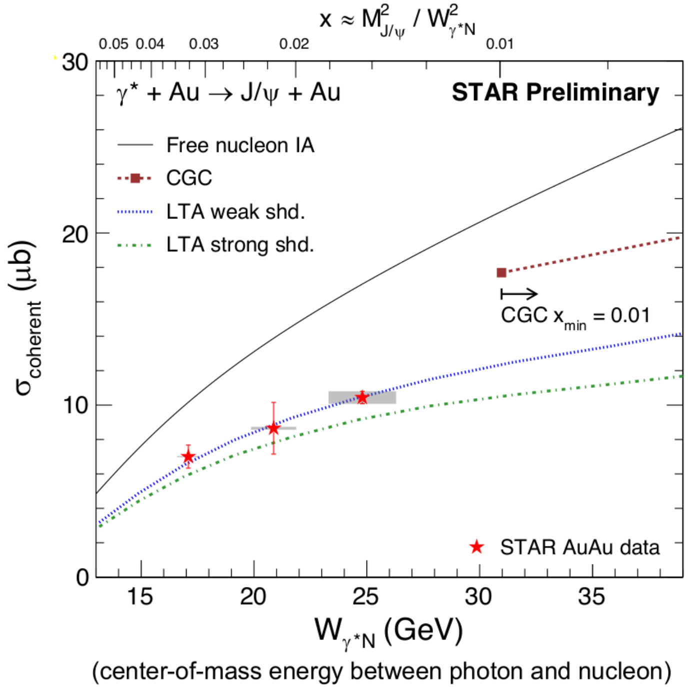
Incoherent J/ψ production is highly correlated with neutron emissions



Summary

- **First J/ψ measurements in heavy-ion UPC at RHIC:**
  - Strong nuclear suppression seen for both coherent (~ 40%) and incoherent (~60%) production
  - Bound nucleon and free proton have similar shape up to p_T^2 ~2 $(GeV/c)^2$

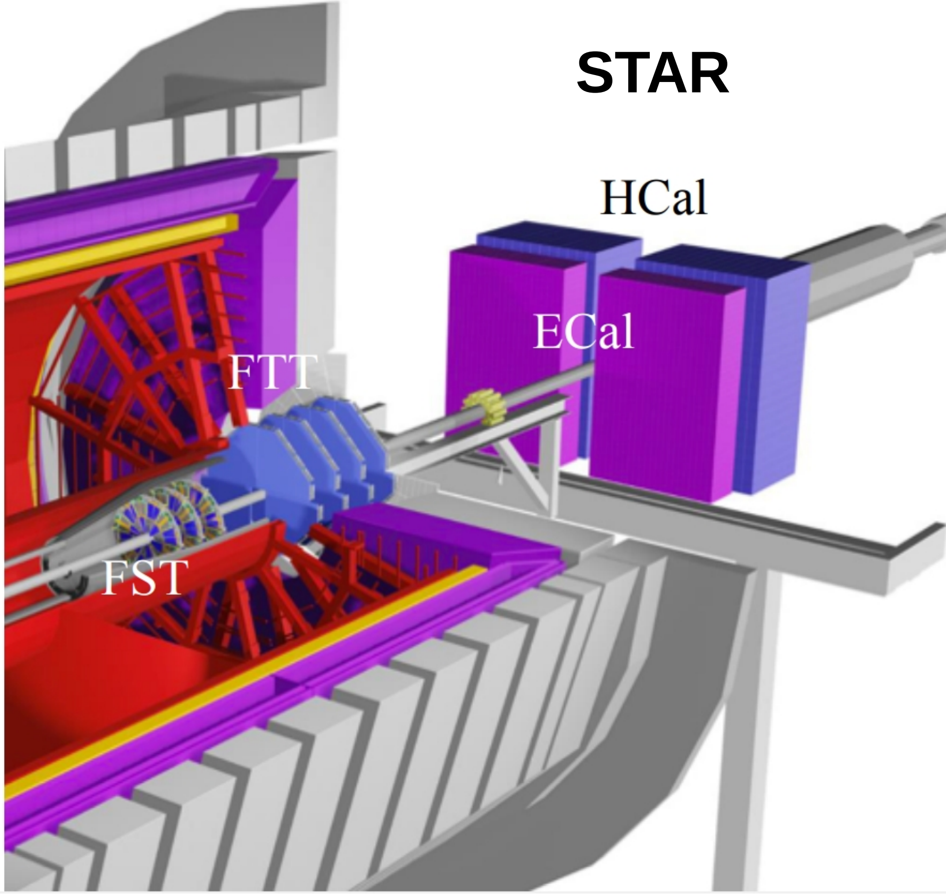




Outlook

STAR

- **Recently completed forward upgrades at STAR**
  - Forward Tracking System
  - Forward Colorimeter System (EM and Hadronic
  - $2.5 < \eta < 4$
- **High-statistics data**
  - transversly-polarized p+p 500 GeV (run 2022)
  - p+p, $p^{\uparrow}$+Au and Au+Au 200 GeV (2024 and 2025
    (p+p, p+Au → baseline for no saturation)
- **Expected physics results**
  - Low W phase space down to W < 10 GeV
  - First-time ϕ meson photoproductio
  - High statistics J/ψ at higher p_T
  - Spin-dependent J/ψ production



Backup

Probing the gluonic structure of the deuteron with J/ψ photoproduction in d+Au ultra-peripheral collisions

