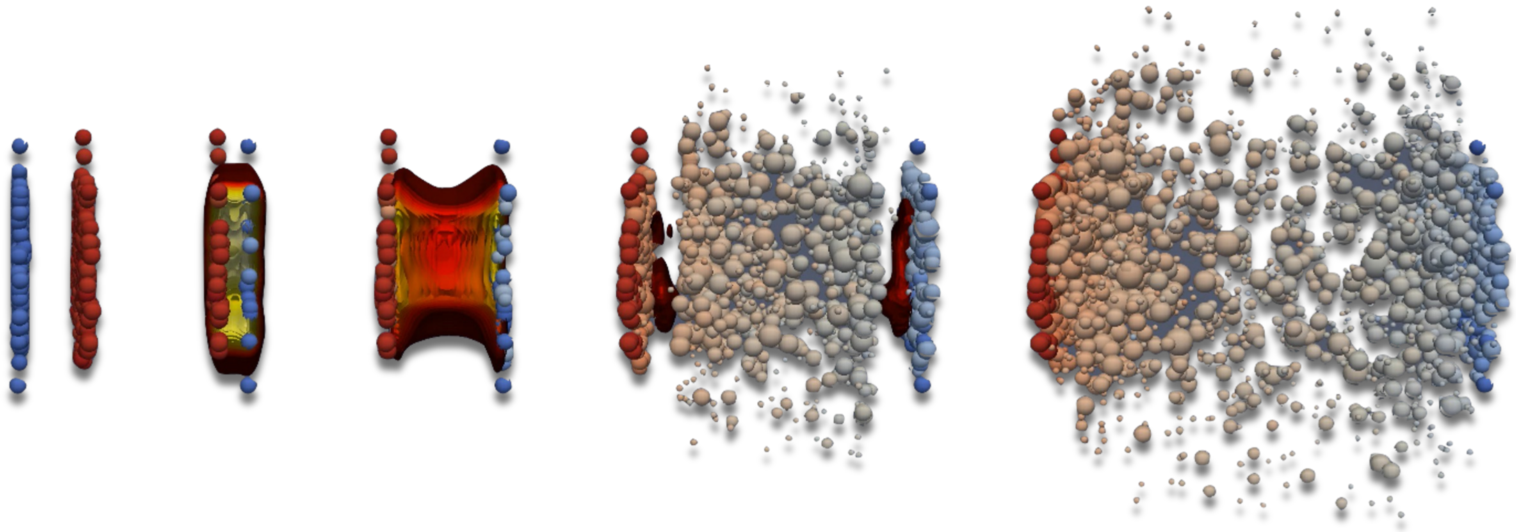
Vector Meson production at RHIC and the EIC

Kong Tu (BNL)

Motivation

- To understand the full QCD evolution of heavy-ion collisions and its medium property



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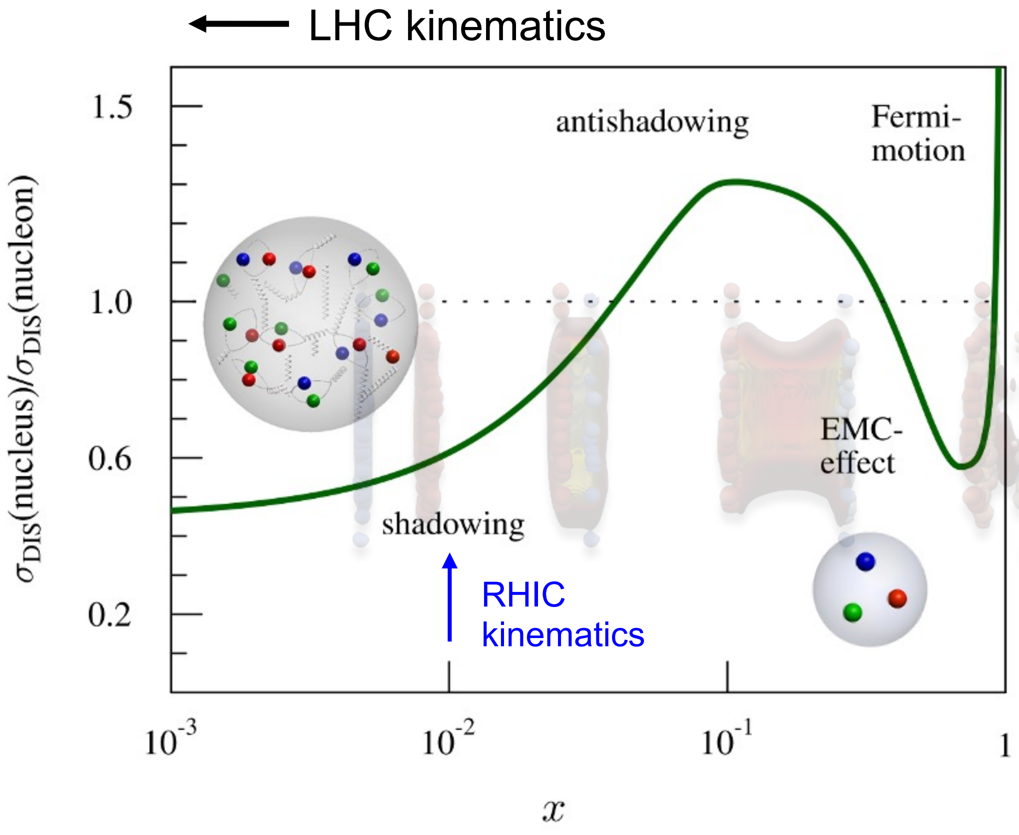
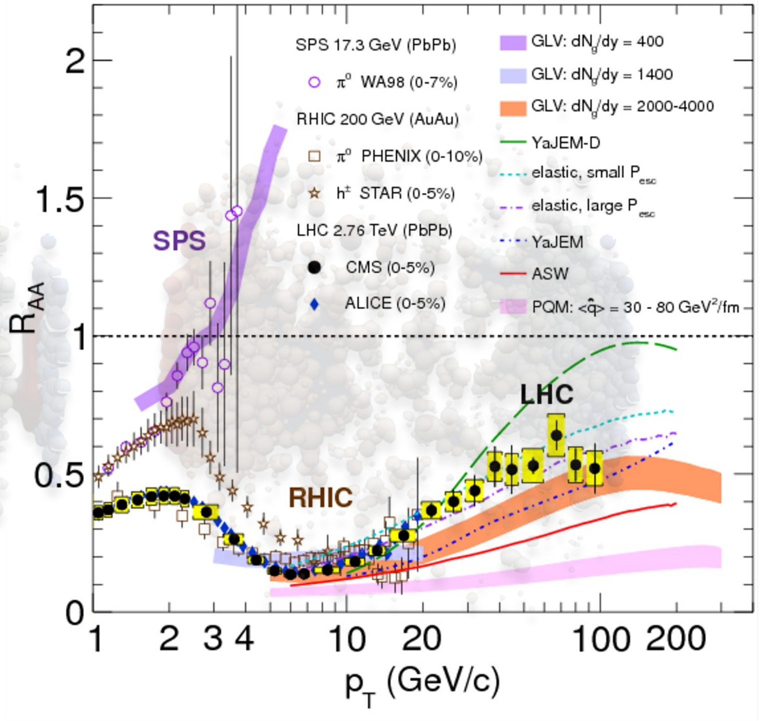
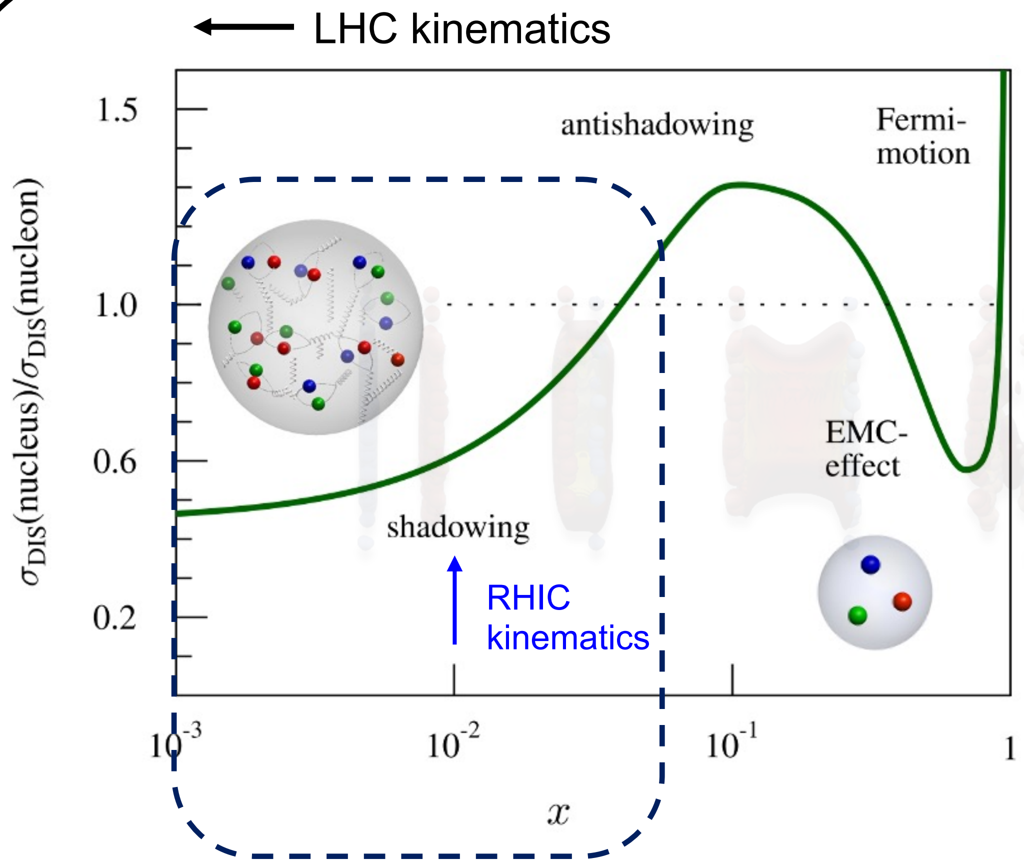


Initial state – cold QCD



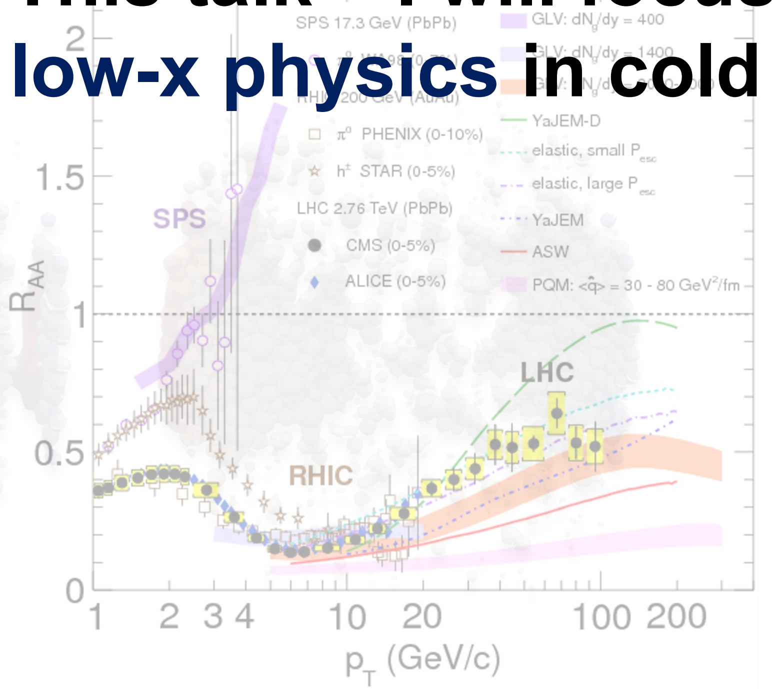
Initial + final state – hot QCD

Motivation



Initial state – cold QCD

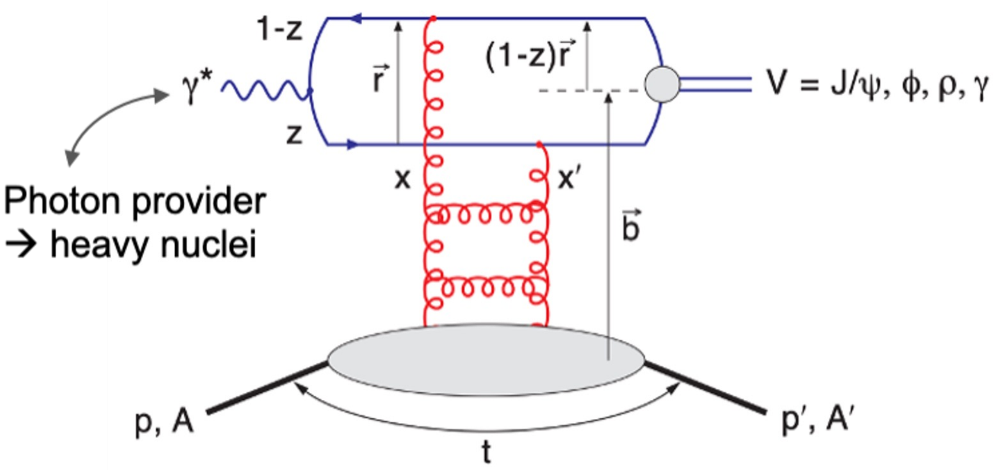
This talk – I will focus on low-x physics in cold QCD.



Initial + final state – hot QCD

Diffractive VM (e.g., J/ψ) production in heavy nuclei

At Leading Order, 2-gluon exchange



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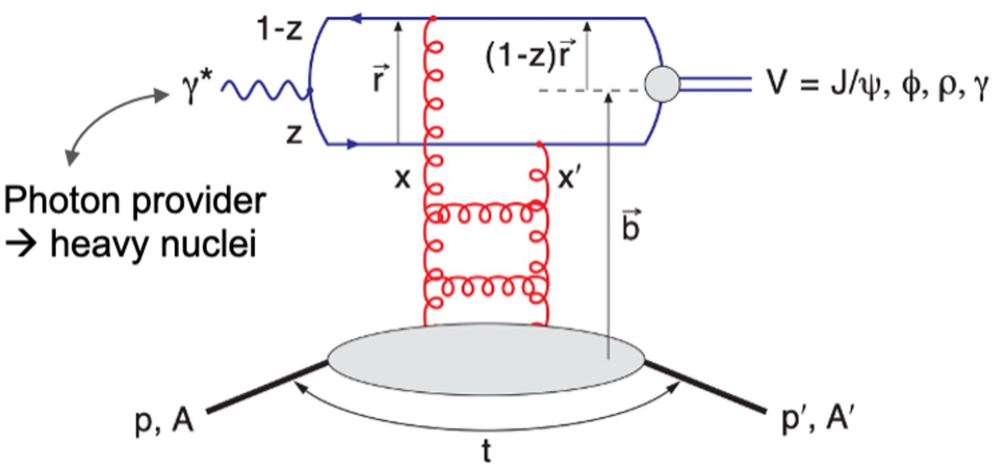

Coherent (target stays intact)	Incoherent (target breaks up)
Average nuclear parton density	Event-by-event parton density fluctuations
Momentum transfer (*t*) and transverse spatial position (*b*) are Fourier transforms of each other;	

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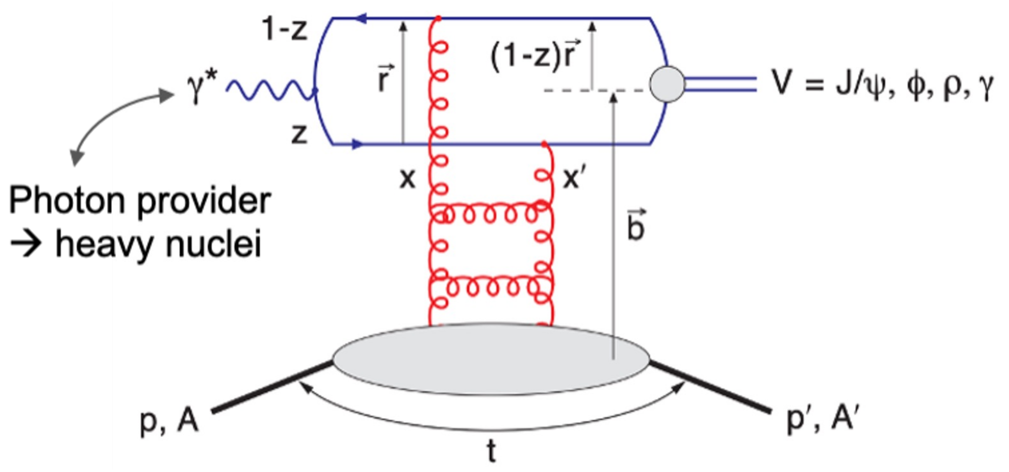

