Nuclear Tomography with Polarized Photon-Gluon Collisions at STAR

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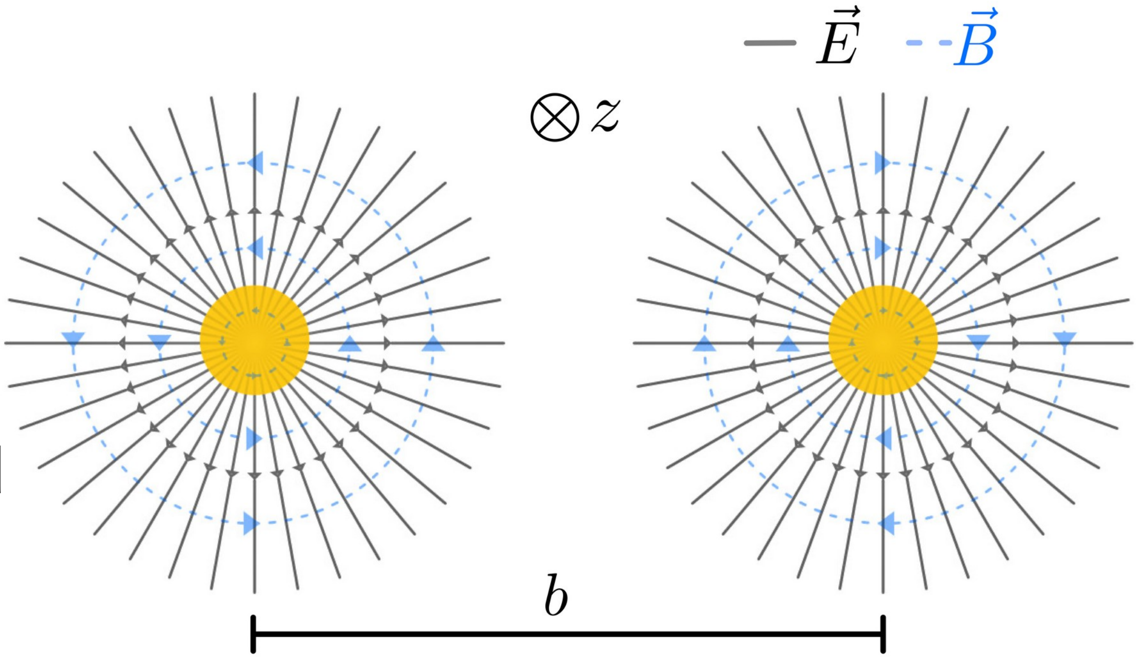
Talk outline

- Introduction
  - Strong EM fields in A+A collisions
  - Origins of photon polarization
- Photon-gluon interactions
  - Coherent vector-meson production in the environment of A+A collisions
  - Extraction of diffraction information via angular distribution of ρ^0 decayed pions
  - Comparisons between different systems
  - Interference-aided extraction of nuclear size
  - Modification from nuclear dynamics and the limits of coherence
- Summary

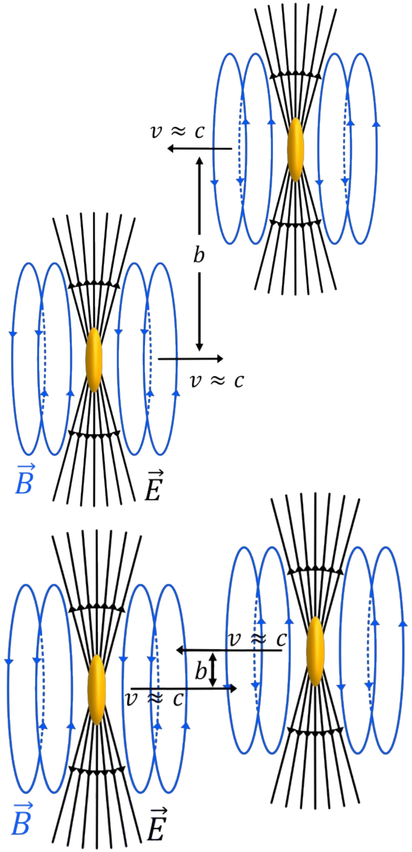
Heavy ions as a photon source

- Strong EM fields in A+A collisions. Highly compressed by Lorentz contraction due to fast-moving nuclei
- Make quasi-real photons which are linearly polarized <u>away</u> from their source
- Photons may interact with the other nucleus to produce particles



