Experimental Overview on UPC Results at STAR

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for the STAR Collaboration

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Outline

- STAR Experiment
- Recent results from photon-photon collisions at STAR

$$e^+e^- \quad \mu^+\mu^- \quad \pi^+\pi^- \quad p\bar{p}$$

- Recent results from photon-nuclear collisions at STAR

$$\rho^0 \to \pi^+\pi^- \quad J/\psi \to e^+e^- \quad \pi^+\pi^-(\pi^+\pi^-) \quad \phi \to K^+K^-$$

- Summary and outlook

Photon-photon and Photon-nuclear Interactions

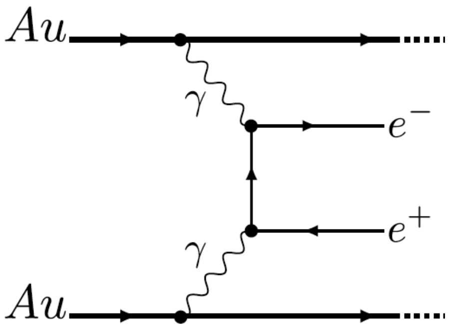
V. Weizsäcker, E.J. Williams:

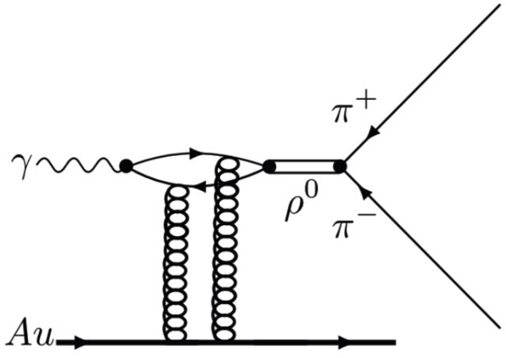
Weizsäcker, C. F. v. Zeitschrift für Physik 88, 612 (1934)

Equivalent Photon Approximation (EPA)

Heavy Ion move close to speed of light → **Highly Lorentz boosted EM field** → **"quasi-real photon"**

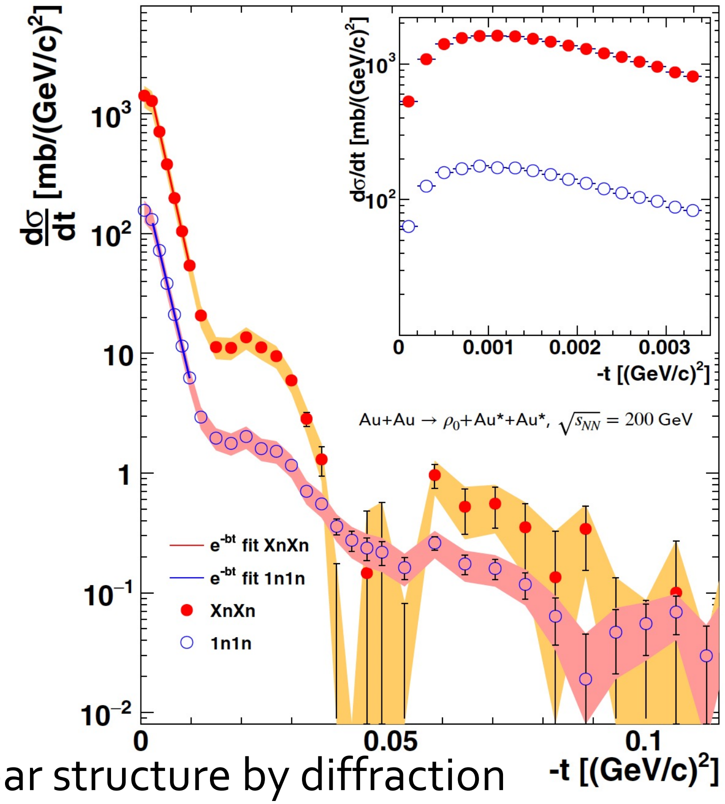
Photon interacts with another photon or with ion





$\gamma\gamma \rightarrow l^+l^-\ (h\bar{h})$

$\gamma A \rightarrow VM \rightarrow l^+l^-\ (h\bar{h})$

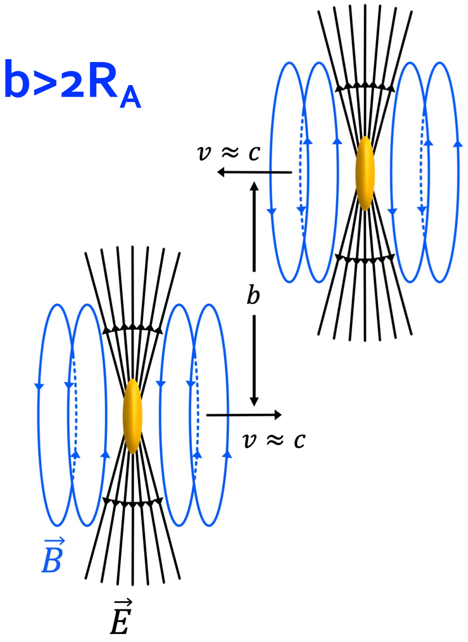


Probe nuclear structure by diffraction

STAR, PRC 96, 054904 (2017)

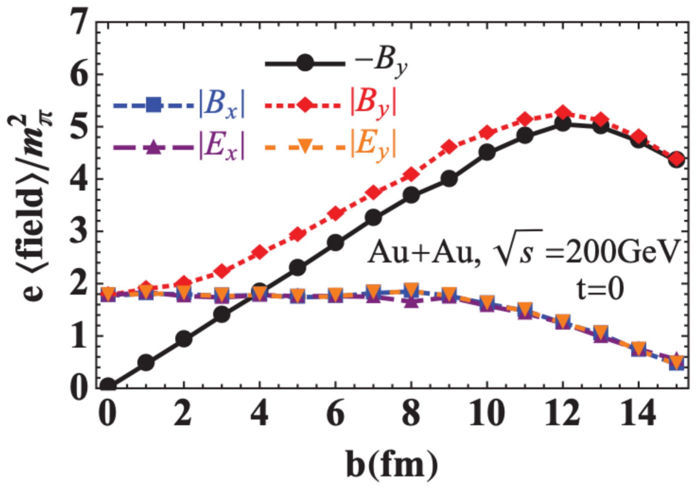
Ultra-Peripheral Collisions (UPCs) at STAR

b>2R$_A$



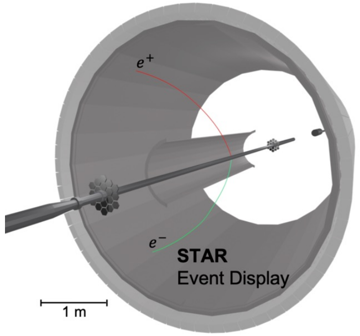
- Clean exclusive measurement
- Highly Lorentz boosted EM field: flux of quasi-real photons
- High photon energy: above 5 GeV at RHIC top colliding energy
- High photon density: $\propto Z^2$ for the flux from one heavy ion
- Small virtuality $Q^2 \lesssim (\hbar/R_A)^2$ in UPCs $\Longrightarrow$ almost real

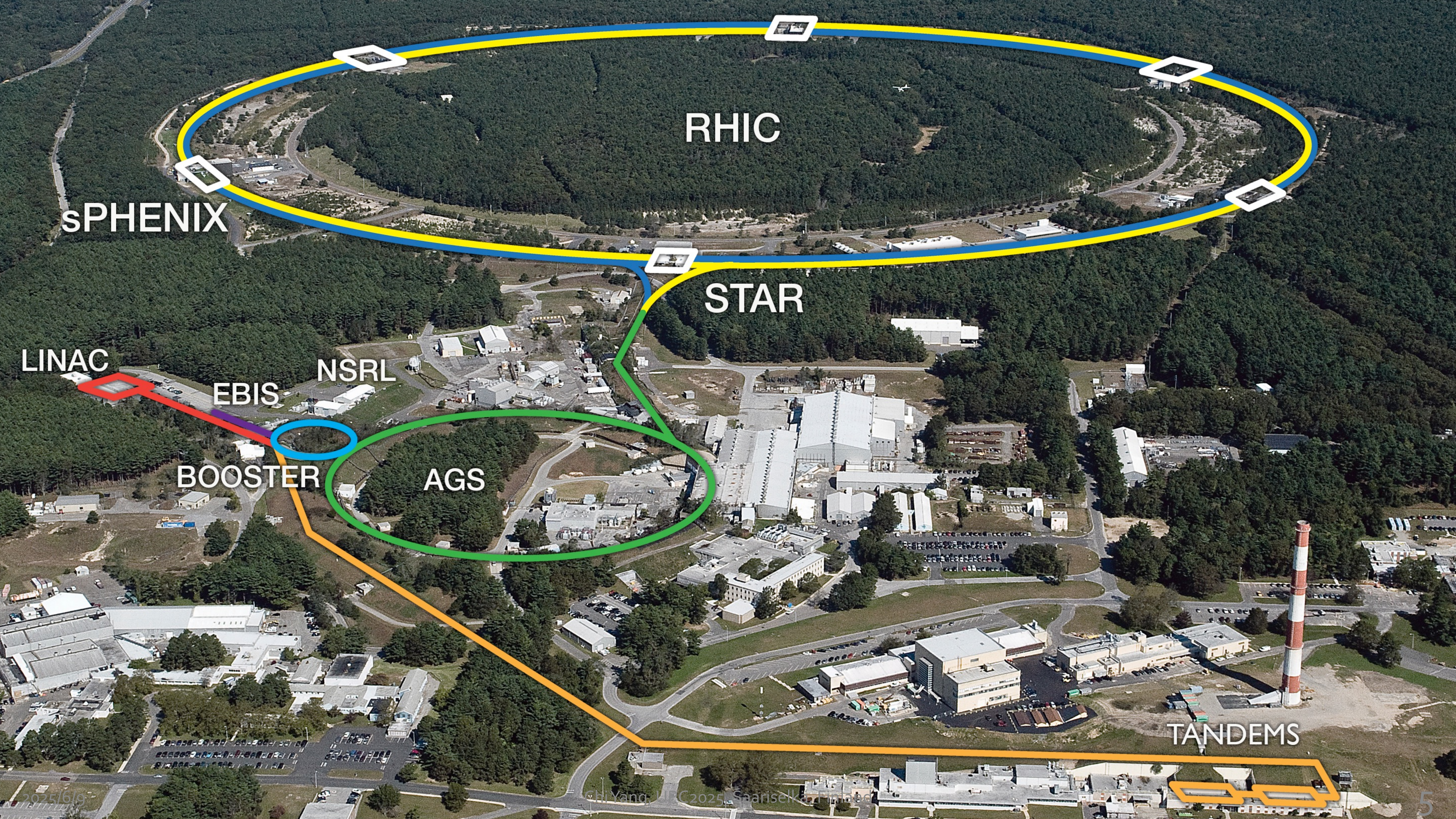
Ann.Rev.Nucl.Part.Sci. 55, 271-310 (2005)

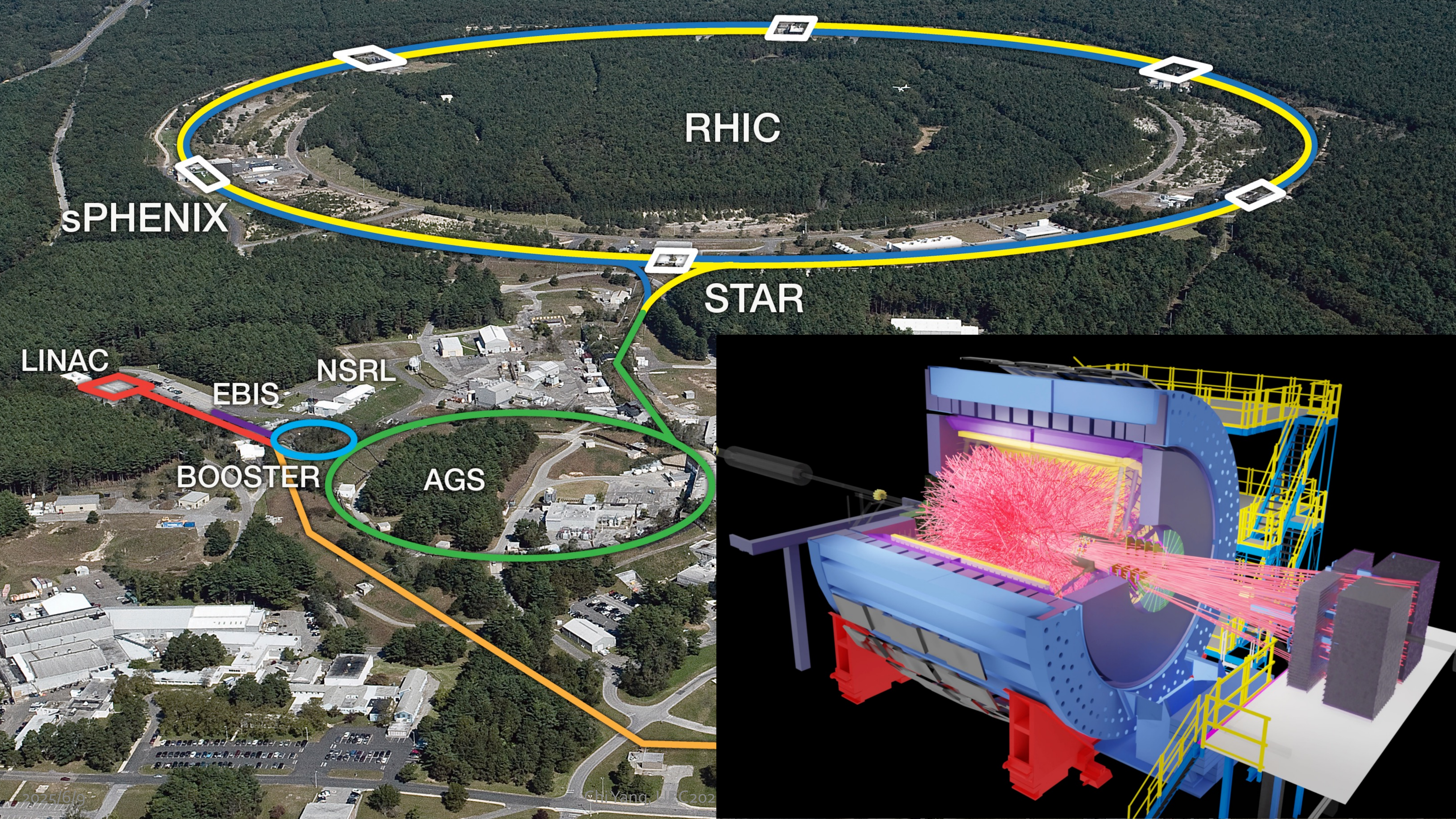


WT Deng, XG Huang, Phys. Rev. C, 85, 044907 (2012)