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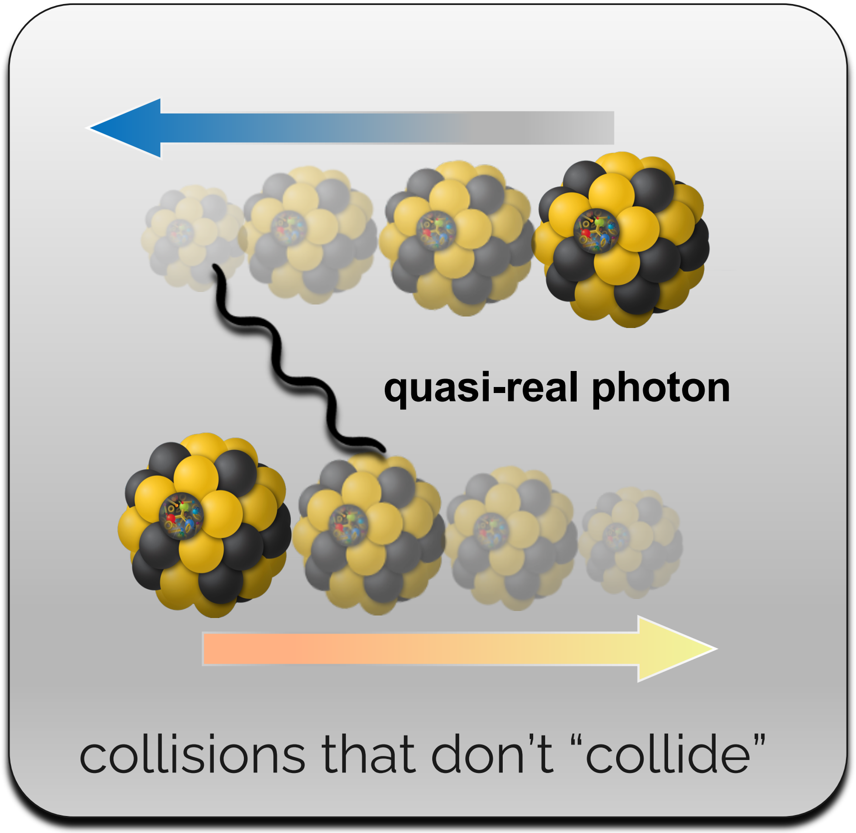
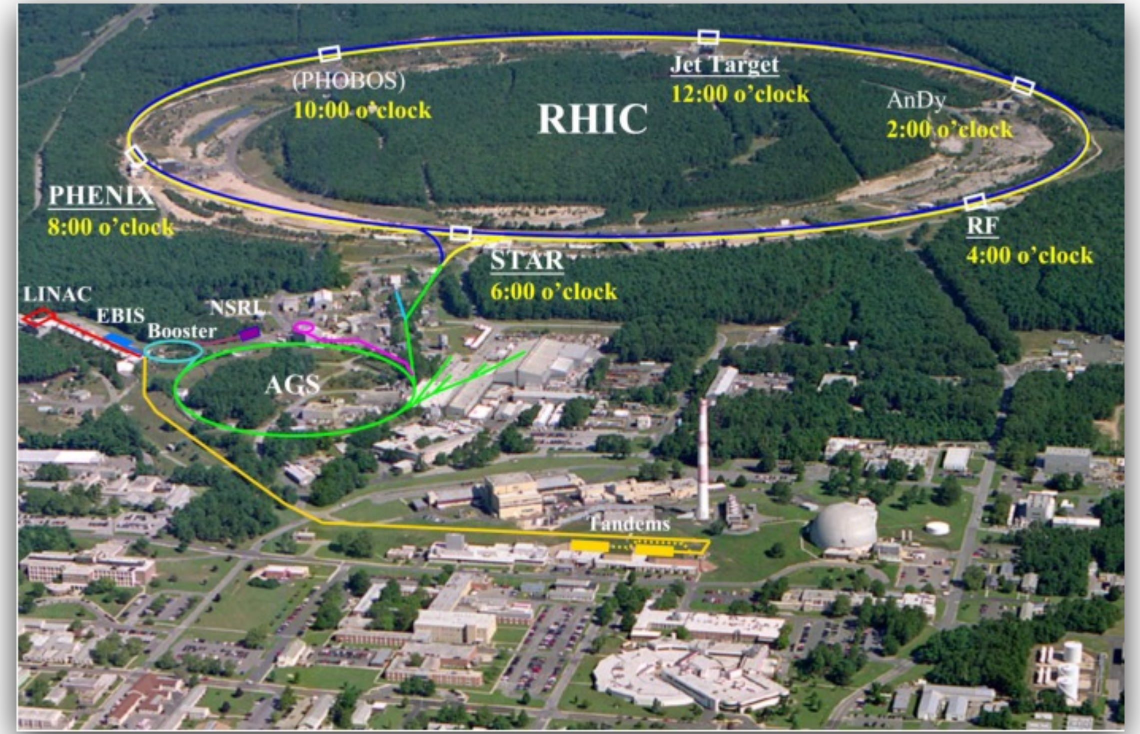
Three main physics goals:

1. Coherent production – **average** nuclear parton density
2. Incoherent production – **E-by-E fluctuations** of nuclear parton density
3. Imaging of nuclear parton **spatial** distribution in nuclei.

Ultra-Peripheral Collisions at RHIC

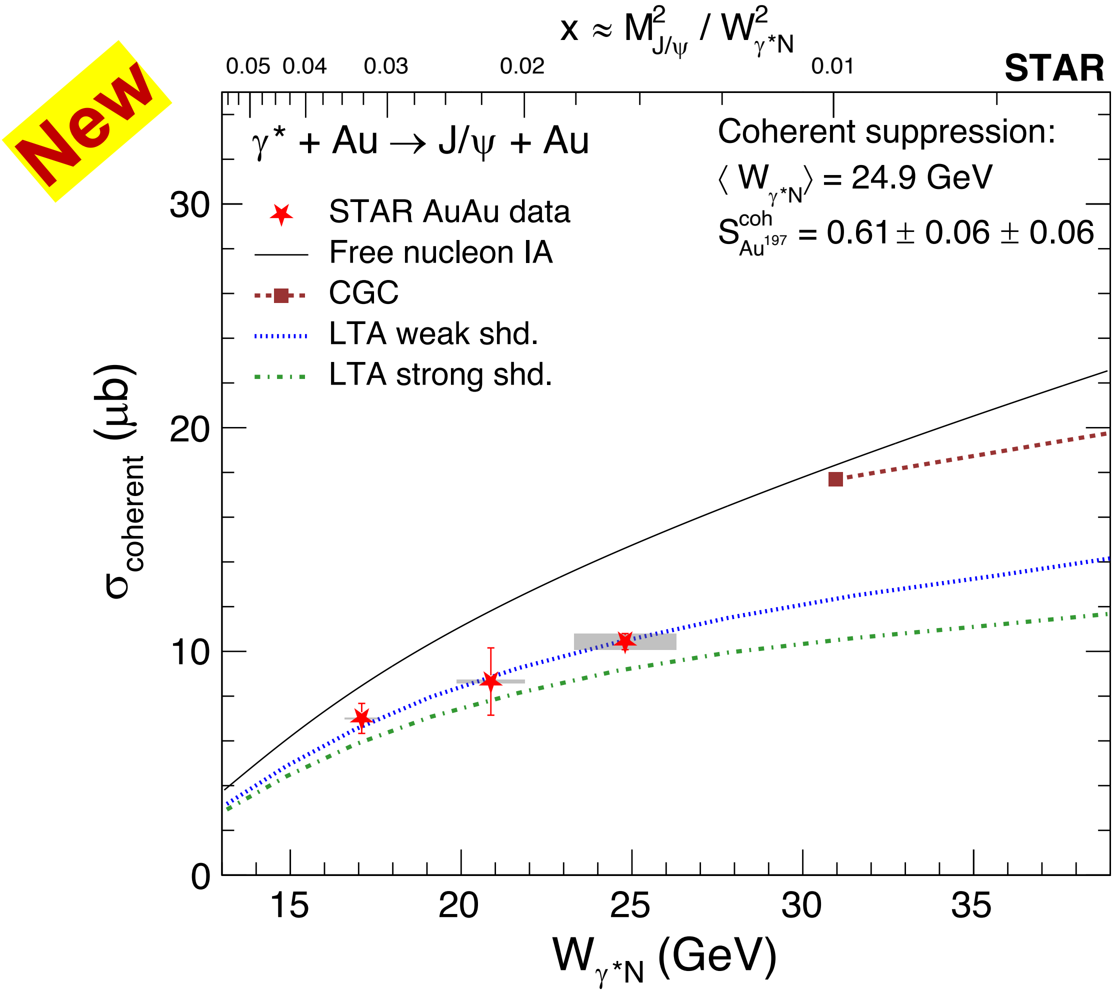




U^{238}, Au^{197}, Zr^{96} , Ru^{96}, d^2 at 200 GeV and *pp* at 510 GeV

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

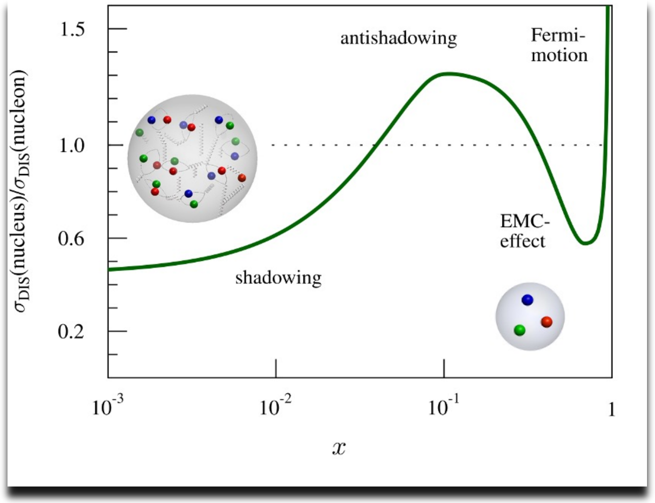
1. Coherent J/ψ photoproduction at RHIC



(submitted to PRC, arXiv:2311.13632)

What we learned:

- Coherent J/ψ photoproduction cross section is suppressed even at x ~ 0.03-0.04.



Technical details of resolving photon energy ambiguity, data corrections, etc. See paper.

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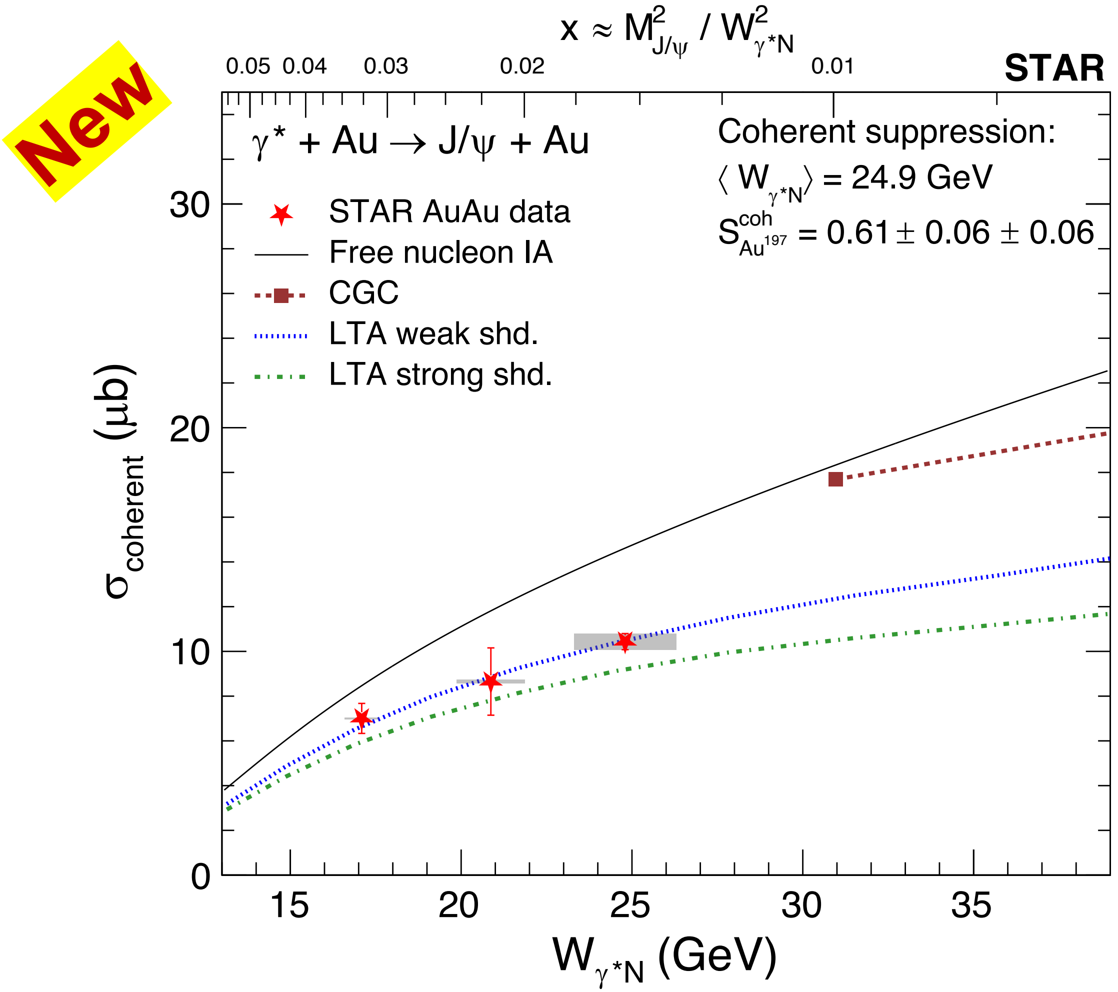

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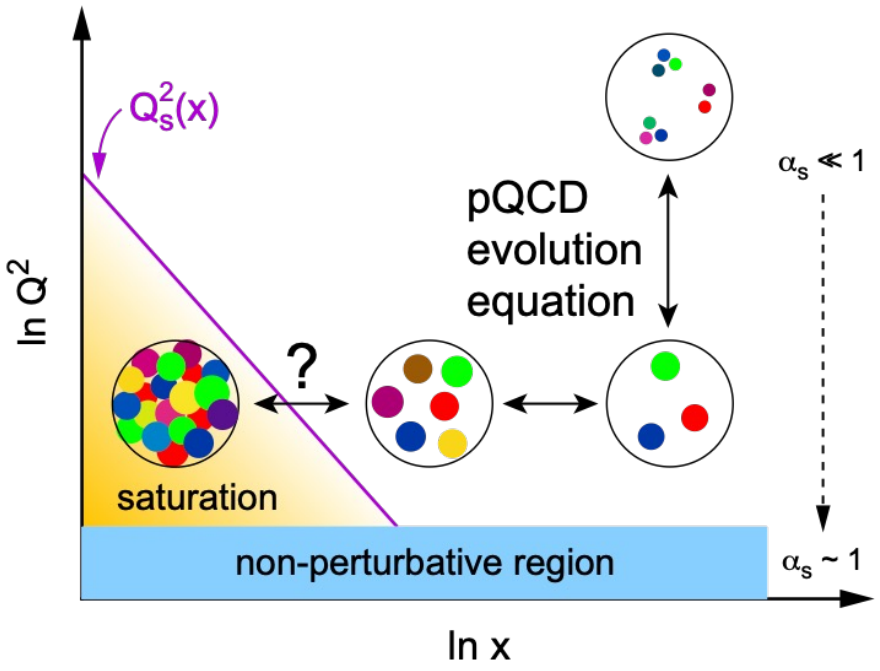
What we learned:

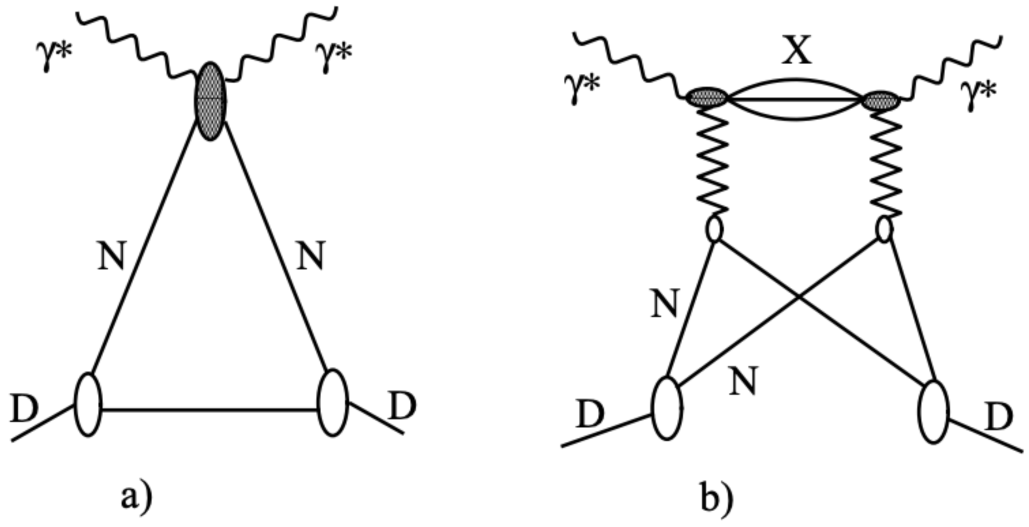
- Coherent J/ψ photoproduction cross section is suppressed even at x ~ 0.03-0.04.
- Gluon saturation model **(CGC)** cannot be applied and overpredicted at x ~ 0.01.
- **Leading twist shadowing** model works almost perfectly (tuning based on LHC data)

Technical details of resolving photon energy ambiguity, data corrections, etc. See paper.

Digression:
– what is saturation and what is Leading twist shadowing?



Color Glass Condensate (CGC)
Dipole-target scattering with small-x evolution equation + saturation scale Q_s



L. Frankfrut,, V. Guzey, M. Strikman (Physics Reports 512 (2012) 255-393)

Leading Twist Approximation (LTA)
Combination of Gribov-Glauber theory, QCD factorization, and HERA diffractive data

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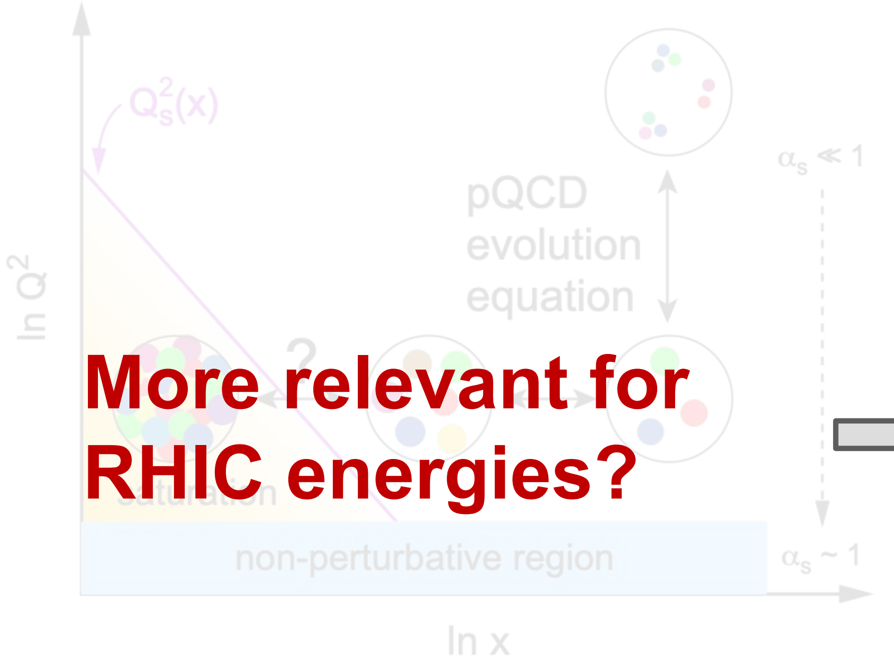

More relevant for RHIC energies?

