Linearly Polarized Photon-Gluon Collisions

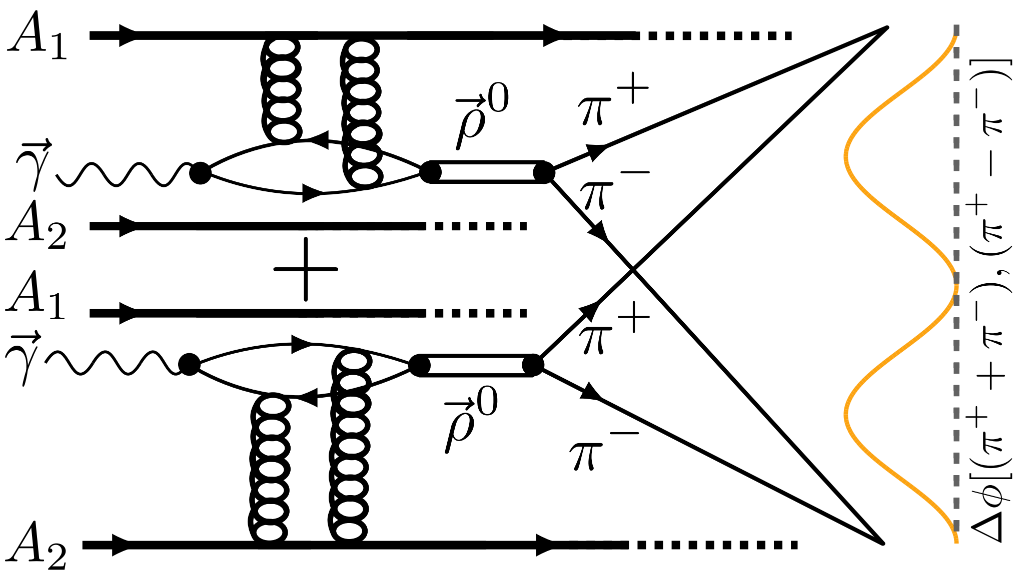
Daniel Brandenburg (BNL/CFNS)

CFNS Workshop:

RHIC Science Programs Informative

Toward EIC in the Coming Years

Tuesday, 25th of May, 2021



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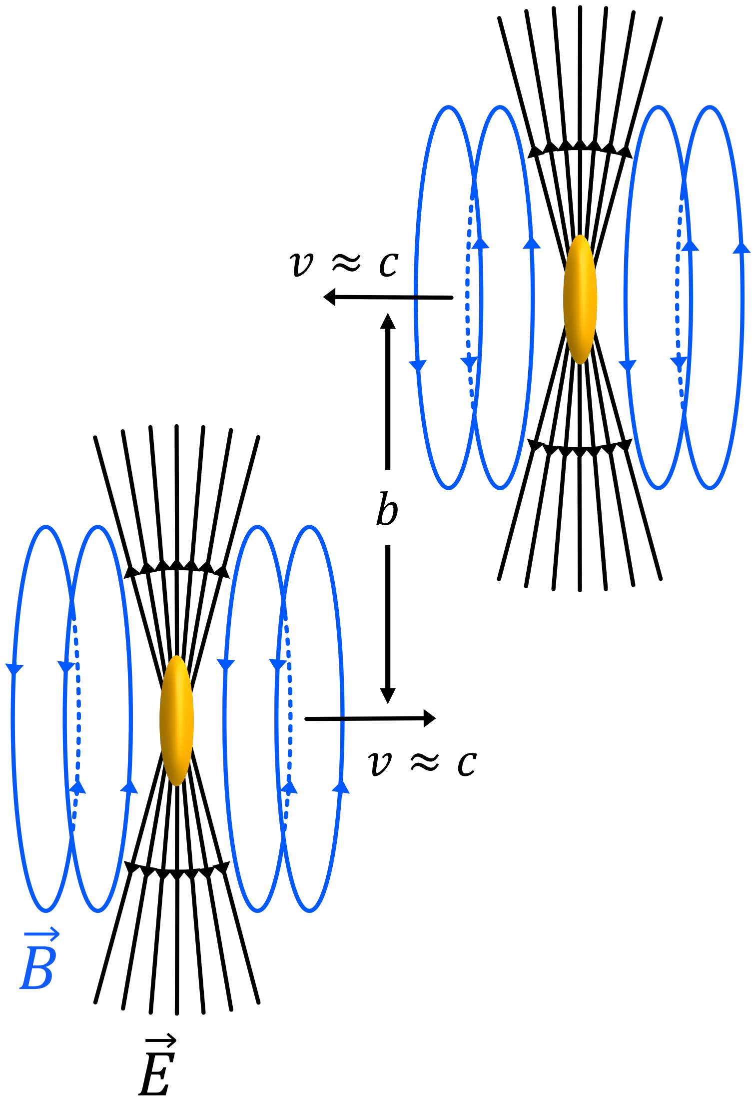
Talk Outline

1. Introduction

   Strong electromagnetic fields and transverse linearly polarized photons

2. Angular modulations of diffractive $\rho^0 \rightarrow \pi^+\pi^-$ in UPCs
3. Comparison between Au+Au and U+U
4. Comparison to theoretical models
5. Prospects and Applications
6. Summary

Ultra-Peripheral Heavy-Ion Collisions



Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic fields

- $\gamma\gamma \to l^+ l^-$: photon-photon fusion
  - One photon from the field of each nucleus interacts
  - Second order process in α
  - $Z\alpha \approx 1$ $\to$ 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).

- $\gamma\mathbb{P} \to \rho^0, J\psi, etc.$: 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

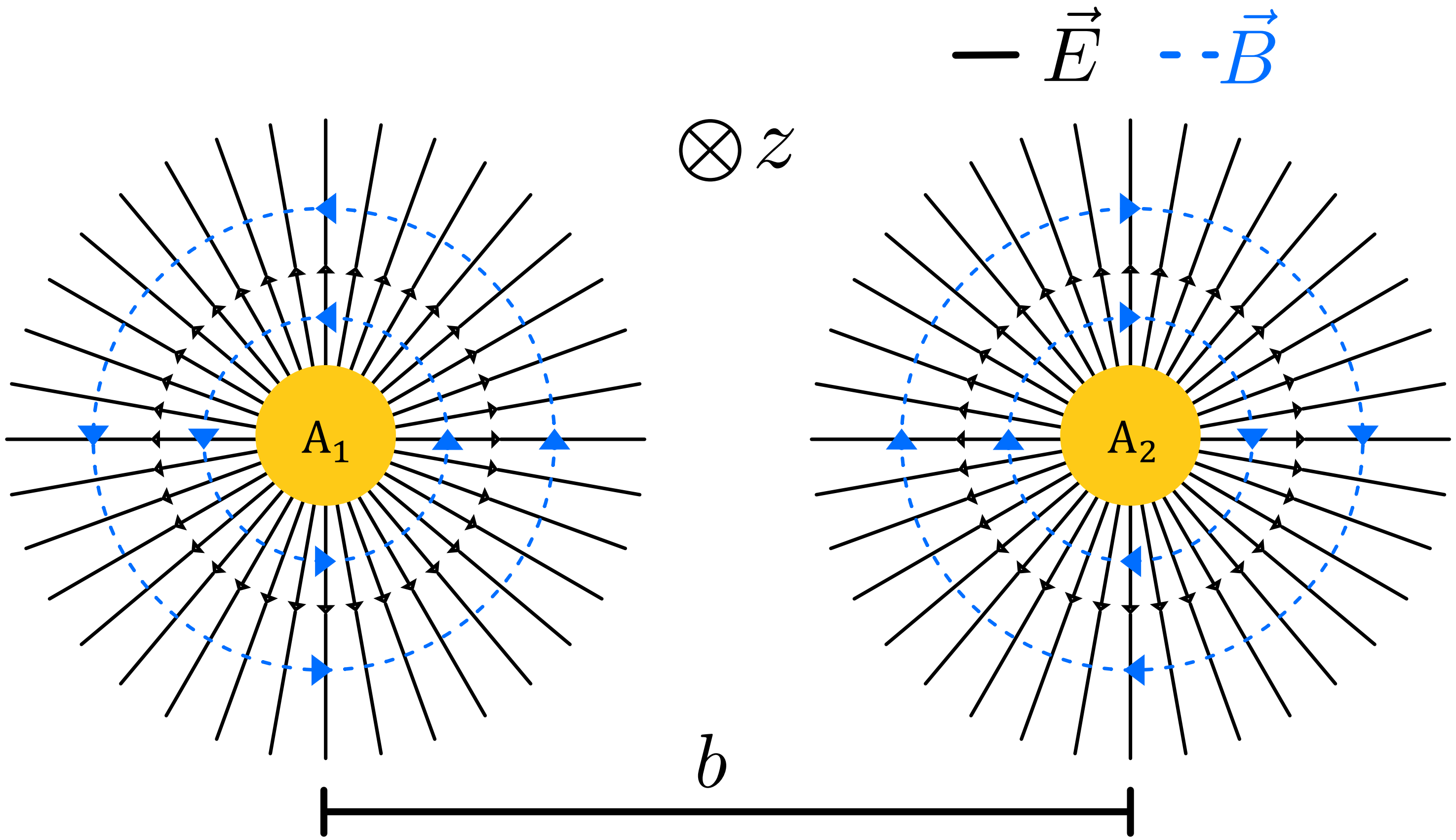
- Extreme Lorentz contraction of EM fields ($\vec{E} \perp \vec{B} \perp \vec{k}$)

  → Quasi-real photons should be linearly polarized in the transverse plane

- Polarization vector : aligned radially with the “emitting” source

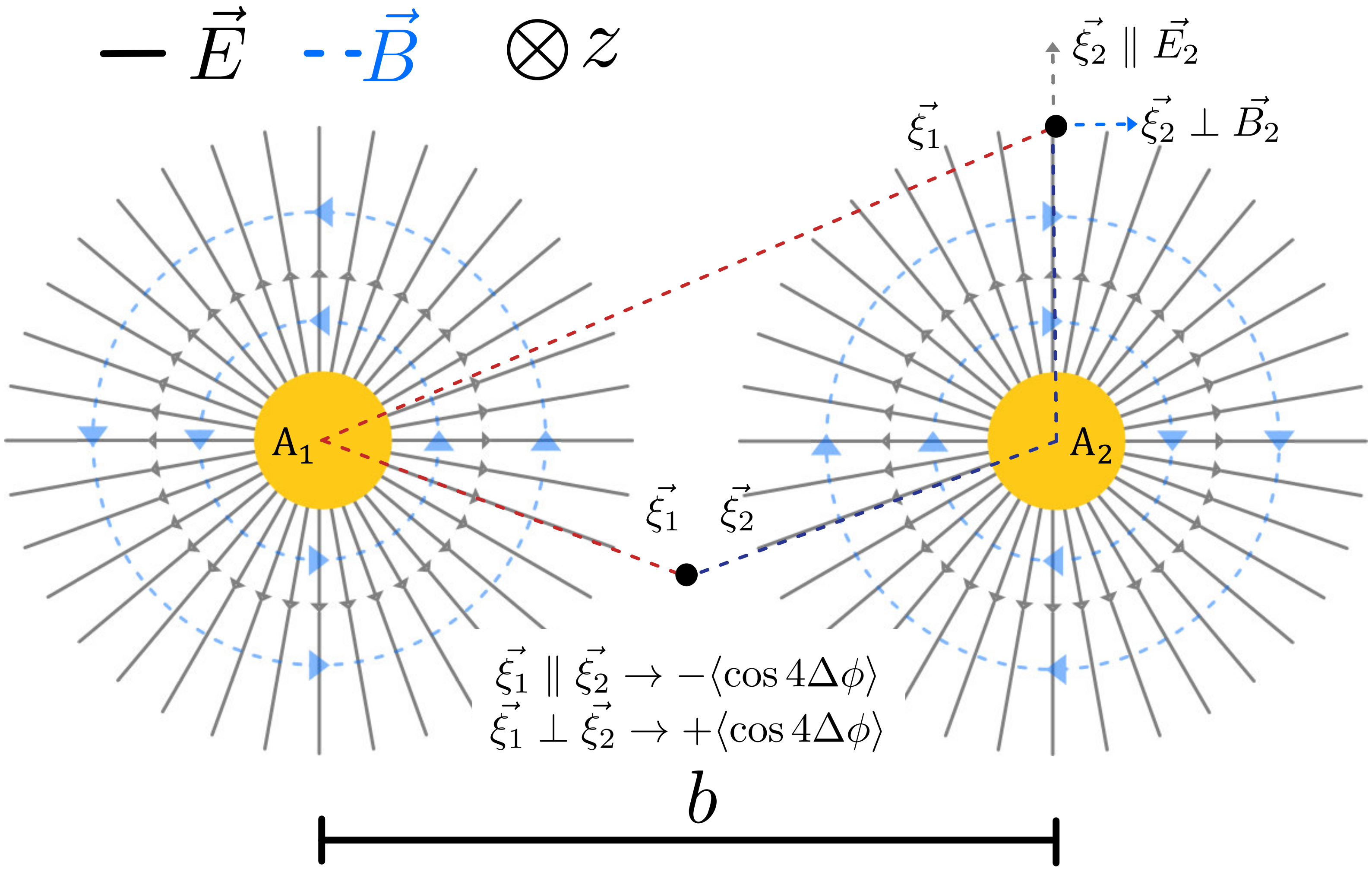
- Well defined in the photon position eigenstates

- Event average, washes out polarization effects, since $\vec{b}$ is random from one event to next



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 $\vec{\xi}_1 \parallel \vec{\xi}_2$ → **Negative** $\cos 4\Delta\phi$ modulation
- Perpendicular photon polarizations $\vec{\xi}_1 \perp \vec{\xi}_2$ → **Positive** $\cos 4\Delta\phi$ modulation



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

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

Birefringence of the QED Vacuum

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

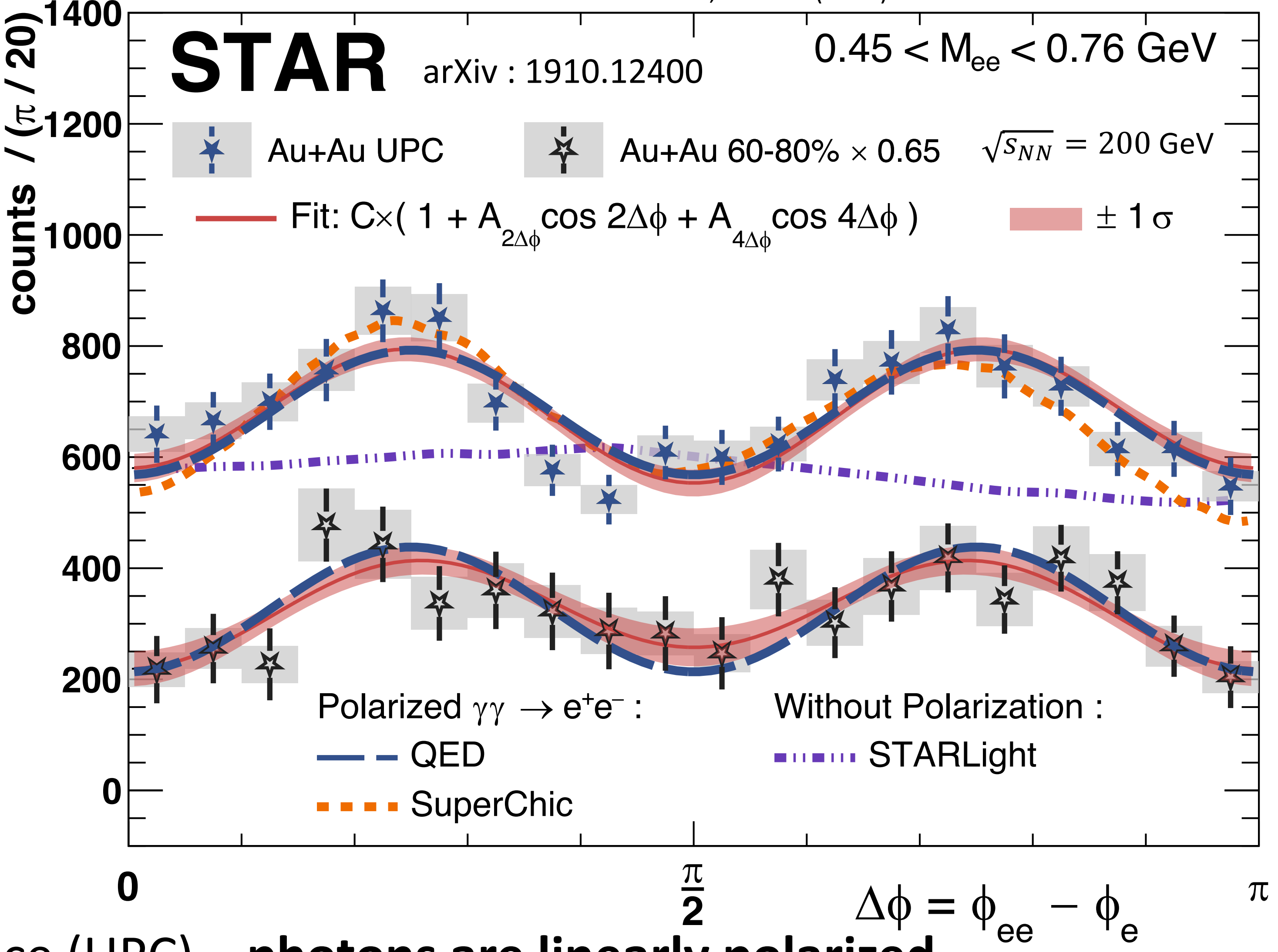
$$\Delta\phi = \Delta\phi[(e^+ + e^-),(e^+ - e^-)]$$
$$\approx \Delta\phi[(e^+ + e^-), e^+]$$

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



$\cos 4\Delta\phi$ 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

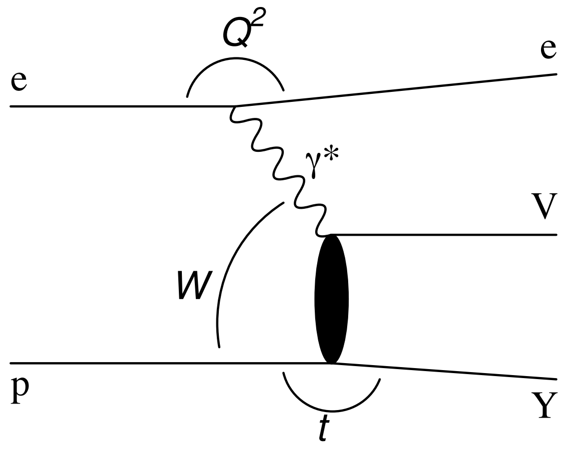


Figure 1: Diffractive vector meson electroproduction.

