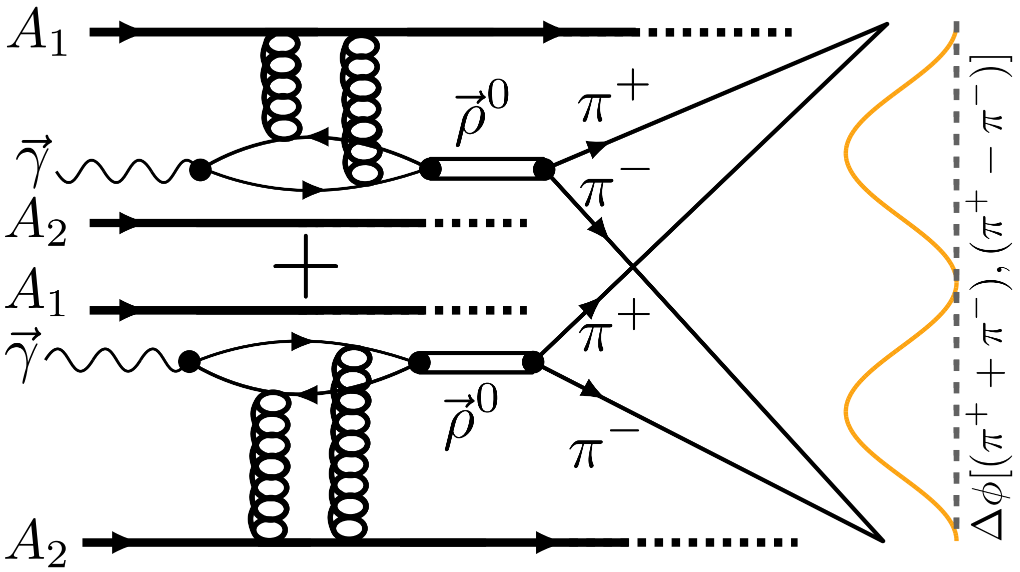
Probing Nuclear Structure with Photon-Gluon Collisions

Daniel Brandenburg (BNL/CFNS) for the STAR Collaboration

RBRC Workshop:

Physics Opportunities from the RHIC Isobar Run

Tuesday, 25th of January, 2022

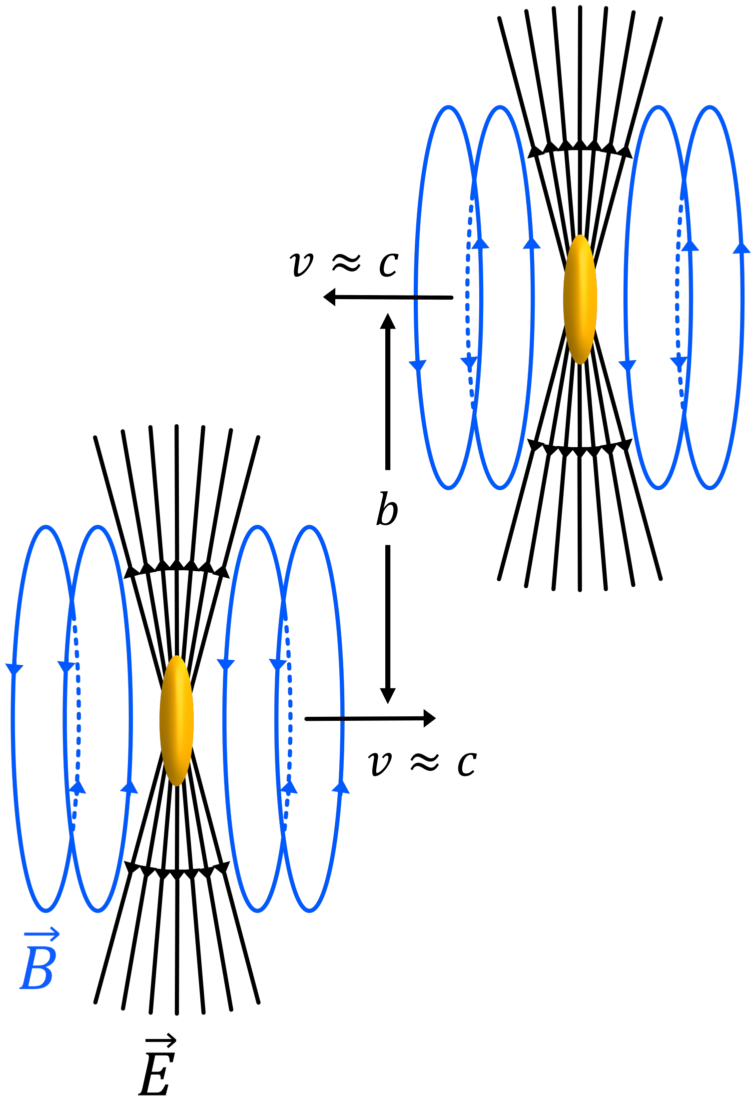


In part supported by U.S. DEPARTMENT OF ENERGY Office of Science

Talk Outline

1. **Introduction**
   - Ultra-strong electromagnetic fields
   - Transverse linearly polarized photons
2. **Polarized Photon-Gluon Collisions**
   - Angular modulations of diffractive $\rho^0 \to \pi^+\pi^-$ in UPCs
   - Comparison between p+Au, Au+Au and U+U
3. **Tomographic Technique**
   - Extracting the nuclear interaction radius
4. **Summary + Isobar**

Ultra-Peripheral Heavy-Ion Collisions



Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic fields

- $\gamma\gamma \rightarrow l^+ l^-$: photon-photon fusion
  - One photon from the field of each nucleus interacts
  - Second order process in α
  - $Z\alpha \approx 1$ $\rightarrow$ High photon density with highly charged nuclei

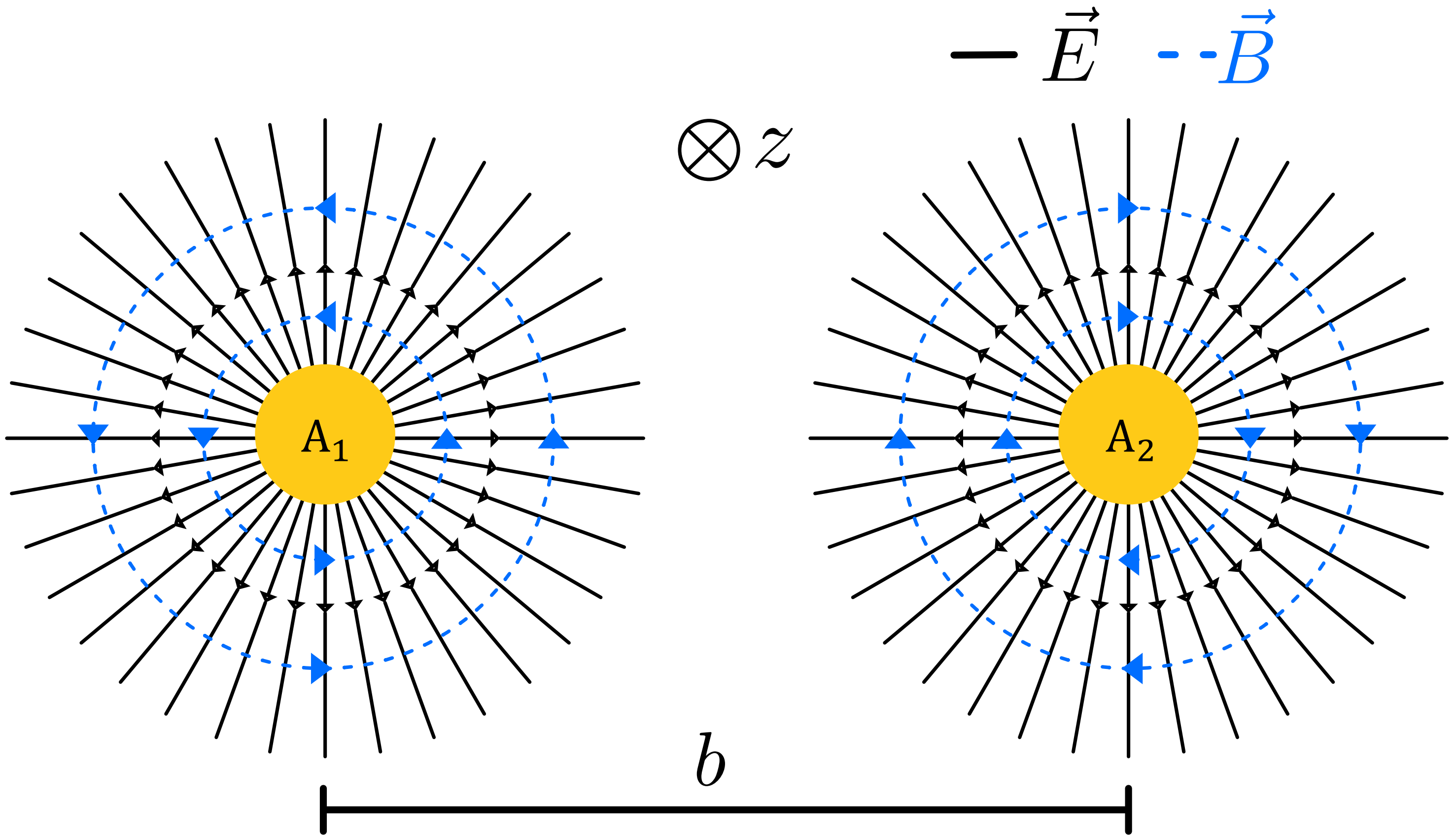
S. J. Brodsky, T. Kinoshita, and H. Terazawa, Phys. Rev. D **4**, 1532 (1971).
M. Vidović, M. Greiner, C. Best, and G. Soff, Phys. Rev. C **47**, 2308 (1993).

- $\gamma\mathbb{P} \rightarrow \rho^0, J/\psi, etc.$: Photo-nuclear production of vector mesons ($J^P = 1^-$)
  - Photon from the EM field of one nucleus fluctuates to a $q\bar{q}$ pair, interacts with pomeron (or Reggeon @ RHIC)
  - Photon quantum numbers $J^{PC} = 1^{--}$

Klein, S. R. & Nystrand, J. *Phys. Rev. C* **60**, 014903 (1999).
Klein, S. R. & Nystrand, J. *Phys. Rev. Lett.* **84**, 2330–2333 (2000).

Transverse linearly polarized photons

- Extreme Lorentz contraction of EM fields ($\vec{E} \perp \vec{B} \perp \vec{k}$)
  - → Quasi-real photons should be linearly polarized in the transverse plane
- Polarization vector : aligned radially with the “emitting” source
- Well defined in the photon position eigenstates
- Event average, washes out polarization effects, since $\vec{b}$ is random from one event to next



[1] C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)
[2] Li, C., Zhou, J. & Zhou, Y. Phys. Rev. D 101, 034015 (2020).

Birefringence of the QED Vacuum

polarized $\gamma\gamma \to e^+e^-$ [1] leads to **$\cos(4\Delta\phi)$ modulations** in

$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)]$$
$$\approx \Delta\phi[(e^+ + e^-), e^+]$$

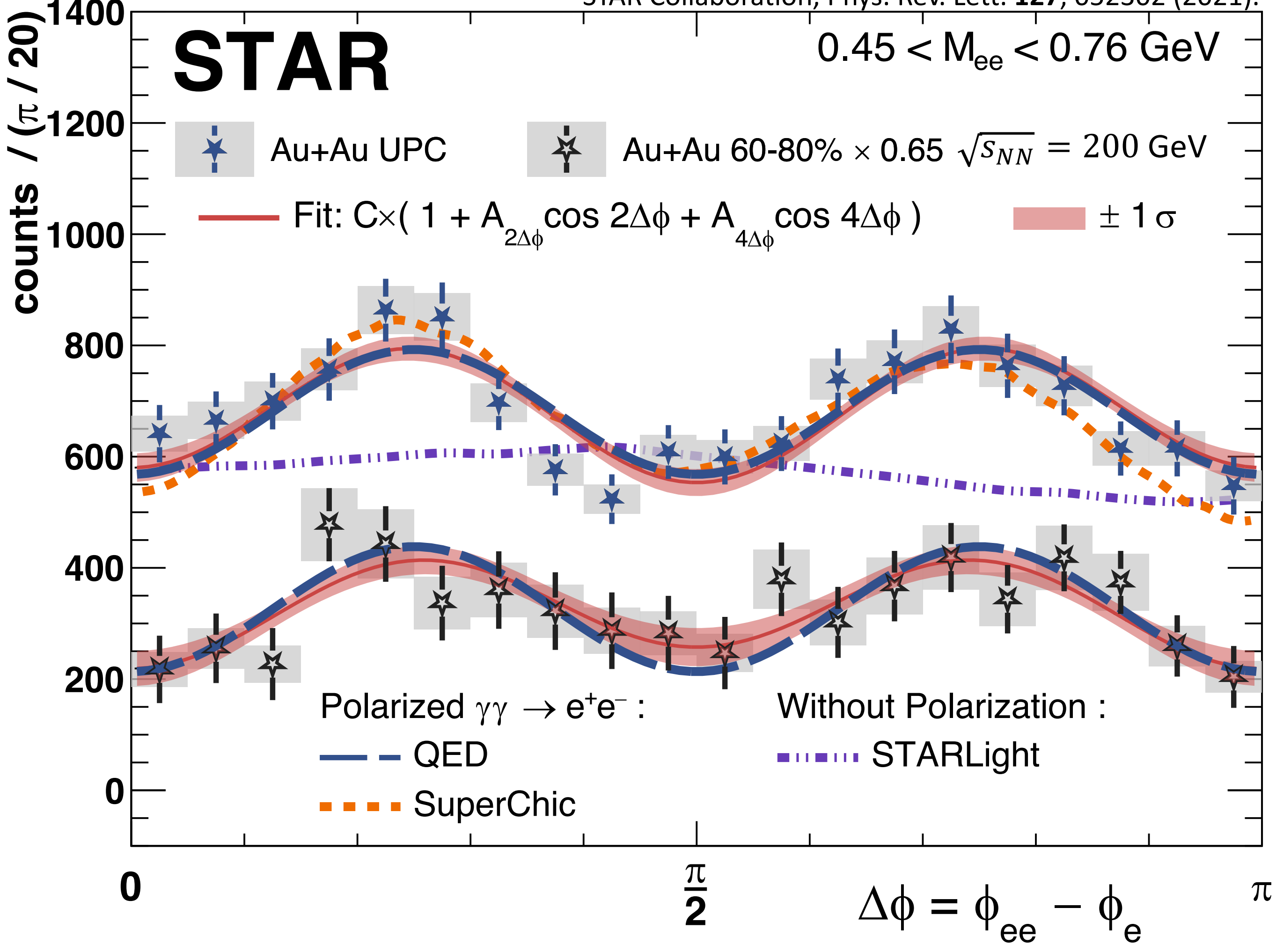
Ultra-Peripheral

Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	16.8 $\pm$ 2.5	16.5	18.8 / 16

Peripheral (60−80%)

Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	27 $\pm$ 6	34.5	10.2 / 17

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



$\cos 4\Delta\phi$ observed at $> 6\sigma$ significance (UPC) – **photons are linearly polarized**

+ First laboratory evidence for vacuum birefringence

Polarized
Photon + gluon Collisions

Photo-Nuclear Interactions

- Photo nuclear interactions have been studied for decades[1, 2, 3]
    - Well known process for probing the hadronic structure of the photon
- Extensive measurements in ep conducted at HERA (H1 and Zeus)
    - Involves virtual (longitudinally polarized) photons with large Q^2
    - Detailed measurements of the spin-density elements

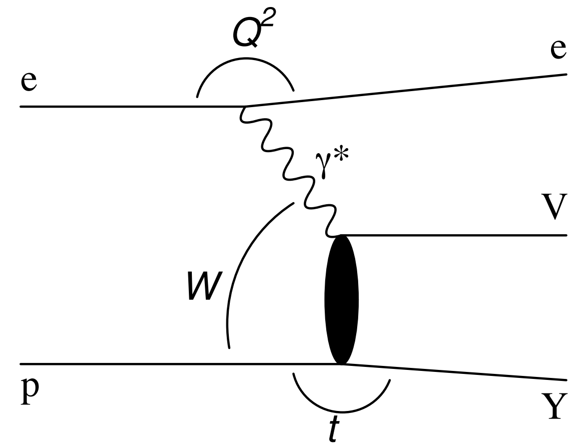


Figure 1: Diffractive vector meson electroproduction.

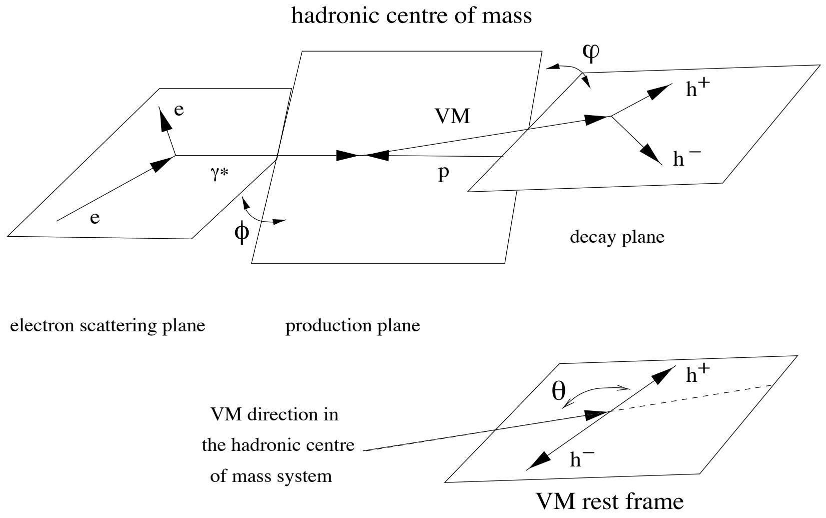


Figure 3: Definition of the angles characterising diffractive VM production and decay in the helicity system.

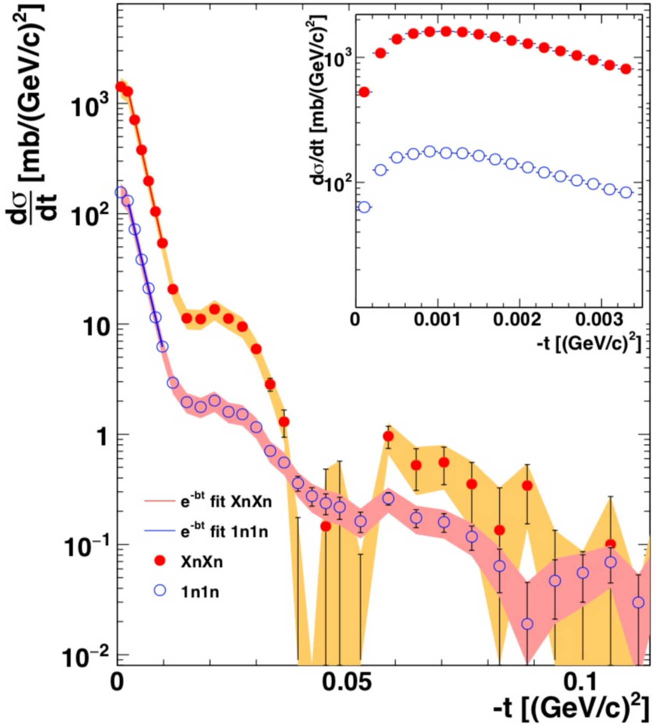
[1] H1 Collaboration. *J. High Energ. Phys.* **2010**, 32 (2010).
[2] ZEUS Collaboration. *Eur. Phys. J. C* **2**, 247–267 (1998).
[3] See refs 1-25 in [2]

Photo-Nuclear processes in UPC

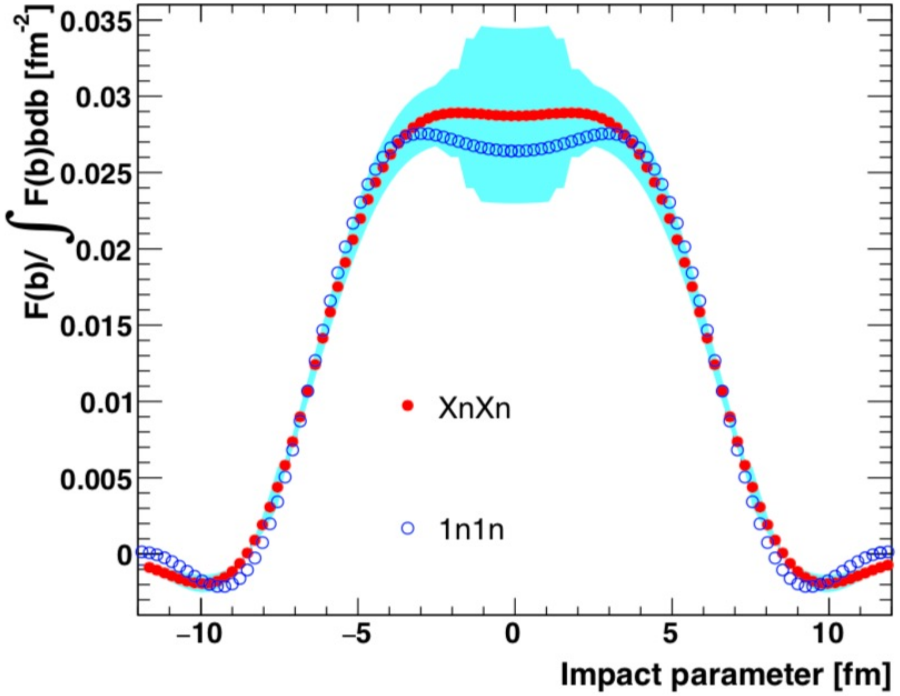
STAR Collaboration *et al. Phys. Rev. Lett.* **89**, 272302 (2002).
STAR Collaboration *et al. Phys. Rev. Lett.* **102**, 112301 (2009).
STAR Collaboration *et al. Phys. Rev. C* **96**, 054904 (2017).

STAR has studied $\gamma\mathbb{P} \rightarrow \rho^0 \rightarrow \pi^+\pi^-$ (and direct $\pi^+\pi^-$ production) in the past

Diffractive structure in $p_T^2 \approx -t$ distribution



Cross section vs. $p_T^2 \approx -t$ sensitive to the gluon density within nucleus



Other measurements in UPC at RHIC & LHC include:

Photoproduction of J/ψ in Au+Au UPC at $\sqrt{s_{NN}}$ = 200 GeV
PHENIX Phys.Lett.B679:321-329,2009

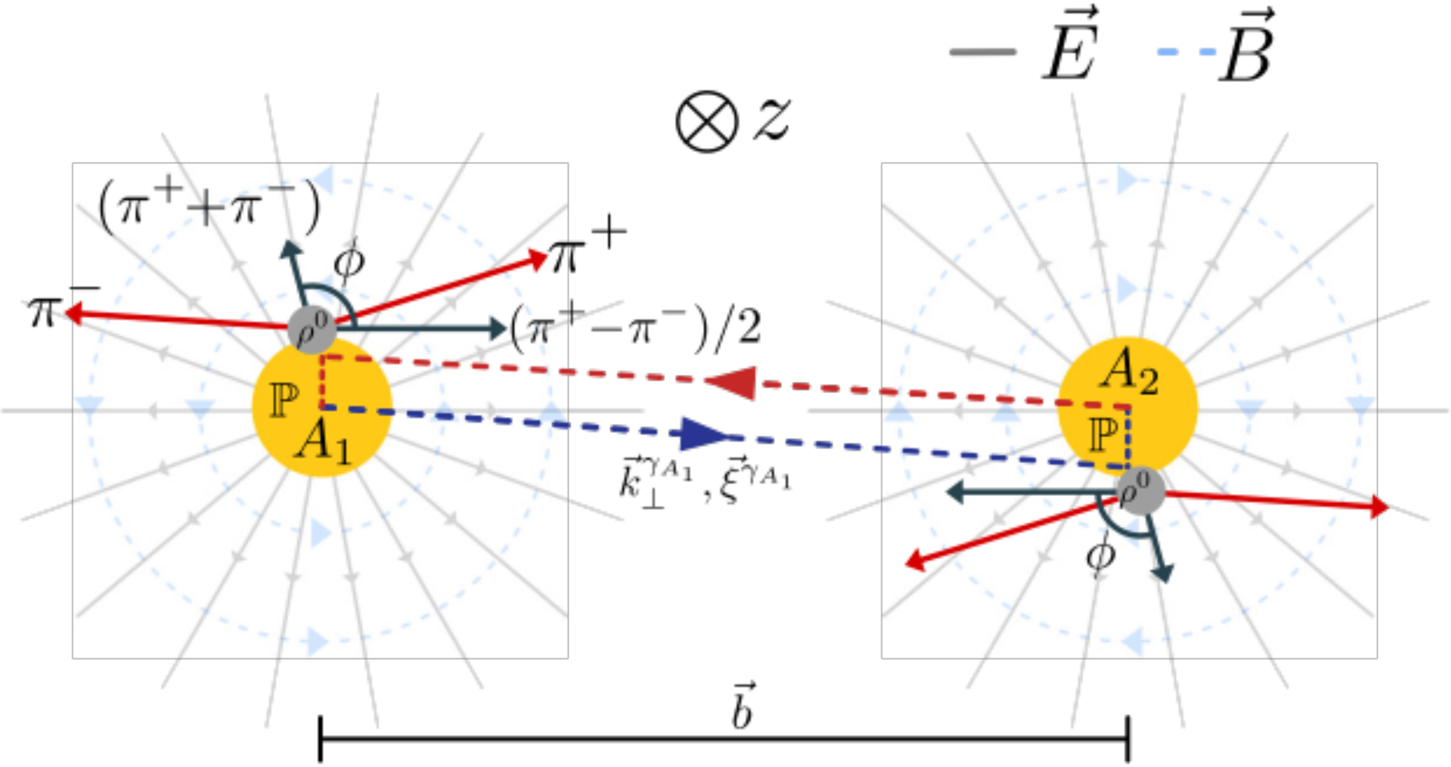
ρ^0 vector mesons in Pb-Pb UPC at $\sqrt{s_{NN}}$ = 5.02 TeV
ALICE, JHEP06 (2020) 35

J/ψ in Pb+Pb UPC at $\sqrt{s_{NN}}$ = 2.76 TeV
CMS, Phys. Lett. B 772 (2017) 489
… and many more

What more can we learn, with transverse linearly polarized photons?

