Probing the Nucleus with Linearly Polarized Photons

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→ for the STAR Collaboration

The VIth conference on the initial stages
Of high-energy nuclear collisions

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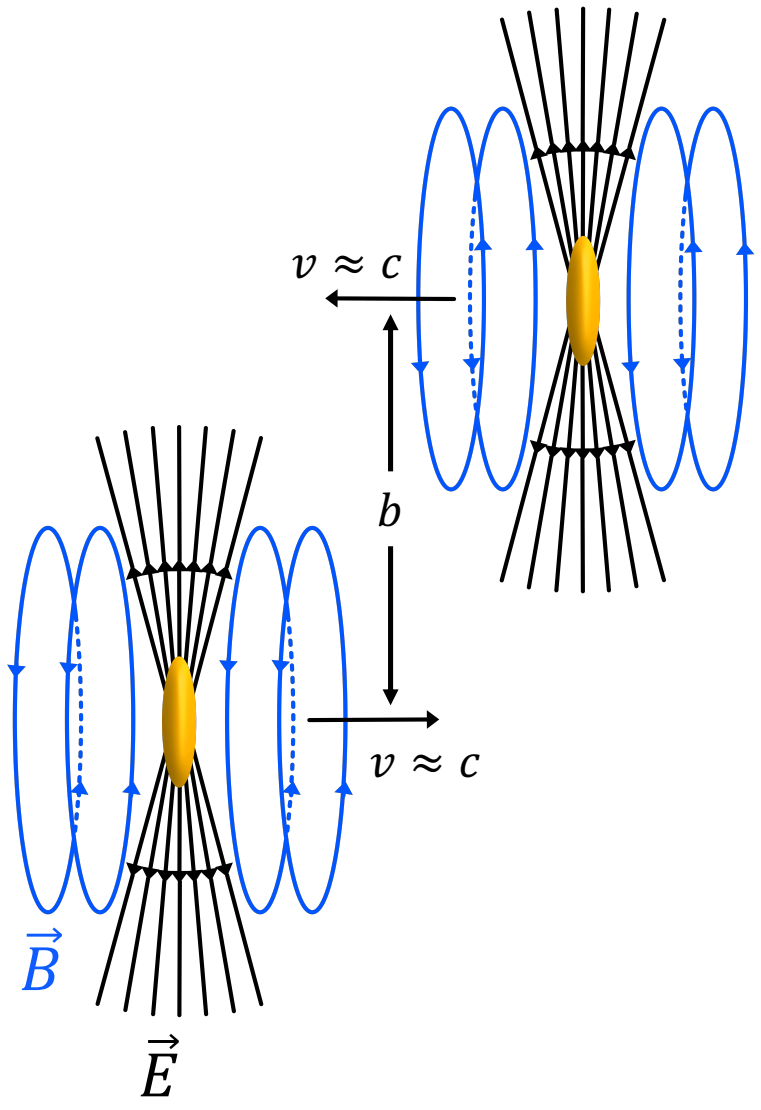
Talk Outline

1. Introduction
   - Ultra-peripheral heavy-ion collisions (UPC)
   - 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 collisions
4. Comparison to theoretical models
5. Summary

Ultra-Peripheral 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
  - $Z\alpha \approx 1$ → High photon density with highly charged nuclei

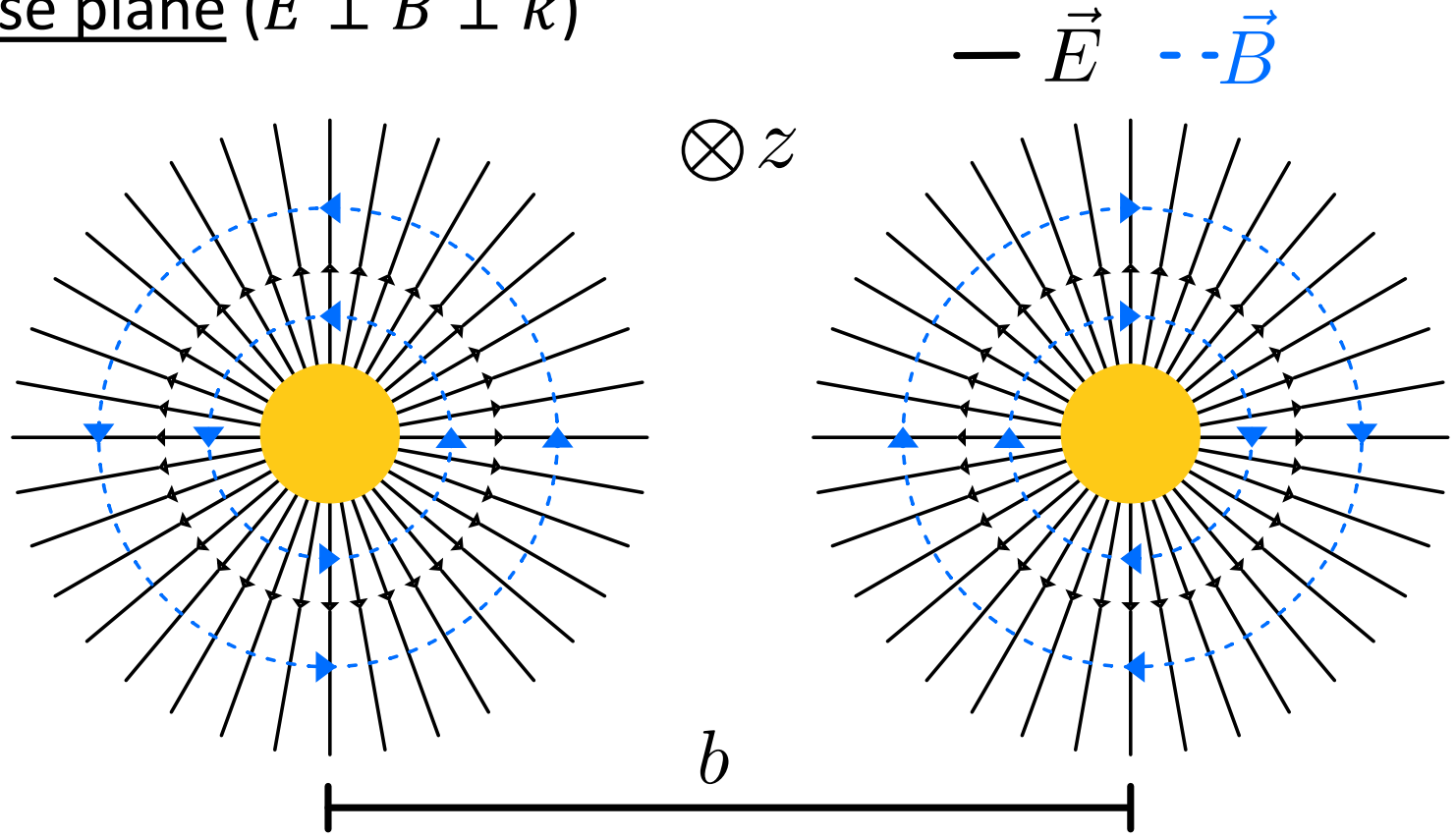
- $\gamma\mathbb{P} \rightarrow \rho^0, J\psi, etc.$: Photo-nuclear production of vector mesons ($J^P = 1^-$)
  - Photon from the EM field of one nucleus fluctuates to a $q\bar{q}$ pair, interacts with pomeron
  - Photon quantum numbers $J^{PC} = 1^{--}$

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).

