Probing the Nucleus with Linearly Polarized Photons

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→ for the STAR Collaboration

Division of Nuclear Physics,

American Physical Society

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Mini-Symposium: Probing nucleons and nuclei in ultra-peripheral collisions and with vector mesons II

OUTLINE

1. Introduction
   - Ultra-peripheral heavy-ion collisions (UPC)
   - Strong electromagnetic fields and transverse linearly polarized photons
2. Angular modulations of diffractive $\rho^0 \to \pi^+\pi^-$ (& direct $\pi^+\pi^-$) in UPCs
3. Summary

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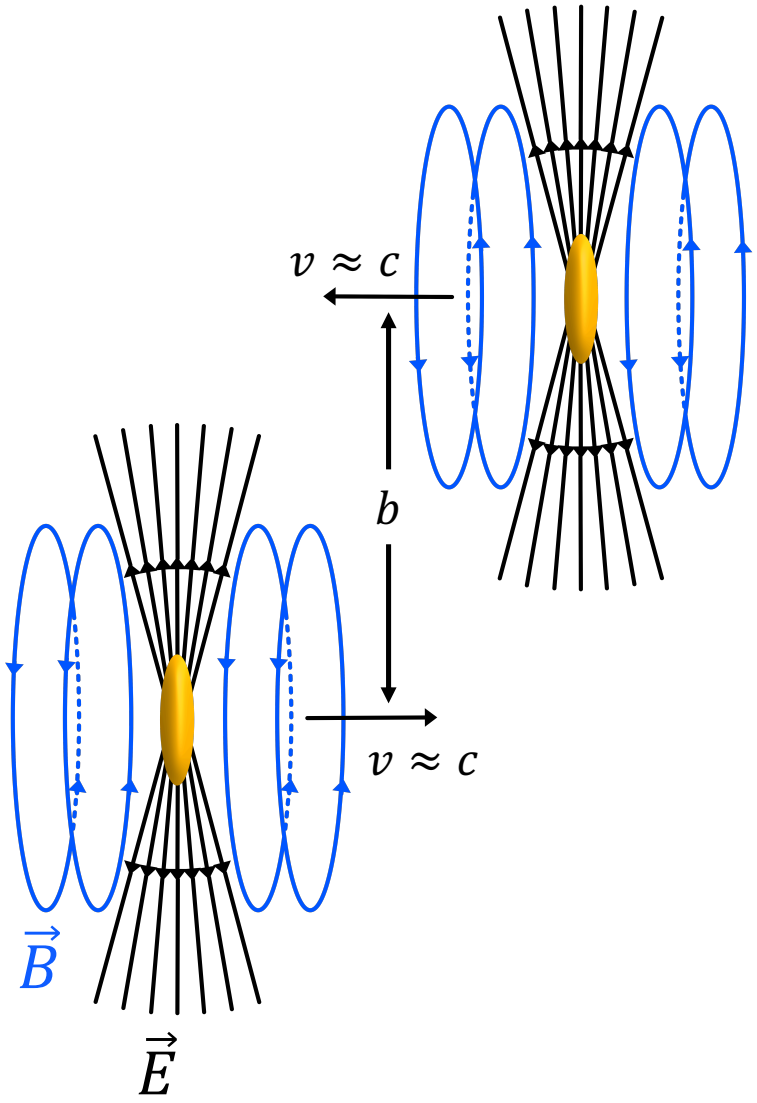
Ultra-Peripheral Collisions



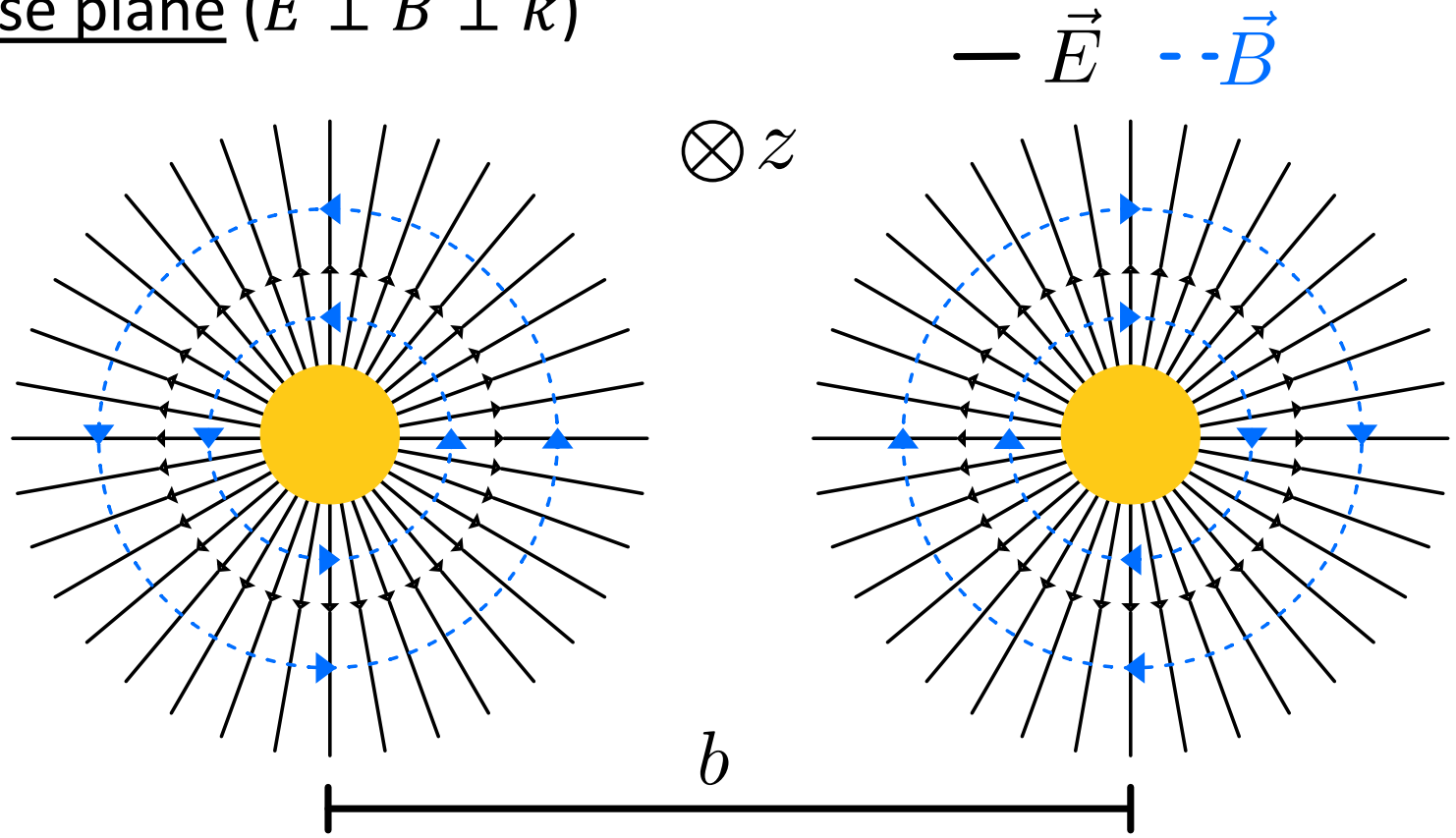
Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic fields

