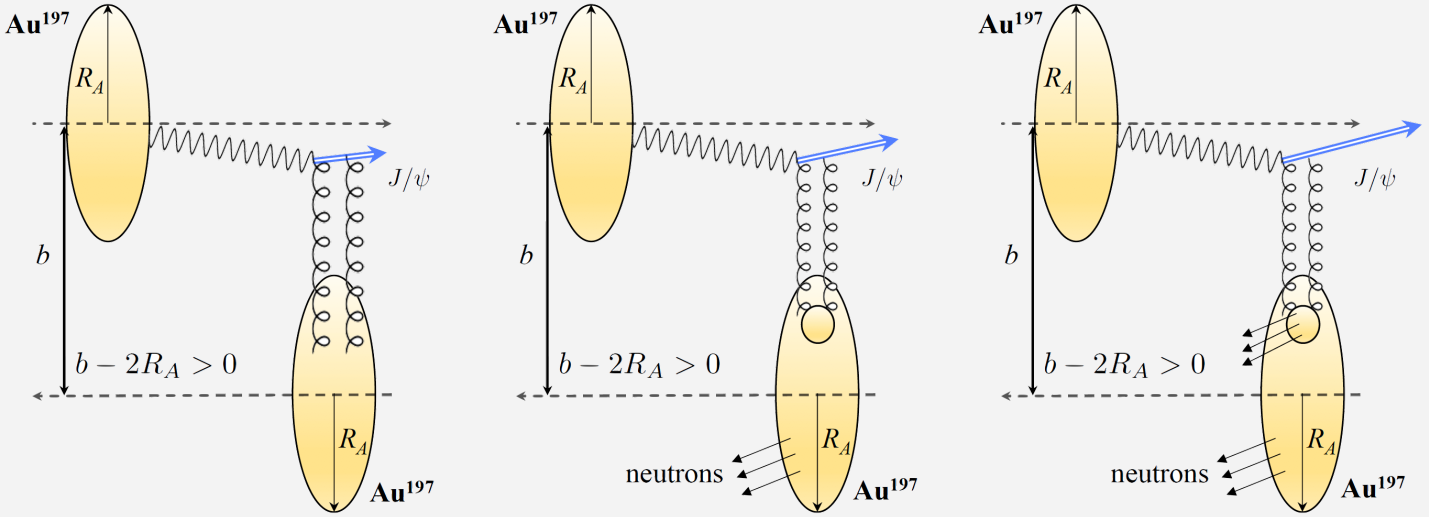
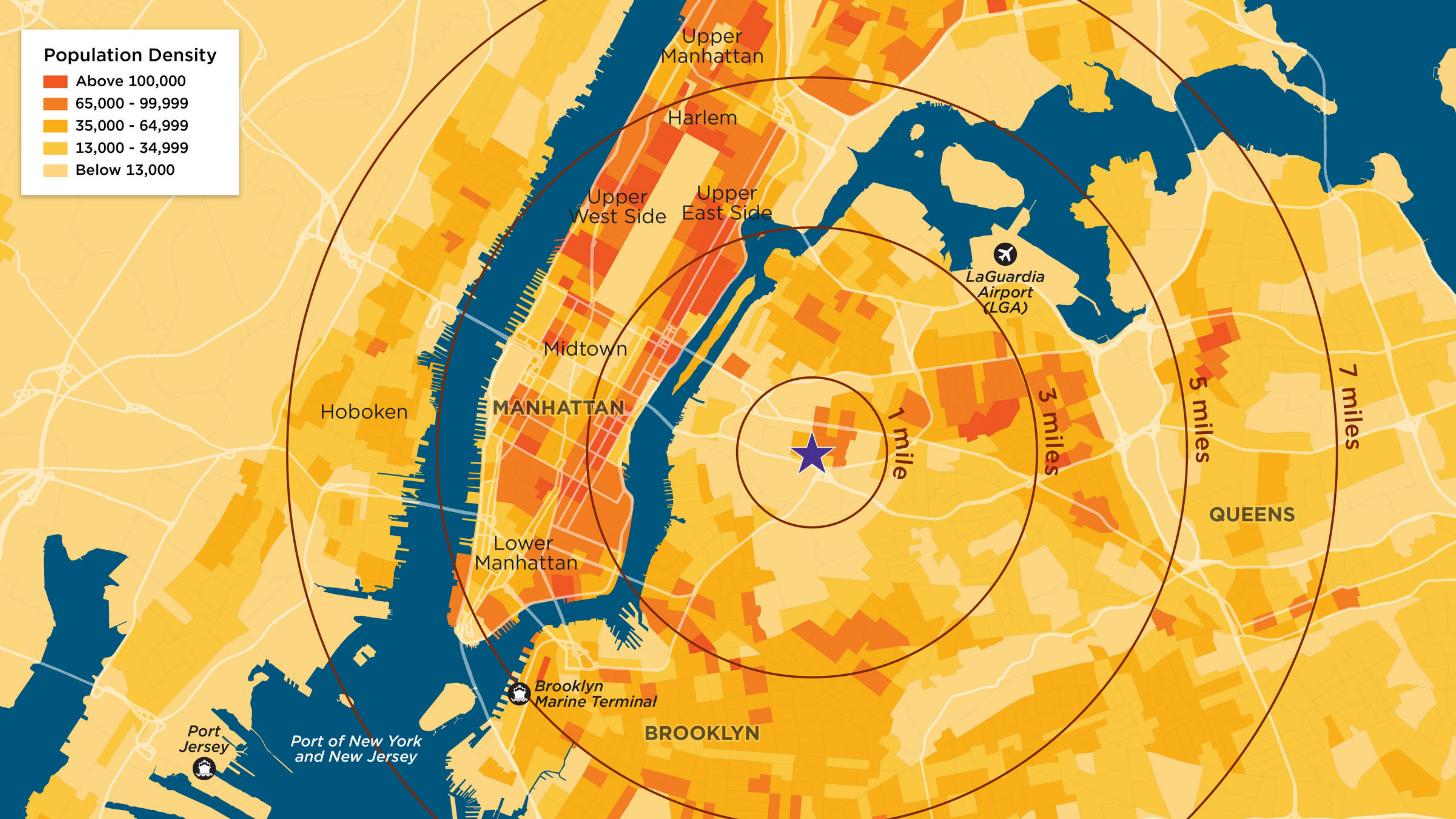
Probing nuclear parton density and fluctuation with ultra-peripheral collisions at RHIC

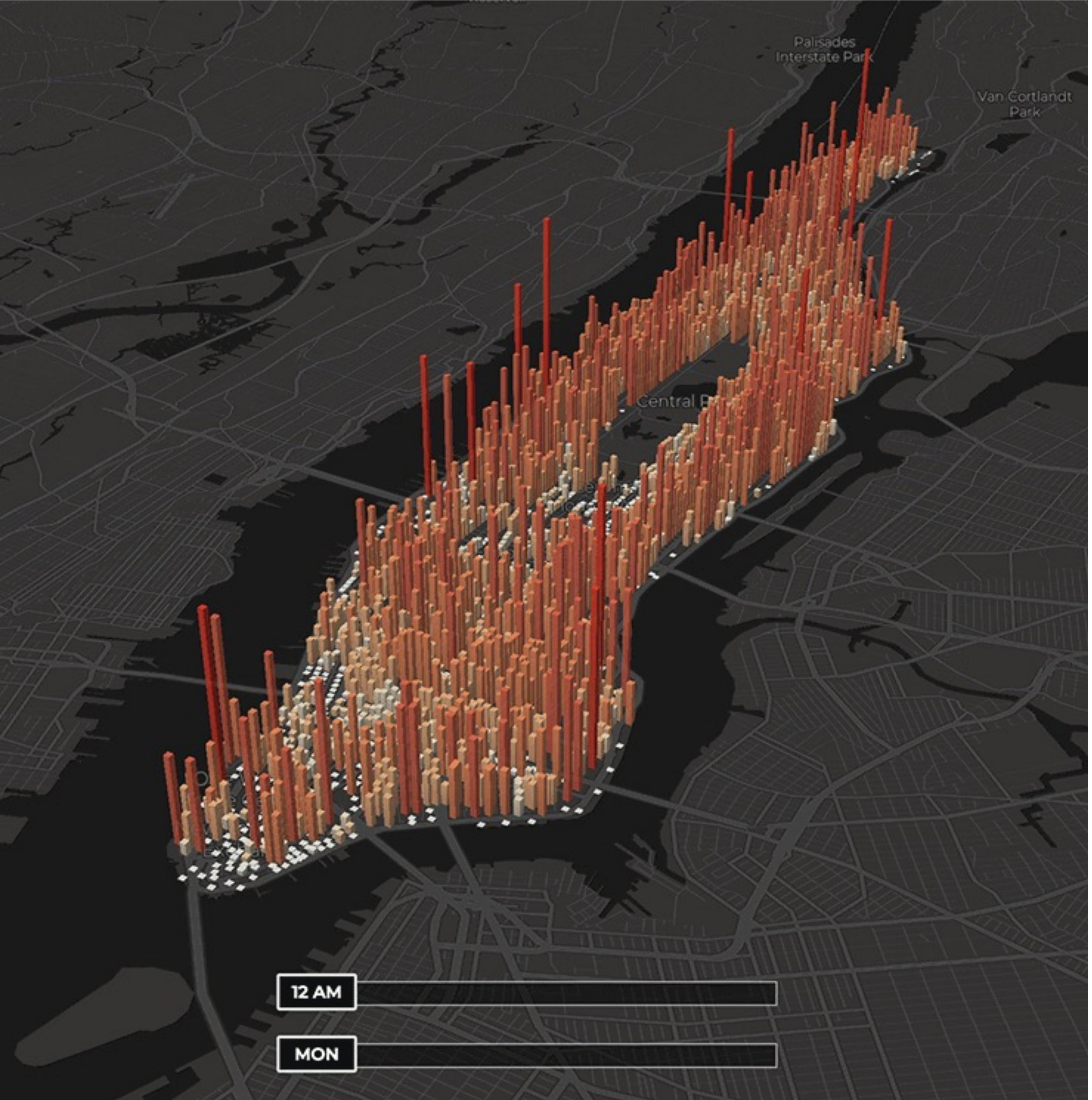
Kong Tu (BNL)



(a) Coherent with nucleus stays intact (b) Incoherent with elastic nucleon (c) Incoherent with nucleon dissociative



Population Density
Above 100,000
65,000 - 99,999
35,000 - 64,999
13,000 - 34,999
Below 13,000
Upper Manhattan
Harlem
Upper West Side
Upper East Side
Midtown
MANHATTAN
Hoboken
Lower Manhattan
LaGuardia Airport (LGA)
1 mile
3 miles
5 miles
7 miles
QUEENS
Brooklyn Marine Terminal
BROOKLYN
Port Jersey
Port of New York and New Jersey

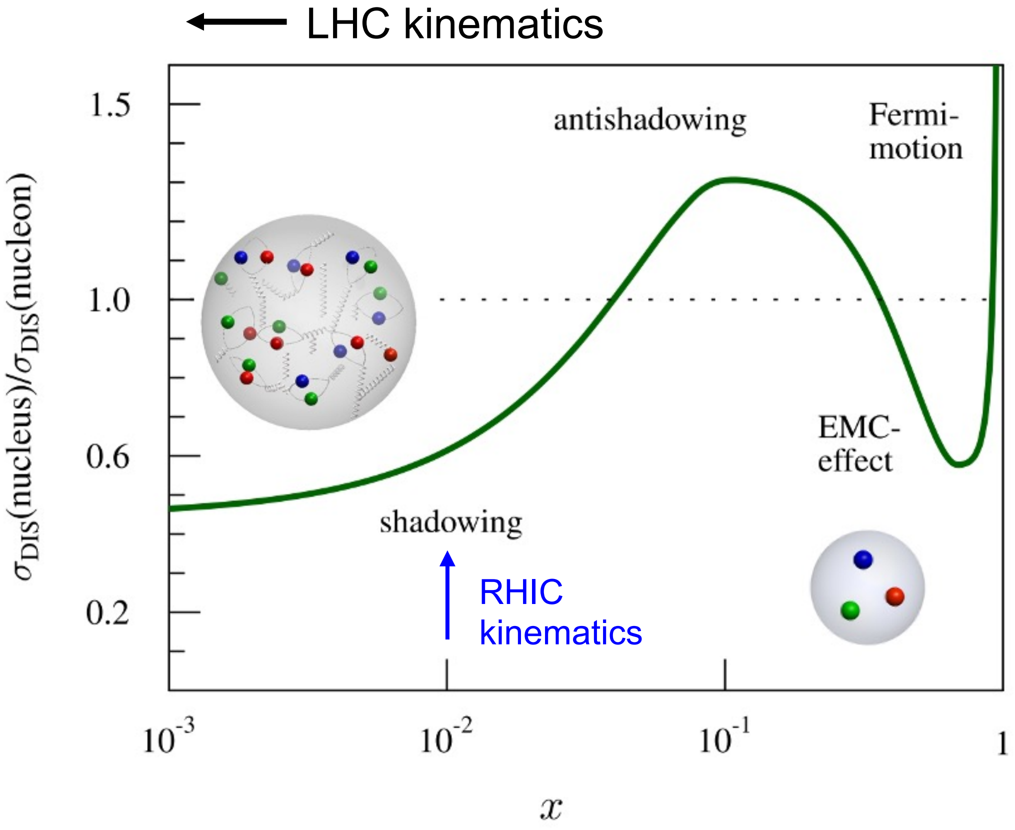


Average density and its **day-by-day, hour-by-hour fluctuation** are two distinct aspects of describing the Manhattan’s populations

Together, we have a **full picture of the structure**

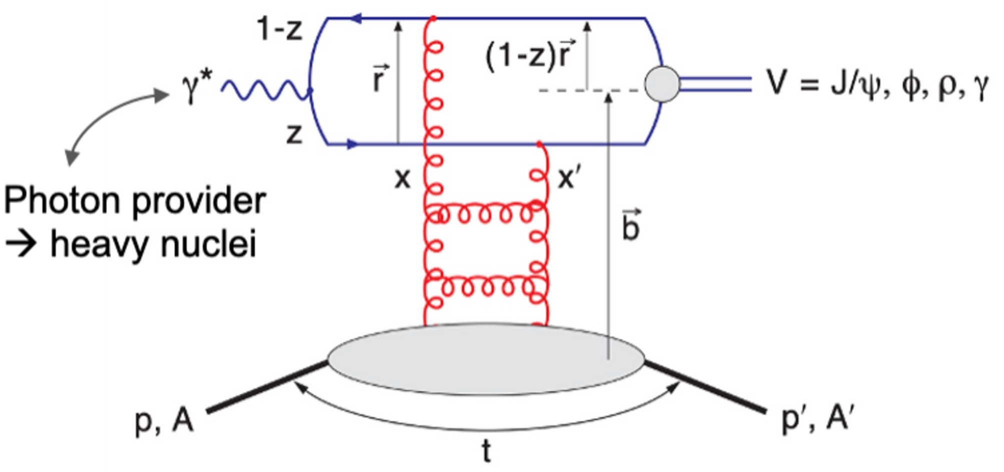
Motivation

- Physics mechanism of **modified parton densities** in heavy nuclei - one of the most pressing questions in both **hot and cold QCD community**.
- Photoproduction of Vector Mesons, e.g., J/ψ, is considered a **clean probe** to the nuclear parton structures.



