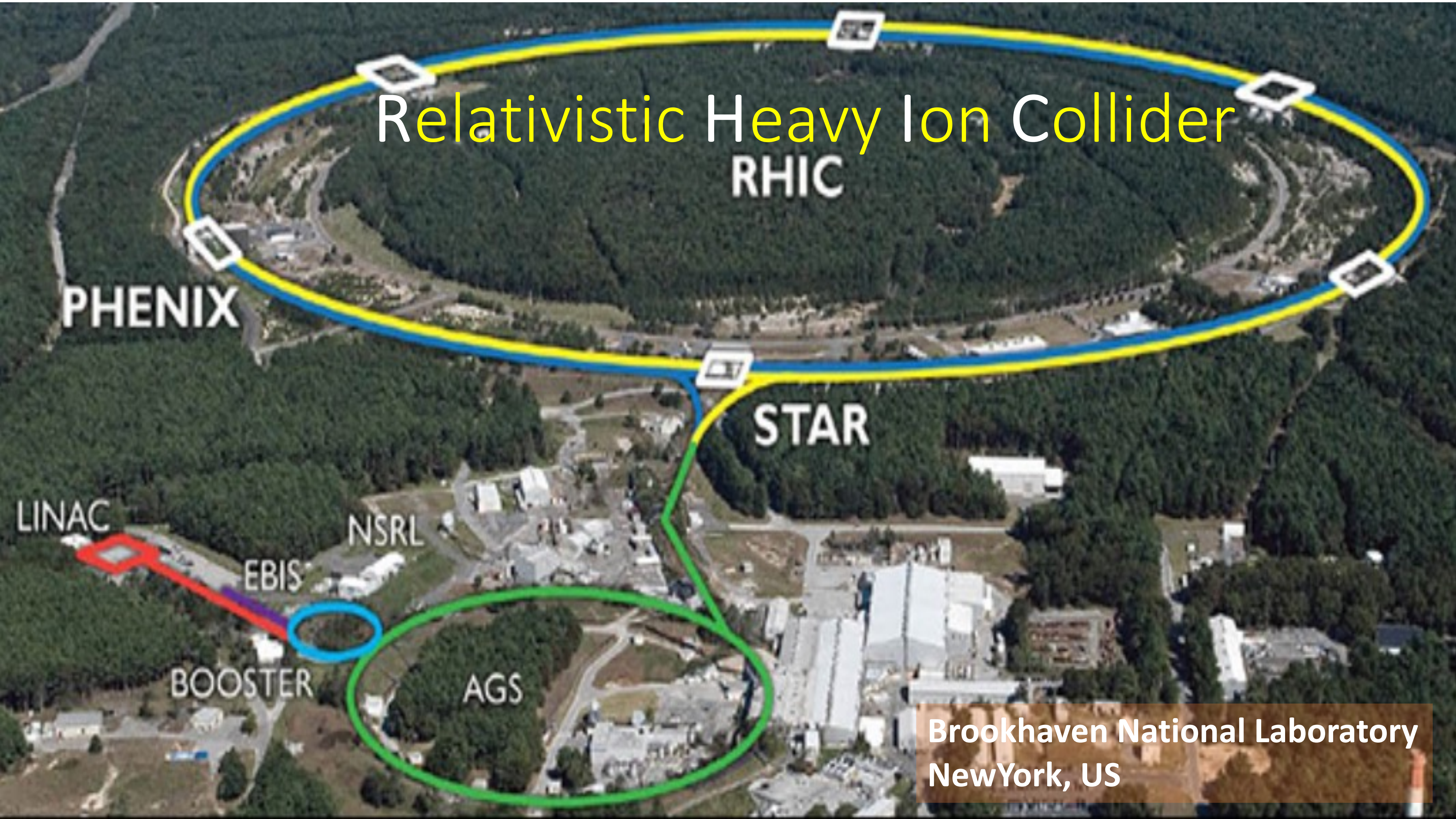
Recent Progress in UPC Physics at RHIC

Zaochen Ye (South China Normal University)

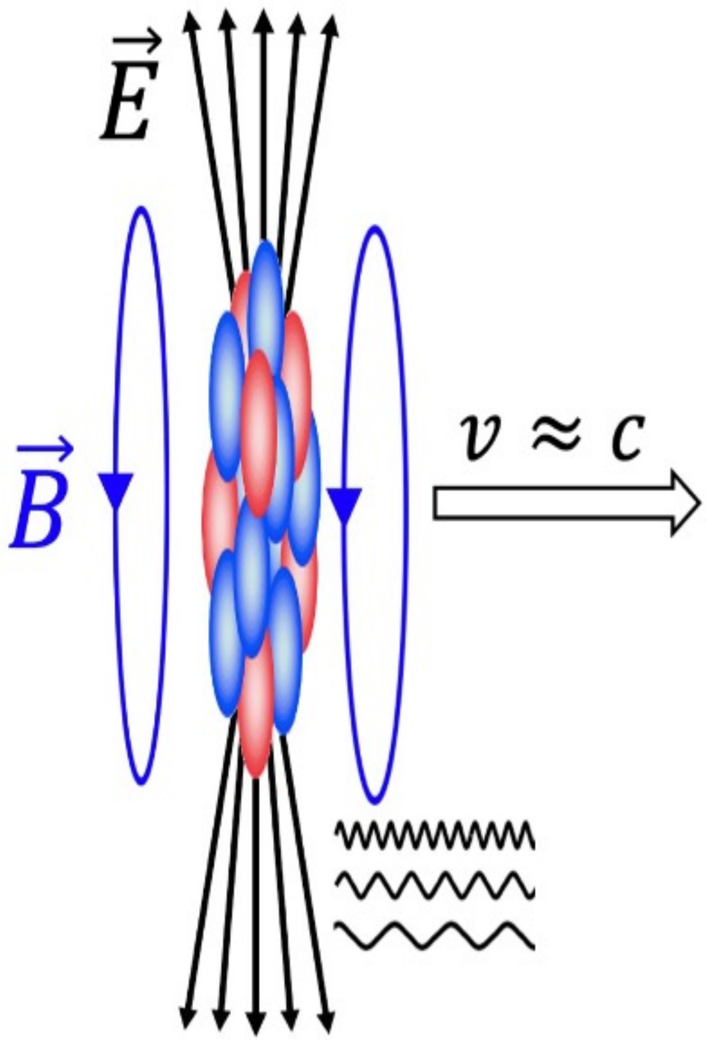
Workshop on Medical and High Energy Physics at Sonora, Mexico

Outline

- The Relativistic Heavy Ion Collider
- Utral-Peripheral Collisions
  - Light-Light Collisions
  - Light-Nucleus Collisions
- Summary

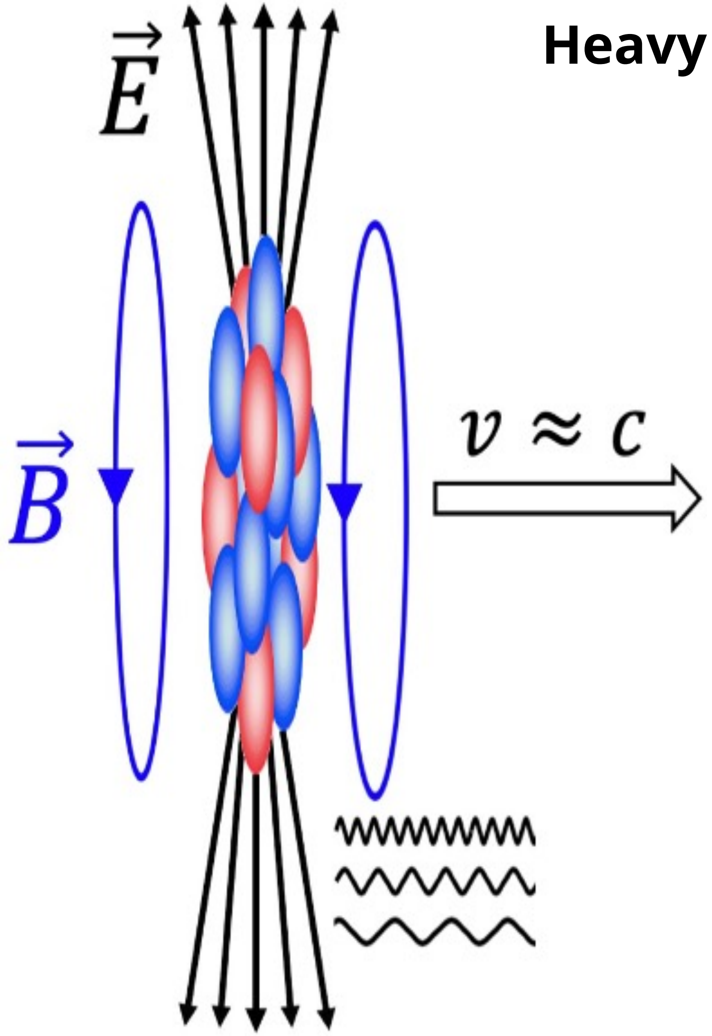

Relativistic Heavy Ion Collider
RHIC
PHENIX
STAR
LINAC
NSRL
EBIS
BOOSTER
AGS
Brookhaven National Laboratory
NewYork, US

A Relativistic Ion Carraries a Clould of Photons

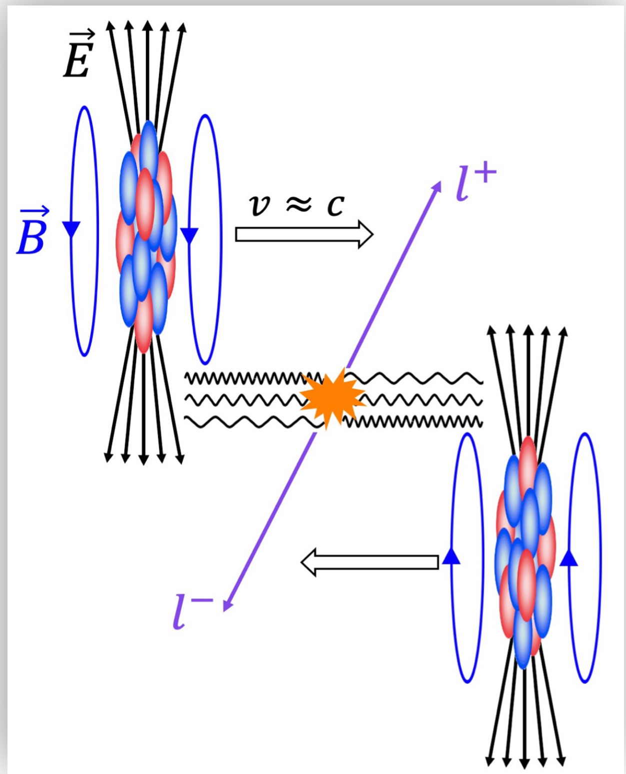


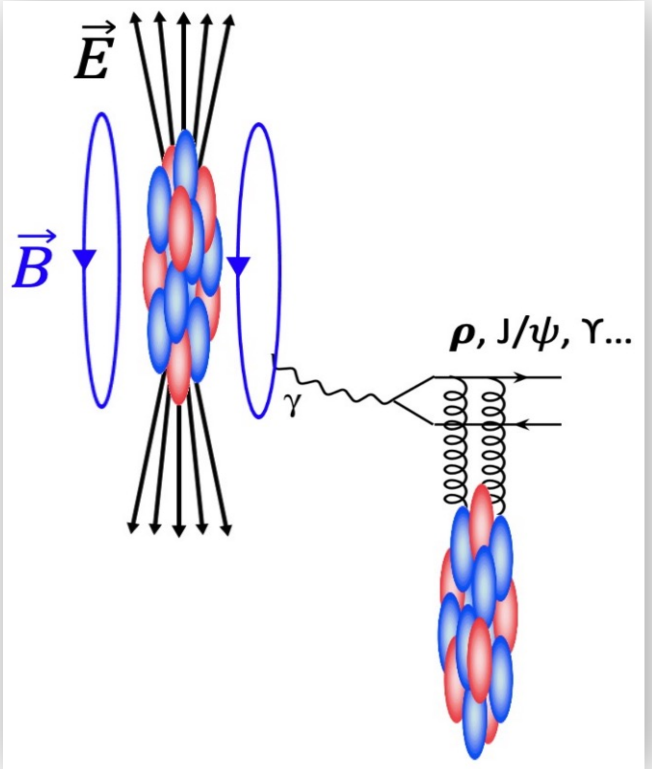
- **Relativistic ion produces highly Lorentz contracted EM field**
  $$E_{max} = \frac{Ze\gamma}{b^2} \approx 5\times10^{16} - 10^{18}\ \text{V/cm}$$
  $$B_{max} \sim 10^{14} - 10^{16}\ \text{T}$$
- **Equivalent Photon Approximation (EPA): transverse EM fields can be quantized as a flux of quasi-real photons ($Q^2<\hbar^2/R^2$) --** Weizsacker&Williams 1934
  - Photon flux $\propto Z^2$
  - Photon kinematics:
    - $p_T < \hbar/R_A$ ~ 30 MeV at both **RHIC** and LHC
    - $E_{max} = \gamma\ (\hbar c/R)$ ~ 3 GeV at **RHIC**, 80 GeV at LHC

Ultra-Peripheral Collisions (UPCs)



