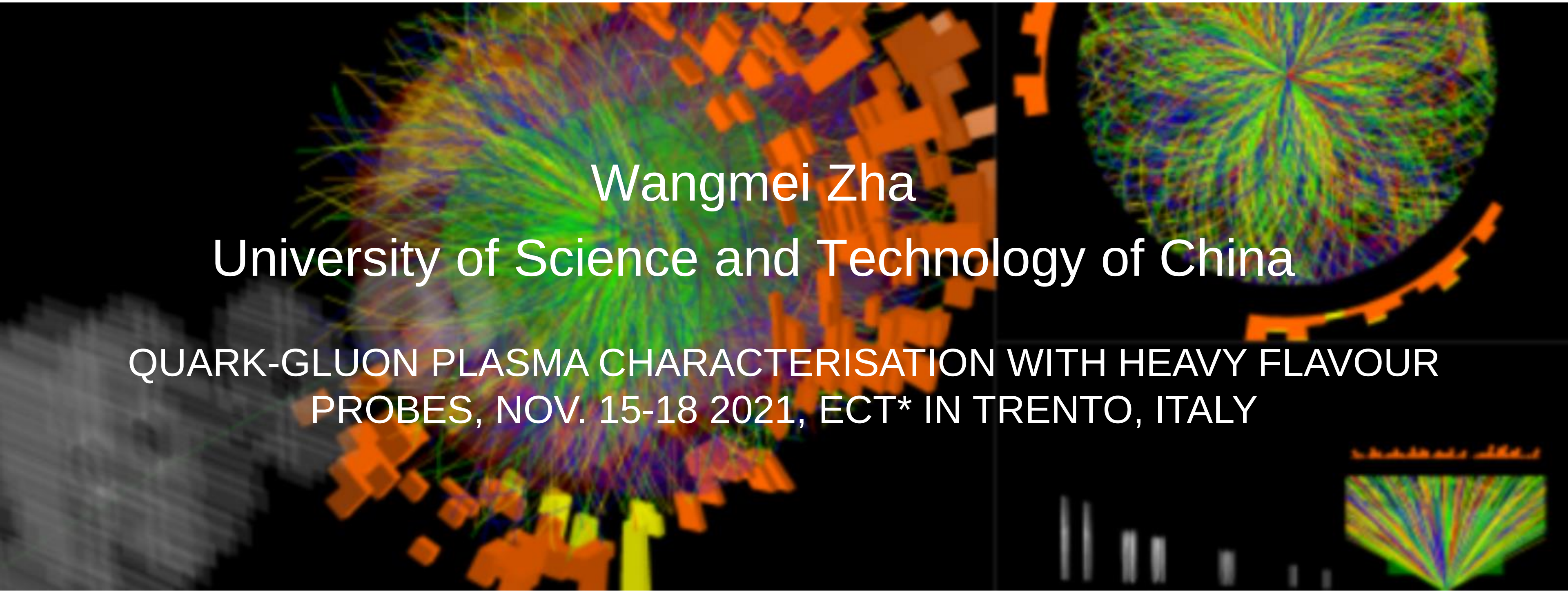
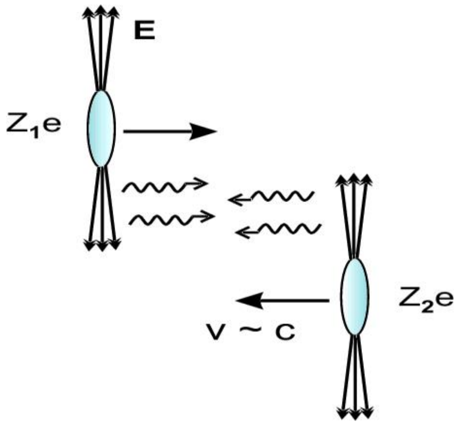
Coherent photoproduction of J/ψ in heavy-ion collisions