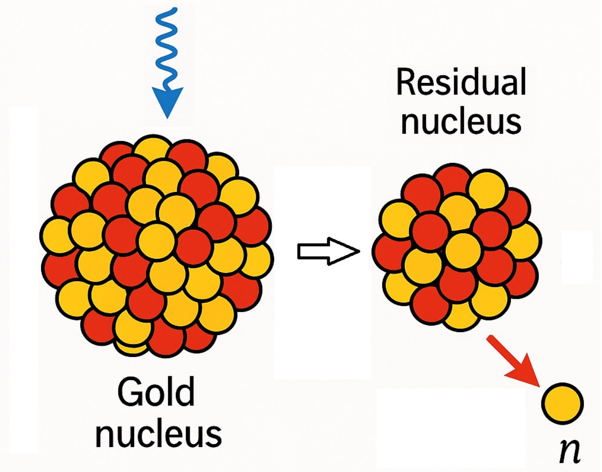
- Large initial EM field: sensitive to nuclear geometry
- Compare with hadronic heavy-ion collisions： EM properties in medium




RHIC
sPHENIX
STAR
LINAC
NSRL
EBIS
BOOSTER
AGS
TANDEMS

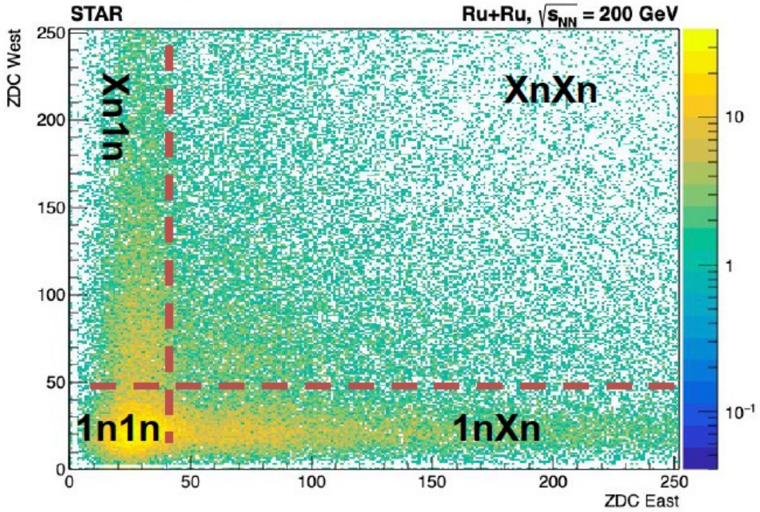

RHIC
sPHENIX
STAR
LINAC
NSRL
EBIS
BOOSTER
AGS

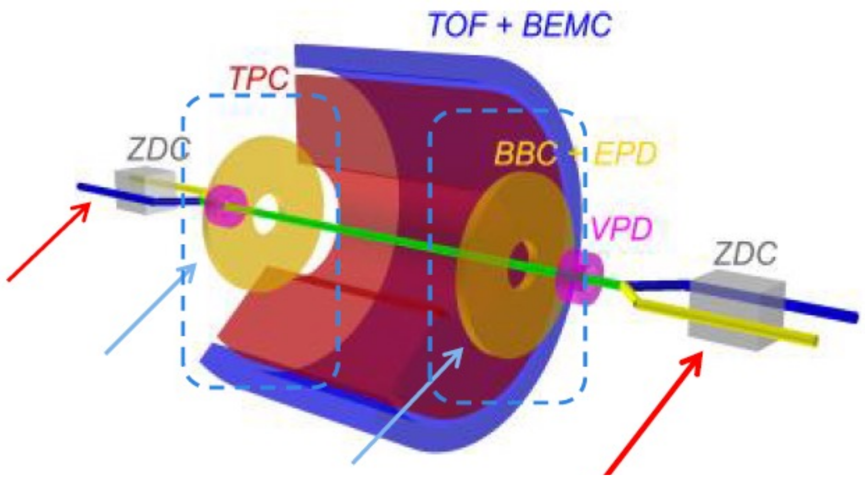
Neutron Tagging in UPCs at STAR

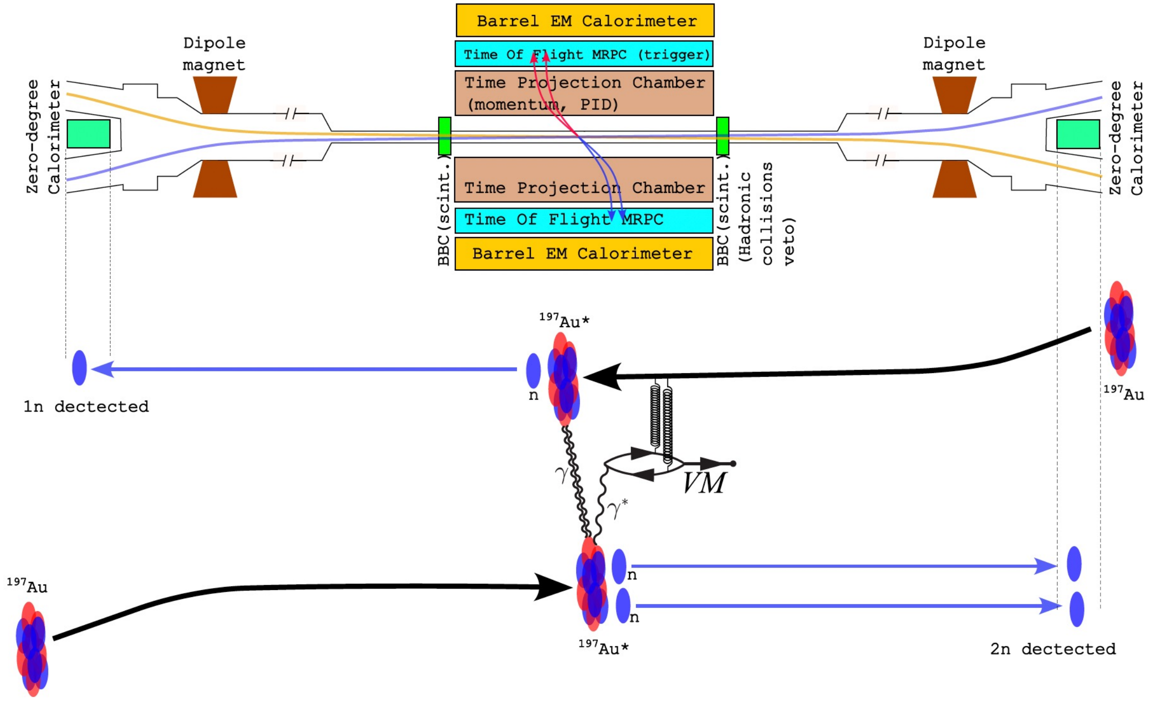


Neutrons from Coulomb Dissociation were used for UPC trigger

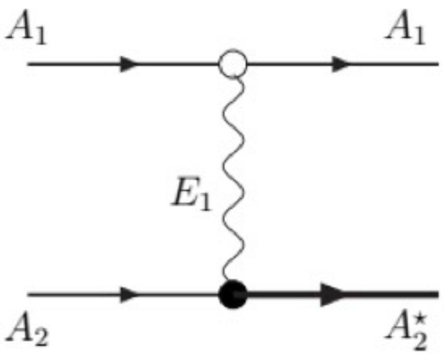
Neutron-tagged events are selected using the ZDC

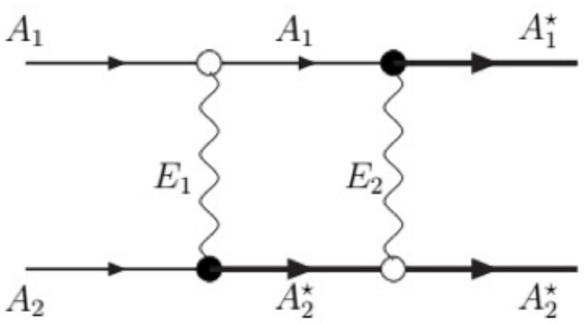






Coulomb Dissociation Measurement in Isobar



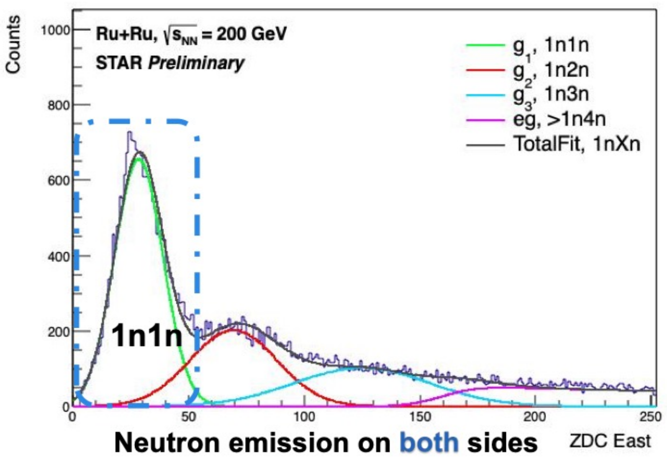


$$AA \rightarrow XnXn + A^*A^*$$

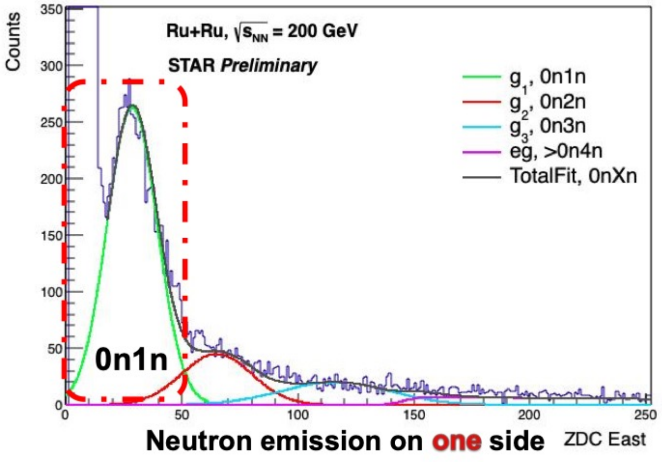
Isobaric Nuclei:
Ruthenium and Zirconium

- Direct comparison of nuclear structures
- Probing the influence of proton number on nuclear properties

b). Single Coulomb dissociation (**SCD**)



c). Mutual Coulomb dissociation (**MCD**)



Neutron	Ratio (Ru/Zr)		
1n1n	2.18	± 0.02	± 0.21
1nXn	1.43	± 0.05	± 0.12
XnXn	0.88	± 0.02	± 0.09

$$\frac{Z_{Ru}^2}{Z_{Zr}^2} \approx 1.21$$

Neutron	Ratio (Ru/Zr)		
0n1n	1.60	± 0.02	± 0.04
0nXn	1.03	± 0.06	± 0.02
0nXn+Xn0n	1.03	± 0.06	± 0.02

The first measurement of Coulomb dissociation with STAR isobar data at 200 GeV

The cross section ratio of Ru/Zr in 0n1n (0nXn) SCD and 1n1n (XnXn) MCD are extracted, not following Z^2 scaling

Thursday 09:40 Huda's talk

Photon-photon Collisions

Link to fundamental QED process

Novel way to test QED under extreme condition

Sensitive to nuclear charge distribution

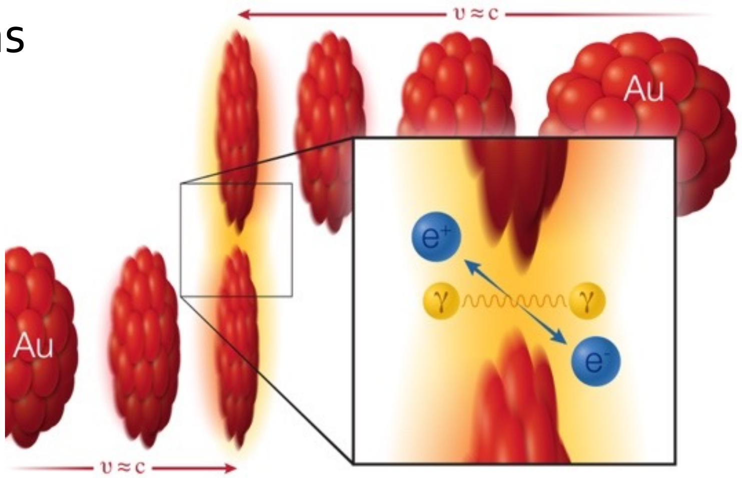
Search for QED vacuum excitation

Search for Breit-Wheeler Pair Production

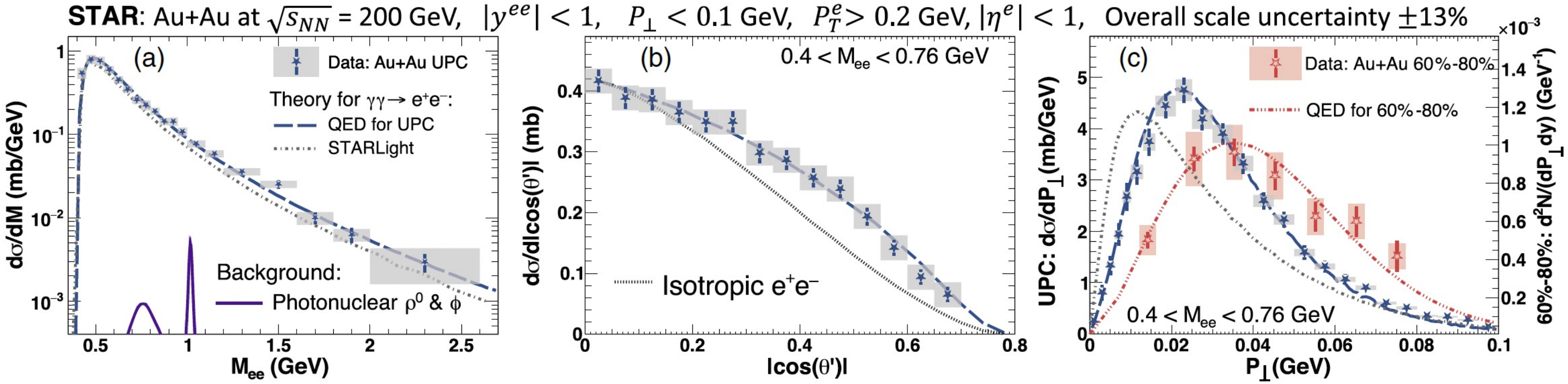
Breit-Wheeler Process at RHIC-STAR

$\gamma\gamma \rightarrow e^+e^-$

- Observe 6085 exclusive e^+e^- pairs from ultraperipheral Au+Au collisions at 200 GeV collected in 2010 by STAR
- No vector meson contribution visible
- Observe significant enhancement in low p_T
- Consistent with QED predictions on various observables

