Photoproduction of J/ψ from ultra-peripheral to central collisions

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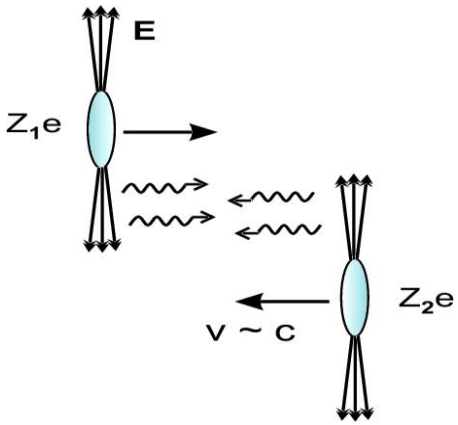
HF2022: Heavy Flavours from small to large systems,
Oct. 3-21 2022, Institut Pascal, Orsay, France

Coherent photons as “partons” in heavy-ion collisions



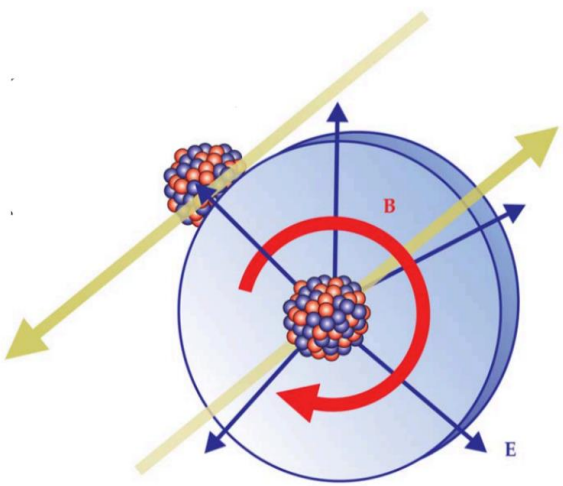
Coherent limitation: $Q^2 \leq 1/R^2$ => quasi-real !

Photon four momentum: $q^u = (\omega,\ \vec{q}_T, \omega/v)$

$$Q^2 = \frac{\omega^2}{\gamma^2} + q_T^2$$

$$\omega \leq \omega_{max} \sim \frac{\gamma}{R}$$

- View photons as “partons” being present with fast moving ions!



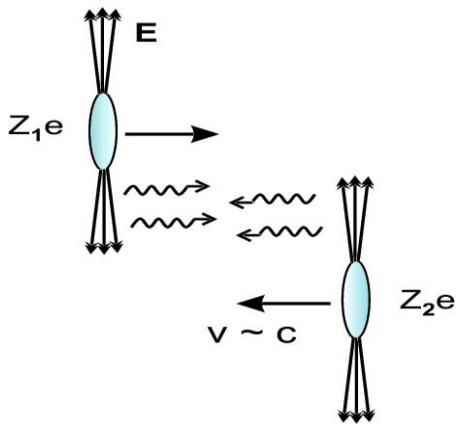
Physics Today **70**, 10, 40 (2017)

The extent of photons swarming about the ions:

The radius of nuclear matter R_{Nuc} ~ 6.3 fm (Au)
$R_{photons}$ >> R_{Nuc}

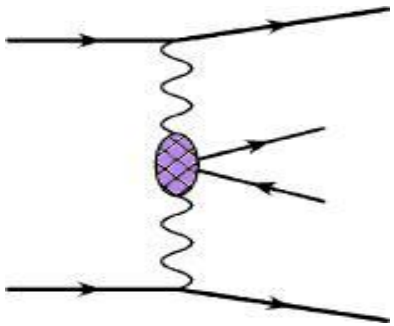
Take the photoproduction of ρ (Au+Au 200 GeV)in ultra-peripheral collisions (UPCs) as example: <$R_{producton}$> ~ 40 fm

Photon interactions in A+A



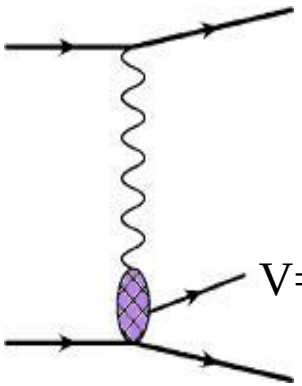
Electromagnetic interaction

=



Photon-photon interactions

+



Photon-nucleus interactions

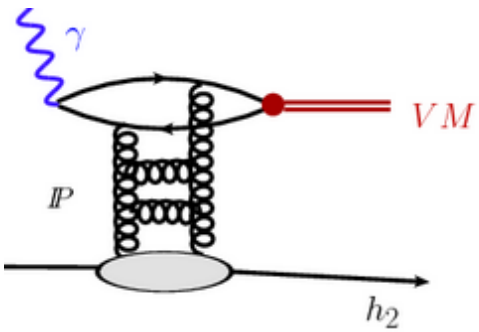
Ann. Rev. Nucl. Part. Sci.**55**:271 (2005)

$V=\rho, \omega, \phi, J/\psi$

- This large flux of quasi-real photons makes a hadron collider also a photon collider!
  - ✓ Photon-nucleus interactions: Vector meson
  - ✓ Photon-photon interactions: dileptons …
- Conventionally believed to be only exist in ultra-peripheral collisions (UPC) to keep “coherent”!

Vector meson photon-production

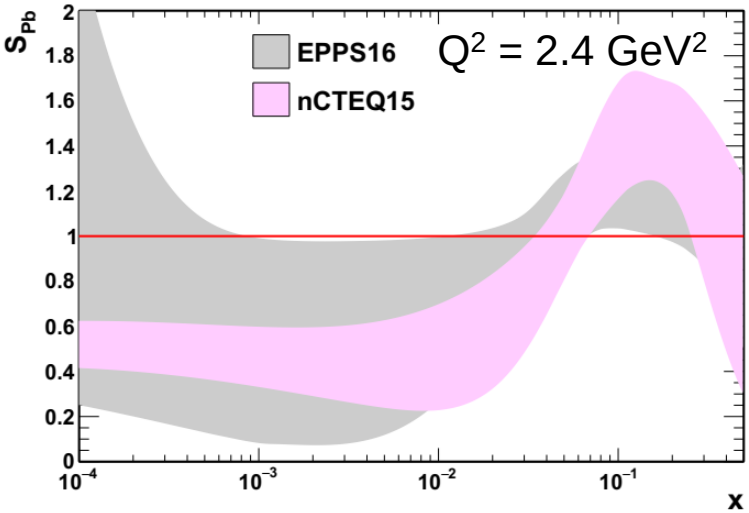
- Vector meson production:
  - ✓ chargeless 'Pomeron exchange'
  - ✓ Light meson production is usually treated via vector meson dominance model: ρ, direct $\pi^+\pi^-$, ω….
  - ✓ Heavy quarkonia production could be treated with pQCD: J/ψ, ψ', Υ(1S), Υ(2S), Υ(3S)…



