Nuclear Tomography with Polarized Photon-Gluon Collisions at STAR

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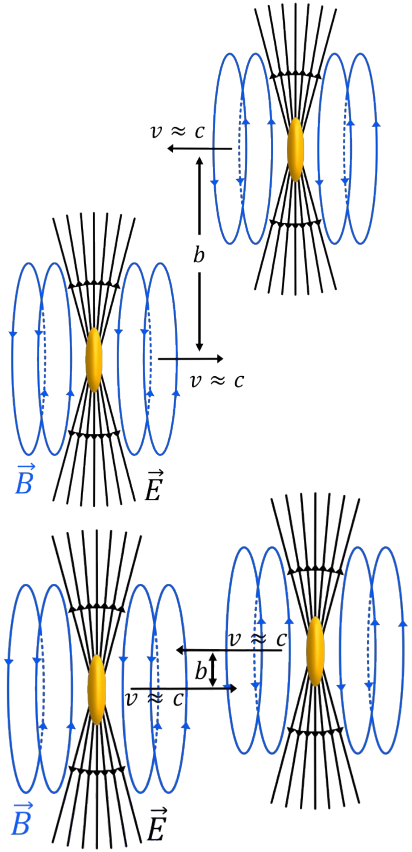
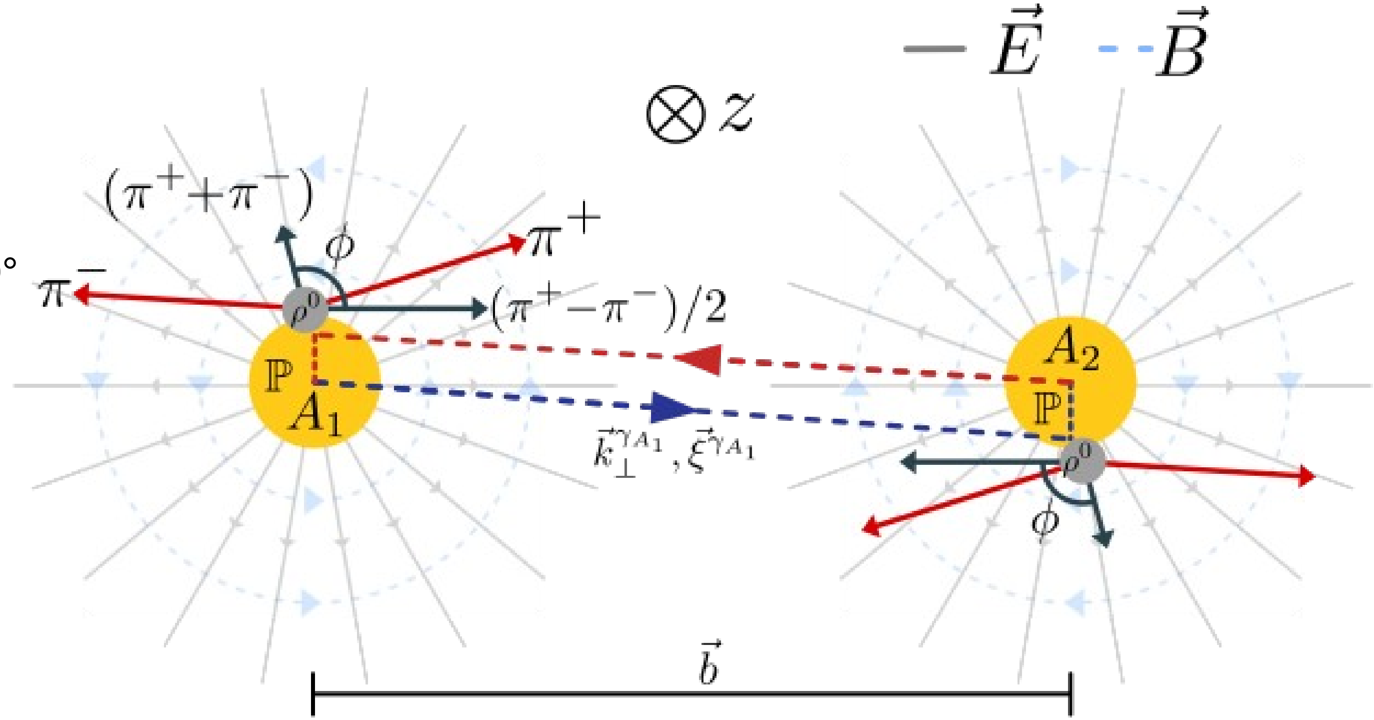
Photonuclear production in HIC