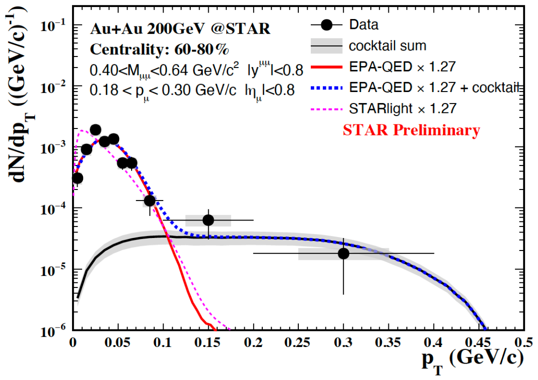


Quantity	Measured	SL	GEPA	QED
$\sigma(\mu b)$	$261 \pm 4 \pm 13 \pm 34$	220	260	260



Breit-Wheeler process observed at STAR

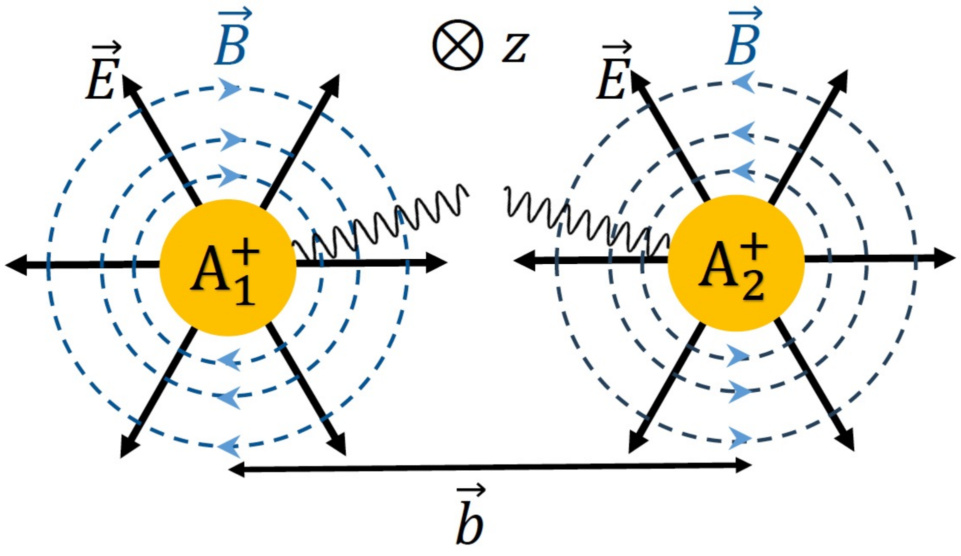
STAR, PRL 127, 052302 (2021)

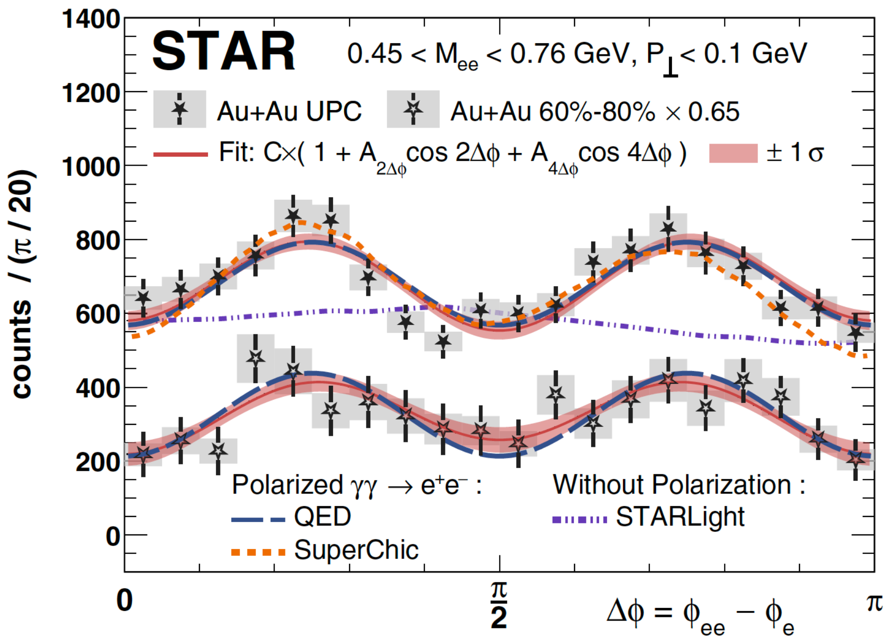


$\gamma\gamma \rightarrow \mu^+\mu^-$ observed in HHICs

Spin-induced OAM Effect in UPCs

STAR, PRL 127, 052302 (2021)



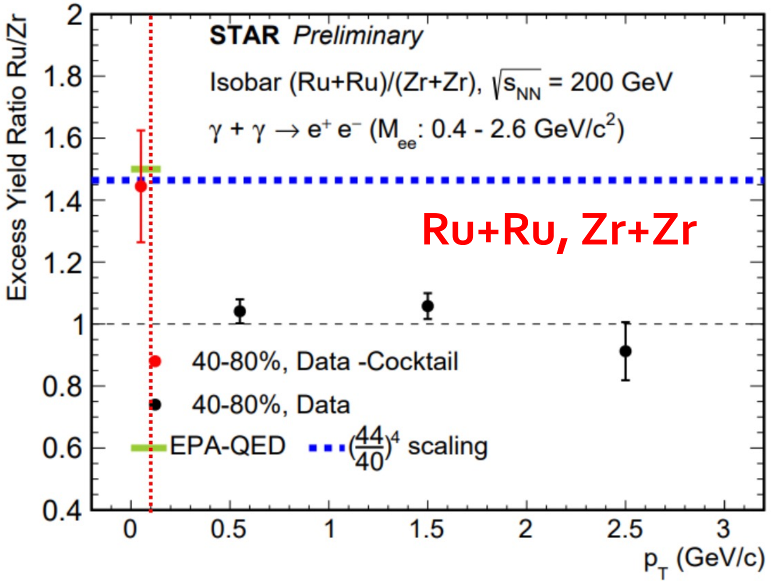


- Quasi-real photons are linearly polarized confirmed by observation of cos($4\Delta\phi$) angular modulation
- QED calculation describe the experimental observation

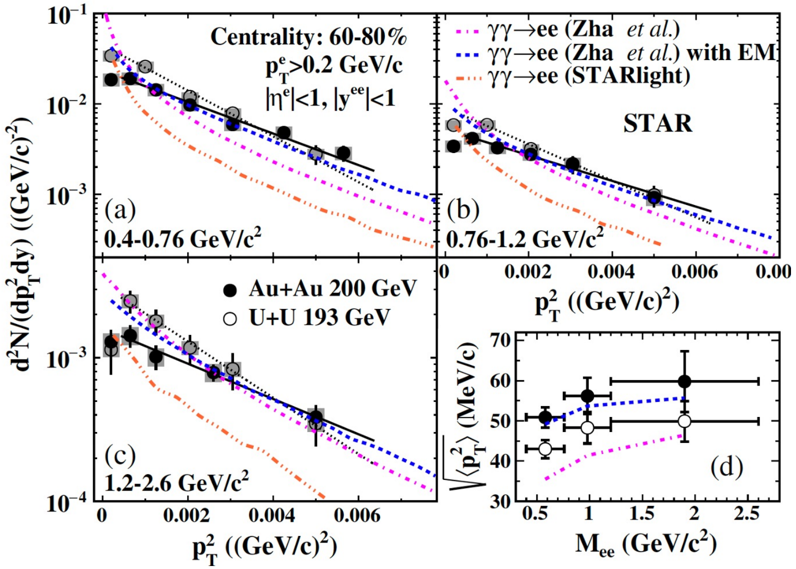
C. Li, J. Zhou, Y.- J. Zhou, PLB 795, 576 (2019); PRD 101, 034015 (2020)

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

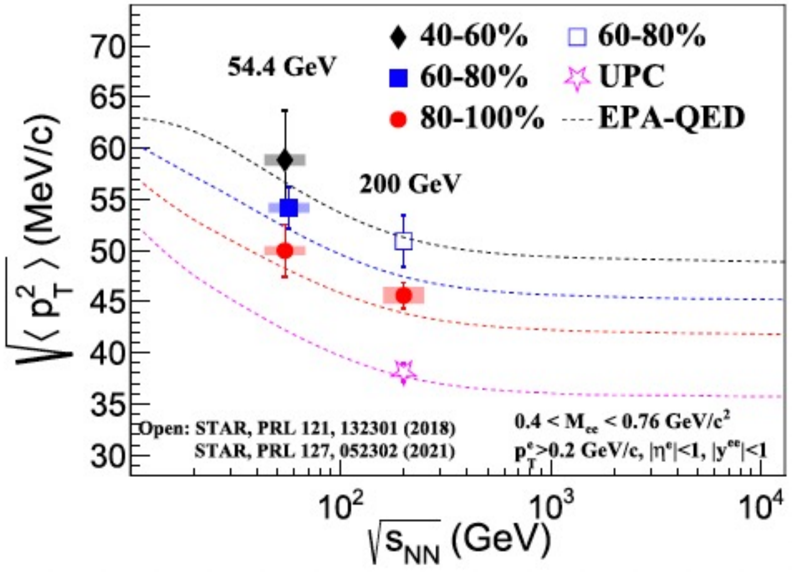
Differential Study on BW Processes



- Excess yields (Ru+Ru vs Zr+Zr):
  study initial magnetic field dependence, consist with Z^4 scaling
- $\sqrt{\langle p_T^2 \rangle}$ (different centralities vs UPC in Au+Au):
  observe b dependence
- $\sqrt{\langle p_T^2 \rangle}$ (54 GeV data vs QED at 200 GeV):
  4.3$\boldsymbol{\sigma}$ (energy dependence + possible final-state effect)



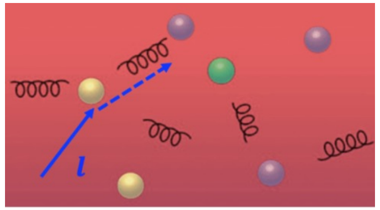
STAR, PRL 121, 132301 (2018)

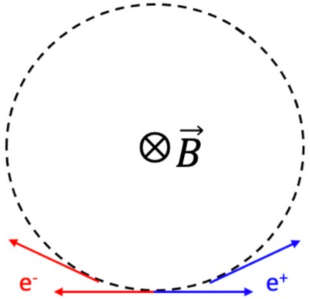


STAR, PRC 111, 014909 (2025)

final-state effect

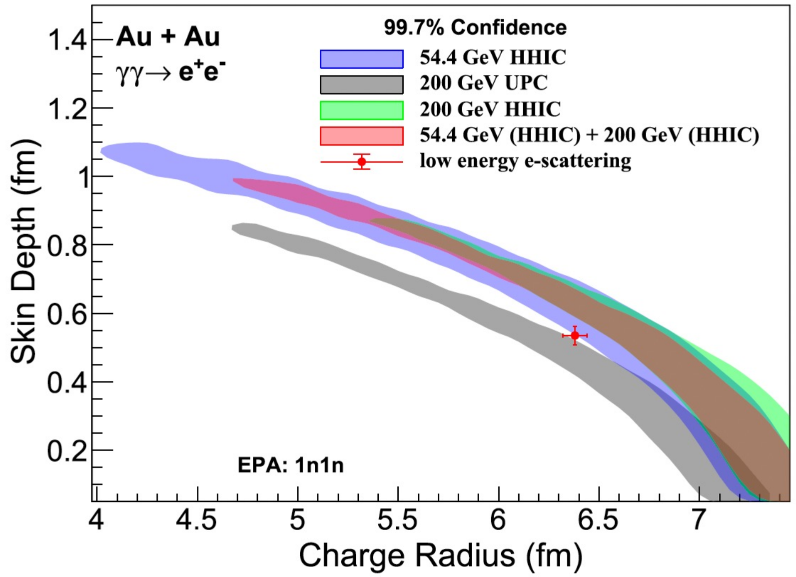
trapped magnetic field or Coulomb scattering in the QGP can lead to p_T broadening





Further study on final-state effect: RHIC Run23-25

Constraining Nuclear Charge Radius

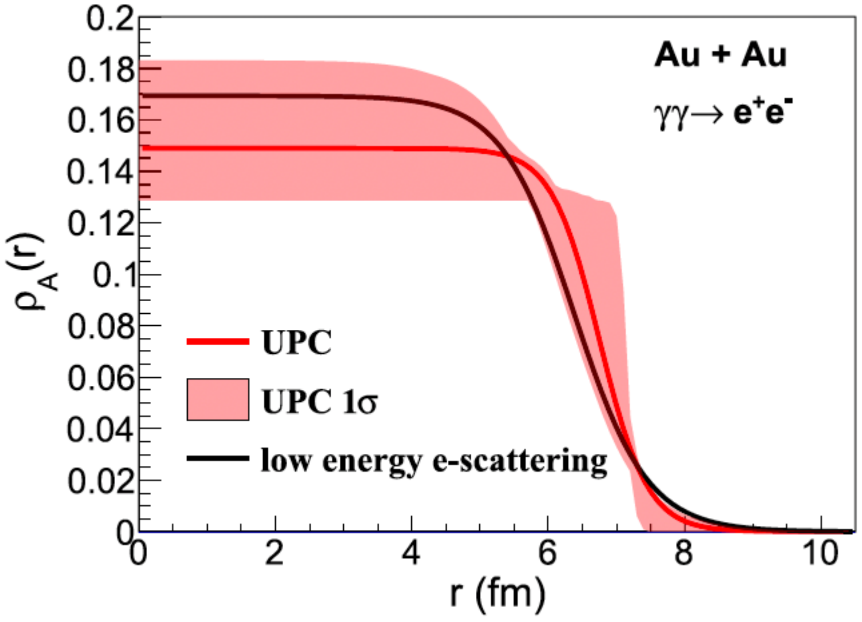


- Compare QED predictions with precise experimental measurement

（assume Wood-Saxon distribution）

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

- Difference between UPCs and hadronic heavy-ion collisions (HHICs)



- Potential final-state effects in HHICs can modify the results of the charge radius extraction and favors an apparent large radius

- Constrain in UPCs： consistent with low energy e-scattering results

X. Wang, et al., PRC 107,044906 (2023)

Provide a new way to constrain nuclear charge radius

STAR, PRC 111, 014909 (2025)