- Sensitive to the gluon distribution:

$$\left.\frac{d\sigma(\gamma A \to VA)}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[xG_A(x,Q^2)\right]$$

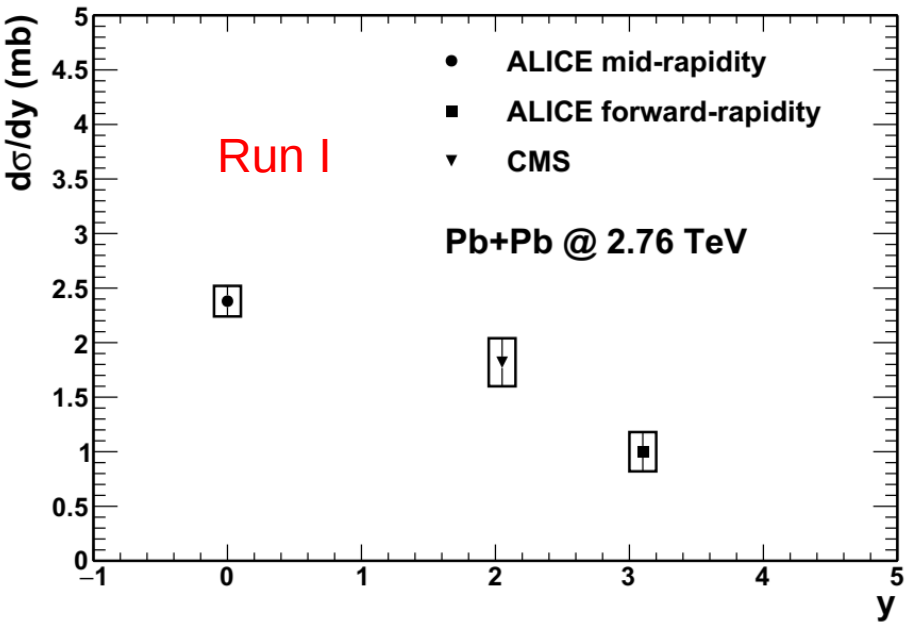
$$x = \frac{M_V e^{\pm y}}{\sqrt{s}} \quad Q^2 = M_V^2/4$$

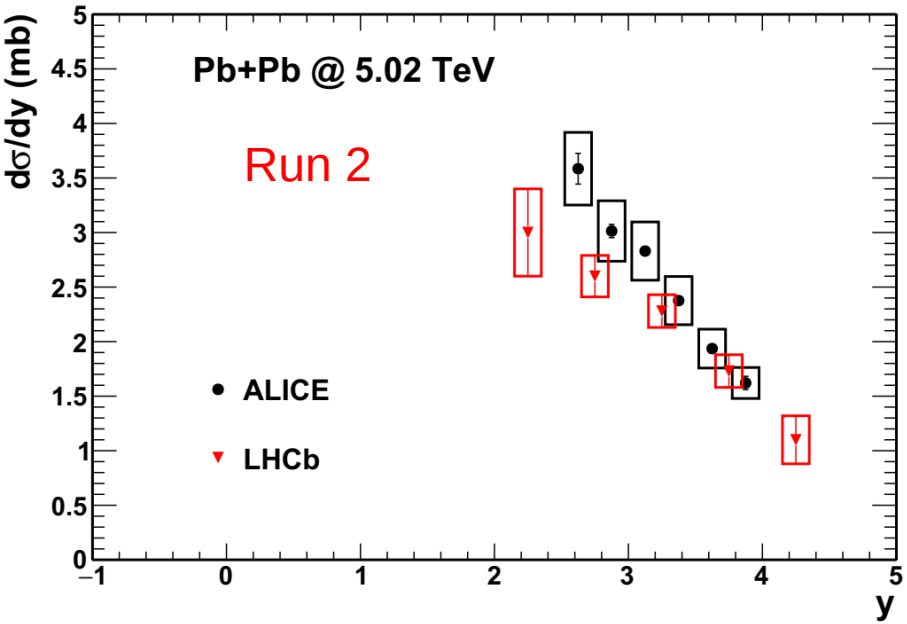


EPPS16: EPJC **77** (2017) 163

nCTEQ15:PRD **93** (2016) 085037

J/ψ photoproduction in Pb+Pb UPCs





ALICE: EPJC **73** (2013) 2617

ALICE: PLB **718** (2013) 1273

CMS: PLB **772** (2017) 489

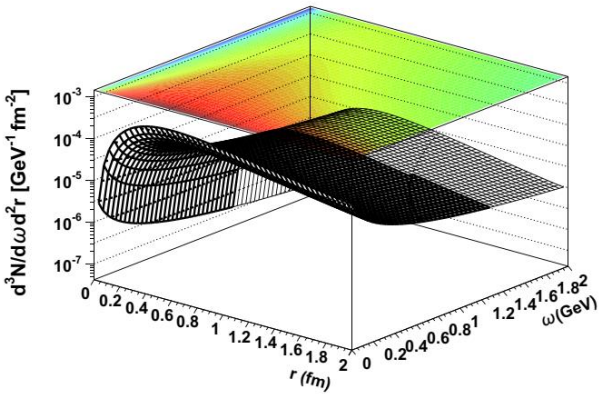
ALICE: PLB **798** (2019) 134926

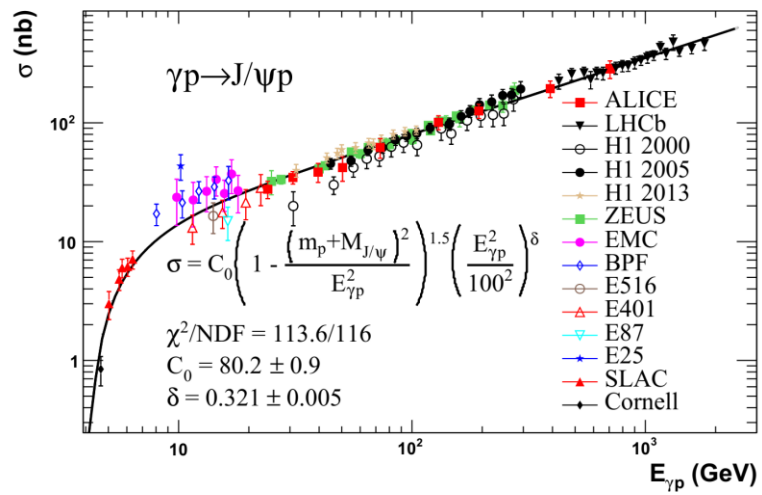
LHCb: LHCb-CONF-2018-003

Various precise measurements!
Powerful to constrain nPDF

The framework: impulse approximation

$$\frac{d\sigma_{AA\to AAJ/\psi}(y)}{dy} = N_{\gamma/A}(y)\sigma_{\gamma A\to J/\psi A}(y) + N_{\gamma/A}(-y)\sigma_{\gamma A\to J/\psi A}(-y)$$