- Photoproduction of vector mesons follow $\gamma\mathbb{P}\rightarrow\rho^0,\ J/\psi,$ etc. $\left(J^P=1^-\right)$
  - Photon from the EM field of one nucleus fluctuates to a $q\bar{q}$ 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

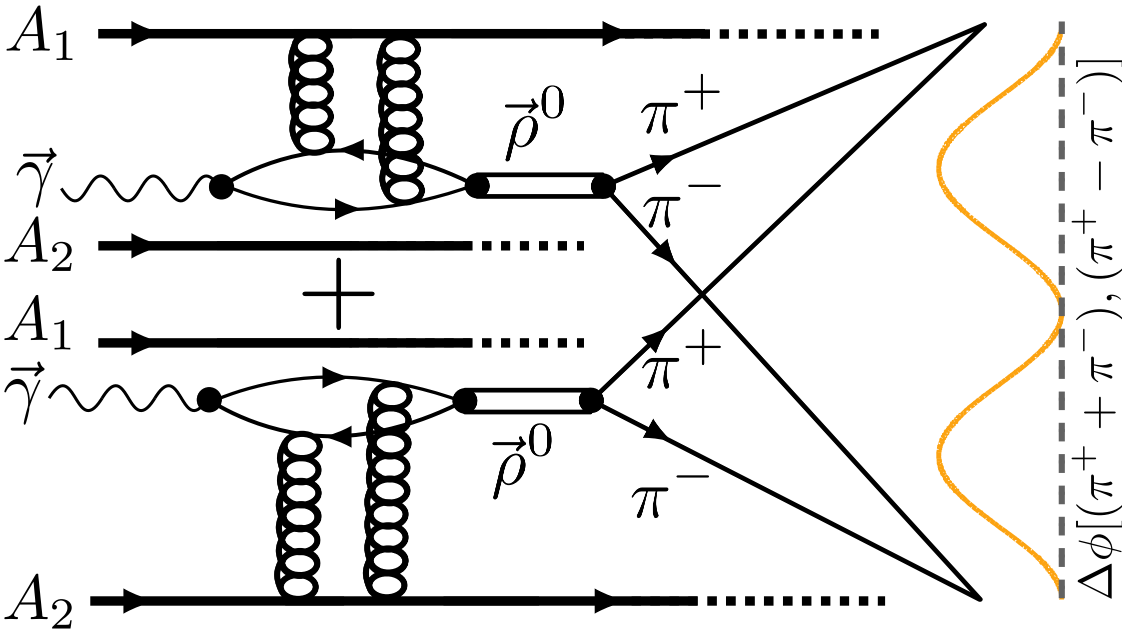
- Photon polarization vector aligned radially with the "emitting" source
  - Polarizations of measured ρ and its (otherwise identical) virtual partner are exactly 180° out of sync
  - Hadronically produced ρs (+pions) have no such spin correlation
    - HBT interference, but not polarization-dependent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



