UPC 2023: International Workshop on the Physics of Ultra Peripheral Collisions

Supported in part by the
U.S. DEPARTMENT OF ENERGY | Office of Science

Creighton UNIVERSITY

DAVID TLUSTY (CREIGHTON UNIVERSITY)
*FOR THE STAR COLLABORATION*

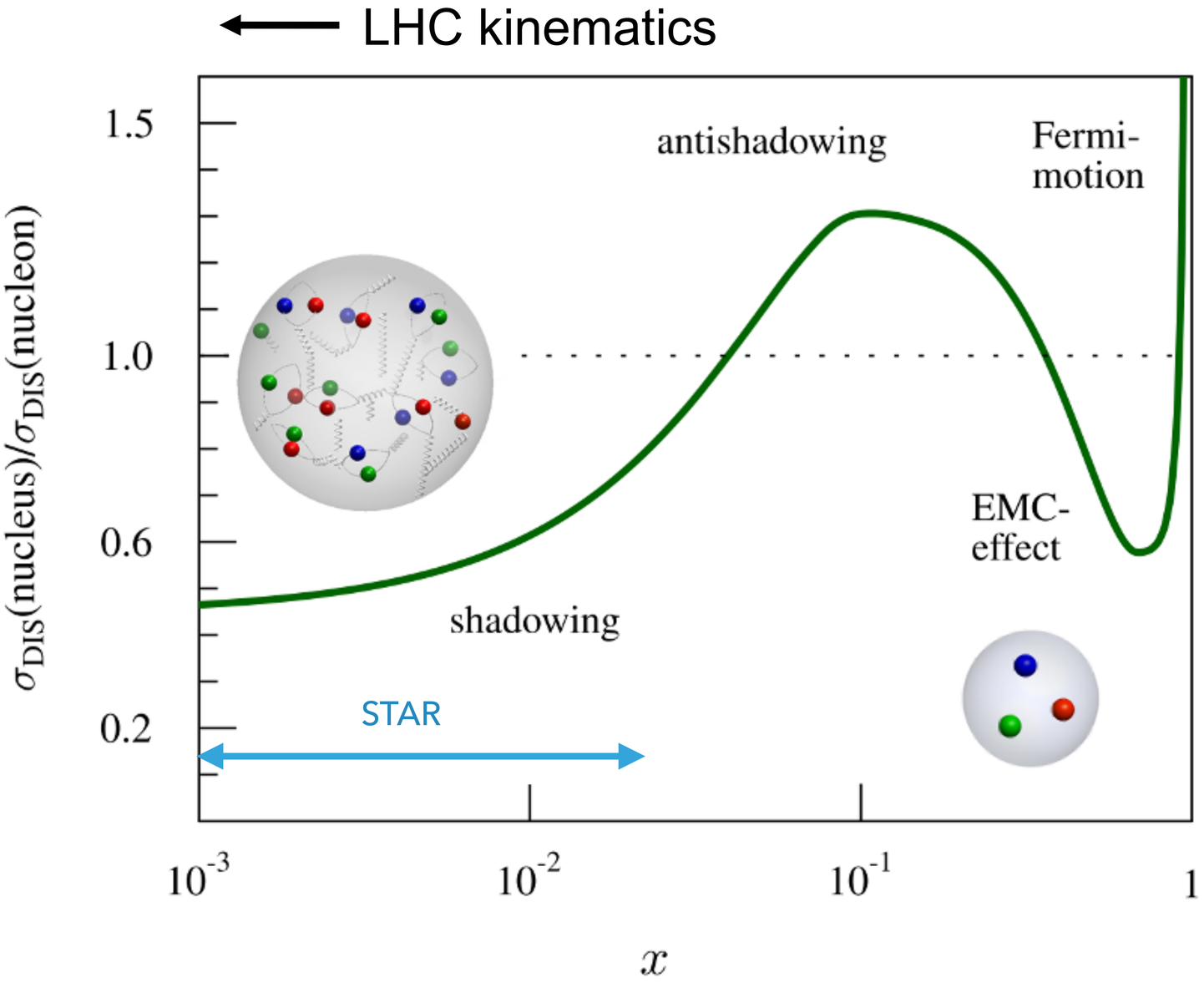
# STAR UPC RESULTS

# OUTLINE

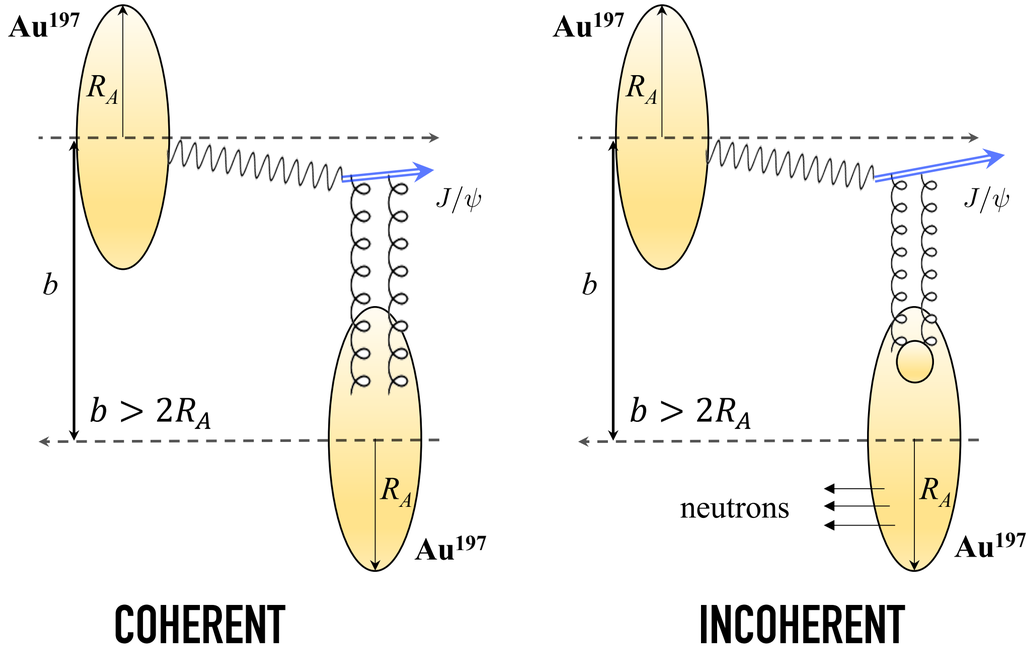
- STAR Experiment
- Recently Published UPC Results from STAR
  - coherent $\rho_0$ and nuclear imaging
  - coherent and incoherent $J/\psi$ photo-production in d+Au and Au+Au
  - coherent $\psi(2S)$ photo-production in Au+Au
  - di-leptons from Breit-Wheeler process
- Highlights of the newest preliminary results
- Outlook
- Summary

# MOTIVATION

- nuclear parton modification - important in cold QCD
- nuclear shadowing at lower x
- anti-shadowing at higher x

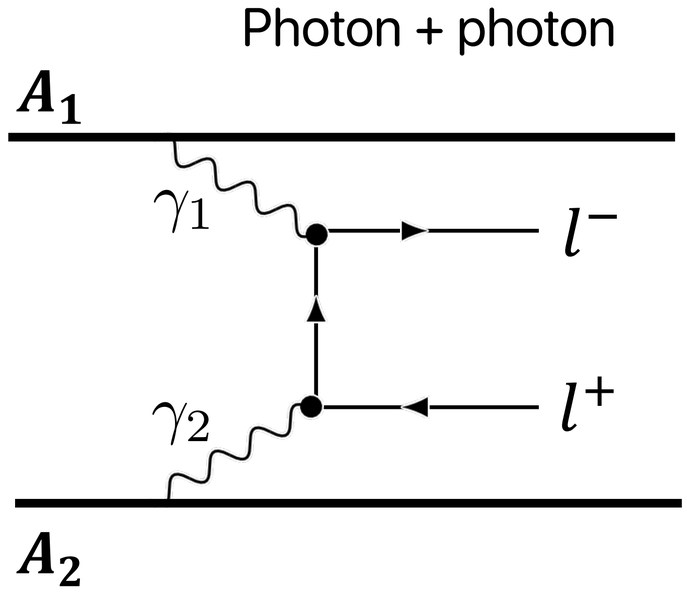


# UPC AS A GREAT TOOL TO EXPLORE NUCLEAR EFFECTS




**COHERENT** **INCOHERENT**

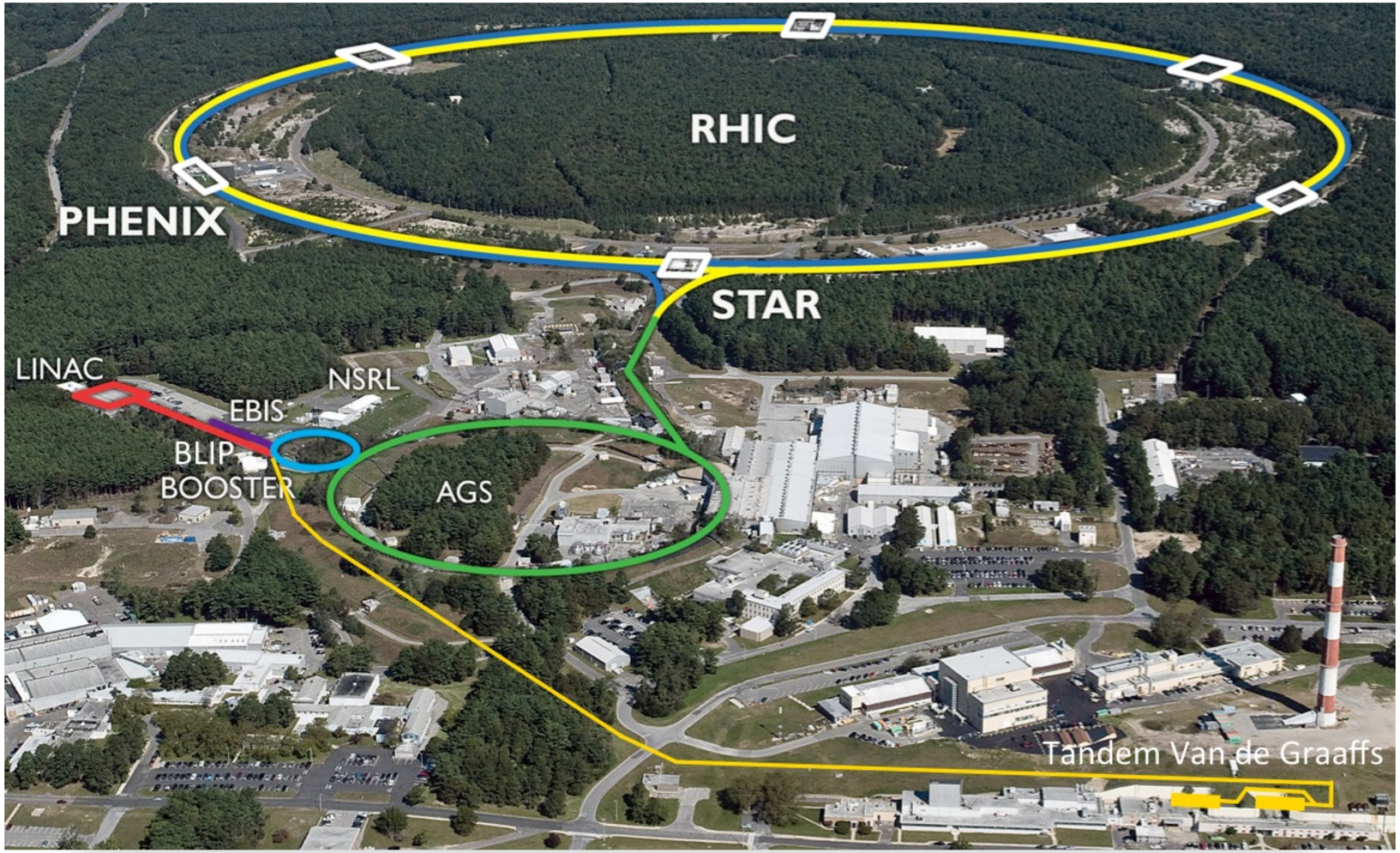
- clean probe to the nuclear parton distributions
- coherent (on nucleus) and incoherent (on nucleons)
- coherent photo production
  - $x = (M_{VM}c^2)^2/W^2$
  - final state is exclusive




- explore non-linear QED
- test for Physics Beyond Standard Model

# UTRA-PERIPHERAL COLLISIONS AT RHIC

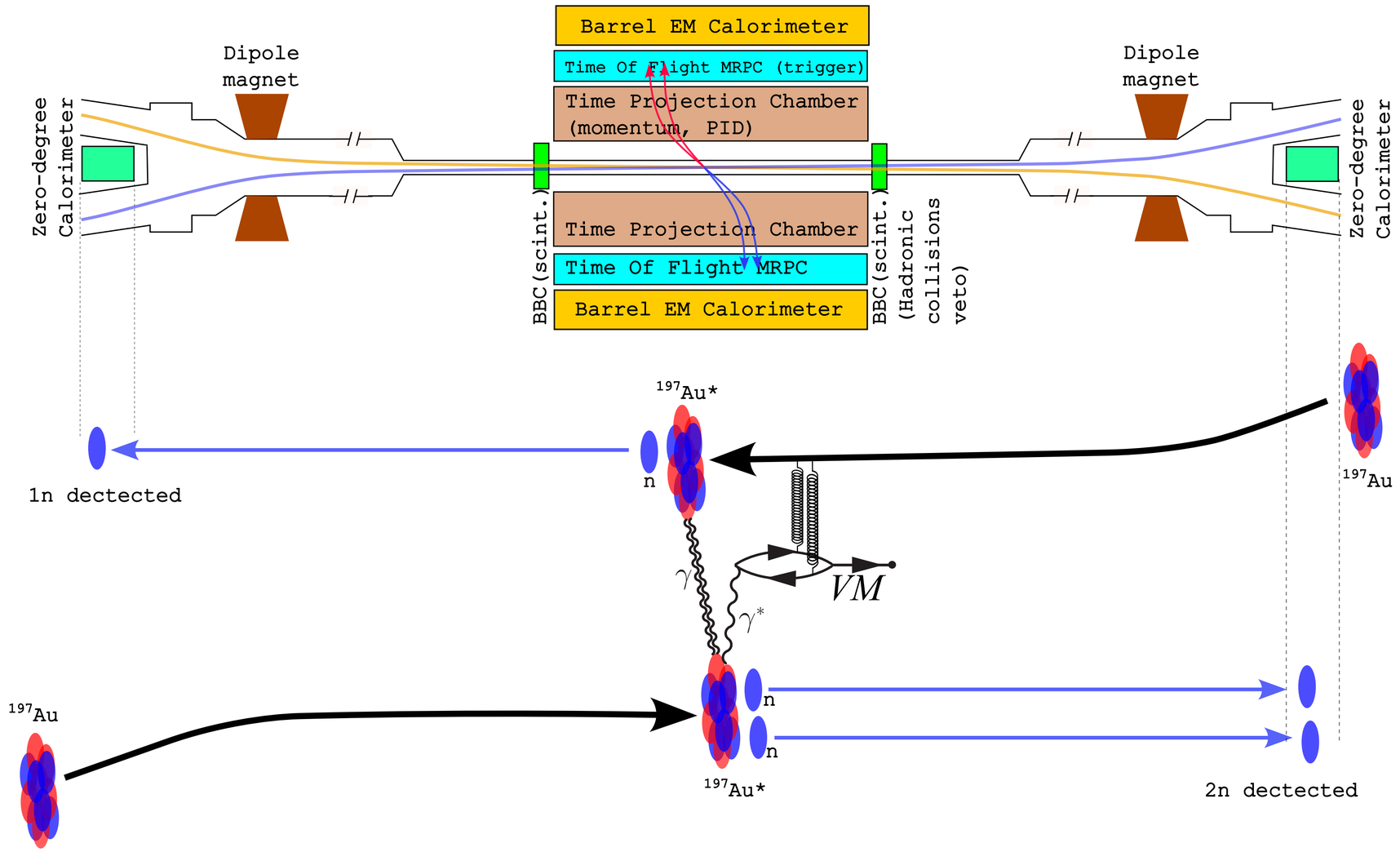
- Relativistic Heavy Ion Collider
  - located in Brookhaven National Laboratory (Long Island, USA)
- different species, energy, and proton polarization




