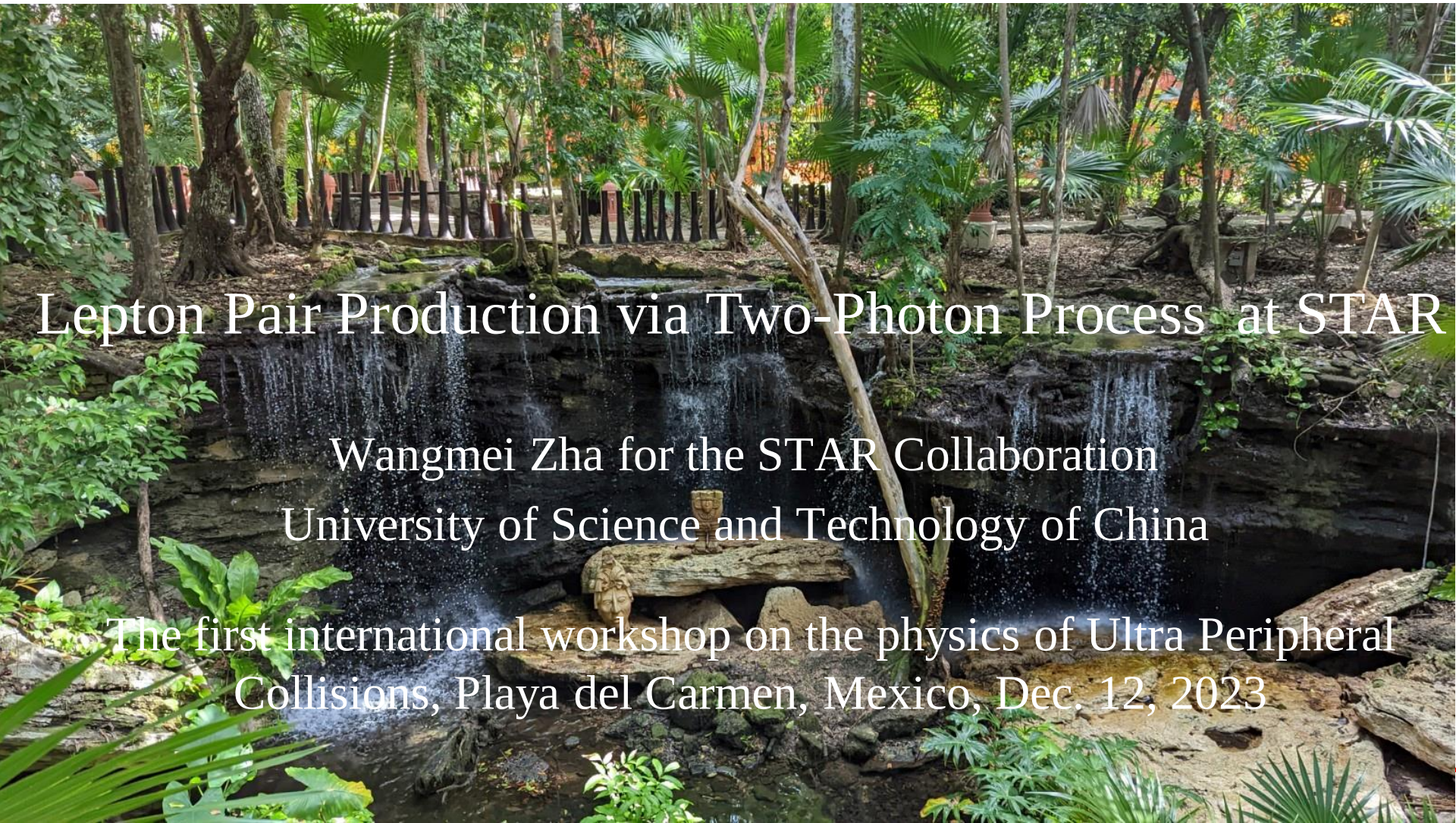
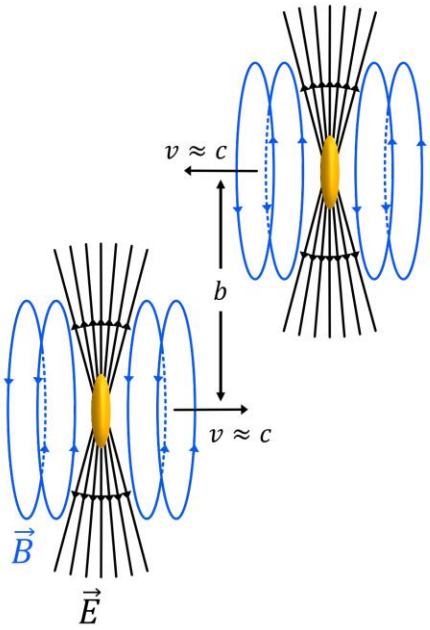


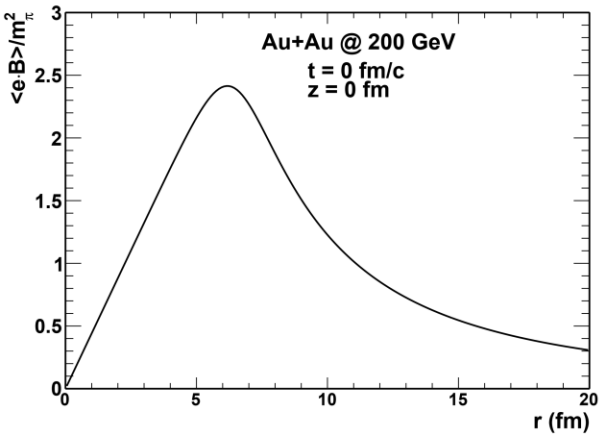
Lepton Pair Production via Two-Photon Process at STAR

Wangmei Zha for the STAR Collaboration
University of Science and Technology of China

The first international workshop on the physics of Ultra Peripheral Collisions, Playa del Carmen, Mexico, Dec. 12, 2023

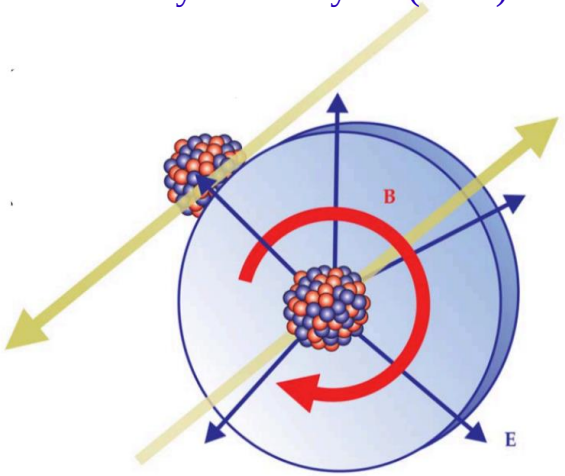
Giant electromagnetic field in heavy-ion collisions