Photo-production with Polarized Photons

- Polarization vector : aligned radially with the "emitting" source
- Well defined in terms of the semi-classical $\vec{E}$ and $\vec{B}$ fields
- Final state $\pi^+\pi^-$ pair is produced through interference of both amplitudes



$$\sigma(p_T, b, y) = |A(p_T, b, y) - A(p_T, b, -y)\exp(i\vec{p}_T \cdot \vec{b})|^2, \quad (1)$$

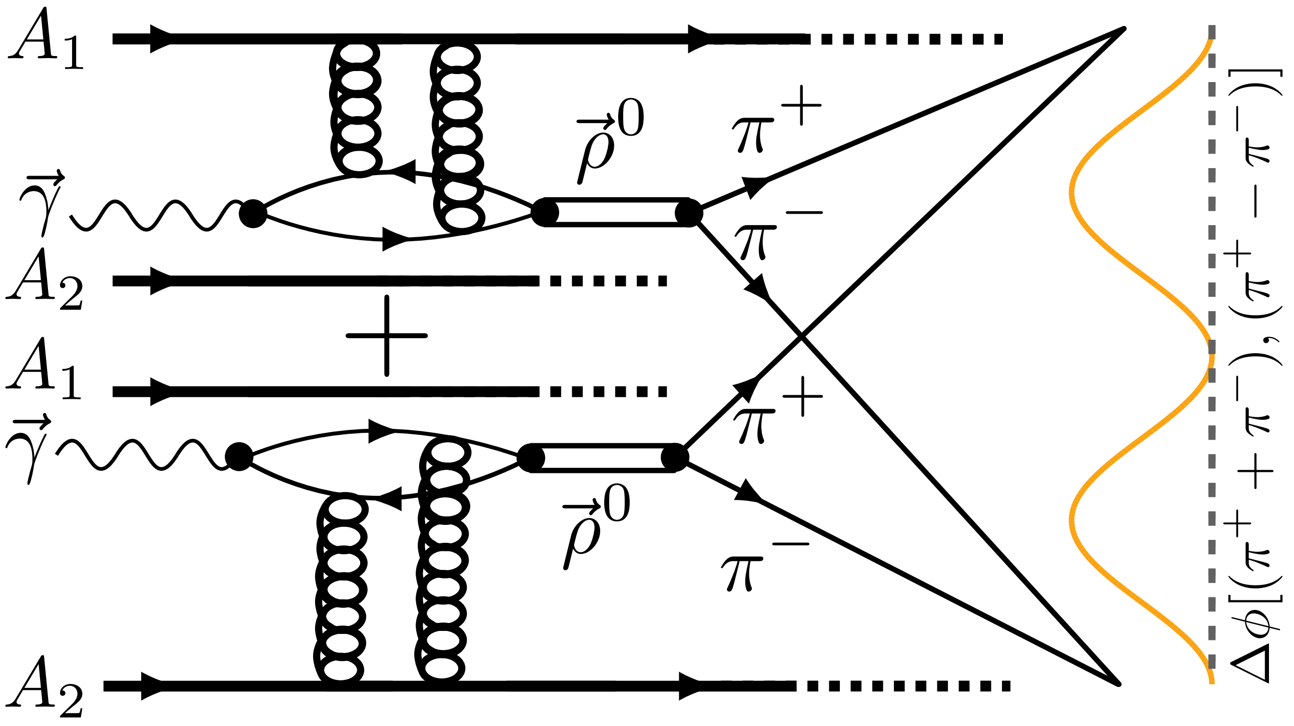
Klein, S. R. & Nystrand, J. *Phys. Rev. Lett.* **84**, 2330–2333 (2000).

Quantum Interference Effects with Polarized Photons

If the photons are linearly polarized in the transverse plane:

→ Modulation due to quantum interference of amplitudes

→ Expect a $\cos 2\Delta\phi$ modulation in the final state[1]



Theoretical calculations indicate that the quantum interference effect is sensitive to:

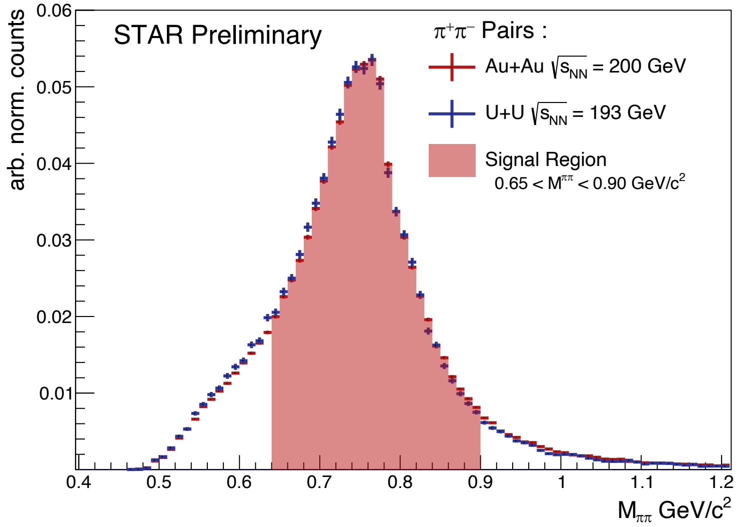
→ Nuclear Geometry (gluon distribution)

→ Impact Parameter (detailed spatial distribution)

Access through measurement of $\Delta\phi$ distribution, like the $\gamma\gamma \rightarrow e^+e^-$ case

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

$\Delta\phi$ in Au+Au and U+U Collisions



Quantify the difference in strength for Au+Au vs. U+U via a fit:

$$f(\Delta\phi) = 1 + a\ \cos 2\Delta\phi$$

Au+Au :

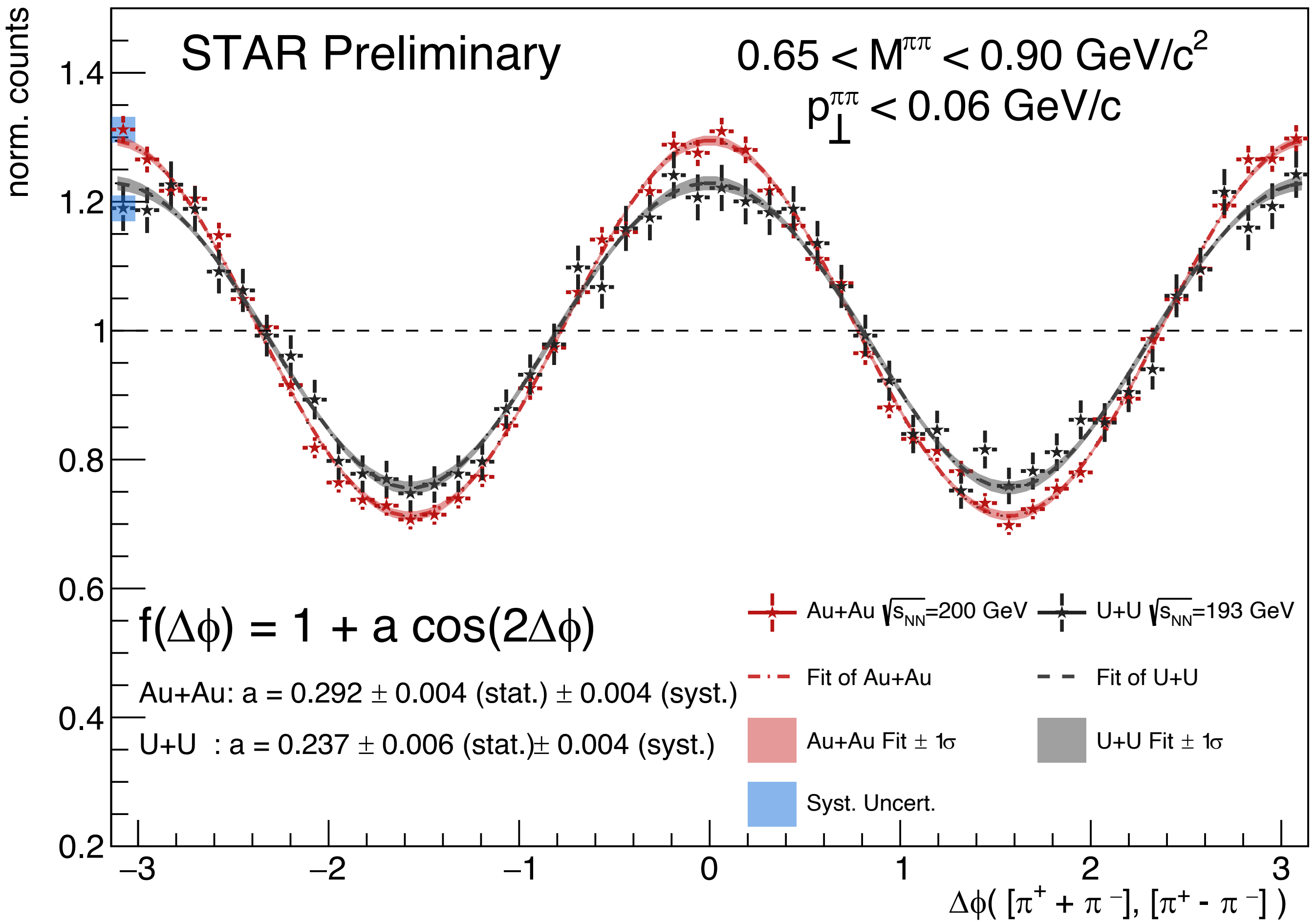
$a = 0.292 \pm 0.004$ (stat) ± 0.004 (syst.)

U+U :

$a = 0.237 \pm 0.006$ (stat) ± 0.004 (syst.)

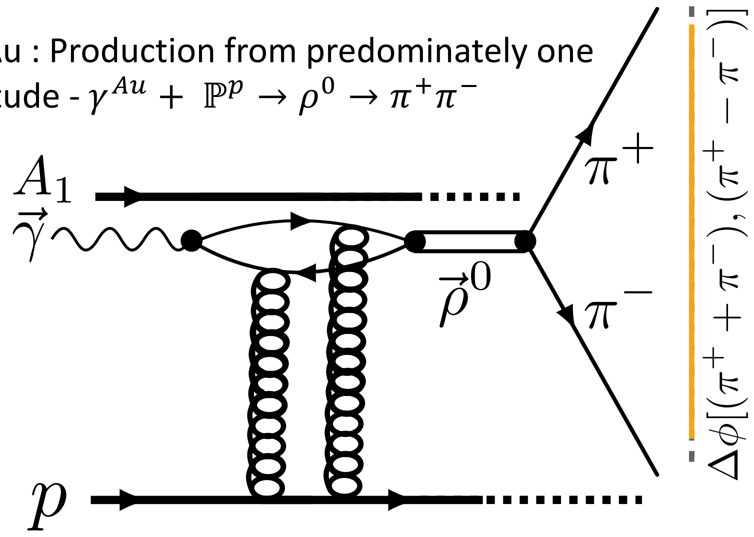
Difference of 4.3σ (stat. & syst.):

- Interference effect is sensitive to the nuclear geometry / gluon distribution



$\Delta\phi$ in Au+Au, U+U, and p+Au Collisions

In p+Au : Production from predominately one amplitude - $\gamma^{Au} + \mathbb{P}^{p} \rightarrow \rho^0 \rightarrow \pi^+\pi^-$



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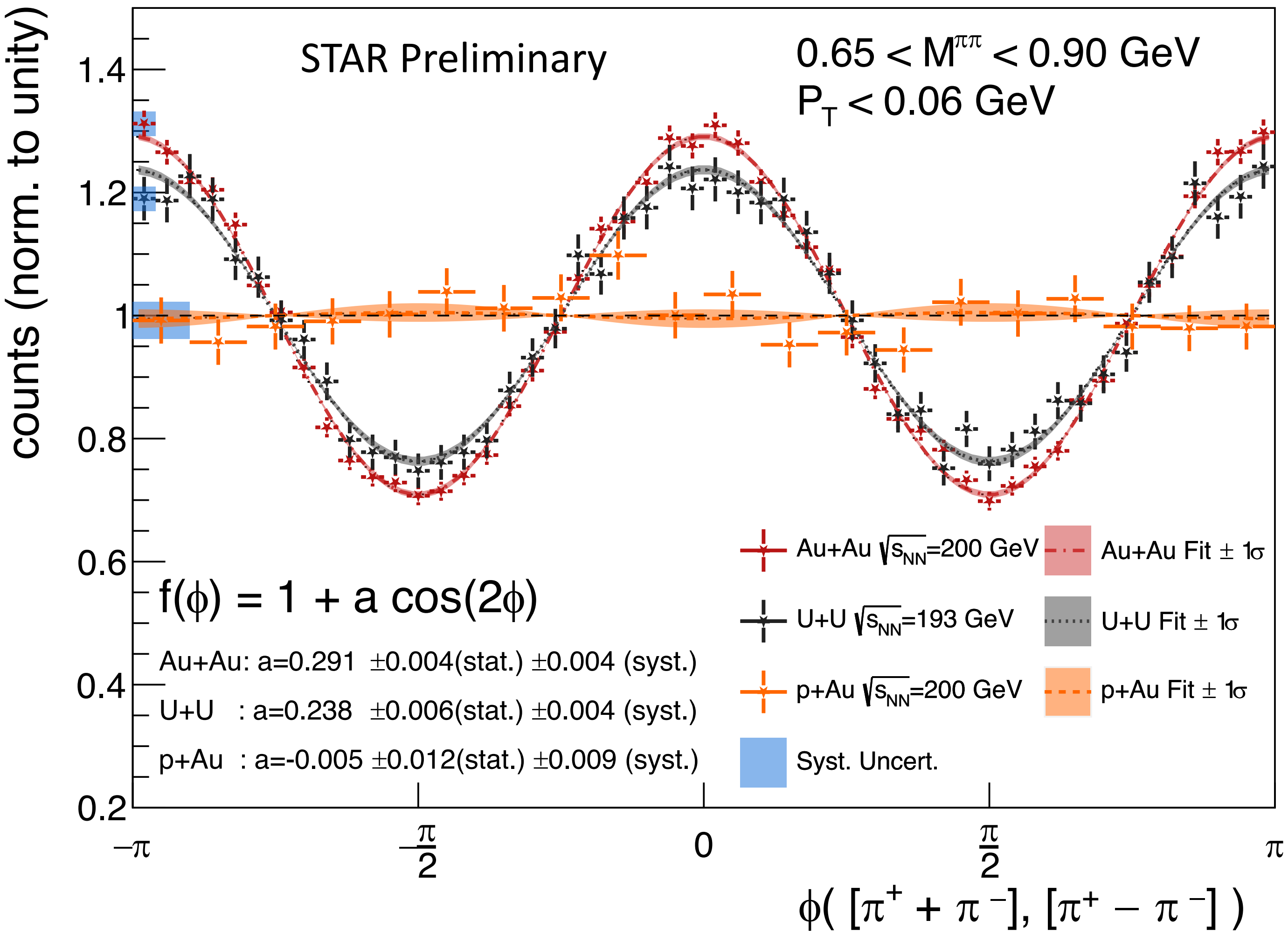
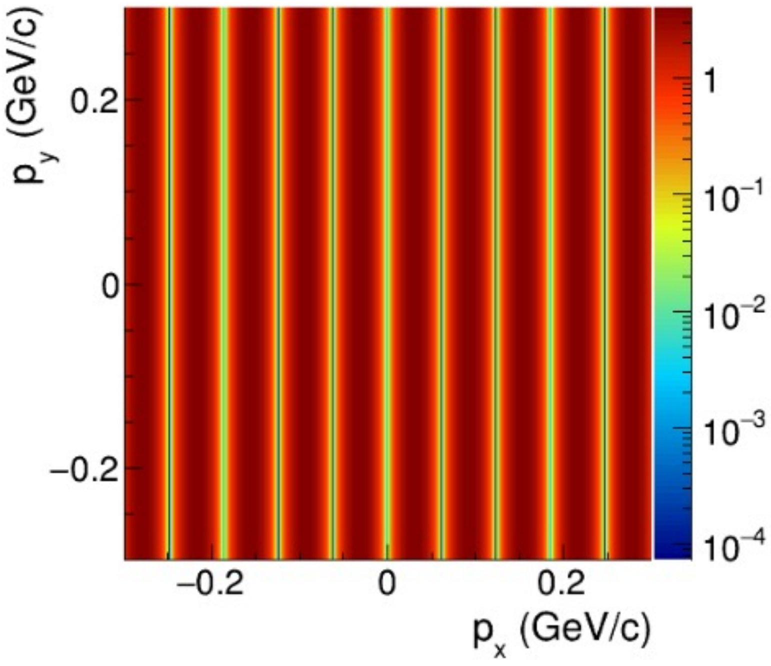


Interference 'turns off' in p+Au

Tomographic Technique

Motivation for 2D Analysis :P_x vs P_y

- Photon polarization is aligned with $\vec{b}$ (exactly for point source)
- Two source interference takes place in x-axis (impact parameter direction)

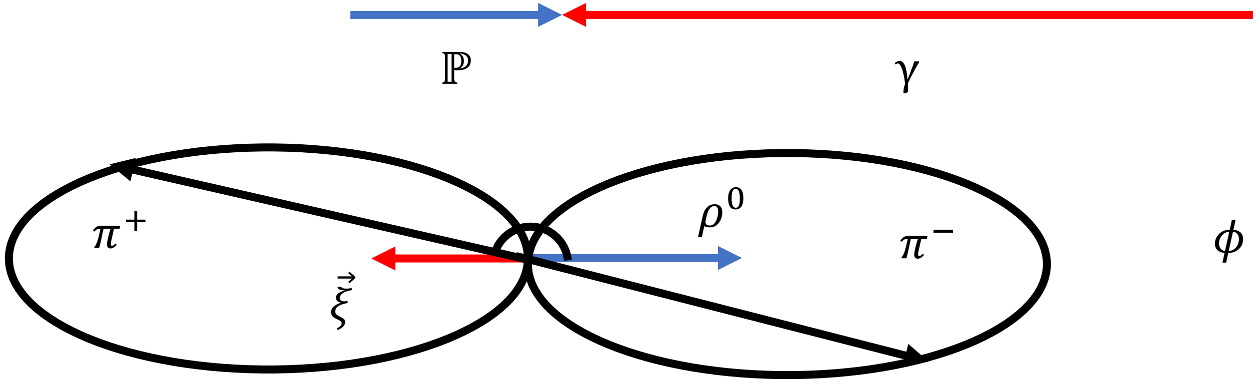


- Interference pattern disappears in P_y direction
- Due to polarization of the ρ^0, daughter pions aligned with photon polarization.
- Express ρ^0 transverse momentum in 2D:
  - $P_x = p_T \times \cos\phi$
  - $P_y = p_T \times \sin\phi$

Phys. Rev. D 103, 033007 (2021), https://arxiv.org/abs/2006.12099

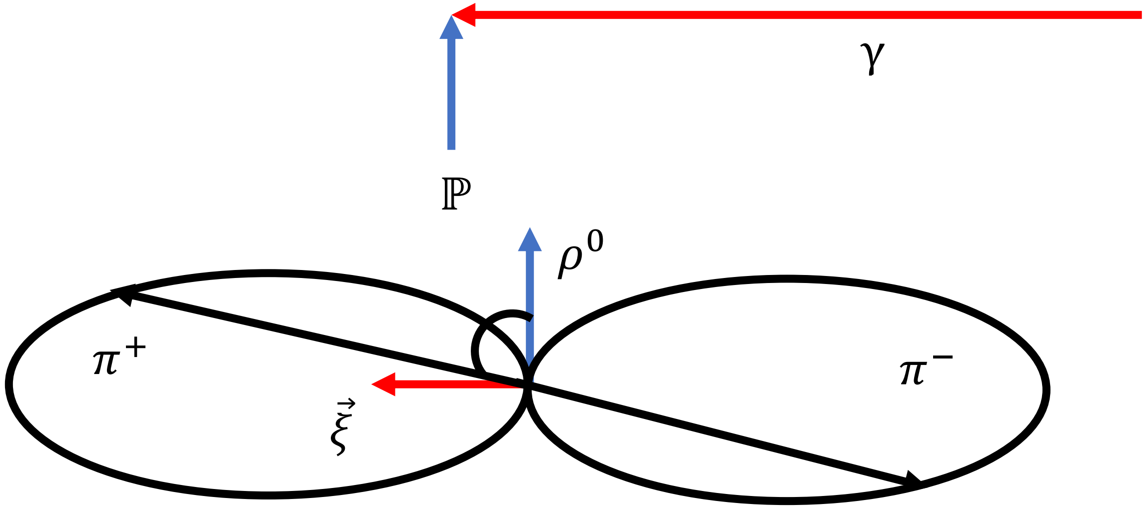
Interference Reveals Event Configurations

- Case I : Photon & Pomeron are (anti-) parallel



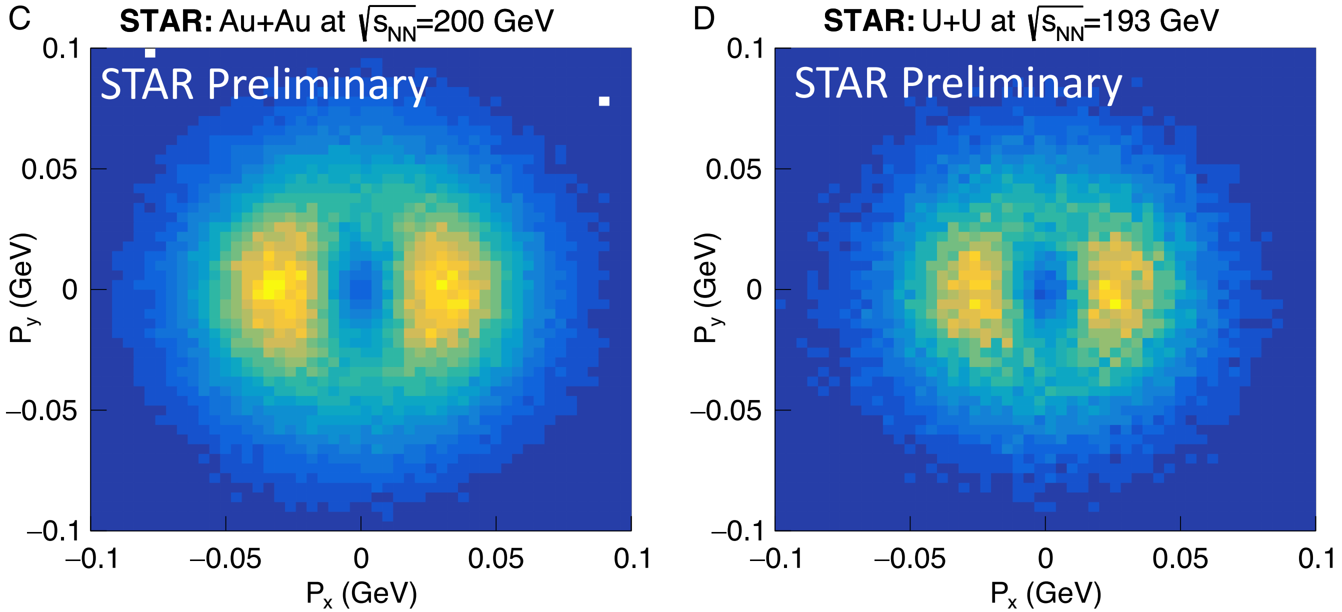
$\phi \approx 0, \pi$

- Case II : Photon & Pomeron are perpendicular



$\phi \approx \pm\pi/2$

2D "Imaging" : Clear difference in P_x vs. P_y



- Express ρ^0 transverse momentum in two-dimensions:
  - $P_x = p_T \times \cos\phi$
  - $P_y = p_T \times \sin\phi$

- Clear asymmetry in P_x vs. P_y due to interference effect in both Au+Au and U+U
- Illustrated "2D" tomography

Nuclear radius is too large?

