The 15th Workshop on QCD Phase Transition and Relativistic Heavy-ion Physics
Zhuhai, Guangdong Province, China
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Probe Strong (Electro–)Magnetic Field in Relativistic Heavy–Ion Collisions

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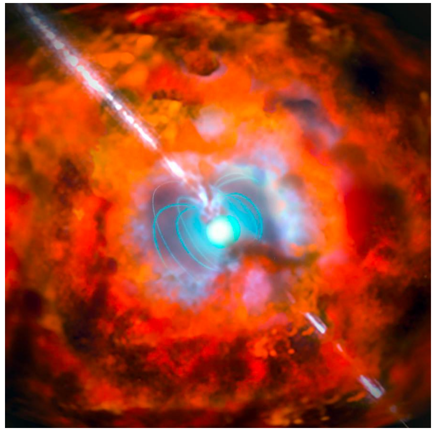
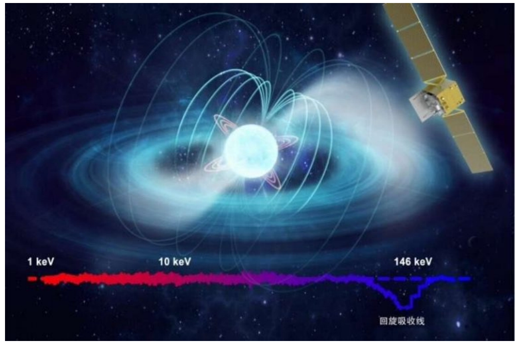
Many thanks to Wangmei Zha, Zhangbu Xu, …

Strong Magnetic Field

Magnetar

O(10^{9-11} T)

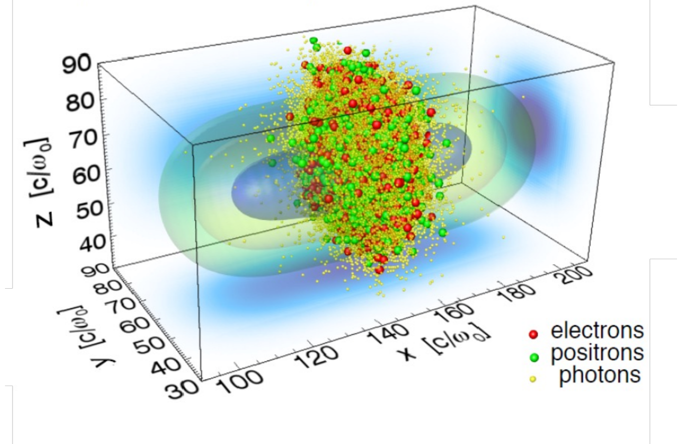




L. Kong, ApJL 933, L3 (2022)

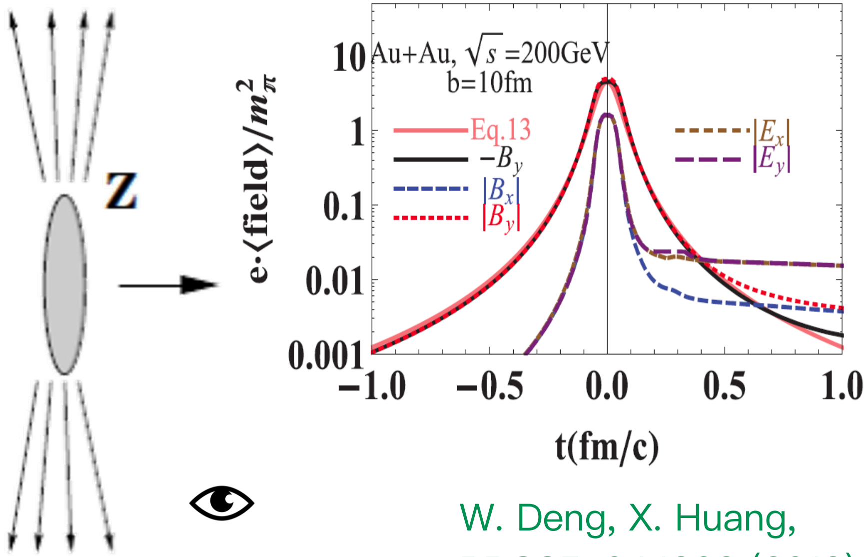
High–power laser

O(10^{10} T), O(10^{-14} s)



Fast–moving heavy ion

O(10^{14-16} T), O(R/γ fm/c)



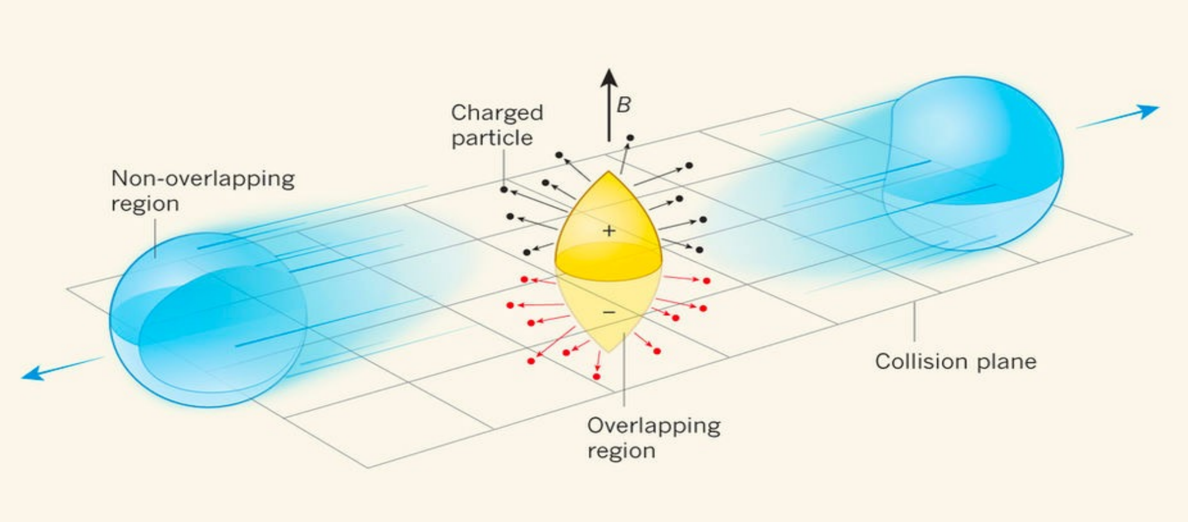
W. Deng, X. Huang, PRC85, 044902 (2012)

Strongest magnetic field, BUT

- In a very limited space
- In a very short time

How to probe it?

Magnetic Field Interaction in Heavy Ion Collisions



When two heavy ions collide,
the strong fields are close enough,
they interact and produce particles

b>2R: Ultra-peripheral collisions (UPC)

EM interactions only, clean

b<2R: Heavy ion collisions with nuclear overlaps (HHIC, usually PC)

EM and hadronic interactions

Fields are closer but more complicated

EM + quark gluon plasma?

QGP with Strong Magnetic Field

- Chiral magnetic effect
  - Deconfinement + chiral symmetry + B field
- Chiral separation effect, chiral magnetic wave, chiral electric separation effect
- The QCD phase diagram in strong magnetic fields
  - EPJA topical collection (24 articles)
- Transition of bound states in strong magnetic fields
- EM-induced directed flow
- Hall effect
- …

See Xu-guang Huang's TDLI/INPAC seminar

Things are different IF there is strong EM field trapped in QGP

Reactions Induced by Strong Magnetic Field

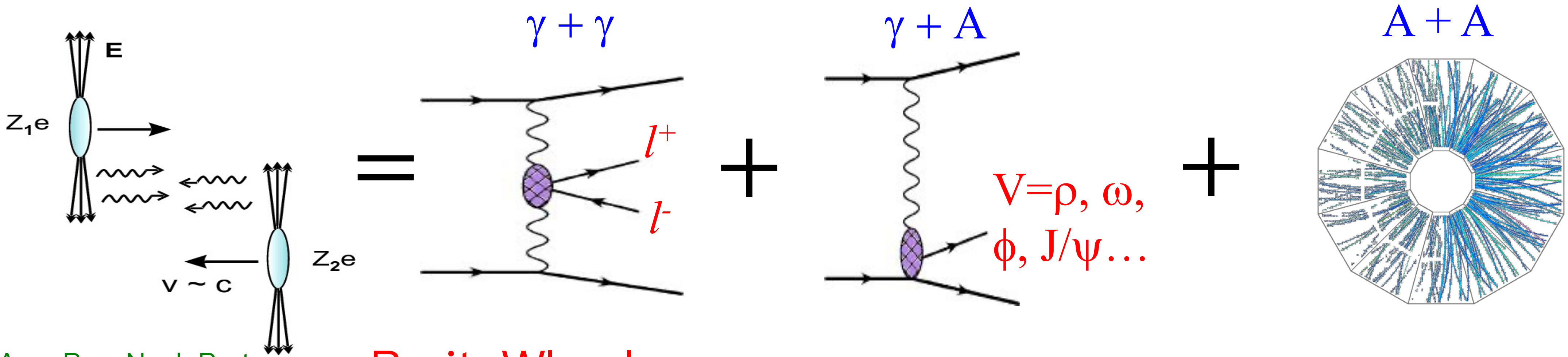
- The Lorentz contracted electromagnetic field can be expressed in terms of equivalent photon flux

$$k_T \sim 1/R = 0.03\ \mathrm{GeV}$$

$$E \lesssim \gamma/R \sim 3\ \mathrm{GeV}\ @\ \mathrm{RHIC}\ (80\ \mathrm{GeV}\ @\ \mathrm{LHC})$$

E. Fermi, Z. Phys. 29, 315 (1924)
C. Weizsacker, ZP88, 612 (1934)
E. Williams, PR45, 729 (1934)

- The photons interact with photons or nuclei in heavy ion collisions



Ann. Rev. Nucl. Part. Sci. 55, 271 (2005)

Breit–Wheeler process

- Dominant process in heavy–ion collisions (200 vs. 7 barn)

Photoproduction of Vector Mesons and Dileptons

$$\sigma(AA \to VAA) = \int d\omega_\gamma \frac{dN_\gamma(\omega_\gamma)}{d\omega_\gamma} \sigma(\gamma A \to VA)$$

$$\sigma(AA \to l^+l^-AA) = \int d\omega_{\gamma 1} \frac{dN_{\gamma 1}(\omega_{\gamma 1})}{d\omega_{\gamma 1}} d\omega_{\gamma 2} \frac{dN_{\gamma 2}(\omega_{\gamma 2})}{d\omega_{\gamma 2}} \sigma(\gamma\gamma \to l^+l^-)$$

Photon flux: Properties of the electromagnetic field

Scattering cross section: Particle production mechanism

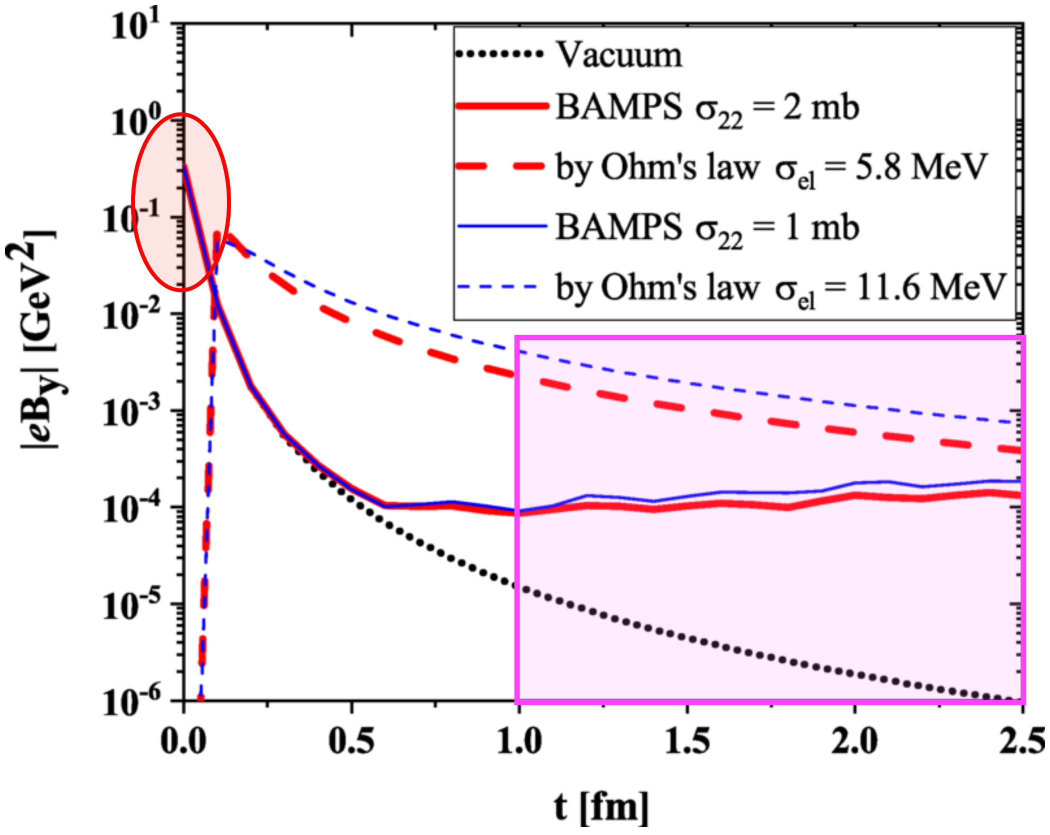
What They Can Tell Us?

