Strong-field induced reaction in UPC

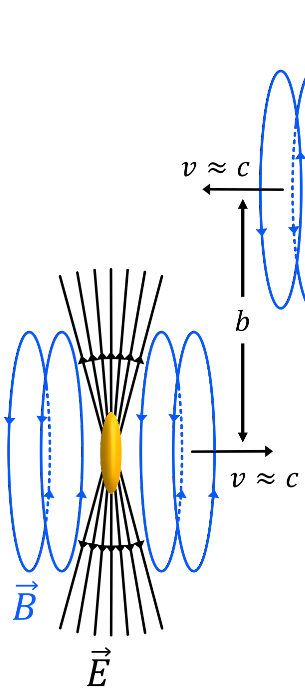
Jie Zhao

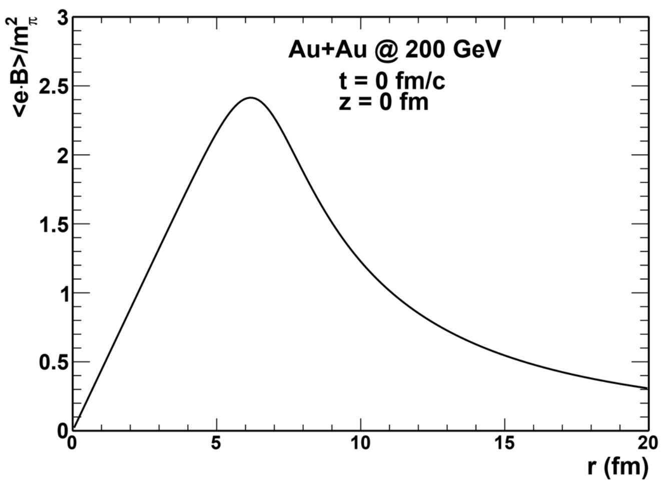
Oct. 19, 2024

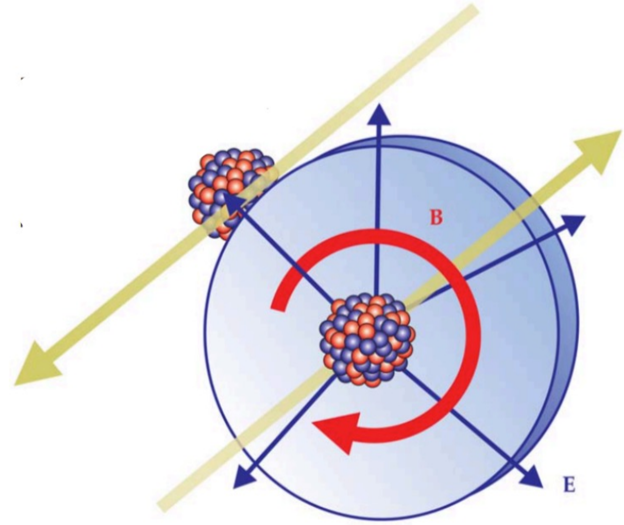
Base on Wangmei, Shuai, Chi's work

The giant electromagnetic field in HIC

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







Ultra-Peripheral Collisions (UPC)

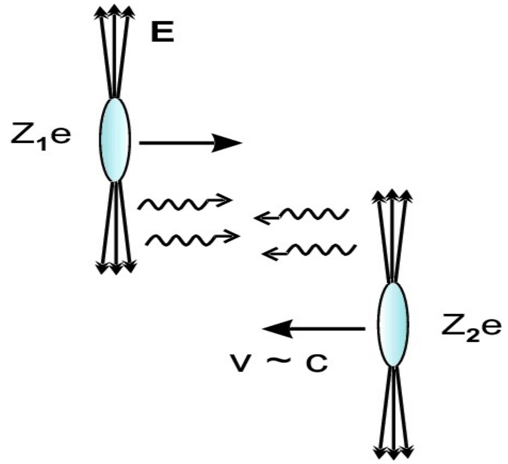
Clouds of quasi-real photons being present with heavy nuclei

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

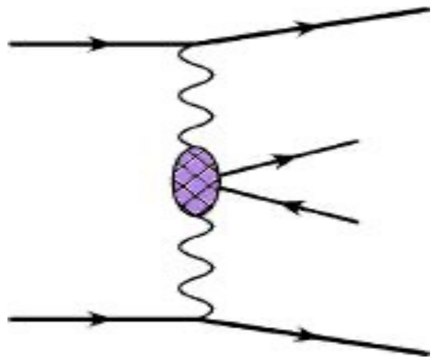
$$\vec{q} = \left(\vec{q}_\perp, \frac{\omega}{\gamma}\right)$$

Equivalent Photon Approximation

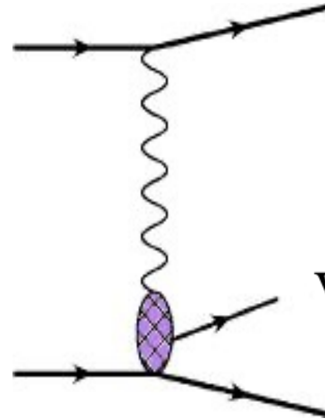
The collisions of the EM. field



Electromagnetic interaction



Photon-photon interactions



Photon-nucleus interactions

The abundant photon induced reactions

UPC related physics

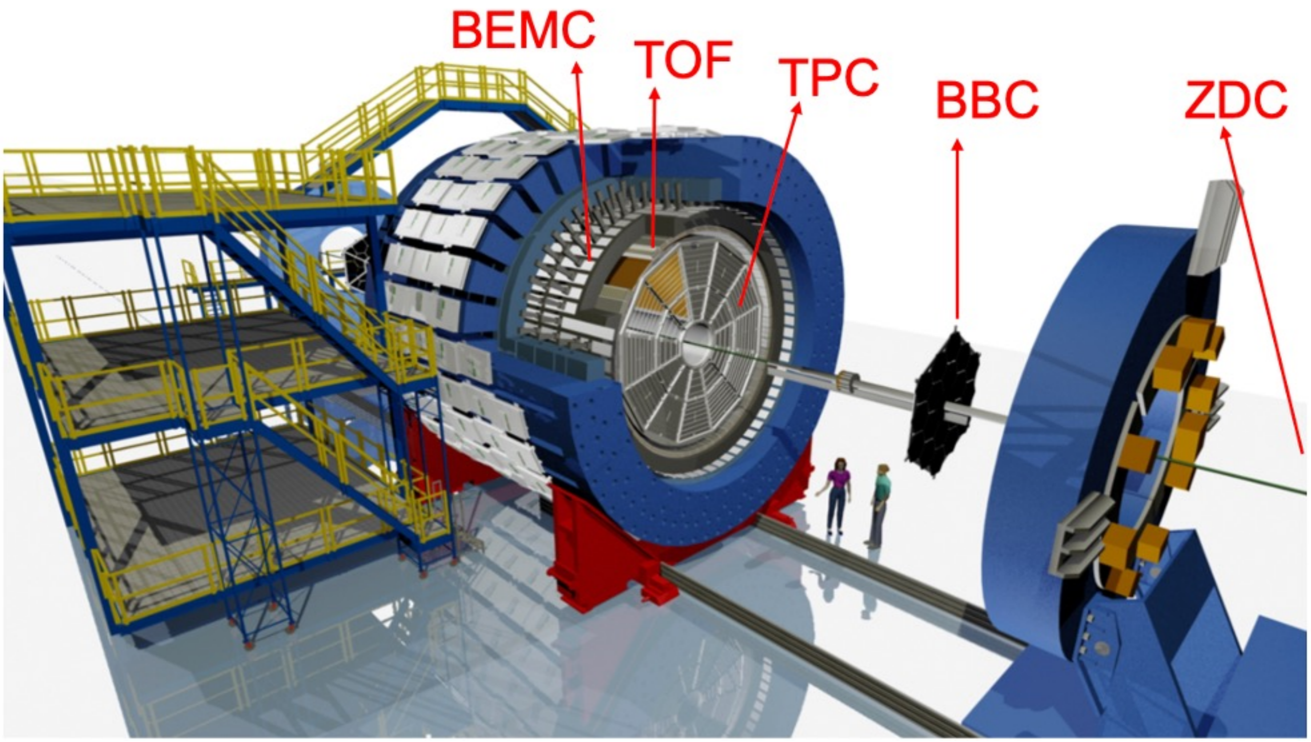
||

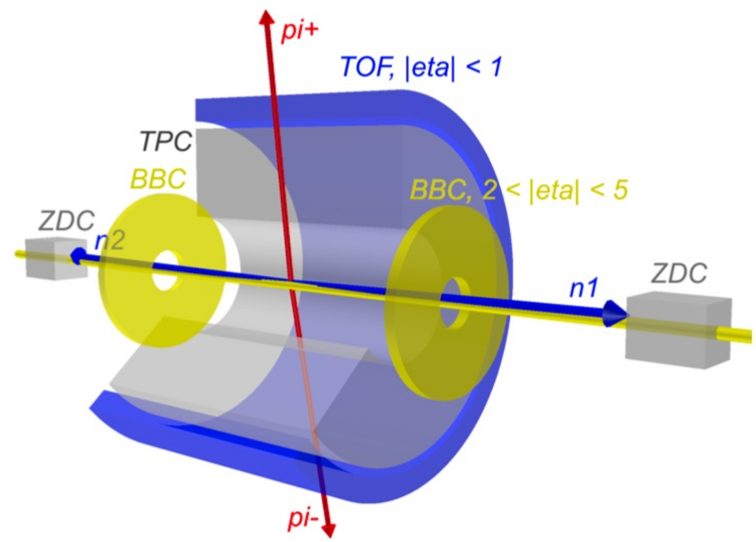
The physics of photoproduction

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

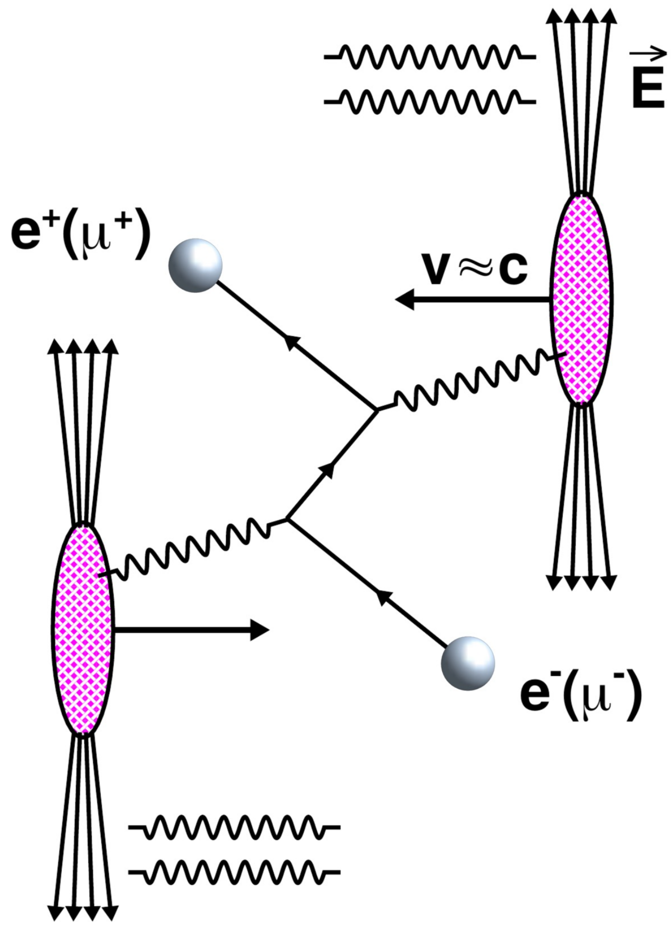
STAR detector





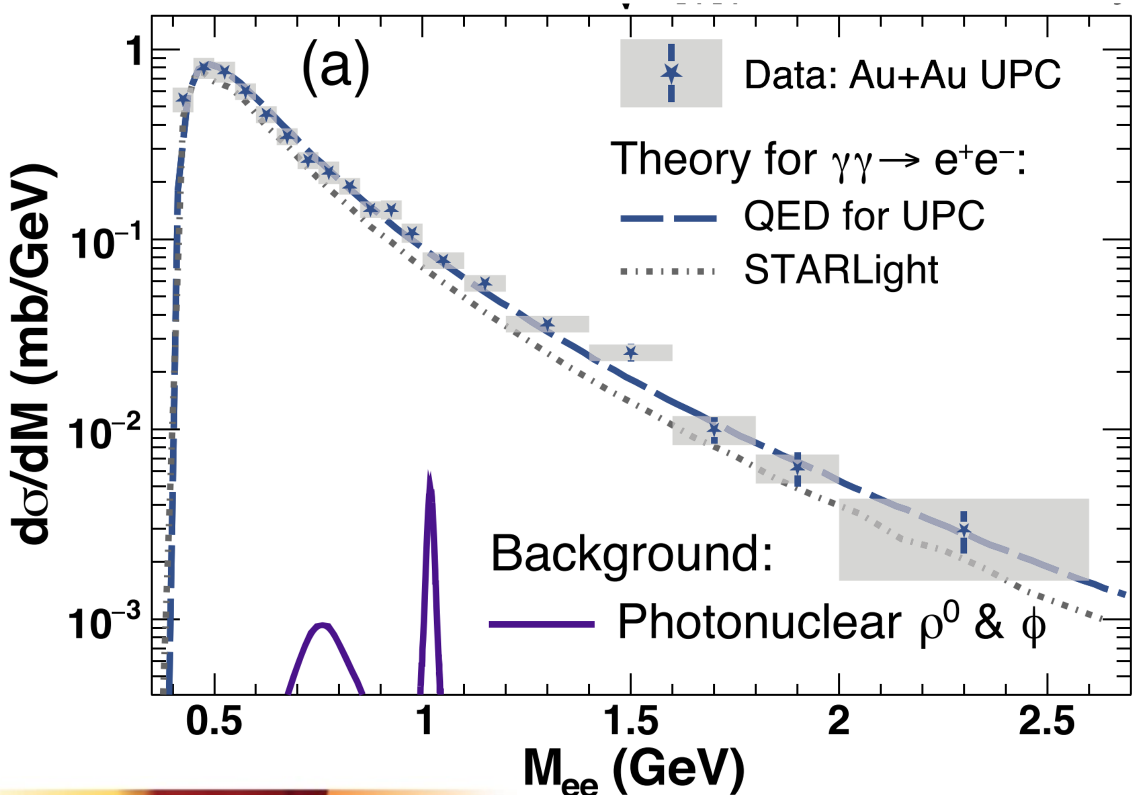
- ➢ Time Projection Chamber: tracking and particle identification within $|\eta|<1$
- ➢ Time Of Flight: multiplicity trigger, particle identification and pile-up track removal
- ➢ Barrel ElectroMagnetic Calorimeter: topology trigger and pile-up track removal
- ➢ Beam-Beam Counters: scintillator counters within $2.1<|\eta|<5.2$, forward veto
- ➢ Zero Degree Calorimeters: detection of very forward neutrons, $|\eta| > 6.6$

