Supported in part by

Latest UPC results from STAR

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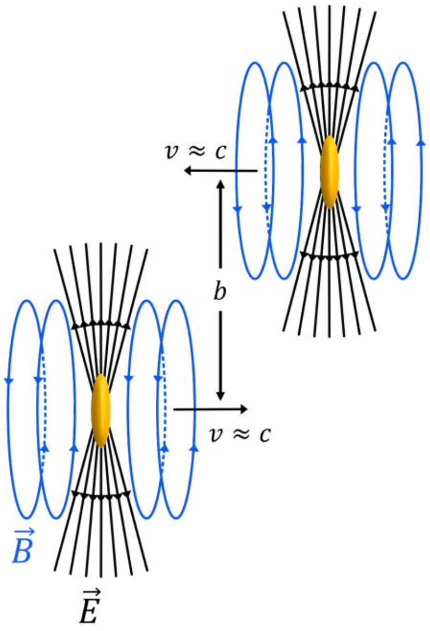
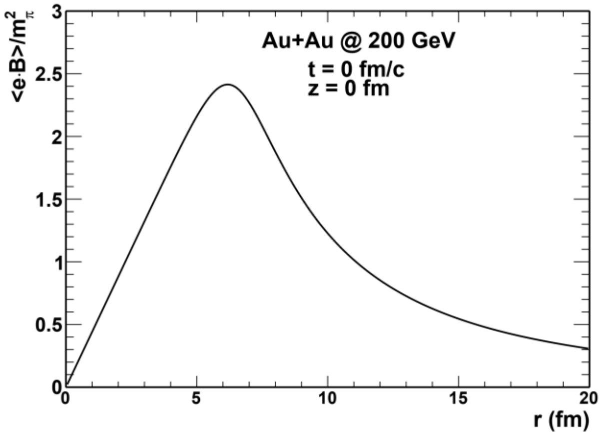
University of Science and Technology of China

Diffraction and Low-x 2024
8–14 Sept 2024, Hotel Tonnara Trabia, Palermo, Sicily

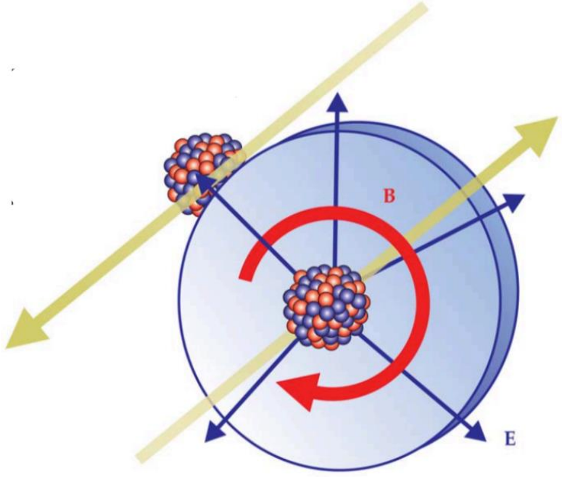
The giant electromagnetic field in heavy-ion collisions

Physics Today **70**, 10, 40 (2017)





m_π^2: $3.3 \times 10^{14}\ T$



Ultra-Peripheral Collisions (UPC)

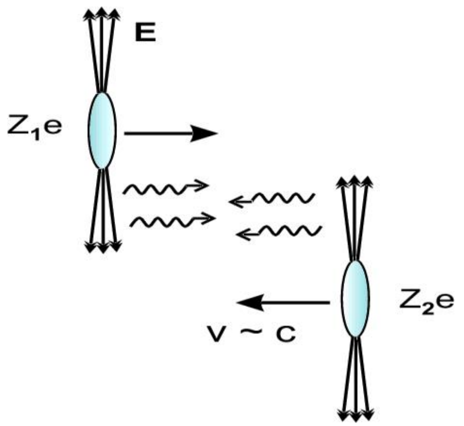
Clouds of quasi-real photons being present with heavy nuclei

$$n(\omega, r_\perp) = \frac{4Z^2\alpha}{\omega}\left|\int \frac{\vec{q}_\perp}{(2\pi)^2}\vec{q}_\perp \frac{f(\vec{q})}{q^2} e^{i\vec{q}_\perp \cdot \vec{r}_\perp}\right|^2$$

$$\vec{q} = \left(\vec{q}_\perp, \frac{\omega}{\gamma}\right)$$

Equivalent Photon Approximation

The collisions of the electromagnetic field



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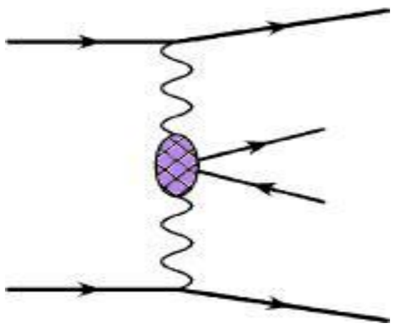

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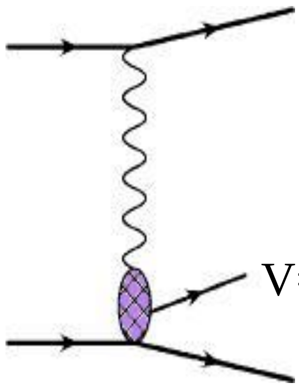

Ann. Rev. Nucl. Part. Sci.**55**:271 (2005)

V=ρ , ω , ϕ , J/ψ

Electromagnetic interaction

Photon-photon interactions

Photon-nucleus interactions

PRC 89 (2014) 014906

collider		RHIC	RHIC	LHC
species		Au+Au	U+U	Pb+Pb
$\sqrt{s_{NN}}$	GeV	200	192.8	5520
BFPP	b	117	329	272
single EMD	b	94.15	150.1	215
mutual EMD	b	*3.79*	*7.59*	*6.2*
nuclear	b	7.31	8.2	7.9
total	b	218.46	487.3	494.9