$m_\pi^2 : 3.3 \times 10^{14}\ T$

S. Klein and J. Nystrand,
Physics Today **70** (2017) 40



Ultra-Peripheral Collisions (UPC)

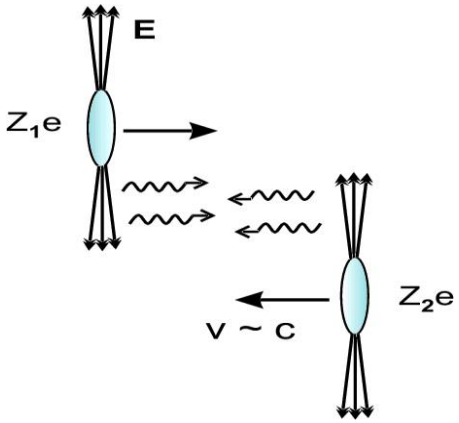
Clouds of quasi-real photons being present with heavy nuclei

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

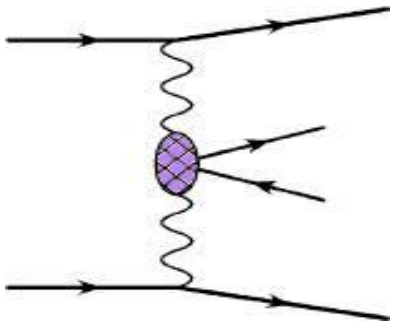
$$\vec{q} = \left(\vec{q}_\perp, \frac{\omega}{\gamma}\right)$$

Equivalent Photon Approximation

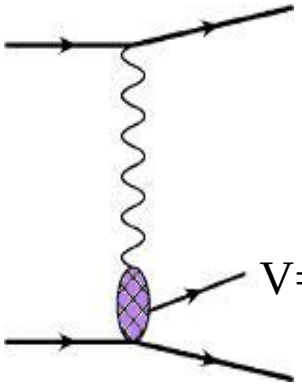
Photoproduction in Ultra-peripherial Heavy-ion Collisions



=



+



C.A. Bertulani, S.R. Klein and J. Nystrand, Ann. Rev. Nucl. Part. Sci.**55**:271 (2005)

V=ρ , ω , ϕ , J/ψ ...