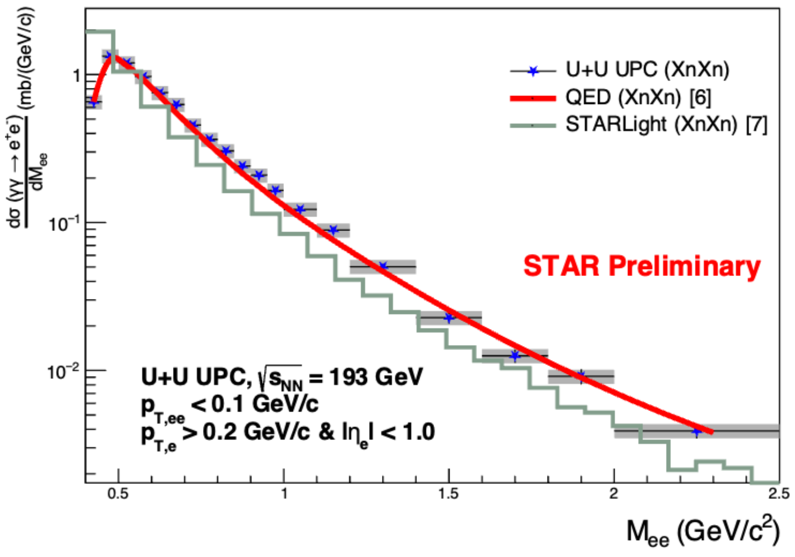
RHIC Run23-25 for future

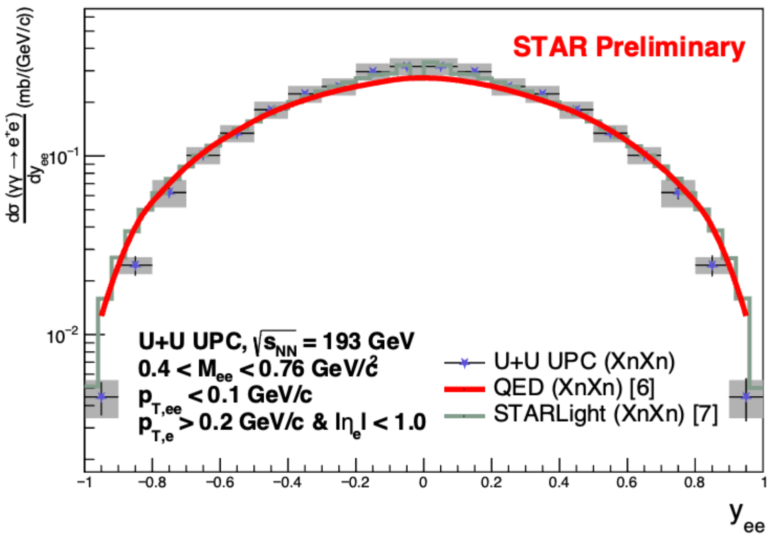
Breit-Wheeler Processes in U+U

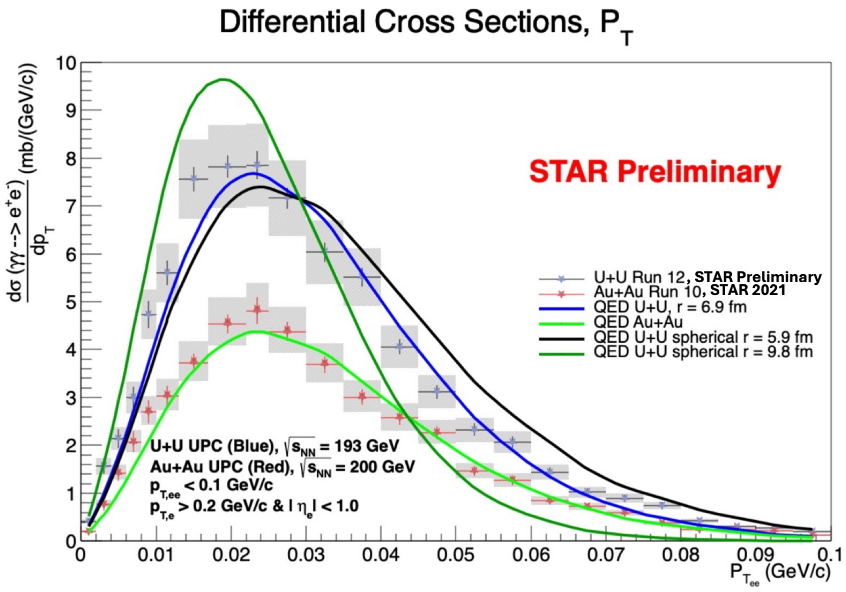
Uranium: more deformation than that in Gold

$\gamma\gamma \rightarrow e^+e^-$

Comparisons between U and Au cross sections will enable new constraints on the nuclear shape





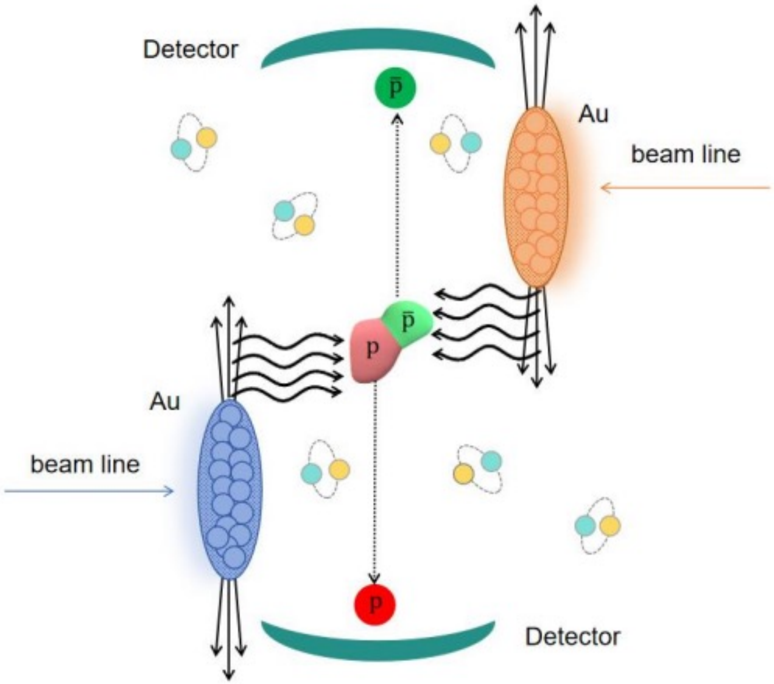


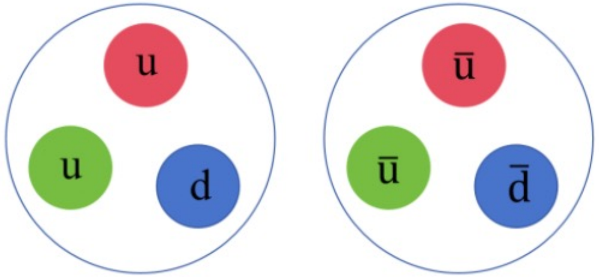
First rapidity dependence measurement of BW process

- QED well describes the mass and rapidity distribution but fails to describe p_T spectrum in U+U collisions (assuming spherical U)
- p_T and cos(n$\boldsymbol{\Delta\phi}$) may provide more constraints on the nonspherical nucleus

Tuesday 17:50 Xihe's talk

Baryon-antibaryon Pair Production



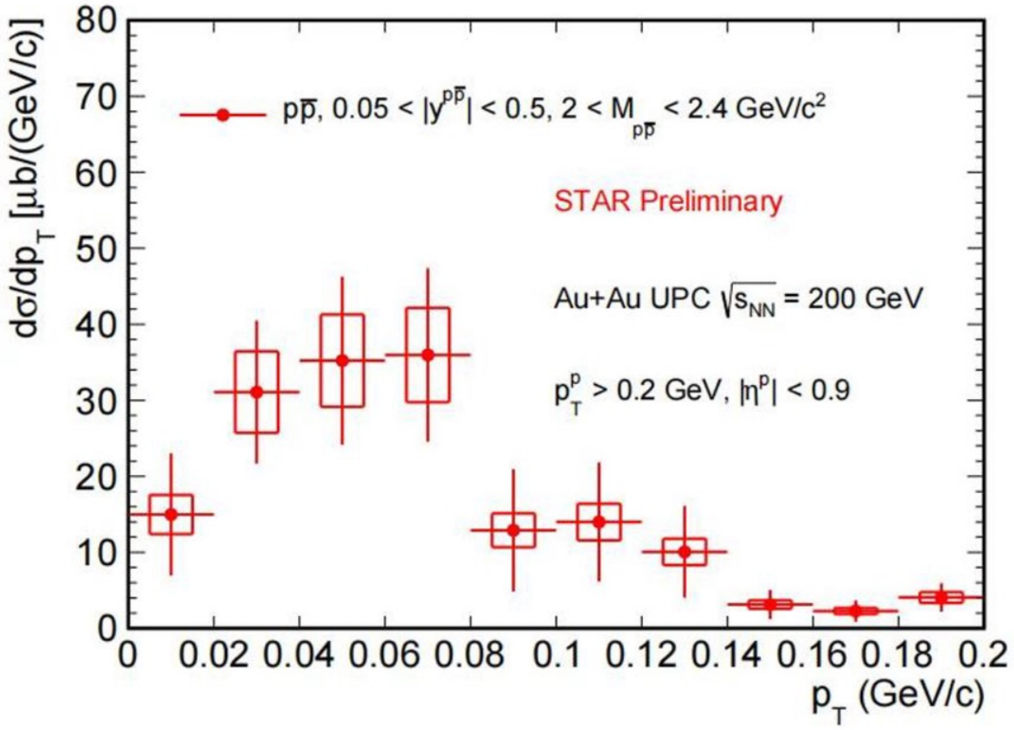


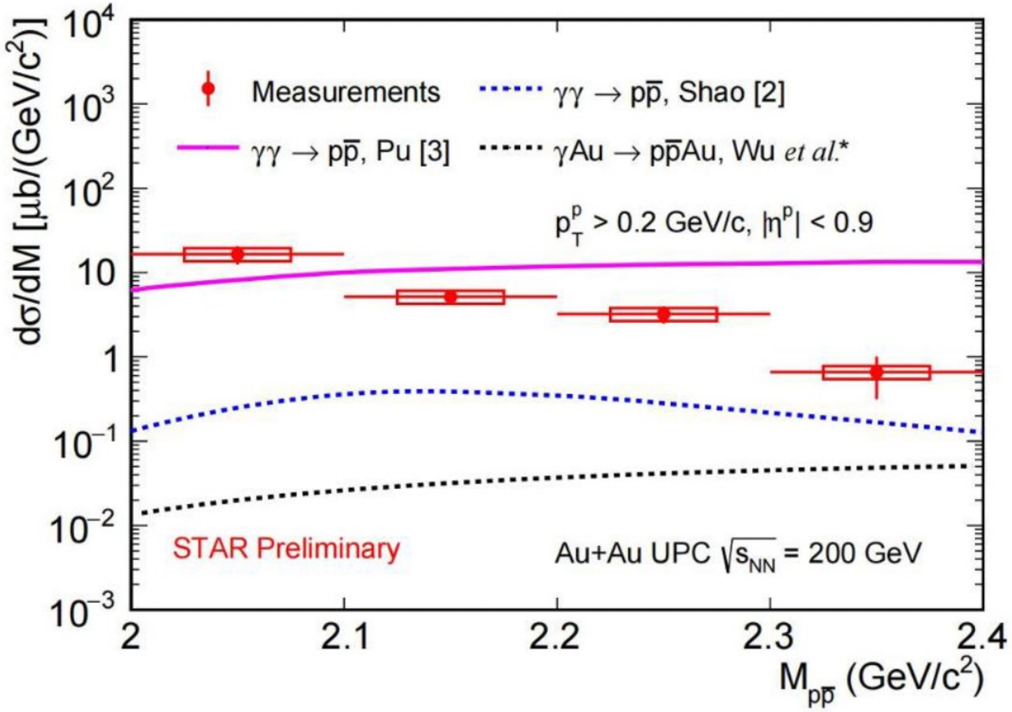
More complex system

- Can more complex system, such as baryon-antibaryon pairs, be produced through QED vacuum excitation?
- Deepens our understanding of the properties of strong-field QED and non-perturbative QCD

Observation of $p\bar{p}$ Pair Production

$\gamma\gamma \rightarrow p\bar{p}$





First observation of the proton-antiproton pair production from the vacuum

(via photon photon process at very low Q^2)