J/ψ photoproduction

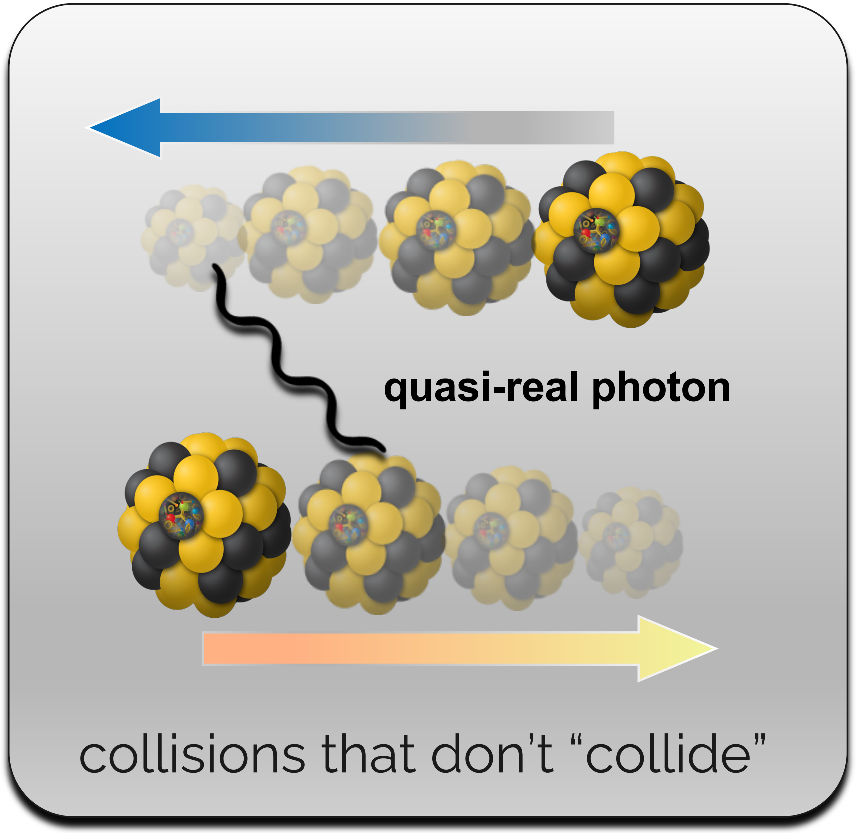
At Leading Order, 2-gluon exchange

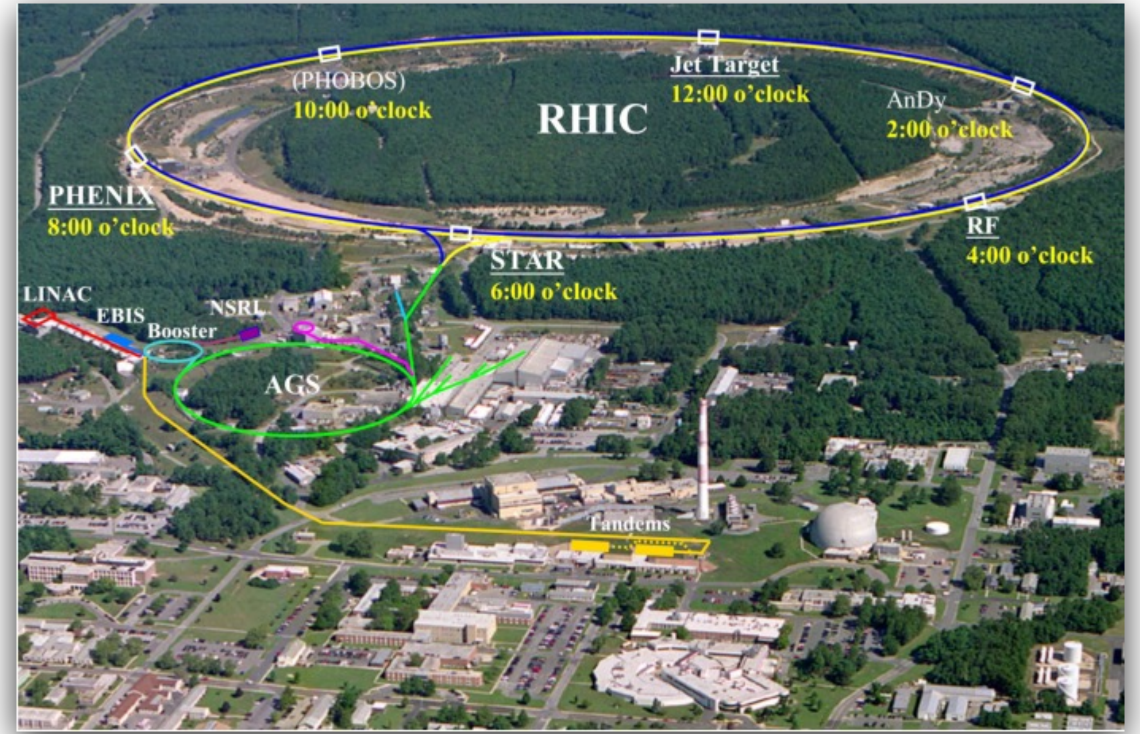


Coherent (target stays intact)	Incoherent (target breaks up)
Average nuclear parton density	Event-by-event parton density fluctuations
Momentum transfer (*t*) and transverse spatial position (*b*) are Fourier transforms of each other;	

What can the **coherent** and **incoherent** J/ψ photoproduction at $x \sim 0.01$ tell us?

Ultra-Peripheral Collisions at RHIC



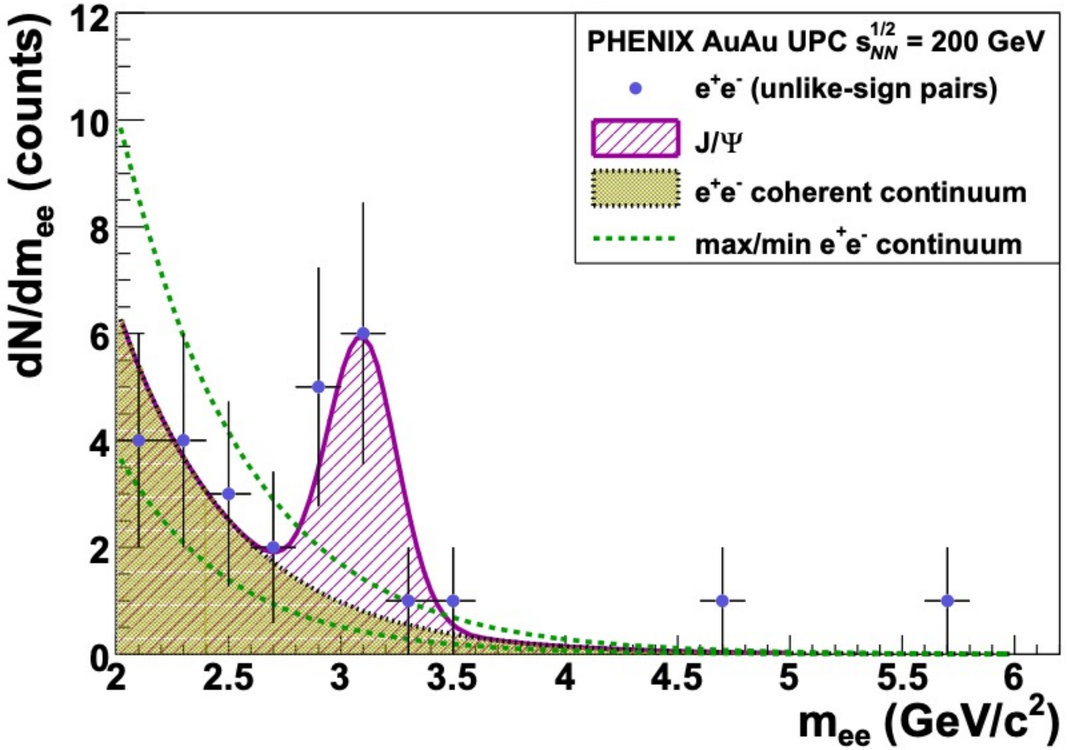


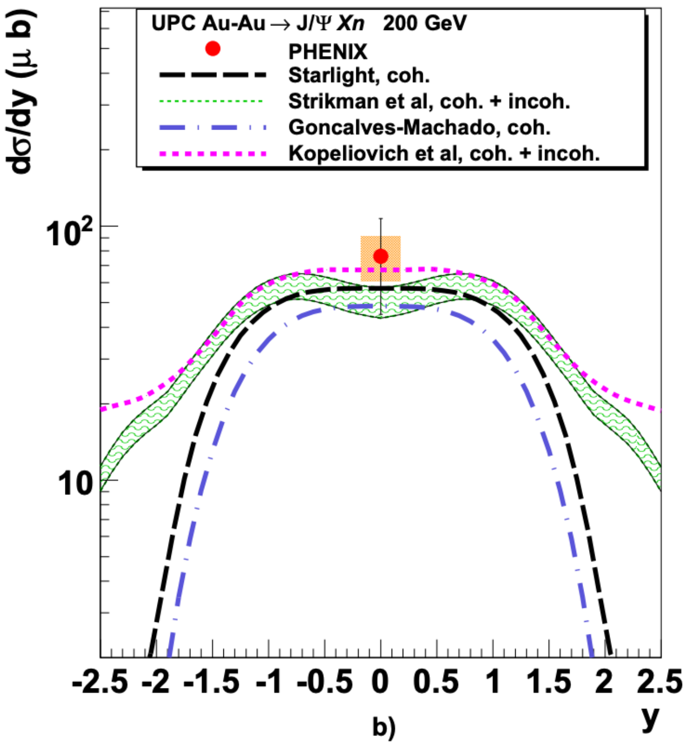
U^{238}, Au^{197}, Zr^{96} , Ru^{96}, d^2 at 200 GeV and *pp* at 510 GeV

A versatile program with different species, energy, and polarization.

Early RHIC data from PHENIX

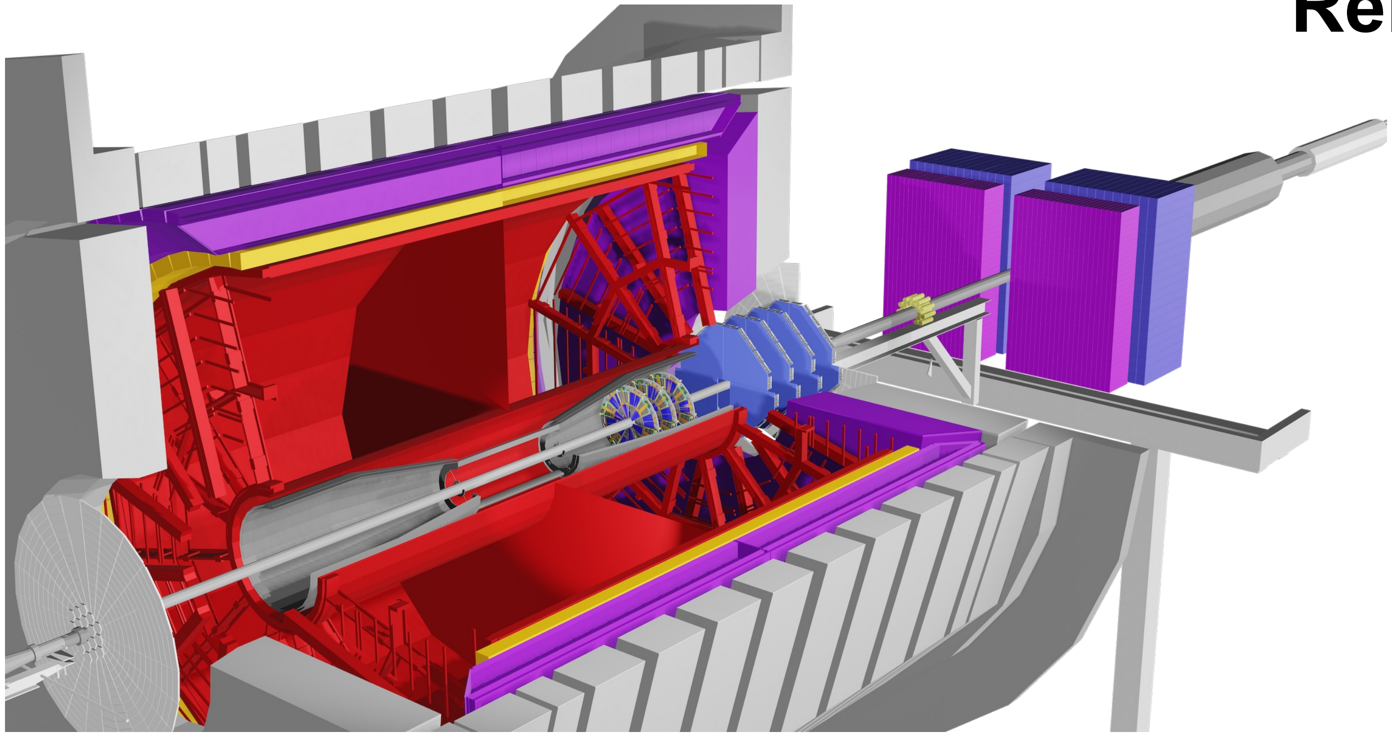
*Phys. Lett. B 679 (**2009**) 321-329*





Statistics was limited, coherent and incoherent were not separated, and with neutron selections