The abundant photon induced reactions

UPC related physics

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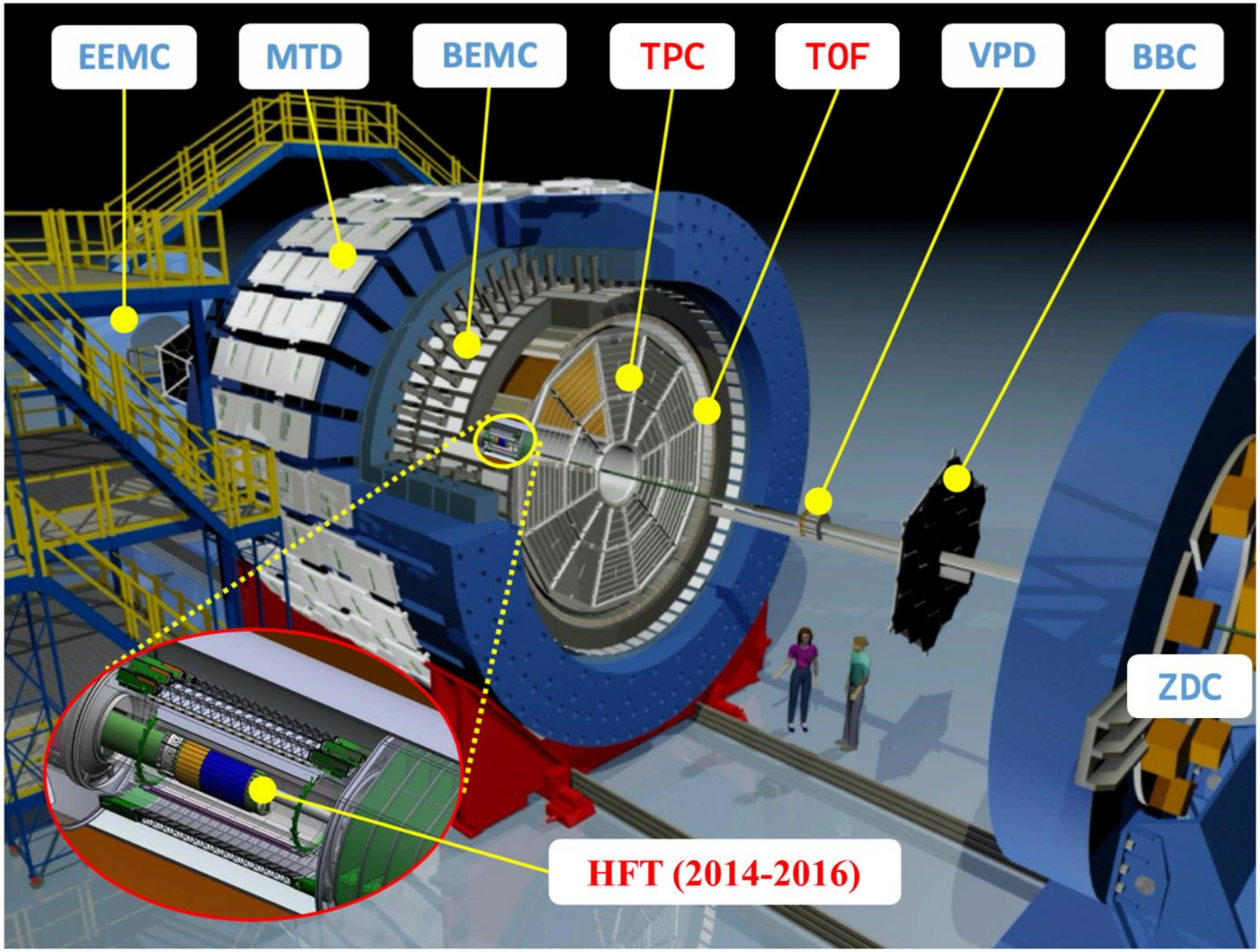
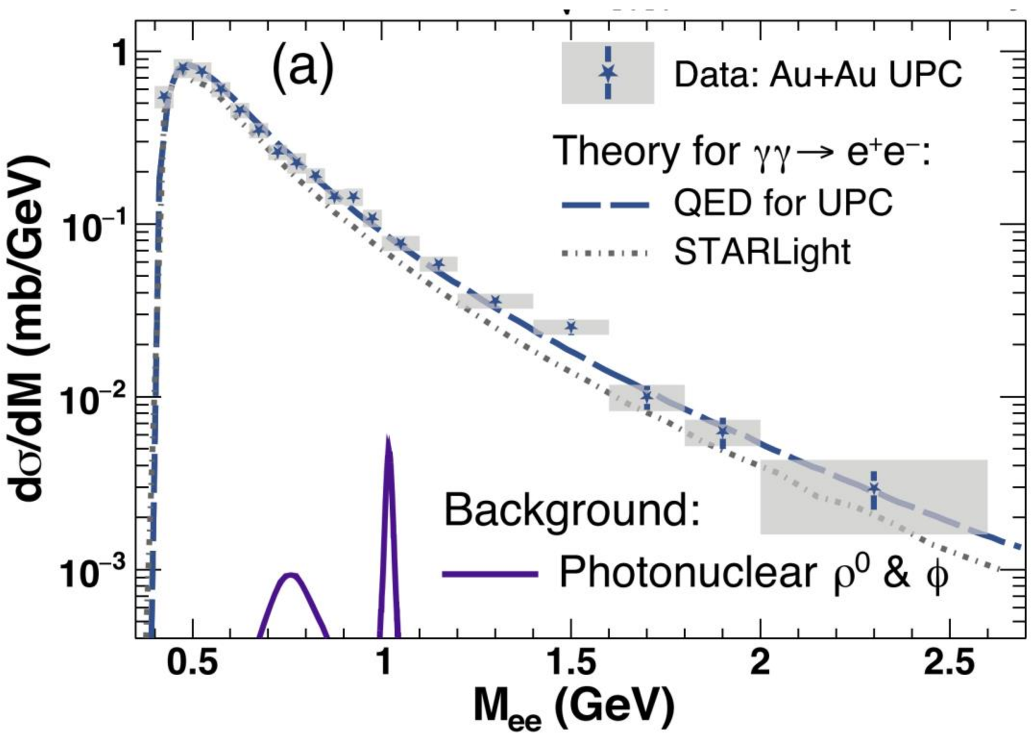
The physics of photoproduction