Transverse linearly polarized photons

- Extreme Lorentz contraction of EM fields → Quasi-real photons should be <u>linearly polarized in transverse plane</u> ($\vec{E} \perp \vec{B} \perp \vec{k}$)

- Polarization vector : aligned radially with the "emitting" source
- Well defined in the photon position eigenstates
- Event average, <u>washes out polarization effects</u>, since $\vec{b}$ is random from one event to next



Polarization Sensitive Observable

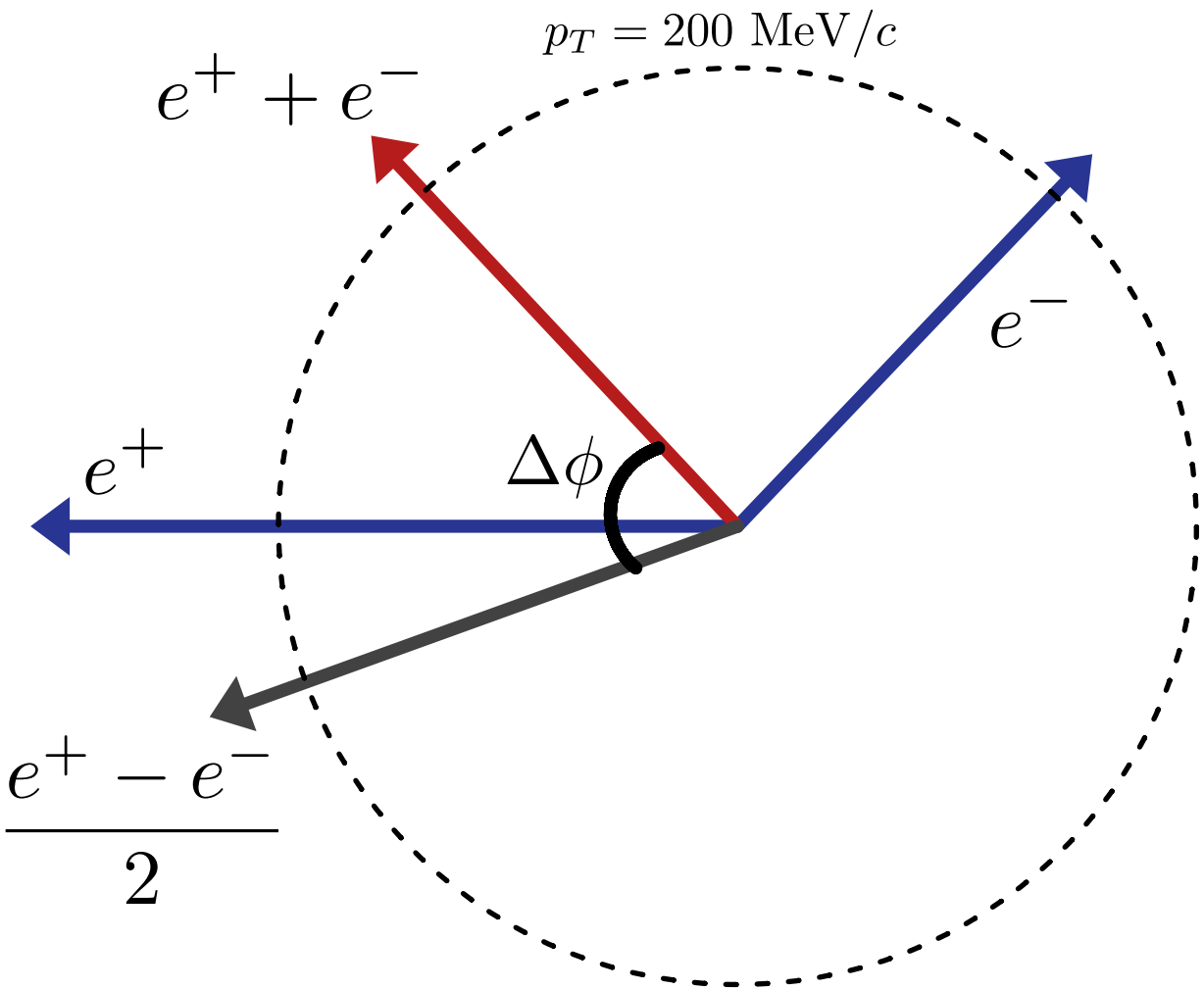
$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)]$$
$$\approx \Delta\phi[(e^+ + e^-), e^+\,] \text{ (for small pair } p_T)$$

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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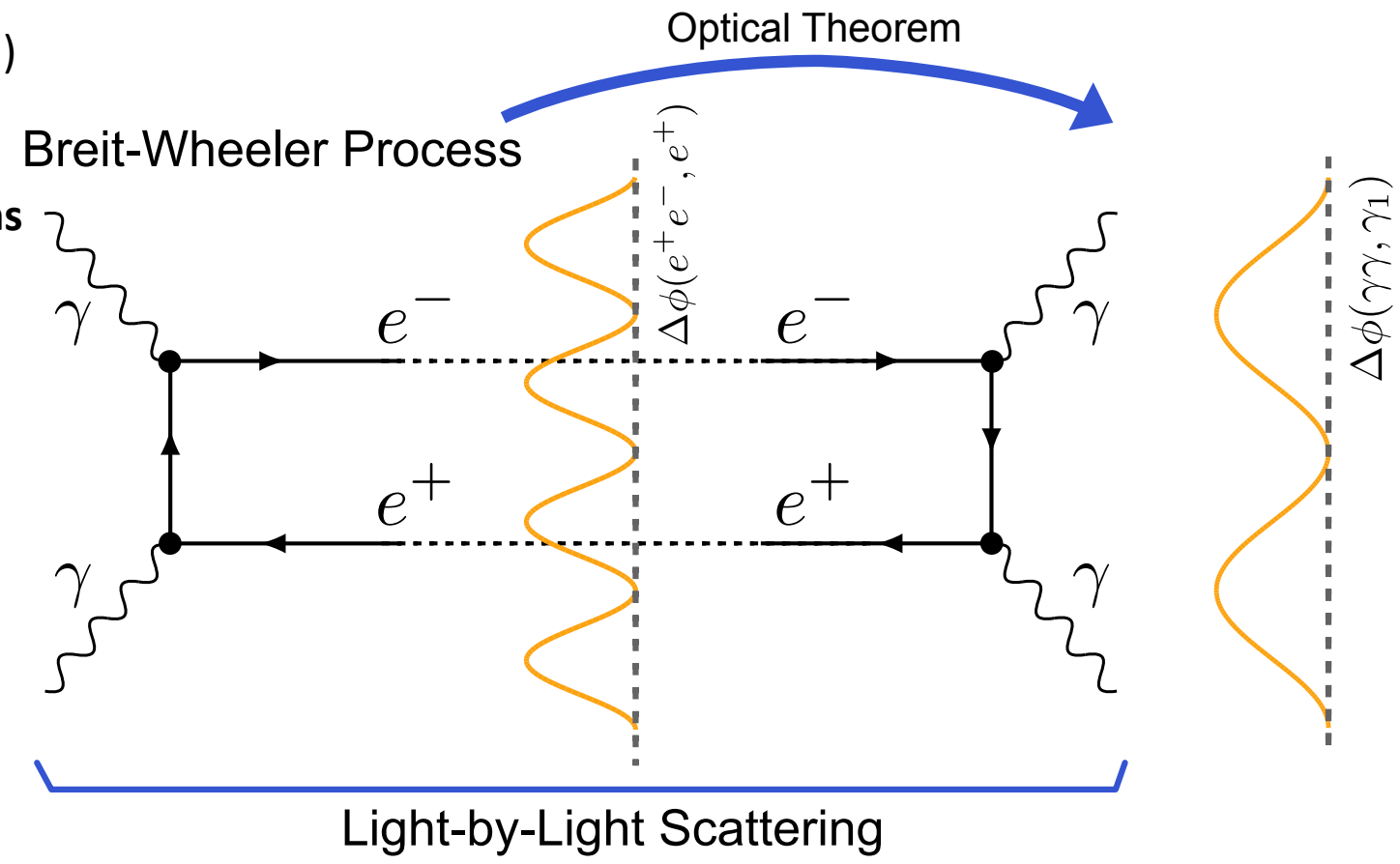

[1] C. Li, J. Zhou, Y.-j. Zhou, Phys. Lett. B 795, 576 (2019)
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Birefringence of the QED Vacuum

[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).