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

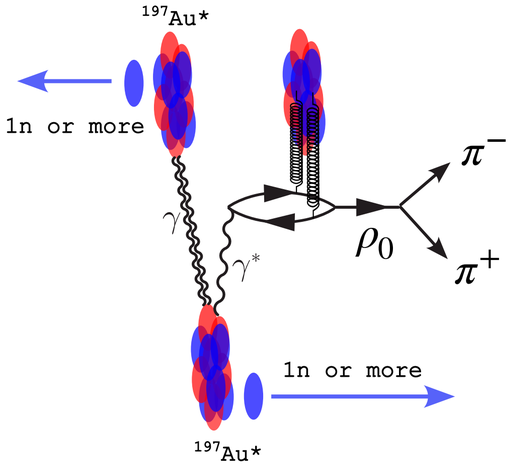
# STAR EXPERIMENTAL SETUP (UPC RELEVANT DETECTORS ONLY)

- Solenoidal Tracker At RHIC
- central rapidity coverage
  - $(-1,1) \overset{2019}{\Longrightarrow} (-1.5,1.5)$
- neutron tagging
- charged hadrons PID
  - plus electron calorimetry including decay topology
- veto particles in the UPCs rapidity gap regions



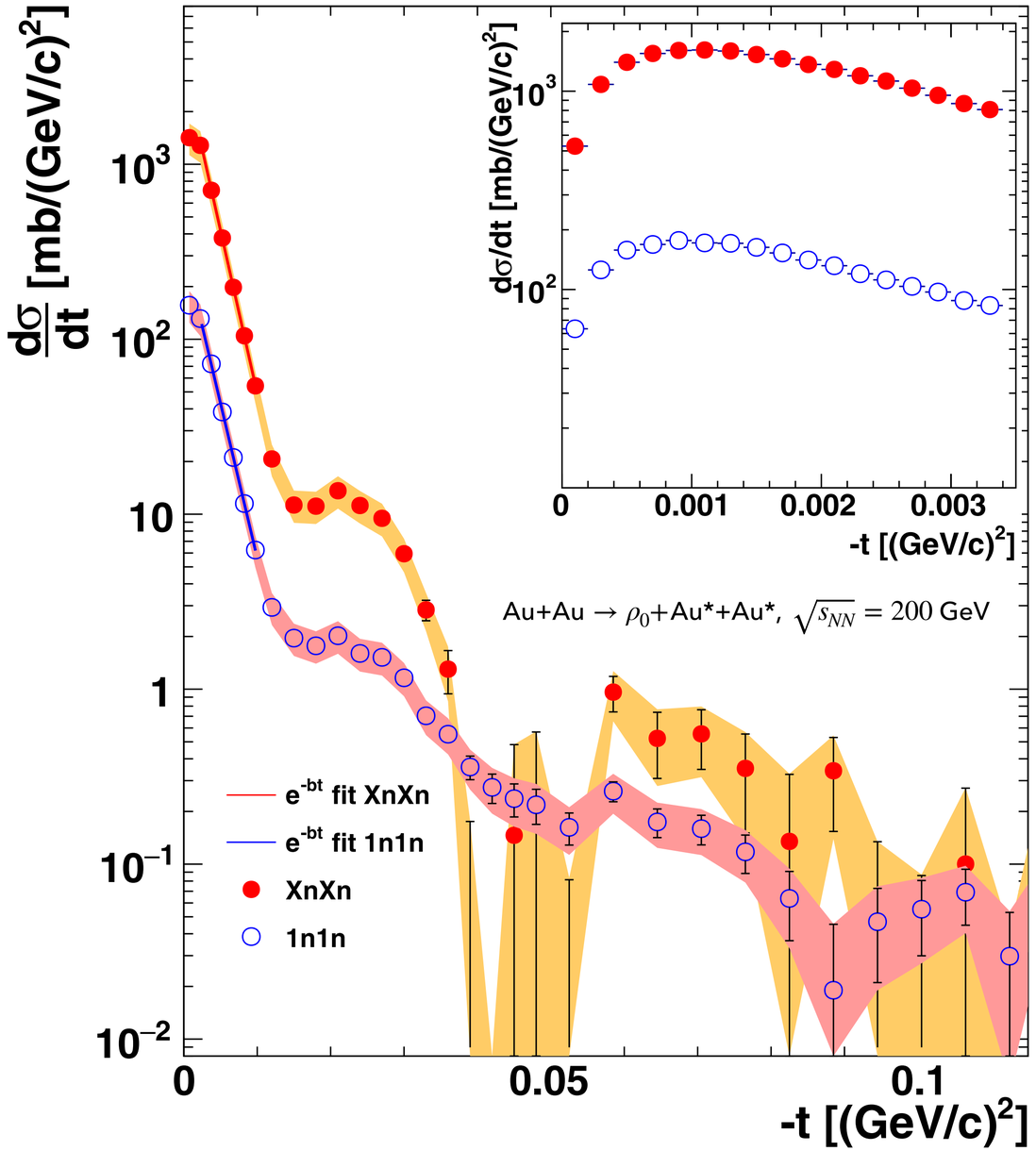
# $\rho_0$ CROSS SECTION AND INTERFERENCE

Phys. Rev. C 96, 054904




- integrated luminosity of 1100±100 $\mu b^{-1}$ of data collected in 2010
- XnXn extrapolated from 1n1n using STARlight

- multiple diffractive minima in the coherent region
  - nucleus is beginning to act like a black disk
  - lowest $-t$: destructive interference between photo production with the photon emitted by any of the two pions
  - position should not depend on energy

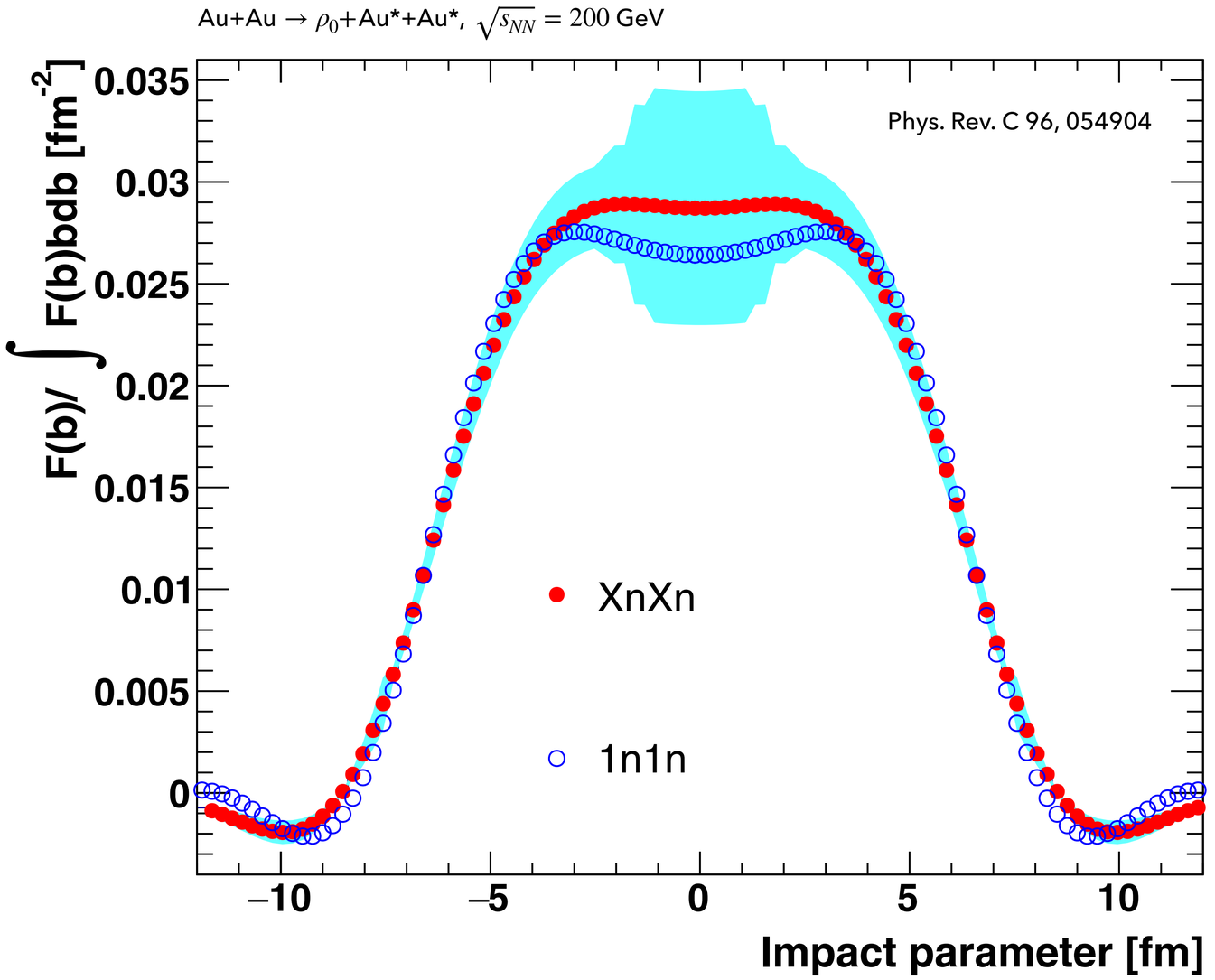


# NUCLEAR IMAGING

- $-t$ is Fourier conjugate to the impact parameter

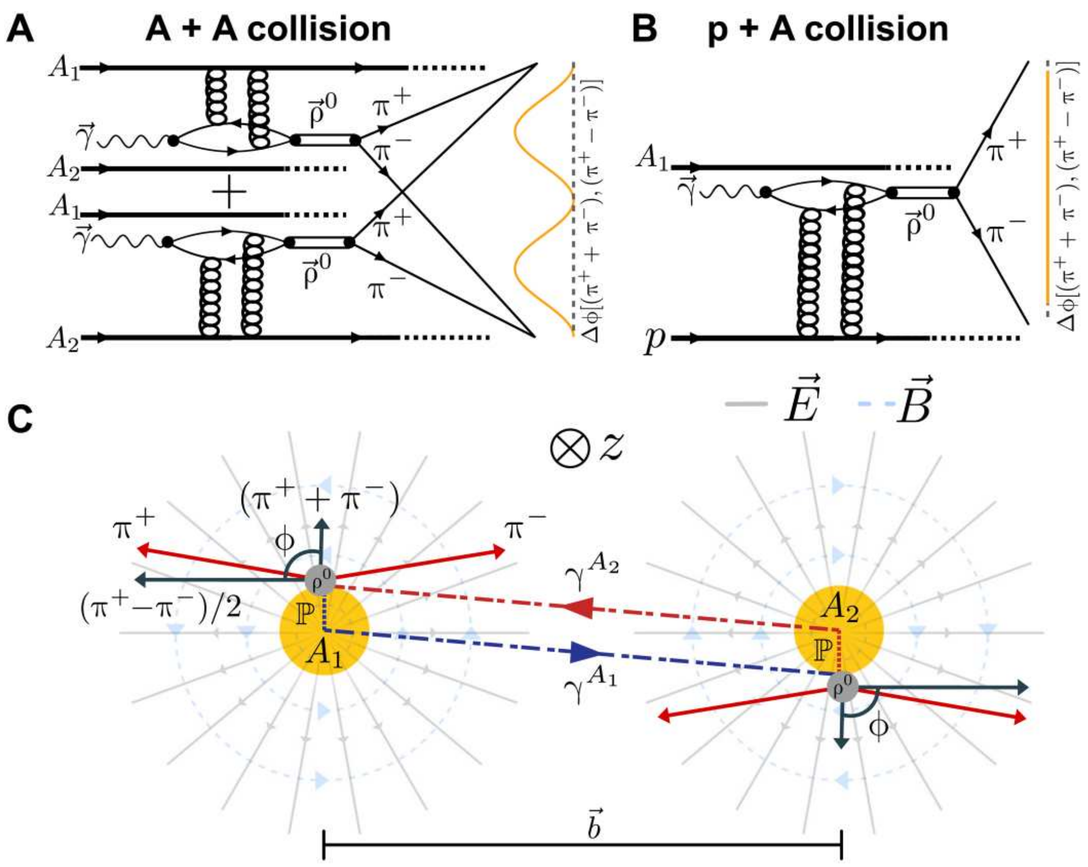
$$F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T\, p_T\, J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$$

  - $|t| < 0.06(\mathrm{GeV}/c)^2$
  - F(b) normalized by mean value to compare XnXn and 1n1n
- the radius include interference effects



# IMAGING A NUCLEUS WITH VECTOR MESON PHOTO-PRODUCTION

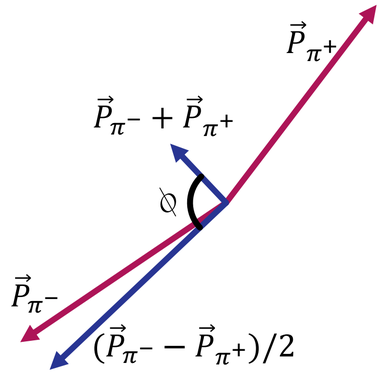
Sci. Adv. 9, eabq3903 (2023)




- photons linearly polarized in transverse plane
  - Spin 1 photon polarization vector => vector meson => orbital angular momentum of the daughter particles => azimuthal $\cos(2\phi)$ modulation in the momentum distribution with respect to the polarization direction
  - interference between two contributing amplitudes (panel A)
- possible in symmetric beams
- still subject of discussions in community

$$\cos\phi = \frac{(\overrightarrow{p_{\pi^-}} + \overrightarrow{p_{\pi^+}}) \cdot (\overrightarrow{p_{\pi^-}} - \overrightarrow{p_{\pi^+}})}{|\overrightarrow{p_{\pi^-}} + \overrightarrow{p_{\pi^+}}| \times |\overrightarrow{p_{\pi^-}} - \overrightarrow{p_{\pi^+}}|}$$

$$|\overrightarrow{p_{\pi^-}} + \overrightarrow{p_{\pi^+}}| \ll |\overrightarrow{p_{\pi^-}} - \overrightarrow{p_{\pi^+}}|$$



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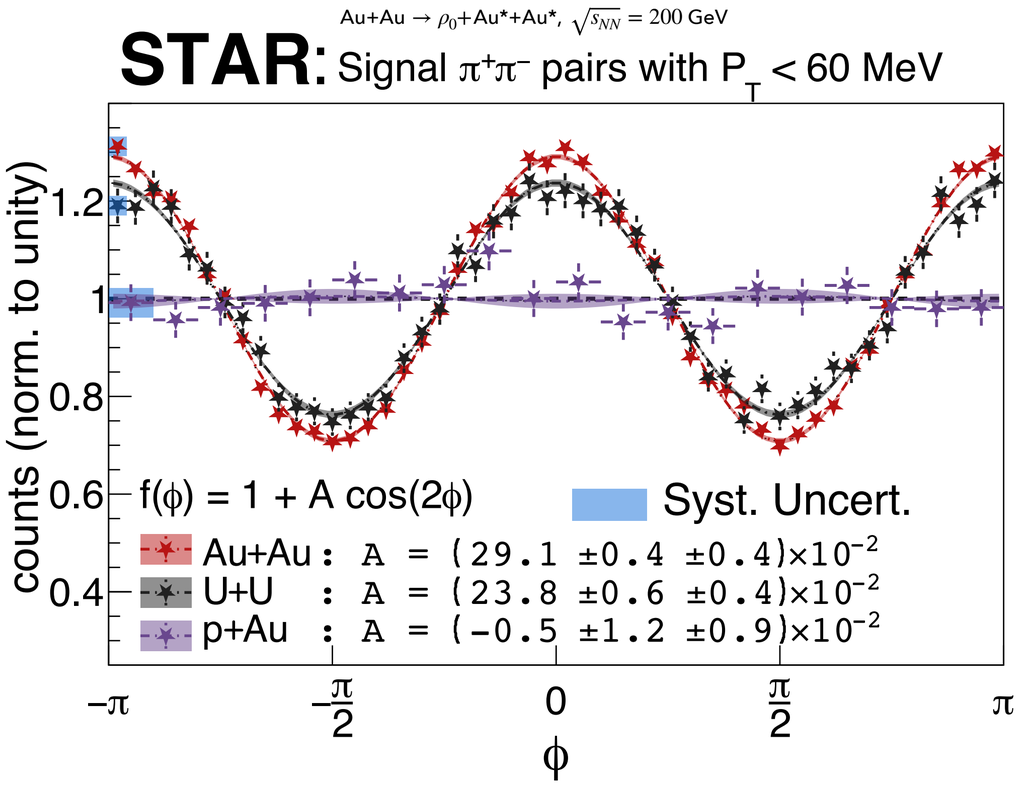
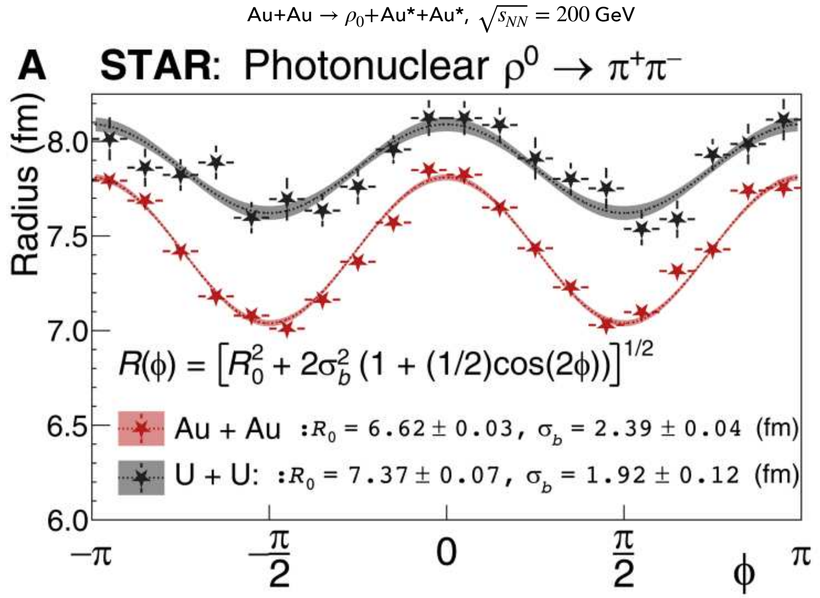