STAR experiment



Since 2022, STAR has forward detectors (2.5 < η < 4.0), which would be crucial to the RHIC Run 23-25 physics program

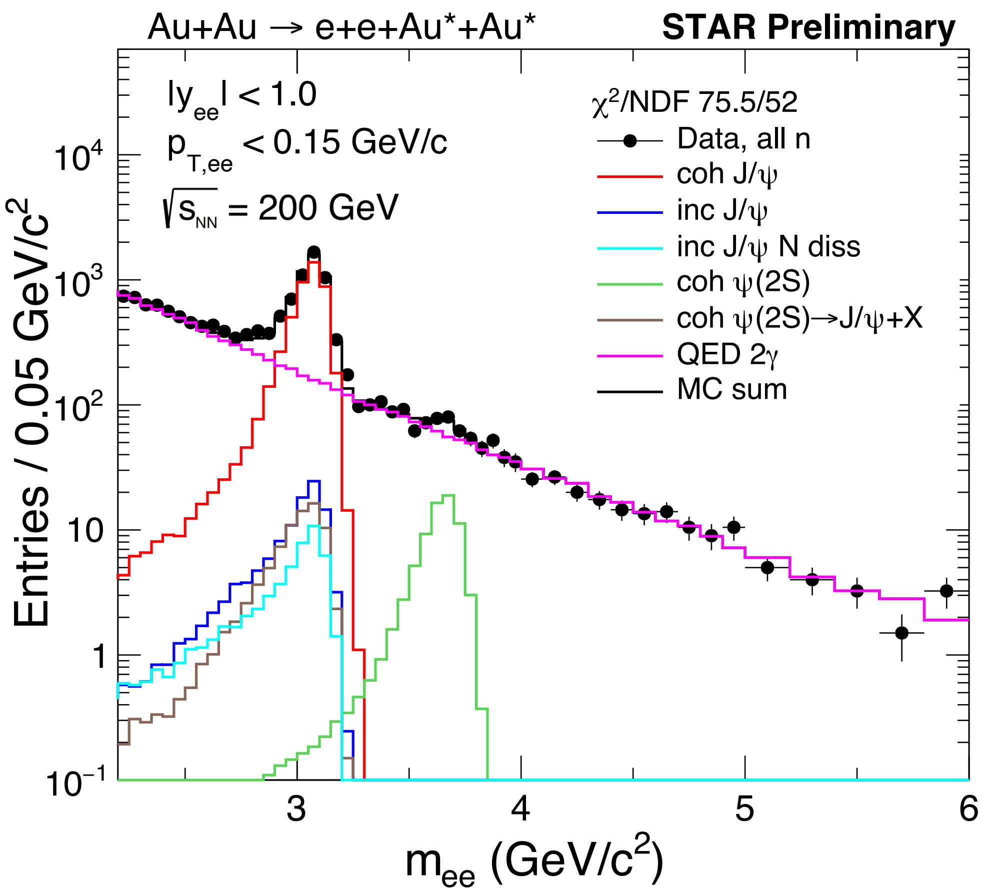
Relevant central detectors

Time Projection Chamber (TPC)

Time-Of-Flight detector (TOF)

Barrel EM Calorimeter (BEMC)

Measuring J/ψ in 200 GeV Au+Au UPCs



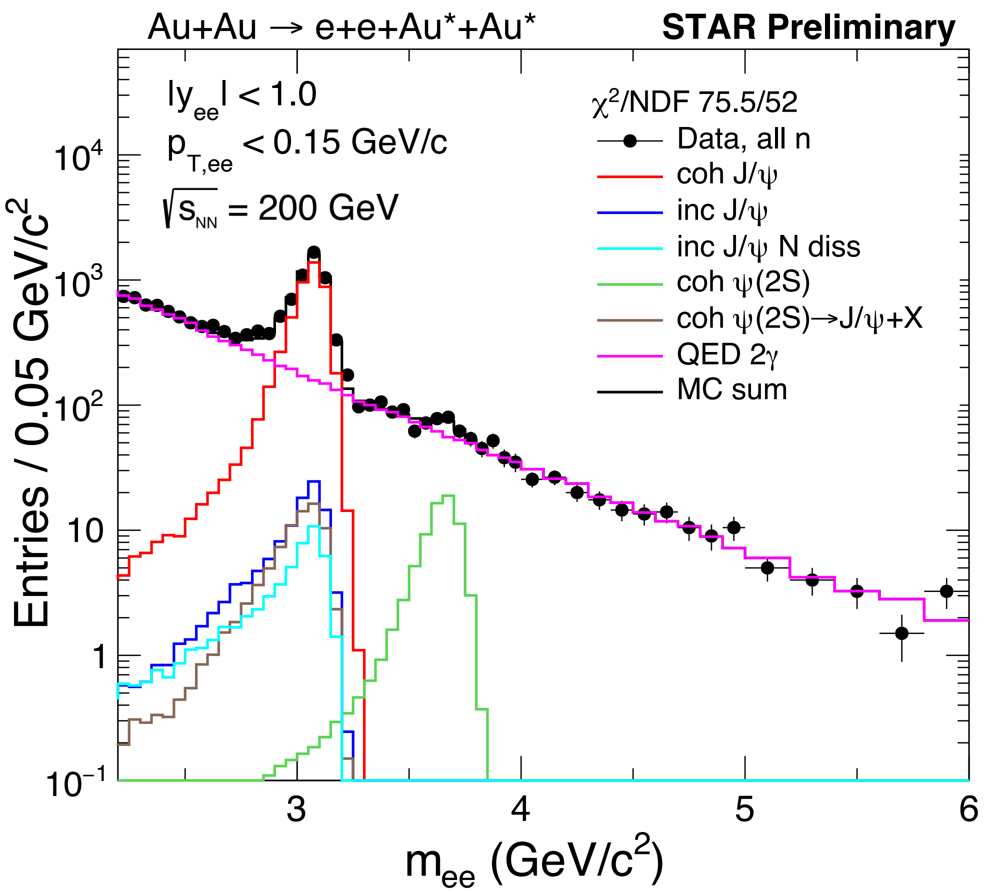
Data analysis:

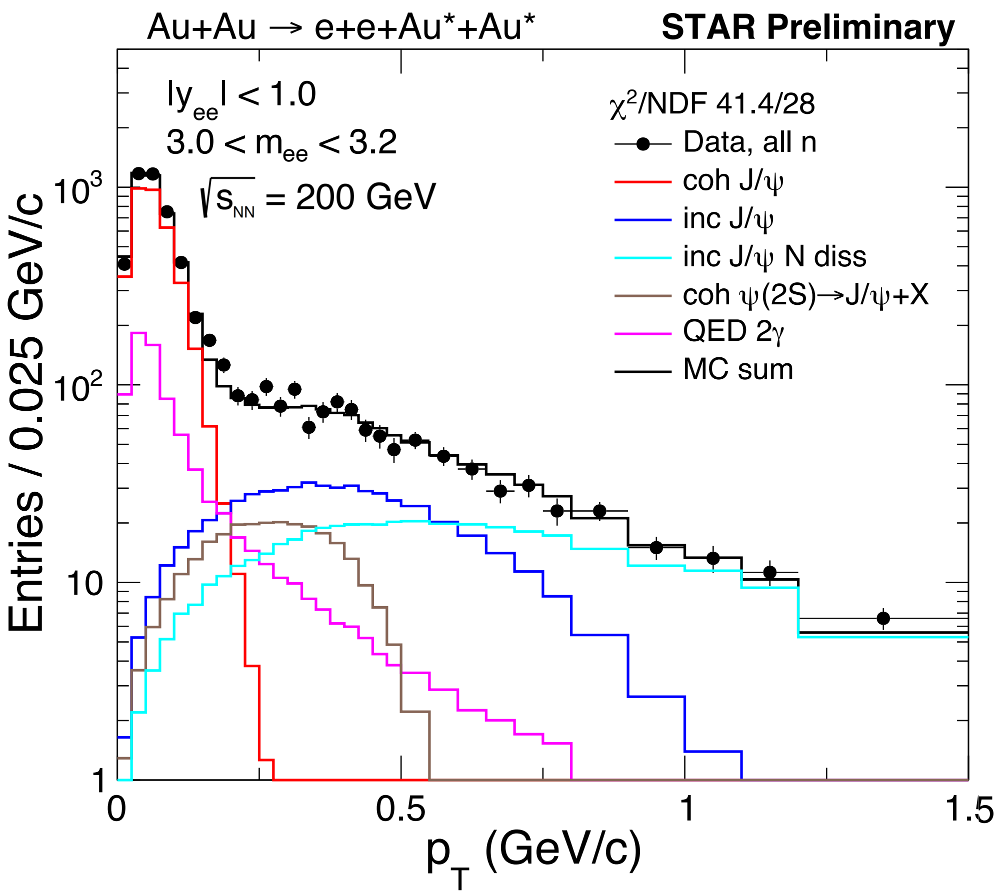
J/ψ→ e^+e^-
(|y| < 1.0 for J/ψ, electrons within |η|<1.0)

STAR PID (e.g., TPC, TOF) capability ensures high purity of electron candidates.

Different templates from STARLight and H1 *ep* data are used to describe the signal and backgrounds.

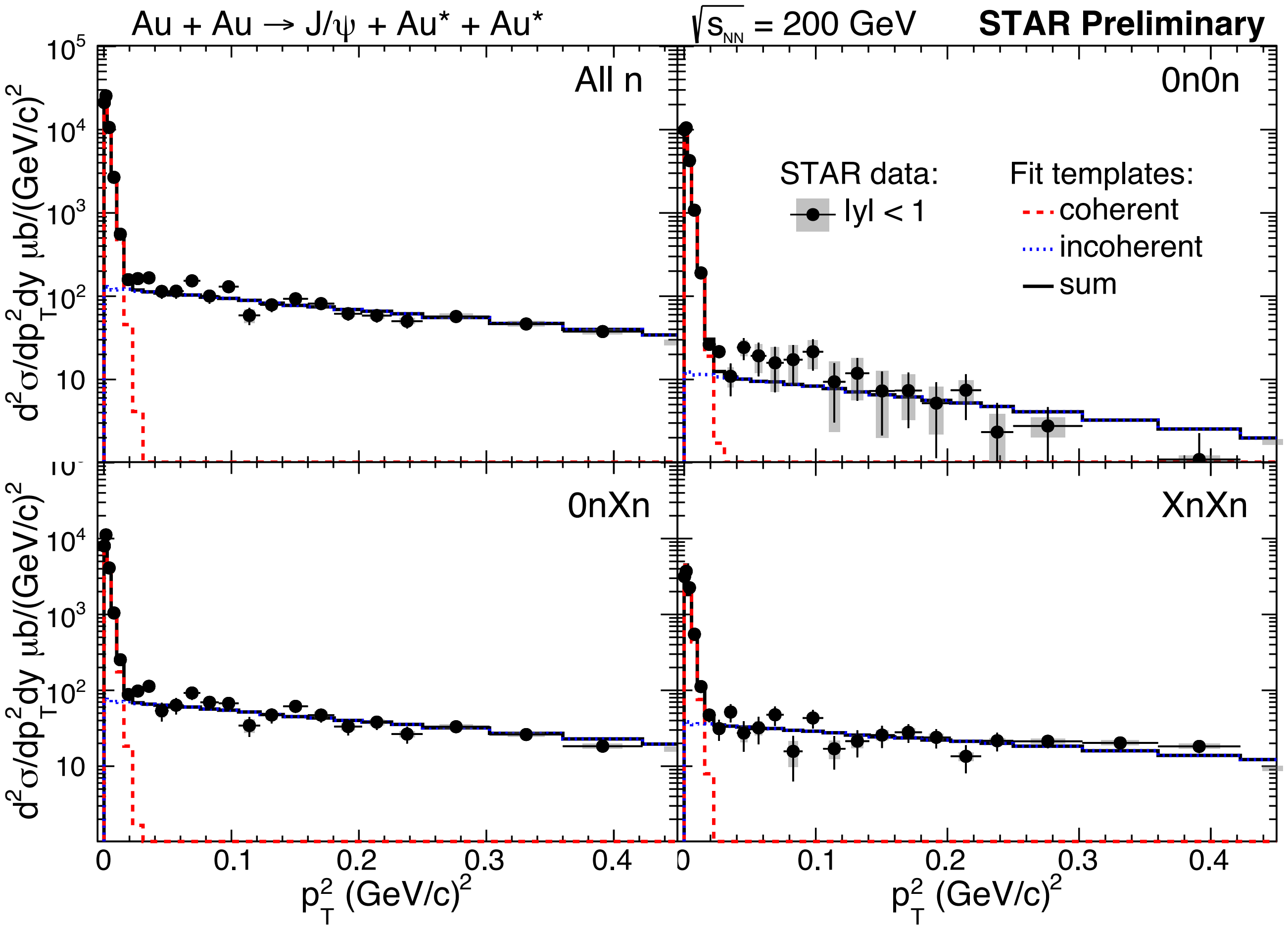
Measuring J/ψ in 200 GeV Au+Au UPCs





when $Q^2 \sim 0$, p_T of J/ψ is directly related to momentum transfer ($t \sim p_T^2$)