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

Two-source modulation

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



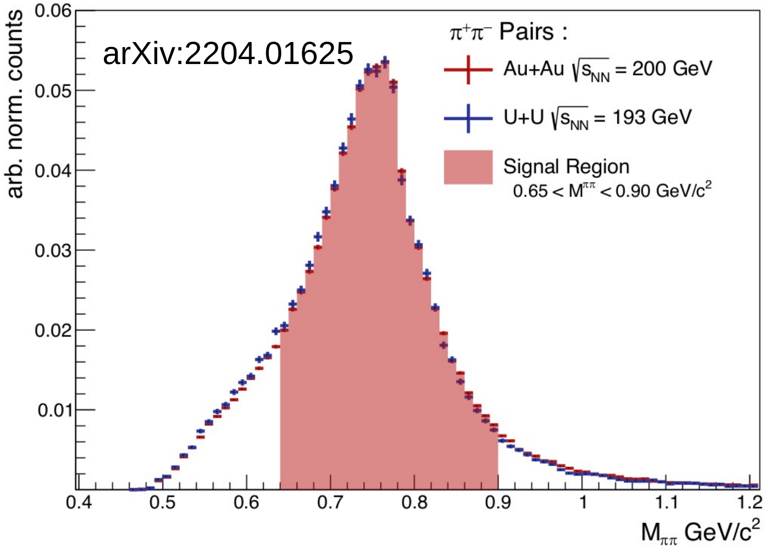
[1] Xing, H et.al. *J. High Energ. Phys.* **2020**, 64 (2020).

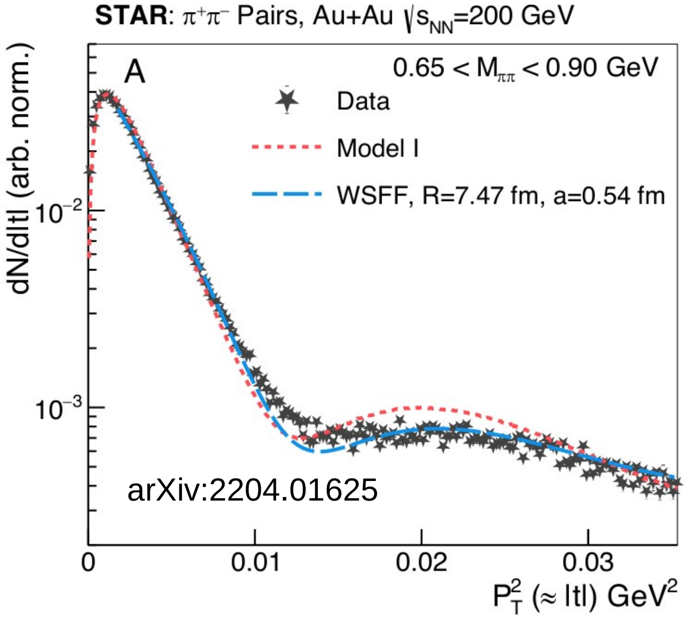
$$\Delta\phi = \phi(\pi^+ + \pi^-) - \phi(\pi^+ - \pi^-)$$