- $\gamma\gamma \rightarrow l^+l^-$: 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 $J^{PC} = 1^{--}$

Transverse linearly polarized photons

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

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



Polarization Sensitive Observable

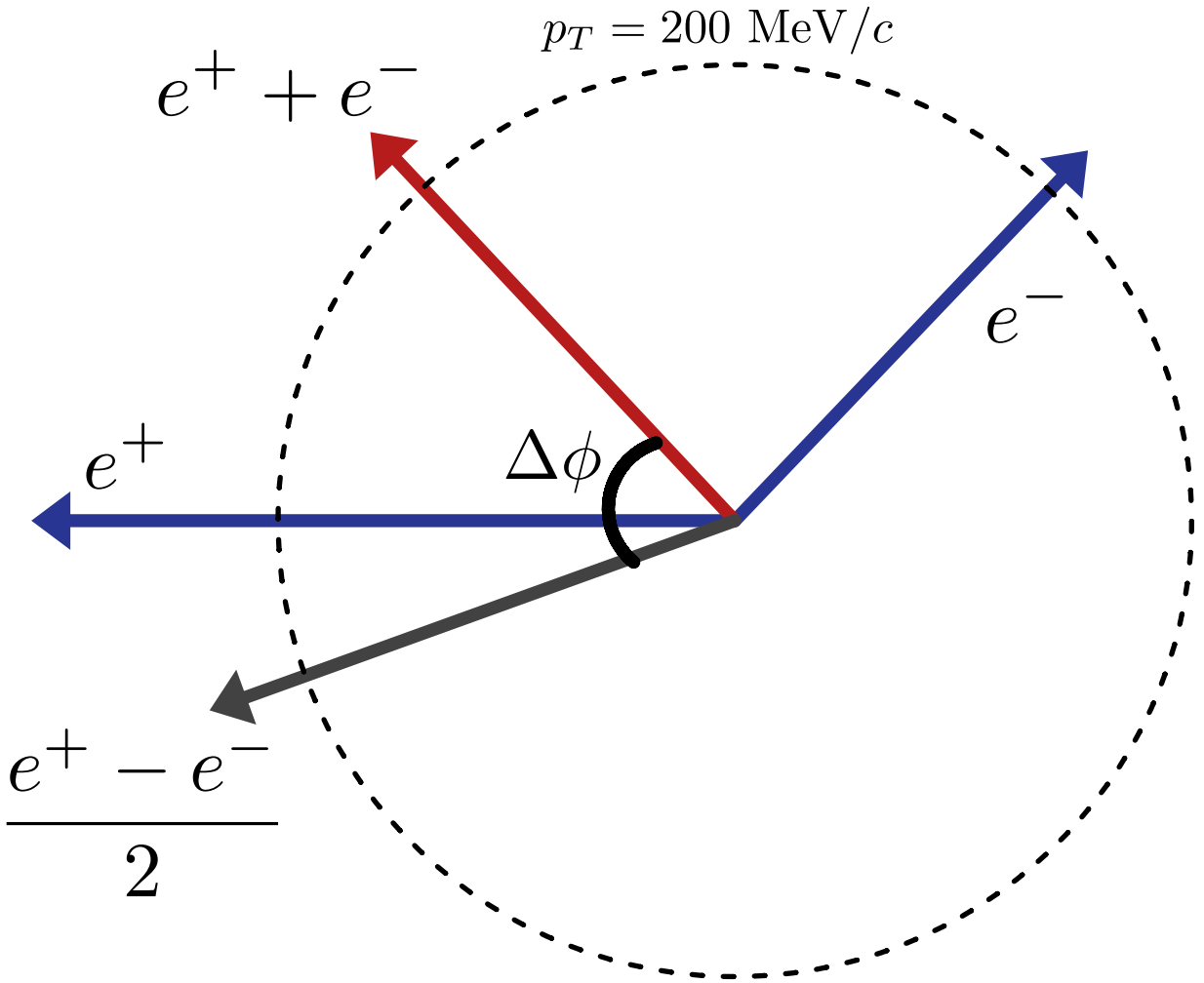
$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)]$$
$$\approx \Delta\phi[(e^+ + e^-), e^+] \text{ (for small pair } p_T)$$