Separating coherent and incoherent J/ψ



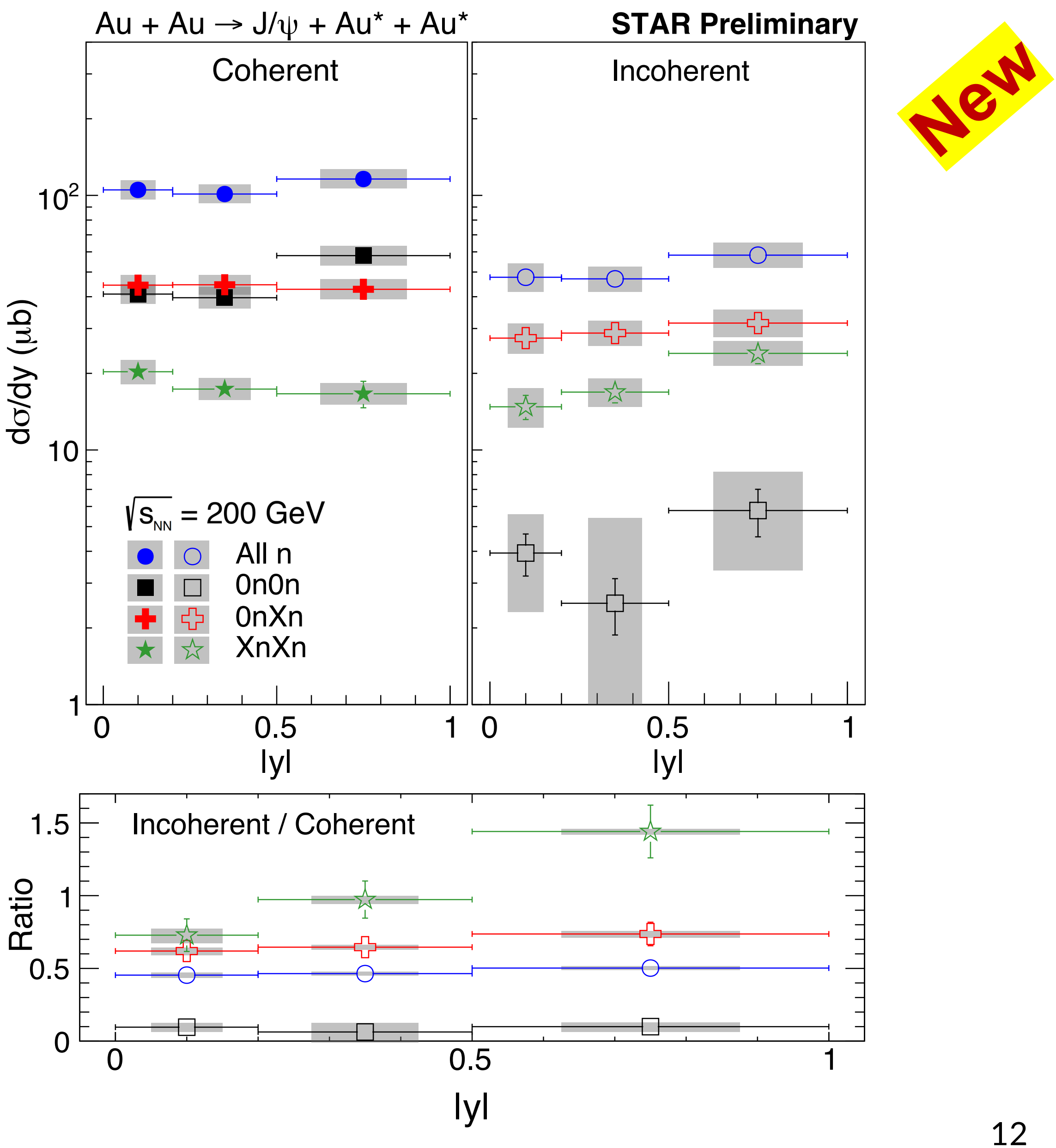
- Low momentum transfer (p_T^2) is dominated by **coherent** photoproduction.
- For incoherent production at low p_T^2, it is extrapolated using different templates.
- These differences, however, are small to the total incoherent production cross section.

First measurement of y-dependence of J/ψ at RHIC

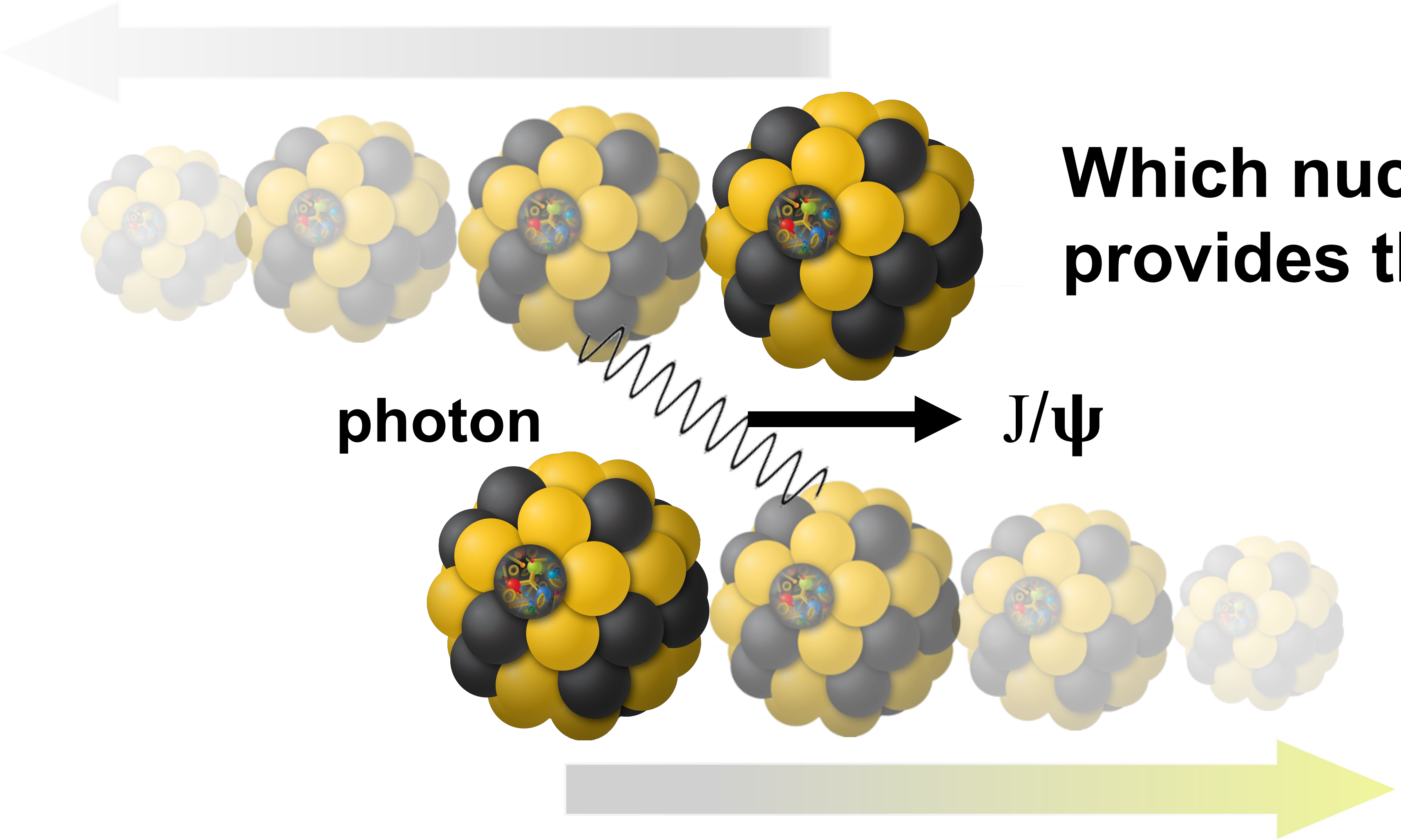
❖ Important measurements to constrain theoretical models

❖ Ratio of incoherent to coherent cross section largely cancels uncertainties both experimentally and theoretically

❖ New studies show this ratio is sensitive to nuclear structure and nuclear deformation (by W. Zhao et al. at a recent INT workshop)

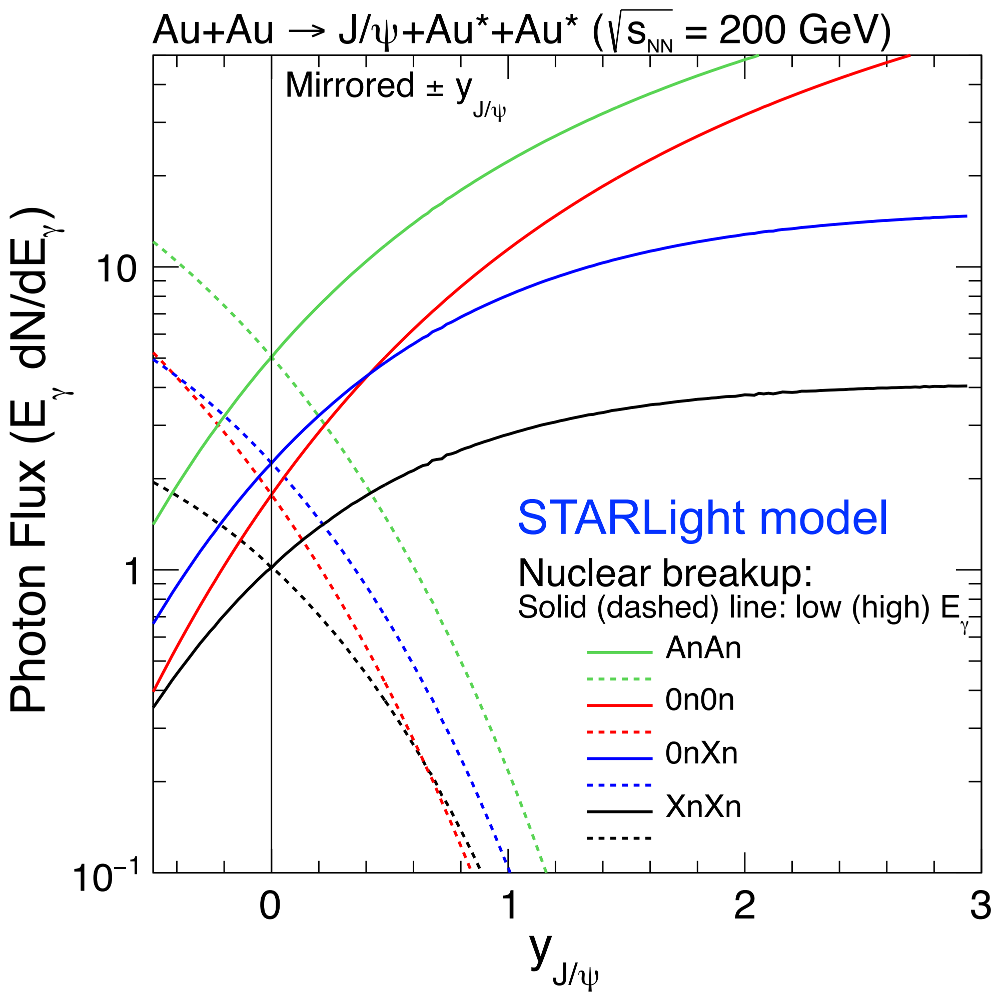


AuAu UPCs: two-source ambiguity



Which nucleus provides the photon?

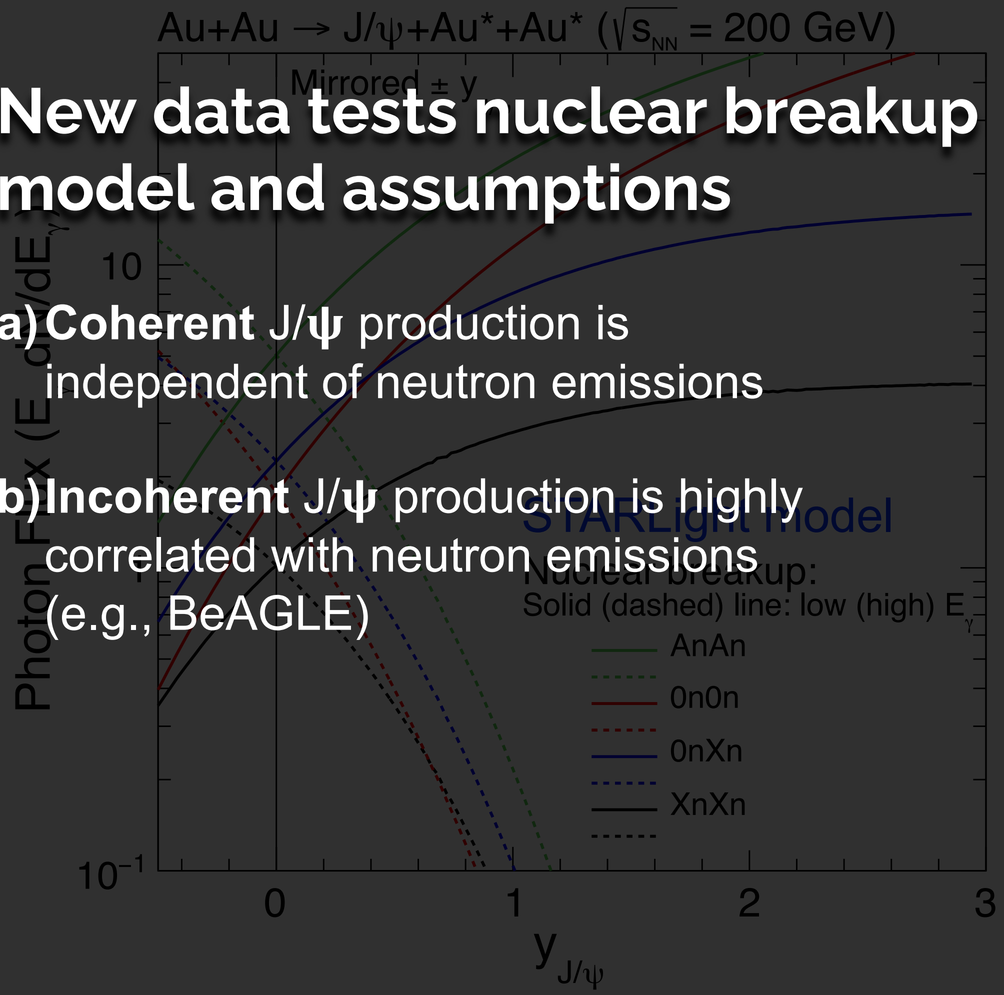
Photon flux and neutron emissions for coherent J/ψ



