Tomography of Ultra-relativistic Nuclei with Polarized Photon-Gluon Collisions

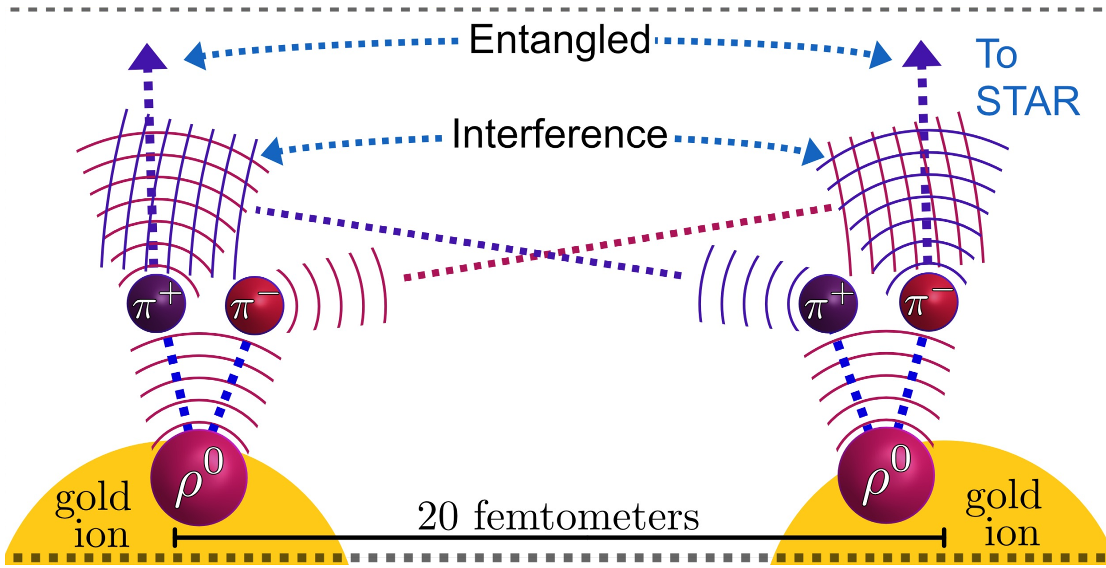
Zhangbu Xu (for the STAR Collaboration)
BNL

iNPC2022
Cape Town, South Africa

In part supported by
Brookhaven National Laboratory
U.S. Department of Energy Office of Science

Spin interference enabled nuclear tomography

- Teaser:
  Polarized photon-gluon fusion reveals quantum wave interference of non-identical particles and shape of high-energy nuclei

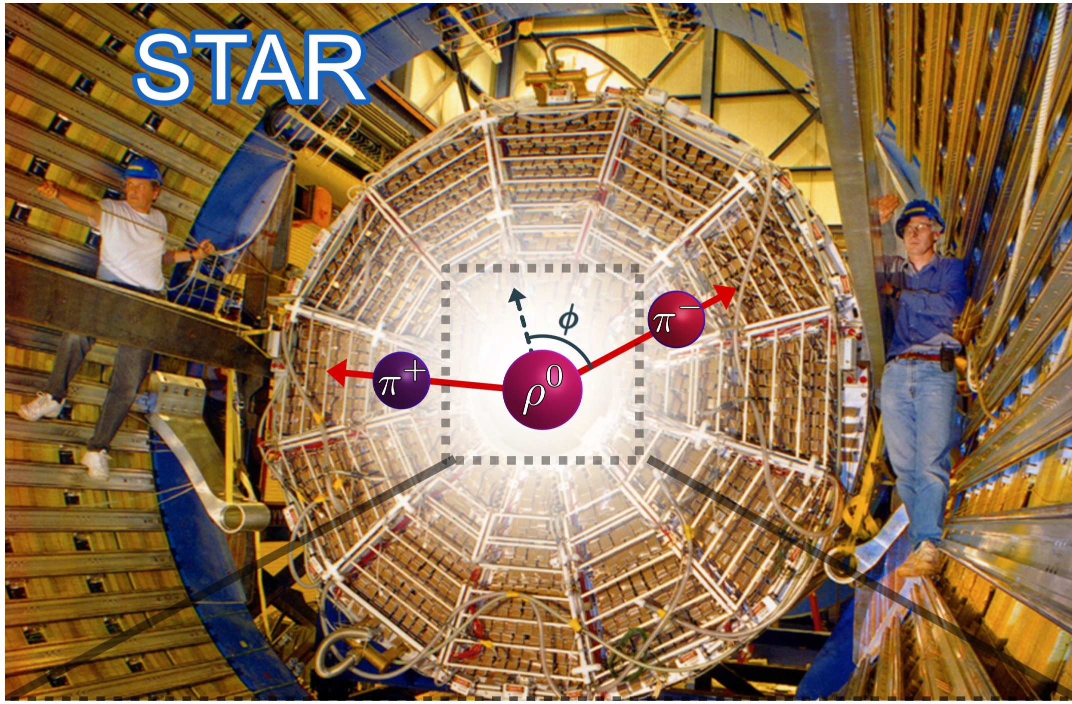


STAR, arXiv:2204.01625,
submitted to Science Advances

Spin interference enabled nuclear tomography

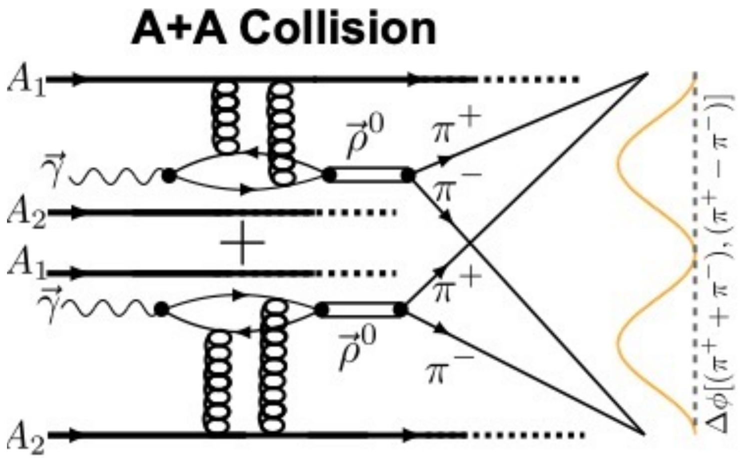
- Teaser:
  Polarized photon-gluon fusion reveals quantum wave interference of non-identical particles and shape of high-energy nuclei

STAR, arXiv:2204.01625, submitted to Science Advances

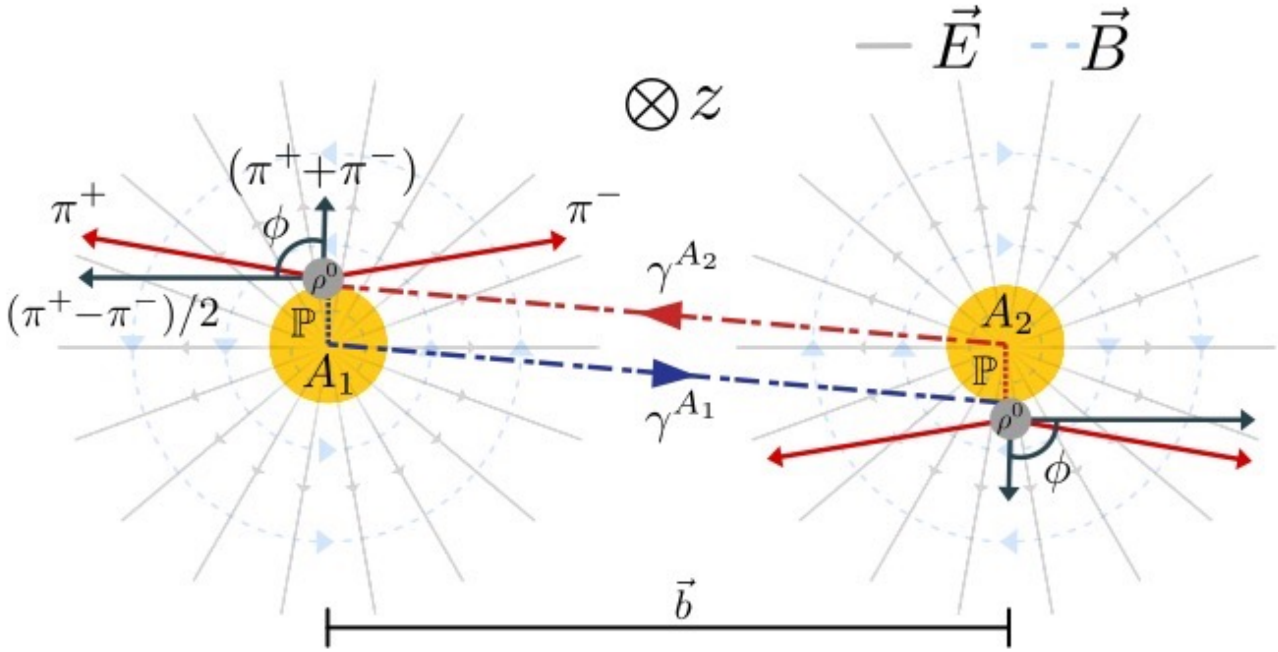


Three ingredients

- Linearly polarized photoproduction of vector meson
- At a distance with two wavefunctions (180^o rotation symmetry)
- Entanglement between $\pi^{\pm}$ from ρ decay and interference between identical pion wavefunction



STAR, arXiv:2204.01625



Imaging the nucleus with high-energy photons

Long history with some puzzling mysteries (20+ years):

Diffractive |t| distribution qualitatively resembles what it should be

Extracted radius is way too large (+1fm)

Cross sections are used for comparison to theory

Klein and Mantysaari, Nature Reviews Physics 1 (2019) 662

ALICE, JHEP06 (2020) 35

STAR, PRC 96 (2017) 54904

ρ^0 photoproduction in Pb–Pb UPC at $\sqrt{s_{NN}} = 5.02$ TeV — ALICE Collaboration