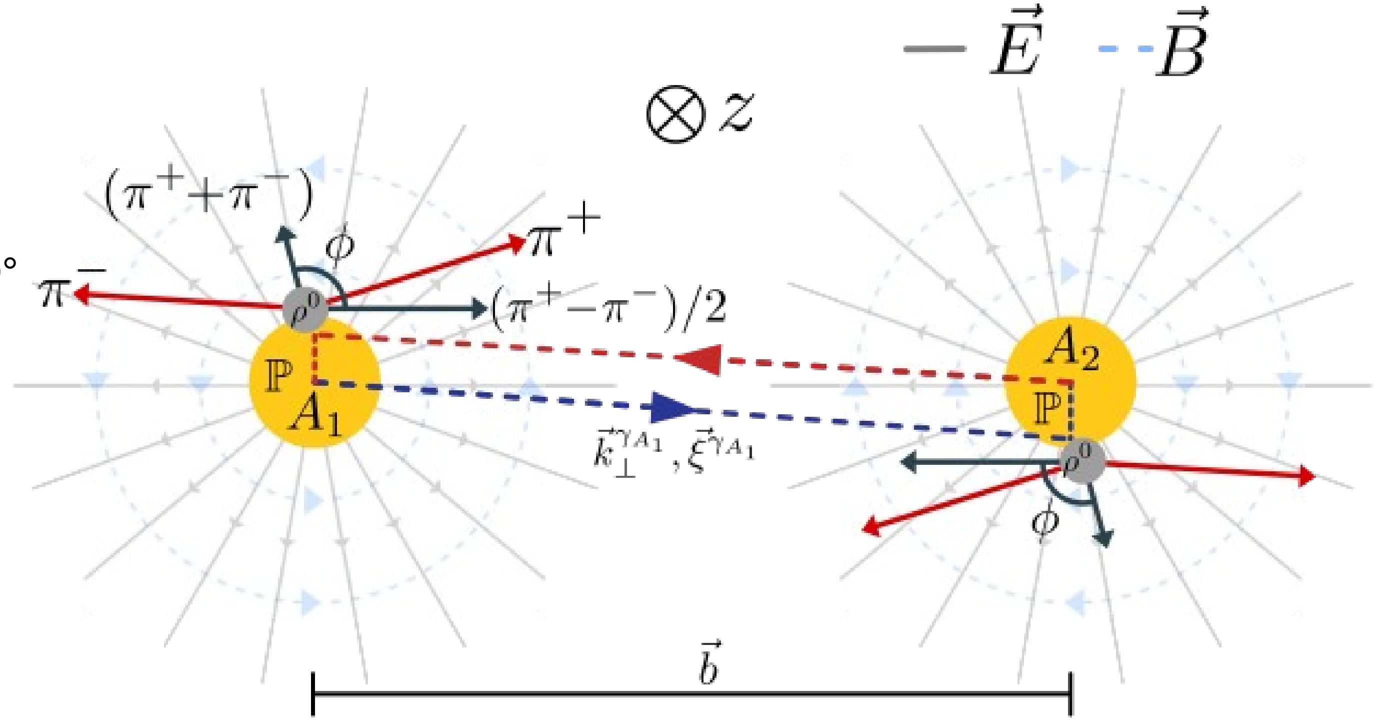
Photonuclear production in HIC

- Photonuclear vector mesons are produced following $\gamma\mathbb{P}\rightarrow\rho^{0},\ J/\Psi,\ \text{etc.}\ (J^{P}=1^{-})$
  - Photon from the EM field of one nucleus fluctuates to a q$\bar{\text{q}}$ pair, interacts with pomeron or reggeon
  - Photon quantum numbers are $J^{PC}=1^{--}$
- ρ^0 has been studied in UPCs
  - C. Adler *et al.* (STAR Collaboration) Phys. Rev. Lett. **89**, 272302
  - L. Adamczyk *et al.* (STAR Collaboration) Phys. Rev. C **96**, 054904
  - S. Acharyai *et al.* (ALICE Collaboration) JHEP06 (2020) 35
  - etc.
- J/Ψ coherent photoproduction has been seen in nuclear collisions (noted as excess yield at low p_T)
  - J. Adam *et al.* (ALICE Collaboration) Phys. Rev. Lett. **116**, 222301
  - J. Adam *et al.* (STAR Collaboration) Phys. Rev. Lett. **123**, 132302



Measure ρ polarization

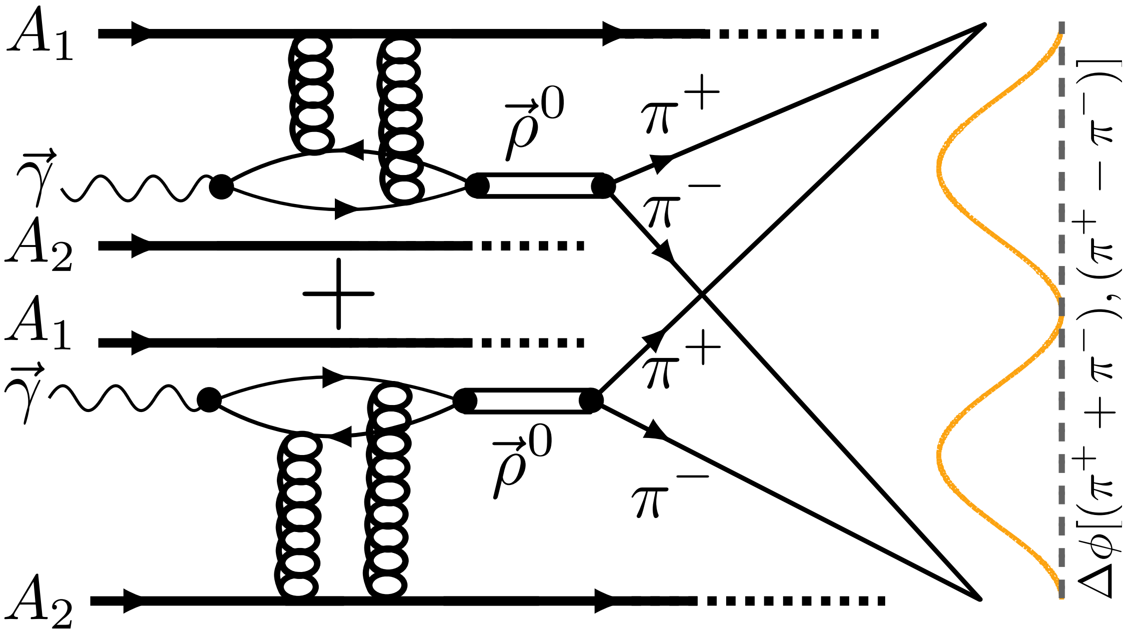
- Photon polarization vector aligned radially with the "emitting" source
  - Polarizations of measured ρ and its (otherwise identical) virtual partner are exactly 180° out of sync
  - Hadronically produced ρs (+pions) have no such spin correlation
    - HBT interference, but not polarization-dependent interference
- Polarization dictates final-state distribution of the $\pi^+\pi^-$ pairs – allows for measurement



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

Double-slit modulation

- Analogous to double-slit pattern
- Expected modulation in Δφ is cos(2Δφ) [1]
- Interference strength depends on
  - Nuclear geometry (gluon distribution)
  - Impact parameter (detailed spatial distribution)



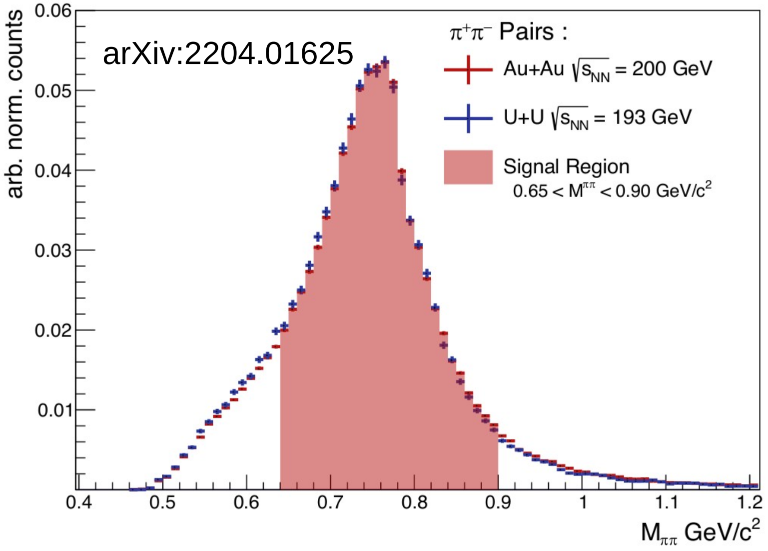
[1] Xing, H et.al. *J. High Energ. Phys.* **2020**, 64 (2020).