Sensitive to polarization through
quantum space-momentum correlations

Birefringence effects:

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

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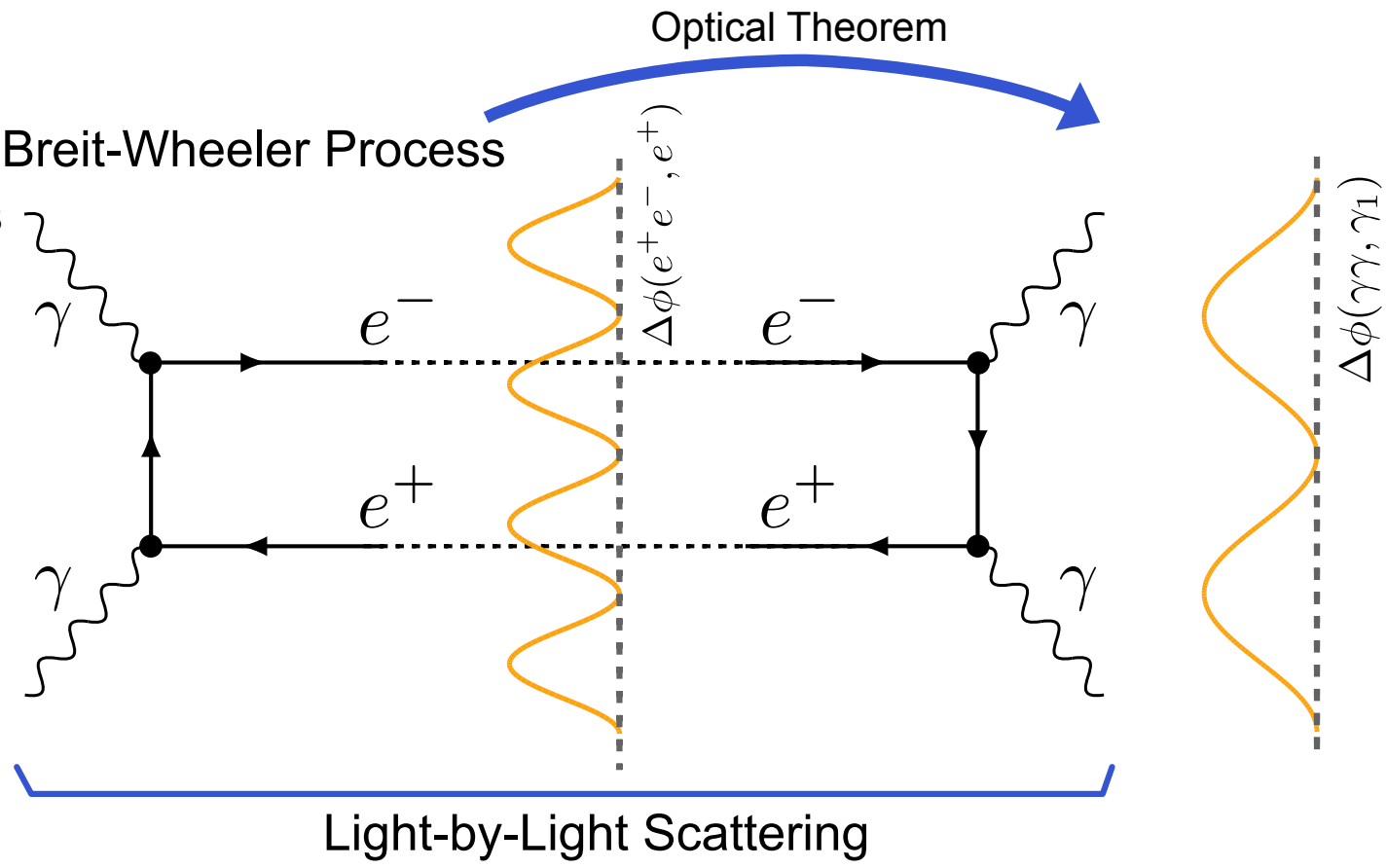

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Birefringence of the QED Vacuum