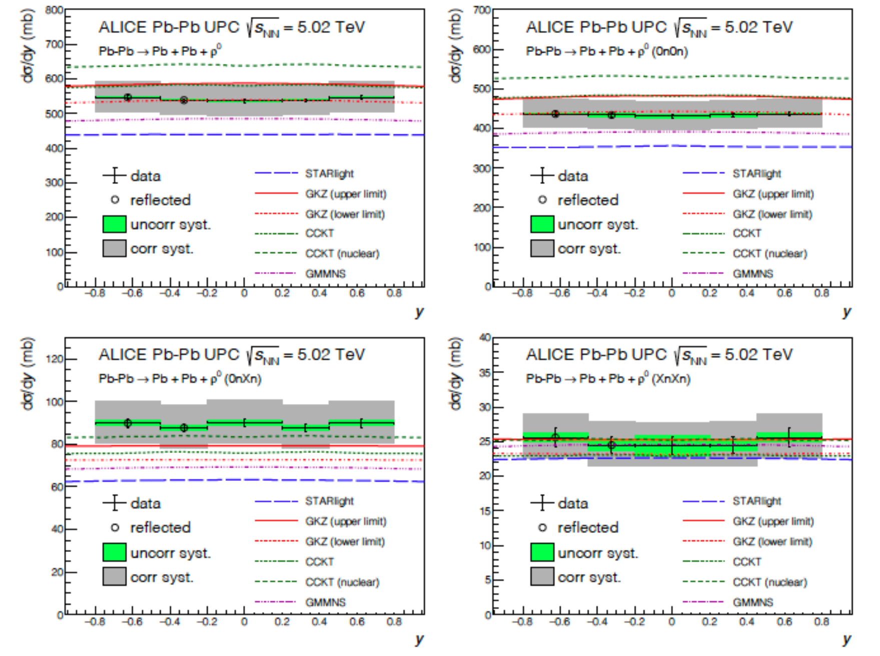
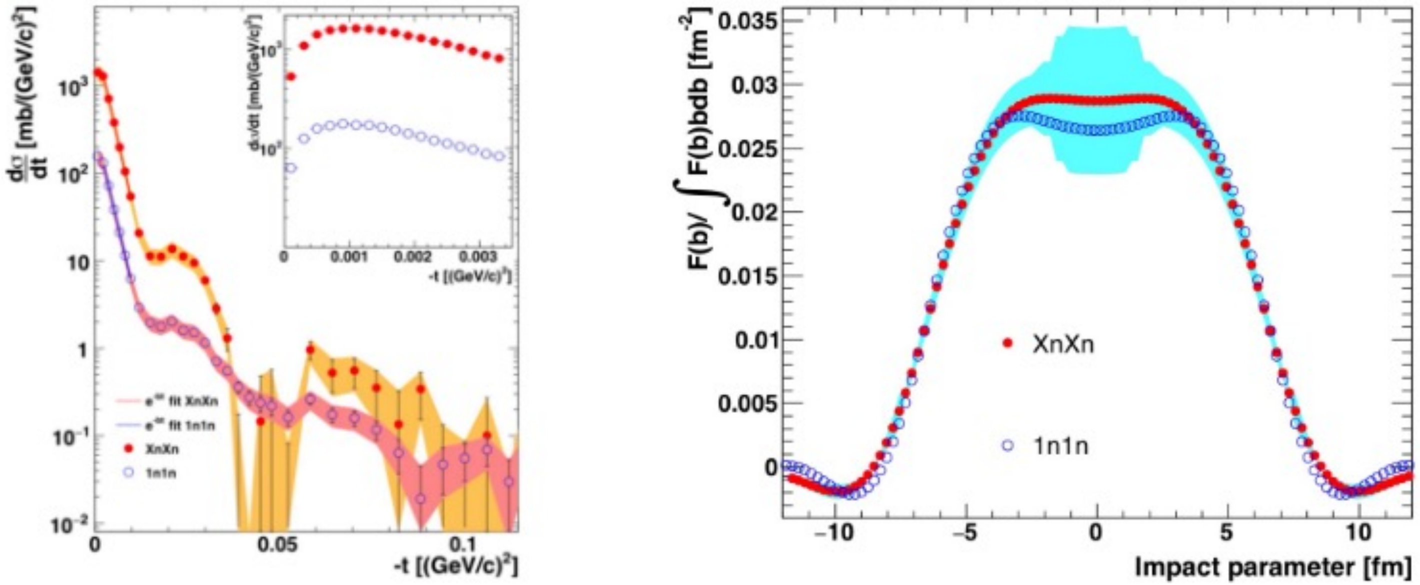


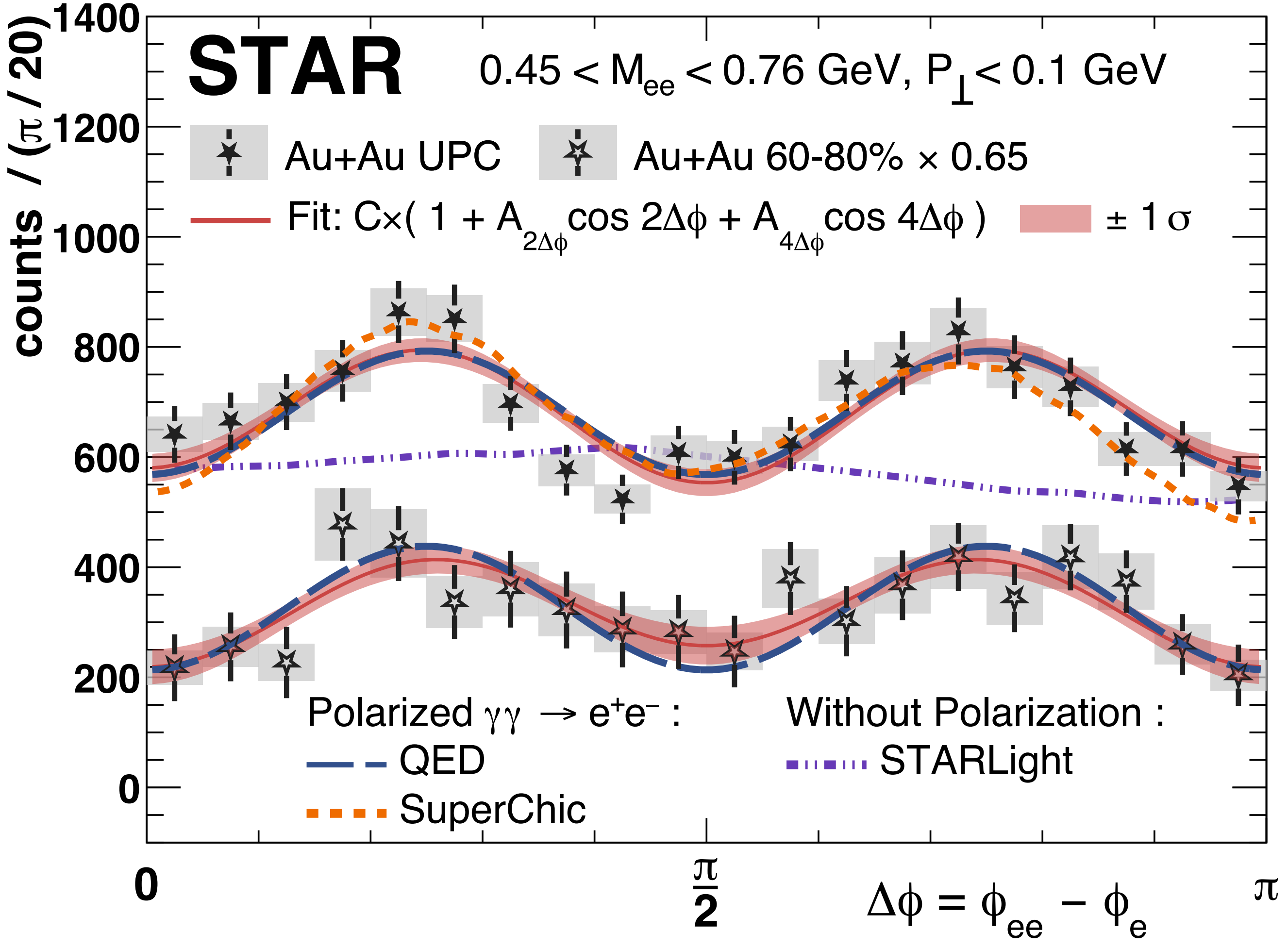
Figure 5: (Colour online). Cross section for the coherent photoproduction of ρ^0 vector mesons in Pb–Pb UPC as a function of rapidity for no forward-neutron selection (top left), and for the 0n0n (top right), 0nXn (bottom left) and XnXn (bottom right) classes. The lines show the predictions of the different models described in the text.

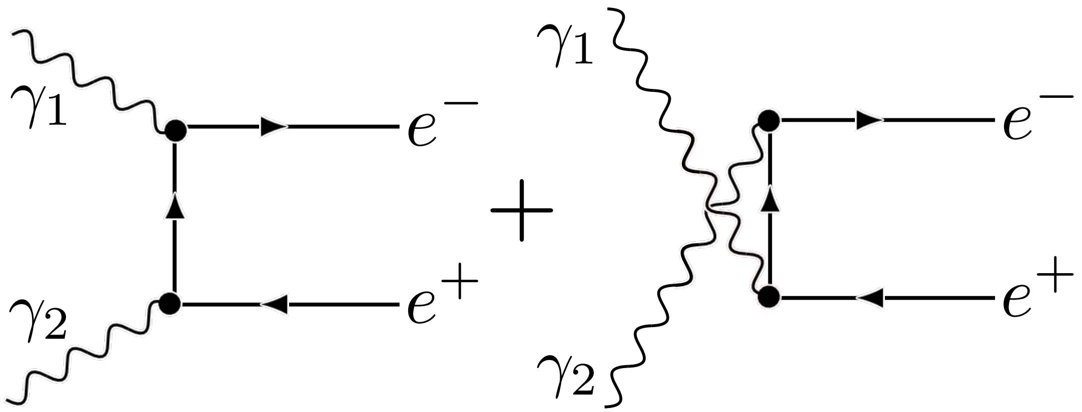


Left: The cross-section as a function of t, the squared momentum transfer to the nucleus. The dips and peaks are a diffraction pattern, akin to the pattern made by a 2-slit interferometer. 'XnXn' and '1n1n' are two different STAR data samples.The inset shows the distribution for very small momentum transfers. **Right:** The two-dimensional Fourier transform of the left panel, showing the density of the interaction sites in the nucleus, as a function of transverse distance from its center. This is a map of where the mesons interacted in the target. Although there is considerable systematic uncertainty (the blue region) near the center of the target, the edges of the nuclei are well defined.