Phys. Rev. Lett. 128, 122303

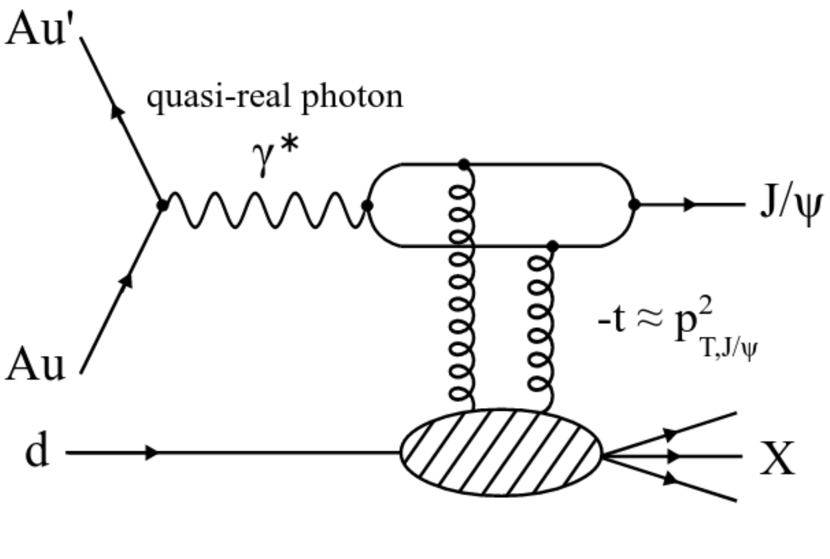
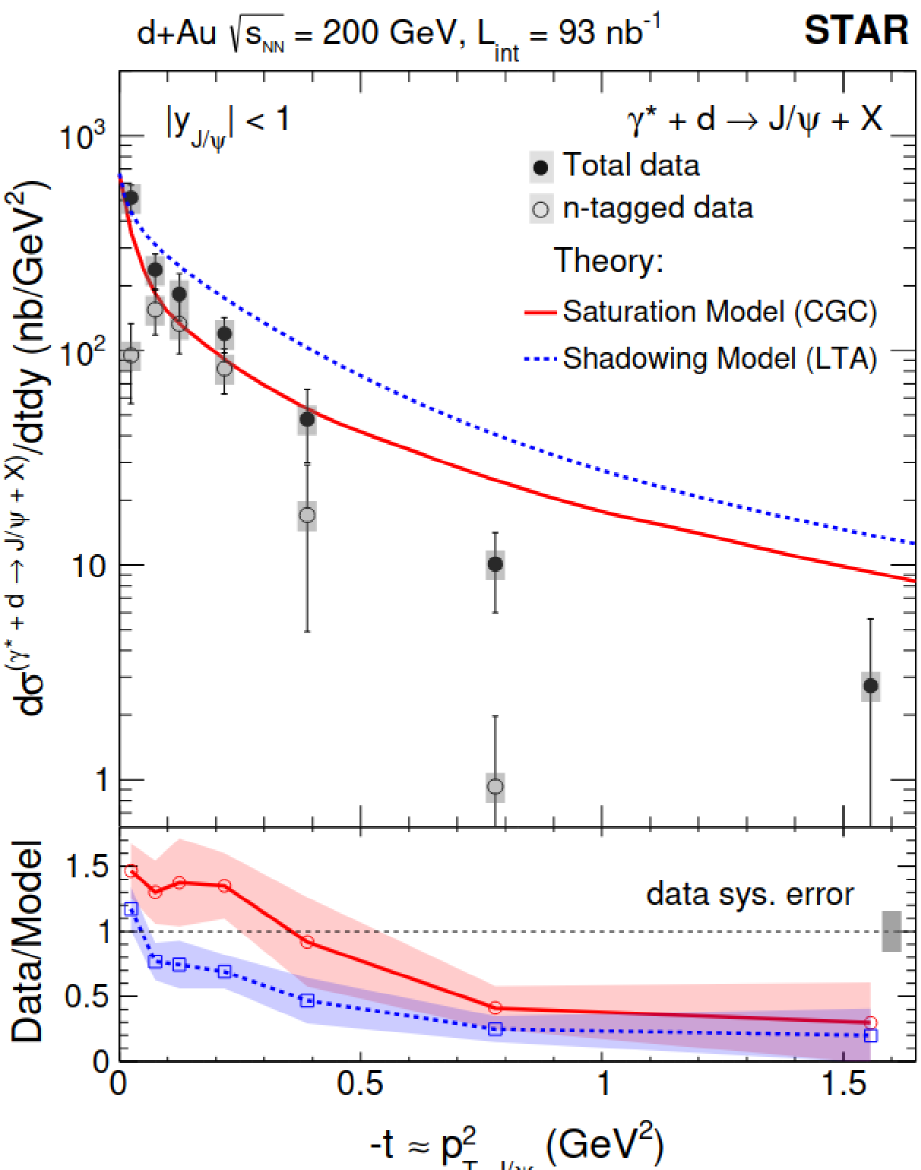
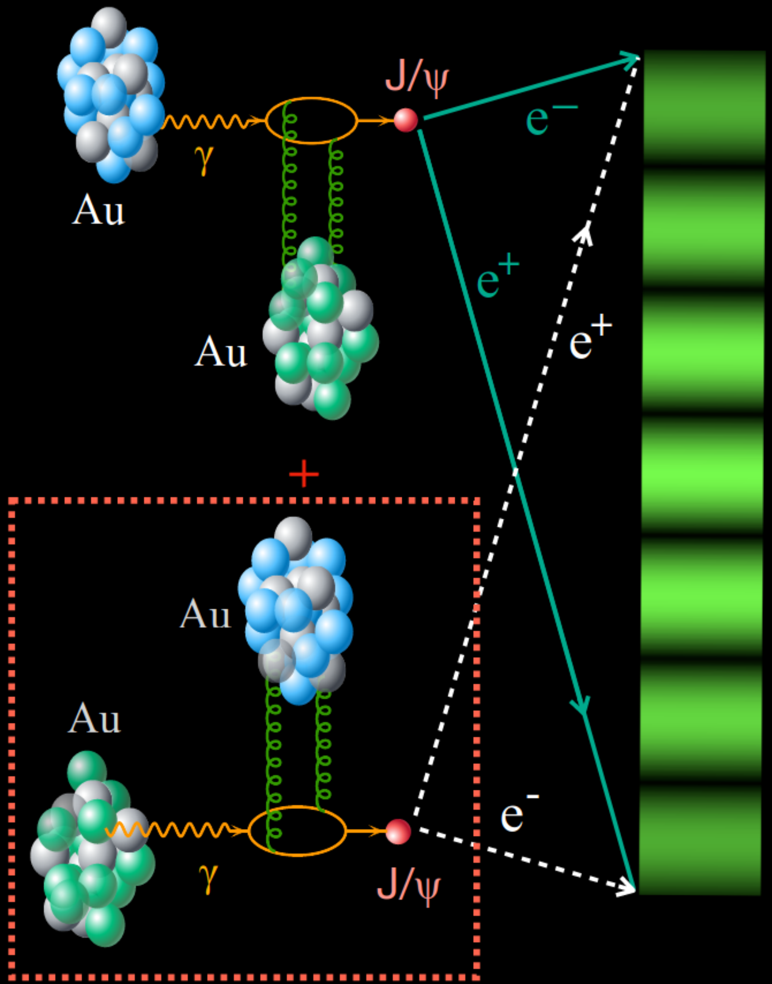