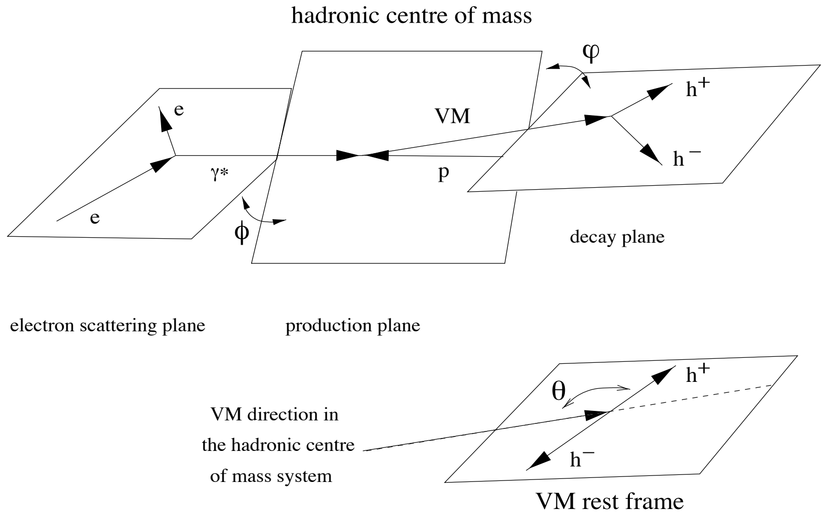


Figure 3: Definition of the angles characterising diffractive VM production and decay in the helicity system.

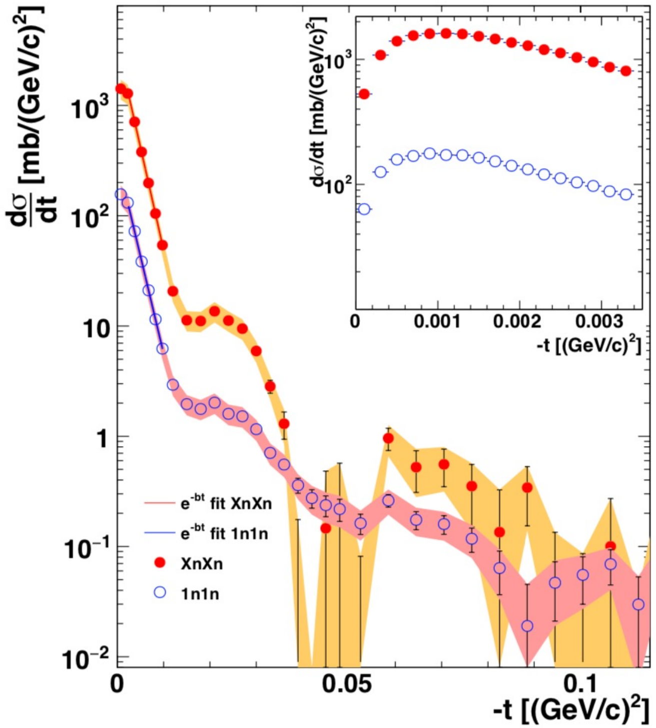
[1] H1 Collaboration. *J. High Energ. Phys.* **2010**, 32 (2010).
[2] ZEUS Collaboration. *Eur. Phys. J. C* **2**, 247–267 (1998).
[3] See refs 1-25 in [2]

Photo-Nuclear processes in UPC

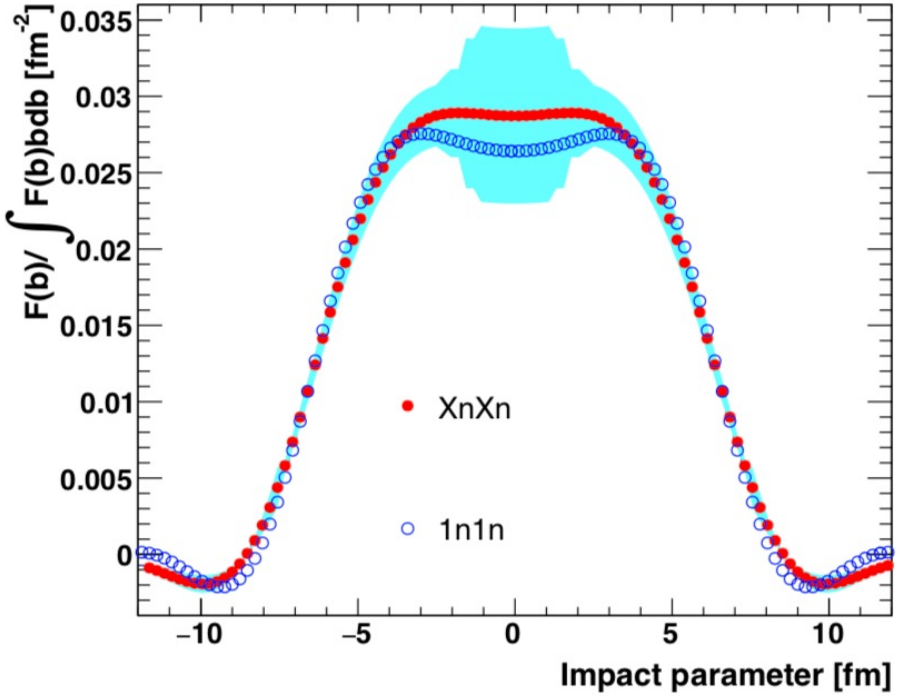
STAR Collaboration *et al. Phys. Rev. Lett.* **89**, 272302 (2002).
STAR Collaboration *et al. Phys. Rev. Lett.* **102**, 112301 (2009).
STAR Collaboration *et al. Phys. Rev. C* **96**, 054904 (2017).

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



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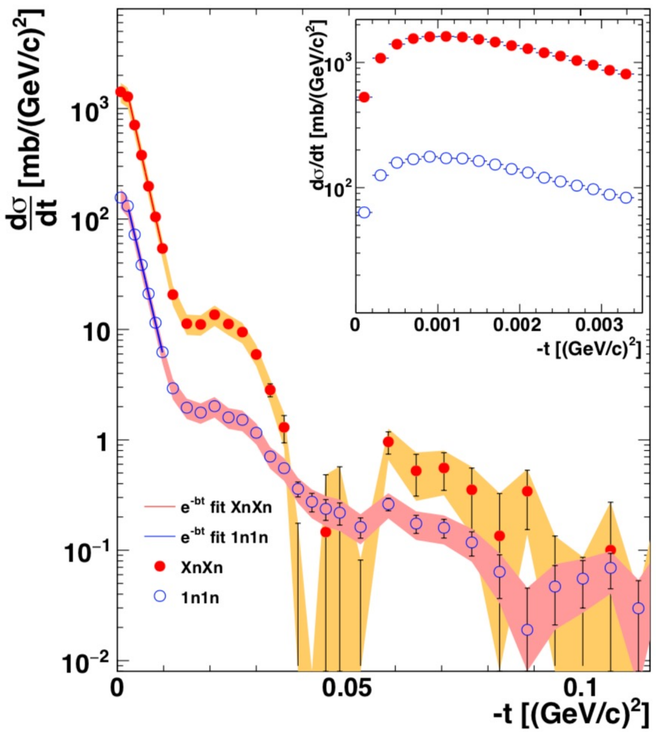

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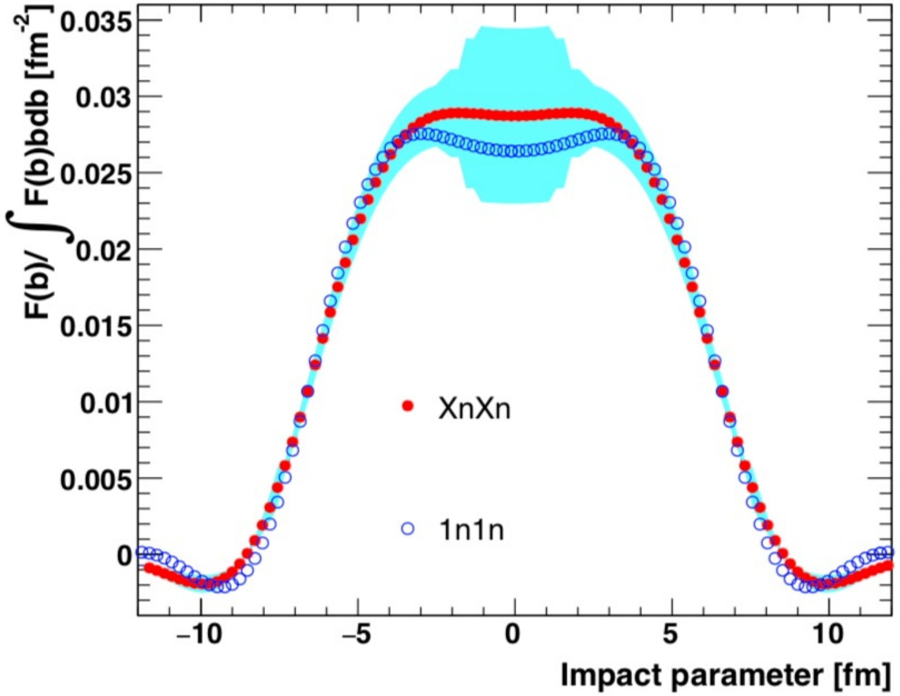

Other measurements in UPC at RHIC & LHC include:

Photoproduction of J/psi 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

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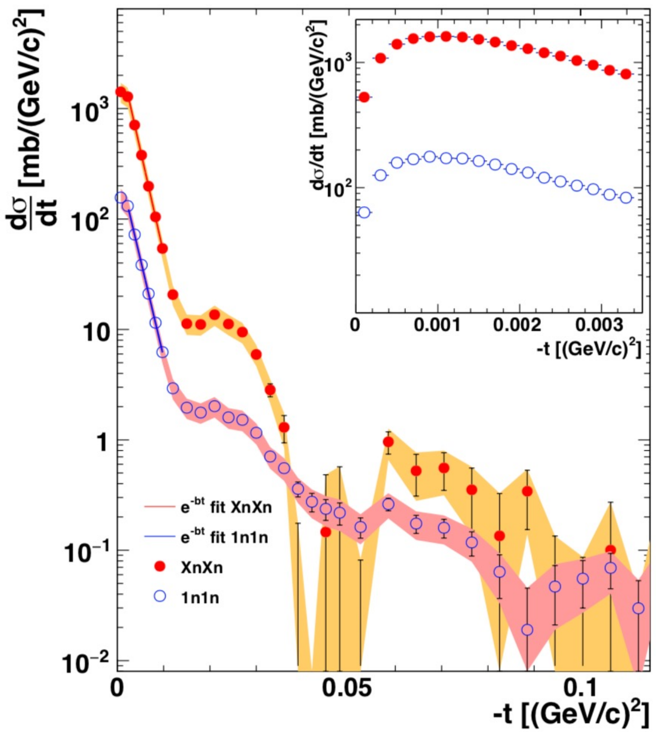

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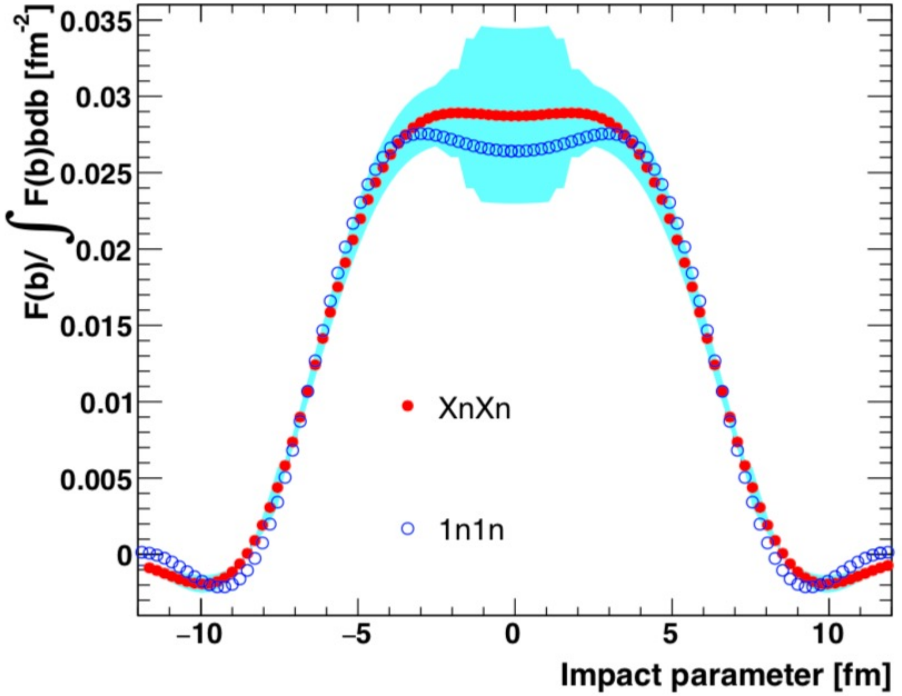

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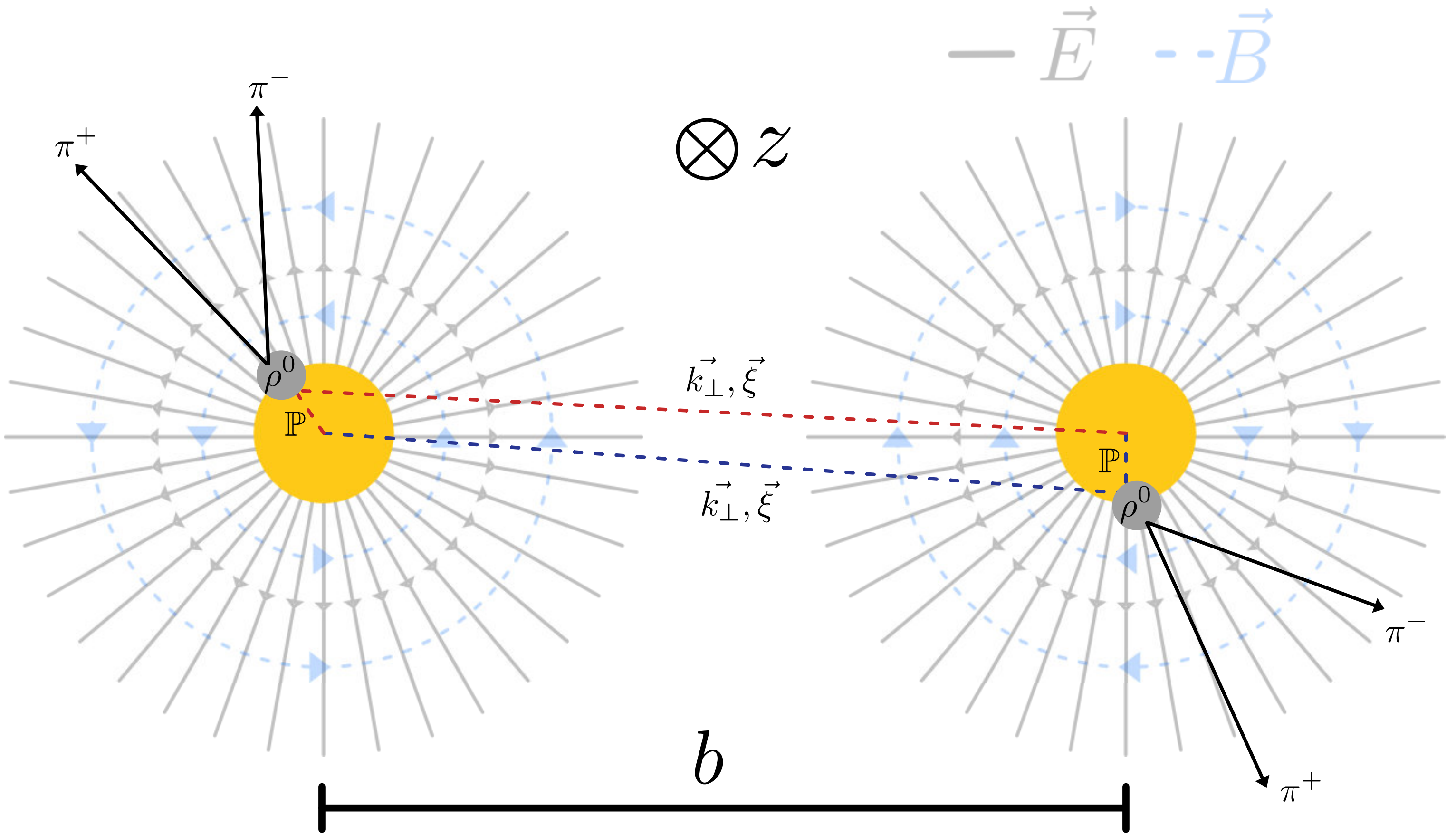
… and many more