Electromagnetic interaction

Photon-photon interactions

Photon-nucleus interactions

The abundant photon induced reactions

UPC related physics

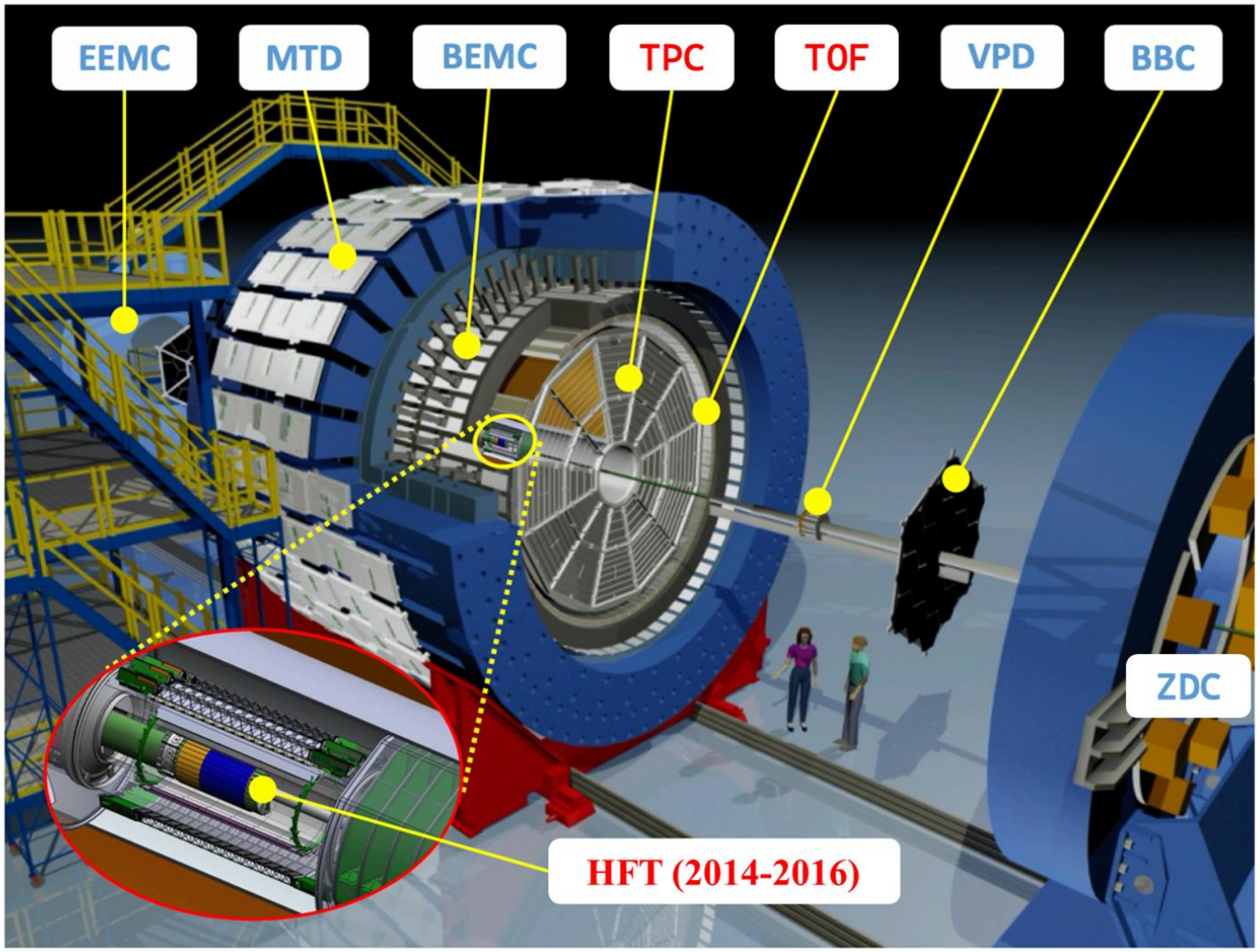
II

The physics of photoproduction

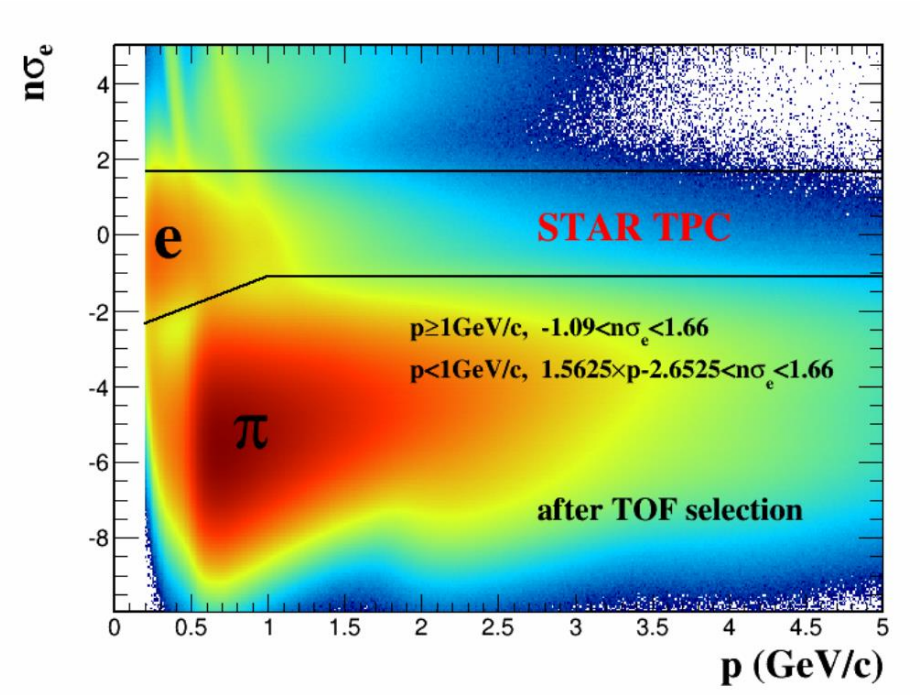
W. Fischer etal., PRC 89 (2014) 014906

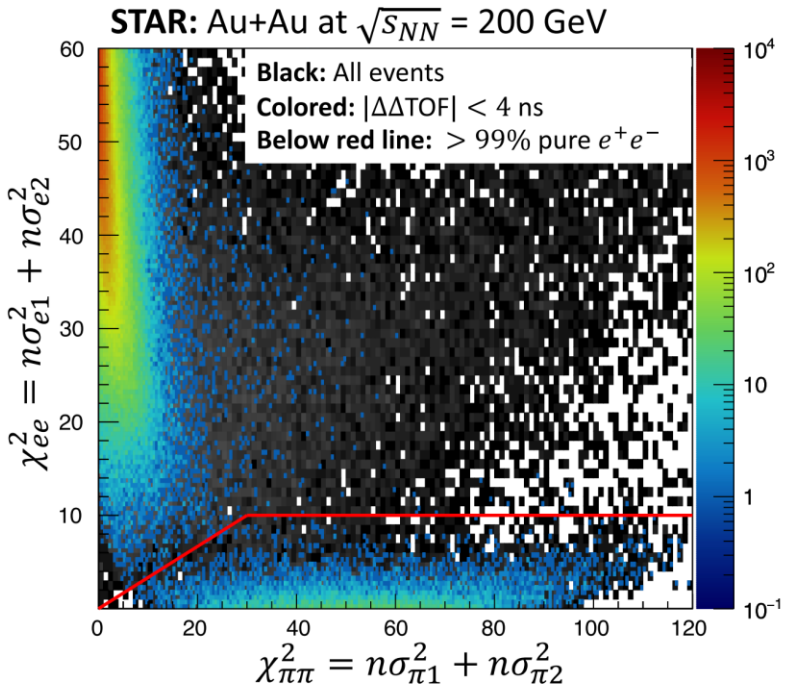
collider		RHIC	RHIC	LHC
species		Au+Au	U+U	Pb+Pb
$\sqrt{s_{NN}}$	GeV	200	192.8	5520
BFPP	b	117	329	272
single EMD	b	94.15	150.1	215
mutual EMD	b	*3.79*	*7.59*	*6.2*
nuclear	b	7.31	8.2	7.9
total	b	218.46	487.3	494.9

The equipment (STAR) to photograph the collisions



Electron Identification at STAR



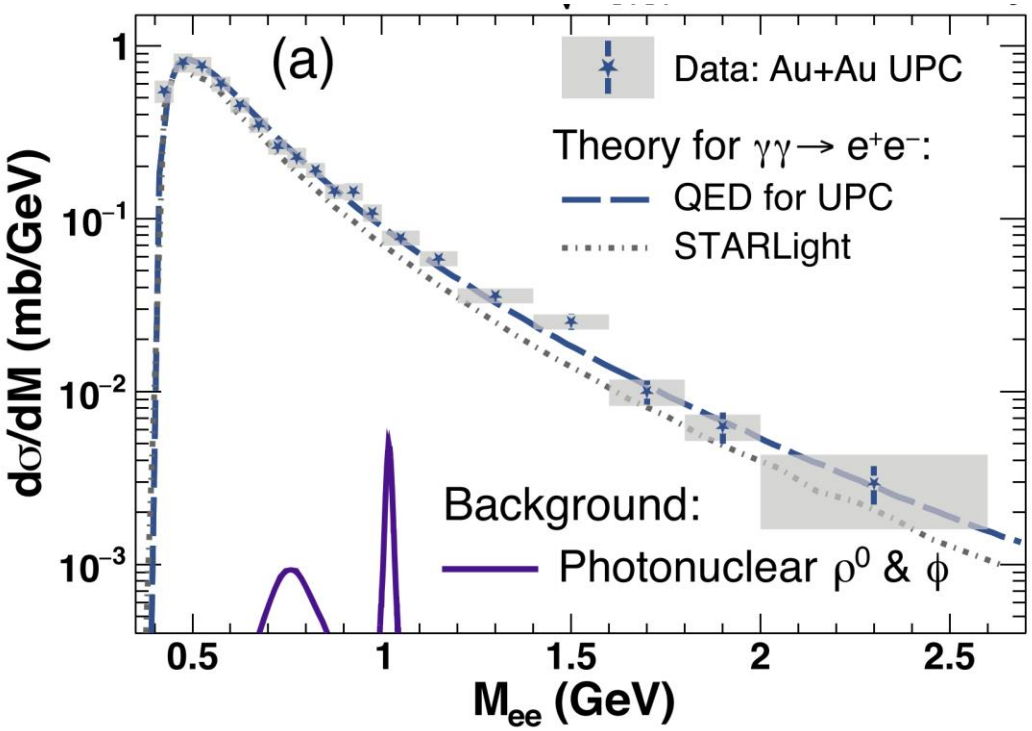


Excellent electron identification in MB and UPC

Purity > 99%

The observation of Breit-Wheeler process

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



MCD

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

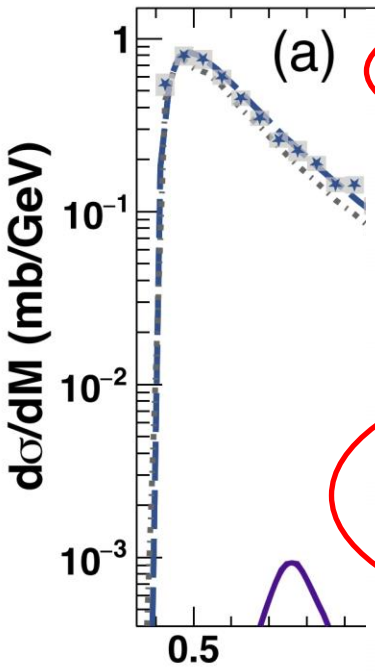
STARLight	gEPA	QED
0.22 mb	0.26 mb	0.26 mb