Friday 09:30 Xinbai's talk

Photon-nuclear Collisions

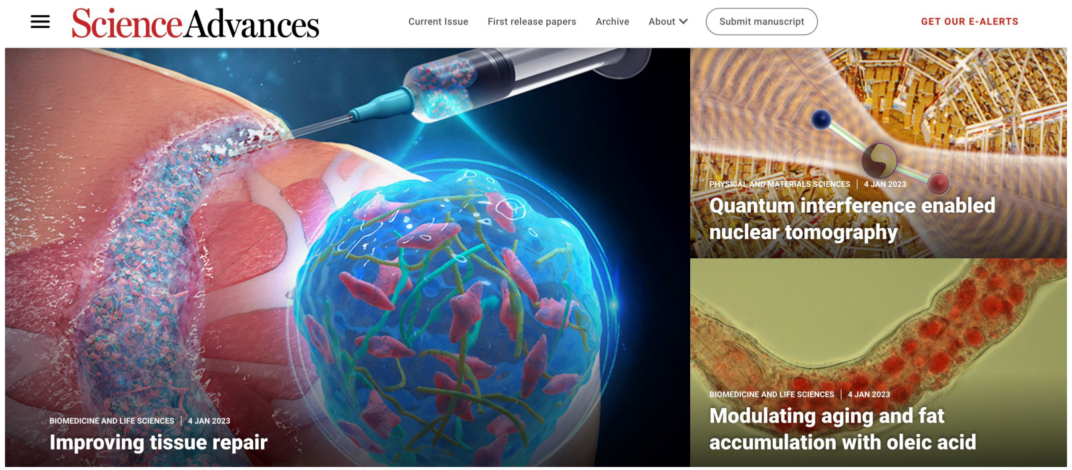
Sensitive to gluon distribution

Spin interference effect

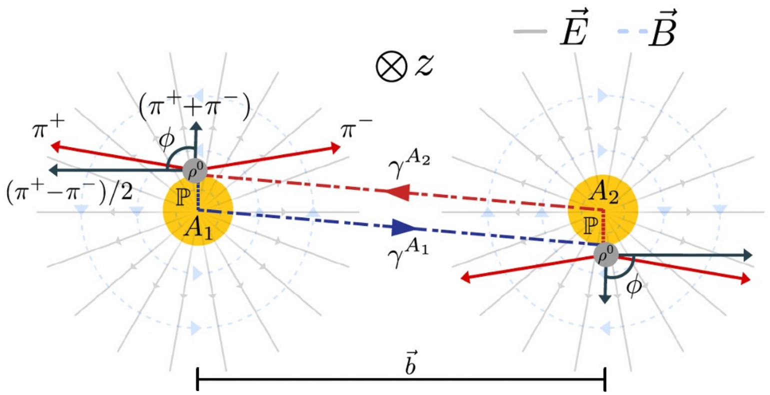
Search for excited states

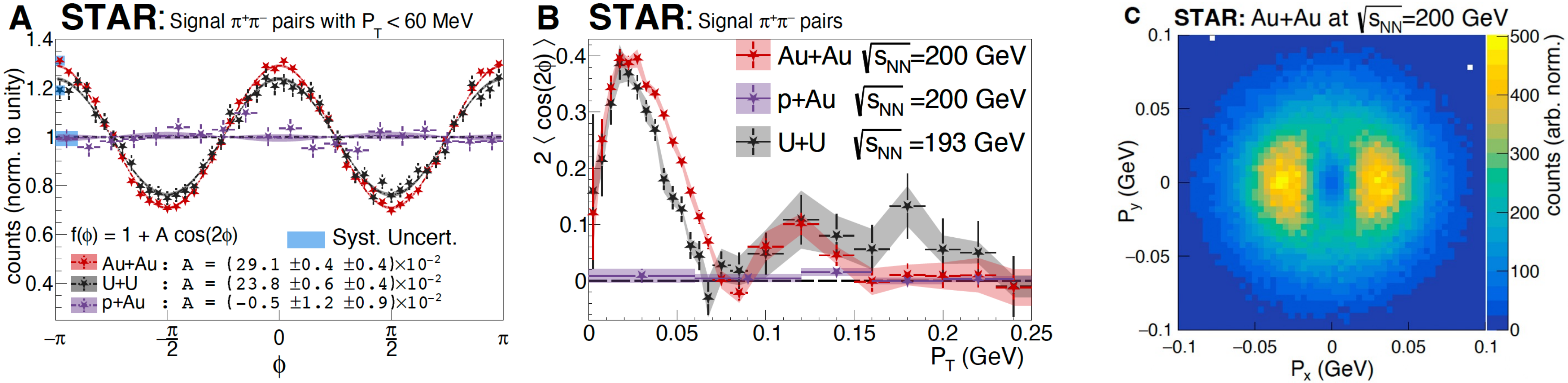
Link to EIC physics

Quantum Interference Enabled Nuclear Tomography



$\gamma A \rightarrow \rho^0 \rightarrow \pi^+\pi^-$





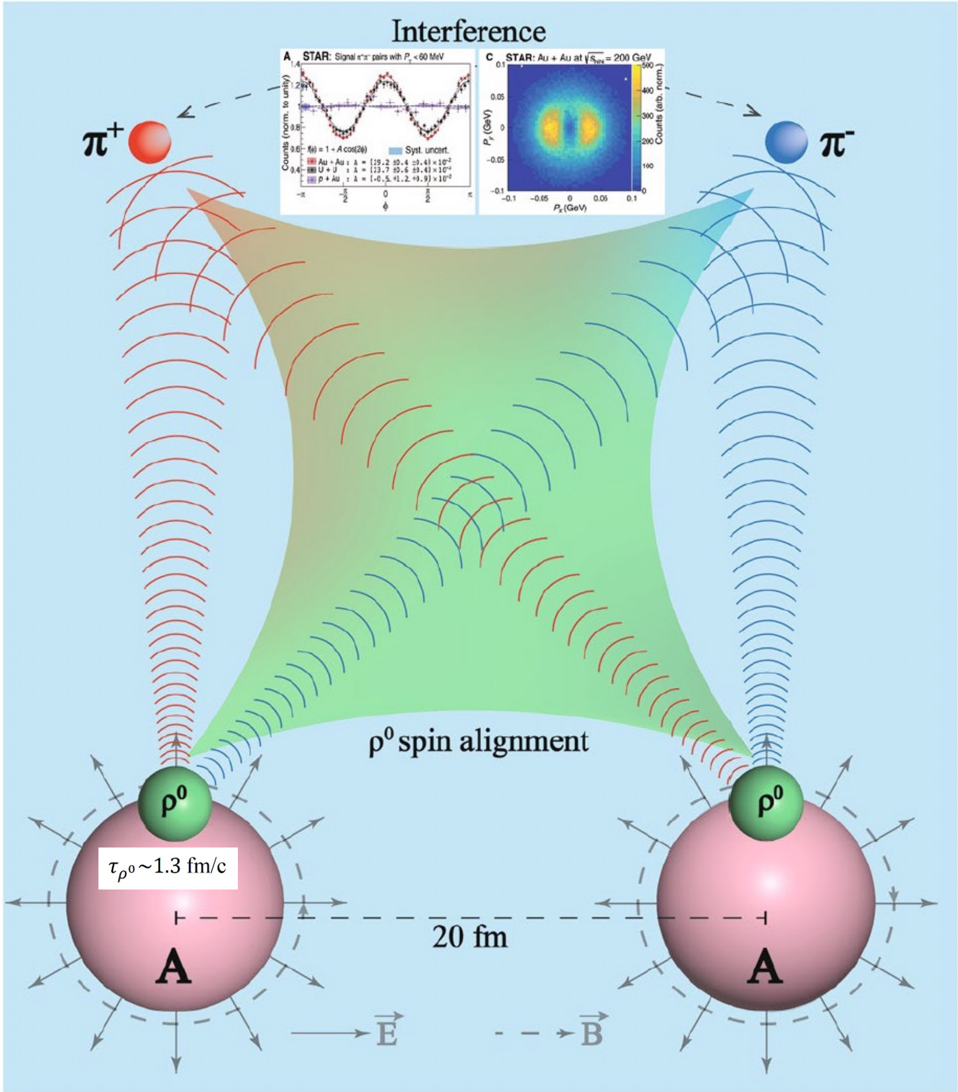
Observation of $\cos 2\Delta\phi$ modulation in Au+Au collisions at 200 GeV

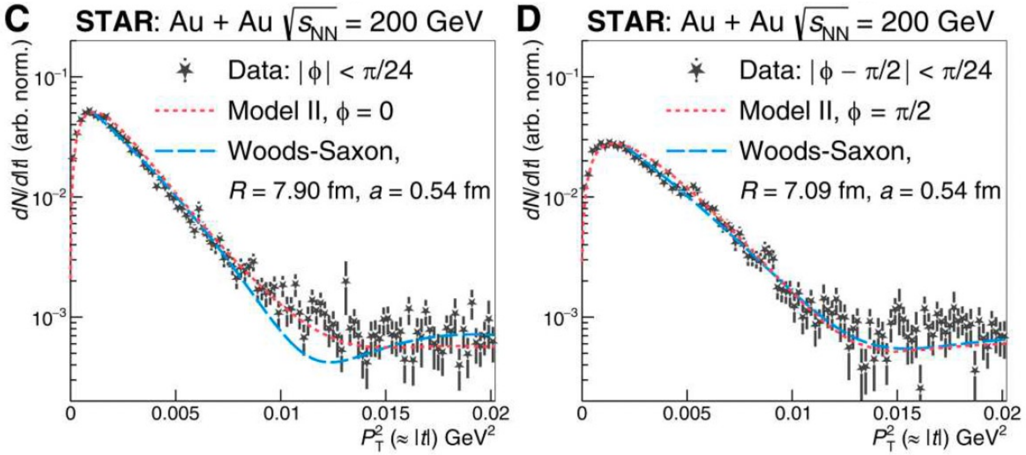
The interference pattern depends on the nuclear radius

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

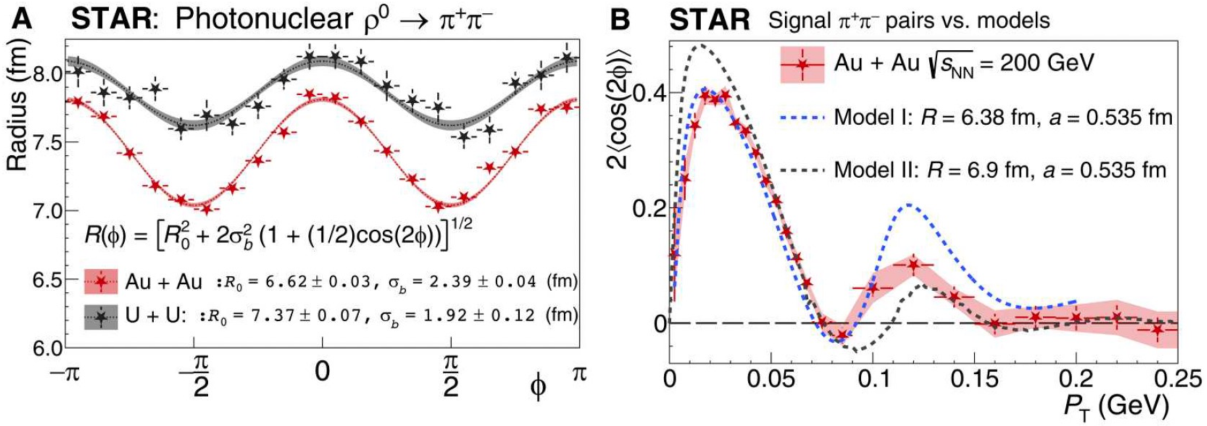
Entanglement Enabled Spin Interference (EESI)

Double Slit Experiment at Fermi Scale





Different -t slopes in different ρ^0 polarization directions



Extracting the "true" mass radius considering EESI effect

Y.- G. Ma, NST 34:16 (2023)
W. - M. Zha, et al., PRD 103, 033007 (2021)

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

Study Nuclear Structure via ρ^0 Photoproduction

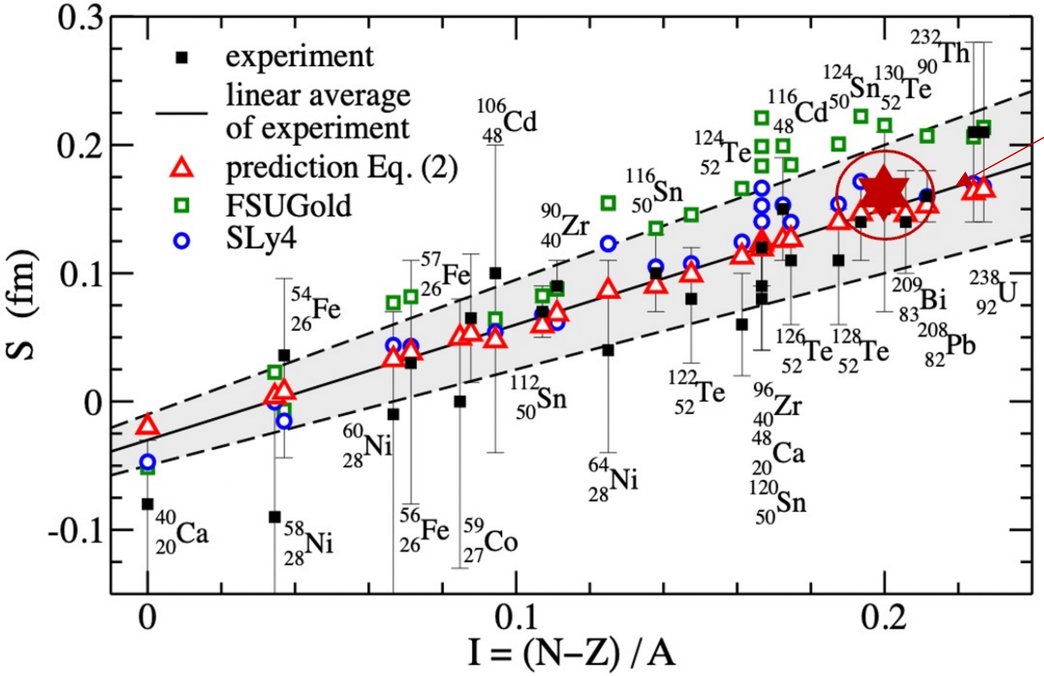
	^{197}Au	^{238}U
STAR *R* (fm)	6.53 ± 0.03 ± 0.05	7.29 ± 0.06 ± 0.05
STAR ⟨cos 2ϕ⟩ (%)	29.2 ± 0.4 (statistical) ± 0.4 (systematic)	23.7 ± 0.6 (statistical) ± 0.4 (systematic)

$\gamma A \rightarrow \rho^0 \rightarrow \pi^+\pi^-$

Extracted neutron skin:

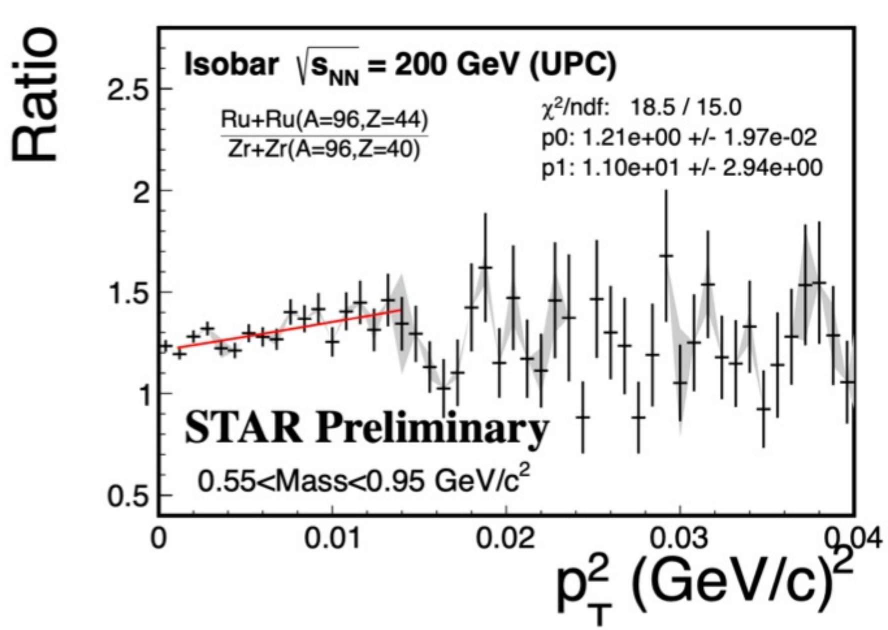
S_{238U} = 0.44 ± 0.05 ± 0.08 fm

S_{197Au} = 0.17 ± 0.03 ± 0.08 fm



Larger radius ("neutron skin") of U :
Indication of the nuclear deformation ?