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

Photo-production with Polarized Photons

- Nuclei “take-turns” emitting photon vs. Pomeron

- 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 are produced through interference of both amplitudes



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

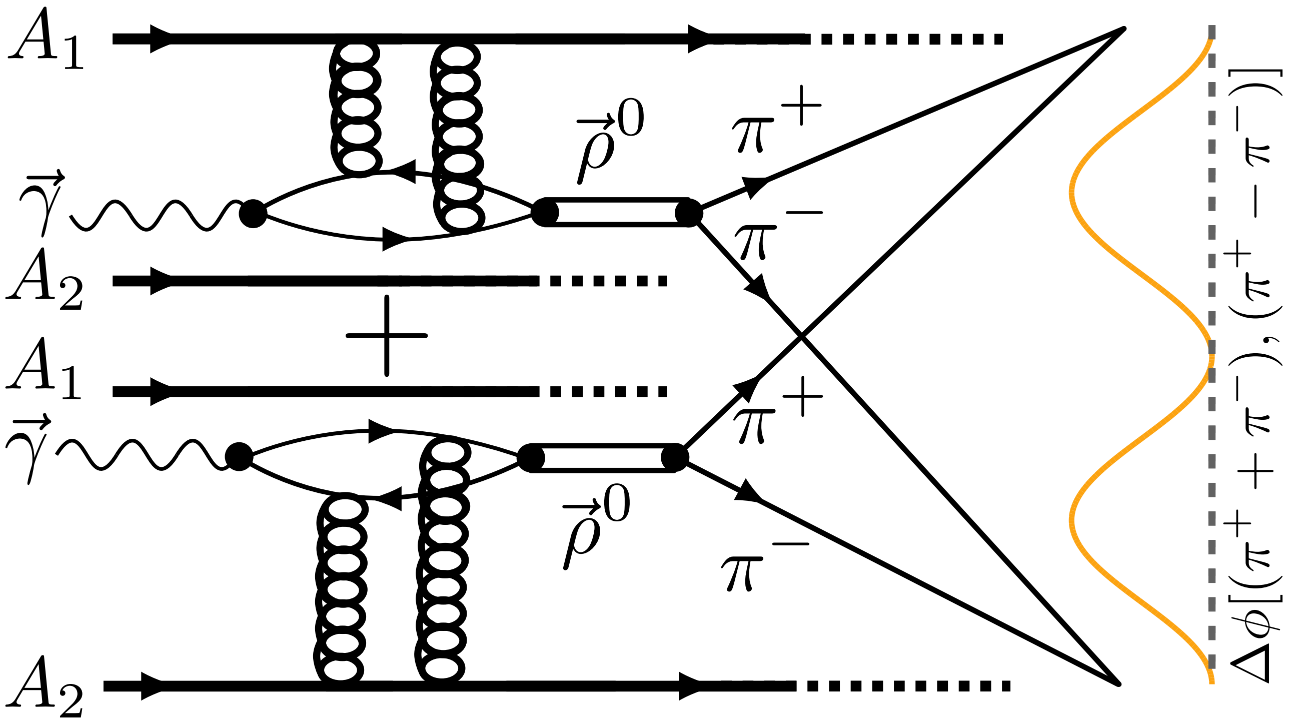
Klein, S. R. & Nystrand, J. *Phys. Rev. Lett.* **84**, 2330–2333 (2000).

Quantum Interference Effects with Polarized Photons

If the photons are linearly polarized in the transverse plane:

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

→ Modulation due to quantum interference of amplitudes



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 $\gamma\gamma \to e^+e^-$ case

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

Photon Polarization → Destructive Interference

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

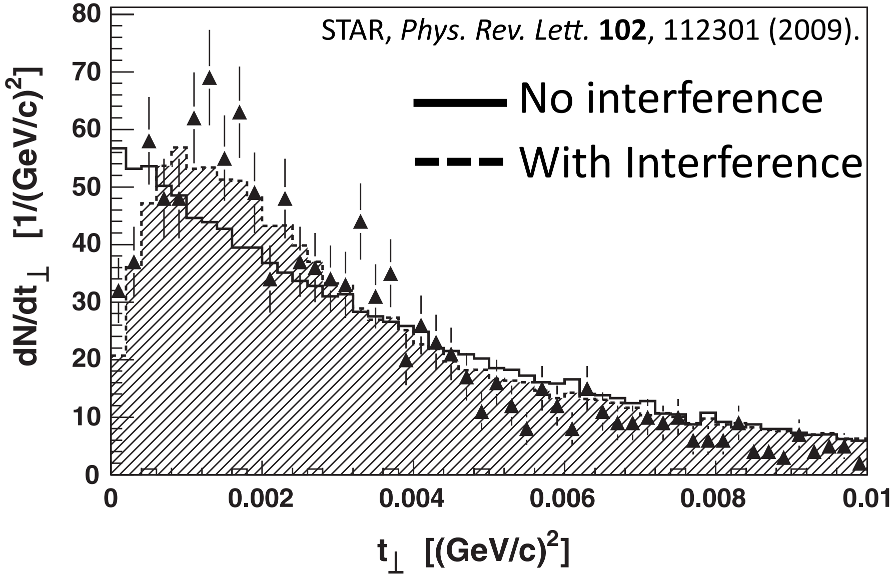


FIG. 2. Raw (uncorrected) ρ^0 $t_\perp$ spectrum in the range $0.0 < |y| < 0.5$ for the MB data. The points are data, with statistical errors. The dashed (filled) histogram is a simulation with an interference term (“Int”), while the solid histogram is a simulation without interference (“NoInt”). The 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.

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- 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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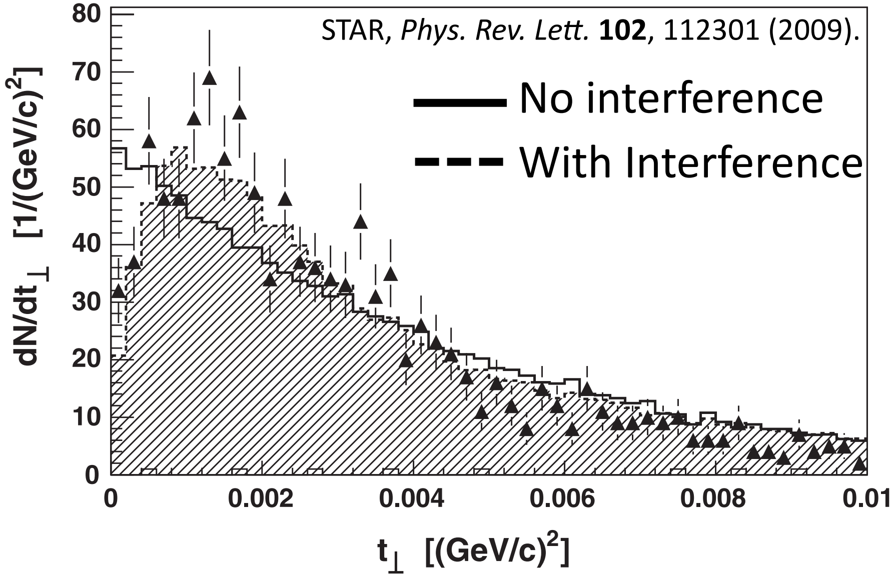

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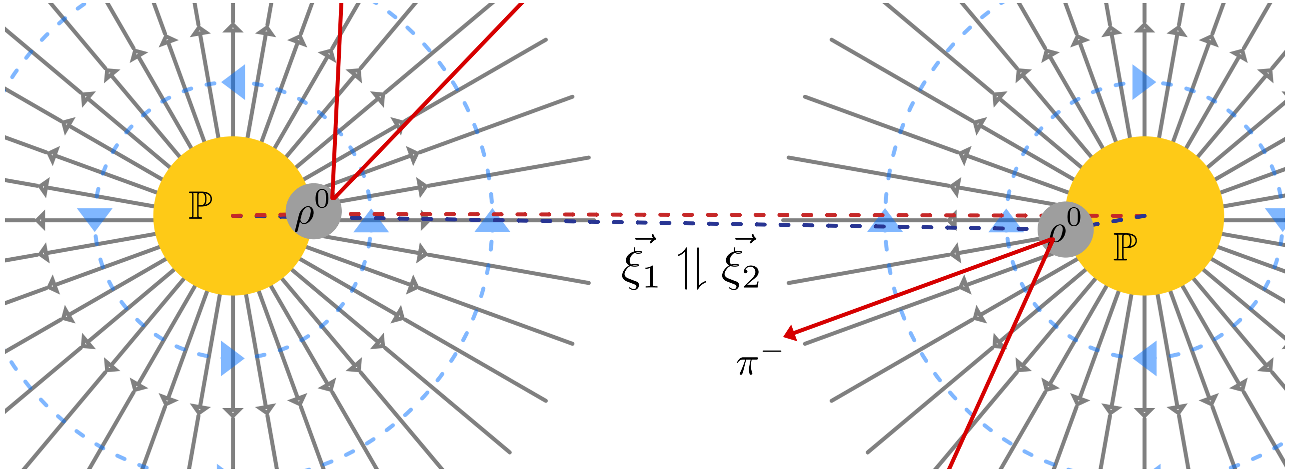
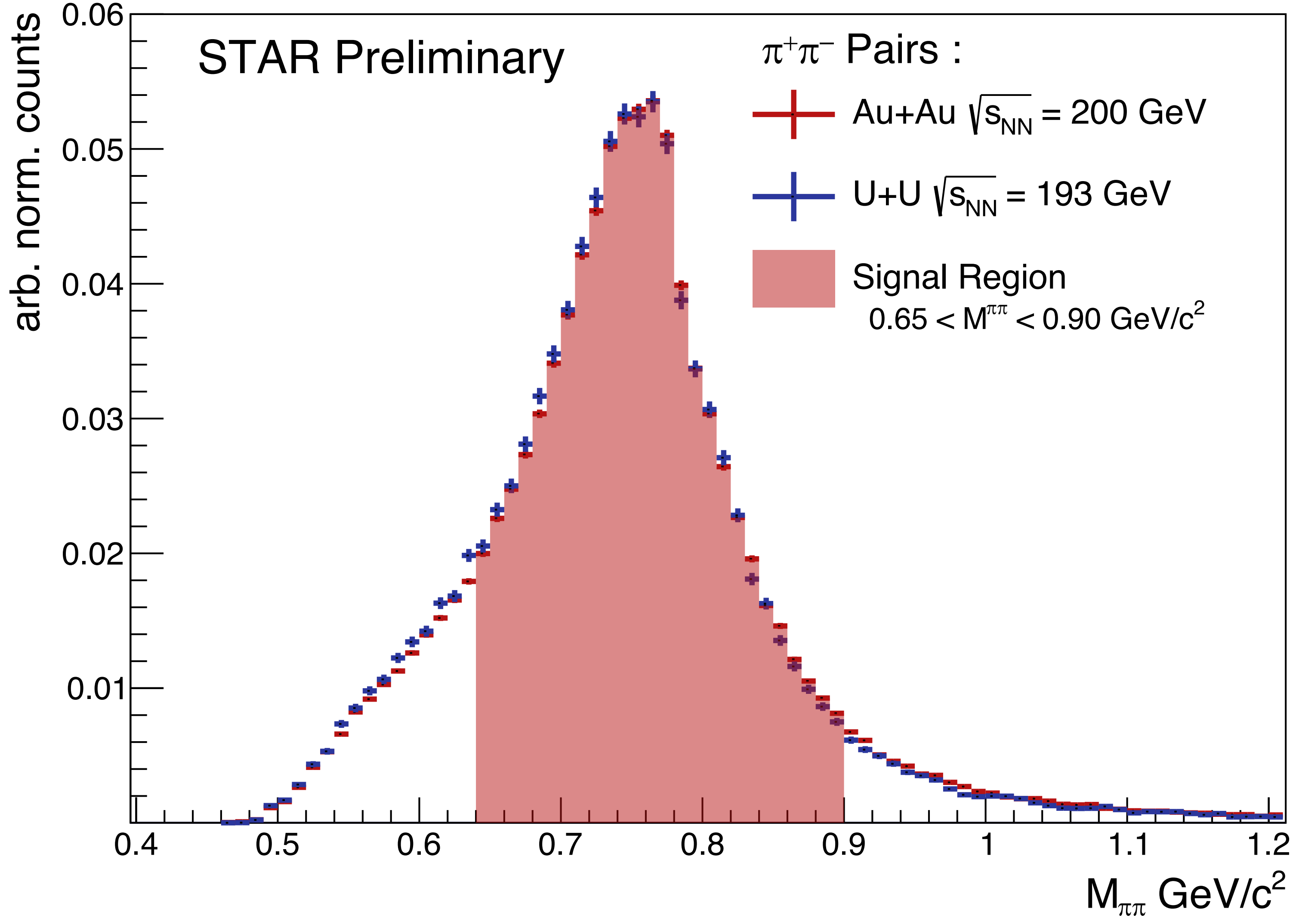


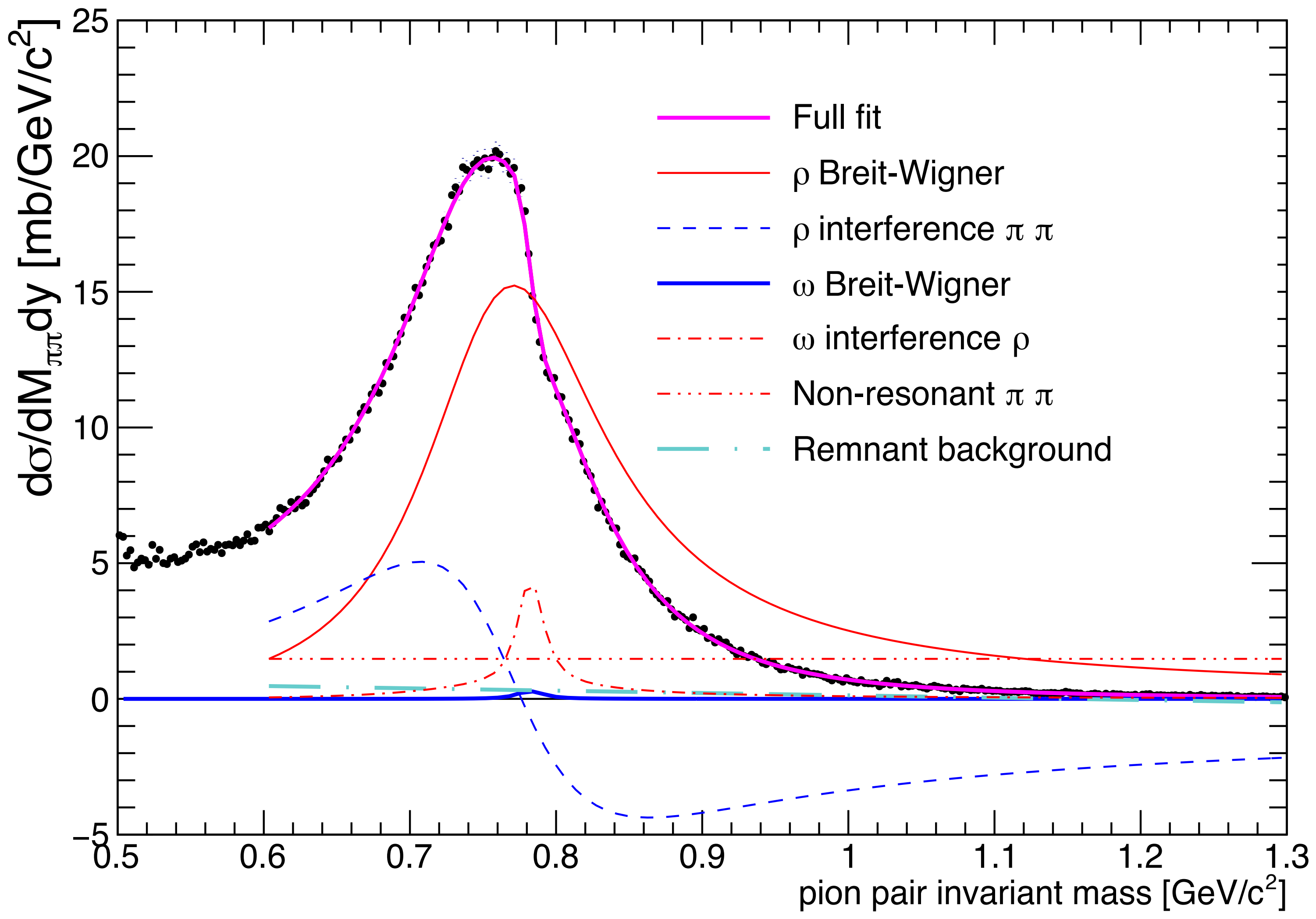
- Production at **zero** P_T must have anti-parallel photon polarization
- Provides an intuitive understanding of destructive interference

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

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

$\Delta\phi$ 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 :