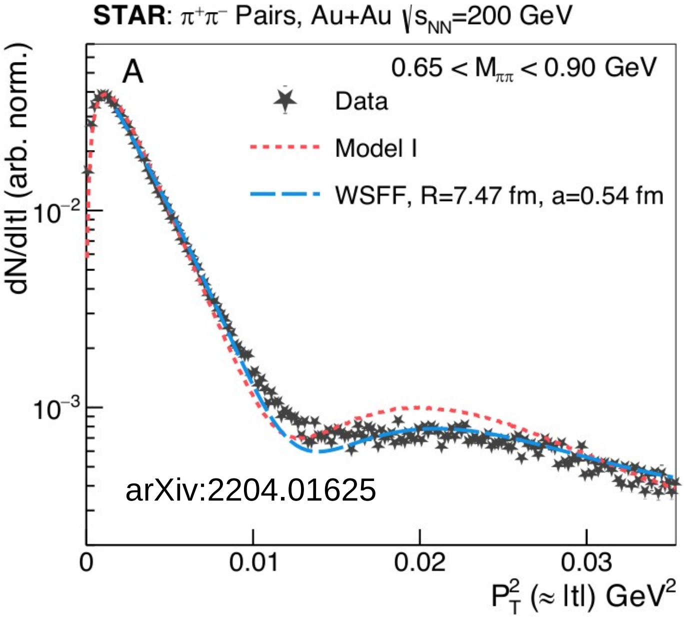
$$\Delta\phi = \phi(\pi^+ + \pi^-) - \phi(\pi^+ - \pi^-)$$

Interference in UPCs

Measurement in UPC

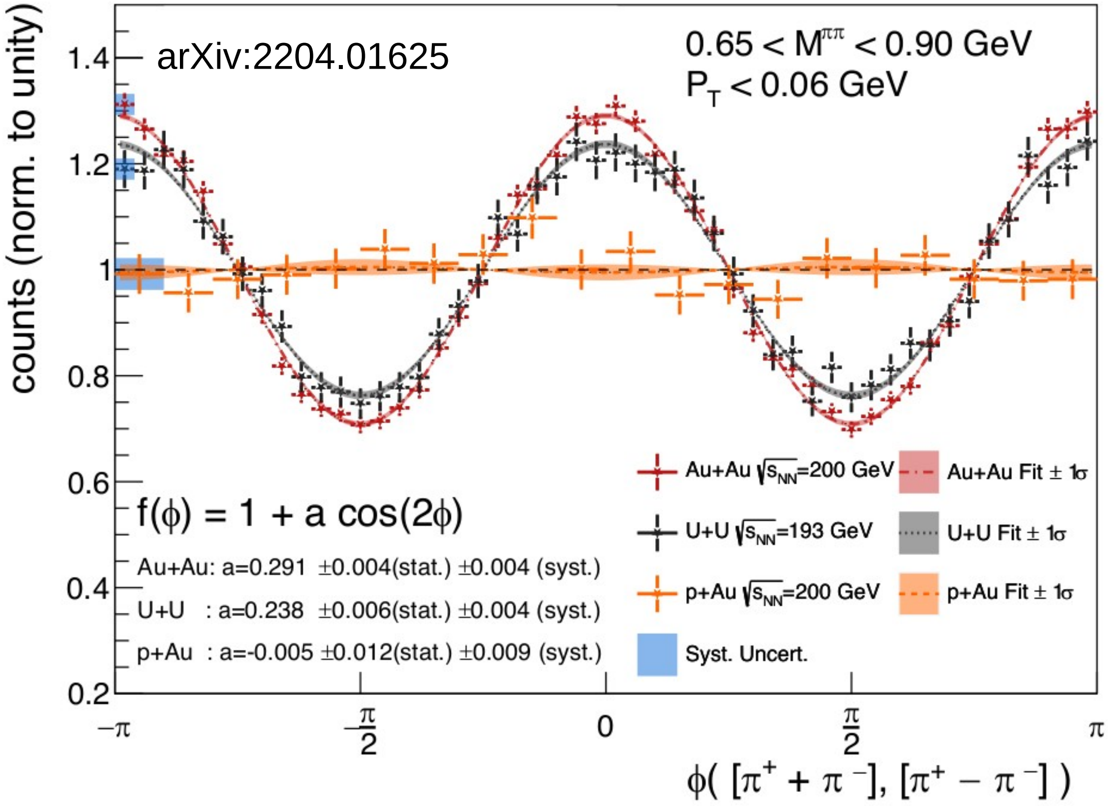
- Combine $\pi^+\pi^-$ from events collected by the STAR UPC trigger
- Extremely clean ρ^0 peak and obvious low-p_T peak
- The p_T peak comes from a diffractive pattern
  - ρs are coherently photoproduced
  - This peak is consistent with model predictions of photoproduction and has only been explained with this production mechanism
  - Second peak of diffraction pattern visible





UPC results

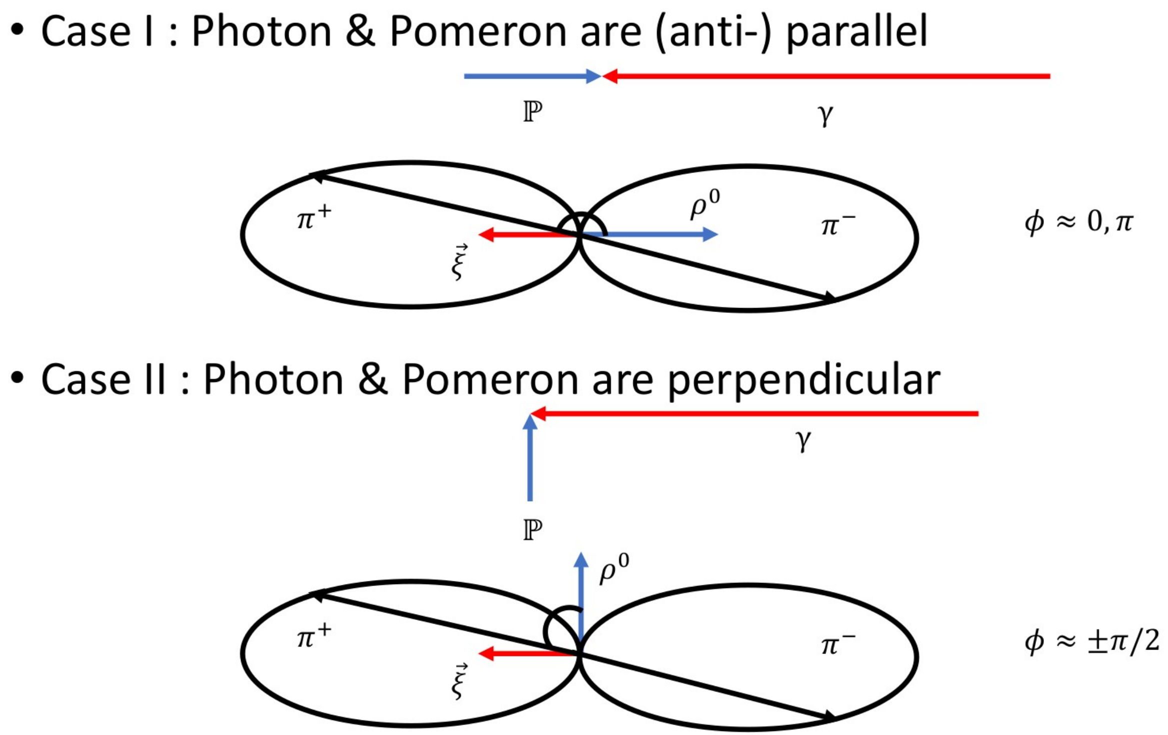
- Strong modulation in A+A collisions
- Difference in Au+Au and U+U demonstrates sensitivity to nuclear geometry
- This can be verified in p+A, where effect is not expected