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.

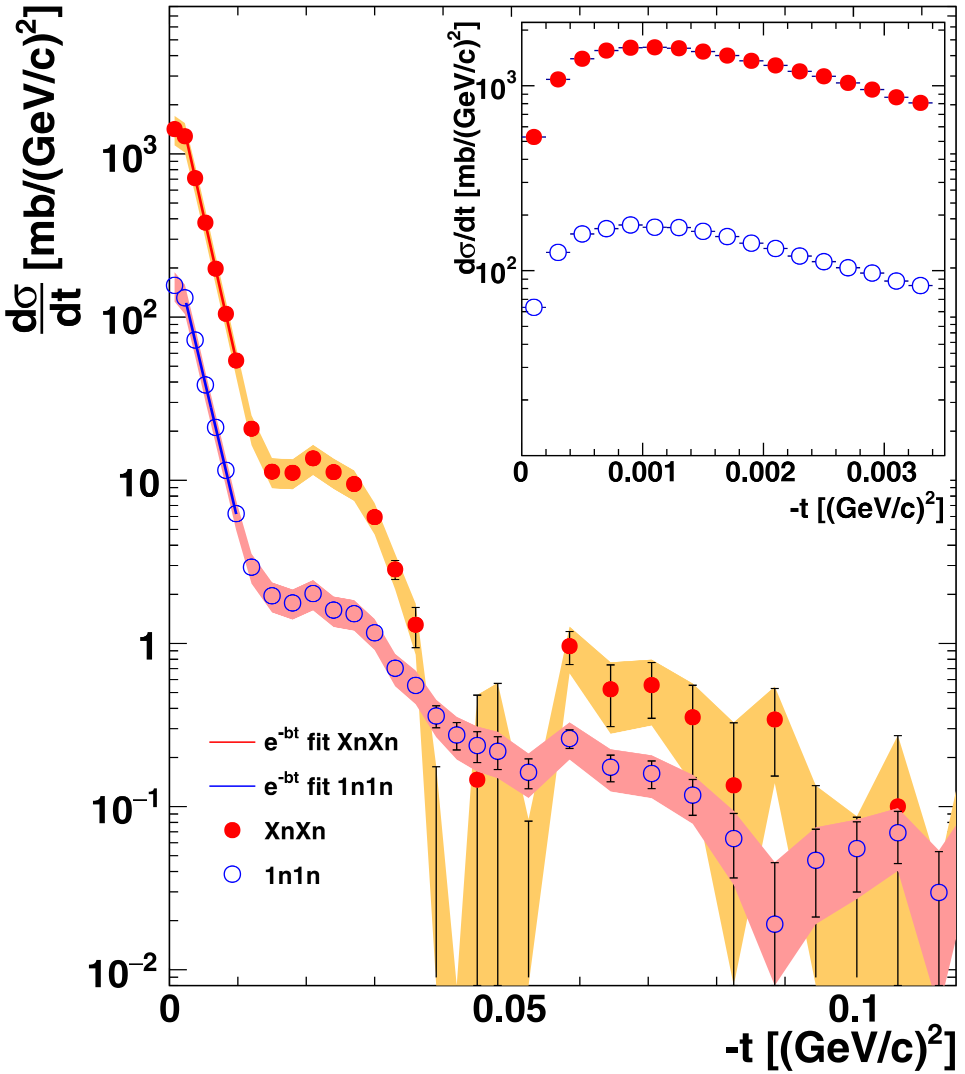


Photo-nuclear measurements have historically produced a |t| slope that corresponds to a **mysteriously large source!**

STAR (2017): |t| slope = $407.8 \pm 3 (GeV/c)^{-2}$
ALICE (Pb) : |t| slope = $426 \pm 6 \pm 15\ (GeV/c)^{-2}$
→ Effective radius of >8 fm?!?
($R_{Au}^{charged} \approx 6.38$ fm, $R_{Pb}^{charged} \approx 6.62$ fm)

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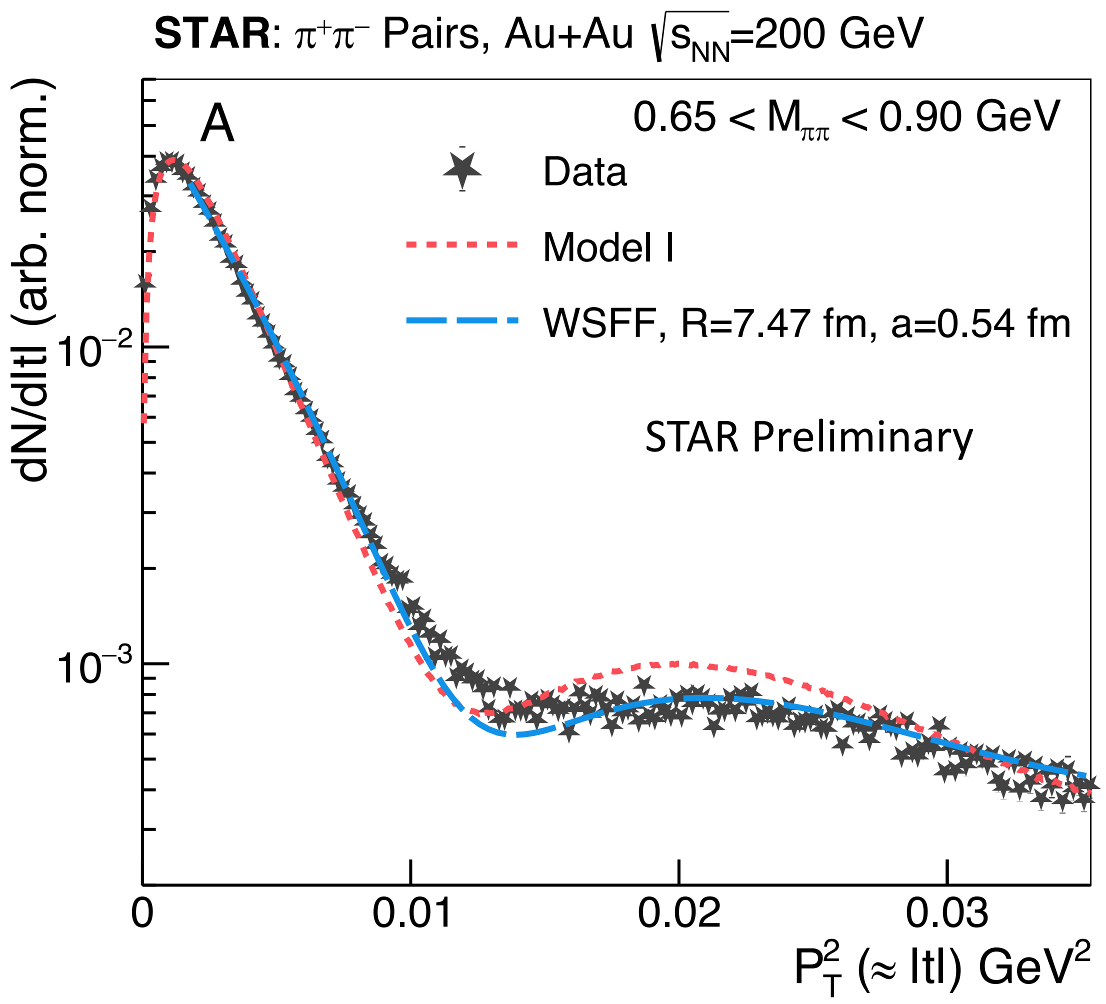

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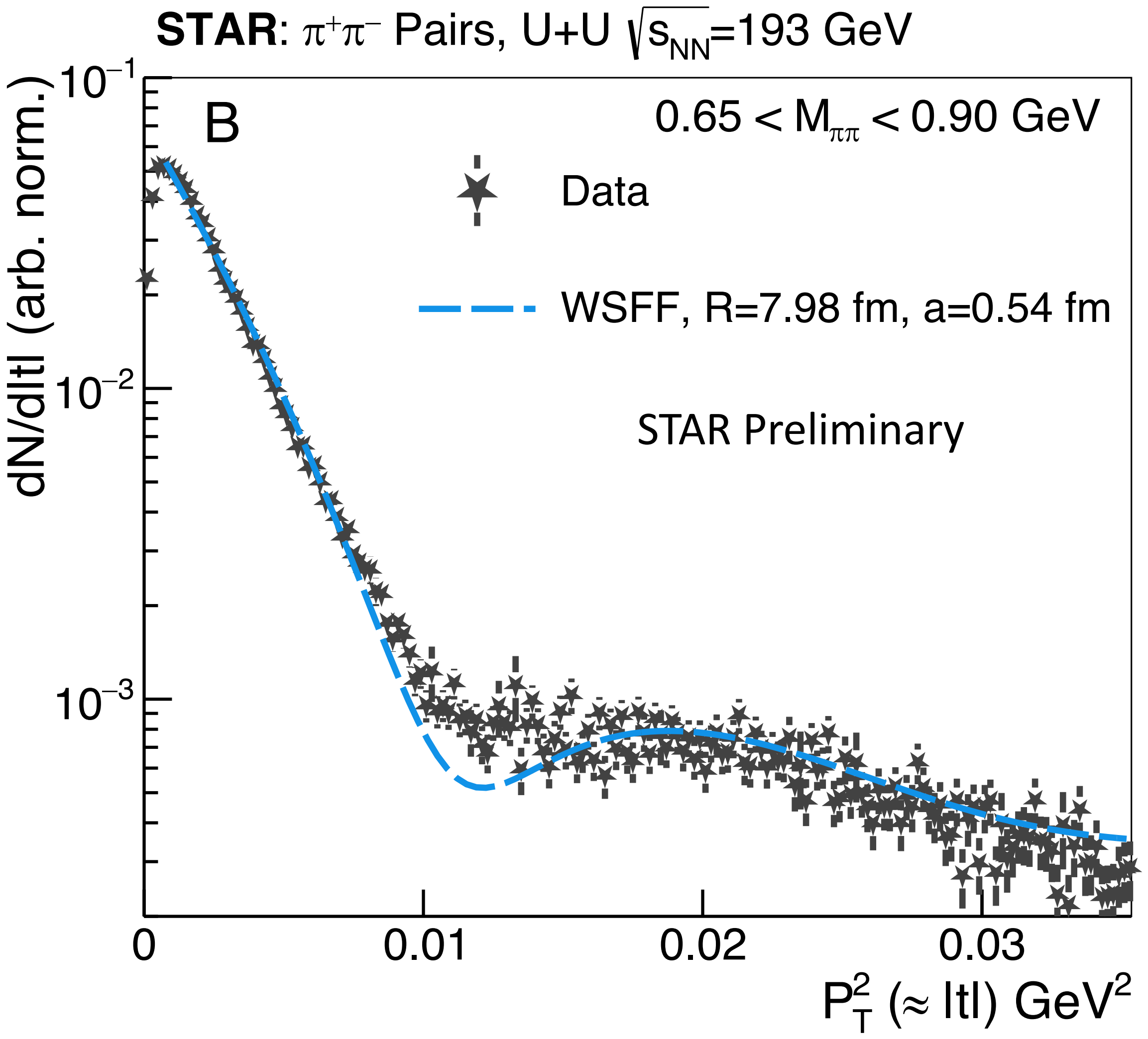

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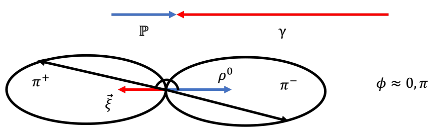
→ Effective radius of >8 fm?!?
($R_{Au}^{charged} \approx 6.38$ fm, $R_{Pb}^{charged} \approx 6.62$ fm)

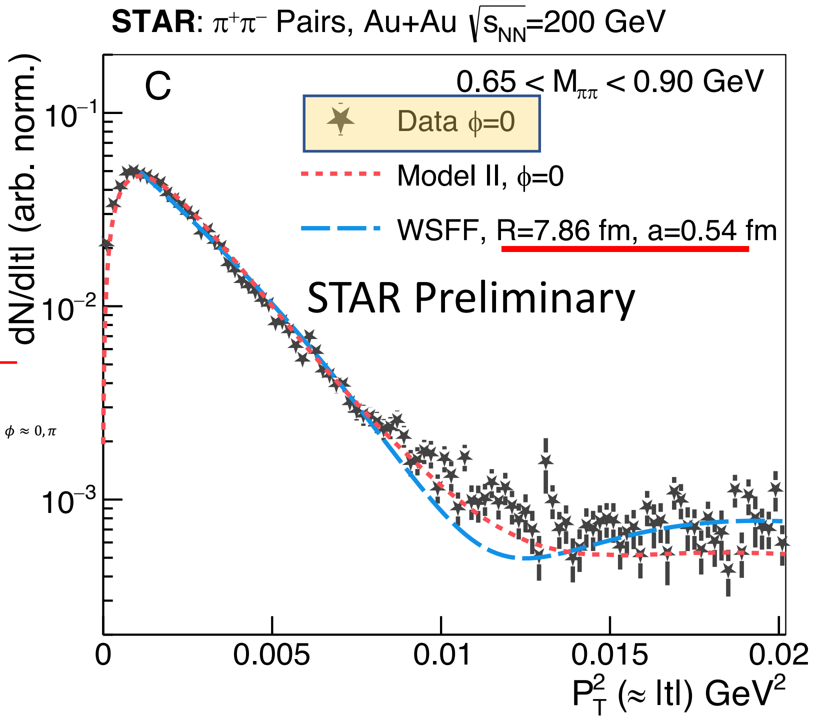
- Is this a deficiency of the exponential fit?
- Use a Woods-Saxon instead, radius is still >1 fm too big

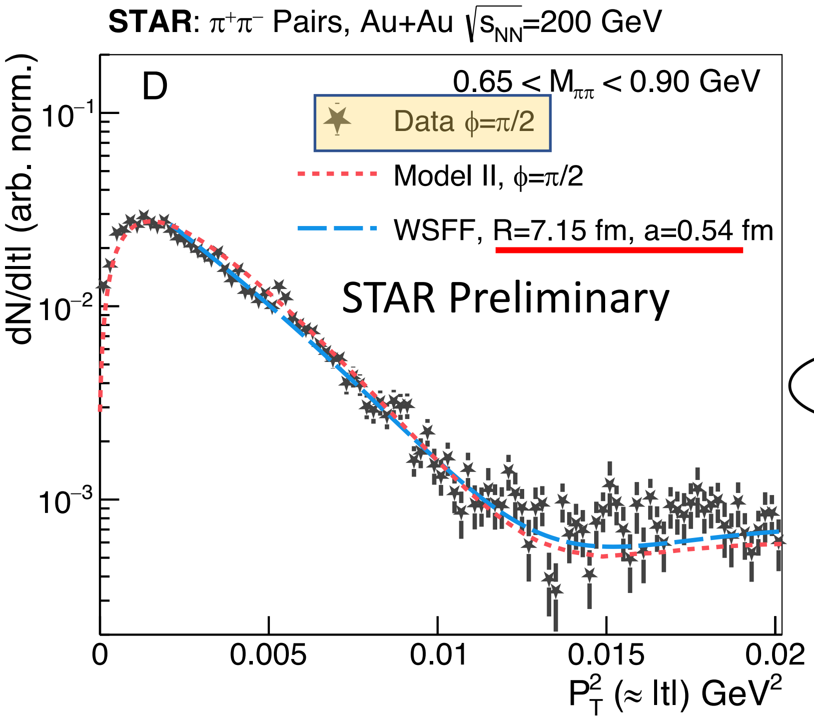
- Uranium has the same issue, >1 fm larger than charge radius ($R_{U}^{charged} \approx 6.81$ fm)

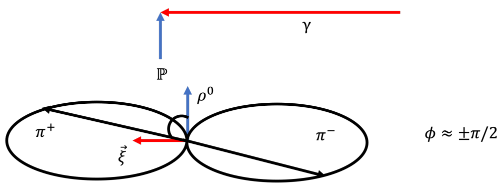
|t| vs. ϕ, which radius is 'correct'?

Now instead of p_x and p_y lets look at $|t|$ with a 2D approach







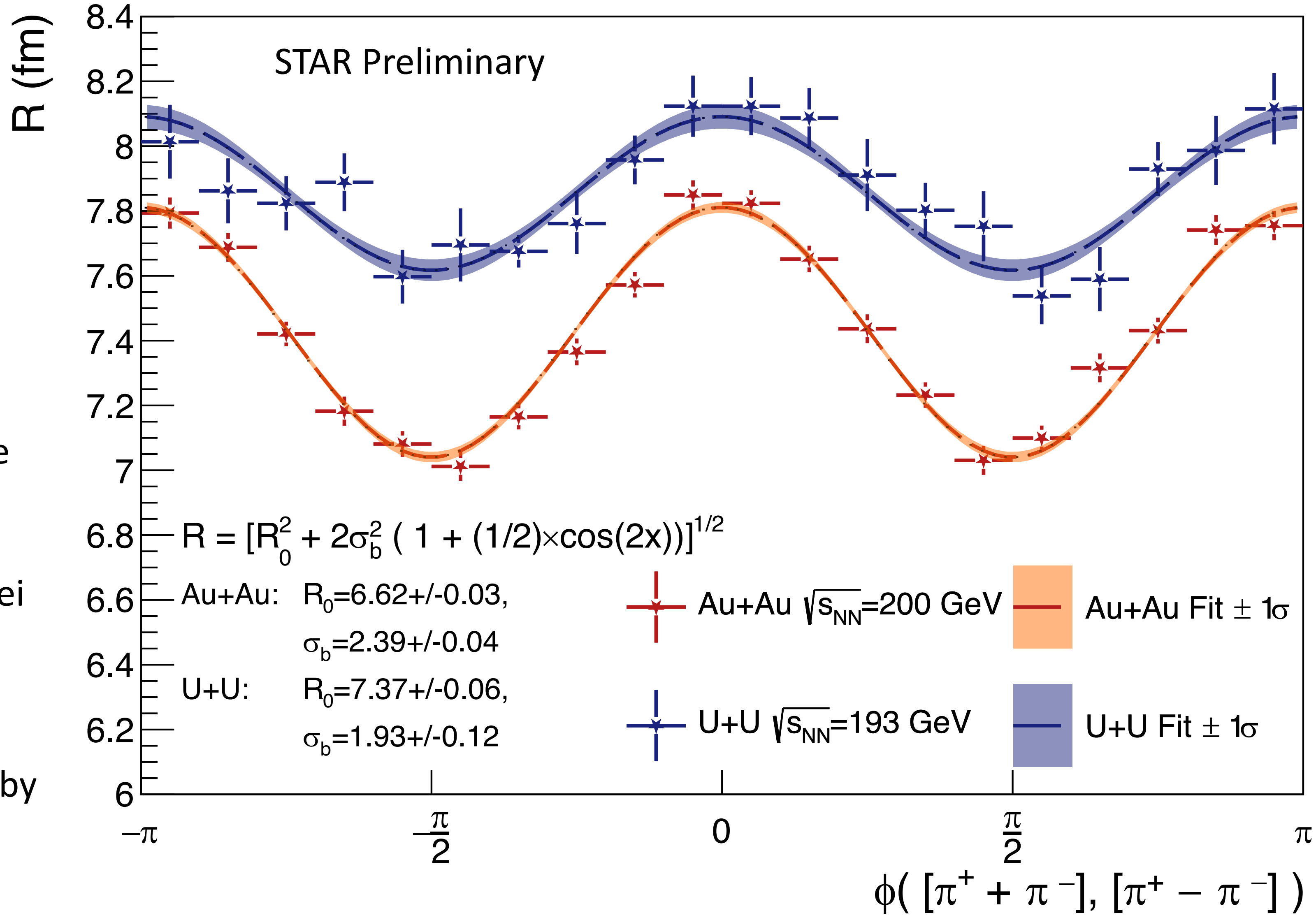


- Drastically different radius depending on ϕ, still way too big
- Notice how much better the Woods-Saxon dip is resolved for $\phi = \pi/2$ -> experimentally able to **remove photon momentum, which blurs diffraction pattern**
- **Can we extract the 'true' nuclear radius from |t| vs. ϕ information?**

|t| vs. ϕ, the whole picture?

- Strong $\cos 2\phi$ modulation
- At $\phi = \pm{}^{\pi}/_{2}$
    - Smearing from photon momentum is removed*
    - Interference effect, which modifies |t| spectra, is at a minimum
- **Goal: extract R_0**
- Correct for the polarization 'resolution' – similar to event plane resolution correction for flow
- Finally, need to correct for depolarization from finite size nuclei (4%) and size of probe (transverse size of the ρ^0 wavefunction)

*: The $\rho^0 \rightarrow \pi^+\pi^-$ decay is governed by a spherical harmonic - not perfectly aligned with the photon momentum



Nuclear Radius Comparison

[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).

	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)	0.09 ± 0.02(stat.) ± 0.05(syst.)	0.41 ± 0.03 (stat.) ± 0.05 (syst.) (Note: for Pb $\approx$ 0.3)

*STAR Preliminary

Precision measurement of nuclear interaction radius at high-energy
Measured radius of Uranium shows evidence of (relatively) large neutron skin

Summary (1)

1. Observed (6.7σ) $\cos 4\Delta\phi$ angular modulation in linear polarized $\gamma\gamma \rightarrow e^+e^-$ (Breit-Wheeler) process
   - <u>Colliding photons are linearly polarized</u>
   - First laboratory evidence for vacuum birefringence
2. First measurements of $\Delta\phi$ modulations in $\gamma\mathbb{P} \rightarrow \rho^0 \rightarrow \pi^+\pi^-$ process
   - Strong $\cos 2\Delta\phi$ modulations due to photon polarization
   - Measurement in Au+Au and U+U collisions
3. Novel Tomographic Technique
   - <u>Experimentally demonstrate sensitivity to gluon distribution within nucleus</u>
   - Measurement of nuclear radii in high-energy heavy ions (Au and U)

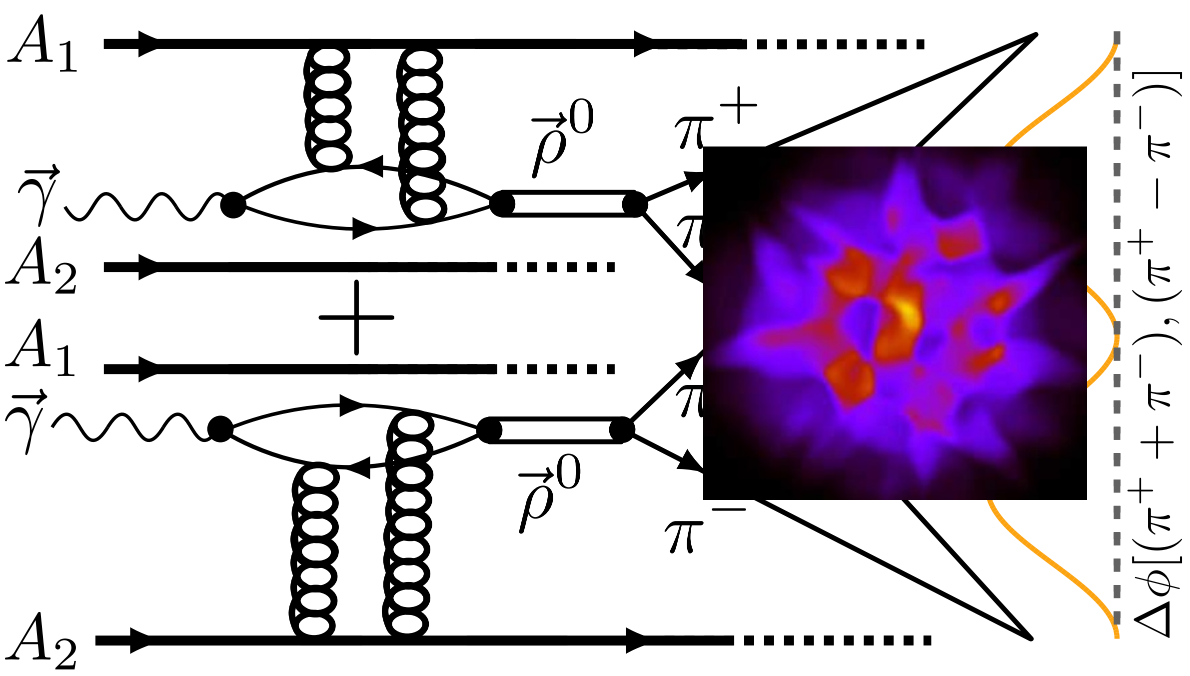
Many open questions from both experimental and theoretical sides

Exciting opportunities at RHIC, LHC, and future EIC

Opportunities in RHIC Isobar Data

STAR Isobar data : Minbias triggers + UPC J/ψ

- Comparison of Zr+Zr vs. Ru+Ru
- Measurement of photonuclear process in peripheral to central MB collisions
- Comparison of $\rho^0 \to \pi^+\pi^-$ vs. $J/\psi \to l^+l^-$ (better from theoretical side)
- Effect is due to interference → can interaction with medium induce decoherence?