[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

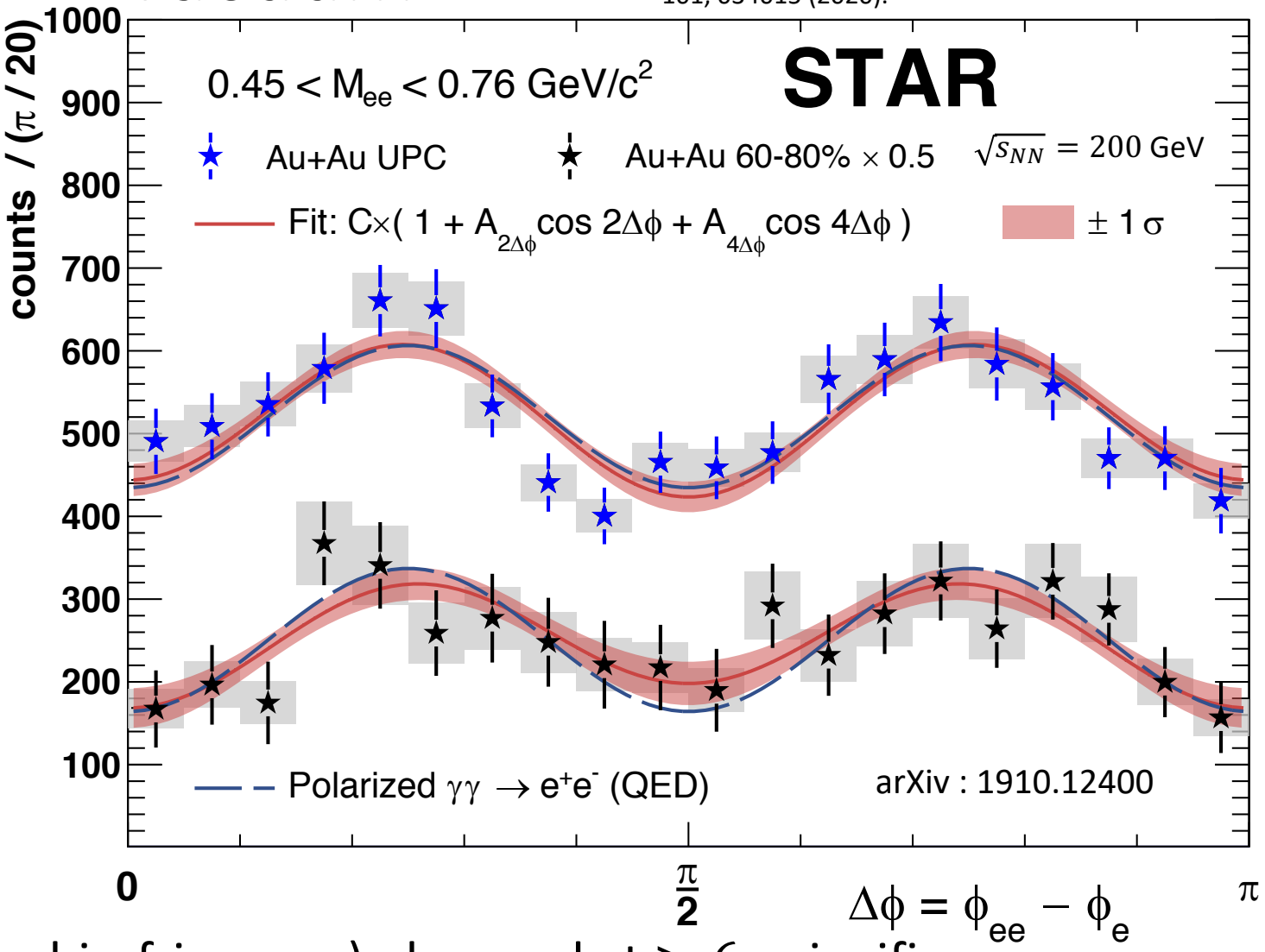
$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)] \approx \Delta\phi[(e^+ + e^-), e^+]$$

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 of vacuum birefringence) observed at $> 6\sigma$ significance

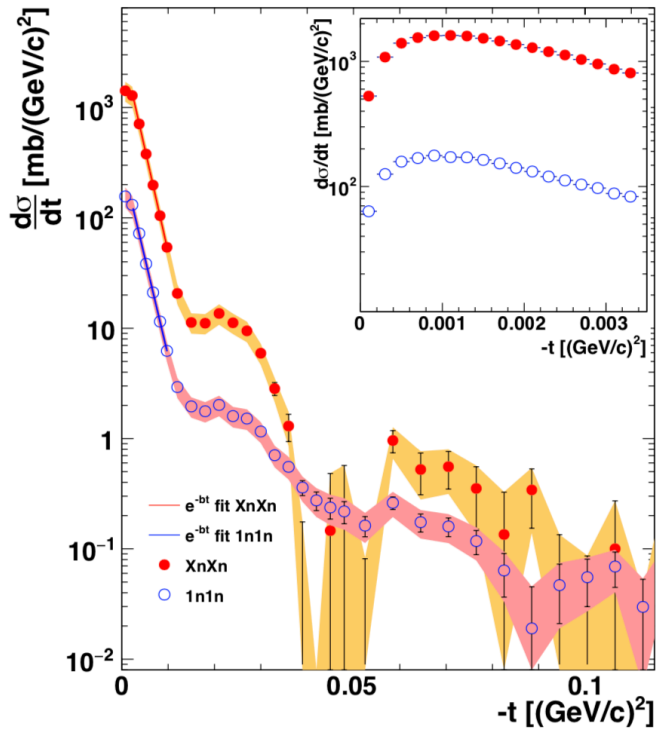
– photons from intense EM fields ($B > 10^{14}$T) are linearly polarized