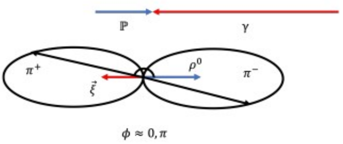
Measuring the Nuclear Radius

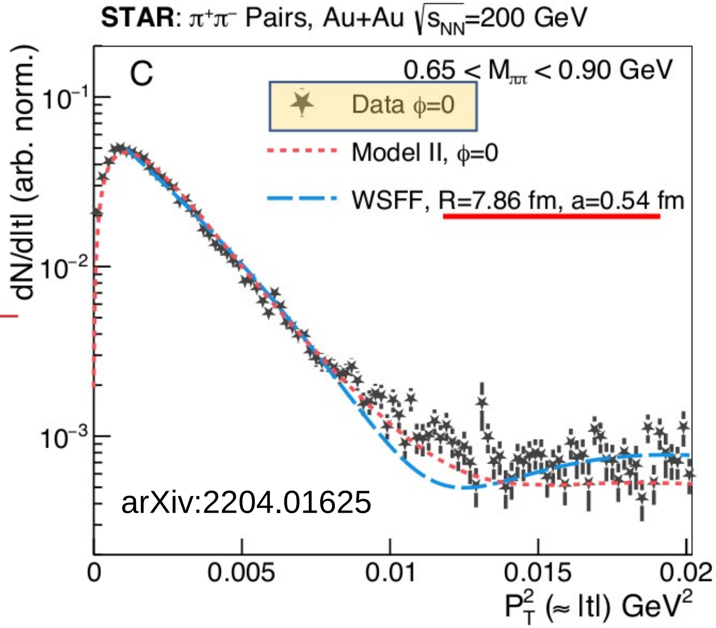
Interference reveals event config.

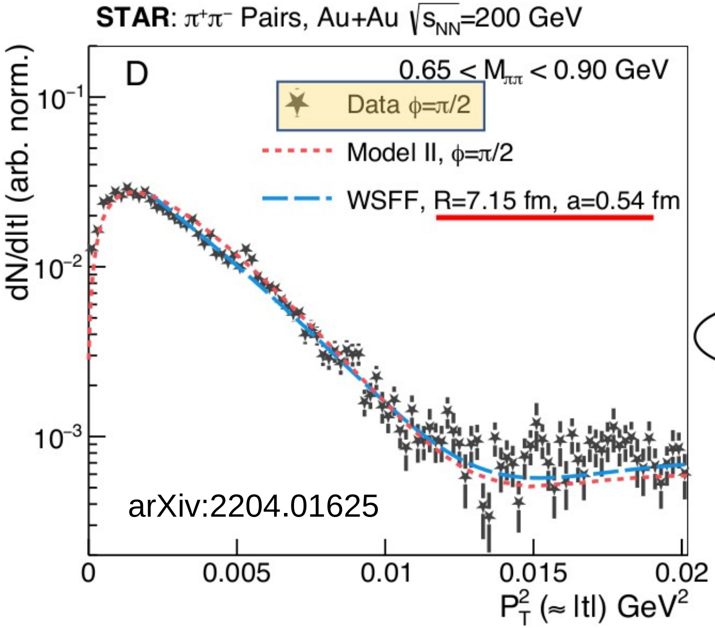
- Polarization is always determined by photon direction, ρ momentum by pomeron direction
- Circles represent harmonic angular probability distribution of pions
- "Case 1" → max interference, "Case 2" → no interference

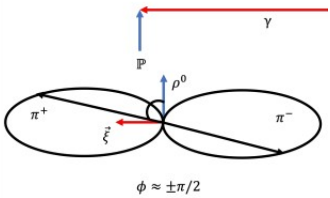


Test of |t| slope





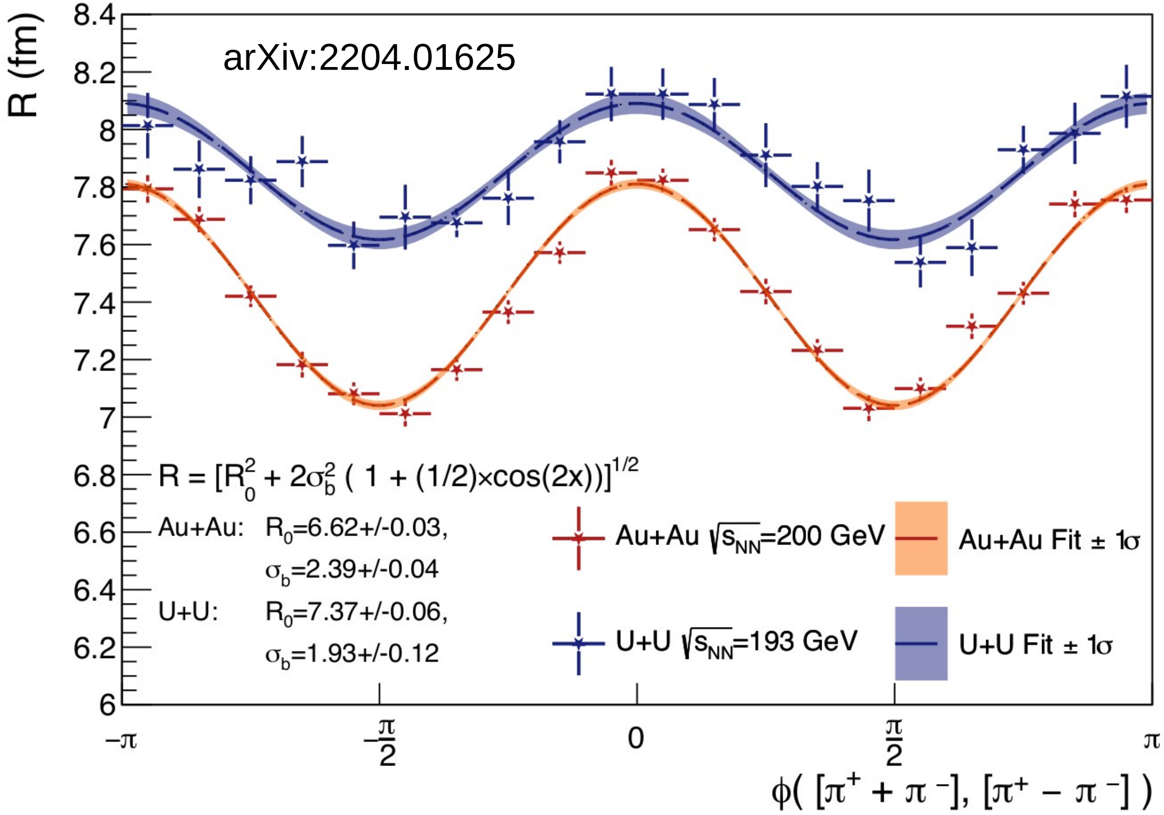




- Extracted slope depends *significantly* on interference!
- Demonstrates flaw in direct extraction of radius from |t| distributions