dN/dt slope difference in Isobar UPC



~3σ effect beyond flat dN/dt slope ratio:
Indication of larger Zr size than Ru

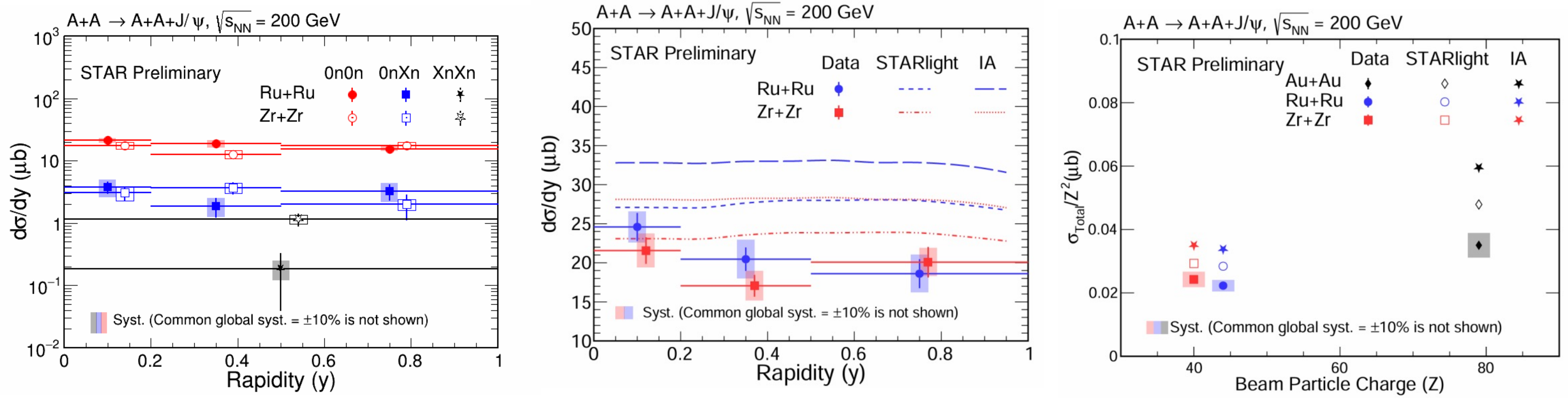
M. Centelles, et al., PRL 102, 122502 (2009)
Q. Shou, et al., Phys. Lett. B 2015
H. De Vries, et al., At. Data Nucl. Data Tables 1987

J/ψ Photoproduction in Au+Au and Isobar UPCs

$\gamma A \rightarrow J/\psi \rightarrow e^+e^-$

Used neutron multiplicity to control b
$b_{XnXn} < b_{0nXn} < b_{0n0n}$

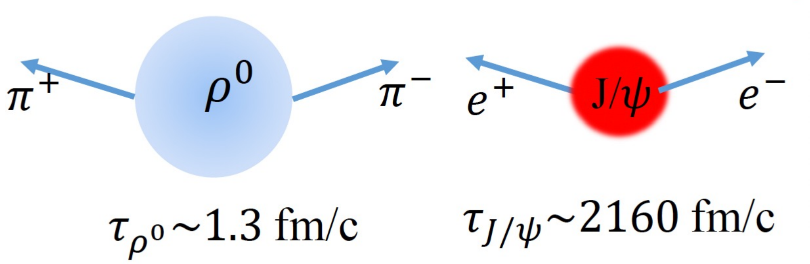
Coherent J/ψ Photoproduction:
probe the average gluon distribution in entire nucleus



- Clear nuclear suppression observed in 200 GeV Au+Au and isobar UPCs
- A hint of enhancement (less than 3σ) from Isobar to Au at the top RHIC energy

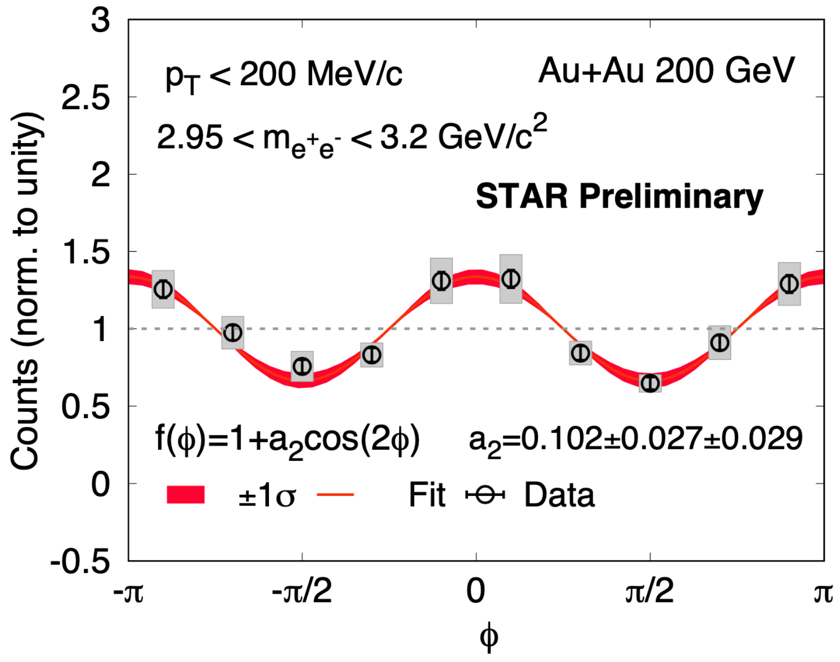
STAR, PRL 133, 052301 (2024)
STAR, PRC 110, 014911 (2024)

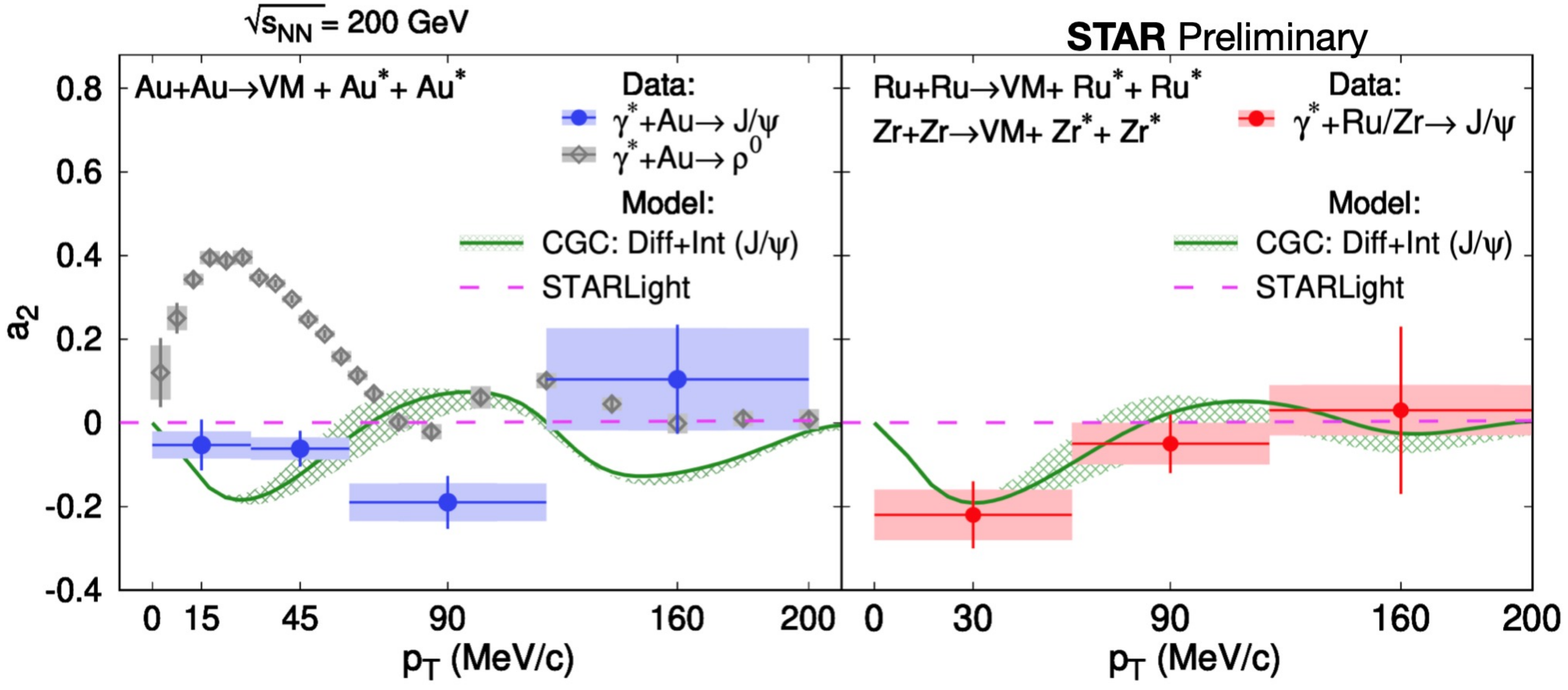
Spin Interference of J/ψ Photoproduction in UPCs



Compared to ρ^0:
- Much longer life time (>>b)
- Larger mass
- Decay to Fermion

$\gamma A \to J/\psi \to e^+e^-$

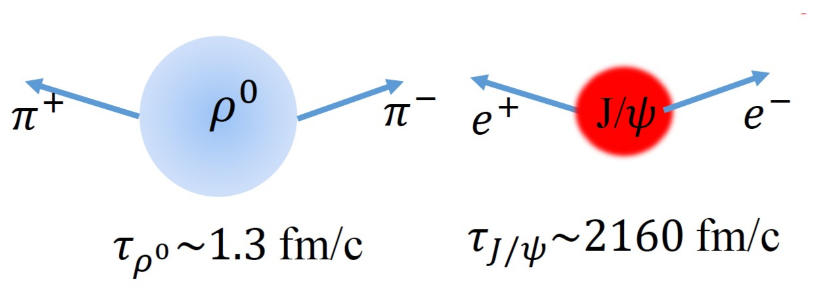




Observed spin interference and its p_T dependence

Opposite modulation for ρ^0 (positive) and J/ψ (negative, 3σ effect)

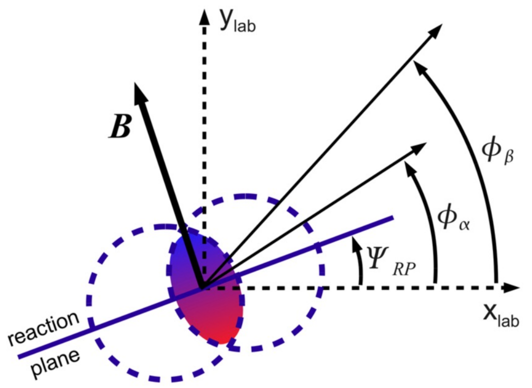
Polarization Effects of J/ψ Photoproduction in HHICs

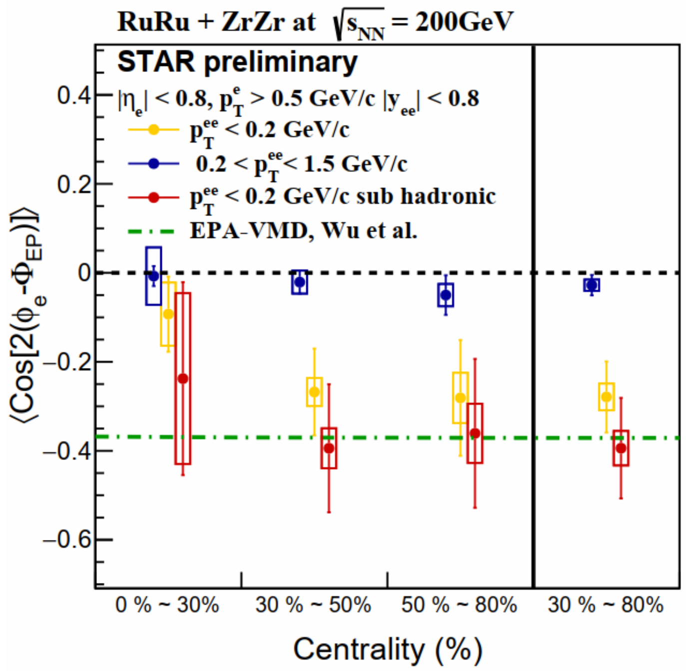


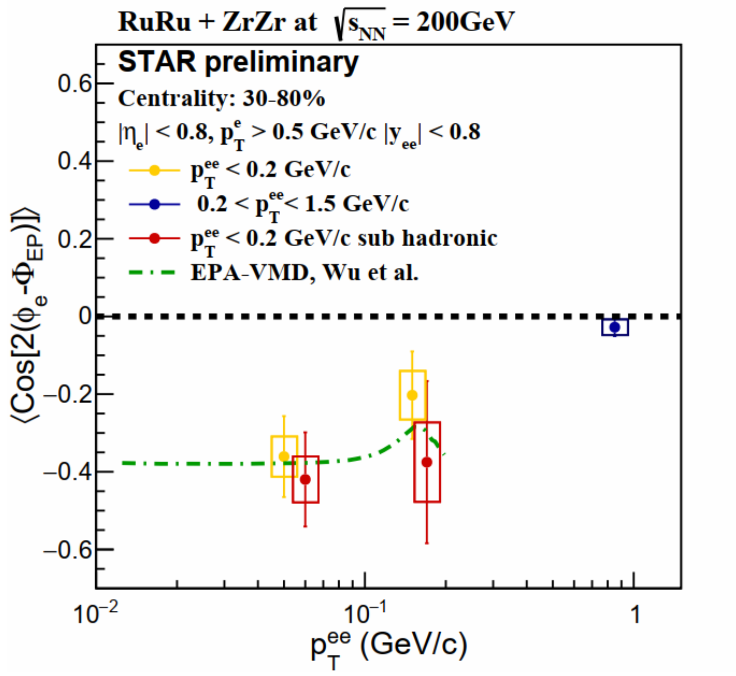
Compared to ρ^0:
- Much longer life time (>>b)
- Larger mass
- Decay to Fermion

$\gamma A \to J/\psi \to e^+e^-$

Decay anisotropy w.r.t event plane in Isobar HHIC







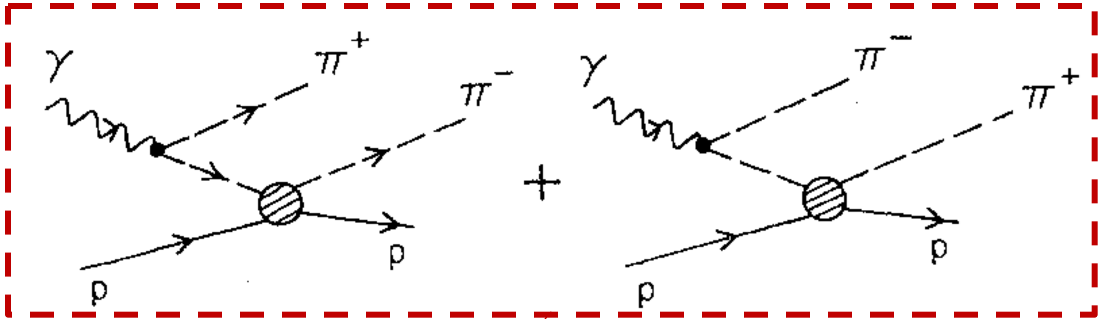
Evidence of decay anisotropy (~39%) from photon polarization aligned with $\vec{b}$

(a way to access $\vec{b}$)