Photo-nuclear process

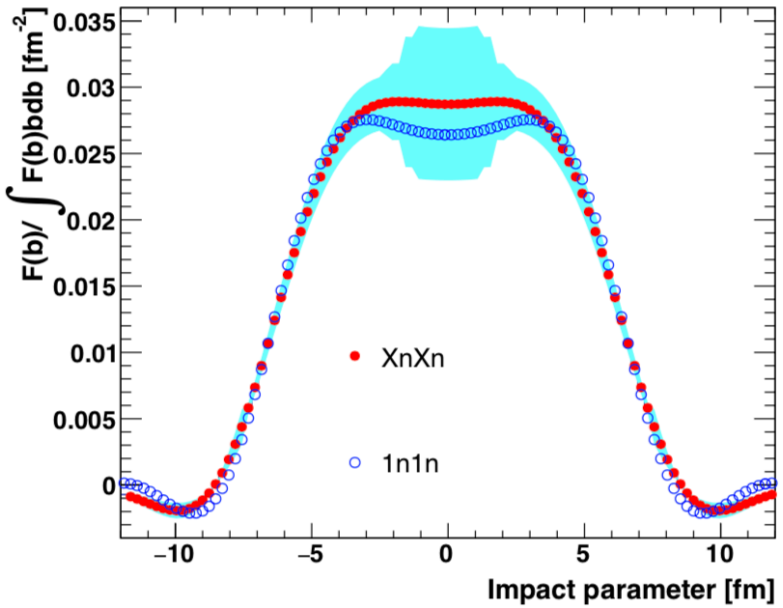
STAR Collaboration *et al. Phys. Rev. Lett.* **89**, 272302 (2002).
STAR Collaboration *et al. Phys. Rev. Lett.* **102**, 112301 (2009).
STAR Collaboration *et al. Phys. Rev. C* **96**, 054904 (2017).

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



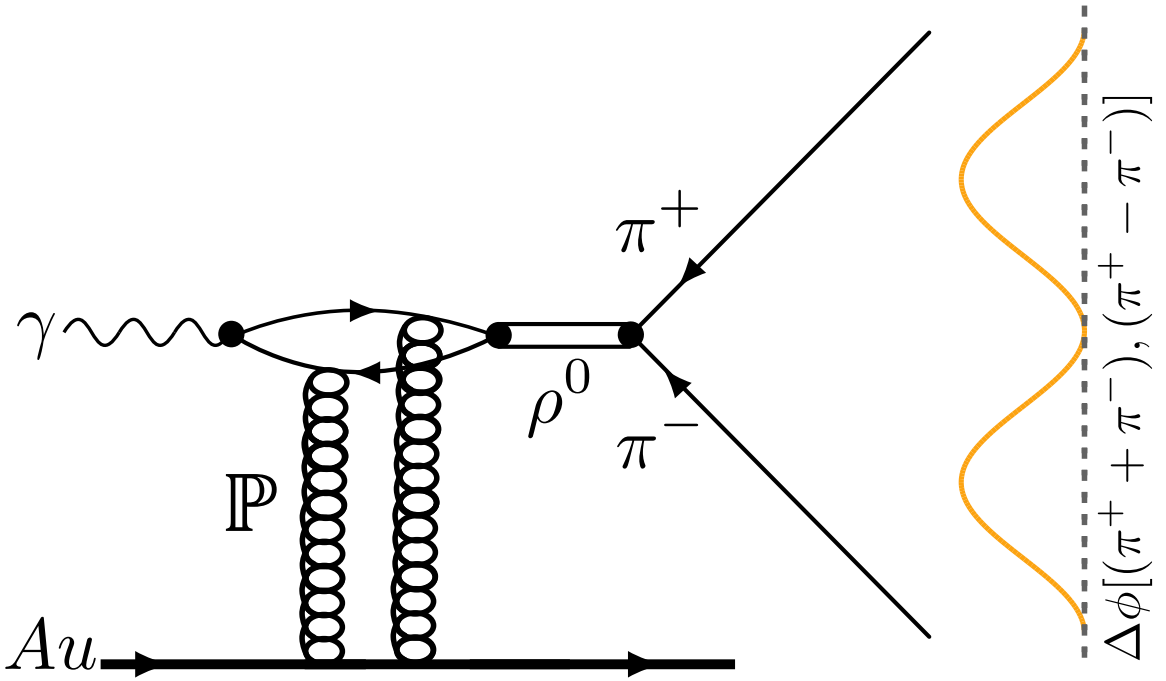
How can we use linearly polarized photons to study the nucleus?

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

If the photons are linearly polarized in the transverse plane:

→ 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).