Radius from interference

- Radius can be extracted directly from harmonic fit
- At ± π/2 smearing from finite photon momentum disappears
- Correct for
  - Smearing from decay kinematics
  - Depolarization from finite size nuclei (4%) and size of probe (transverse size of the ρ wavefunction)
- Extraction removes known effects



Comparison of radii

	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 ≈ 0.3)
		*arXiv:2204.01625

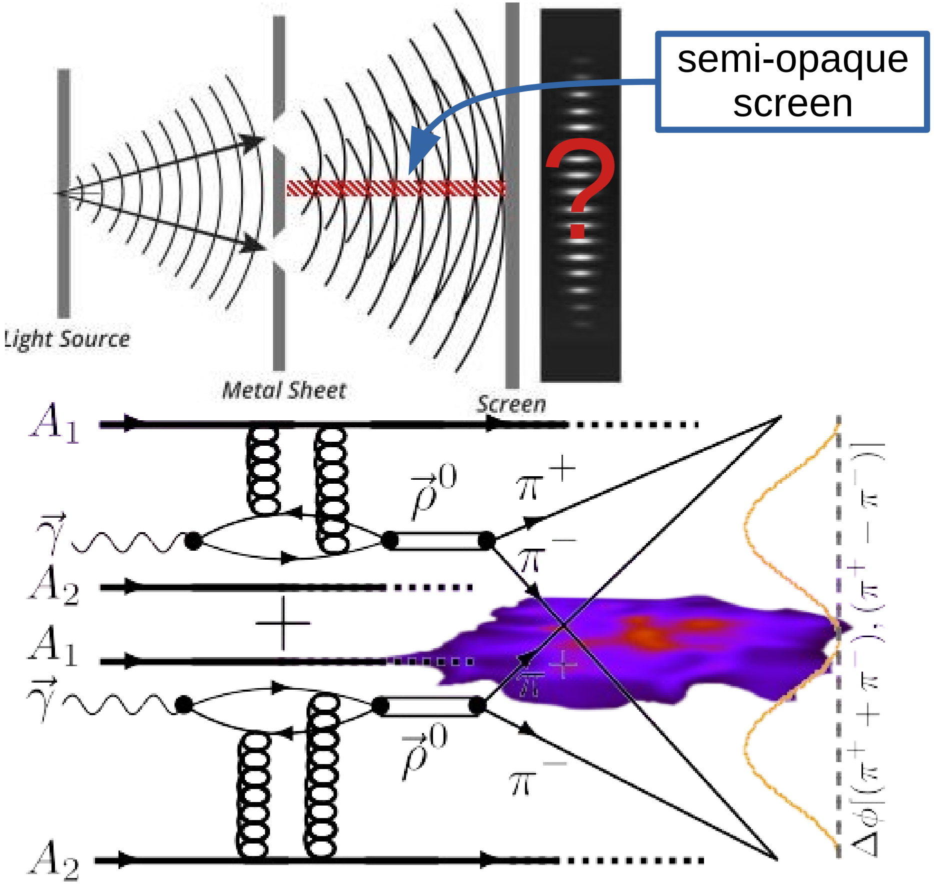
- Precision measurement of nuclear interaction radius at high energy
- Uranium shows evidence of (relatively) thick neutron skin, gold consistent with previous measurements

[1] STAR Collaboration, L. Adamczyk, *et al.*, *Phys. Rev. C* 96, 054904 (2017).
[2] H. Alvensleben, *et al.*, *Phys. Rev. Lett.* 24, 786 (1970).
[3] G. McClellan, *et al.*, *Phys. Rev. D* 4, 2683 (1971).

Limits of coherent diffractive production in nuclear medium

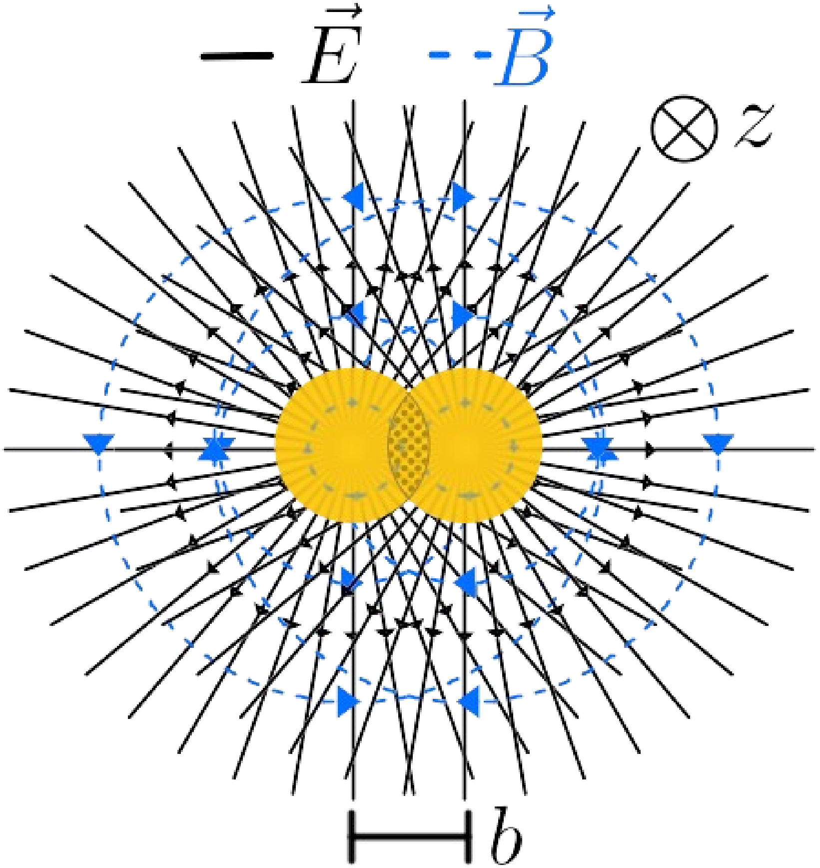
Modification of double-slit

- In double-slit analogy hadronic interactions might be semi-opaque screen dividing the holes
- J/Ψ measurements demonstrate coherent photoproduction in peripheral collisions, but do not investigate how these hadronic interactions affect the wave function