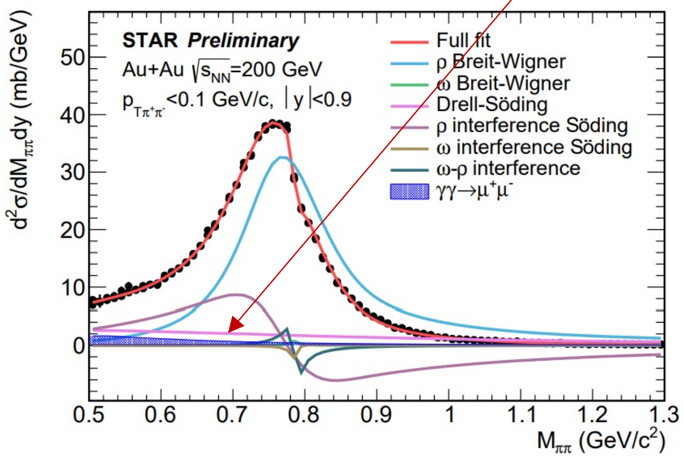
Search for Drell-Söding Process

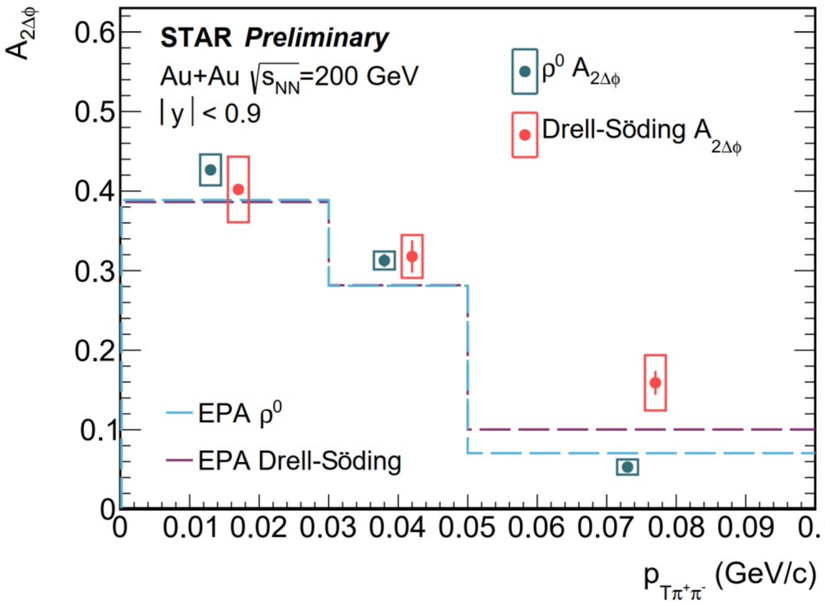
S.D. Drell, Phys. Rev. Letters 5, 278 (1960)

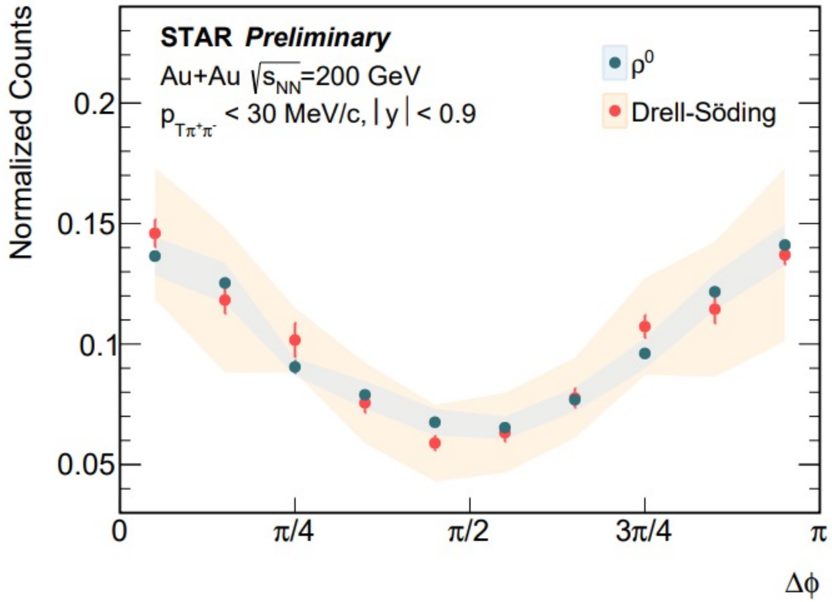
$\gamma A \rightarrow \pi^+\pi^-$



- Does ρ^0 and Drell-Söding via photon nuclear interaction have the same p_T distribution?
- How to distinguish from ρ^0 photoproduction?
- Dose EESI exist in the Drell-Söding process?



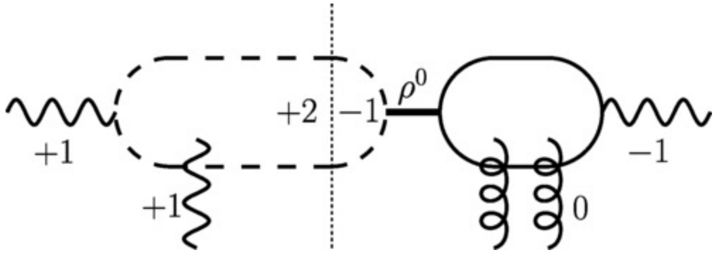




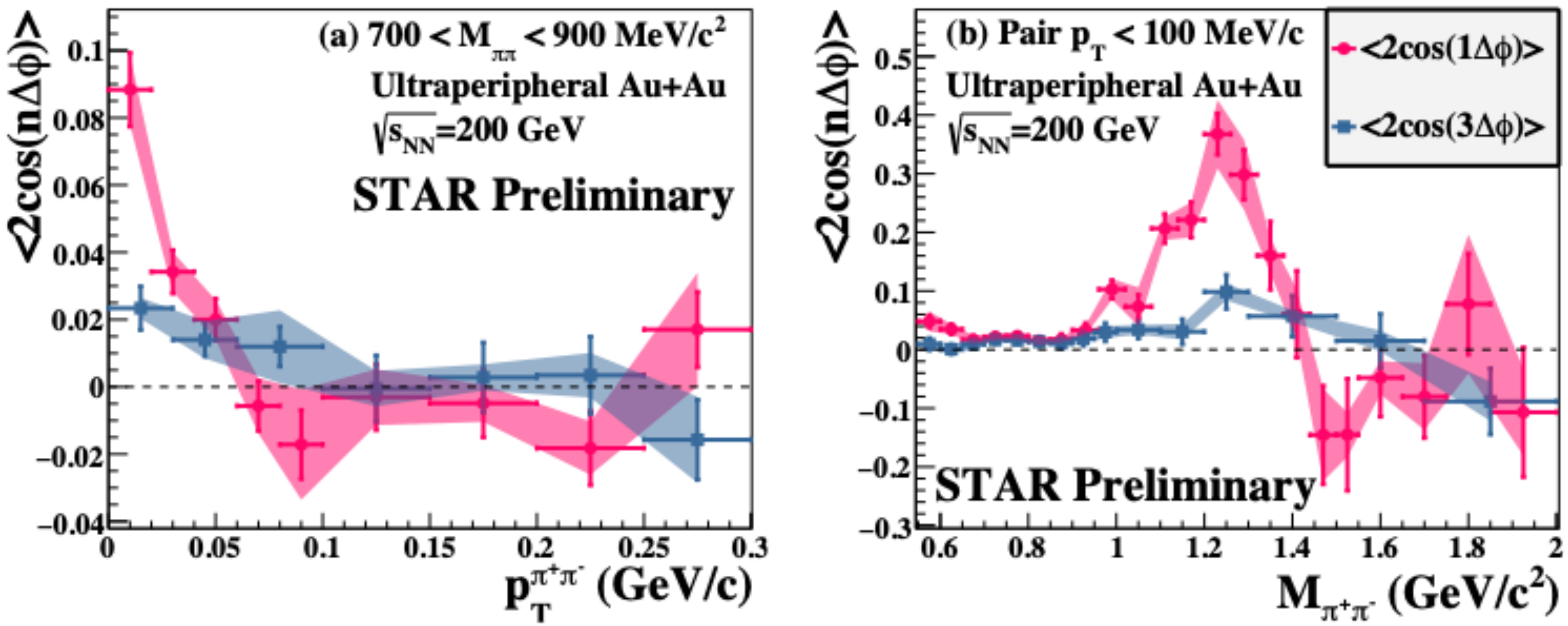
First measurement of pair p_T and spin-interference of Drell-Söding process

Friday 09:30 Xinbai's talk

EESI in $\pi^+\pi^-$ Final State



$\gamma A \rightarrow \rho^0 \rightarrow \pi^+\pi^-$
$\gamma\gamma \rightarrow \pi^+\pi^-$



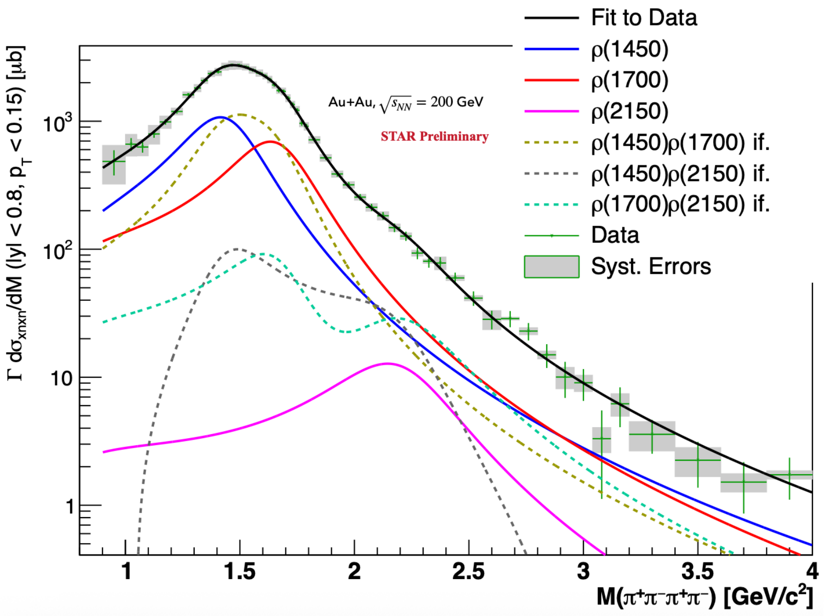
Non-zero $A_{1\Delta\phi}$ and $A_{3\Delta\phi}$ around the ρ^0 mass

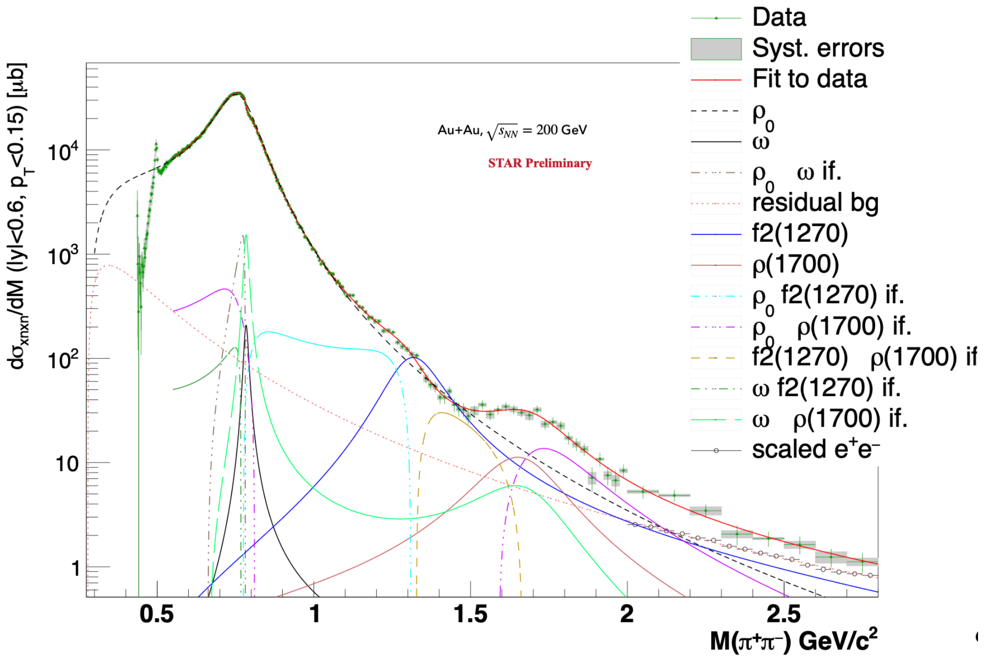
- Evidence for spin interference between photonuclear and hadronic light-by-light production of $\pi^+\pi^-$
- Indication of the contribution from $f_2(1270)$

Friday 10:30 Samuel's talk

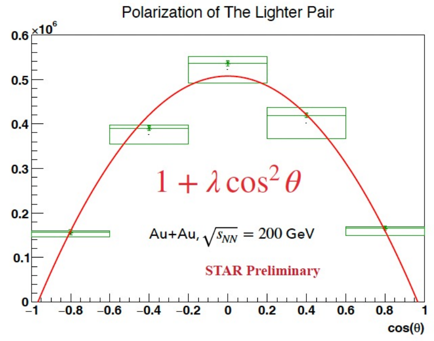
Search for Excited States and its Polarization

Mass distribution of $\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-$ (Run10 + Run11 +Run14)

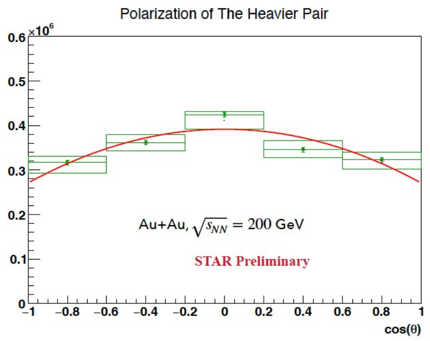




$$\rho(1450) + \rho(1700) \rightarrow (\pi^+\pi^-)_{\text{heavy}} + (\pi^+\pi^-)_{\text{light}} \rightarrow \pi^+\pi^-\pi^+\pi^-$$



$\lambda = -1.062 \pm 0.076$



$\lambda = -0.303 \pm 0.084$

- Non-zero polarization effect observed
- May be affected by EESI in the measurement?