The equipment (STAR) to photograph the collisions



The observation of Breit-Wheeler process

STAR, PRL **127** (2021) 052302



Mutual Coulomb Dissociation triggered
B-W integrated cross section

Data : 0.261 ± 0.004 (stat.) ± 0.013 (sys.) ± 0.034 (scale) mb

STARLight	gEPA	QED
0.22 mb	0.26 mb	0.26 mb

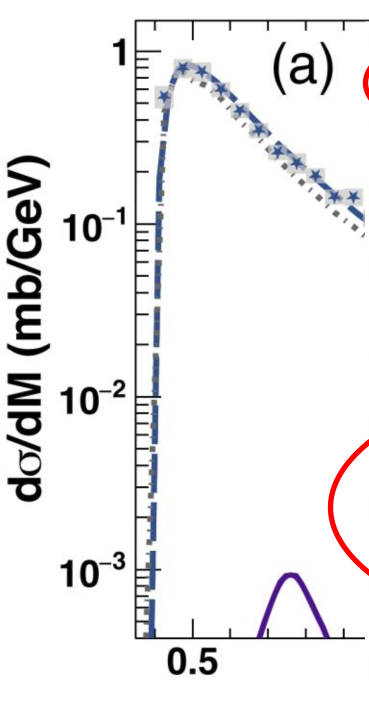
Consistent with theoretical calculations with $\pm 1\sigma$ level!

The Simplest process to convert energy to matter

$$\gamma + \gamma \rightarrow e^+ + e^-$$

The observation of Breit-Wheeler process

STAR, PRL **127** (2021) 052302



> rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or γ rays meeting each other on account of the smallness of σ and the insufficiently large available densities of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number of nucleii available in unit volume of ordinary materials, increases the effect to observable amounts. Analyzing the field of the nucleus into

MCD

4 (stat.) ±

34 (scale) mb

QED

nb 0.26 mb

theoretical

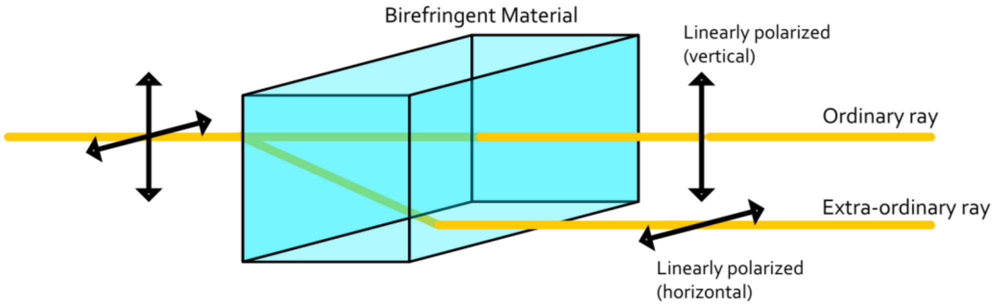
n $\pm 1\sigma$ level!

$$\rho^{a,a'} = \begin{pmatrix} \rho^{++} & \rho^{+0} & \rho^{+-} \\ \rho^{+0} & \rho^{00} & \rho^{+0} \\ \rho^{+-} & \rho^{+0} & \rho^{++} \end{pmatrix}$$

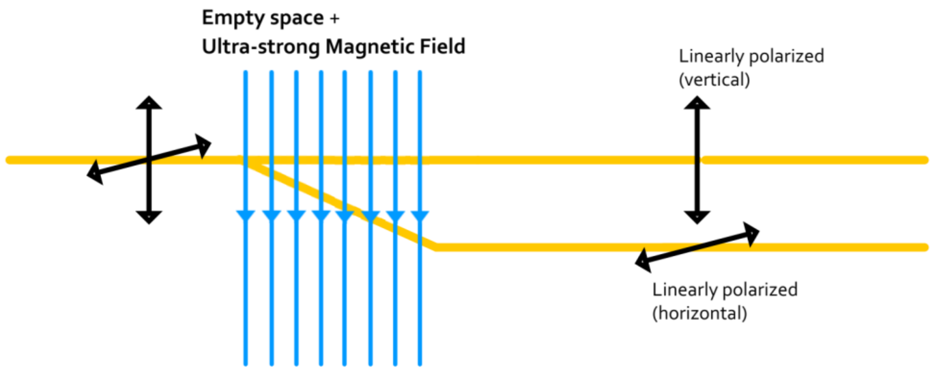
1934 Breit & Wheeler : "Collision of two Light Quanta"
Physical Review **46** (1934): 1087

The linear polarization and Birefringence

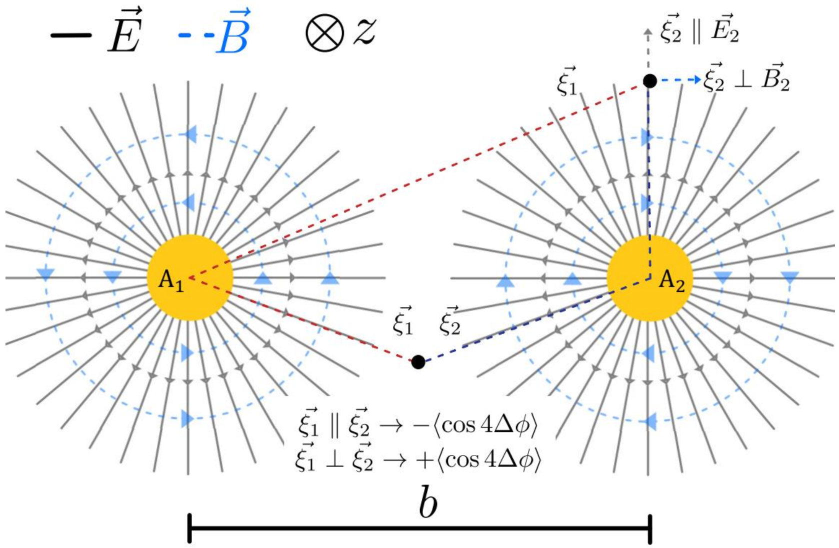
Birefringence



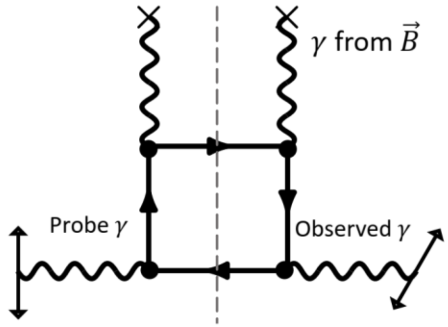
QED Vacuum Birefringence



The photons are linearly polarized!