Polarized photons from boosted Coulomb field

How do we know photons are polarized?

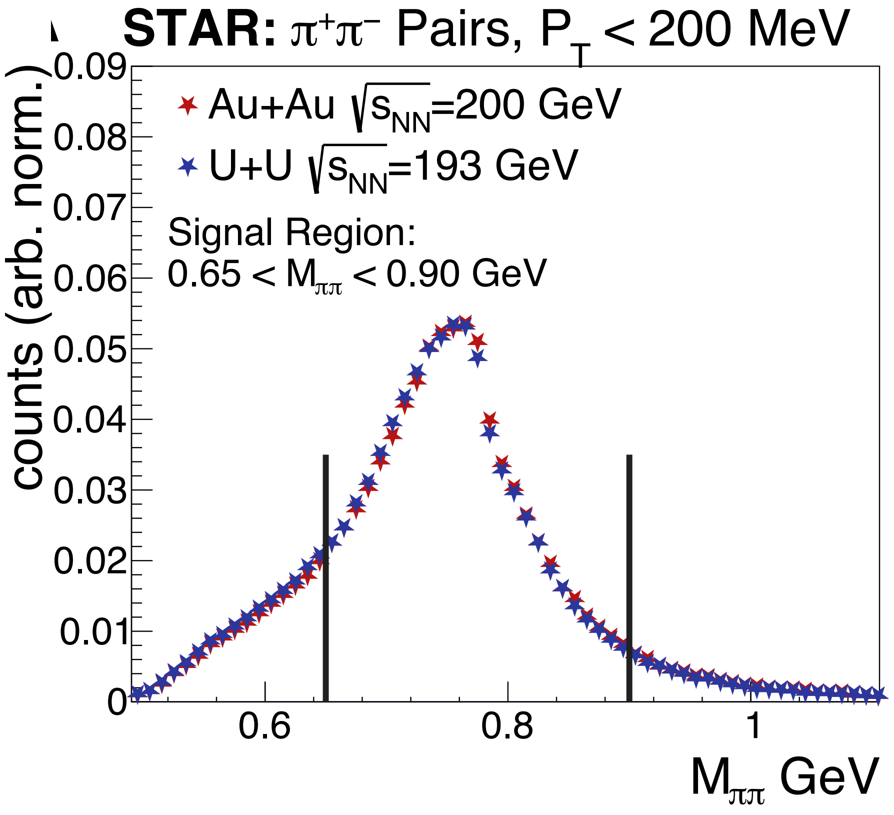


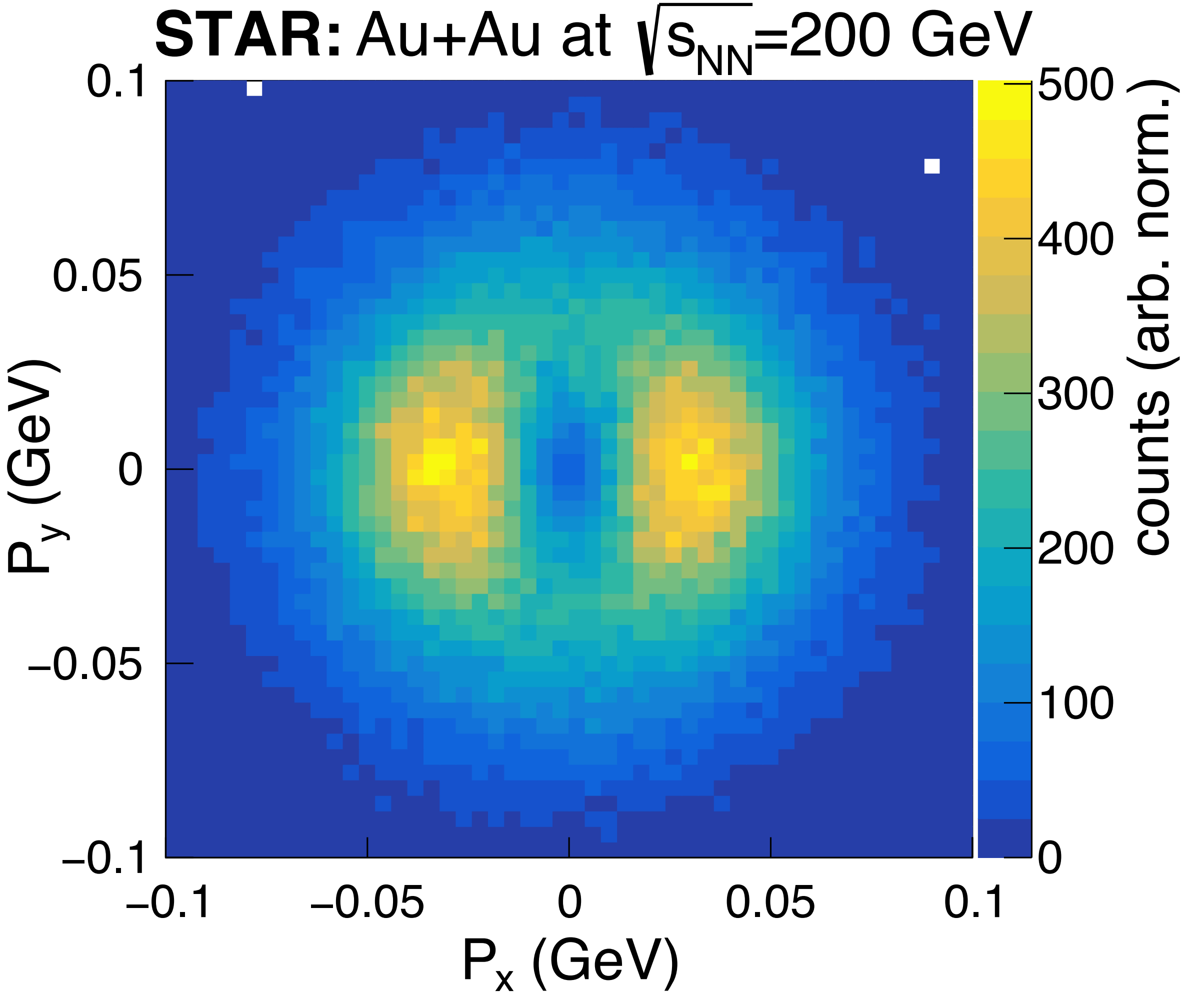


The Breit-Wheeler process shows: $\gamma\gamma \rightarrow e+e-$ angular distribution from 100% linearly polarized photon collisions

STAR, Phys. Rev. Lett. **127** (2021) 52302
e-Print Archives (1910.12400)

Azimuthal angular dependence of diffraction





Standard ρ^0 relativistic Breit-Wigner function

ρ^0 spin aligned along impact parameter direction

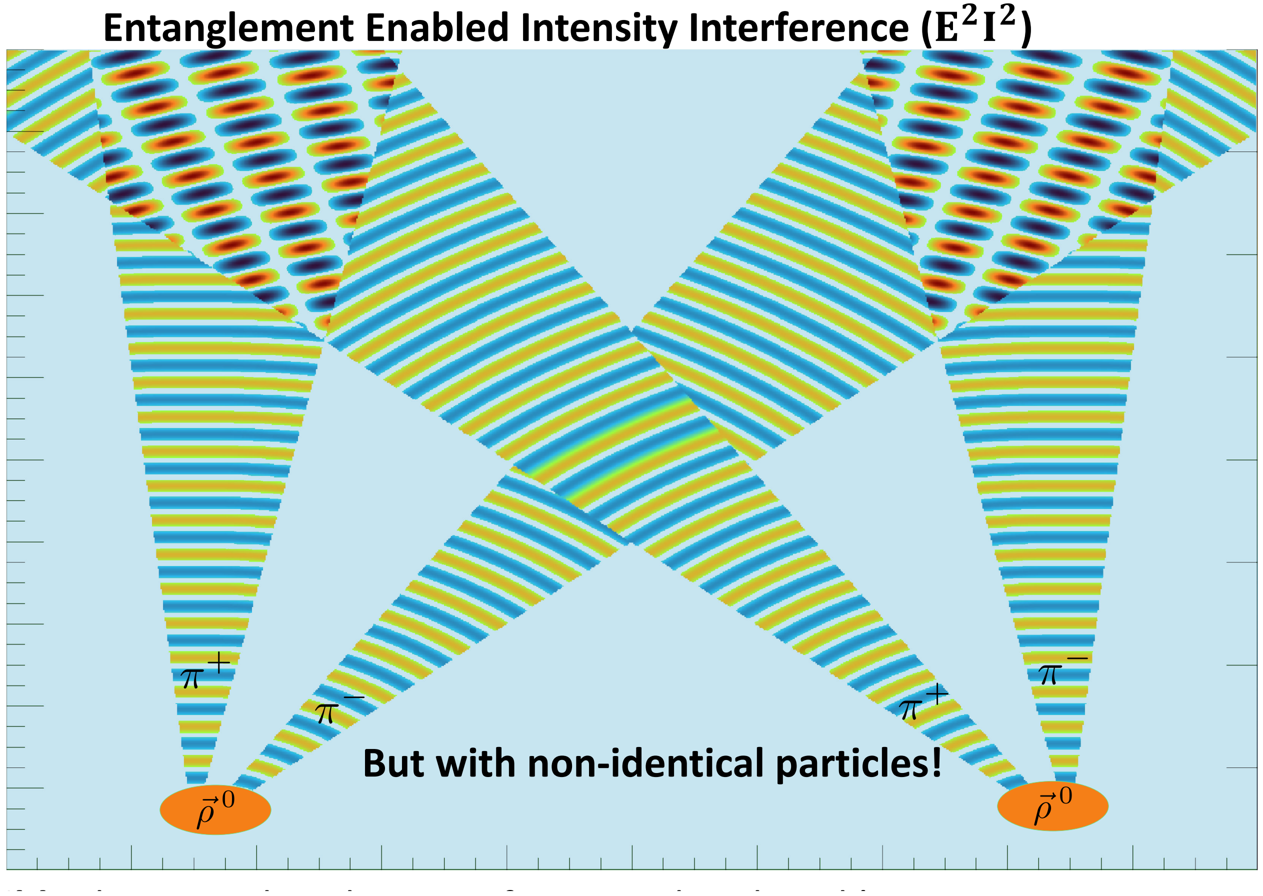
Project ρ^0 momentum along the daughter pion momentum direction