Heavy ion collider is also a Photon-Photon and Photon-Ion collider





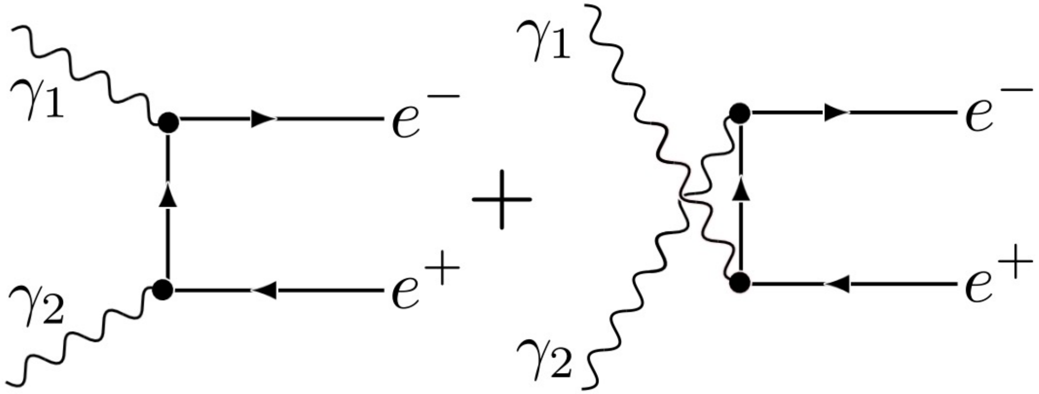
Skokov, V., et. al. *Int. J. Mod. Phys. A* 24 (2009): 5925–32

Light-Light Collision

Collision of Two Light Quanta

G. Breit* and John A. Wheeler,** *Department of Physics, New York University*

(Received October 23, 1934)



Breit-Wheeler Process

- **Hopeless**

As has been reported at the Washington meeting, pair production due to collisions of cosmic rays with the temperature radiation of interstellar space is much too small to be of any interest. We do not give the explicit calculations, since the result is due to the orders of magnitude rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or γ-rays meeting each other on account of the smallness of σ and the insufficiently large available densities of quanta. In the considerations of Williams,

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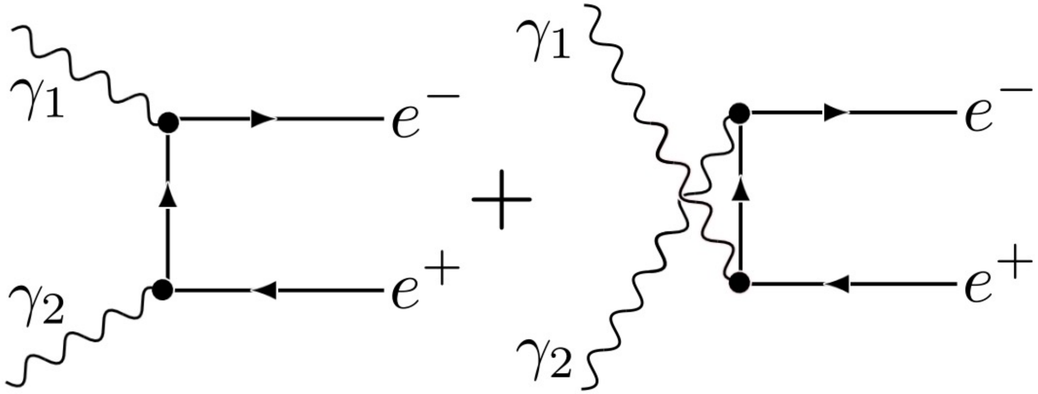

Breit-Wheeler Process

- **Hopeless**
- **But not impossible**

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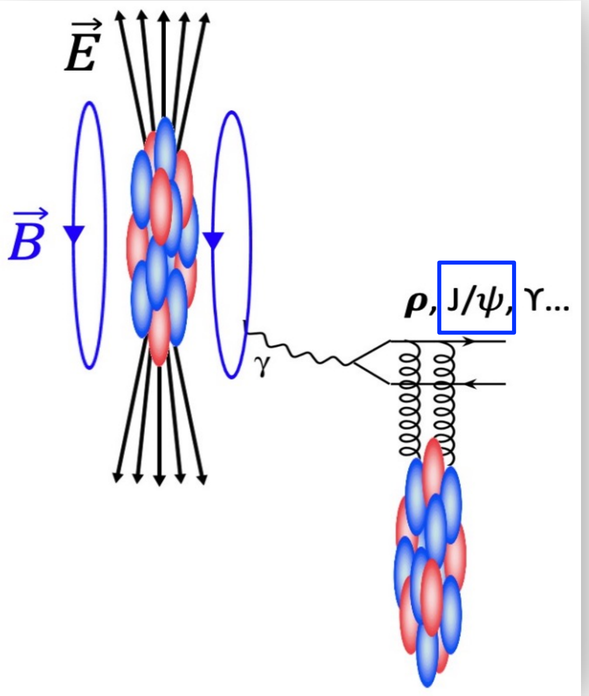
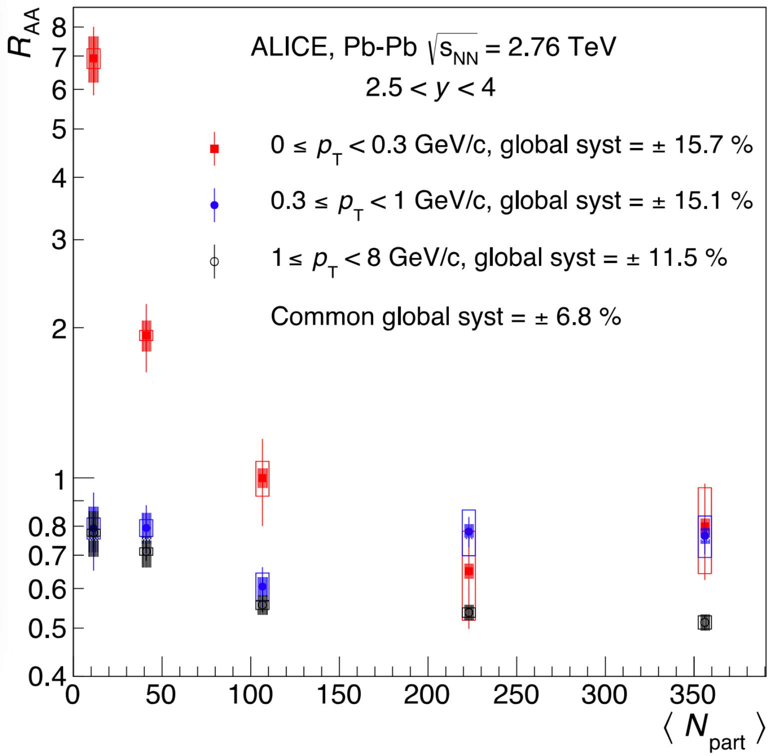
of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number of nucleii available in unit volume of ordinary materials, increases the effect to observable amounts. Analyzing the field of the nucleus into quanta by a procedure similar to that of v. Weizsäcker,[4] he finds that if one quantum $h\nu$

E. J. Williams Phys. Rev. **45**, 729 (1934),
K. F. Weizsacker, Z. Physik , 612 (1934)

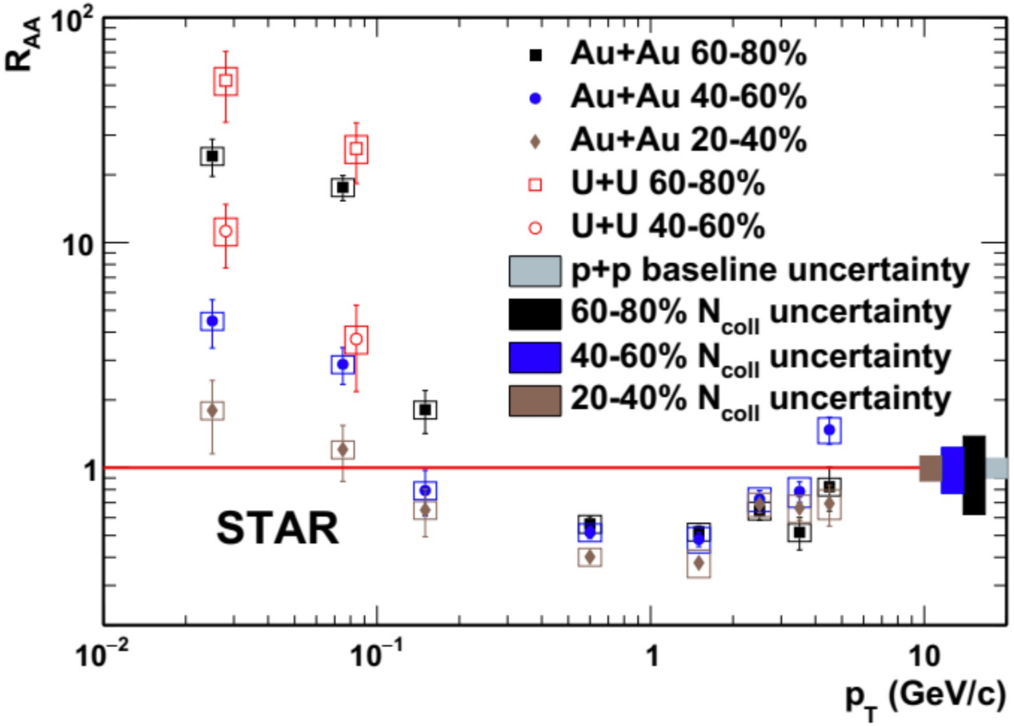
Evidence of Photons in Heavy-Ion Collisions



ALICE: PRL 116, 222301 (2016)

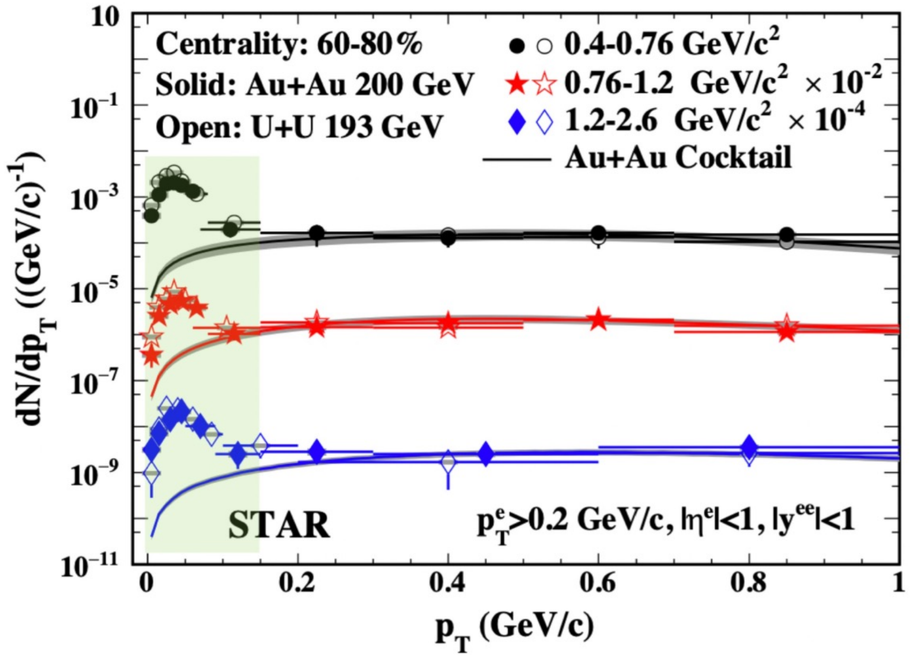


STAR: PRL 123 (2019) 132302



- **Significant enhanced J/Psi yield at very low pT region in peripheral A+A collisions**
  - → Coherent **Photon-Nuclear** Interactions → **Evidence of photon beams induced by relativistic ions**.

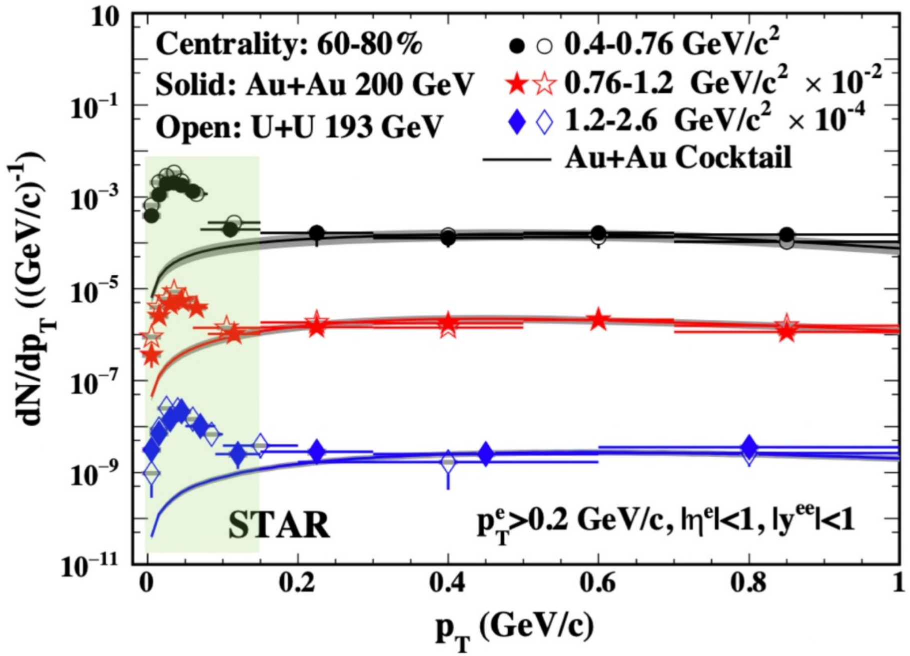
Light-Light Collision at RHIC Peripheral Collisions

