UPC MEASUREMENTS AT STAR

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RHIC & AGS Users' Meeting 2022

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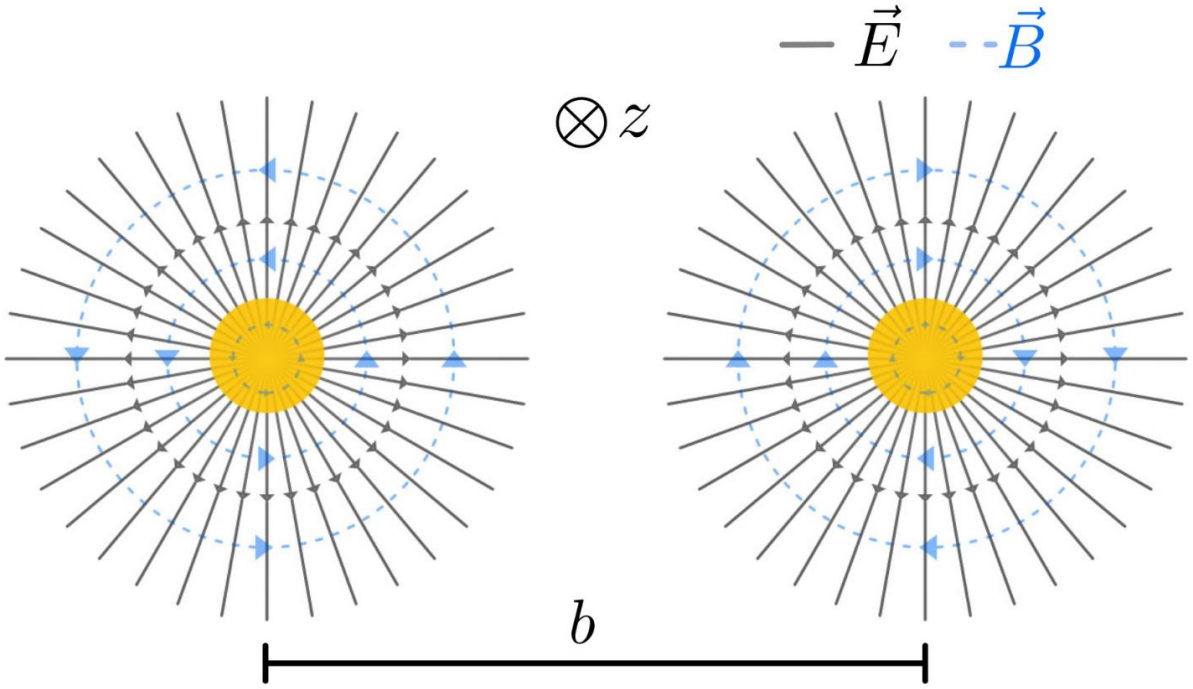
Ultraperipheral Collisions

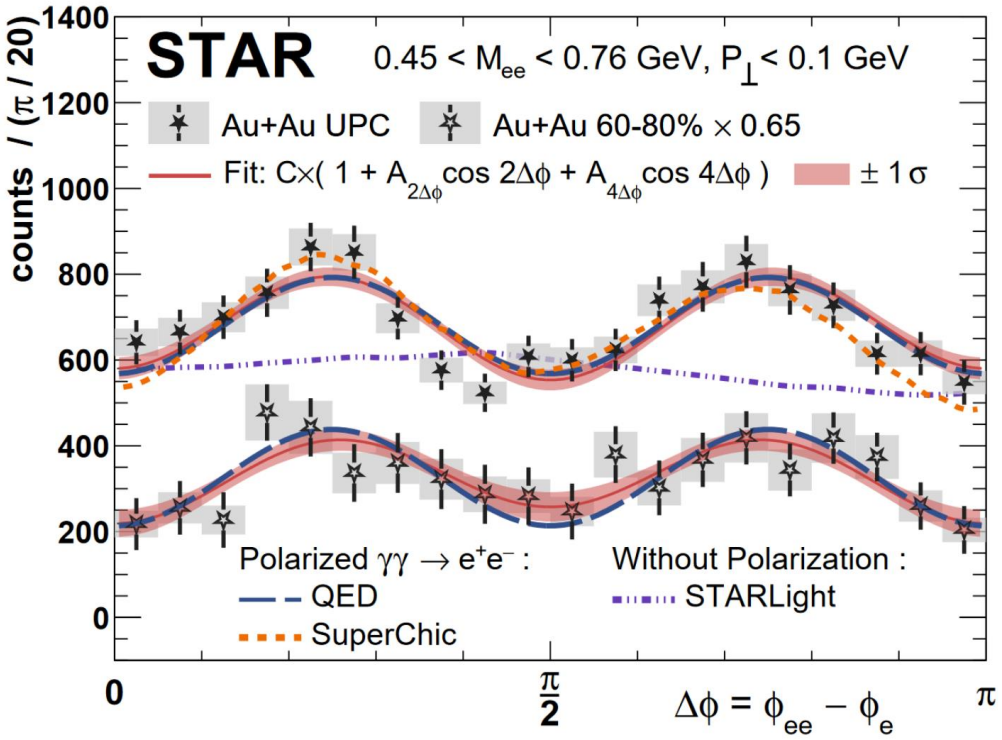


- Heavy ion collisions when the impact parameter is so large, no hadronic collision can occur ($b > 2R$)
- Ultrarelativistic nuclei produce highly Lorentz contracted electromagnetic fields
  - Equivalent Photon Approximation (EPA): (in a specific phase space) transverse EM fields can be quantized as a flux of quasi-real photons

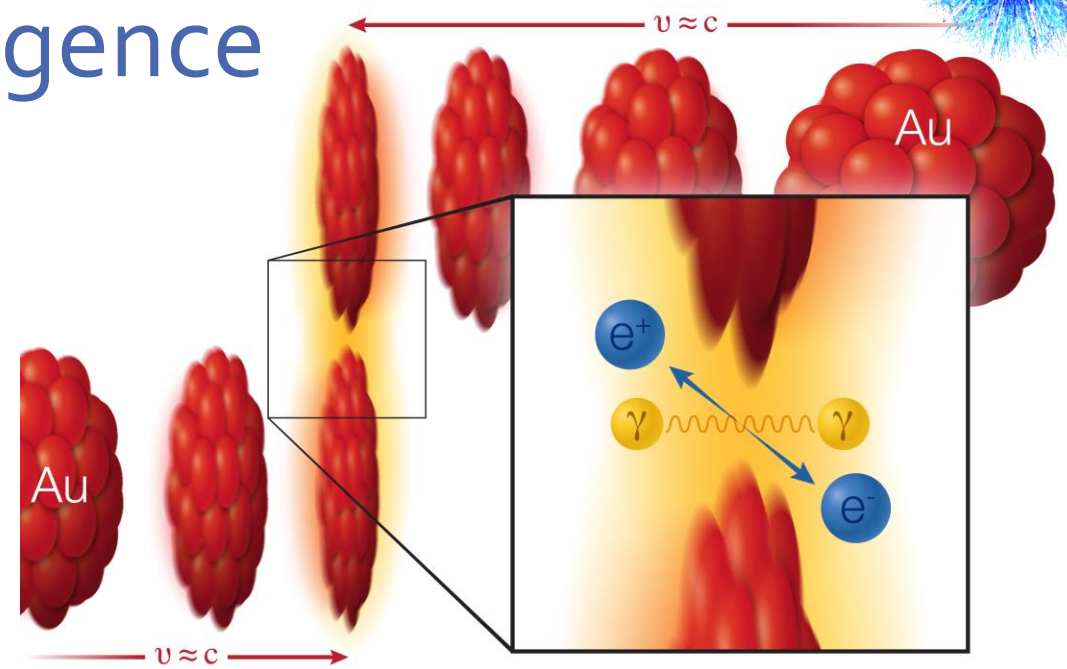
    C. F. V. Weizsäcker, Z. Phys. **88,** 612 (1934)

    E. J. Williams, Phys. Rev. **45,** 729 (1934).
  - High photon density with highly charged nuclei ($\propto Z^2$)

Observation of Breit-Wheeler Process and Vacuum Birefringence in Ultraperipheral Collisions



STAR Collaboration, Phys. Rev. Lett. **127**, 052302 (2021)



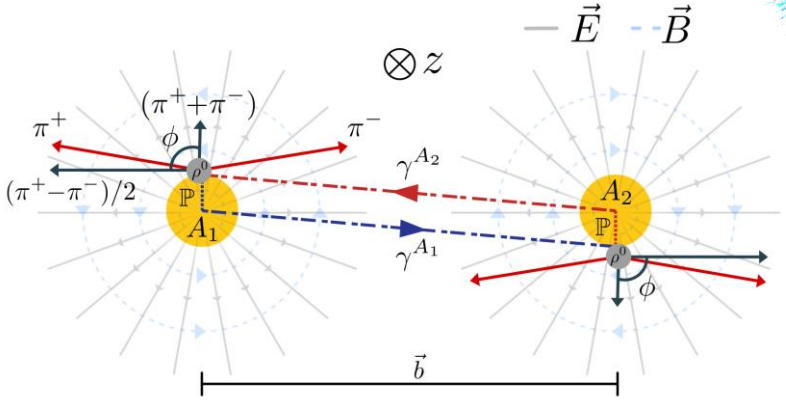
"Collisions of Light Produce Matter/Antimatter from Pure Energy". Brookhaven National Laboratory. July 28, 2021

- Breit-Wheeler Process: $\gamma\gamma \rightarrow e^+e^-$
- Demonstrates colliding photons are linearly polarized

Novel Quantum Entanglement Discovered with Diffractive ρ

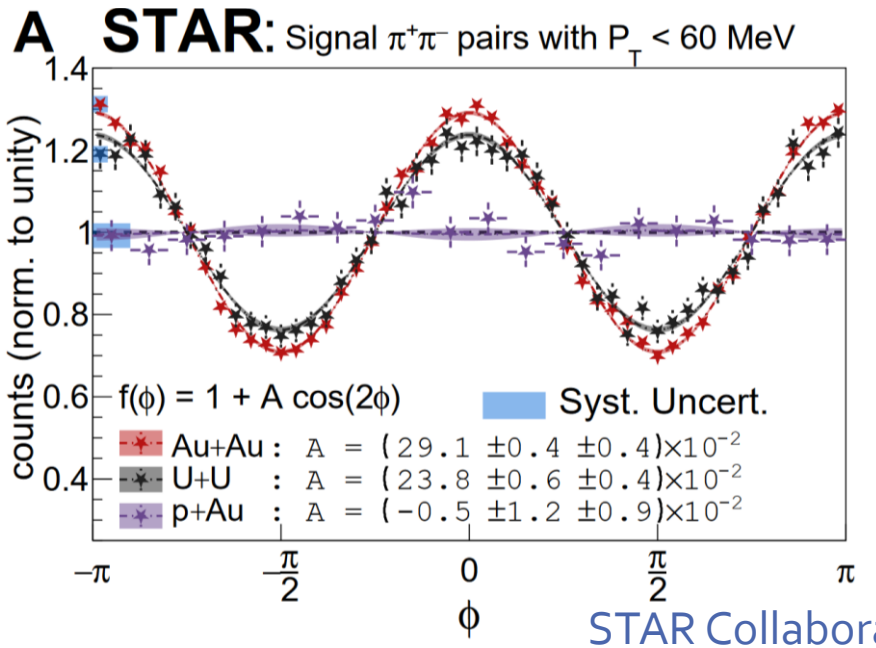
- Quantum interference between one ion emitting the ρ versus the other
  - Analogous to a double-slit pattern
  - Expected $\cos(2\phi)$ modulation

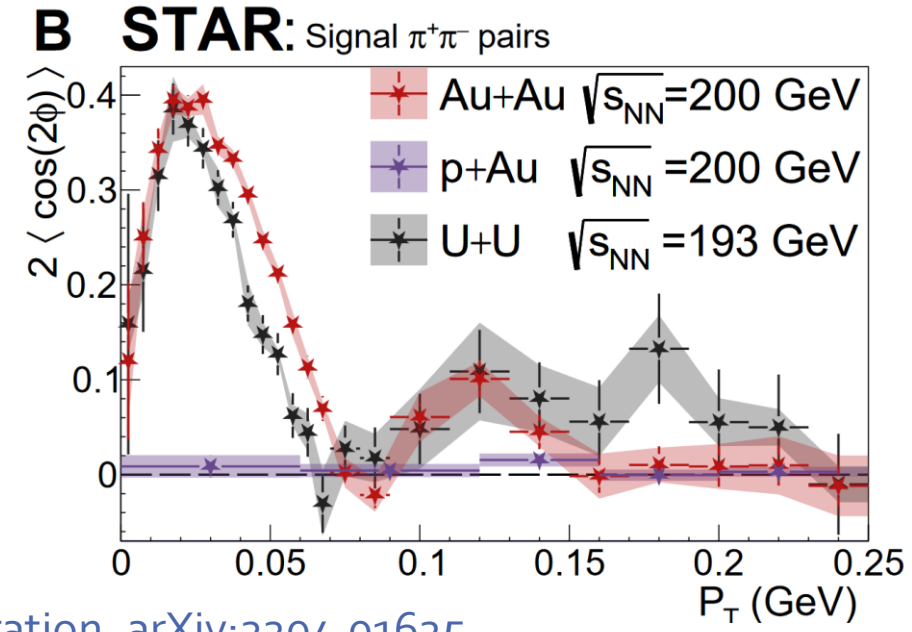
H. Xing, *et al.* J. High Energ. Phys. **2020,** 64 (2020)



$$\phi = \phi(\pi^+ + \pi^-) - \phi(\pi^+ - \pi^-)$$

- No entanglement in $p + \mathrm{Au}$
- Strong Modulation in $A + A$ collisions
  - Difference in $\mathrm{Au} + \mathrm{Au}$ versus $\mathrm{U} + \mathrm{U}$ demonstrates sensitivity to nuclear geometry