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



Link to Vacuum Birefringence!

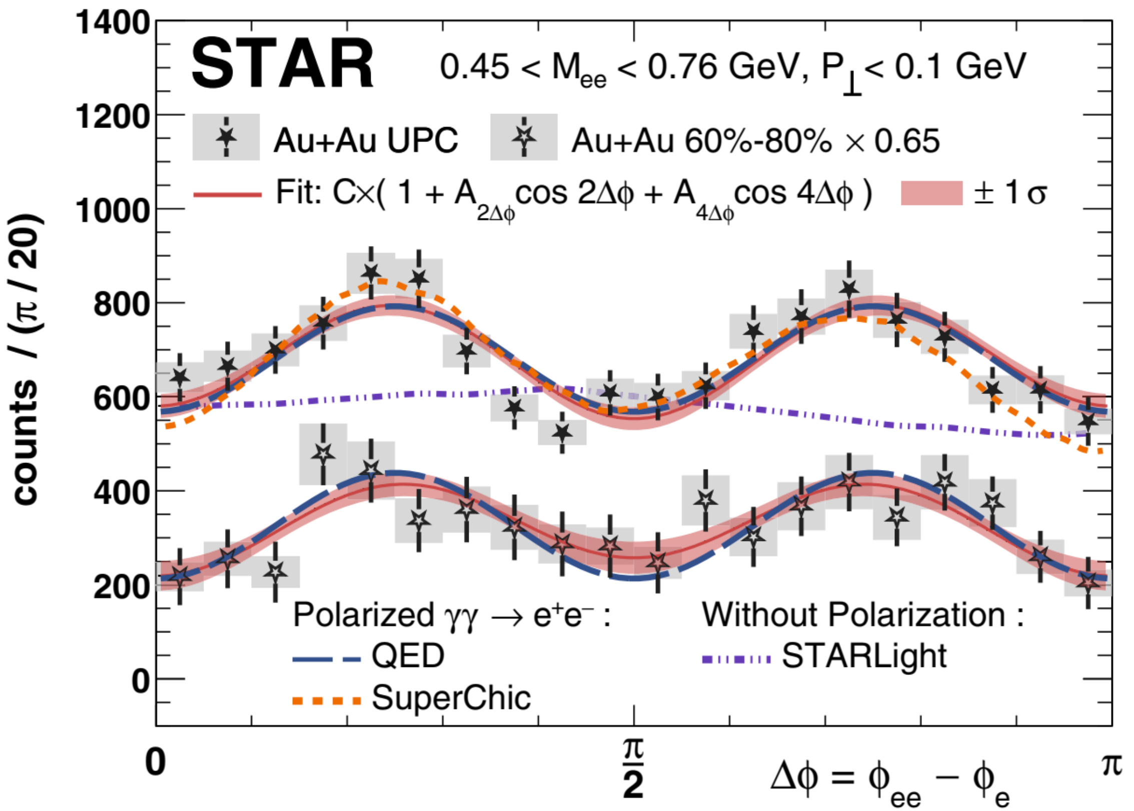
Birefringence of the QED vacuum

$\Delta\sigma = \sigma_{\parallel} - \sigma_{\perp}$ leads to $\cos n\phi$ modulation for polarized two gamma fusion

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

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

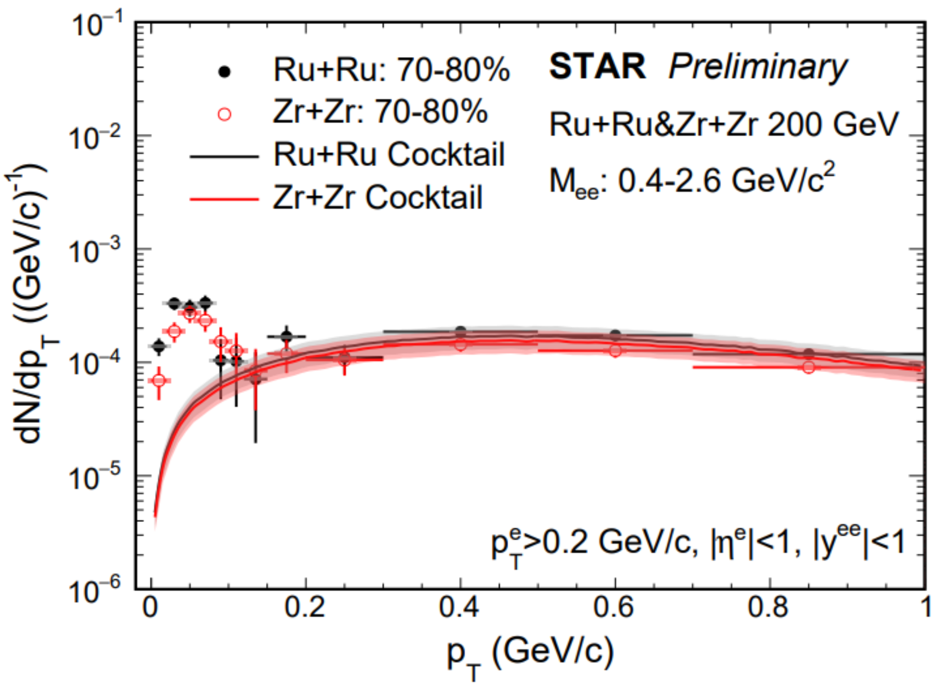
	Peripheral (60−80%)		
Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	27 ± 6	34.5	10.2 / 17