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

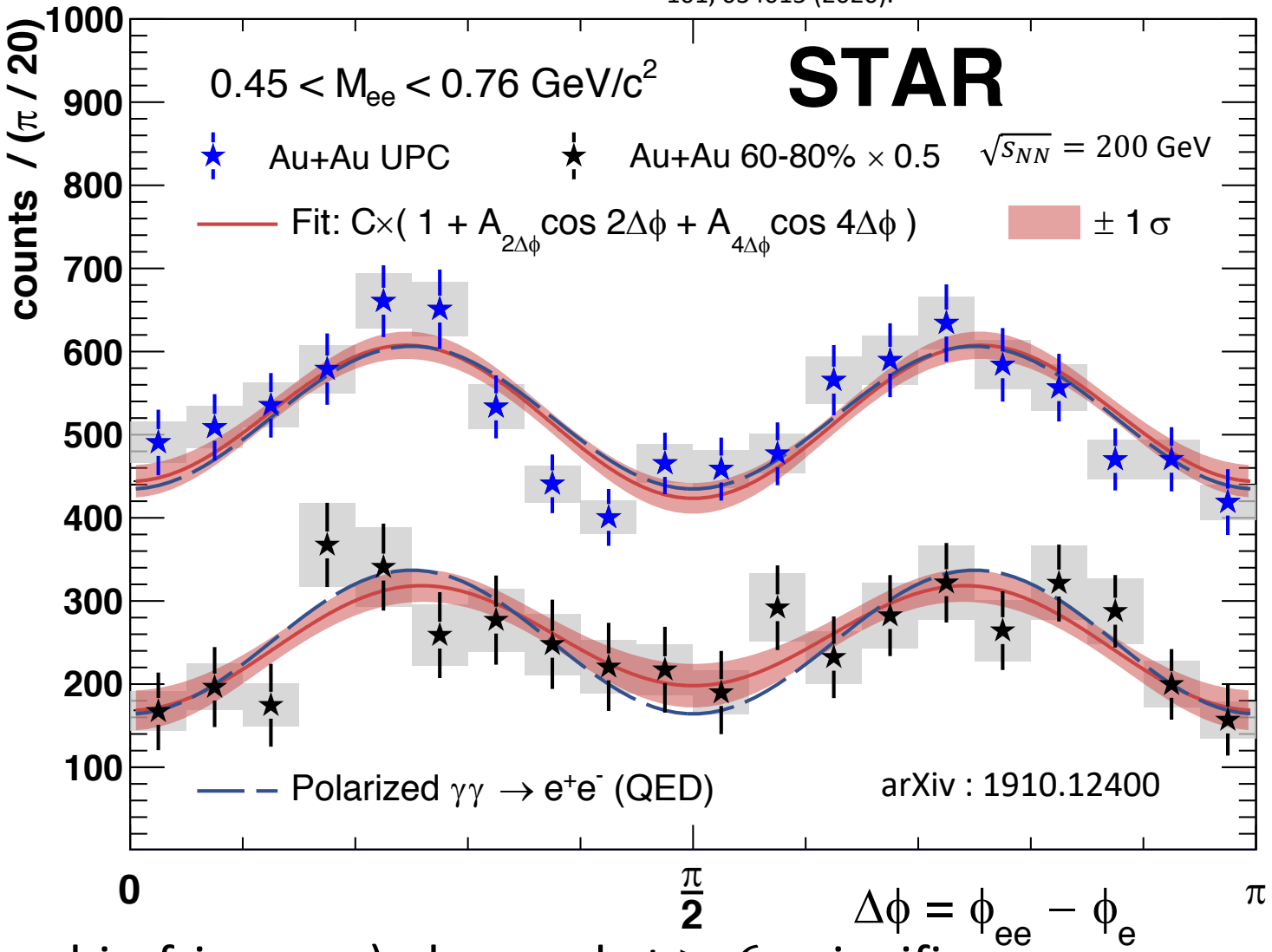
$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)]$$
$$\approx \Delta\phi[(e^+ + e^-), e^+]$$

Ultra-Peripheral

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

Peripheral (60−80%)

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



$\cos 4\Delta\phi$ (First lab evidence for vacuum birefringence) observed at $> 6\sigma$ significance

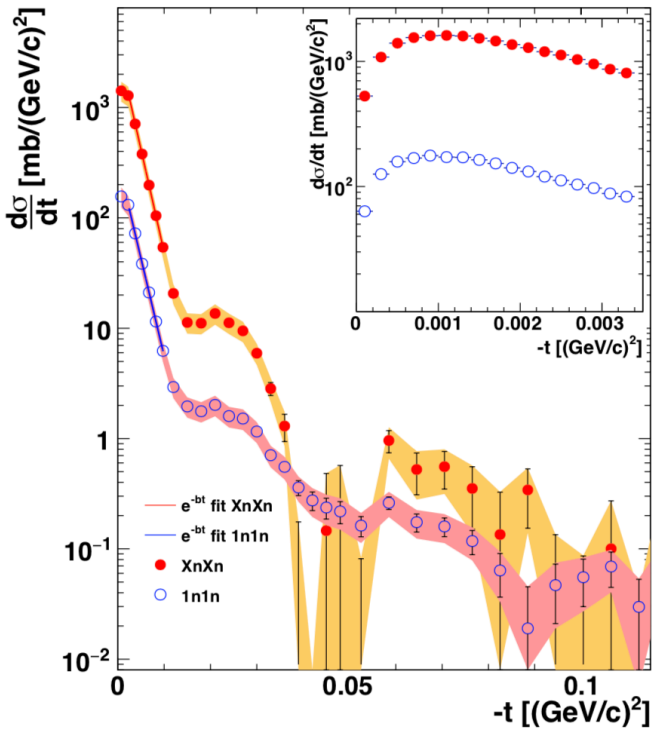
– photons from intense EM fields ($B > 10^{14}$T) are linearly polarized

Photo-nuclear process

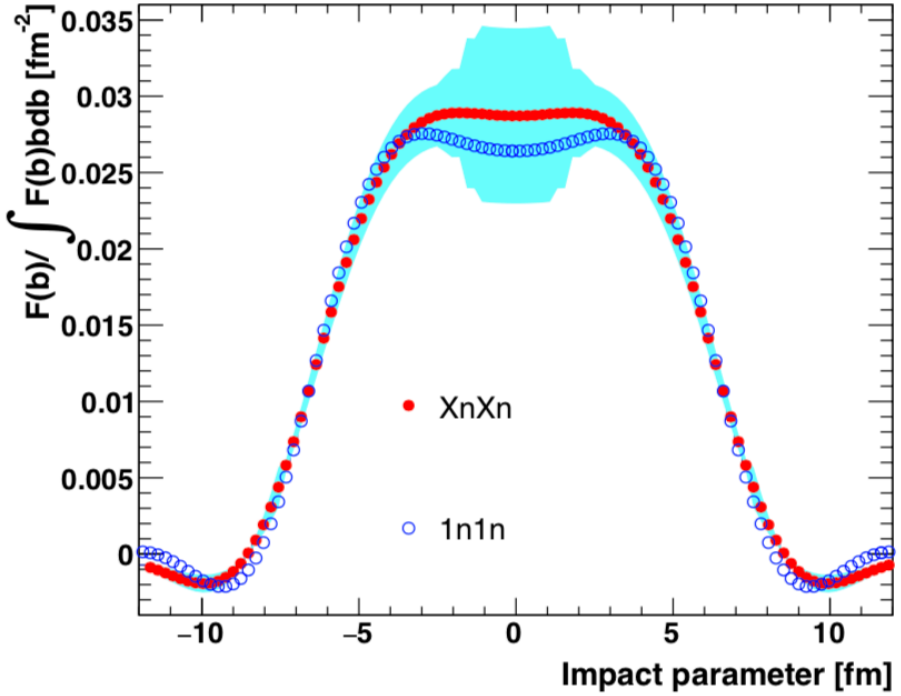
STAR Collaboration *et al. Phys. Rev. Lett.* **89**, 272302 (2002).
STAR Collaboration *et al. Phys. Rev. Lett.* **102**, 112301 (2009).
STAR Collaboration *et al. Phys. Rev. C* **96**, 054904 (2017).