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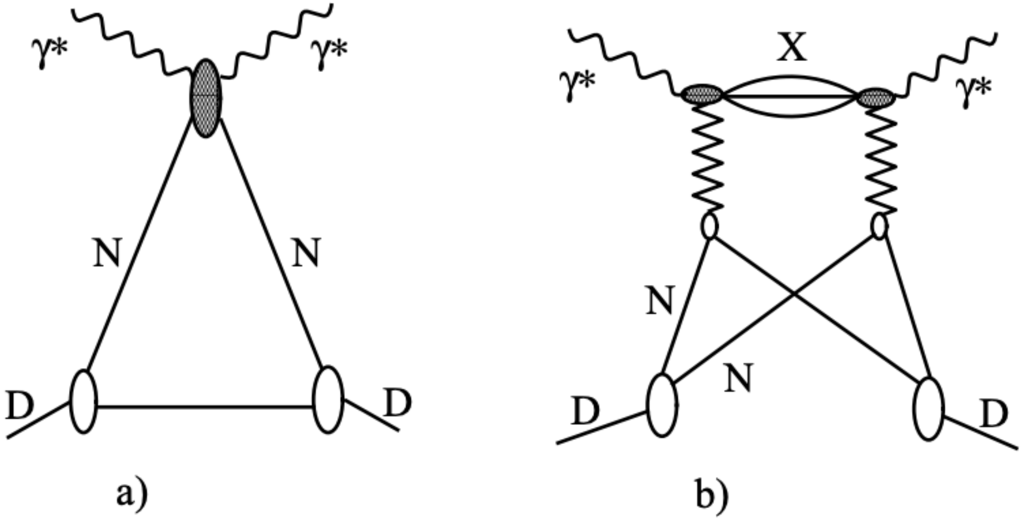

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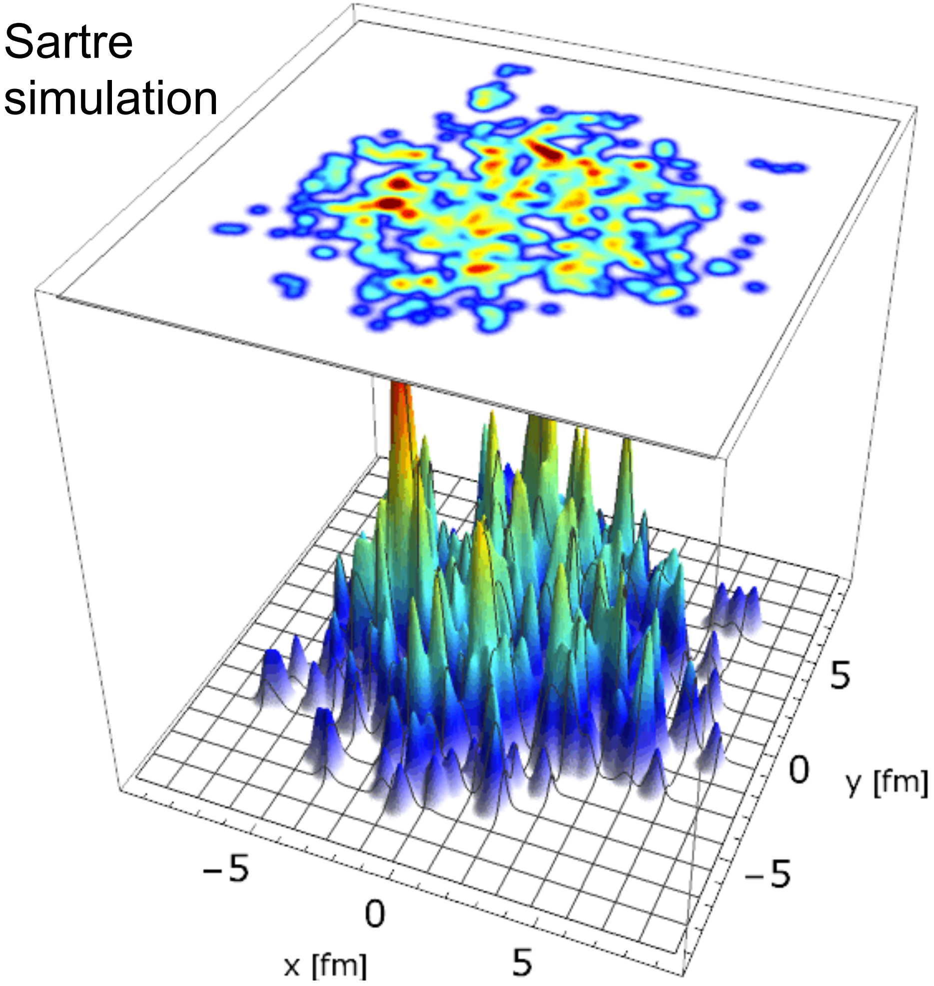
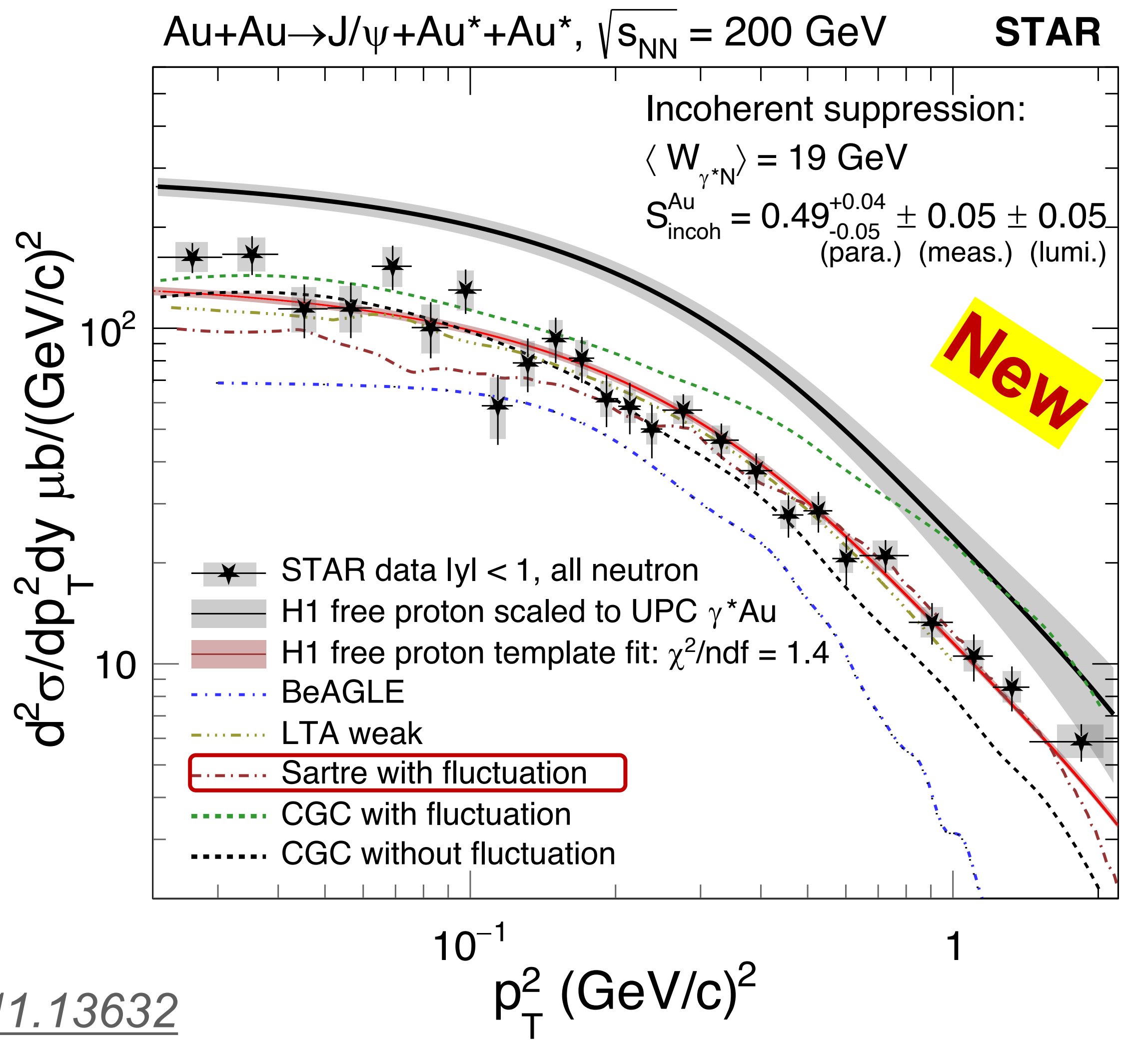
2. Incoherent J/ψ photoproduction at RHIC

Sartre simulation



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

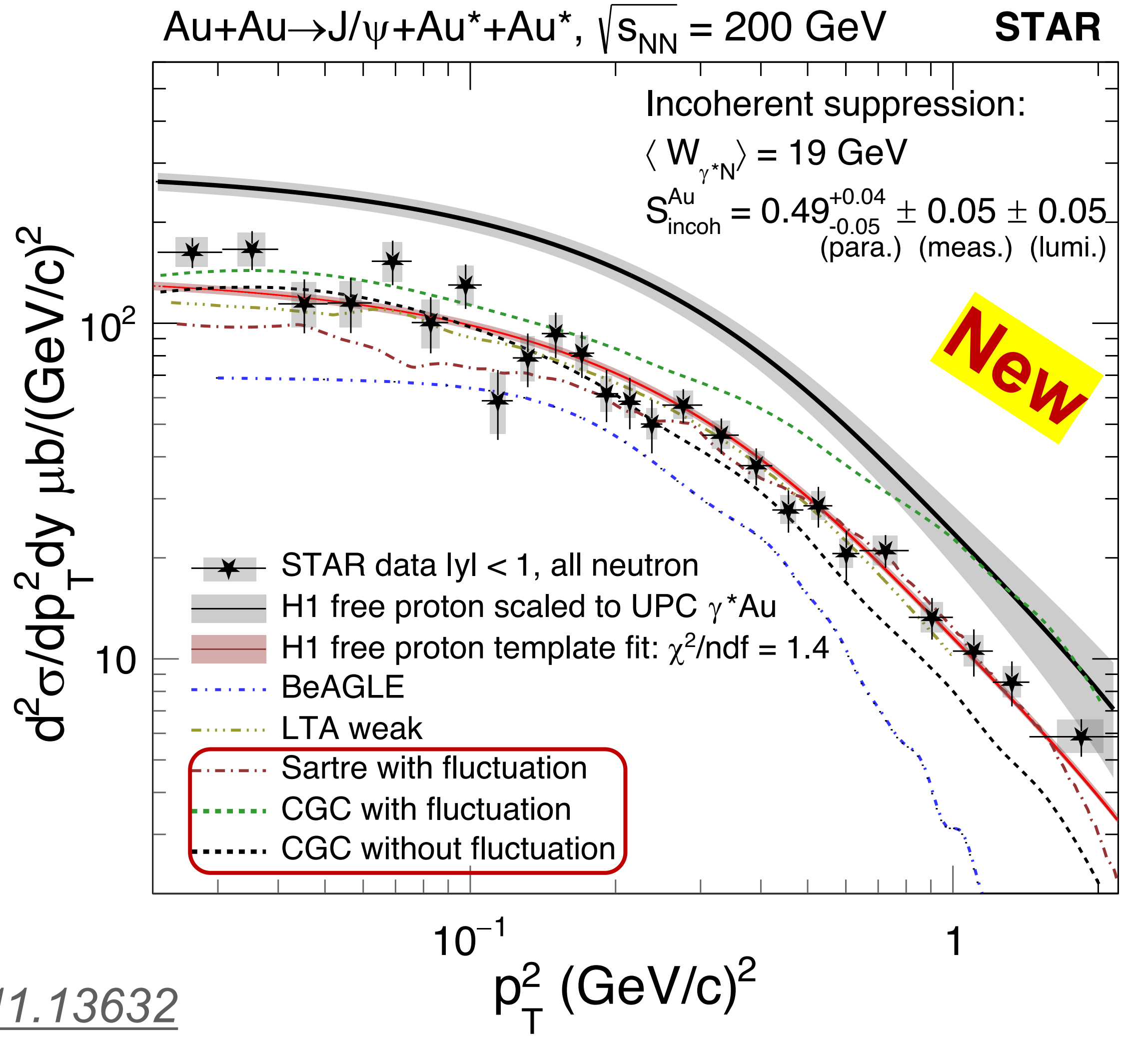


arXiv:2311.13632

2. Incoherent J/ψ photoproduction at RHIC

What we learned:

- CGC with and without fluctuation of gluon density are compared (shape only), while **none can describe the data.**



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2. Incoherent J/ψ photoproduction at RHIC

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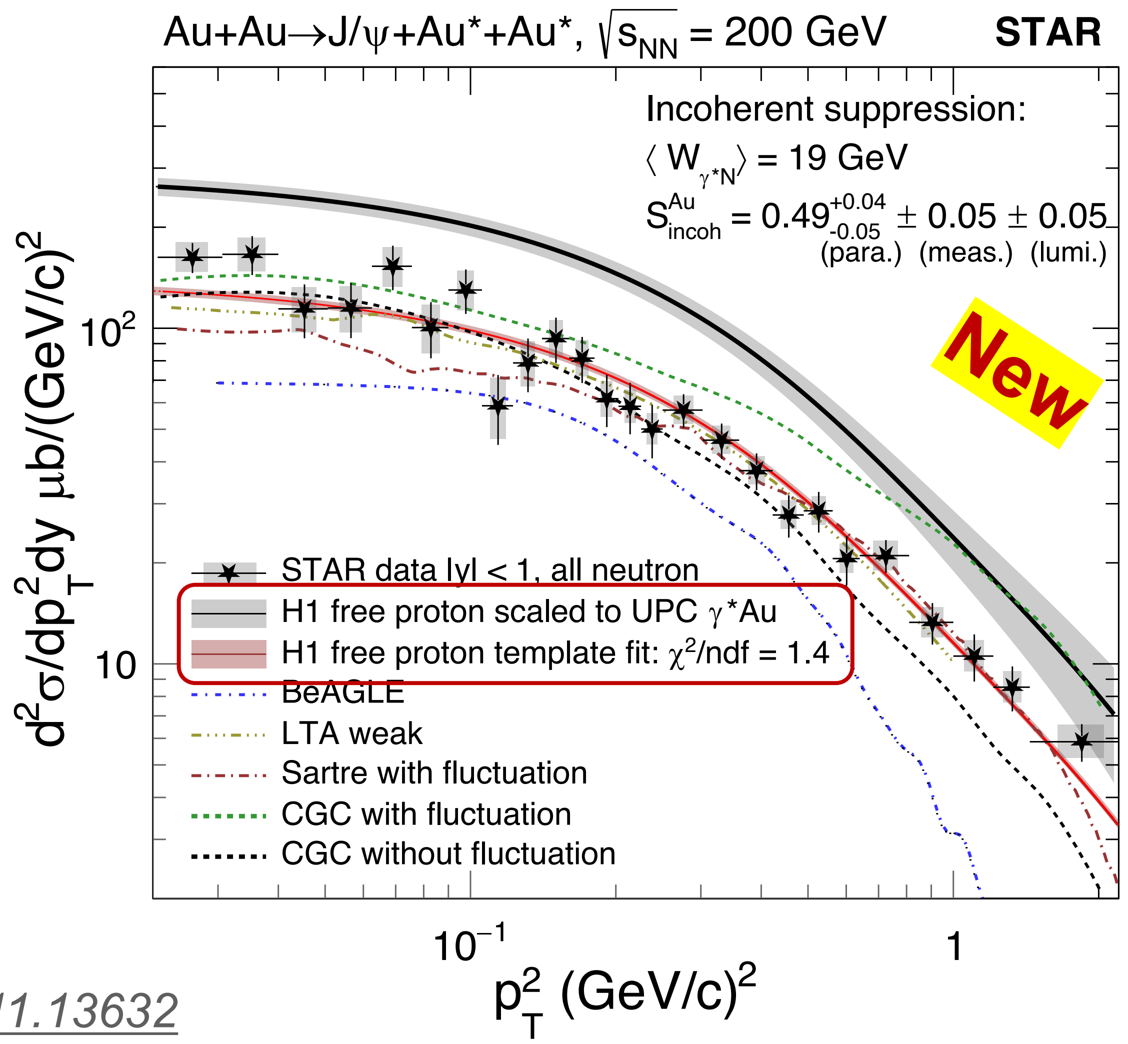