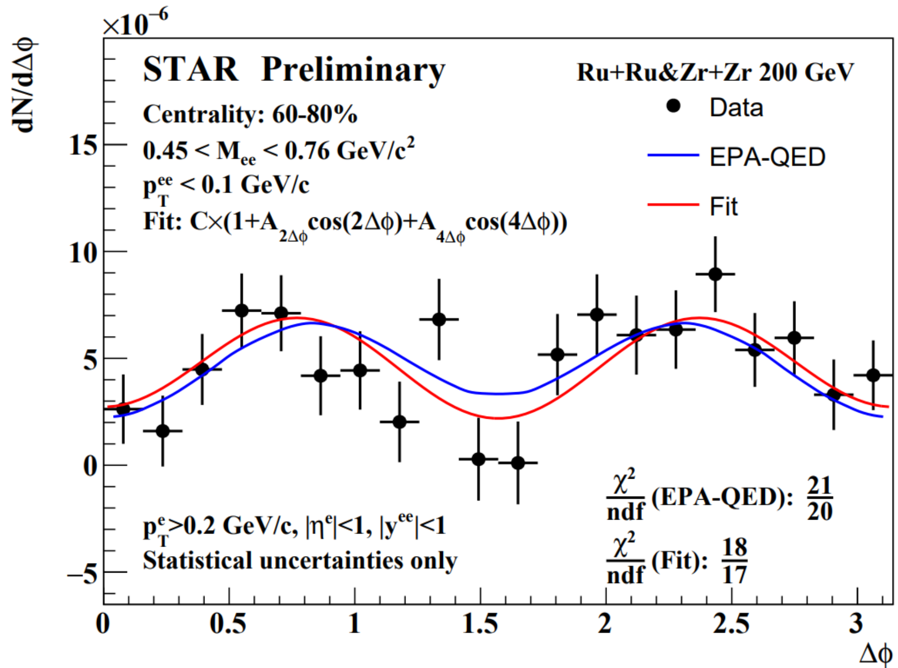


STAR, PRL **127** (2021) 052302

The first observation of angular modulation for B-W process in heavy-ion collisions.

The B-W production in isobaric collisions



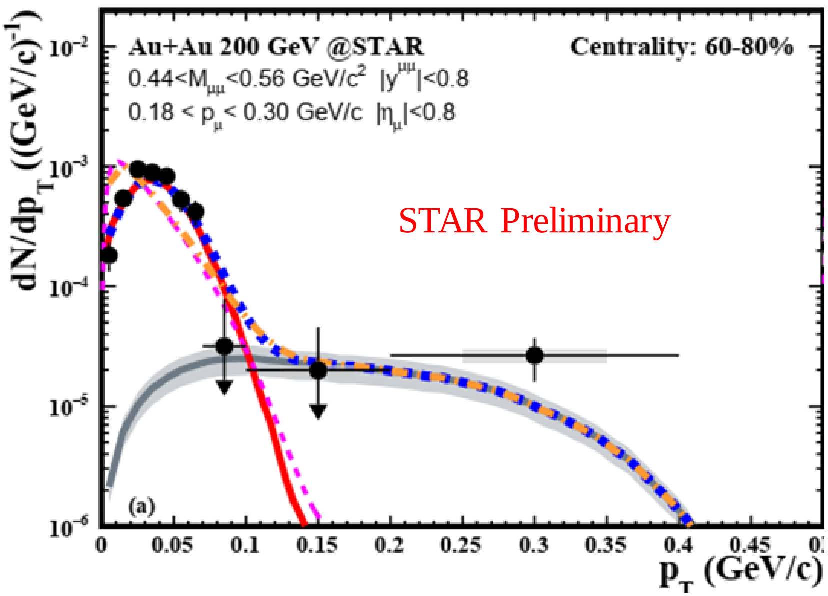


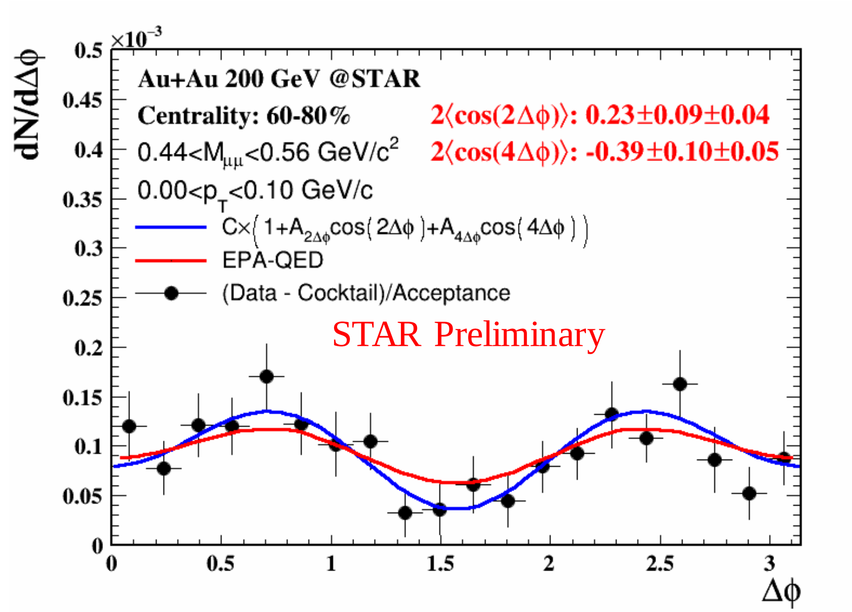
	$\lvert A_{4\Delta\phi}\rvert$ (%)	$\lvert A_{2\Delta\phi}\rvert$ (%)	χ^2/ndf
Isobar(60-80%)	47±14	6±13	18/17
Au+Au(60-80%)	27±6	6±6	10/17
Au+Au (UPC)	17±3	2±2	19/16

- ✓ Stronger modulation strength
  - In comparison with Au+Au case
  - Impact parameter dependence
- ✓ Zero cos2$\Delta\phi$ modulation
  - $< \cos 2\Delta\phi > \propto m^2/p_\perp^2$

How about massive muon?