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

The simplest process to convert energy to matter

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

ıb 0.26 mb

theoretical

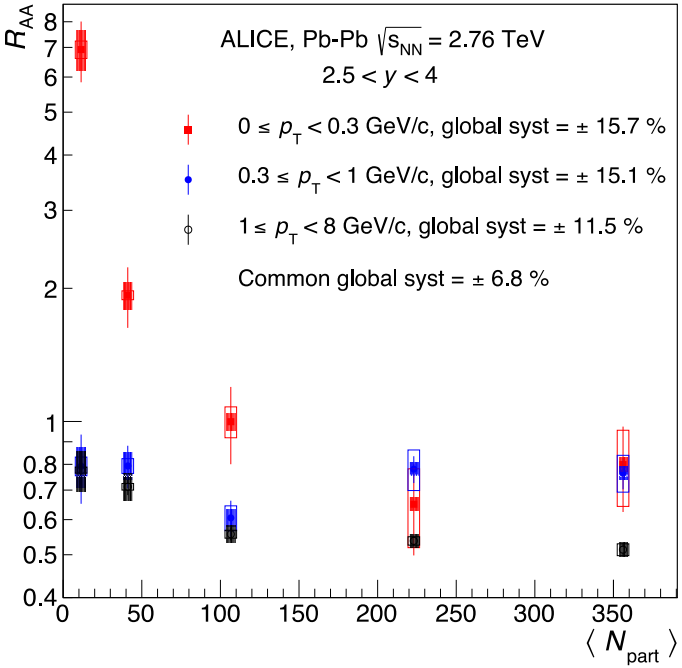
ı ±1σ level!

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

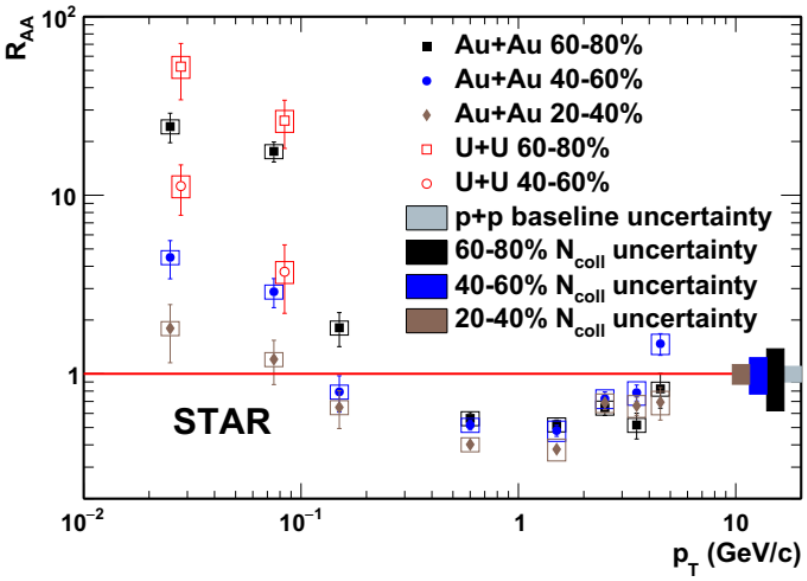
1934 Breit & Wheeler : "Collision of two Light Quanta"
Physical Review **46** (1934): 1087

Story began from the peripheral heavy-ion collisions (Non-UPCs)

ALICE: PRL **116**, 222301 (2016)