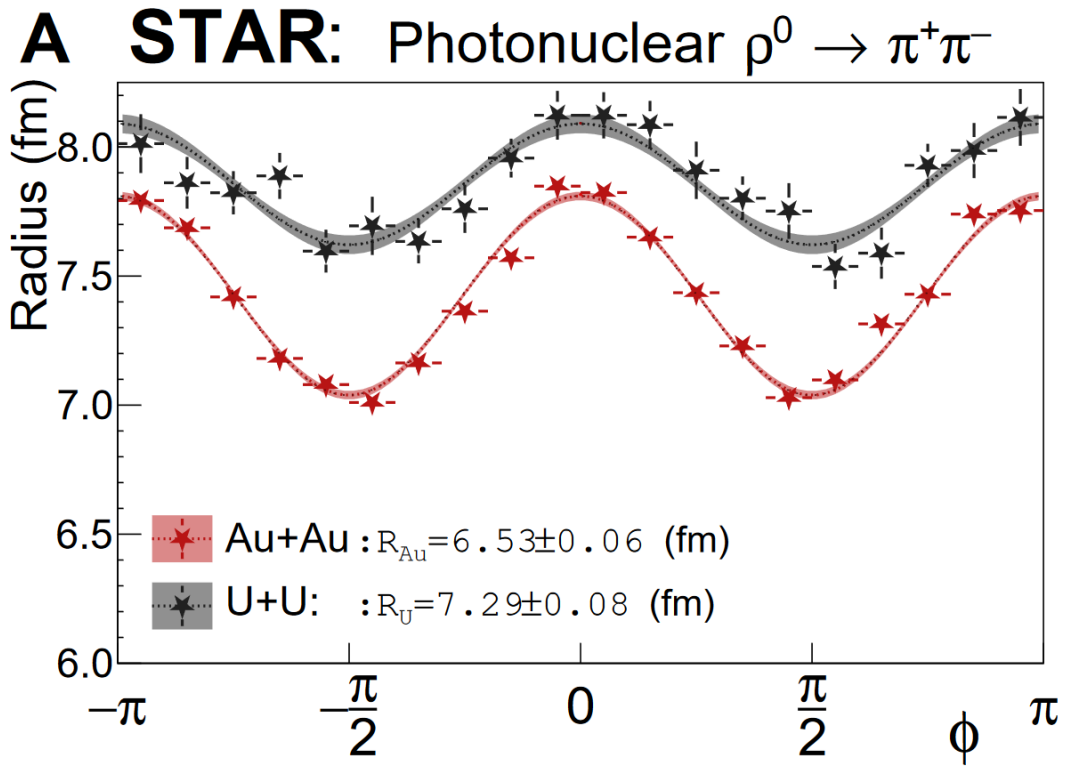


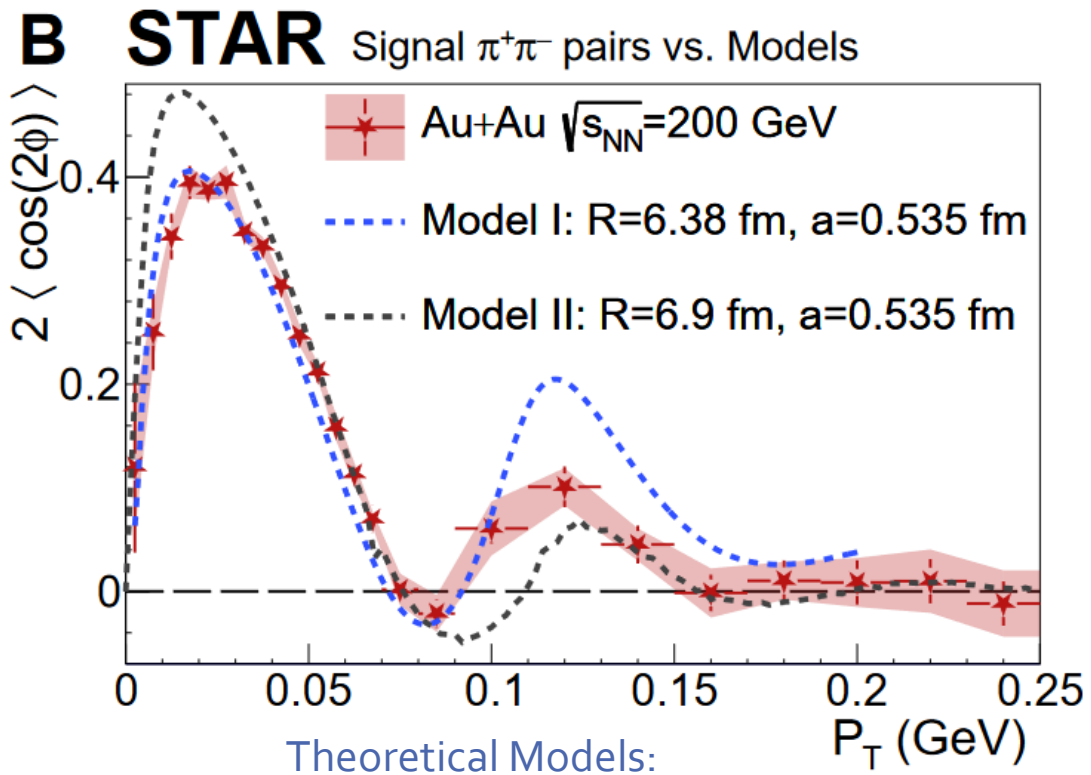


STAR Collaboration, arXiv:2204.01625

Novel Quantum Entanglement Discovered with Diffractive ρ

Precision extraction of the nuclear mass (strong-interaction) radius





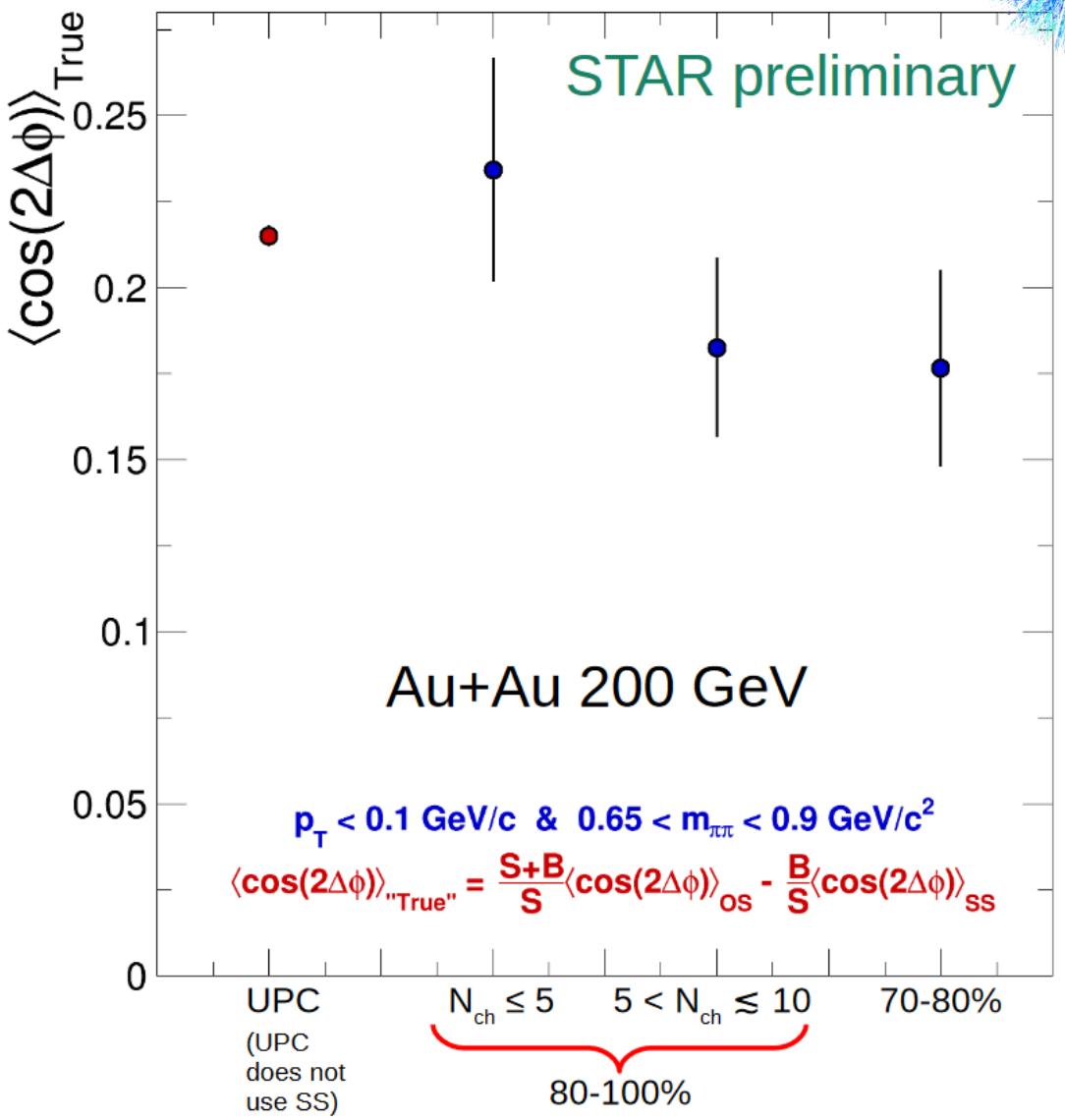
STAR Collaboration, arXiv:2204.01625

Theoretical Models:
W. Zha, et al Phys. Rev. C **99**, 061901 (2019)
W. Zha, et al, Phys. Rev. D **103**, 033007 (2021)
H. Xing, et al, JHEP **10**, 064 (2020)

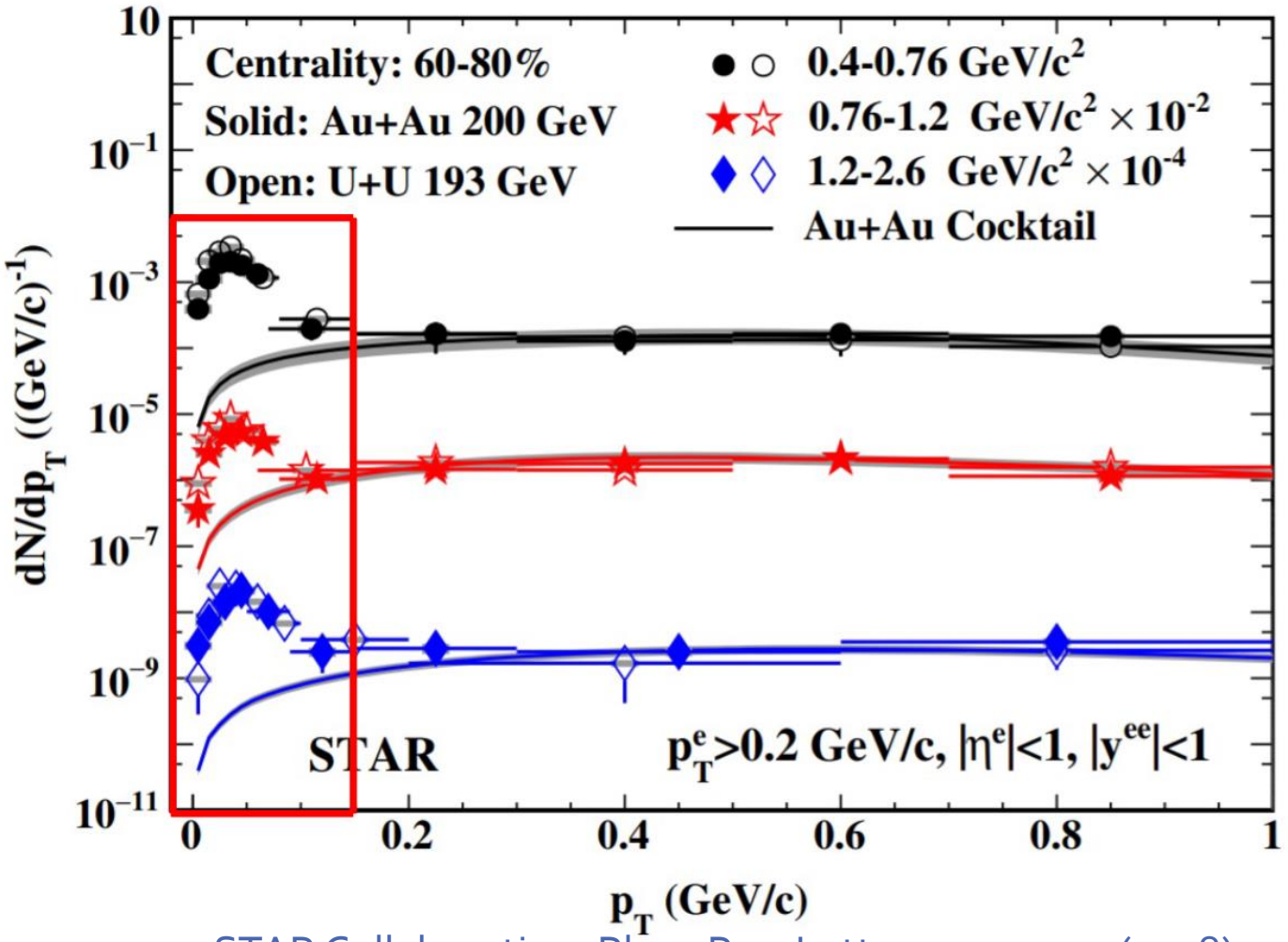
Diffractive ρ Signal Persists Even in Peripheral Events