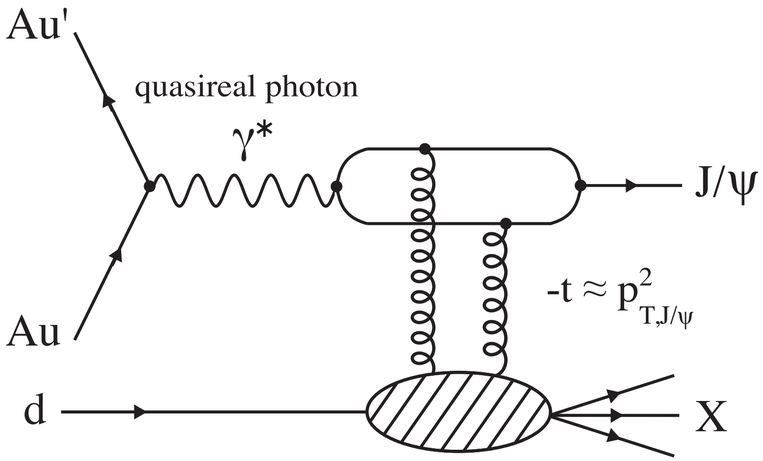

- the modulation is observed both in Au+Au and U+U, but not in p+Au

- fit of Fourier conjugated Wood-Saxon into $\rho_0$ $p_T^2$ spectra => extract Radius $R(\phi)$ Ashik Ikbal Sheikh (Tuesday 11:45am)
- $R_0$ - radius from nuclear form factor - consistent with low energy experiments
- $\sigma_b$ quantifies the strength of the interference effect
- solves 20 year puzzle of seemingly higher than expected nuclear radius



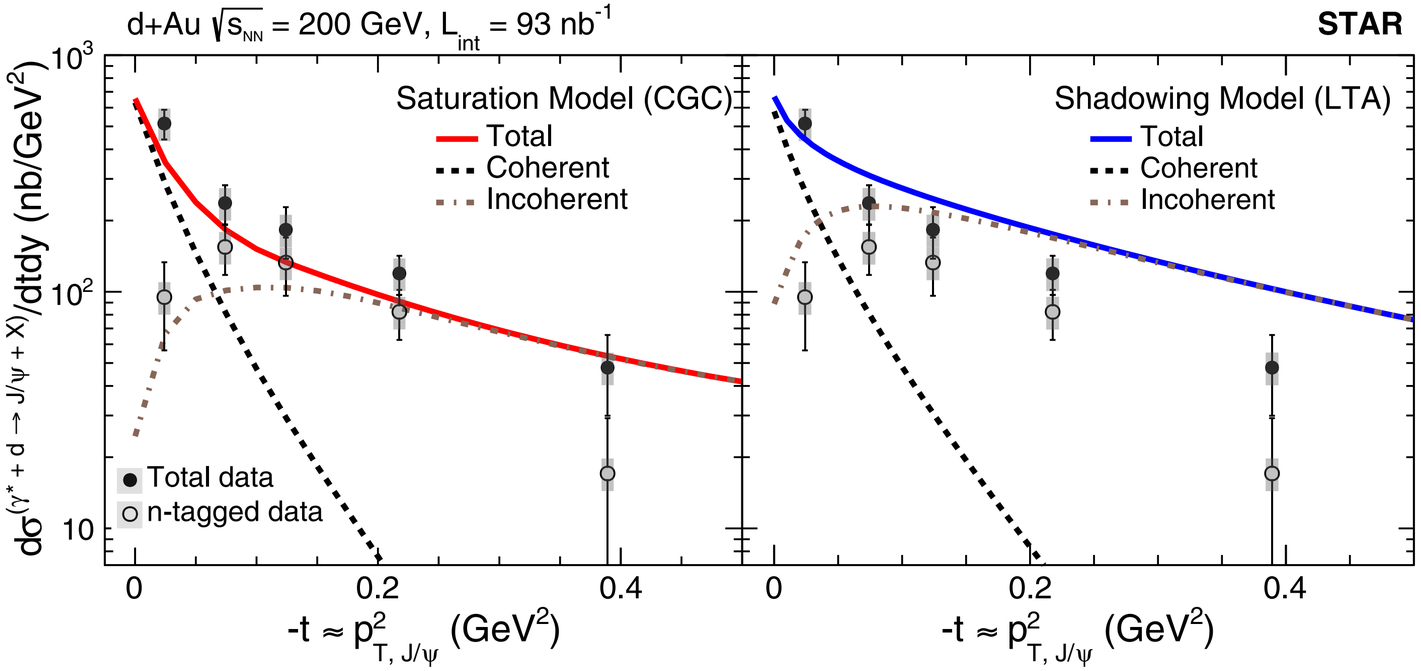
# $J/\psi$ CROSS SECTION IN D+AU UPC EVENTS AT 200 GEV

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




- integrated luminosity of 93 $nb^{-1}$ of d+Au data collected in 2016
- $J/\psi \rightarrow e^+e^-$ decay channel

- first $J/\psi$ produced off a light ion
  - deuteron loosely bound => ideal for testing baseline nuclear effects



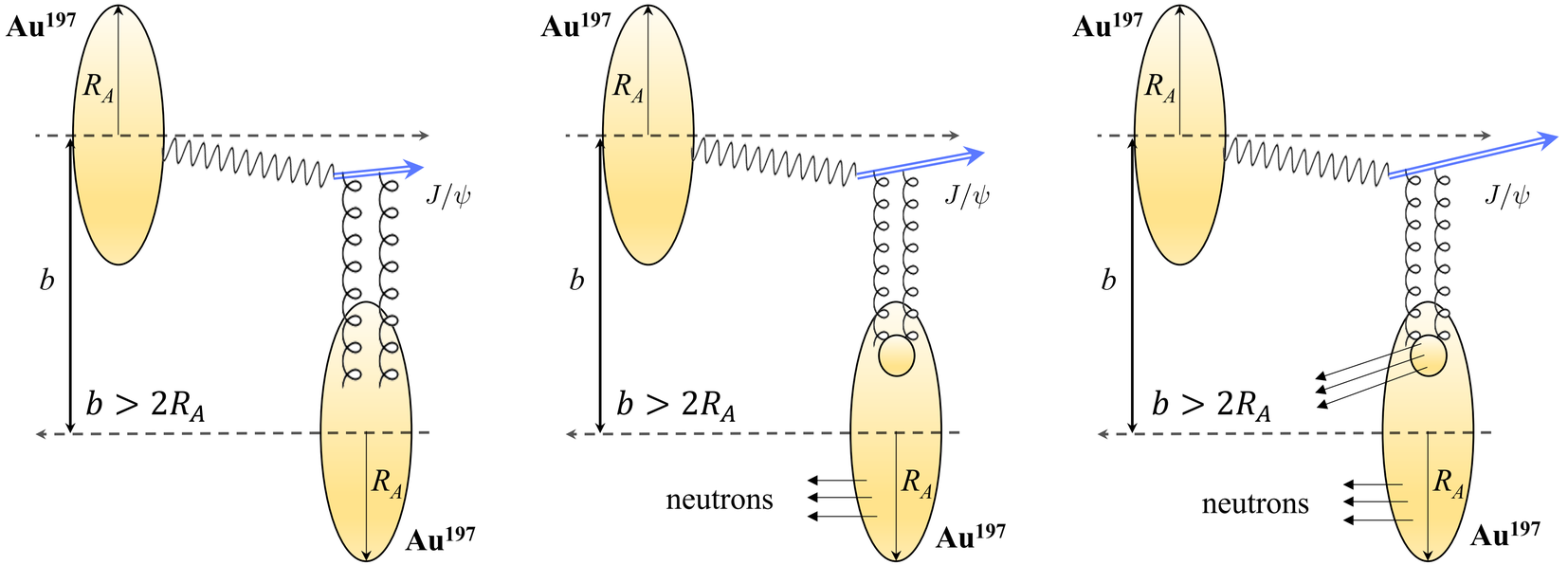

CGC Model Ref: H. Mäntysaari and B. Schenke, Phys. Rev. C 101, 015203 (2020), arXiv:1910.03297 [hep-ph].

LTA Model: V. Gauzy, M. Strickman, E. Kryshen, and M. Zhalov (2021)

- n-tagged data provide the first direct measurement of incoherent diffractive $J/\psi$ production at low $-t$
- essential experimental baseline for a high precision measurement at EIC

# $J/\psi$ PHOTOPRODUCTION IN AU+AU UPC EVENTS AT 200 GEV

- integrated luminosity of 13.5 $nb^{-1}$ of Au+Au data collected in 2016
- $J/\psi \rightarrow e^+e^-$ decay channel

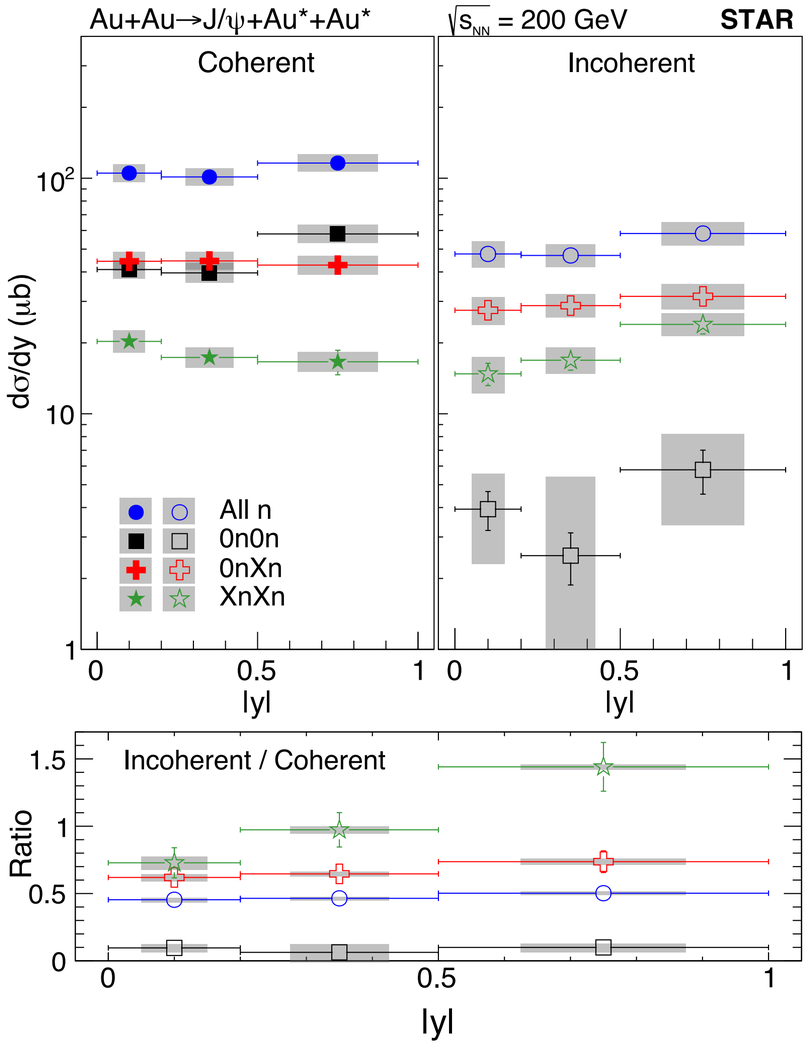



(a) Coherent, nucleus stays intact

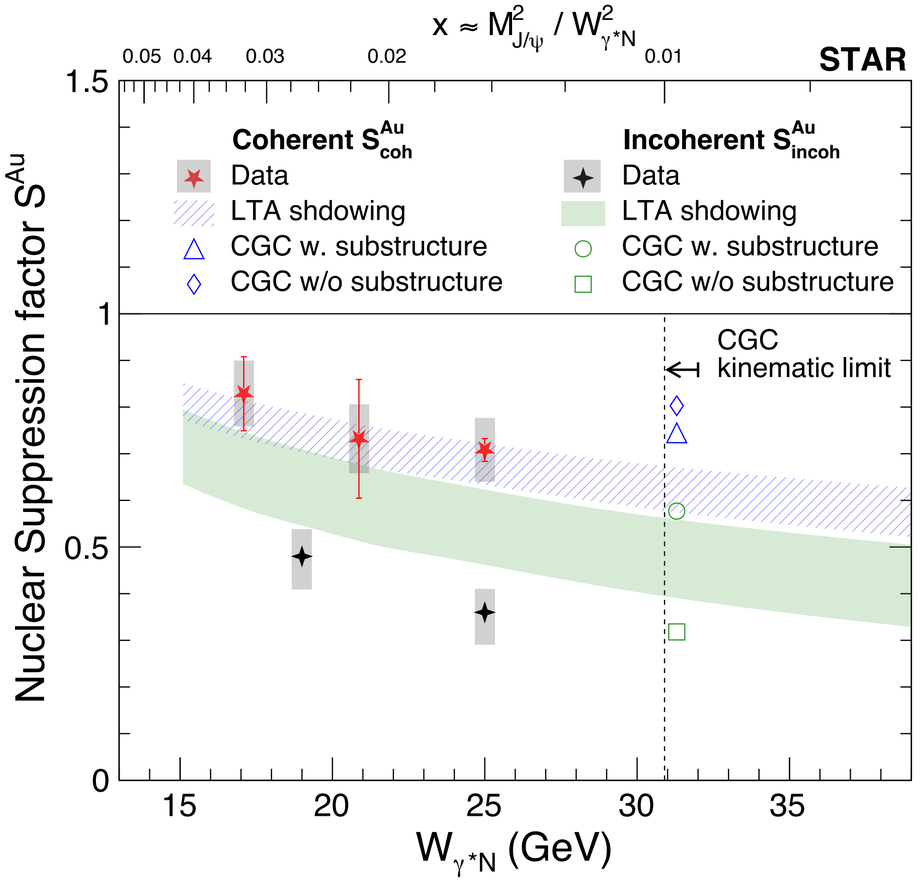
(b) Incoherent with elastic nucleon

(c) Incoherent with nucleon dissociation

# NUCLEAR SUPPRESSION FACTOR




- $S^{Au}_{coh}$ - ratio of all n (regardless of #n) and Impulse Approximation (IA)
- $S^{Au}_{incoh}$ - ratio of all n and HERA H1 Ref: Eur. Phys. J. C 73, 2466 (2013)
- Incoherent production more suppressed than Leading Twist Approximation (LTA) prediction
- $W_{\gamma^*N}$ range will be extended by STAR forward upgrade
- more details in Jaroslav Adam's talk (Tuesday 11:15)

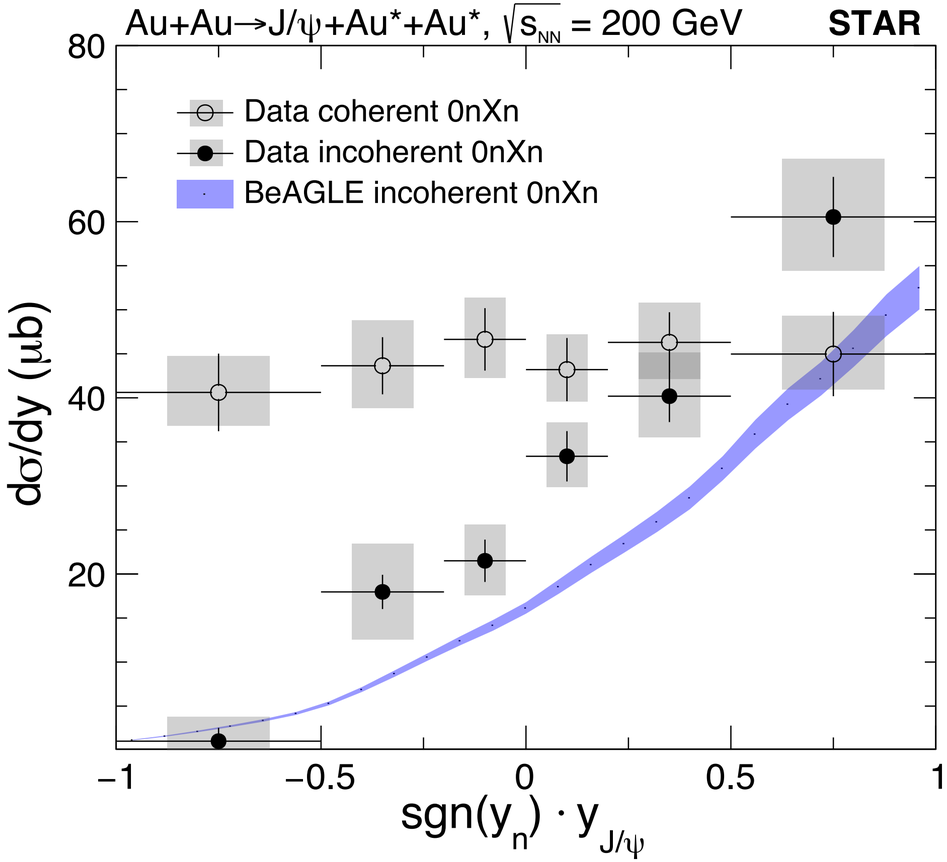



CGC Model Ref.: H. Mäntysaari and B. Schenke, arXiv:2207.03712 [hep-ph] (2022).