Interference in UPCs

Measurement in UPC

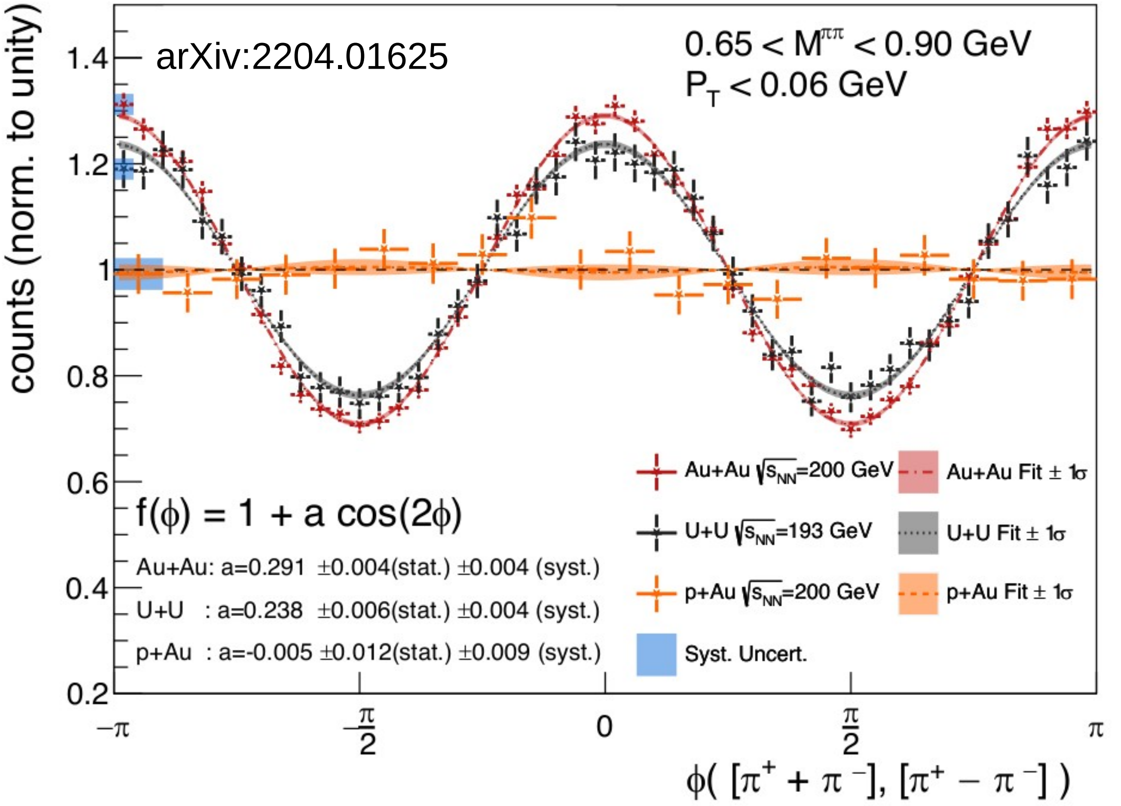
- Combine $\pi^+\pi^-$ pairs from events collected by the STAR UPC trigger
- Extremely clean ρ^0 peak and obvious low-p_T peak
- The p_T peak comes from a diffractive pattern
  - ρs are coherently photoproduced
  - This peak is consistent with model predictions of photoproduction and has only been explained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





UPC results

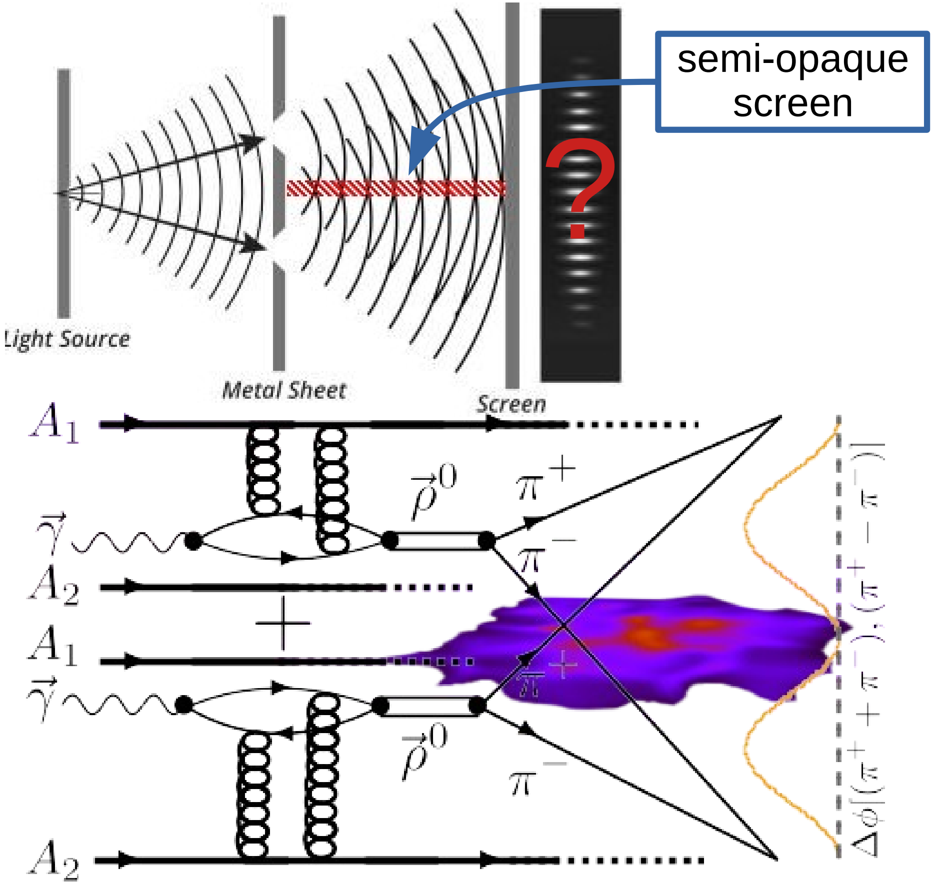
- Strong modulation in A+A collisions
- Difference in Au+Au and U+U demonstrates sensitivity to nuclear geometry
- No interference pattern seen in p+A, as expected