- Does the presence of strongly interacting matter force the wave function collapse?
- Modulation still present in peripheral collisions
  - Polarization and quantum entanglement survive the abundant hadronic interactions
  - Detailed quantitative analysis underway to put limits on wave function collapse
- No clear dependence on centrality, despite strong centrality dependence predicted by theoretical calculations

H. Xing, et al, JHEP **10**, 064 (2020)



Photoproduction of Lepton Pairs in Hadronic Collisions



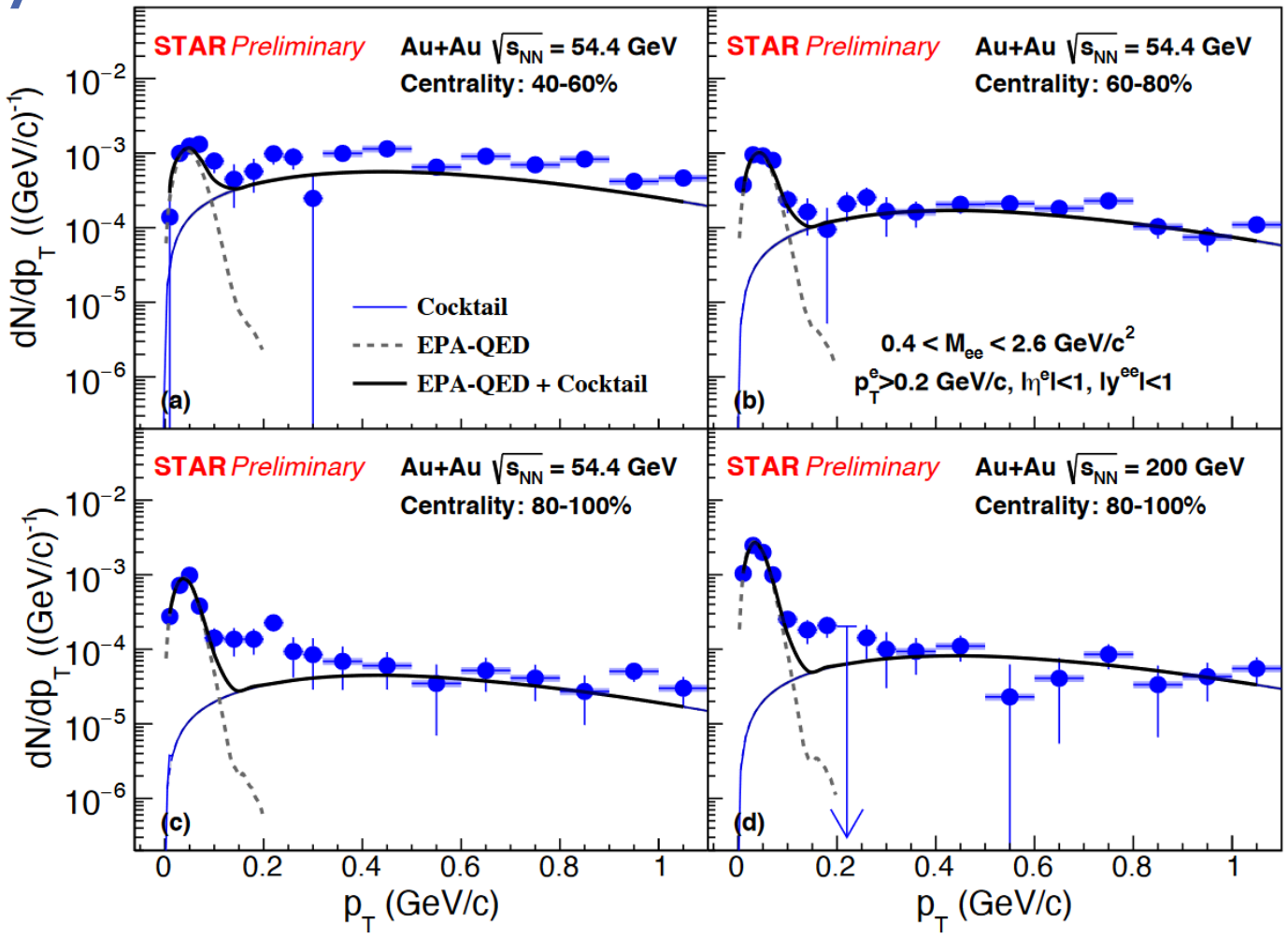
STAR Collaboration, Phys. Rev. Lett. **121,** 132301 (2018)

- Low p_T excess of e^+e^- in peripheral collisions
  - Cocktail used to estimate the contribution from hadronic interactions
  - No significant centrality dependence
  - Can't be explained through in-medium broadened ρ spectral function
- Qualitatively described by photon-photon interaction process in violent hadronic $A + A$ collisions
  - Observation of $\gamma\gamma \rightarrow e^+e^-$ in hadronic heavy ion collisions

Excess of e^+e^- Changes with Beam Energy and Centrality

- Excesses above hadronic production are observed at low-p_T
  - Studying dependence on energy (54.4 vs 200 GeV) and centrality
- Observed excess consistent with lowest-order EPA-QED predictions

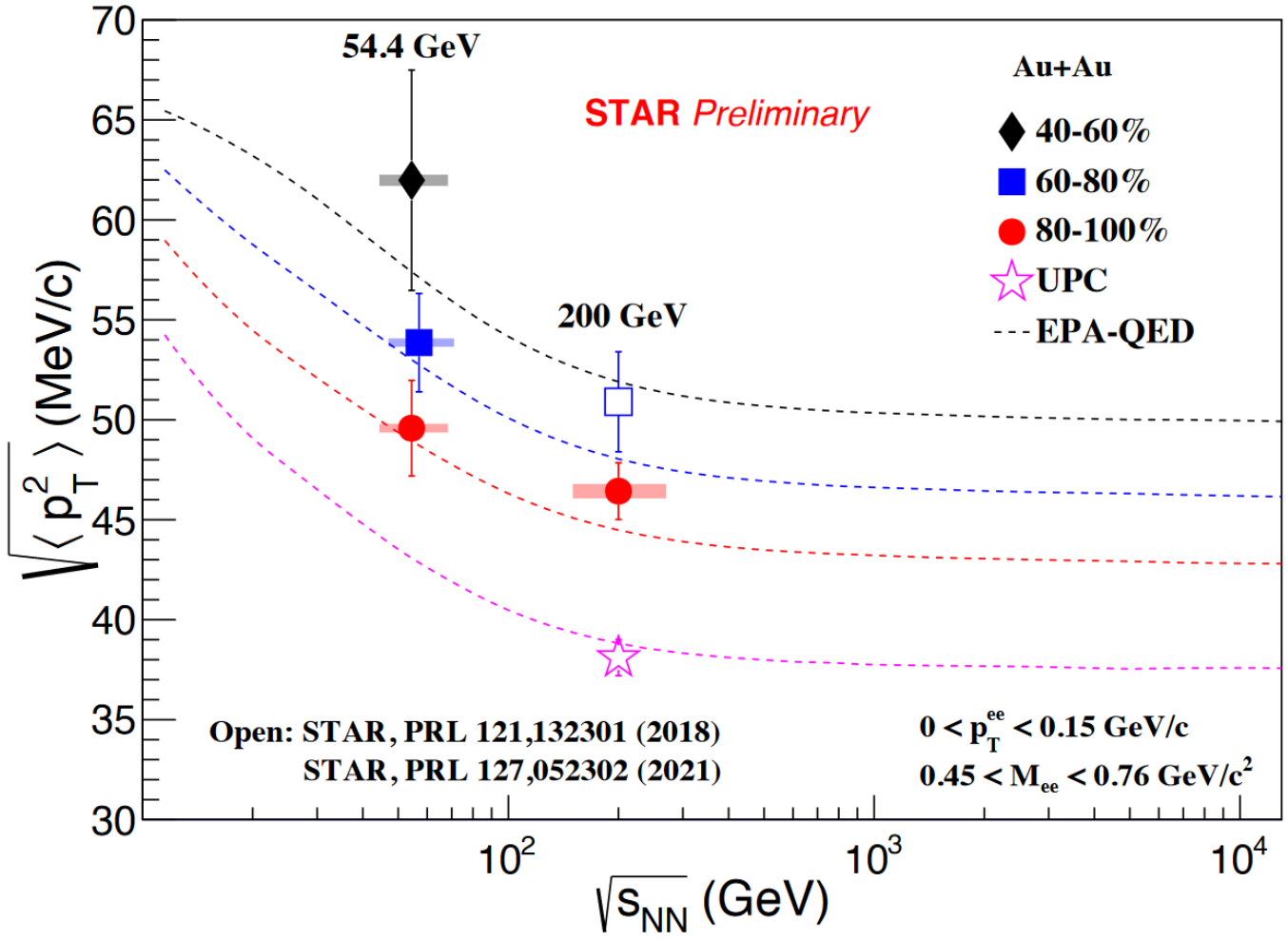
  W. Zha *et al*, Phys. Lett. B **800,** 135089 (2020)



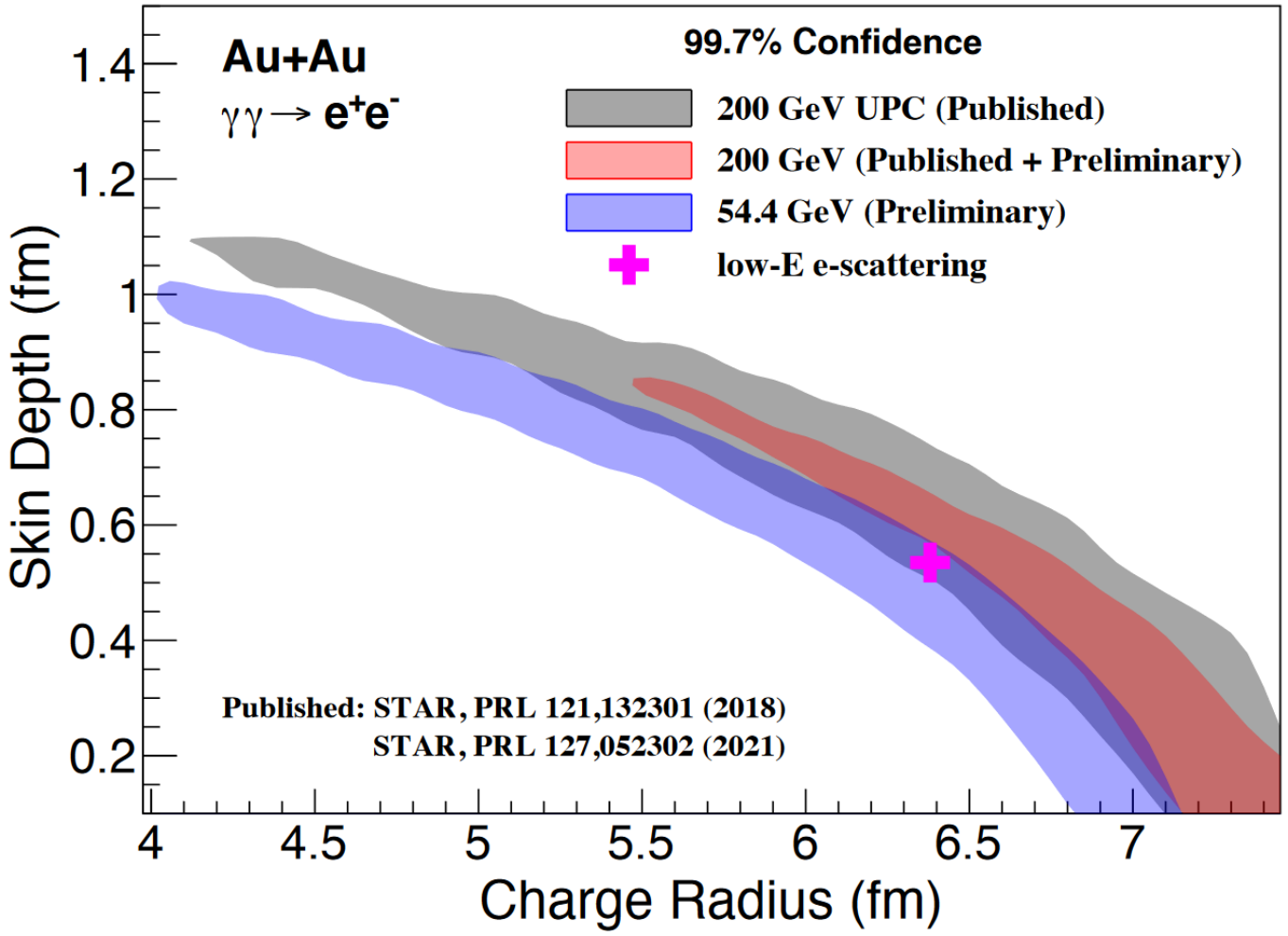
Excess of e^+e^- Changes with Beam Energy and Centrality