LTA Model Ref.: M. Strickman, E. Kryshen, and M. Zhalov arXiv:2303.12052 [hep-ph] (2023).

# RAPIDITY OF COHERENT AND INCOHERENT $J/\psi$ PHOTO PRODUCTION

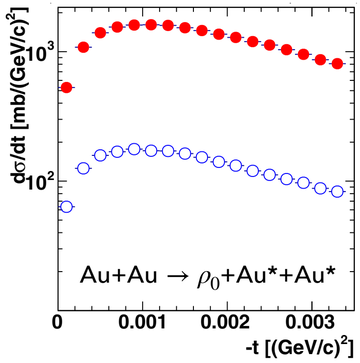
- STAR can tag processes by neutron detection in ZDC
- $y_n$ - rapidity of the neutron
- coherent $J/\psi$ symmetric => neutron emission through mutual Coulomb excitation

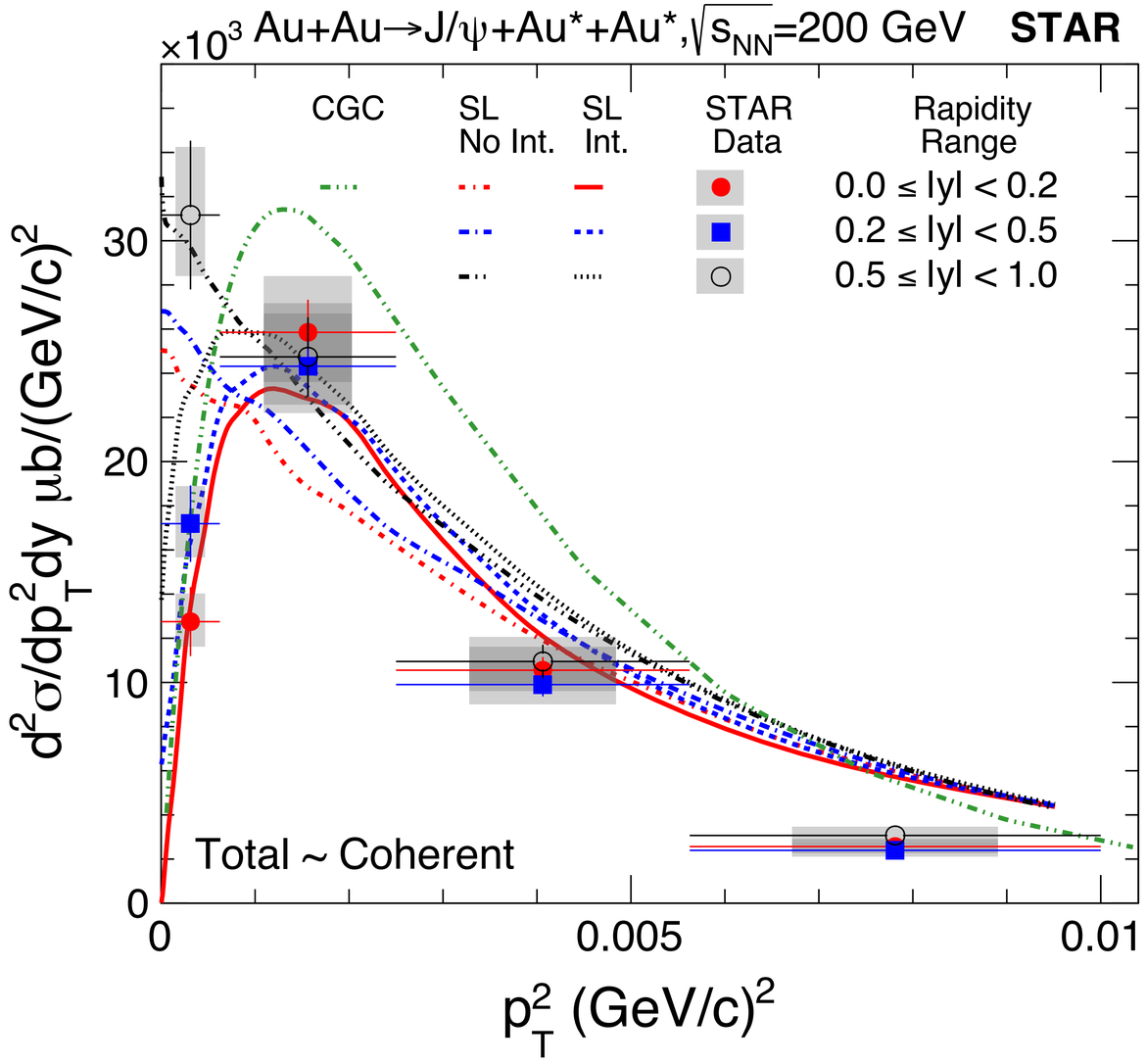



BeAGLE - model of incoherent $J/\psi$ production
Pays. Rev. D 106, 012007 (2022)

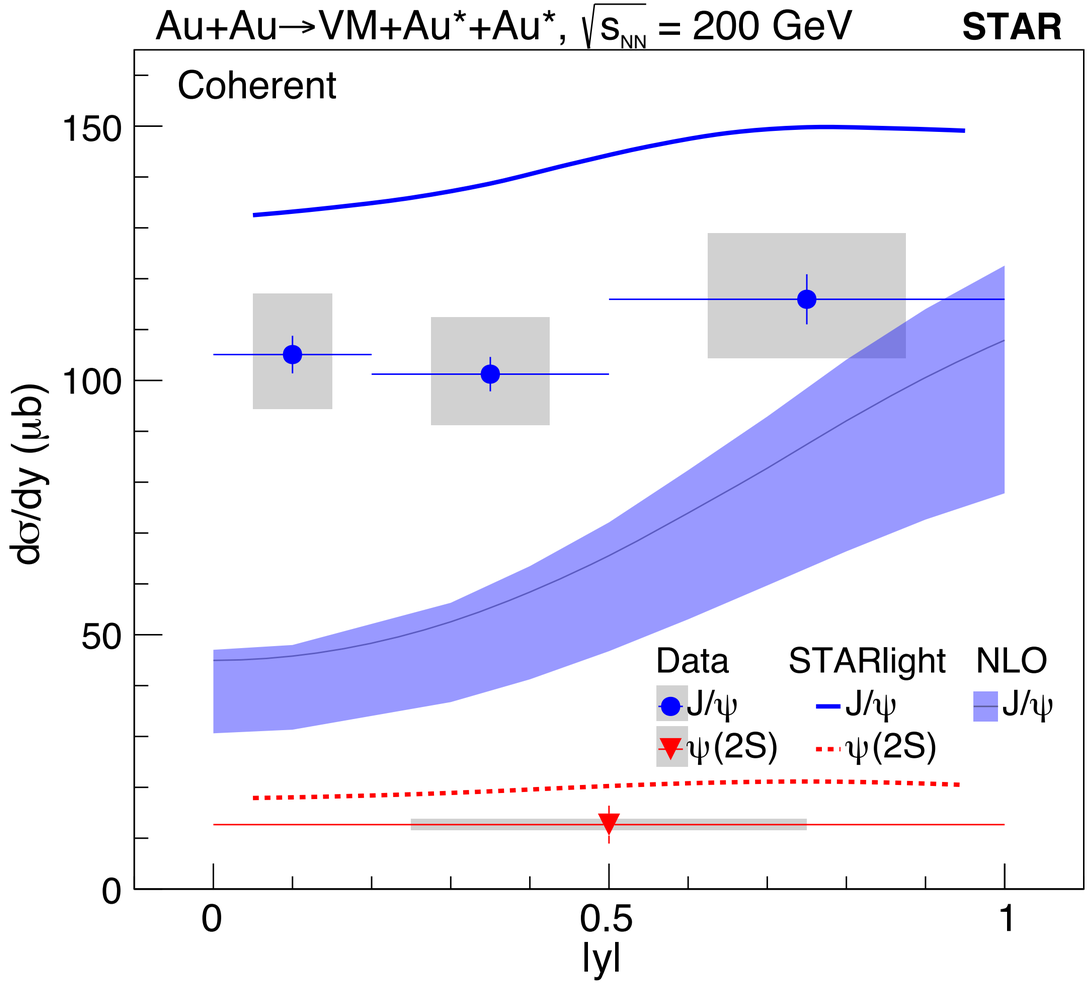
# QUANTUM INTERFERENCE IN SYMMETRIC AU+AU UPCS

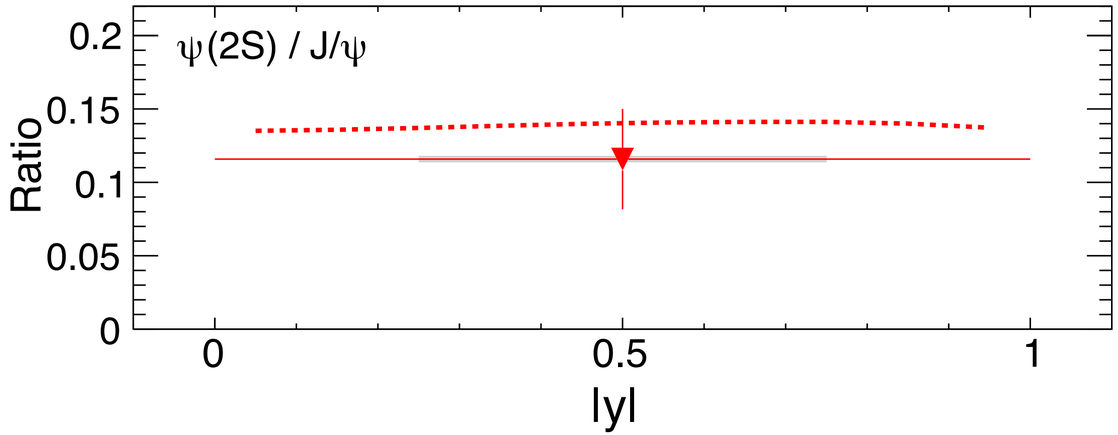
- ambiguity of which nucleus is the hard photon source
- comparison with STARlight (SL) and Color Glass Condensate (CGC)
- the destructive interference at lowest $p_T^2$ confirmed with rapidity dependent data
  - much weaker outside mid rapidity



# J/$\psi$ AT NLO AND $\psi(2S)$ PRODUCTION CROSS SECTION

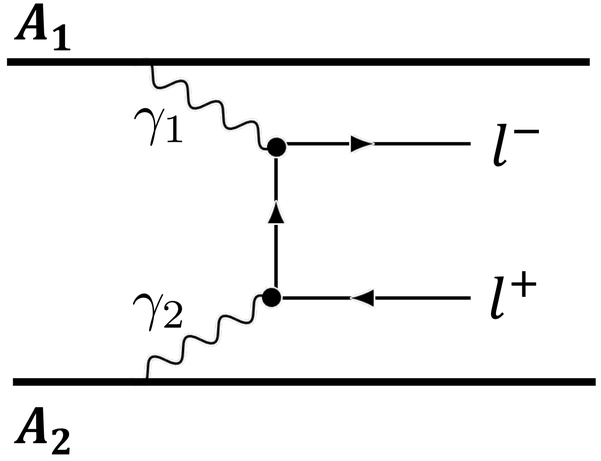


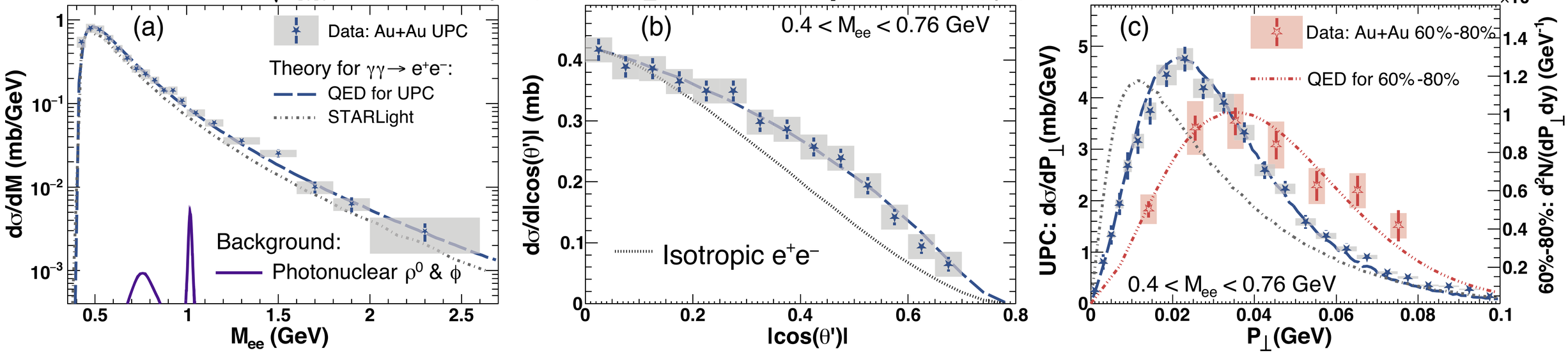

- first $\psi(2S)$ photo-production measurement at RHIC
- inconsistency with NLO prediction
- the ratio $\frac{\psi(2S)}{J/\psi}$ can be sensitive to non-linear QCD effect (see Martin Hentschinski talk on Wednesday 11:15)

# FIRST OBSERVATION OF BREIT-WHEELER PROCESS

- integrated luminosity of 700 $nb^{-1}$ of Au+Au data collected in 2010
- high purity of $e^+e^-$ pairs in UPC data necessary




**STAR**: Au+Au at $\sqrt{s_{NN}}$ = 200 GeV, $|y^{ee}| < 1$, $P_\perp < 0.1$ GeV, $P_T^e > 0.2$ GeV, $|\eta^e| < 1$, Overall scale uncertainty ±13%