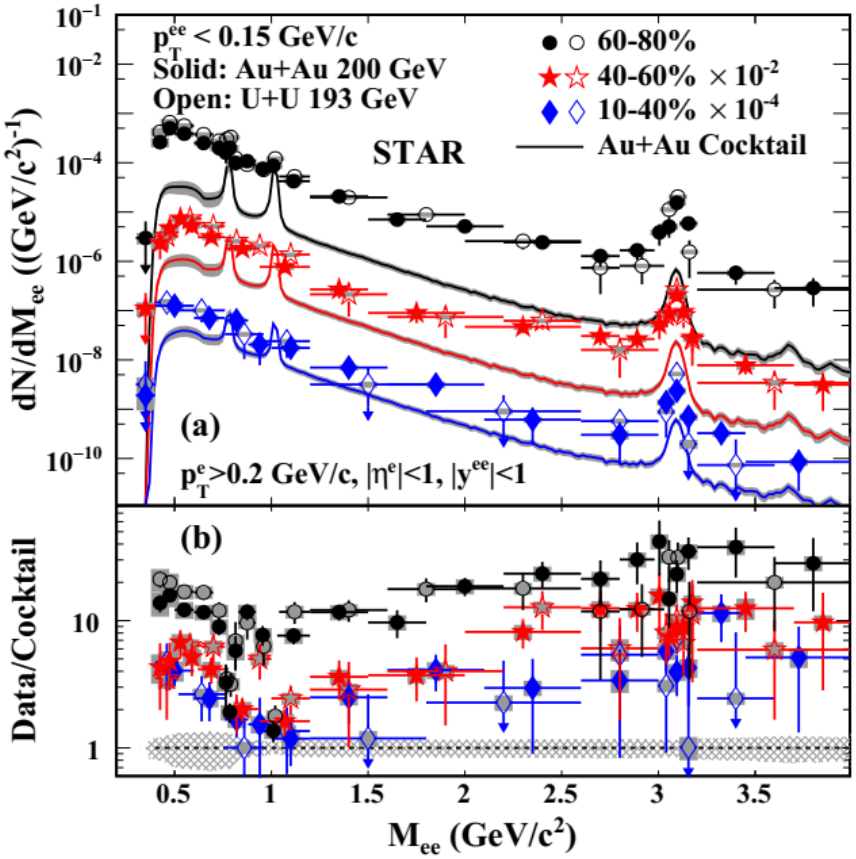


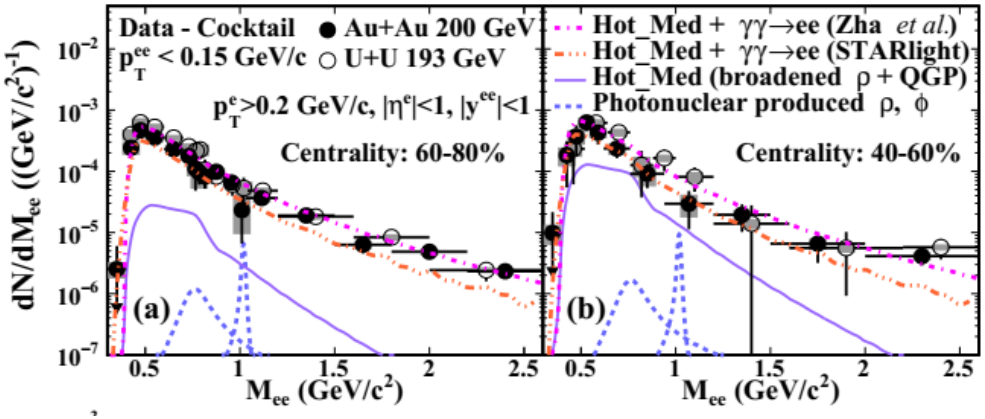
STAR: PRL **123** (2019) 132302



- Significant enhancement of J/ψ yield observed at very low p_T in peripheral heavy-ion collisions.
- Origin from coherent photon-nucleus interactions!
- New probe for QGP?

Breit-Wheeler process in non-UPCs





STAR, PRL **121** (2018) 132301

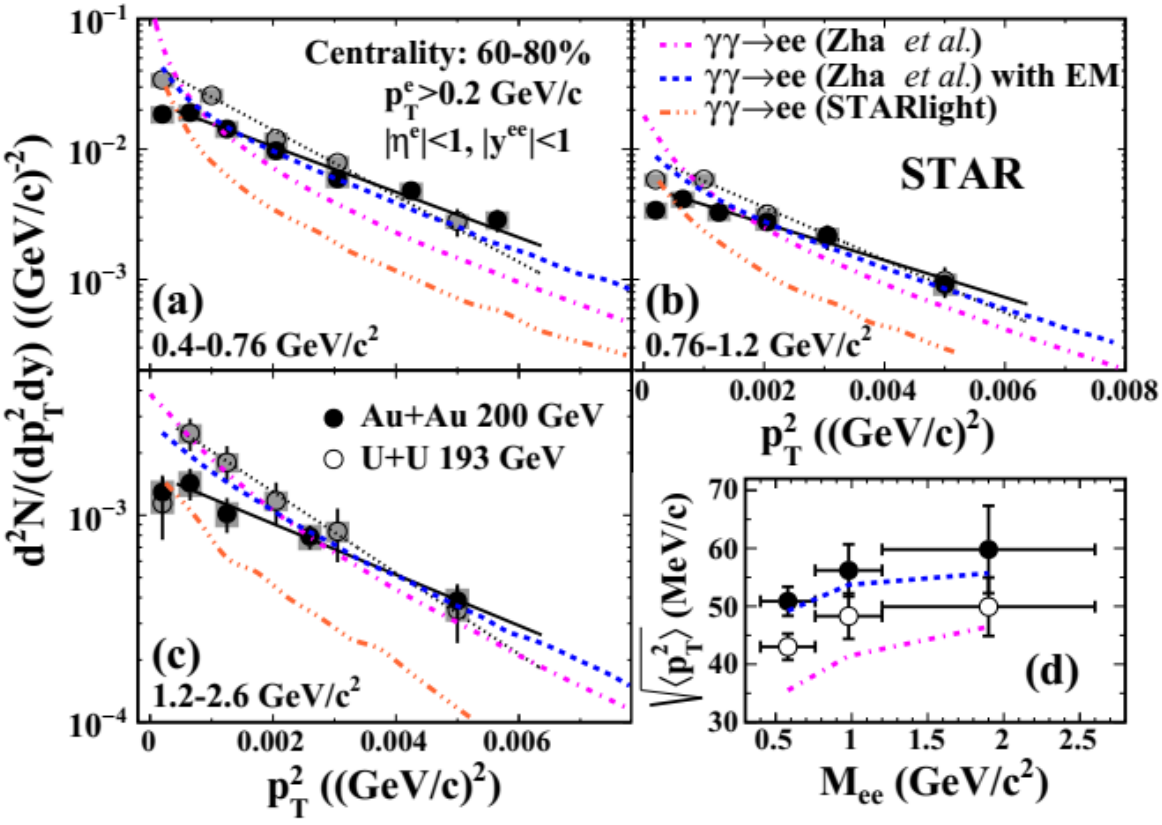
S.R. Klein, PRC **97** (2018) 054903

W. Zha etal., PLB **781** (2018) 182

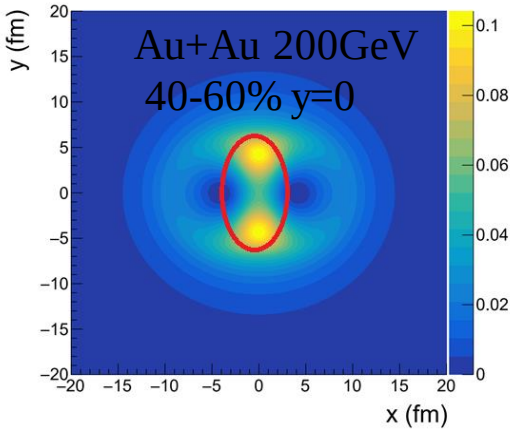
Negligible ρ photoproduction!

- Significant excess in 60-80% central Au + Au and U + U collisions for the whole invariant mass range!
- The excess can be described by the coherent photon-photon process!