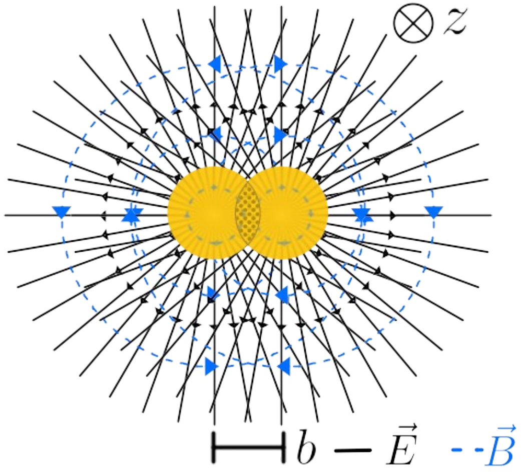
EM studies and non-UPC

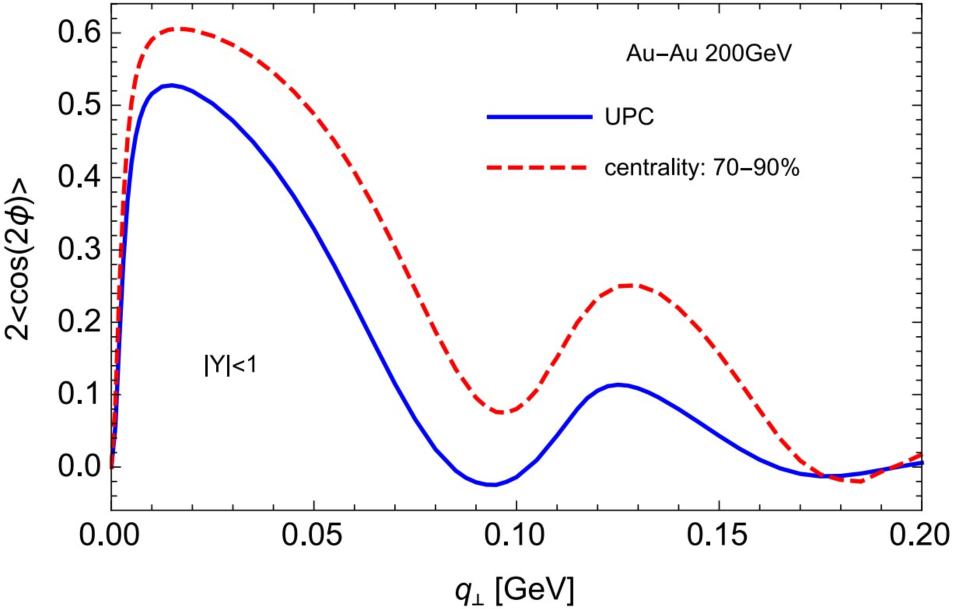
- UPC studies
  - Clean signal representative of only photon production
  - Unmuddied by effects of hadronic interactions
  - Ideal environment for studying pure photon interactions
- Non-UPCs: greater degree of polarization overlap between photons from their respective nuclei (larger initial signal)
- Signals from pure photoproduction may be modified by the collision medium
- Studying this process in non-UPCs tests our understanding of what “coherence” really means
  - How much can a nucleus break up and still have coherent interactions?
  - How might this breakup affect the overall wave function?



Non-UPC collisions

- Photoproduction signal expected to increase in non-UPCs
  - Theory plot is a prediction of the size of this effect with ***no*** hadronic interactions
- Measures both polarization and quantum interference. These have been measured in A+A (global polarization + HBT), but not yet together
- Can polarization and quantum entanglement survive the abundant hadronic interactions of a non-UPC?
  - If so, how might they be modified?

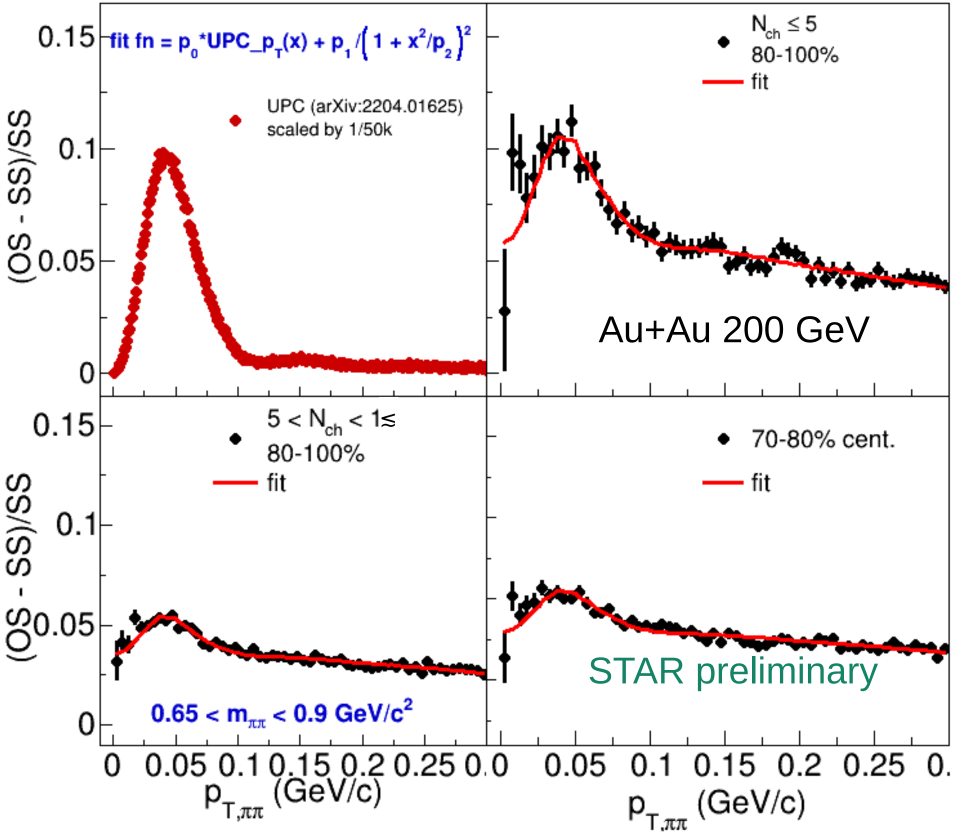




Xing, H et.al. *J. High Energ. Phys.* **2020**, 64 (2020)