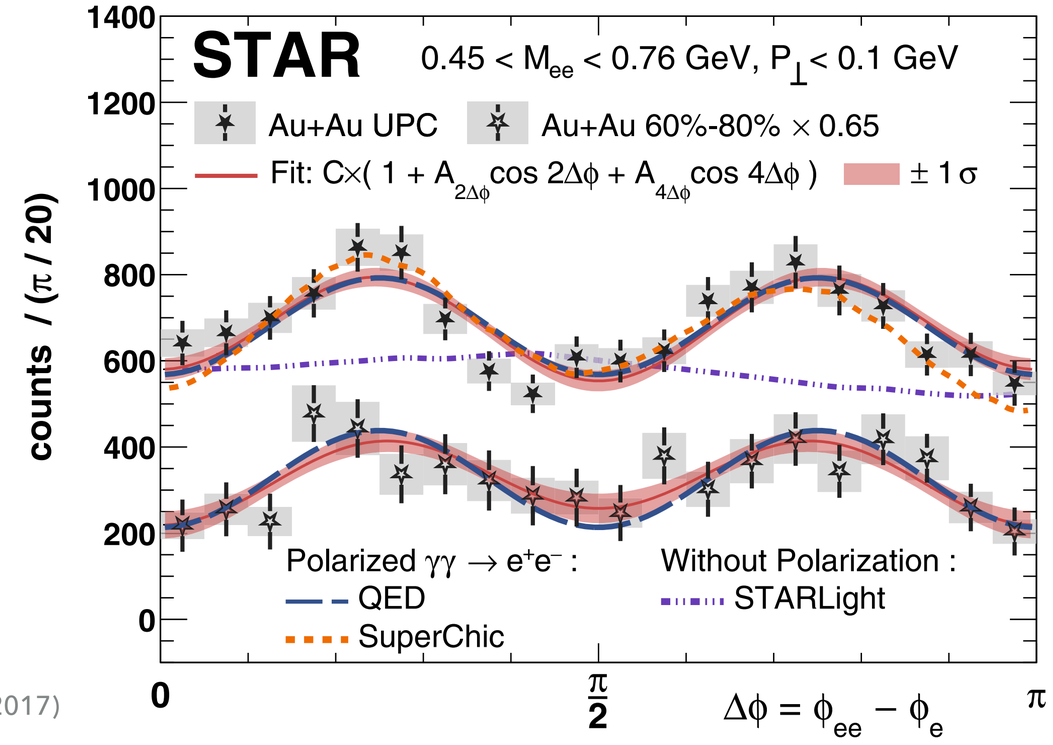

QED Ref: Phys. Lett. B 800, 135089 (2020)

# FIRST OBSERVATION OF BREIT-WHEELER PROCESS

- intrinsic photon spin converted into orbital angular momentum => anisotropy in $e^{\pm}$ momentum
- results consistent with QED but not STARlight
- experimental access to photon polarization demonstrated

| Quantity | Measured | SL | GEPA | QED |
|---|---|---|---|---|
| $\sigma(\mu b)$ | $261 \pm 4 \pm 13 \pm 34$ | 220 | 260 | 260 |

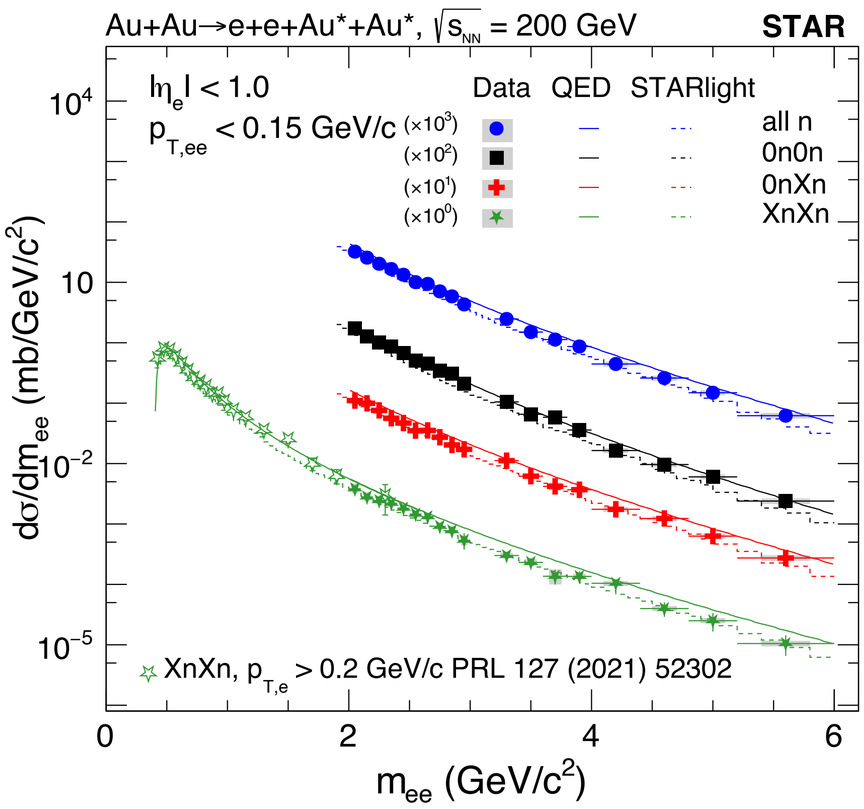
| | Ultraperipheral | | | | Peripheral | |
|---|---|---|---|---|---|---|
| | Measured | QED | SC | SL | Measured | QED |
| $\lvert A_{4\Delta\phi}\rvert$ (%) | $16.8 \pm 2.5$ | 16.5 | 19 | 0 | $27 \pm 6$ | 34.5 |
| $\lvert A_{2\Delta\phi}\rvert$ (%) | $2.0 \pm 2.4$ | 0 | 5 | 5 | $6 \pm 6$ | 0 |
| $\sqrt{\langle P_\perp^2 \rangle}$ (MeV) | $38.1 \pm 0.9$ | 37.6 | 35.4 | 35.9 | $50.9 \pm 2.5$ | 48.5 |

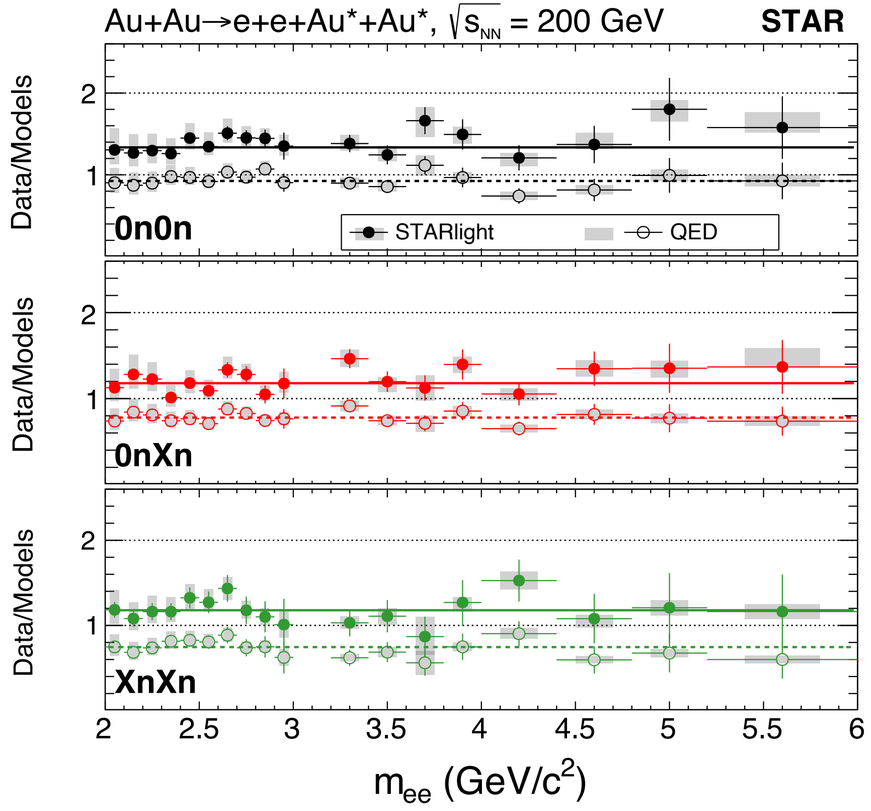



Ref SuperChic: L. A. Harland-Lang, V. A. Khoze, and M. G. Ryskin, Eur. Phys. J. C 79, 39 (2019).
Ref SL: S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, and J. Butterworth, Comput. Phys. Commun. 212, 258 (2017)
Ref QED, GEPA: W. Zha, J.D. Brandenburg, Z. Tang, and Z. Xu, Phys. Lett. B 800, 135089 (2020).

# $\gamma\gamma \rightarrow e^+e^-$ CROSS SECTIONS

arXiv:2311.13632v1

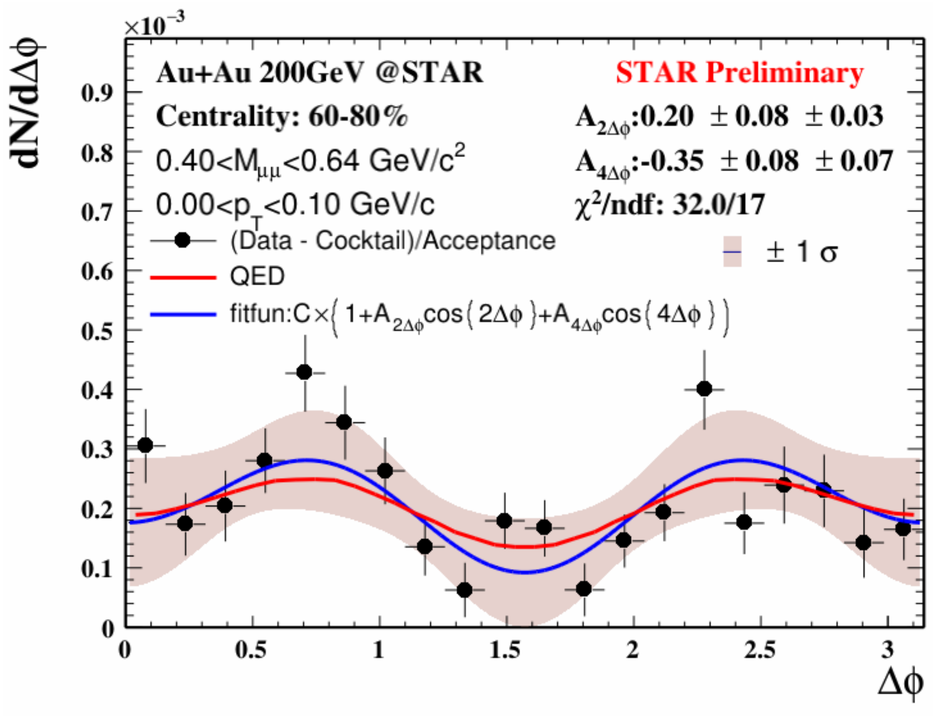


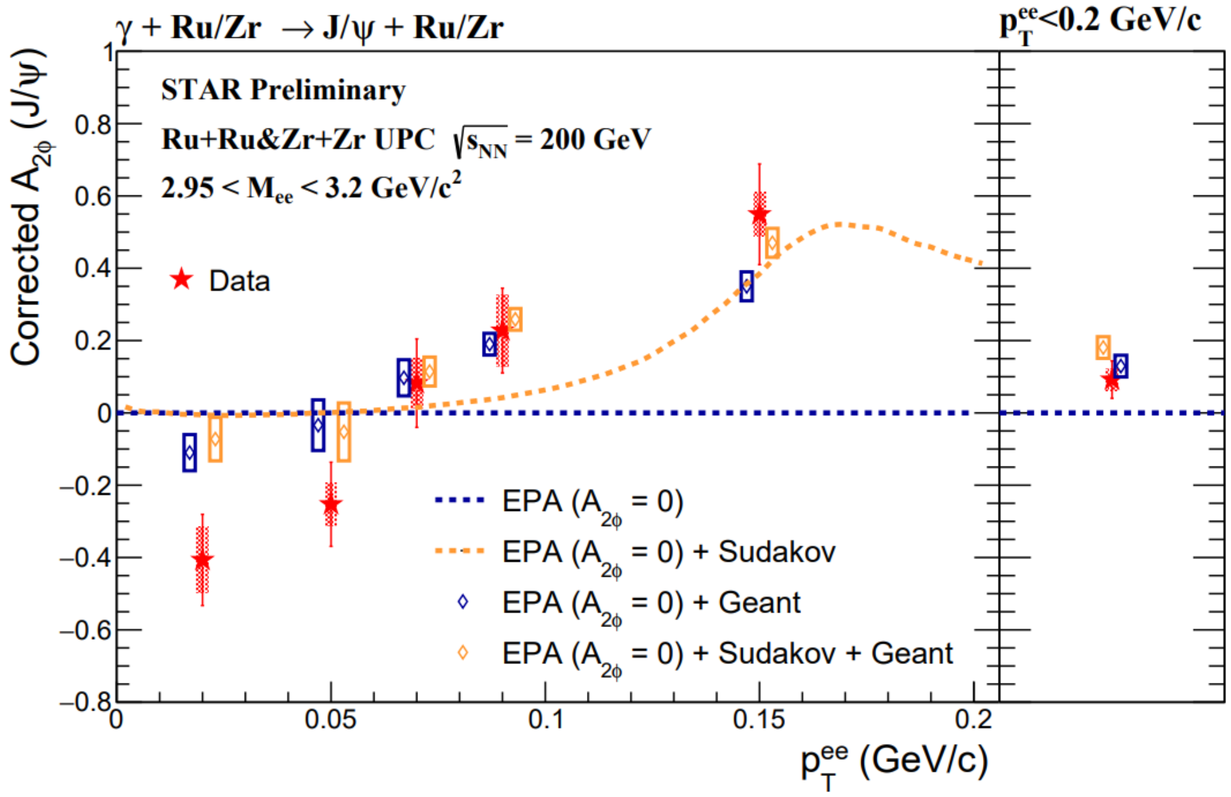

- first measurement up to 6 GeV/$c^2$
- constrains modeling of neutron emission and photon flux