The collisions of two photons



Observation of Breit-Wheeler process

STAR, PRL 127 (2021) 052302

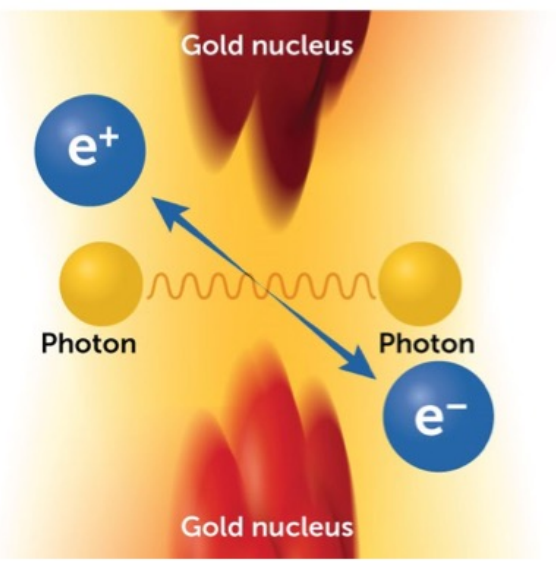


MCD

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 ±1σ level!

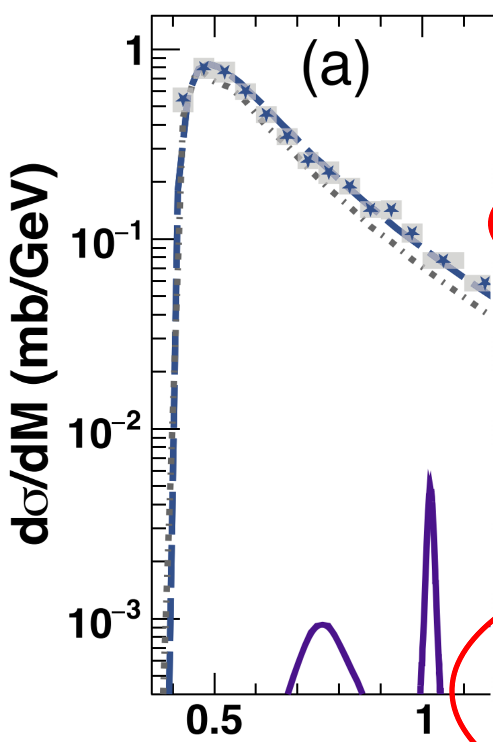


The Simplest process to convert energy to matter

Wangmei, Shuai, Chi et.al's work

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

Data : 0.261±0.004 (stat.) ±

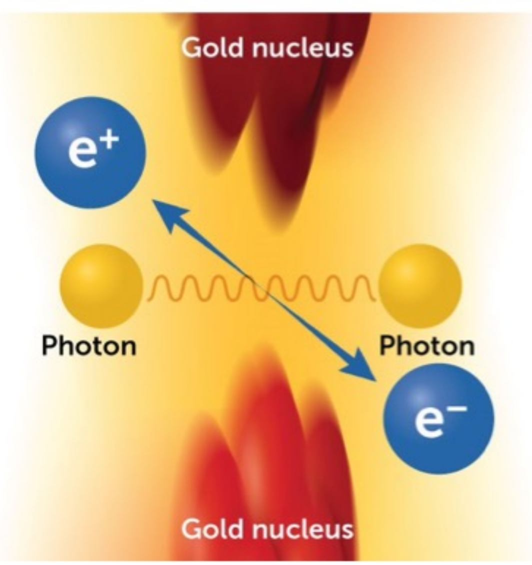
)34 (scale) mb

QED

nb 0.26 mb

heoretical

±1σ level!

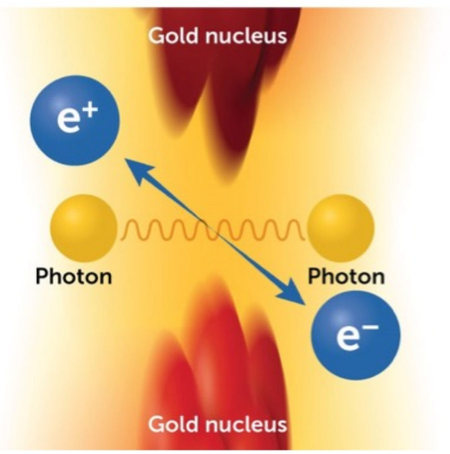


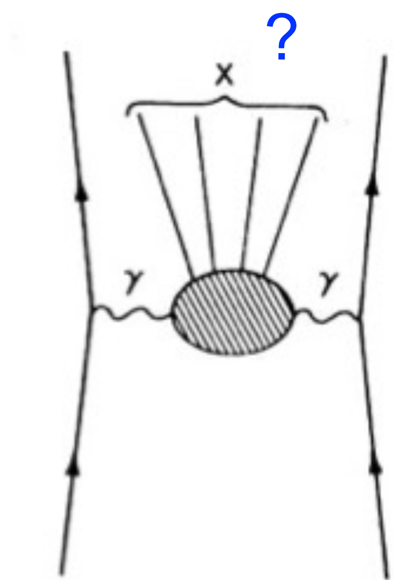
The Simplest process to convert energy to matter

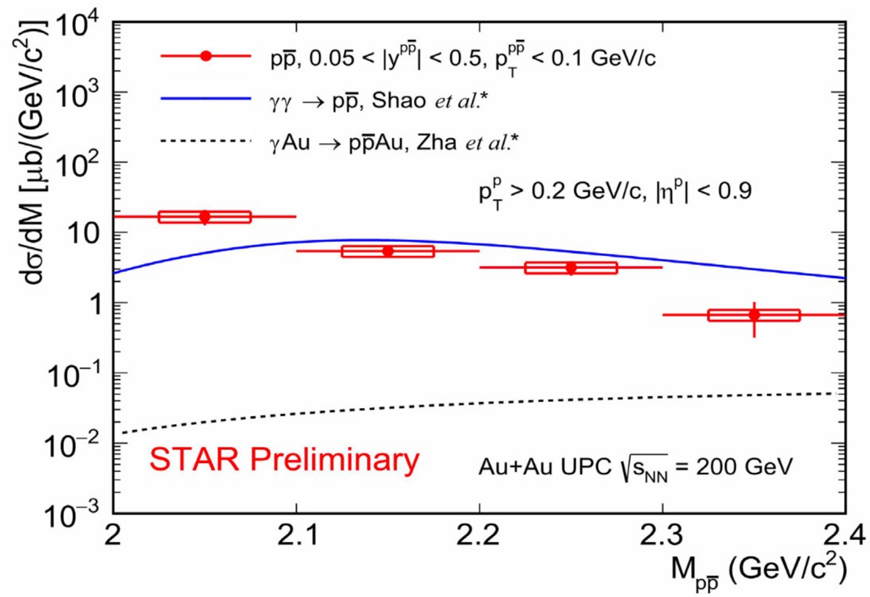
p-pbar pairs from QED vacuum excitation

Xin Wu' SQM2024

BW - the Simplest process to convert energy to matter







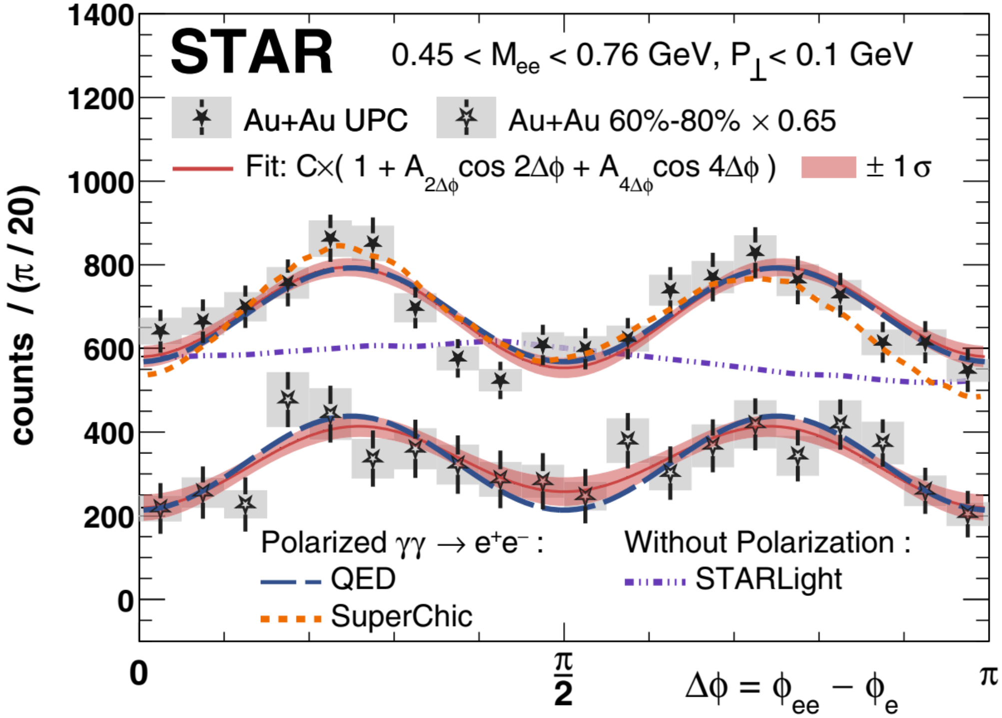
Dingyu, Wangmei, Shi et.al's calculation

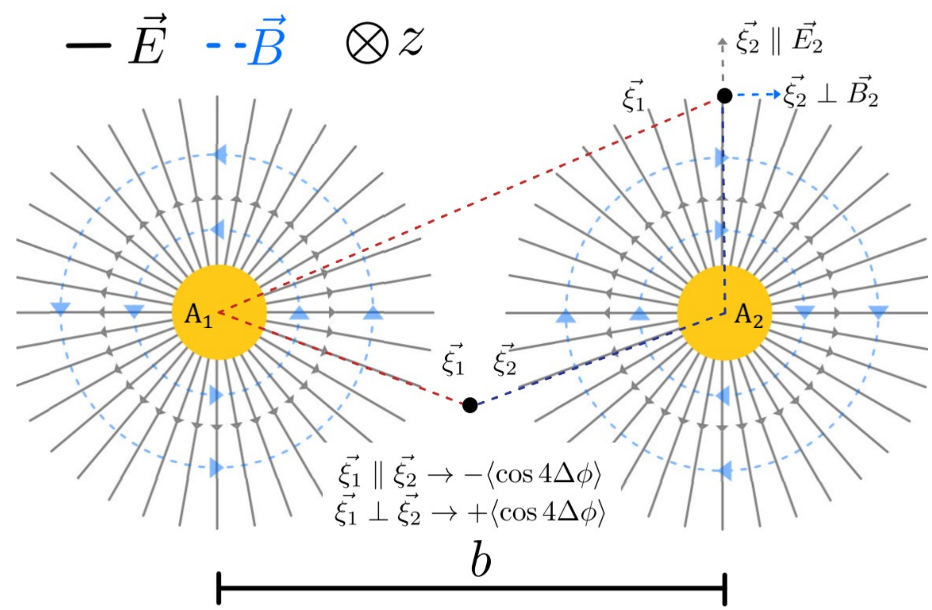
$\lambda + \lambda \to h^+ + h^-$ higher excitation of the QED vacuum

First observation of vacuum excitation leading to the production of the simplest atomic nucleus.