- $\sqrt{\langle p_T^2 \rangle}$ is sensitive to p_T broadening
- $\sqrt{\langle p_T^2 \rangle}$ decreases for more peripheral collisions
  - Impact parameter dependence
- Energy dependence
  - Some discrepancy between 200 GeV points and EPA-QED prediction

W. Zha *et al*, Phys. Lett. B **800,**135089 (2020)



Constraining the Nuclear Charge Radius



EPA-QED: J. D. Brandenburg *et al*, Eur. Phys. J. A **57,** 299 (2021)

$$\rho = \frac{\rho_0}{1 + \exp[(r - R)/a]}$$

Charge Radius

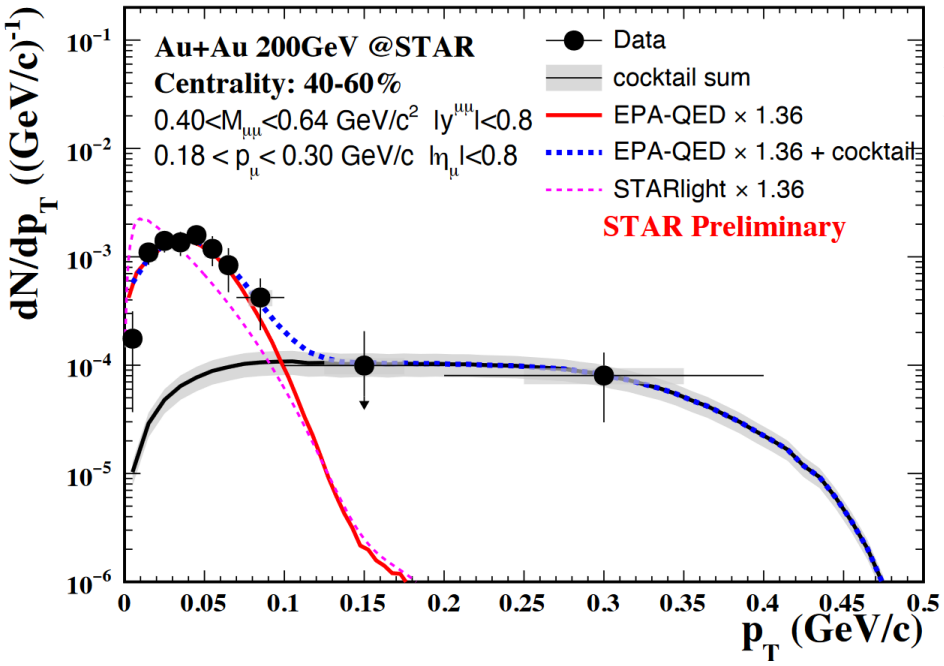
Skin Depth

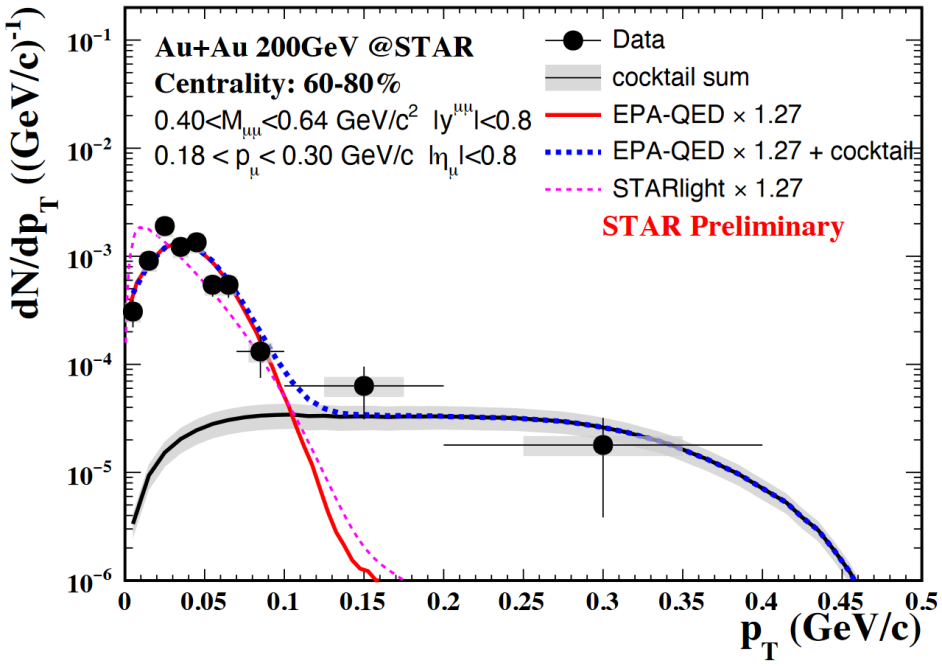
- Comparing to low energy e-scattering
  - $R = 6.38$ fm, $d = 0.535$ fm

  R. C. Barrett and D. F. Jackson, Nuclear Sizes and Structure (Oxford University Press, 1977)
- Low-energy vs RHIC
  - Maybe due to energy dependence of charge distribution and/or final state effect
- Difference in 200 GeV vs 54 GeV
  - Maybe due energy dependence of charge distribution

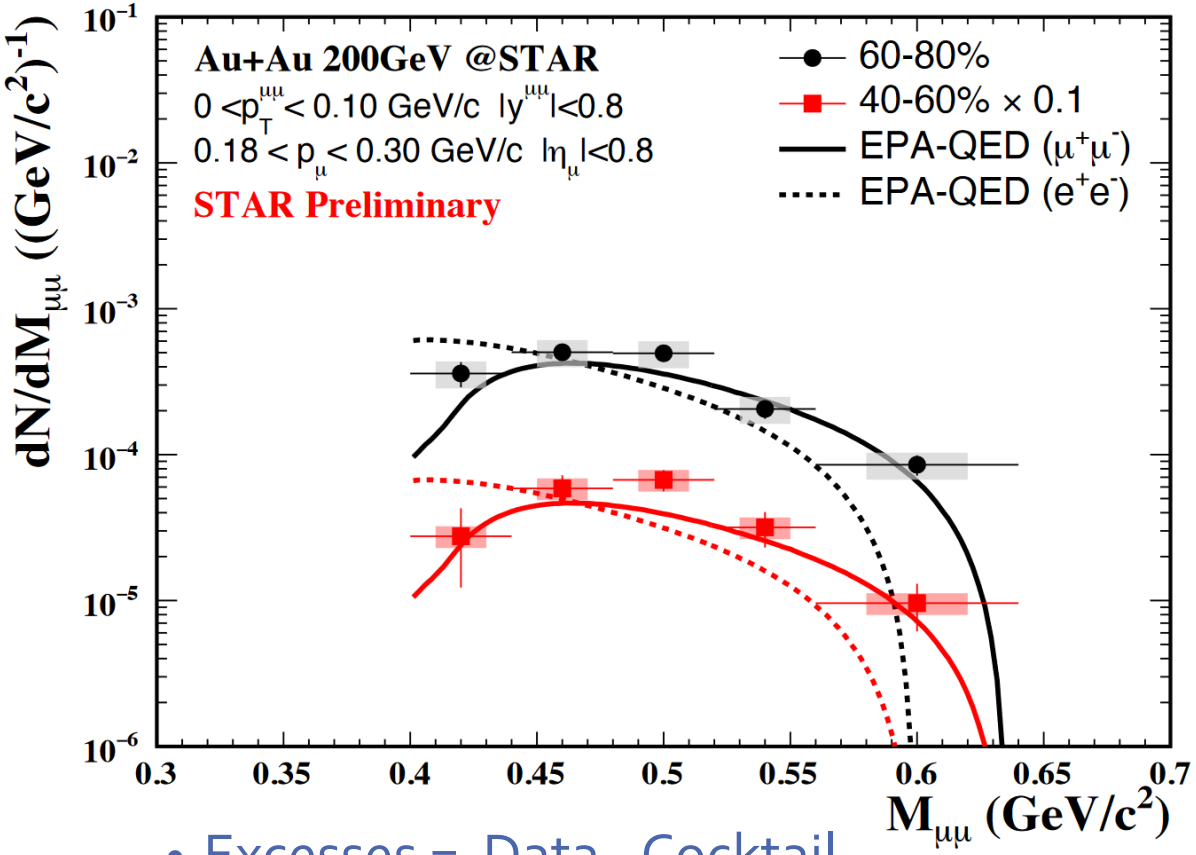
Excess of $\mu^+\mu^-$

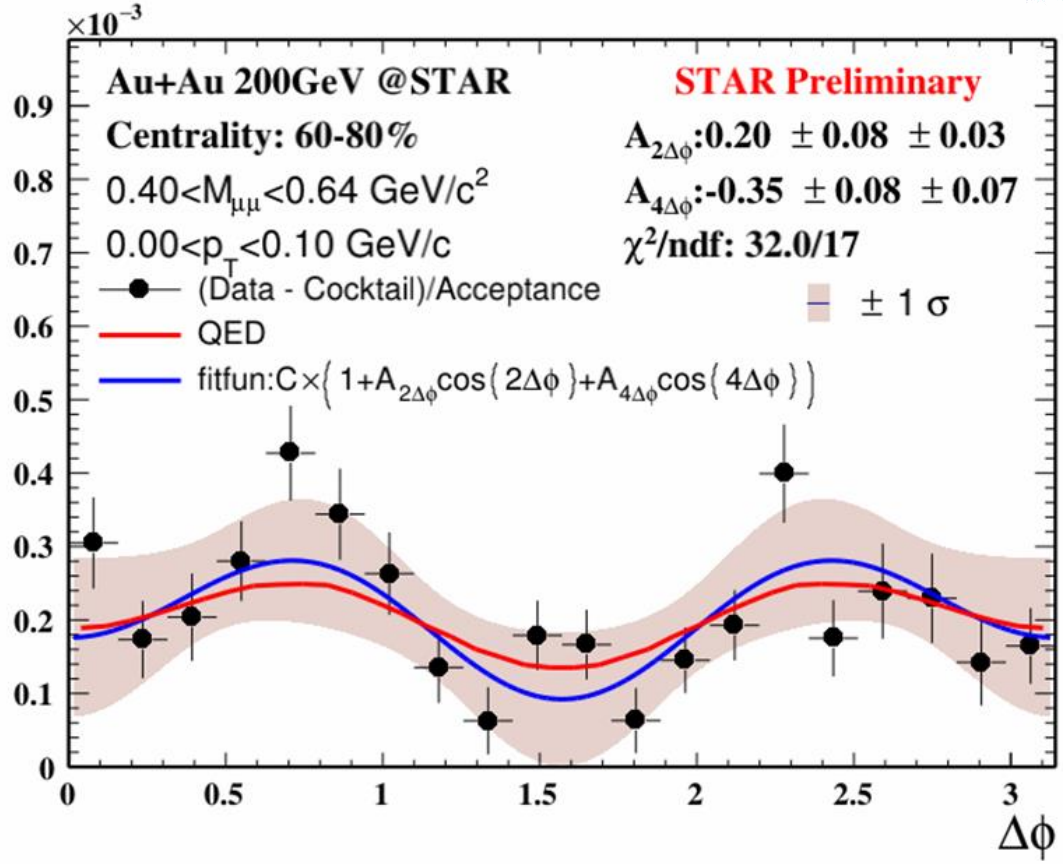
- First cross section measurement of photo-produced $\mu^+\mu^-$ in heavy ion collisions at low p_T
  - Excess concentrated at $p_T \lesssim 0.1$ GeV/c
- Comparing to:
  EPA-QED: W. M. Zha *et al*, Phys. Lett. B **800,** 135089 (2020)
  STARlight: S.R. Klein, Phys. Rev. C **97,** 054903 (2018)
  - $\sqrt{\langle p_T^2 \rangle}$ is consistent with EPA-QED calculation





Excess of $\mu^+\mu^-$

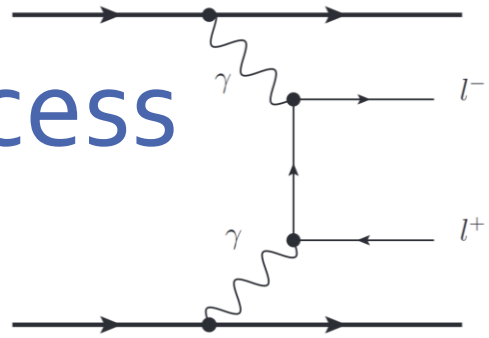




- Excesses = Data - Cocktail
- Well described by lowest-order EPA-QED predictions

Indication of both 2nd- and 4th-order azimuthal angular modulation in $\mu^+\mu^-$