FIG. 1. Photoproduction of J/ψ in d+Au UPCs, where X represents the deuteron (coherent) or deuteron-dissociative (incoherent) system.

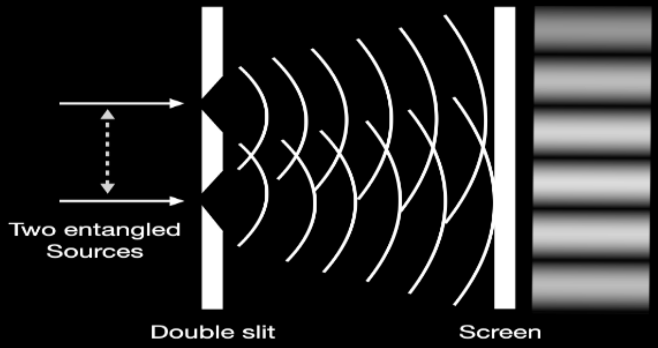


Spin interference effect with J/ψ

Klein et. al, Phys. Rev. Lett. **84**, 2330 (2000)
Brandenburg et. al, Phys. Rev. D 106, 074008 (2022)



- Polarization direction changes event-by-event => <cos(2ϕ)> vanishes over many events
- Two ways for J/ψ photoproduction— the two wave functions are created independently
- Wave functions locked in phase through phase entanglement of initial γ and Pomeron
- Entanglement makes sure to observe the interference => (cos(2ϕ)) pattern survives
- Analogy: Double slit experiment with two entangled sources

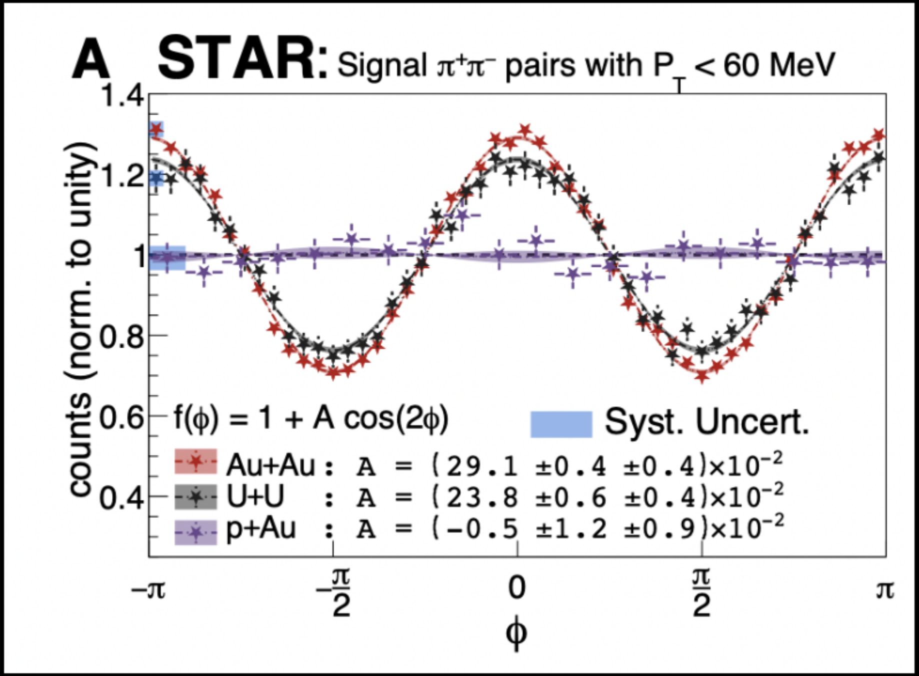


=> Entanglement ensures the spin interference in J/ψ photoproduction

New insight on spin interference effect with J/ψ

- STAR observed the entanglement-enabled spin interference effect with UPC ρ^0
- $\rho^0 \to \pi^+\pi^-$: short lifetime (1 fm), localized wave function << b — interference occurs in the daughter pions (spin 0) level