Observation of the linear polarization

STAR, PRL 127 (2021) 052302





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

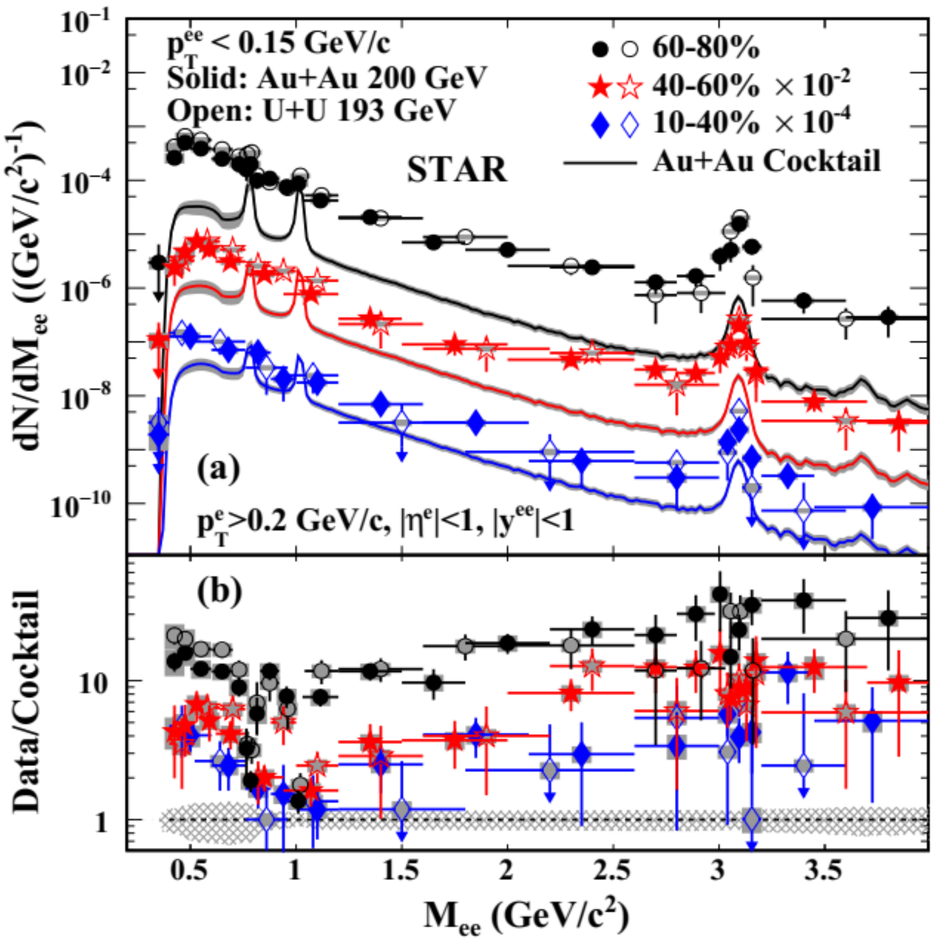
	Ultra-Peripheral		
Quantity	Measured	QED	χ^2/ndf
$-A_{4\Delta\phi}(\%)$	16.8 ± 2.5	16.5	18.8 / 16

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

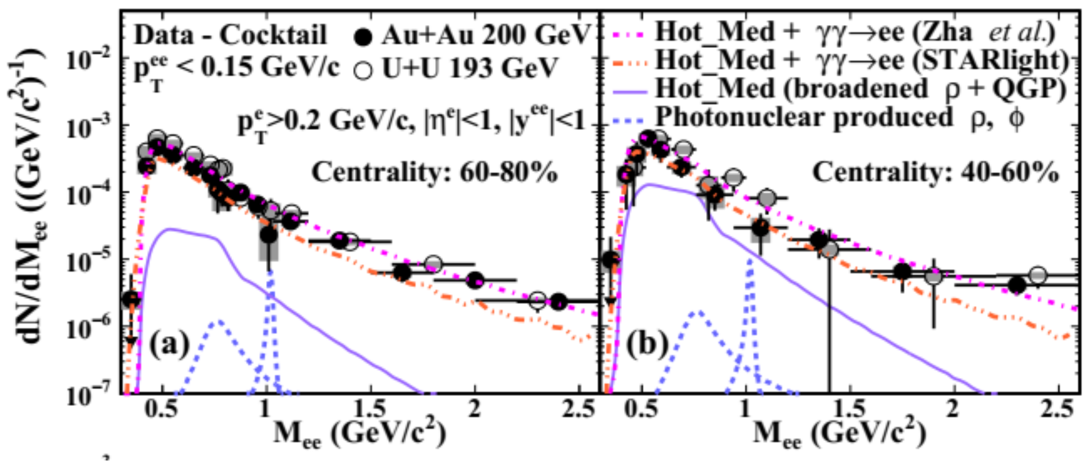
The photons are linearly polarized!

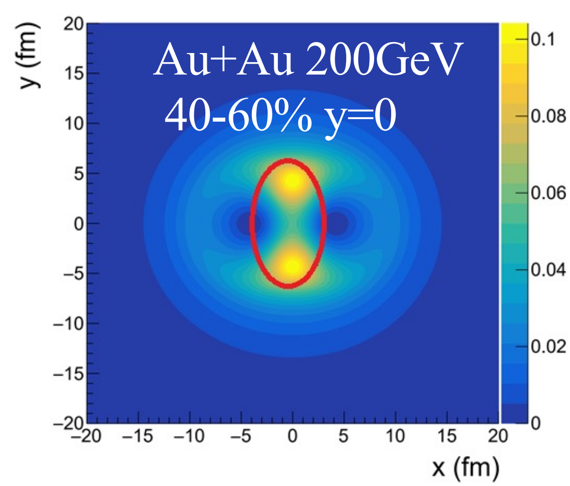
Observation in hadronic HIC

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



PLB **781** (2018) 182



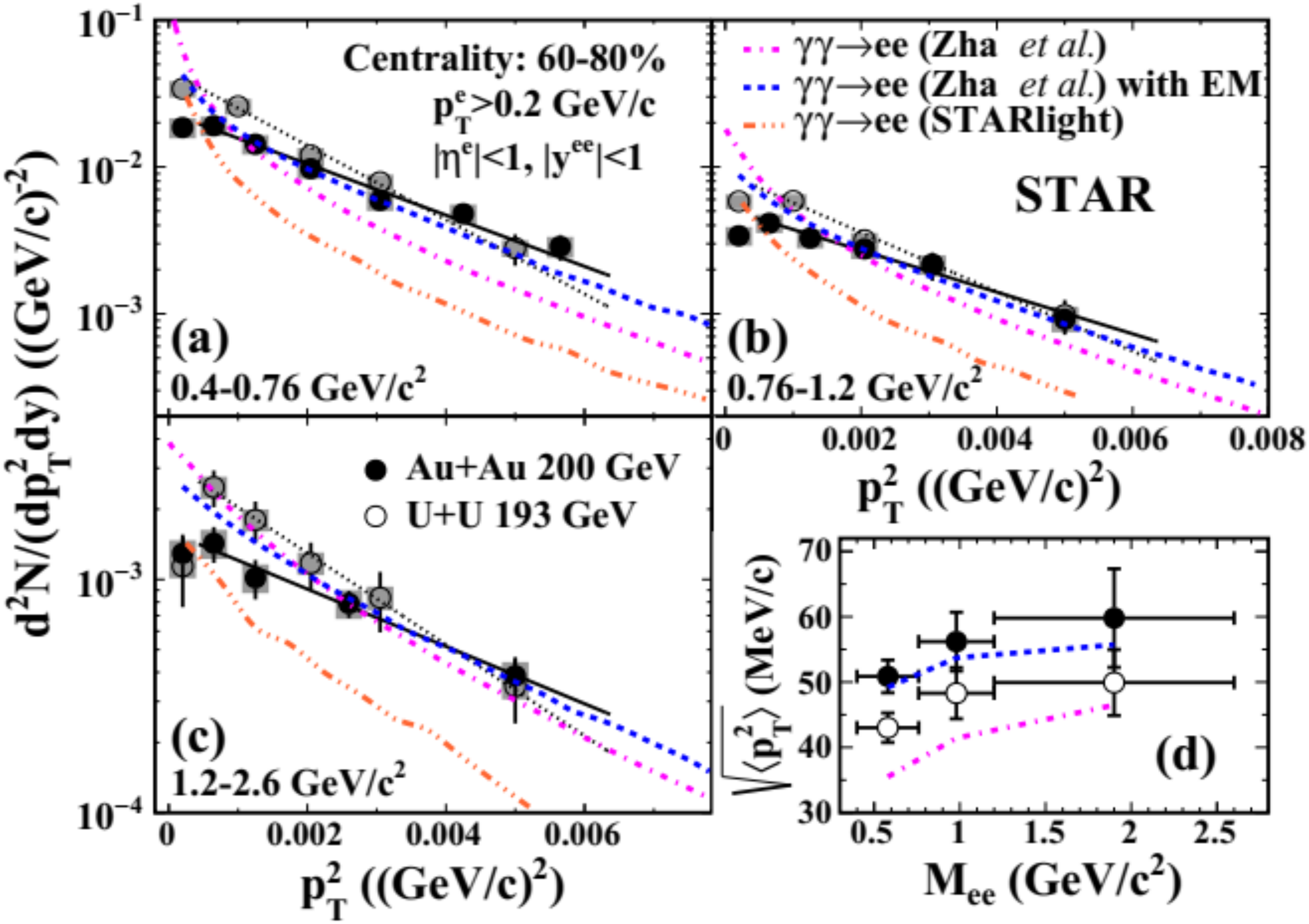


12% in nuclear overlap region

Existence of photoproduction in hadronic heavy-ion collisions!

Novel probe for QGP?

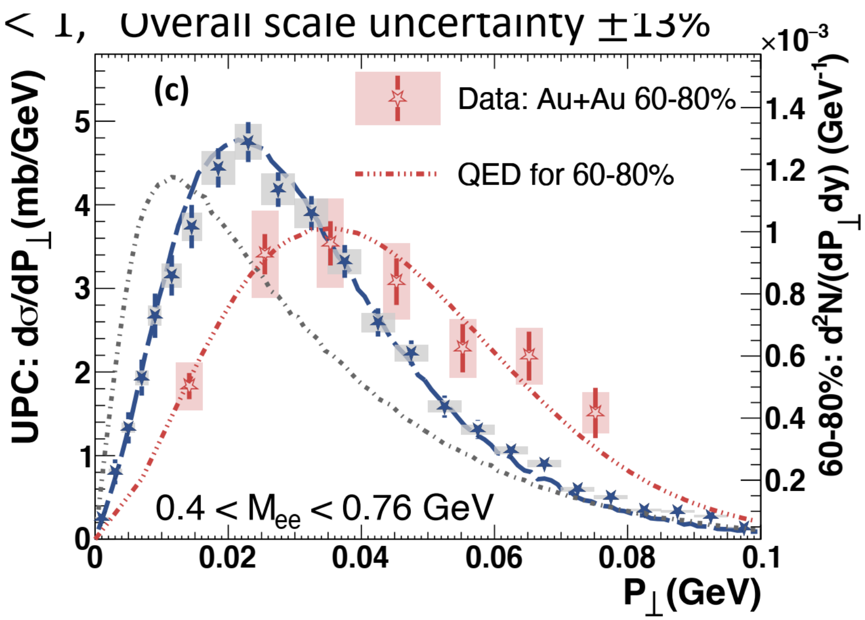
The transverse momentum broadening



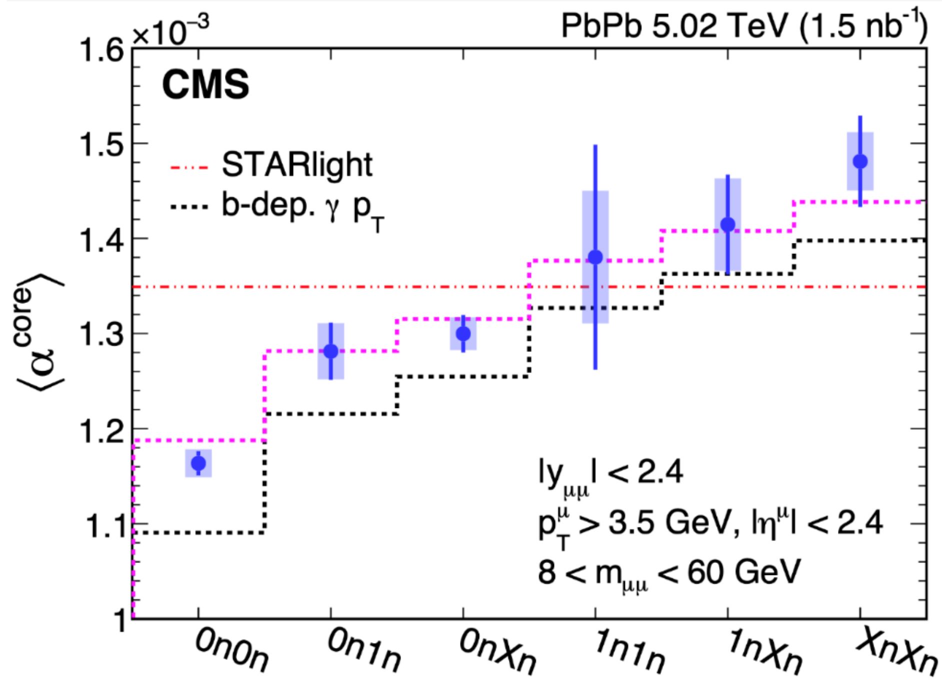
Possible medium effects --- magnetic field trapped in the QGP?