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



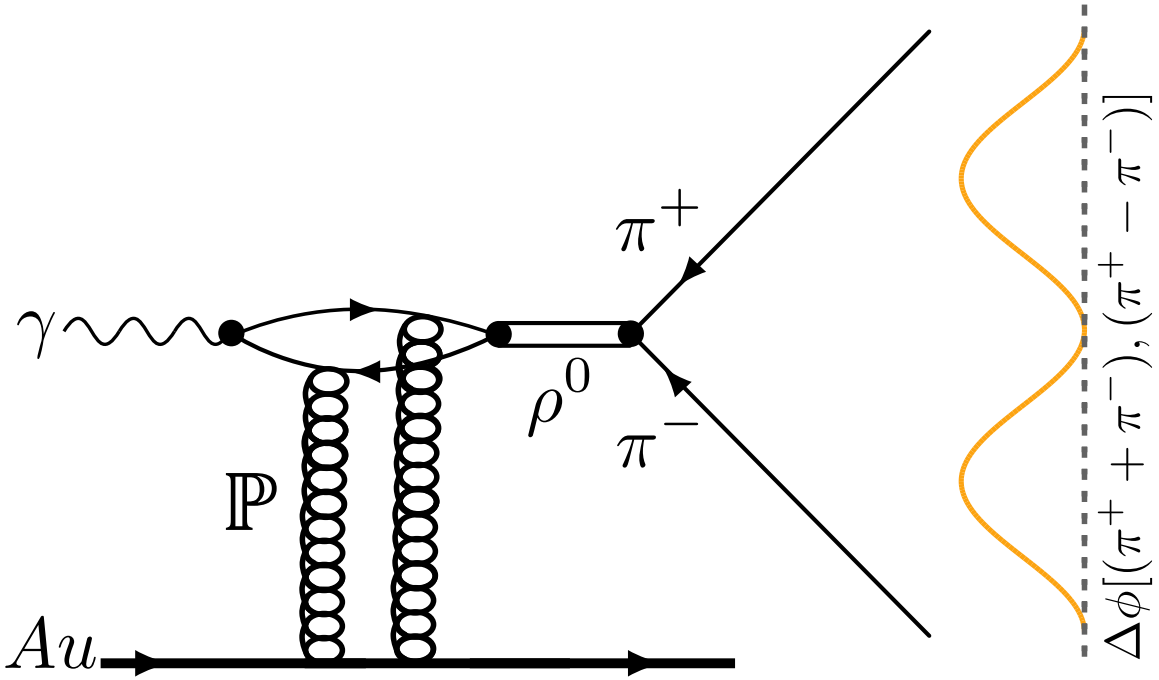
How can we use linearly polarized photons to study the nucleus?

Measure $\Delta\phi$ observable in $\gamma\mathbb{P} \rightarrow \rho^0 \rightarrow \pi^+\pi^-$

If the photons are linearly polarized in the transverse plane:

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

- Quantized spin is encoded into the orbital angular momentum of the $\pi^+\pi^-$ pair

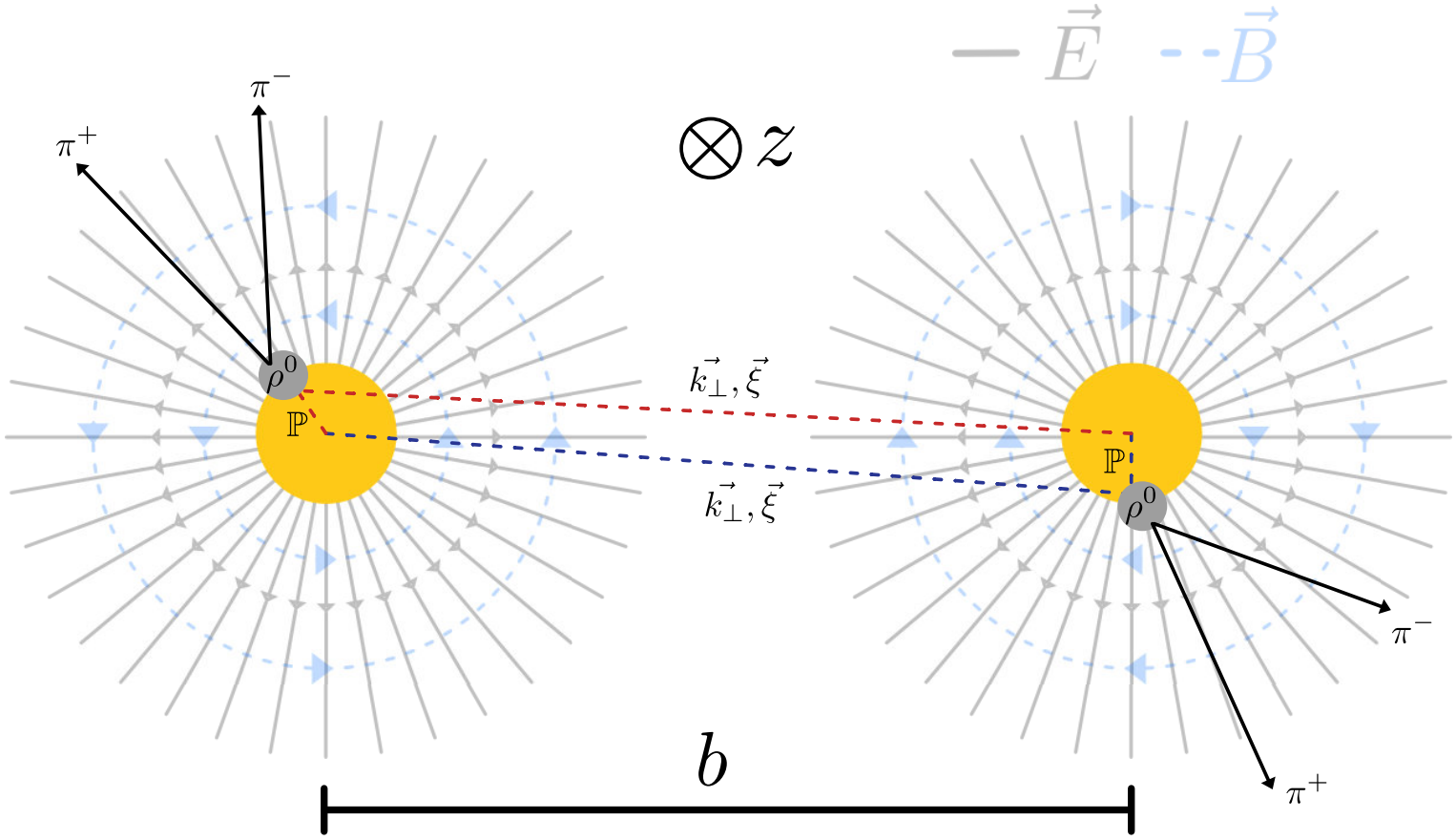


[1] Xing, H et.al. *J. High Energ. Phys.* **2020**, 64 (2020).