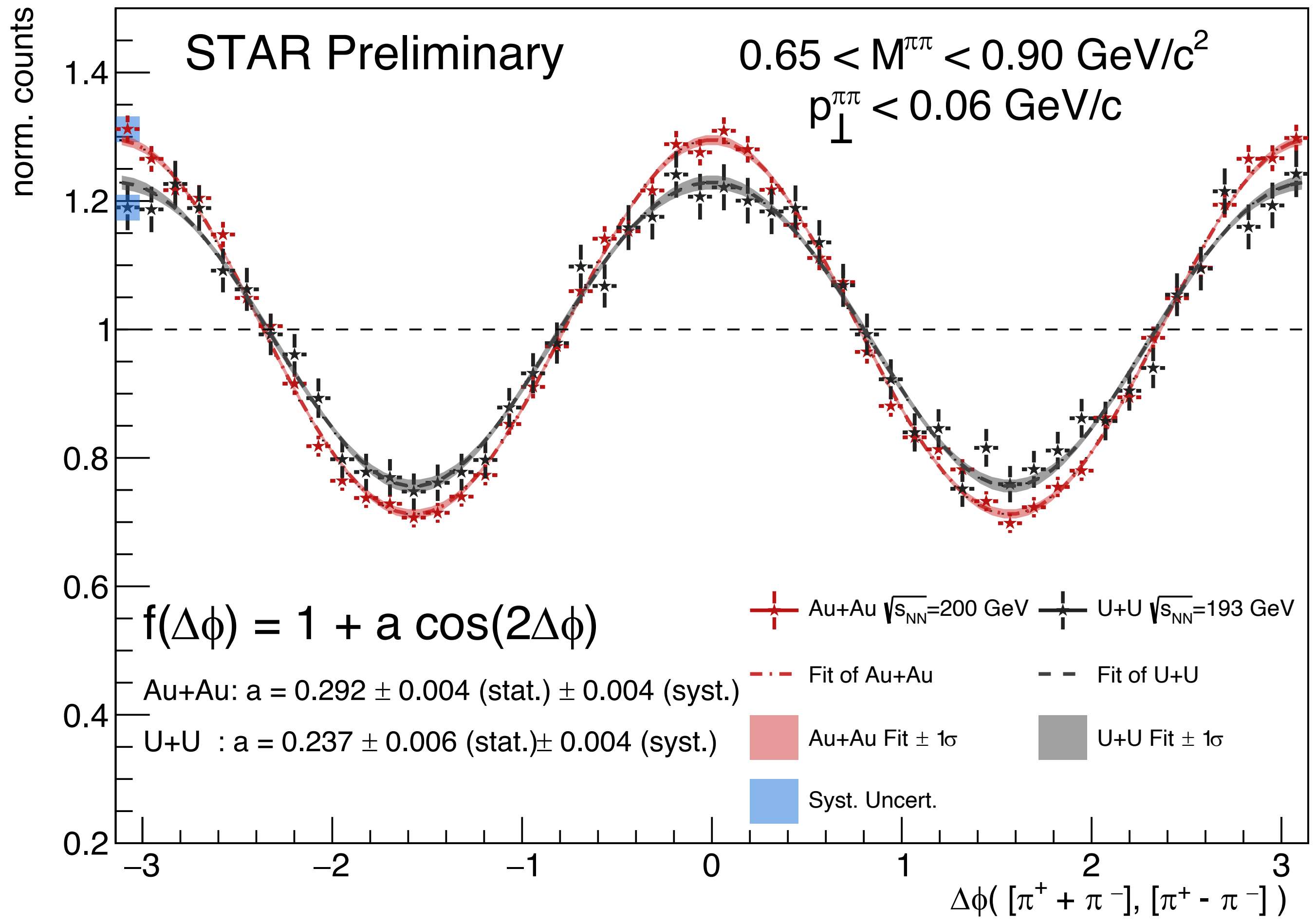
$a = 0.292 \pm 0.004$ (stat) ± 0.004 (syst.)

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



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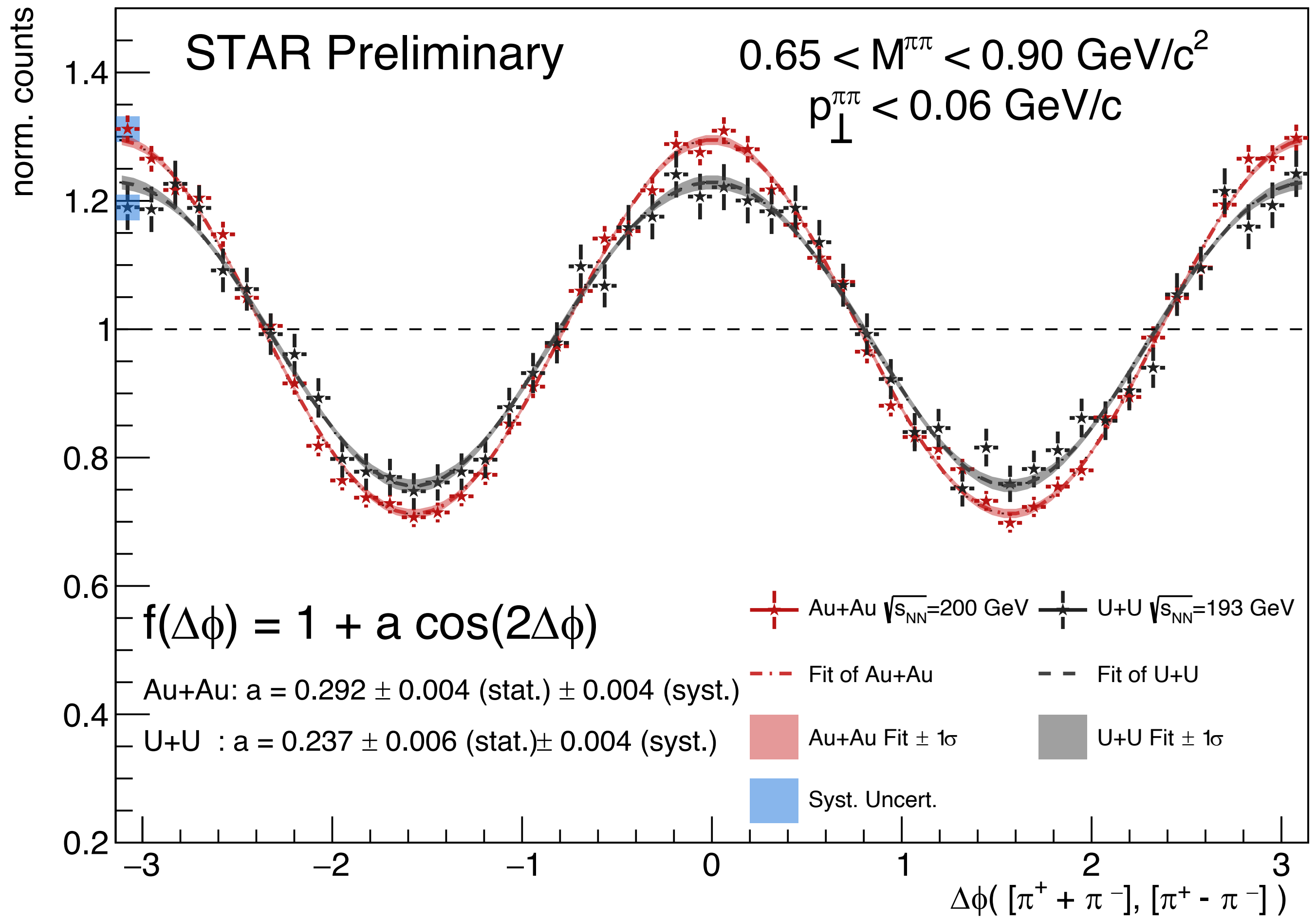
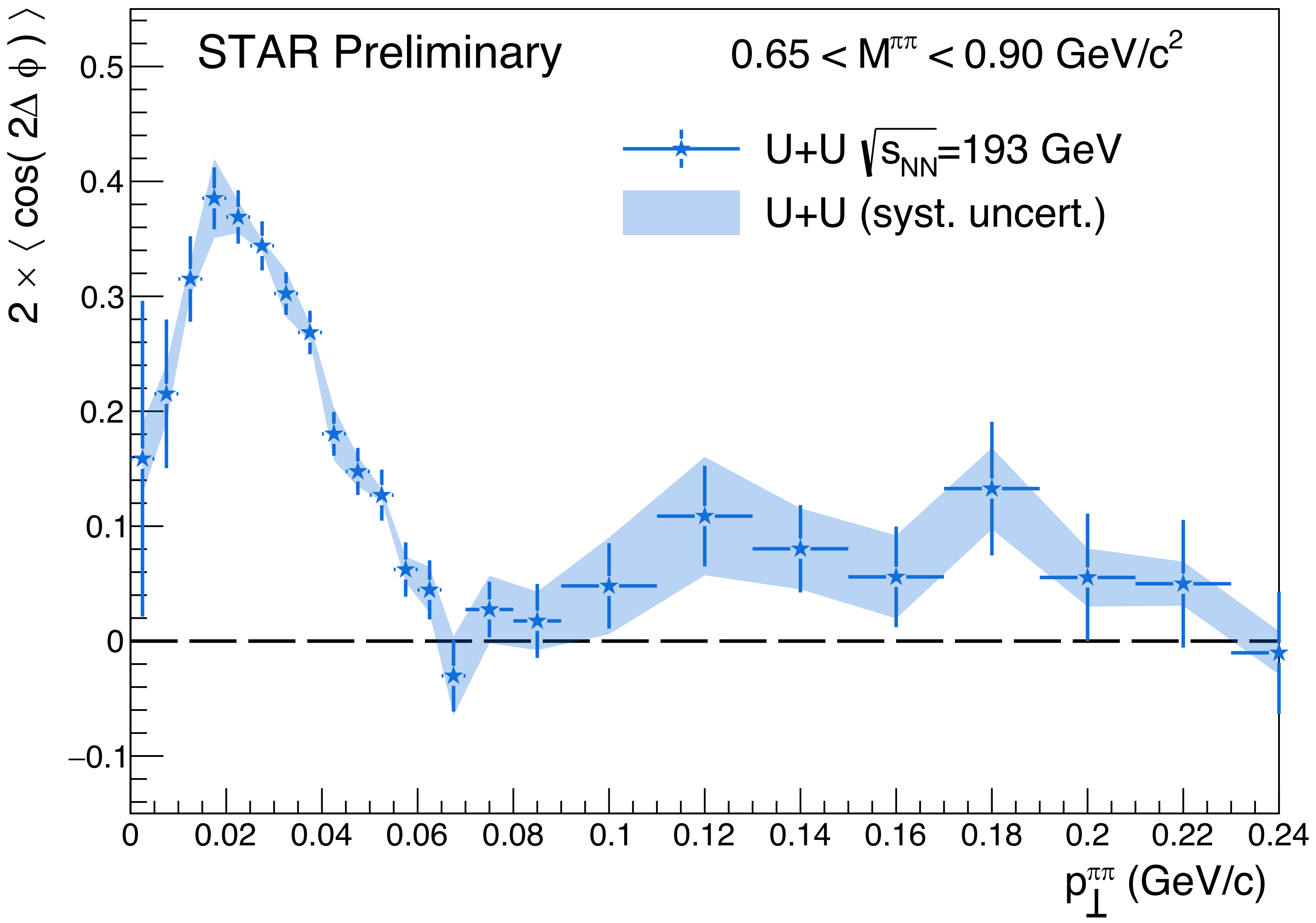


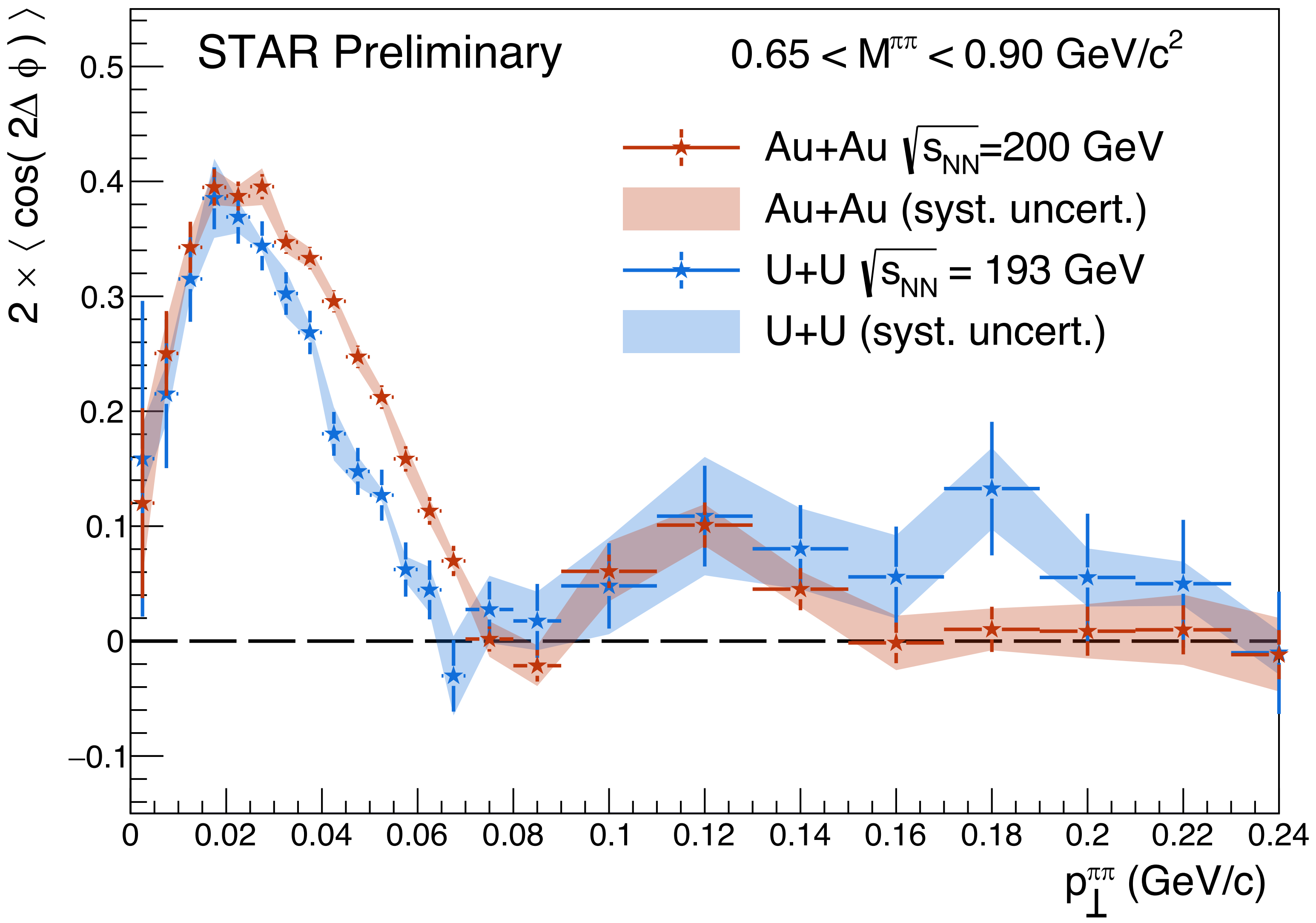
Investigate the interference effect in more detail through p_T structure

$\cos 2\Delta\phi \;\; vs. \, p_T$ in U+U at $\sqrt{s_{NN}} = 193$ GeV



- Strong $\cos 2\Delta\phi$ modulation observed at $\mathrm{p}_T < \sim 60$ MeV/c
- Broad second “peak” above 80 MeV/c
- Includes both coherent and incoherent sources
- Fully corrected for STAR acceptance
- Systematic uncertainty shown in colored band

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

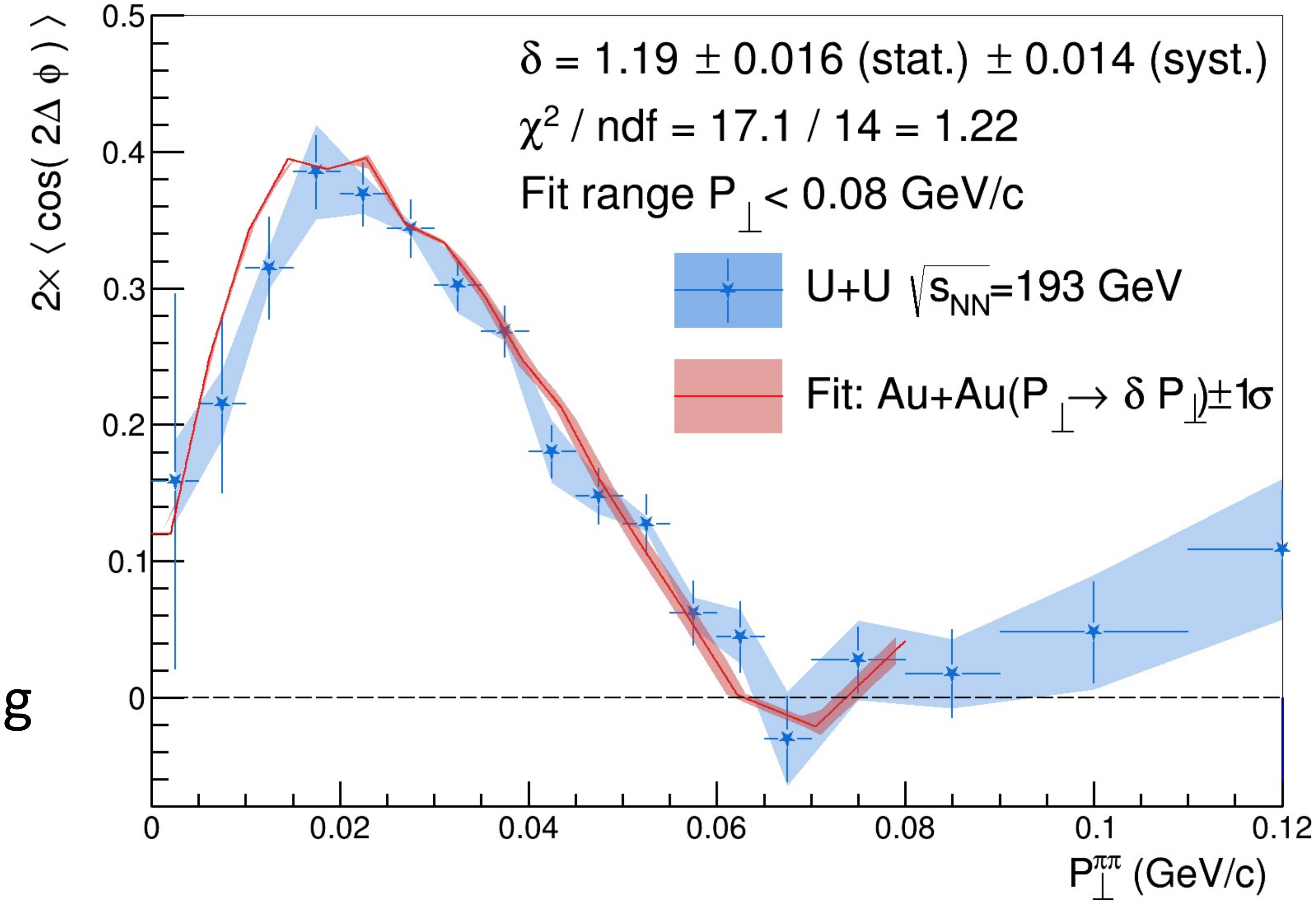


- Strong $\cos 2\Delta\phi$ modulation observed at $p_T < \sim 60$ MeV/c
- In U+U: Broad second "peak" above 80 MeV/c
- In Au+Au: more definite second peak around $80 < p_T < 160$ MeV/c