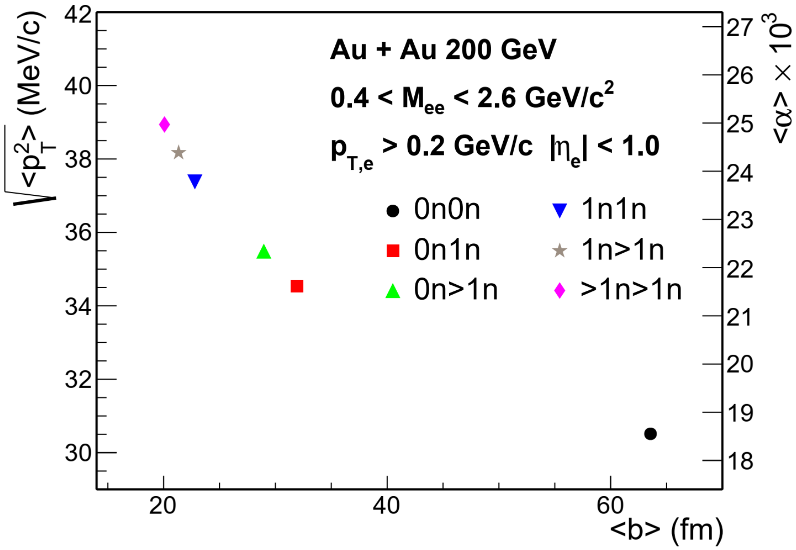
The impact parameter dependence

PLB 800 (2020) 135089



CMS, PRL 127 (2021) 122001





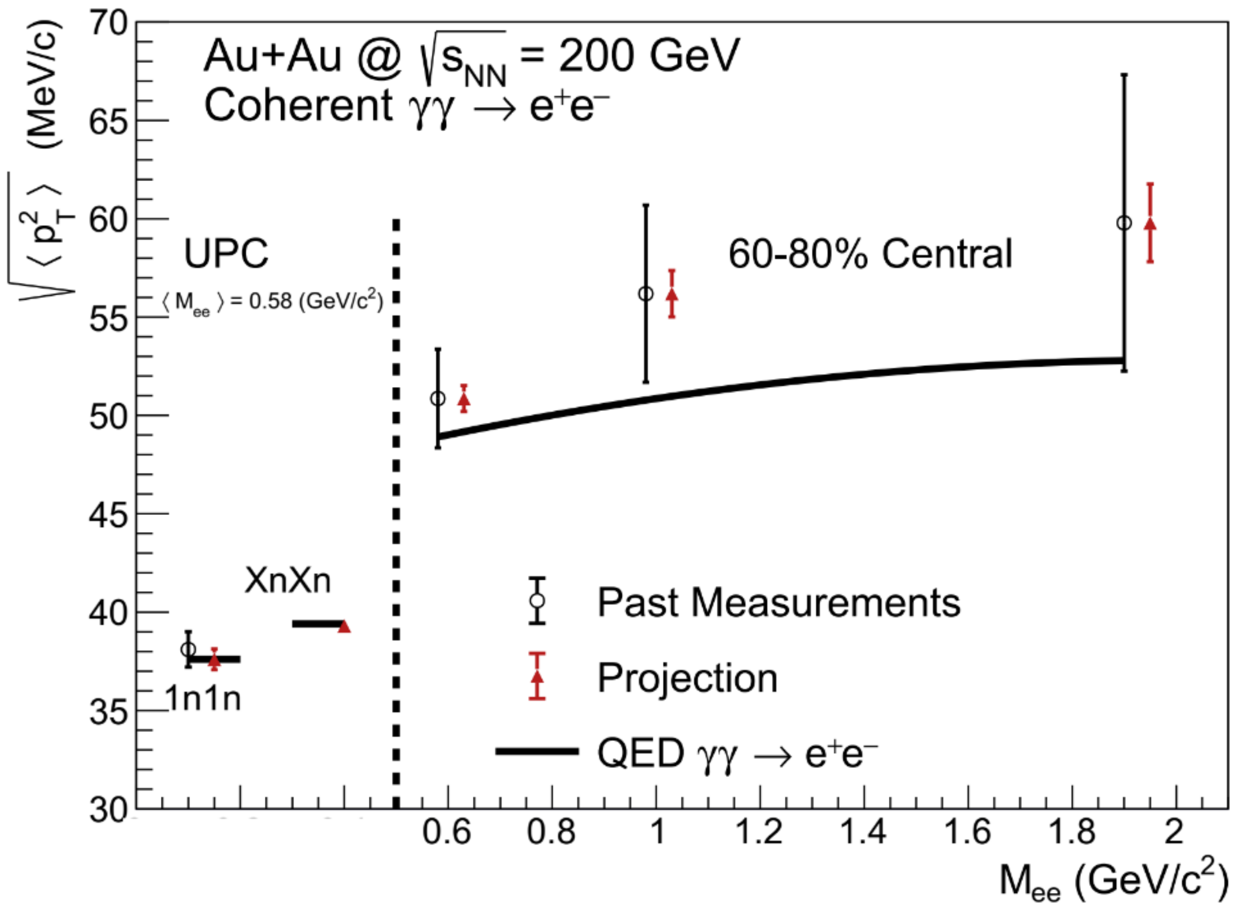
arXiv:2006.07365

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

浦实，肖博文，周剑， 周雅瑾；
Acta Phys. Sin. 72 (2023) 072503

The room for QGP effect

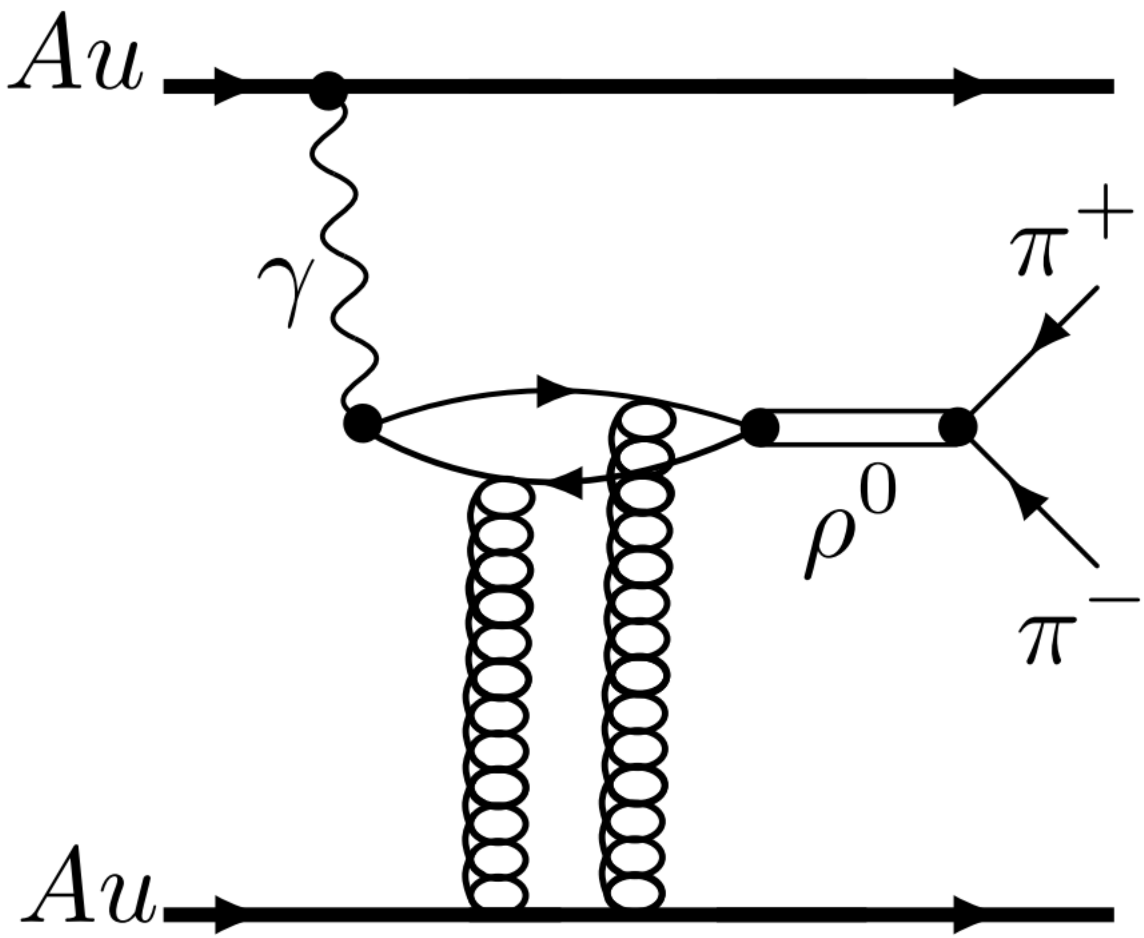
J.D. Brandenburg etal., Rep. Prog. Phys. **86** (2023) 083901