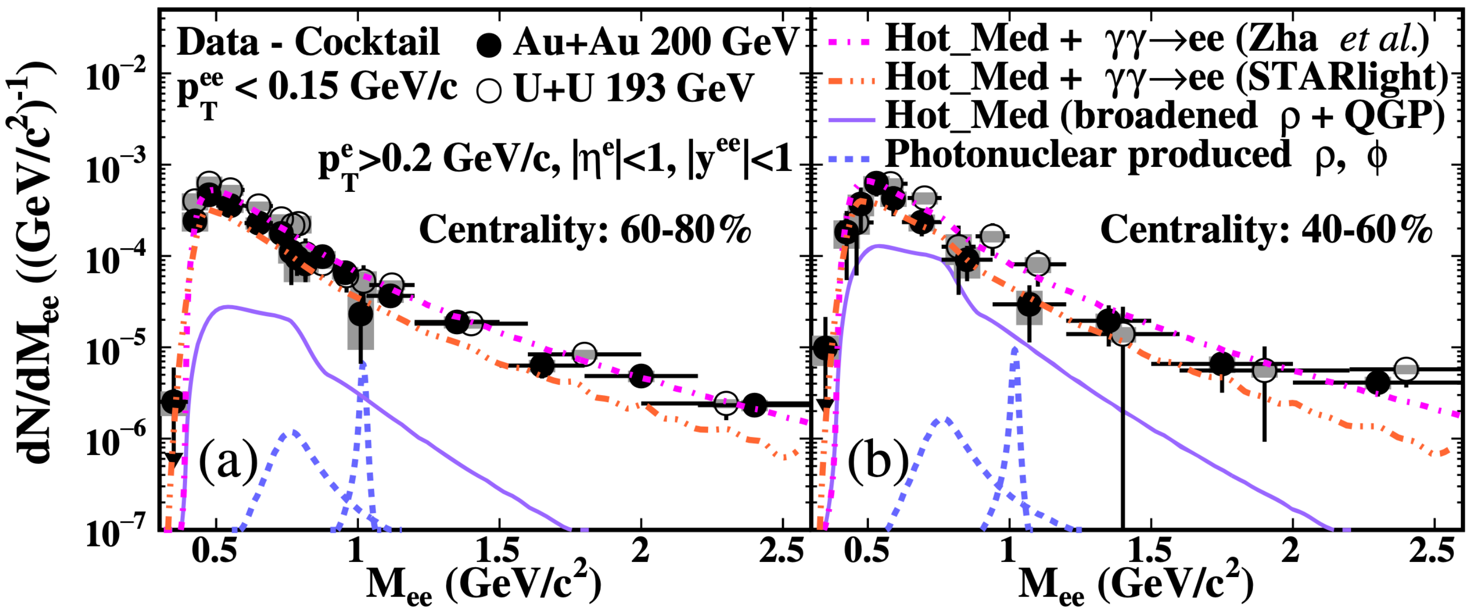


STAR, PRL 121 (2018) 132301

- Significant e^+e^- enhancement at very low-p_T region,

Light-Light Collision at RHIC Peripheral Collisions

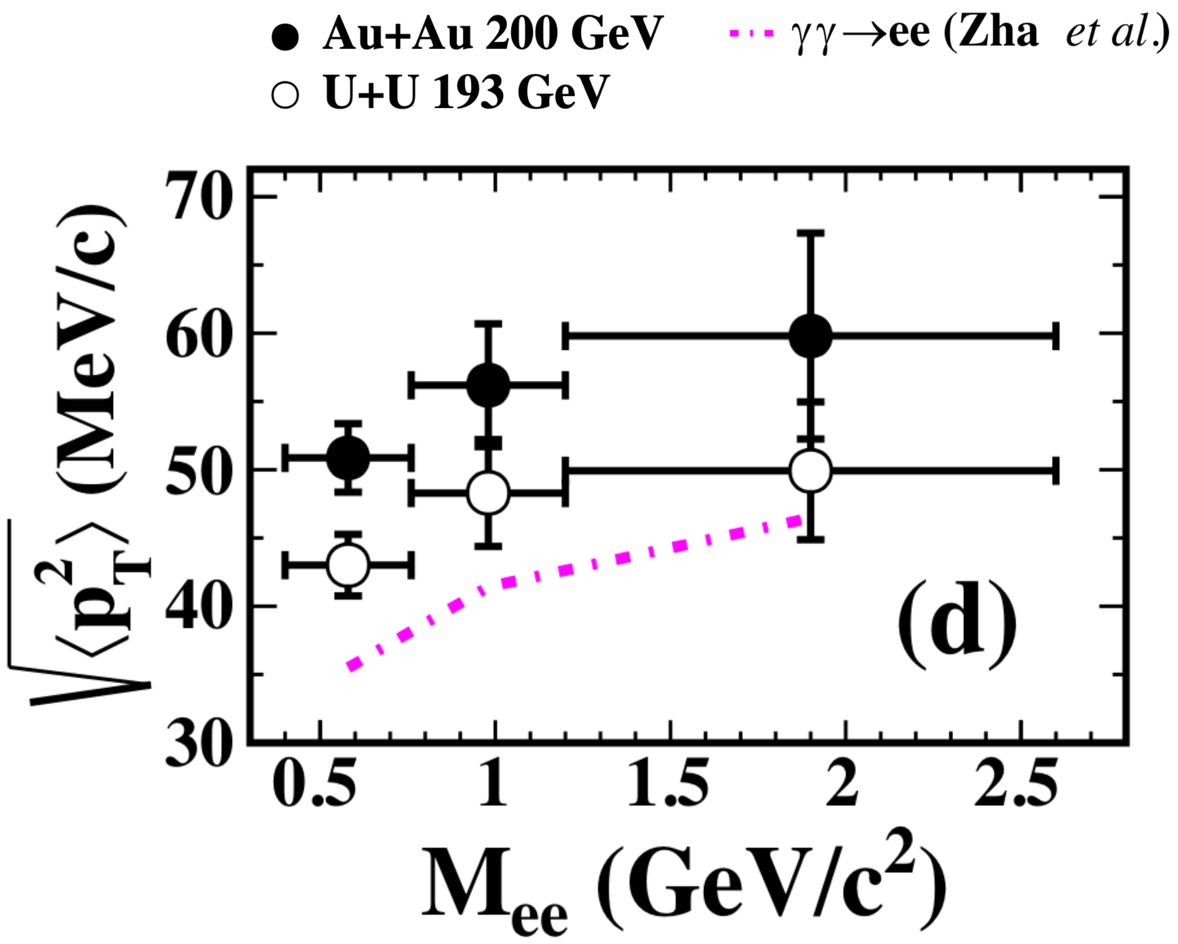




STAR, PRL 121 (2018) 132301

- Significant e^+e^- enhancement at very low-p_T region
- Excess dielectron mass spectra can be well explained by models considering the coherent photon-photon interactions → **Light-Light Collisions**.

Broaden p_T Due to Final State Effects?



STAR, PRL 121 (2018) 132301

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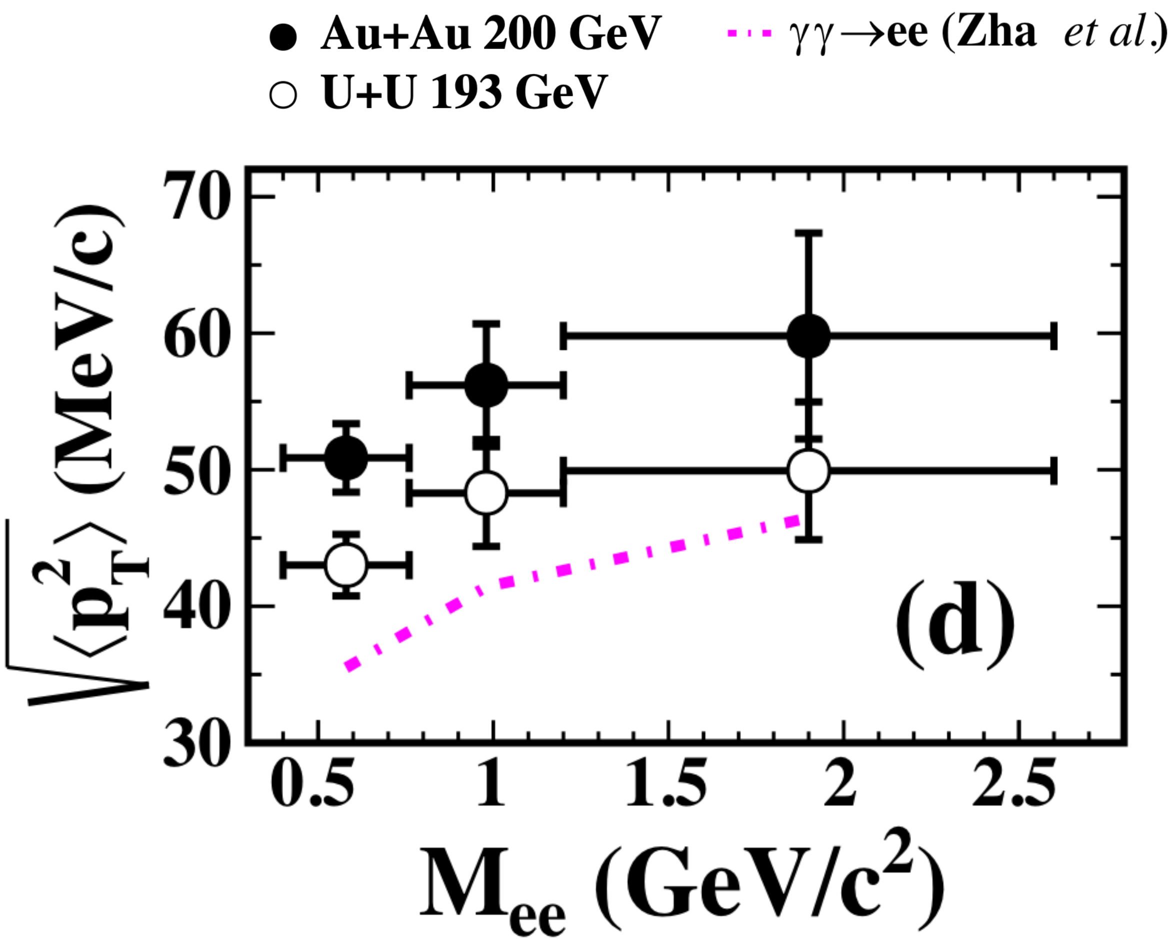

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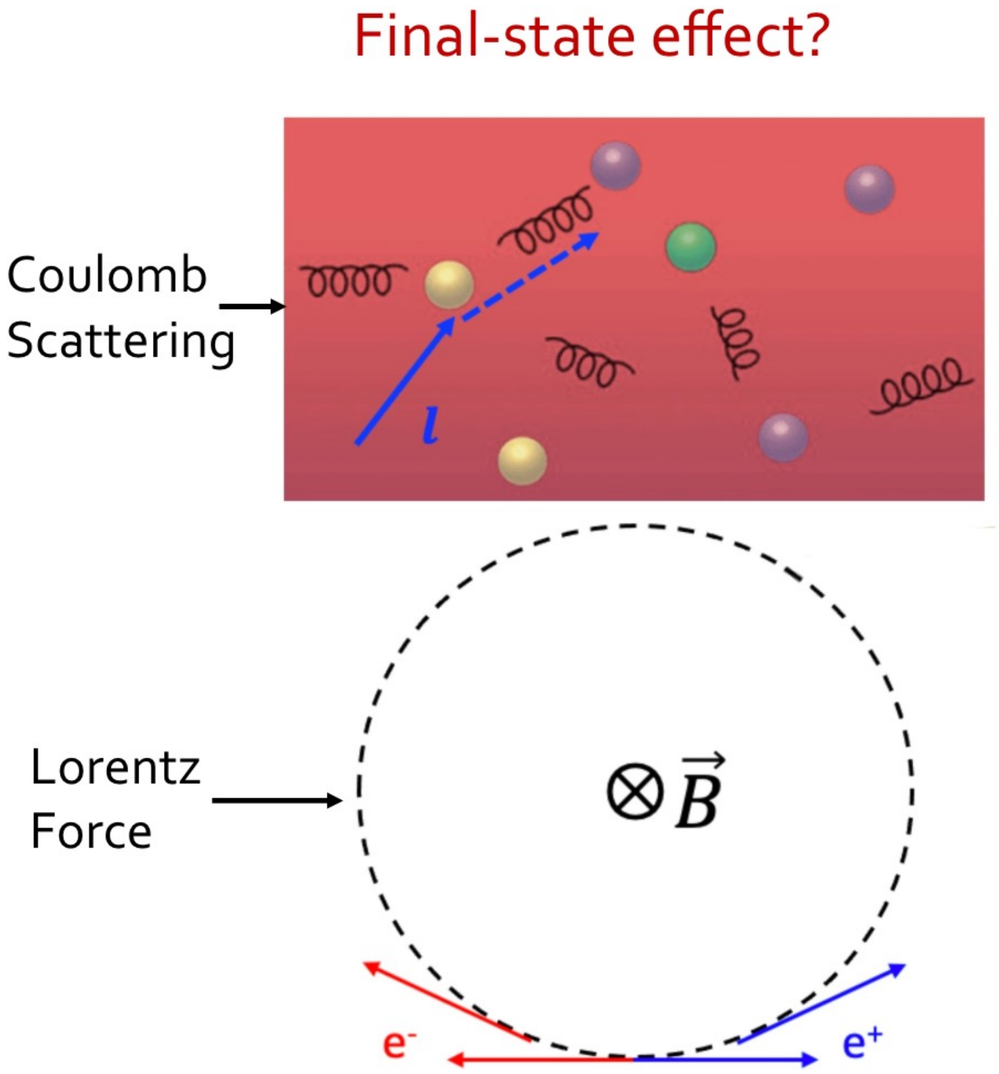
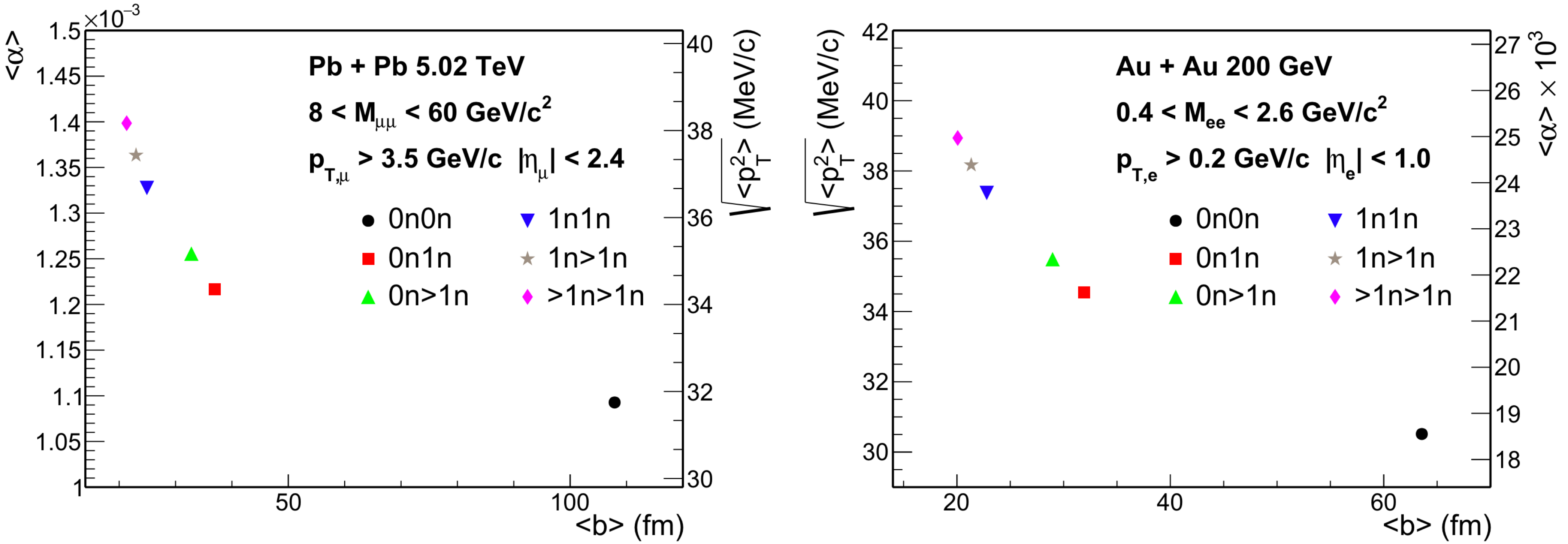