Striking azimuthal dependence of the diffraction

Novel Form of Quantum Entangled Interference

- Different from Young's double-slit experiment in which identical photons originate from one source

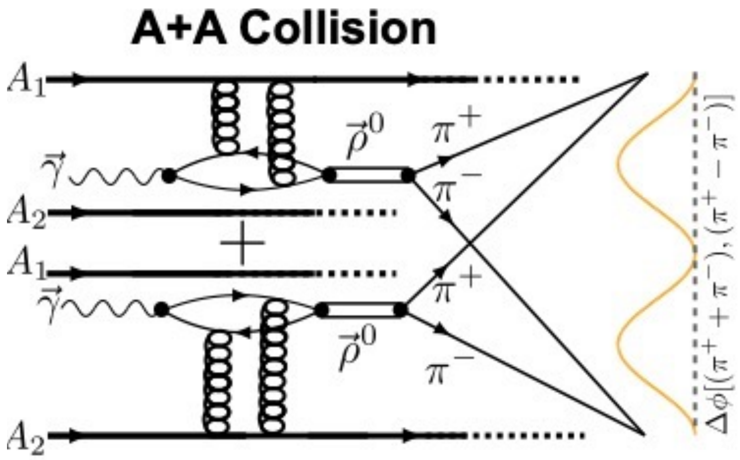
- What we have are non-identical particles ($\pi^{\pm}$) from two difference sources interfere



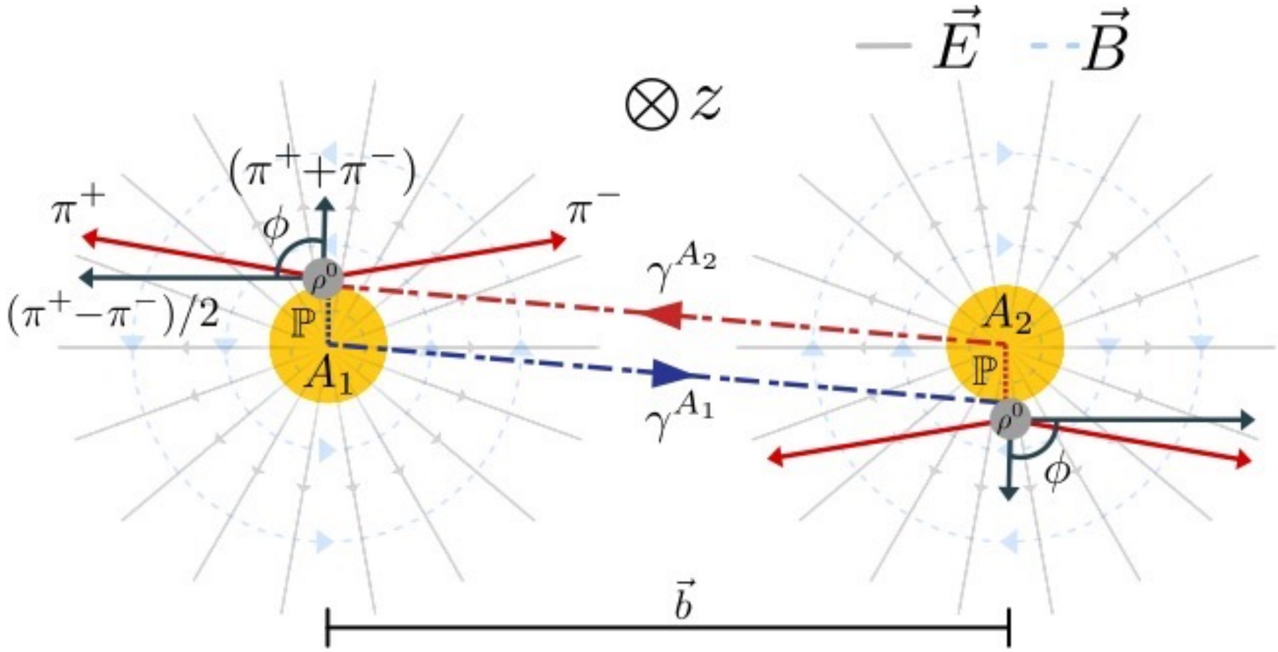
Possible similarity proposed by Frank Wilczek's group at MIT:
"Entanglement Enabled Intensity Interference of different wavelengths of lasers"
J. Cotler, F. Wilczek, V. Borish, Annals of Physics, 424 (2021) 168346

Three ingredients

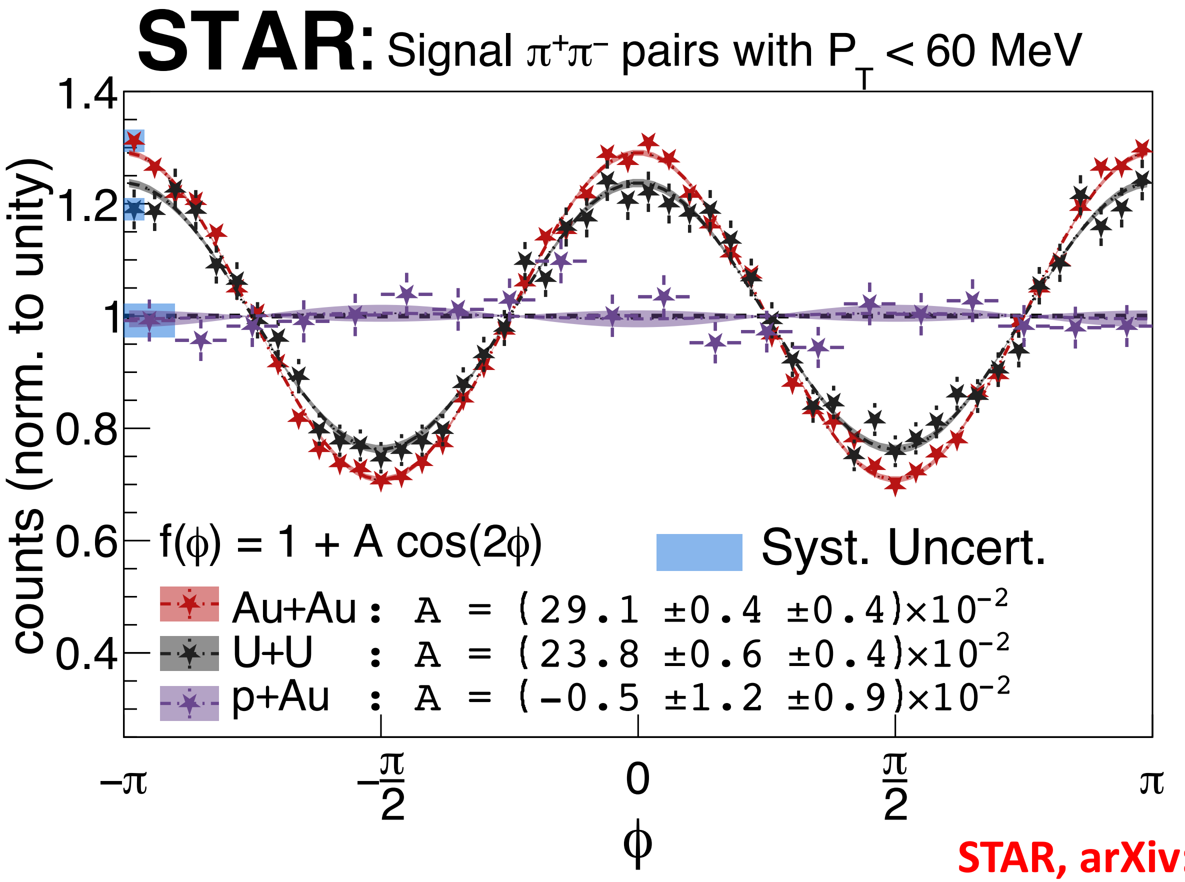
- Linearly polarized photoproduction of vector meson
- At a distance with two wavefunctions (180^o, π rotation symmetry)
- Entanglement between $\pi^{\pm}$ from ρ decay and interference between identical pion wavefunction