Polarization Interference Effect

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

- Polarization vector : aligned radially with the “emitting” source
- Well defined in the photon position eigenstates



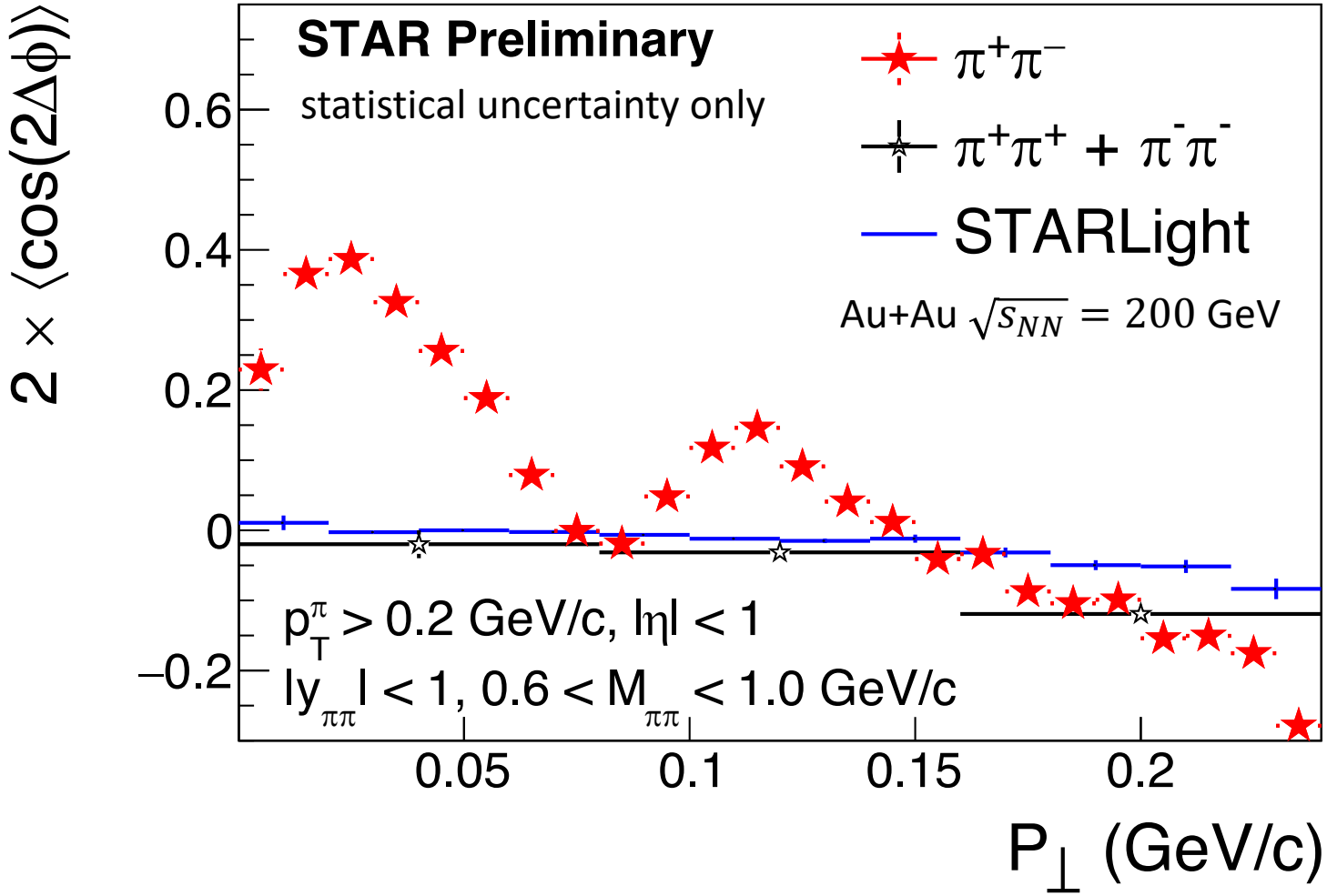
Interference is sensitive to:

→ Nuclear Geometry (gluon distribution)

→ Impact Parameter

Results : $\langle \cos 2\Delta\phi \rangle$ vs. $P_\perp$

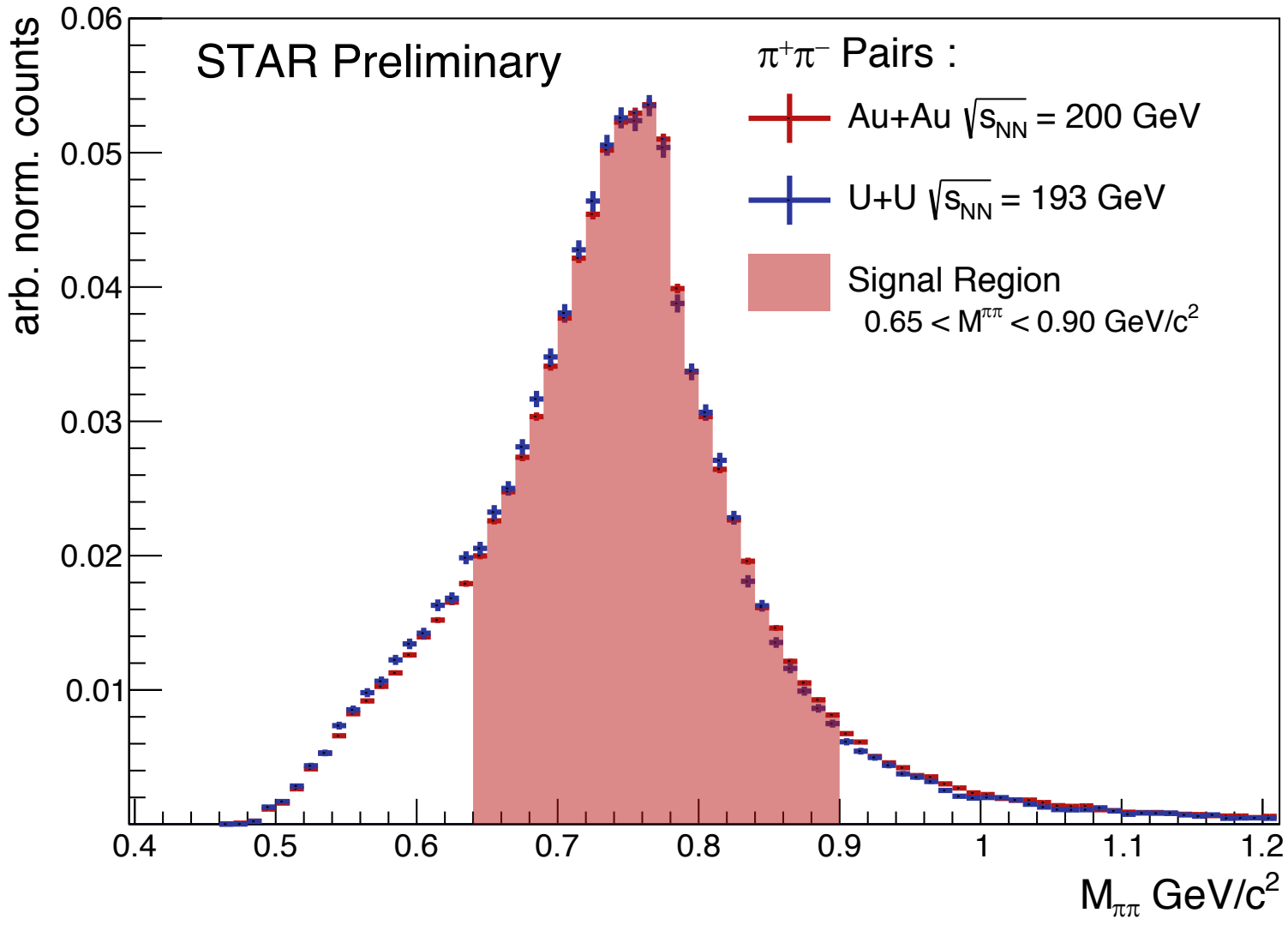
Shown at QM2019



- Strong $\cos 2\Delta\phi$ modulation observed at pair $p_\perp^{\pi\pi} < \sim 60$ MeV/c
- Interference structure visible → dip and peak in modulation at higher $p_\perp^{\pi\pi}$
- STARLight[1] does not include polarization effect
- Qualitatively consistent with theoretical calculation including two-source interference effects[2]
- Like-sign pairs roughly illustrate the effect of the STAR acceptance.
- Acceptance effect is very small at low $p_\perp^{\pi\pi}$ and grows to $\sim -10\%$ at $p_\perp^{\pi\pi} = 200$ Me/c

[1] S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258
[2] Xing, H et.al. *J. High Energ. Phys.* **2020**, 64 (2020).