- If VM at rapidity $y \neq 0$, there is a high energy photon (k_1) candidate and a low energy photon (k_2) one;
- Different photon energies correspond to different flux factors (~number of photons)
- Different neutron emission classes associate with different flux factors

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

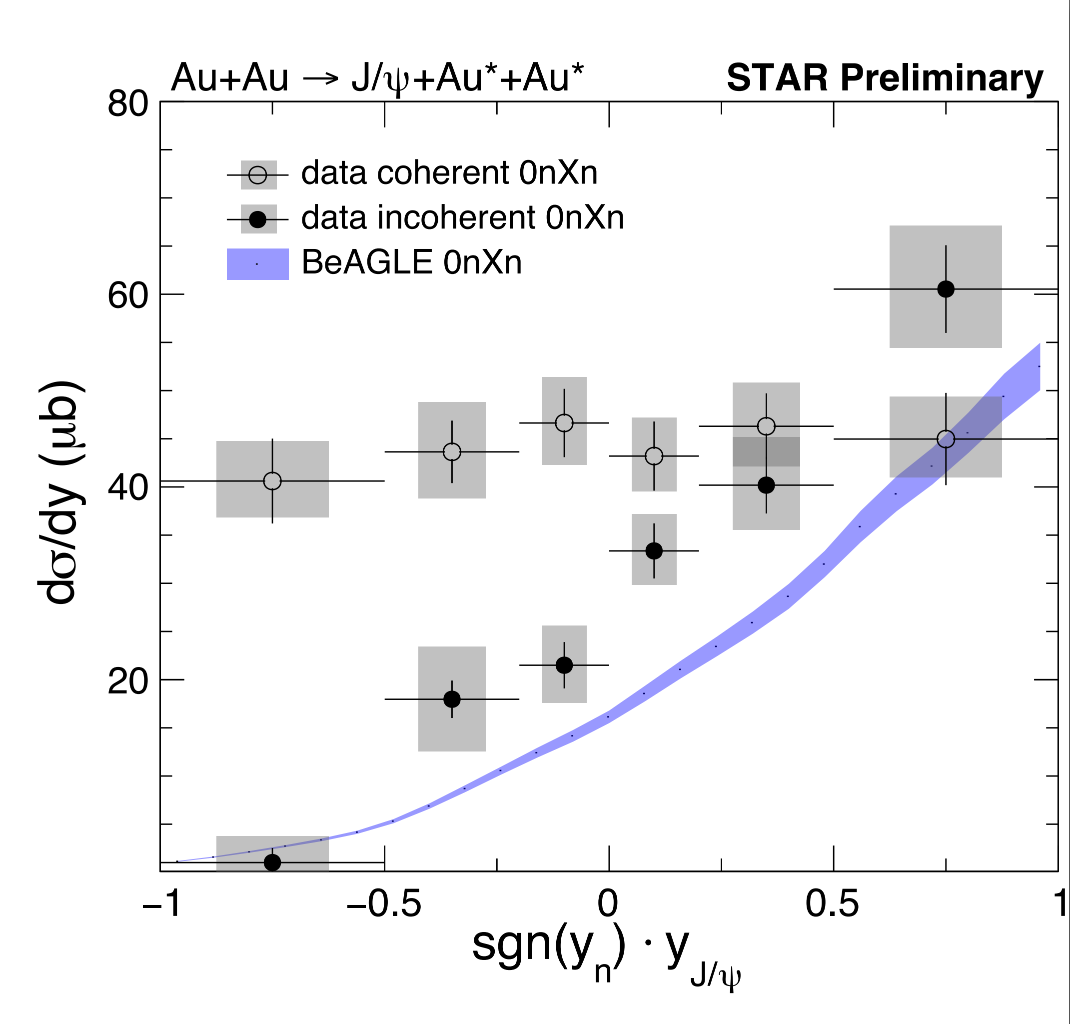
Photon flux and neutron e... New



New data tests nuclear breakup model and assumptions

a) **Coherent** J/ψ production is independent of neutron emissions

b) **Incoherent** J/ψ production is highly correlated with neutron emissions (e.g., BeAGLE)



- XnXn: >=1 neutron on both sides

Reference to BeAGLE: *Phys. Rev. D* 106 (2022) 1, 012007

Neutron emission helps resolve the two-source ambiguity

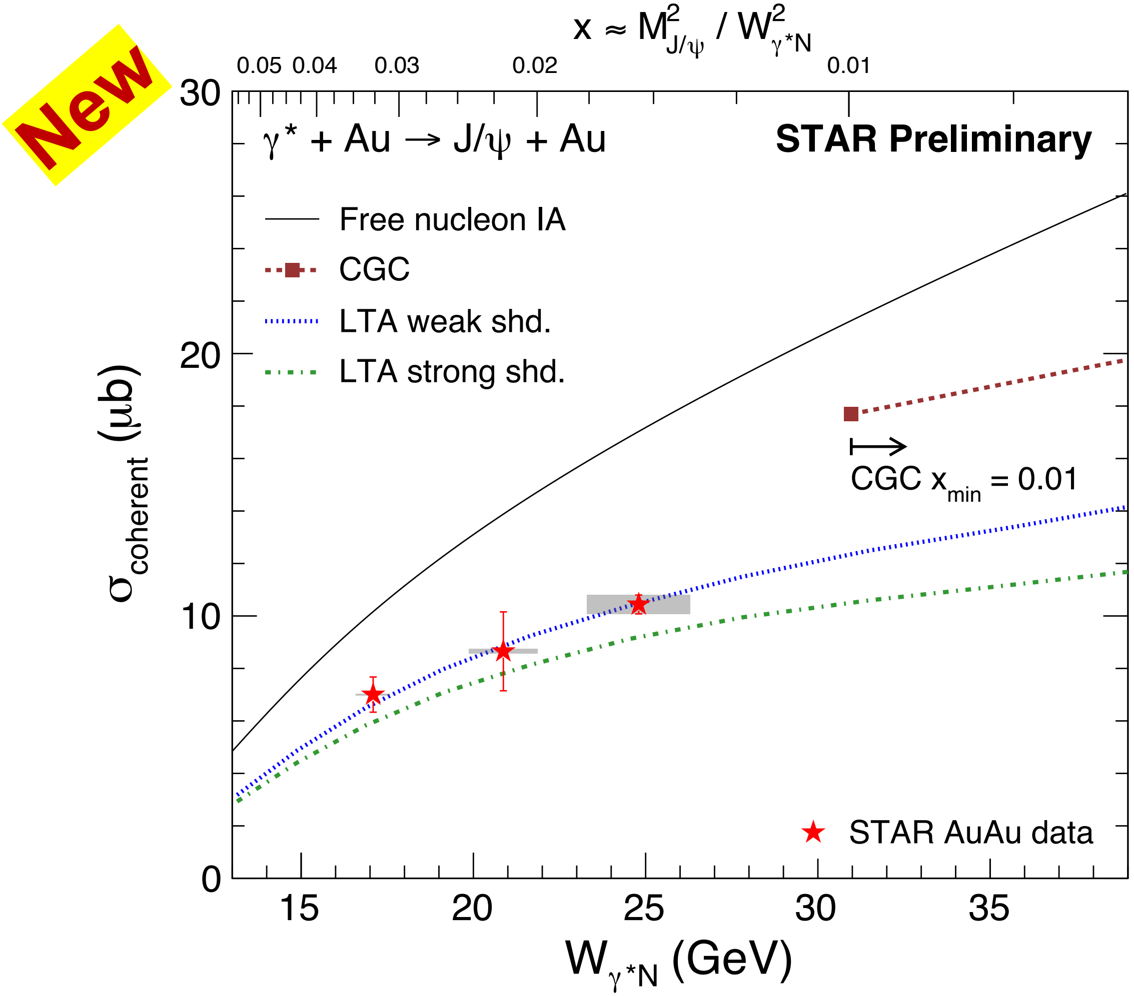
$$d\sigma^{AnBn}/dy = \Phi^{AnBn}_{T.\gamma}(k_1)\sigma_{\gamma^*+\mathrm{Au}\to\mathrm{J}/\psi+\mathrm{Au}}(k_1) + \Phi^{AnBn}_{T.\gamma}(k_2)\sigma_{\gamma^*+\mathrm{Au}\to\mathrm{J}/\psi+\mathrm{Au}}(k_2)$$

Measurements (slide 12) | Photon fluxes (slide 14) | Unknowns

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

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

Coherent J/ψ cross section vs energy W



(center-of-mass energy between photon and nucleon)

❖ STAR kinematics is unique to the low *W* region, while gluon saturation models generally focus on higher energy.

❖ Shadowing model LTA describes the data very well. **The suppression factor (data/IA) is ~ 60%**

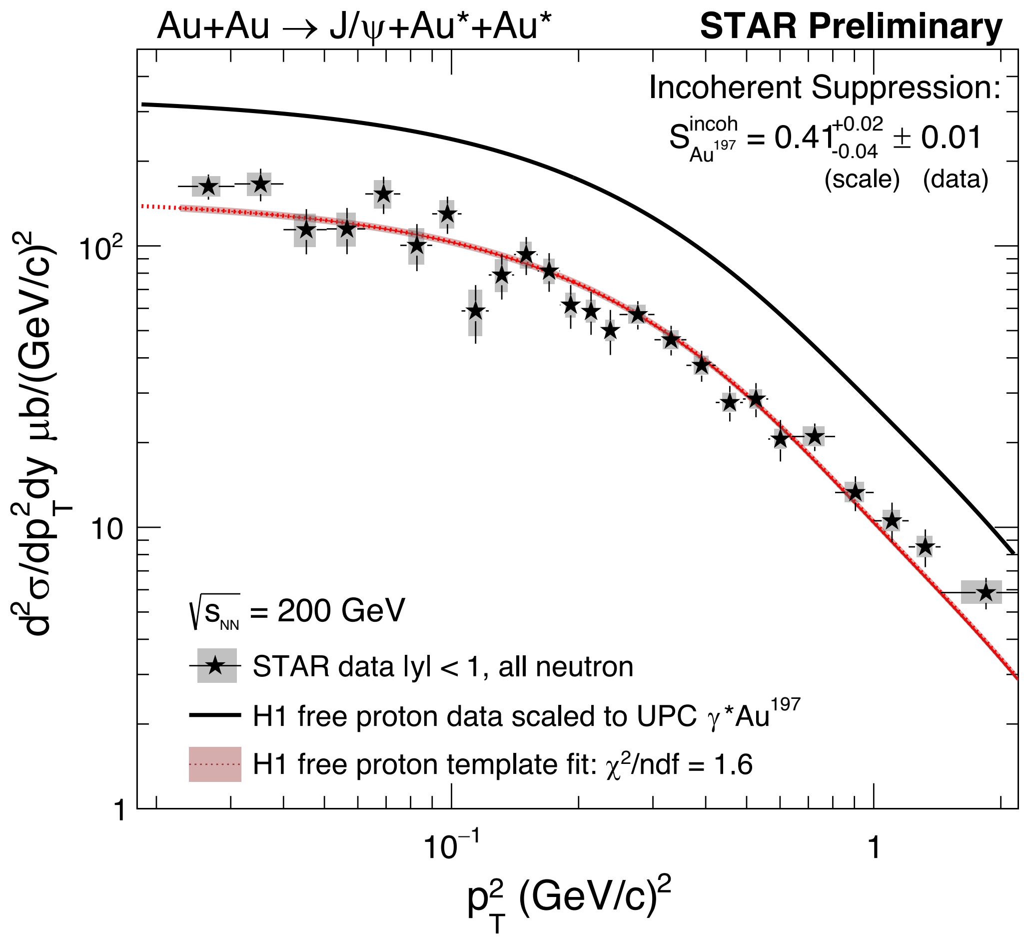
❖ Sensitive to the transition region between high-x and low-x.

Reference to CGC: *Phys. Rev. D* 106 (2022) 7, 074019
Reference to LTA: 1) Guzey, Strikman, Zhalov, EPJC 74 (2014) 7, 2942 2. Strikman, Tverskoy, Zhalov, PLB 626 (2005) 72-79

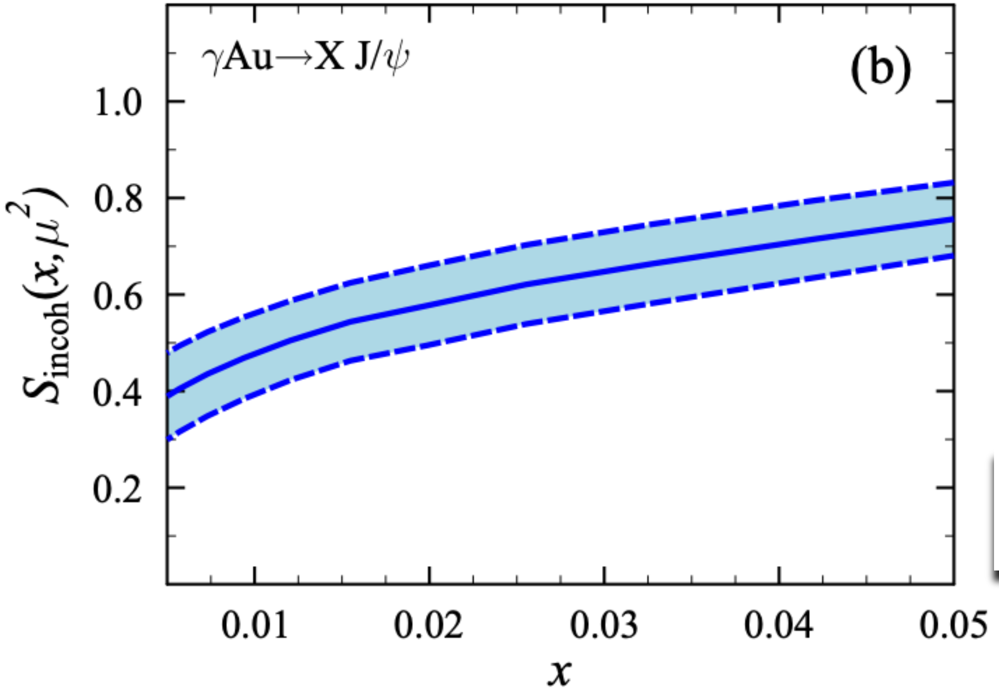
Incoherent J/ψ cross section vs p_T^2

New

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



Shadowing in incoherent J/ψ photoproduction



This ratio is driven by multi-nucleon interactions, nuclear thickness function, diffractive parton distributions, etc.