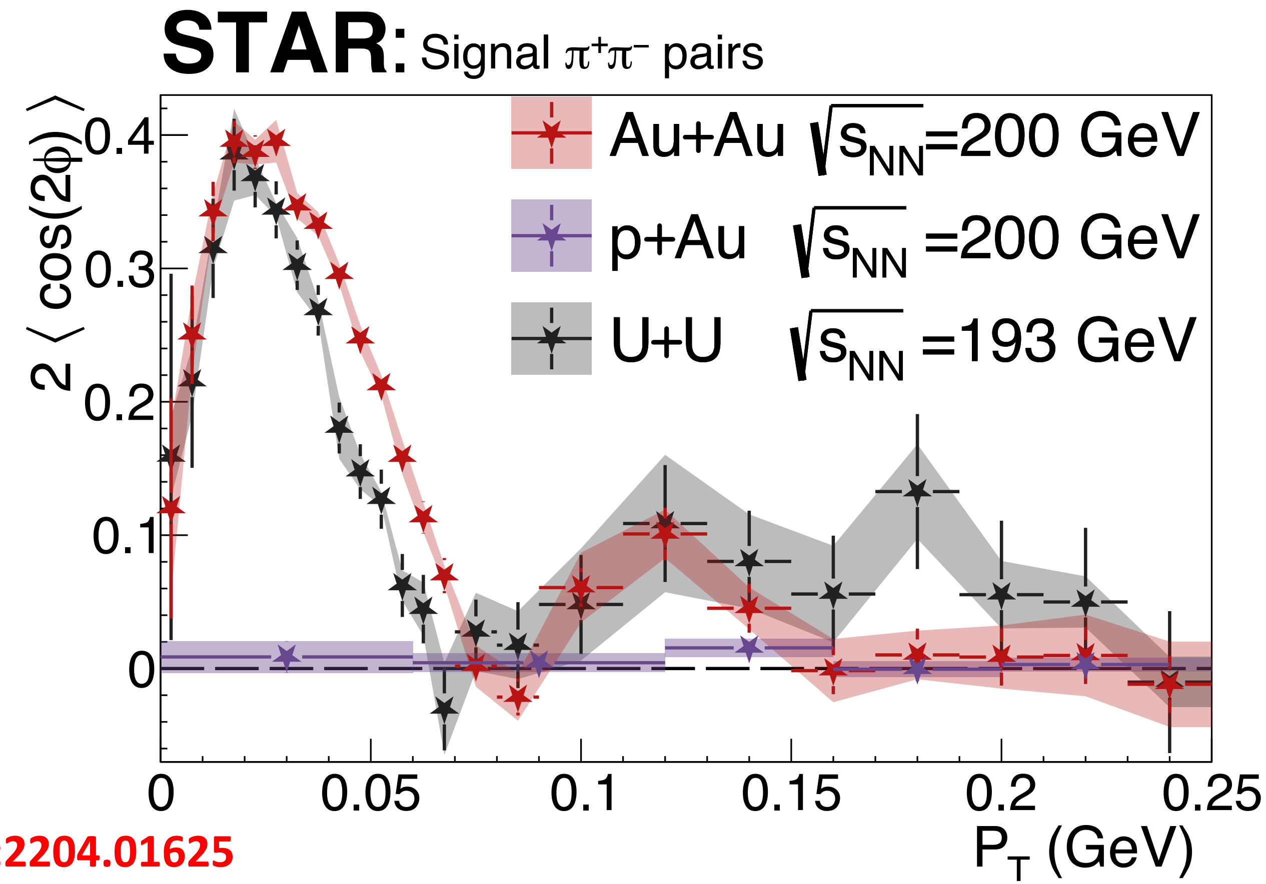


STAR, arXiv:2204.01625



Interference depends on P_T and species





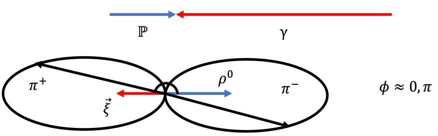
STAR, arXiv:2204.01625

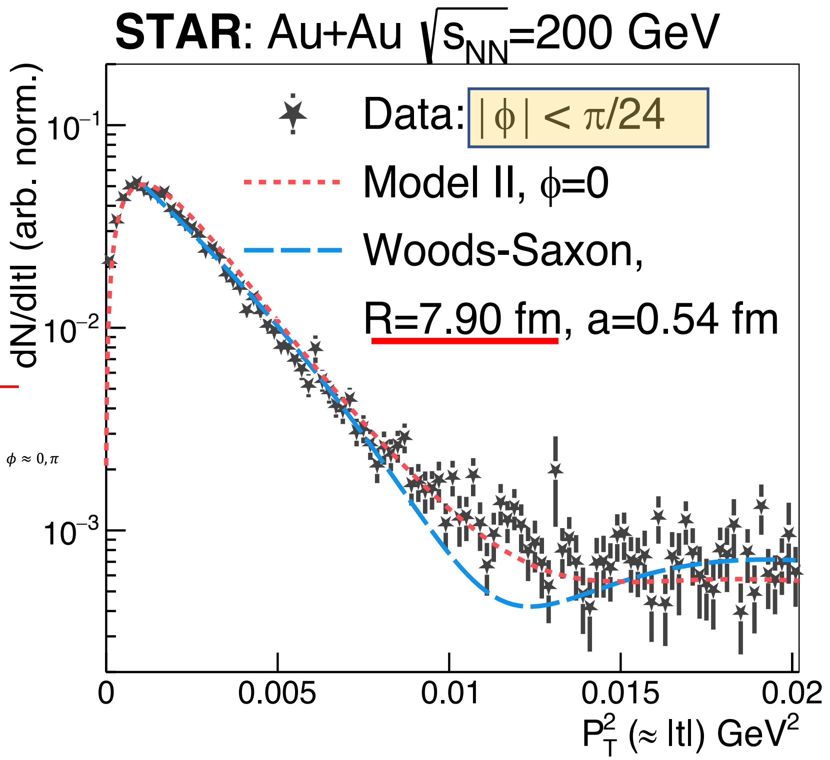
Amplitude different between Au+Au and U+U, absent in p+Au

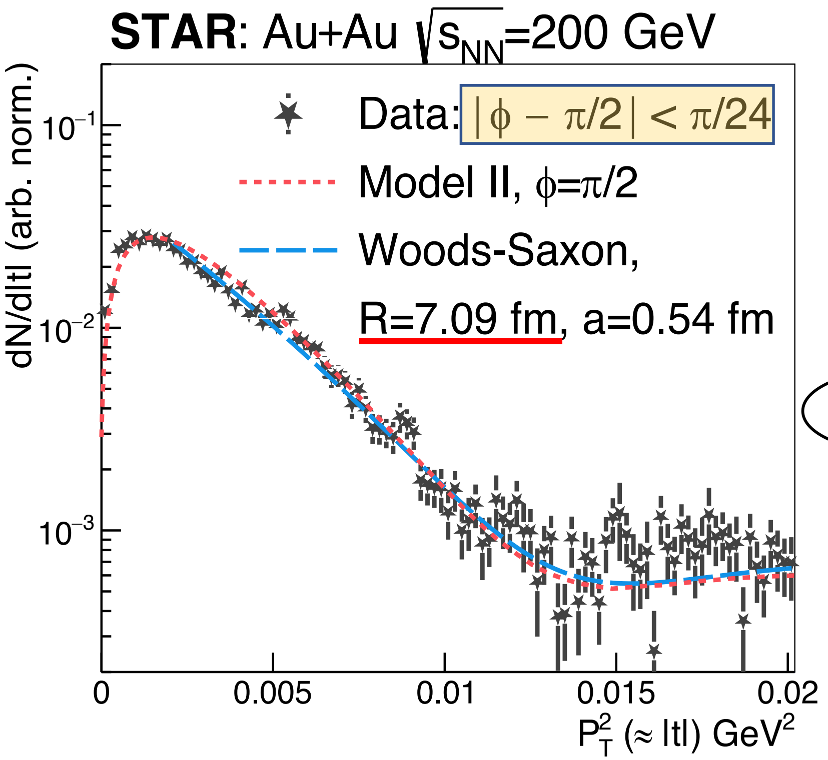
=>Requires two photon sources

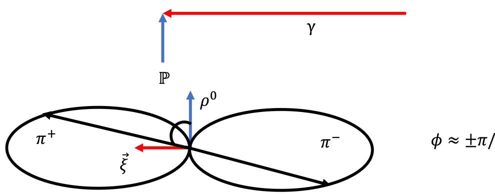
Show classic interference pattern vs ρ^0 P_T
Different pattern in Au+Au and U+U
(qualitatively consistent with size of Au and U)

Angular differential |t| distribution









STAR, arXiv:2204.01625

- Drastically different radius depending on ϕ, still way too big
- Notice how much better the Woods-Saxon dip is resolved for $\phi = \pi/2$ -> experimentally able to **remove photon momentum, which blurs diffraction pattern**
- **Can we extract the 'true' nuclear radius from |t| vs. ϕ information?**

arXiv:2204.01625

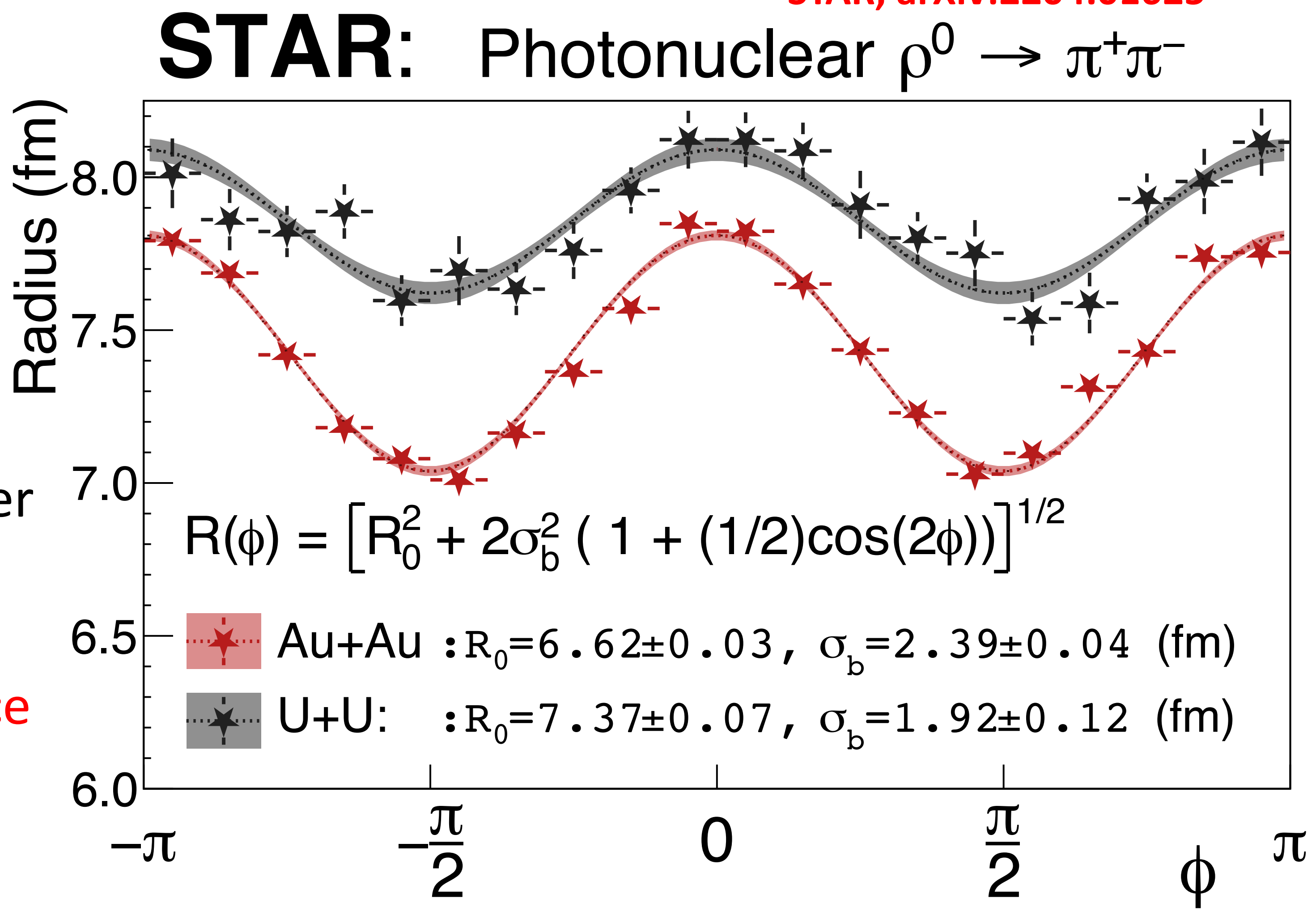
Precision radius measurement with interference