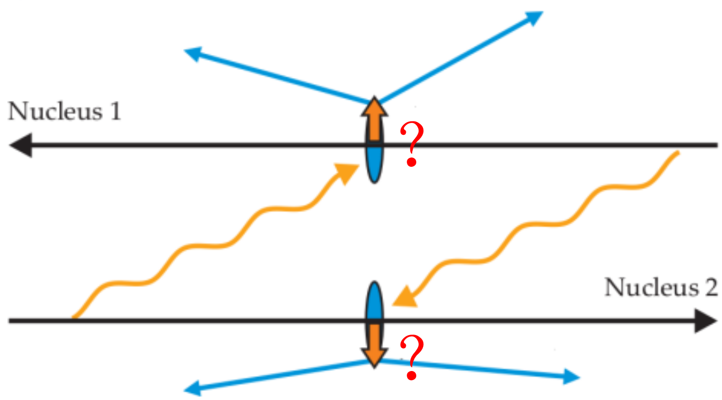
~20 times more statistics

Push for more precise multi-differential measurements

Collisions between photons and nuclei

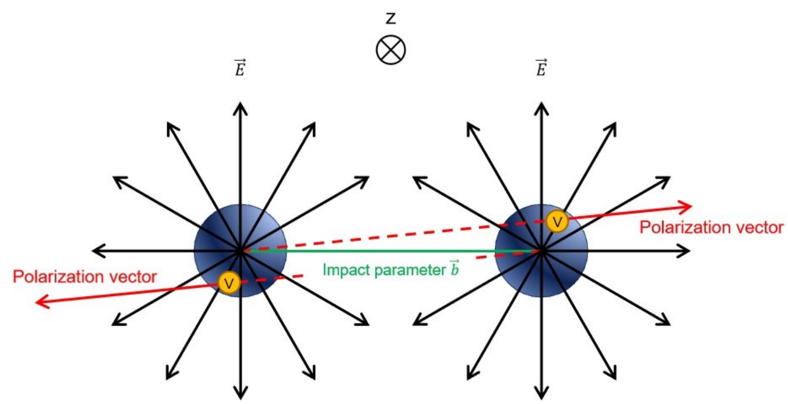


The double slits interference



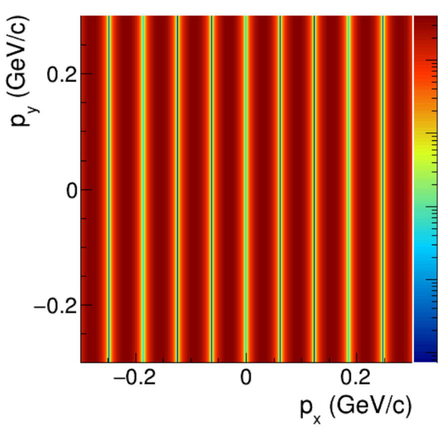
PRD 103 (2021), 033007

Linearly polarized photons

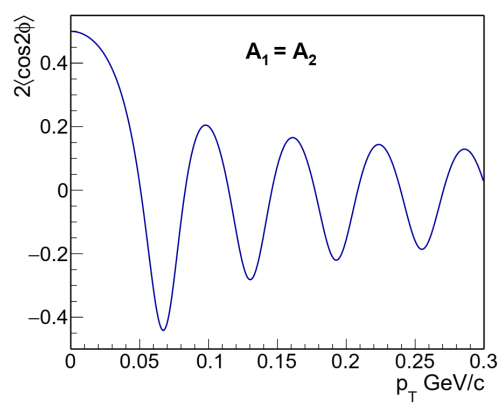


Decay along the impact parameter

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

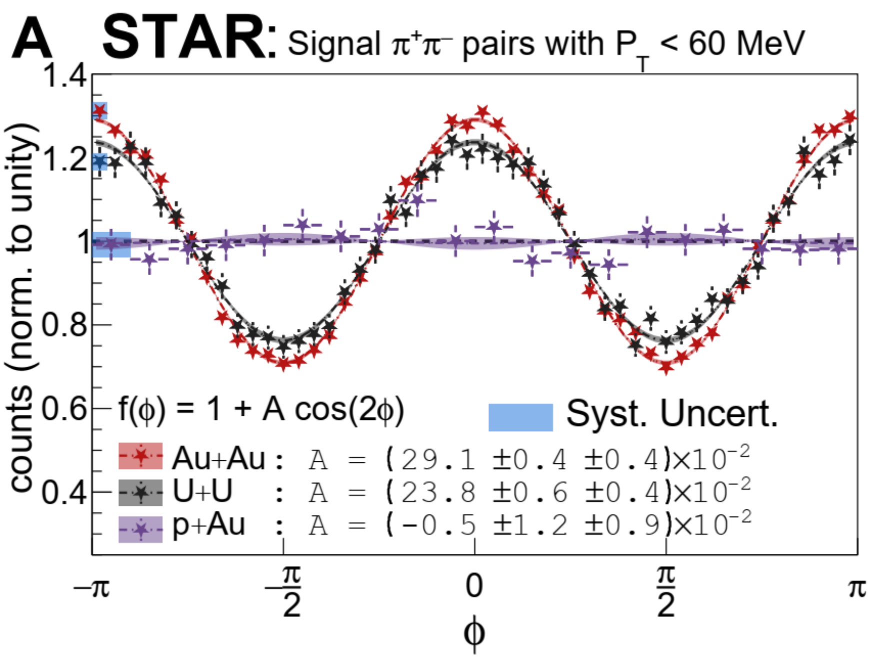


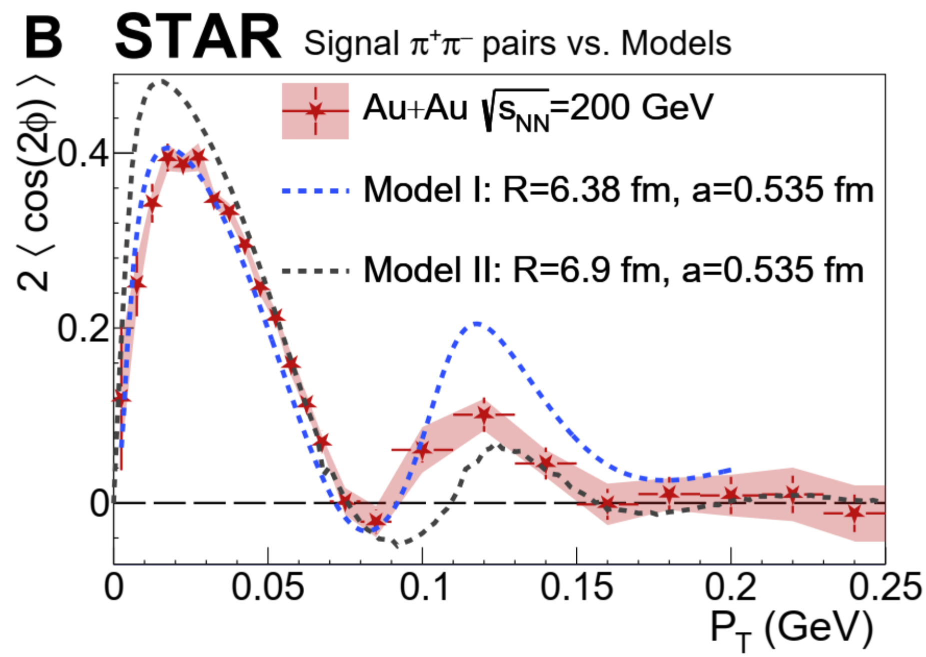
The second order modulation



The double slits interference

STAR， Sci. Adv. 9 (2023) eabq3903





Significant difference between Au and U

[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)

Sensitive to the nuclear geometry/gluon distribution

The double slits interference

STAR，Sci. Adv. **9** (2023) eabq3903

Example of EPR paradox

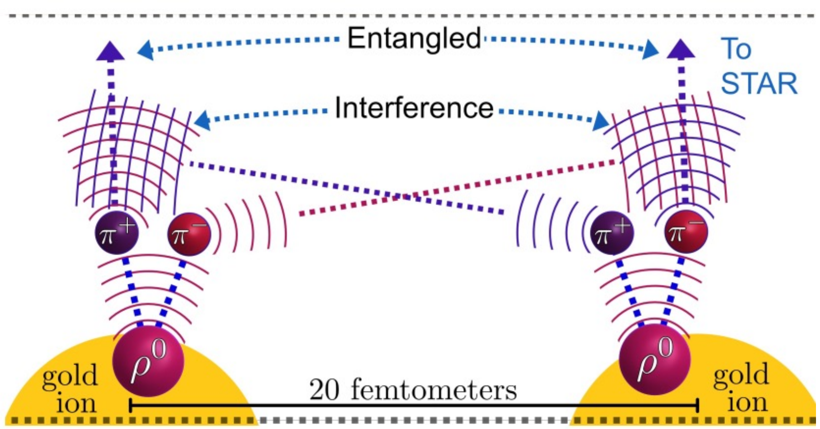
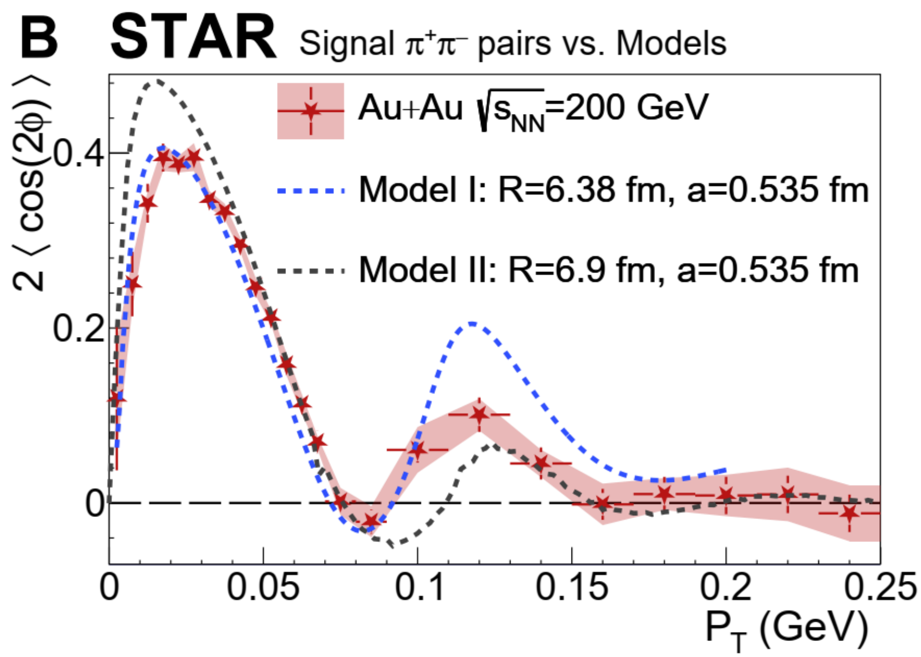


Figure from Zhangbu



The life time ρ : ~1fm/c

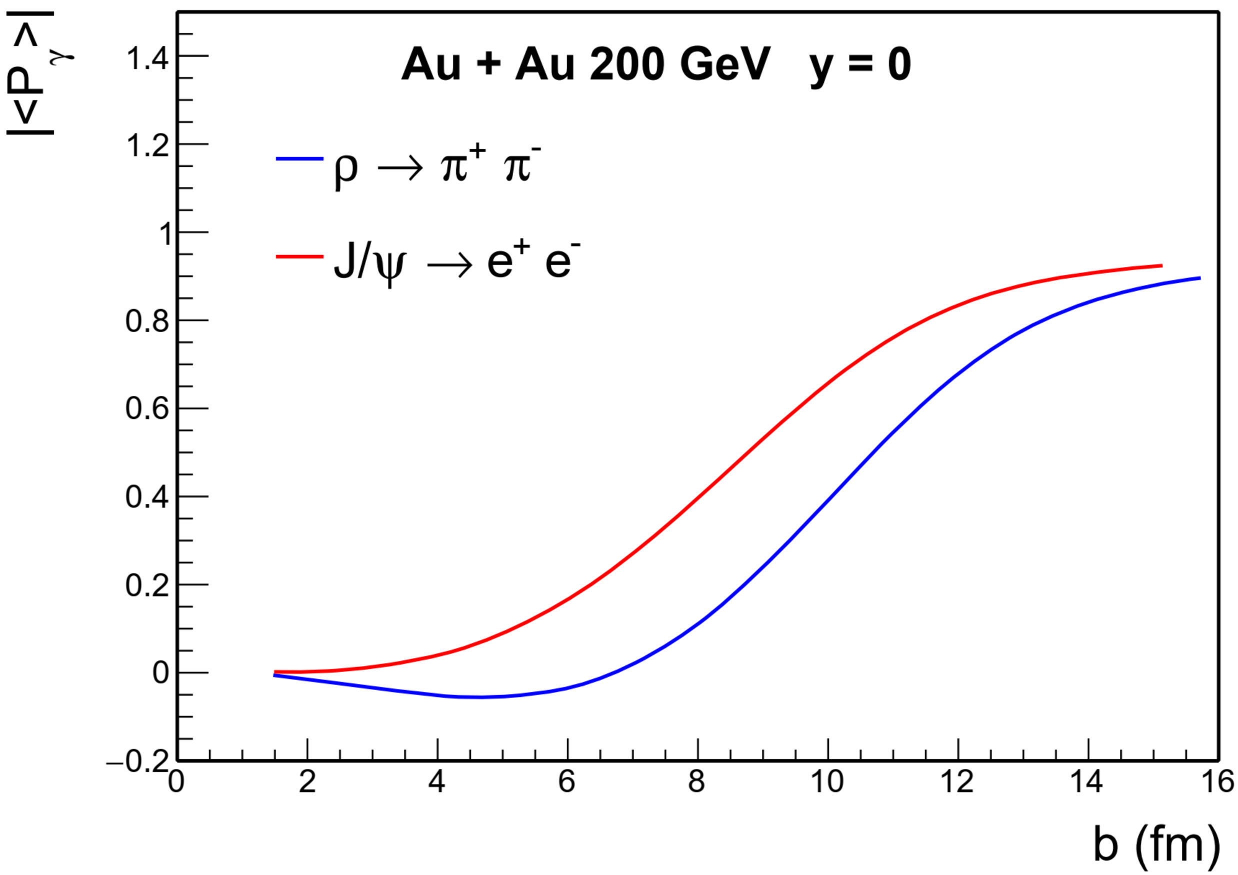
b ~20fm

[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)

Sensitive to the nuclear geometry / gluon distribution

Application: Align the reaction plane

Xin Wu, Xinbai Li, Zebo Tang, Pengfei Wang, Wangmei Zha, PRR 4, L042048 (2022)



$$P_\gamma = < \frac{E_x^2 - E_y^2}{E_x^2 + E_y^2} >$$

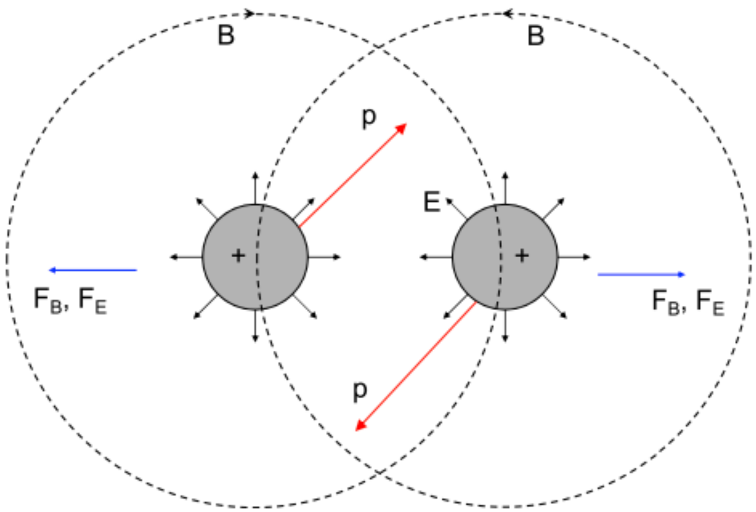
- ✓ Determined by collision geometry
- ✓ Natural resistance to non-flow correlation
- ✓ No event-event fluctuation
  -Good-Walker paradigm

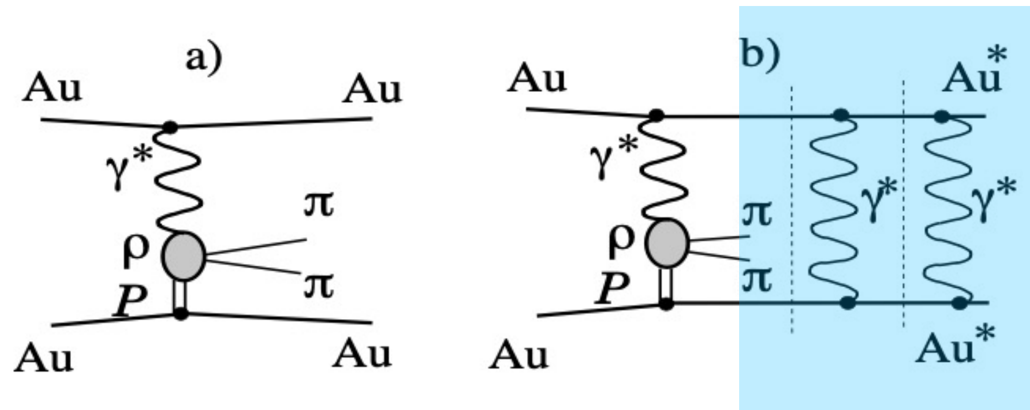
Phys. Rev. D94, 034042 (2016)

Could directly link the final flow to initial geometry!