Wangmei Zha
University of Science and Technology of China

QUARK-GLUON PLASMA CHARACTERISATION WITH HEAVY FLAVOUR PROBES, NOV. 15-18 2021, ECT* IN TRENTO, ITALY

Coherent photons as “partons” in heavy-ion collisions



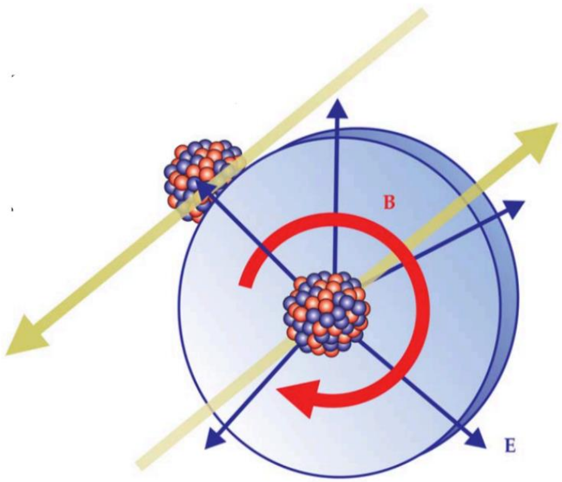
Coherent limitation: $Q^2 \leq 1/R^2$ => quasi-real !

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)

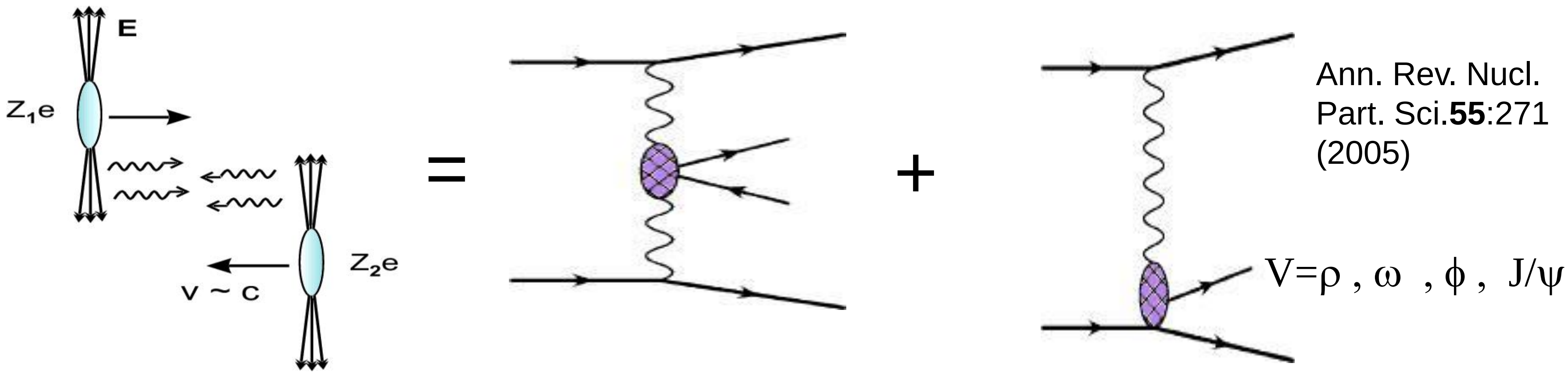
The extent of photons swarming about the ions:

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

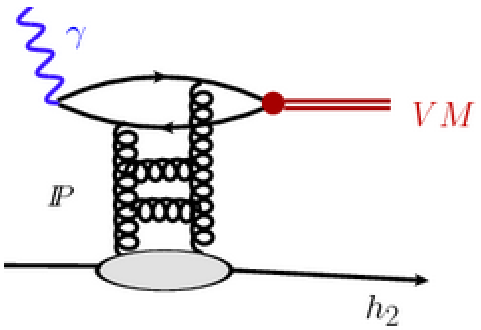
Photon-photon interactions

Photon-nucleus interactions

- 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

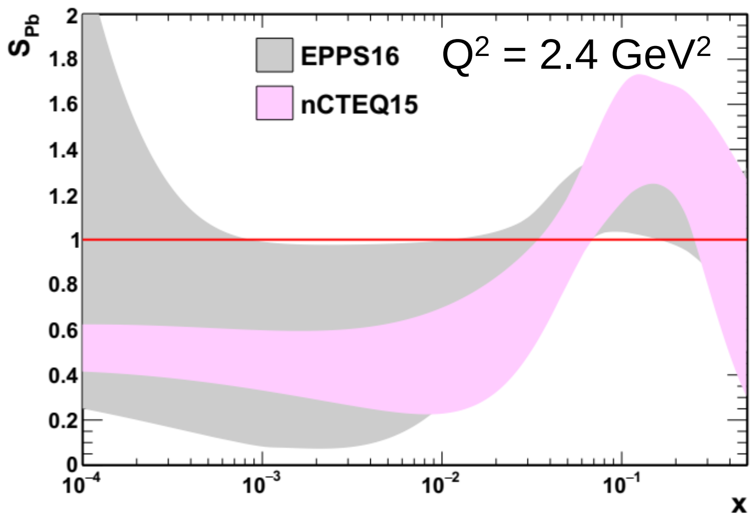
- Vector meson production:
  - ✓ chargeless 'Pomeron exchange'
  - ✓ Light meson production is usually treated via vector meson dominance model: ρ, direct $\pi^+\pi^-$, ω….
  - ✓ Heavy quarkonia production could be treated with pQCD: J/ψ, ψ', $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$…



- Sensitive to the gluon distribution:

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

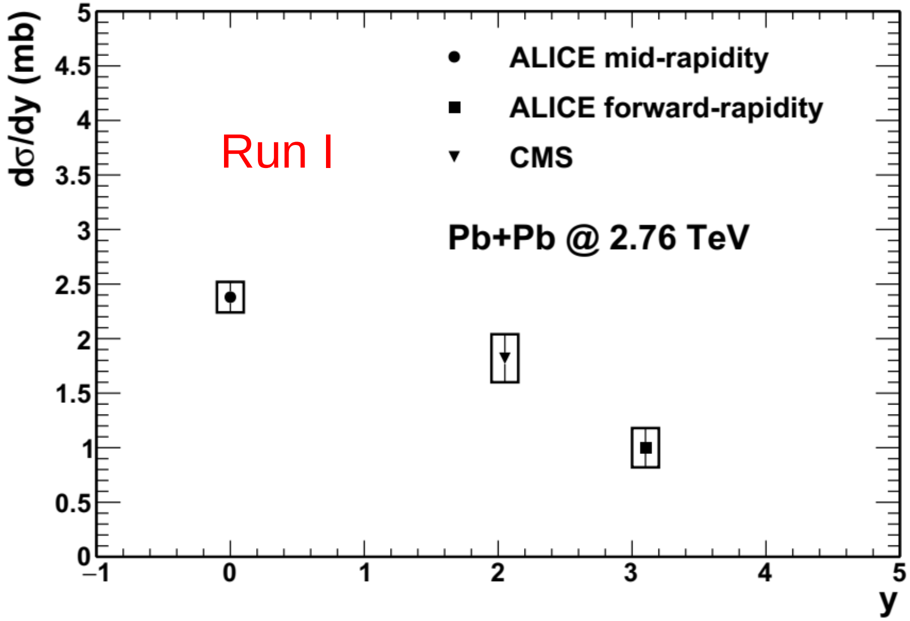
$$x = \frac{M_V e^{\pm y}}{\sqrt{s}} \quad Q^2 = M_V^2/4$$