Azimuthal variation due to:

- Photon linear polarization,
- Spin transfer to VM
- Photon finite k_T
- VM spin 1 decay to spin 0 pions
- Interference along impact parameter

These image blurring effects can be improved with the angular dependence

STAR, arXiv:2204.01625



Extracted neutron skins and comparison to world data

	Au+Au (fm)	U+U (fm)
Charge Radius	6.38 (long: 6.58, short: 6.05)	6.81 (long: 8.01, short: 6.23)
Inclusive |t| slope (STAR 2017) [1]	7.95 ± 0.03	--
Inclusive |t| slope (WSFF fit)*	7.47 ± 0.03	7.98 ± 0.03
Tomographic technique*	6.53 ± 0.03 (stat.) ± 0.05 (syst.)	7.29 ± 0.06 (stat.) ± 0.05 (syst.)
DESY [2]	6.45 ± 0.27	6.90 ± 0.14
Cornell [3]	6.74 ± 0.06	--
Neutron Skin (Tomographic Technique)*	0.17 ± 0.03(stat.) ± 0.08(syst.) $\sim 2\sigma$	0.44 ± 0.05 (stat.) ± 0.08 (syst.) $\sim 4.7\sigma$ (Note: for Pb $\approx$ 0.3)

M. Centelles, X. Roca-Maza, X. Viñas, and M. Warda
Phys. Rev. Lett. **102**, (2009) 122502

GIULIANO GIACALONE, July 22, 2022

$$\Delta r_{np} = 0.283 \pm 0.071 \text{ fm}$$

$$L = (106 \pm 37) \text{ MeV}$$

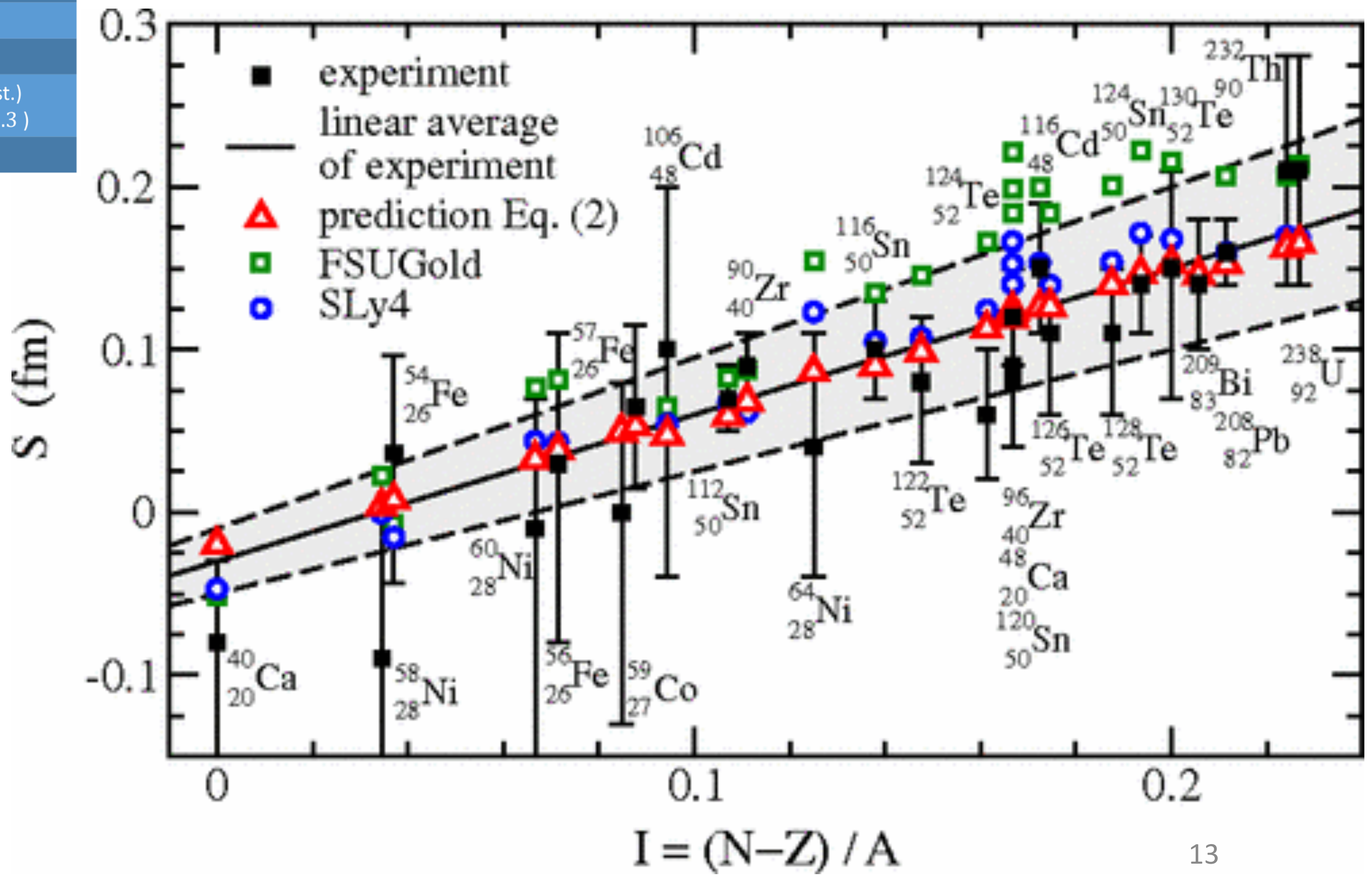
[PREX-II experiment, PRL **126** (2021) 17, 172502]

Stiffer EoS than expected.

[Reed et al., PRL **126** (2021) 17, 172503]
[Fattoyev et al., PRL **120** (2018) 17, 172702]

From GW170817

of $\Lambda_{1.4} \lesssim 580$ [44], we eagerly await the next generation of terrestrial experiments and astronomical observations to verify whether the tension remains. If so, the softening of the EOS at intermediate densities, together with the subsequent stiffening at high densities required to support massive neutron stars, may be indicative of a phase transition in the stellar core [42].



Can we get an independent estimate at RHIC?

Extracted neutron skins and comparison to world data

	Au+Au (fm)	U+U (fm)
Charge Radius	6.38 (long: 6.58, short: 6.05)	6.81 (long: 8.01, short: 6.23)
Inclusive |t| slope (STAR 2017) [1]	7.95 $\pm$ 0.03	--
Inclusive |t| slope (WSFF fit)*	7.47 $\pm$ 0.03	7.98 $\pm$ 0.03
Tomographic technique*	6.53 $\pm$ 0.03 (stat.) $\pm$0.05 (syst.)	7.29 $\pm$ 0.06 (stat.) $\pm$ 0.05 (syst.)
DESY [2]	6.45 $\pm$ 0.27	6.90 $\pm$ 0.14
Cornell [3]	6.74 $\pm$ 0.06	--
Neutron Skin (Tomographic Technique)*	0.17 $\pm$ 0.03(stat.) $\pm$0.08(syst.) $\sim 2\sigma$	0.44 $\pm$ 0.05 (stat.) $\pm$0.08 (syst.) $\sim 4.7\sigma$ (Note: for Pb $\approx$ 0.3)

M. Centelles, X. Roca-Maza, X. Viñas, and M. Warda
Phys. Rev. Lett. **102**, (2009) 122502

GIULIANO GIACALONE, July 22, 2022

$\Delta r_{np} = 0.283 \pm 0.071$ fm

$L = (106 \pm 37)$ MeV

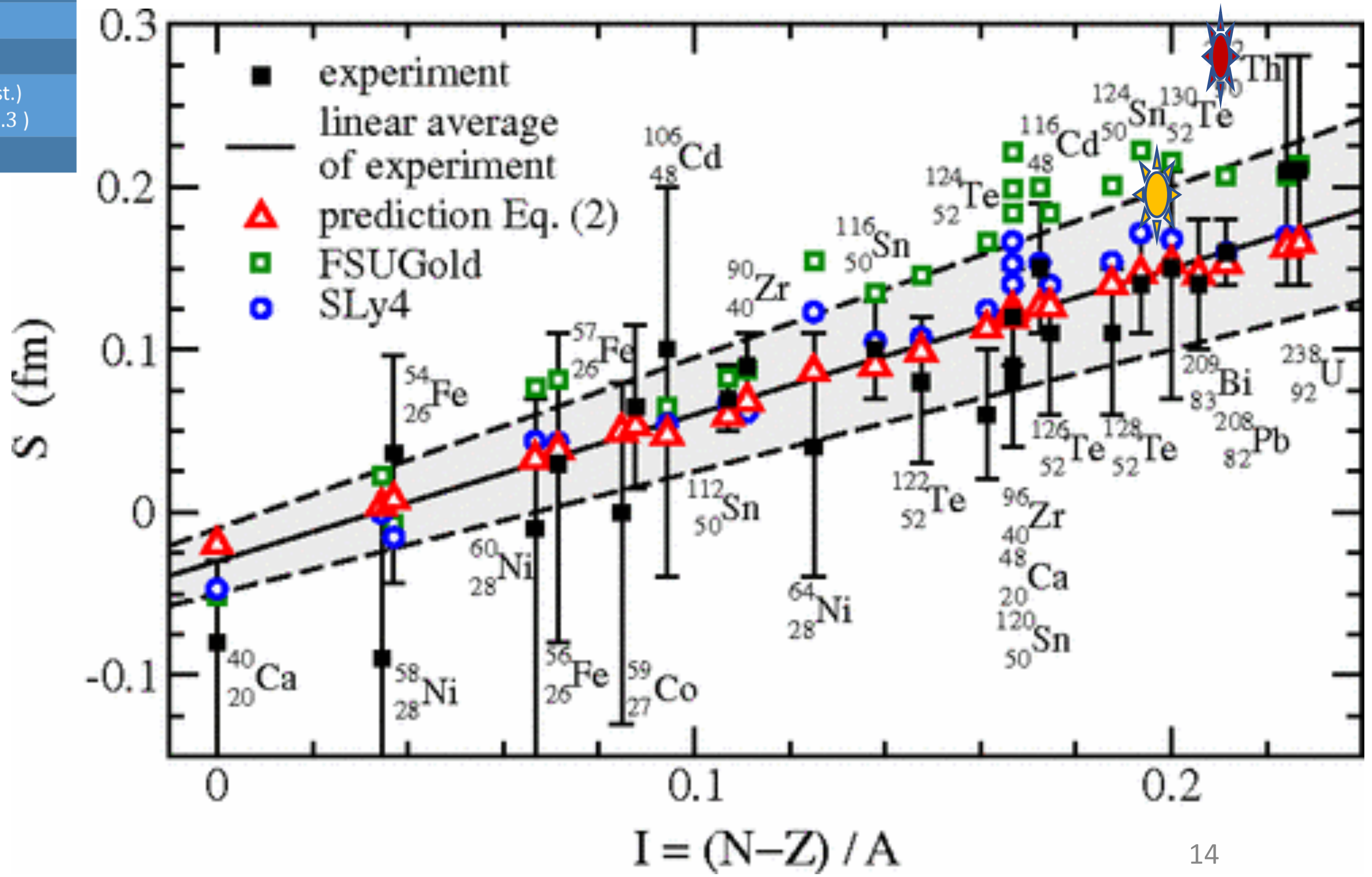
[PREX-II experiment, PRL **126** (2021) 17, 172502]

Stiffer EoS than expected.