Comparison between Au+Au and U+U Collisions



- Clear ρ^0 peak in both Au+Au and U+U UPC events.
- First measurement of diffractive coherent photonuclear production in U+U collisions.
- Select region around ρ^0 mass with roughly uniform acceptance

Comparison between Au+Au and U+U Collisions

- Compare the $\cos 2\Delta\phi$ modulation in ultra-peripheral events from Au+Au at $\sqrt{s_{NN}} = 200$ and 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 :

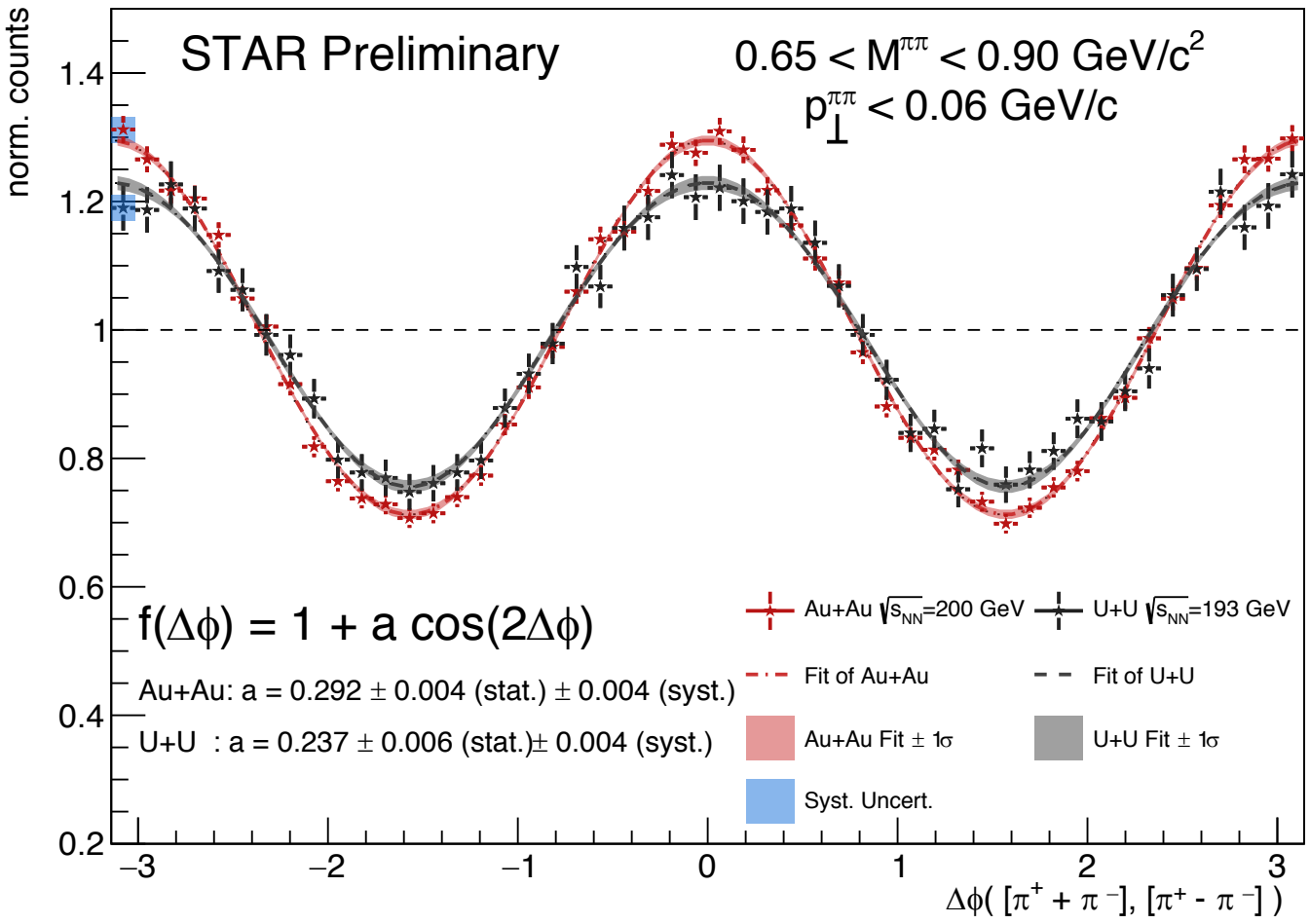
$a = 0.292 \pm 0.004$ (stat) ± 0.004 (syst.)

U+U :

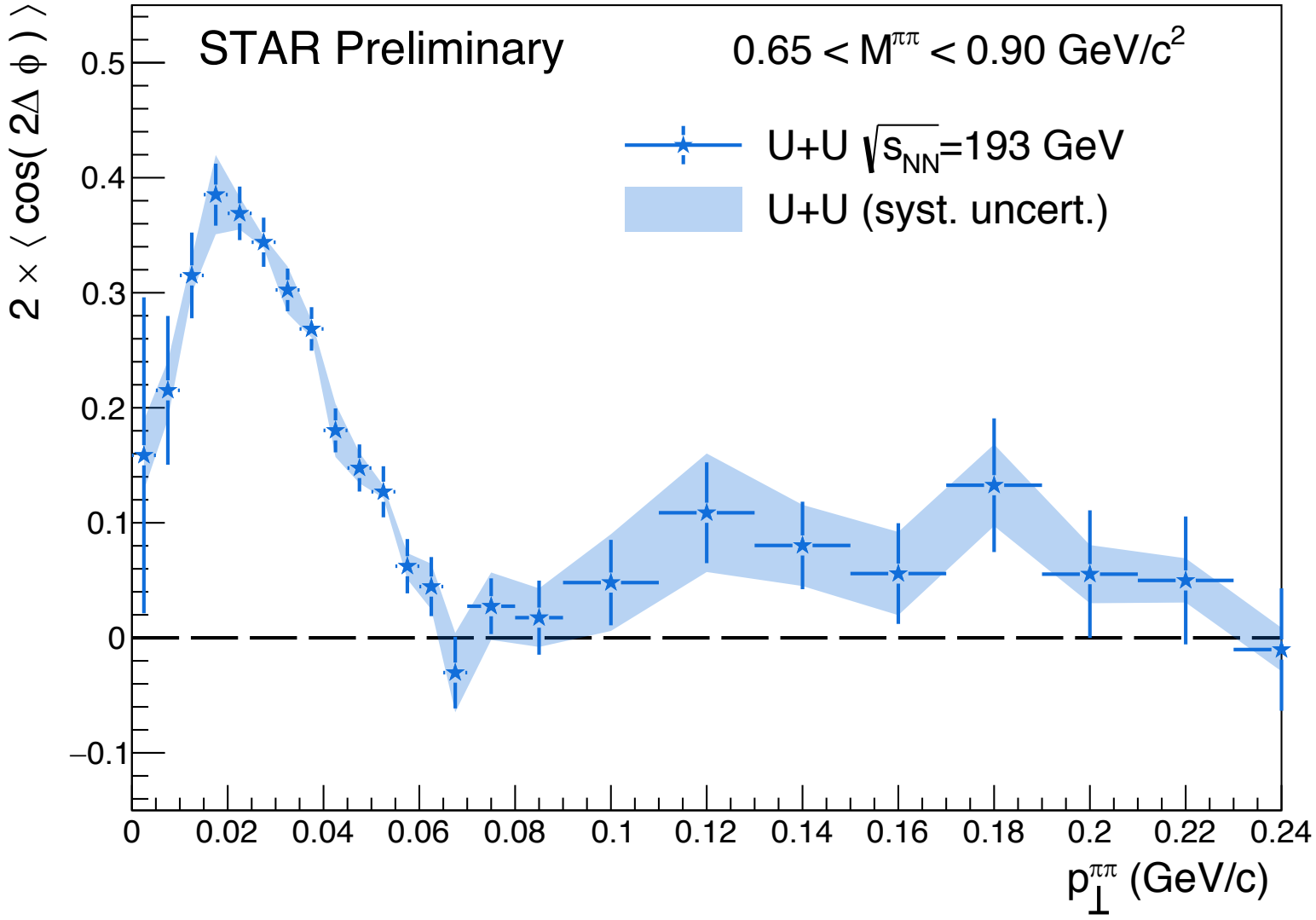
$a = 0.237 \pm 0.006$ (stat) ± 0.004 (syst.)