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

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

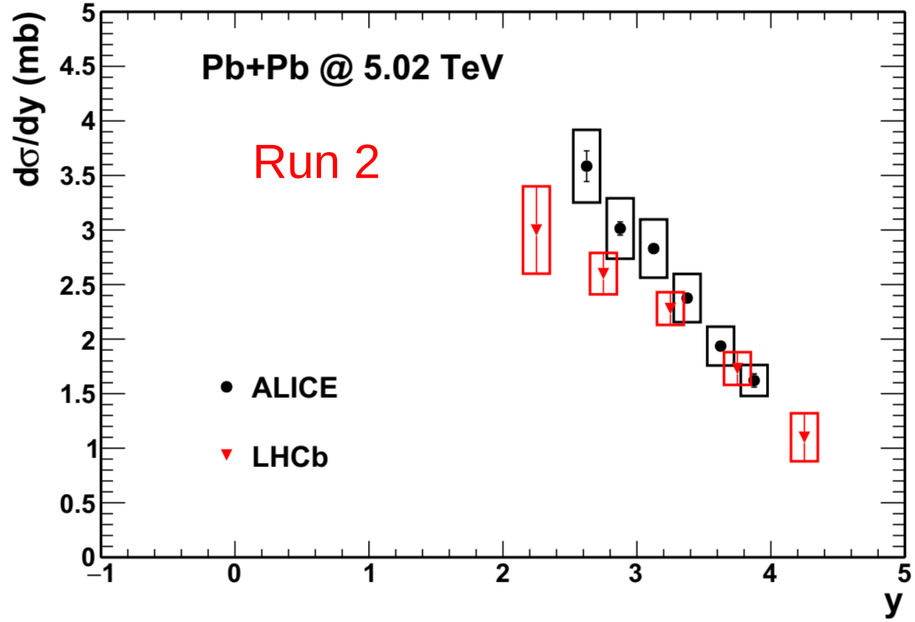
J/ψ photoproduction in Pb+Pb UPCs



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

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

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



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

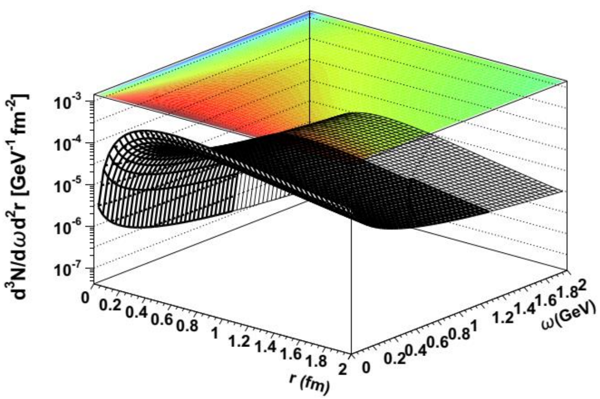
LHCb: LHCb-CONF-2018-003

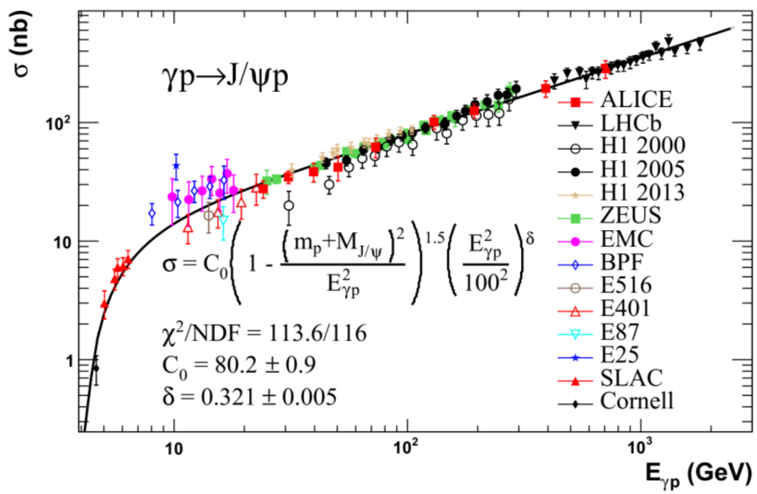
Various precise measurements!