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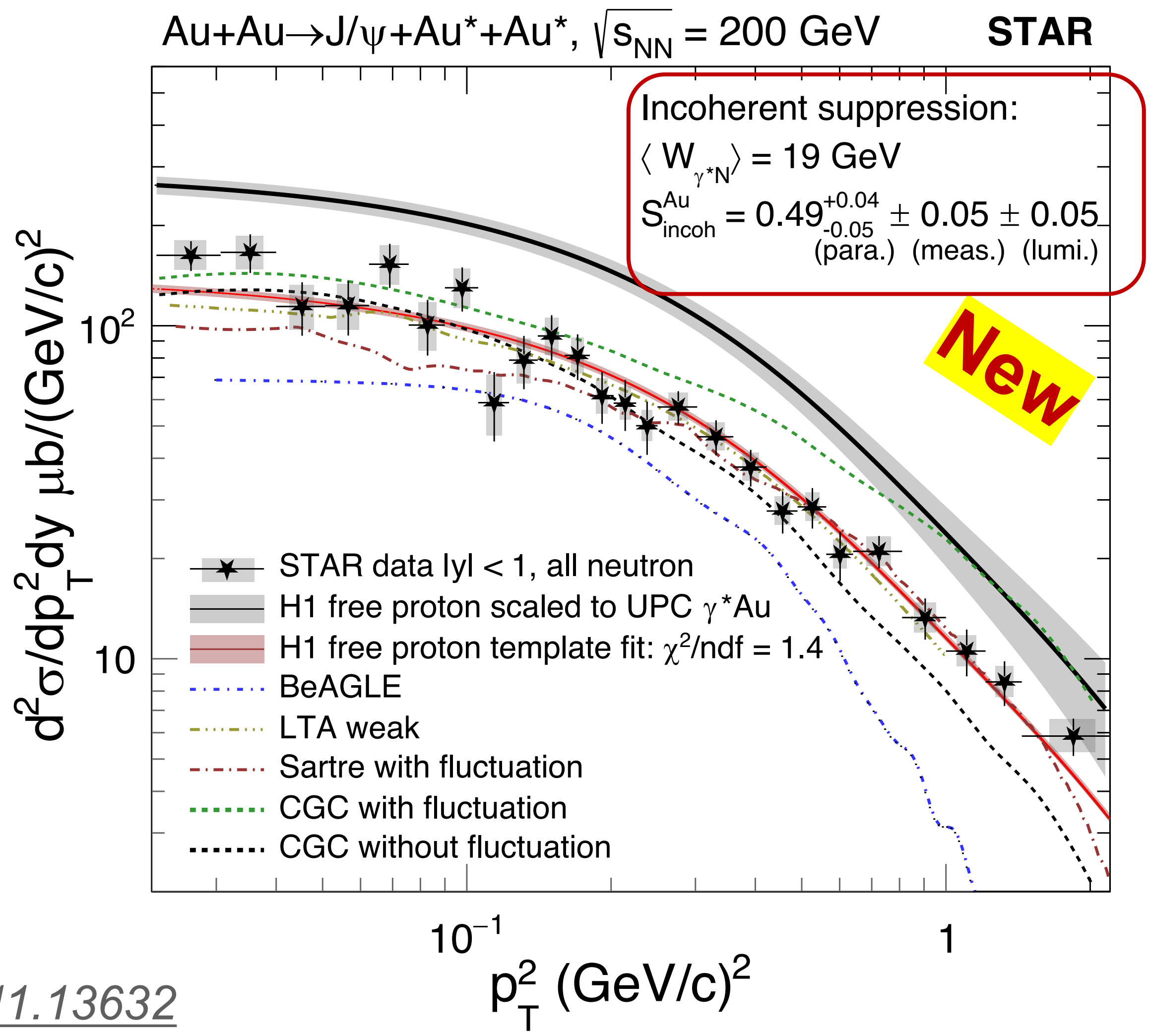
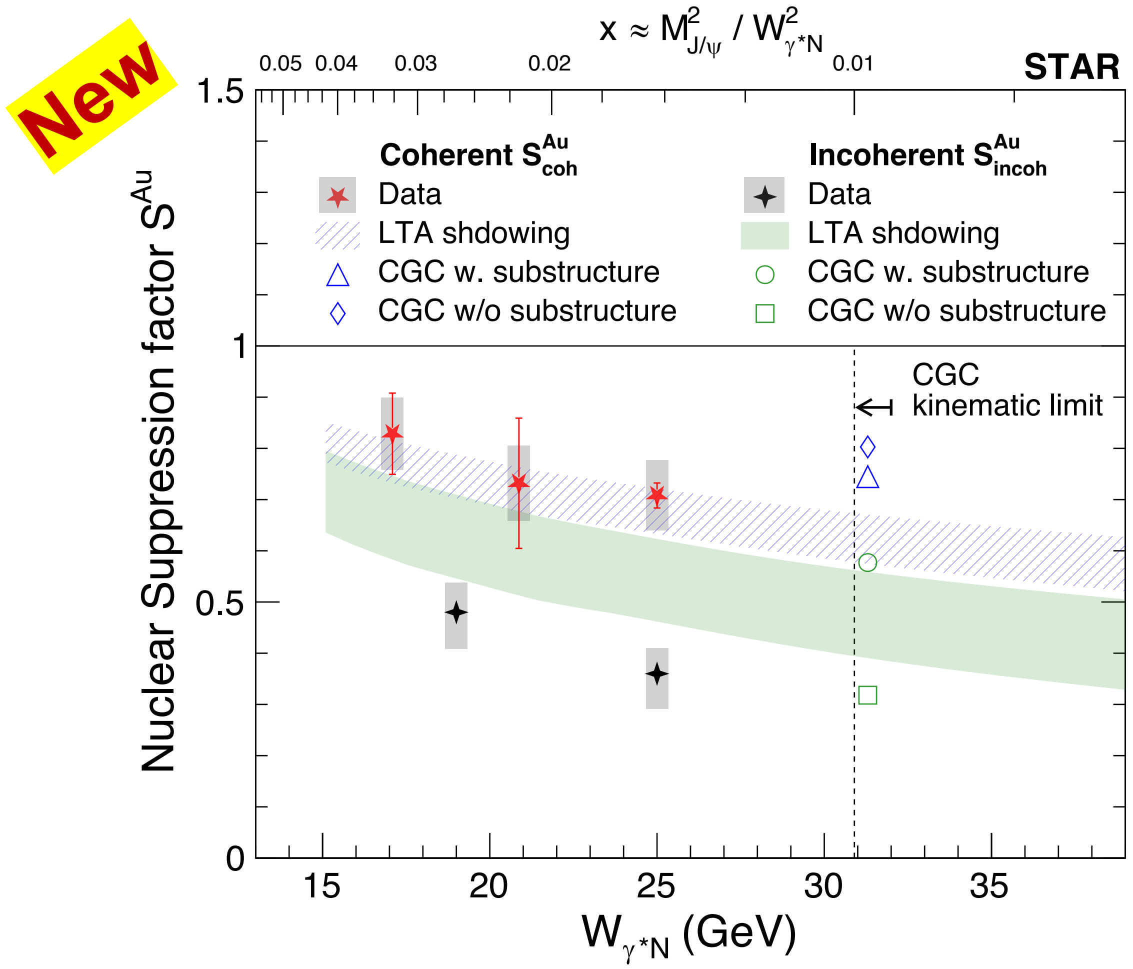
- The shape of the p_T^2 is consistent with free proton. **No additional \`fluctuation\`.**
- Incoherent cross section is also suppressed w.r.t free proton, and stronger than coherent!



arXiv:2311.13632

Nuclear suppression factor

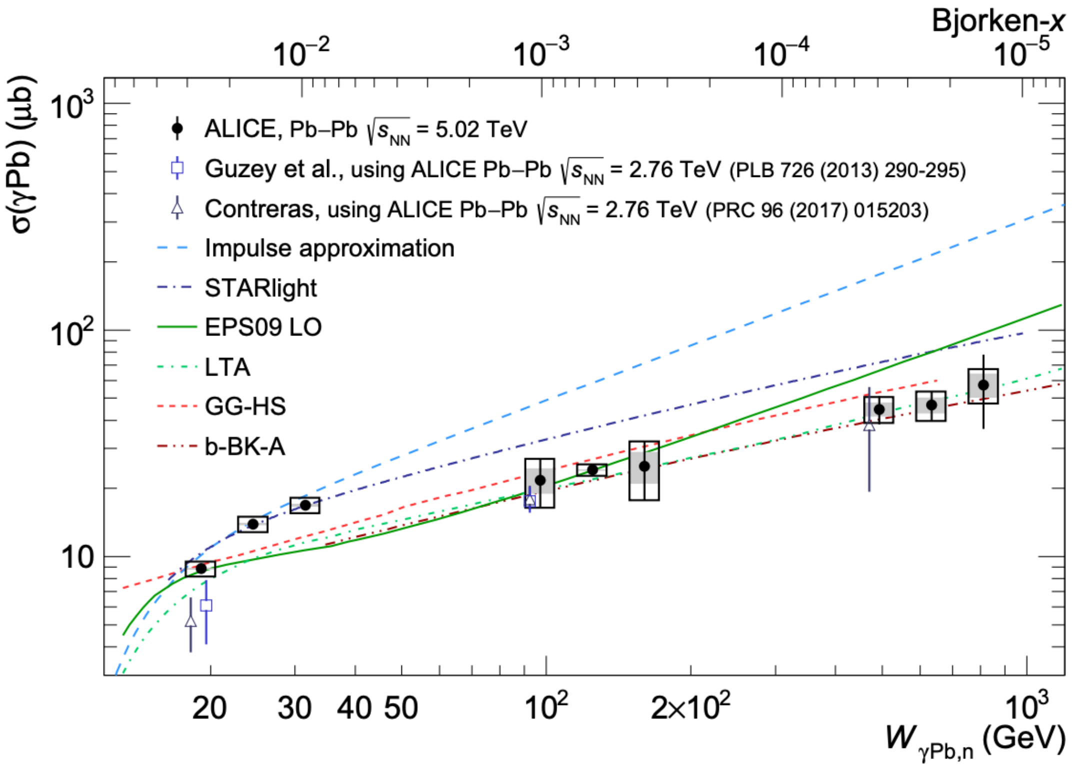


What we learned:

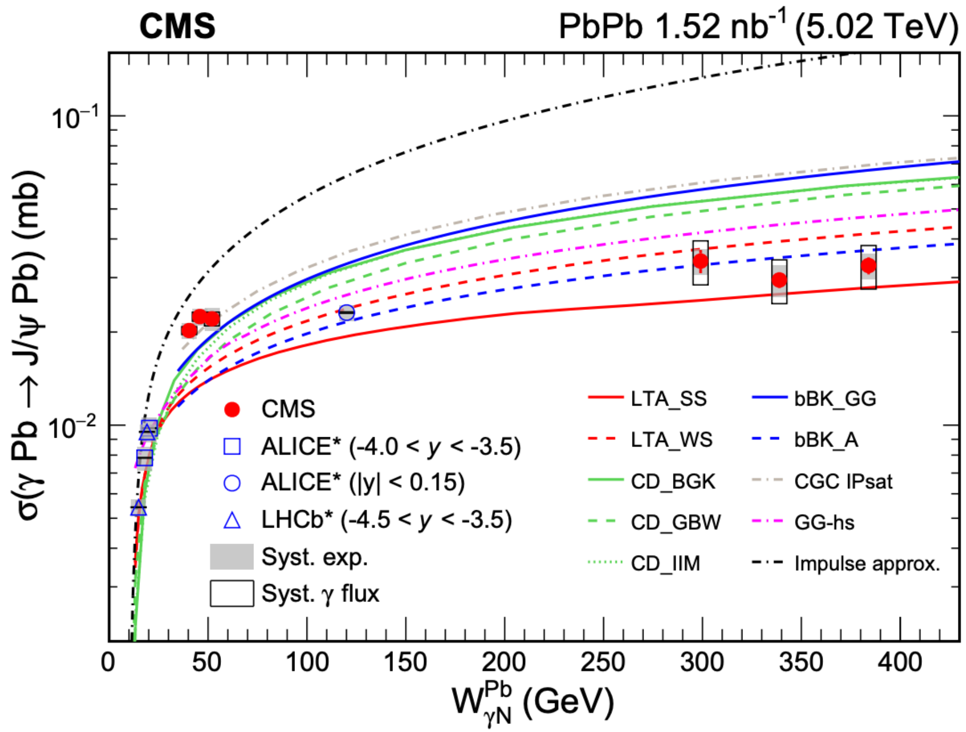
- Significant suppression of both coherent and incoherent J/ψ photoproduction.
- Incoherent is **twice as suppressed** as that of coherent. Even **stronger than the "strong" shadowing mode** in Leading twist shadowing model.
- Another observable to **disfavor** fluctuation model.

(submitted to PRL, arXiv:2311.13637)

CGC describes better at higher energies?



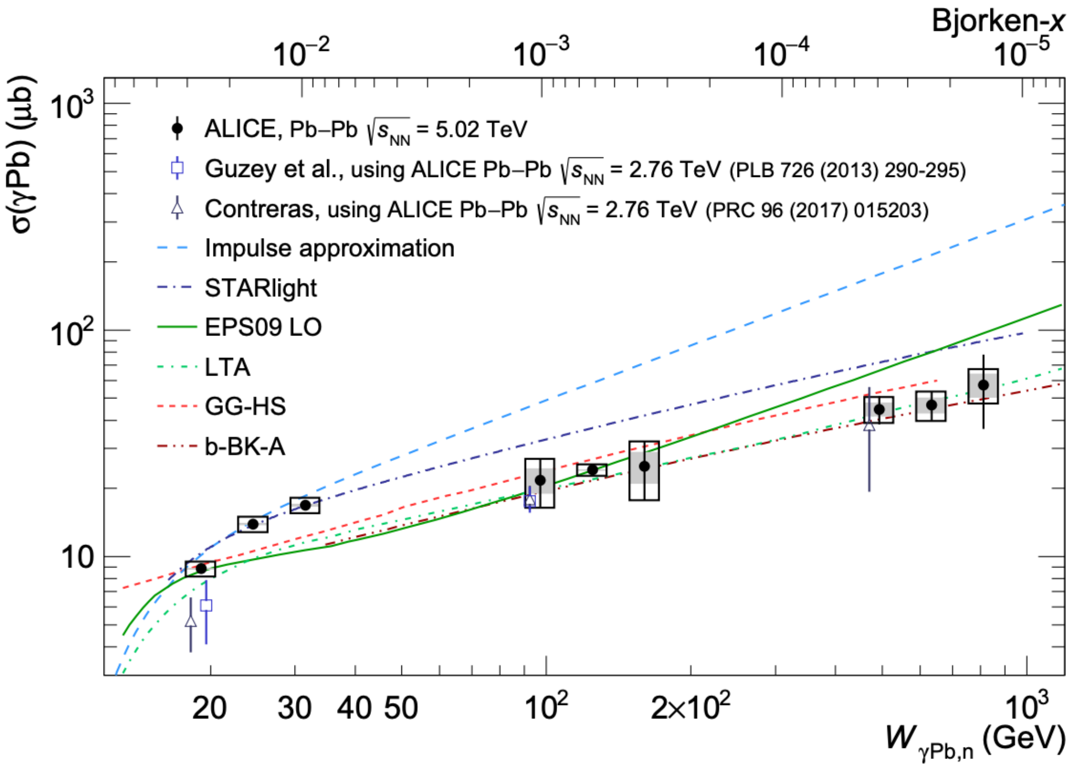
JHEP 10 (2023) 119



Phys. Rev. Lett. 131 (2023) 262301

- Yes, but LTA describes the data equally well.
- None of these models can describe the entire energy dependence and **all models generally reach a “similar conclusion”.**

CGC describes better at higher energies?