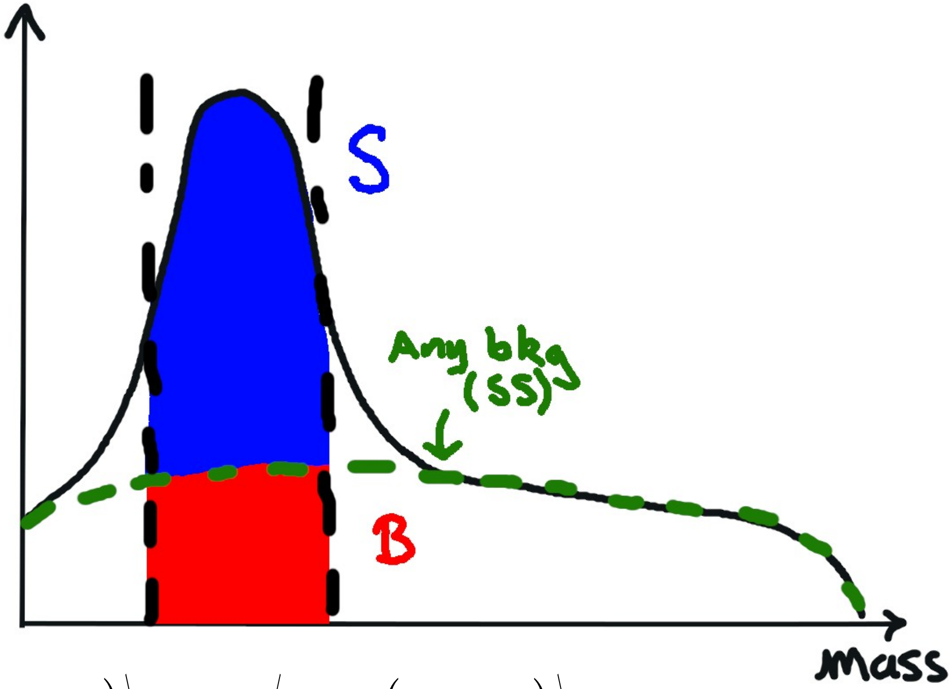
p_T distributions

- Au+Au 200 GeV (taken in 2014 and 2016)
- ρ^0 swamped by combinatorics in central collisions → focus on peripheral collisions
- Hadronic component of the p_T distribution can be divided out (OS – SS)/SS
- Fit with $p_0 * \mathrm{UPC}_{p_T}(x) + p_1 / (1 + x^2 / p_2)^2$
- Clear signal of coherent photoproduction!
- Distributions fit using UPC results to demonstrate this effect
  - Coherent part of fit from UPC (p_0 parameter) is ~ 8 standard deviations for each fit



Subtracting background in Δφ

- Dominant background makes subtraction much more important than in the UPC data
- Background estimated by same-sign pairs
- Subtraction method:

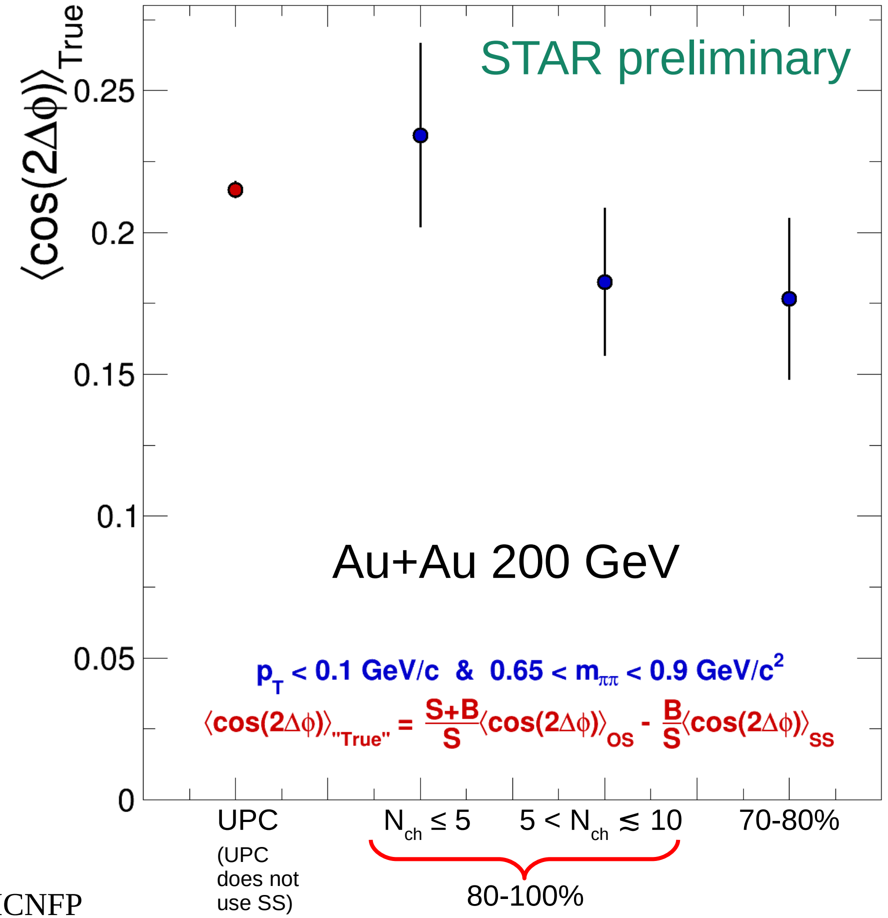


$$(S+B)\langle\cos(2\Delta\phi)\rangle_{\mathrm{OS}} = B\langle\cos(2\Delta\phi)\rangle_{\mathrm{SS}} + S\langle\cos(2\Delta\phi)\rangle_{\mathrm{True}}$$

$$\Rightarrow \langle\cos(2\Delta\phi)\rangle_{\mathrm{True}} = \frac{S+B}{S}\langle\cos(2\Delta\phi)\rangle_{\mathrm{OS}} - \frac{B}{S}\langle\cos(2\Delta\phi)\rangle_{\mathrm{SS}}$$

Comparison to UPC

- Signal persists in peripheral events
- Wavefunction is surviving potential decoherence from hadronic interactions
- There does not appear to be a strong centrality dependence
  - Though expectation is increasing signal