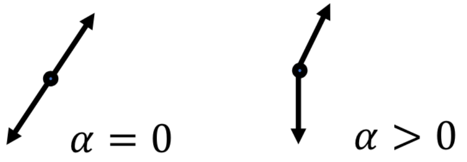
Broaden p_T Due to **Initial** State Effects?

QED calculations considering the b-dependent initial photon p_T predicted the the dilepton pair p_T should have strong impact parameter dependence

arXiv:2006.07365v1

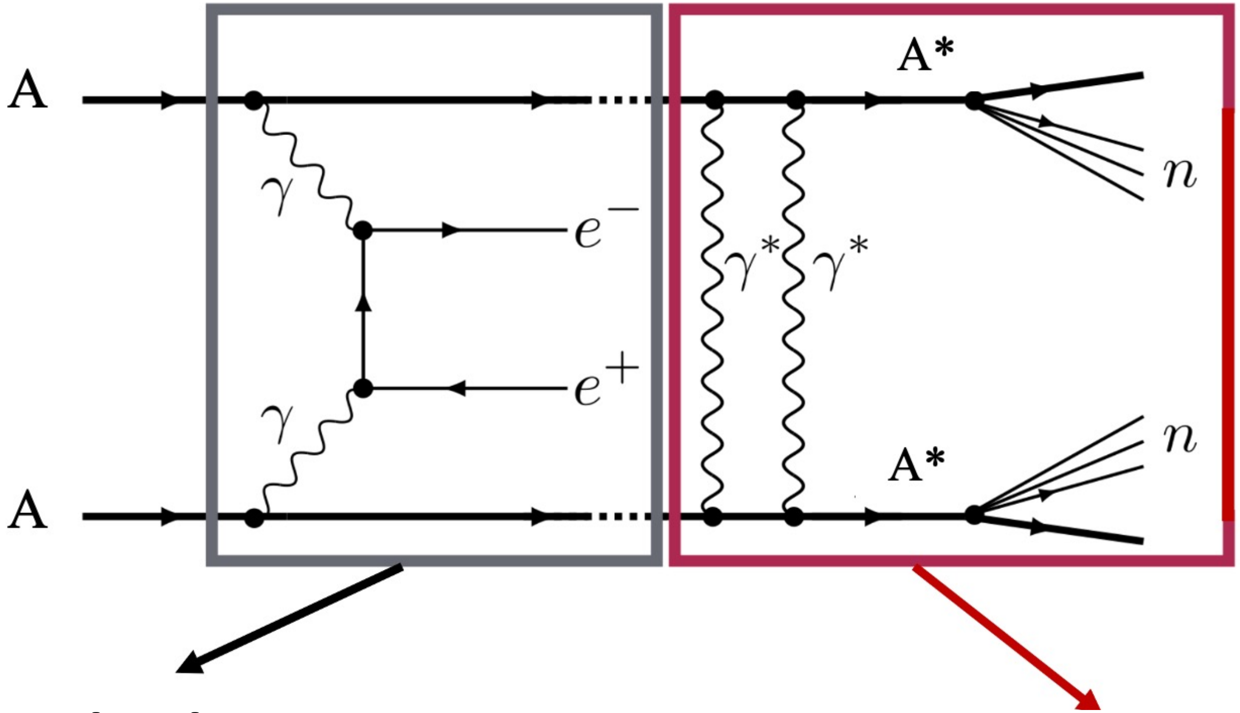


$$\alpha = 1 - \frac{|\phi^+ - \phi^-|}{\pi},\ \alpha \propto p_T^{ll}/M_{ll}$$



Light-Light Collision in UPCs and b Dependence

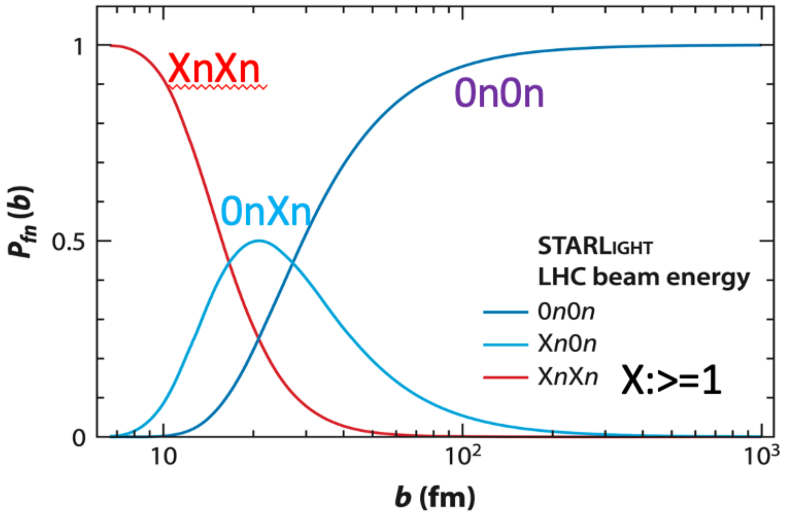
Study photon-photon interactions in a clean environment, where no hadronic collisions.



Breit-Wheeler process

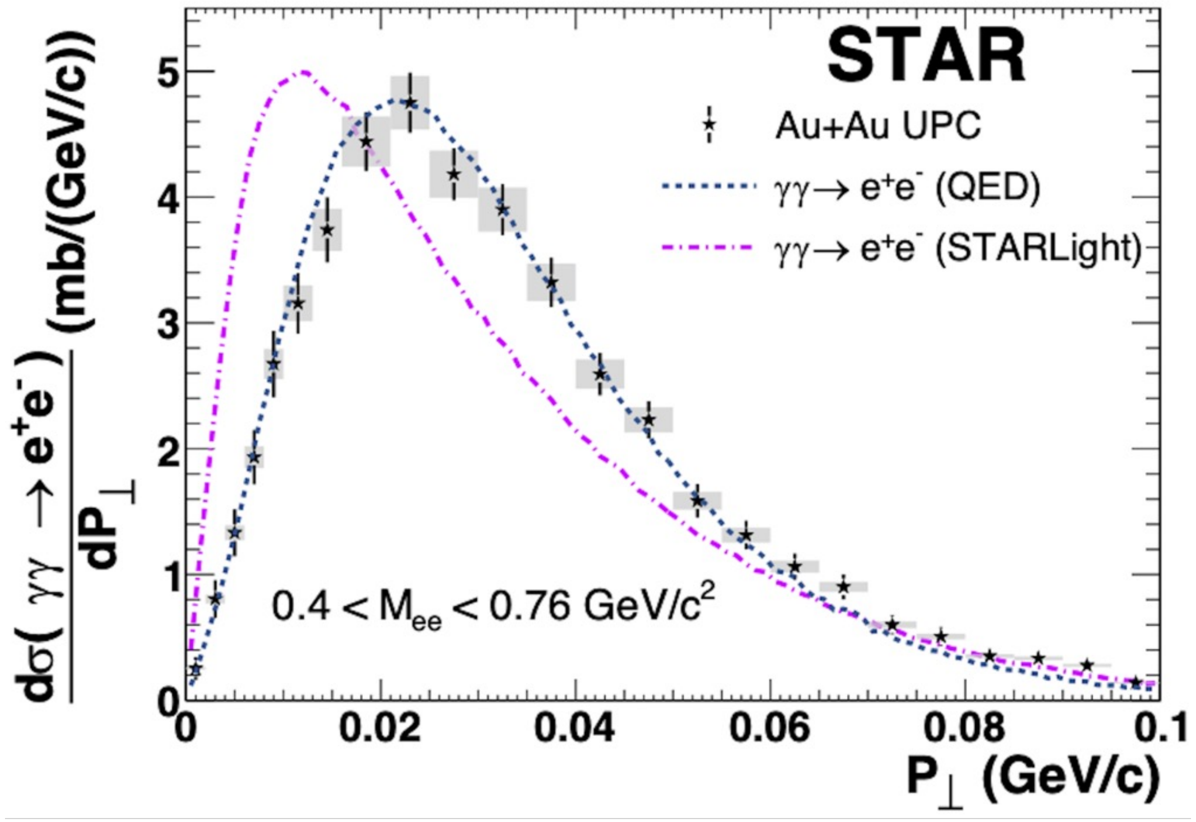
Extra photon exchange induced Coulumb exitation and neutron emission → Control b by neutron multiplicity