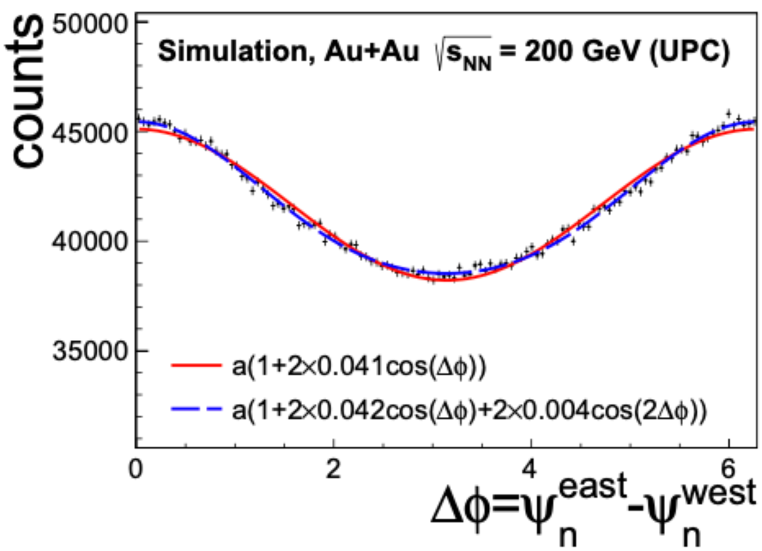
Application: Align the reaction plane

Jie Zhao, Jinhui Chen, Xu-Guang Huang, Yu-Gang Ma, NST, 35, 20 (2024)





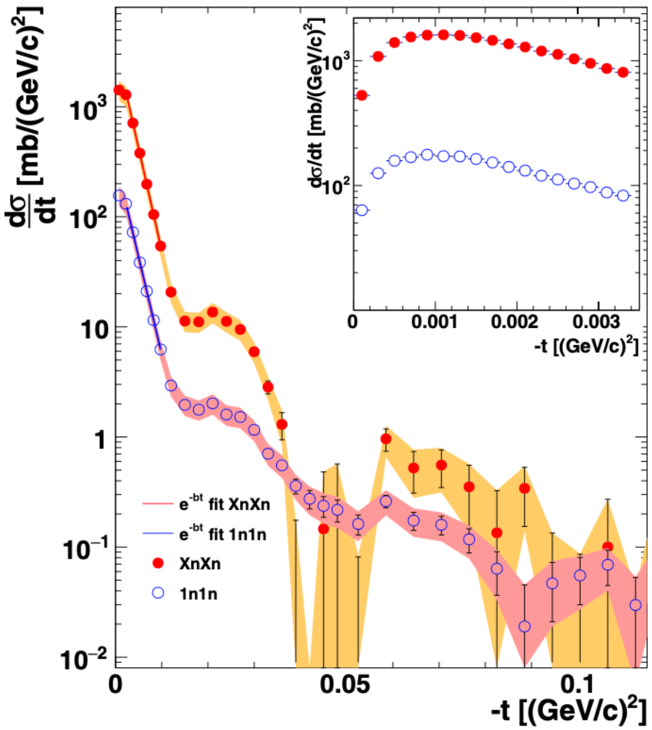
nuclear excitation



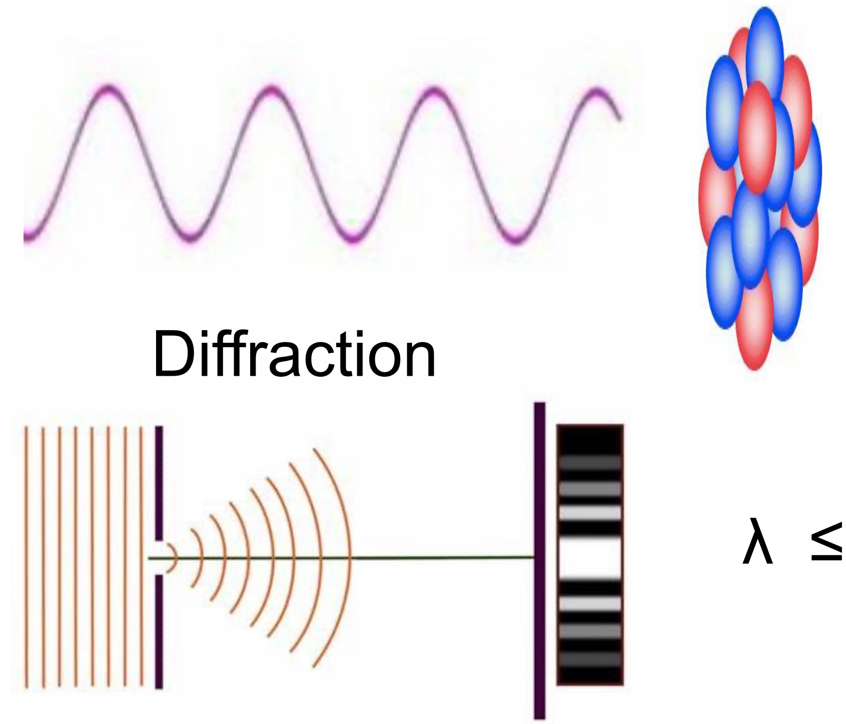
- ρ production with nuclear excitation, giant dipole resonance (GDRs)
- back-to-back correlation in the emitted neutrons from GDRs
- Which provide an unique way to measure global variables in UPC. such as flow and polarization

Application: Tomography

杨驰,杨帅,查王妹,赵杰. 中国科学: 物理学,力学与天文学 (2024)



STAR, PRC 96, 054904 (2017)
STAR, PRL 89, 272302 (2002)
Spencer, et.al, PRC 60, 014903, (1999)



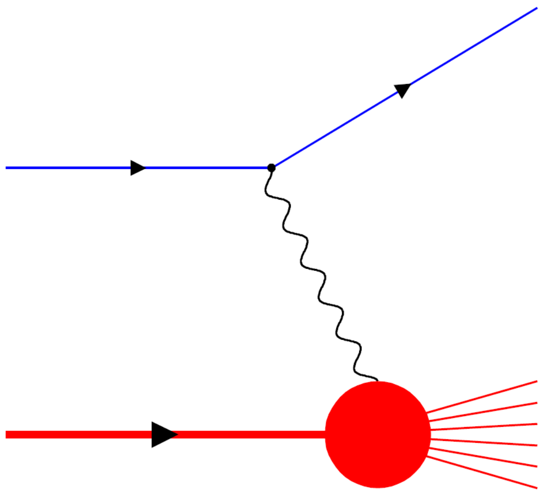
$\lambda \leq L$

F. Bulos, et.al, Phys. Rev. Lett. 22, 490 (1969)
H. Alvensleben et.al, Phys. Rev. Lett. 24, 786 and 792 (1970)
H. Mäntysaari, F. Salazar, B. Schenke, arXiv:2207.03712

- Diffractive ρ^0 meson production to measure the nuclear structure.
- the slopes of the diffraction patterns measure directly the nuclear density distribution. For example, at t->0, the diffraction pattern behaves as e^{-at}, where a is a measure of the nuclear size.

Charge radius

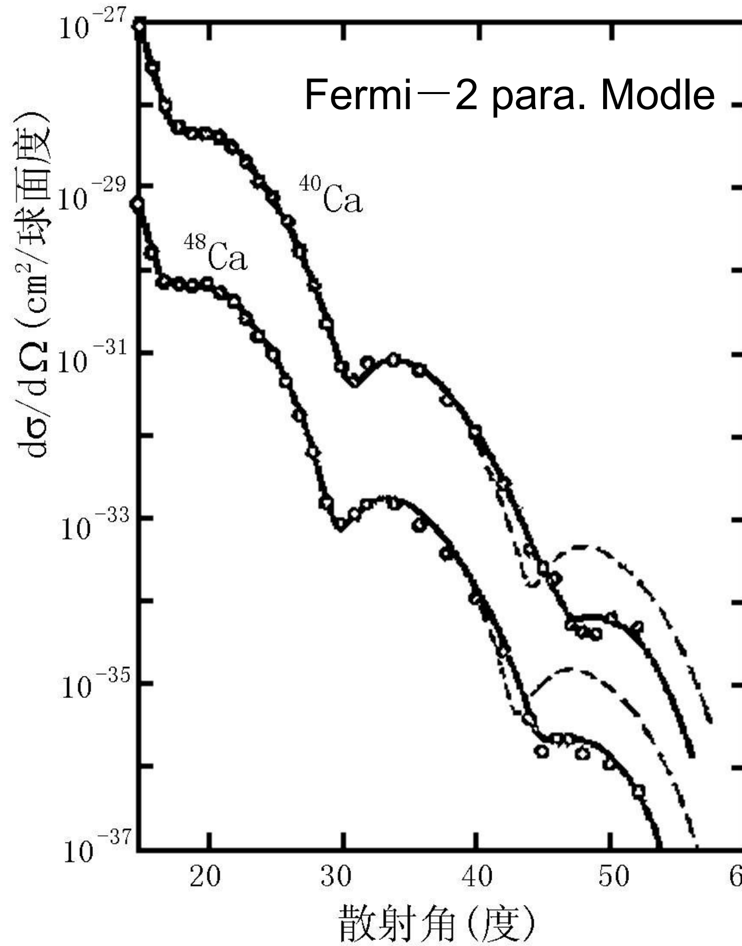
R. Hofstadter, Rev. Mod. Phys. 28 214-254 (1956)



$$\frac{d\sigma}{d\Omega} \square \left(\frac{d\sigma}{d\Omega}\right)_{point} \left|F(\vec{q})\right|^2 \qquad F(\vec{q}) \square \int d\vec{r}^3 e^{i\vec{q}.\vec{r}} \rho(\vec{r})$$

$$F(q^2) \square \int d\vec{r}^3 \rho(r) e^{i\vec{q}.\vec{r}} \xrightarrow{qR\square\square 1} 1-\frac{1}{6}q^2\int dr d\Omega r^4 \rho(r) \ \square \cdots$$

$$\cdots\cdots\cdots \square 1-\frac{1}{6}q^2\left\langle r^2\right\rangle \square \cdots$$

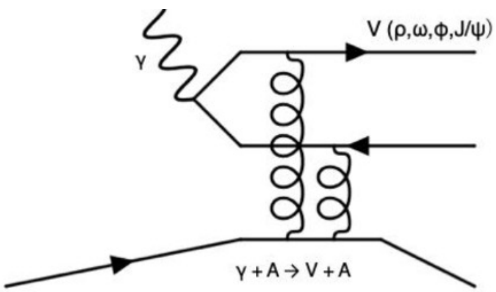


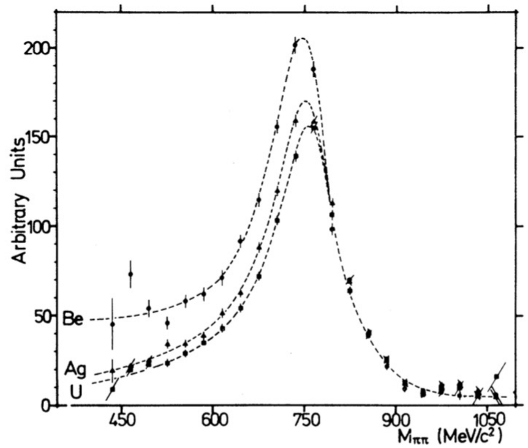
G.F. Chew, et.al, Phys. Rev. 106, 1345 (1957); R.A. Schrack, et.al, Phys. Rev. 127, 1772 (1962);

➢ Electron scattering measures the form factor, charge radius

Strong-Interaction Nuclear Radii

γ □ (Z, A) → ρ □ □Z□A□





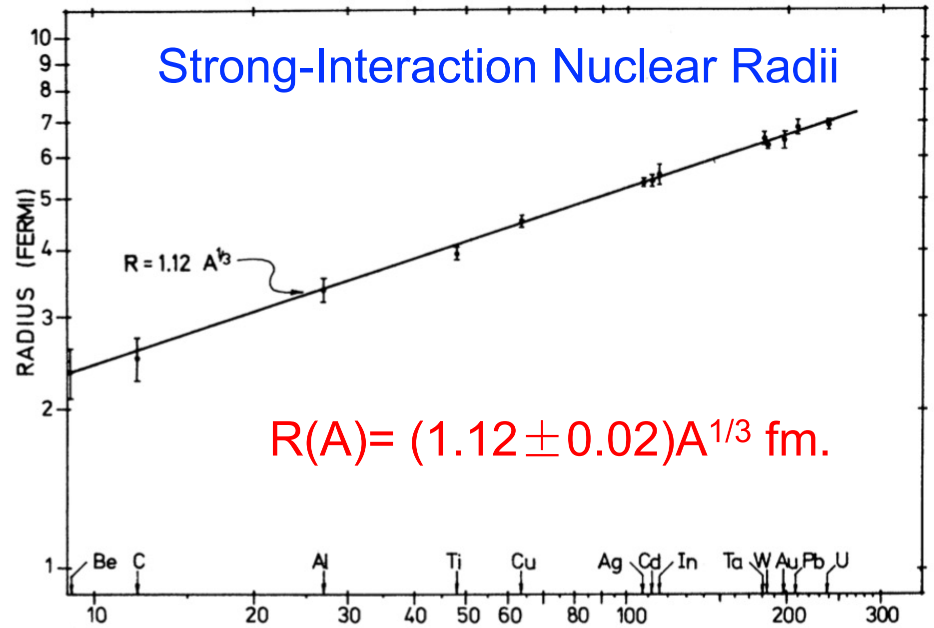


FIG. 1. Results on $R(A)$ and the best fit with $R = r_0 A^{1/3}$.