# HIGHLIGHTS OF STAR PRELIMINARY RESULTS

# ANGULAR MODULATION OF PHOTON-INDUCED $J/\psi$ AND LEPTON PAIRS IN HEAVY ION COLLISIONS AT STAR



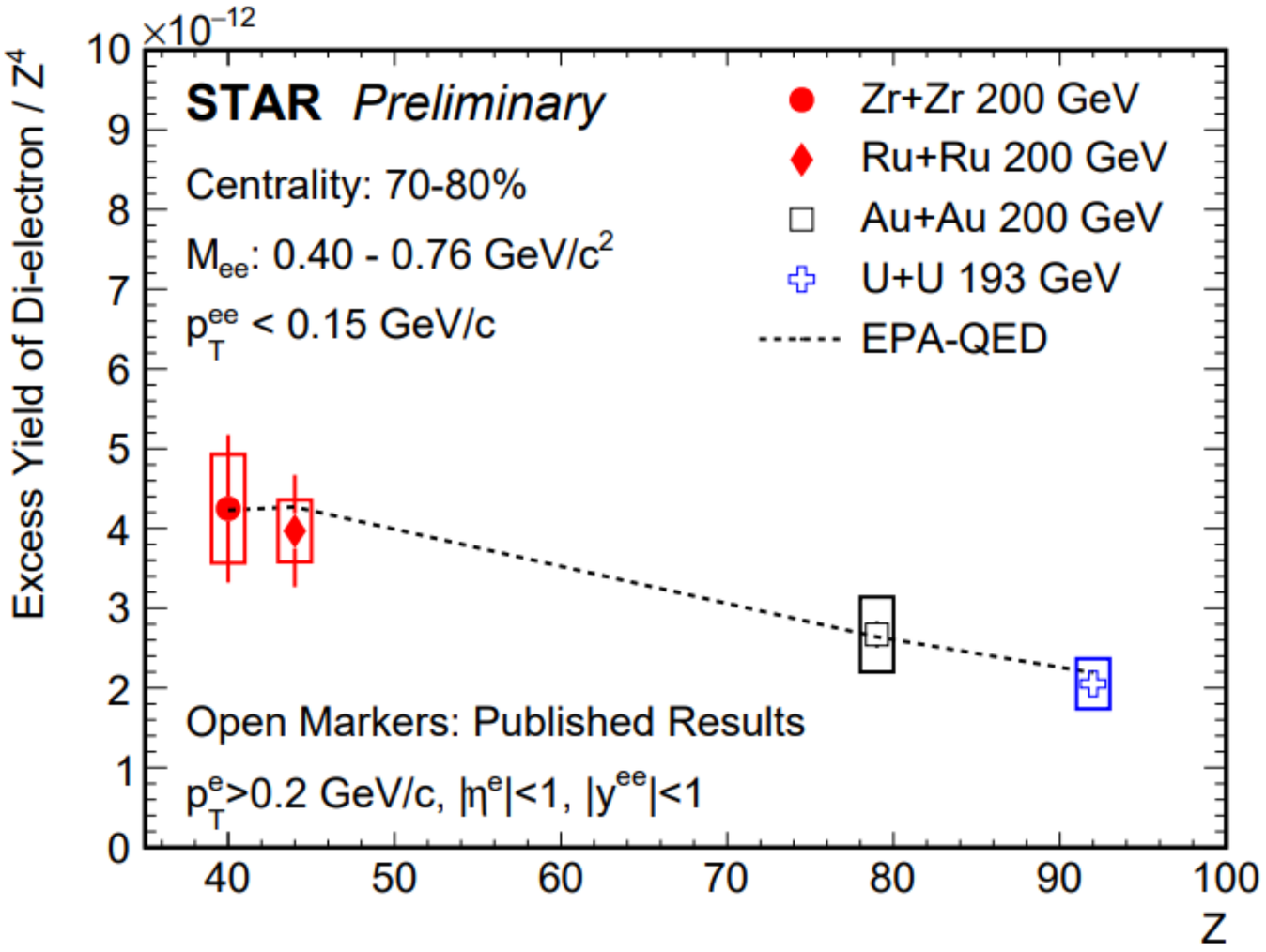

di-muons



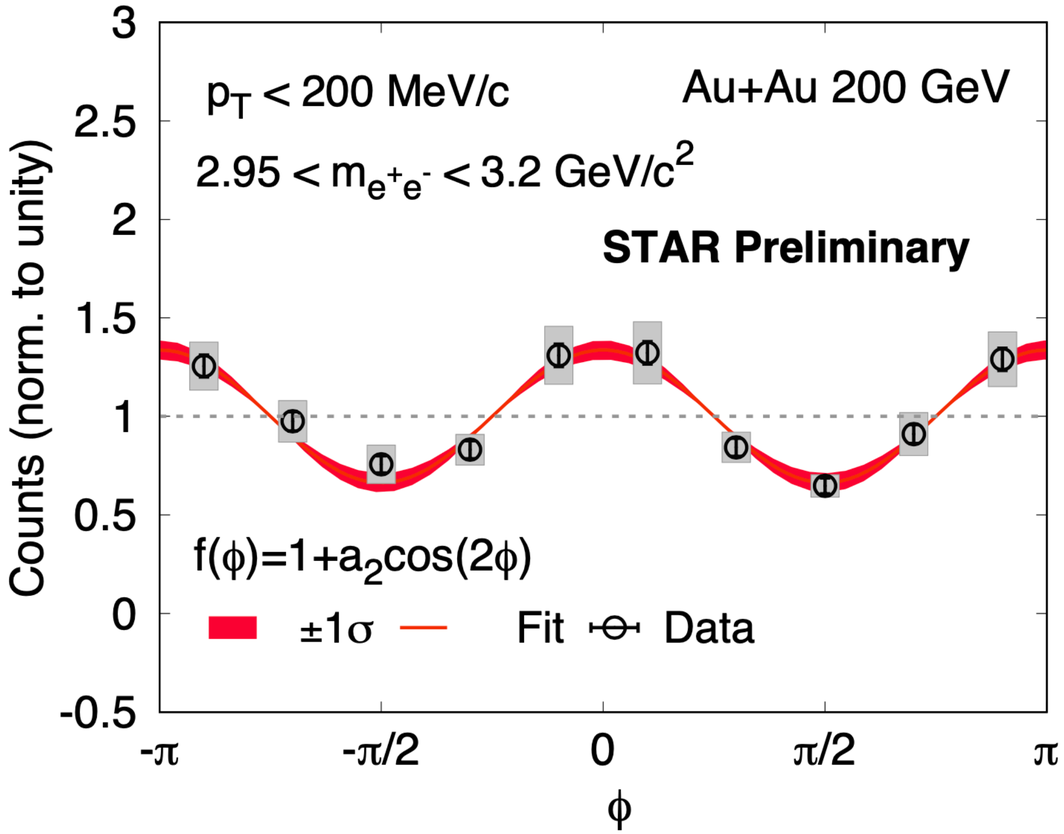

- $\Delta\phi$ modulation observed in peripheral di-muon data
- $p_T$ - dependent interference of J/$\psi$
- Kaiyang Wang (Tuesday 10am)

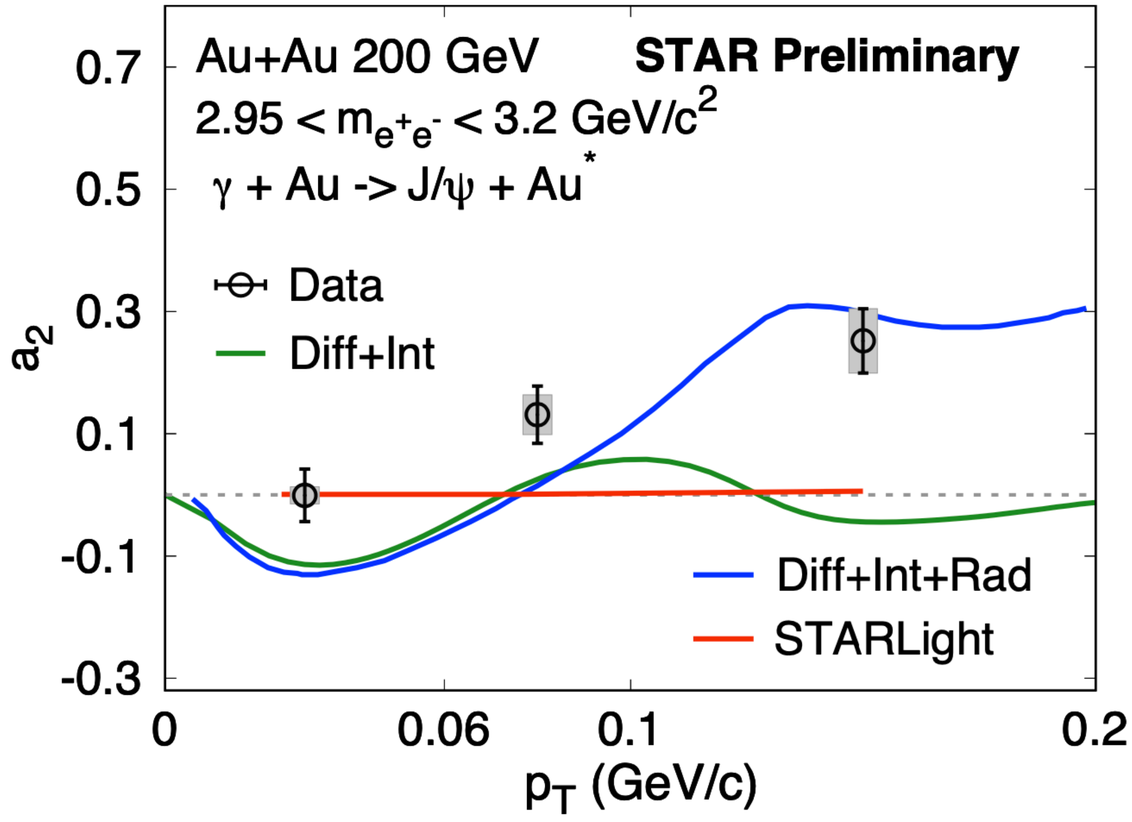
# INITIAL ELECTROMAGNETIC FIELD DEPENDENCE OF PHOTON-INDUCED PRODUCTION IN ISOBARIC COLLISIONS

- collision system dependence
- Kaifeng Shen (Tuesday 10:30am)



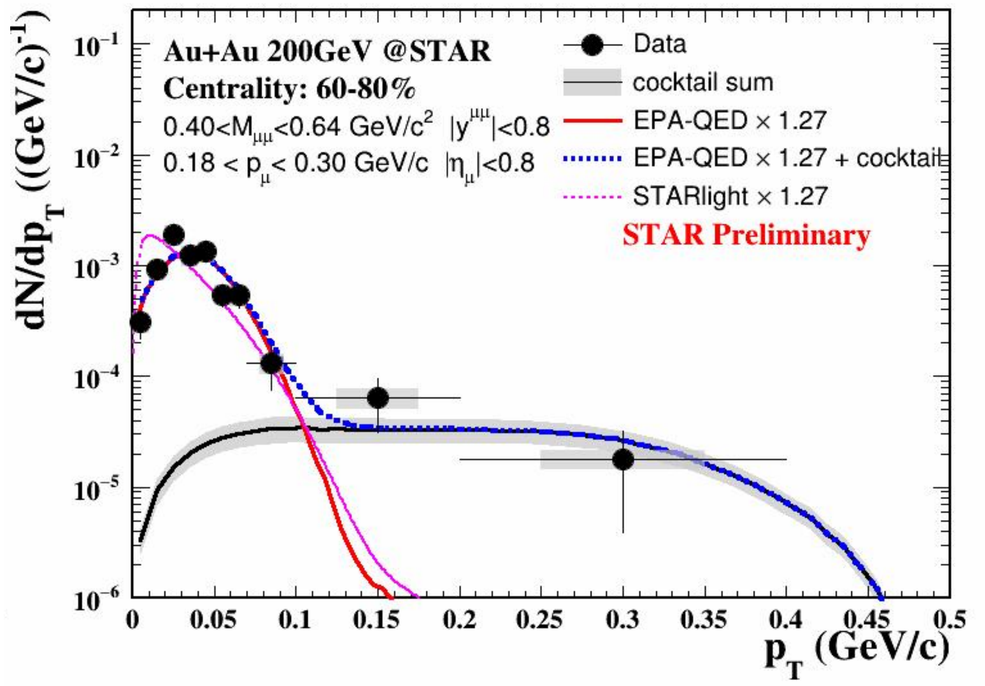
# EXCLUSIVE $J/\psi$ PHOTOPRODUCTION AND ENTANGLEMENT-ENABLED SPIN INTERFERENCE IN ULTRA-PERIPHERAL COLLISIONS AT STAR

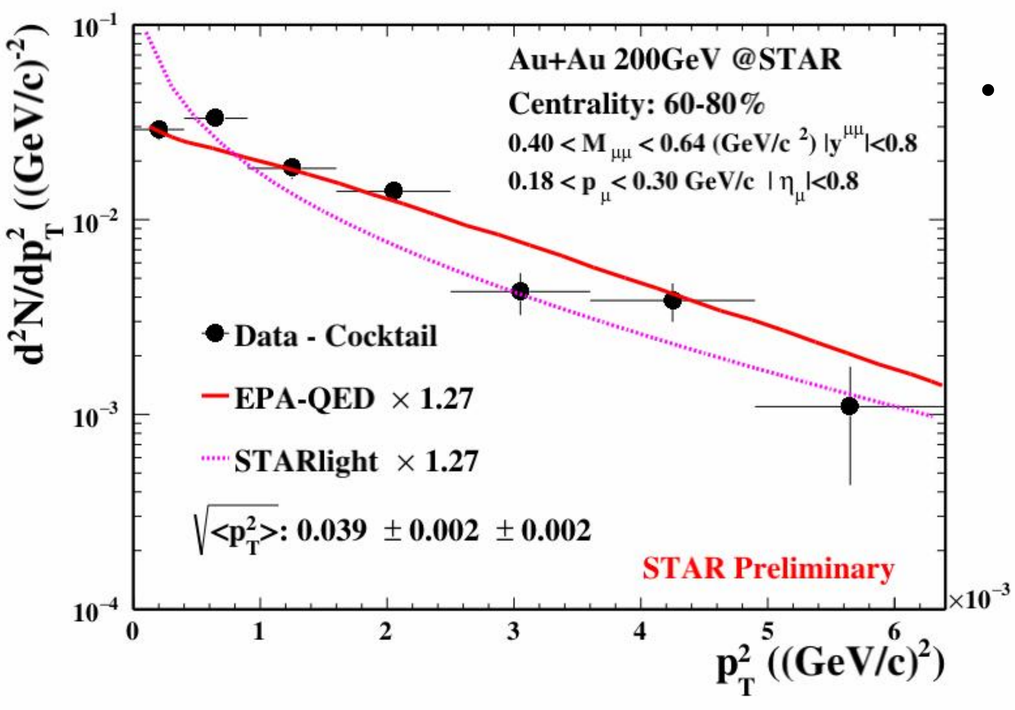



- Ashik Ikbal Sheikh (Tuesday 11:45am)
- interference of $J/\psi$ depends on $p_T$