Klein & Steinberg,
Ann. Rev. Nucl. Part. Sci. 70 (2020) 323

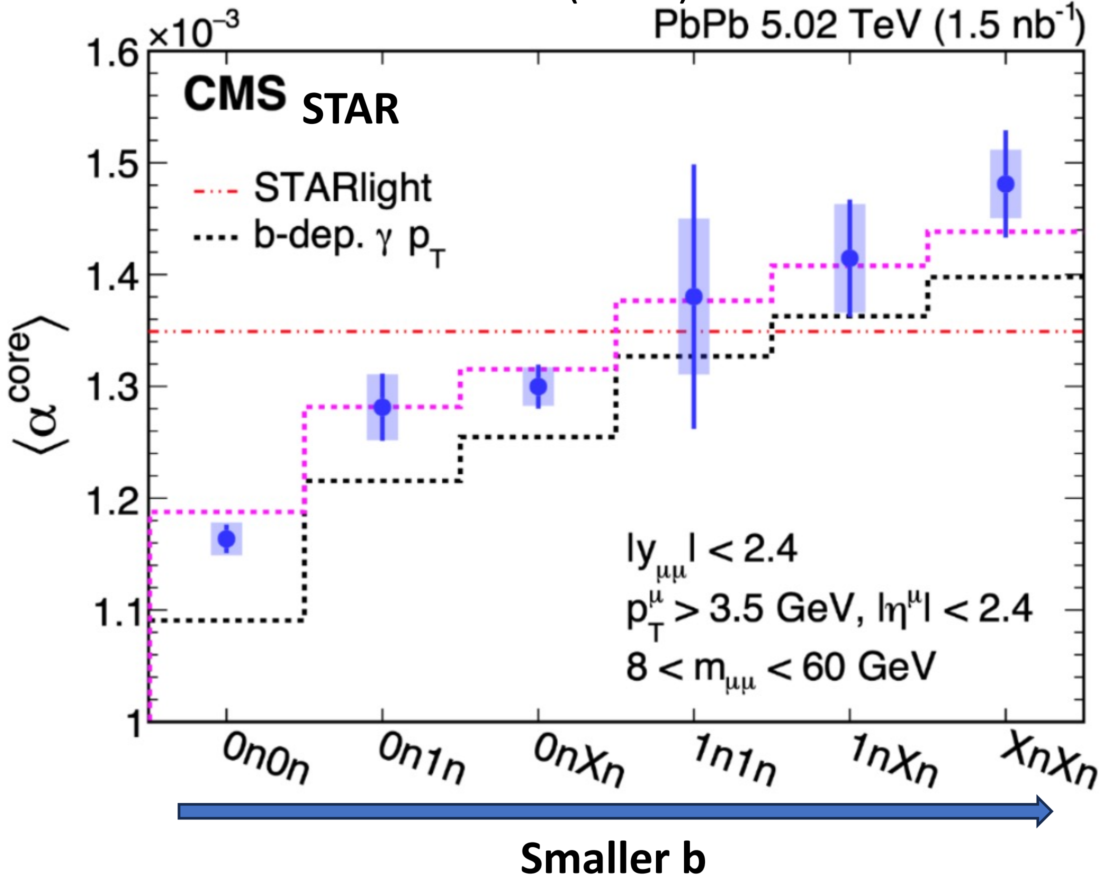


- Analogous to centrality:
  - $b_{XnXn} < b_{0nXn} < b_{0n0n}$ **in UPC**

Broaden p_T Mainly Due to **Initial** State Effects

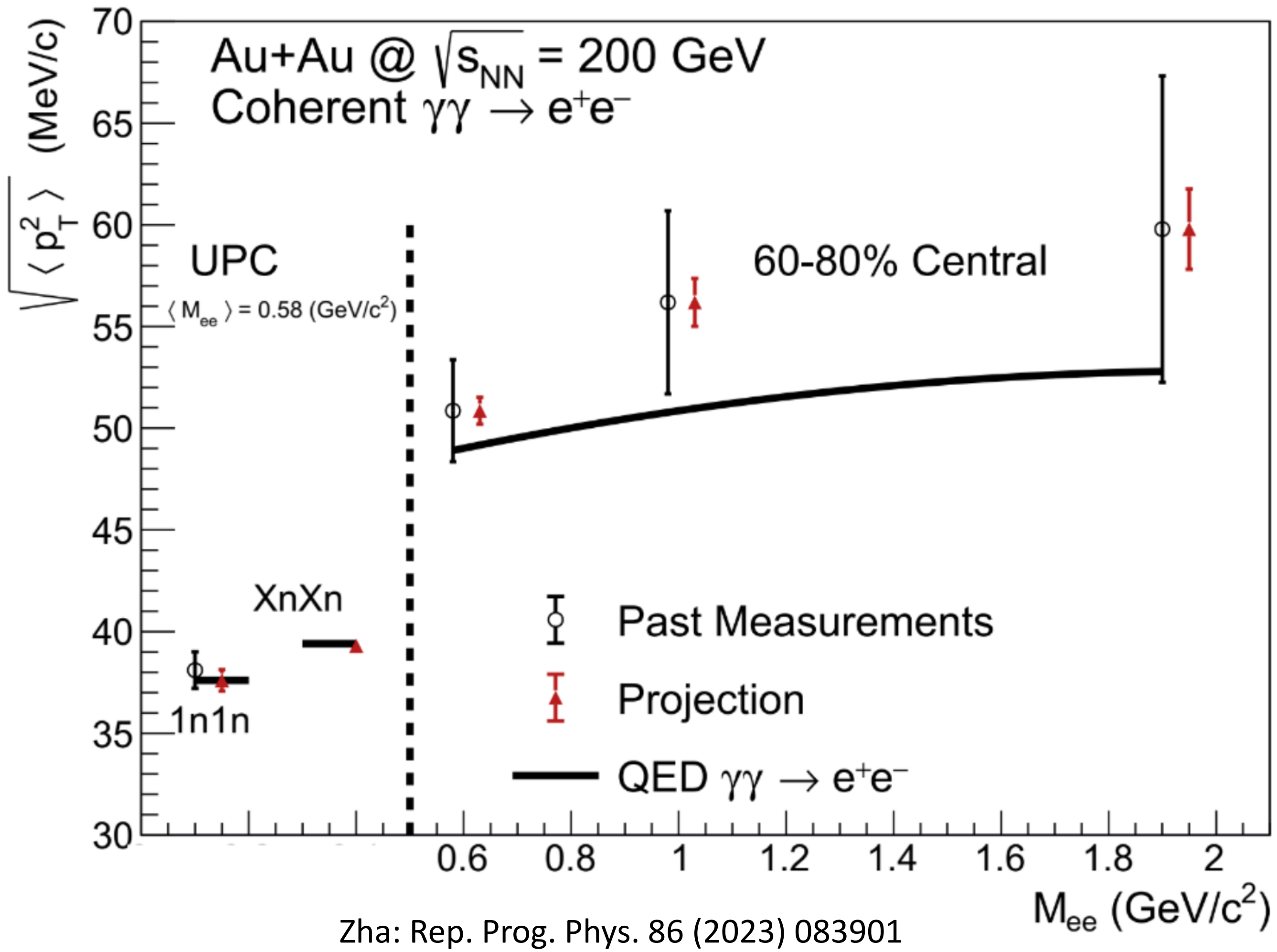


CMS: PRL 127 (2021) 122001



- **QED calculations considering b-dependent photon p_T well describe experimental data from both RHIC and LHC**

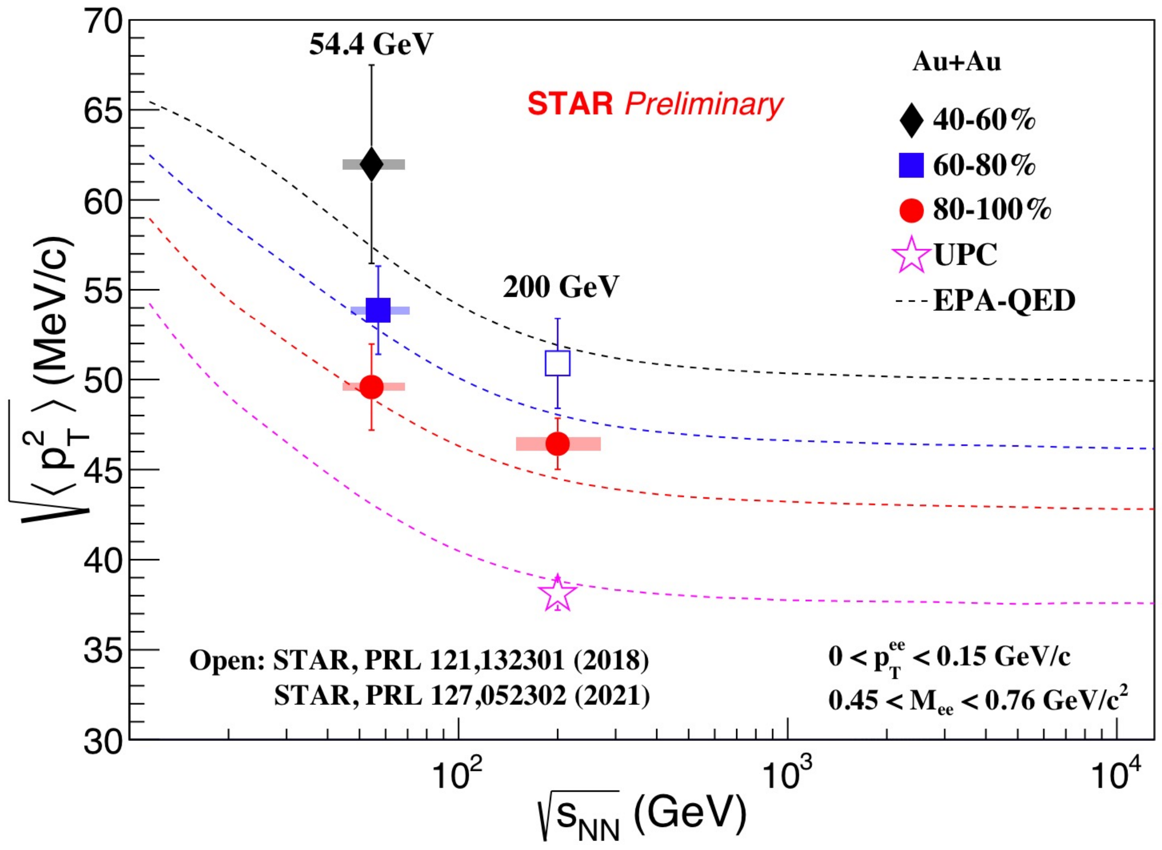
Lessons for Future Exploration of QGP Effects



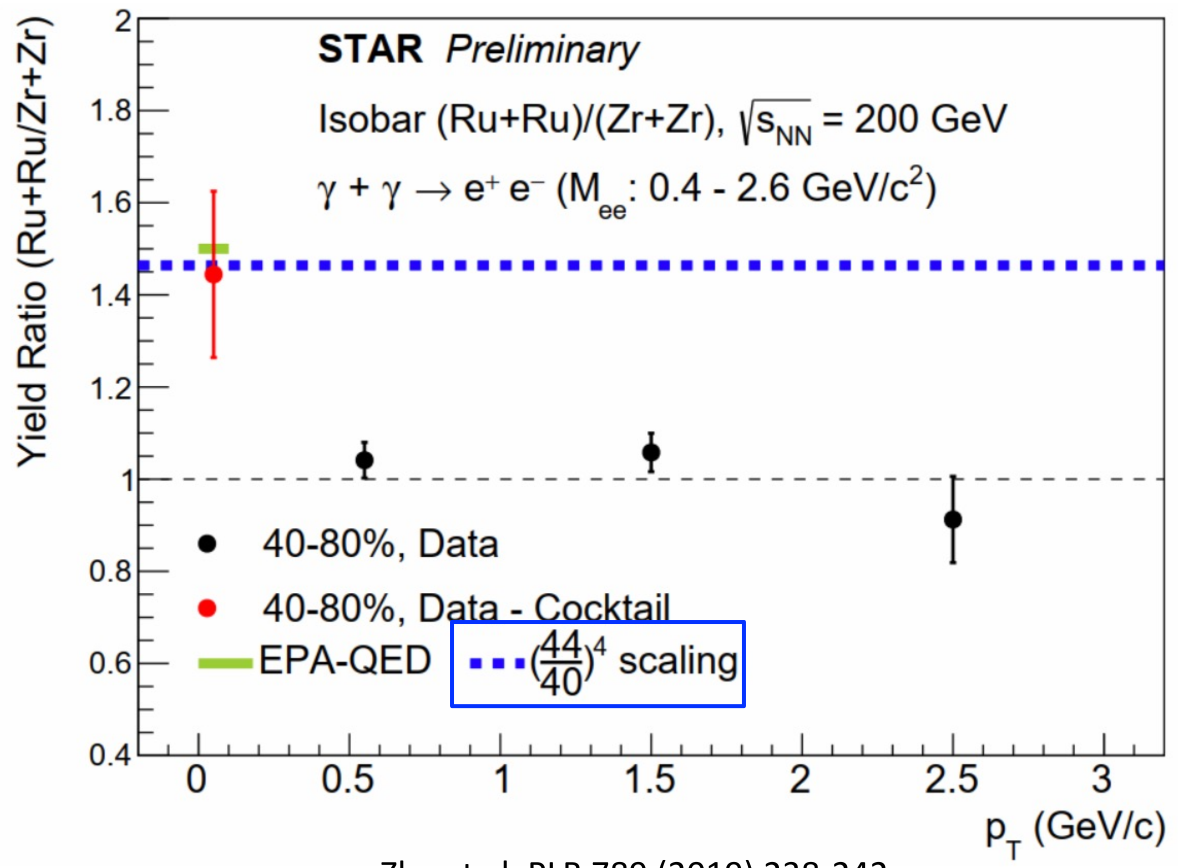
Zha: Rep. Prog. Phys. 86 (2023) 083901

- b-dependent effects dominate mean p_T of dilepton pairs, for both UPC and PC collisions
- High precision measurements are needed to observe the potential effects from QGP
- Future high precision measurements:
  - RHIC Run 2023-2025
  - LHC Run3 & Run4

Collision Energy and Nuclei Charge Dependences



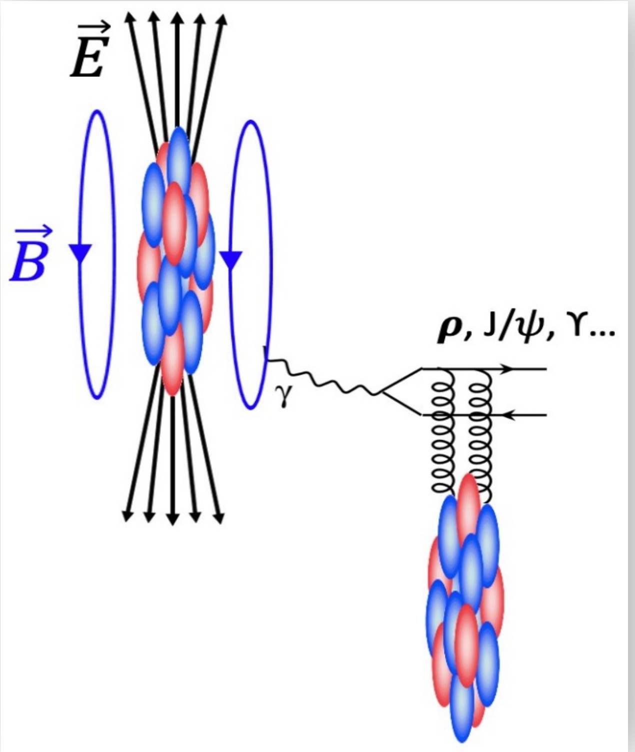
QED: Zha et al., PLB 800 (2020) 135089



Zha et al, PLB 789 (2019) 238-242

Vector Meson Production via Photon-Nuclear Interaction

Probing the gluonic structure of target nucleus or nucleons



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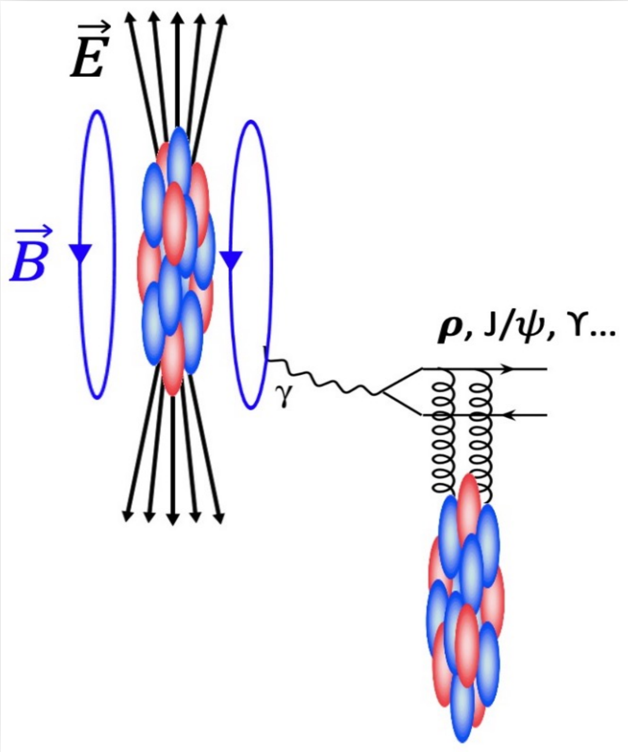