(*Phys. Rev. C* 108 (2023) 2, 024904)

$$S_{\mathrm{incoh}}(x,\mu^2) = \frac{1}{A}\int \mathrm{d}^2\mathbf{b}\, T_A(\mathbf{b}) \left[1 - \frac{\sigma_2(x,\mu^2)}{\sigma_3(x,\mu^2)}\left[1 - e^{-\frac{\sigma_3(x,\mu^2)}{2}T_A(\mathbf{b})}\right]\right]^2 .$$

Intuitively, the incoherent J/ψ production is the convolution of: J/ψ production off a nucleon inside of a nucleus ⊗ probability of the J/ψ survives on its way out of the nucleus.

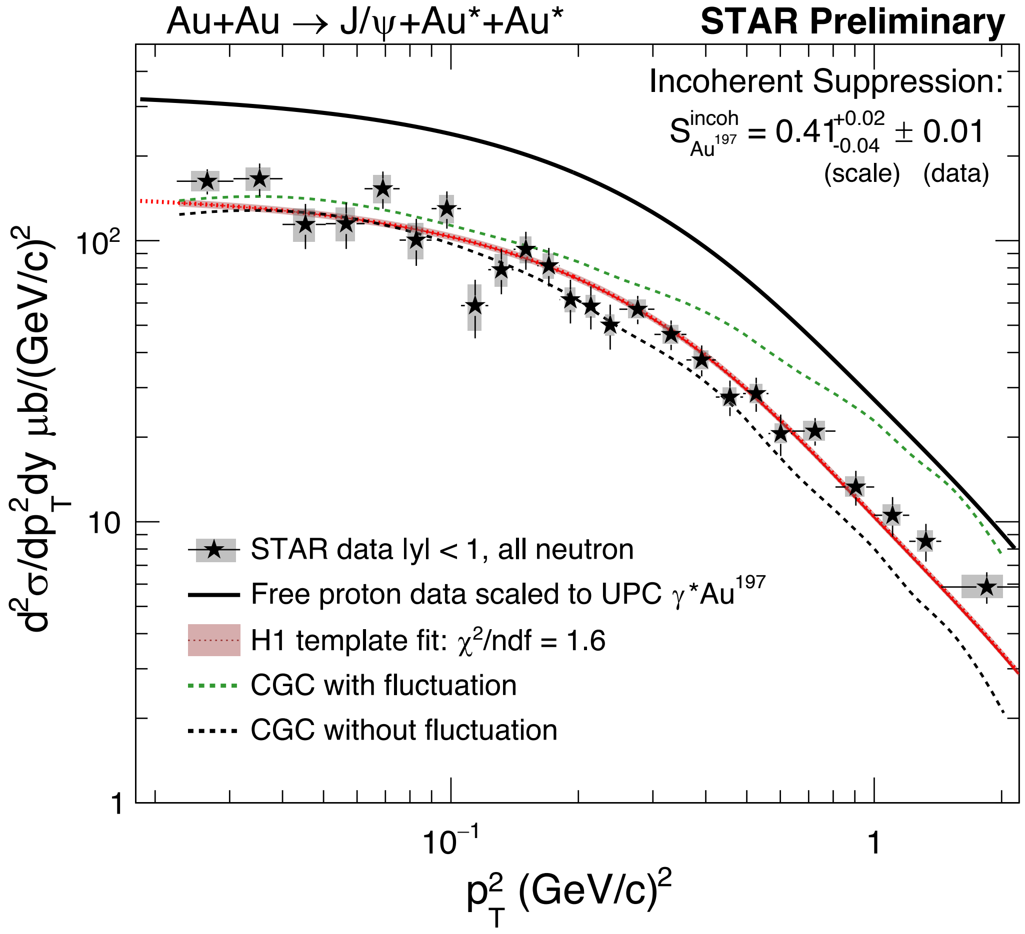
Incoherent J/ψ cross section vs p_T^2

New

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

- Models have found that the H1 data supports **sub-nucleonic fluctuation**. *[Phys. Rev. Lett. 117 (2016) 5, 052301]*

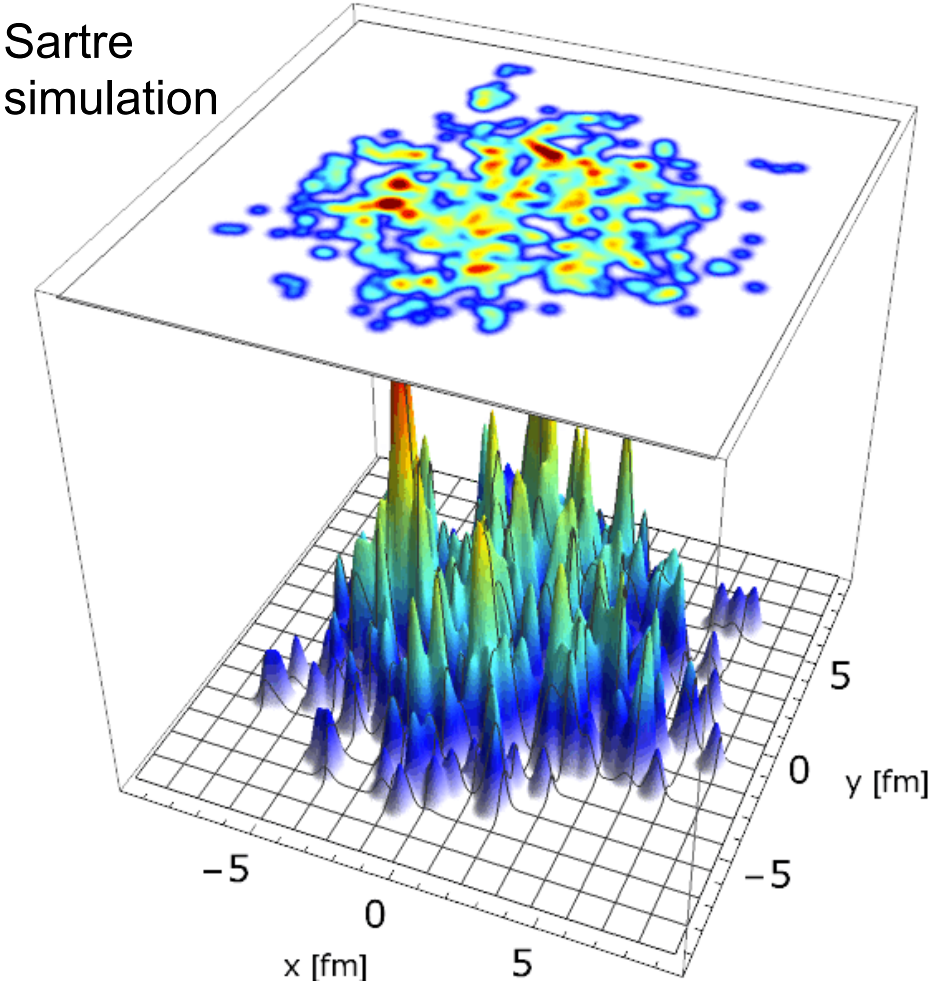
- STAR data shows the bound nucleon has a similar shape in p_T^2 as the free proton, indicating **similar sub-nucleonic fluctuation in heavy nuclei.** *[Phys. Rev. D 106 (2022) 7, 074019]*



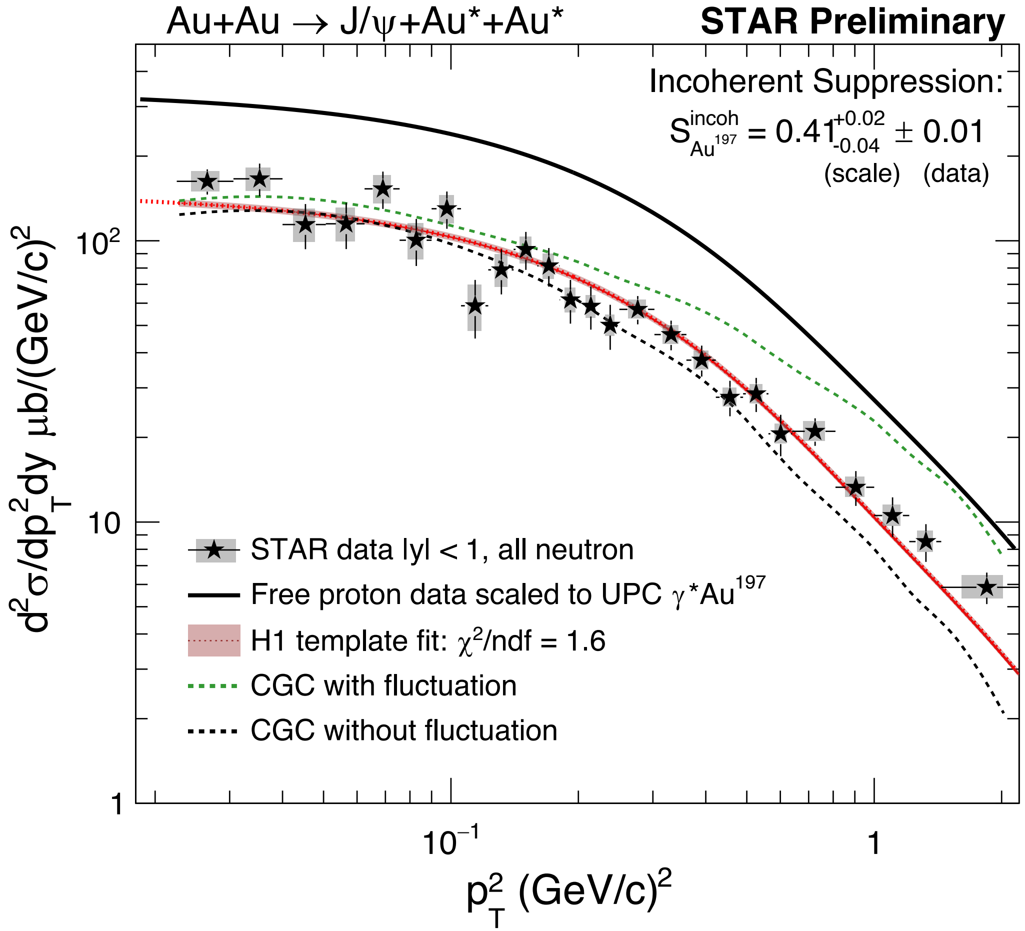
Incoherent J/ψ cross section vs p_T^2

New

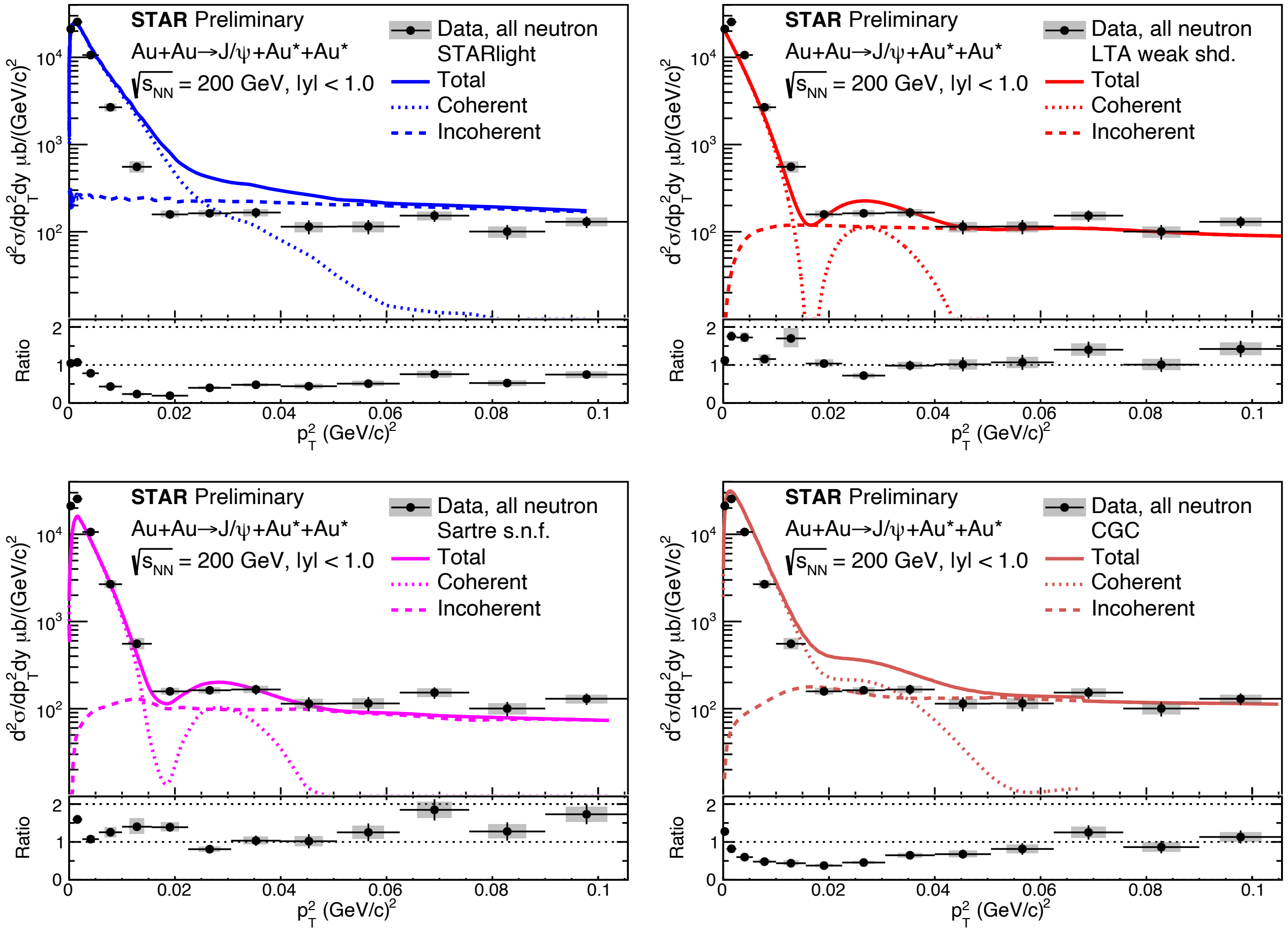
Sartre simulation



[made by A. Kumar (IIT, Delhi)]