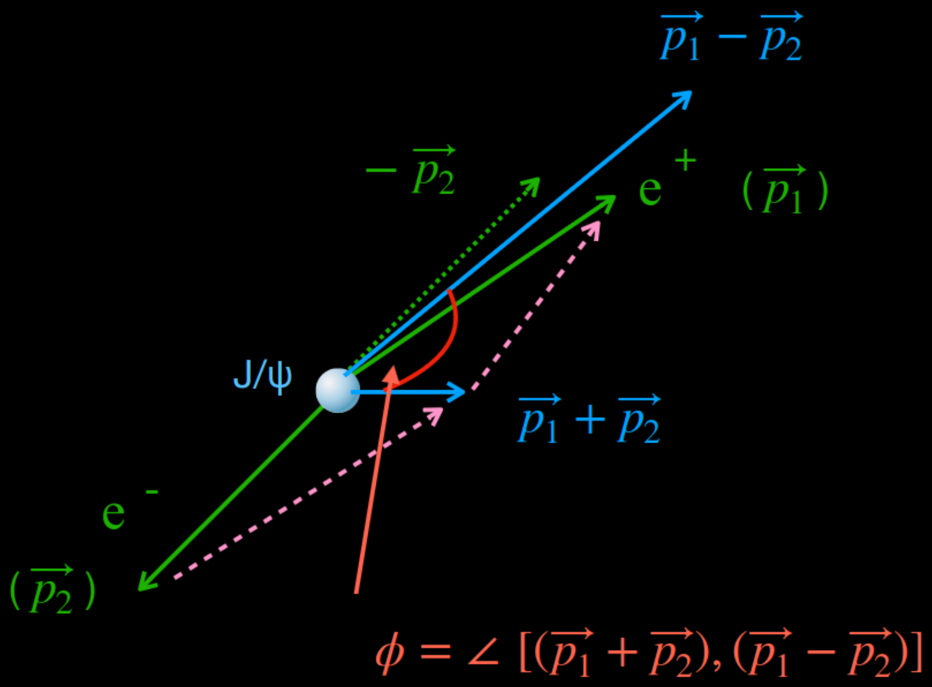
STAR Collaboration, Sci. Adv. 9, eabq 3903 (2023)

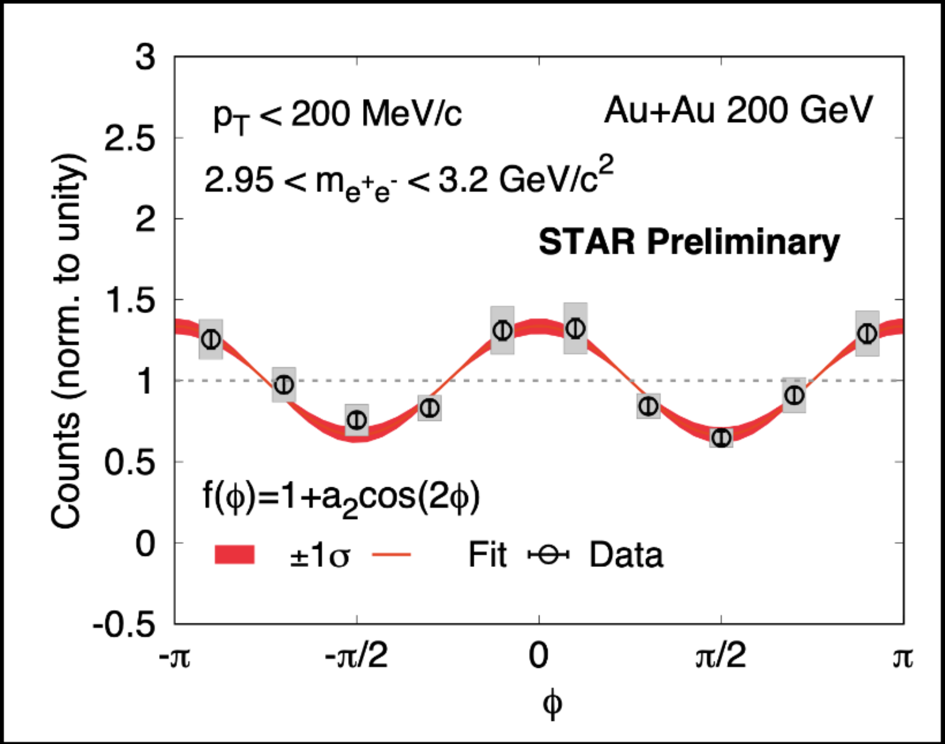


- J/ψ has longer lifetime, extended wave function
- J/ψ decay daughters, electrons (spin 1/2) are fermions, $J/\psi \to e^+e^-$
- Measurements of the spin interference with J/ψ will bring more info