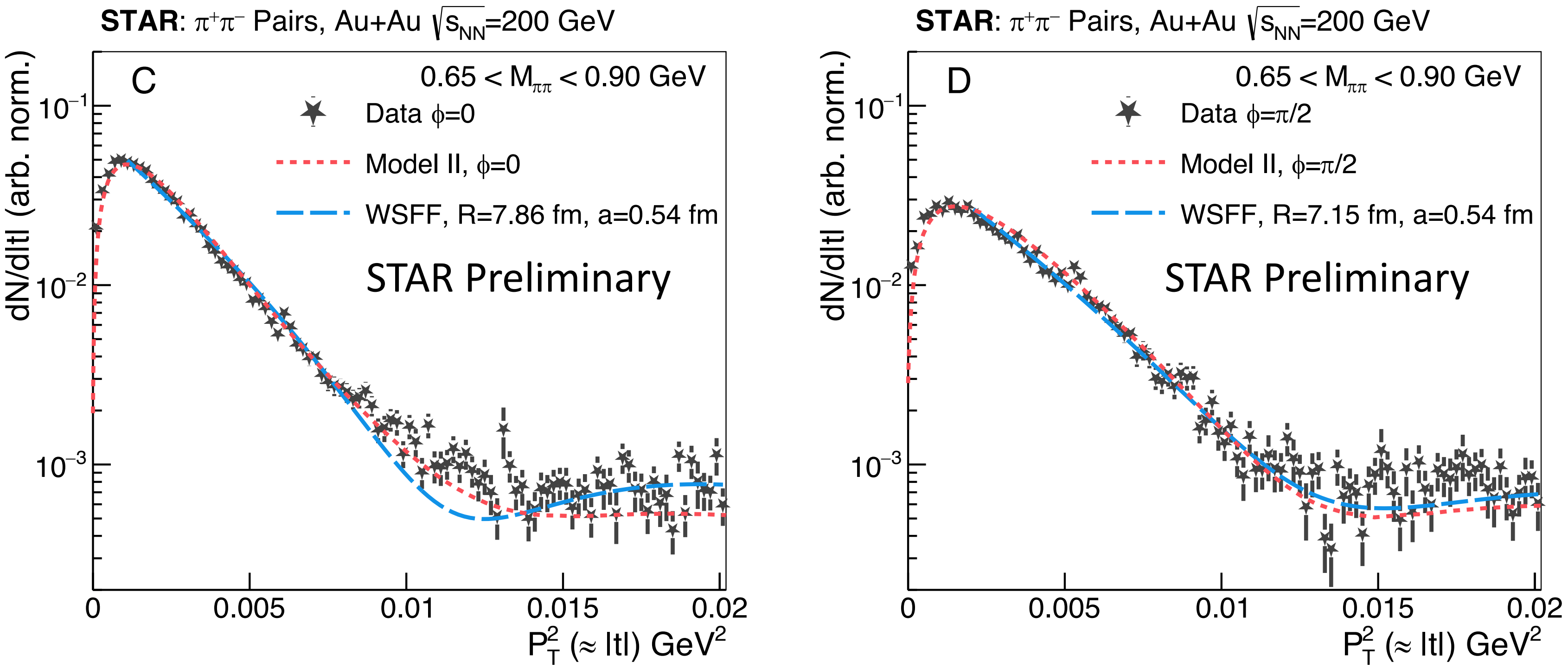


- Unlike leptons, π interact via strong force
- Presence of strongly interacting medium → **wavefunction collapse?**
  - **I.e. no interference?**
  - **Difference between pion vs. lepton final states?**

Additional Slides

Data v.s. Model Revisited (Au+Au)

- Model II with interference effect accurately describes |t| spectra for $\phi = 0$ and $\phi = \pm\pi/2$ cases
- Model uses $R_{Au} = 6.38$ fm (charge radius)
- **Interference effect is essential for proper interpretation**



Photon Polarization → Destructive Interference

- Observation of **DESTRUCTIVE** interference in vector meson production

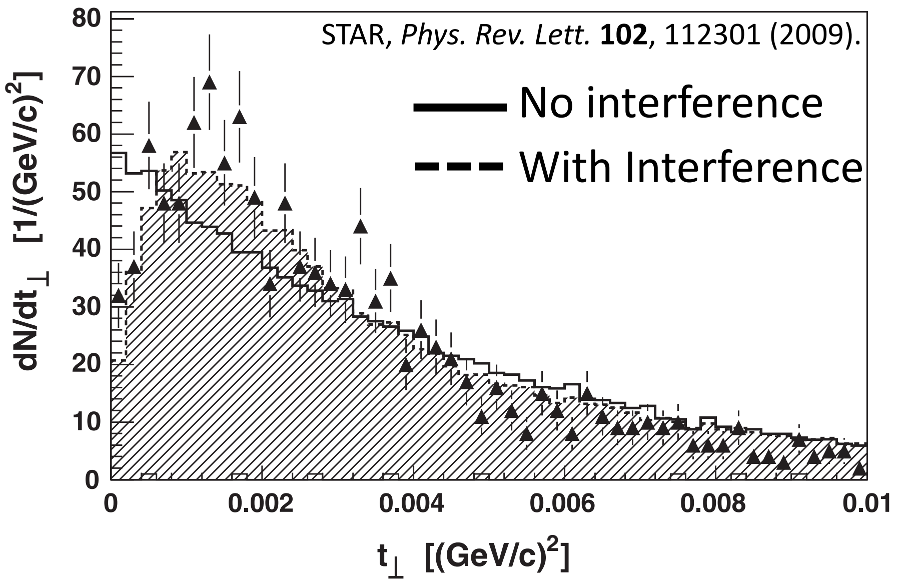


FIG. 2. Raw (uncorrected) ρ^0 $t_\perp$ spectrum in the range $0.0 < |y| < 0.5$ for the MB data. The points are data, with statistical errors. The dashed (filled) histogram is a simulation with an interference term (“Int”), while the solid histogram is a simulation without interference (“NoInt”). The handful of events histogrammed at the bottom of the plot are the wrong-sign ($\pi^+\pi^+ + \pi^-\pi^-$) events, used to estimate the combinatorial background.

Klein, S. R. & Nystrand, J. *Phys. Rev. C* **60**, 014903 (1999).

Klein, S. R. & Nystrand, J. *Phys. Rev. Lett.* **84**, 2330–2333 (2000).

- Explanation of destructive interference attributed to odd parity under $A_1 \Leftrightarrow A_2$ exchange

- However, strictly speaking **real** photons do not have well defined parity
  - → Photon intrinsic parity is defined by the radiation field

Yang, C. N. *Phys. Rev.* **77**, 242–245 (1950).

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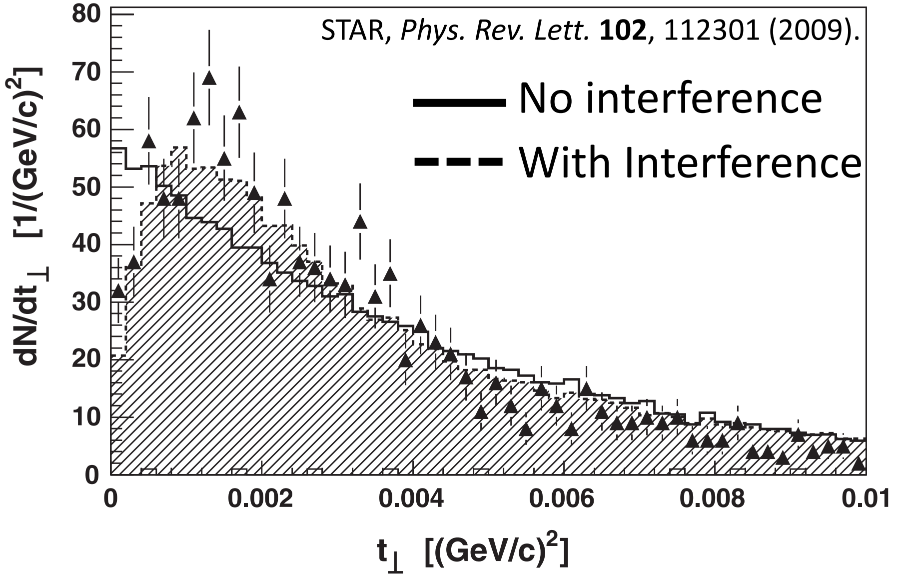

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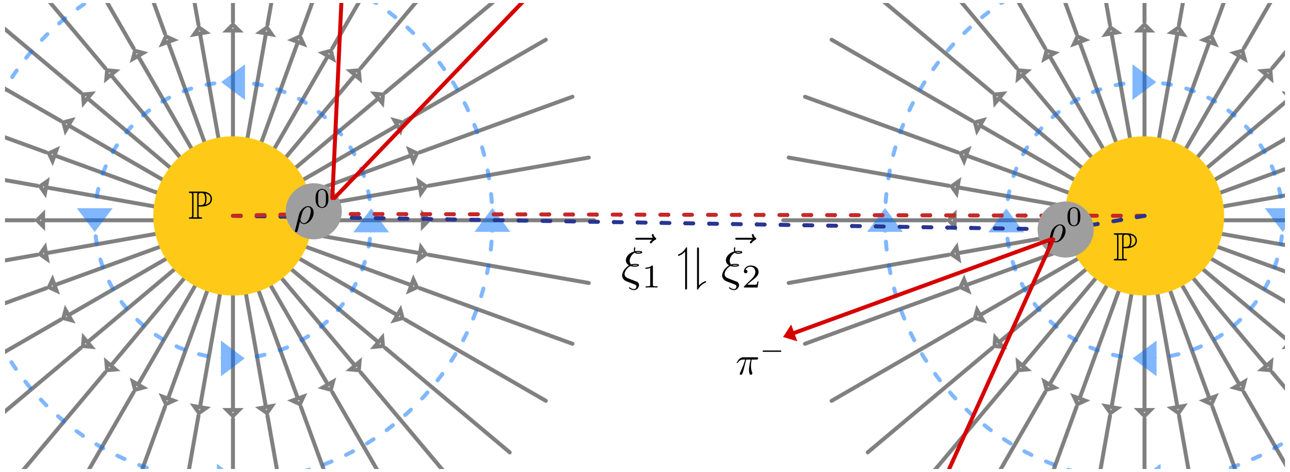


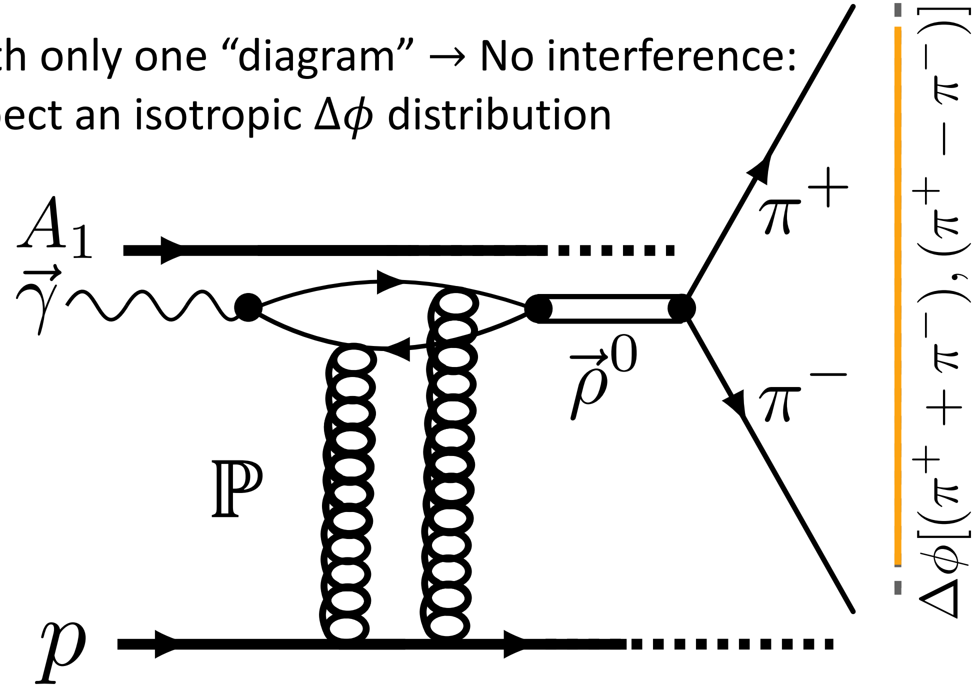
- Production at **zero** P_T must have anti-parallel photon polarization
- Provides an intuitive understanding of destructive interference

Can we "turn off" the interference effect?

In p+Au there is a significant difference in charge (Z) between the colliding beams:

- Photon emission from the field of the proton is Z^2 down compared to a photon emitted from the field of the Au
- Production from predominately one amplitude - $\gamma^{Au} + \mathbb{P}^{p} \rightarrow \rho^0 \rightarrow \pi^+\pi^-$

With only one "diagram" → No interference:
Expect an isotropic $\Delta\phi$ distribution



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

$\Delta\phi$ in Au+Au and U+U Collisions

Ultra-peripheral events from:

- Au+Au at $\sqrt{s_{NN}} = 200$
- U+U at $\sqrt{s_{NN}} = 193$
- At low p_T where the modulation is strongest ($p_T < 60\ MeV/c$)

Quantify the difference in strength for Au+Au vs. U+U via a fit:

$$f(\Delta\phi) = 1 + a\ \cos 2\Delta\phi$$

Au+Au :

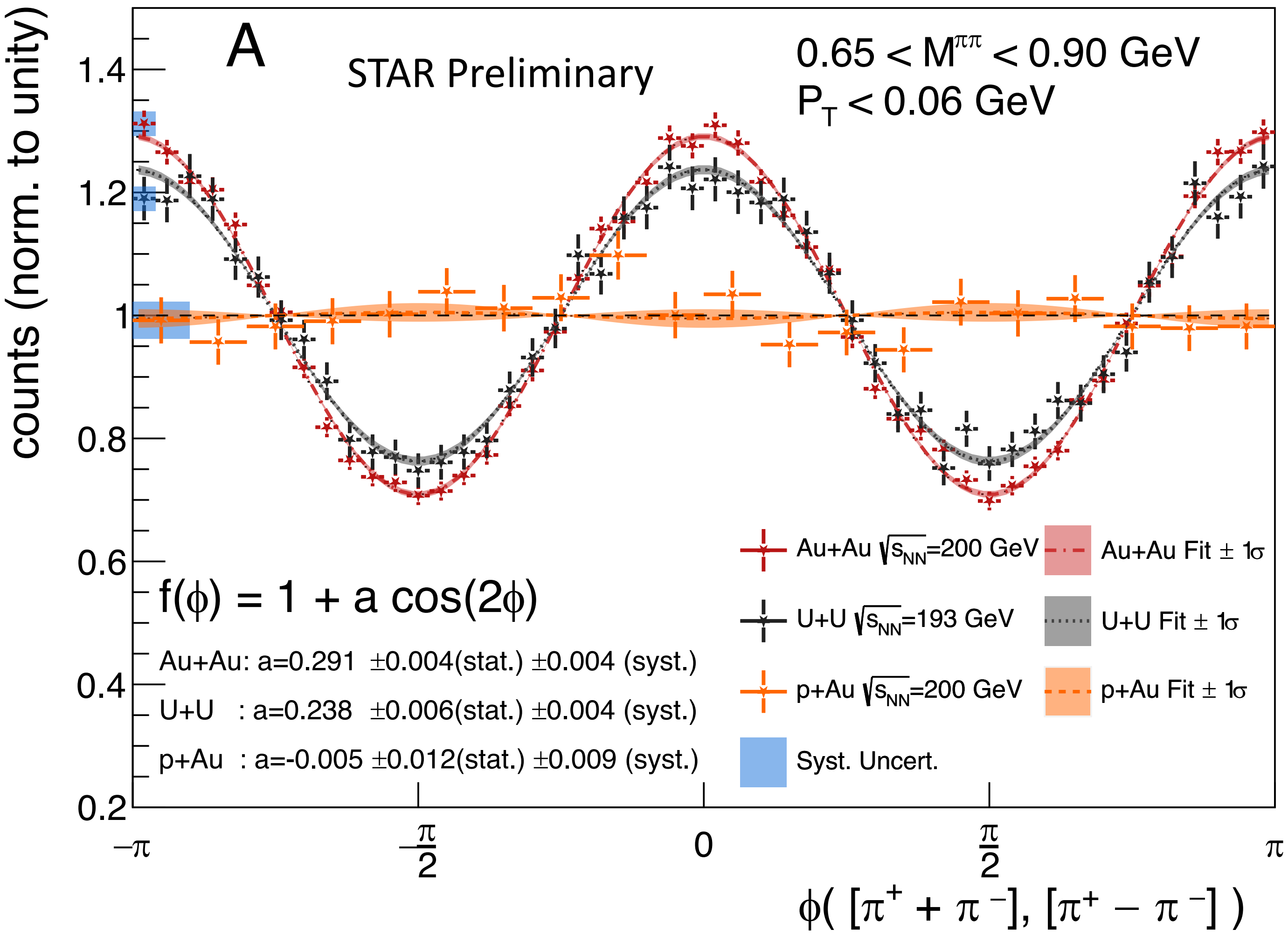
$a = 0.291 \pm 0.004$ (stat) ± 0.004 (syst.)

U+U :

$a = 0.238 \pm 0.006$ (stat) ± 0.004 (syst.)

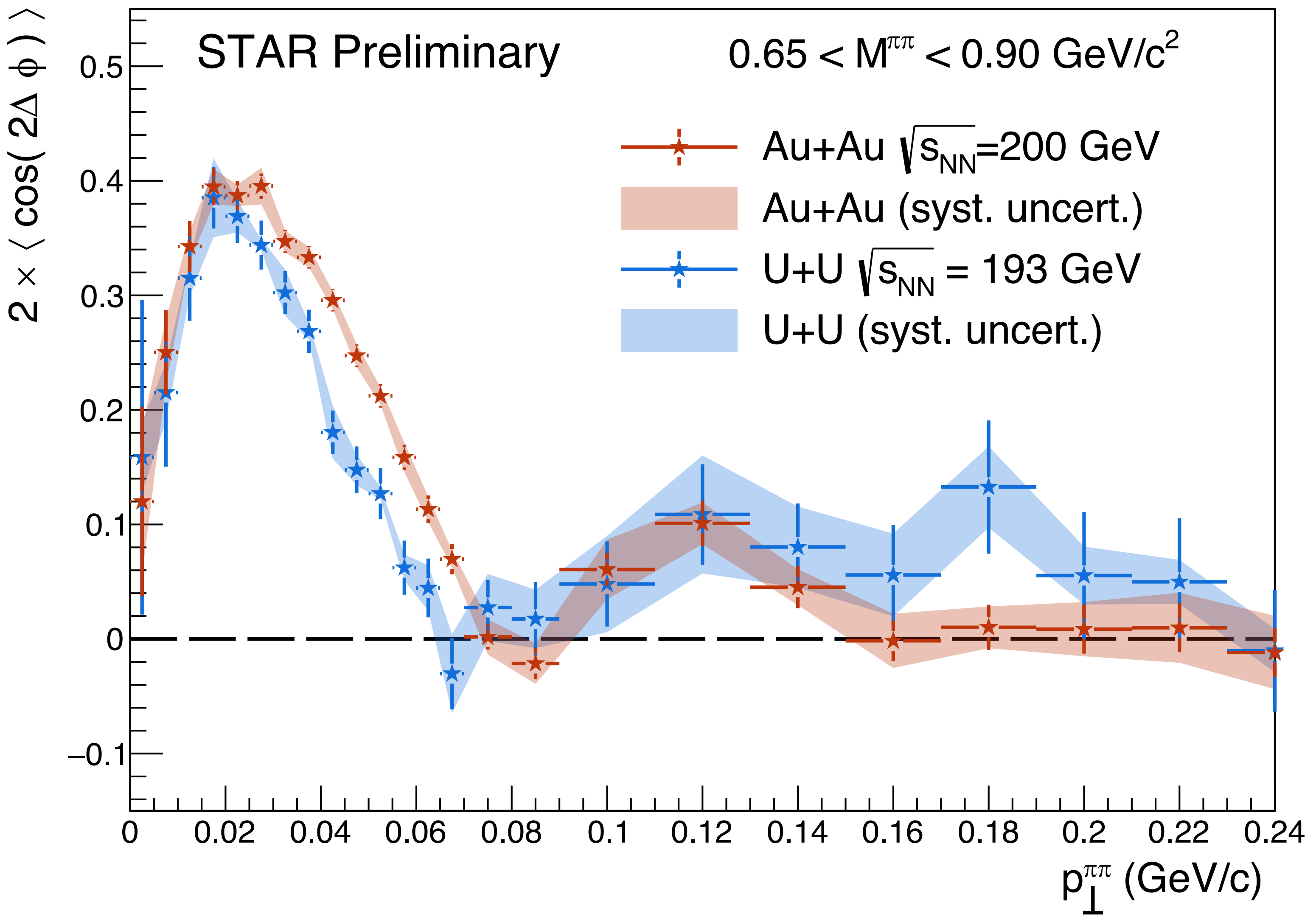
Difference of 4.3σ (stat. & syst.):