- Includes both coherent and incoherent sources
- Fully corrected for STAR acceptance
- Systematic uncertainty shown in colored band

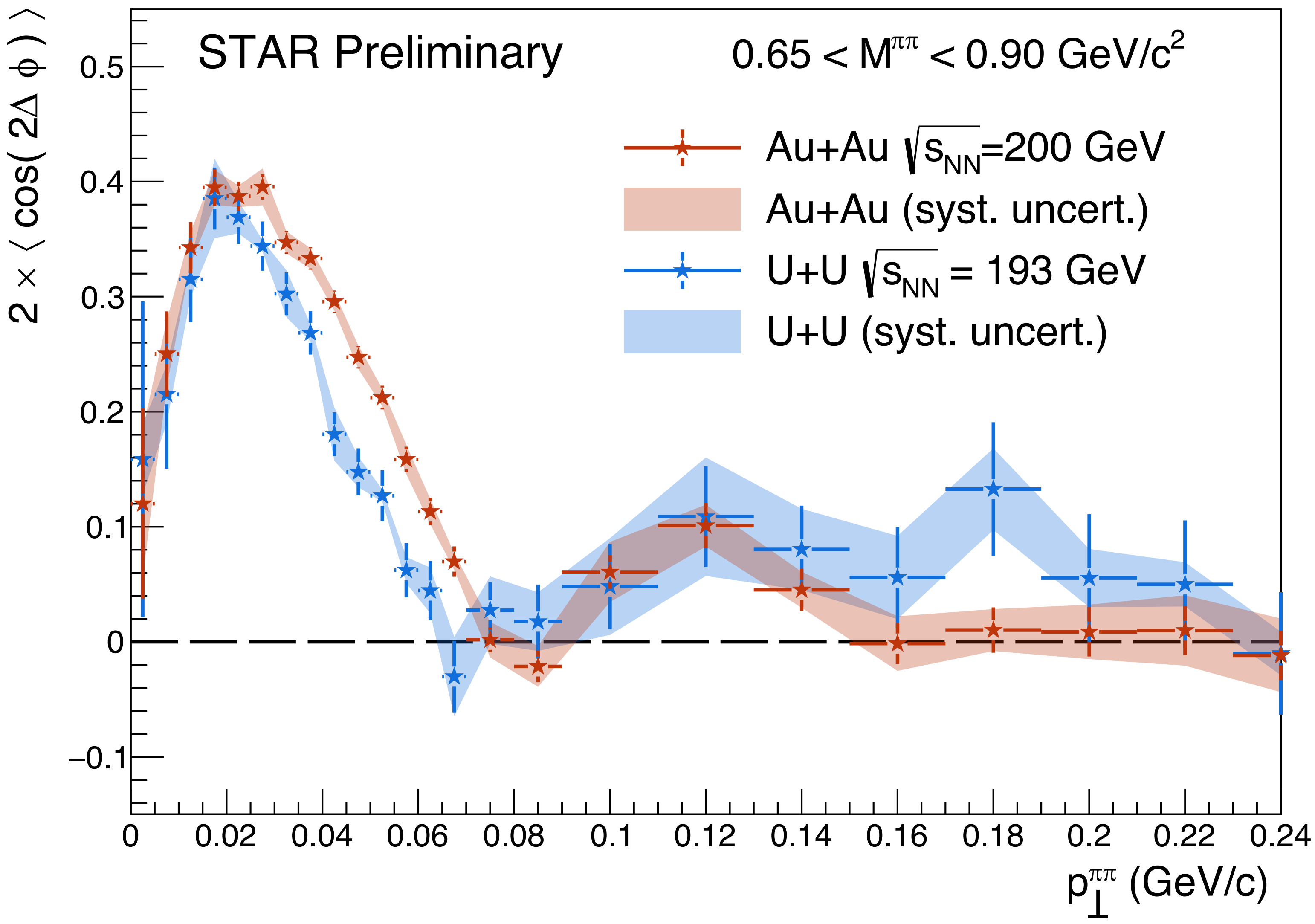
Quantitative Comparison : Au+Au and U+U

- Fit U+U curve with scaled Au+Au curve ($\delta p_\perp \rightarrow p_\perp$)
- Robust best fit for $\delta = 1.194 \pm 0.021$ (stat. and syst. uncert) $\rightarrow 9\sigma$ significant difference
- Consistent with ratio of long axes (U/Au) of 1.22 ± 0.02



[1] Q. Y. Shou, Y. G. Ma, et al., Physics Letters B **749**, 215 (2015).

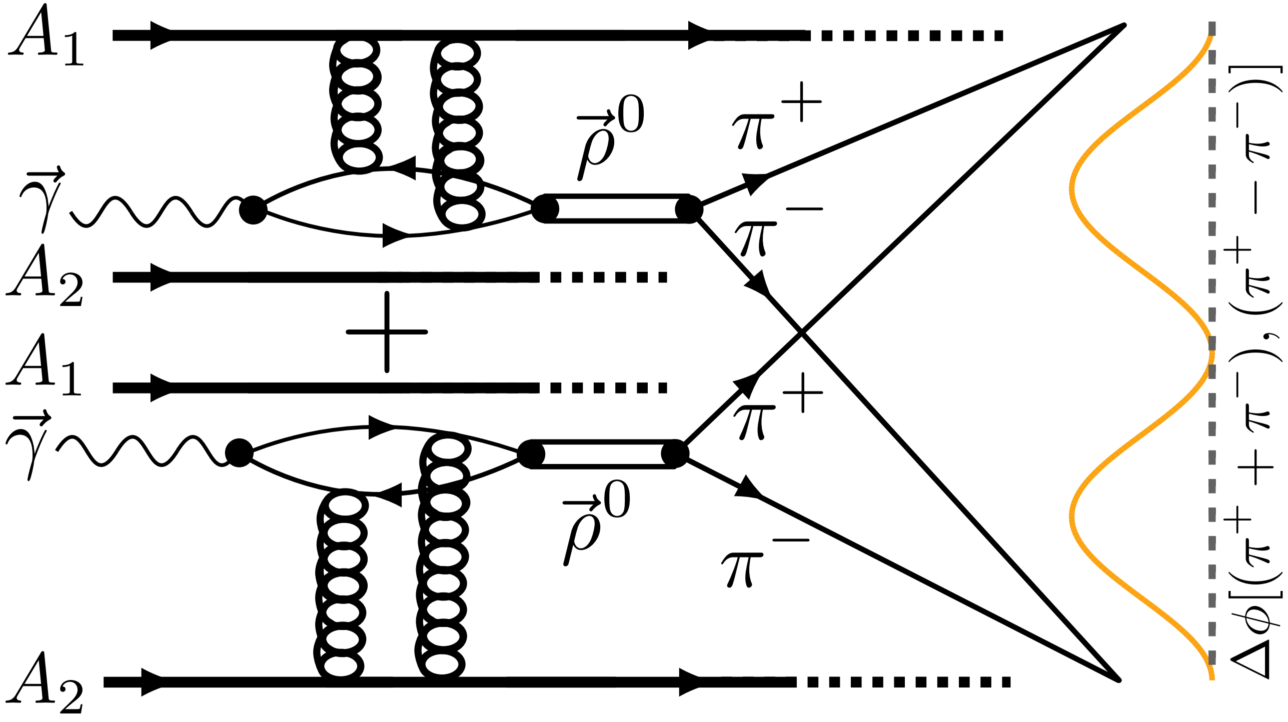
Effect of Incoherent Production?



- Both Au+Au and U+U show no modulation at high p_T where incoherent production dominates
- Experimentally we observe that the incoherent production does not contribute to $\Delta\phi$ modulation
- Provides new information for improved separation of coherent / incoherent from the theoretical side

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

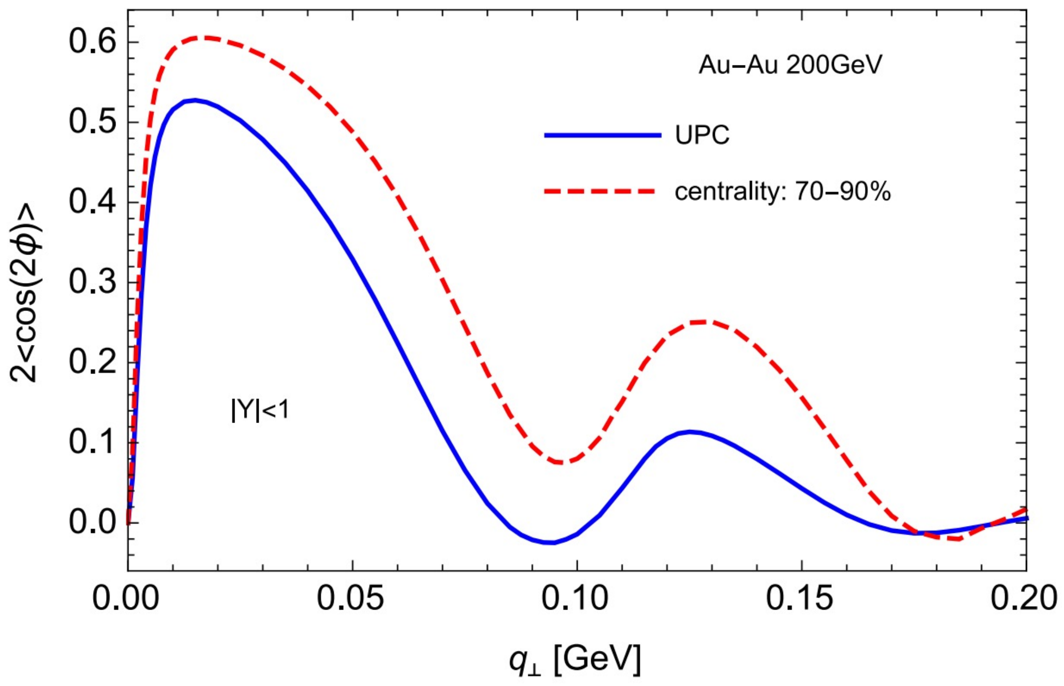


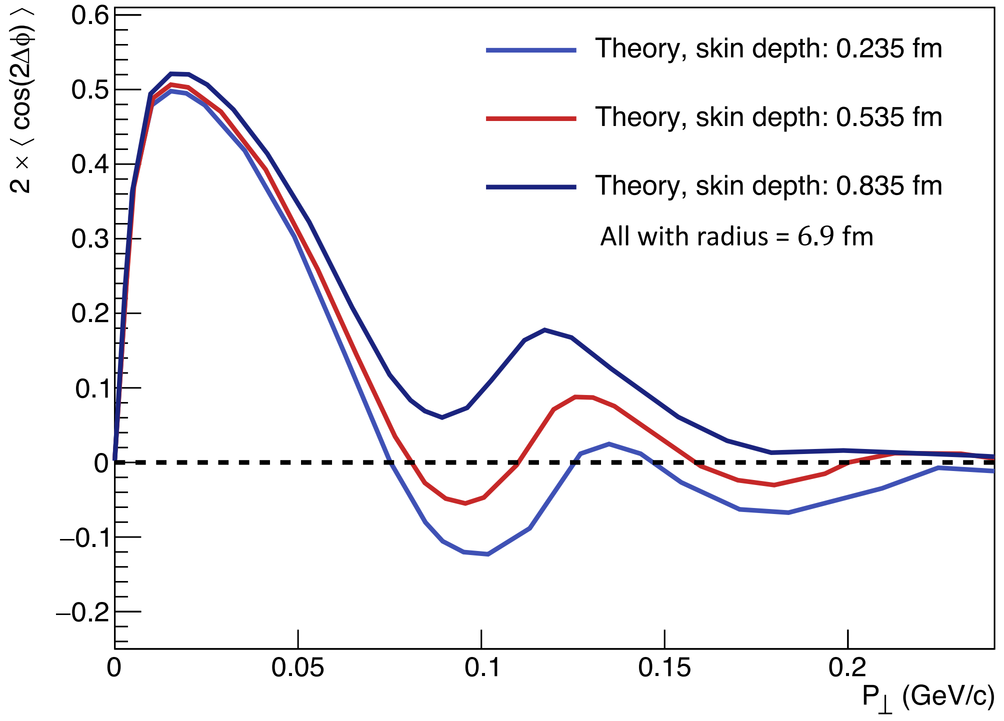
- Look at both theory calculations in detail
- Compare predictions to the STAR measurements

[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).

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:

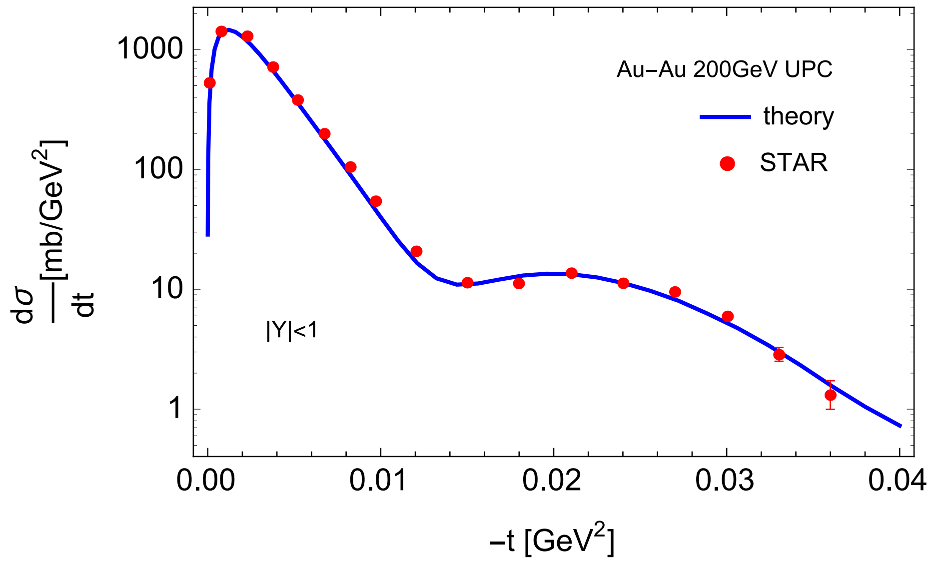
→ Nuclear Geometry / gluon distribution

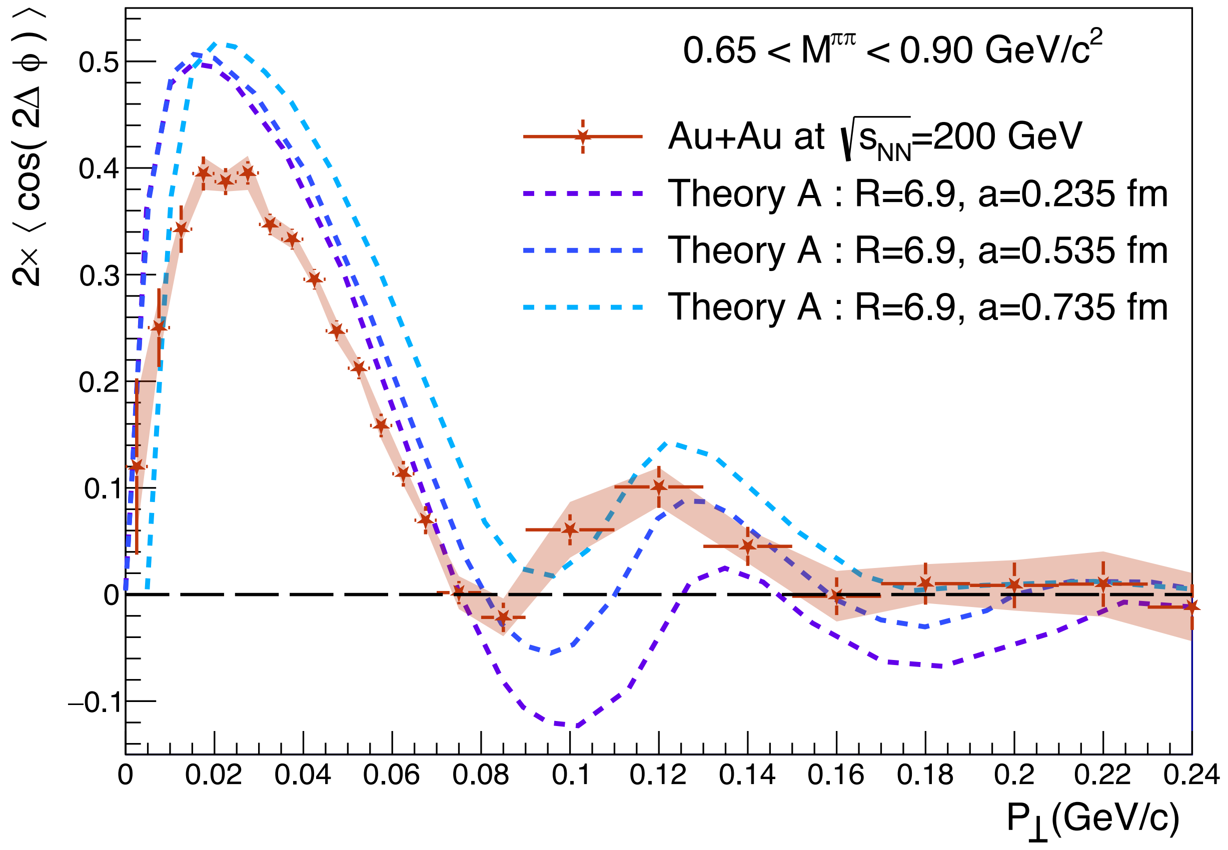
(Skin depth = Woods-Saxon diffusivity a)