The dimuon channel



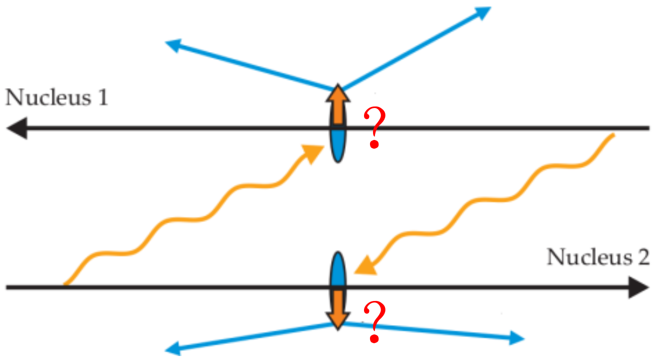


- ✓ Observation of dimuon excess from photoproduction
- ✓ Consistent with impact parameter dependence picture

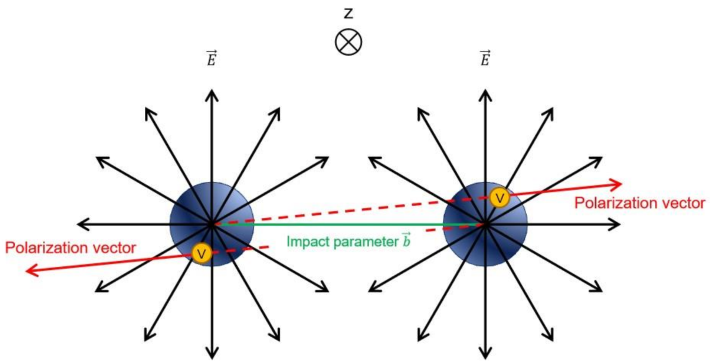
- ✓ Evidence of the 4th-order azimuthal angular modulation
- ✓ First indication of the 2nd-order azimuthal angular modulation

$$< \cos 2\Delta\phi > \propto m^2/p_\perp^2$$

Linear polarization and double-slit interference



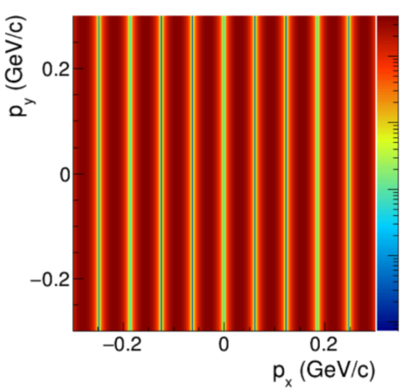
Linearly polarized photons



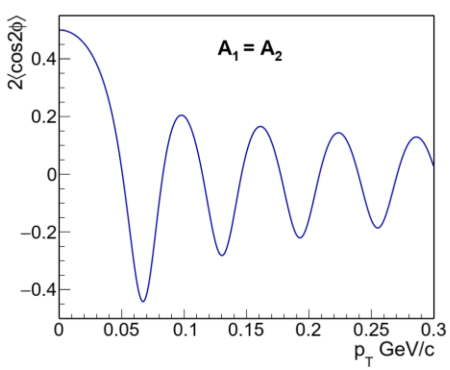
PRD 103 (2021), 033007

Decay along the impact parameter

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



The second order modulation



Linear polarization and double-slit interference

STAR，Sci. Adv. **9** (2023) eabq3903

Example of EPR paradox

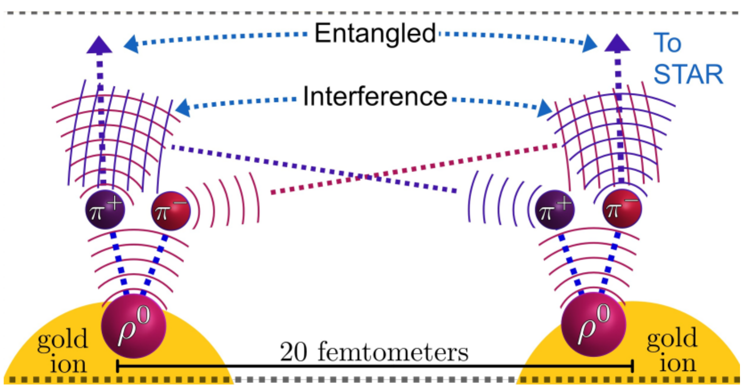
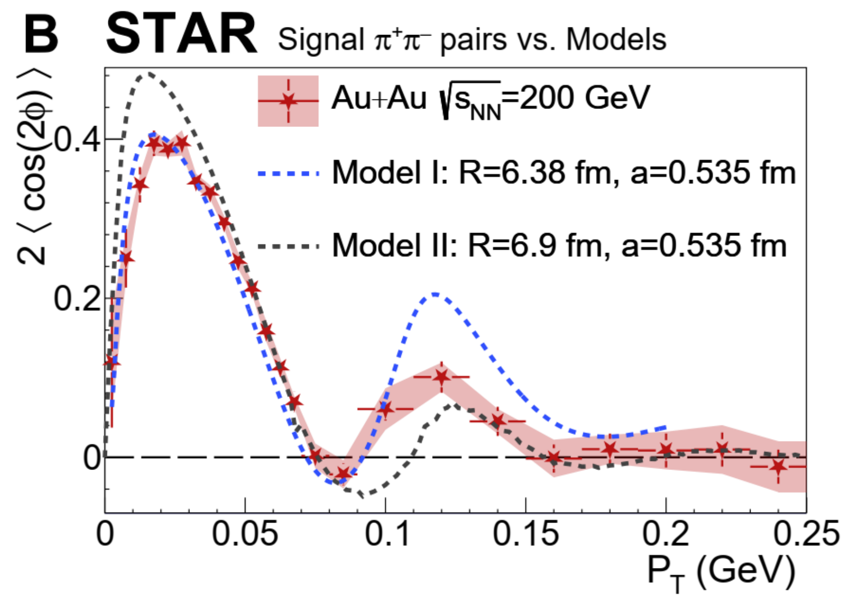