Powerful to constrain nPDF

The framework: impulse approximation

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





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

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

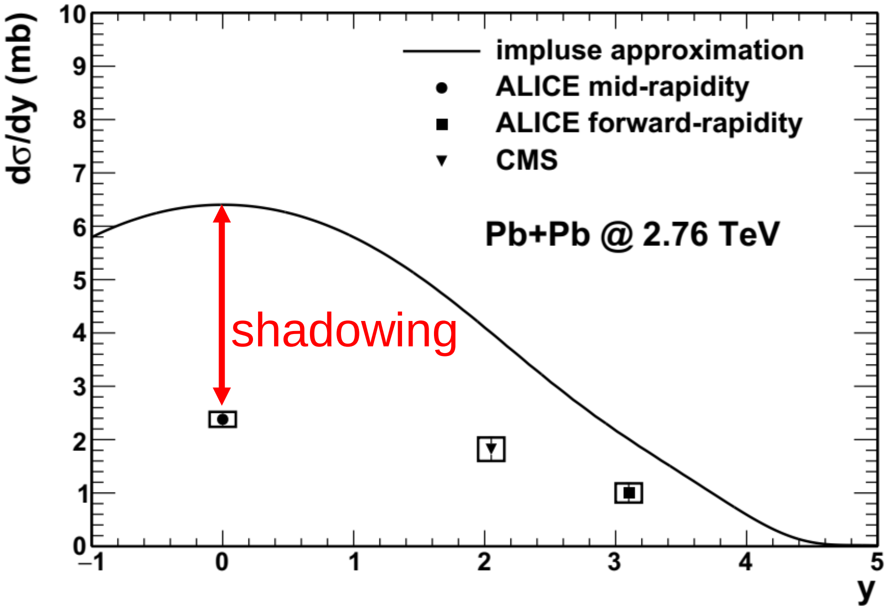
Impulse approximation

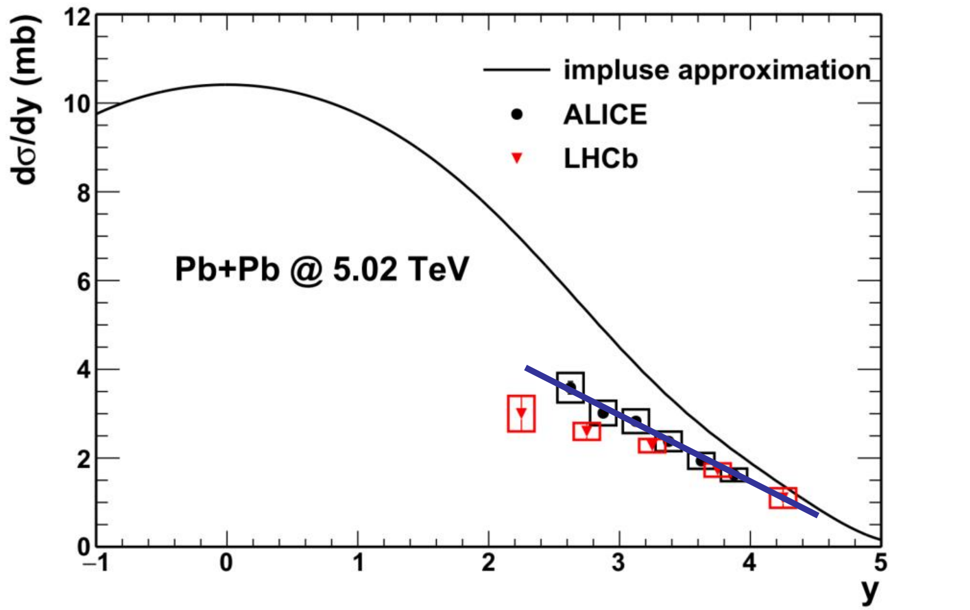
$$d\sigma_{\gamma A}/dt|_{t=0} = d\sigma_{\gamma p}/dt|_{t=0} \times A^2$$

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

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

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

The Bayesian reweighting of nuclear PDFs

The PDFs replica f_k can be constructed by the Hessian error set:

$$f_k \equiv f_{S_0} + \sum_i \left(\frac{f_{S_i^+} - f_{S_i^-}}{2} \right) R_{ik}$$

JHEP**08** (2012) 052

Any quantity $\mathcal{O}[f]$ depending on PDFs can be determined via:

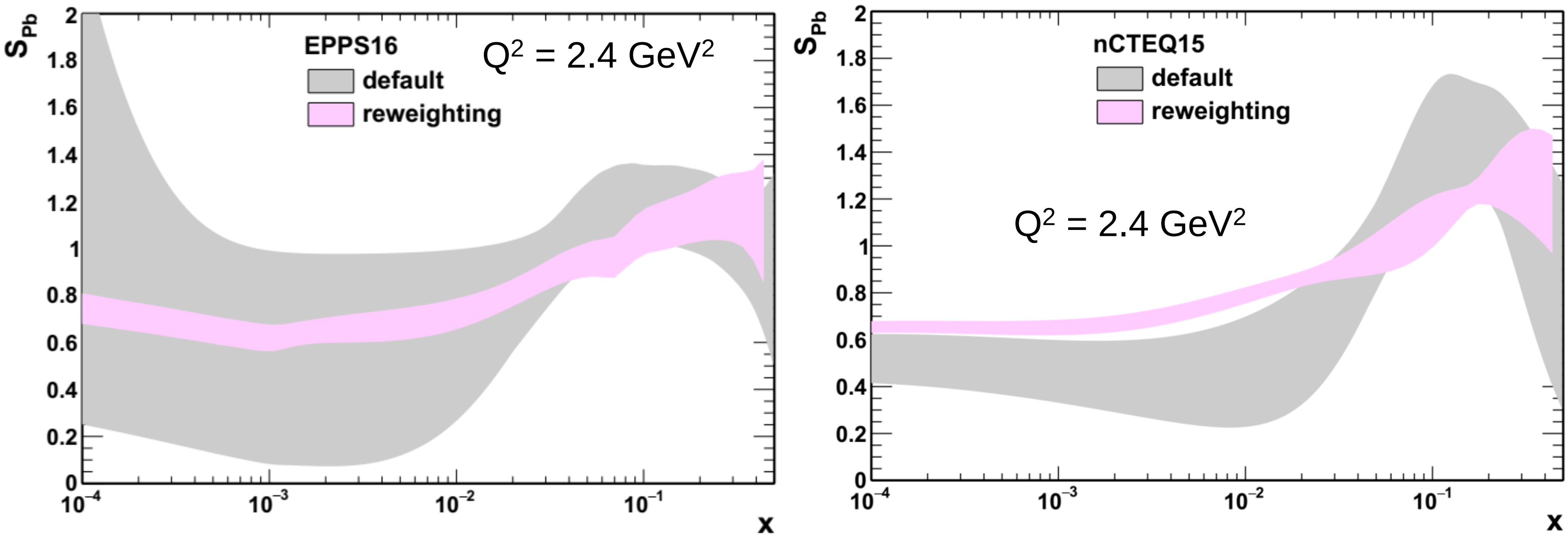
$$\langle \mathcal{O} \rangle = \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} \mathcal{O}[f_k]$$

For a new measurement, $y = \{y_1, y_2, ..., y_n\}$, the reweighted PDF could be evaluated by:

$$\langle \mathcal{O} \rangle_{\rm new} = \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} w_k \mathcal{O}[f_k]$$

$$w_k = \frac{(\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\chi_k^2/2}}{\frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} (\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\chi_k^2/2}} \quad \chi_k^2(y, f_k) = \sum_{i,j=1}^{n} (y_i - y_i[f_k]) {\rm cov}_{ij}^{-1} (y_j - y_j[f_k])$$

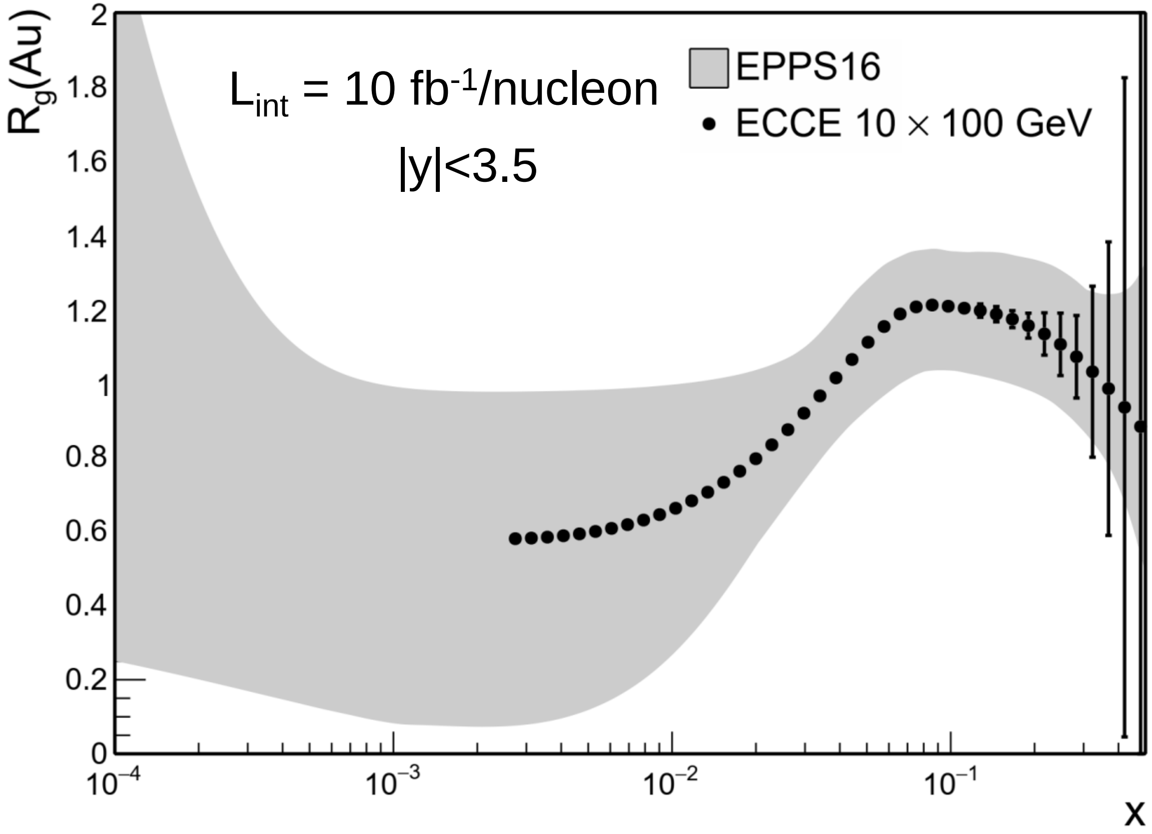
Nuclear shadowing from J/ψ measurements in UPCs