→ 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)

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

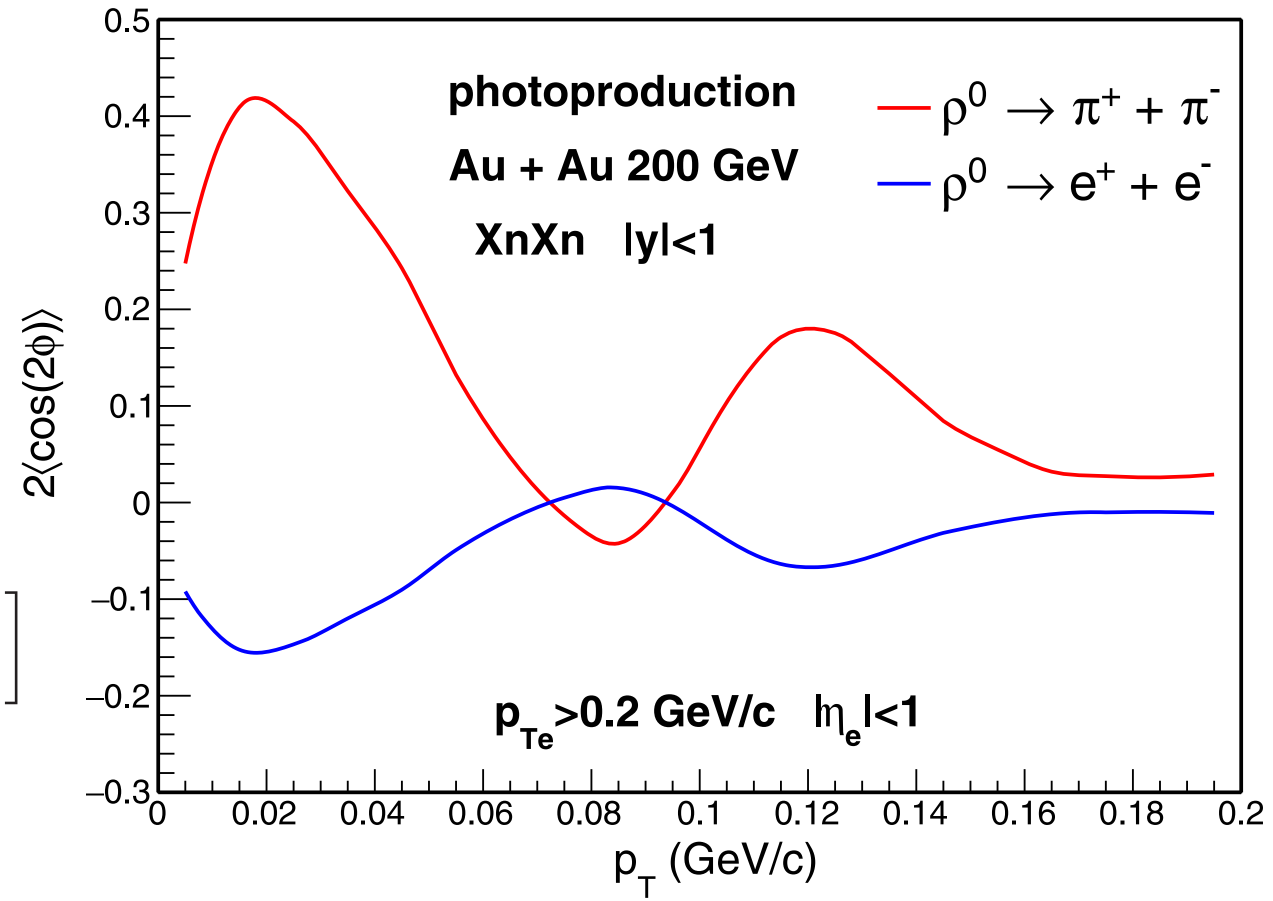
$$2\langle\cos(2\phi)\rangle = \cos(2\Phi)$$

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

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

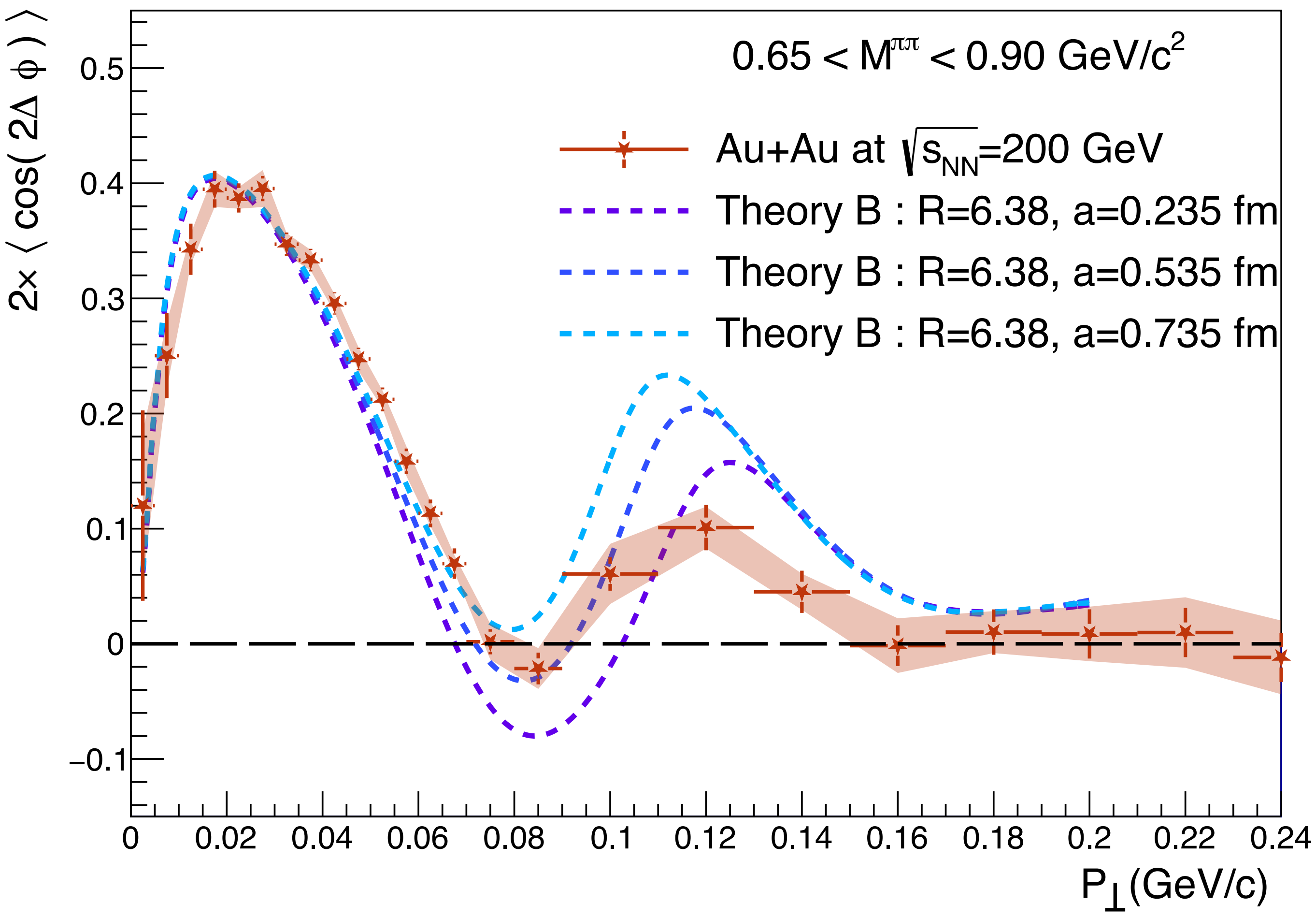
$$2\langle\cos(2\phi)\rangle = -\frac{\sin^2\theta}{1+\cos^2\theta}\cos(2\Phi)$$

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]

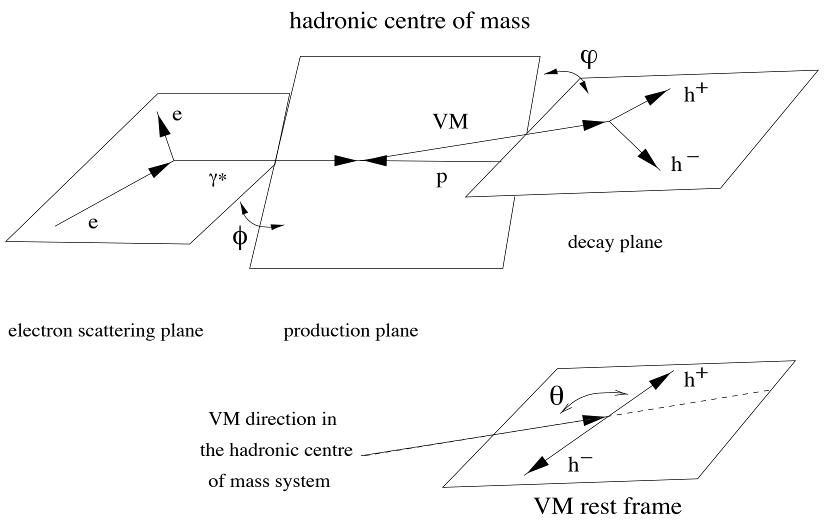


Figure 3: Definition of the angles characterising diffractive VM production and decay in the helicity system.

[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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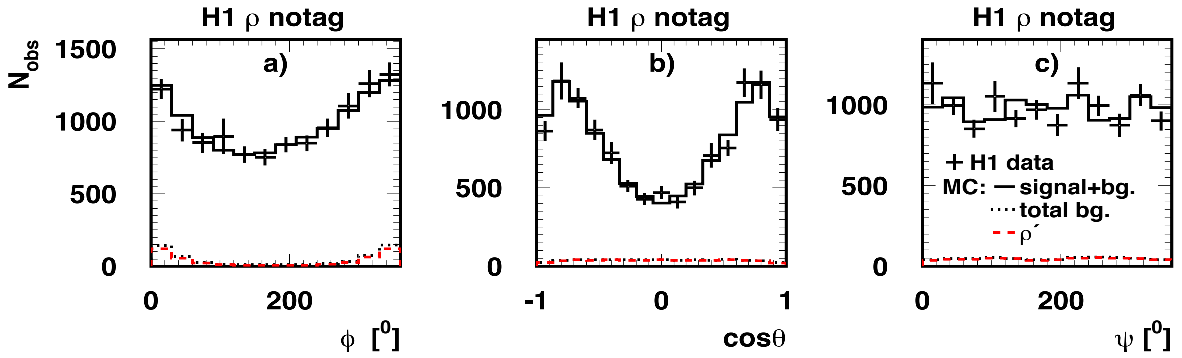

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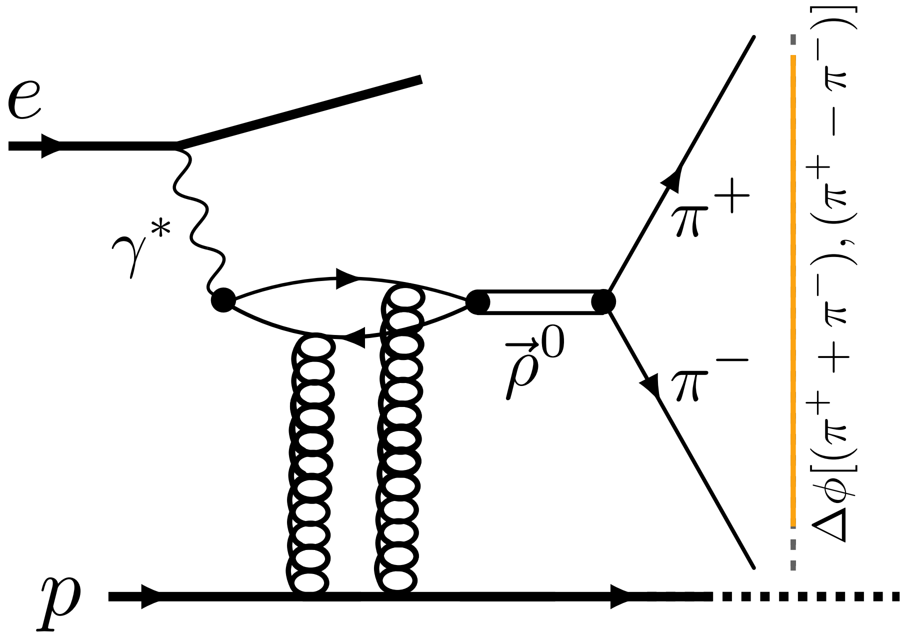

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2. At HERA the outgoing electron was tagged
   - The photon momentum vector is known
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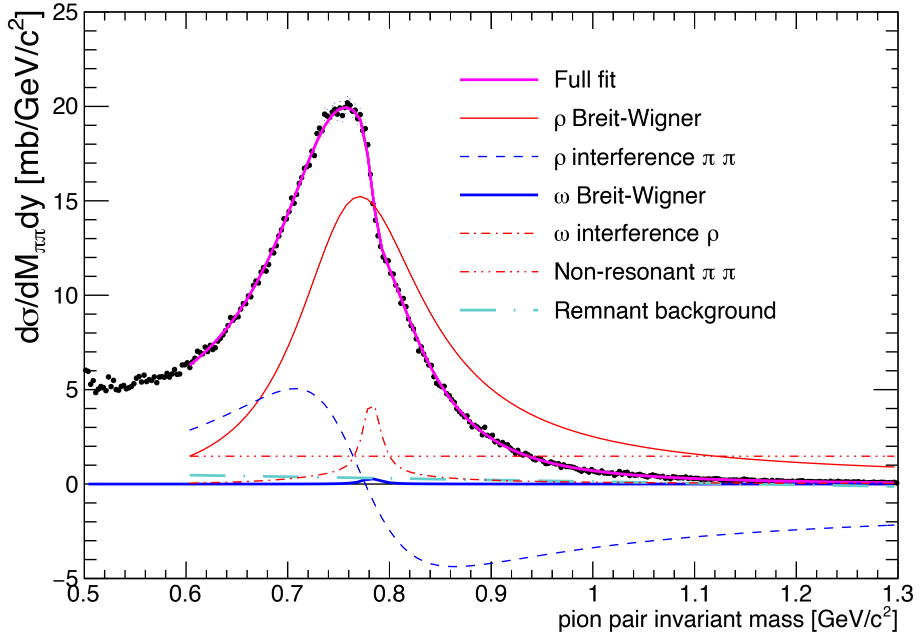
3. In ep the photon is high Q^2 and predominately longitudinally polarized $\langle \xi_{long} \rangle \approx 0.98$
4. There is only one contributing amplitude - no interference effect

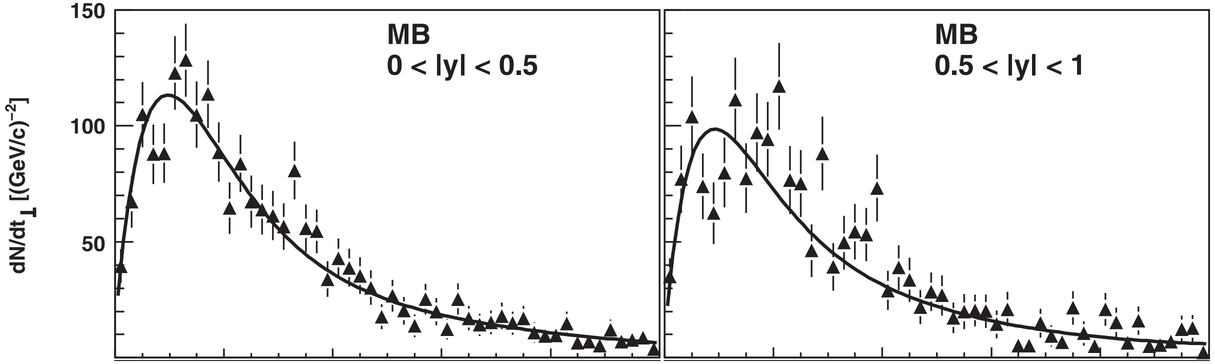
[1] H1 Collaboration. *J. High Energ. Phys.* **2010**, 32 (2010).
[2] STAR, Phys. Rev. C77, 034910 (2008).

Prospects & Applications

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?