Z. Cao etal., Chin. Phys. C**43** (2019) 064103

Equivalent photon approximation

$$\sigma(\gamma A \to \mathrm{J}/\psi A) = \left.\frac{d\sigma(\gamma A \to \mathrm{J}/\psi A)}{dt}\right|_{t=0} \times$$

$$\int |F_P(\vec{k}_P)|^2 d^2\vec{k}_{P\perp} \qquad \vec{k}_P = (\vec{k}_{P\perp}, \frac{\omega_P}{\gamma_c})$$

$$\omega_P = \frac{1}{2}M_{\mathrm{J}/\psi}e^{\pm y} = \frac{M^2_{\mathrm{J}/\psi}}{4\omega_\gamma}$$

V. Guzey and M. Zhalov, JHEP 10 (2013) 207

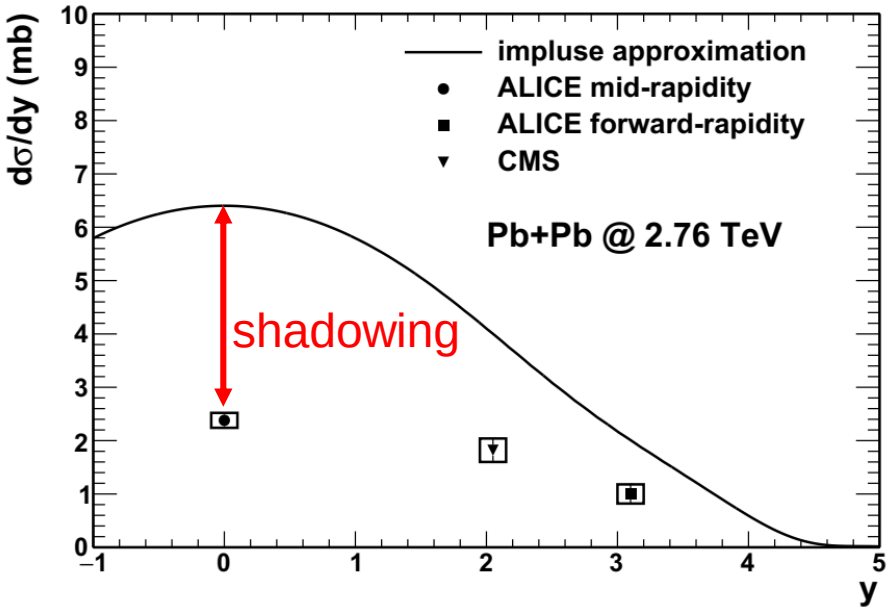
Impulse approximation

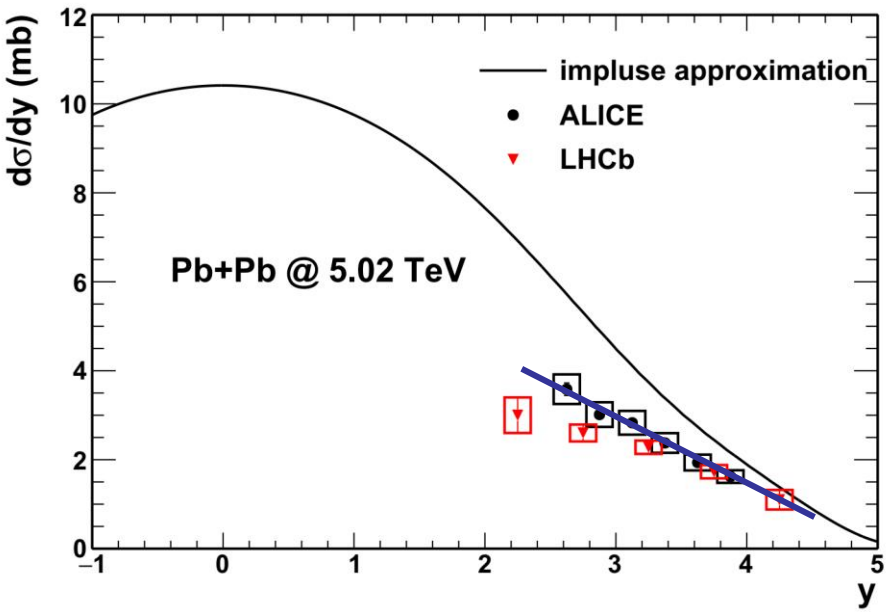
$$d\sigma_{\gamma A}/dt|_{t=0} = d\sigma_{\gamma p}/dt|_{t=0} \times A^2$$

$$d\sigma_{\gamma p}/dt = \sigma_0 \times e^{-bt}$$

$$d\sigma_{\gamma p}/dt|_{t=0} = \sigma_{\gamma p} \times b$$

The results: impulse approximation

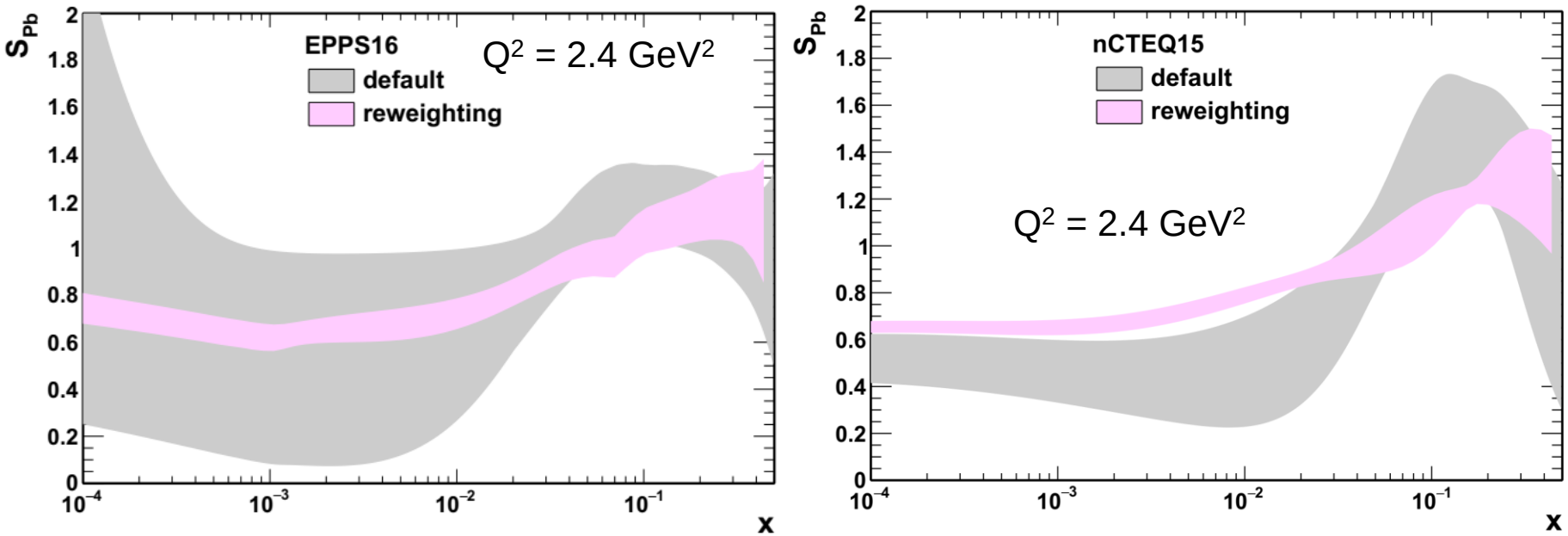




Ambiguity for x determination in forward rapidity (y!=0)!