The initial EM field

- Strength
- Spatial distribution
- Polarization
- …

Things involved:

- Nuclear charge dis.
- nPDF
- QED
- Quan. entanglement
- …



Z. Wang, J. Zhao, C. Greiner, Z. Xu and P. Zhuang, PRC105, L041901 (2022)

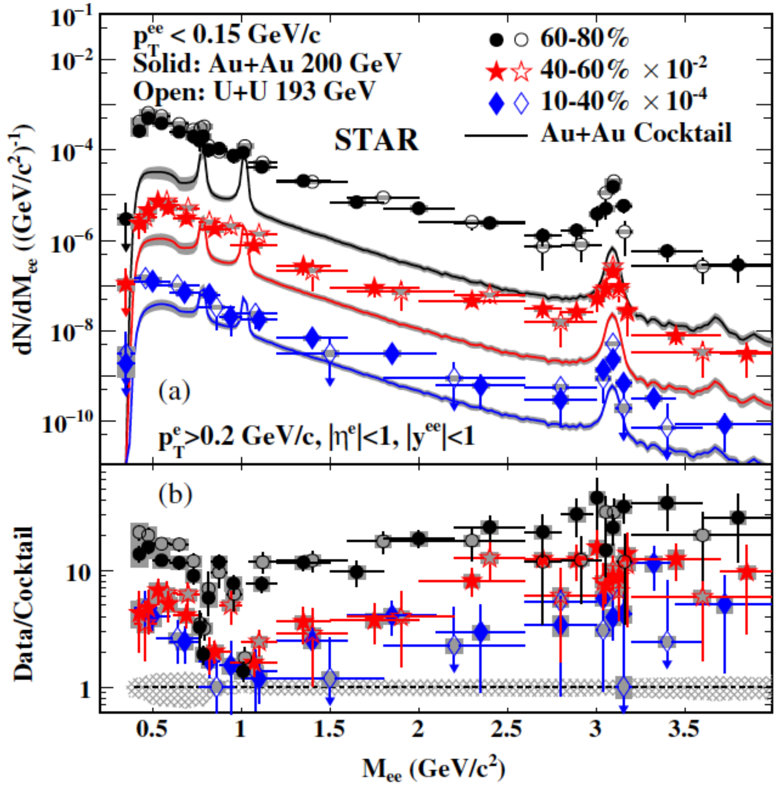
The possible EM field trapped in QGP

- Photoproducts produced early and almost at rest

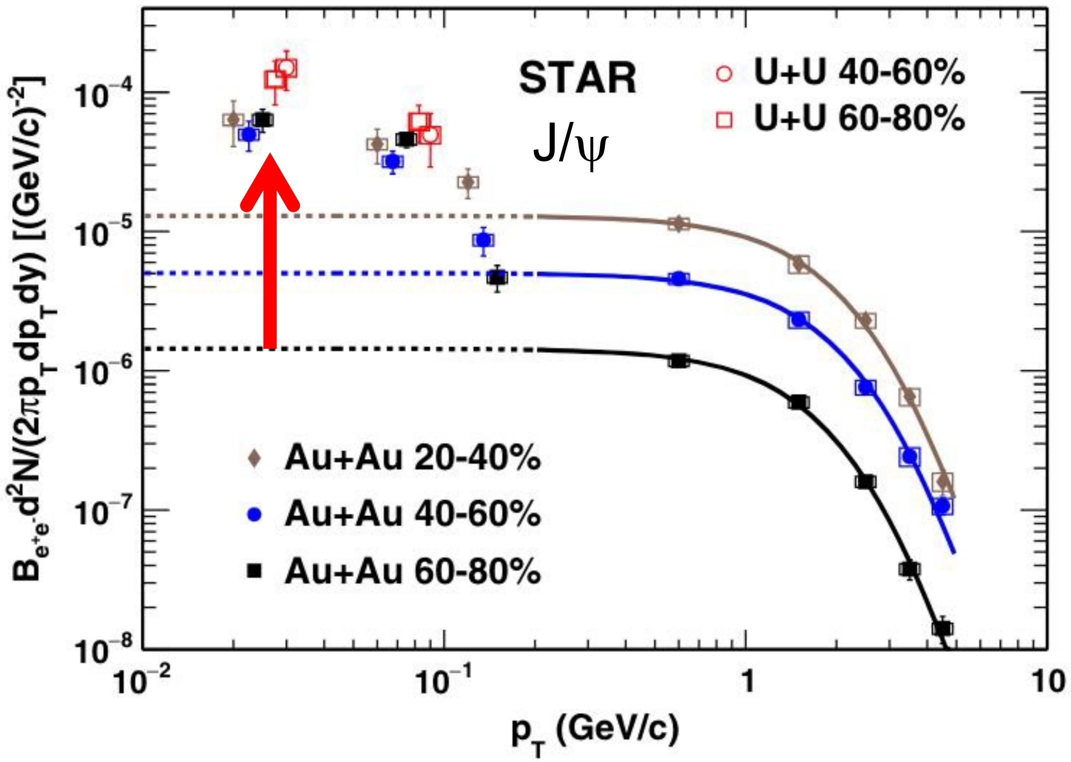
Cross Section

Very-low-p_T Dilepton Production at STAR

STAR, PRL123, 132302 (2019)



STAR, PRL123, 132302 (2018)



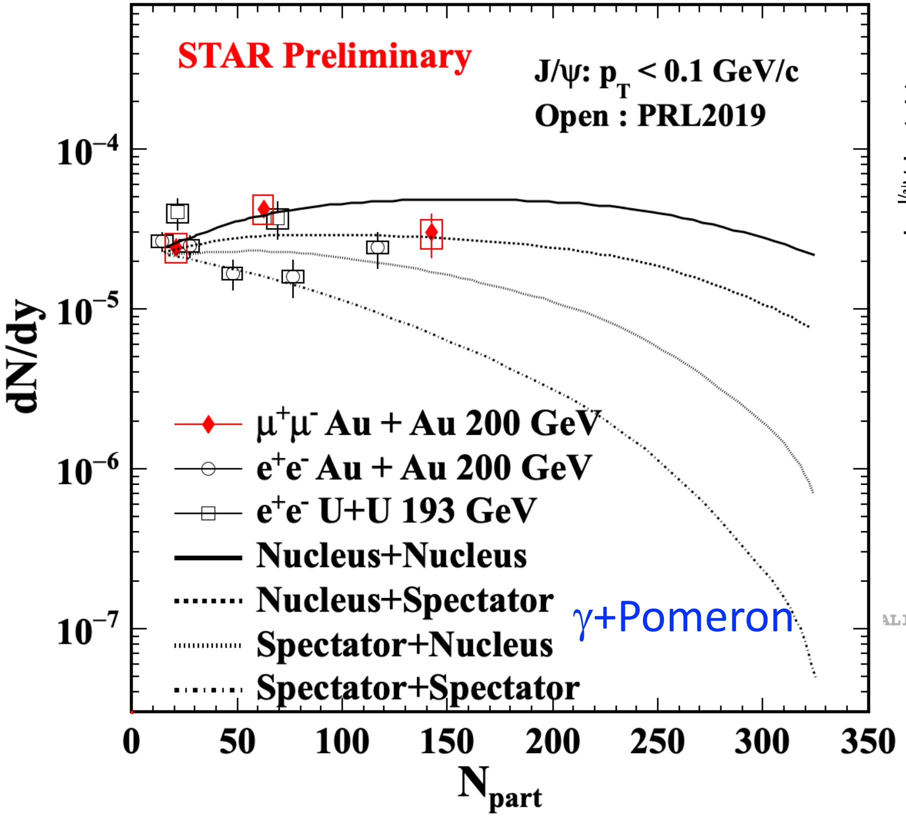
Significant enhancement of dilepton continuum and J/ψ yield at low p_T in Au+Au and U+U collisions

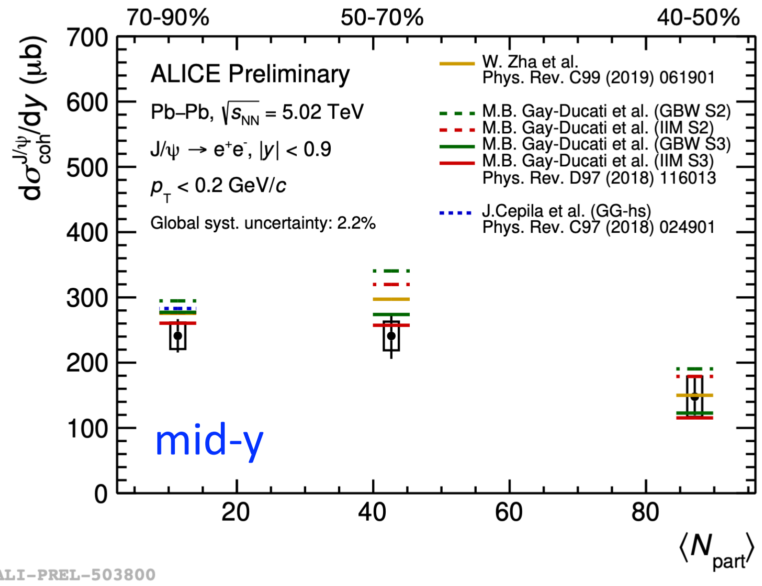
More obvious in peripheral than central collisions

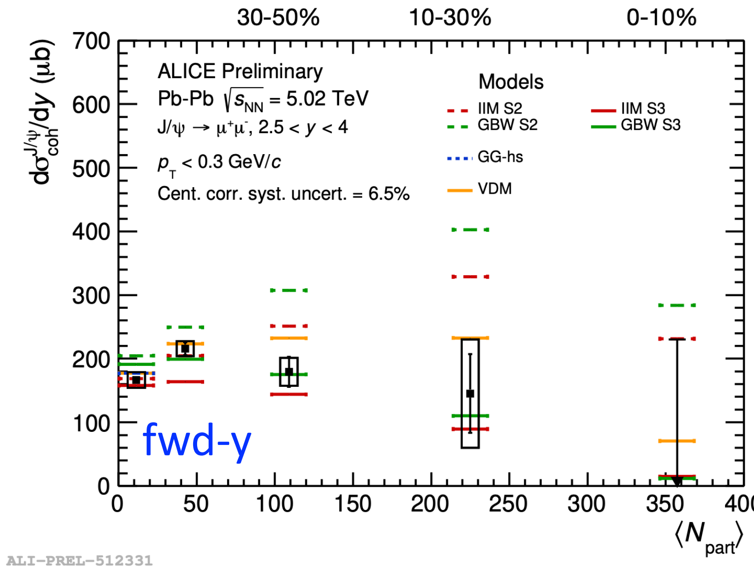
Centrality Dependence of J/ψ Yield

Ziyang Li (for STAR), ICHEP2022

Alexandra Neagu (for ALICE), UPC2023







Weak dependence on centrality

Scenario of

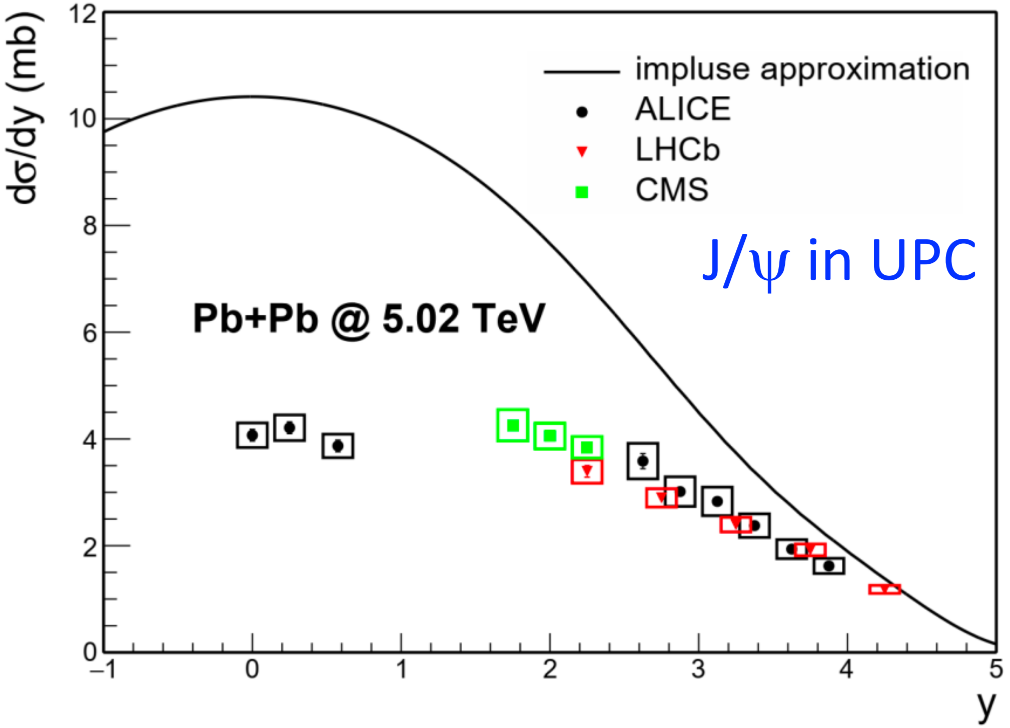
- Whole nucleus as photon emitter
- Spectator as Pomeron emitter

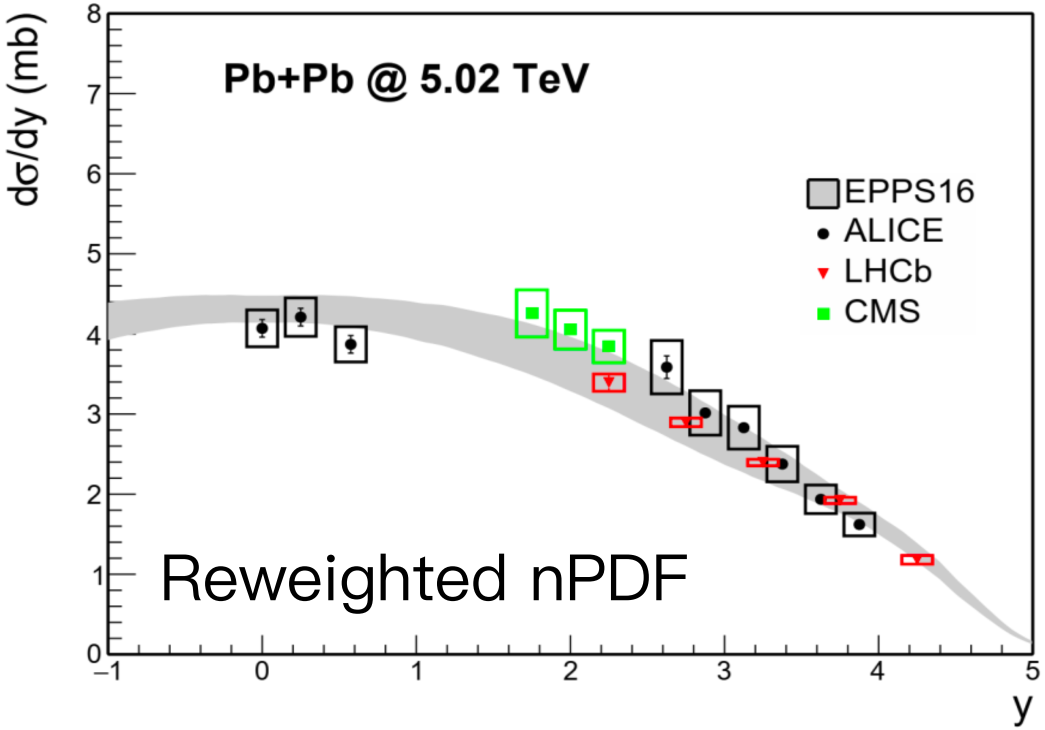
is favored

W. Zha*, L. Ruan, ZBT*, et. al., PRC99, 061901(R) (2019)
W. Zha, …, ZBT*, et. al., PRC97, 044910 (2018)

Gluon Distribution Function

Wangmei Zha et. al., in preparation





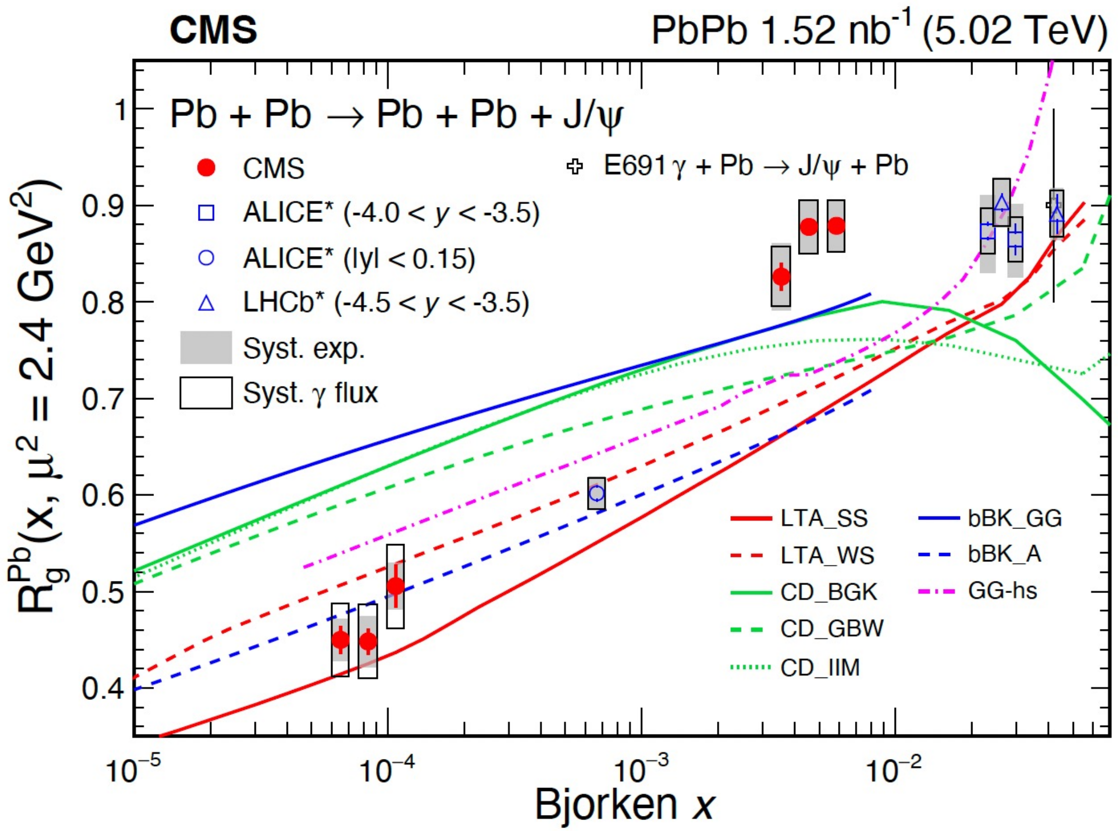
Clear suppression with respect to impulse approximation