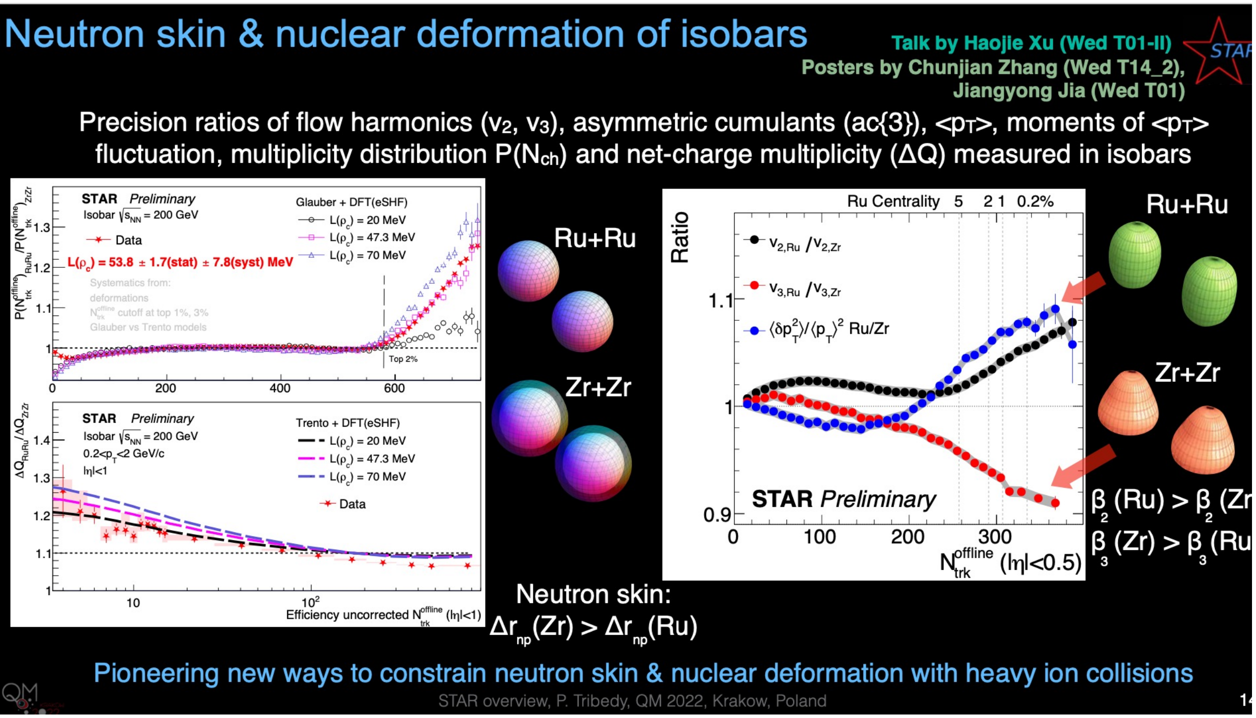
G.F. Chew, et.al, Phys. Rev. 106, 1345 (1957); R.A. Schrack, et.al, Phys. Rev. 127, 1772 (1962);
C.M. Tarbert, et.al, Phys. Rev. Lett. 112, 242502 (2014)
F. Bulos, et.al, Phys. Rev. Lett. 22, 490 (1969); L.J. Lanzerotti, et.al, Phys. Rev. 166, 1365 (1968)
H. Alvensleben et.al, Phys. Rev. Lett. 24, 786 and 792 (1970)

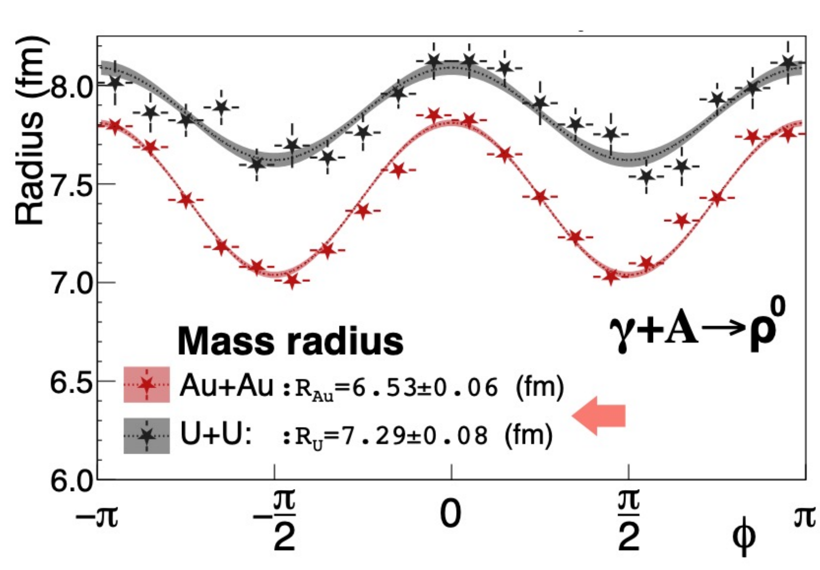
- Electron scattering measures the form factor, charge radius
- Photoproduction of π^0 meson: Δ(1232), the mass radius (1960s)
- Photoproduction of ρ^0 meson:
  "Determination of Strong-Interaction Nuclear Radii" (1970s)

Isobaric Ru and Zr nuclear structure

STAR, Phys. Rev. C 105 (2022), 014901
T. Prithwish (for STAR), QM2022

STAR, Sci. Adv. 9 (2023) 1



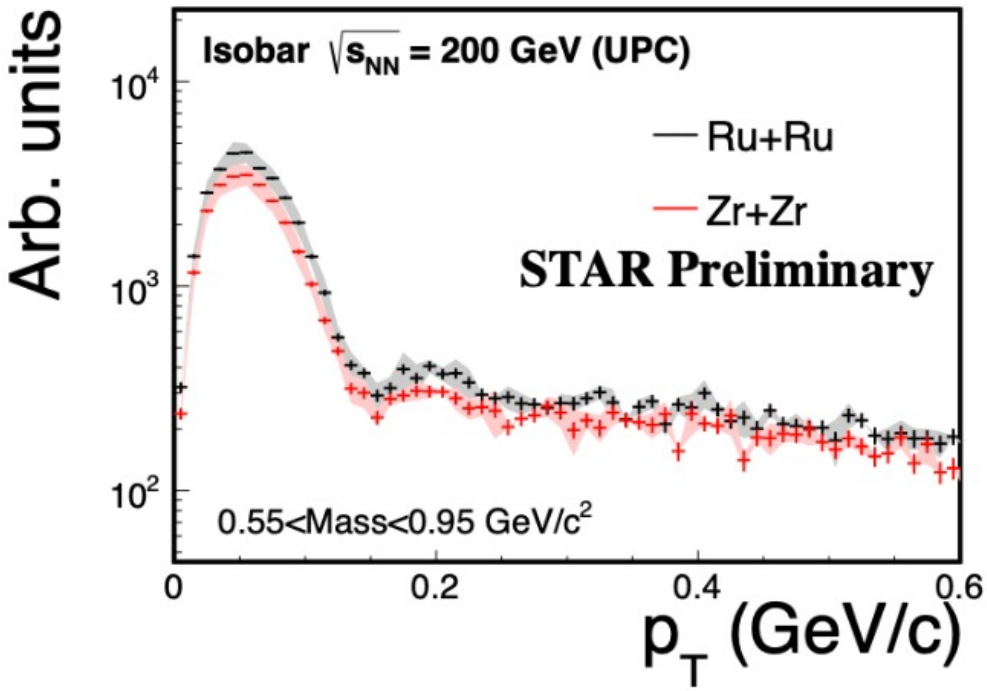


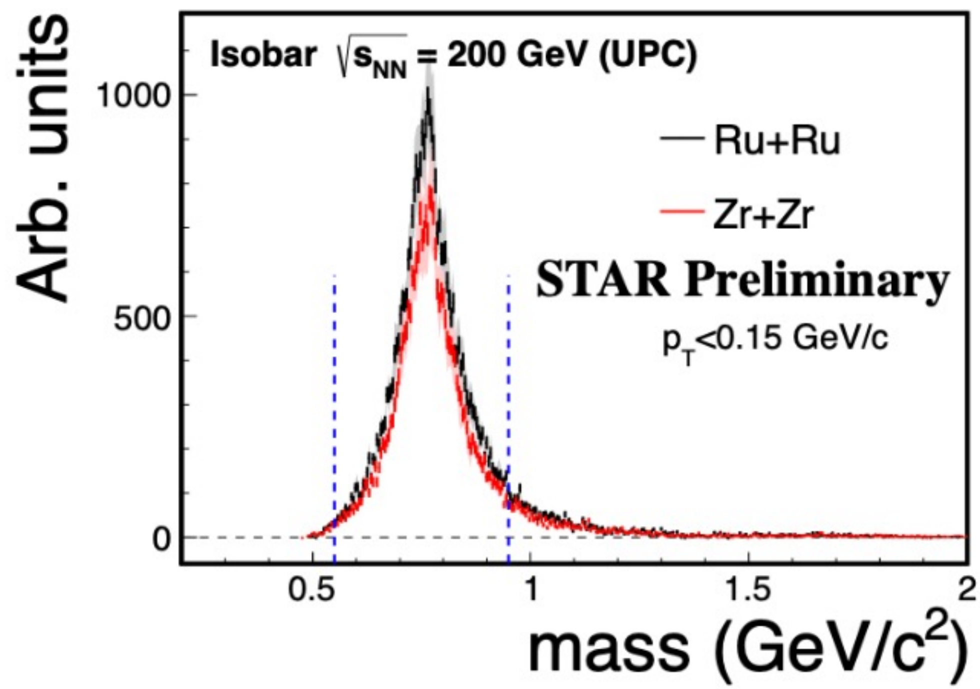
Tomography of ultra-relativistic nuclei with polarized photon-gluon collisions.

➢ The γ-A interaction may help to understand the structure of the isobar Ru and Zr nuclei ?

Spencer, et.al, PRC 60, 014903, (1999); STAR, PRL 89, 272302 (2002), PRC 96, 054904 (2017)

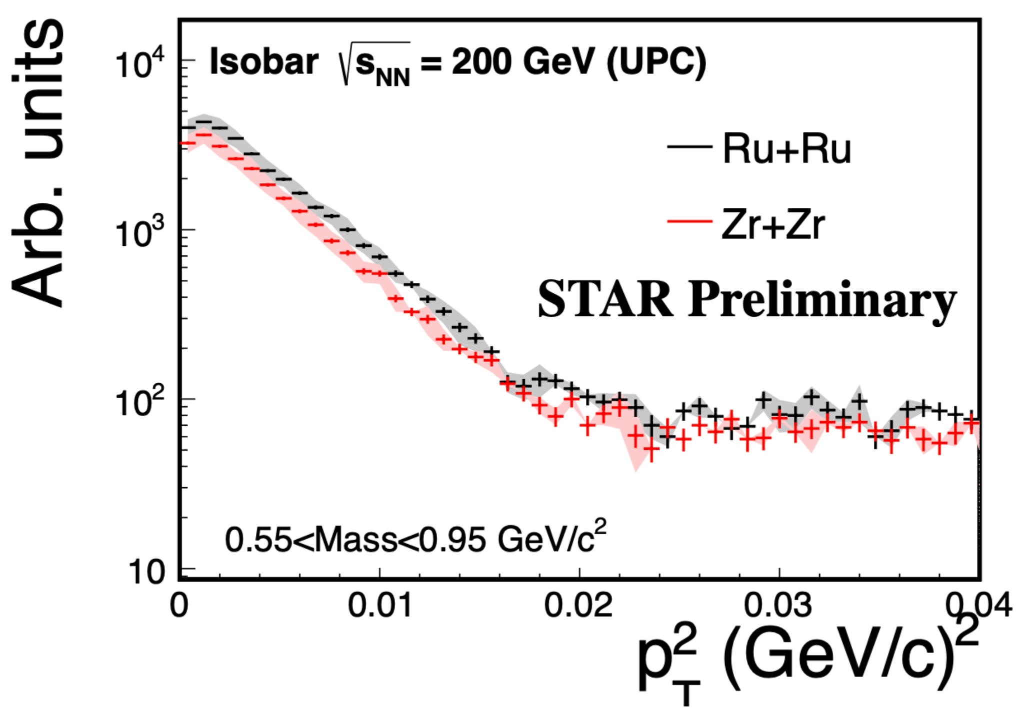
Diffractive photoproduction of ρ0 in isobar