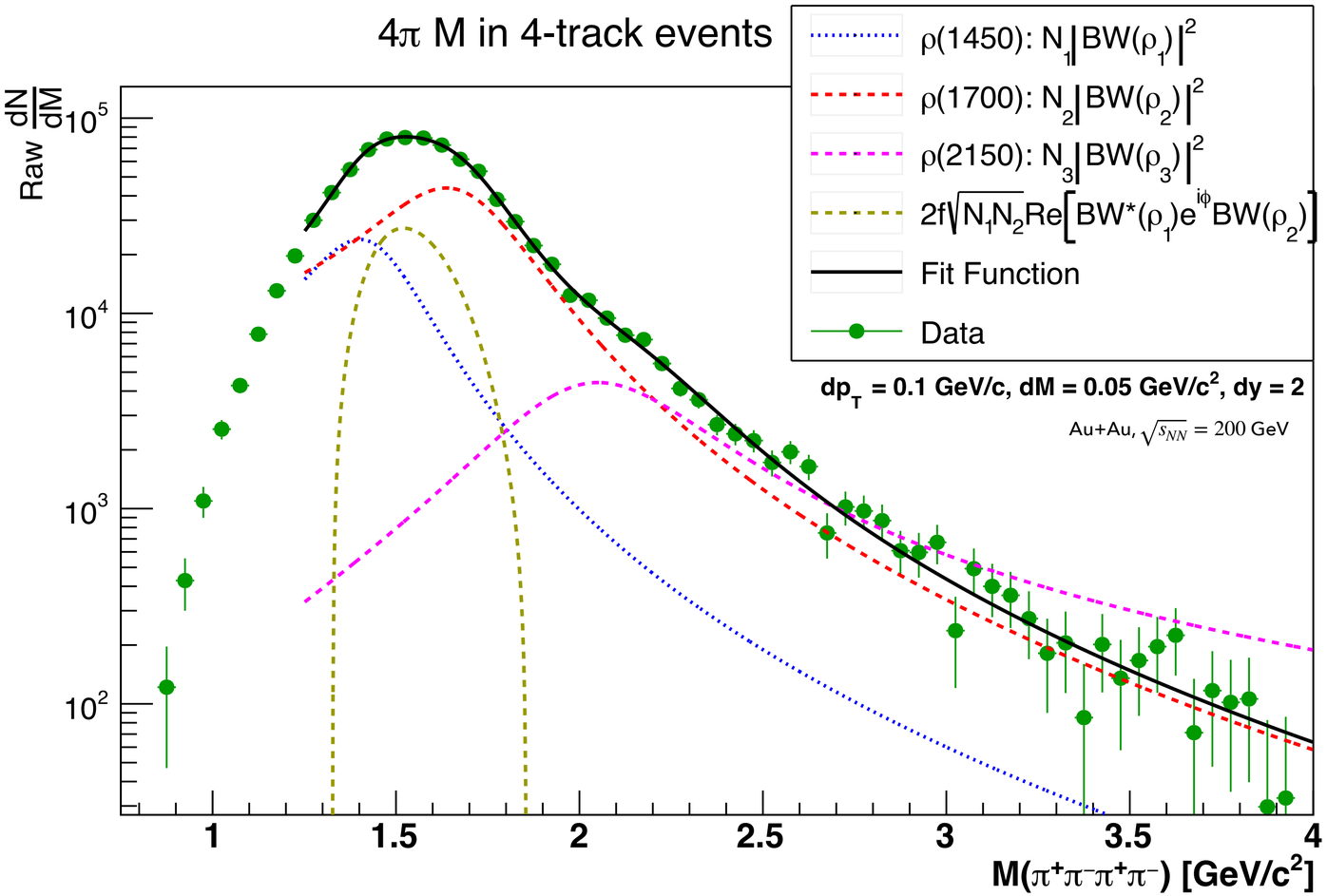
# DIMUON PRODUCTION AT LOW-PT PERIPHERAL AU+AU COLLISIONS




- Ziyang Li (Thursday 18:30)
- EPA-QED more consistent with data than STARlight

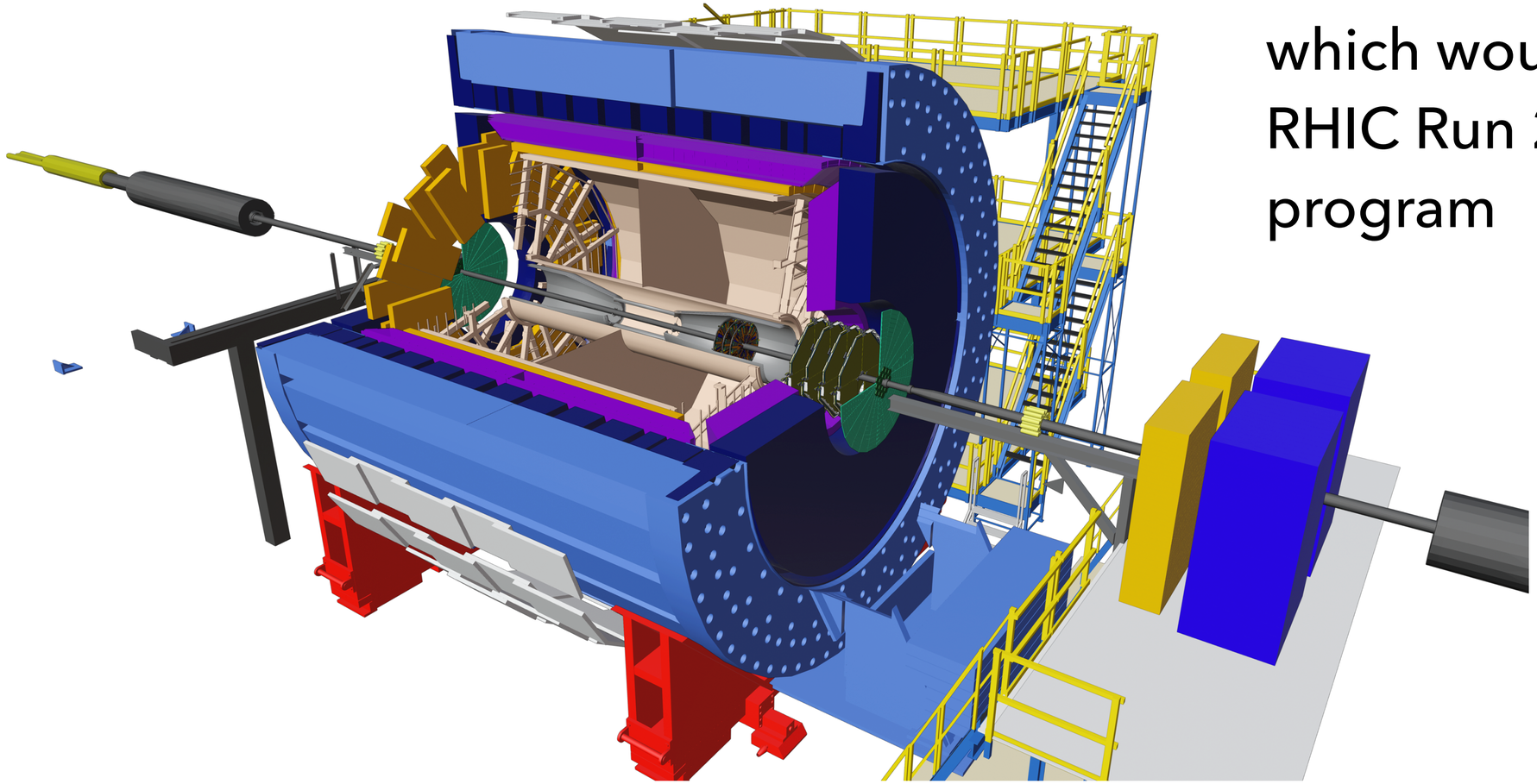
# $4\pi$ PHOTO-PRODUCTION – SEARCH FOR EXCITED $\rho$ MESONS




| Resonance | $M$ [MeV/c²] | PDG $M$ [3] | $\Gamma$ [MeV/c²] | PDG $\Gamma$ [3] |
|---|---|---|---|---|
| $\rho(1450)$ | 1454 ± 32 | 1465 ± 25 | 357 ± 98 | 400 ± 60 |
| $\rho(1700)$ | 1714 ± 26 | 1720 ± 20 | 467 ± 38 | 250 ± 100 |
| $\rho(2150)$ | 2100 ± 47 | - | 656 ± 132 | - |

- Double resonance structure with $\rho(1450)$ and $\rho(1700)$ masses consistent with PDG best estimation observed
- The shape is expected to change (in lower mass region particularly) after corrections
- $\rho(1700)$ width larger than PDG best estimation, but consistent with $\gamma p \rightarrow p4\pi$ experiments [5,6]
- Another possible resonance in the $\rho(2150)$ location, need to investigate further if it indeed is $\rho(2150)$ - possibly in $6\pi$ decay channel

# STAR EXPERIMENT – FORWARD UPGRADE



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

- $W_{\gamma^* N}$ < 10 GeV
- first-time $\phi$ meson photo production
- high statistics VM at higher $p_T^2$
- spin-dependent VM production

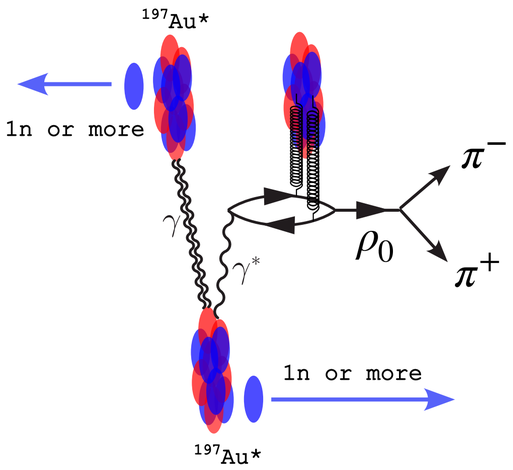
# SUMMARY

- STAR has made many first-time or otherwise significant measurements in UPCs at RHIC
  - coherent $\rho_0$ photo-production and nuclear imaging - Au radius consistent with low energy experiment
  - Strong nuclear suppression in $J/\psi$ seen for both coherent (~ 30%) and incoherent (~60%) production
  - nuclear interference
  - $J/\psi$ in d+Au and $\psi(2S)$ in Au+Au (first time at RHIC)
  - observation of Breit-Wheeler process (mass spectra up to 6 GeV/$c^2$)
- STAR program continues
  - stay tuned to following talks about new preliminary results
  - the detector has just been upgraded with forward tracking and calorimeter system

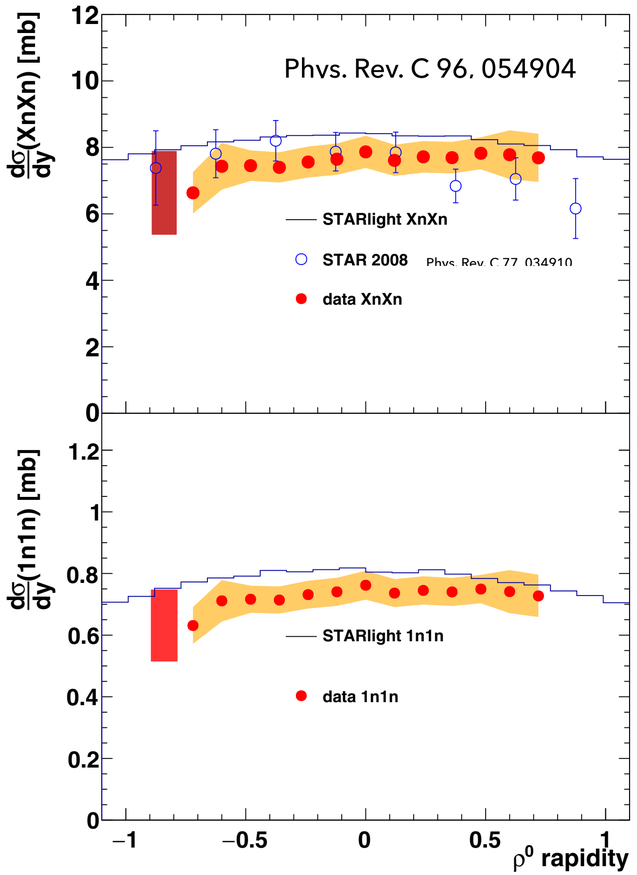
# THANK YOU

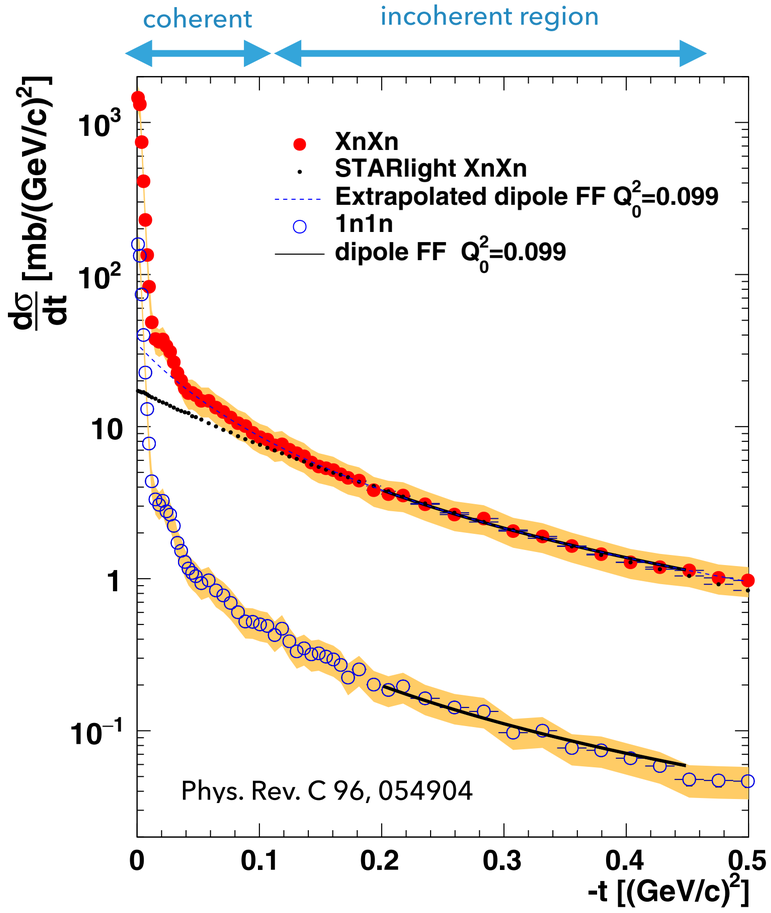
# BACKUP SLIDES

# $\rho_0$ CROSS SECTION




- integrated luminosity of 1100±100 μb−1 of data collected in 2010
- XnXn extrapolated from 1n1n using STARlight
- incoherent components in $d\sigma/dt$ are fit in range $-t = (0.2,0.45)$
  - $\sigma_{incoh}$ are integrals of the fits



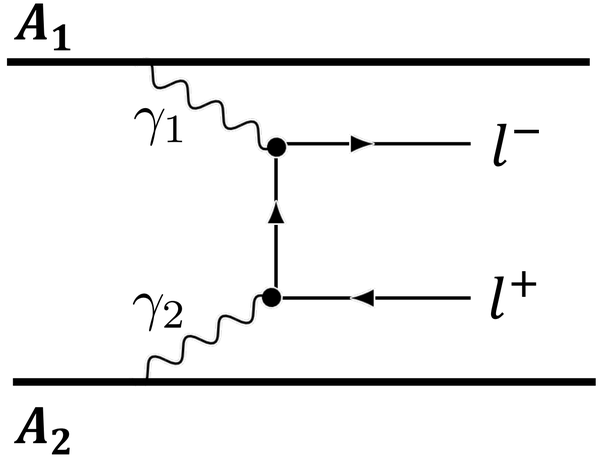




| Parameter | $XnXn$ | $1n1n$ |
|---|---|---|
| $\sigma_{\text{coh.}}$ | $6.49 \pm 0.01\,(\text{stat.}) \pm 1.18\,(\text{syst.})$ mb | $0.770 \pm 0.004\,(\text{stat.}) \pm 0.140\,(\text{syst.})$ mb |
| $\sigma_{\text{incoh.}}$ | $2.89 \pm 0.02\,(\text{stat.}) \pm 0.54\,(\text{syst.})$ mb | $0.162 \pm 0.010\,(\text{stat.}) \pm 0.029\,(\text{syst.})$ mb |
| $\sigma_{\text{incoh.}}/\sigma_{\text{coh.}}$ | $0.445 \pm 0.015\,(\text{stat.}) \pm 0.005\,(\text{syst.})$ | $0.233 \pm 0.007\,(\text{stat.}) \pm 0.007\,(\text{syst.})$ |

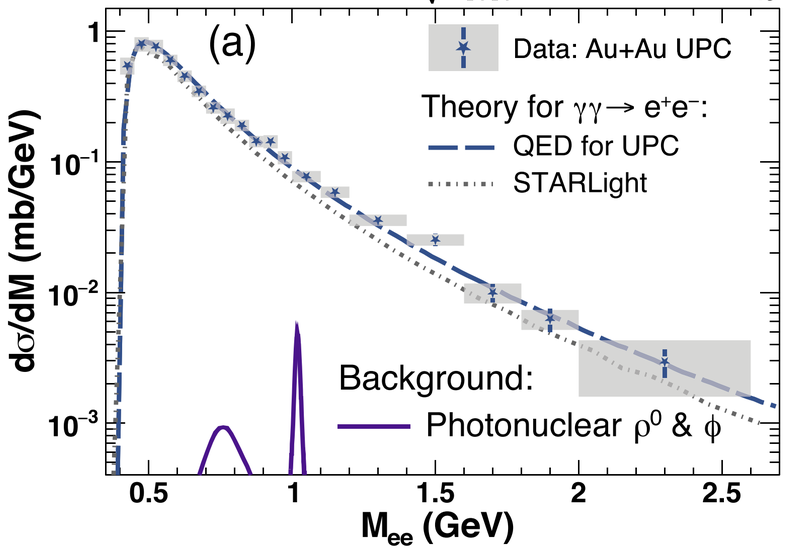
Nuclear excitation and $\rho_0$ photo production are not completely independent

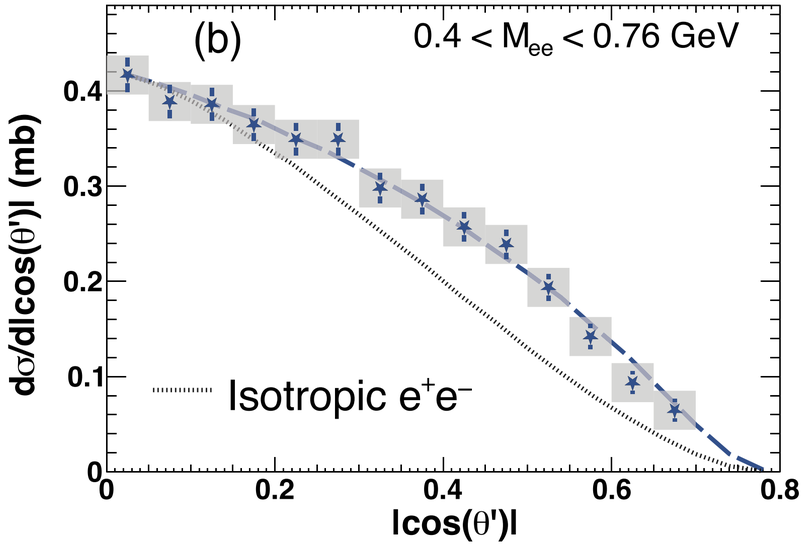
# FIRST OBSERVATION OF BREIT-WHEELER PROCESS

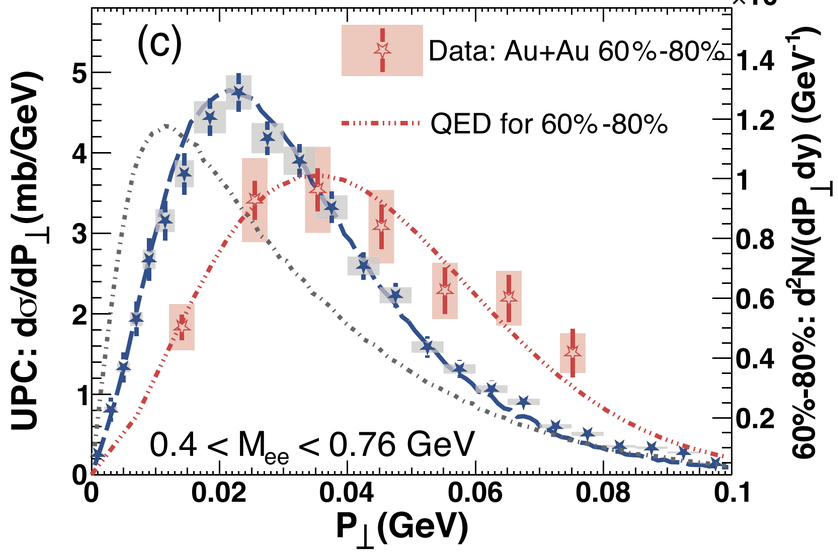
- integrated luminosity of 700 $nb^{-1}$ of Au+Au data collected in 2010
- high purity of $e^+e^-$ pairs in UPC data necessary




**STAR**: Au+Au at $\sqrt{s_{NN}}$ = 200 GeV, $|y^{ee}| < 1$, $P_\perp < 0.1$ GeV, $P_T^e > 0.2$ GeV, $|\eta^e| < 1$, Overall scale uncertainty ±13%