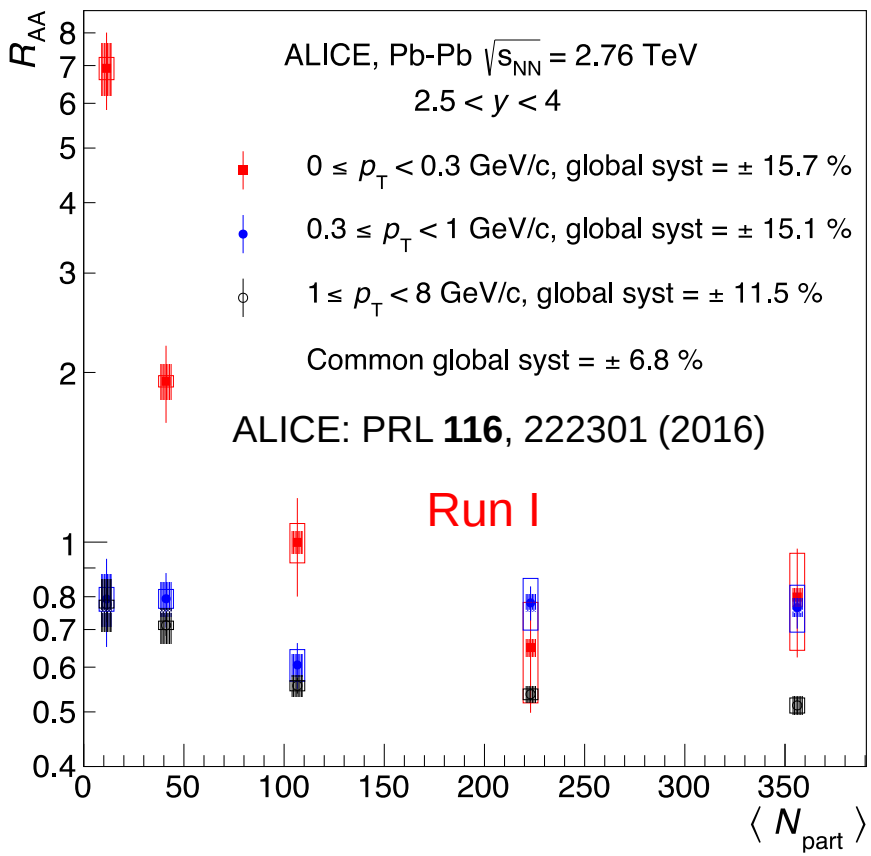
- The impulse approximation significantly overestimates the data => Significant shadowing effect
- The difference becomes smaller towards forward rapidity => Less shadowing effect towards high x

Nuclear shadowing from J/ψ measurements in UPCs



- The UPC measurements dramatically reduce the uncertainty band of EPPS16 and nCTEQ15 PDF sets.
- Significant shadowing effect has been observed in both PDF sets at small x.

Anomalous excess of J/ψ production observed at ALICE

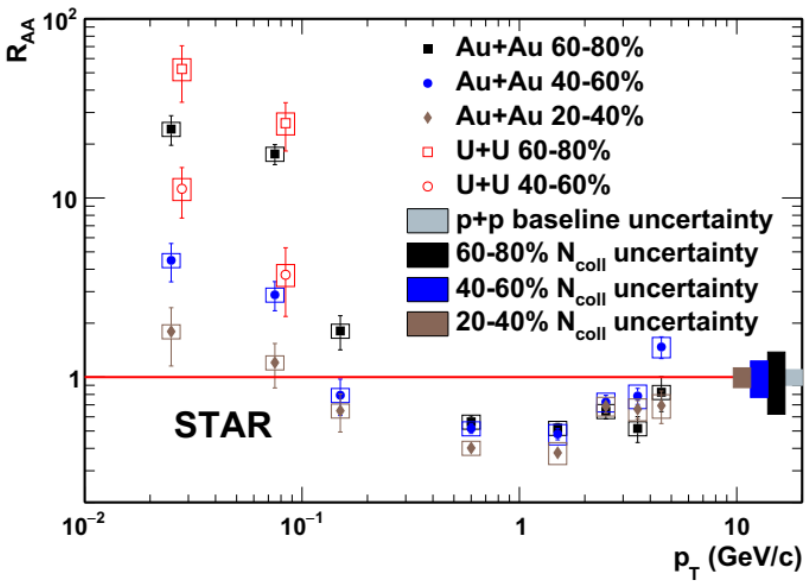


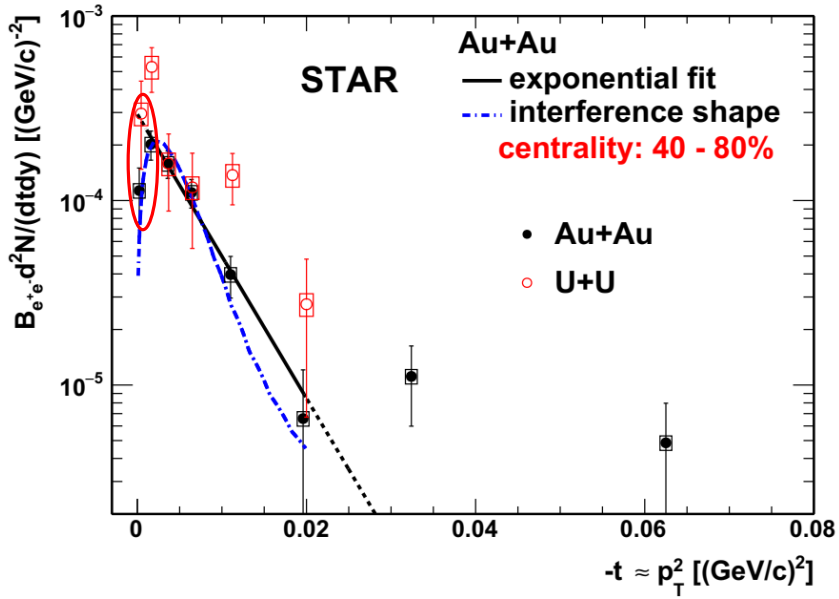
- Significant enhancement of J/ψ yield observed in p_T interval 0 – 0.3 GeV/c for peripheral collisions (50 – 90%).
- Can not be described by hadronic production modified by the hot medium or cold nuclear matter effects!