Broadening of transverse momentum



12% in nuclear overlap region

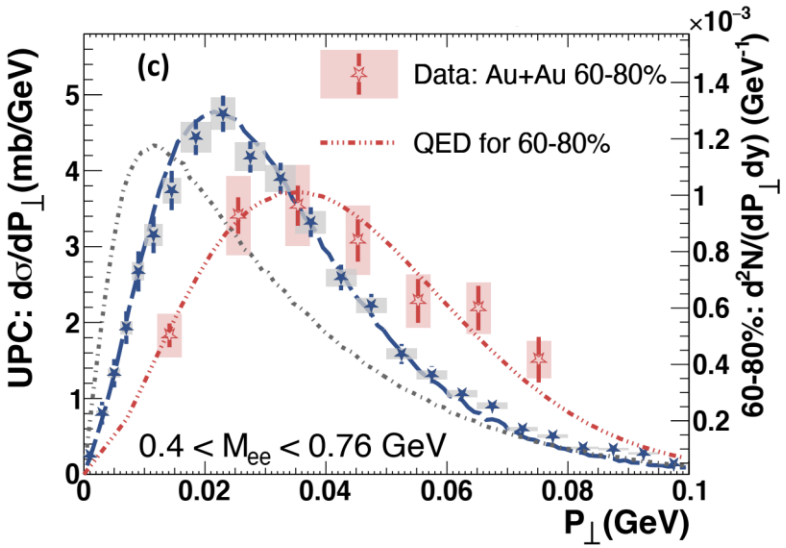


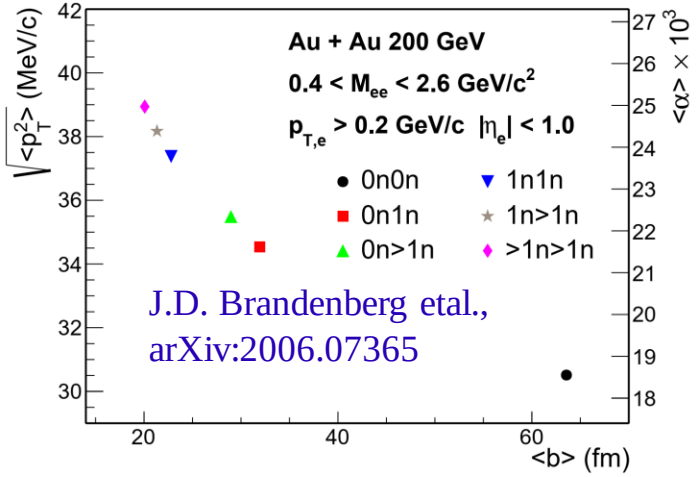
W. Zha etal., PLB **781** (2018) 182

Novel probe for QGP?

Possible medium effects --- magnetic field trapped in the QGP?

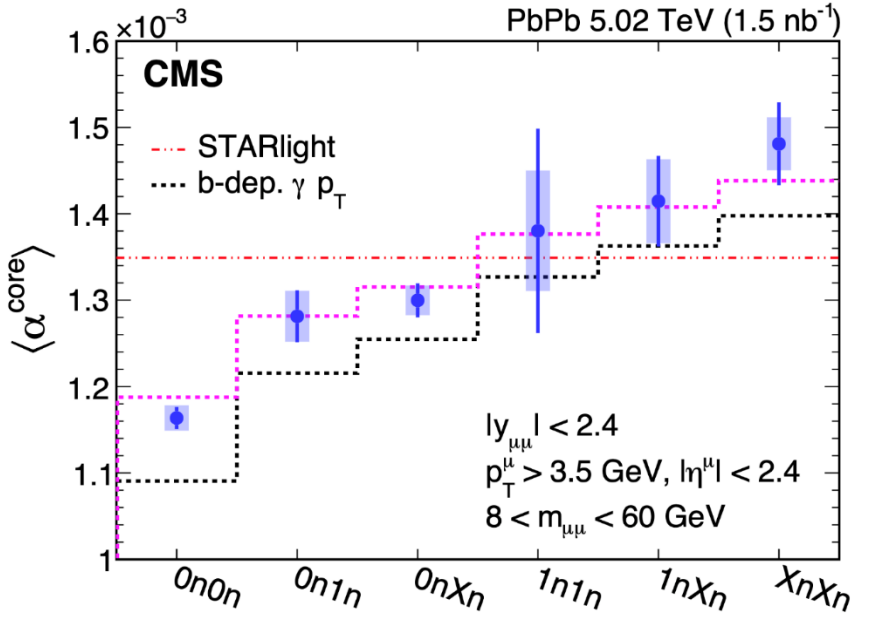
Impact parameter dependent broadening





J.D. Brandenberg etal., arXiv:2006.07365

CMS, PRL 127 (2021) 122001



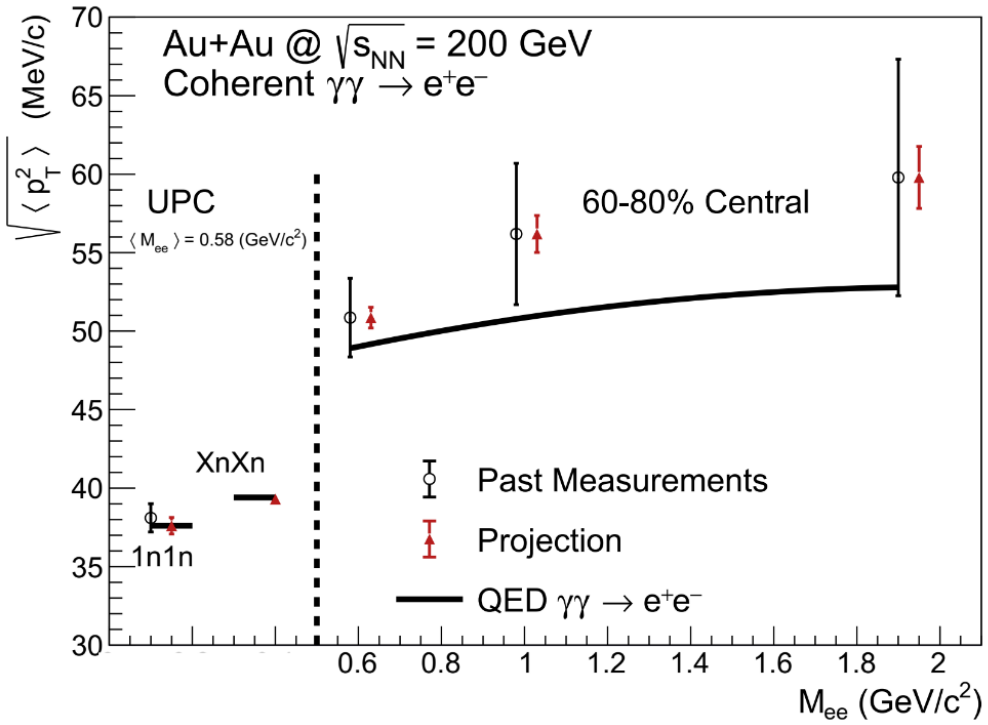
W. Zha etal, PLB 800 (2020) 135089

The "broadening" mainly originates from the lack of impact parameter dependence in traditional EPA approaches.

Shi Pu etal., Acta Phys. Sin. 72 (2023) 072503.