Limits of coherent diffractive production in nuclear medium

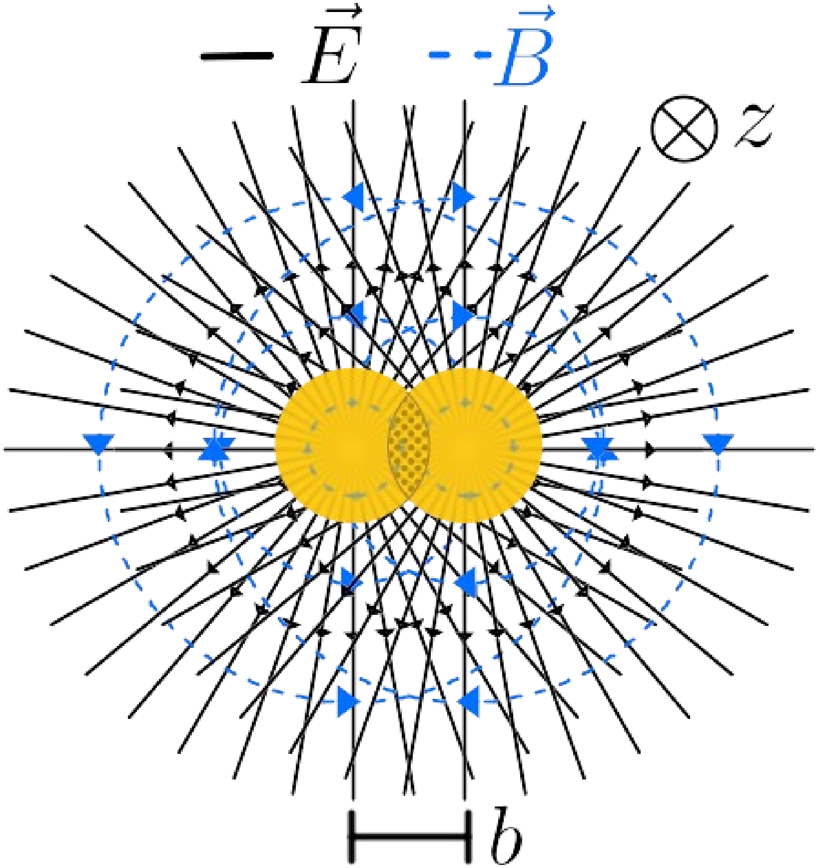
Modification of two-source

- In two-source analogy hadronic interactions could be viewed as semi-opaque screen dividing the holes
- J/ψ measurements demonstrate coherent photoproduction in hadronic Au+Au collisions, but do not investigate how these hadronic interactions affect the wave function