Can be used to constrain gluon nPDF

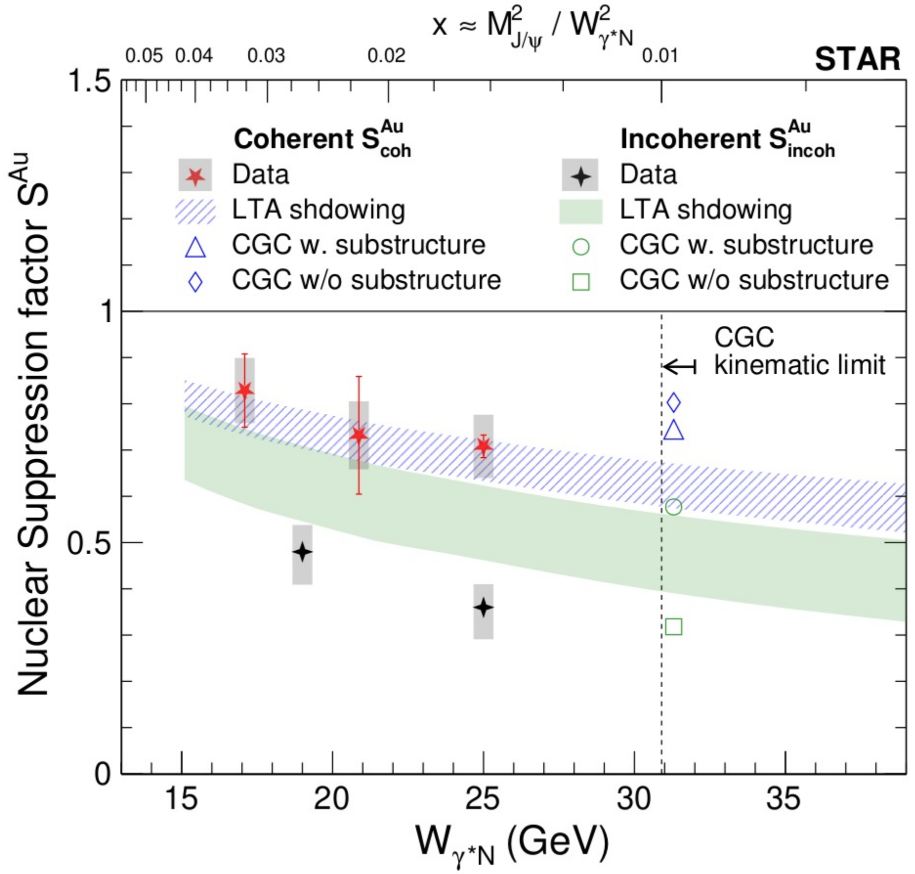
Reweighted nPDF describe data

Gluon Distribution Function

CMS, arXiv:2303.16984, accepted by PRL



STAR, arXiv:2311.13637



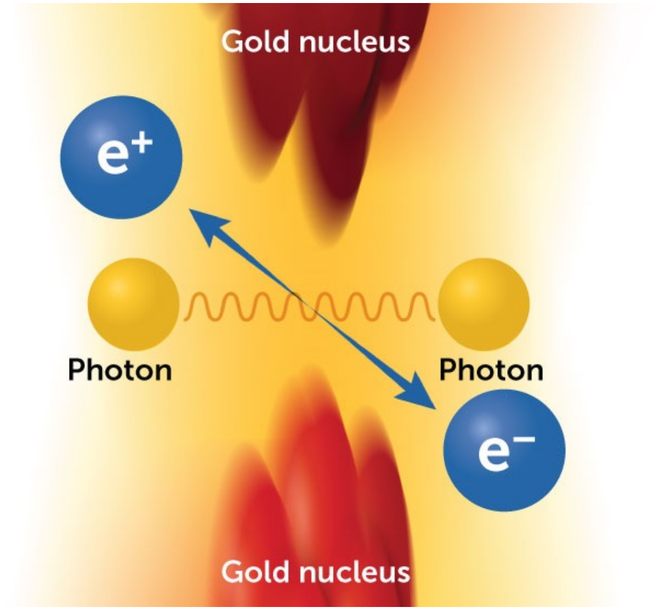
Clear suppression with respect to impulse approximation

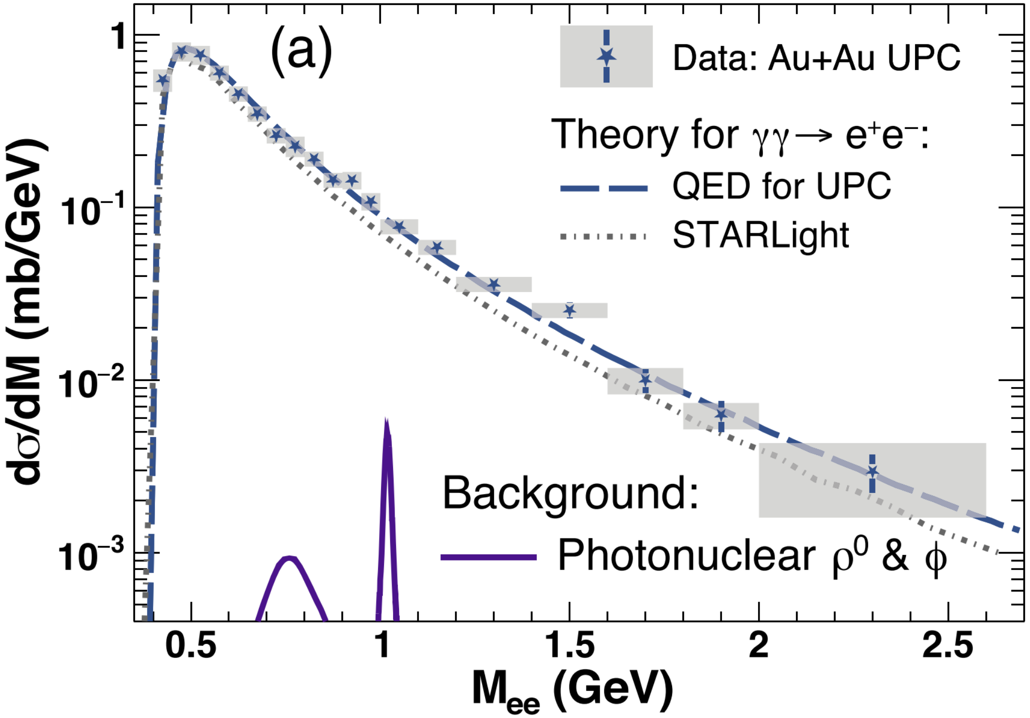
No theory can consistently describe the data

Breit–Wheeler Process

The simplest process to convert energy to matter

STAR, PRL127, 052302 (2021)
W. Zha et. al., PLB 800, 135089 (2020)

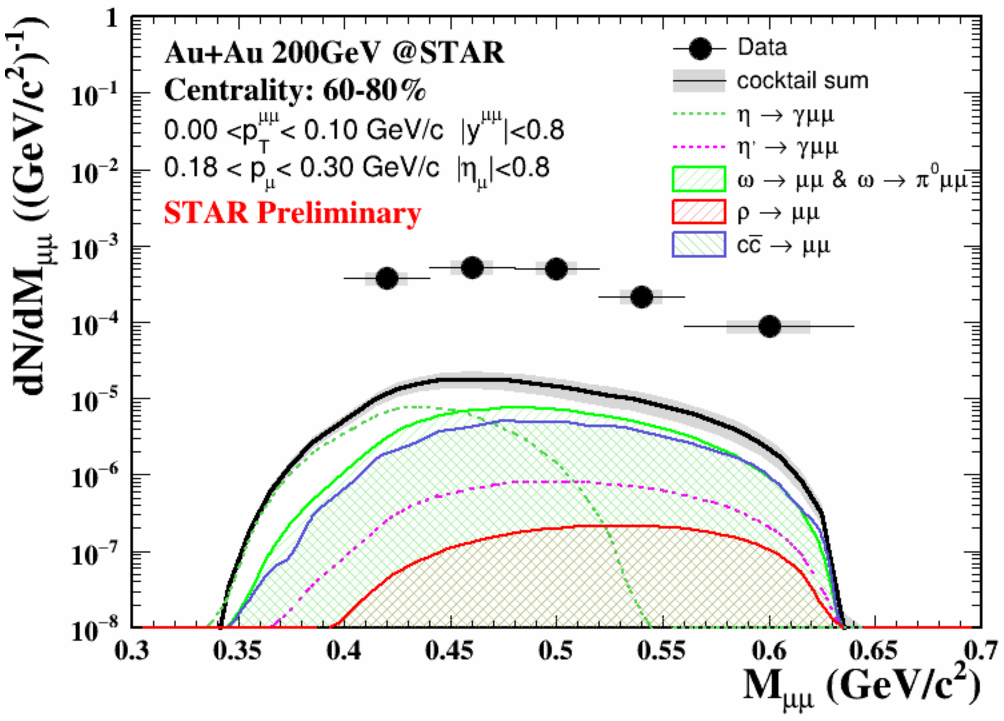


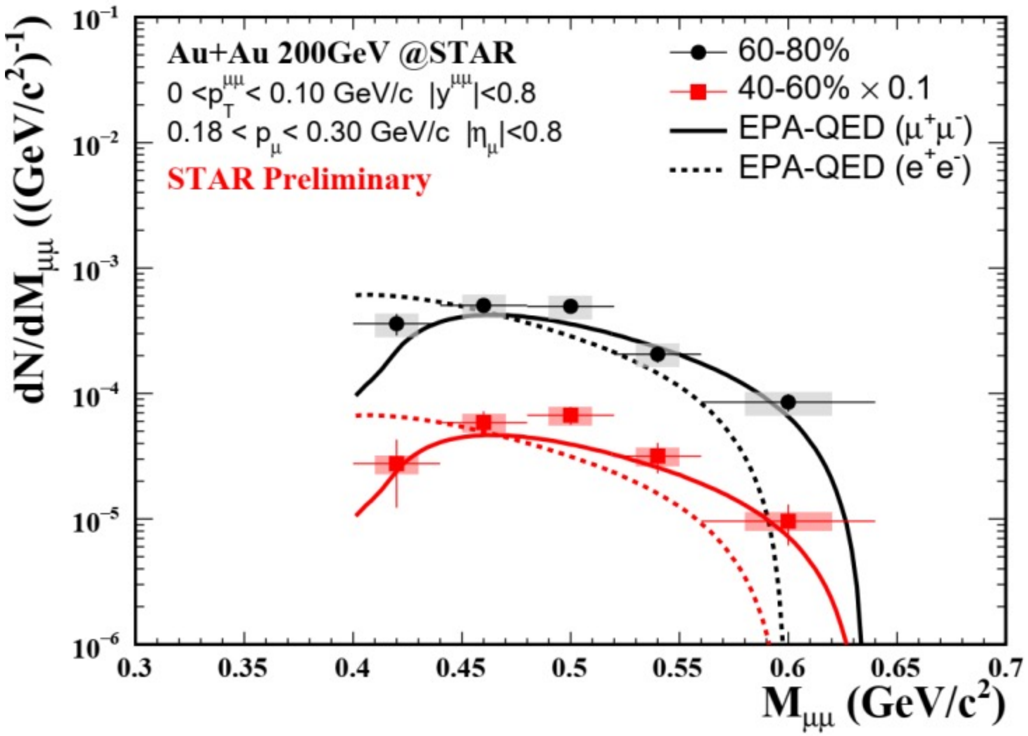


Data	0.261±0.004 (stat.) ± 0.013 (sys.) ± 0.034 (norm.) mb		
Theory	STARLight	gEPA	QED
	0.22 mb	0.26 mb	0.26 mb

Dimuon Production

周健 (for STAR), QM2022



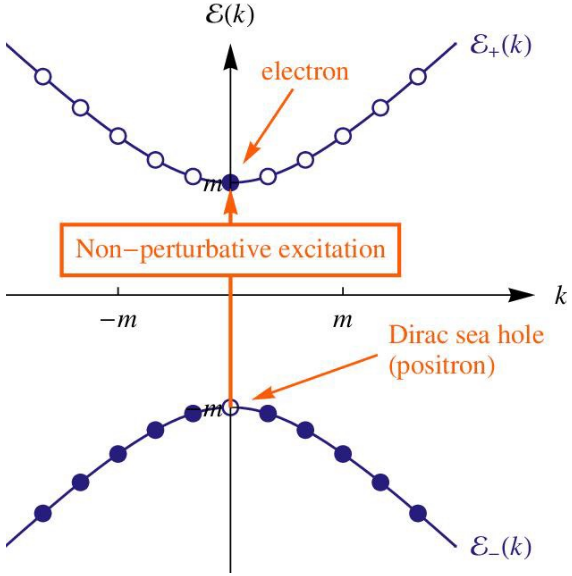


Significant enhancement of dimuon in peripheral Au+Au collisions

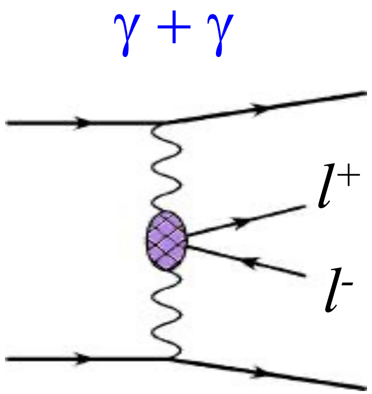
Same production mechanism as dielectron though 200x larger mass