The room for QGP effect

J.D. Brandenburg, J. Seger, Z. Xu and W. Zha, Rep. Prog. Phys. **86** (2023) 083901

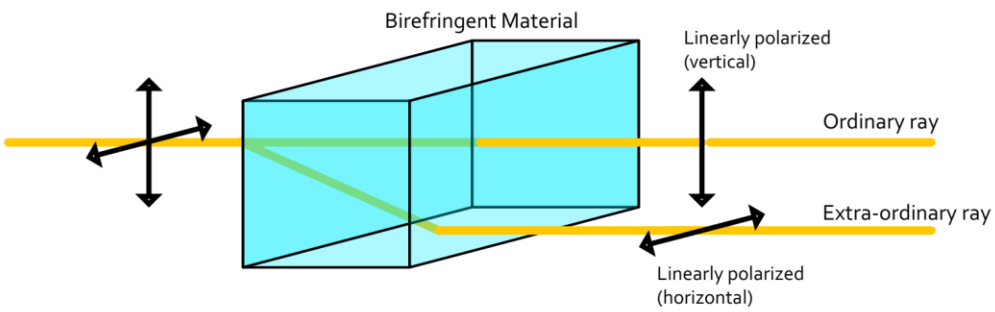


~20 times more statistics

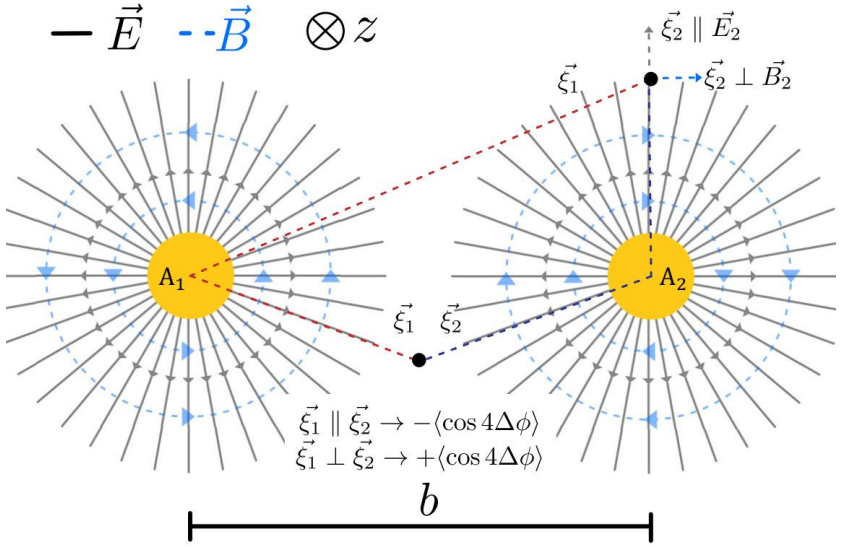
Push for more precise multi-differential measurements

Birefringence and linear polarization

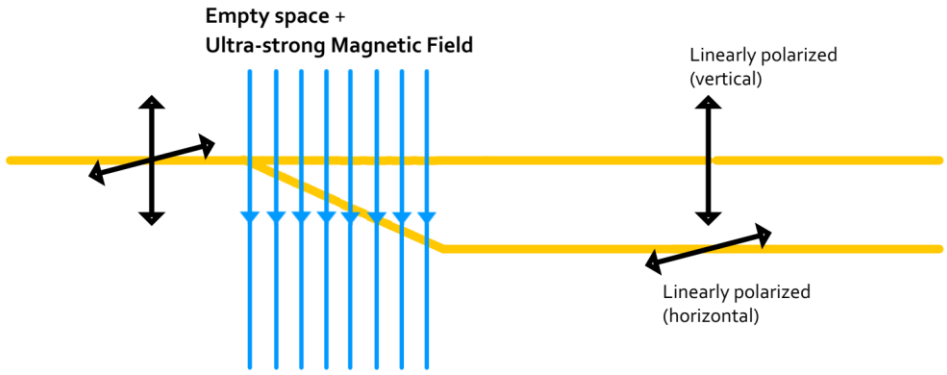
Birefringence



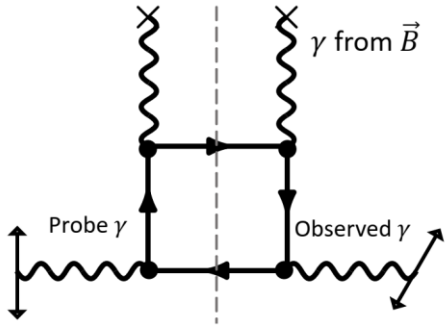
The photons are linearly polarized!



QED Vacuum Birefringence



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

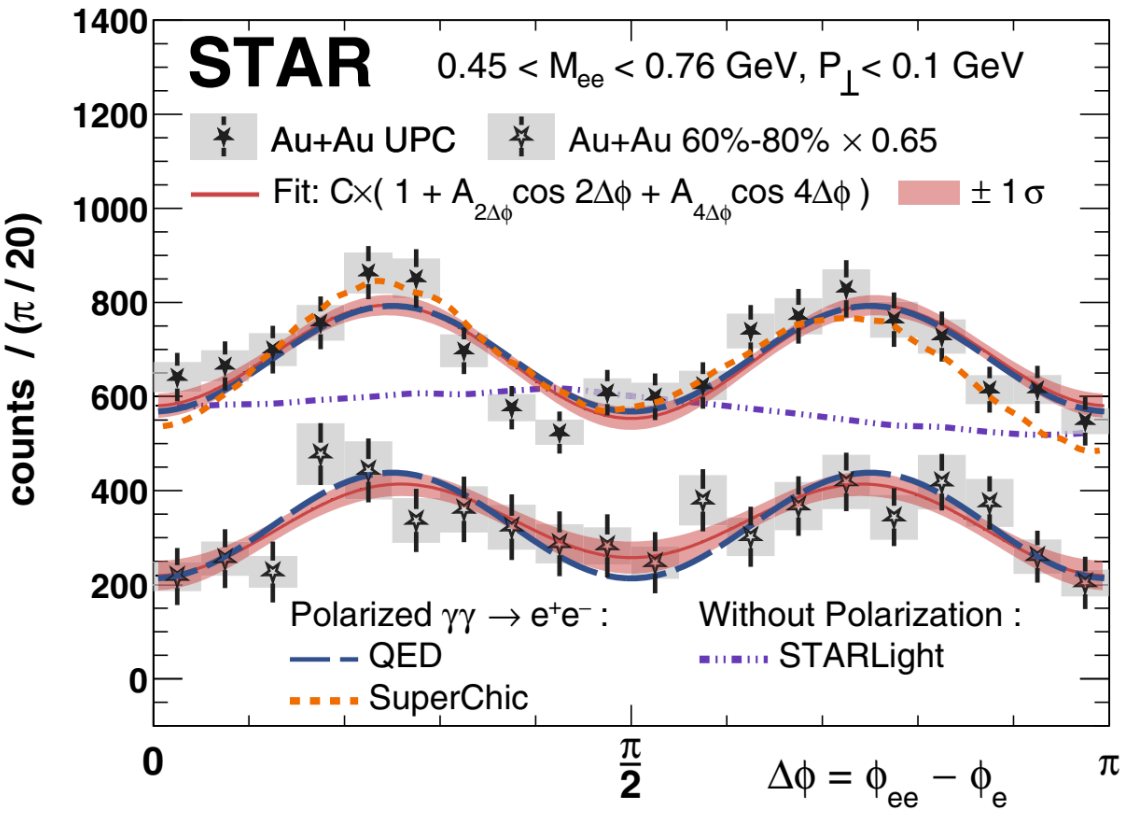
$$\Delta\phi = \Delta\phi[(e^+ + e^-), (e^+ - e^-)] \approx \Delta\phi[(e^+ + e^-), e^+]$$