Coherent production:

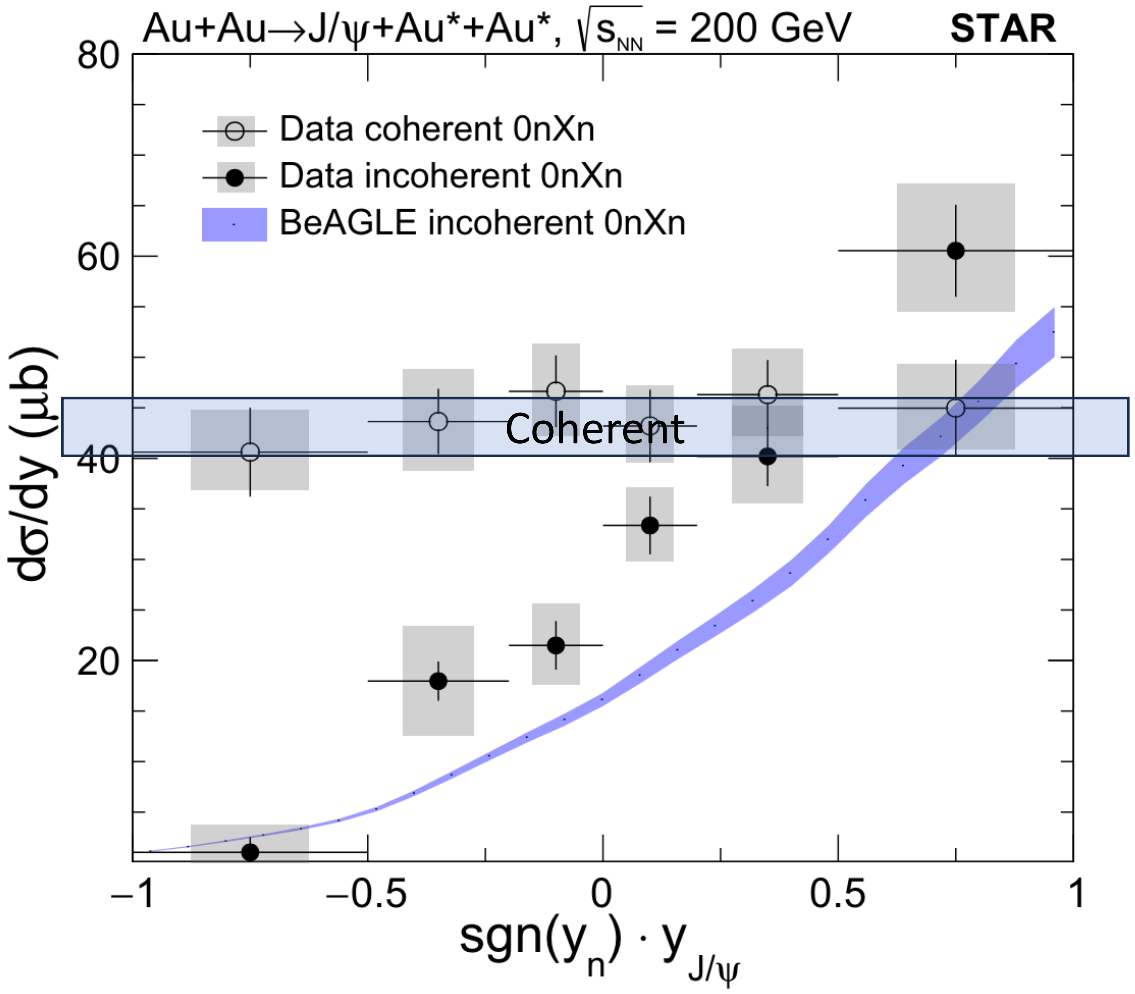
- Photon fluctuated dipole couples coherently to entire nucleus
- Target nucleus remains intact
- VM $\langle p_T \rangle$ ~ 50 MeV
- Probing the averaged gluon density

Incoherent production:

- Photon fluctuated dipole couples to individual nucleons
- Target nucleus usually breaks
- VM $\langle p_T \rangle$ ~ 500 MeV
- Probing the local gluon density and fluctuations

$$\omega = \frac{M_{VM}}{2} e^{\pm y} \qquad x = \frac{M_{VM}}{\sqrt{s_{\mathrm{NN}}}} e^{\mp y} \qquad \mathrm{W}_{\gamma\mathrm{p}} = 2\sqrt{\omega \cdot \mathrm{E}_{\mathrm{beam}}}$$

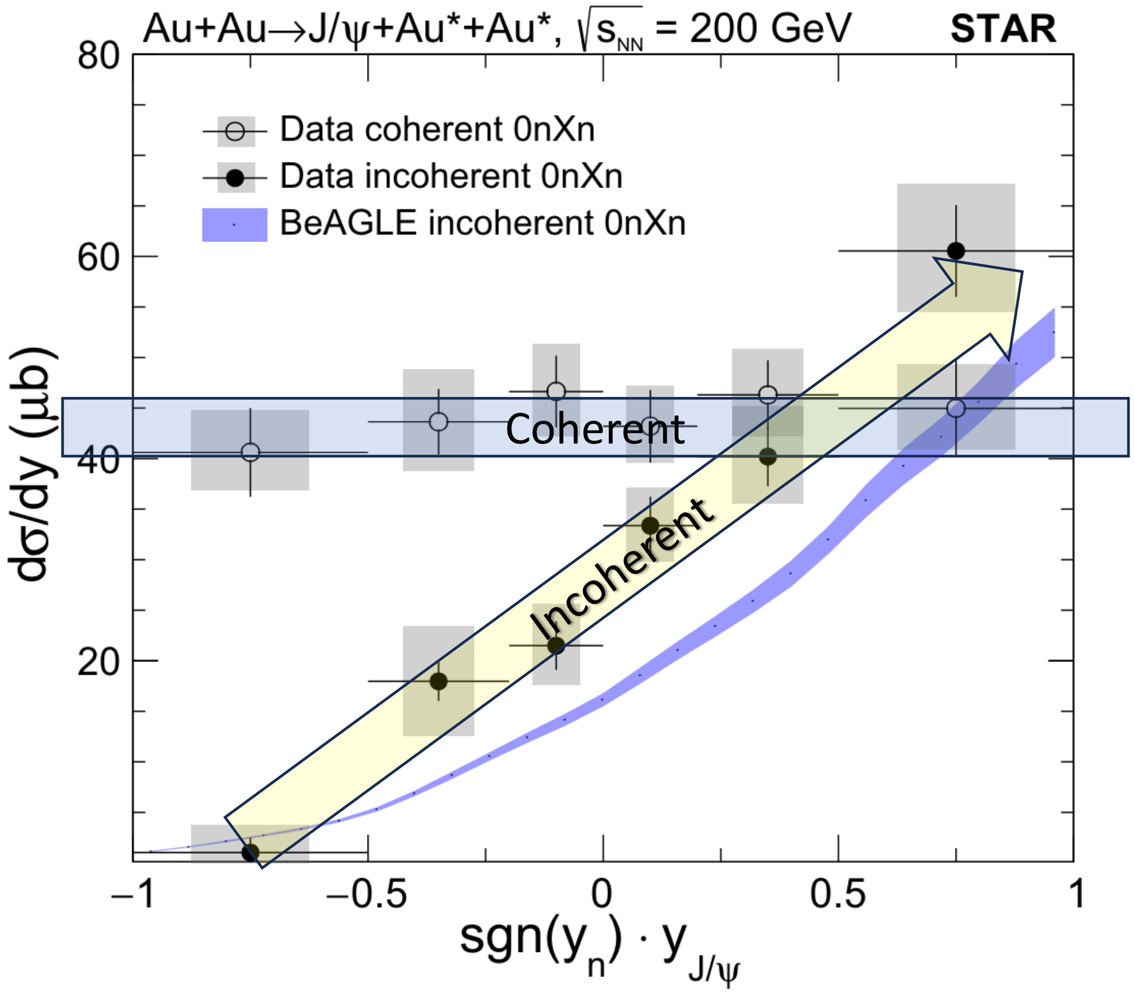
Correlation btw Forward Neutrons and J/Psi



STAR: arXiv:2311.13637

- 0nXn UPCs: neutron emissions from single nuclei
- Coherent J/Psi has no direction correlation with the forward neutrons

Correlation btw Forward Neutrons and J/Psi



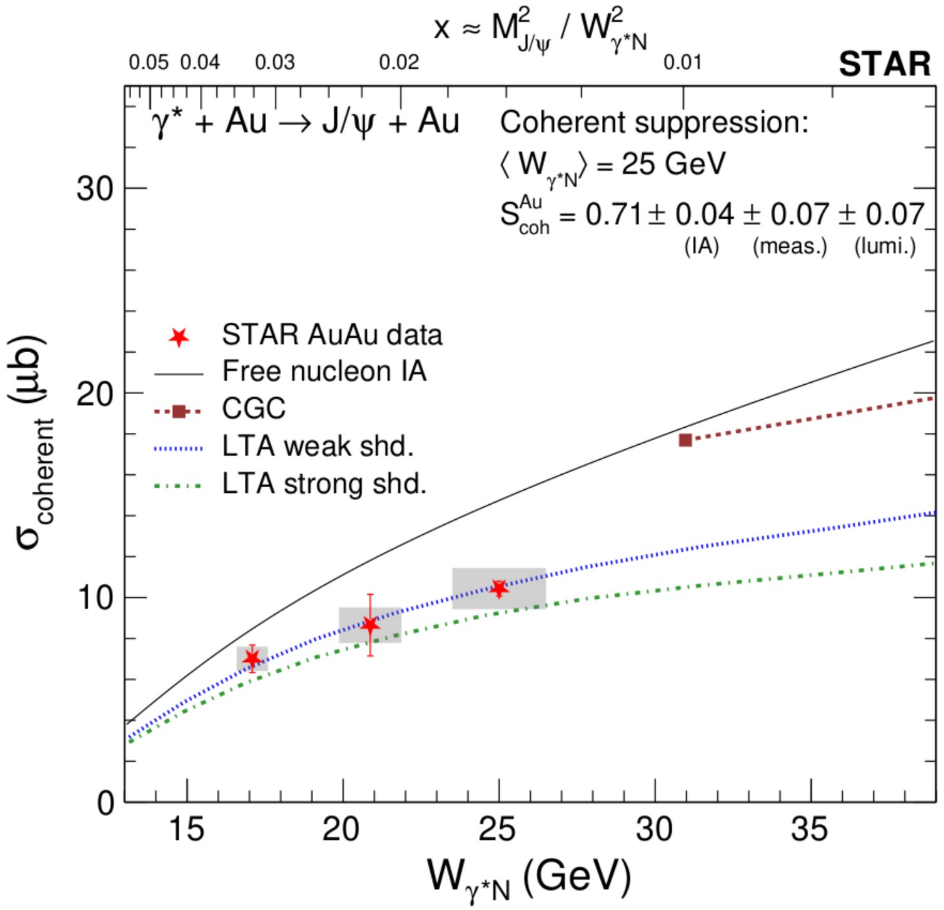
STAR: arXiv:2311.13637

- 0nXn UPCs: neutron emissions from single nuclei
- Coherent J/Psi has no direction correlation with the forward neutrons
- Incoherent J/Psi exhabits strong direction correlation with the forward neutrons
  - First experimental validation on this assumption.