=> J/ψ spin interference is an opportunity to study new physics in this domain

Spin interference of J/ψ

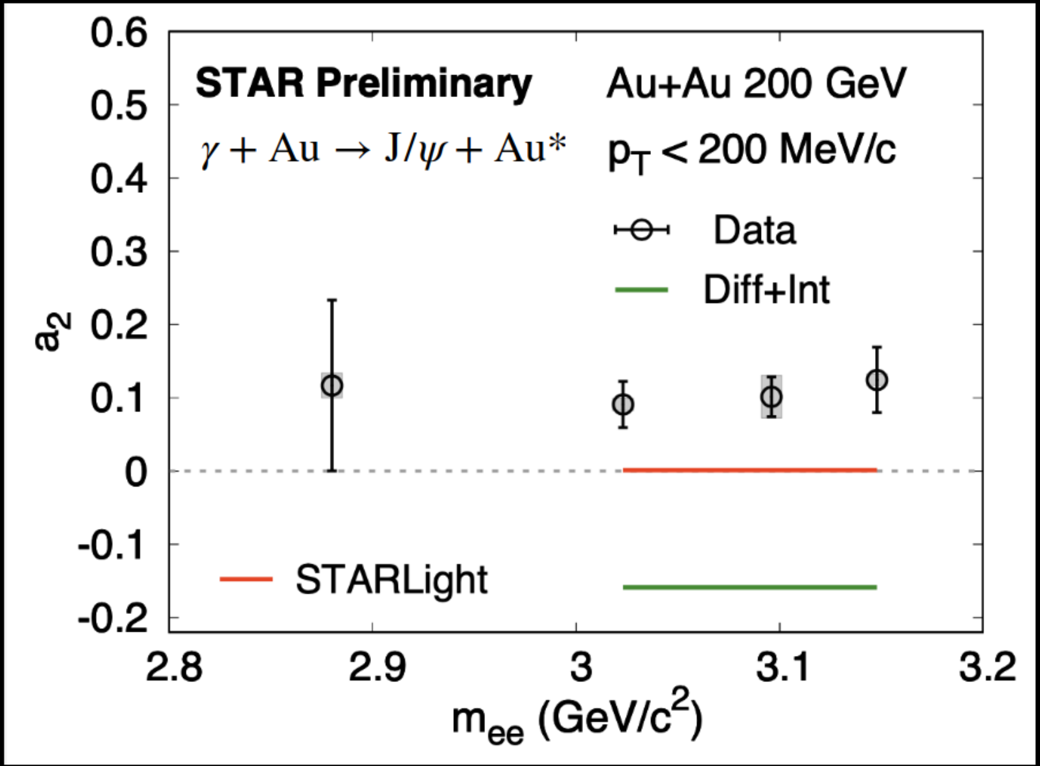




- Measured the raw cos(2ϕ) modulations for J/Ψ $(2.95 < m_{ee} < 3.2$ GeV) with p_T < 200 MeV/c
- The cos(2ϕ) modulation strength obtained from fit: 1+ a_2 cos(2ϕ) => a_2 is the measure of the modulation

=> Cos(2ϕ) modulation is present in the raw data — Need to extract the modulation strength

Signal for J/ψ Spin interference



- Measured and corrected signal for J/Ψ spin interference:

$$a_2 = 0.102 \pm 0.027 \pm 0.029$$

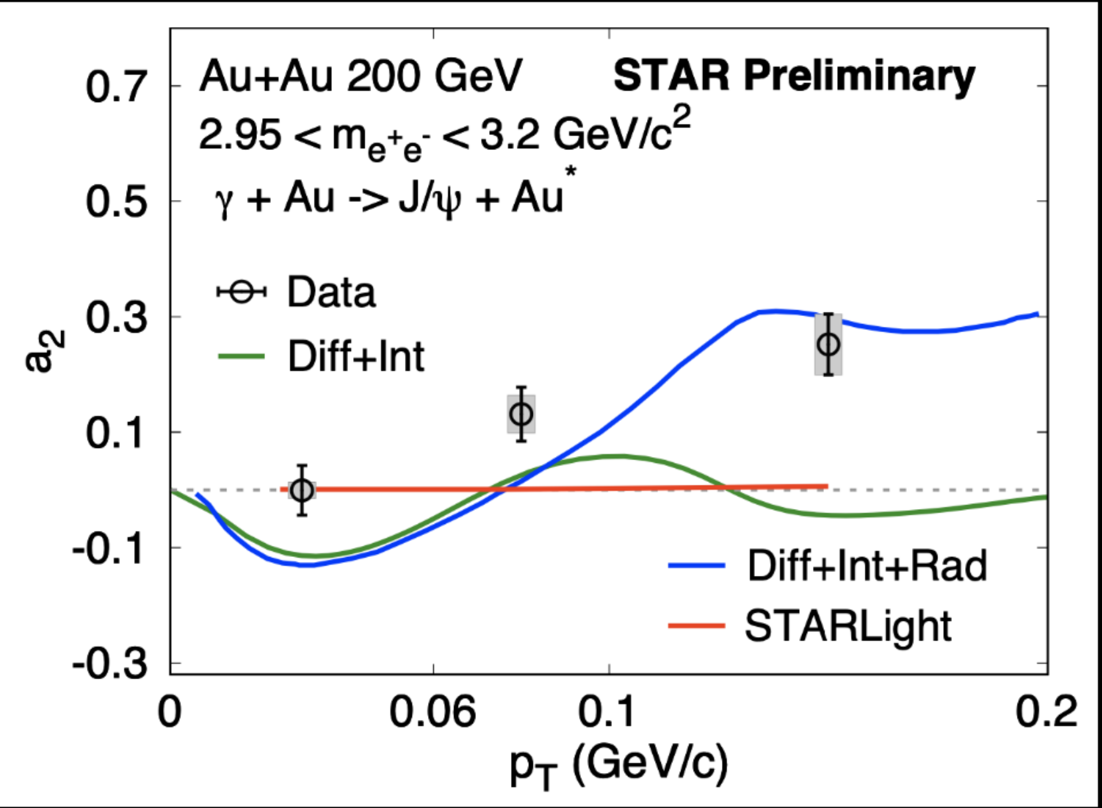
- Measurement has ~3σ significance above zero
- Compared with STARLight and theory calculations
- STARLight has no spin interference physics — consistent with zero
- Theory (Diffractive+Interference) predicts negative modulation

Theory predictions : W.B. Zhao et al. (private communication) & arXiv:2207.03712

=> Observed spin interference signal ~10% in the measured kinematic range

The p_T-dependent interference of J/ψ

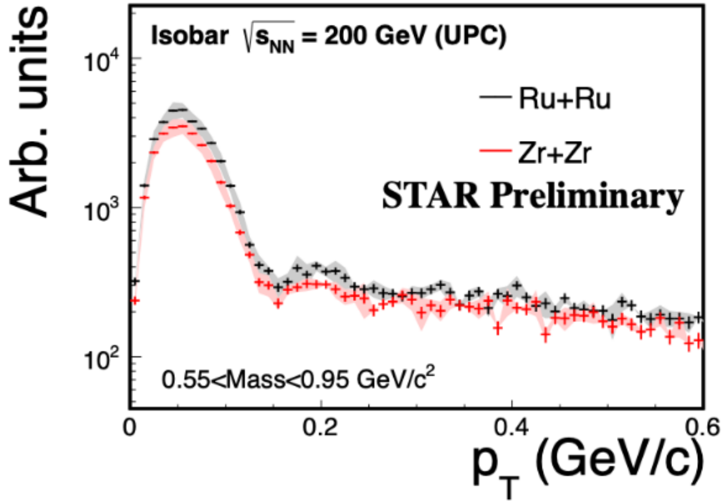
- Measured interference signal shows strong p_T dependence and rises toward positive
- STARLight prediction is consistent with zero
- Diffractive+interference calculations are negative at low and high p_T
- Diffractive+interference with additional γ radiation predicts negative at low p_T and rises towards positive value at higher p_T