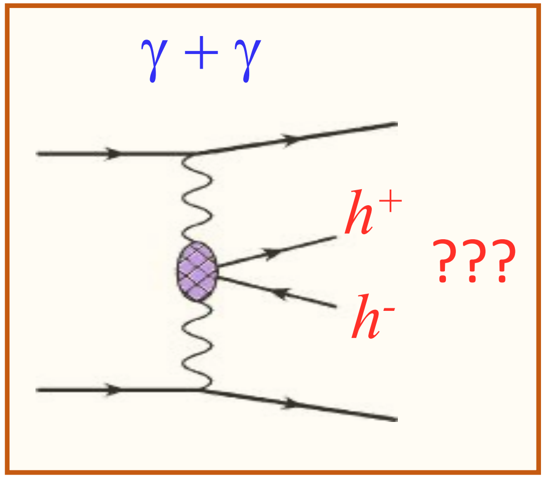
Search for Dihadron Production

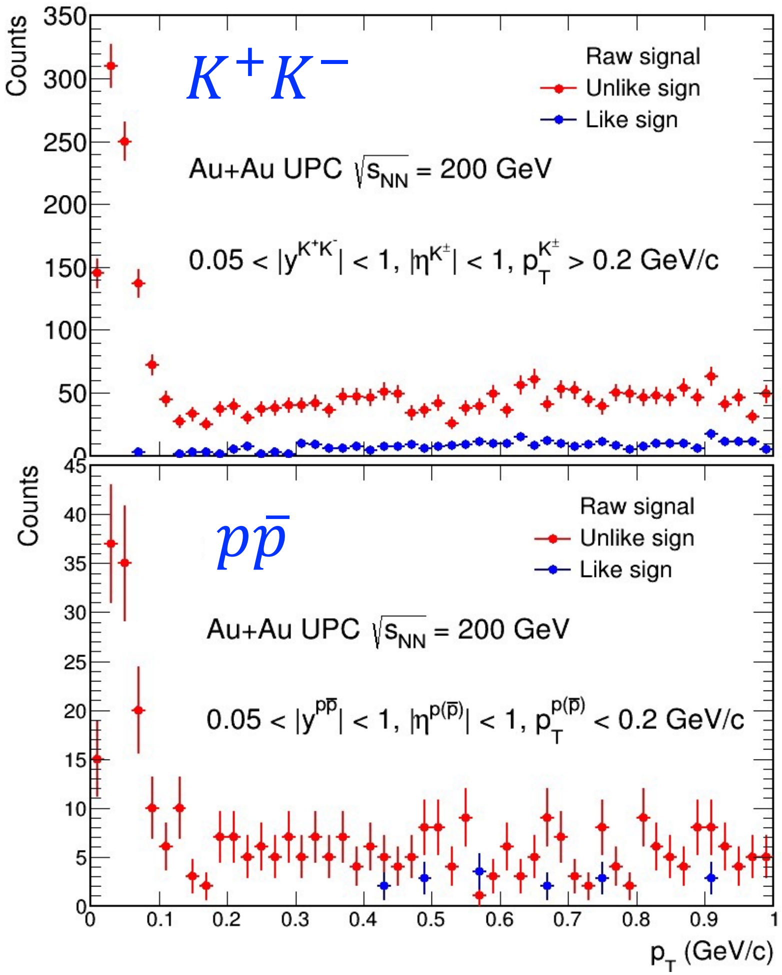
Xin Wu (for STAR), QM2023



QED vacuum excitation



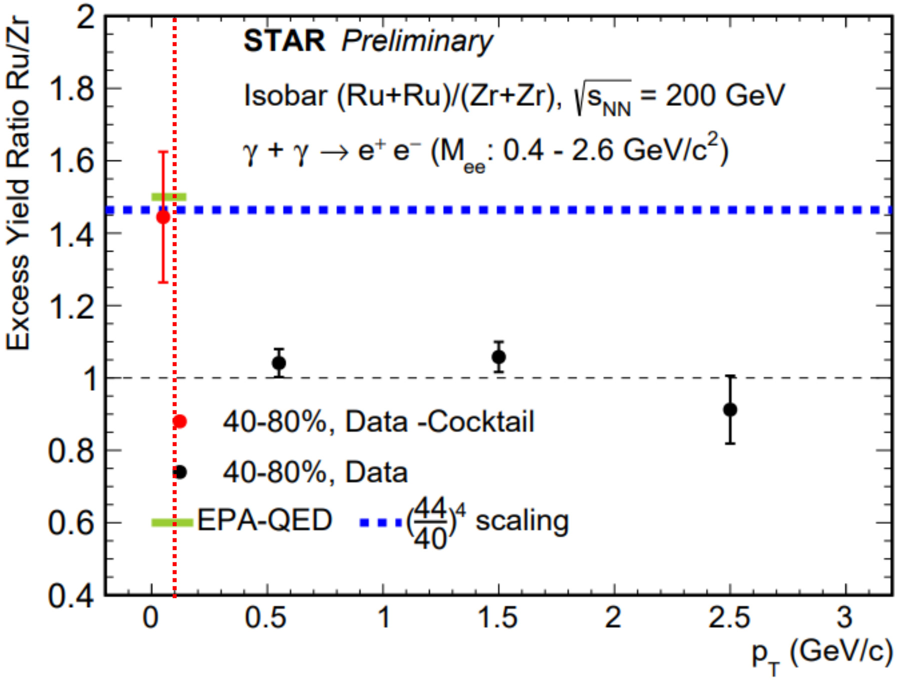


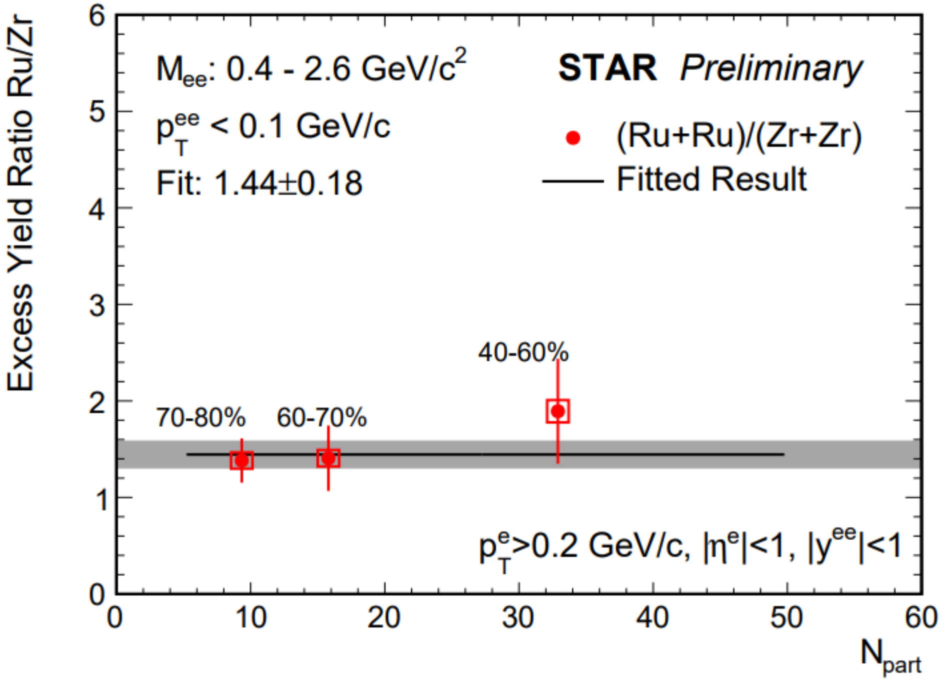


Significant signal of K^+K^- and $p\bar{p}$ observed at $p_T < 1$ GeV/c in Au+Au UPC

Charge Dependence of Dielectron Production

- How different is the magnetic field in $^{96}_{44}Ru + ^{96}_{44}Ru$ / $^{96}_{40}Zr + ^{96}_{40}Zr$?

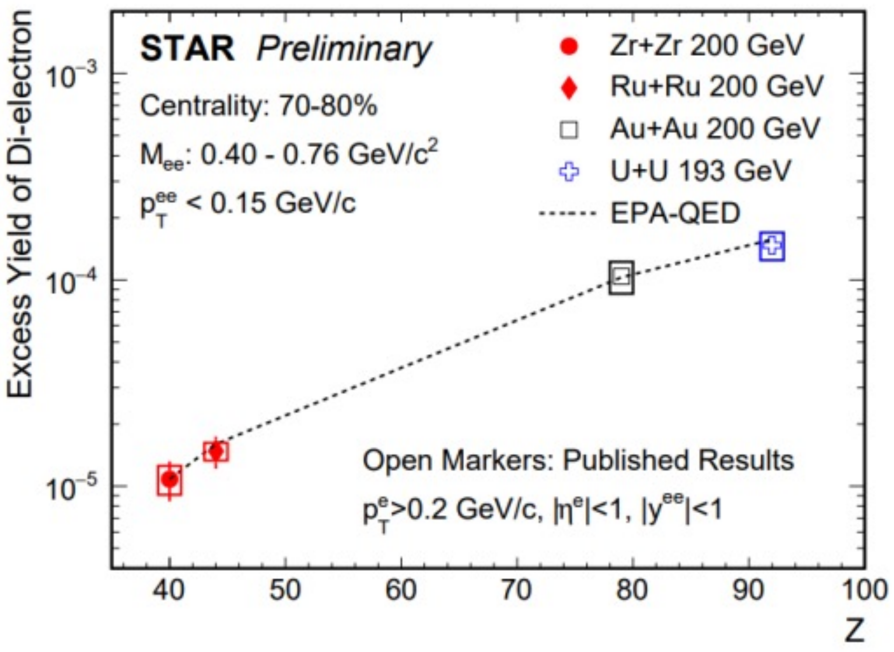


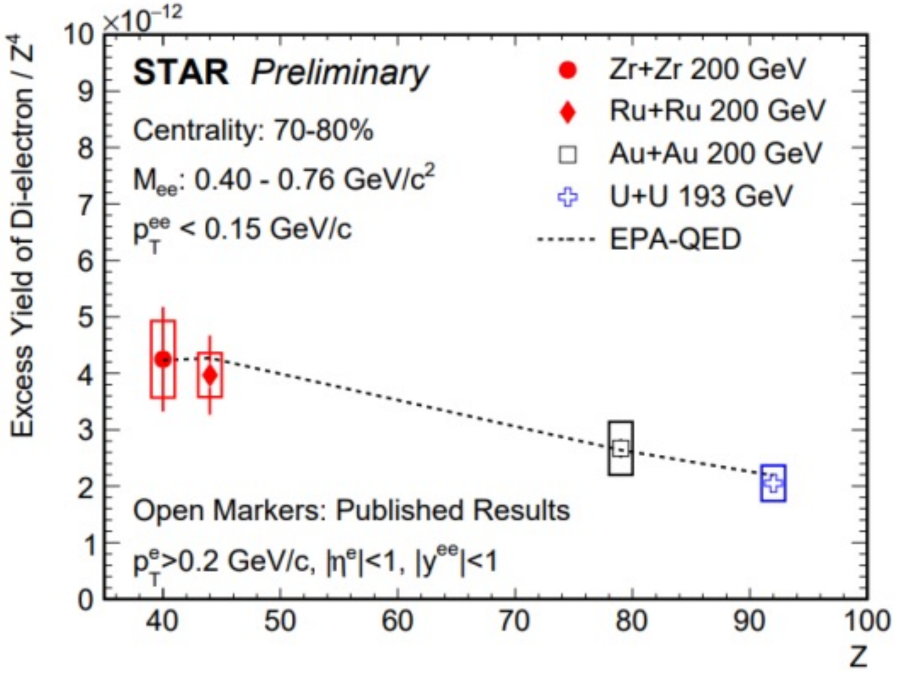


- The dielectron yield at p_T>0.1 GeV/c is consistent in Ru+Ru and Zr+Zr
- The excess yield at p_T<0.1 GeV/c is ~40% higher in Ru+Ru collisions
- And shows no centrality dependence

Dielectron from Z = 40 to 92

Kaifeng Shen (for STAR), SQM 2022

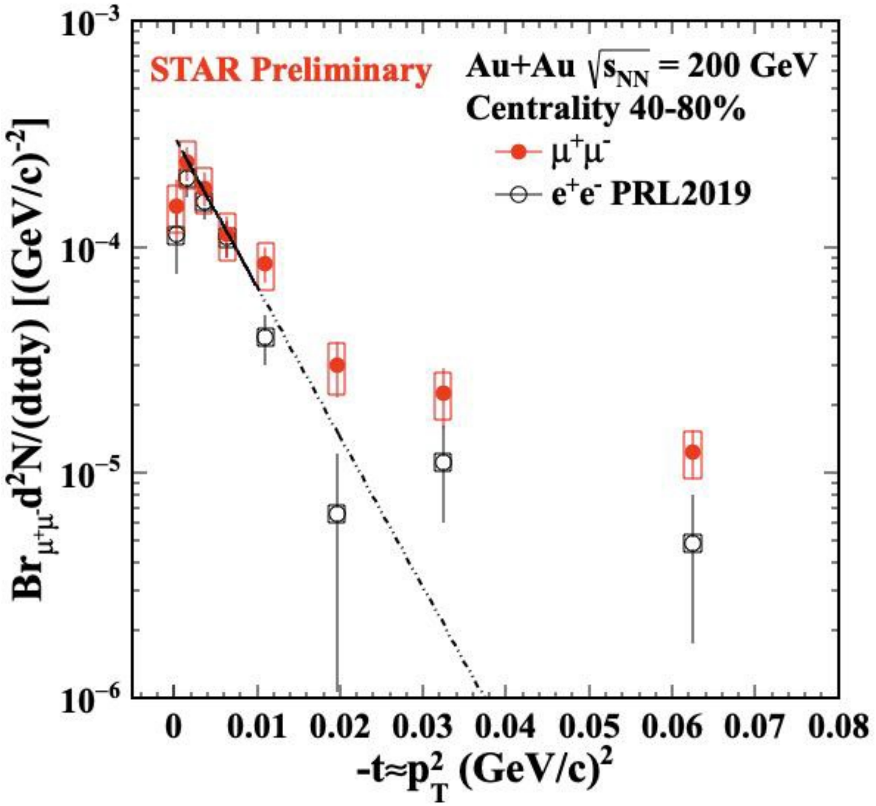


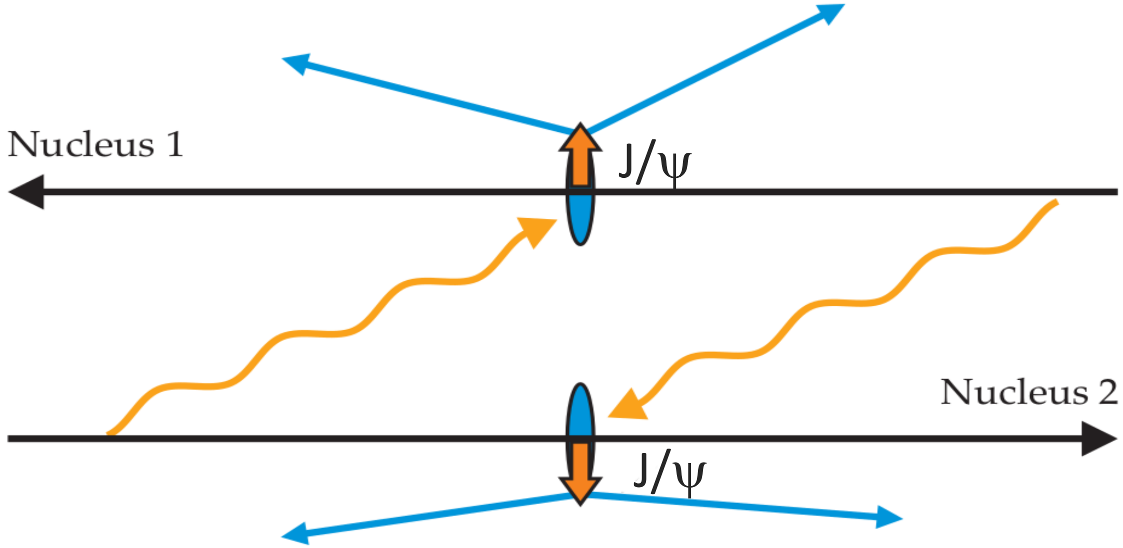


- Excess yield increase significantly with Z from Zr+Zr to U+U collisions
- Z^4–scaled yield decrease with Z, likely originating from different *b*
- Consistently described by EPA–QED calculations