- Interference effect is sensitive to the nuclear geometry / gluon distribution



Investigate the interference effect in more detail through p_T structure

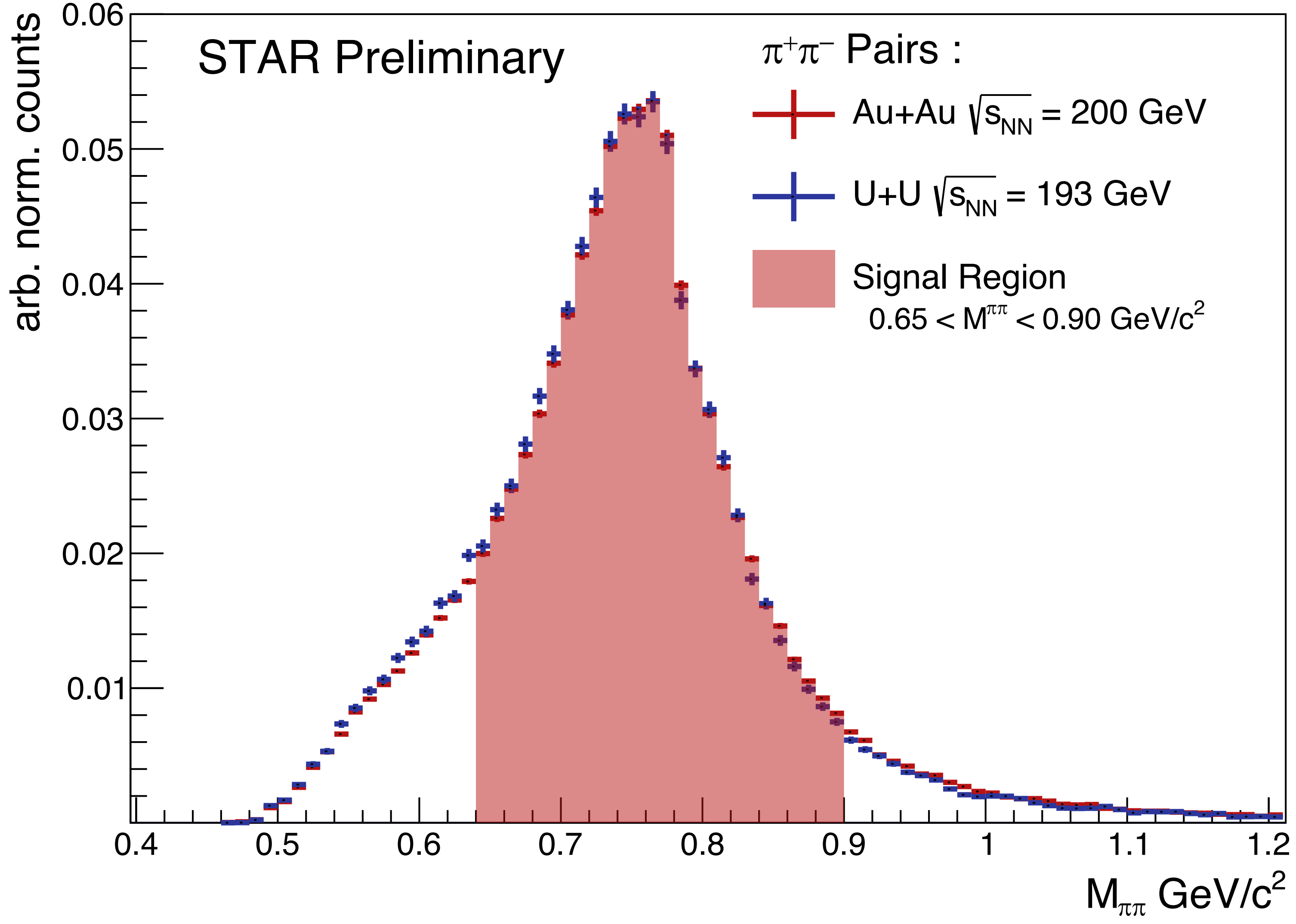
$\cos 2\Delta\phi$ $vs. p_T$ in U+U and Au+Au



- Strong $\cos 2\Delta\phi$ modulation observed at $\mathrm{p}_T < \sim 60$ MeV/c
- In U+U: Broad second "peak" above 80 MeV/c
- In Au+Au: more definite second peak around $80 < p_T < 160$ MeV/c

- Systematic uncertainty shown in colored band
- Novel input for discriminating coherent + incoherent contributions

Measurements in Au+Au and U+U UPC events

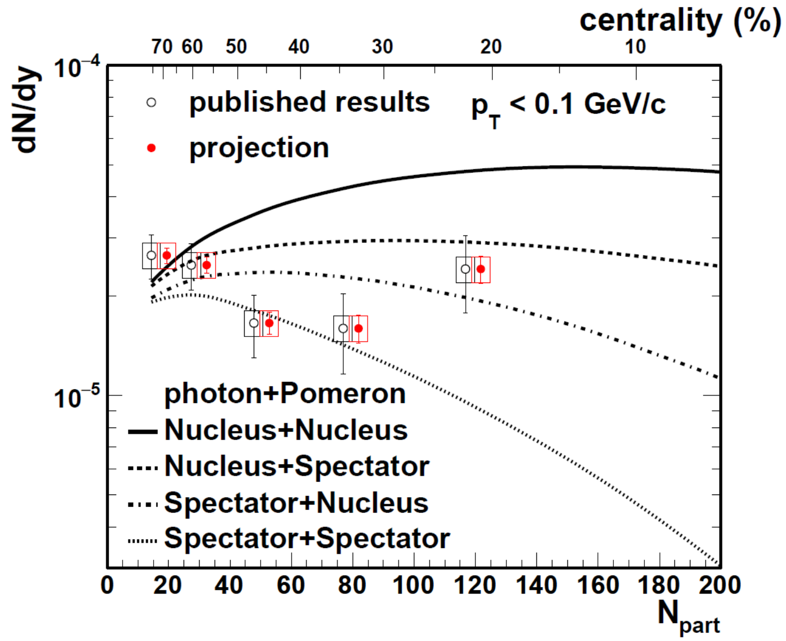


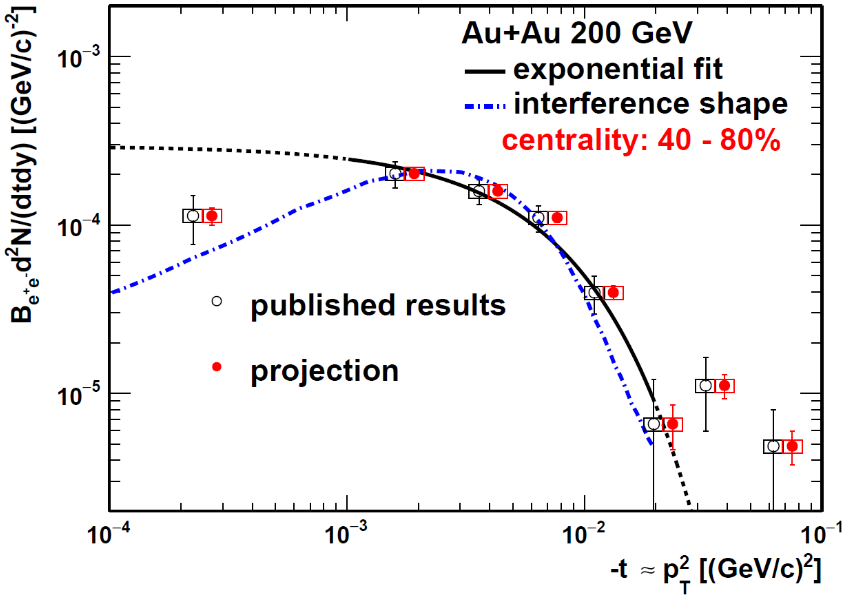
- Clear ρ^0 peak in both Au+Au and U+U UPC events.
- First measurement of diffractive coherent photonuclear production in U+U collisions.
- For the $\Delta\phi$ measurement, we select region around ρ^0 mass with roughly uniform acceptance

Future Tests of Interference Effects

3. Measurement $\Delta\phi$ distribution in non-UPC events

Answer Question: What is coherently interaction?



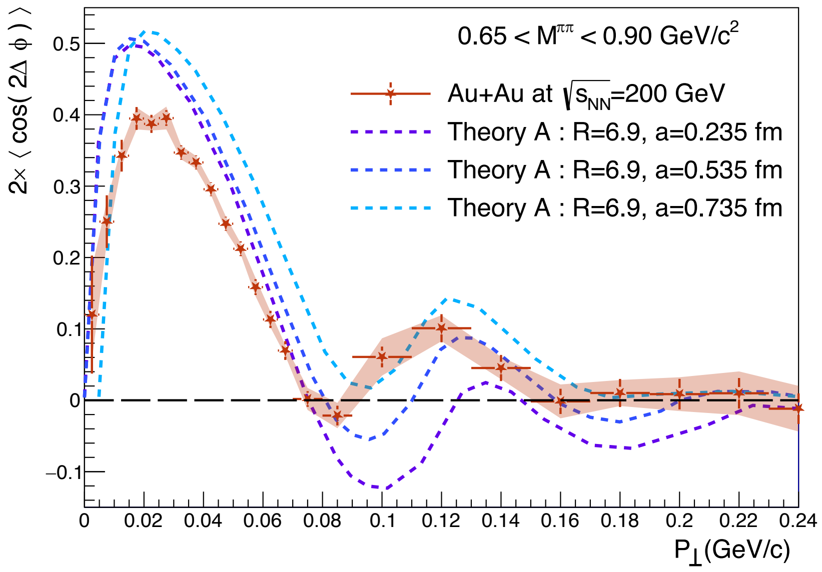


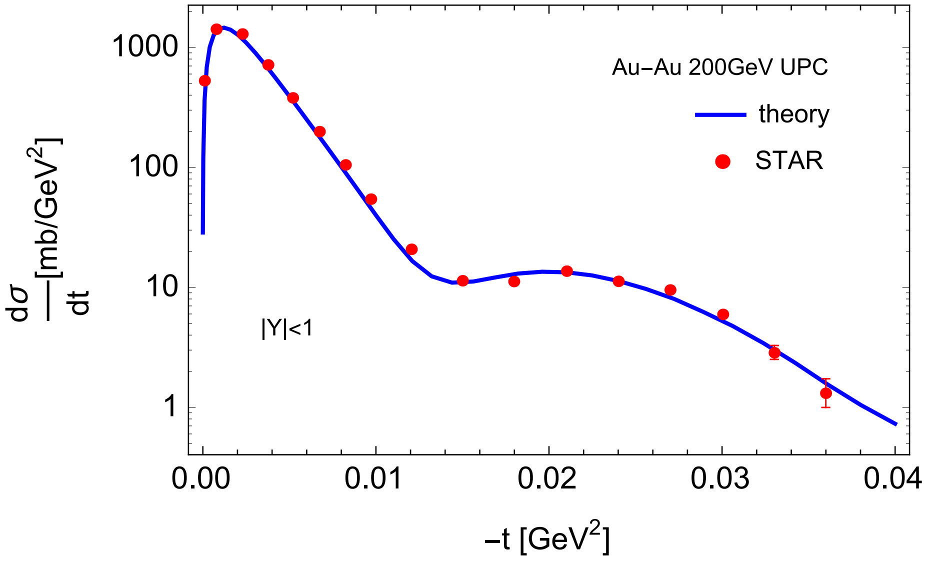
- STAR Measurements of $J/\psi \rightarrow l^+l^-$ in peripheral collisions already indicate interference
- Coherent measurements in peripheral collisions can help distinguish coherent emitter
- $\Delta\phi$ Interference pattern should provide much more information

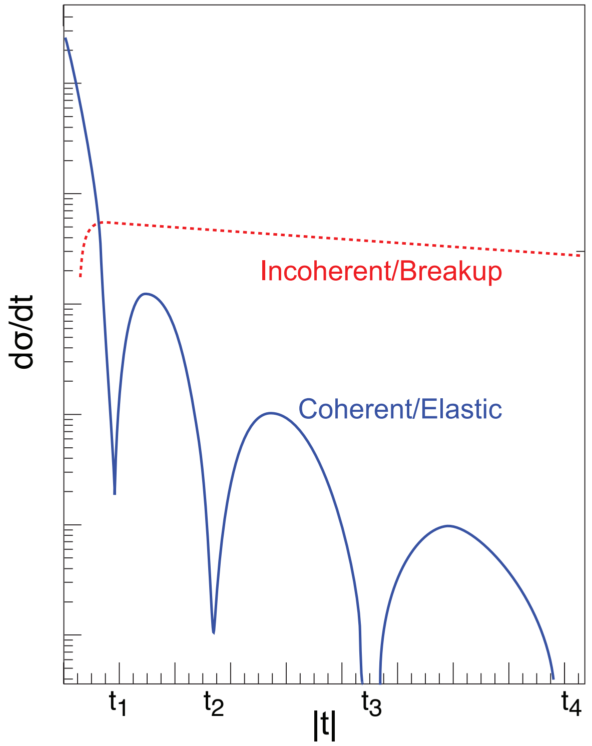
Use interference to separate Coherent/Incoherent

- Experimentally, we observe that incoherent does not contribute to interference pattern (Zero above pT > 160 MeV/c)
- Once quantitative agreement is reached between data & theory for $\Delta\phi$
  → Use interference effect to help disentangle coherent vs. incoherent
  - Simultaneous fit measured spectra (coherent + incoherent) with $\cos 2\Delta\phi$

Separation of coherent vs. incoherent is the essential experimental challenge for EIC measurements







- Proof of concept already carried out in [1], however STAR t spectra had incoherent pre-subtracted using a dipole form factor.

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

Other Polarization Effects

1. Hagiwara, Y., Zhang, C., Zhou, J. & Zhou, Y. Coulomb nuclear interference effect in dipion production in ultraperipheral heavy ion collisions. *Phys. Rev. D* **103**, 074013 (2021).

- $\Delta\phi$ is sensitive to Coulomb-nuclear interference

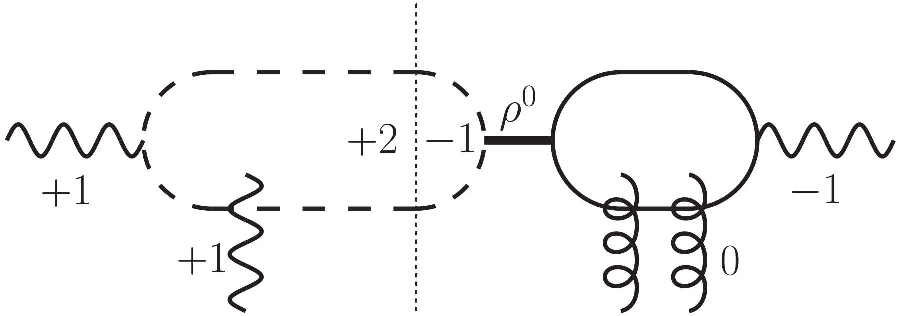
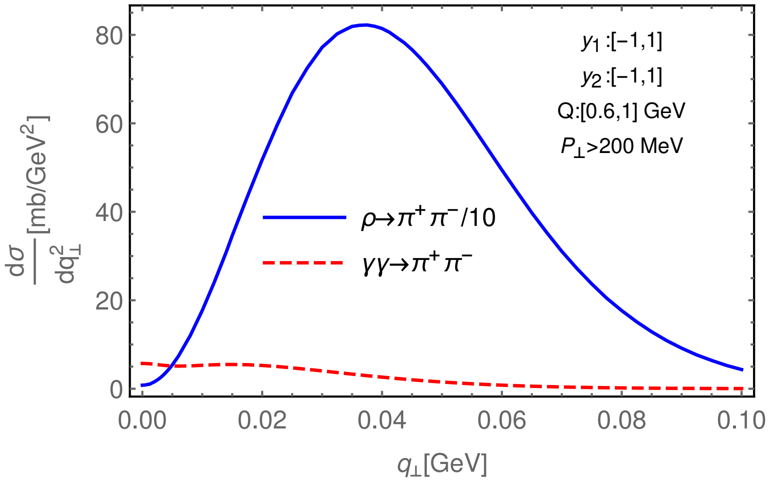
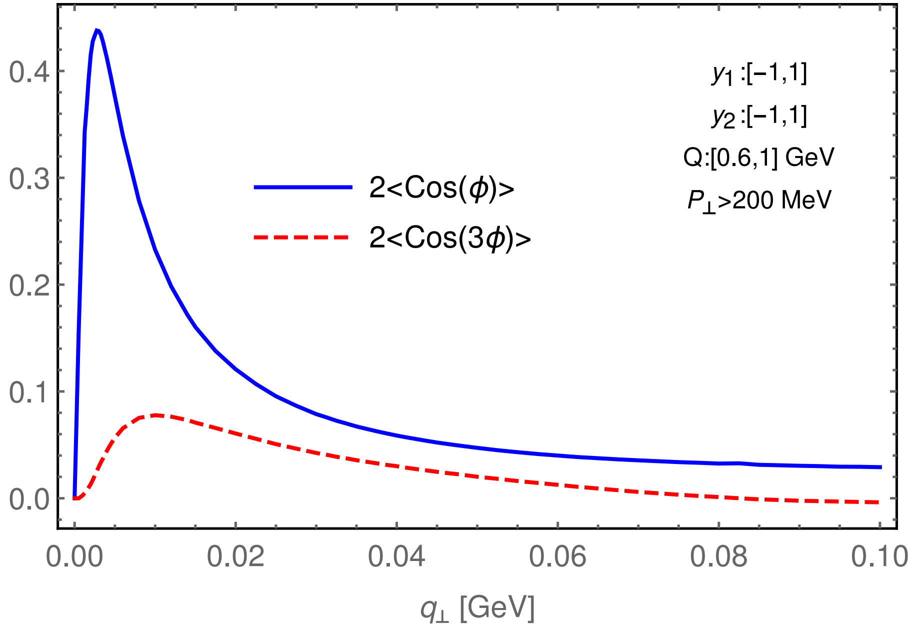


FIG. 1: An illustration of the mechanism giving rise to $\cos 3\phi$ azimuthal asymmetry. The solid line represents the quark propagator, while the pion propagator is indicated by the dashed line.

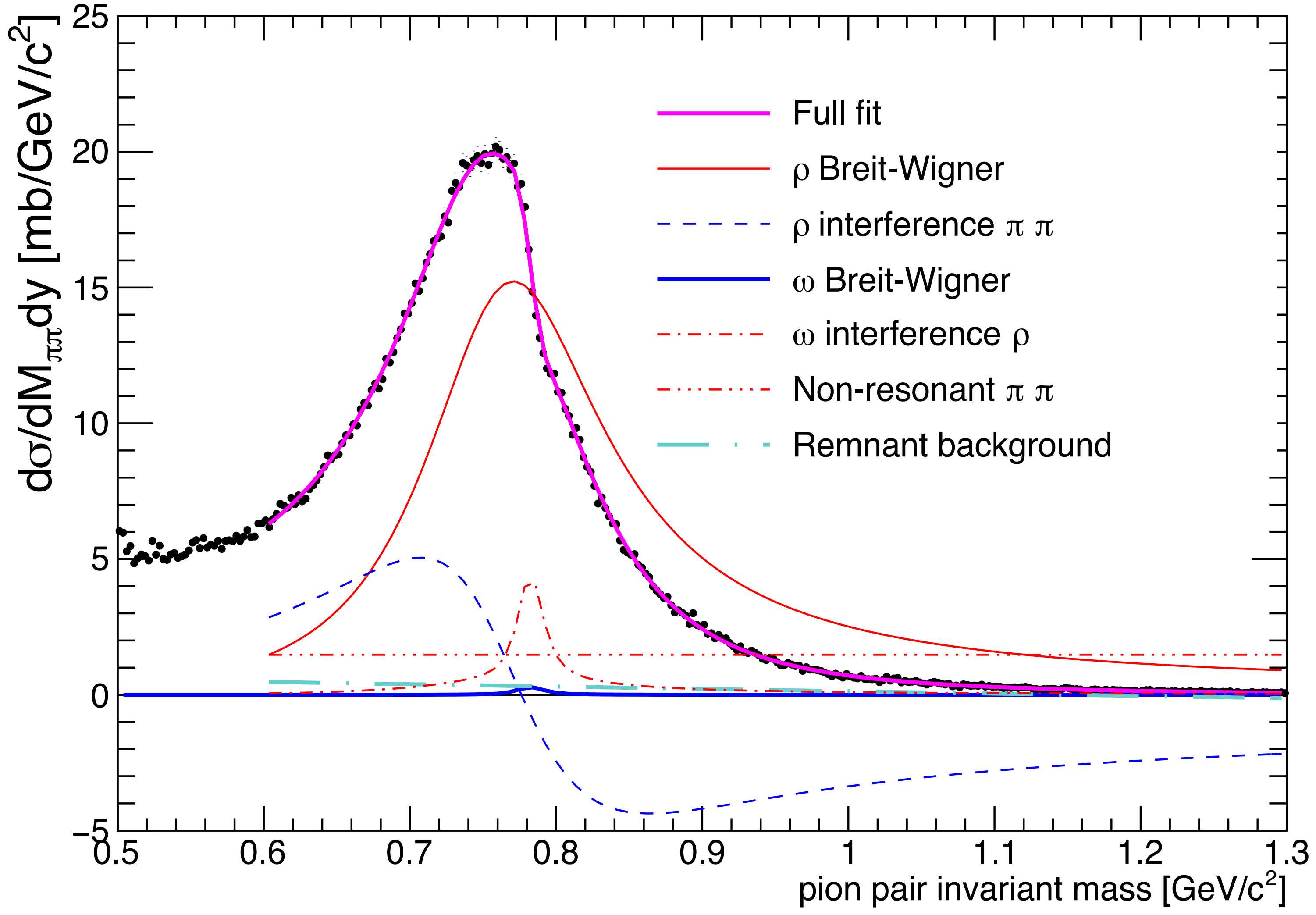




Coulomb-nuclear interference should produce odd harmonics ($\cos\phi$ & $\cos 3\phi$)

NOTE: Existing STAR measurement applies charge shuffling to simplify corrections
→ odd harmonics are zero by construction

Measurements in Au+Au and U+U UPC events



Not only ρ^0, interference from other states:

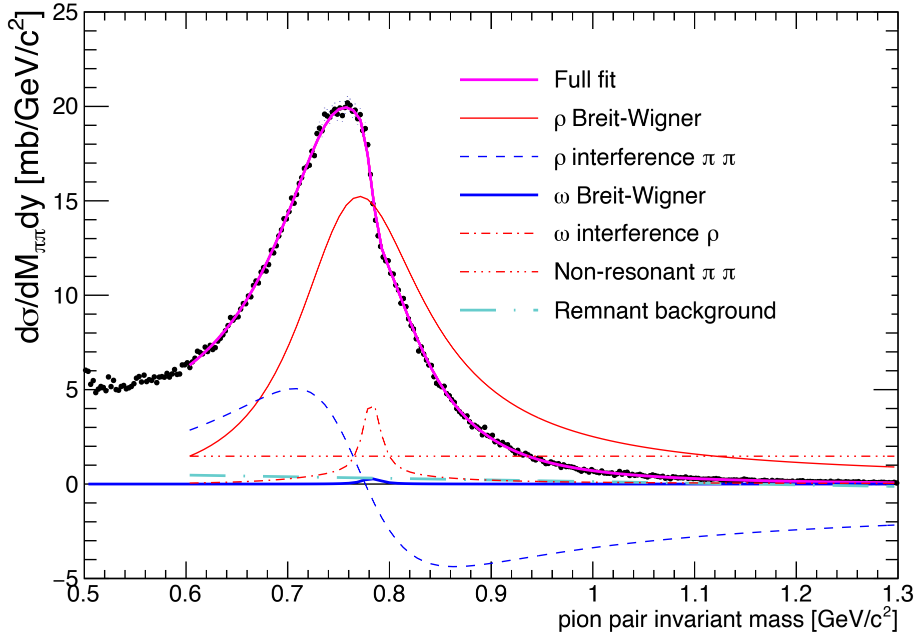
- Drell-Söding (Direct $\pi^+\pi^-$)
- ω interference

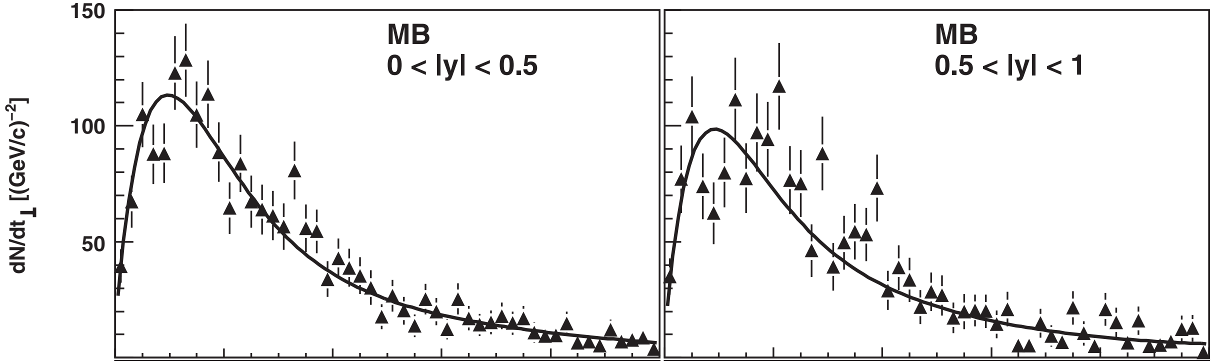
For the analysis in this talk we do not attempt to separate them

Additional statistical power may allow future mass-differential studies

Future Tests of Interference Effects

1. Differential Measurement $\Delta\phi$ distribution vs. $M^{\pi\pi}$ and rapidity





STAR Collaboration *et al. Phys. Rev. Lett.* **102**, 112301 (2009).