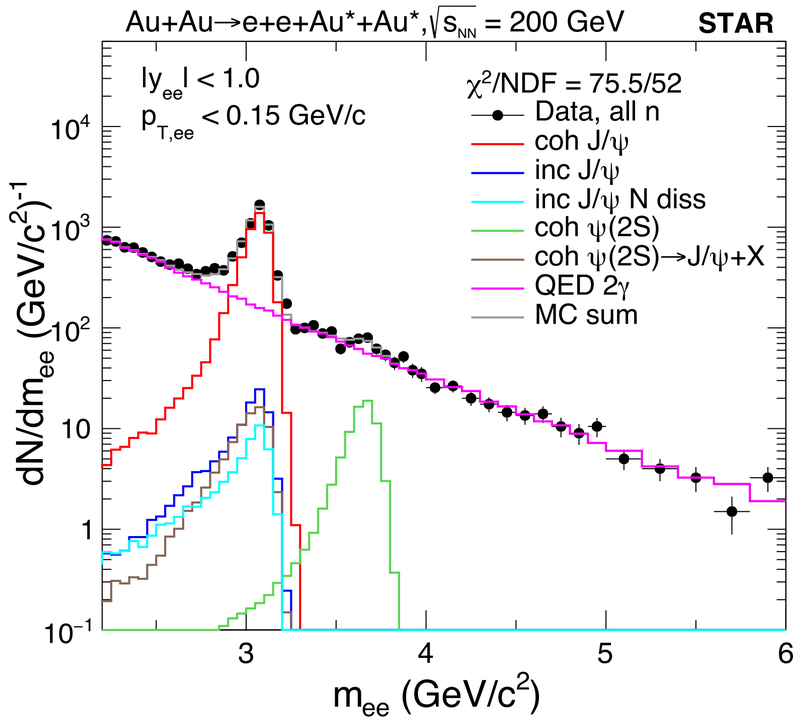



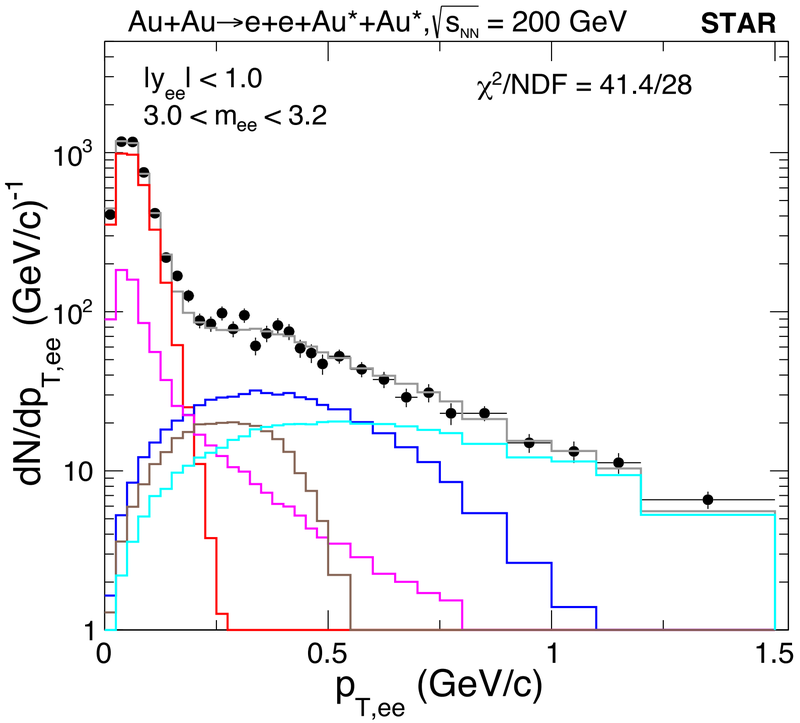



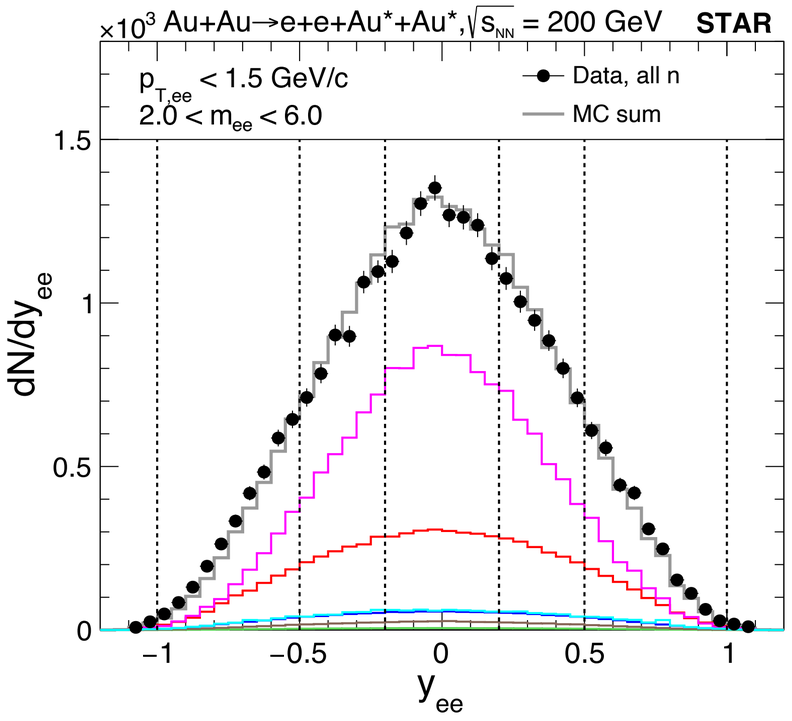

Phys. Rev. Lett. 127, 052302 (2021)

QED Ref: Phys. Lett. B 800, 135089 (2020)

# $J/\psi$ PHOTOPRODUCTION IN AU+AU UPC EVENTS AT 200 GEV

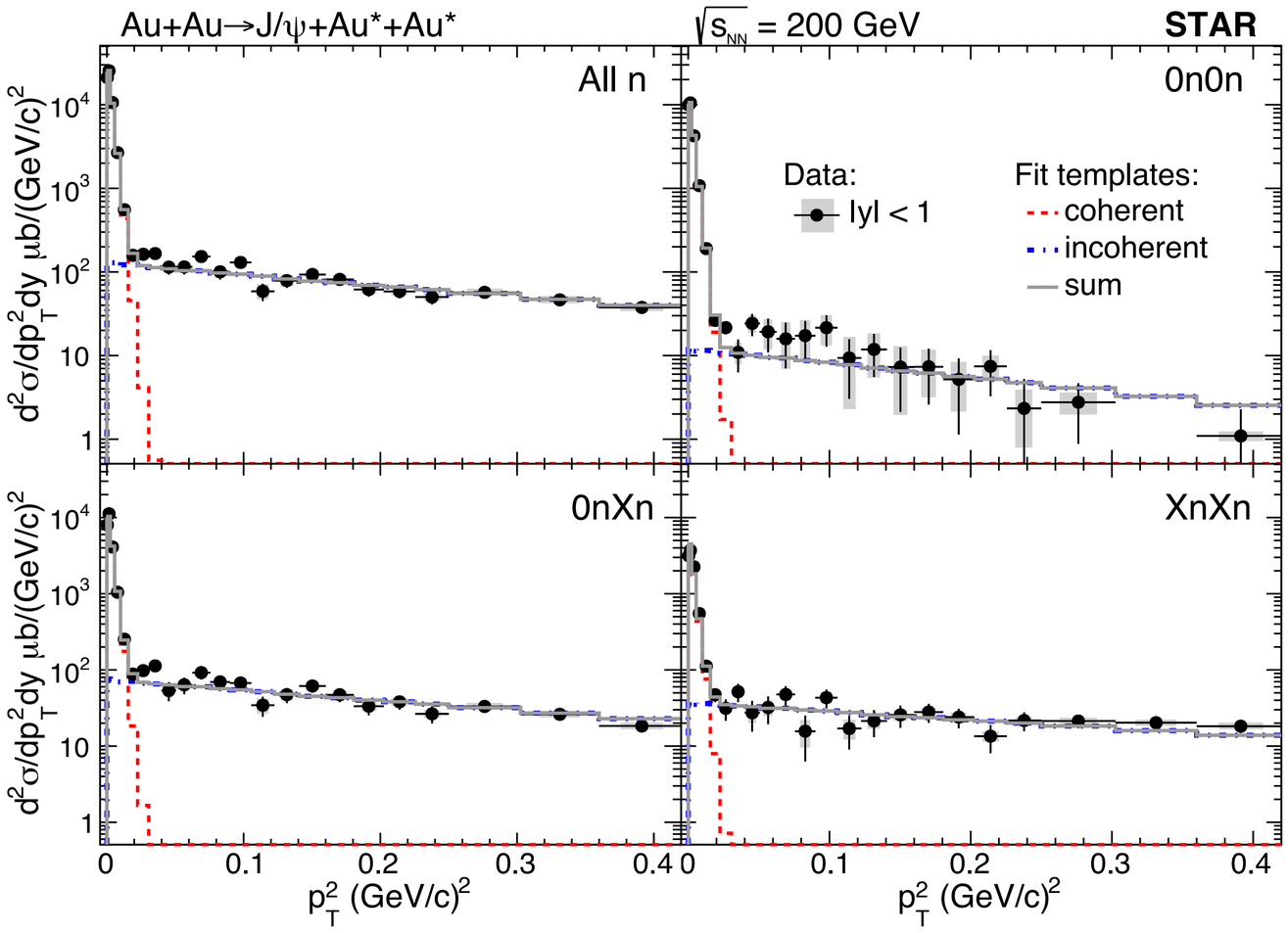


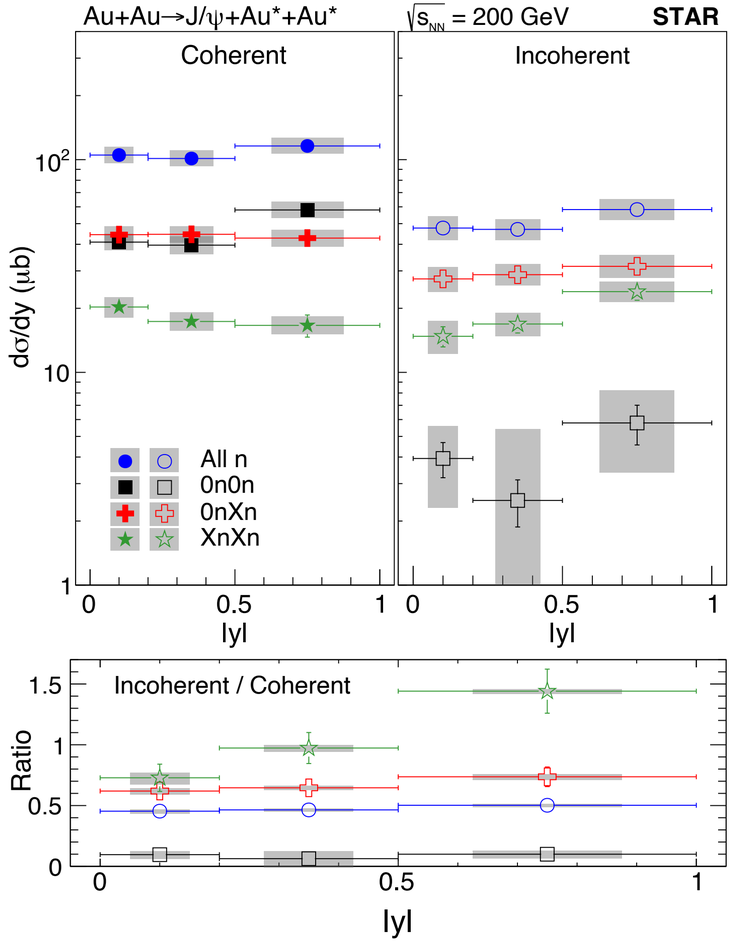




- when $Q^2 \sim 0$, $p_T$ of $J/\psi$ is directly related to momentum transfer ($t \sim p_T^2$)

# $J/\psi$ PHOTOPRODUCTION CROSS SECTION SEPARATED BY NEUTRON TAGGING




Separation of coherent and incoherent photo production




First measurement of y-dependance at RHIC

# $J/\psi$ CROSS SECTION VS ENERGY $W_{\gamma^*N}$

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

Ref: Kong Tu, DIS 2023

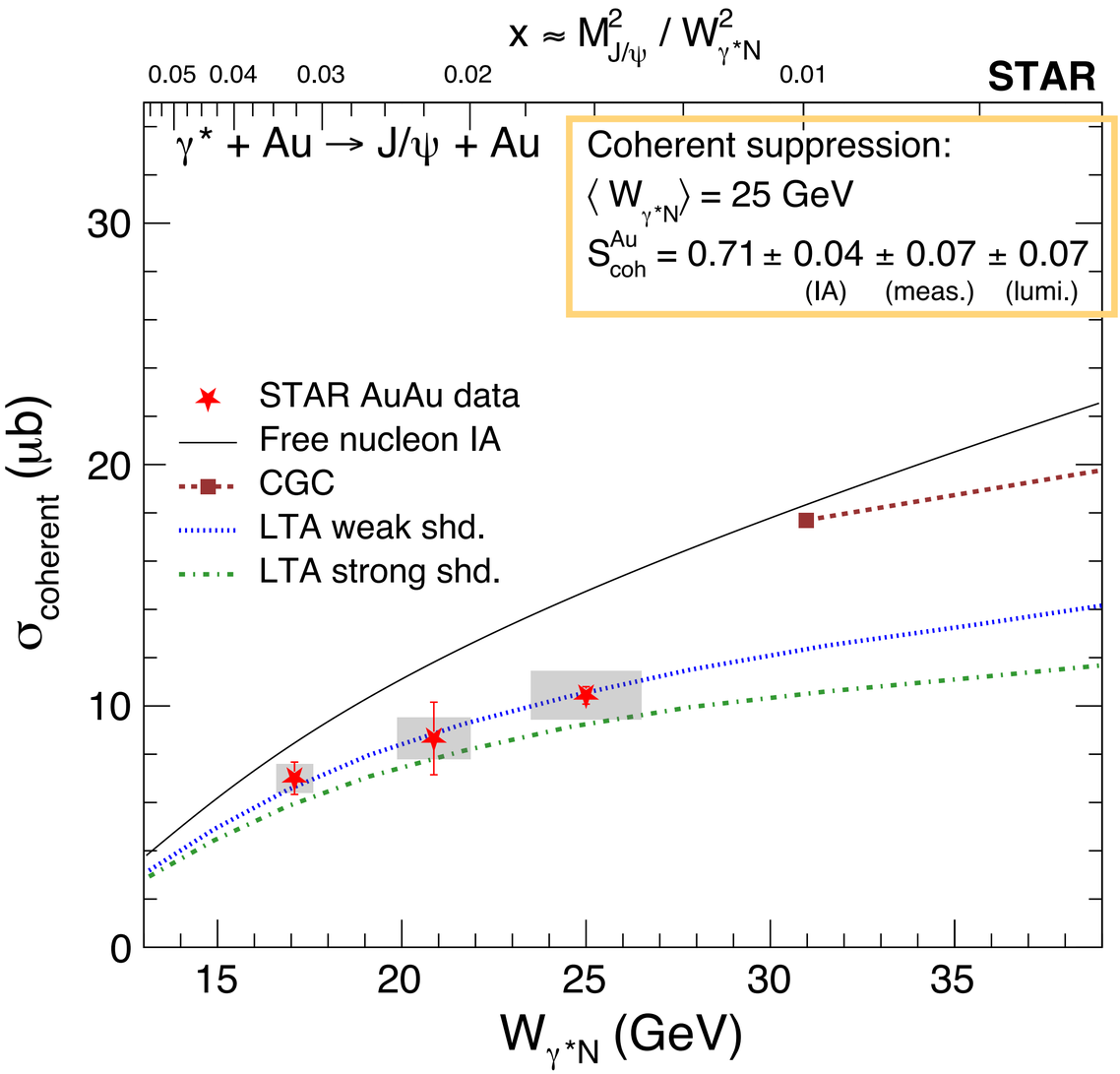
$$d\sigma^{AnBn}/dy = \Phi^{AnBn}_{T.\gamma}(k_1)\sigma_{\gamma^*+\mathrm{Au}\to \mathrm{J}/\psi+\mathrm{Au}}(k_1) + \Phi^{AnBn}_{T.\gamma}(k_2)\sigma_{\gamma^*+\mathrm{Au}\to \mathrm{J}/\psi+\mathrm{Au}}(k_2)$$

Measurements (previous slide) Photon fluxes (STARlight) Unknowns

Incoherent suppression:

$\langle W_{\gamma^*N} \rangle = 19$ GeV

$S^{Au}_{incoh} = 0.49^{+0.04}_{-0.05}$ (para.) $\pm 0.05$ (meas.) $\pm 0.05$ (lumi.)




IA: Impulse Approximation (no shadowing)

**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