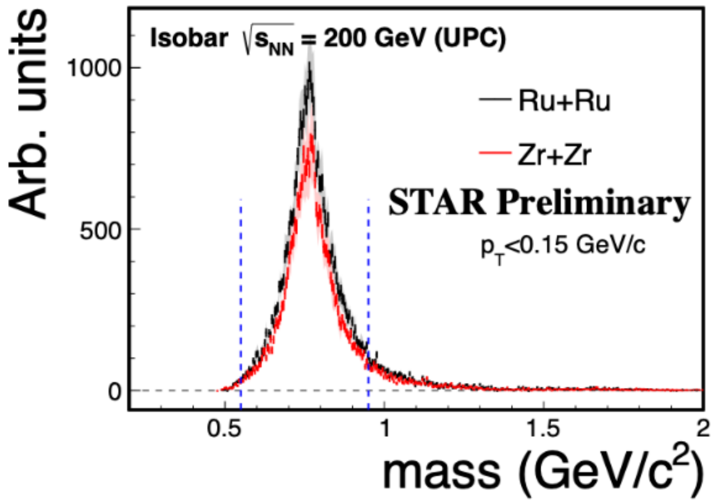


Diff+Int predictions : W.B. Zhao et al. (private communication) & arXiv:2207.03712
Diff+Int+Rad predictions : Brandenburg et. al, Phys. Rev. D 106, 074008 (2022)

=> Modulation strength positively increases with p_T

Diffractive photoproduction of ρ^0 in isobar

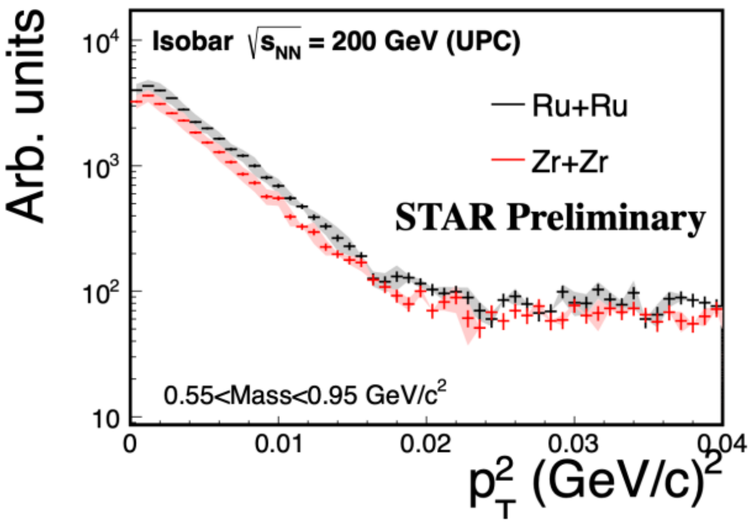


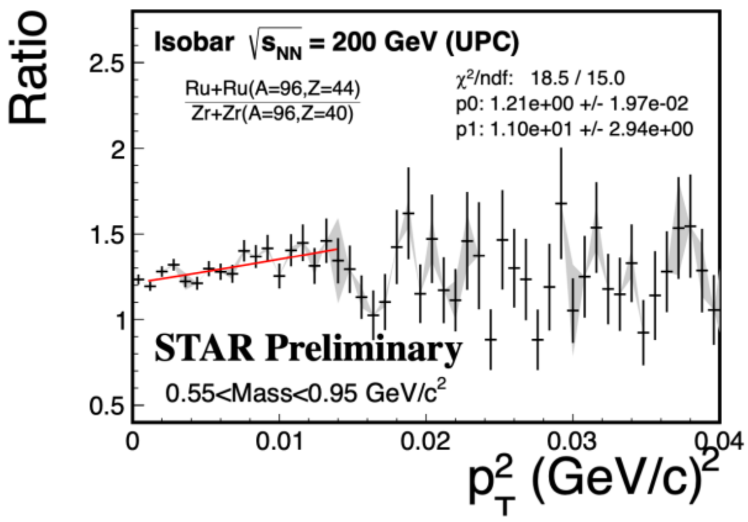


- Systematic uncertainty sources:

  dca: 1.0, 2.0 (3.0) cm; nHitsFit: 20 (15); $|V_Z|$: 50 (100) cm
- Total systemic uncertainty : RMS(σ (dca)) $\otimes$ σ(nHit) $\otimes$ σ(Vz)
- Diffraction pattern (minima) of the coherent ρ^0 production