[Reed et al., PRL **126** (2021) 17, 172503]
[Fattoyev et al., PRL **120** (2018) 17, 172702]

From GW170817

of $\Lambda_{1.4} \lesssim 580$ [44], we eagerly await the next generation of terrestrial experiments and astronomical observations to verify whether the tension remains. If so, the softening of the EOS at intermediate densities, together with the subsequent stiffening at high densities required to support massive neutron stars, may be indicative of a phase transition in the stellar core [42].



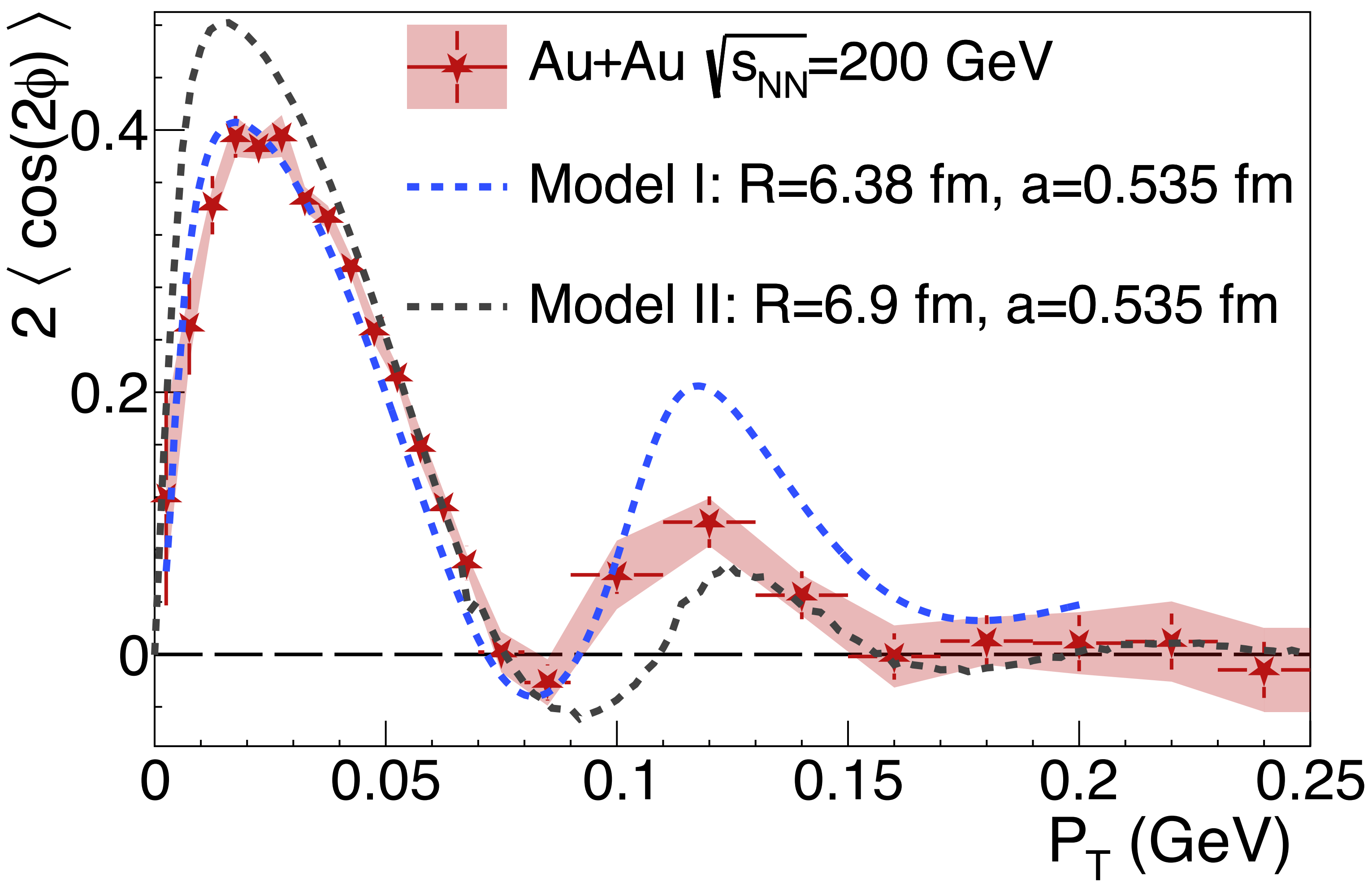
Can we get an independent estimate at RHIC?

Comparison to models

STAR, arXiv:2204.01625

Comparison to models with the interference effect

- Model I:
  VM production cross section from HERA ep data
  Glauber with smooth NN overlap function
- Model II:
  dipole model with gluon saturation in A+A



Improvements of future measurements

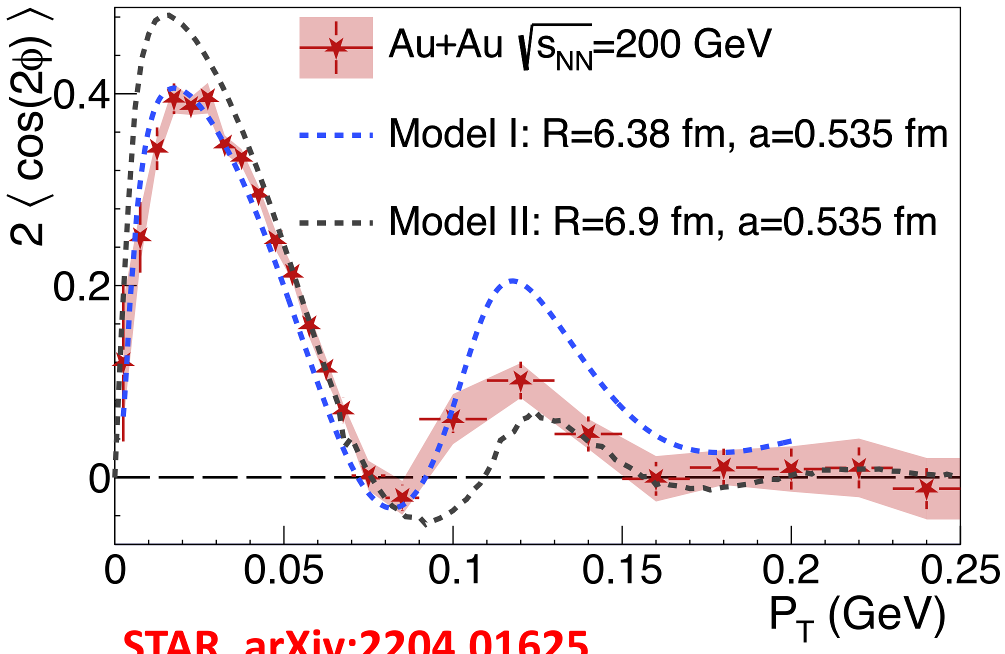
- Both interference and Woods-Saxon models only describe the first peak well

- The neutron skin syst. uncertainty mainly due to WS vs Gaussian, and the actual distribution seems to be flatter (more prominent second peak)

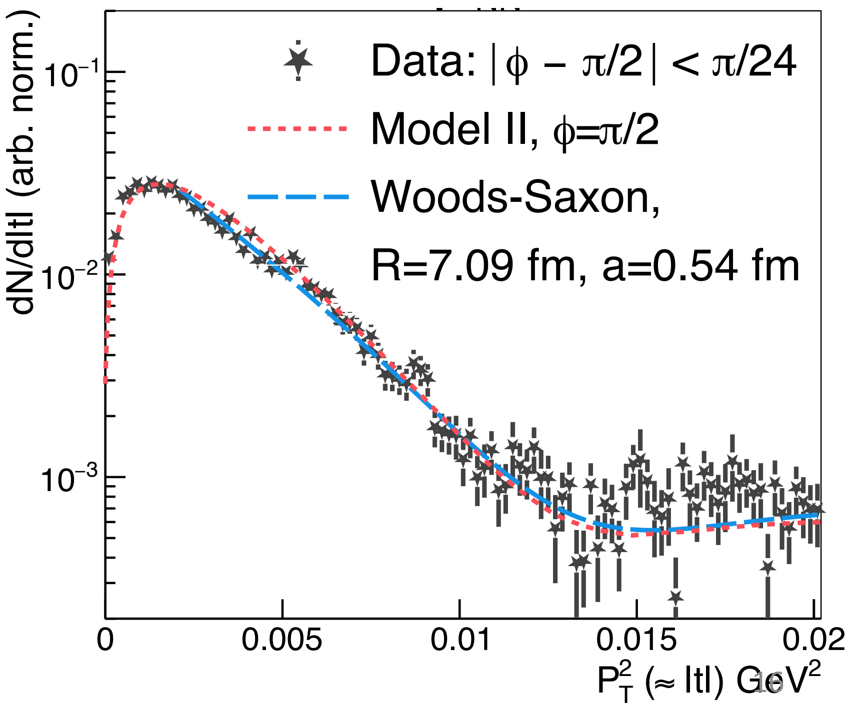
W. Zha, L. Ruan, Z. Tang, Z. Xu, S. Yang, *Phys. Rev. C* **99**, 061901 (2019).