- Origin from **coherent photon-nucleus interactions**?

The observations at STAR

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





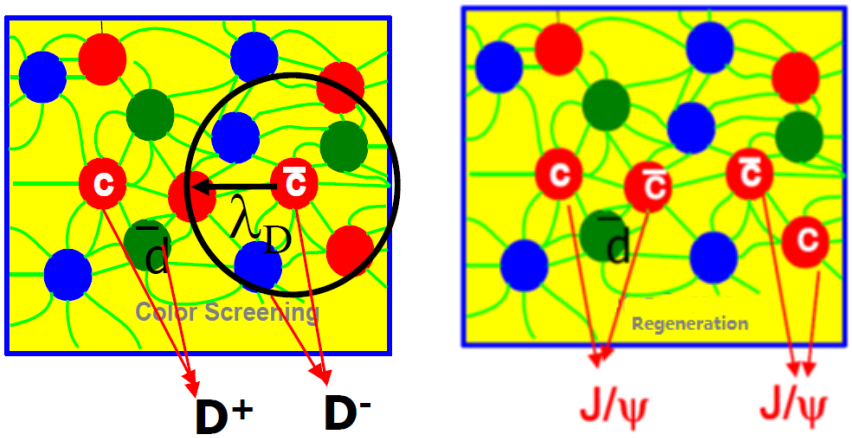
- Significant enhancement of J/ψ yield observed at p_T interval 0 – 0.2 GeV/c for peripheral collisions.
- No significant difference between Au+Au and U+U collisions.

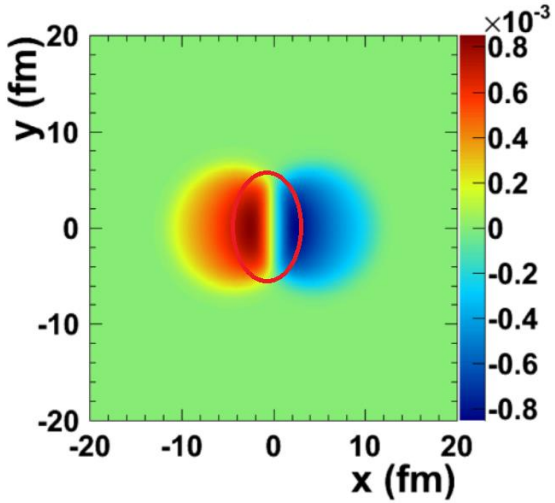
- Similar structure to that in UPC case!
- Indication of interference!
  - ✓ Interference shape from calculation PRC **97** (2018) 044910
- Similar slope parameter!
  - ✓ Slope from STARLIGHT prediction in UPC case – 196 (GeV/c)$^{-2}$
  - ✓ Slope w/o the first point: 177 ± 23(GeV/c)$^{-2}$ χ^2/NDF = 1.7/2

A novel probe for QGP?

- Hot medium effects:
  - ✓ Color Screening
    - -"Smoking gun" signature for QGP PLB **178** (1986) 416
  - ✓ Regeneration
    - -Recombination of charm quarks
- Cold Nuclear Matter effects:
  - ✓PDF modification in nucleus
  - ✓Initial state energy loss
  - ✓…

A cleaner probe of color screening?



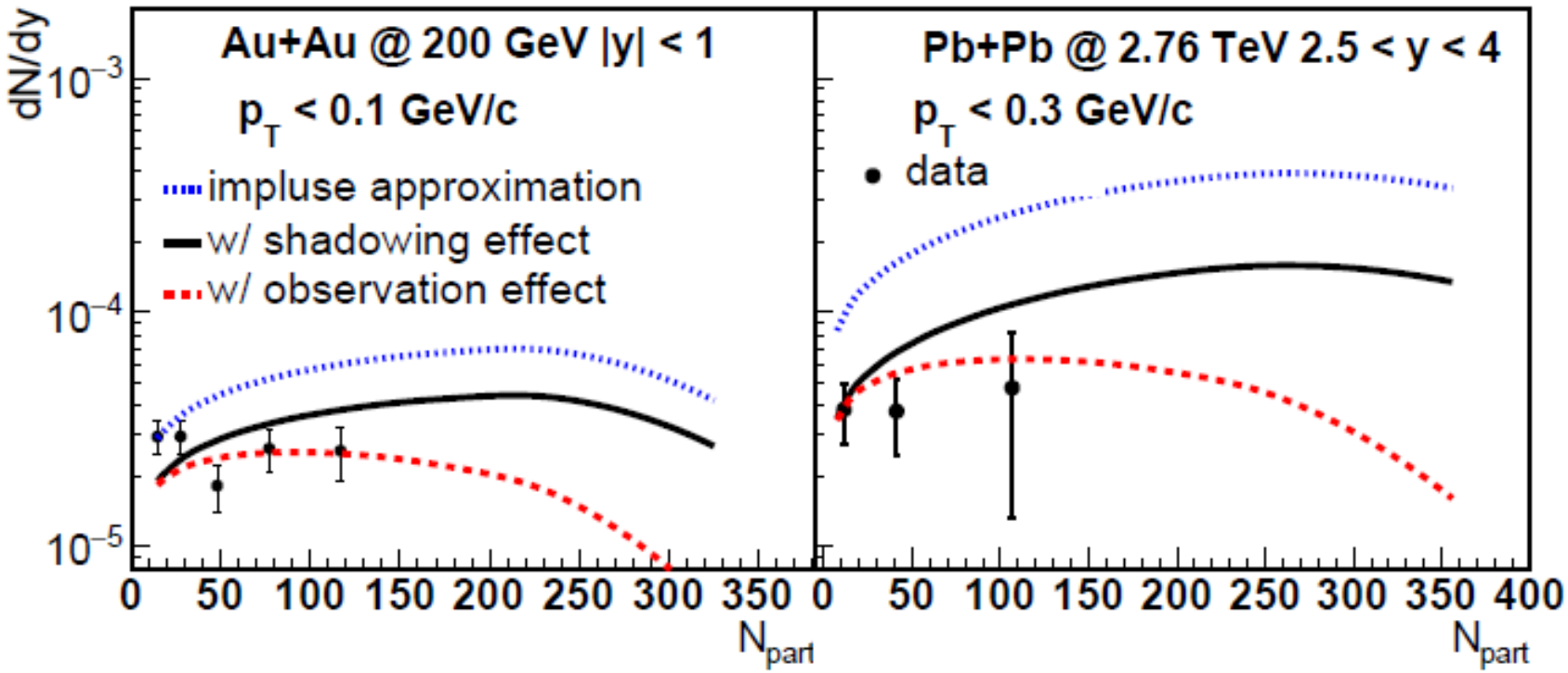


b=10fm

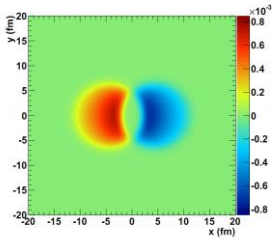
PRC 99 (2019) 6, 061901

The key question: baseline?