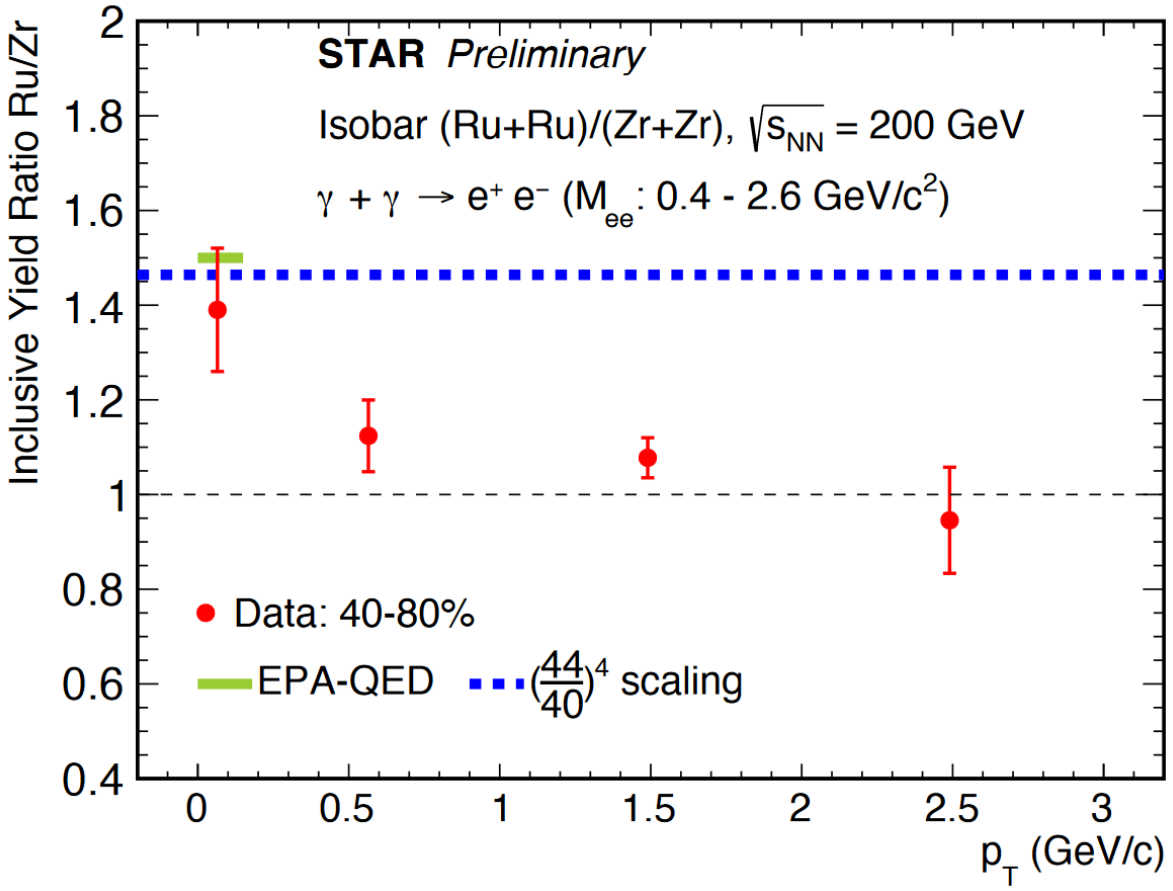
EM Field Dependence of e^+e^- Excess



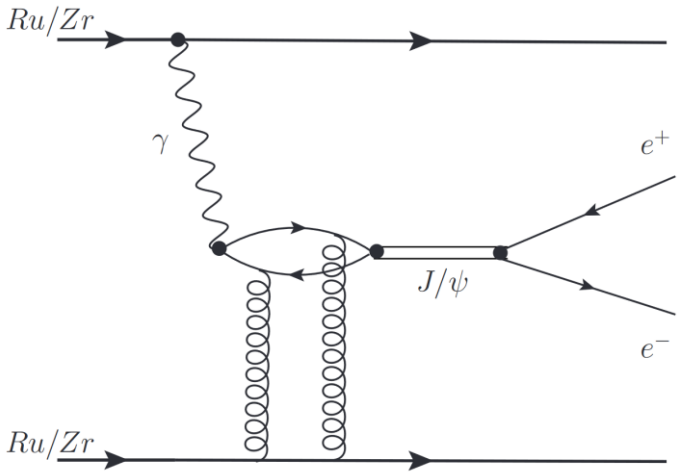
- The isobar collisions provide a unique opportunity to test the electromagnetic field dependence

$$^{96}_{44}\mathrm{Ru} \text{ vs } ^{96}_{40}\mathrm{Zr}$$

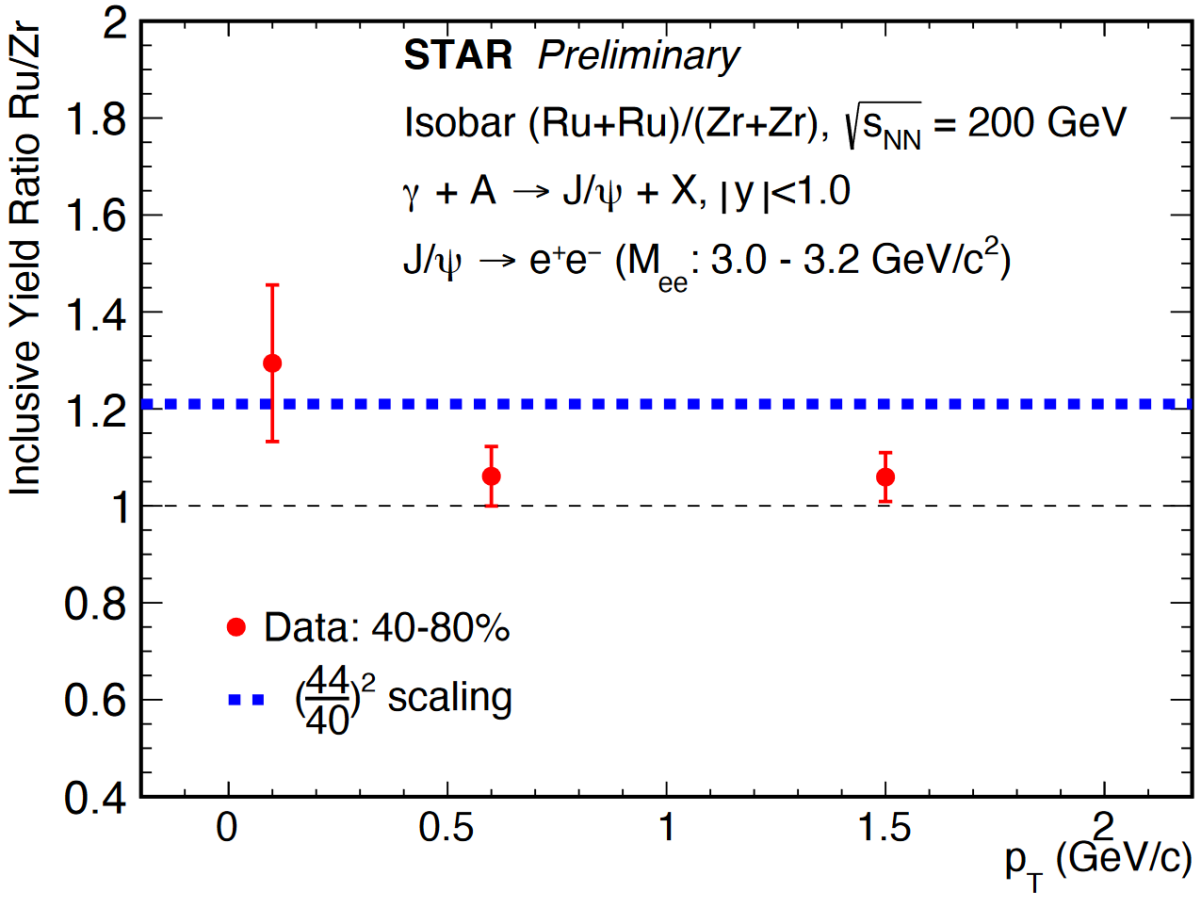
- At very low p_T (< 0.15 GeV/c) e^+e^- production is dominated by $\gamma\gamma \rightarrow e^+e^-$
  - Hadronic contributions are similar in $\mathrm{Ru} + \mathrm{Ru}$ and $\mathrm{Zr} + \mathrm{Zr}$
  - Ratio is consistent with $\left(\frac{Z_{\mathrm{Ru}}}{Z_{\mathrm{Zr}}}\right)^4 = \left(\frac{44}{40}\right)^4$
  - **Initial EM field is different in $\mathbf{Ru} + \mathbf{Ru}$ versus $\mathbf{Zr} + \mathbf{Zr}$ by $\sim 3\sigma$**



EM Field Dependence of J/ψ Excess

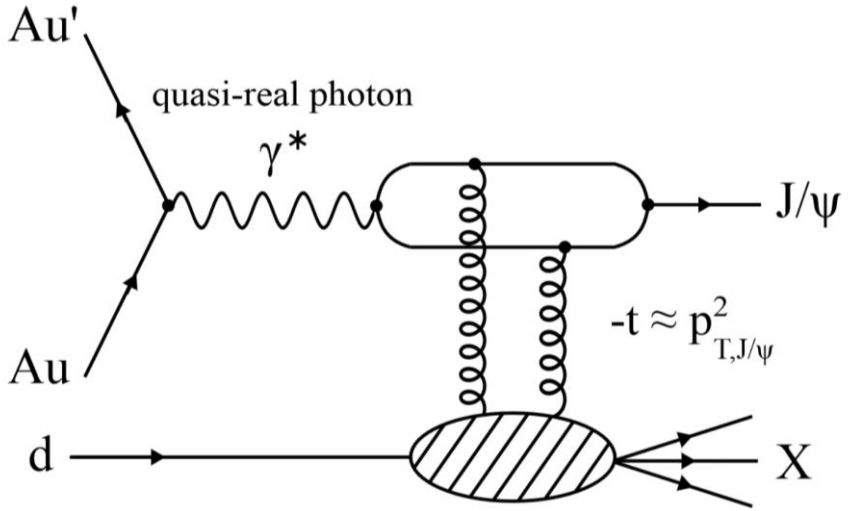


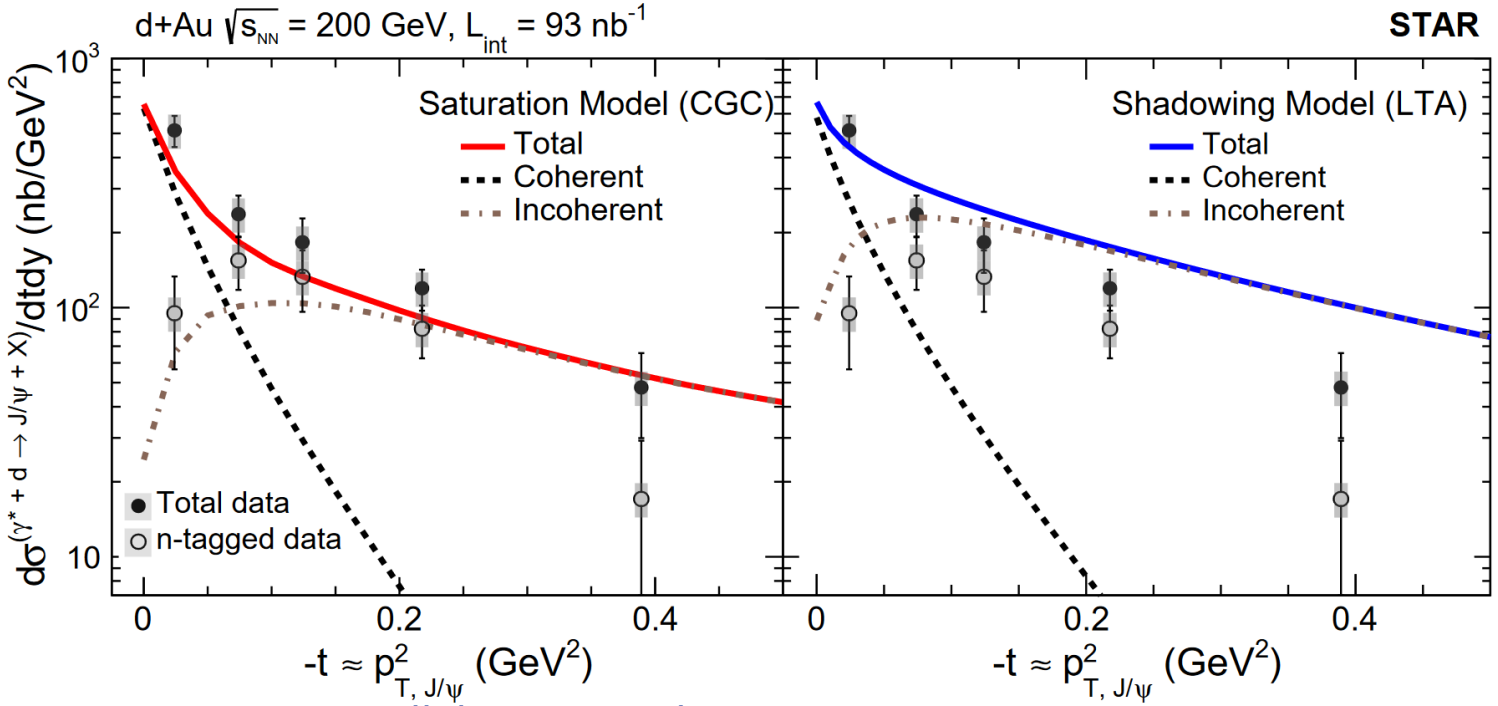
- At very low p_T, J/ψ production is dominated by $\gamma A \rightarrow J/\psi$
  - Ratio is consistent with $\left(\frac{Z_{Ru}}{Z_{Zr}}\right)^2 = \left(\frac{44}{40}\right)^2$
  - **Initial EM field is different in $\mathbf{Ru + Ru}$ vs $\mathbf{Zr + Zr}$ by $\sim 1.7\sigma$**