J/ψ Momentum Transverse Squared Distribution

Ziyang Li (for STAR), ICHEP2022

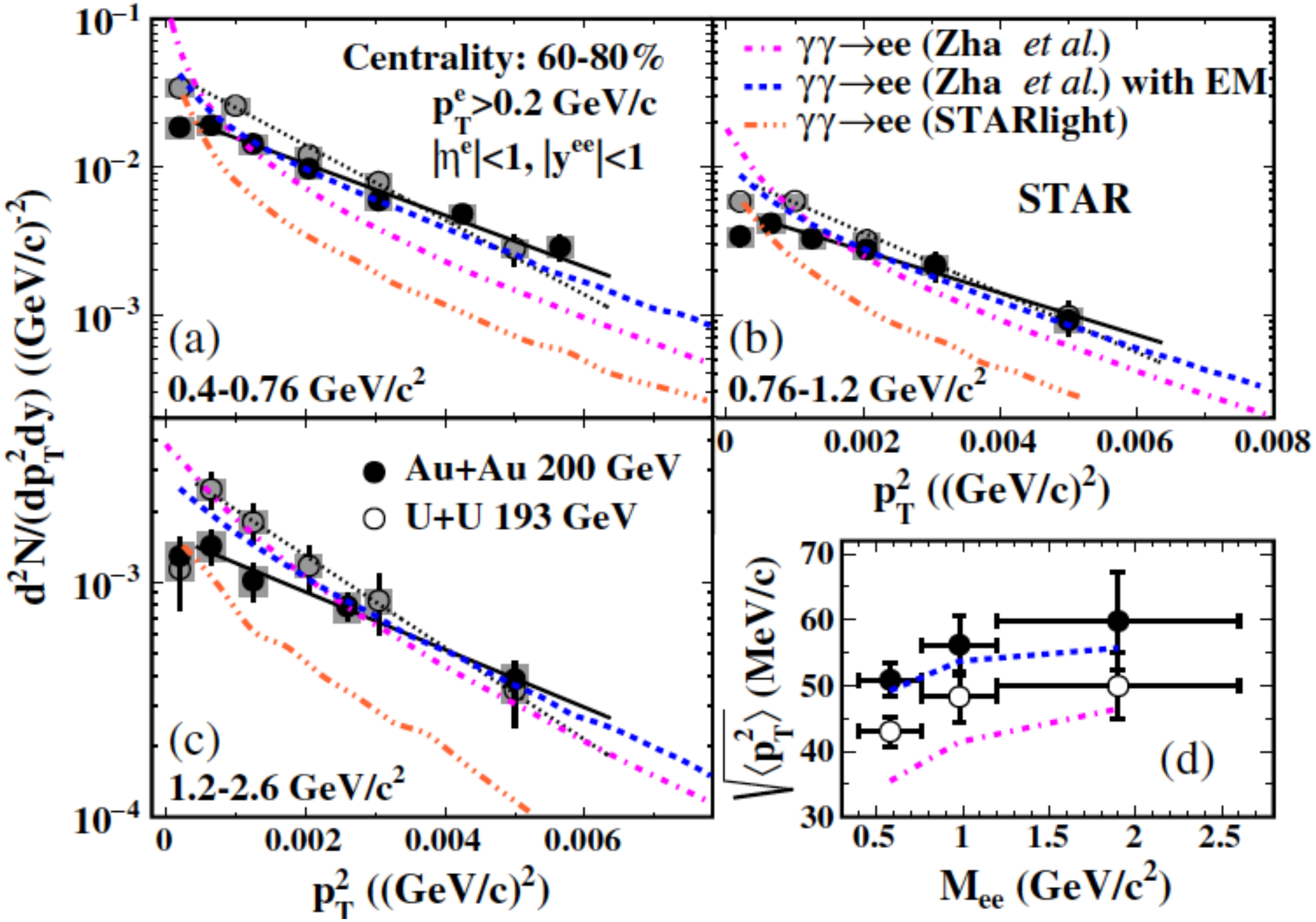




- Very–low–p_T J/ψ results via μμ are consistent with those via ee
  - Slop reflects nuclear charge form factor
  - Drop at the lowest p_T bin indicates interference effect

Broadening of Dielectron t Distribution at RHIC

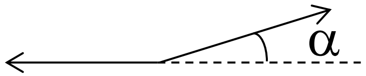
STAR, PRL121, 132301 (2018)



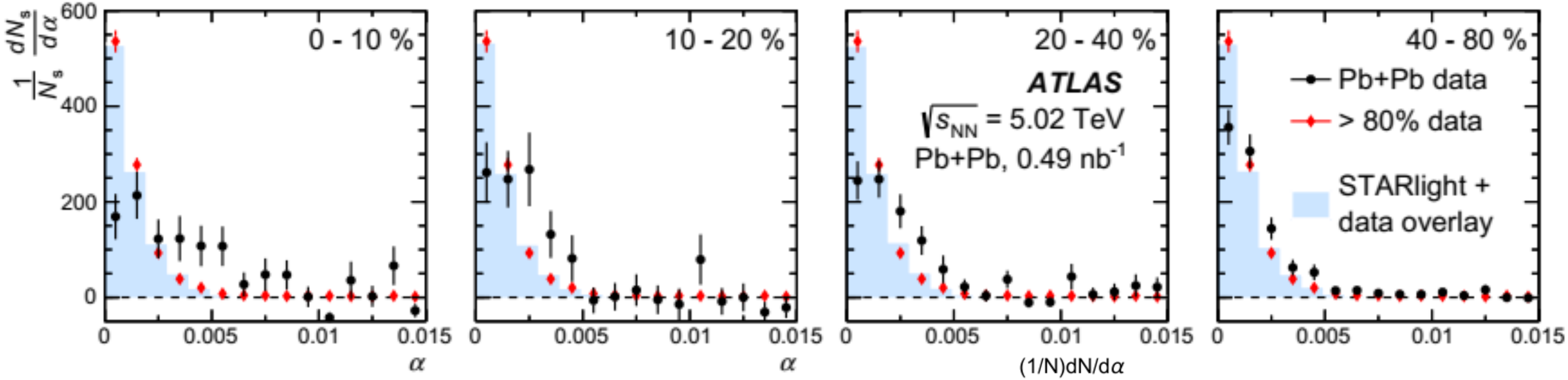
- p_T^2 distribution in data is broader than both models
  → QGP effects? (bending)

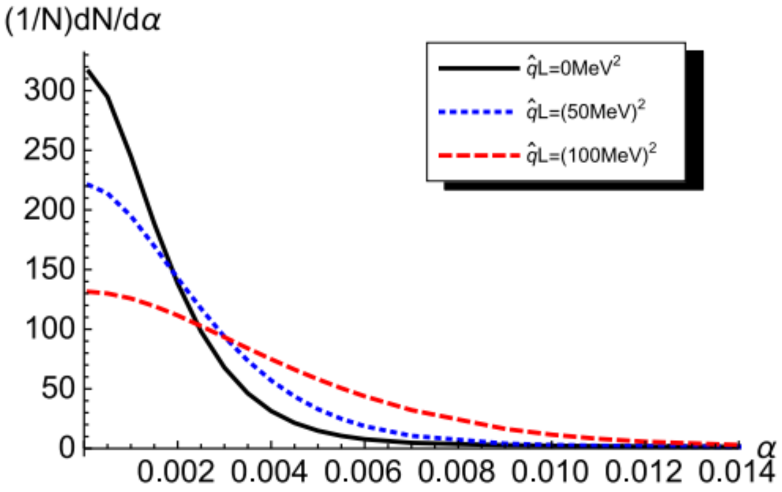
Acoplanarity of Dielectron at LHC

ATLAS, PRL121, 212301 (2018)



$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$



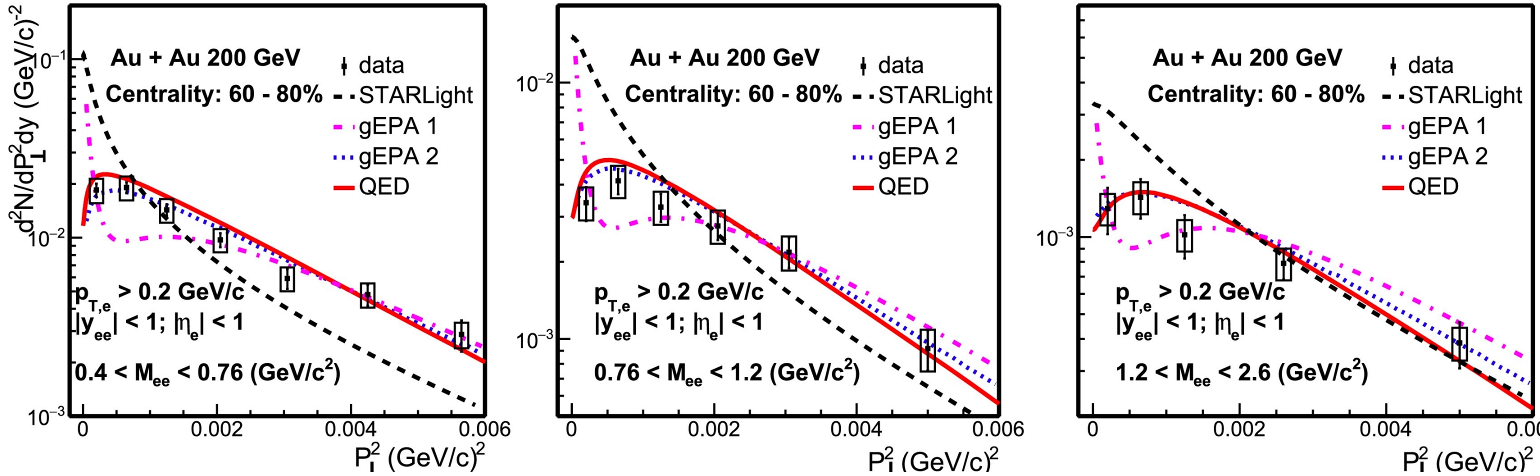


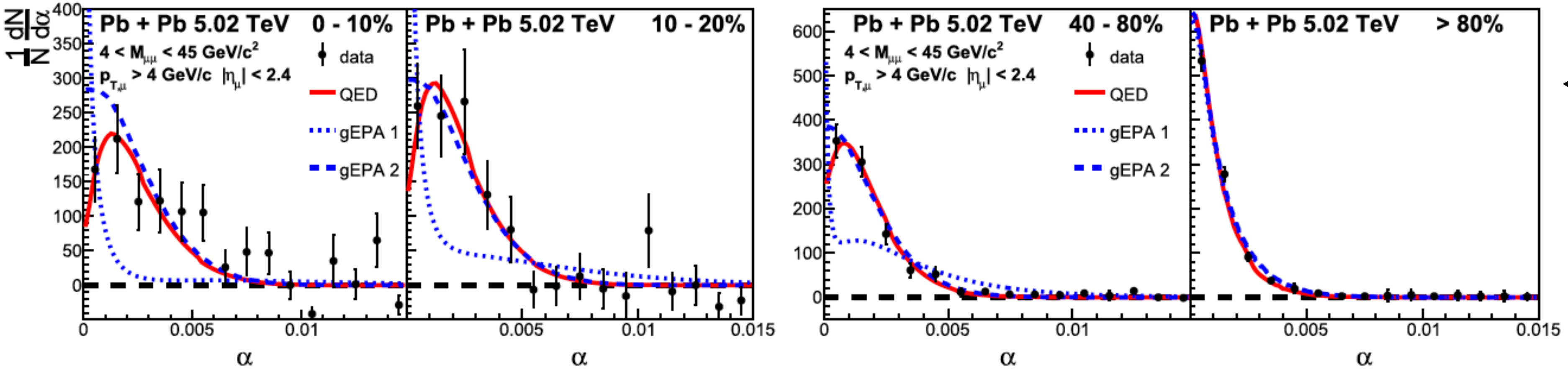
S.R. Klein et al, PRL122 (2019) 132301

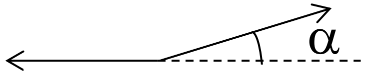
- Acoplanarity increases towards central collisions

→QGP effects? (multiple scattering)

Initial-state “Broadening”







$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

ATLAS, PRL121, 212301 (2018)

Broadening of p_T distribution observed by STAR and acoplanarity observed by ALTAS simultaneously explained by introducing impact parameter dependence of photon p_T

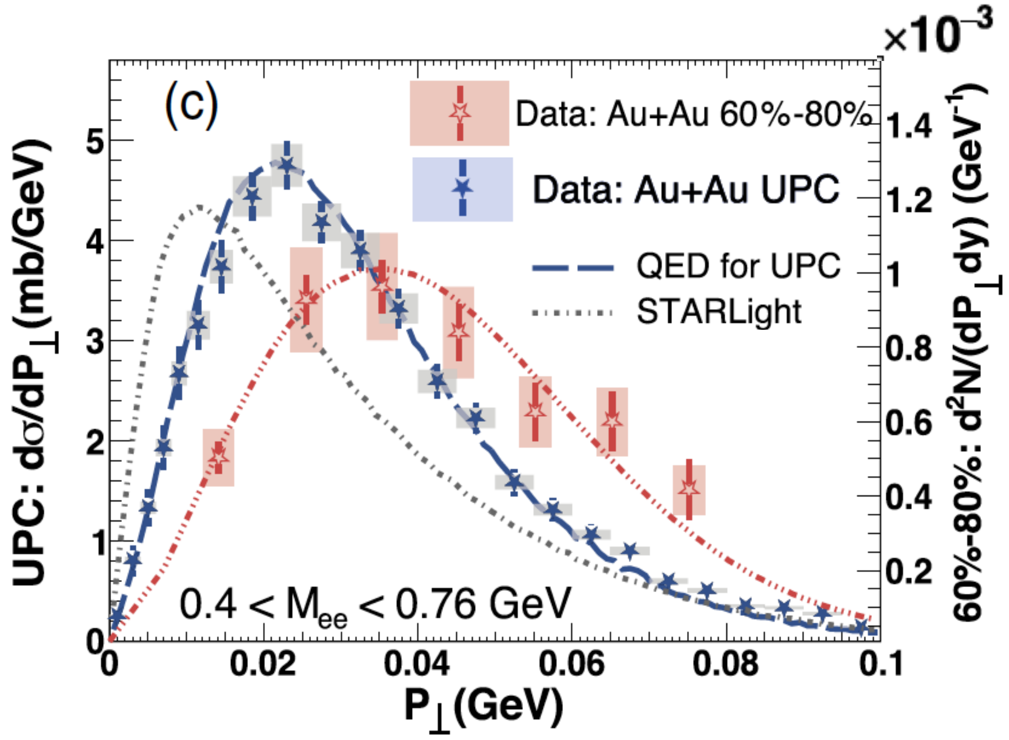
W. Zha, J. Brandenburg, ZBT and Z. Xu*, PLB 800, 135089 (2020)