Comparison with model calculation

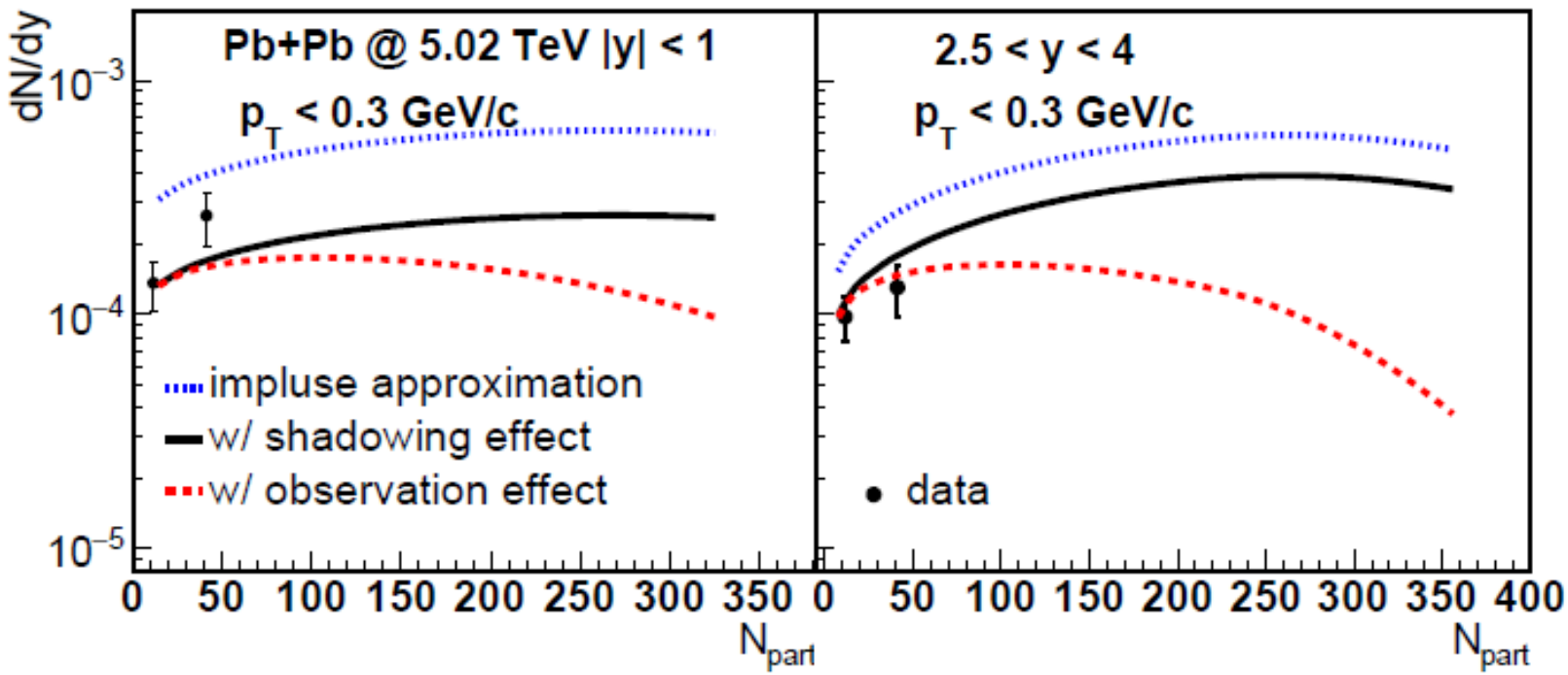


- Well described by the coherent photoproduction mechanism for peripheral collisions
- Hint of disruption from the medium
  - ✓ The observation effect
  - ✓ The QGP swallowing



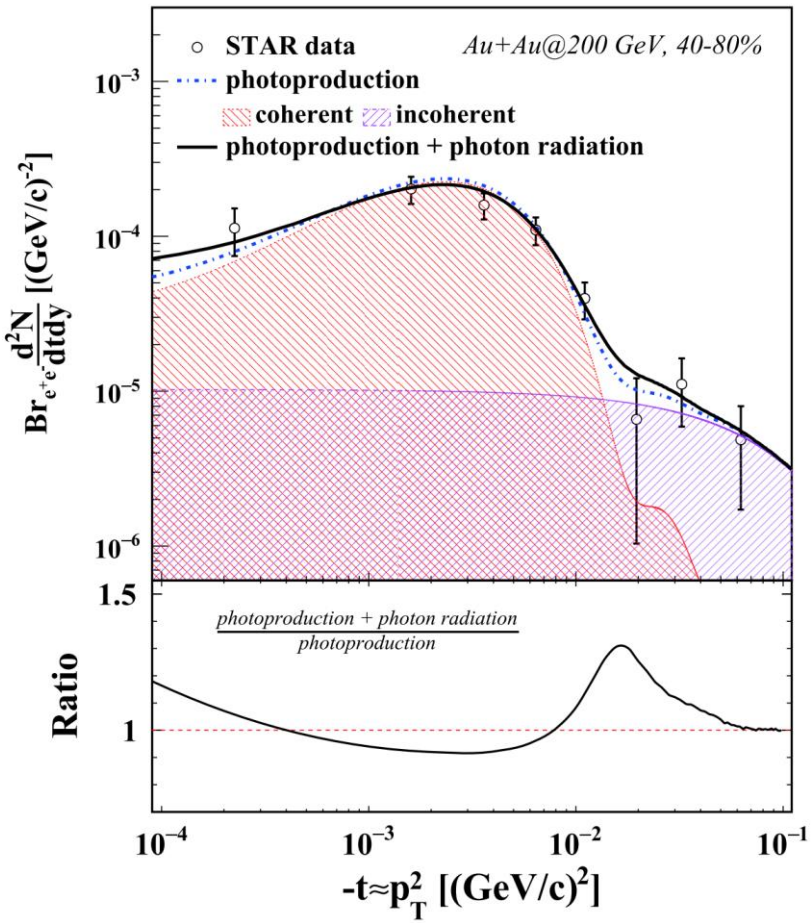
Comparison with model calculation

ALICE: ALI-PREL-309953



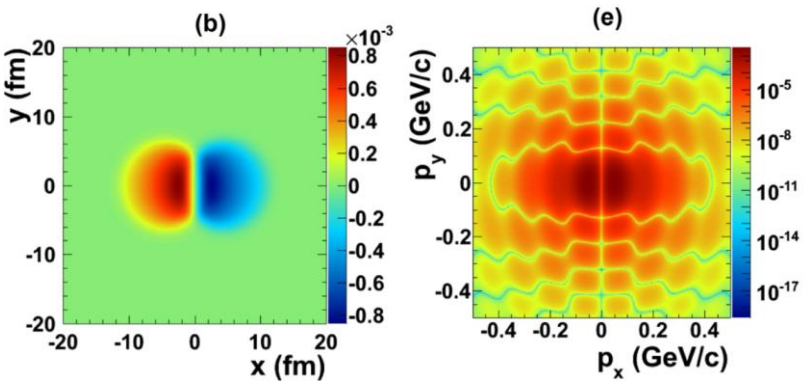
- Well described by the coherent photoproduction mechanism for peripheral collisions
- Hint of disruption from the medium
  - ✓ More statistics at mid-rapidity
  - ✓ More precise measurements toward central collisions