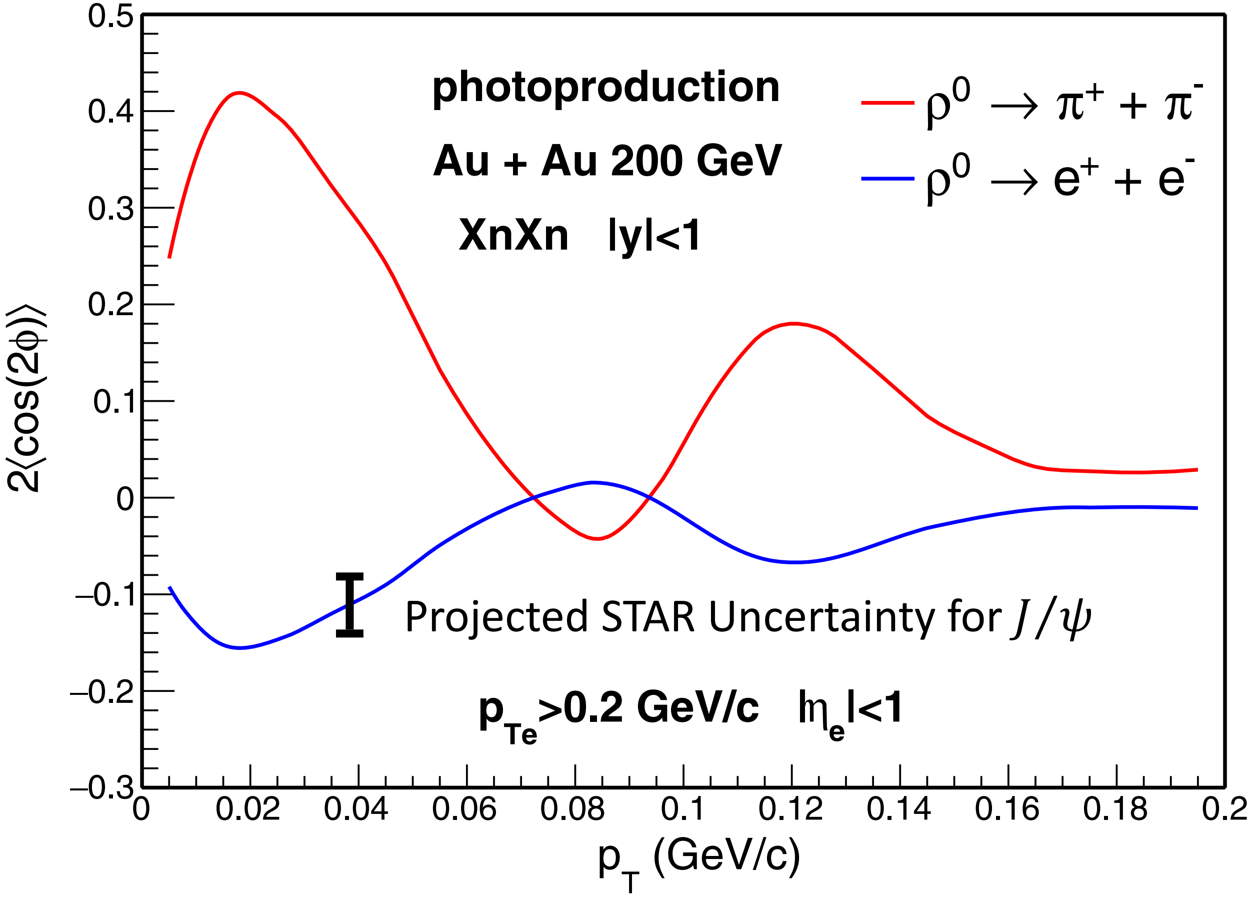
$$\sigma(p_T, b, y) = |A(p_T, b, y) - A(p_T, b, -y)\exp(i\vec{p}_T \cdot \vec{b})|^2, \quad (1)$$

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

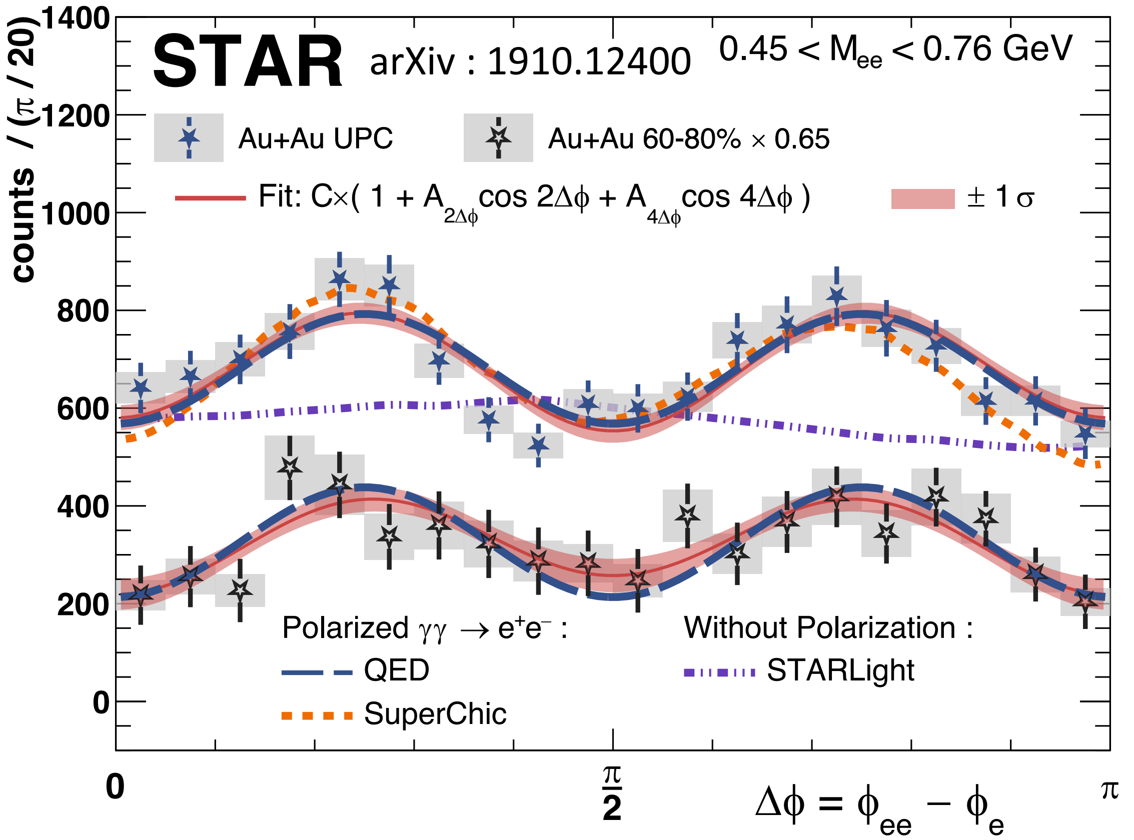


$\rho^0 \rightarrow e^+e^-$: Relevant for $J/\psi \rightarrow e^+e^-$ case
STAR J/ψ measurement in 2023-2025 : $\pm$4% @ 50 MeV/c

- 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

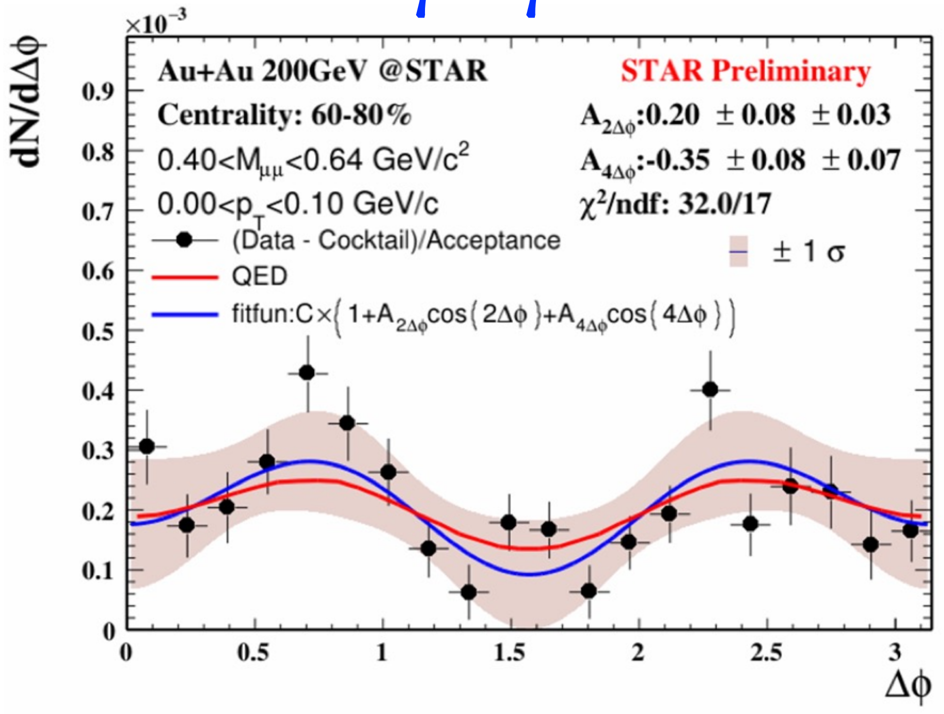
Future Tests of Interference Effects

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



$\mu^+\mu^-$

J. Zhou, sQM 2021



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

Future Tests of Interference Effects

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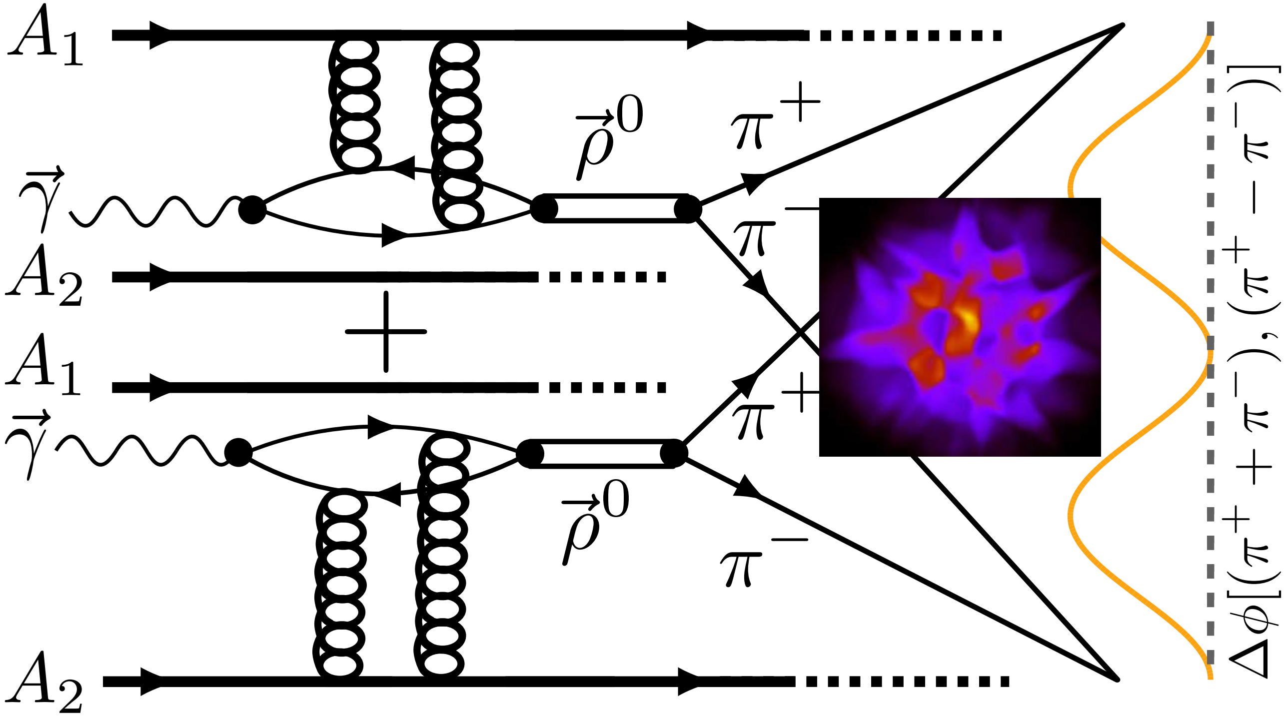
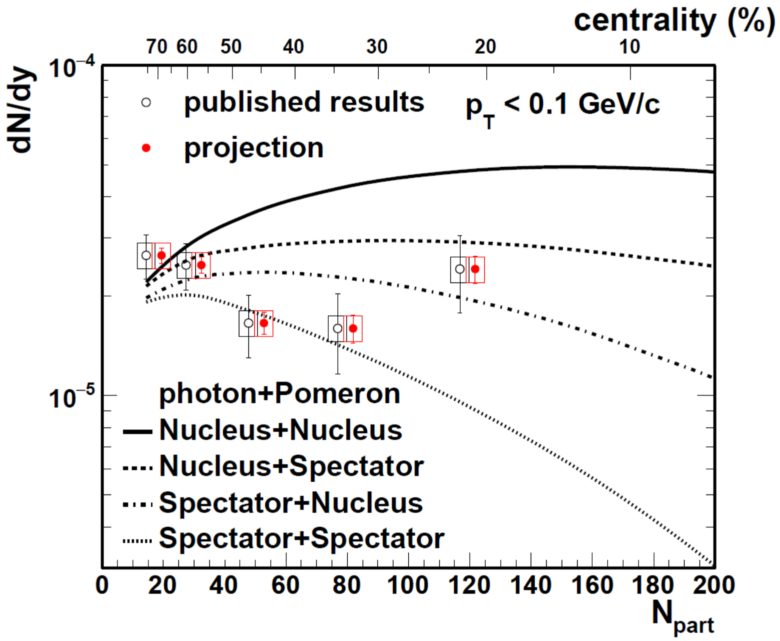


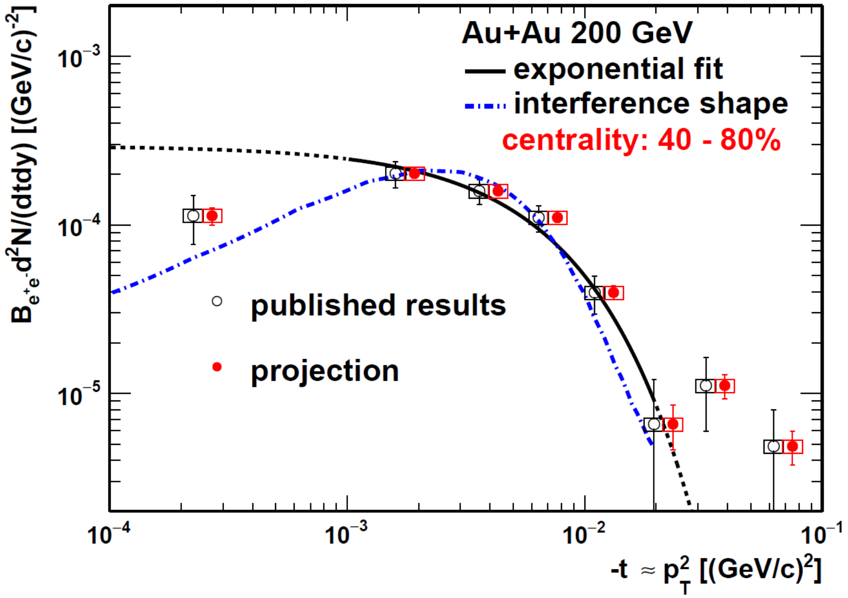
- Unlike leptons, π interact via strong force
- Presence of strongly interacting medium → **wavefunction collapse?**
  - **I.e. no interference**
- In this case comparison of $\rho^0 \to \pi^+\pi^-$ vs. $J/\psi \to l^+l^-$ would be very interesting

Future Tests of Interference Effects

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

Answer Question: What is coherently interaction?