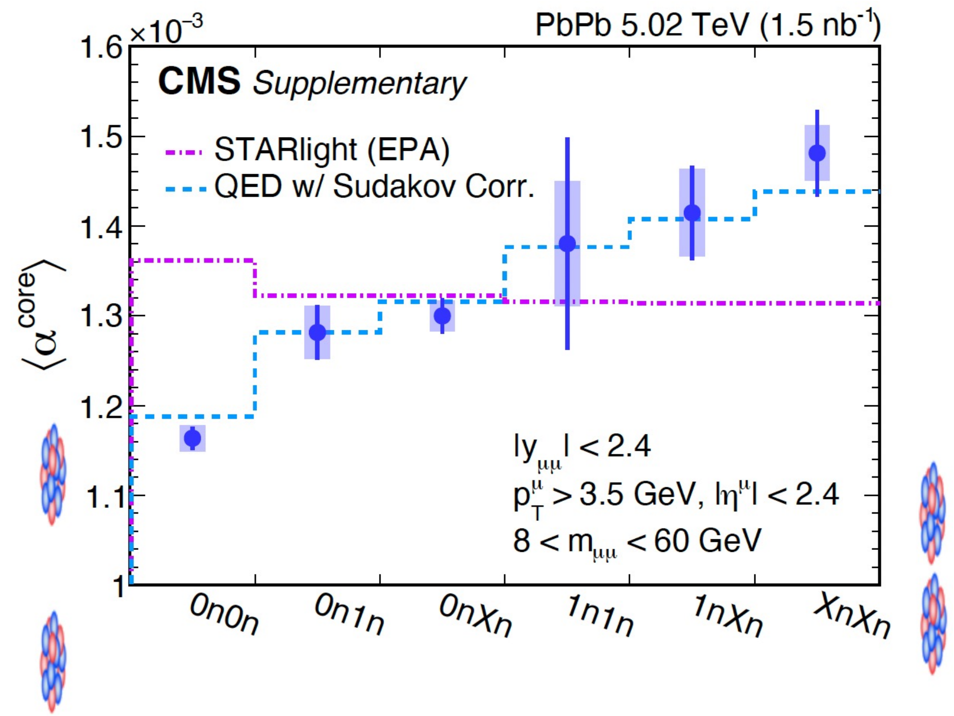
Confirmation of Impact Parameter Dependence

STAR, PRL127, 052302 (2021)

J. Brandenburg, ..., W. Zha*, arXiv:2006.07365

CMS, PRL127, 122001 (2021)





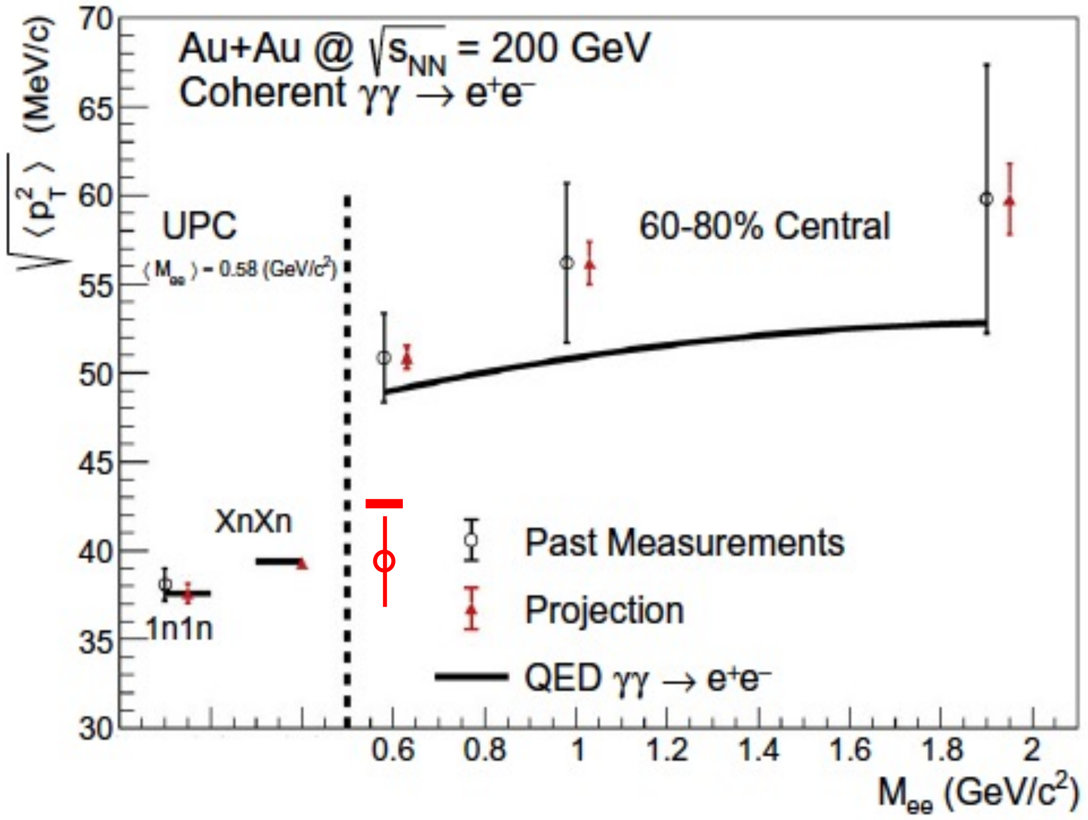
Narrower p_T distribution in UPC

Acoplanarity decreases with *b*

Initial–state broadening confirmed in UPC collisions by STAR and CMS

QGP Effects Ruled out?

J.D. Brandenburg et. al., Rep. Prog. Phys. 86, 083901 (2023)
周健 (for STAR), QM2022

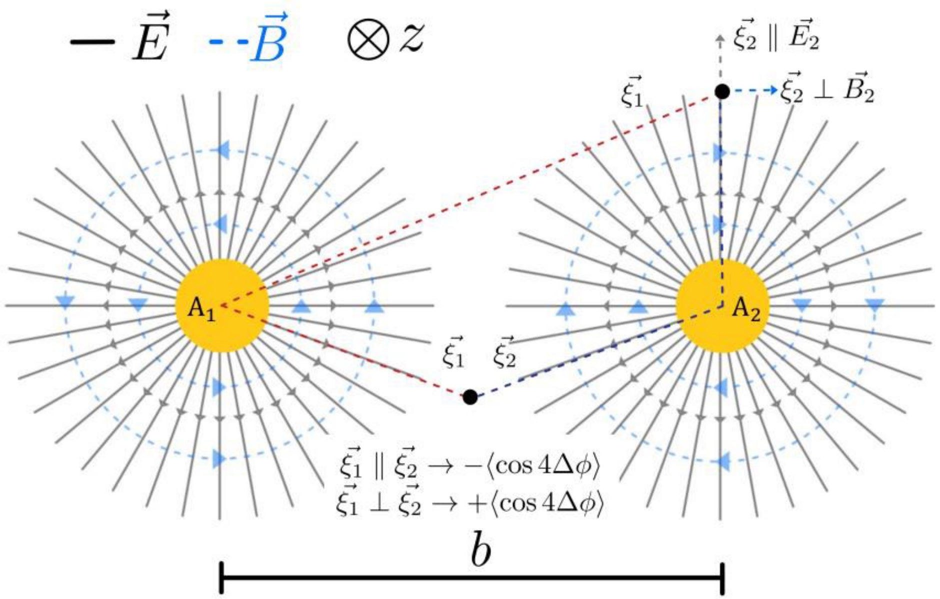


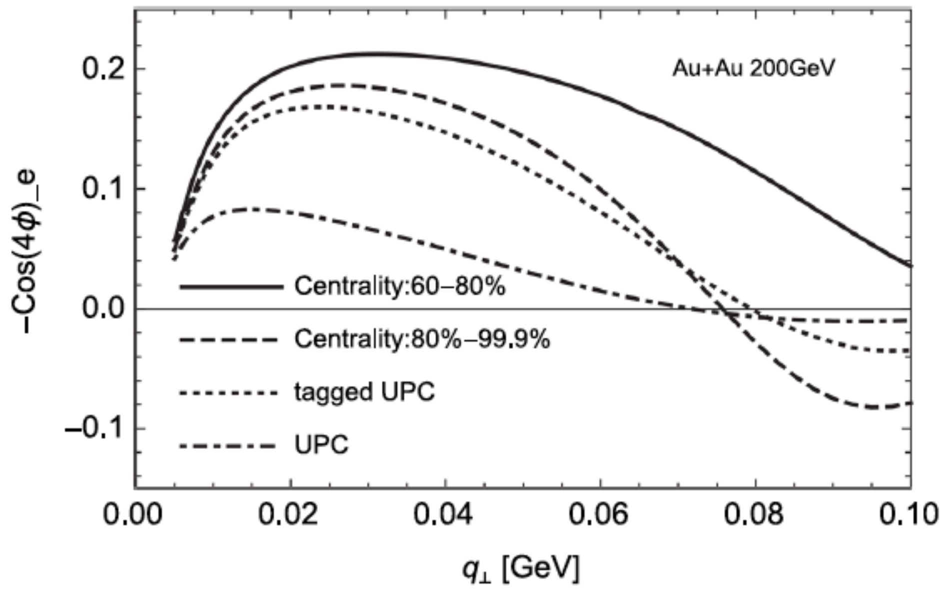
There is still room for QGP effects

Looking forward to precision data from RHIC 23–25 and LHC Run3

Polarization

Linearly Polarized Photons



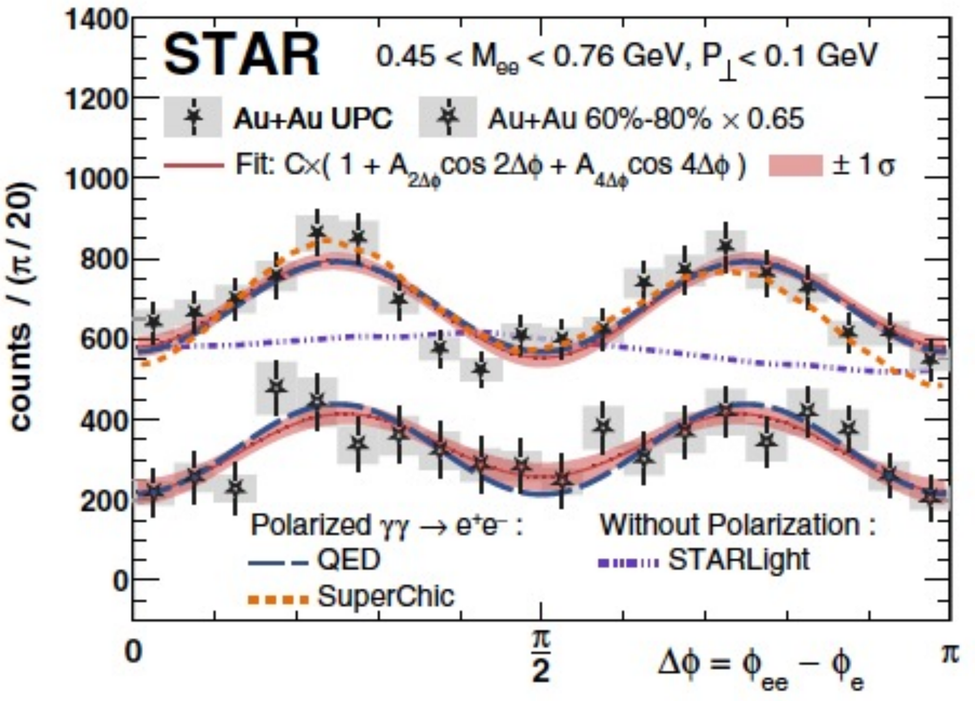


C. Li, Y. Zhou, 周剑, PLB795, 576 (2019)

- Photons from the highly Lorentz contracted EM filed are linearly polarized in the transverse plane
- Polarization vectors coincide with the positions and thus p_T
- Spin interference effect in QED predicts cos4ϕ modulation

Evidence of Angular Modulation

STAR, PRL127, 052302 (2021)



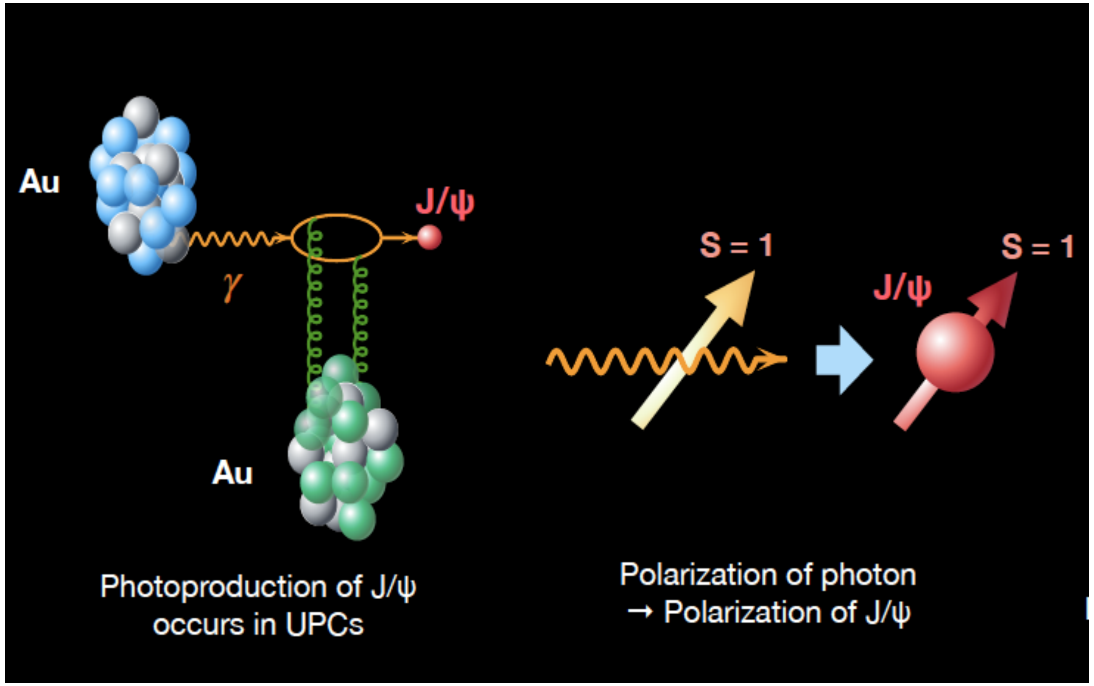
				Data	QED
$A_{4\Delta\phi}$	Au+Au	UPC	ee	16.8 ± 2.5	16.5
	Au+Au	PC	ee	27 ± 6	34.5
	Ru/Zr	PC	ee	47 ± 14	40
	Au+Au	PC	μμ	35 ± 8± 7	22
$A_{2\Delta\phi}$	Au+Au	UPC	ee	2.0 ± 2.4	0
	Au+Au	PC	ee	6 ± 6	0
	Ru/Zr	PC	ee	6 ± 13	0
	Au+Au	**PC**	**μμ**	**20 ± 8± 3**	**13**