“Double-Slit” Interference

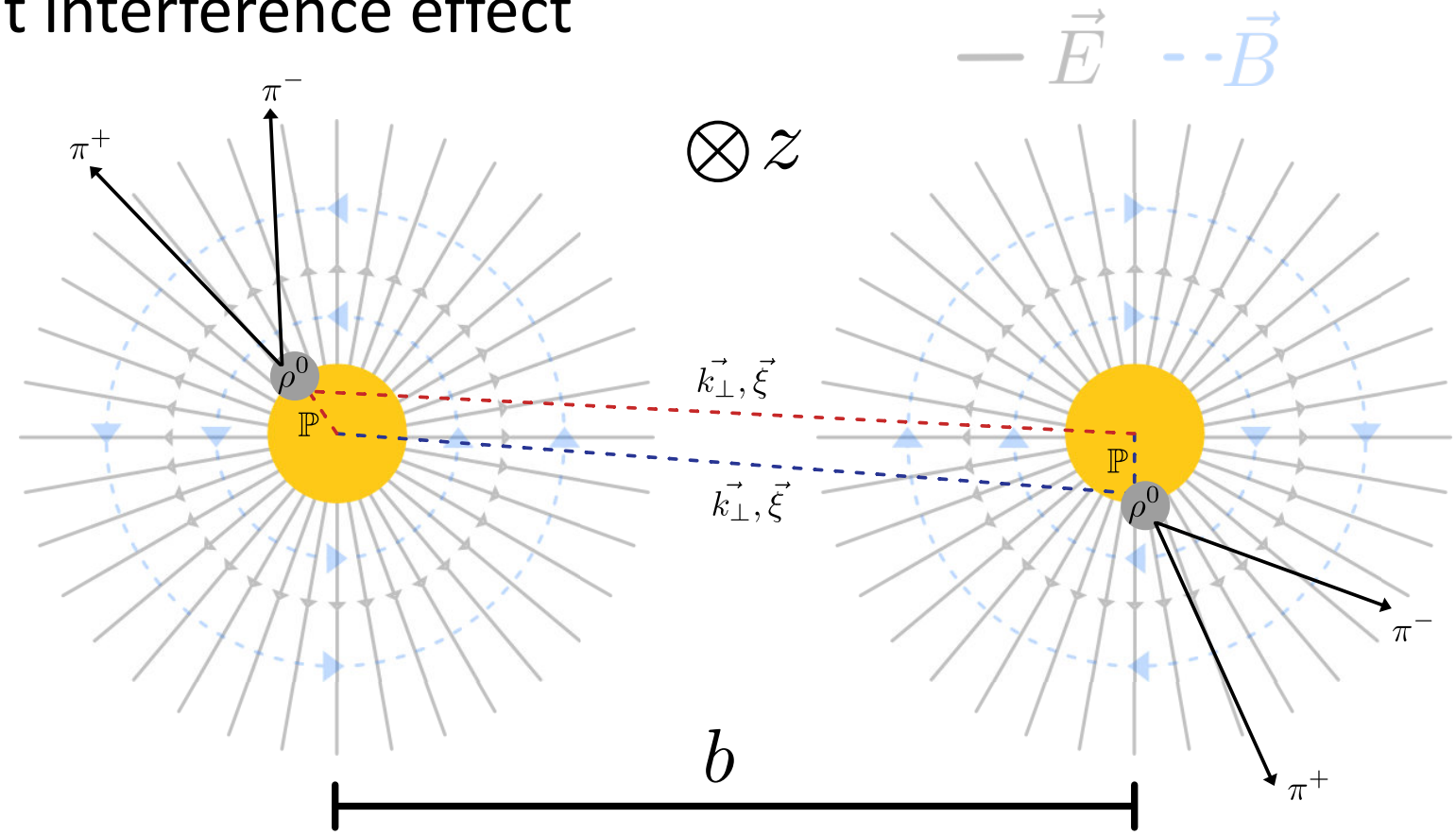
- Nuclei “take-turns” emitting photon vs. Pomeron
- Analogous to double-slit interference effect

- Intuitively, “double-slit” interference should be sensitive to the “slit” width and the distance between the two slits

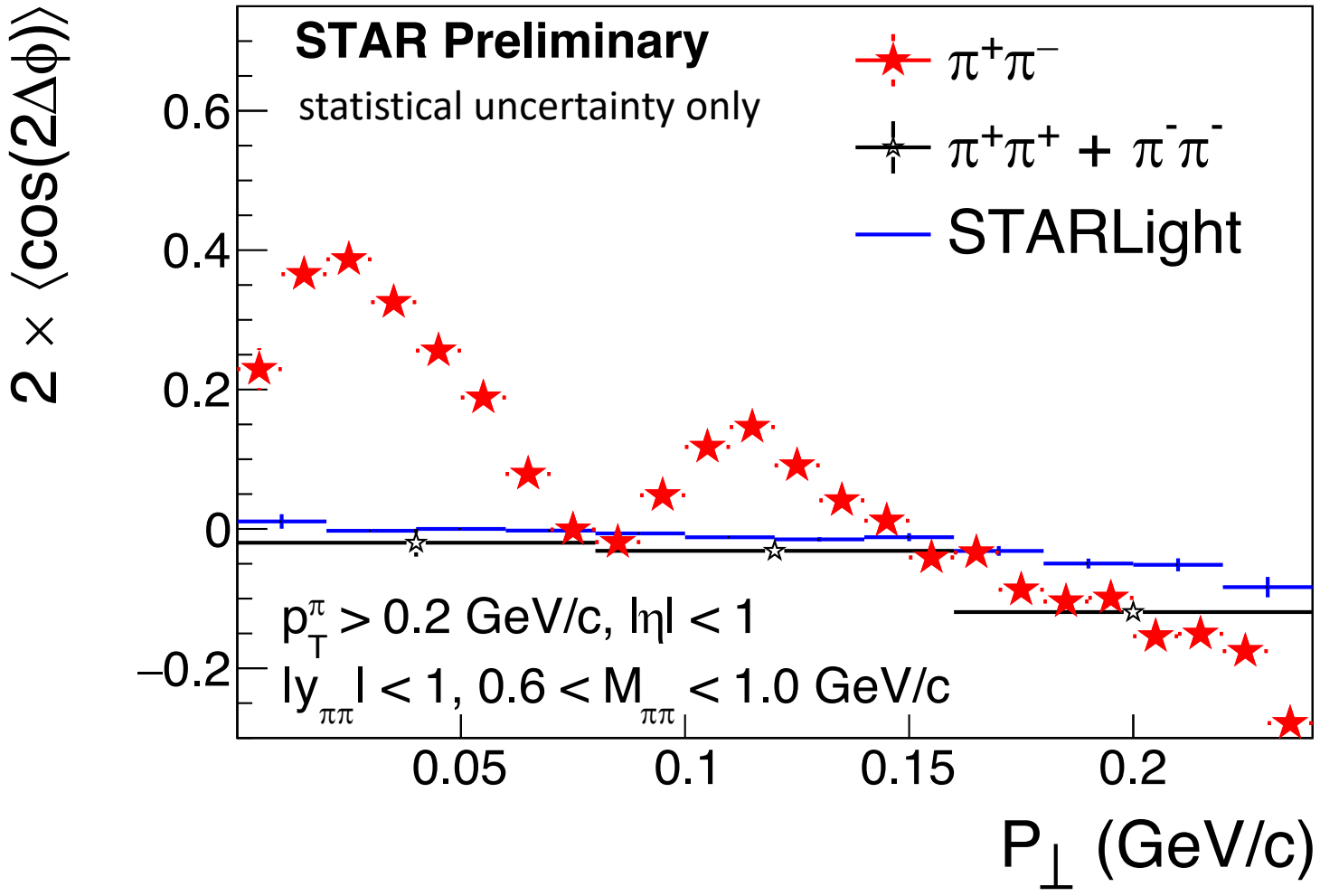
Interference is sensitive to:

→ Nuclear Geometry

→ Impact Parameter



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

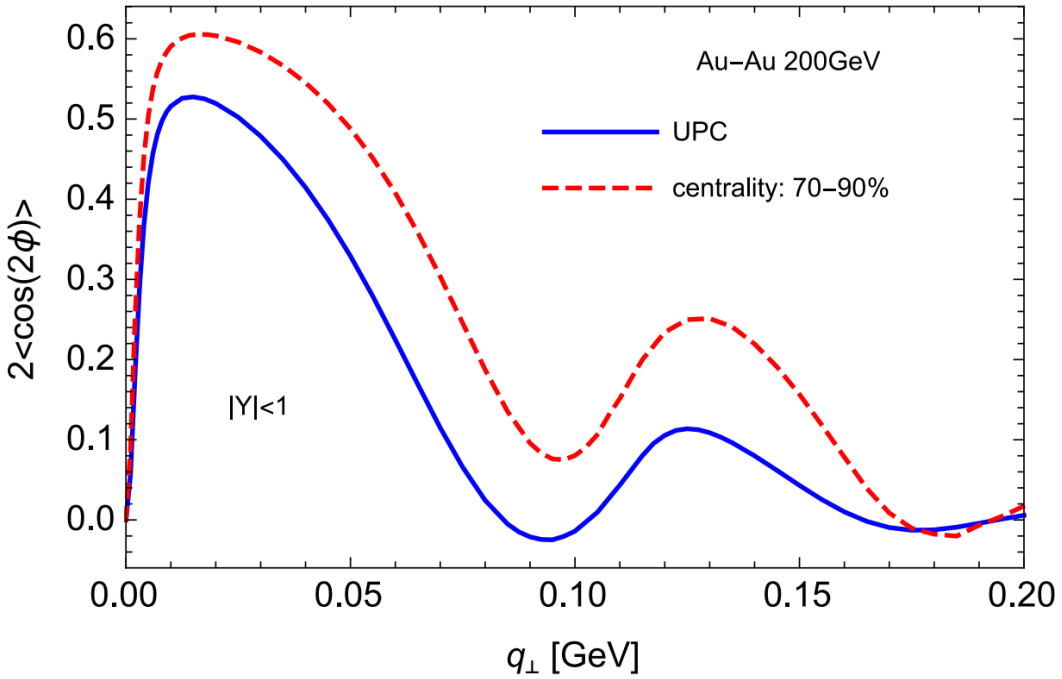


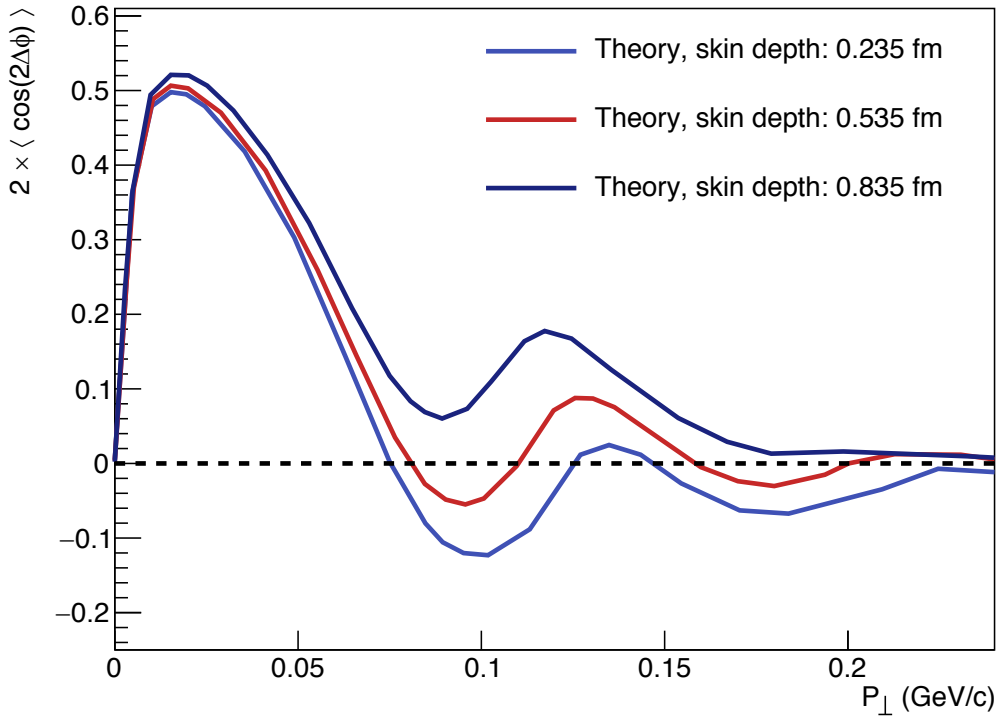
- Strong $\cos 2\Delta\phi$ modulation observed at $P_\perp < 50$ MeV/c
- Interference pattern visible → dip and peak in modulation at higher $P_\perp$
- STARLight[1] does not include polarization effect
- Qualitatively consistent with theoretical calculation including two-source interference effects