A full picture: coherent + incoherent



- ❖ STAR data compared with four theory/MC models.
- ❖ Sartre with sub-nucleonic fluctuation (s.n.f) & CGC are similar models but different by a normalization factor ~ 0.65.
- ❖ **Question to theorists: Why?**

Reference to CGC: Phys. Rev. D 106 (2022) 7, 074019
Reference to LTA: arXiv:2303.12052

NLO calculation

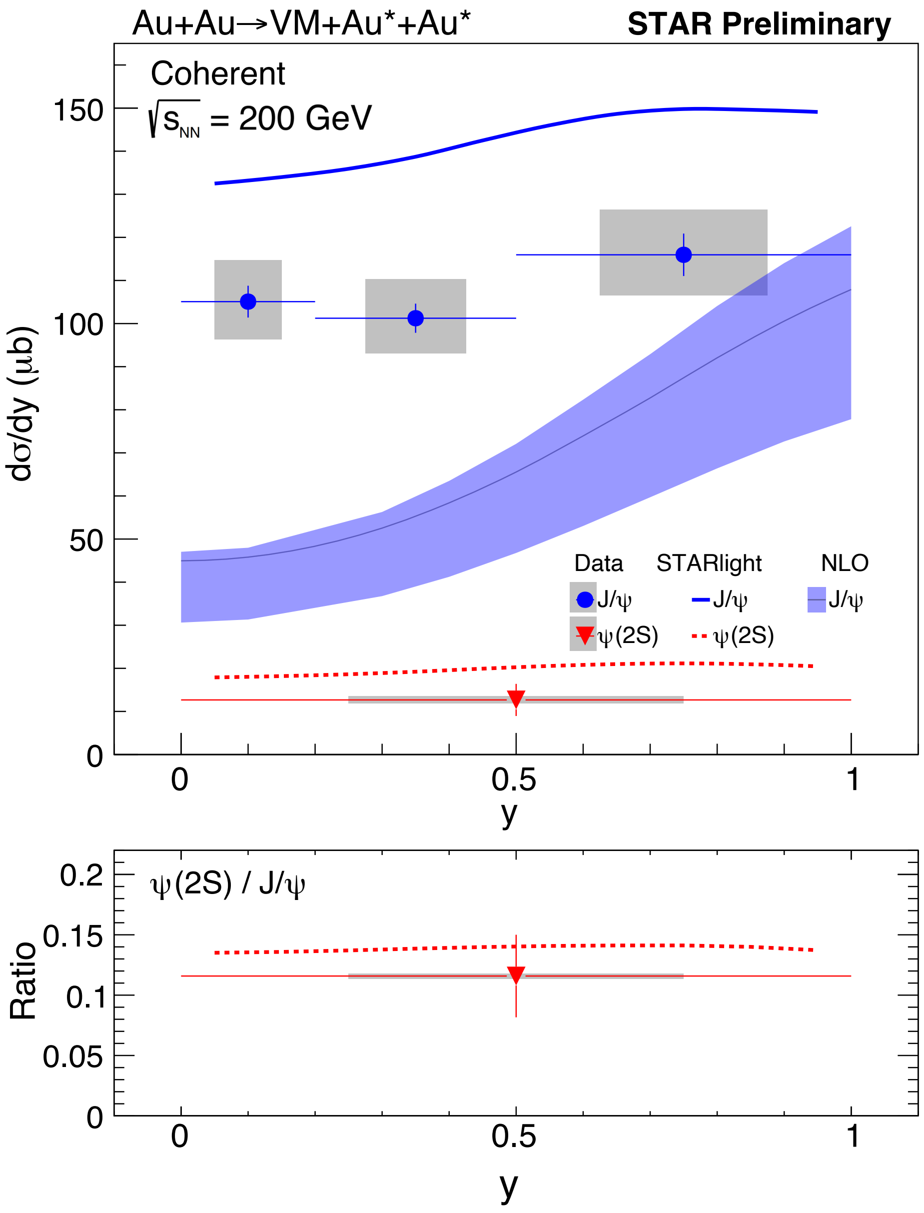
Next-to-Leading Order (NLO) pQCD calculation, constrained **by the LHC data**

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

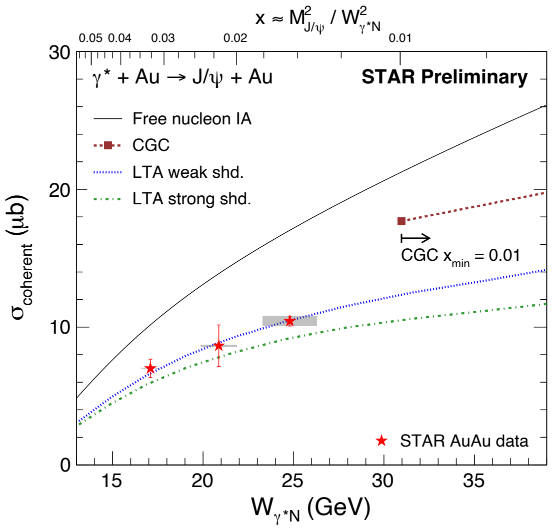
Could not describe the STAR data at y = 0.

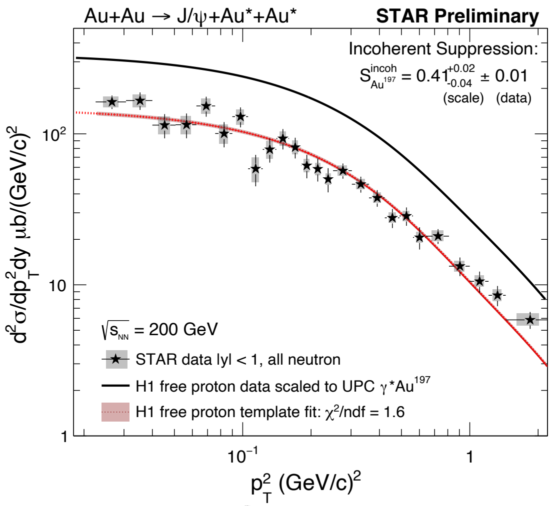
Reference to NLO pQCD calculation:

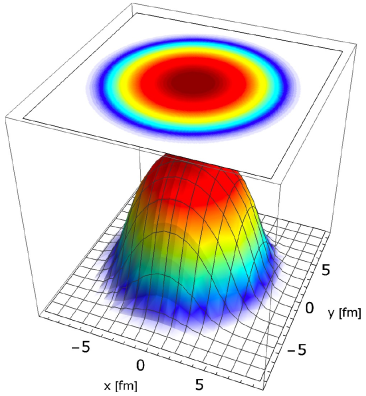
a) arXiv:2210.16048
b) Phys. Rev. C 106 (2022) 3, 035202

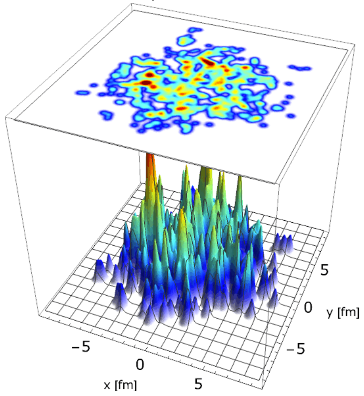


Summary – coherent and incoherent J/ψ photoproduction





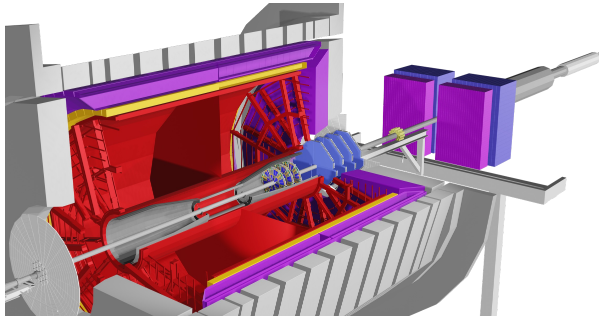




STAR has made many **first-time** J/ψ measurements in UPCs at RHIC:

- ✓ Strong **nuclear suppression** seen for both coherent (~ 40%) and incoherent (~60%) production.
- ✓ **Bound** nucleon and **free** proton have similar shape in p_T^2 up to ~ 2.2 $(GeV/c)^2$
- ✓ Coherent is sensitive **average** parton density (or imagining if measure momentum) and Incoherent is sensitive to the parton density **fluctuation**.

Future UPCs opportunities



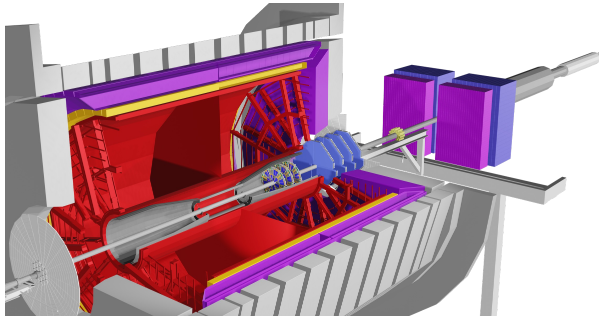
Since 2022, STAR has forward detectors (**2.5 < η < 4.0**):

- J/ψ coherent and incoherent production with **high precision**. Lower W towards a few GeV, and high t to better understand fluctuation.
- **ϕ photoproduction.**
- **Photoproduction of jets.**
- **New observables.**

RHIC 23-25

2023 2025 2029 2034+

Future UPCs opportunities



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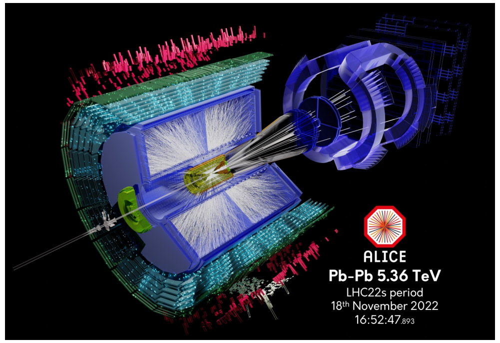
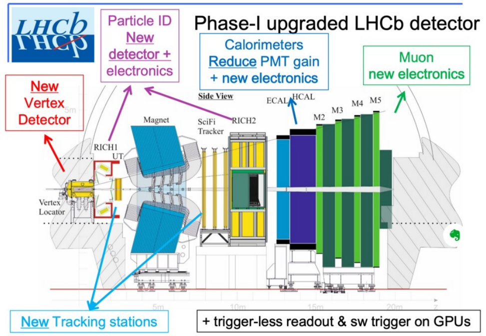
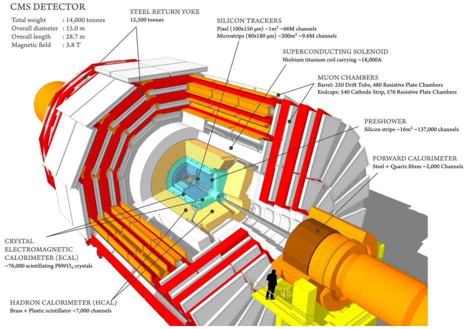
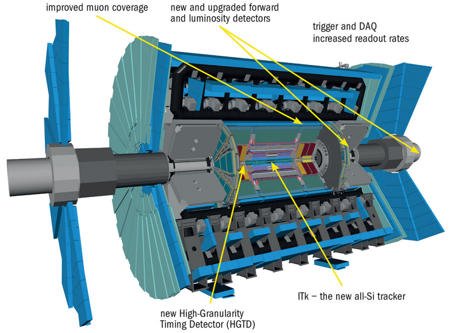






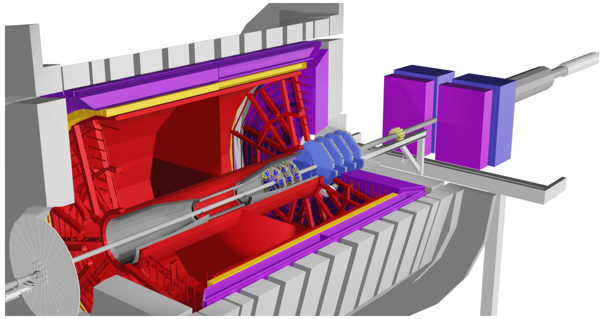


All LHC experiments will have significant upgrades in Run 3 & 4 (e.g., wide acceptances, ALICE FoCal, etc.). **Lower-x reach!**

RHIC 23-25 & LHC Run 3 — LHC Run 4

2023 | 2025 | 2029 | 2034+

Future UPCs opportunities



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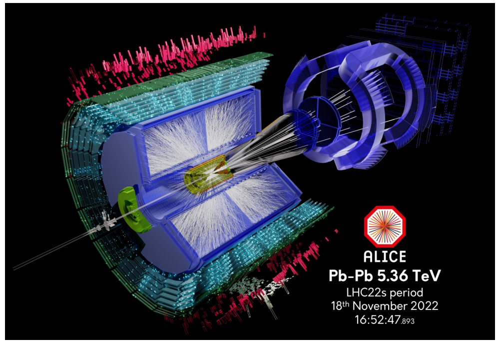

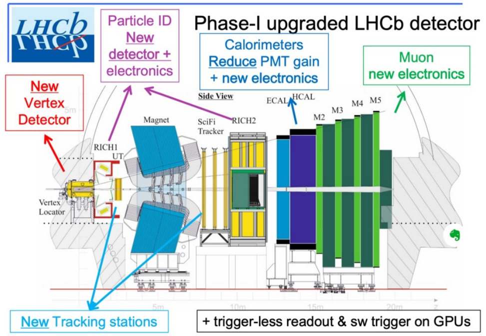

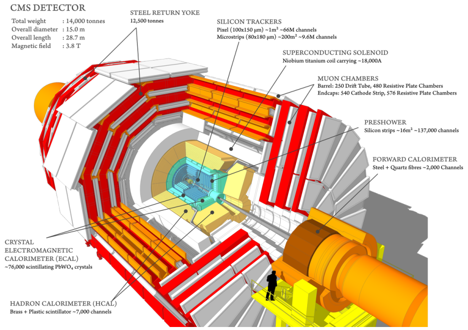

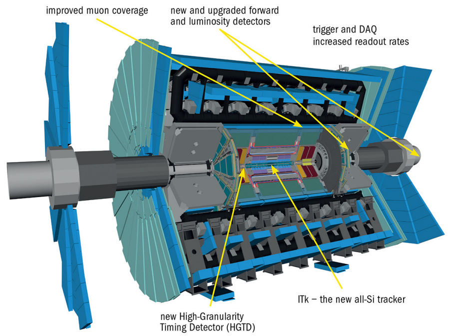

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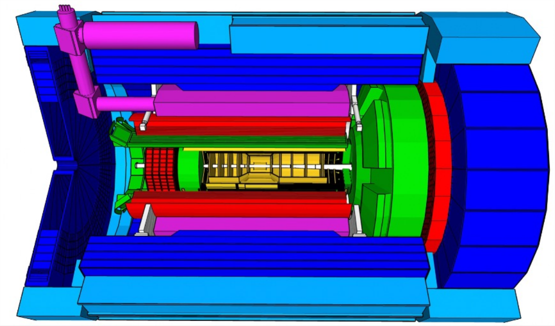
EIC era

The ePIC detector and possible a 2nd detector: the ultimate machine for understanding saturation quantitatively with a wide variety of observables.