Difference of 4.3σ (stat. & syst.):

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



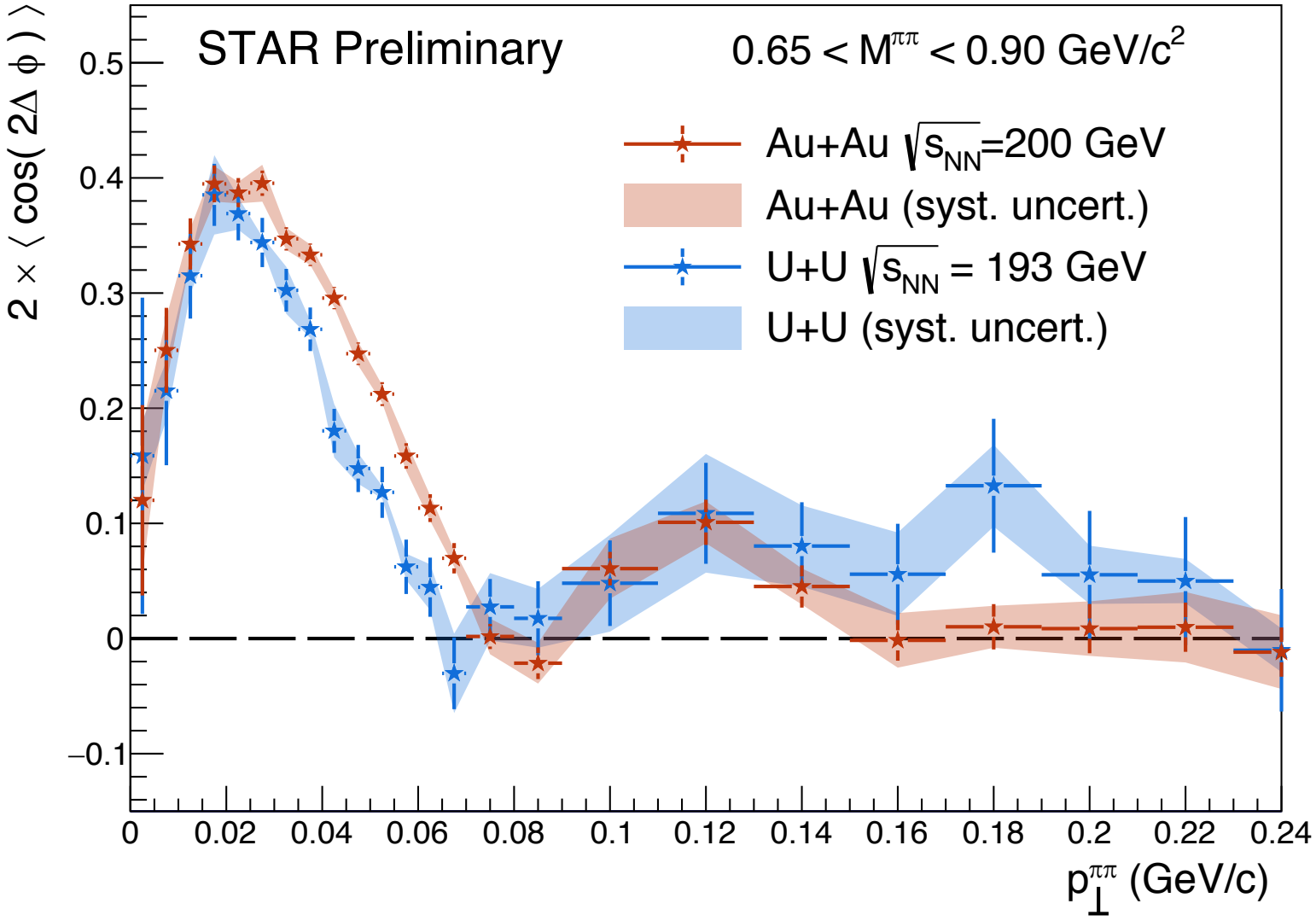
$\cos 2\Delta\phi \ vs. p_T$ in U+U at $\sqrt{s_{NN}} = 193$ GeV



- Strong $\cos 2\Delta\phi$ modulation observed at $p_T < \sim 60$ MeV/c – similar to Au+Au
- U+U curve is fully corrected for STAR acceptance
- Systematic uncertainty shown in blue band

- Similar structure observed with respect to Au+Au
- Narrower main peak than Au+Au
- Broader second peak, large uncertainty