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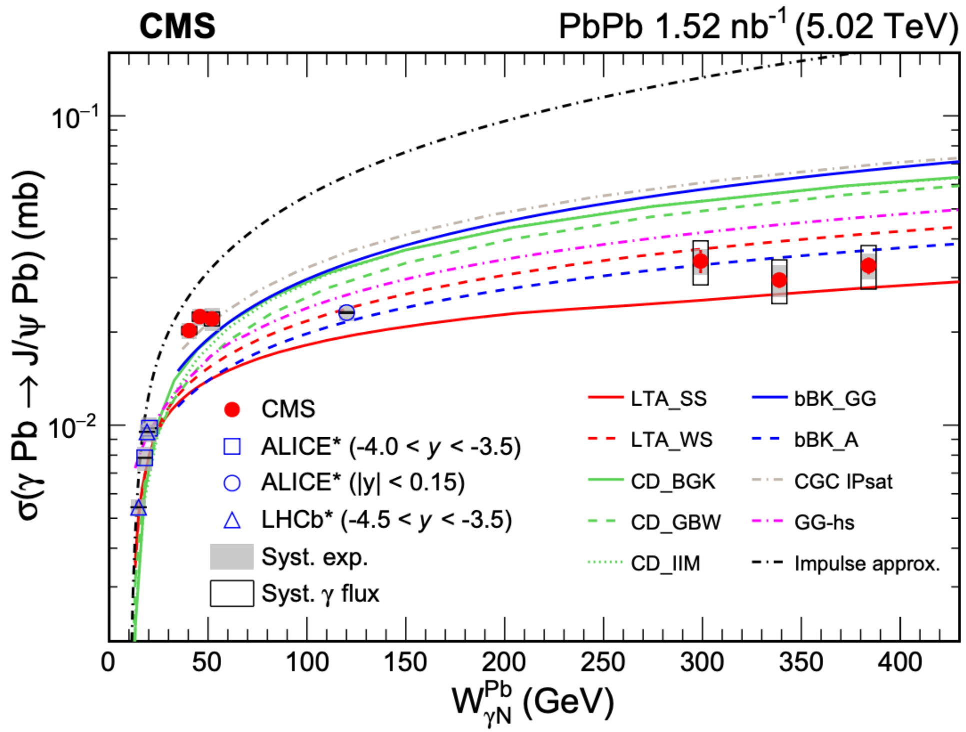

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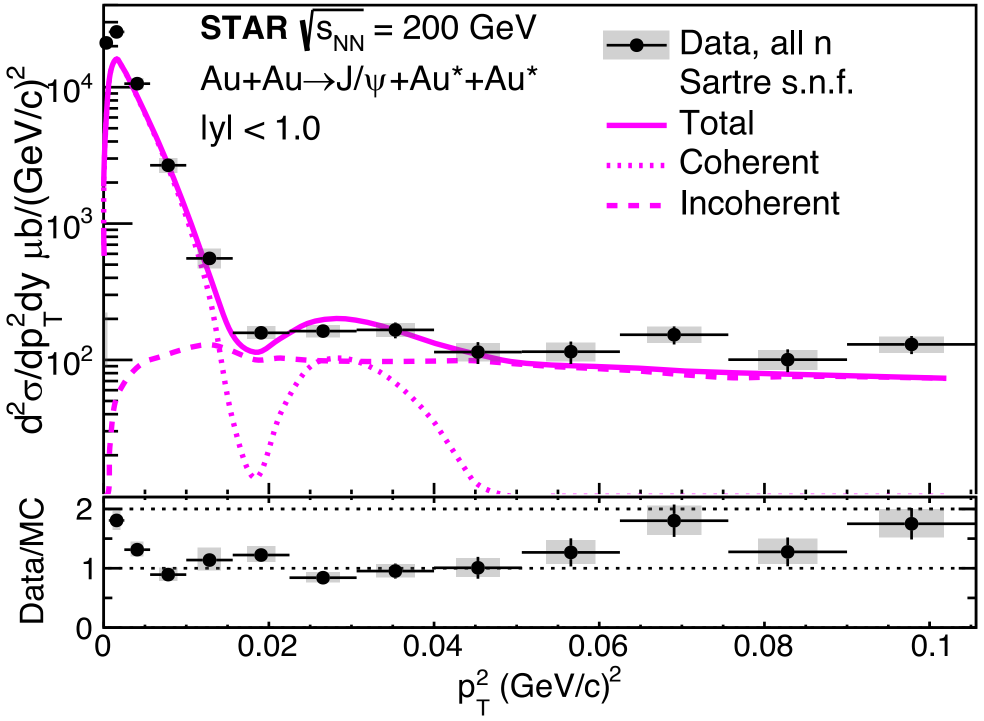
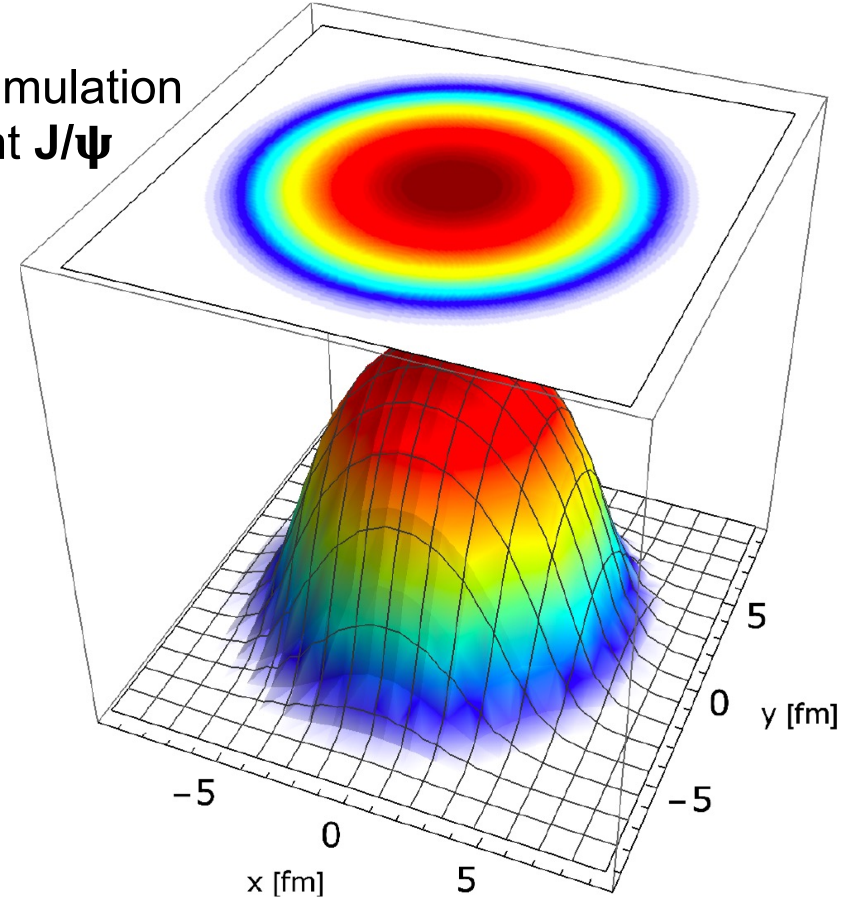
Separating the two models is one of the most pressing questions in UPC Vector Meson physics

3. Imaging the parton spatial distribution



Sartre simulation
Coherent **J/ψ**



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

Overwhelming incoherent at higher p_T^2 →
cannot constrain the gluon spatial distribution

What's next?

Two questions:

a) Separating CGC vs LTA at low-x or LHC energies
b) Separating Coherent and Incoherent as a function of p_T^2

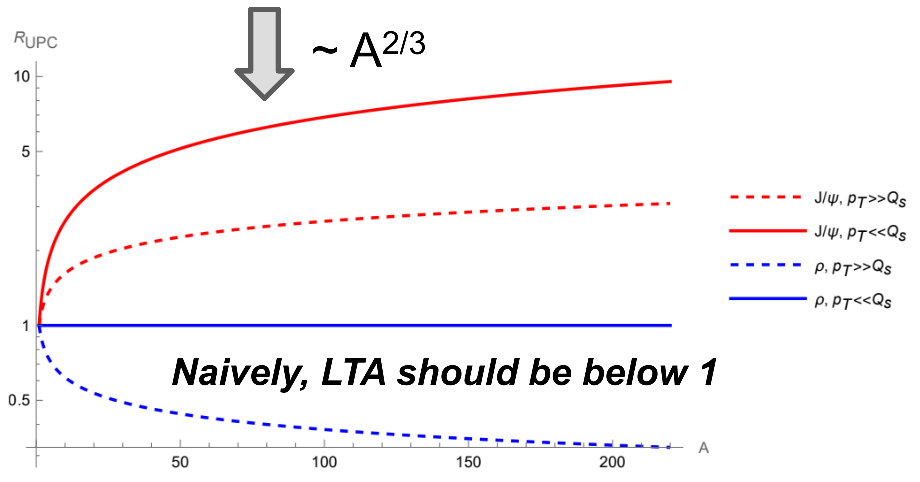
a) Separating CGC vs LTA at low-x or LHC energies

New proposal

- Diffractive Vector Meson over inclusive jet/hadron photoproduction in UPCs

$$R_{\mathrm{UPC}} = \frac{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{jet}} / \mathrm{d}^2 \mathrm{p_T}\right)\right]_{\mathrm{A+A}}}{\left[\sigma_{\mathrm{el}}^{\mathrm{VM}} / \left(\mathrm{d}\sigma_{\mathrm{inclusive}}^{\mathrm{jet}} / \mathrm{d}^2 \mathrm{p_T}\right)\right]_{\mathrm{p+A}}}.$$

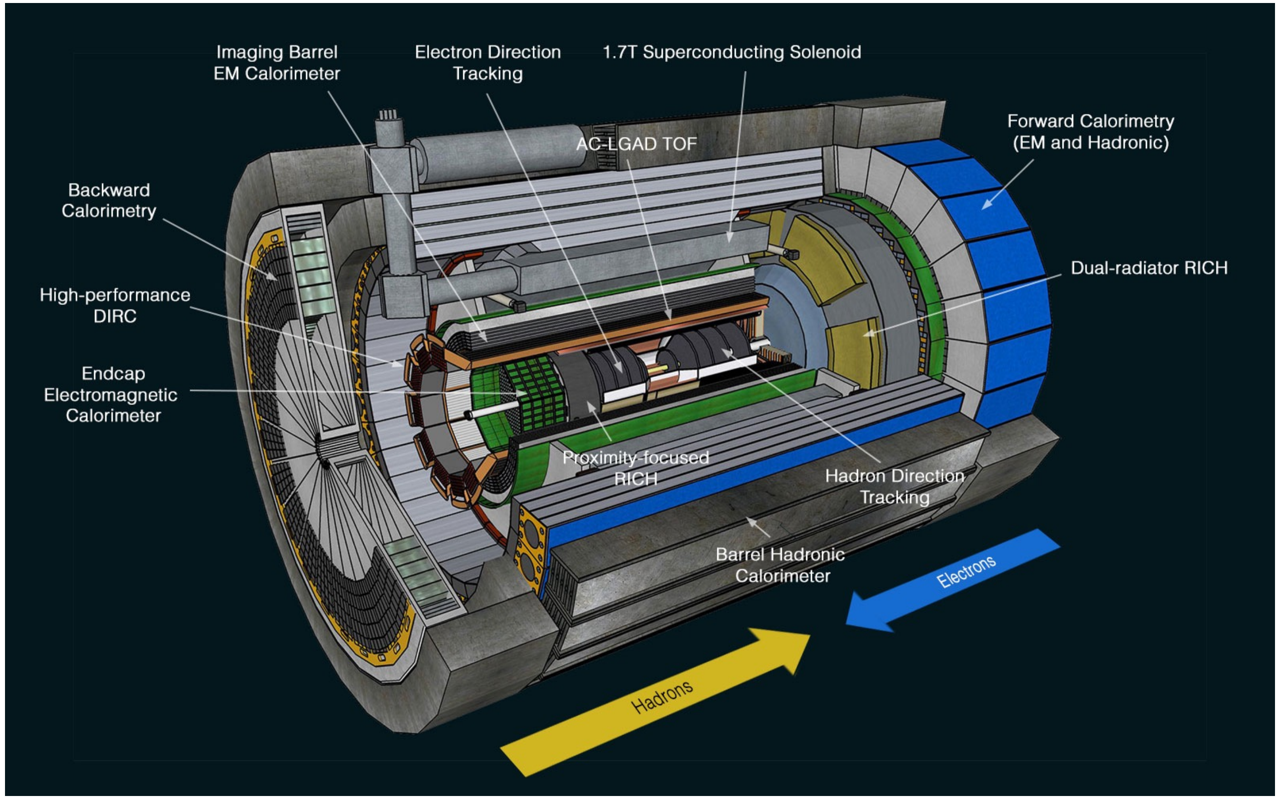
Unambiguous signal of saturation from **J/ψ**



New

*Y. Kovchegov, H. Sun, **ZT** (2023), arXiv:2311.12208, submitted to PRD*

b) Separating Coherent and Incoherent as a function of p_T^2



The ePIC detector – at the Electron-Ion Collider

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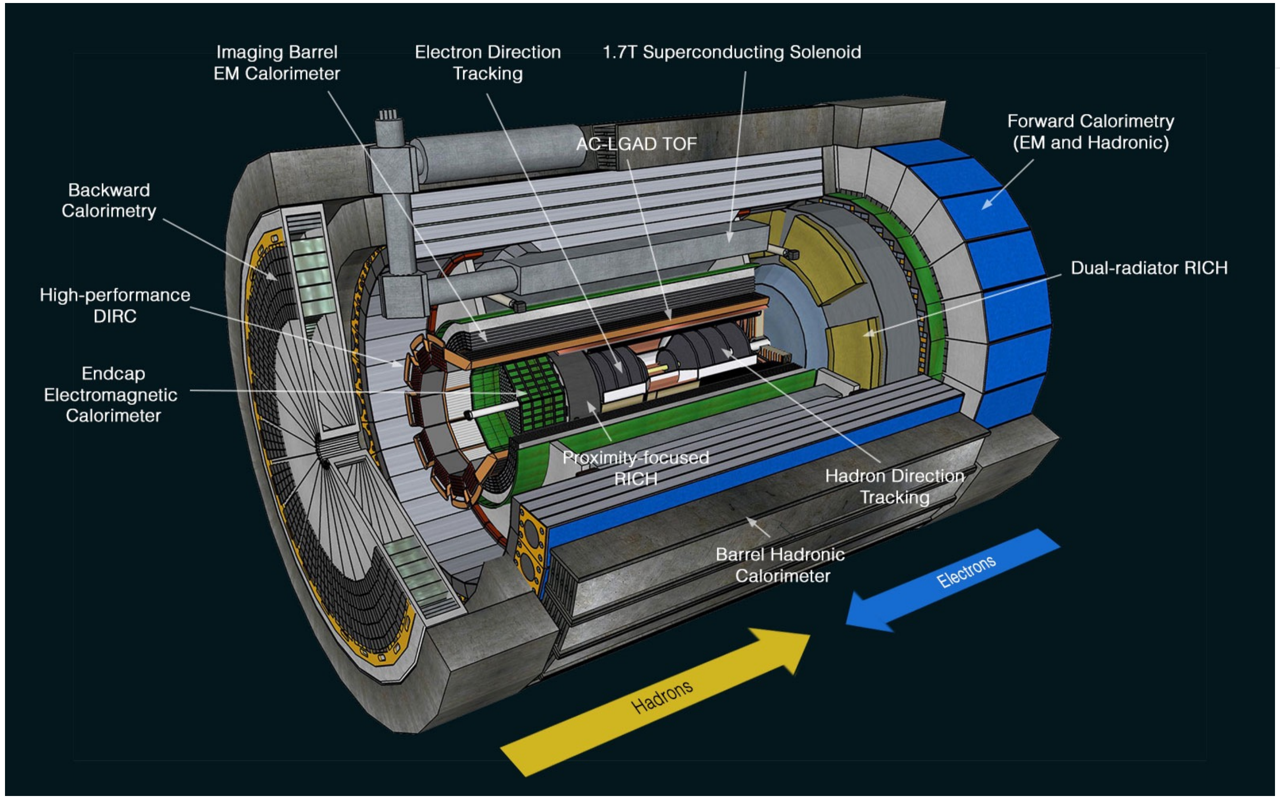

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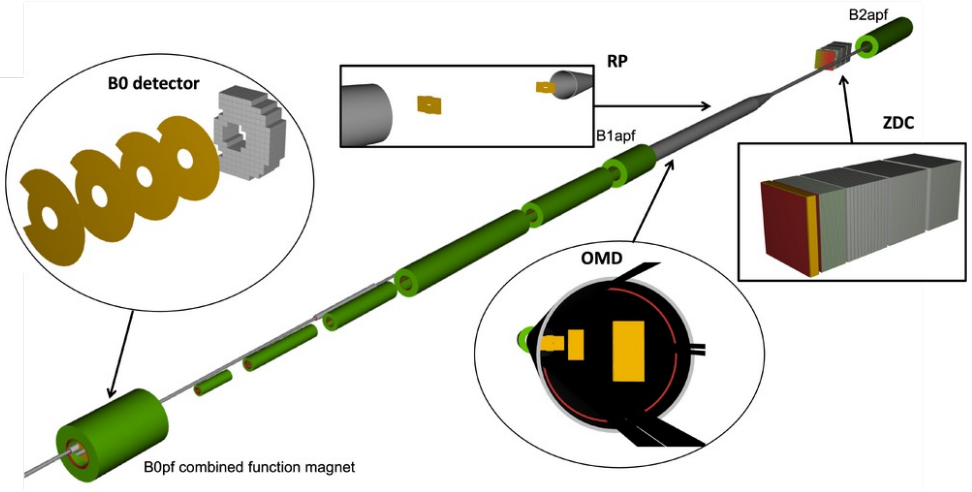
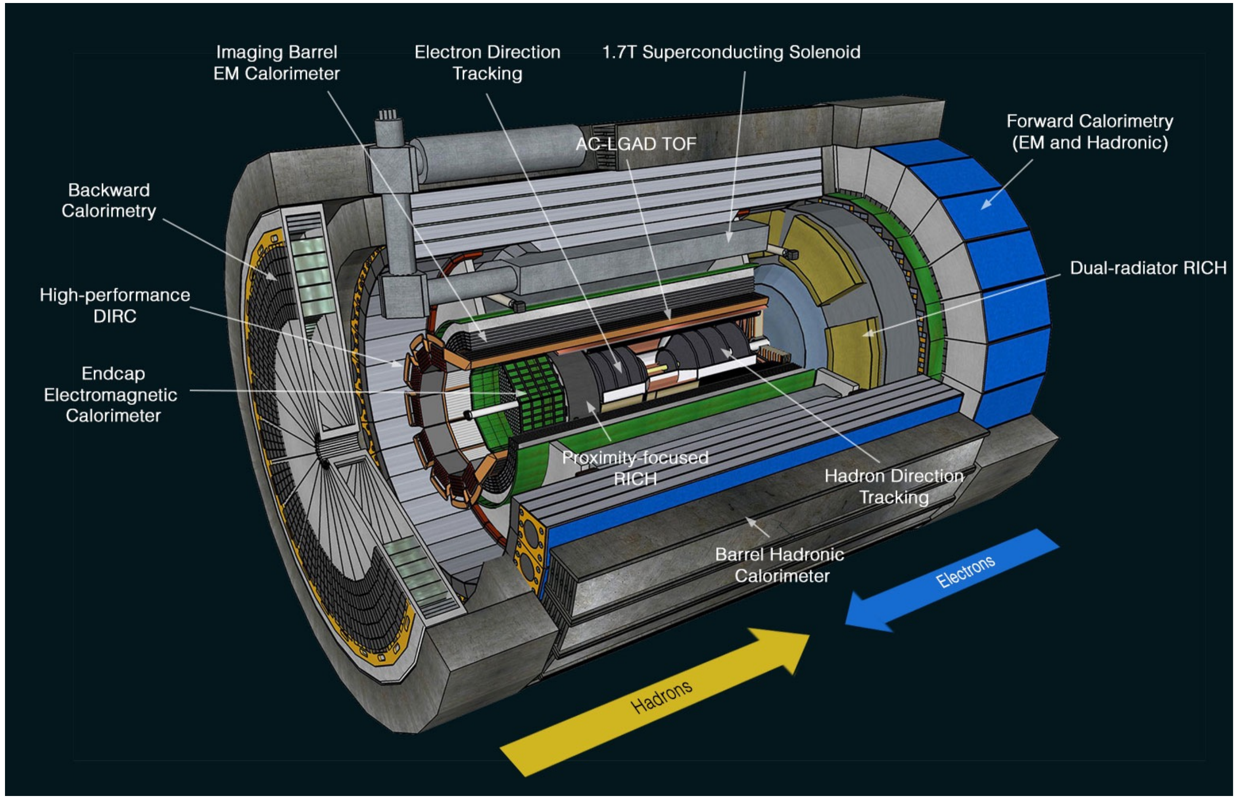
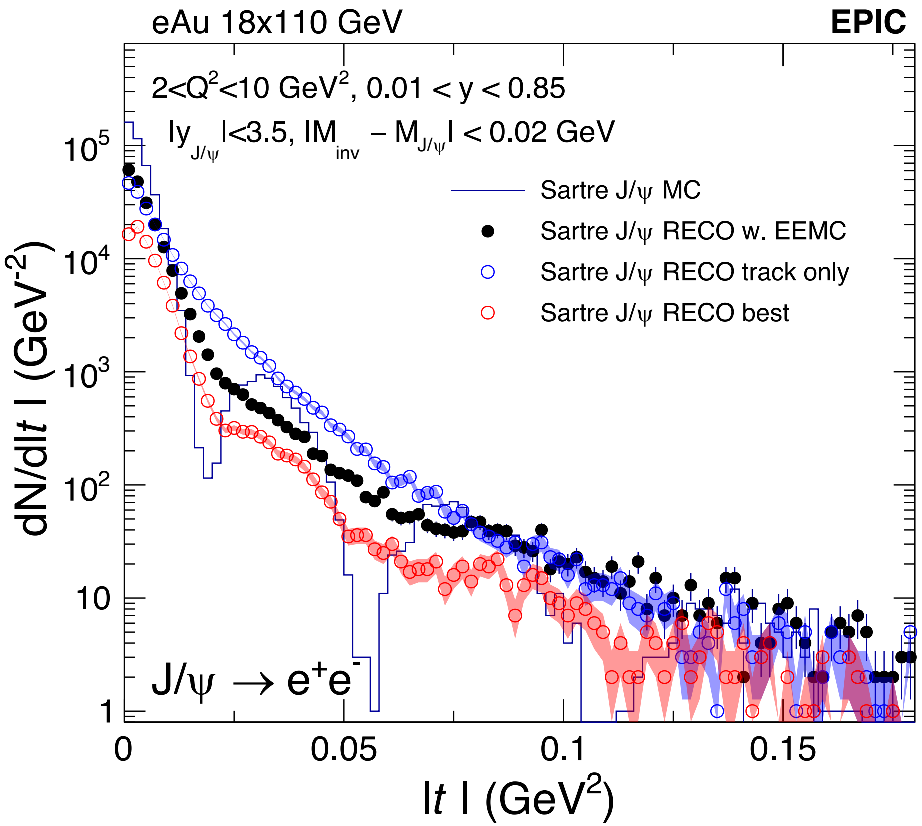