- The $\pi^+\pi^-$ spectra includes several interfering states.
- From theoretical side, should this effect the observed interference pattern?
- Should there be any mass dependence?

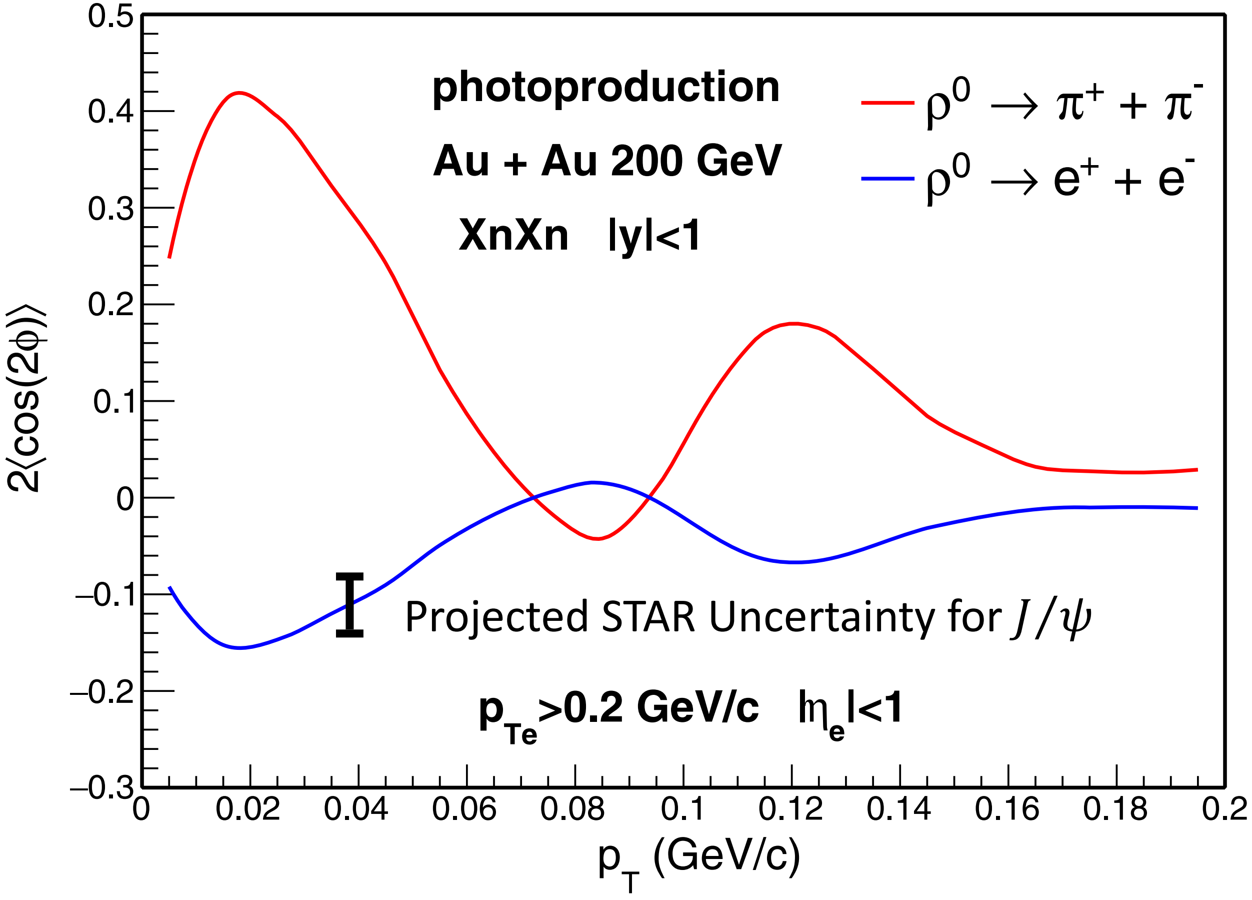
$$\sigma(p_T, b, y) = |A(p_T, b, y) - A(p_T, b, -y)\exp(i\vec{p}_T \cdot \vec{b})|^2, \quad (1)$$

Klein, S. R. & Nystrand, J. *Phys. Rev. Lett.* **84**, 2330–2333 (2000).

- Interfering amplitudes should depend on rapidity
- Experimentally, need more statistics + coverage

Future Tests of Interference Effects

2. Measurement $\Delta\phi$ distribution from $J/\psi \rightarrow e^+e^-$

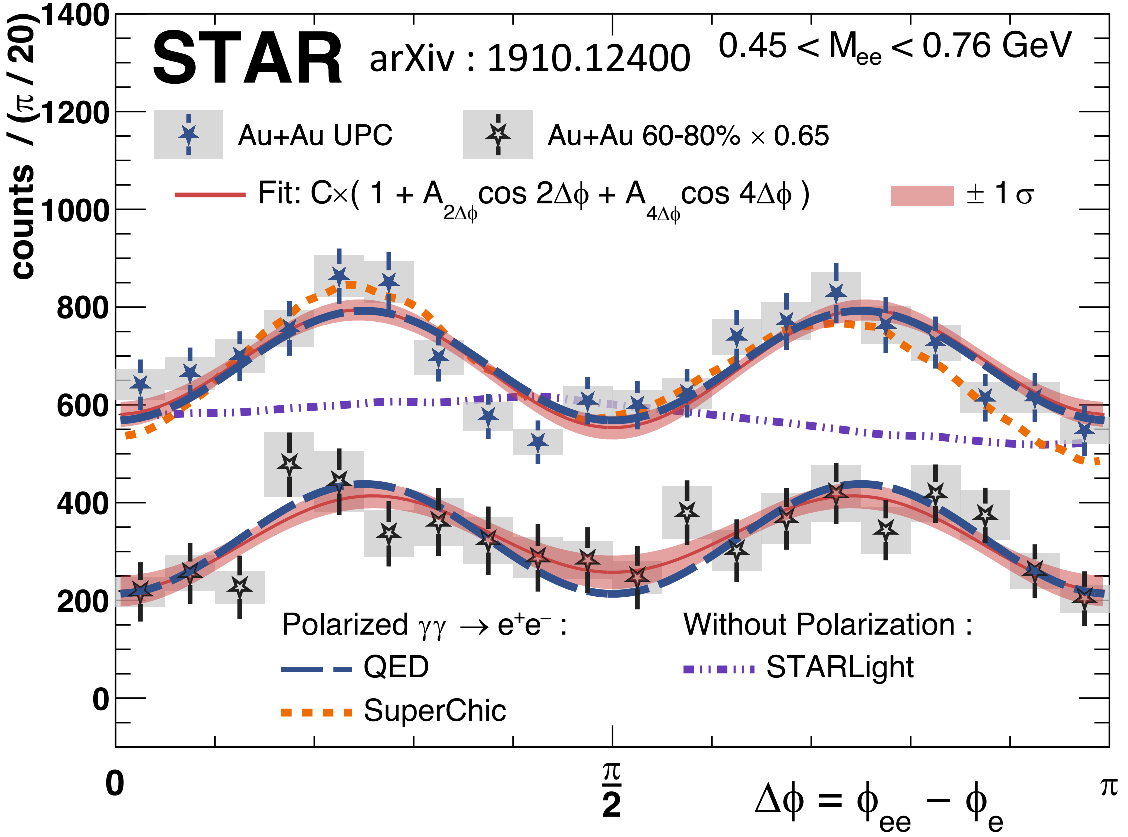


$\rho^0 \rightarrow e^+e^-$: Relevant for $J/\psi \rightarrow e^+e^-$ case
STAR J/ψ measurement in 2023-2025 : $\pm$4% @ 50 MeV/c

- Large mass of J/ψ provides hard scale for calculations
- Provides test of daughter spin coefficients – further test concept
- J/ψ is a single state, unlike the $\pi^+\pi^-$ where there are multiple interfering states

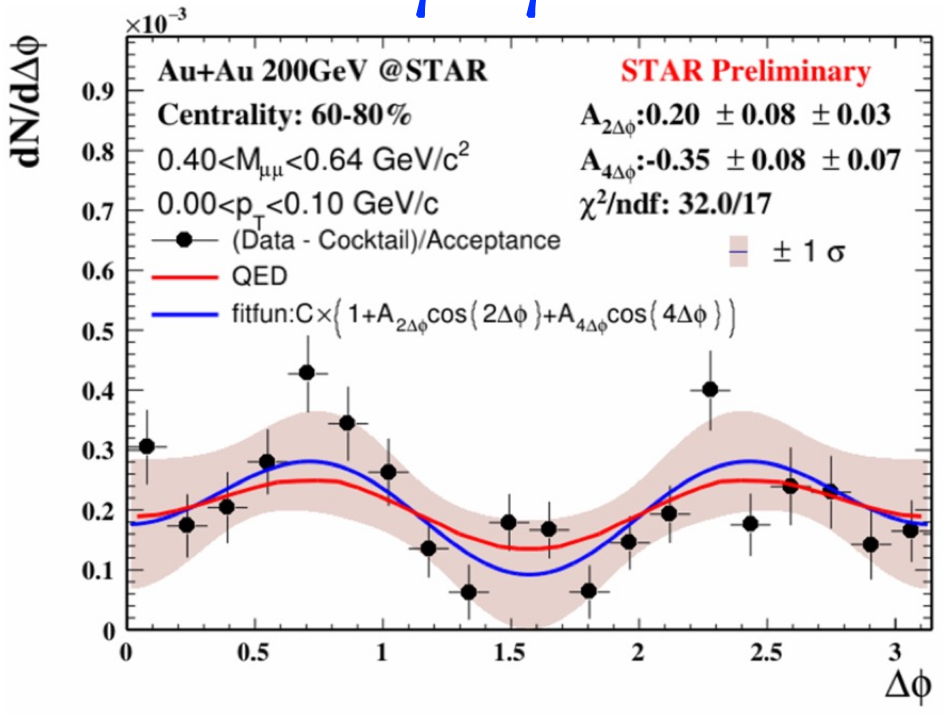
Future Tests of Interference Effects

3. Measurement $\Delta\phi$ distribution in non-UPC events



$\mu^+\mu^-$

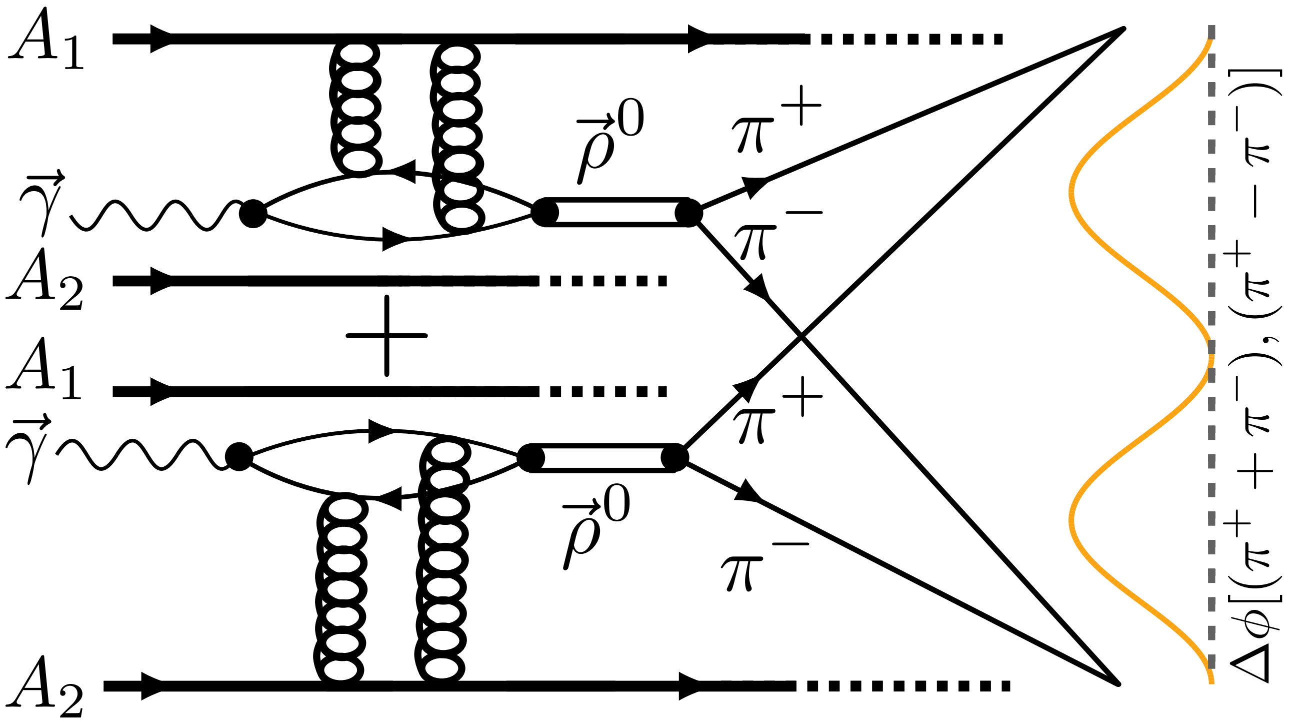
J. Zhou, sQM 2021



Measurement of $\gamma\gamma \to l^+l^-$ already shows interference effects in hadronic collisions

Understanding the Effect : Theory

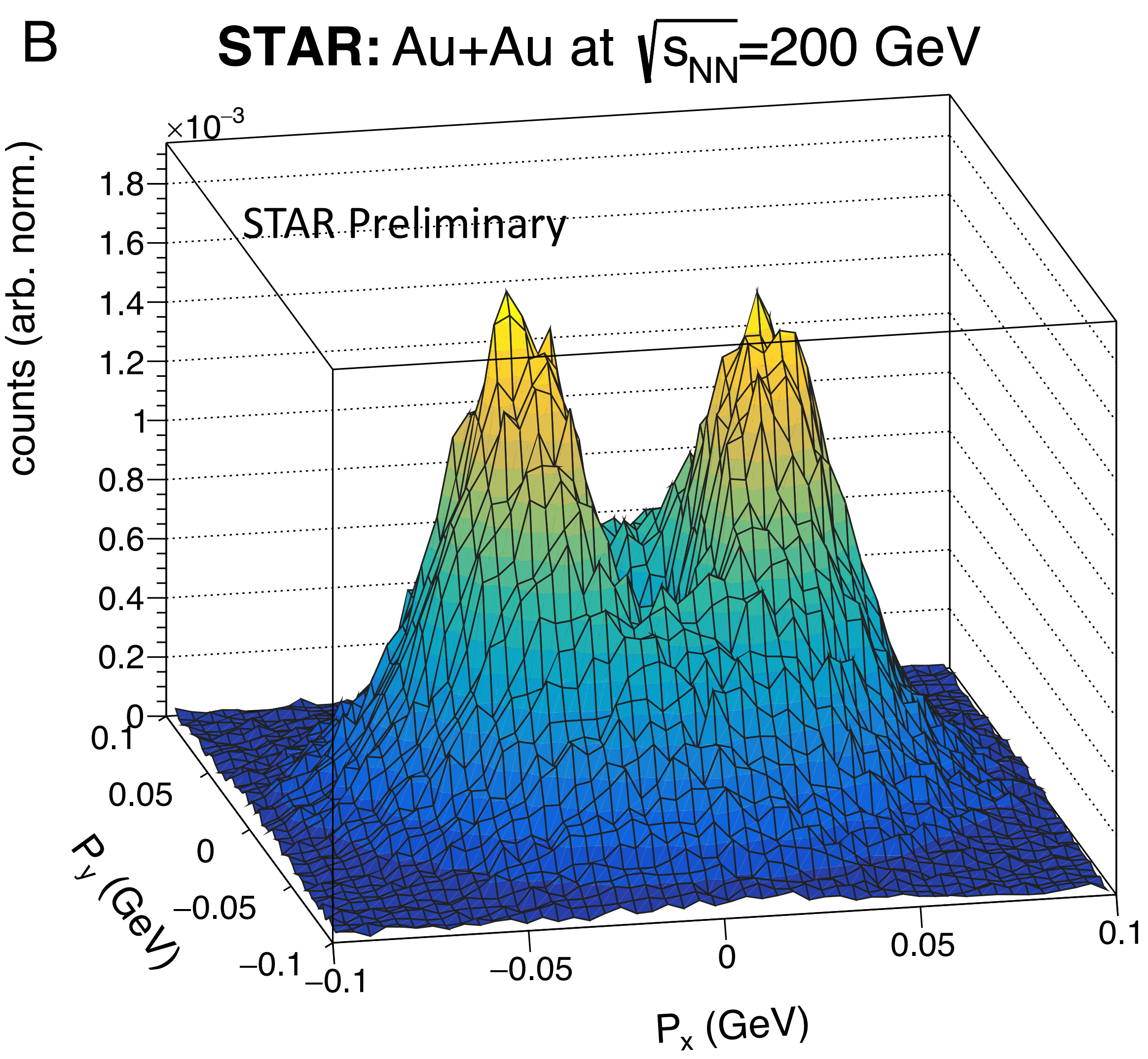
- Currently there are two theory calculations[1,2]
- Both describe effect as a two-source interference pattern resulting from quantum spin-momentum correlations



- Look at both theory calculations in detail
- Compare predictions to the STAR measurements

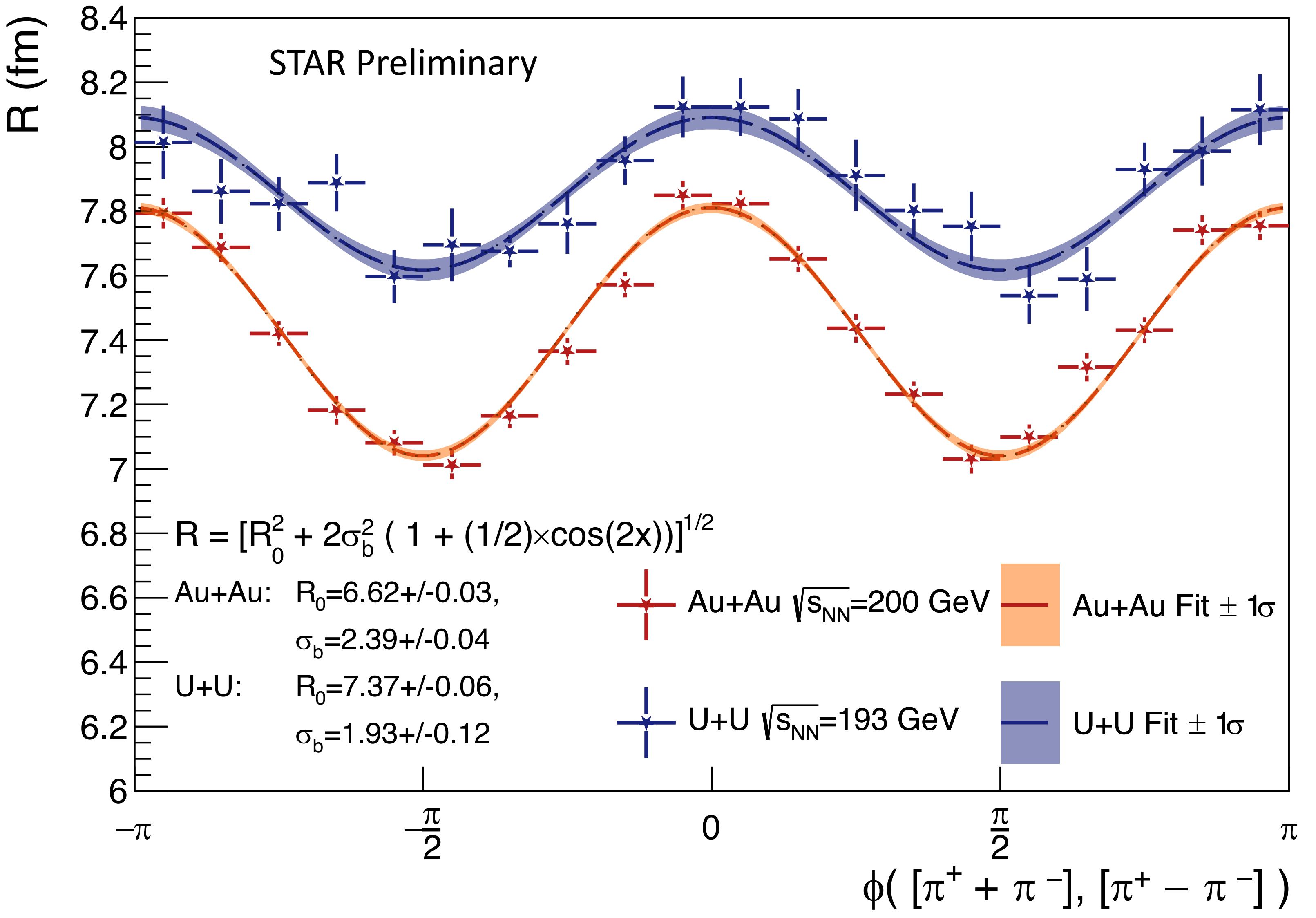
[1] Xing, H et.al. *J. High Energ. Phys.* **2020**, 64 (2020).
[2] Zha, W., JDB, Ruan, L. & Tang, Z. *Phys. Rev. D* **103**, 033007 (2021).

2D "Imaging" : Clear difference in p_x vs. p_y



- Express ρ^0 transverse momentum in two-dimensions:
  - $p_x = p_T \times \cos\phi$
  - $p_y = p_T \times \sin\phi$
- Clear asymmetry in p_x vs. p_y due to interference effect in both Au+Au and U+U
- Illustrated "2D" tomography
- In principle interference would completely "turn off" in p_y except for resolution effect

|t| vs. ϕ, the whole picture?