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



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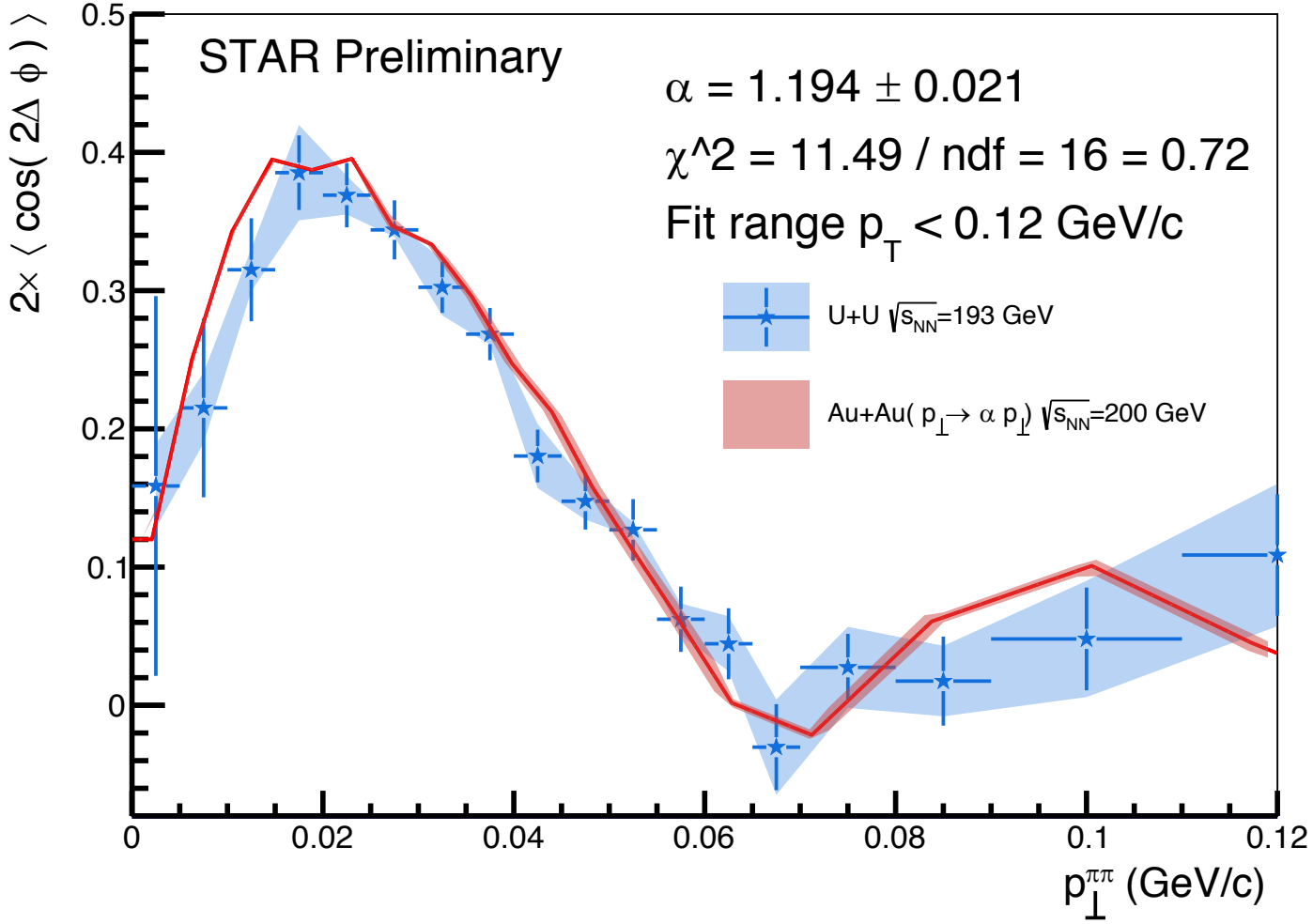
- U+U curve is fully corrected for STAR acceptance
- Systematic uncertainty shown in blue band

- Similar structure observed with respect to Au+Au
- Narrower main peak than Au+Au
- Au+Au : acceptance and background corrected with syst. uncert.

Quantitative Comparison : Au+Au and U+U

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

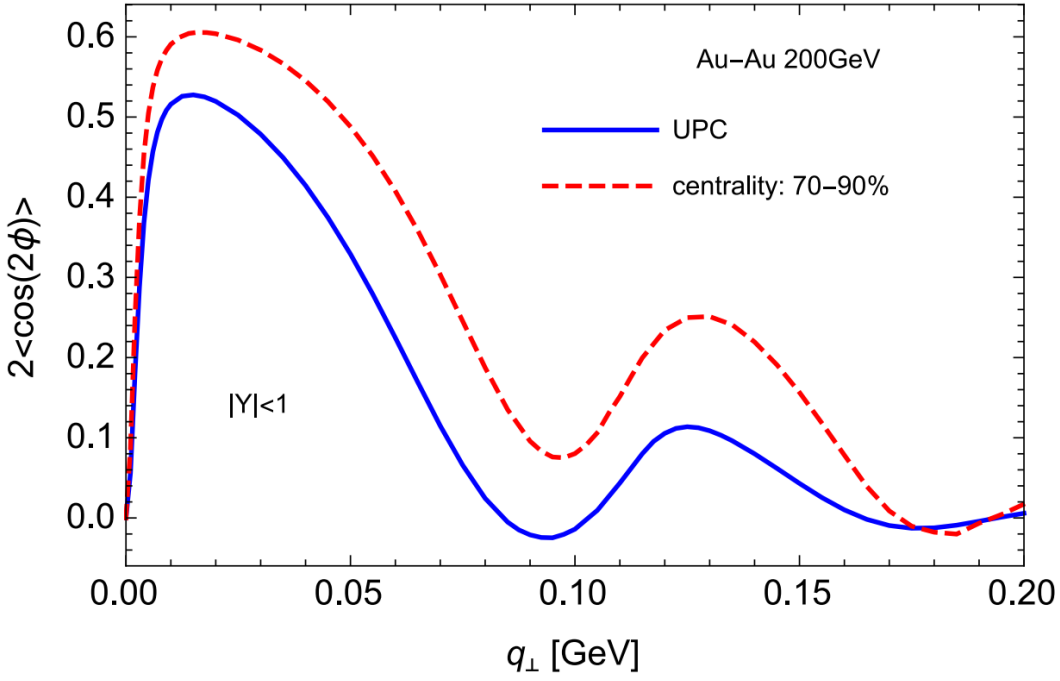


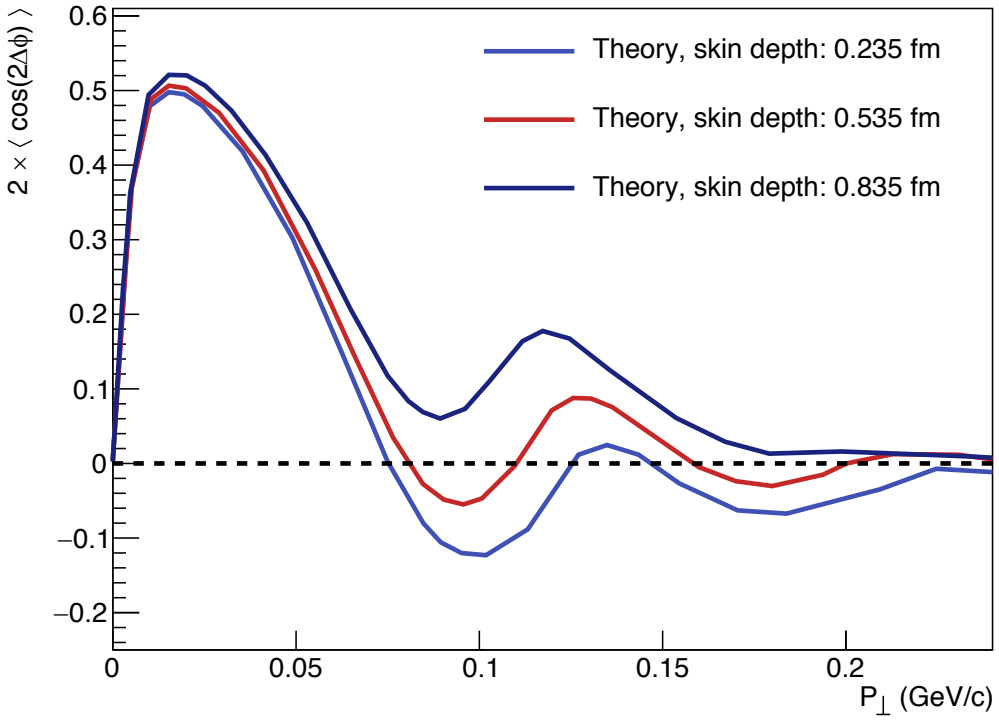
[1]

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

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

Predicted modulation shows structure vs. pair $p_\perp$





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

→ Nuclear Geometry / gluon distribution

Nuclear skin depth (right)

→ Impact parameter

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

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

Summary

1. Observed (6.7σ) $\cos 4\Delta\phi$ angular modulation in linear polarized $\gamma\gamma \rightarrow e^+e^-$ (Breit-Wheeler) process
   - First laboratory evidence for vacuum birefringence
   - Colliding photons are linearly polarized

2. First measurement 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
     - Strong structure observed vs. pair p_T
   - Measurement in Au+Au and U+U collisions
     - Experimentally demonstrate sensitivity to gluon distribution within nucleus
   - Results are qualitatively consistent with theoretical predictions
     - Sensitive to nuclear geometry → gluon density within nucleus
     - Sensitive to “double-slit” interference of photon polarization

- Looking forward to more theoretical developments