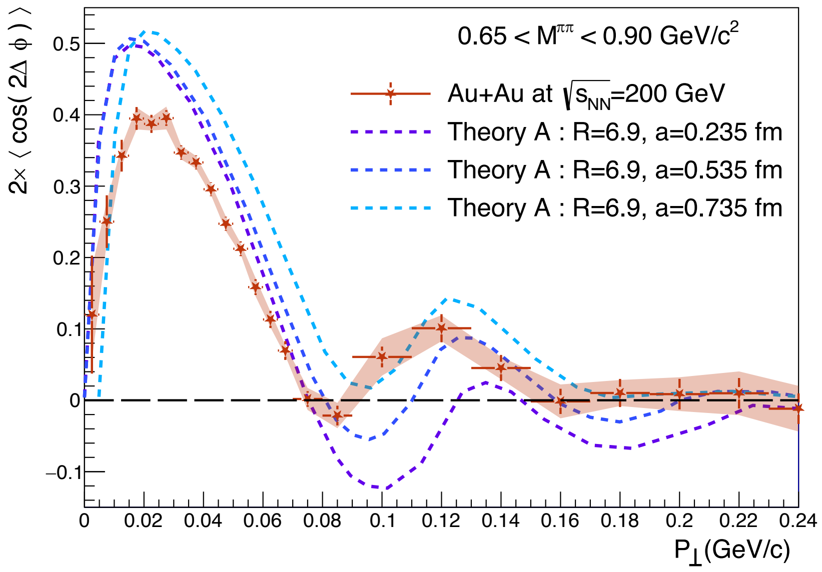


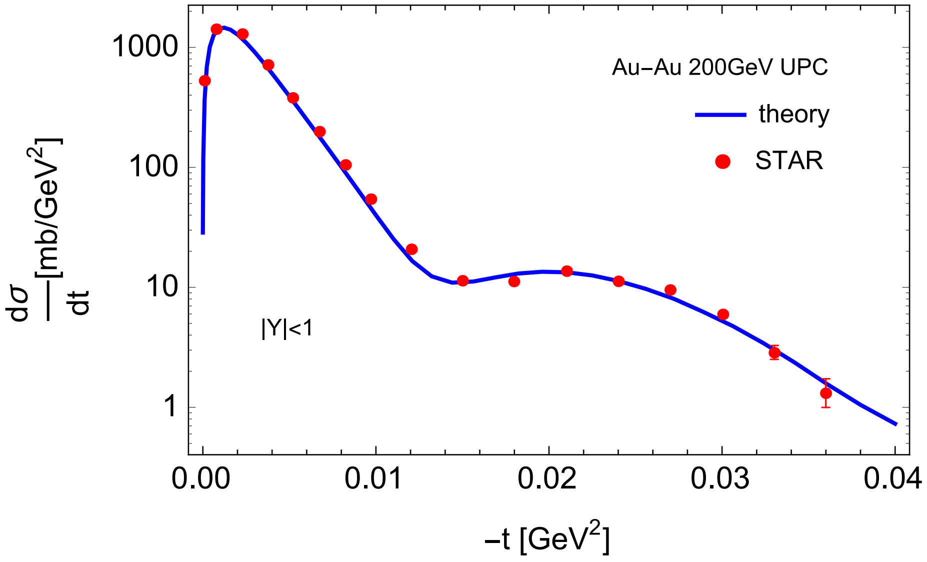
- STAR Measurements of $J/\psi \to l^+l^-$ in peripheral collisions already indicate interference
- Coherent measurements in peripheral collisions can help distinguish coherent emitter
- $\Delta\phi$ Interference pattern should provide much more information

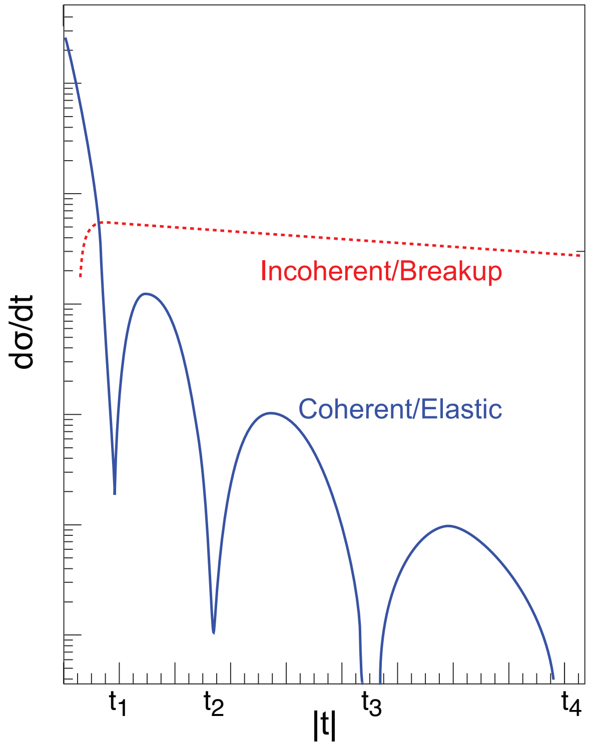
Use interference to separate Coherent/Incoherent

- 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

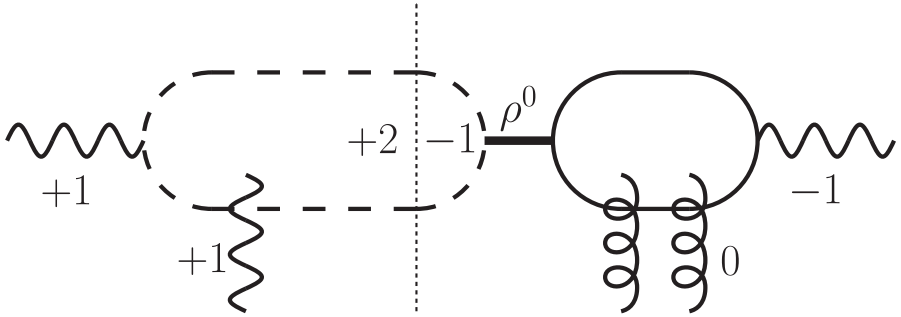
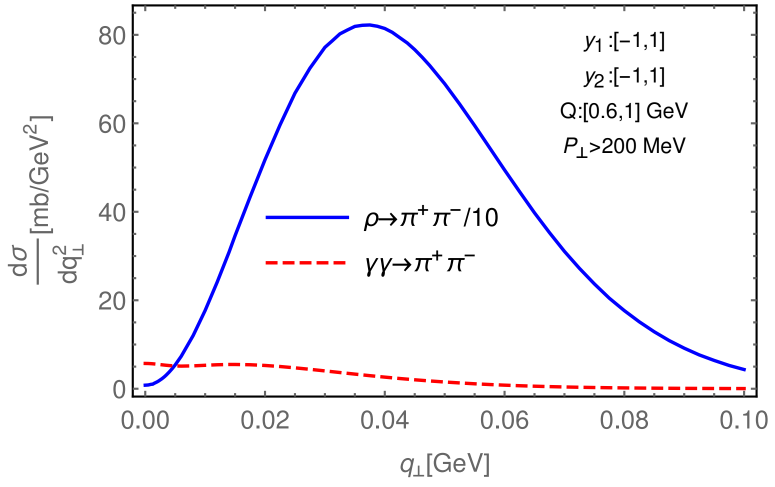
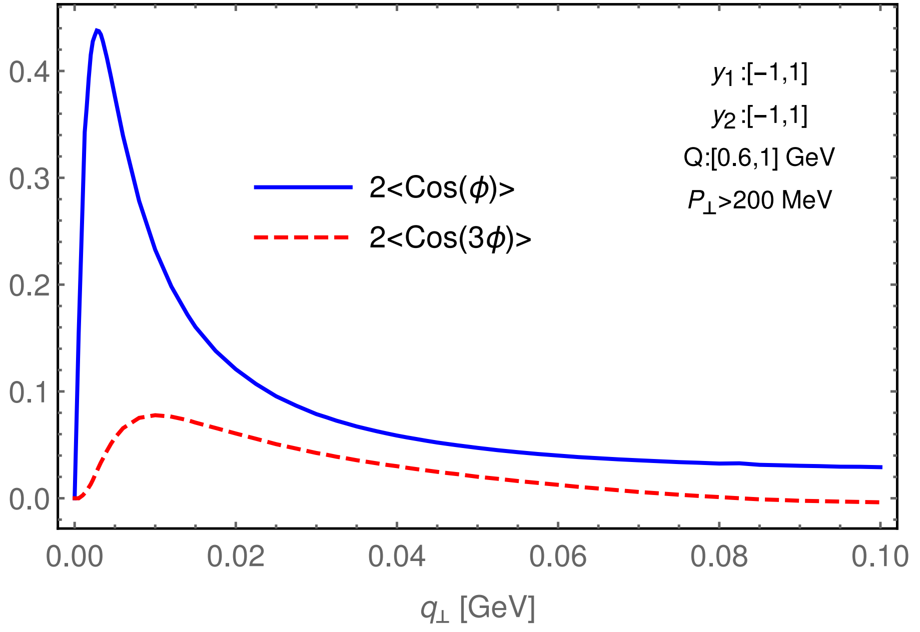


FIG. 1: An illustration of the mechanism giving rise to $\cos 3\phi$ azimuthal asymmetry. The solid line represents the quark propagator, while the pion propagator is indicated by the dashed line.





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

Summary

1. Observed (6.7σ) $\cos 4\Delta\phi$ angular modulation in linear polarized $\gamma\gamma \rightarrow e^+e^-$ (Breit-Wheeler) process
    - Colliding photons are linearly polarized
    - 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
        - Experimentally demonstrate sensitivity to gluon distribution within nucleus
    - Results are qualitatively consistent with theoretical predictions

Many open questions from both experimental and theoretical sides

Polarization Sensitive Observable

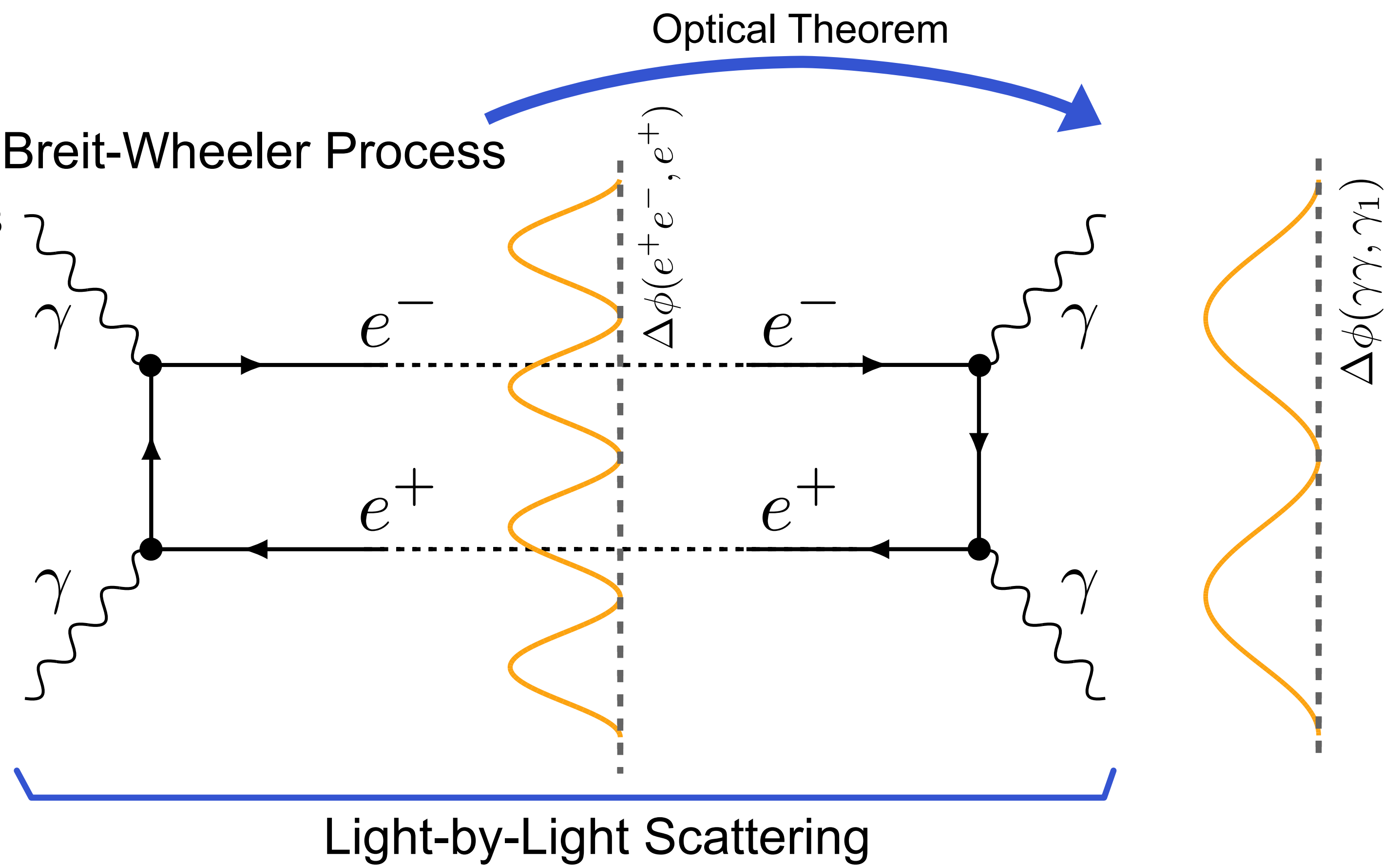
$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)]$$
$$\approx \Delta\phi[(e^+ + e^-), e^+] \text{ (for small pair } p_T\text{)}$$

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 $\gamma\gamma \to e^+e^-$ 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).

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

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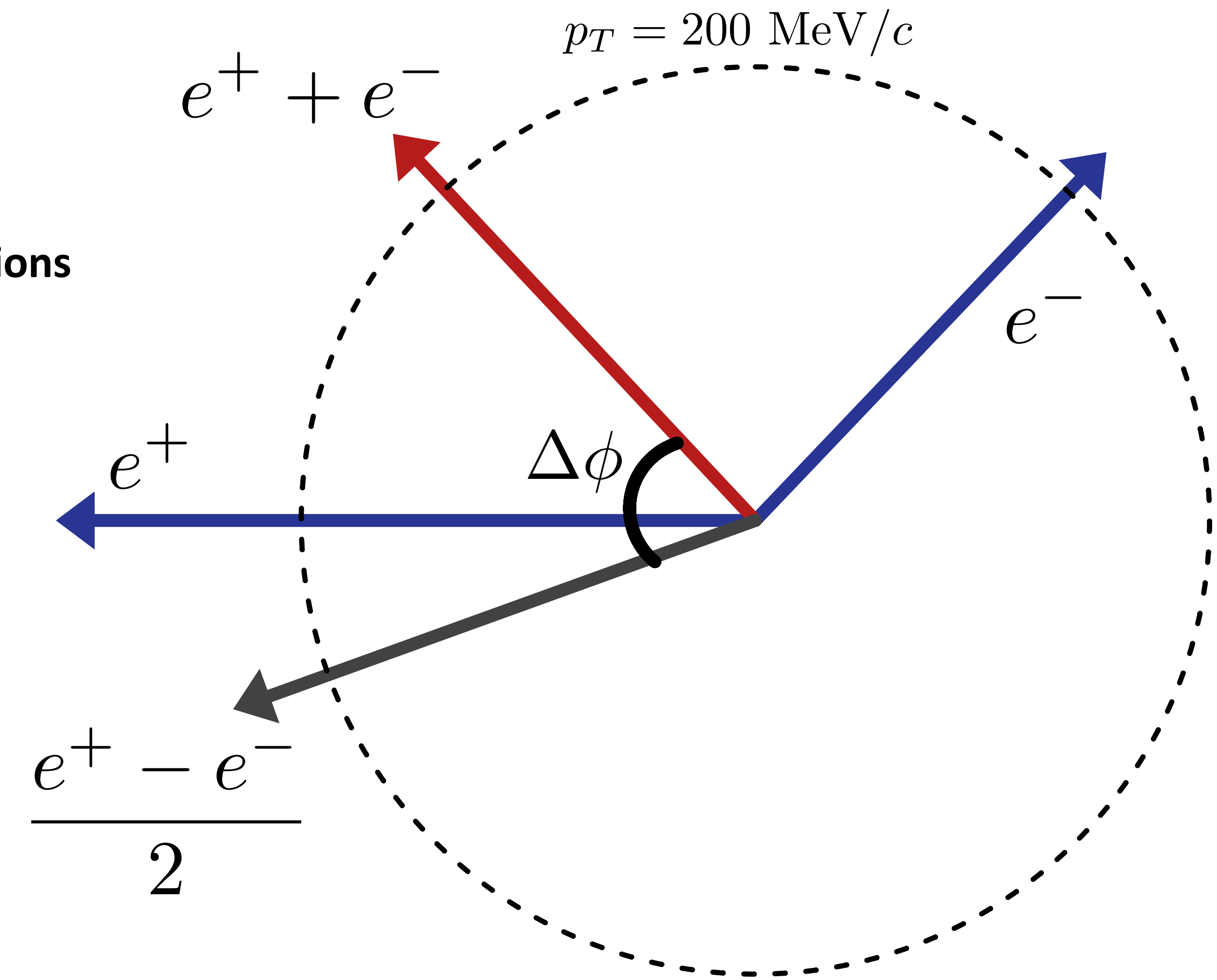
The corresponding vacuum LbyL scattering[2] is expected to display a $\cos(2\Delta\phi)$ **modulation** at midrapidity

These effects are related to vacuum birefringence[3]



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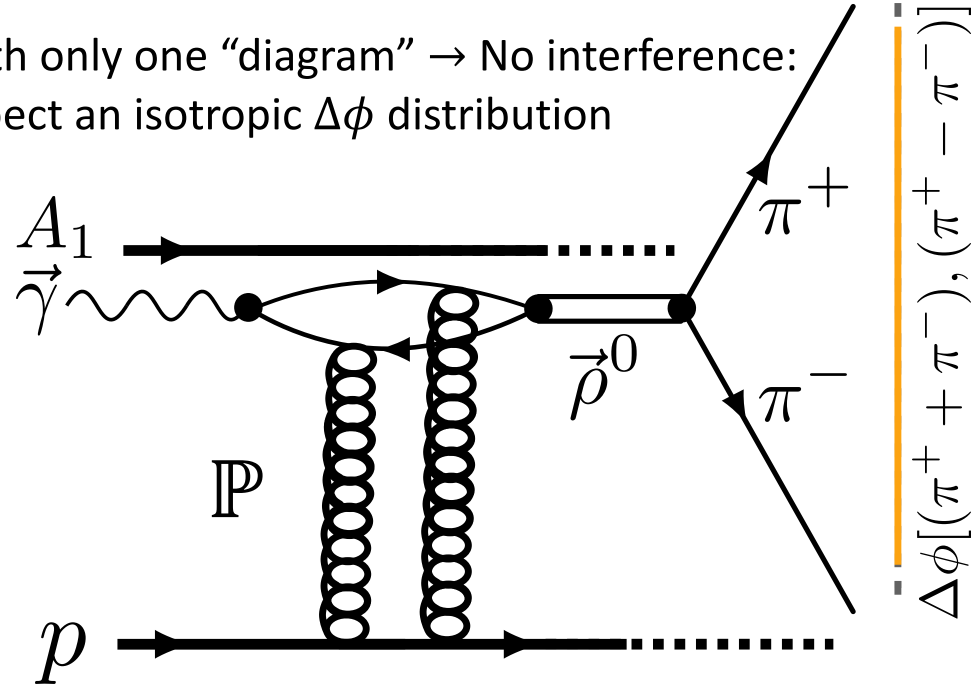
[3] John S. Toll "The Dispersion relation for light and its application to problems involving electron pairs", Princeton (1952)

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



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