Neutrons emissions:

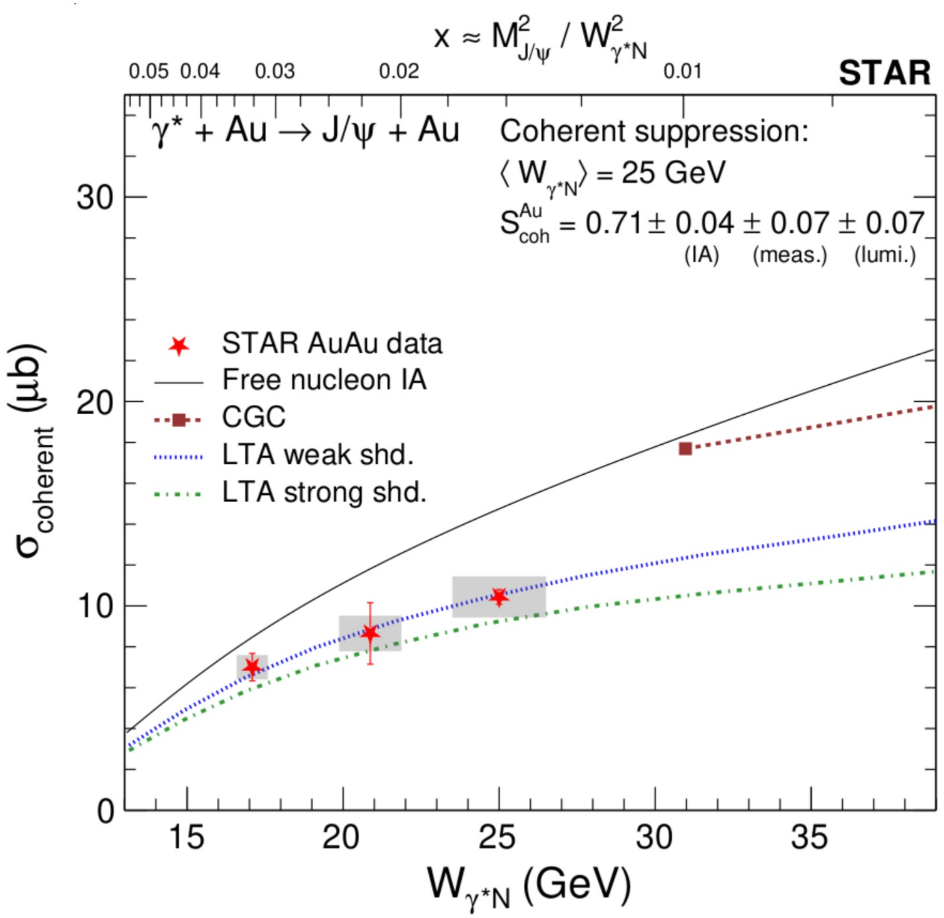
- For cohererent J/Psi, mainly from the additional photon exchange
- For incoherent J/Psi, mainly induced by the incoherent interaction itself

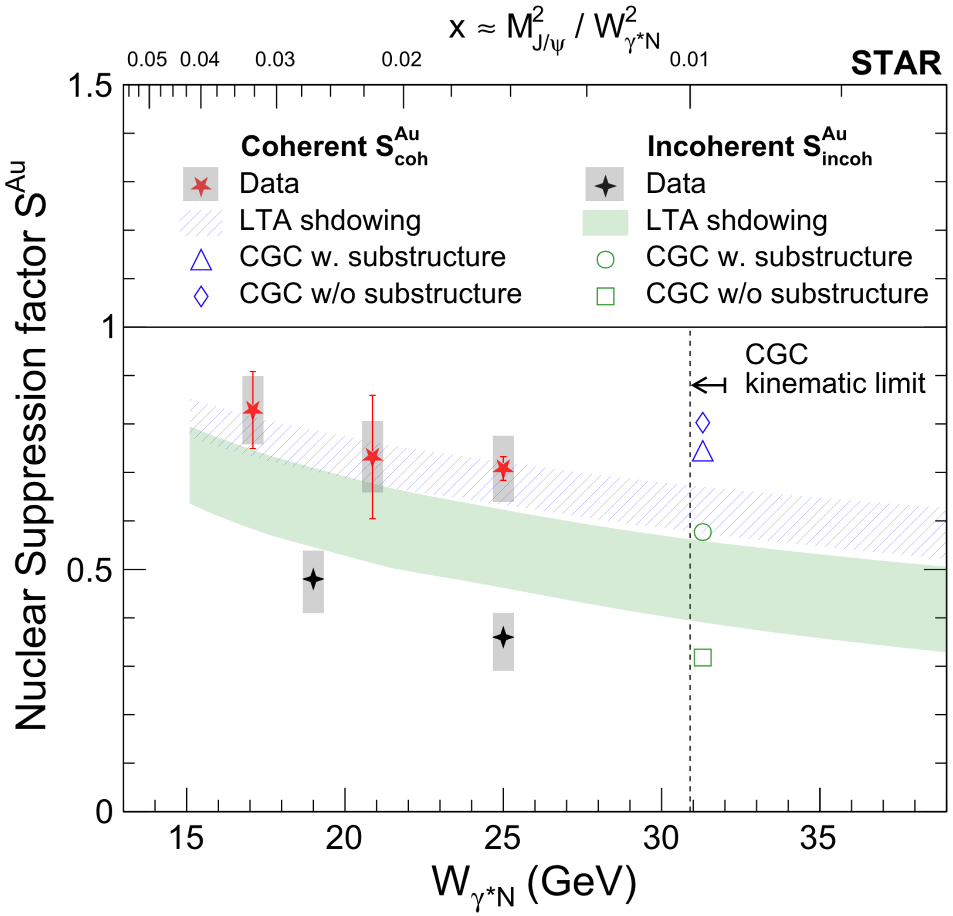
J/Psi Photoproduction and Nuclear Suppression



- **Coherent J/Psi Xsec well described by Leading Twist Approximation (LTA) model**

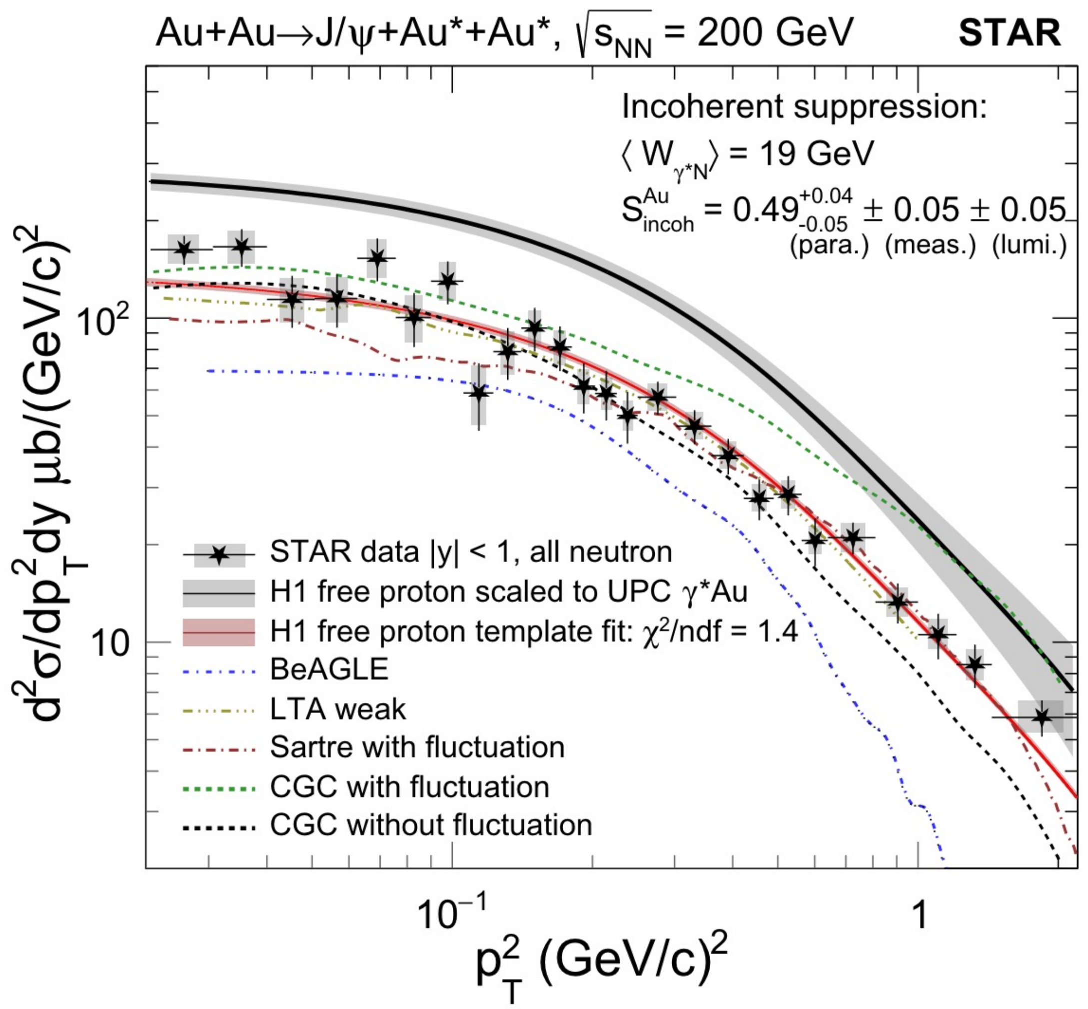
J/Psi Photoproduction and Nuclear Suppression





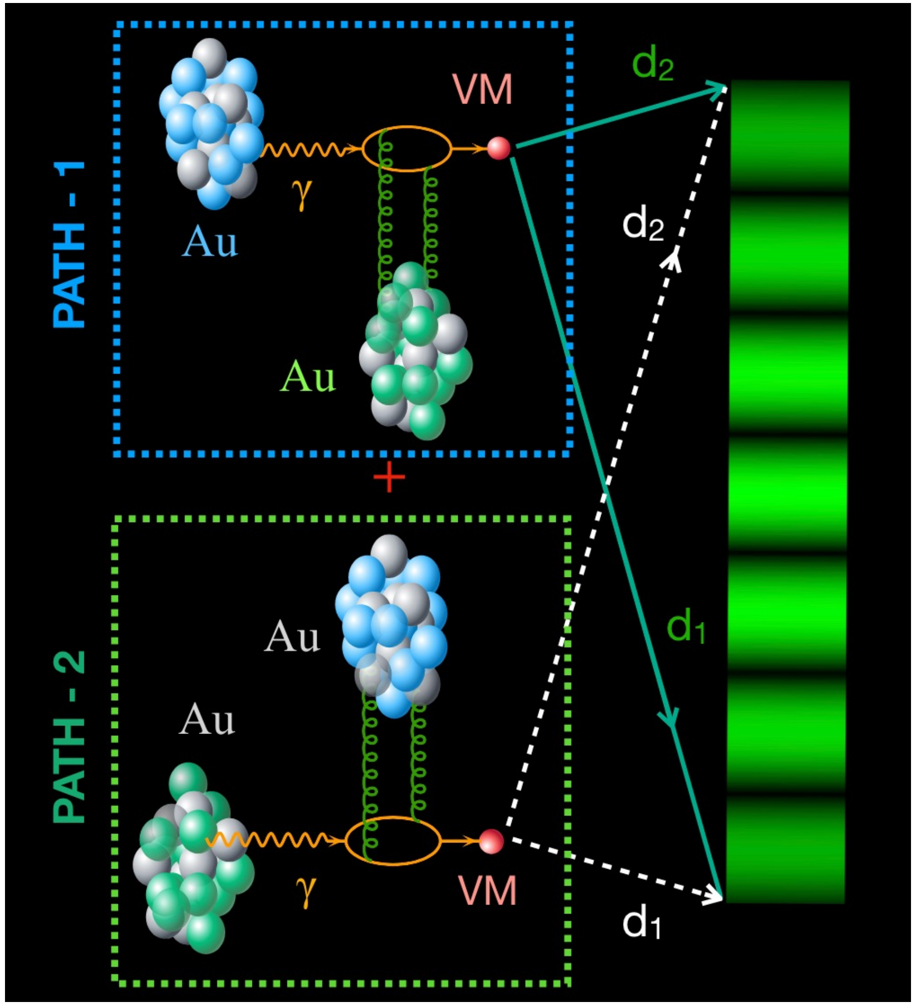
- **Coherent J/Psi Xsec well described by Leading Twist Approximation (LTA) model**
- **Significant nuclear suppression effects are observed for both coherent and incoherent J/Psi photoproductions**

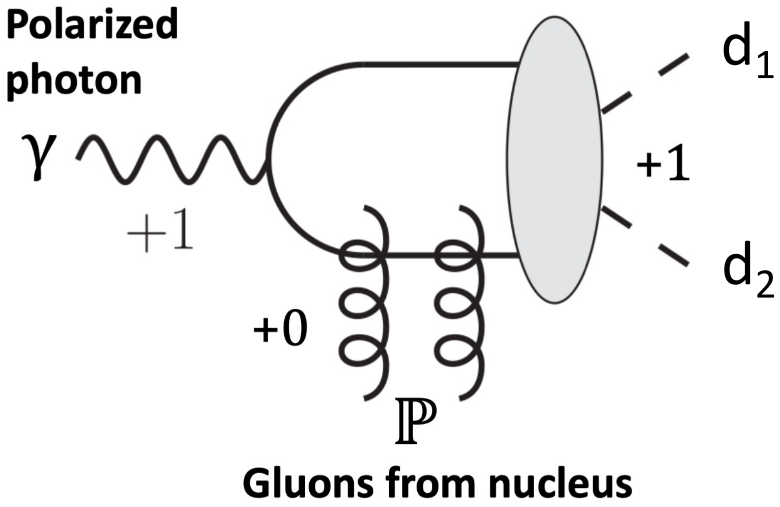
p_T^2 of Incoherent J/Psi Photoproduction



- Strongly suppressed compare to the reference scaled from photon-proton data (HERA)
- However, the spectra keep the similar shape as H1 data
  - Supporting the sub-nucleon fluctuations
  - Bound nucleon shows similar shape and fluctuations as free nucleon