Comparison with model calculation



Chinese Phys. C (2022) **46** 074103

The destructive interference



The internal photon radiation

$$J/\psi(p_0) \rightarrow e^-(p_1) + e^+(p_2) + \gamma(k)$$

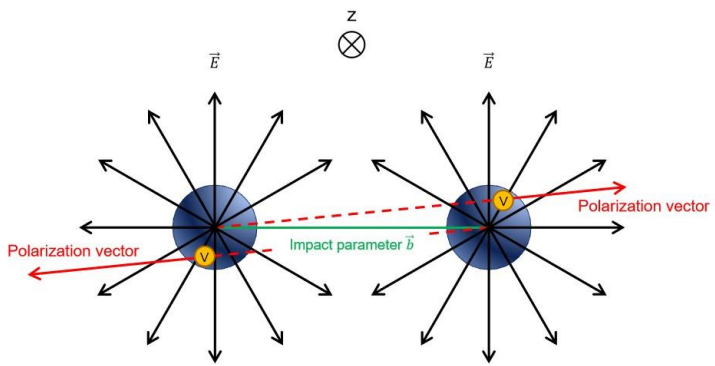
Consistent with current picture

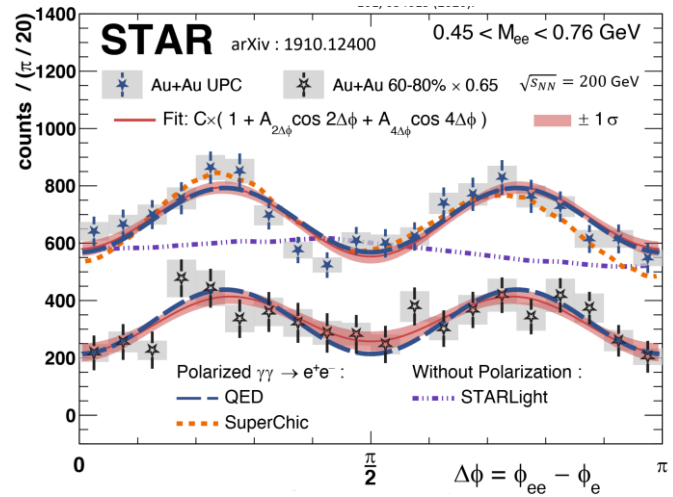
Medium effect?

- ✓ Hidden in the error, if exist

The interference in polarization space

Linearly polarized photons





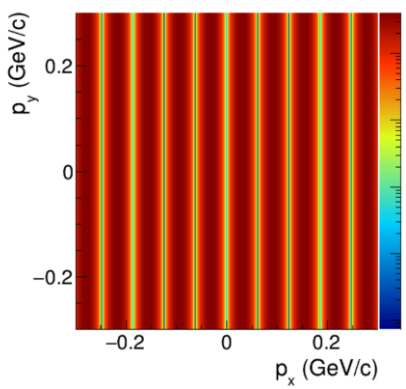
Decay along the impact parameter

Experimental evidence: PRL 127 (2021) 052302 (STAR)

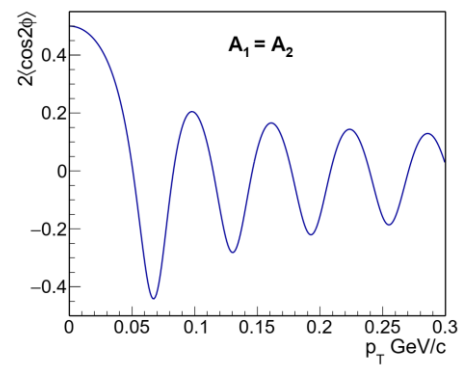
$$\frac{d^2N}{d\cos\theta d\phi} = \frac{3}{8\pi}\sin^2\theta[1+\cos 2(\phi-\Phi)]$$