W. Zha, J. D. Brandenburg, L. Ruan, Z. Tang, *Phys. Rev. D* **103**, 033007 (2021).

H. Xing, C. Zhang, J. Zhou, Y.-J. Zhou, *JHEP* **10**, 064 (2020).

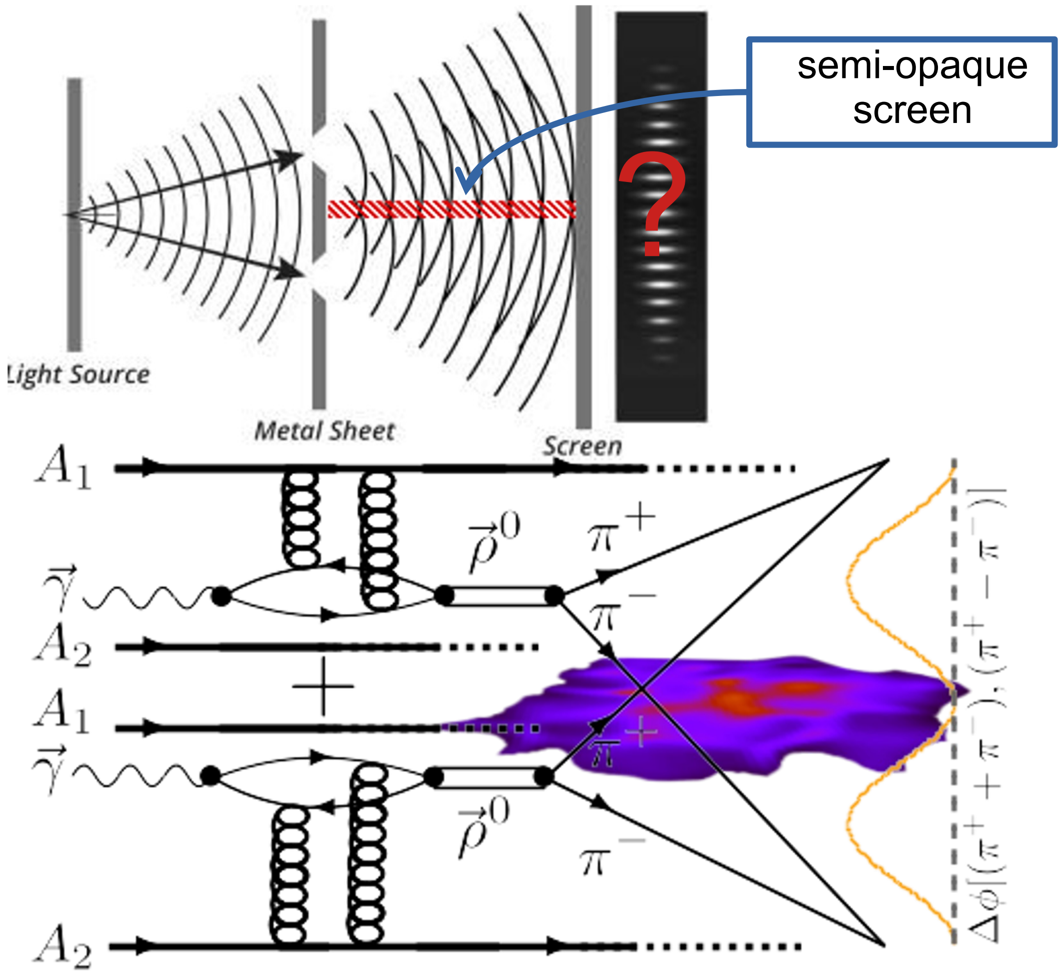


STAR, arXiv:2204.01625

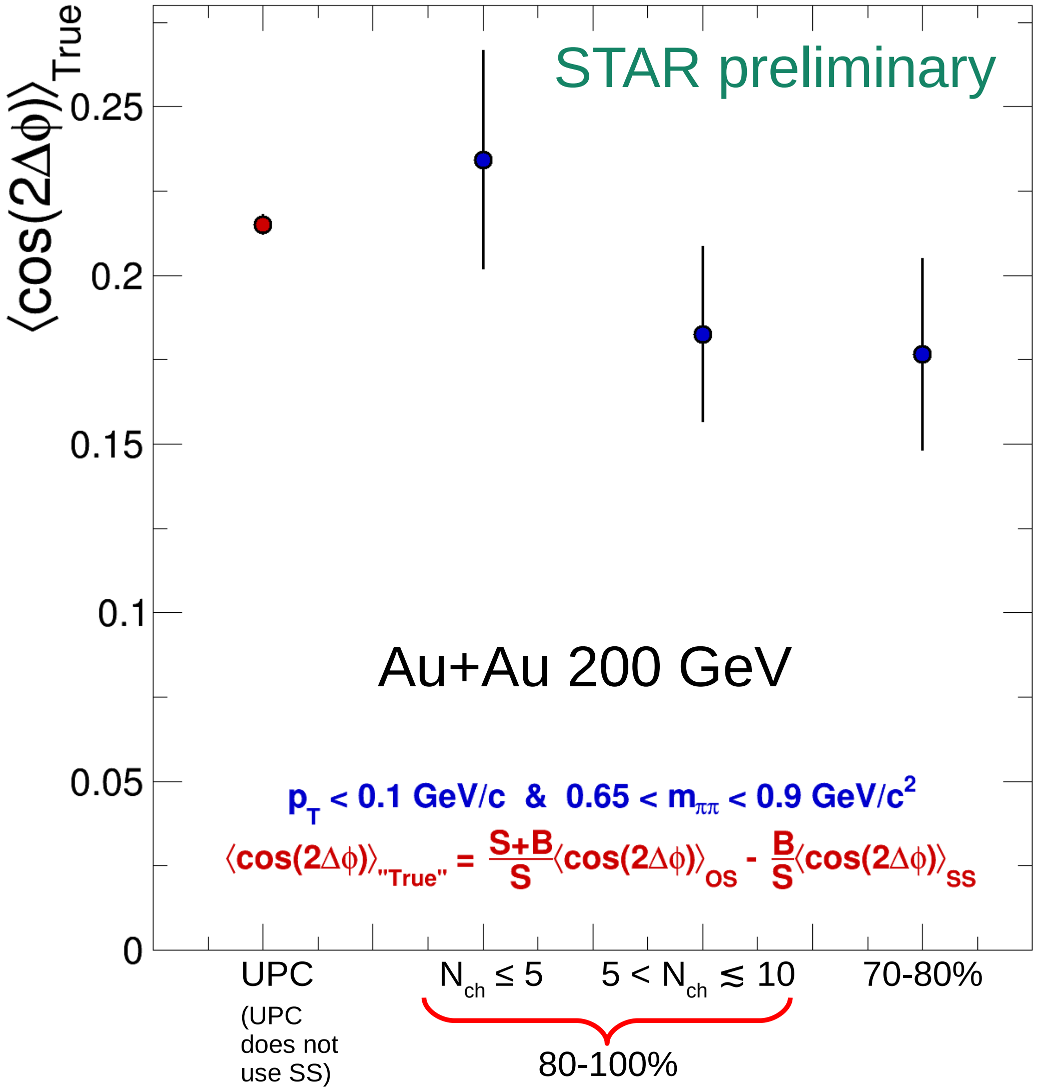


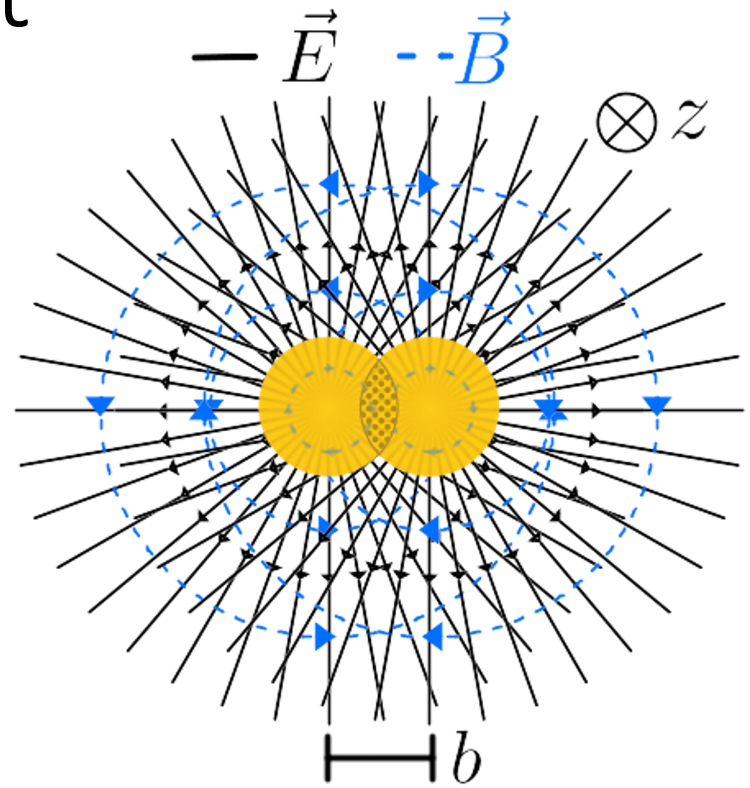
Coherent diffraction with added noise

- Coherent diffraction is usually defined with initial and final-state nuclei intact
- Do violent A+A collisions accompanying diffraction exist?
- Do violent A+A collisions collapse the wavefunctions of the rho decay?
- Does interference persist with the added noisy environment?



Photoproduction with spin alignment in peripheral collisions





Spin **interference and coherent** diffraction persist into peripheral heavy-ion collisions

The alignments along impact-parameter cancel

The spin alignment becomes along the B-field direction
Does this phenomenon have anything to do with global polarization?

Summary and future perspectives

- STAR observed spin interference effect in vector meson photoproduction
- The effect is observed in Au+Au and U+U, and is enabled by non-identical particle entanglement from ρ^0 decay.
- The angular dependence removes photon blurring effect and enables precise nuclear radius measurements of ^{197}Au and ^{238}U, possible ^{208}Pb
- Future tests of coherent and quantum effects with diffraction in non-UPC and other particles (ϕ, J/Ψ)
- RHIC, LHC and future EIC experiments can provide further experimental insights into these phenomena