Far-forward detector system:
What we use to select/veto the incoherent production

b) Separating Coherent and Incoherent as a function of p_T^2

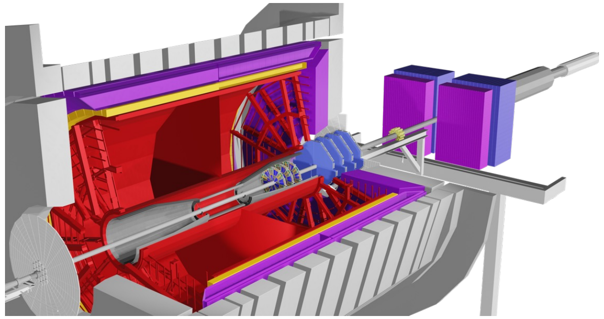
DIS 2023





The ePIC detector – at the Electron-Ion Collider *It's still challenging to measure the gluon spatial distribution*

Future opportunities



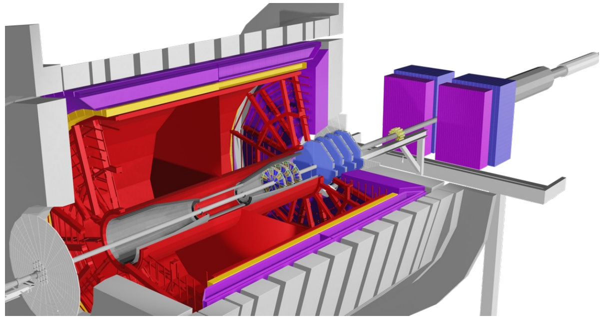
Since 2022, STAR has forward detectors (**$2.5 < \eta < 4.0$**):

- 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 opportunities



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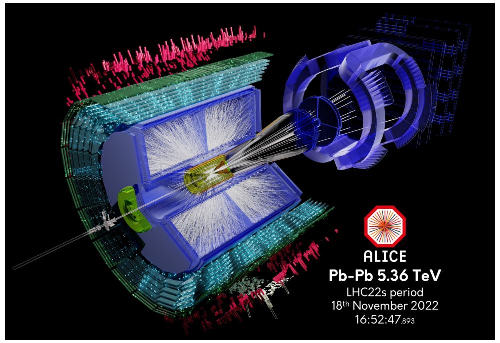
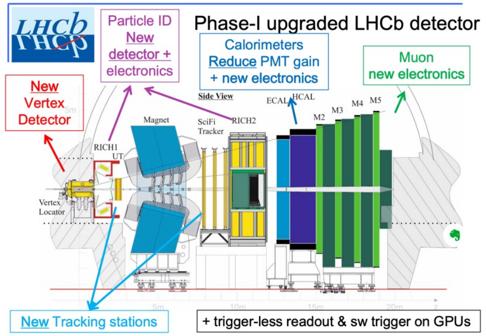
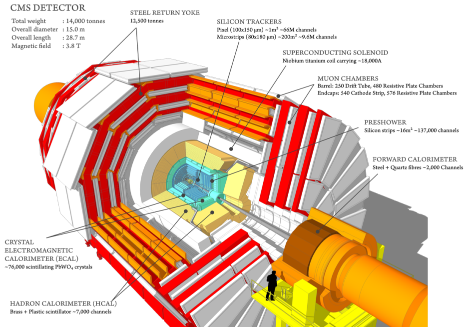
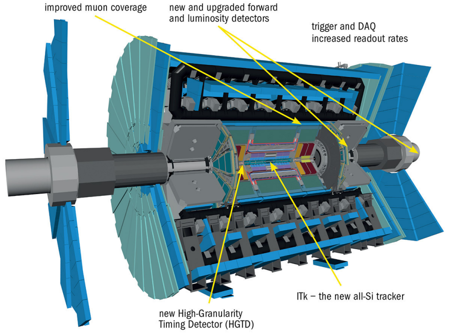






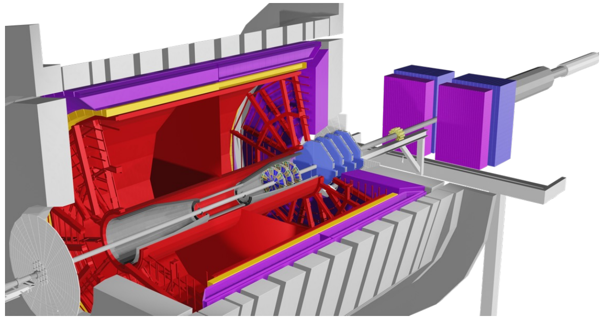


All LHC experiments will have significant upgrades in Run 3 & 4 (e.g., wide acceptances, ALICE FoCal, etc.). **Lower-x reach!**

RHIC 23-25 & LHC Run 3 → LHC Run 4

2023 | 2025 | 2029 | 2034+

Future opportunities



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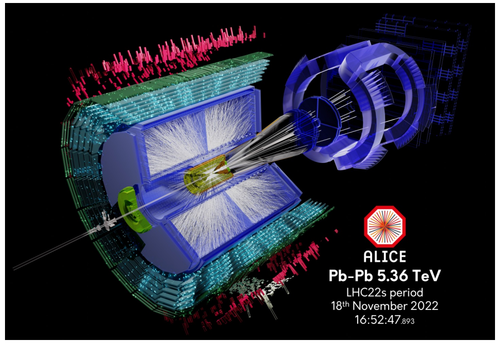

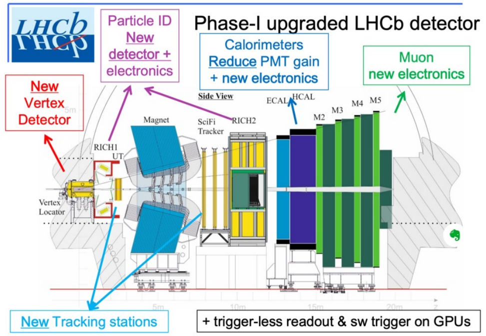

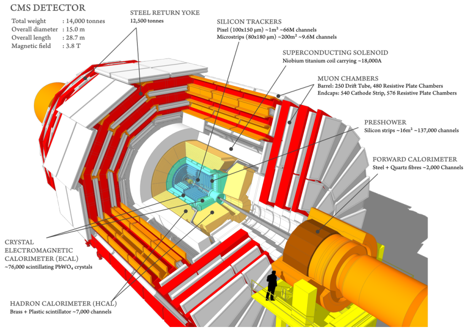

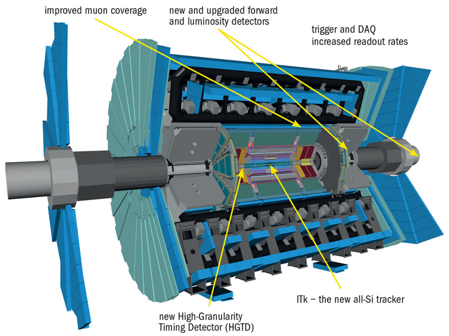

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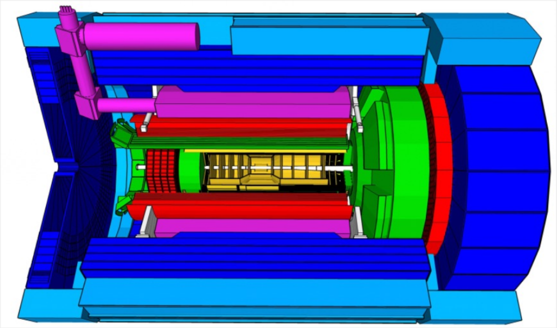
EIC era

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+

Summary

- Diffractive Vector-Meson production is a powerful probe for understanding the cold QCD physics in nuclei.
  - *Large nuclear suppression of* **J/ψ *photoproduction***.
  - *Leading Twist Shadowing describes better the RHIC data, while for the LHC we need new observables to differentiate models.*

- RHIC and LHC UPC data are complimentary, together spans a wide range of energy and kinematic phase space.

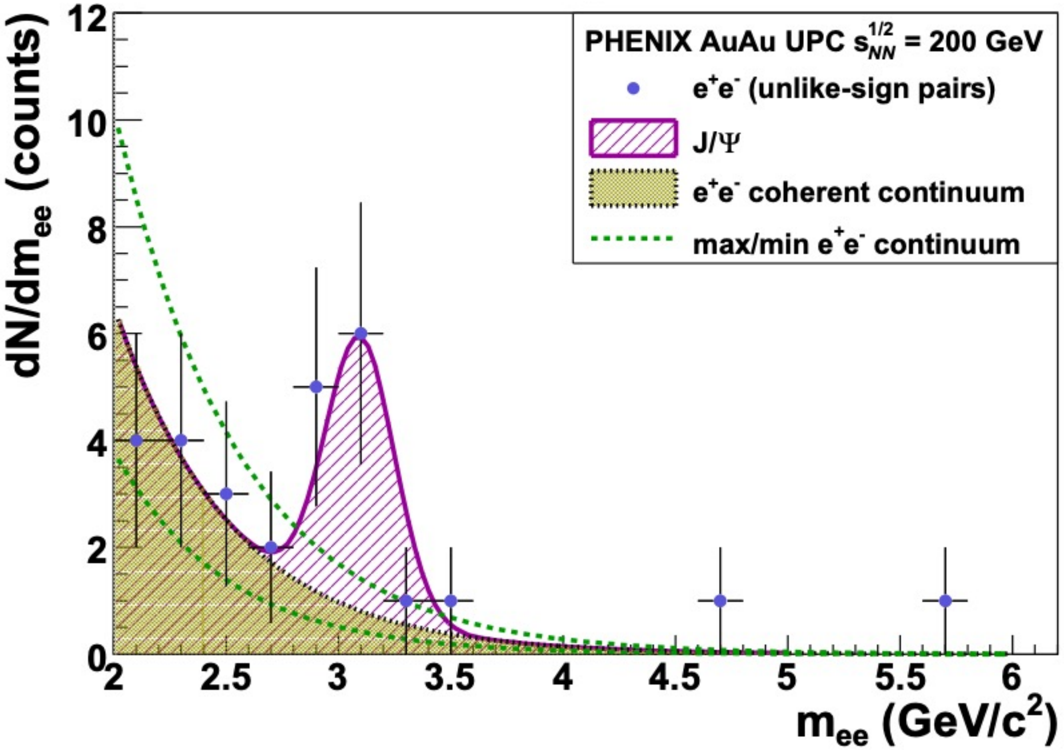
Energy frontier: UPCs at RHIC and the LHC can help understand the nuclear parton modification at low-x.

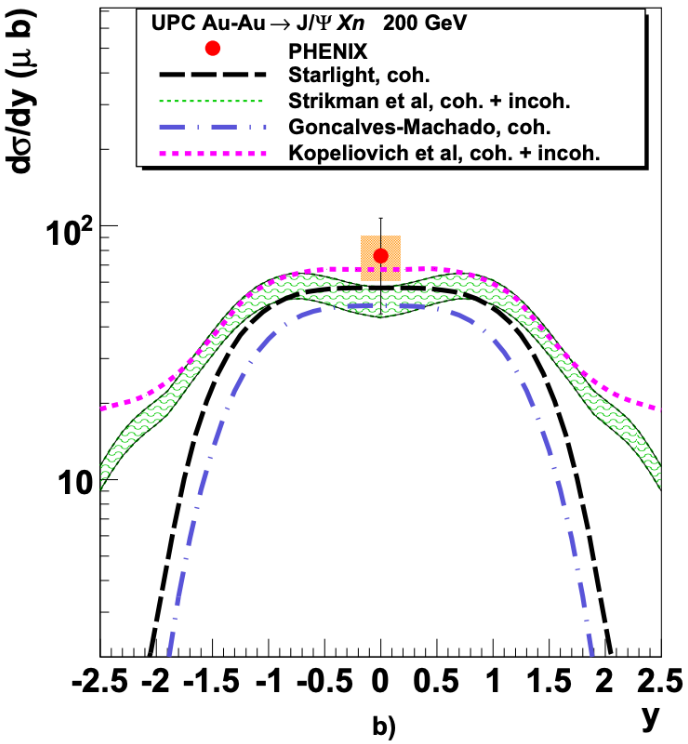
Precision frontier: EIC will be the ultimate machine to understand the detail of nuclear dynamics in 3D.