Decay along the polarization direction

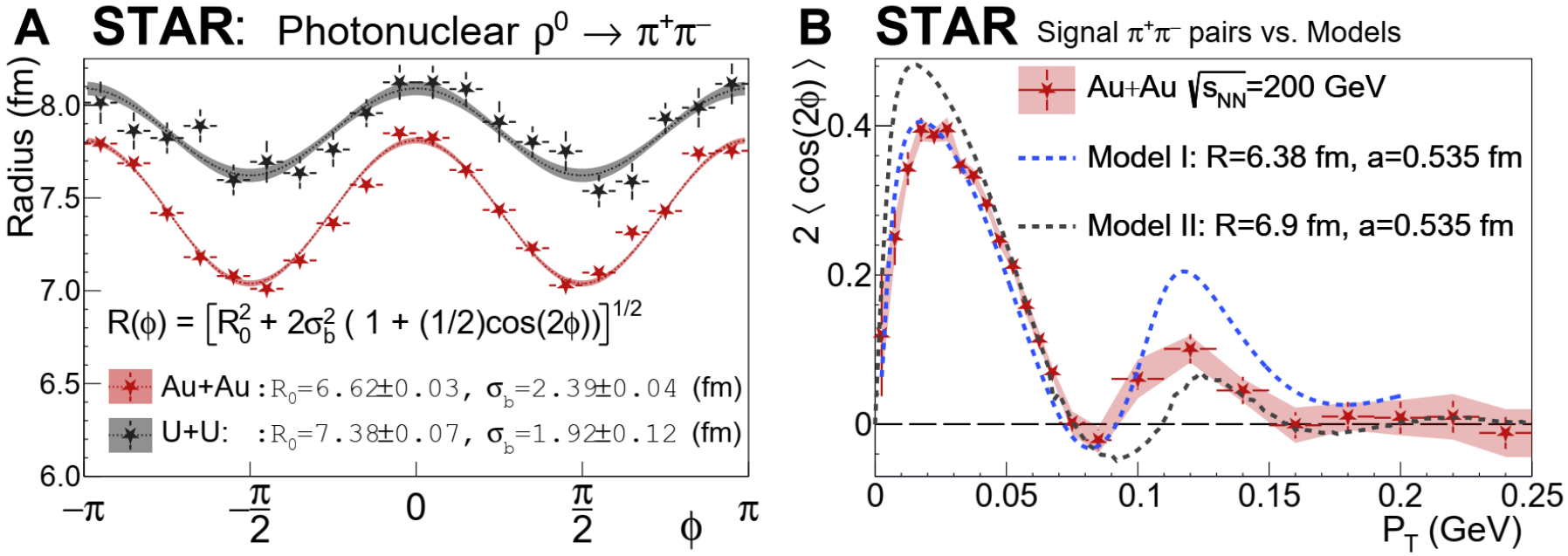
PRD 103 (2021), 033007



The second order modulation



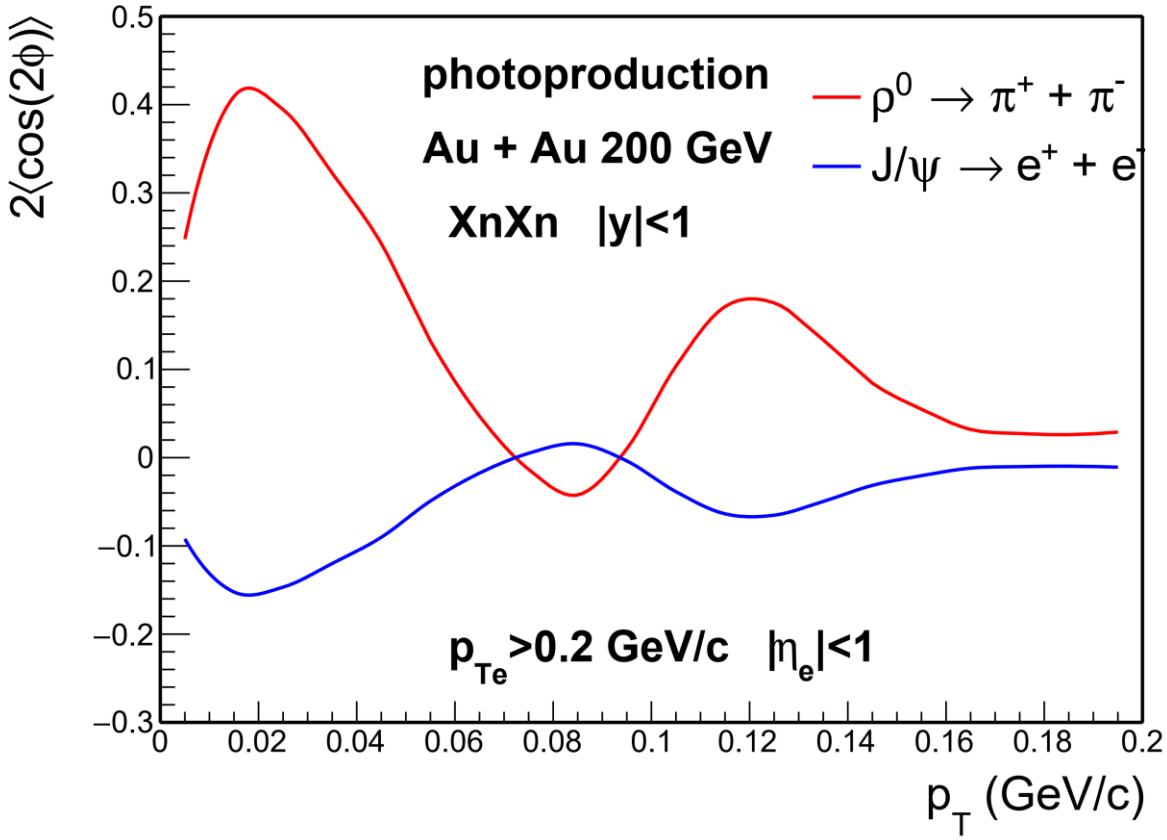
The interference in polarization space



STAR Collaboration，arXiv：2204.01625

Double slits interference in polarization space

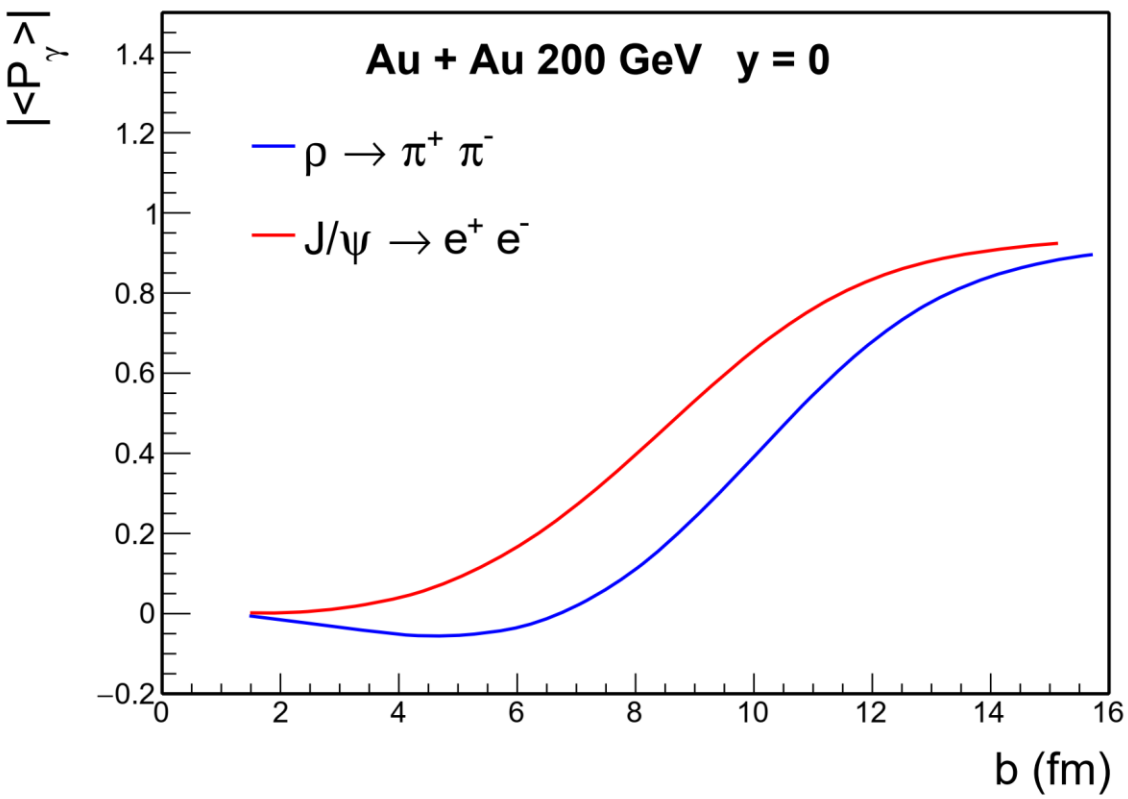
The prediction for J/ψ



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

Also significant for J/ψ -> e^+e^-

Align the reaction plane with coherent produced J/ψ



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

- ✓ 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!

Summary

- The J/ψ photoproduction in UPCs
  - ✓Constrain the nPDF (theoretical uncertainties?)

- Existence of J/ψ photoproduction in peripheral collisions
  - ✓Novel probe for QGP?
  - ✓More precise measurement toward central collision
  - ✓More solid theoretical baseline
  - ✓Determine the initial geometry (reaction plane)?