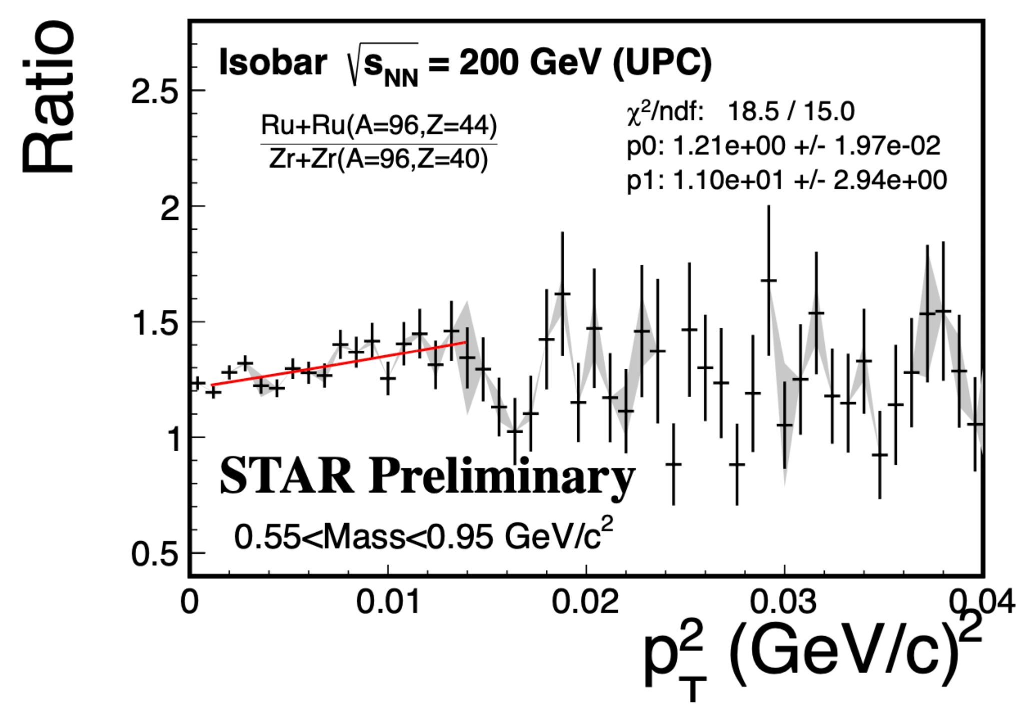




- Clear signal of coherent ρ0 production in isobar
- Diffraction pattern (minima) of the coherent ρ0 production

Ru and Zr nuclear structure



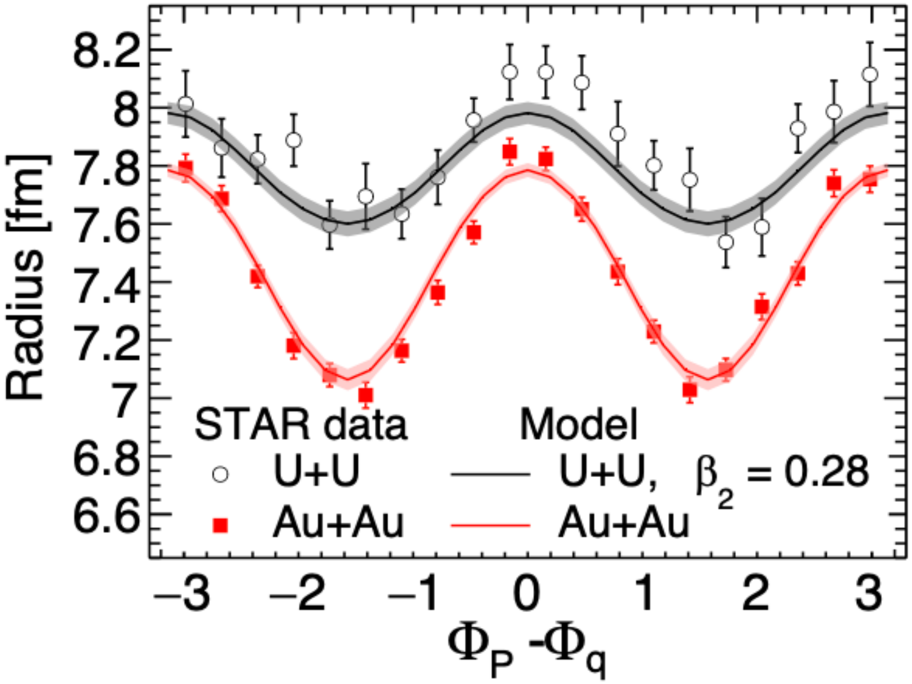


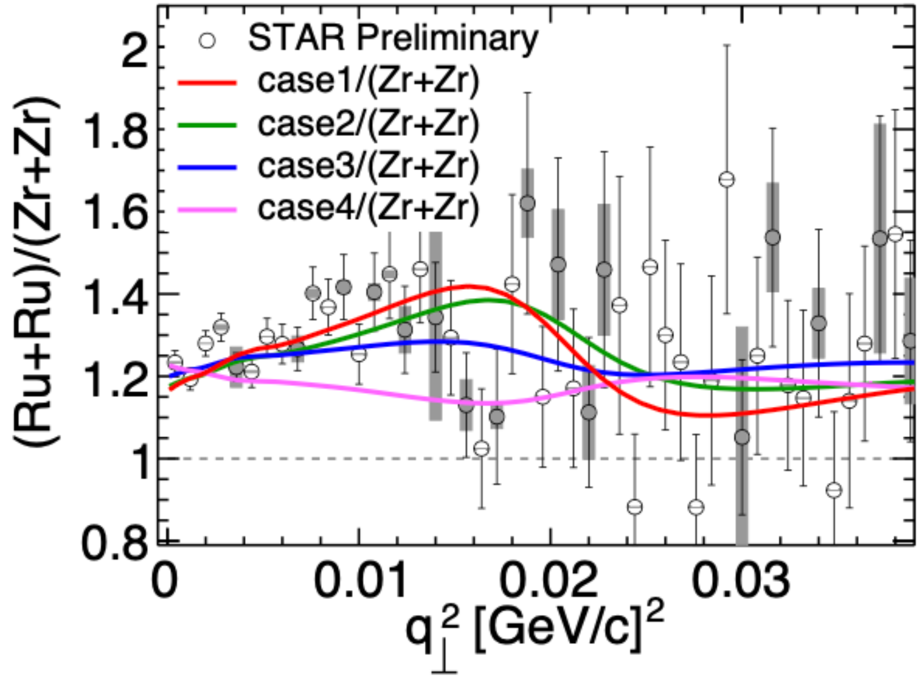
$A^*e^{-b^*t}$, $(t \simeq -p_T^2)$

- Indication of larger Zr size than Ru from the γ-A interaction. The slope of the dN/dt ratio is 11.0+/- 2.9 +/- 0.3 (~3σ sigma effect)
- Interference and deformation effects need to be considered

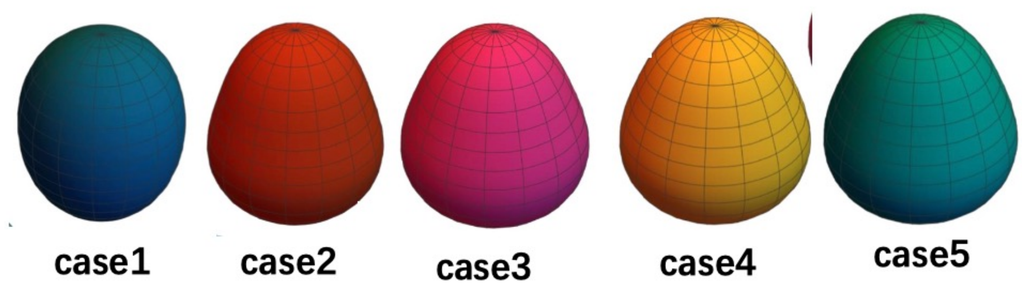
Ru and Zr nuclear structure

W. Zhao QM2023





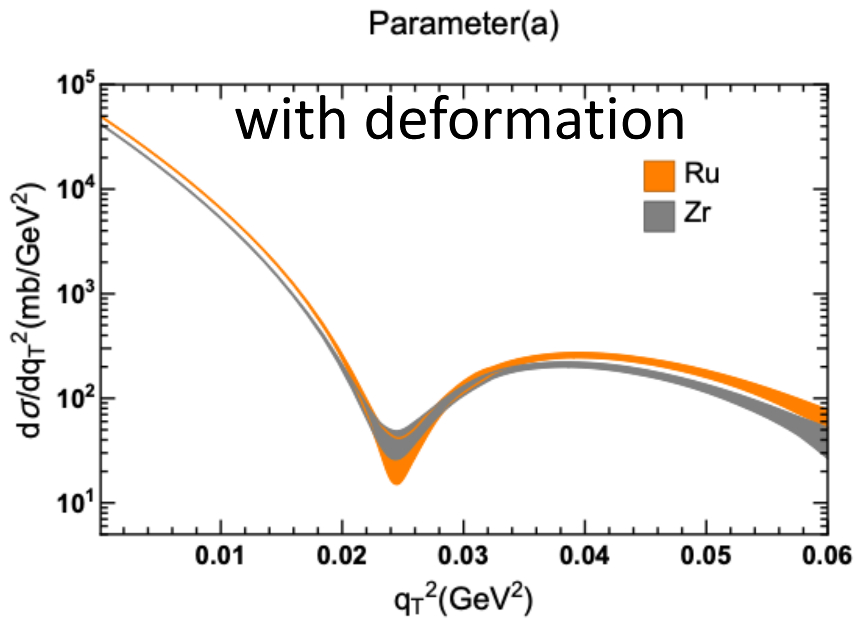
system	R_0 [fm]	a_0 [fm]	β_2	β_3	β_4
case1 (Ru+Ru)	5.09	0.46	0.16	0.0	0.0
case2 (Ru+Ru)	5.09	0.46	0.16	0.20	0.0
case3 (Ru+Ru)	5.09	0.46	0.06	0.20	0.0
case4 (Ru+Ru)	5.09	0.52	0.06	0.20	0.0
case5 (Zr+Zr)	5.02	0.52	0.06	0.20	0.0

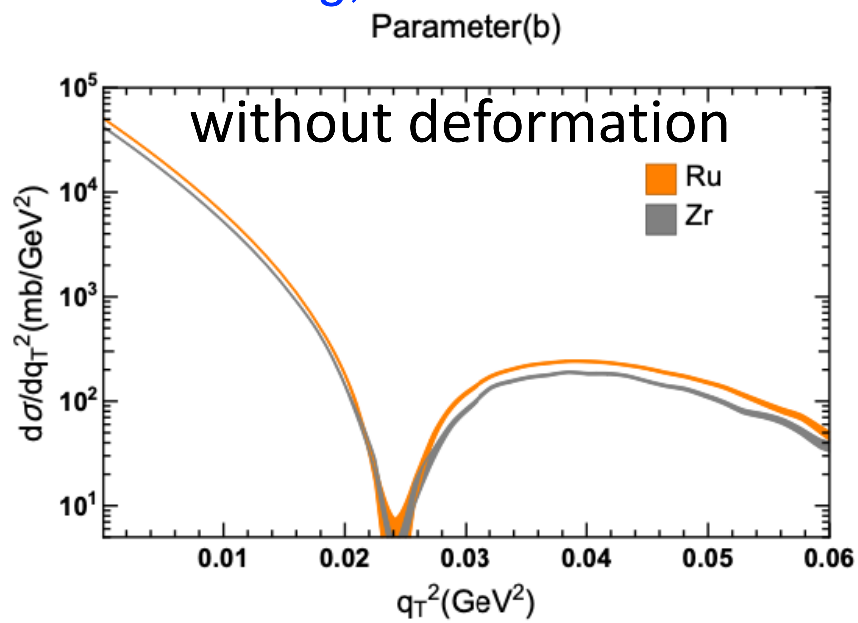


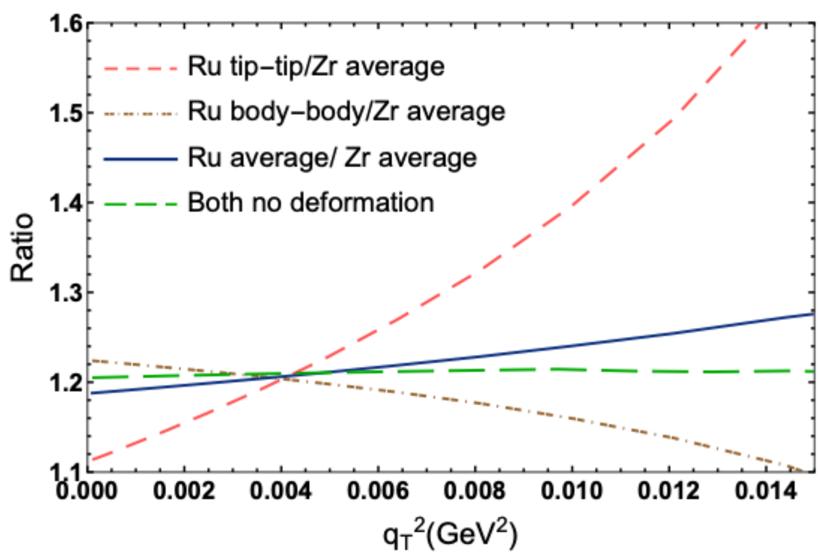
- The vector meson produc2on in isobar UPCs is sensitive to the nuclear structures
- “By eyes”, the ``full’’ Ru/Zr (case1/case5) is closest to data

Ru and Zr nuclear structure

Shuo Lin, Jin-Yu Hu, Hao-Jie Xu, Shi Pu, and Qun Wang, arXiv:2405.16491







The deformation effects can result in an approximate linear increase with q_T^2

This pattern aligns with the trends observed in experimental data.

Summary

- Observation of Breit-Wheeler process
  - -Linearly polarize photons
  - -Impact parameter dependence
- The linearly polarized photon-gluon collisions
  - -Double slits interference in polarization space
  - -Align reaction plane
  - -Tomography …
- More coherent photon induced products