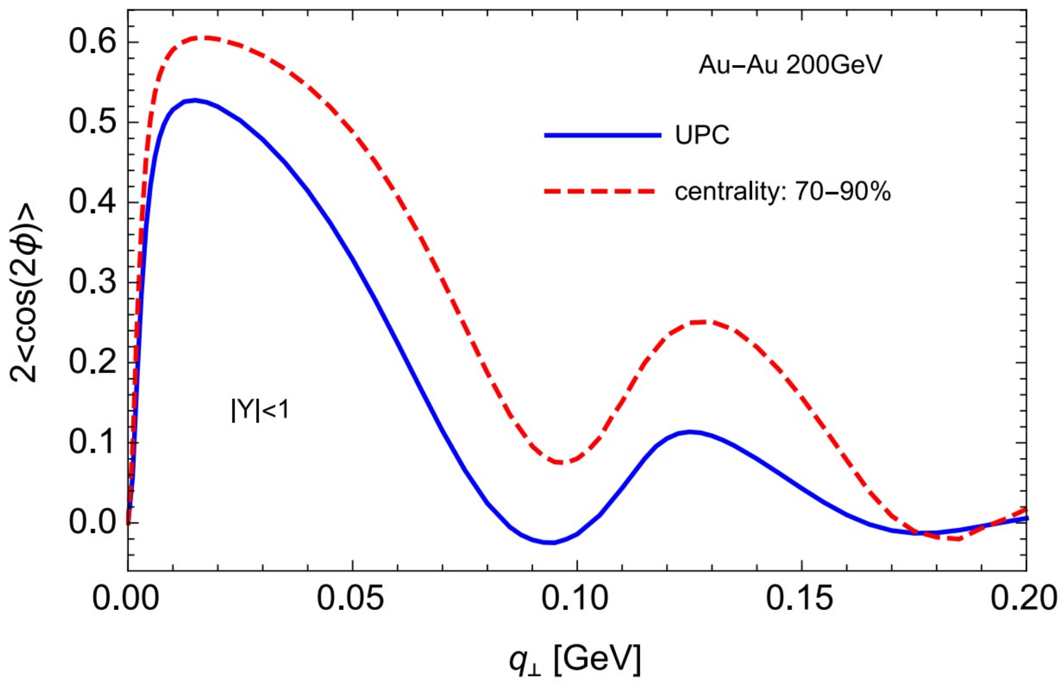


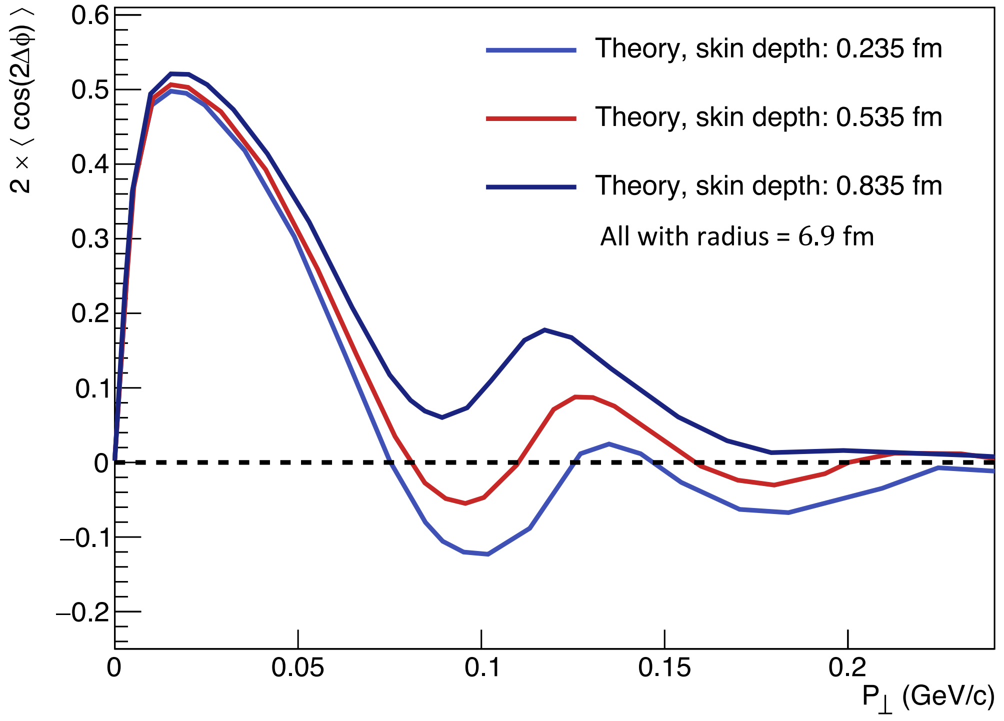
Extracting the 'true' nuclear radius still requires 2 more corrections:

- Depolarization from finite-size nuclei:
  $1 - (R_0/\langle b\rangle)^2/4 \approx 4\%$
- The ρ wavefunction has a transverse 'size' (~1.03 fm from HERA) which limits the measurements resolution
- Both are small effects for large nuclei

Theoretical Predictions for $\gamma\mathbb{P} \rightarrow \rho^0 \rightarrow \pi^+\pi^-$

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





Structure in $\cos 2\Delta\phi$ signal is sensitive to:

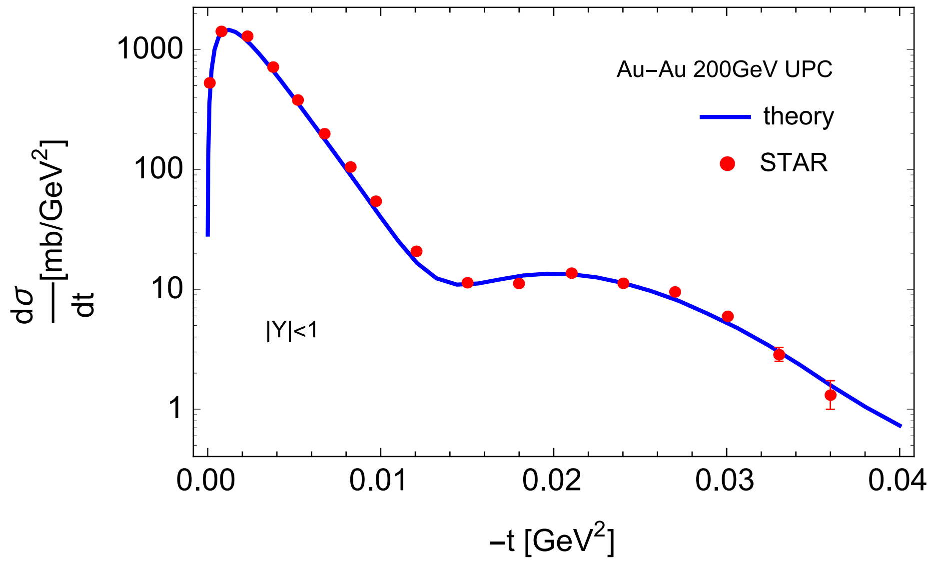
→ Nuclear Geometry / gluon distribution

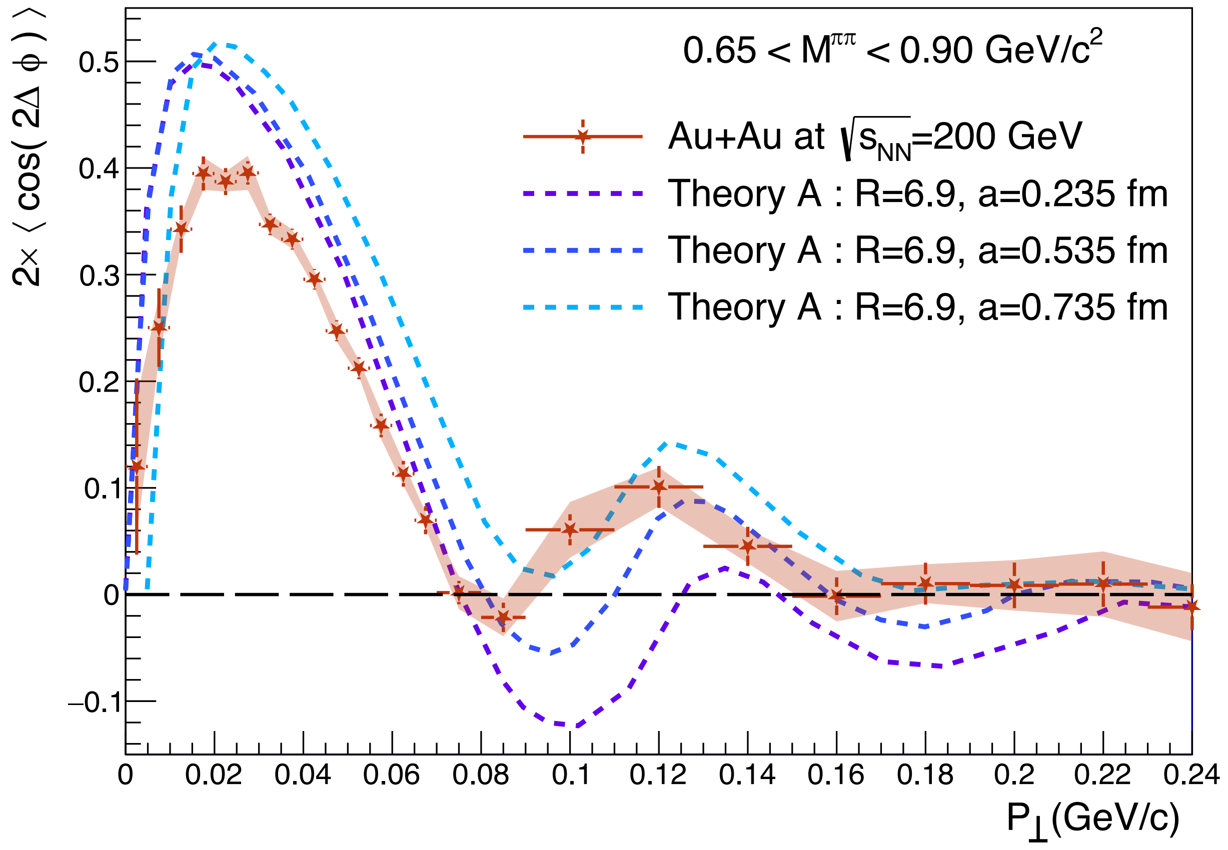
(Skin depth = Woods-Saxon diffusivity a)

→ Impact parameter

UPC (blue) vs. 70-90% central (red)

Comparison to STAR Measurements





- Simultaneous fit STAR Coherent spectra (incoherent subtracted using dipole FF)
- Good description of total coherent cross section $R_A = 6.9$ fm and $a = 0.64$ fm
- Gluon distribution given the Golec-Biernat and Wüsthoff (GBW) model

- Good qualitative description of data including structure
- Overpredicts strength of main peak
- Higher p_T region shows strong sensitivity to gluon distribution

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

Exploring the double-slit interference with linearly polarized photons

Calculation from Zha, W., Brandenburg, J. D., Ruan, L. & Tang, Z. *Phys. Rev. D* **103**, 033007 (2021). (**Theory B**)

- For $\rho^0 \rightarrow \pi^+\pi^-$ (spin 0 daughters)

$$\frac{d^2N}{d\cos\theta d\phi} = \frac{3}{8\pi}\sin^2\theta[1+\cos 2(\phi-\Phi)], \qquad (1)$$

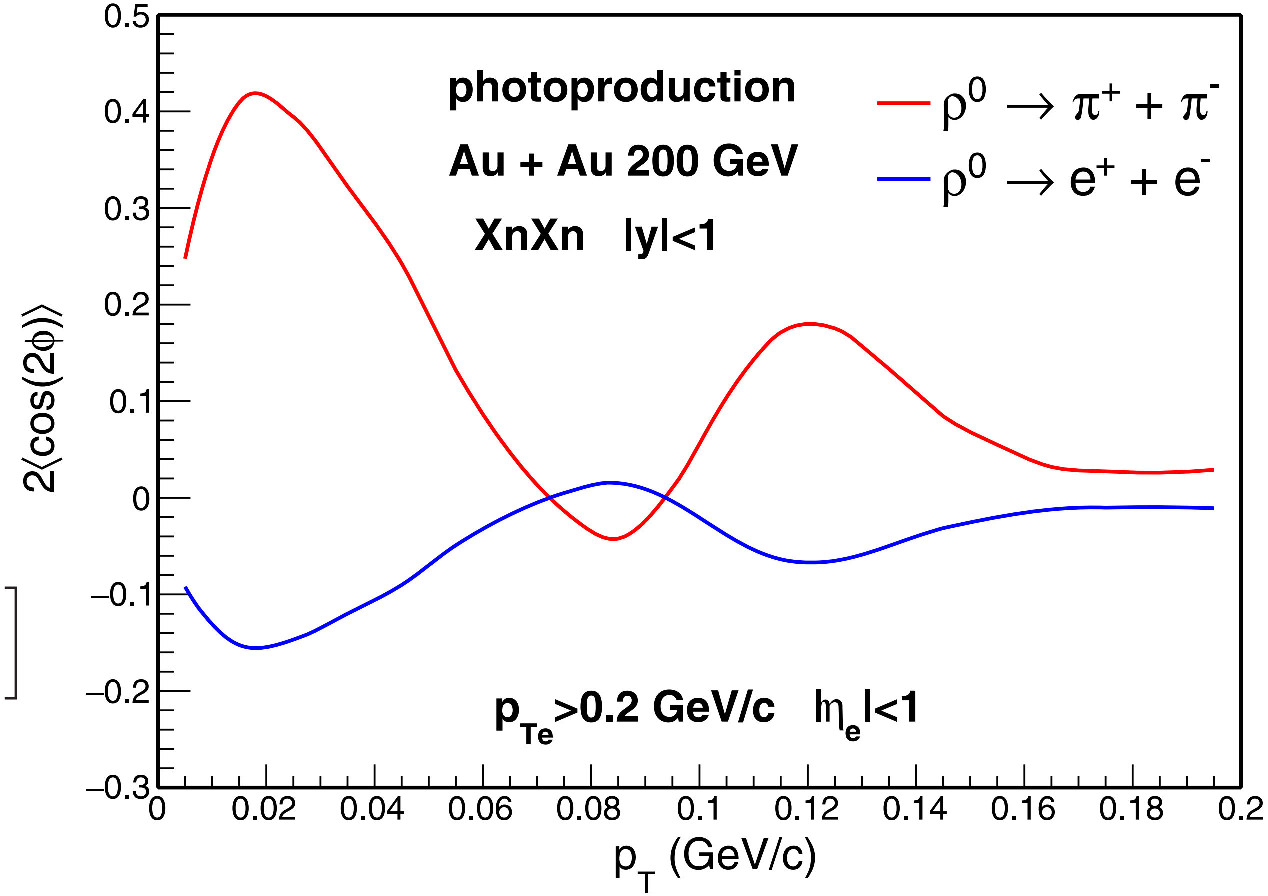
$$2\langle\cos(2\phi)\rangle = \cos(2\Phi)$$

- For $\rho^0 \rightarrow e^+e^-$ (spin 1/2 daughters)

$$\frac{d^2N}{d\cos\theta d\phi} = \frac{3}{16\pi}(1+\cos^2\theta)\left[1-\frac{\sin^2\theta}{1+\cos^2\theta}\cos 2(\phi-\Phi)\right]$$

$$2\langle\cos(2\phi)\rangle = -\frac{\sin^2\theta}{1+\cos^2\theta}\cos(2\Phi)$$

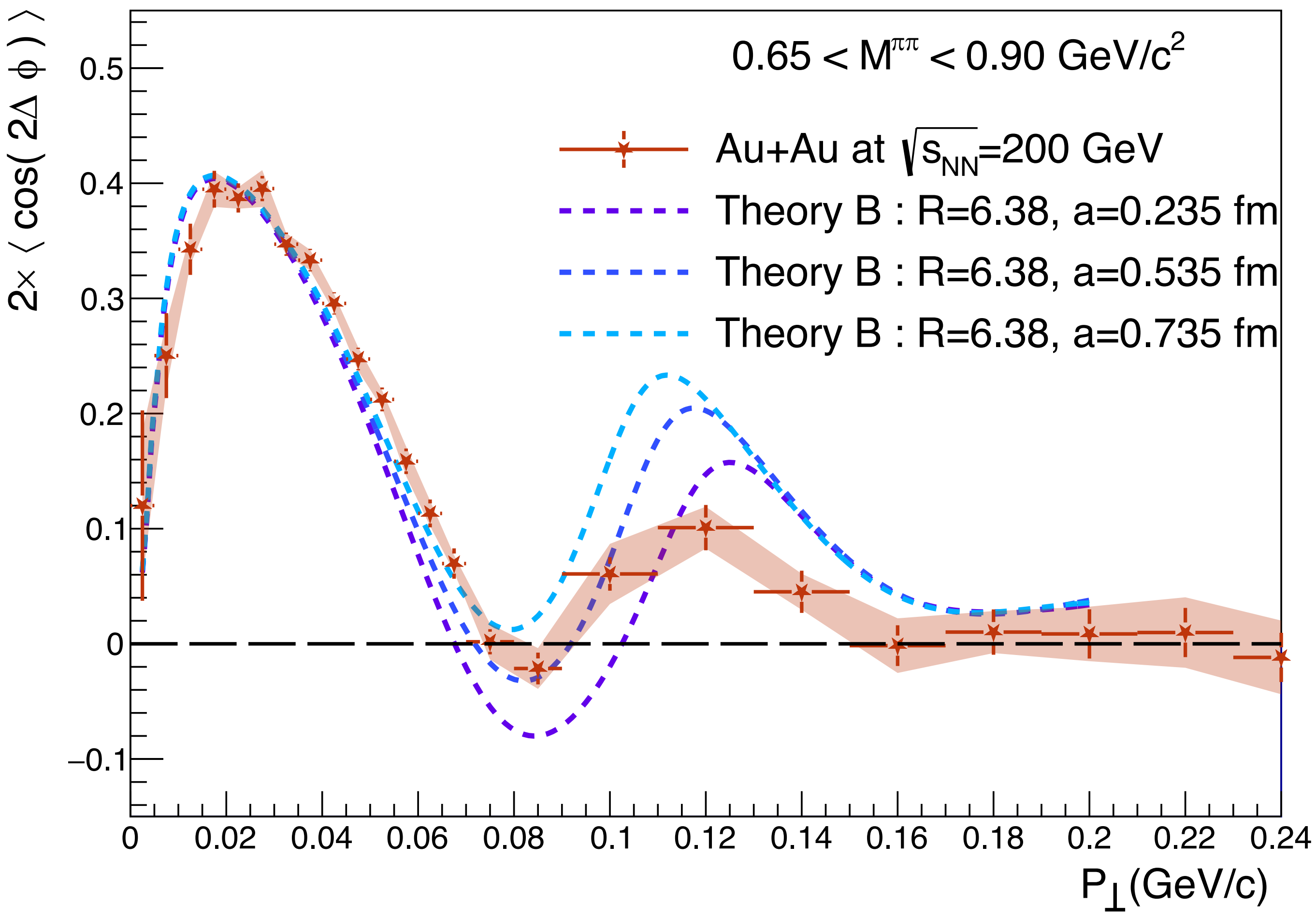
Where the angle Φ denotes the angle between the photon polarization plane and vector meson production plane.



$\rho^0 \rightarrow e^+e^-$: Relevant for $J/\psi \rightarrow e^+e^-$ case

STAR J/ψ measurement in 2023-2025 : $\pm$4% @ 50 MeV/c

Theory & Au+Au Data Comparison



- Qualitative description of the data
  - Large first peak
  - Approximate location of second peak

- Magnitude of 1st peak shows very good agreement
- First peak in the calculation is shifted to slightly lower P_T compared to data

- Second peak ($P_T > 80$ MeV/c) shows strong dependence on details of nuclear geometry (gluon density)

- Looking forward to predictions for U+U data

Interjection: Relation to past measurements

- Detailed measurements of the spin-density matrix elements have been carried out in the past, e.g. at HERA[1] and by STAR[2]

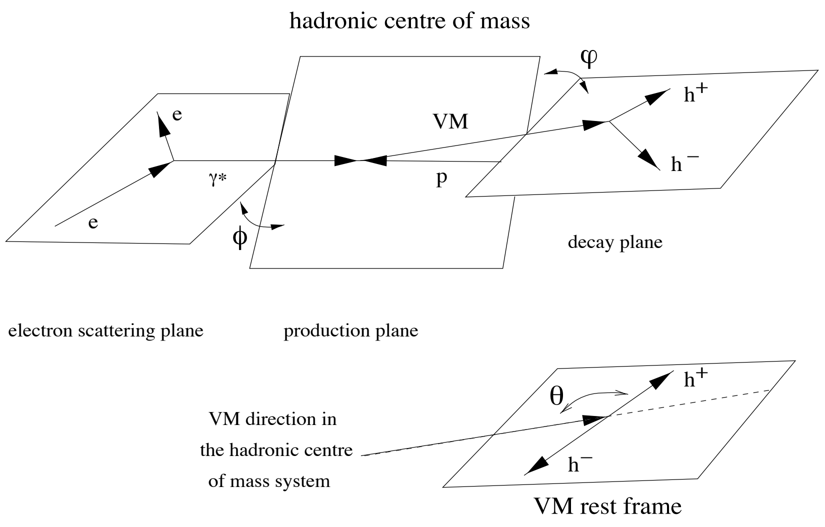


Figure 3: Definition of the angles characterising diffractive VM production and decay in the helicity system.

[1] H1 Collaboration. *J. High Energ. Phys.* **2010**, 32 (2010).
[2] STAR, Phys. Rev. C77, 034910 (2008).

A few points to consider:

1. The $\Delta\phi$ angle is related to the φ angle in the spin-density formalism
2. At HERA the outgoing electron was tagged
   - The photon momentum vector is known
   - Provides event-by-event alignment of angular distributions
3. In ep the photon is high Q^2 and predominately longitudinally polarized $\langle \xi_{long} \rangle \approx 0.98$

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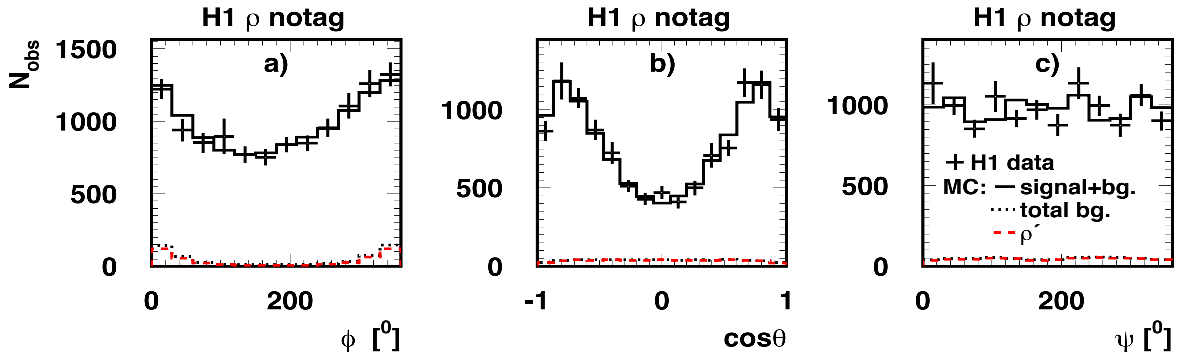

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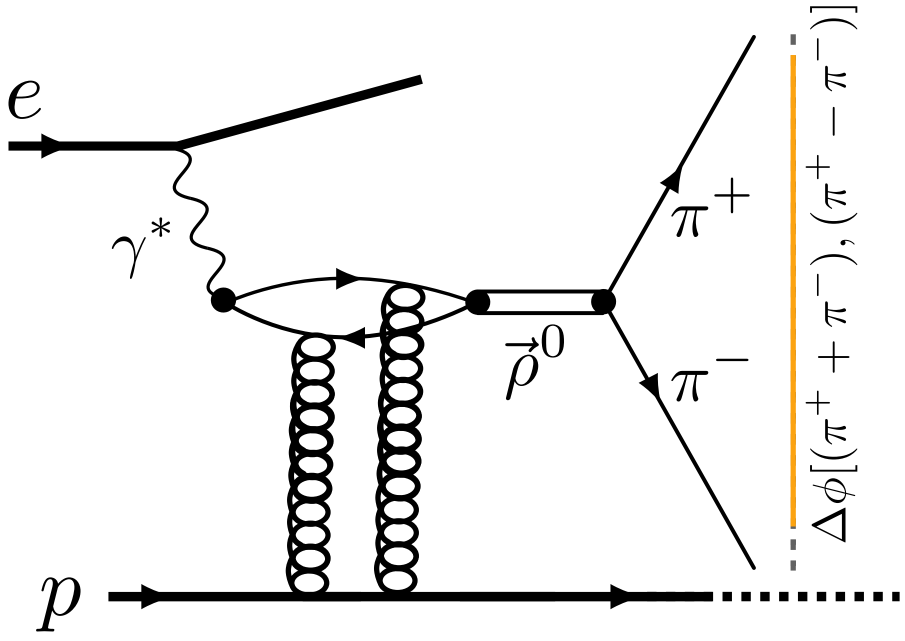

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   - The photon momentum vector is known
   - Provides event-by-event alignment of angular distributions
3. In ep the photon is high Q^2 and predominately longitudinally polarized $\langle\xi_{long}\rangle \approx 0.98$
4. There is only one contributing amplitude - no interference effect

[1] H1 Collaboration. *J. High Energ. Phys.* **2010**, 32 (2010).
[2] STAR, Phys. Rev. C77, 034910 (2008).