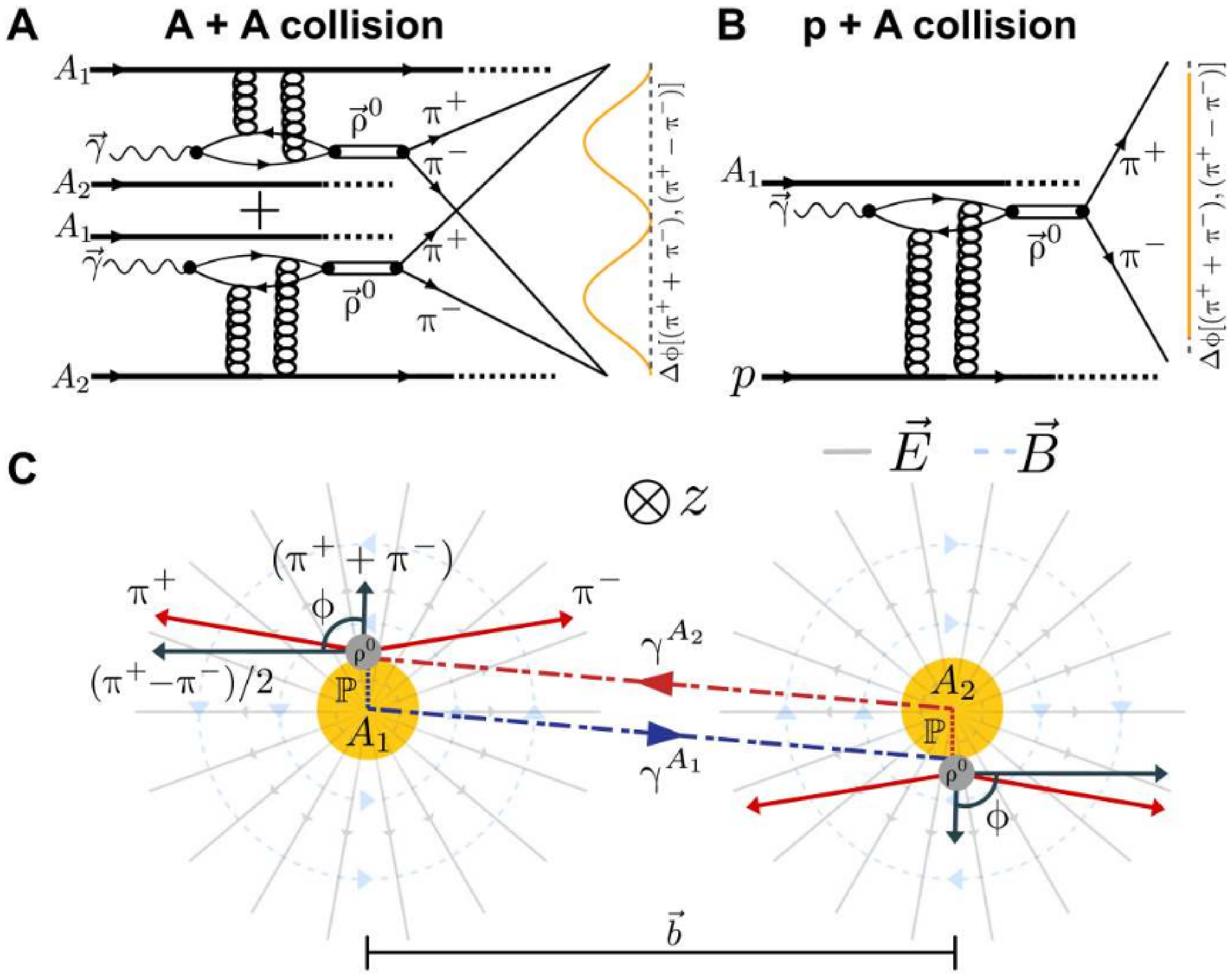
Ru and Zr nuclear structure





$A^*e^{-b^*t}$, $(t \simeq -p_T^2)$

- Indication of larger Zr size than Ru from the γ-A interaction. The slope of the dN/dt ratio is 11.0+/- 2.9 +/- 0.3 (~3σ sigma effect)
- Interference and deformation effects need to be considered



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

Au and U nuclear structure

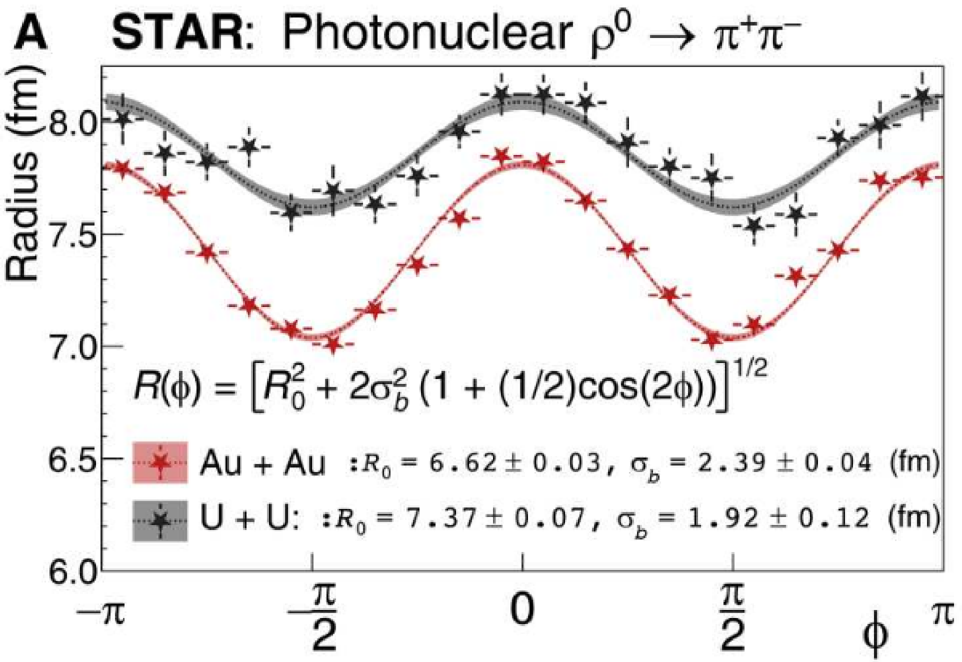


Table 2. Comparison between measurements and theory. Radius and ⟨cos 2ϕ⟩ from STAR data and those used or predicted in the models and nuclear charge radius (R_p). The reported ⟨cos 2ϕ⟩ corresponds to $\pi^+\pi^-$ pairs with 0.65 < $M_{\pi\pi}$ < 0.9 GeV and P_T < 0.06 Gev.