Ultra-Peripheral

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

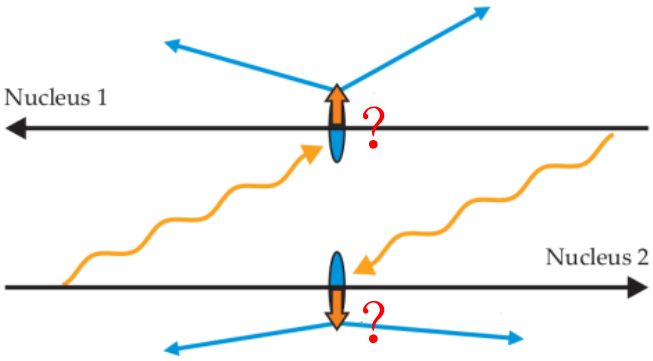
Peripheral (60−80%)

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



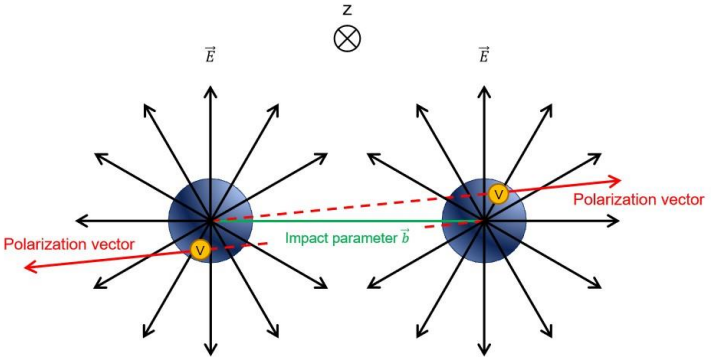
The first observation of angular modulation for B-W process in heavy-ion collisions (both for UPC and non-UPC).

Double slits interference in polarization space



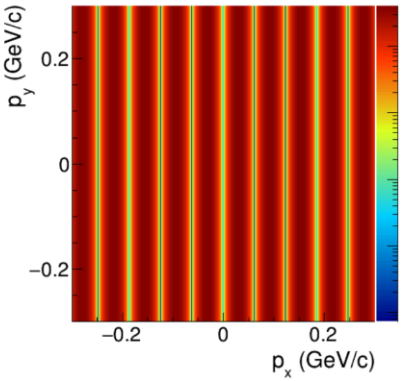
PRD 103 (2021), 033007

Linearly polarized photons

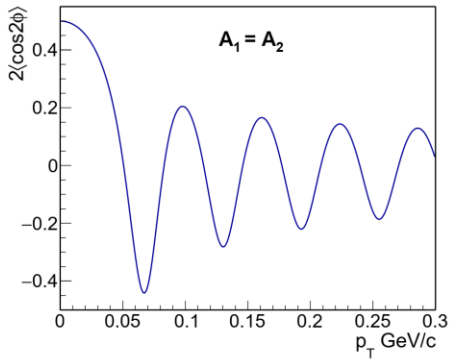


Decay along the impact parameter

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



The second order modulation



Double slits interference in polarization space

STAR， Sci. Adv. **9** (2023) eabq3903

Example of EPR paradox

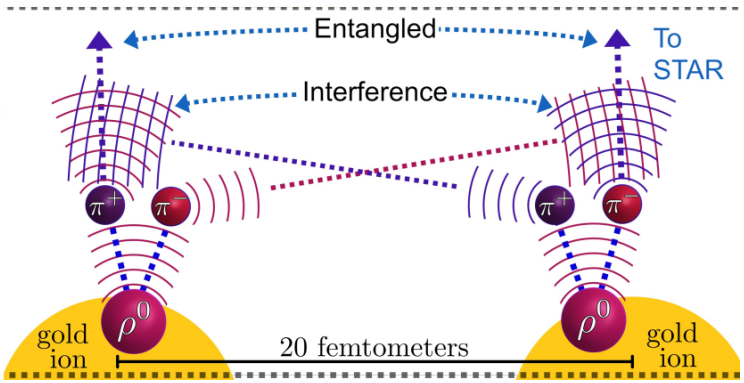
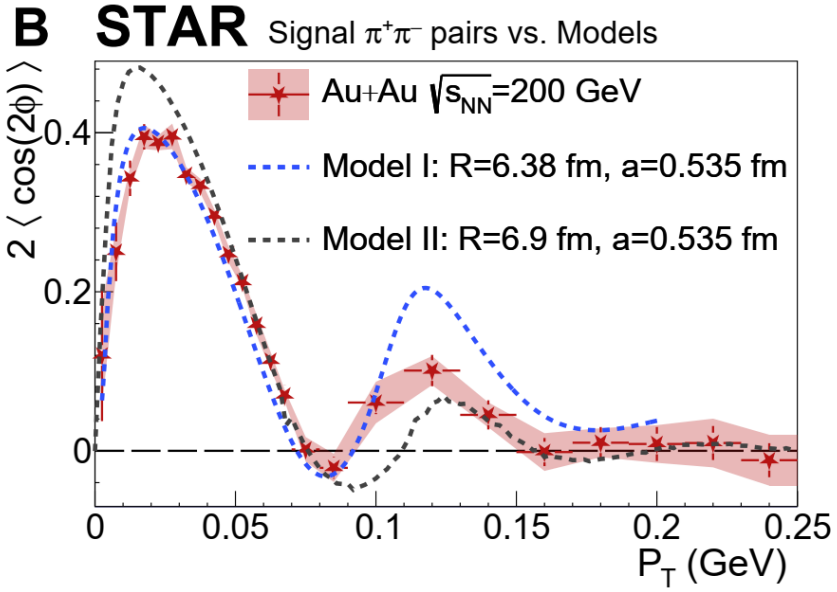


Figure from Zhangbu

The life time 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

Summary

- Observation of Breit-Wheeler process in HIC

- Existence of B-W process in non-UPCs – Novel probe for QGP
  - -Impact parameter dependence
  - -More precise measurement toward central collision
  - -More solid theoretical baseline

- The linearly polarized photons in HIC
  - -Angular modulation for B-W process --- link to Vacuum Birefringence
  - -Double-slit interference in polarization space for photoproduction