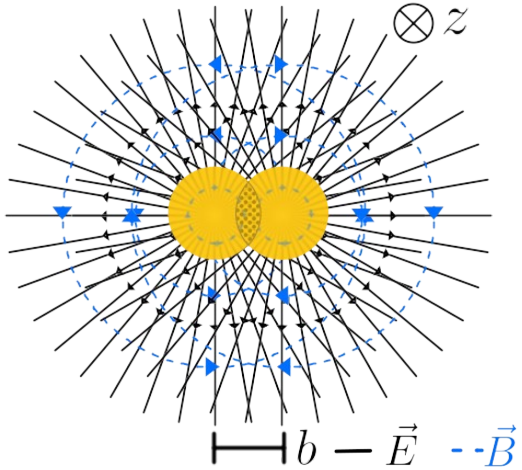


EM studies and non-UPC

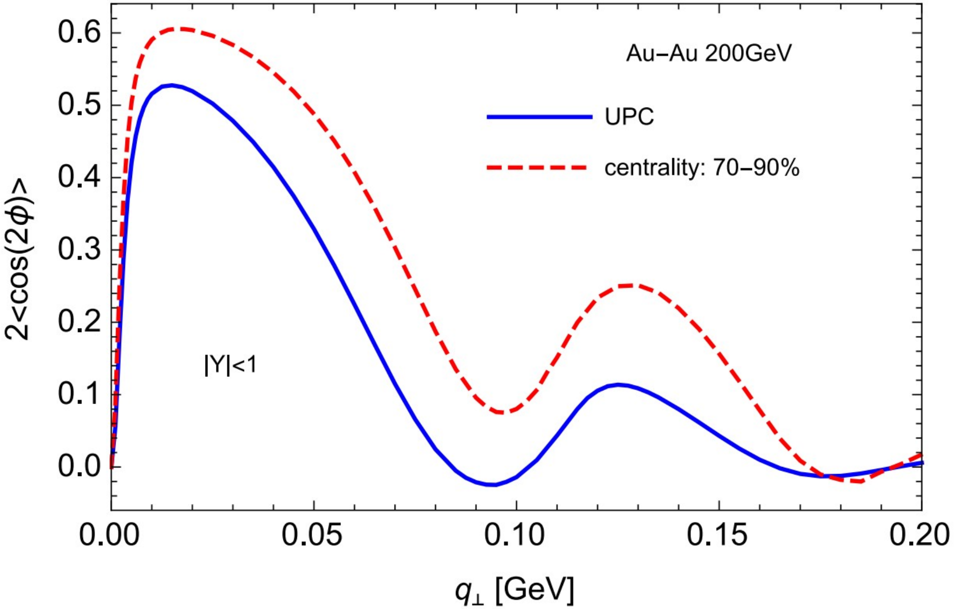
- UPC studies
  - Clean signal representative of only photon production
  - Unmuddied by effects of hadronic interactions
  - Ideal environment for studying pure photon interactions
- Non-UPCs: greater degree of polarization overlap between photons from their respective nuclei (larger initial signal)
- Signals from pure photoproduction may be modified by the 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