周健（for STAR), QM 2022

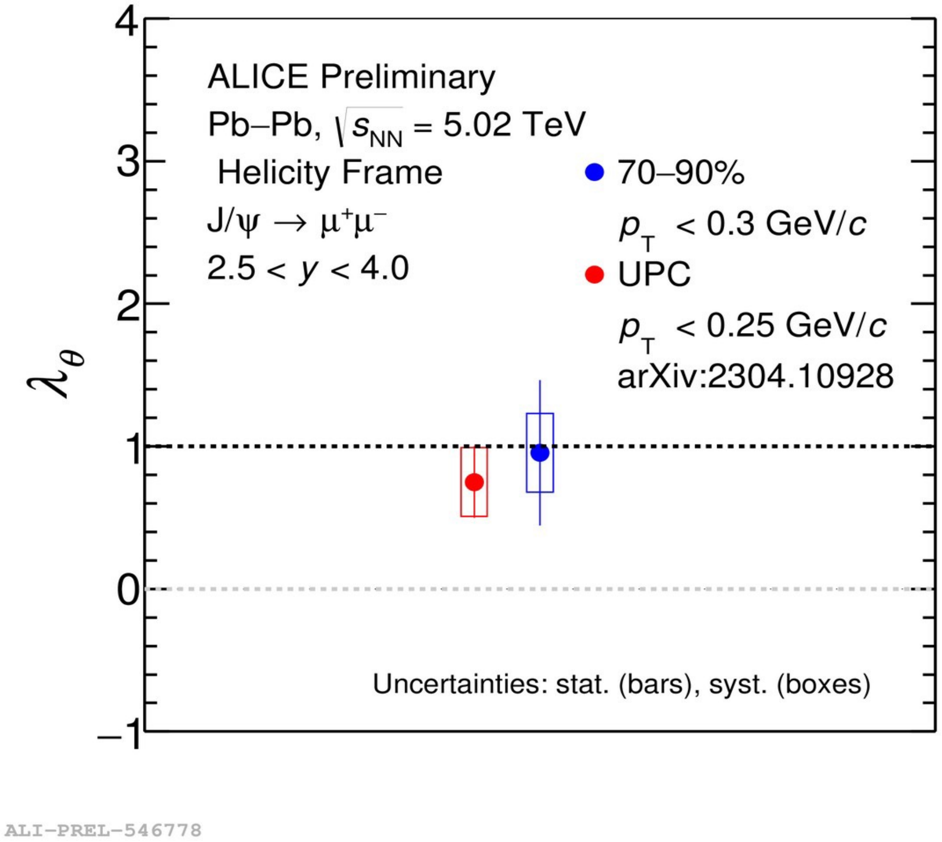
- Cos4ϕ modulation predicted by QED is observed
  - Modulation increases with decreasing b
- Cos2ϕ modulation observed in dimuon ($\propto m_l^2/p_T^2$)

Very–low–p_T J/ψ Polarization

Ashik Sheikh (for STAR), UPC 2023



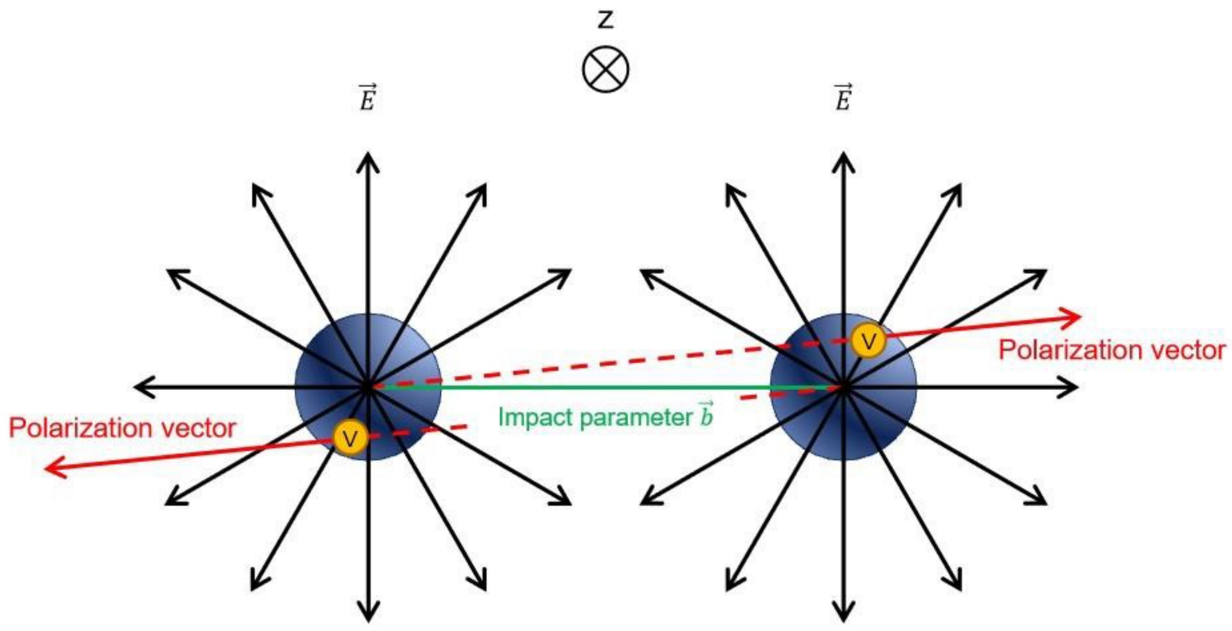
Afnan Shatat (for ALICE), QM 2023

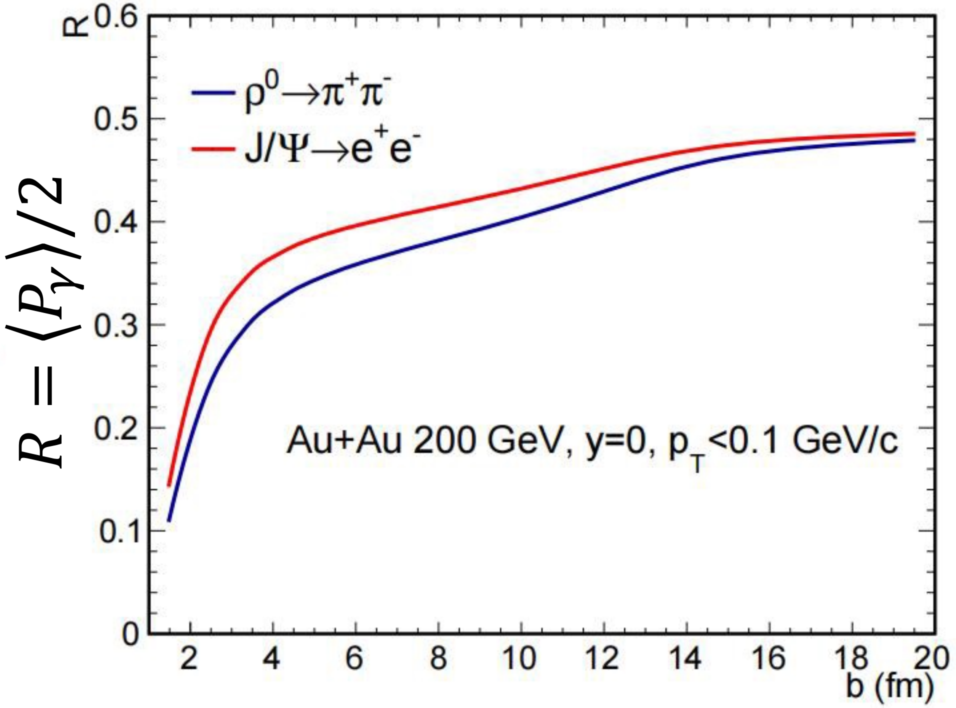


Transfer of helicity from photon to the produced vector meson J/ψ

Align the Reaction Plane in Heavy Ion Collisions

X. Wu..., W. Zha*, Phys. Rev. Res. 4, L042048 (2022)



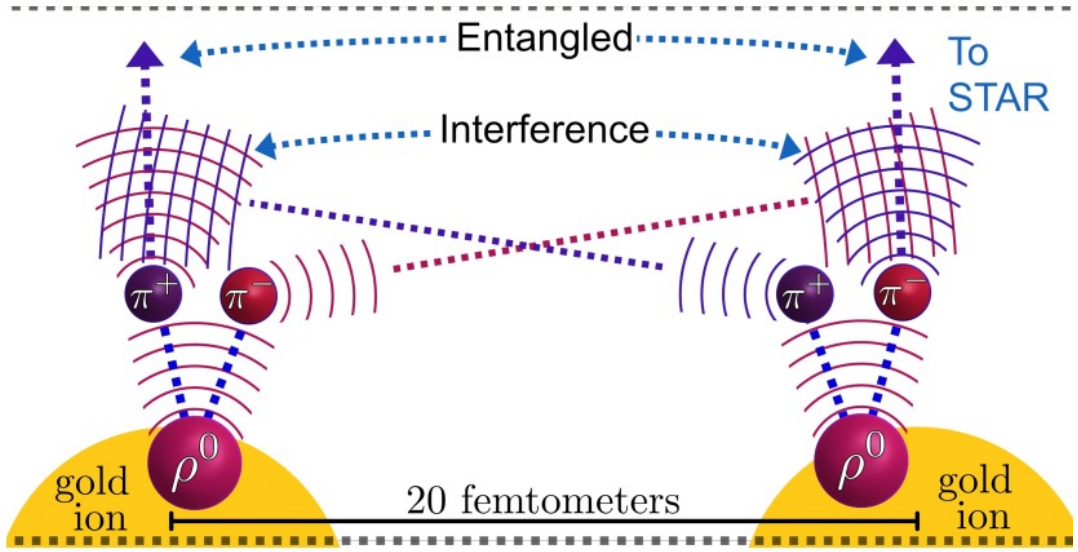


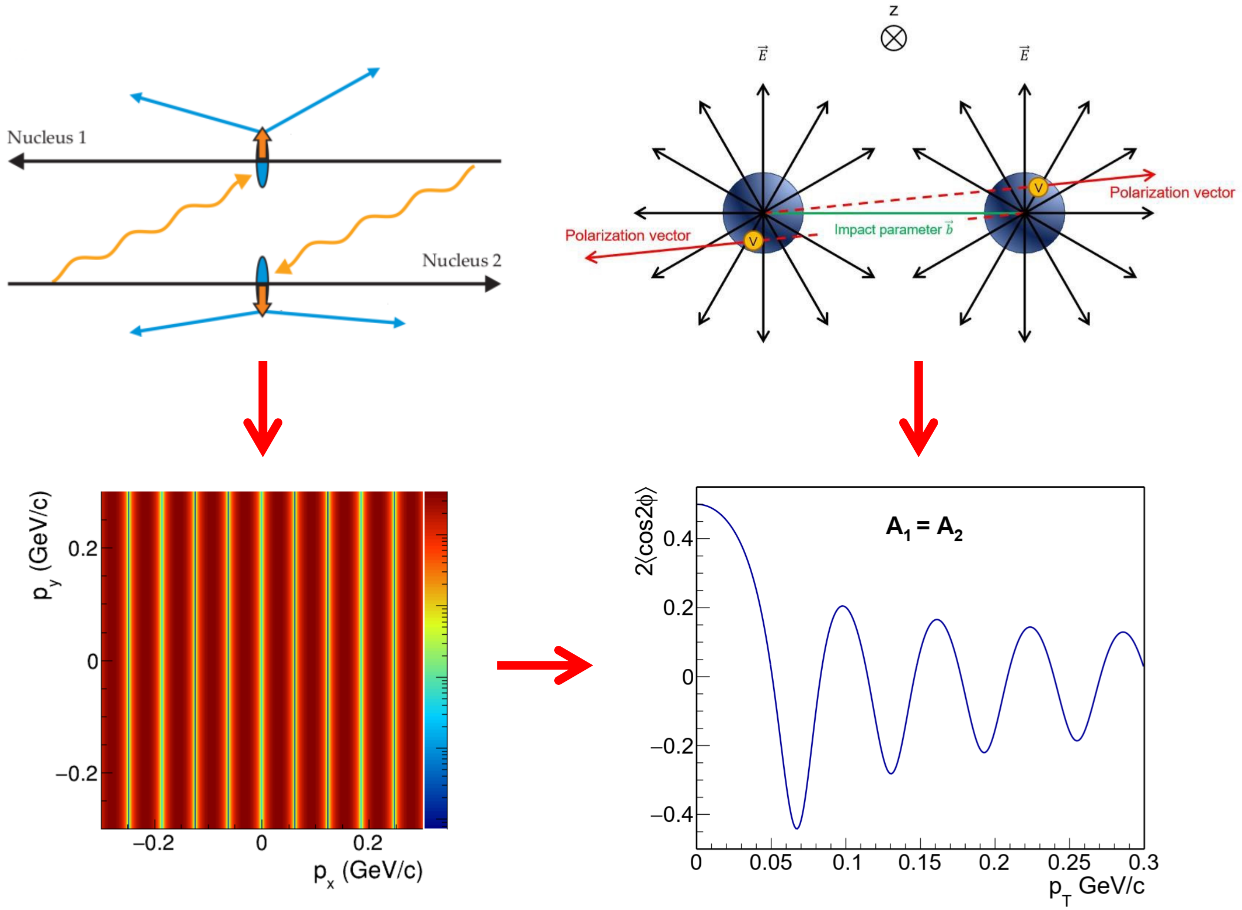
- Photoproduced vector mesons inherit the polarization of photons, which is completely determined by the initial collision geometry
- Reaction plane resolution is better than traditional approach in semi–central and (ultra)peripheral collisions

Linear Polarization + Double-slit Interference

STAR, Sci. Adv. 9, eabq3903 (2023)

W. Zha et. al., PRD103, 033007 (2021)

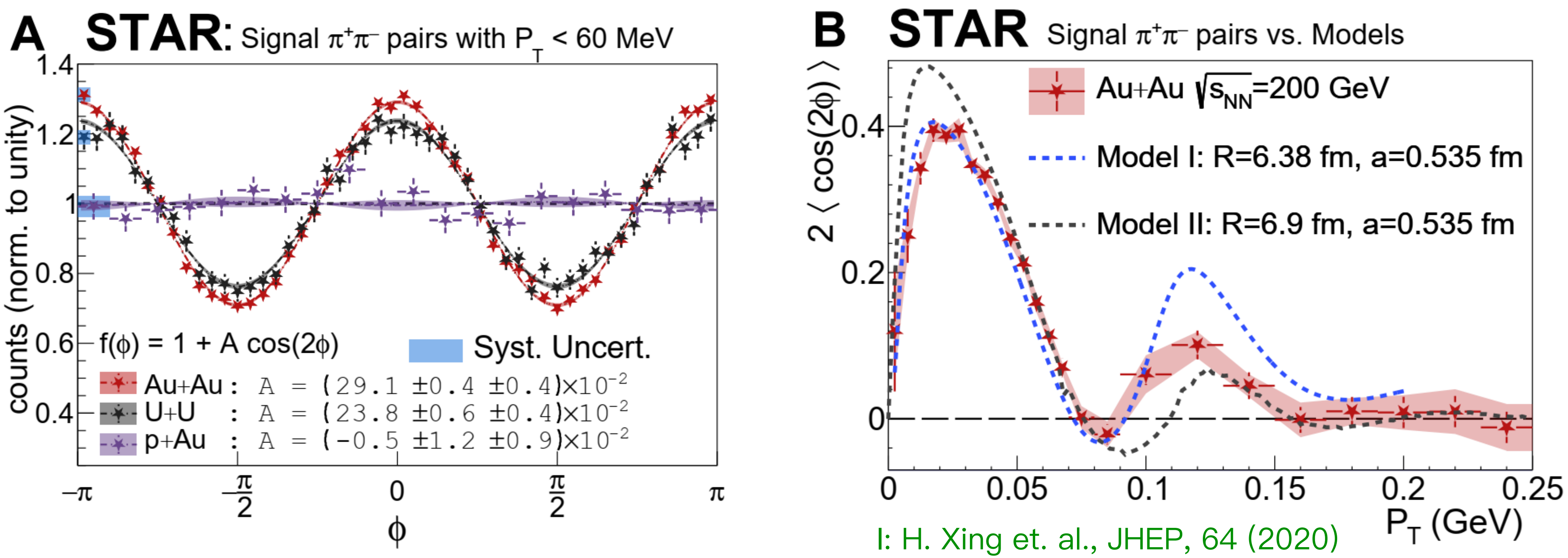




Result in p_T dependent second order $\Delta\phi$ modulation

Modulation of ρ−meson Decay

STAR, Sci. Adv. 9, eabq3903 (2023)