Backup

Early RHIC data from PHENIX

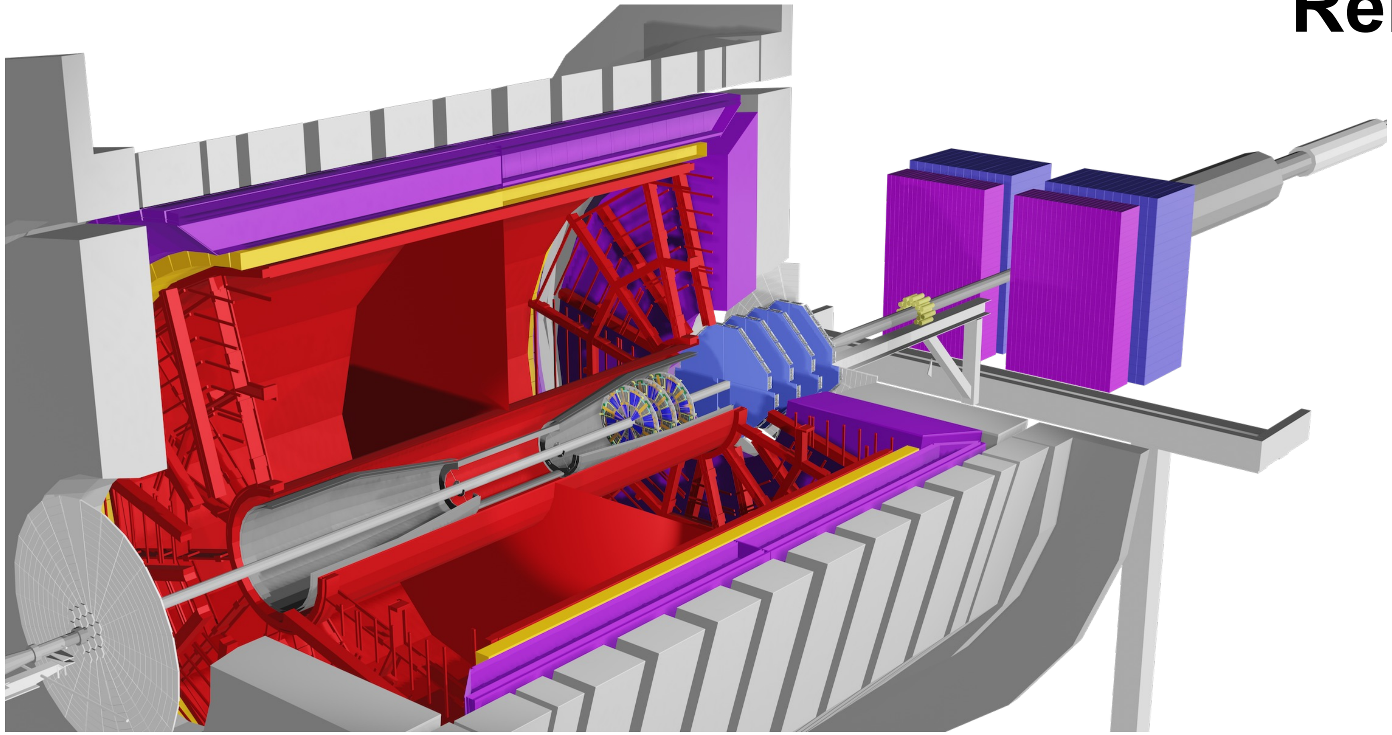
*Phys. Lett. B 679 (**2009**) 321-329*





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

STAR experiment



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

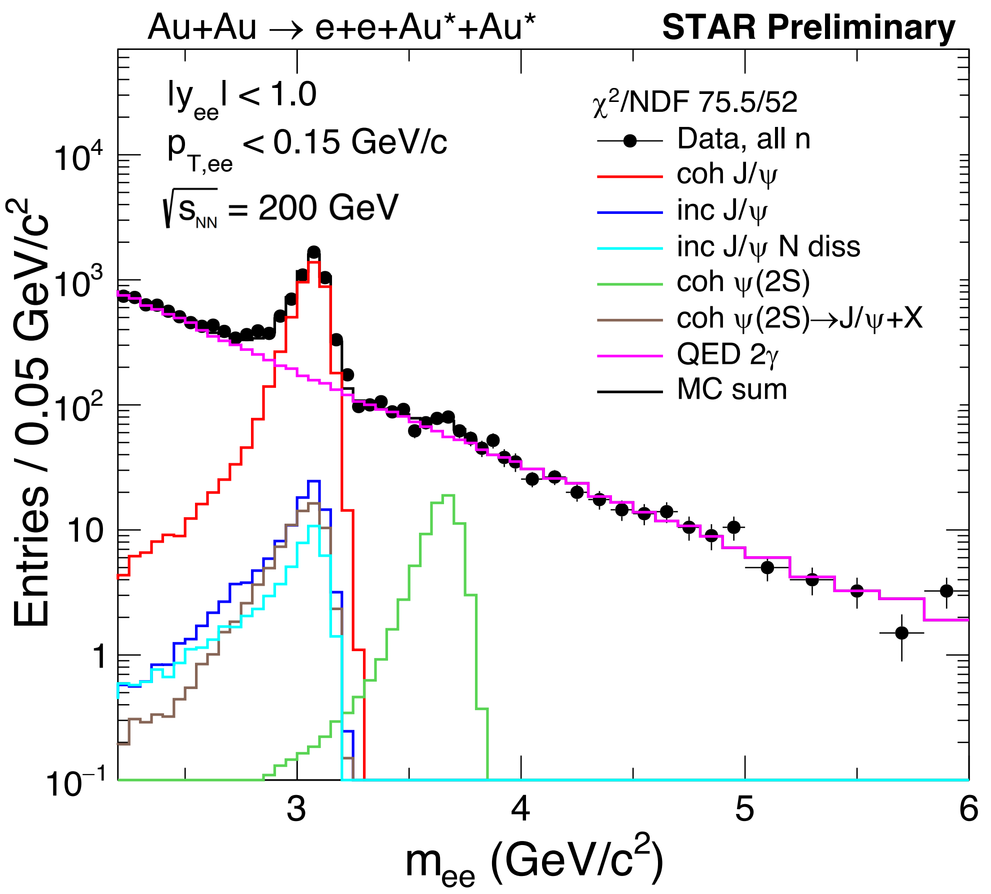
Relevant central detectors

Time Projection Chamber (TPC)

Time-Of-Flight detector (TOF)

Barrel EM Calorimeter (BEMC)

Measuring J/ψ in 200 GeV Au+Au UPCs



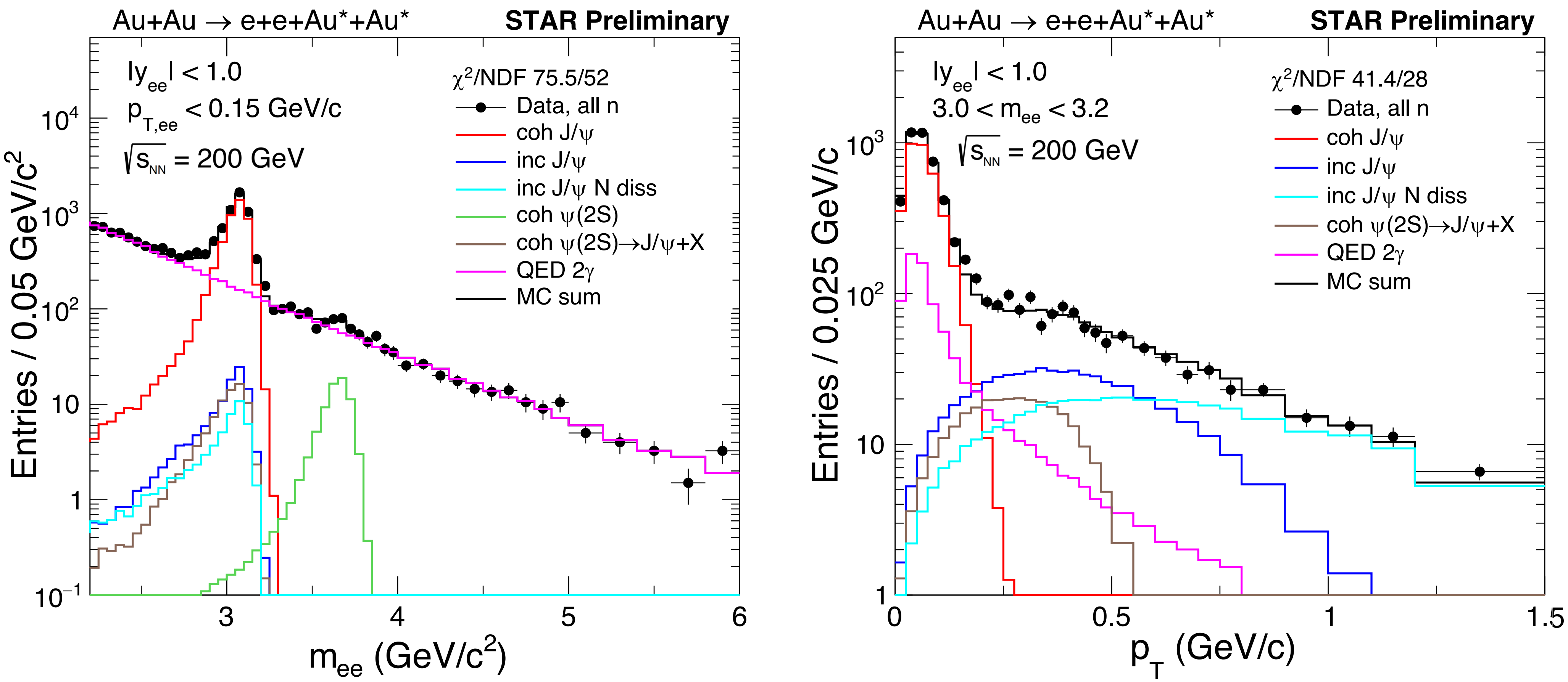
Data analysis:

$J/\psi \rightarrow e^{+}e^{-}$
(|y| < 1.0 for J/ψ, electrons within |η|<1.0)

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

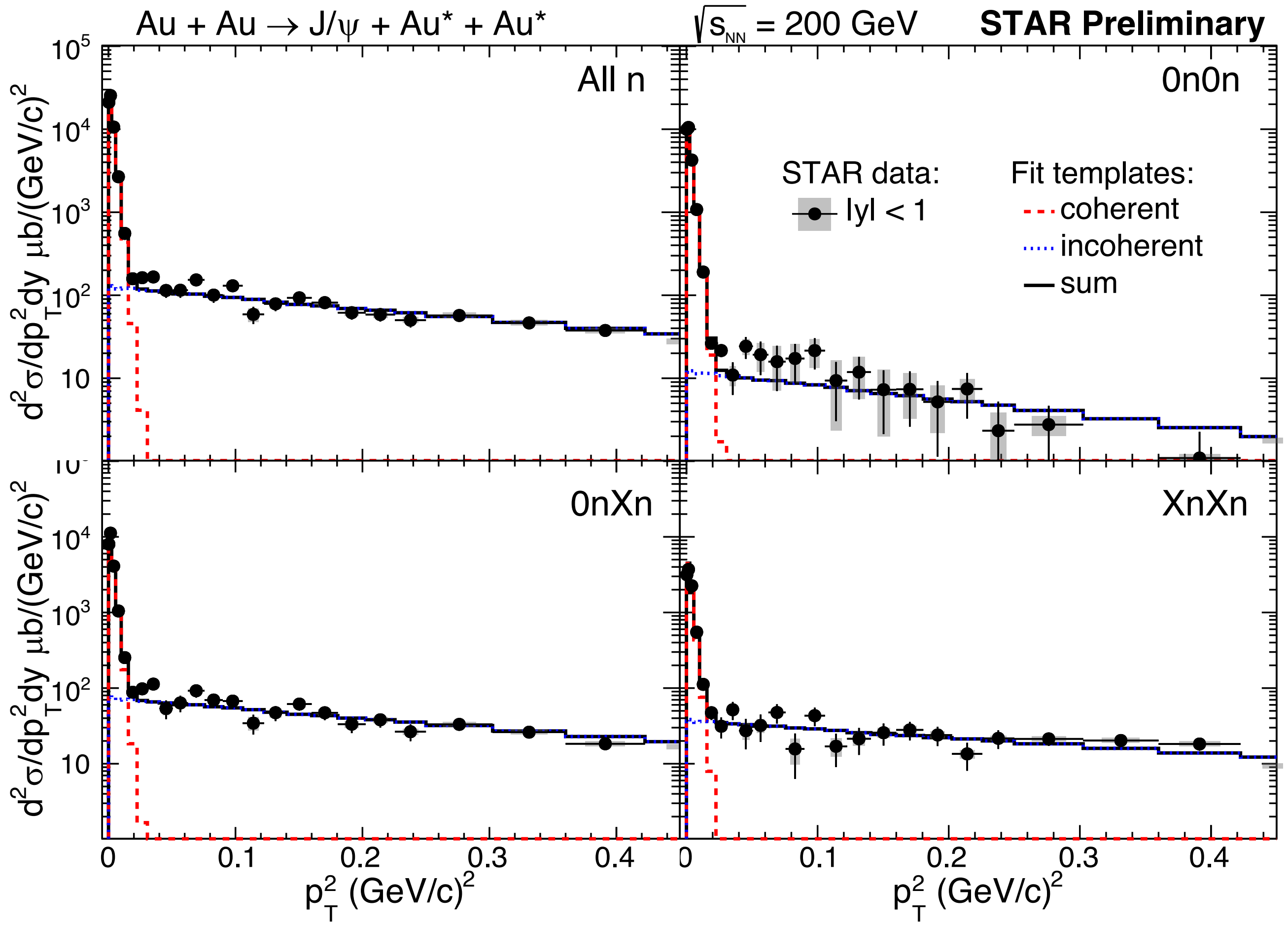
Different templates from STARLight and H1 *ep* data are used to describe the signal and backgrounds.

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 ($t \sim p_T^2$)

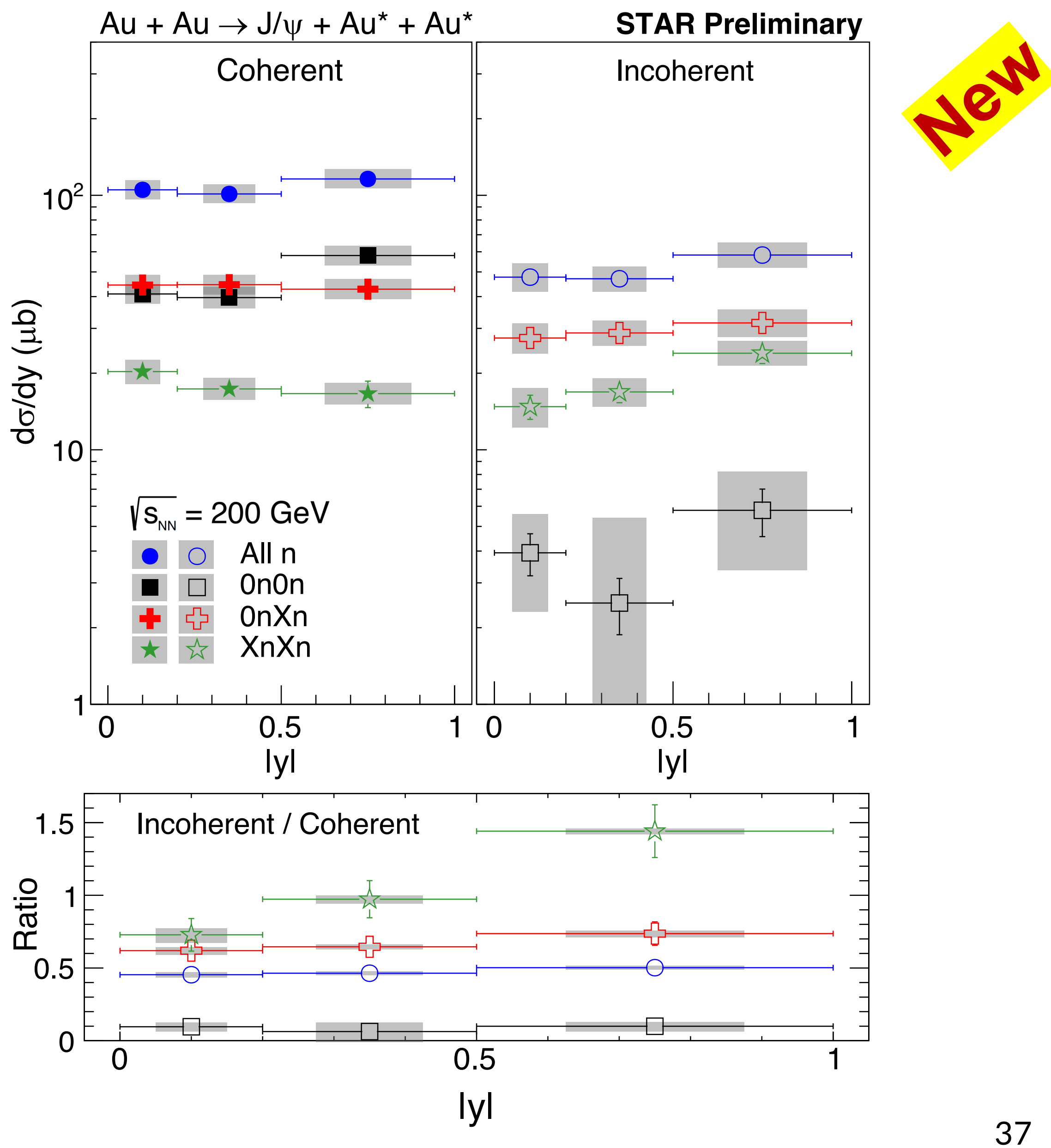
Separating coherent and incoherent J/ψ



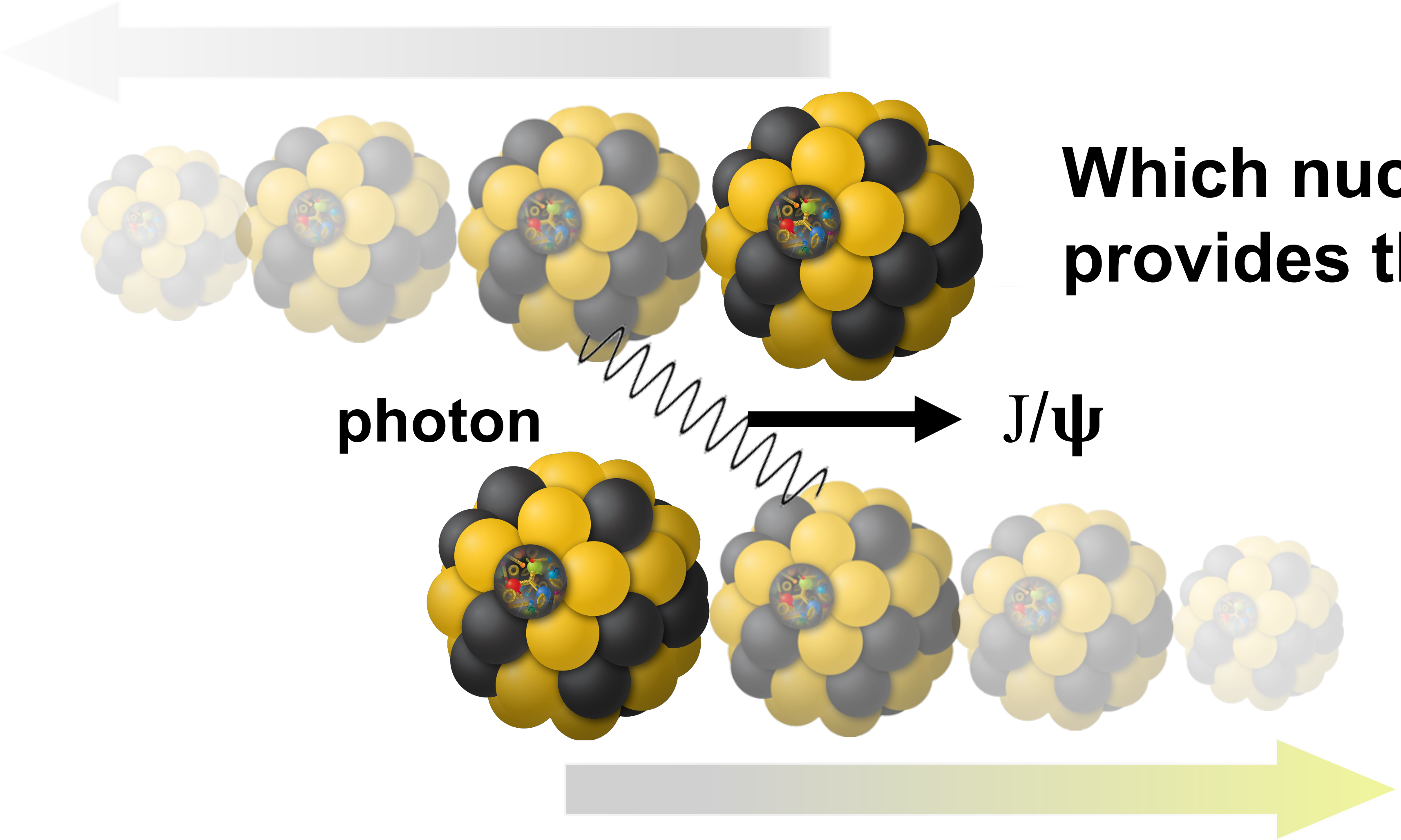
- Low momentum transfer (p_T^2) is dominated by **coherent** photoproduction.
- For incoherent production at low p_T^2, it is extrapolated using different templates.
- These differences, however, are small to the total incoherent production cross section.