J/ψ in d + Au UPC

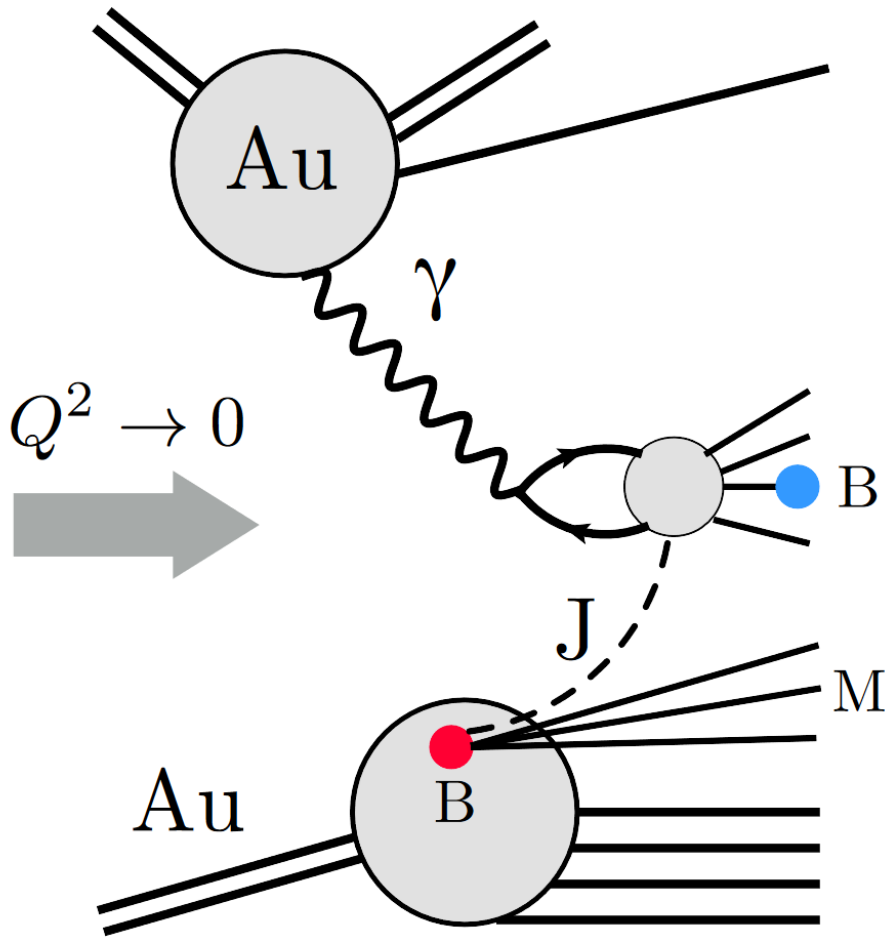
- First measurement of J/ψ in d + Au ultra-peripheral collisions
- Probes the gluon density of the deuteron
  - Important step to understanding nuclear effects in heavier nuclei
- Spectator tagging technique explored for the first time at a collider facility
  - Serve as an experimental baseline for the EIC



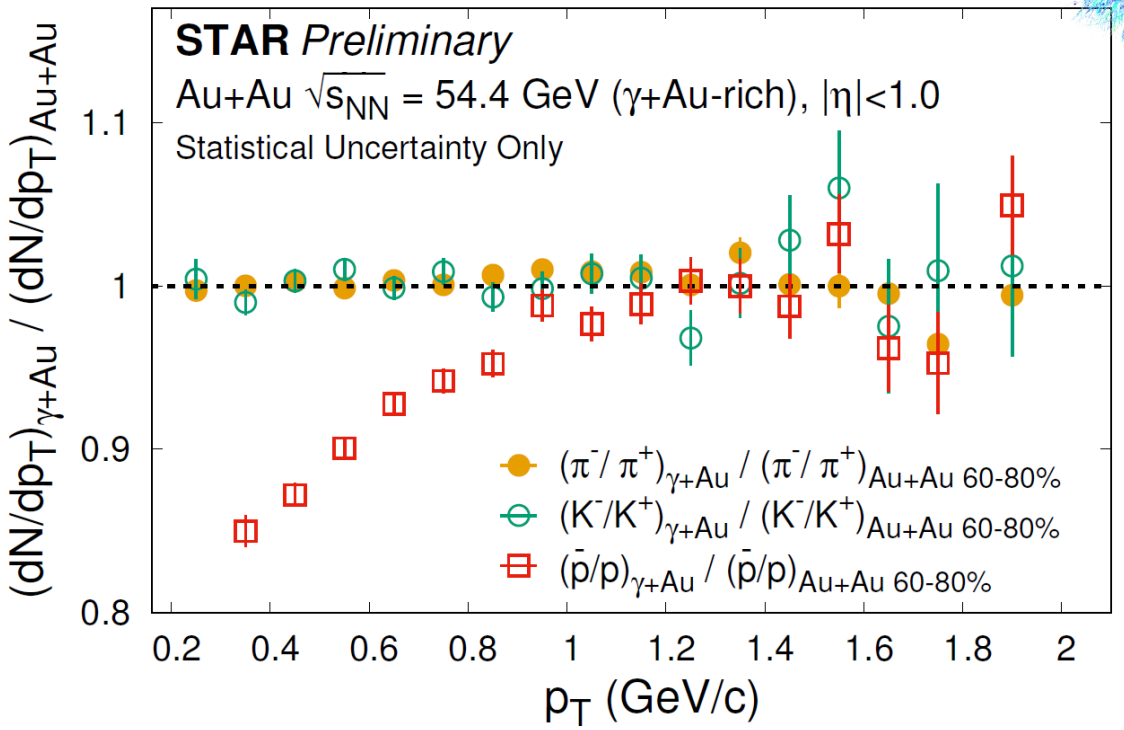


STAR Collaboration, Phys. Rev. Lett. **128,** 122303 (2022)

Low p_T Baryon Enhancement in γA



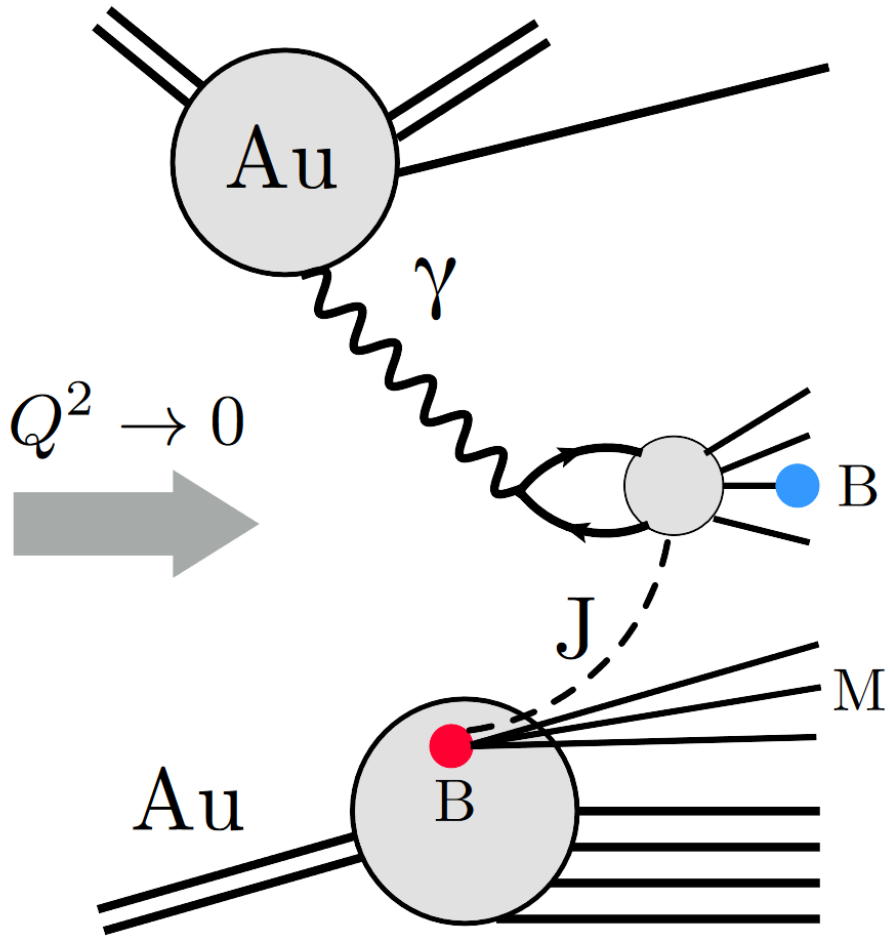
J. D. Brandenburg *et al*, arXiv 2205.05685



- Double ratio: $\bar{p}/p < 1$ at lower p_T
- Soft baryon stopping that is **stronger** in γA compared to peripheral AA
  - Indication of a baryon junction existing inside nucleon