RHIC 23-25 & LHC Run 3 — LHC Run 4

2023 — 2025 — 2029 — 2034+

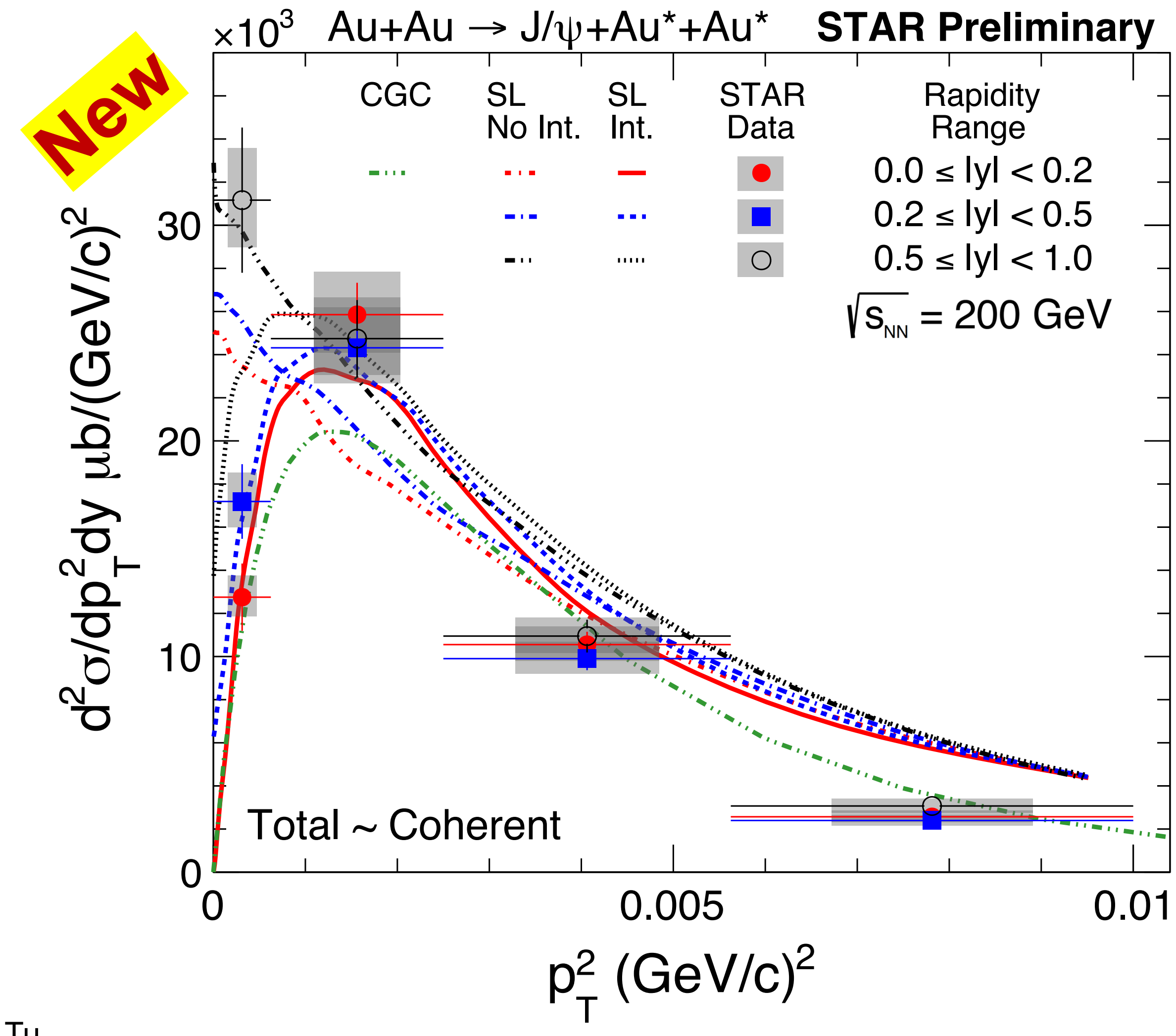
Special thanks to:

CGC: Heikki Mäntysaari, Farid Salazar, Björn Schenke
Sartre: Tobias Toll, Arjun Kumar
Nuclear shadowing: Vadim Guzey, Mark Strikman, Mikhail Zhalov
NLO pQCD: Topi Löytäinen et al.
Saturation observables: Brian Sun, Y. Kovchegov

For discussions and inputs.

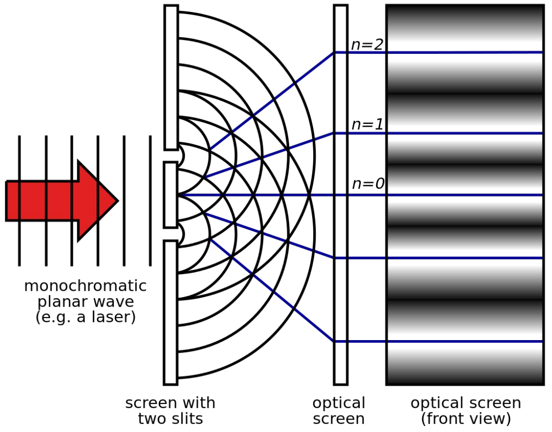
Backup

Two-source interference



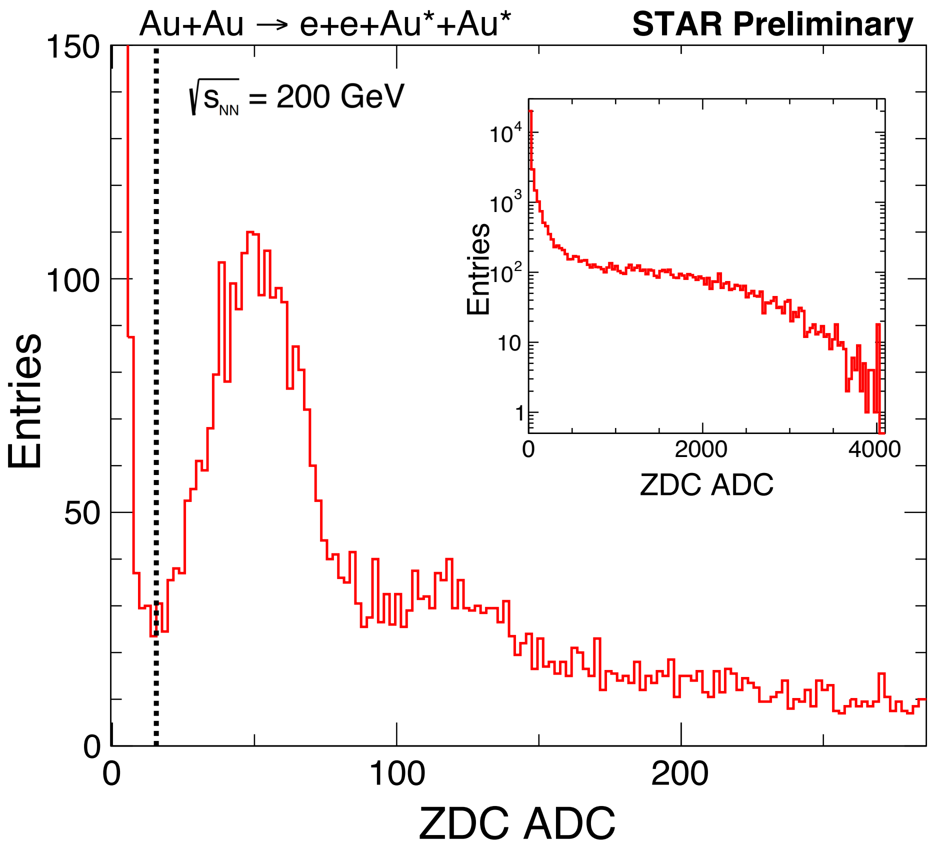
Reference to CGC: *Phys. Rev. D* 106 (2022) 7, 074019

Rapidity dependence is consistent with theory/model; interference effect is stronger if photon energies are similar.



First observed w. ρ^0 in 2008 by STAR (Phys.Rev.Lett.102:112301,2009)

Neutron emissions in UPCs



Neutron classes:

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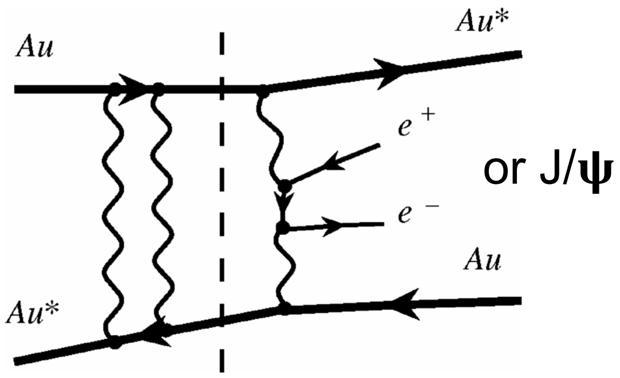
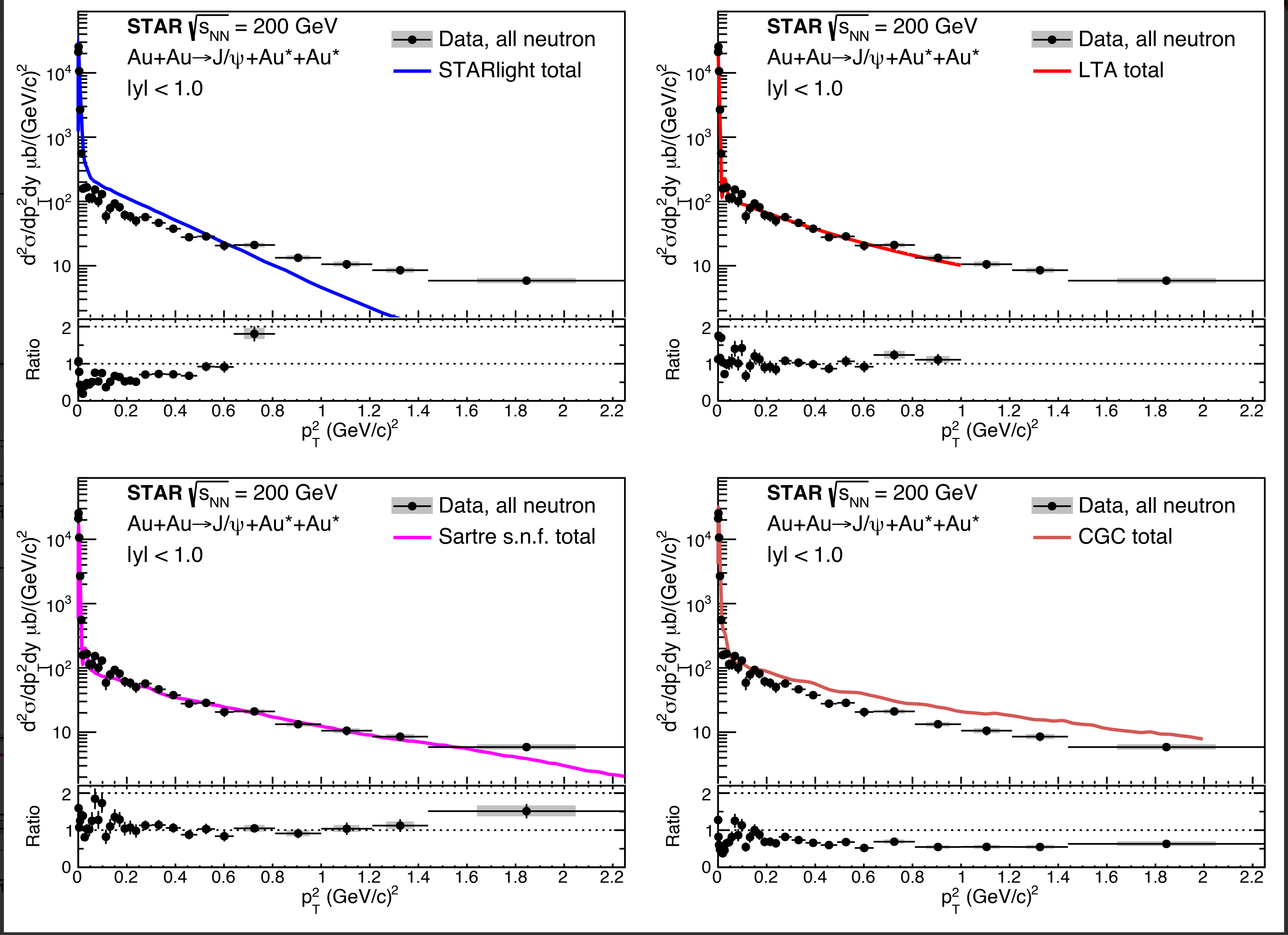


UPCs have large contributions from QED Coulomb excitations

A full picture:

Full momentum region

STAR data is important to understand



Comparison to CGC