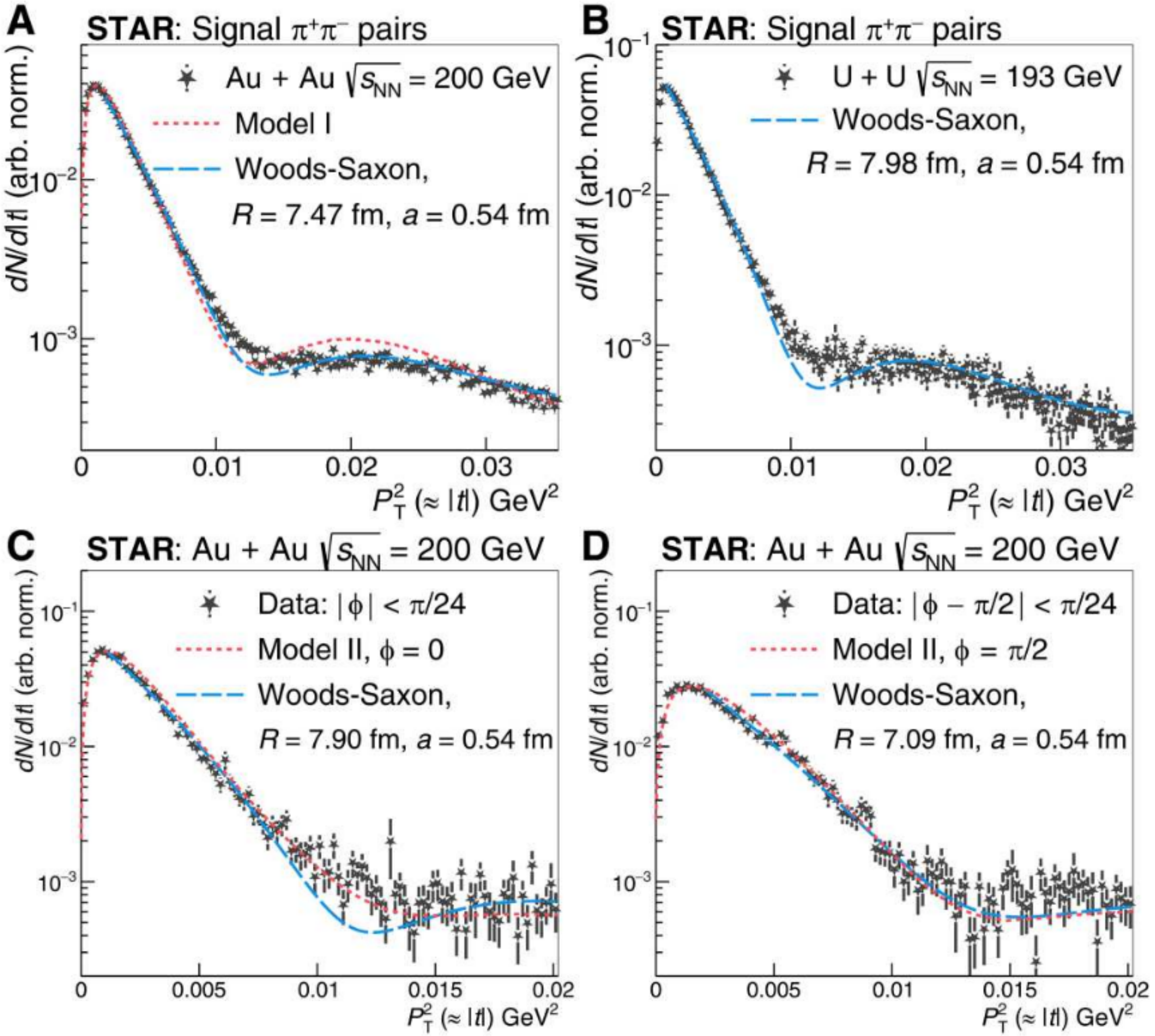
	^{197}Au	^{238}U
STAR *R* (fm)	6.53 ± 0.03 ± 0.05	7.29 ± 0.06 ± 0.05
STAR ⟨cos 2ϕ⟩ (%)	29.2 ± 0.4 (statistical) ± 0.4 (systematic)	23.7 ± 0.6 (statistical) ± 0.4 (systematic)
R_p (fm)	6.38	6.87
Model I (II) *R* (fm)	6.38 (6.9)	

Model I: W. Zha, et al. Phys. Rev. D 103, 033007 (2021); Phys. Rev. C 99, 061901 (2019)

Model II: H. Xing et al., J. High Energ. Phys. 2020, 064 (2020).

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

Au and U nuclear structure



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

Neutron emission helps resolve the two-source ambiguity

$$d\sigma^{AnBn}/dy = \Phi^{AnBn}_{T.\gamma}(k_1)\sigma_{\gamma^*+\mathrm{Au}\to \mathrm{J}/\psi+\mathrm{Au}}(k_1) + \Phi^{AnBn}_{T.\gamma}(k_2)\sigma_{\gamma^*+\mathrm{Au}\to \mathrm{J}/\psi+\mathrm{Au}}(k_2)$$

Measurements (slide 9) | Photon fluxes (slide 11) | Unknowns

Eur. Phys. J C (2014) 74:2942

See also CMS talk on Tuesday by Z. Ye

Need to measure differential cross section in *y* and in neutron emission classes; **at least 2 equations to solve 2 unknowns.**

k_1, k_2 → high energy (k_1) and low-energy (k_2) photon candidate