D. Kharzeev, Physics Letters B **378**, 238-246 (1996)

Low p_T Baryon Enhancement in γA



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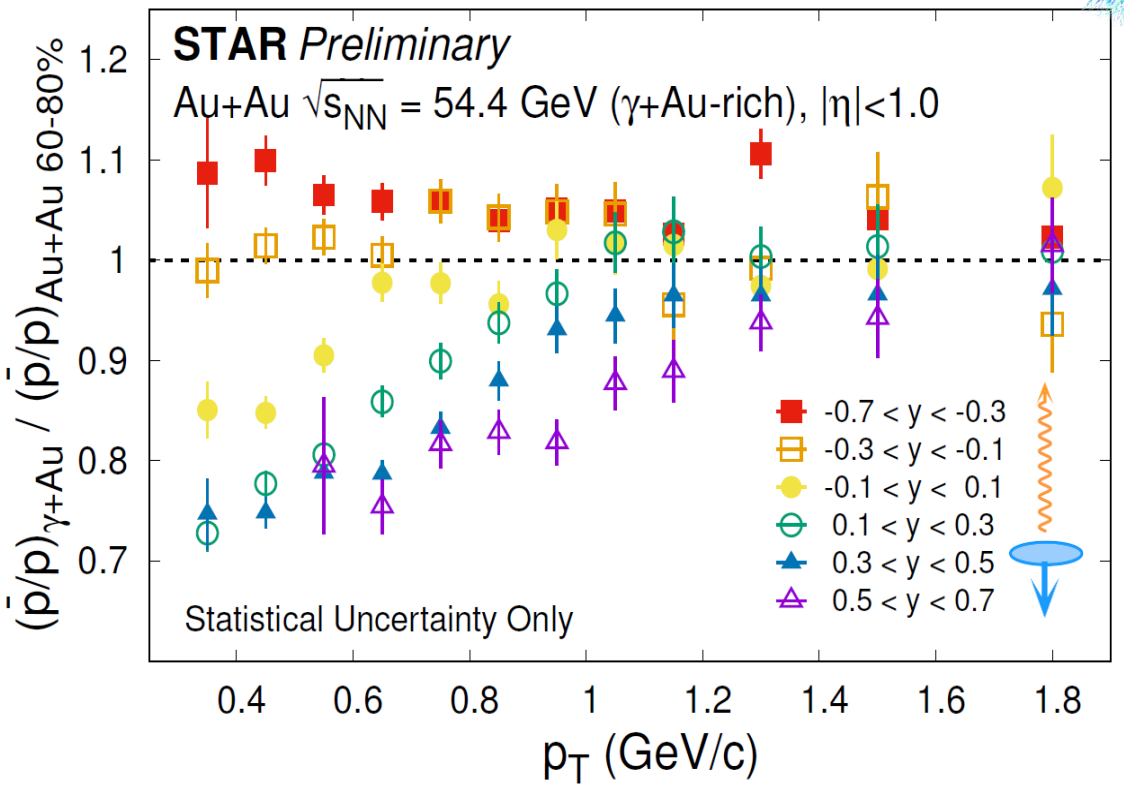
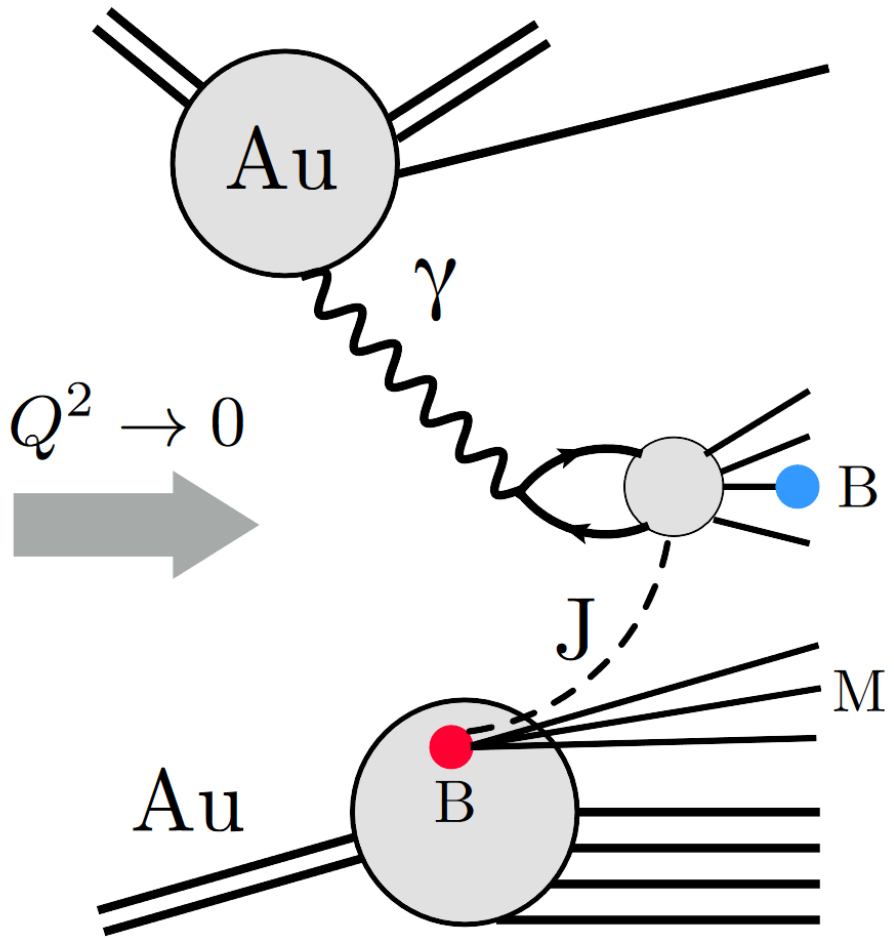
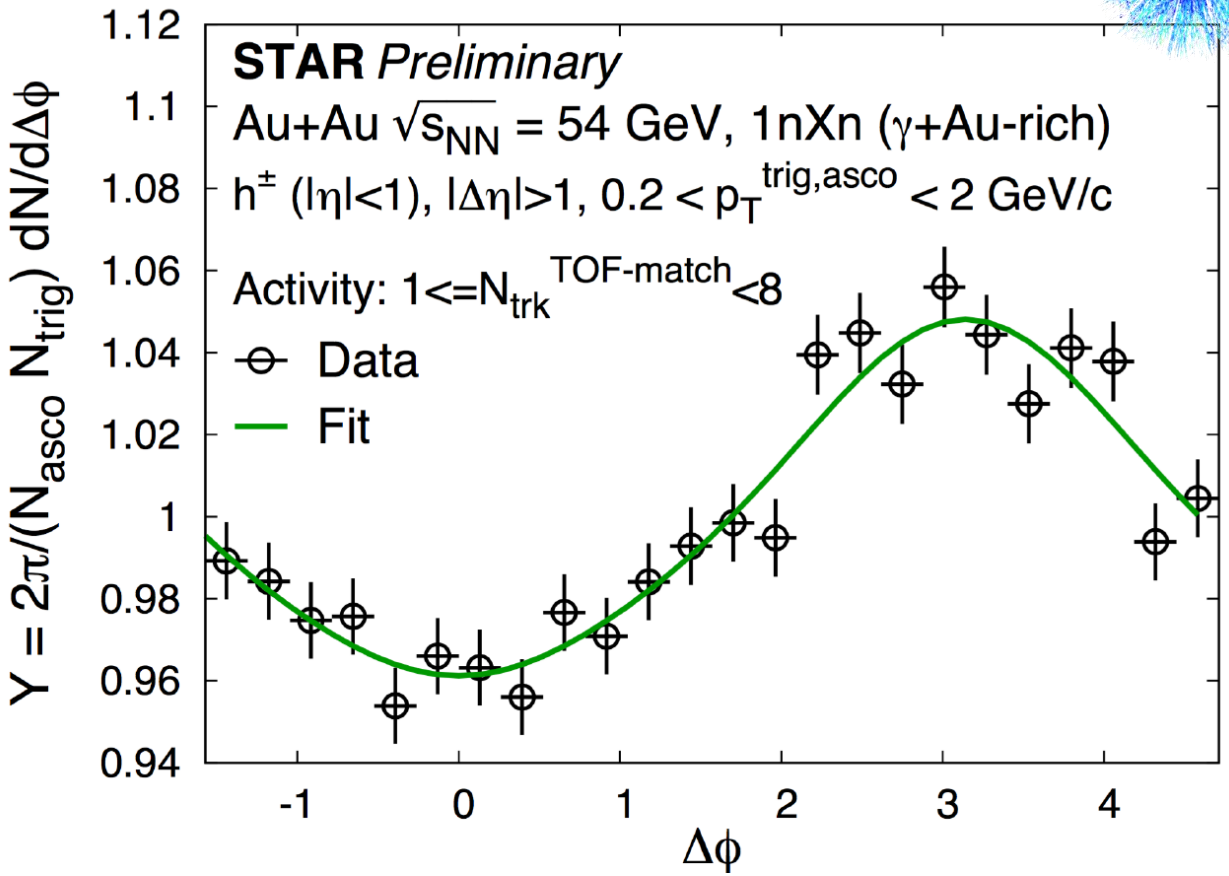


- Double ratio: $\bar{p}/p < 1$ at lower p_T
  - Soft baryon stopping that is **stronger** in γA compared to peripheral AA
  - Ratio is smaller at higher rapidity (A-going side)

Collectivity in γA

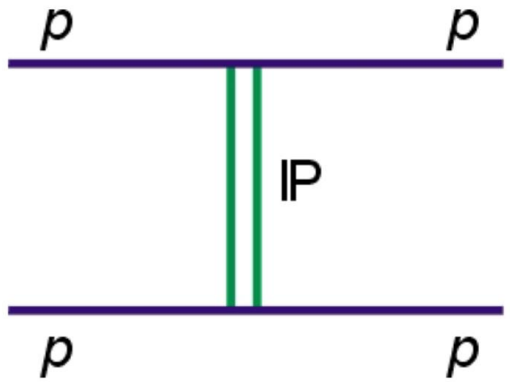


J. D. Brandenburg *et al*, arXiv 2205.05685



- No near-side ridge in the selected multiplicity class
- Higher energy and event activity events under investigation with STAR forward upgrades

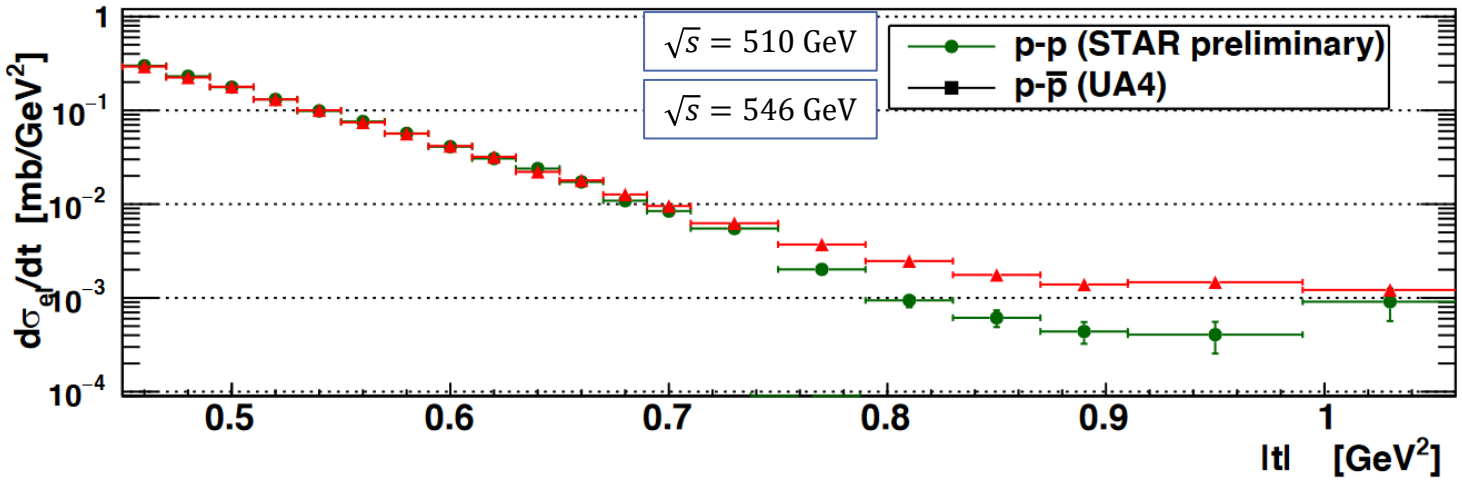
Elastic Cross Section in $p + p$ Collisions

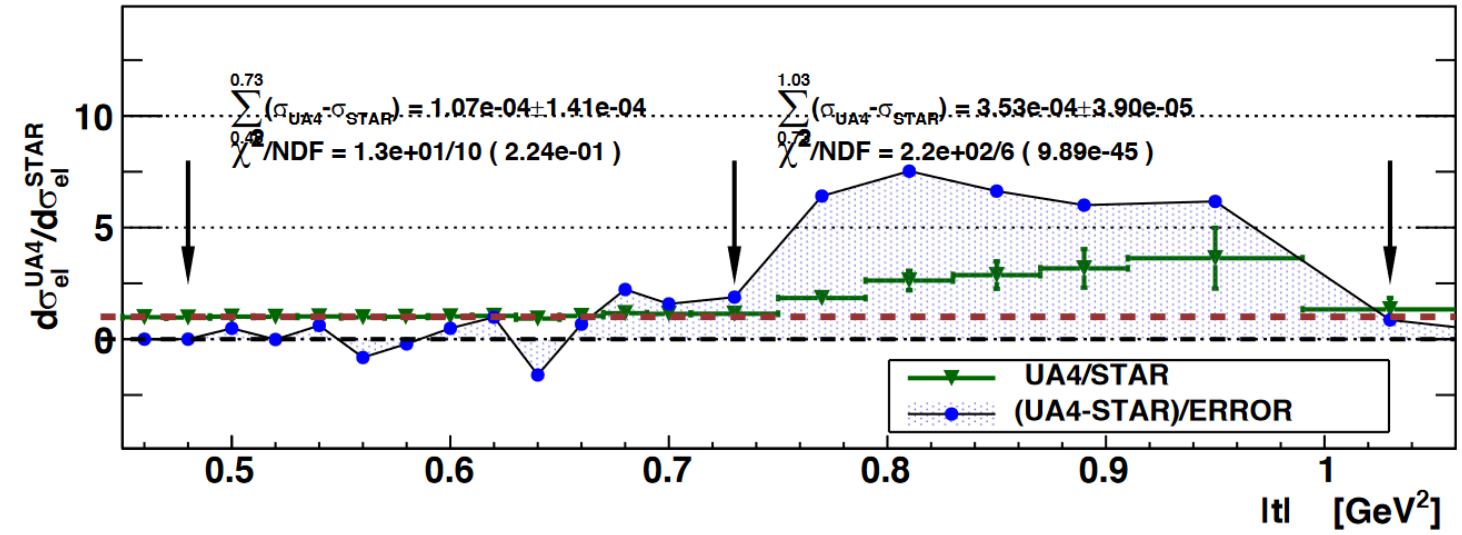


Measured using Roman Pots

Comparing $p + p \rightarrow p + p$ cross section with $p + \bar{p} \rightarrow p + \bar{p}$