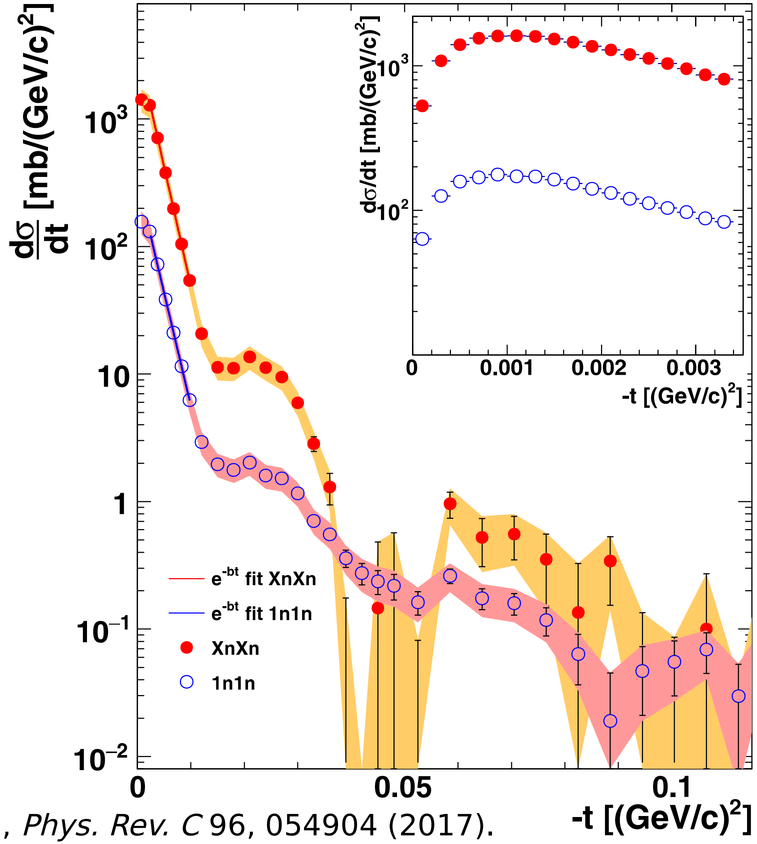
Conclusions

- Clear excess at low p_T is evidence of coherent production
- First measurements of a cos(2Δφ) modulation in the angular distribution of ρ daughters due to photon polarization
  - Strong modulation in measurements of Au+Au and U+U UPC events
  - Interference is also excellent tool for measuring nuclear size
  - This interference survives the strongly-interacting medium of a peripheral HIC (Au+Au data)
    - Possible effects from wave function collapse are relatively small

Backup

Nuclear radius is too large!

- Photo-nuclear measurements have historically produced a |t| slope that corresponds to a mysteriously large source!
- Charged radii for Au and Pb are 6.38 fm and 6.62 fm respectively
- |t| slopes measured in HICs:
  - STAR (2017): 407.8 ± 3 $(GeV/c)^{-2}$
  - ALICE (Pb): 426 ± 6 ± 15 $(GeV/c)^{-2}$
- These correspond to an effective radius of > 8 fm!
- Where is this discrepancy coming from?

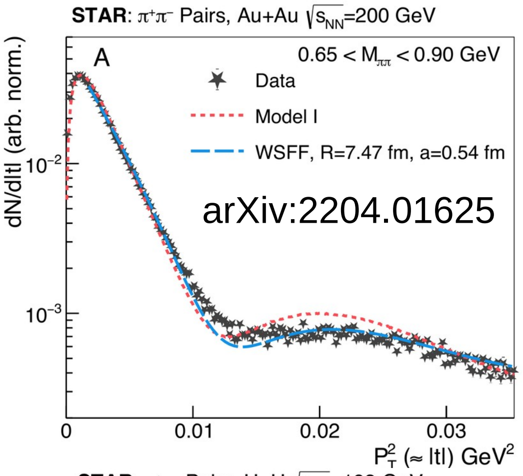


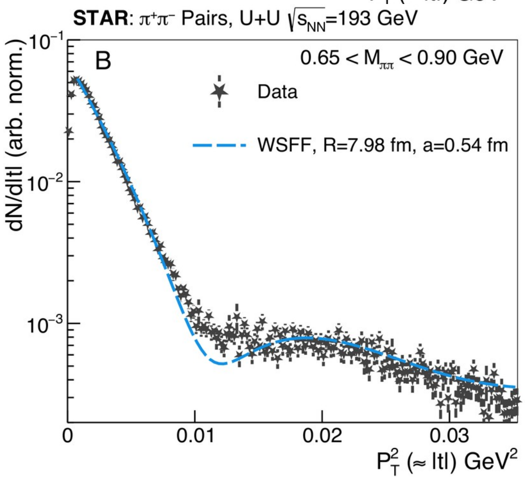
STAR Collaboration, L. Adamczyk, *et al.*, *Phys. Rev. C* 96, 054904 (2017).
J. Adam *et al.* (ALICE Collaboration), J. High Energy Phys. 1509 (2015) 095.

Measurements using Woods Saxon

- New STAR measurements also a large radius
- Is this a deficiency of the exponential fit?
- Use a Woods-Saxon instead, radius is still >1 fm too big
- Uranium has the same issue, >1 fm larger than charge radius

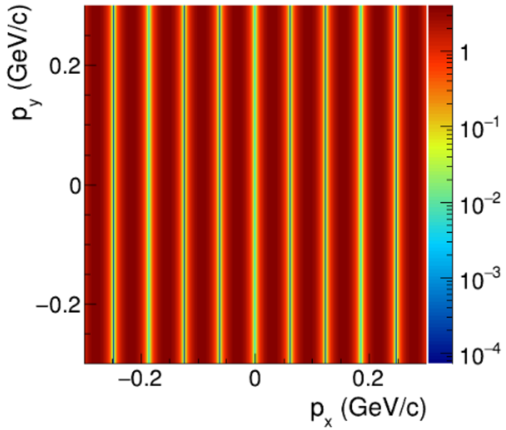
arXiv:2204.01625

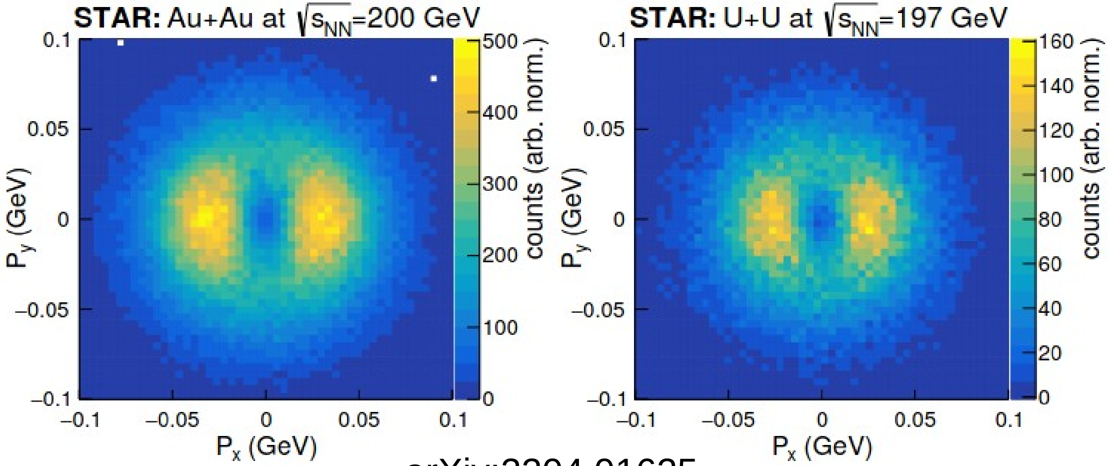




New method

- Two-source interference takes place in x-axis (impact parameter direction)
- Interference pattern disappears in y direction
- Can select event orientations





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