Figure from Zhangbu



The lifetime ρ : ~1fm/c

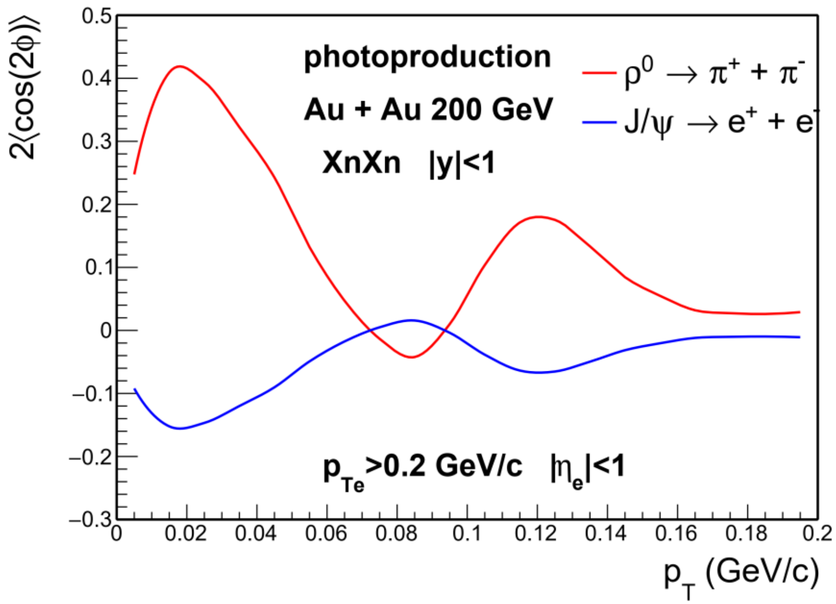
b ~20fm

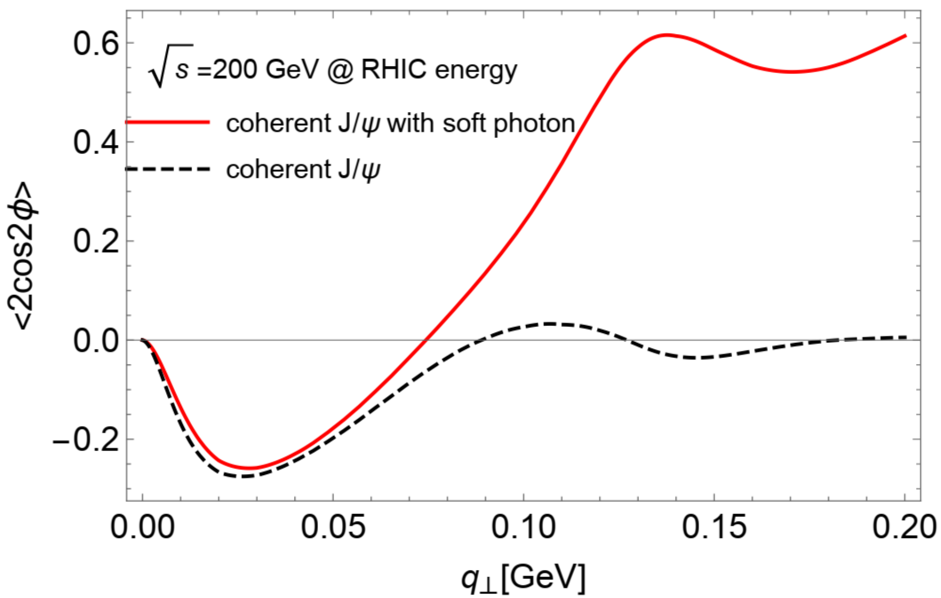
[1] Xing, H et.al. J. High Ener. Phys. **2020**, 64 (2020).
[2] Zha, W., JDB, Ruan, L. & Tang, Z. Phys. Rev. D **103**, 033007 (2021)

Prediction for U? Second peak?

Sensitive to the nuclear geometry / gluon distribution

Spin-interference for J/ψ photoproduction



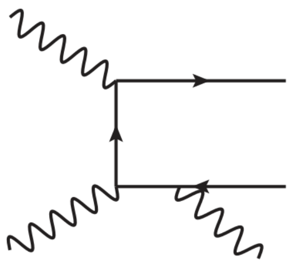


$$\frac{d^2N}{d\cos\theta d\phi} = \frac{3}{16\pi}(1+\cos^2\theta)\left[1 - \frac{\sin^2\theta}{1+\cos^2\theta}\cos 2(\phi - \Phi)\right]$$