Testing the Odderon hypothesis in a model independent way



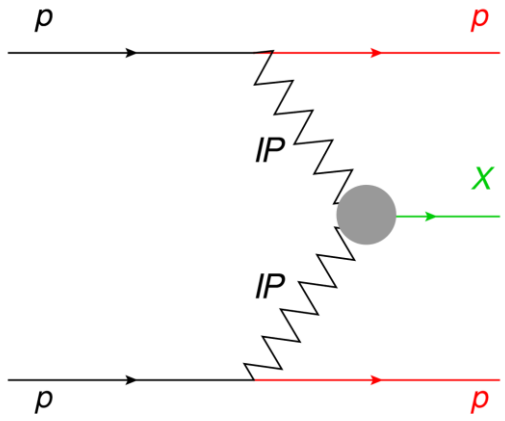


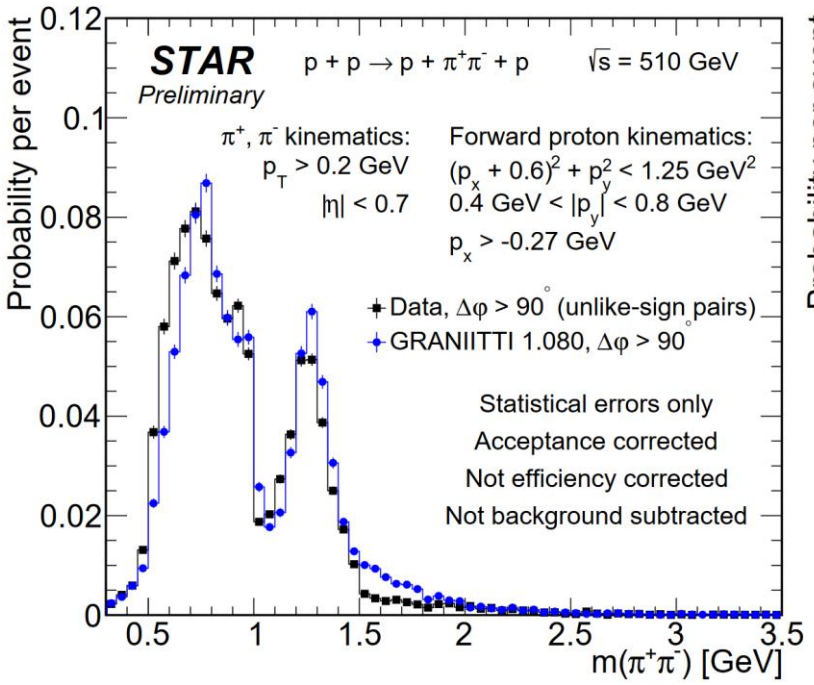
Central Exclusive Production in $p + p$

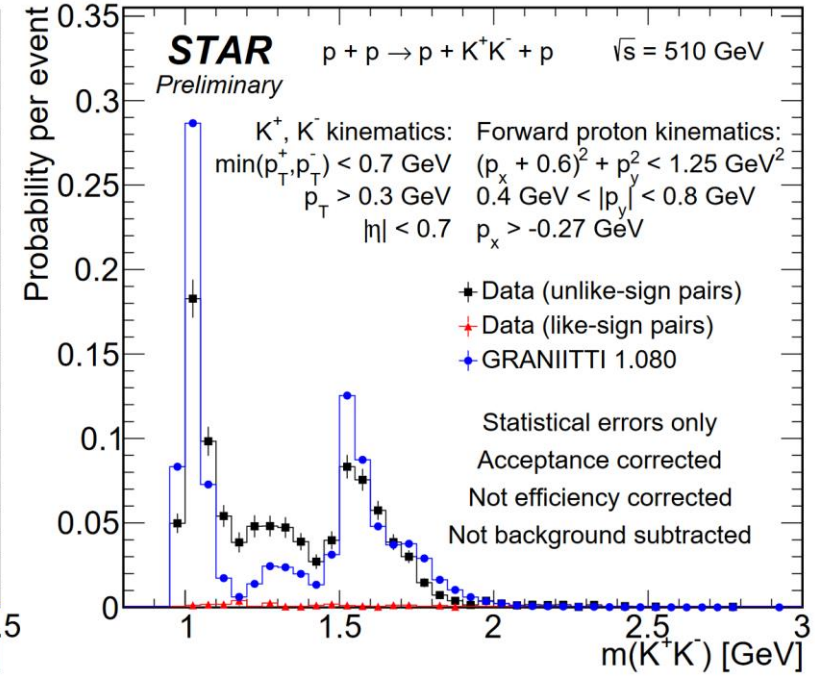
Studying Double Pomeron Exchange

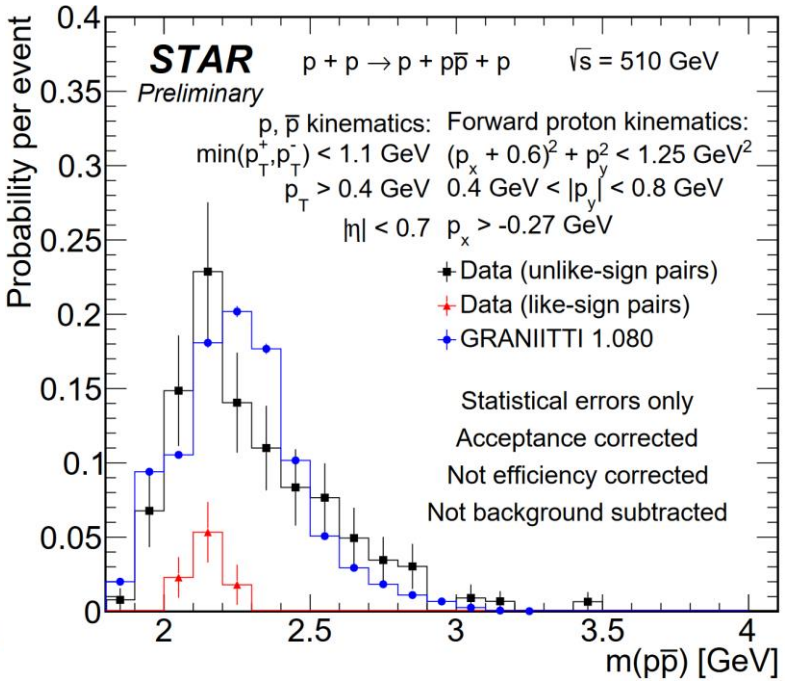
- Both protons emit a pomeron → protons measured with Roman Pots
- Two pomerons fuse into an h^+h^- → measured with STAR central PID detectors

$$p_T^{\text{miss}} = 0 = \left(\vec{p}_1 + \vec{p}_2 + \vec{h}_+ + \vec{h}_-\right)_T$$





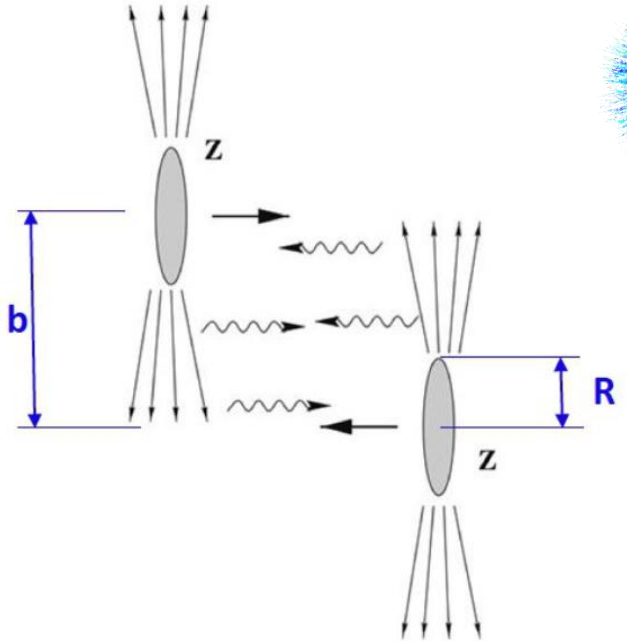


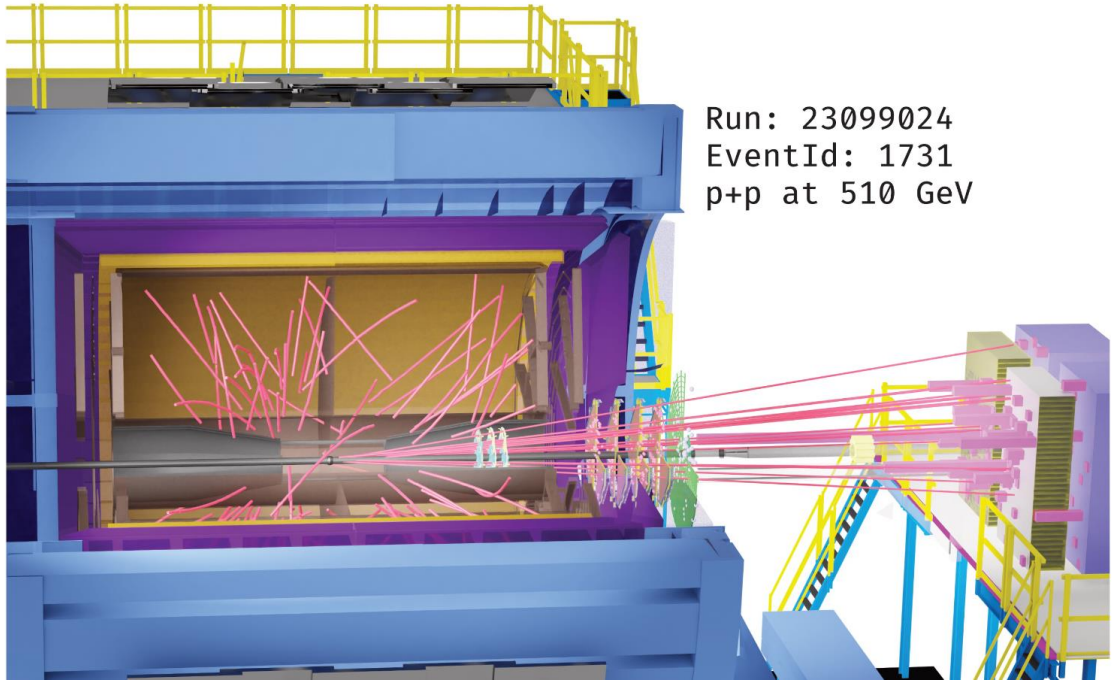


Summary

Ultra-peripheral collisions provide a unique opportunity to study nuclei

- Discovery of Breit-Wheeler process and vacuum bifringence
- Discovery of novel form of quantum entanglement in diffractive ρ
- Energy and lepton dependence of Breit-Wheeler process in $A + A$
- Probe gluon density through $\gamma + d$
- Investigating pompon exchange in $p + p$





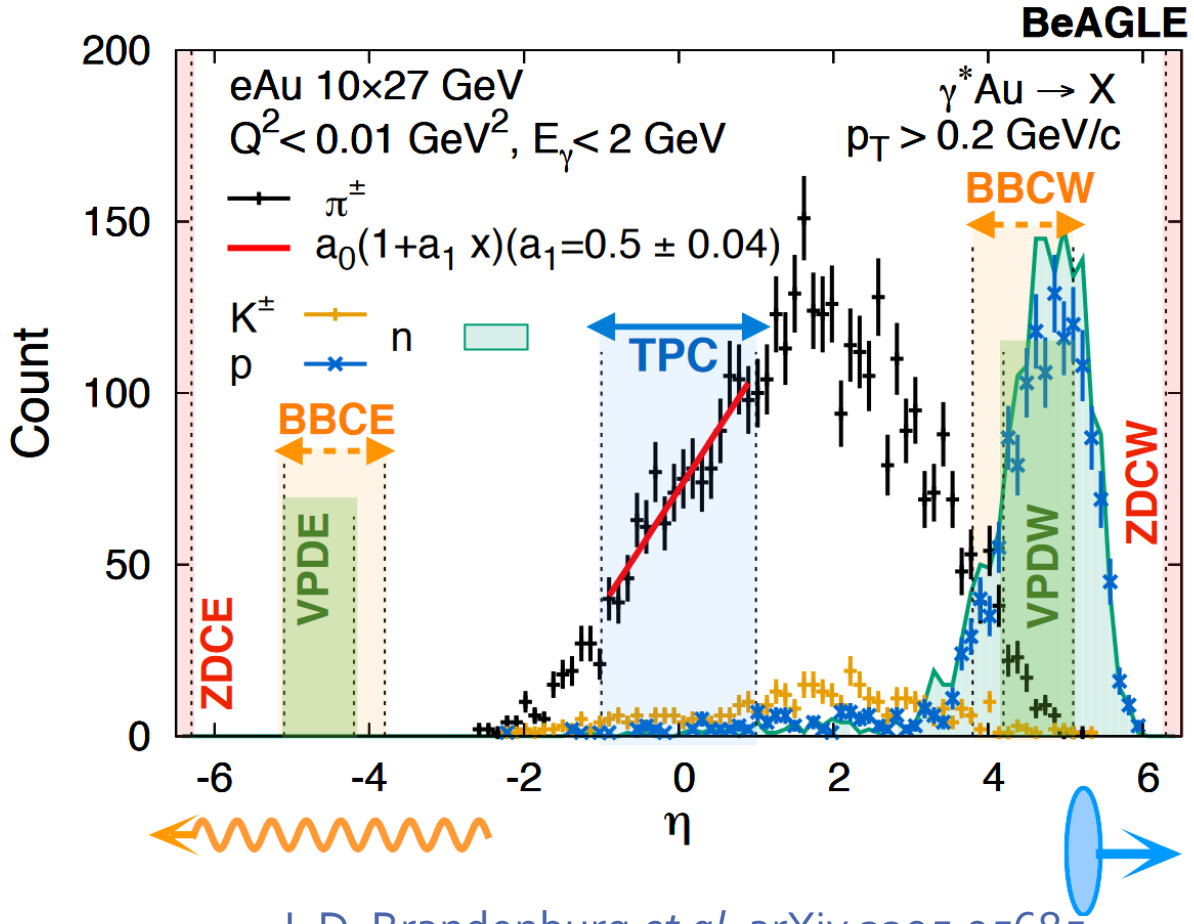
The STAR forward upgrade provides tracking and calorimetry close to the beam line $2.5 < \eta < 4$

Important for studying photoproduction

- Diffractive ρ^0, ϕ, and J/ψ
- Dijets cross sections
- Baryon stopping and charged particle correlations

Back Up

Measuring Photonuclear Collisions at STAR



J. D. Brandenburg *et al*, arXiv 2205.05685