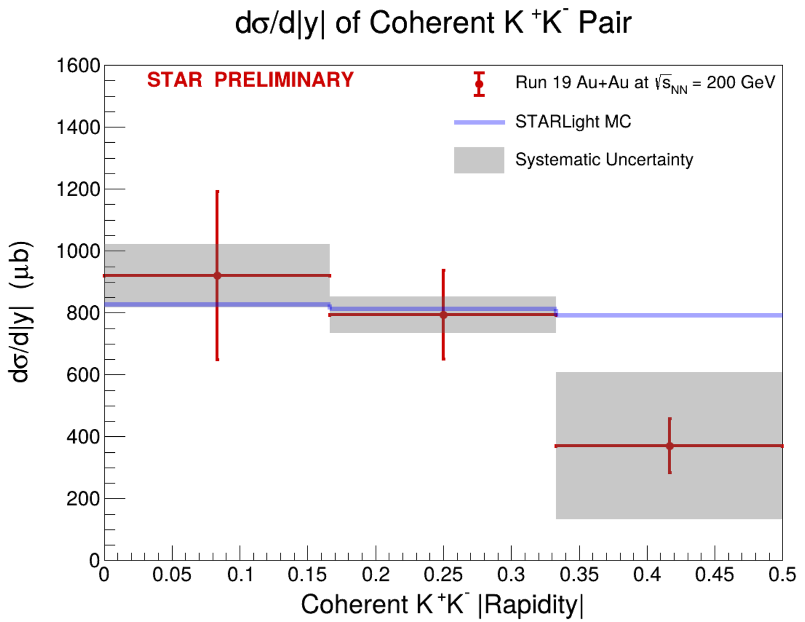
$$\cos\theta = \frac{\overrightarrow{P_{\pi^+\pi^-}} \cdot \overrightarrow{p_\pi}^*}{\|\overrightarrow{P_{\pi^+\pi^-}}\|\,\|\overrightarrow{p_\pi}^*\|}$$

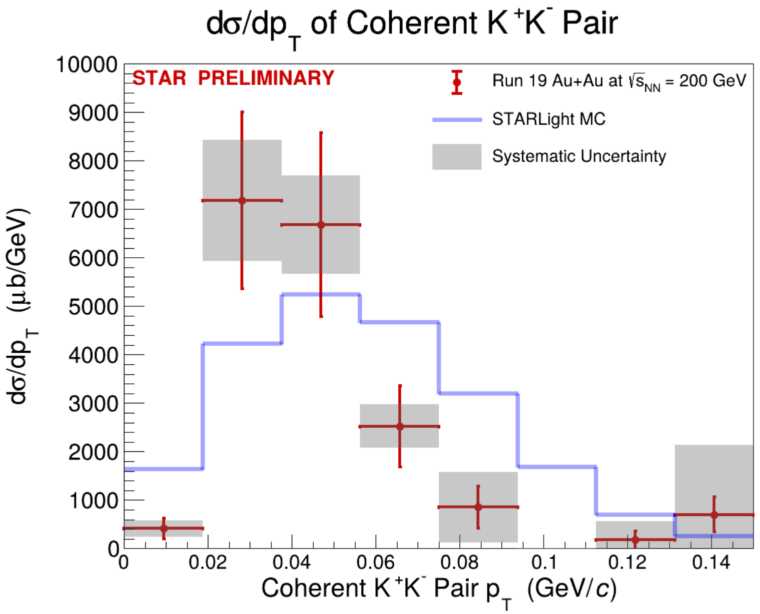
Thursday 17:10 David's talk

ϕ Meson Photoproduction

$\gamma A \rightarrow \phi \rightarrow K^+K^-$

- ϕ meson as an ideal probe for gluon momentum-dependent parton distribution function
- Search for mass-dependent coherent cross section of vector meson production in UPCs
- Challenges in statistics due to the constraint from $\phi \rightarrow K^+K^-$ decay kinematics
- Inner TPC at STAR helps to identify low p_T Kaons

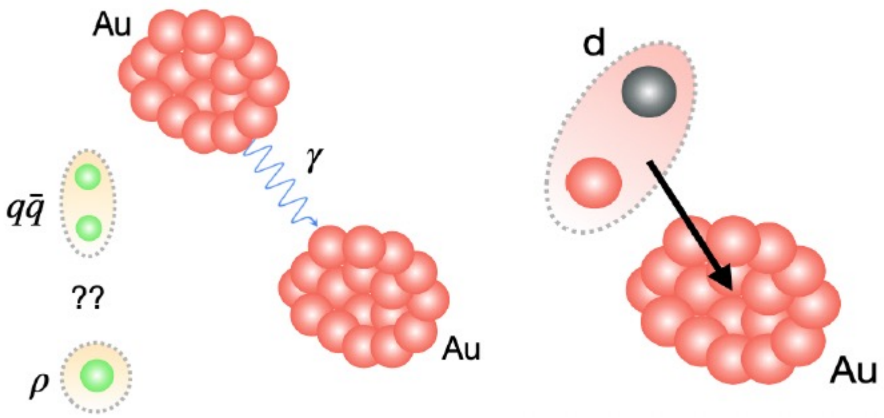




First observation of coherent photoproduced ϕ meson at STAR

Tuesday 17:50 Xihe's talk

Search for Collectivity in UPCs

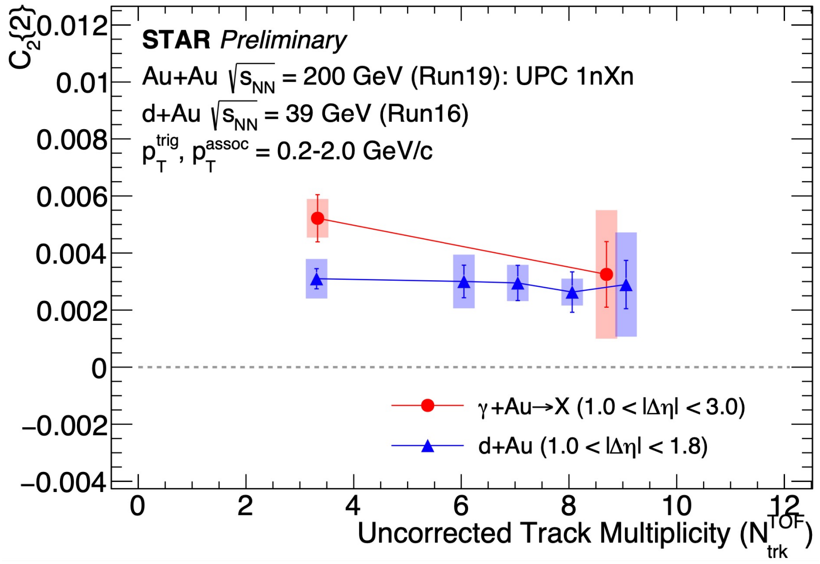


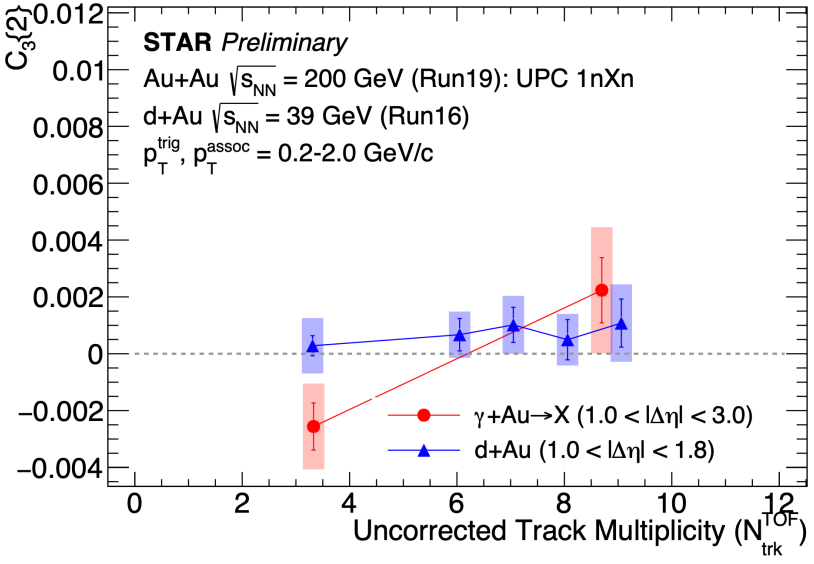
Exclusive ρ production as a trigger for inclusive γA process

Choice of d+Au for Comparison

- Measurements in γAu processes at $W_{\gamma N} \sim 34$ GeV, comparable to d+Au collisions at 39 GeV
- Similar multiplicity range for d+Au and γ+Au accessible at STAR

$$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n C_n\{2\}\cos(n\Delta\phi)$$





C_n results comparable for γAu and dAu

Friday 12:30 Souvik's talk

Summary

Various photon-photon and photon-nuclear processes were measured at STAR

$\gamma\gamma$	e^+e^-	$\mu^+\mu^-$	$\pi^+\pi^-$	$p\bar{p}$
γA	$\rho^0 \rightarrow \pi^+\pi^-$	$J/\psi \rightarrow e^+e^-$	$\pi^+\pi^-(\pi^+\pi^-)$	$\phi \rightarrow K^+K^-$

Initial linearly polarized photon was confirmed and its spin-induced OAM effects were studied in BW process

- ✓ Test QED under extreme condition
- ✓ New way to constrain nuclear structure / initial EM field
- ✓ Access final state effect by comparing UPC and HHIC
- ✓ Observation of the proton-antiproton pair production from the vacuum

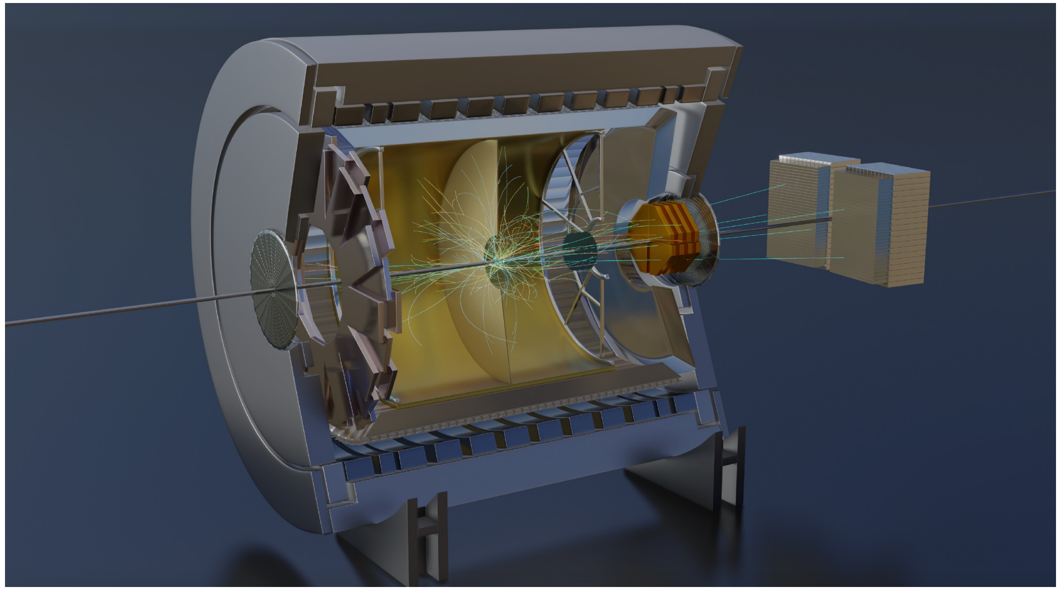
New method of nuclear tomography was developed and EESI effects were studied in VM photoproduction

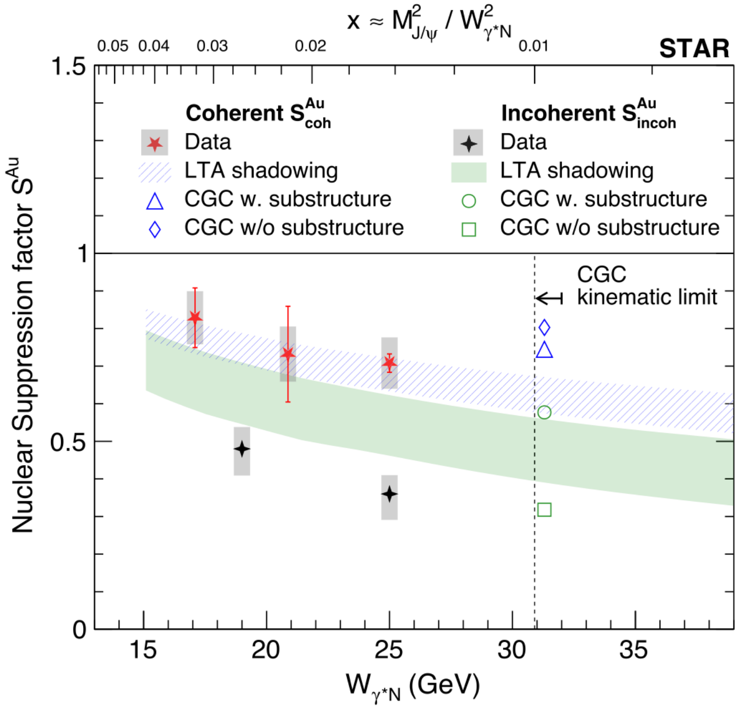
- ✓ Study nuclear structure considering EESI
- ✓ Probe gluon distribution considering b and system size dependence
- ✓ Observation of Drell-Söding Process and its EESI effect
- ✓ Observation of $A_{1\Delta\phi}$ and $A_{3\Delta\phi}$ in $\pi^+\pi^-$ final state
- ✓ Observation of coherent photoproduced $\boldsymbol{\phi}$ meson
- ✓ Search for excited states via $\pi^+\pi^-(\pi^+\pi^-)$
- ✓ Collectivity

STAR: 25 years and beyond

- Runs 22-25: with detector upgrades at forward rapidity
- High statistics AA and pp data
- STAR is at the peak of performances from Run 22

STAR, PRL 133, 052301 (2024)





UPCs at RHIC provide great opportunities to access the physics in EIC!

LIST of All STAR talks in UPC2025

Title	Speaker	Time
Experimental overview on UPC results at STAR	Chi Yang	6/9 10:40
Probing the Nuclear and Electromagnetic Structure of Heavy Nuclei at STAR	Xihe Han	6/10 17:50
Coulomb Dissociation Measurement in Isobaric Collisions at $\sqrt{s_{NN}}$ = 200 GeV with the STAR Experiment	Huda Nasrulloh	6/12 09:40
Observation of $\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-$ final state photoproduction in ultraperipheral heavy-ion collisions at $\sqrt{s_{NN}}$ = 200 GeV at the STAR detector	David Tlusty	6/12 17:10
Measurements of proton-antiproton pairs from QED vacuum excitation in Au+Au ultra-peripheral collisions at $\sqrt{s_{NN}}$ = 200 GeV from STAR	Xinbai Li	6/13 09:30
Investigating Entanglement Enabled Spin Interference in photonuclear $\rho^0 \to \pi^+\pi^-$ and $\gamma\gamma \to \pi^+\pi^-$ in Au+Au collisions at STAR	Samuel Corey	6/13 10:30
Search for Collectivity in Photo-nuclear Processes at RHIC using STAR Detector	Souvik Paul	6/13 12:30