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)

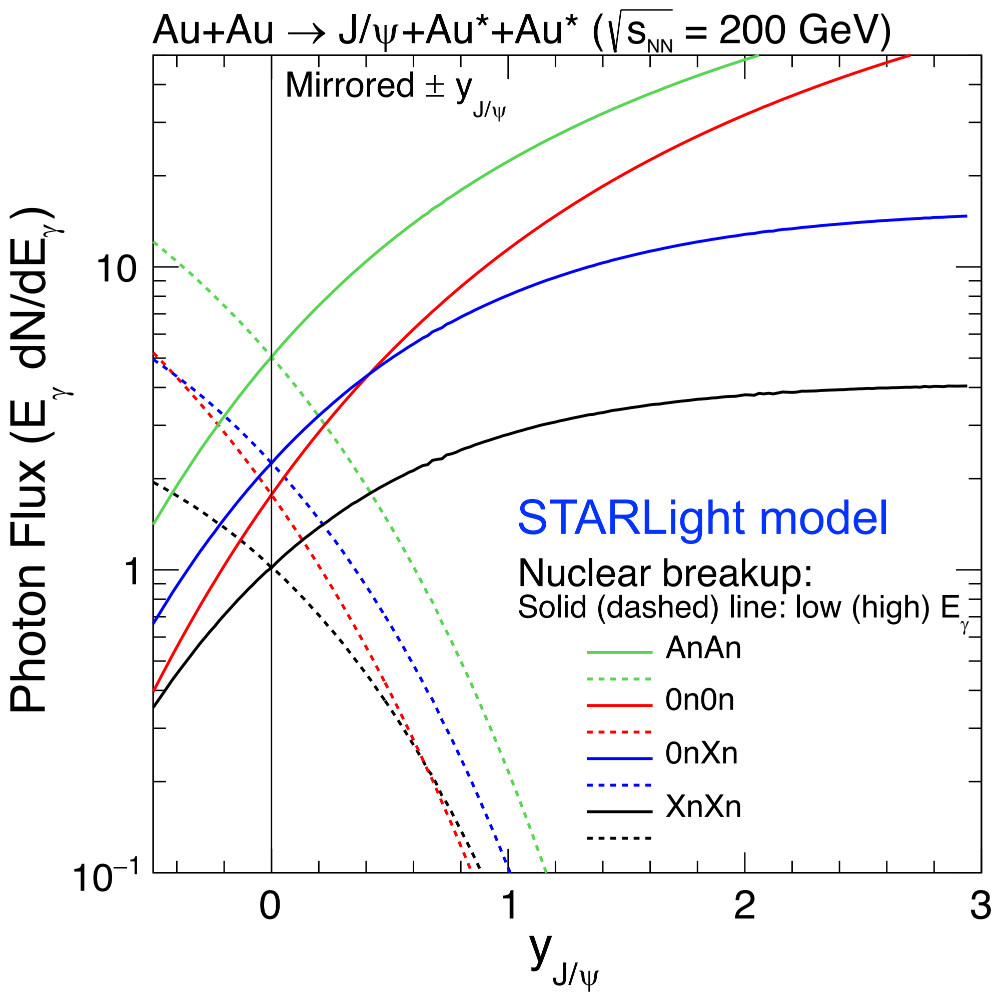


AuAu UPCs: two-source ambiguity



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

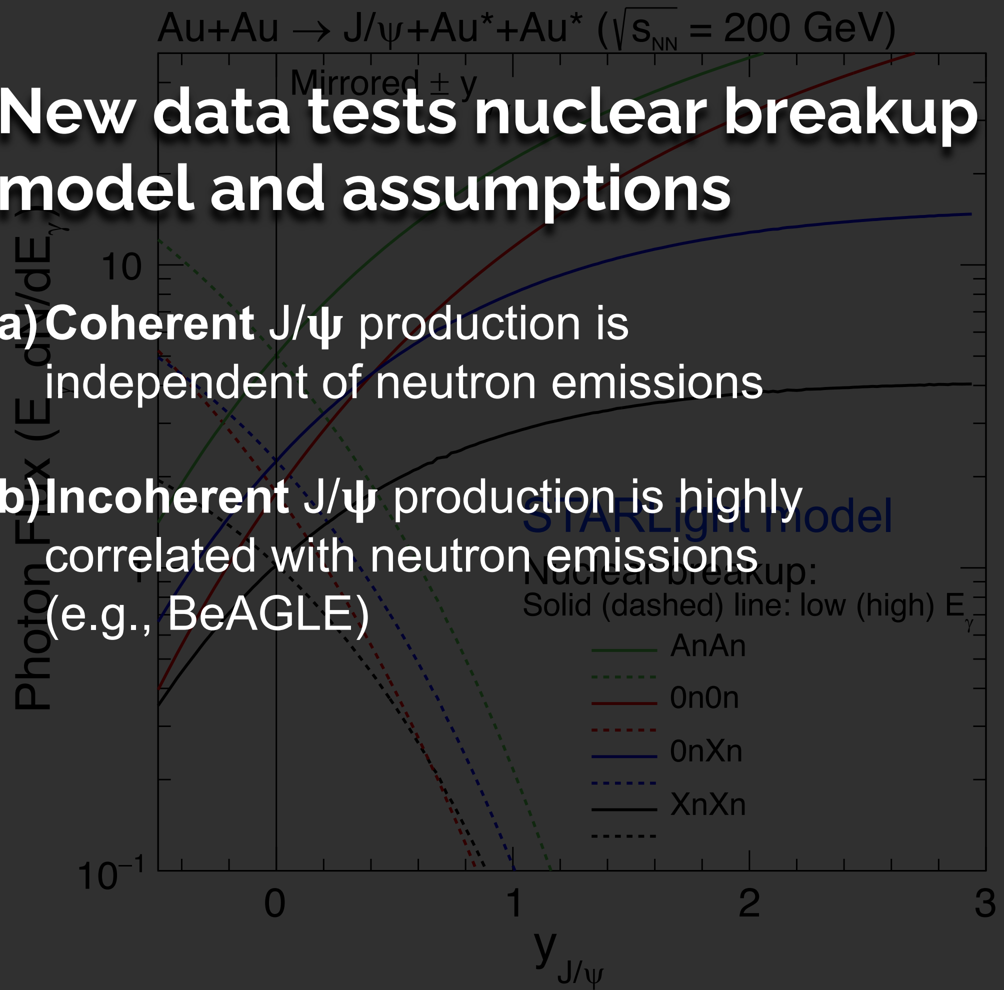
Photon flux and neutron e... s

New

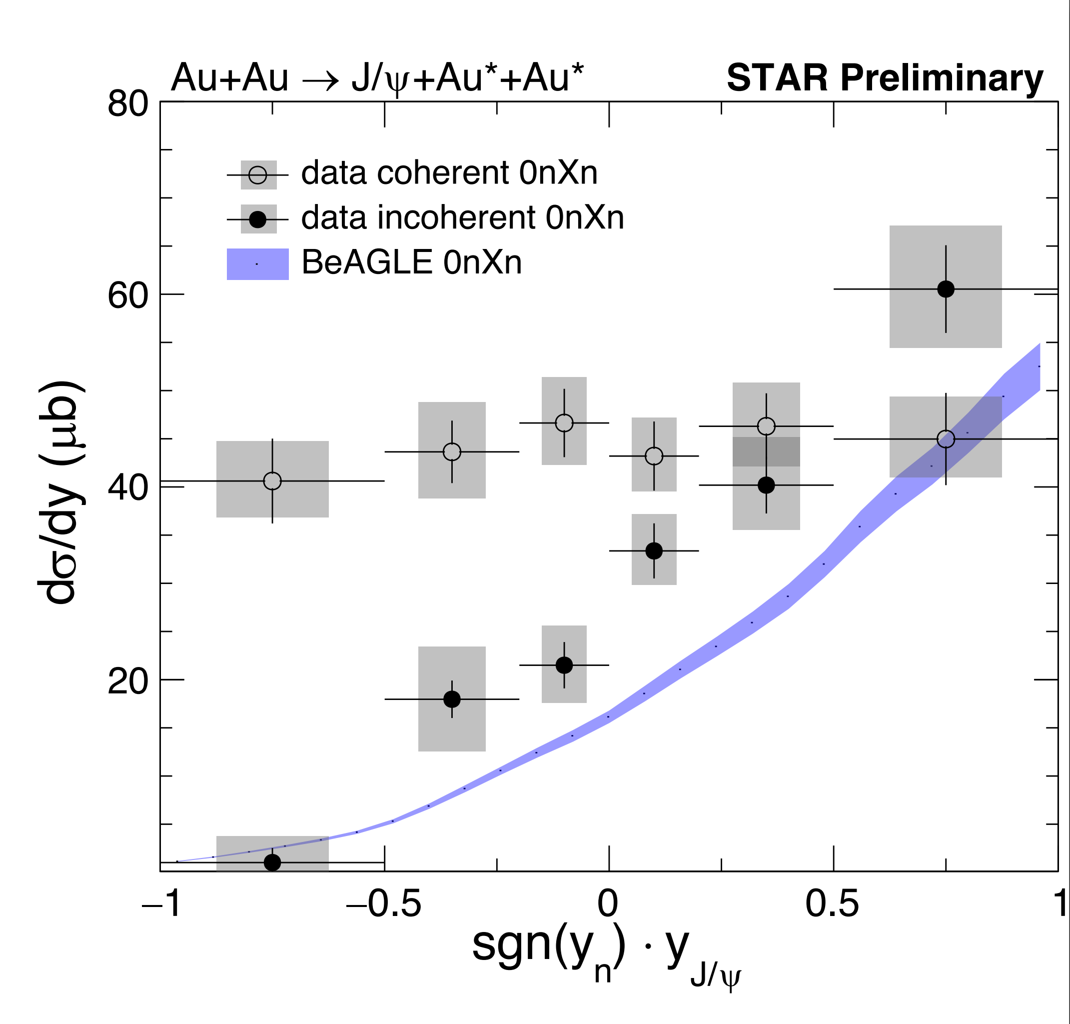
New data tests nuclear breakup model and assumptions

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

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



- If V... ene... ene...
- Diff... diffe...
- **Eac...** emi...



- **XnXn:** >=1 neutron on both sides

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

Neutron emission helps resolve the two-source ambiguity

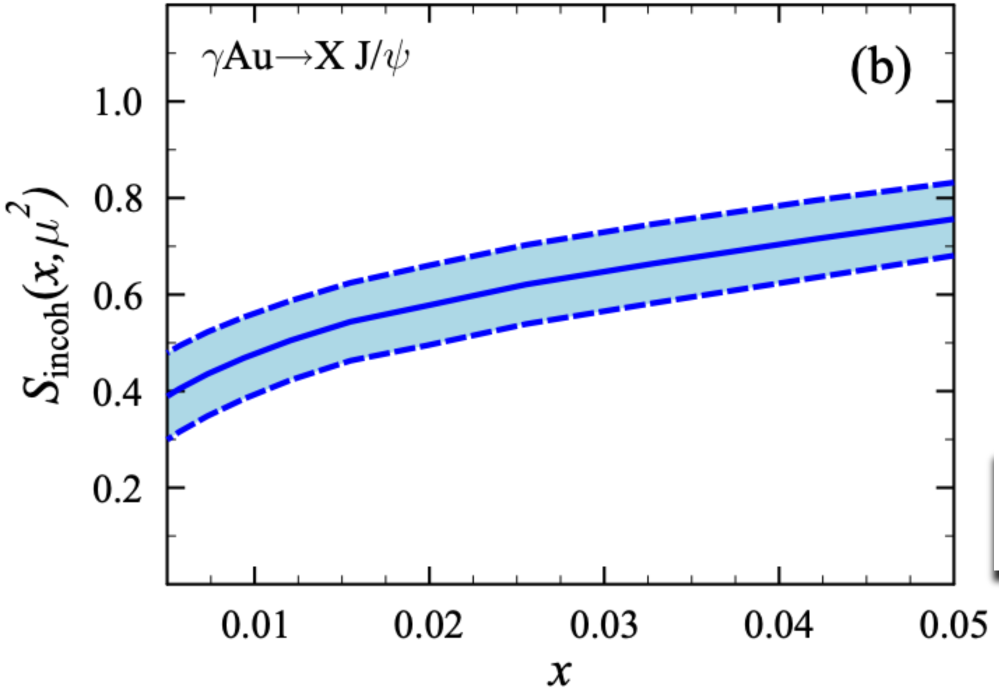
$$d\sigma^{AnBn}/dy = \Phi^{AnBn}_{T.\gamma}(k_1)\sigma_{\gamma^*+\mathrm{Au}\to \mathrm{J}/\psi+\mathrm{Au}}(k_1) + \Phi^{AnBn}_{T.\gamma}(k_2)\sigma_{\gamma^*+\mathrm{Au}\to \mathrm{J}/\psi+\mathrm{Au}}(k_2)$$

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.**

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)

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

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.

NLO calculation

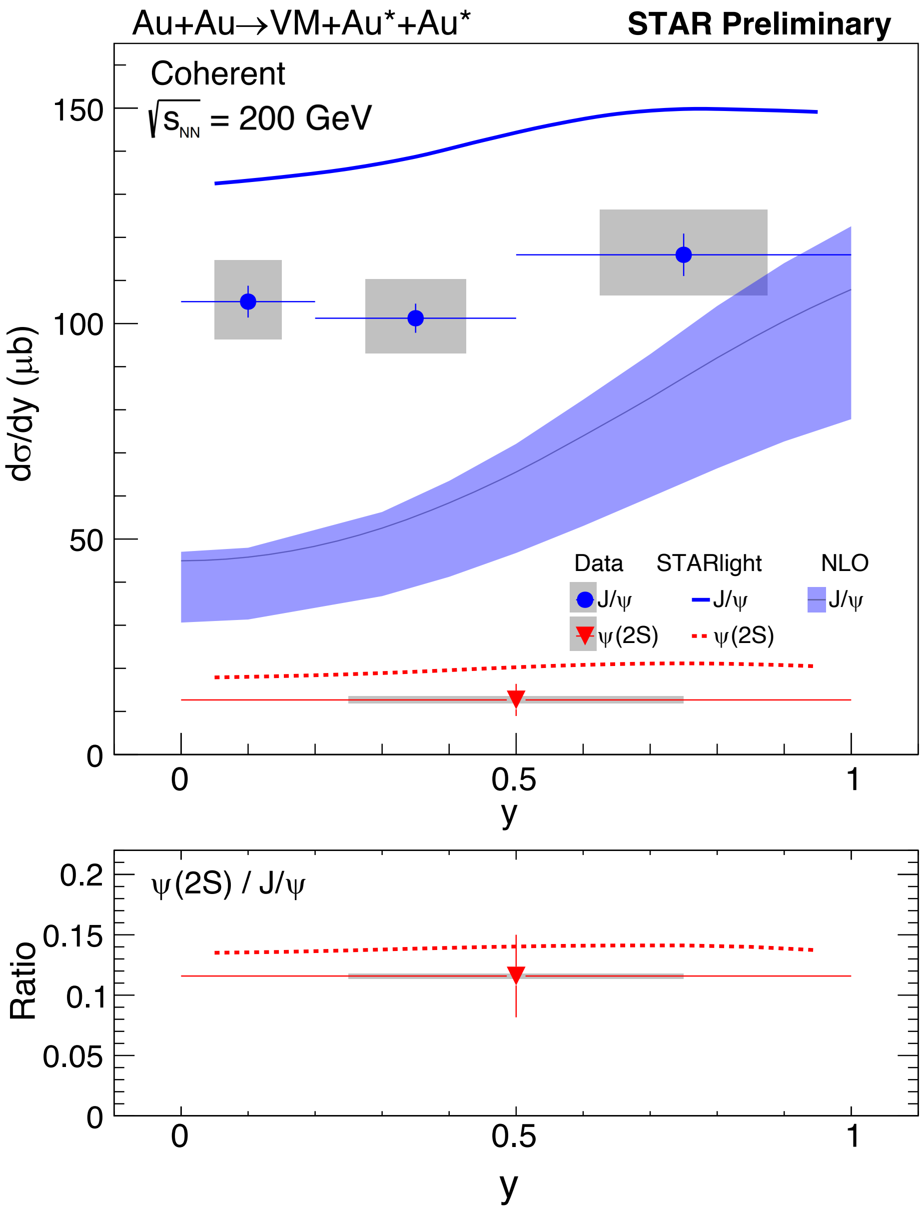
Next-to-Leading Order (NLO) pQCD calculation, constrained **by the LHC data**

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



New

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Saturation observables: Brian Sun, Y. Kovchegov

For discussions and inputs.