J. D. Brandenburg etal.,Phys. Rev. D 106 (2022) 074008

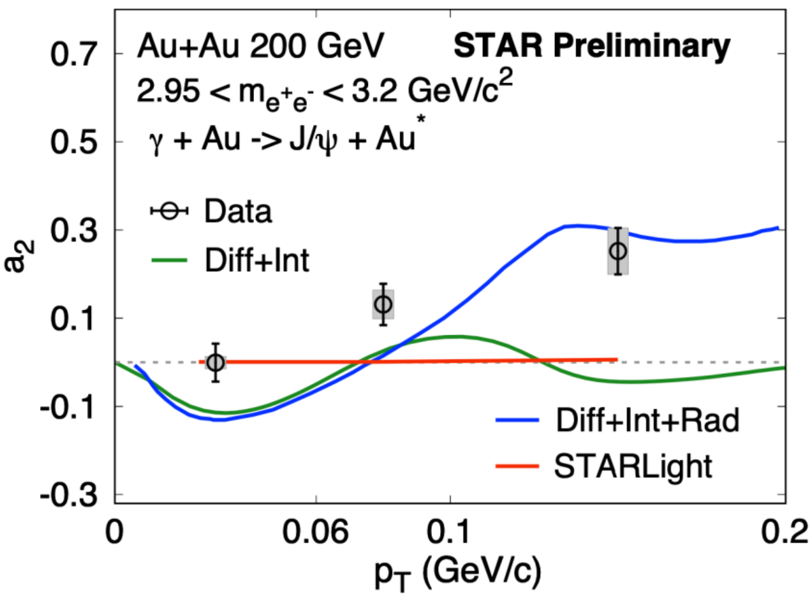
The negative modulation

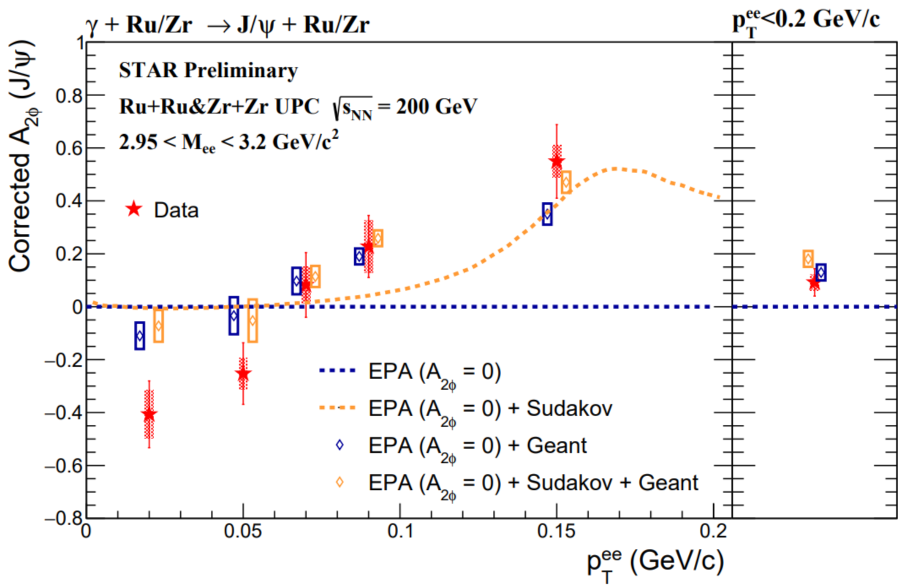
Decay daughters, l^+l^- are fermions



Internal Photon Radiation Effect

Spin-interference for J/ψ photoproduction





Complex analysis of multiple factors

- Background from gamma+gamma
- Soft photon radiation
- Bremsstrahlung & detector effect

- Hint of spin interference of J/ψ photoproduction
- New techniques for multidimensional imaging of nuclei

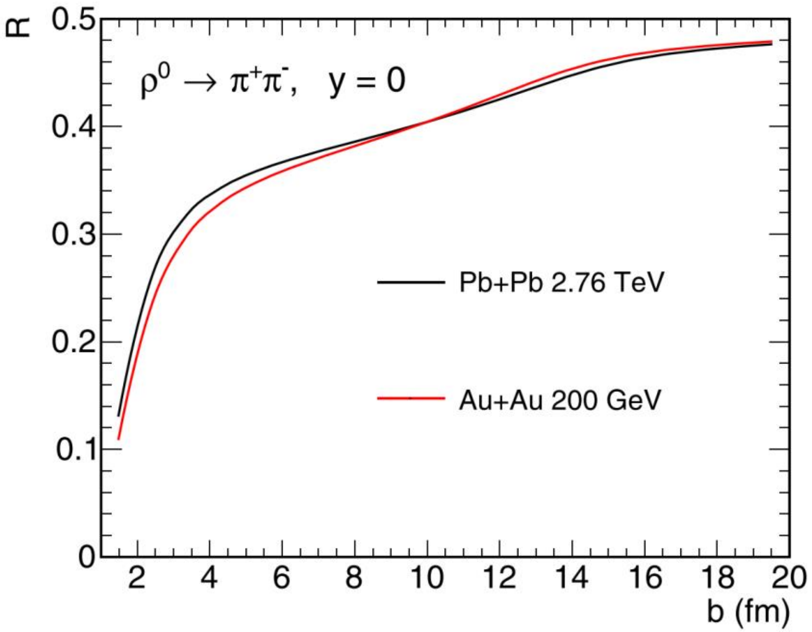
Spin-interference for J/ψ photoproduction

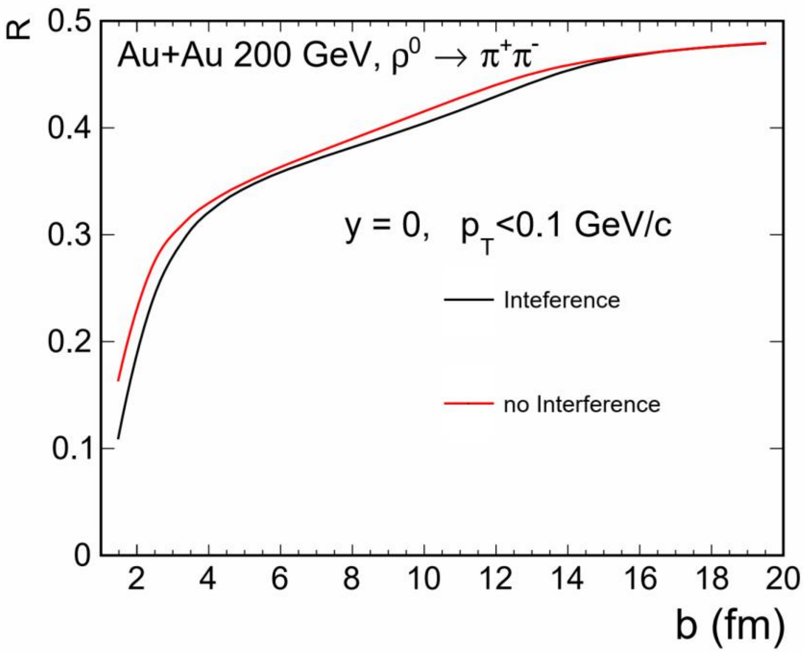
$$\Delta\phi = \Delta\phi[(e^+ + e^-),(e^+ - e^-)]$$
$$\approx \Delta\phi[(e^+ + e^-), e^+]$$

Negligible effect from detector and soft radiation

Reaction Plane

Replaced by new direction





Stay tuned for new results!

Summary

- Observation of Breit-Wheeler process in HIC

- The linearly polarized photons in HIC

  -Angular modulation for B-W process --- link to Vacuum Birefringence

  -Double-slit interference in polarization space for photoproduction

- The application of linearly polarization

  -Gluon tomography in nuclei

  -Nuclear charge distribution

  -Probe of QGP

THANK YOU