[1] S. R. Klein, et. al. *Comput. Phys. Commun.* 212 (2017) 258

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

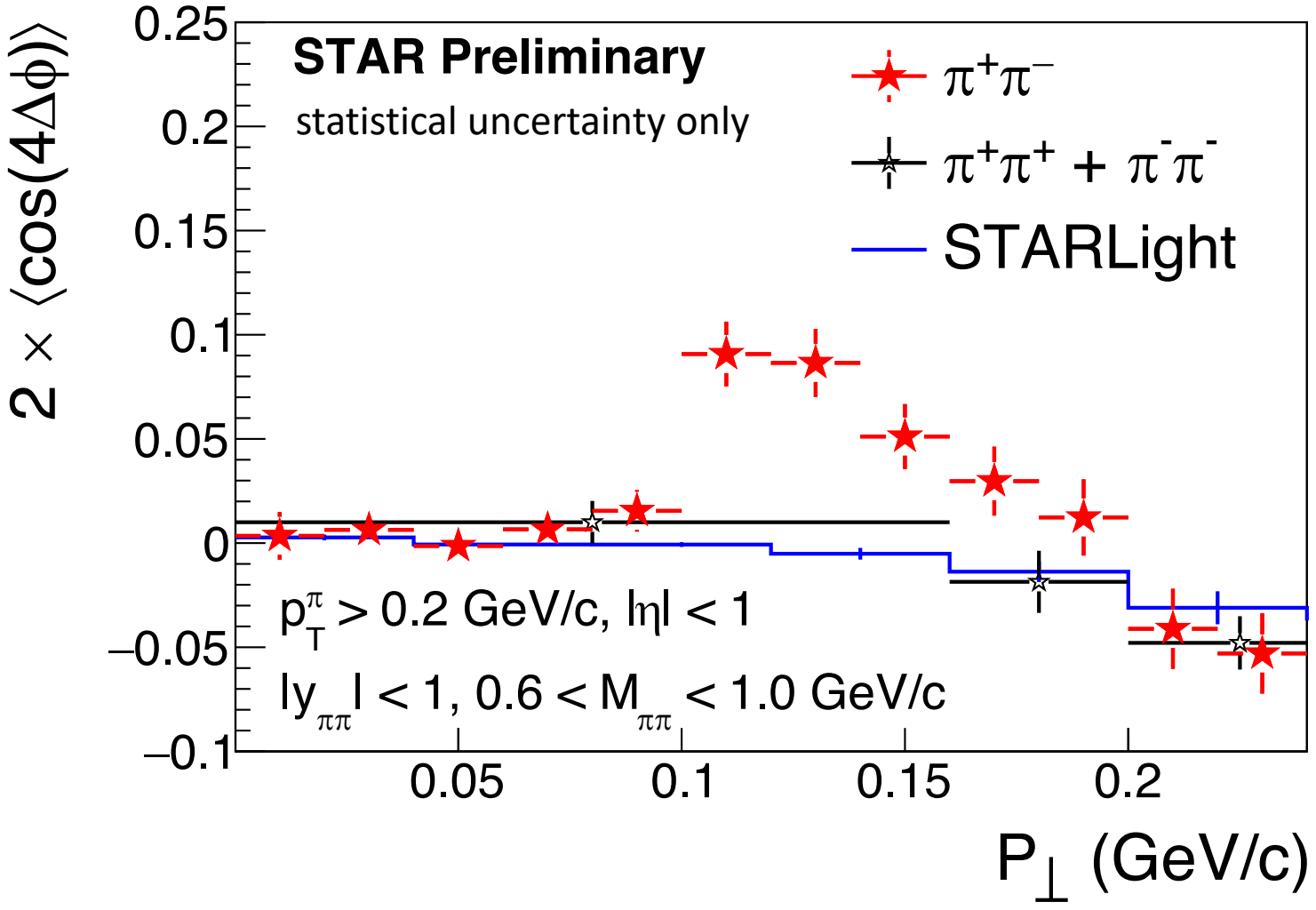
Nuclear skin depth (right)

→ Impact parameter

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

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

Results : $\langle \cos 4\Delta\phi \rangle$ vs. $P_\perp$



- Sizeable $\langle \cos 4\Delta\phi \rangle$, in addition to the $\langle \cos 2\Delta\phi \rangle$ modulation
- May be sensitive to the gluon Generalized Transverse Momentum Dependent (GTMD) Distribution [1]
- Looking forward to more theoretical developments

[1] J. Zhou Phys. Rev. D **94** (2016), 114017

Summary

1. Observed $(6.7\sigma)\cos 4\Delta\phi$ angular modulation in linear polarized $\gamma\gamma \to e^+e^-$ (Breit-Wheeler) process
   - First laboratory evidence of vacuum birefringence
   - For new measurements, see talk by Xiaofeng Wang (11/01/2020 : 10:42 am)

2. First measurement of $\Delta\phi$ modulations in $\gamma\mathbb{P} \to \rho^0 \to \pi^+\pi^-$ process
   - Strong $\cos 2\Delta\phi$ modulations due to photon polarization
     - Structure observed vs. pair p_T
   - 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