Polarization Sensitive Observable

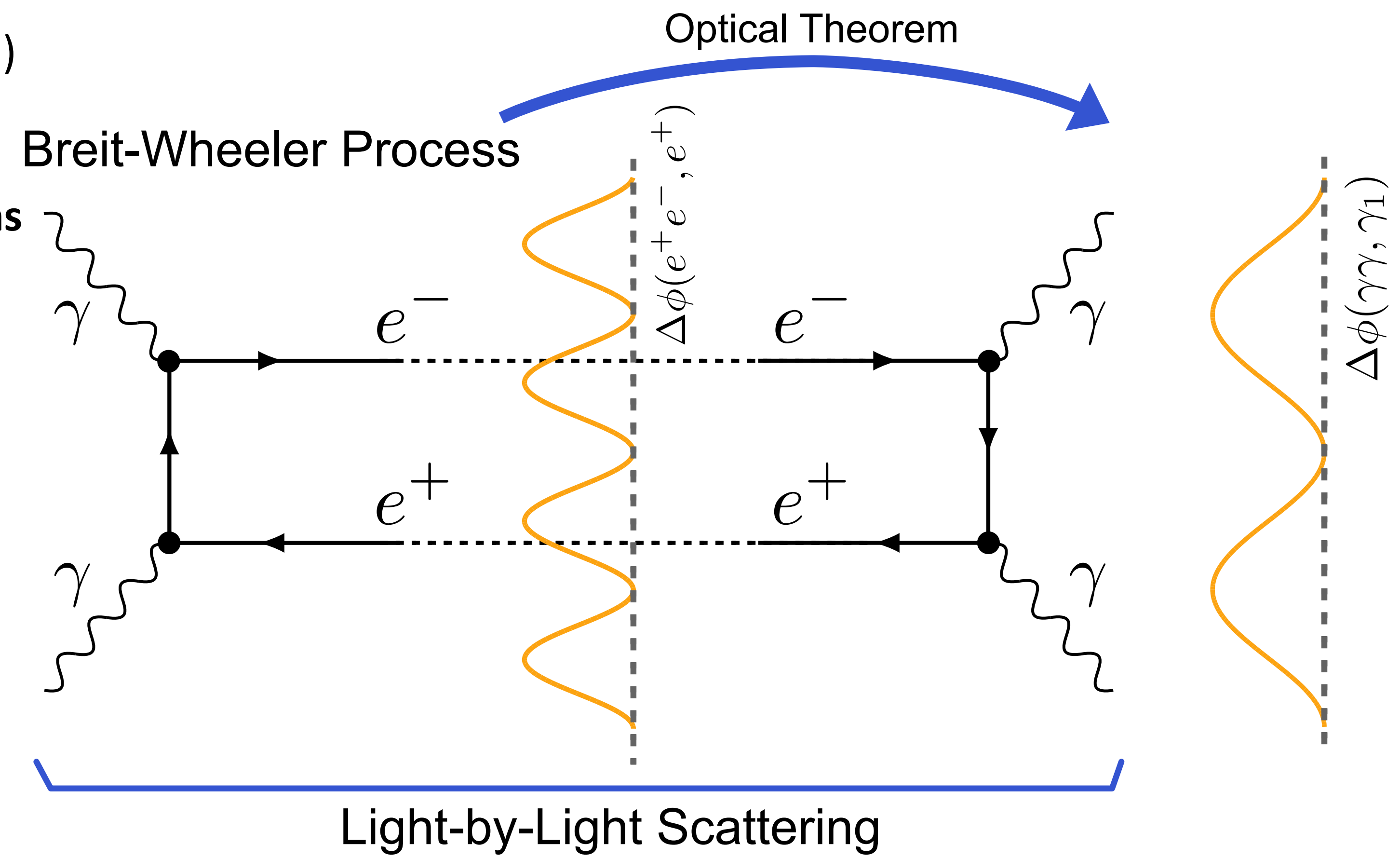
$$\Delta\phi = \Delta\phi[(e^+ + e^-),(e^+ - e^-)]$$
$$\approx \Delta\phi[(e^+ + e^-), e^+]\ \text{(for small pair } p_T\text{)}$$

Sensitive to polarization through
quantum space-momentum correlations

Birefringence effects:

Recently realized, collision of linearly polarized photons leads to a $\mathbf{cos(4\Delta\phi)}$ **modulation** in polarized $\gamma\gamma \rightarrow e^+e^-$ process [1]

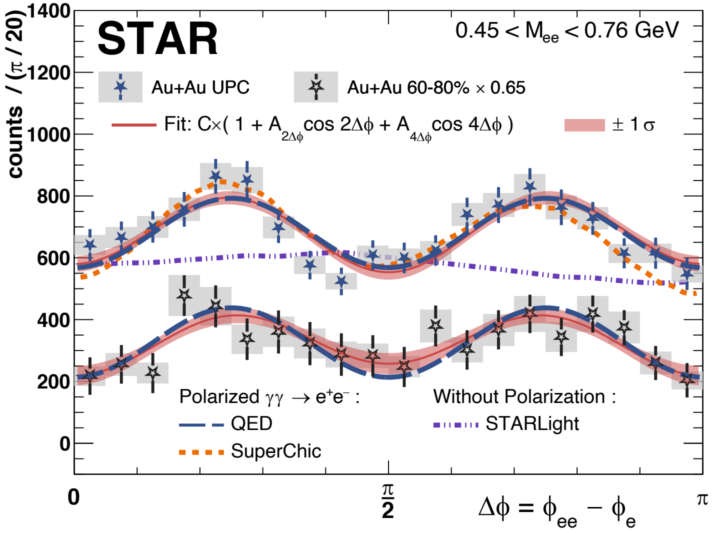
The corresponding vacuum LbyL scattering[2] is expected to display a $\mathbf{cos(2\Delta\phi)}$ **modulation**



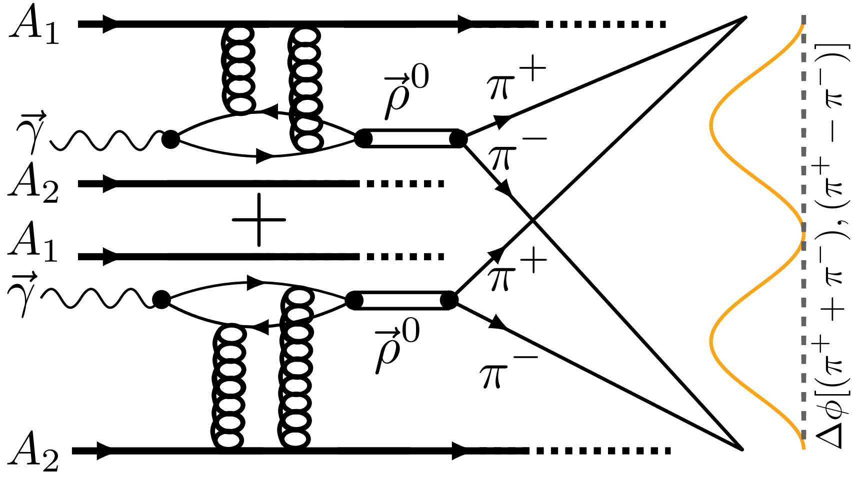
[1] C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)
[2] Harland-Lang, L. A., Khoze, V. A. & Ryskin, M. G. Eur. Phys. J. C 79, 39 (2019).

Highlights I : Polarized Photon-Gluon Collisions

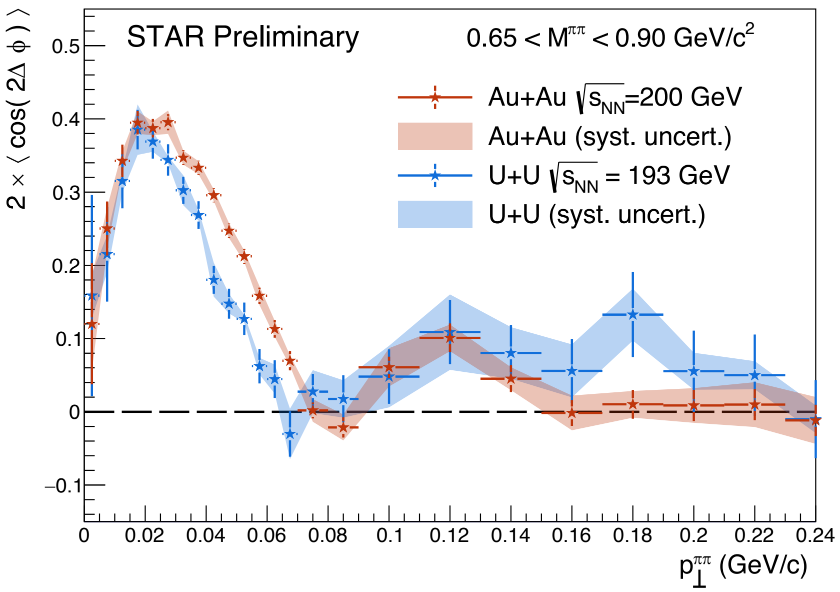
Significant $\cos 4\Delta\phi$ modulation in $\gamma\gamma \rightarrow e^+e^-$ process: Experimental demonstration of linear polarization of quasi-real photons



Two source interference in VM production → $\cos 2\Delta\phi$ modulation in $\rho^0 \rightarrow \pi^+\pi^-$



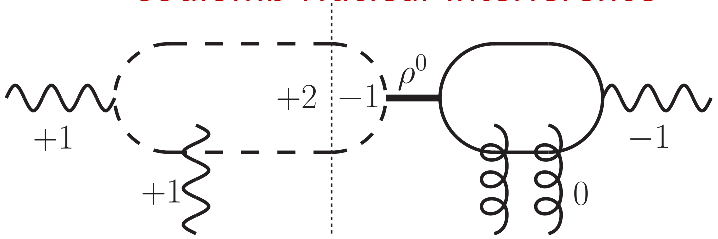
Interference shows rich structure vs. P_T



New Interference pattern observed in diffractive photo-nuclear interactions

- Experimental demonstration of sensitivity to gluon distribution and that incoherent does not contribute to interference pattern
- New measurement possibilities:
  - J/ψ, which provides hard scale for theoretical calculations,
  - Measurements in non-UPC, comparison of $\rho^0 \rightarrow \pi^+\pi^-$ vs. $J/\psi \rightarrow l^+l^-$ to see if interference exists in both
  - Differential measurements w.r.t. mass, rapidity to test interference characteristics
  - Observation of Coulomb-Nuclear Interference

Coulomb-Nuclear Interference

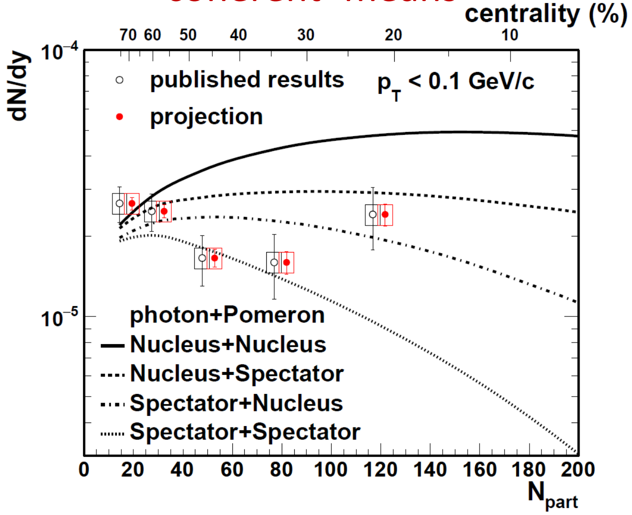


Highlights II : Theory Questions and EIC

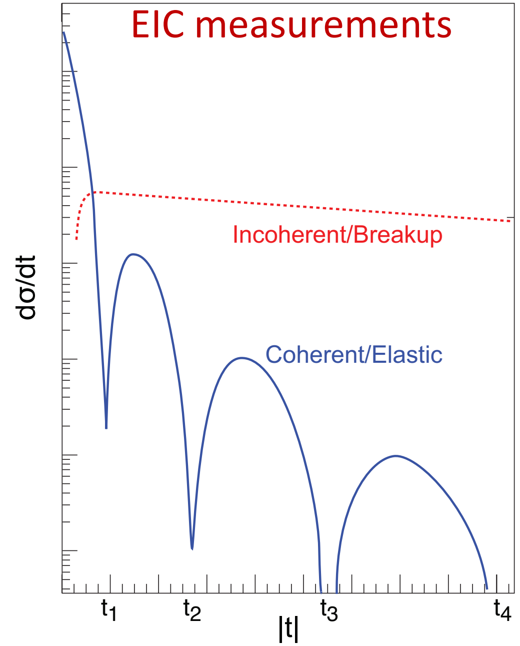
Theory Wish List:

- Full calculations for J/ψ etc.
- Predictions for U+U considering deformation
- Rapidity and mass dependence
- Pursue calculations for EIC case – do correlations exist and if so, what can we learn?
- Quantify effects of saturation/ modified gluon distribution?

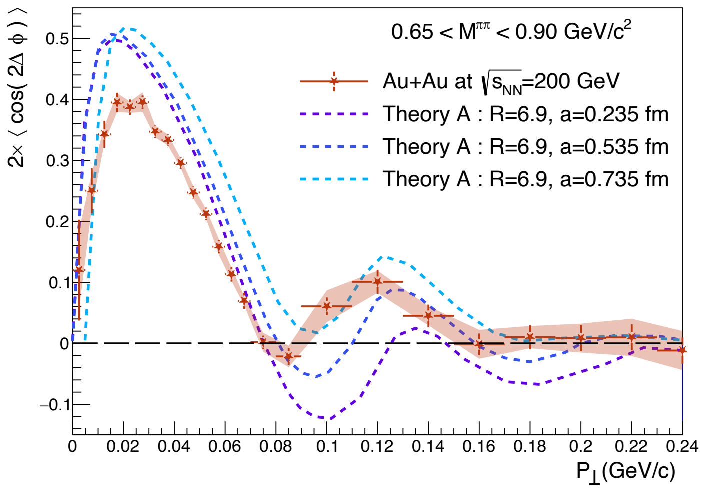
Gain a deeper understanding of what 'coherent' means

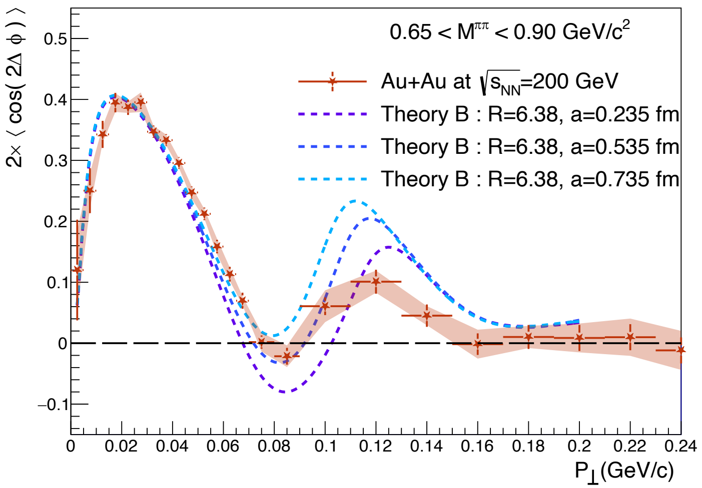


Separation of coherent vs. incoherent is the essential experimental challenge for EIC measurements

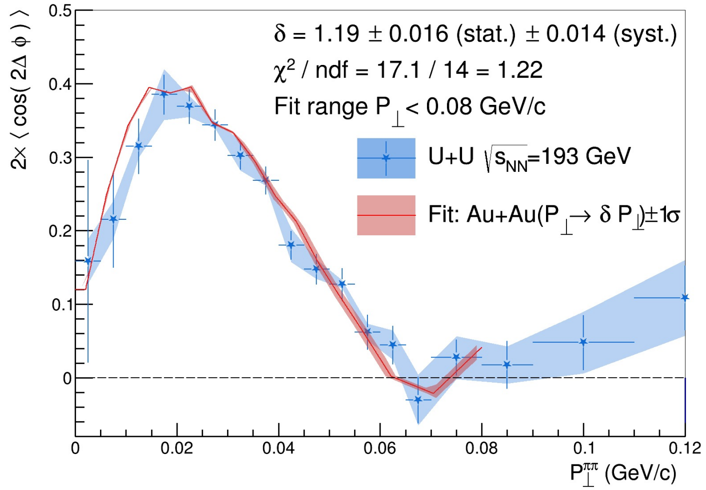


- Continue to pursue theory – gain quantitative agreement



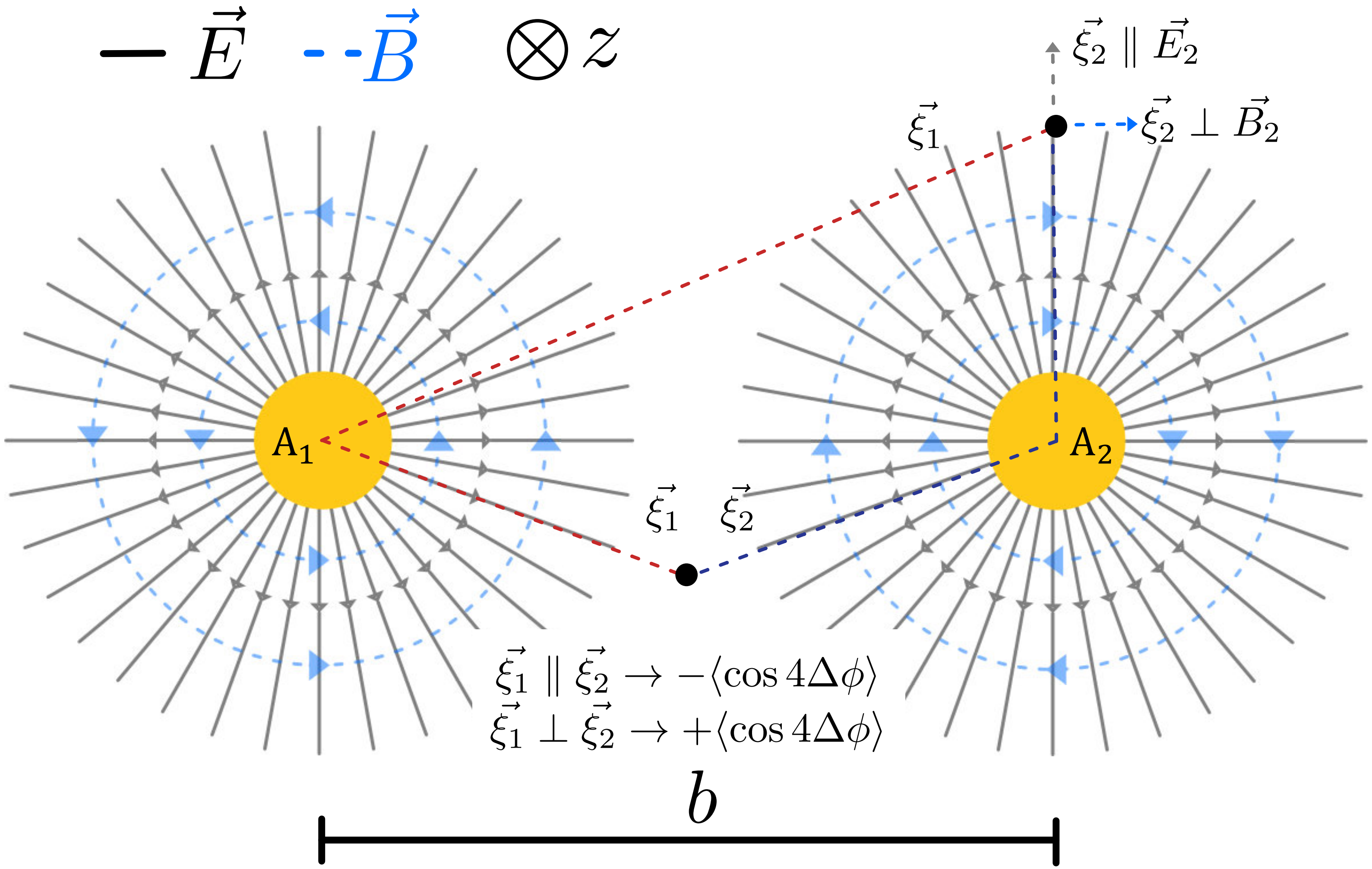


Why are we sensitive primarily to the 'long'-axis



Experimental Signature of Linearly Polarized Photons

- The different helicity amplitude combinations for linear polarization leads to a splitting of the angular distribution
- Parallel photon polarizations $\vec{\xi}_1 \parallel \vec{\xi}_2$ $\rightarrow$ **<u>Negative</u>** $\cos 4\Delta\phi$ modulation
- Perpendicular photon polarizations $\vec{\xi}_1 \perp \vec{\xi}_2$ $\rightarrow$ **<u>Positive</u>** $\cos 4\Delta\phi$ modulation



[1] C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)

Polarization Sensitive Observable

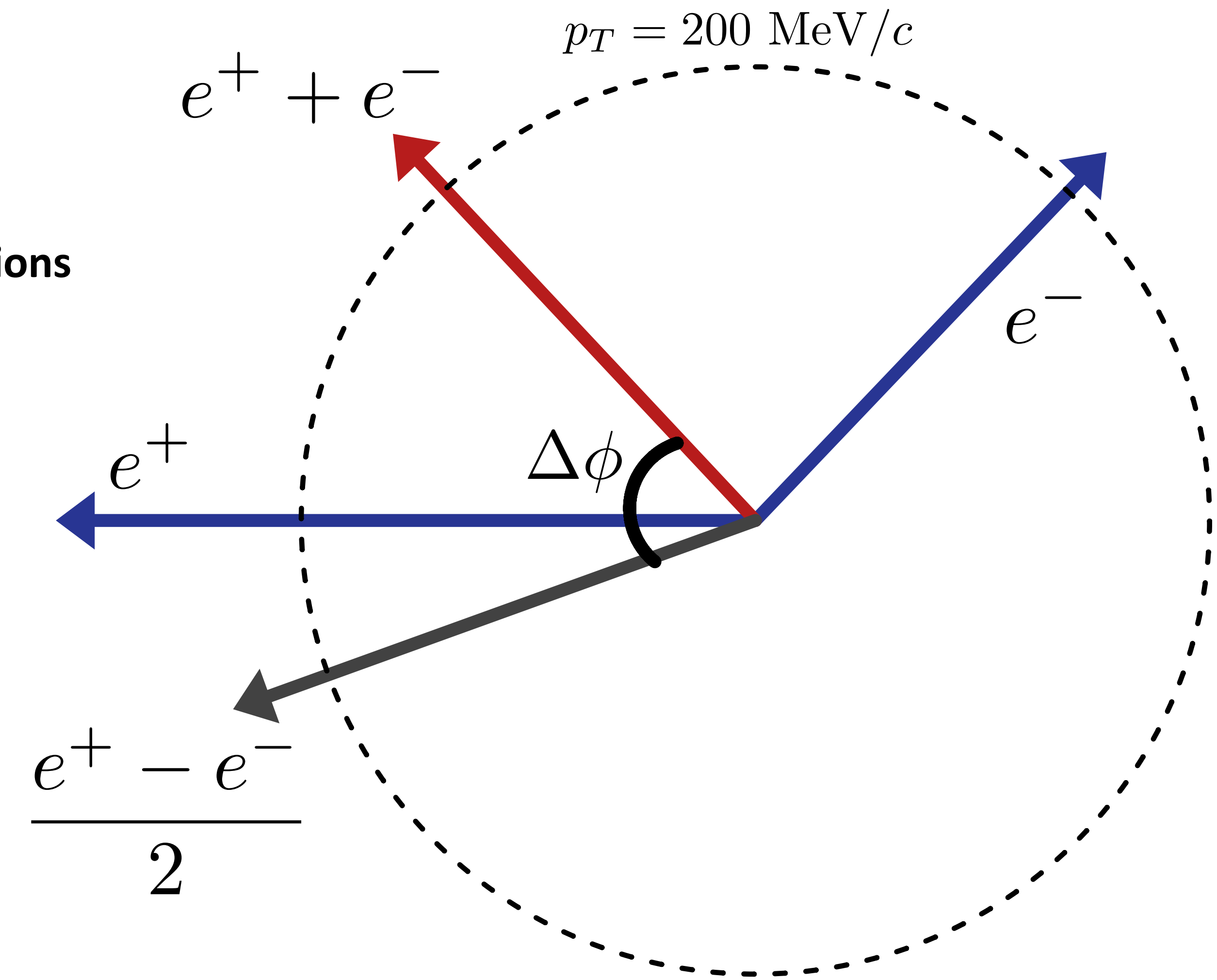
$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)]$$
$$\approx \Delta\phi[(e^+ + e^-), e^+] \text{ (for small pair } p_T\text{)}$$

Sensitive to polarization through
quantum space-momentum (spin-momentum) correlations

Recently realized, collision of linearly polarized photons leads to a $\mathbf{cos(4\Delta\phi)}$ **modulation** in polarized $\gamma\gamma \rightarrow e^+e^-$ process [1]

The corresponding vacuum LbyL scattering[2] is expected to display a $\mathbf{cos(2\Delta\phi)}$ **modulation** at midrapidity

These effects are related to vacuum birefringence[3]



[1] C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)
[2] Harland-Lang, L. A., Khoze, V. A. & Ryskin, M. G. Eur. Phys. J. C 79, 39 (2019).
[3] John S. Toll "The Dispersion relation for light and its application to problems involving electron pairs", Princeton (1952)