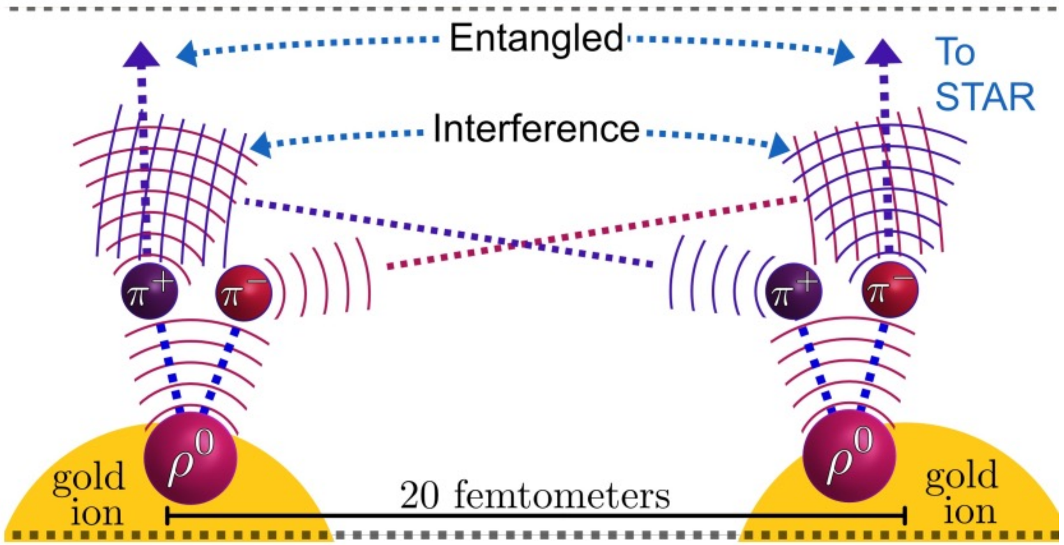
I: H. Xing et. al., JHEP, 64 (2020)
II: W. Zha et. al., PRD103, 033007 (2021)

Significant second order modulation of $\Delta\phi$ observed in A+A but not in p+A

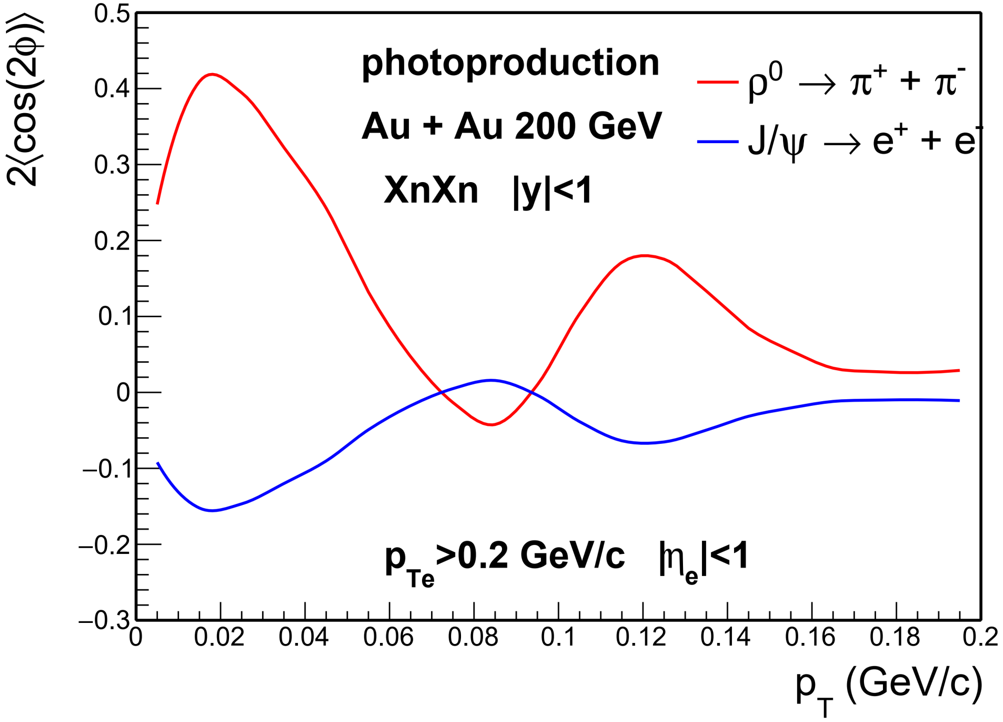
Clear difference between Au+Au and U+U

- Sensitive to nuclear geometry / gluon distribution

The Case for J/ψ



W. Zha et. al., PRD103, 033007 (2021)



Difference between J/ψ and ρ

- Lifetime: 2160 fm/c vs. 1.3 fm/c

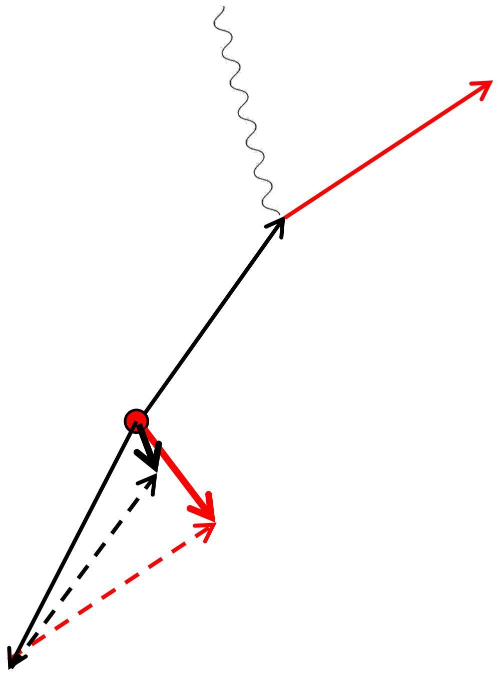
→ Decay length is much larger than the impact parameter

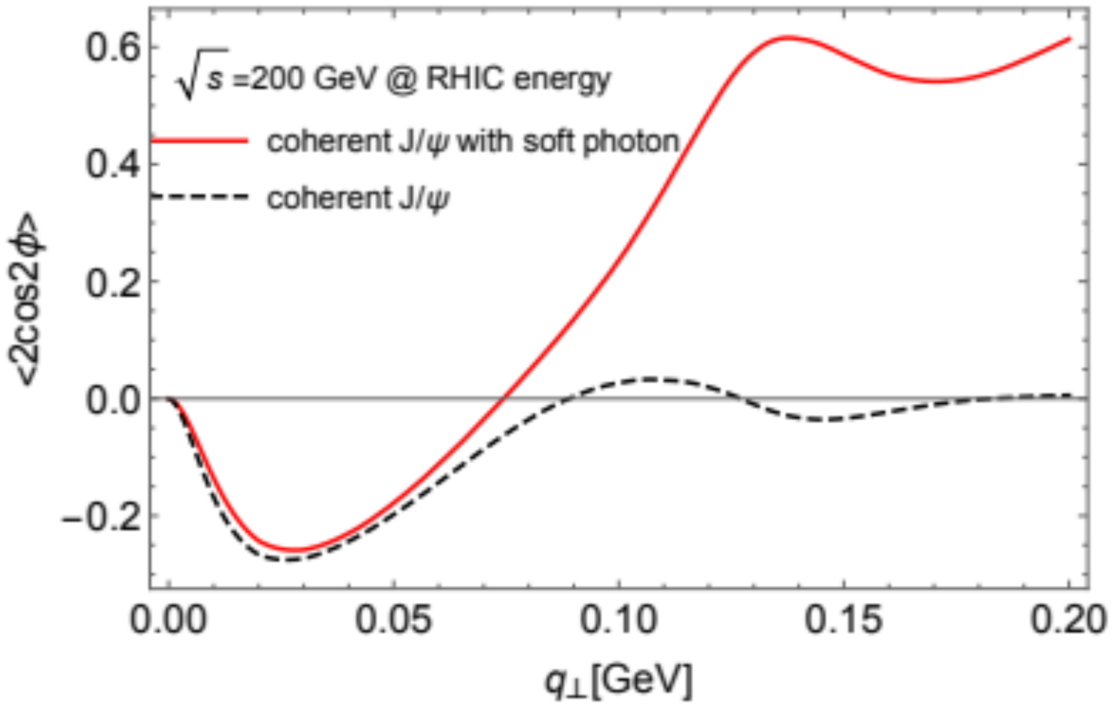
- Daughters: electrons (fermions) vs. pions (bosons)

→ Opposite sign of second modulation

Effect of Soft Photon Radiation

J. Brandenburg, Z. Xu, W. Zha, C. Zhang, 周剑 and Y. Zhou, PRD106, 074008 (2022)



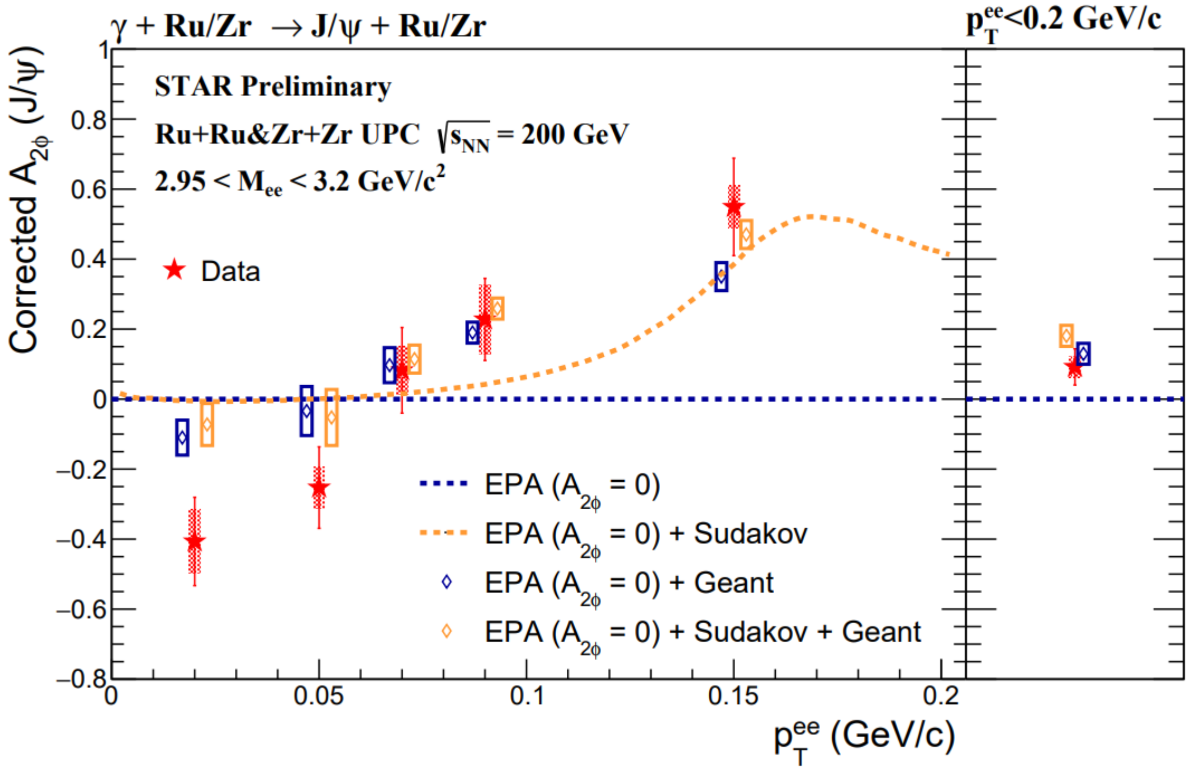


Soft photon radiation change both ϕ and $q_{\perp}$

Generates large $A_{2\phi}$ at relative large $q_{\perp}$

J/ψ Angular Modulation in Isobaric Collisions

Kaiyang Wang (for STAR), UPC2023



Increasing trend of modulation for J/ψ observed in Ru+Ru/Zr+Zr

p_T>0.1 GeV/c: dominated by internal and external radiation

p_T<0.1 GeV/c: 2.4σ lower than MC with zero modulation input

Summary

- Photoproduct in HIC is a golden probe of the strong electromagnetic field
  - Results provide strong constraint on the spatial distribution of the field
  - All the results support linear polarization
  - Spin interference generates many interesting phenomena
- It also provides a great laboratory to study:
  - Quantum entanglement
  - QGP in EM field
  - Nuclear charge/gluon distributions
  - QED high order effect
  - Exotics (τ g–2, axion–like particle)
  - …

Thank you!

The 2nd Workshop on Ultra-Peripheral Collision Physics: Strong Electromagnetic fields, UPC and EIC

2024年4月
Asia/Shanghai 时区

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The 2nd Workshop on Ultra-Peripheral Collision Physics:

Strong Electromagnetic fields, UPC and EIC/EICC

In relativistic heavy ion collisions, two charged nuclei collide with each other and generate the strong electromagnetic (EM) fields of the order or 10^17 - 10^18 Guass. The strong EM field provides a new platform to study novel phenemeona. It can induce the chiral or spin transport, associated with chiral anomaly and parity violation of QCD. In the ultraperipheral collisions (UPC), photon-photon and photon-nuclear interactions have been widely studied.

The 2nd workshop on UPC Physics will be held in April at University of Science and Techonolgy of China (USTC). It will feature a range of presentations and discussion sessions covering a broad range of topics related to UPC physics, including quark matter under strong EM fields, photon-nuclear interaction, Electron-Ion Collider (EIC) and the Electron-Ion Collider in China (EicC) physics. The workshop will provide an excellent opportunity for researchers, students, and experts to exchange ideas, share insights, and develop collaborations that can help to advance the field.

Key topics to be covered at the workshop include:

- Theoretical and experimental studies of UPCs
- Advancing technology for UPC experiments
- Quark matter under strong EM fields or rotation
- Probing the structure of the nucleus
- Photon-photon and photon-nulcear interaction in EIC/EICC

We invite researchers, students, and experts in the field related to UPC physics to participate in the 2nd workshop on UPC and contribute to a lively and stimulating scientific exchange. Register now to secure your place and take part in this exciting event. We look forward to seeing you there!