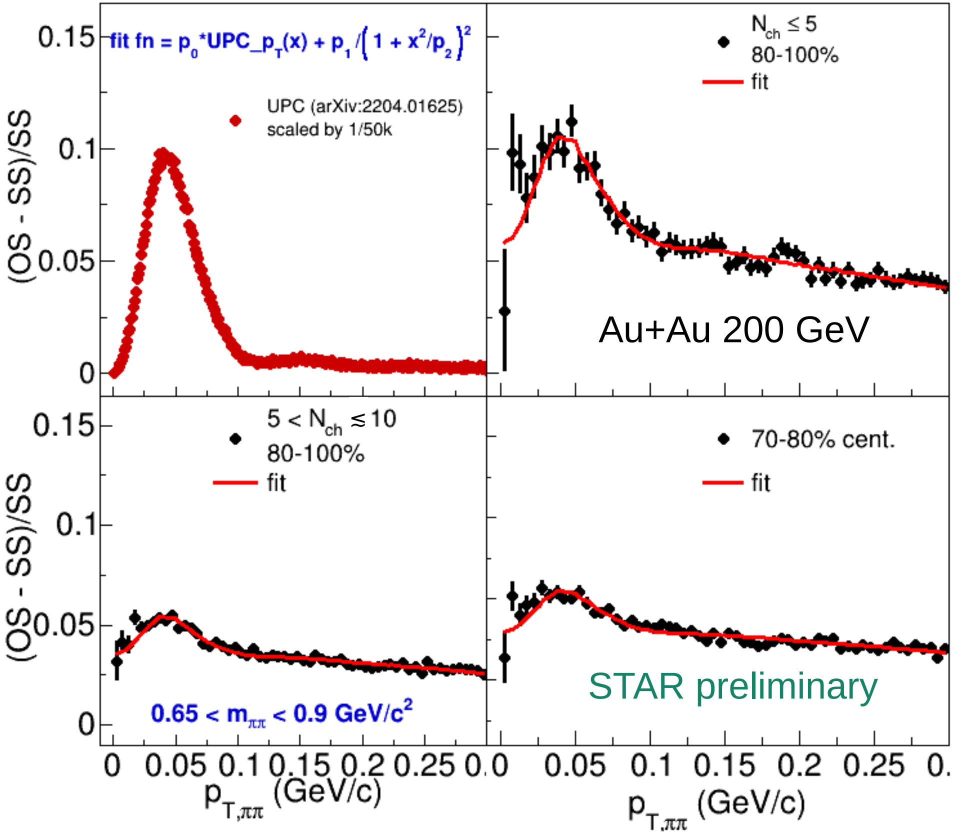
- Photoproduction signal expected to increase in non-UPCs
  - Theory plot is a prediction of the size of this effect with ***no*** hadronic interactions
- Measures both polarization and quantum interference. These have been measured in A+A (global polarization + HBT), but not yet together
- Can polarization 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)

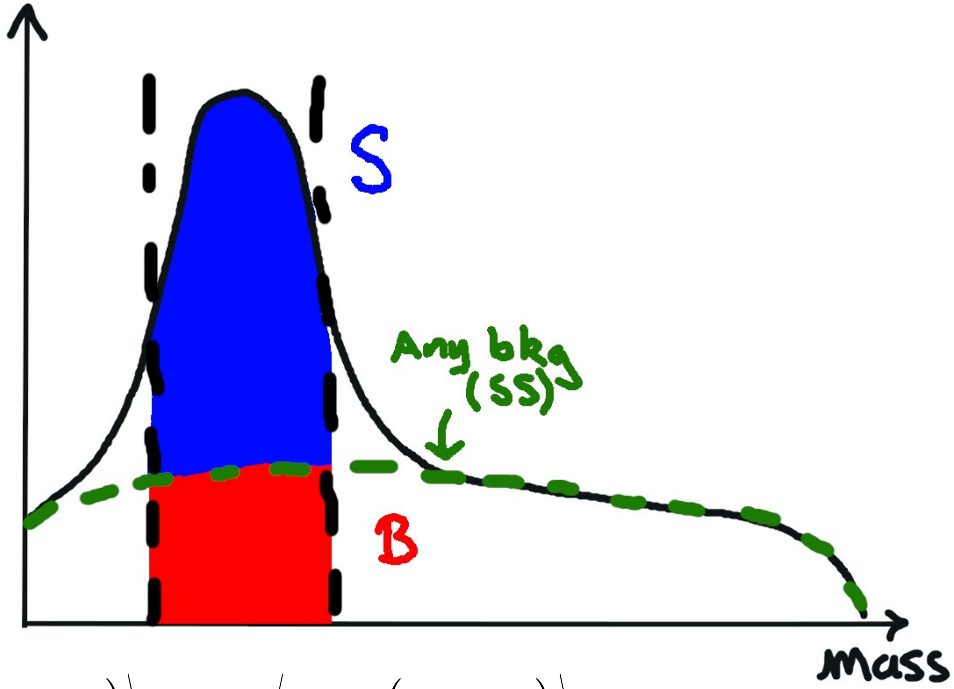
p_T distributions

- Au+Au 200 GeV (taken in 2014 and 2016)
- ρ⁰ 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:

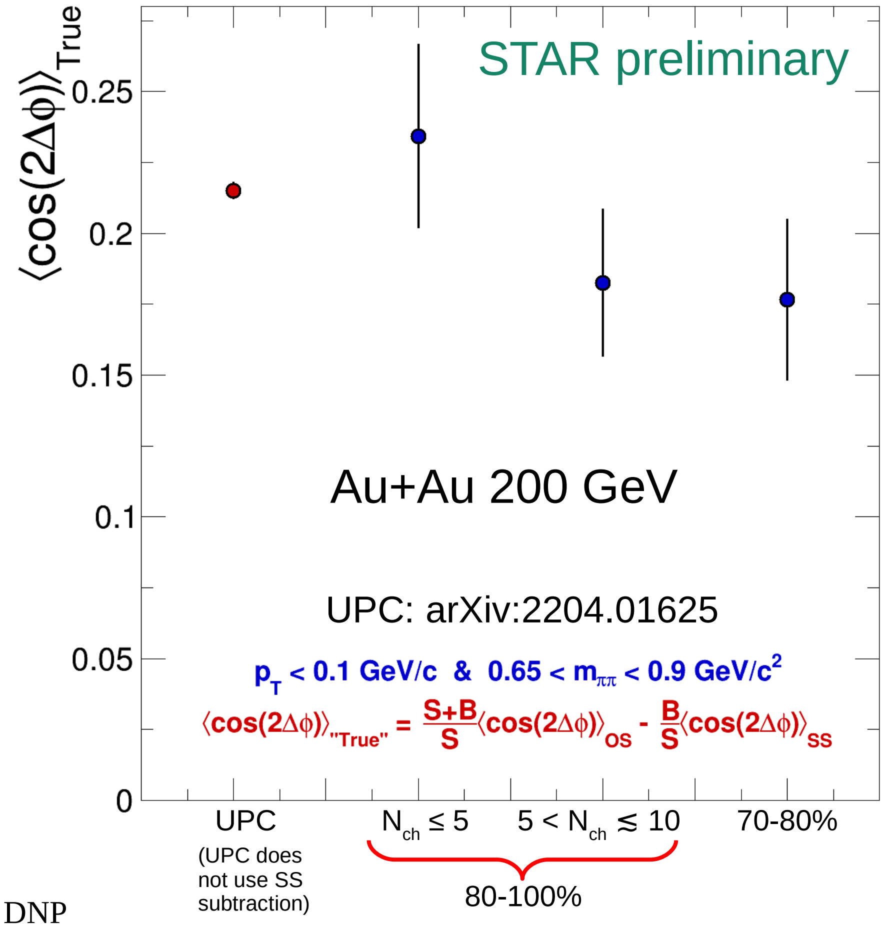


$$(S+B)\langle\cos(2\Delta\phi)\rangle_{\mathrm{OS}} = B\langle\cos(2\Delta\phi)\rangle_{\mathrm{SS}} + S\langle\cos(2\Delta\phi)\rangle_{\mathrm{True}}$$

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

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 in peripheral Au+Au collisions.
- First measurements of a $\cos(2\Delta\varphi)$ modulation in the angular distribution of ρ daughters due to photon polarization (arXiv:2204.01625)
  - Strong modulation in measurements of Au+Au and U+U UPC events
  - This interference survives the strongly-interacting medium of a peripheral HIC (Au+Au data)
    - Possible effects from wave function collapse are relatively small