Double Slit Interference of VM Photoproduction in UPCs

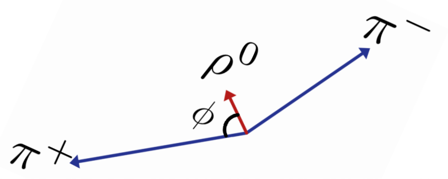


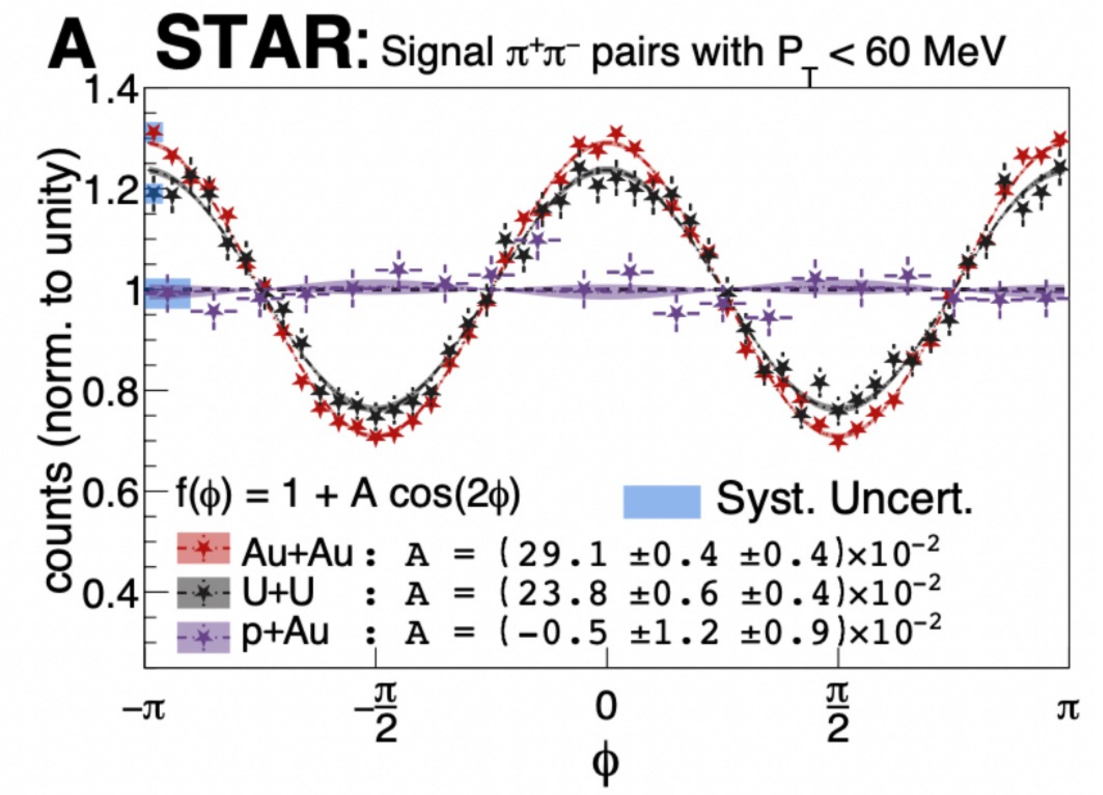


- Polarization of photon inherited by produced VM
- VM spin converted into orbital angular momentum between decayed daughters
- Anisotropy in daughters' momentum

Two indistinguishable paths interfere and make angular modulation observable

Observation of Interference in $\rho^0 \rightarrow \pi^+\pi^-$





STAR: Sci. Adv. **9**, eabq3903 (2023)

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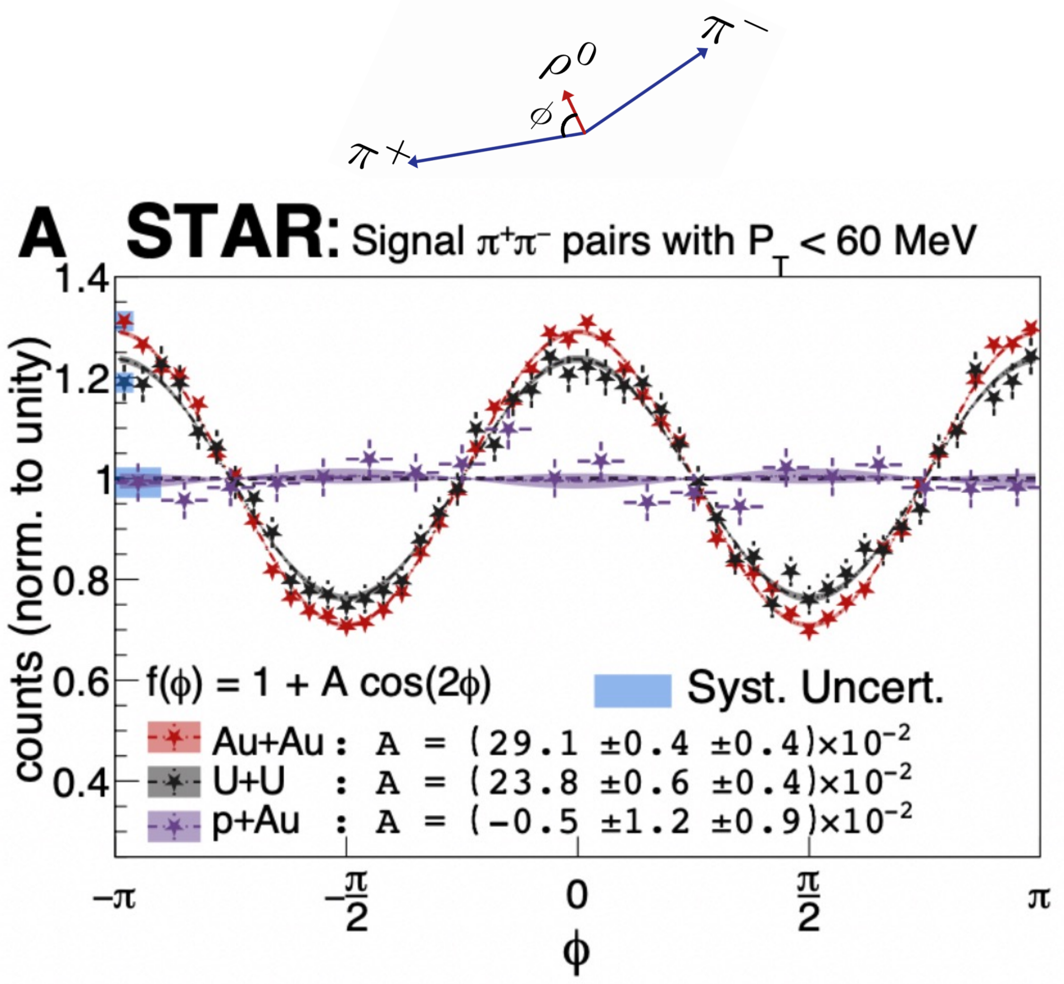
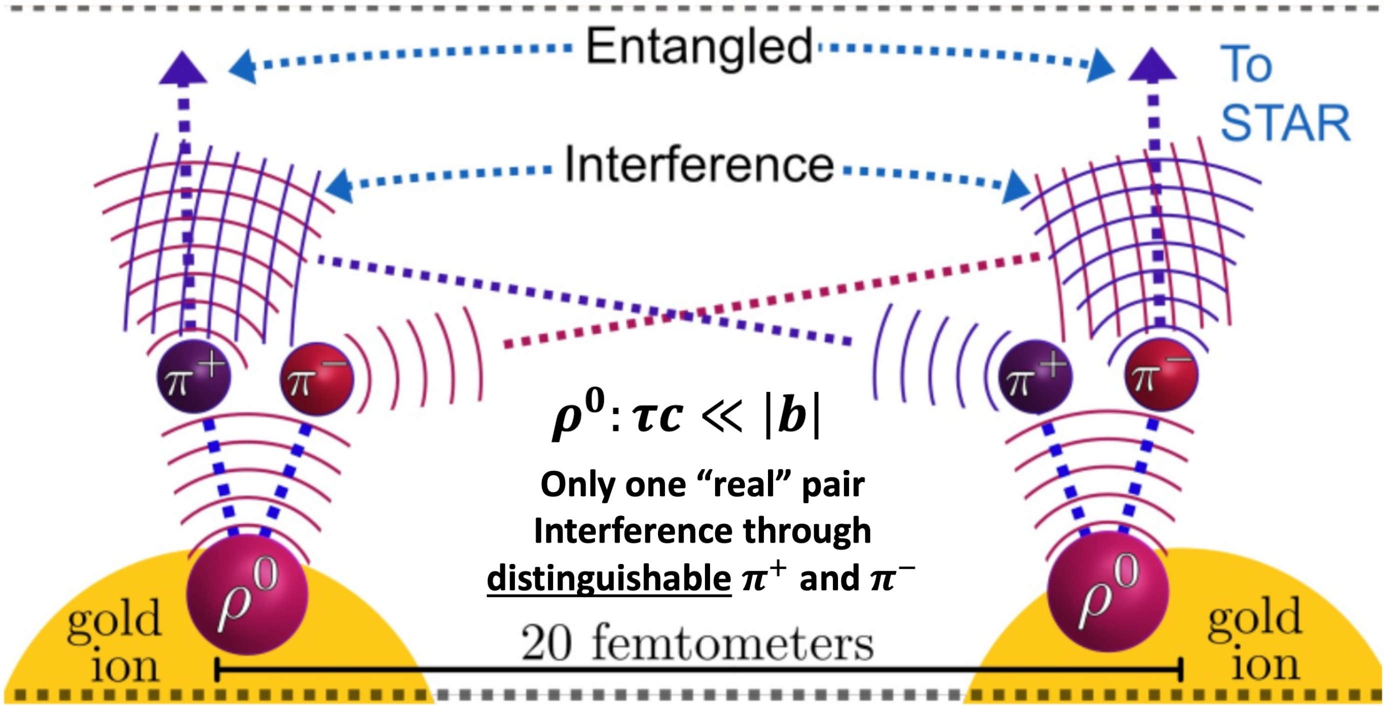


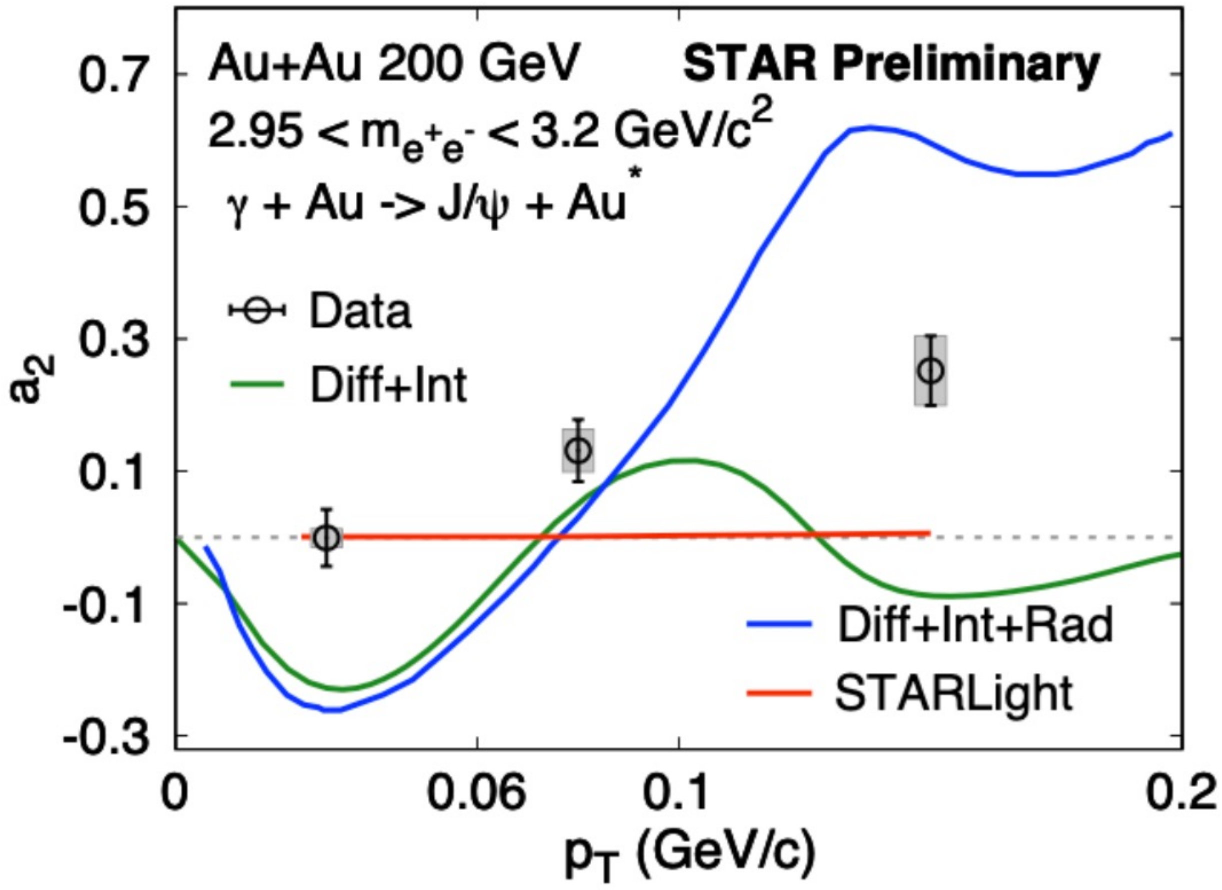


$\boldsymbol{\rho^0: \tau c \ll |b|}$

Only one "real" pair
Interference through
<u>distinguishable</u> π^+ and π^-

STAR: Sci. Adv. **9**, eabq3903 (2023)

Inteference in J/Psi → e^+e^-



J/Psi → e^+e^- vs. $\rho^0 \to \pi^+\pi^-$:

- lifetime ρ^0 : 1.3 fm/c; **J/Psi: 2160 fm/c**
- π is boson; e is fermion

The much longer lifetime of J/Psi allows the overlap between two possible J/Psi wavefunctions.

Positive modulation is observed and it increases vs. p_T

Summary

- Light-Light Collisions: Breit-Wheeler process has been studied in both UPCs and PCs
  - Significant enhancement at very low-pT in PCs
  - Mean p_T is dominated by b-dependent initial photon p_T
  - Collision energy and Z dependences
- Light-Nucleus Collisions:
  - Incoherent photoproduced J/psi has strong direction correlation with the forward neutrons while coherent one doesn’t
  - Both coherent and incoherent photoproduced J/psi experience strong nuclear suppression effects
  - Similar shape and fluctuation of nucleon in nucleus as free proton
  - Augular modulation due to entanglement enabled interference are observed
- Outlook: 20 times larger datasets in Au+Au@200 GeV with iTPC are on the way

THANKS