- 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.

The future opportunities at EIC

Projection with ECCE detector setup

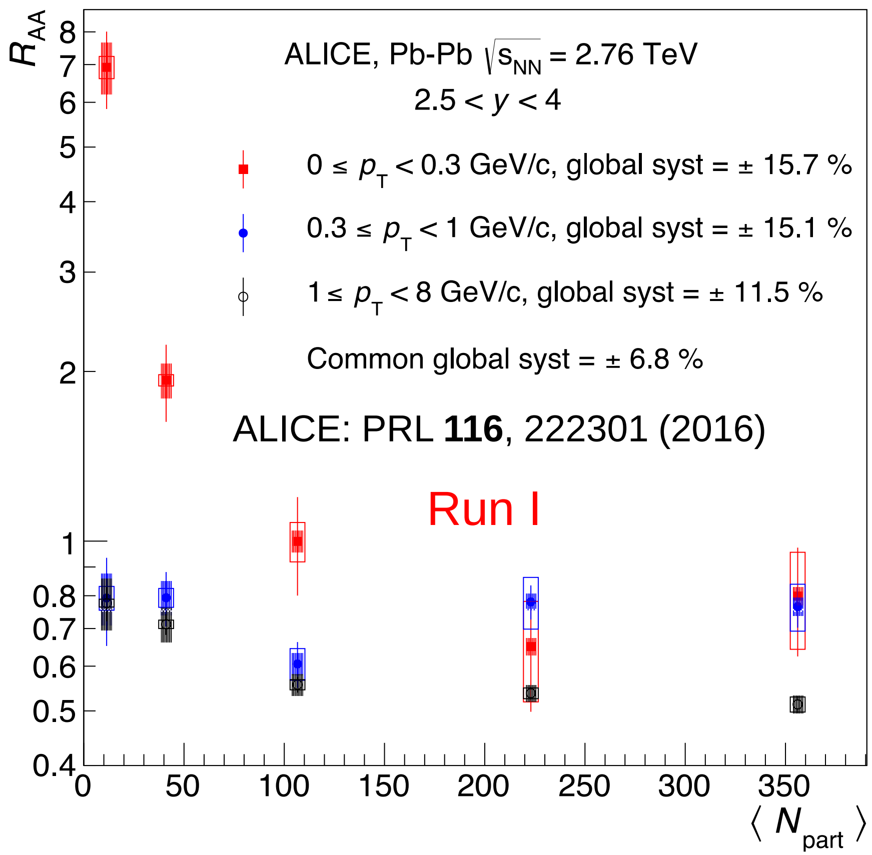


No ambiguity for x determination!

Negligible statistical uncertainties!

Xinbai Li, Physics Opportunities with Heavy Quarkonia at the EIC, https://indico.bnl.gov/event/12899/timetable/

Anomalous excess of J/ψ production observed at ALICE

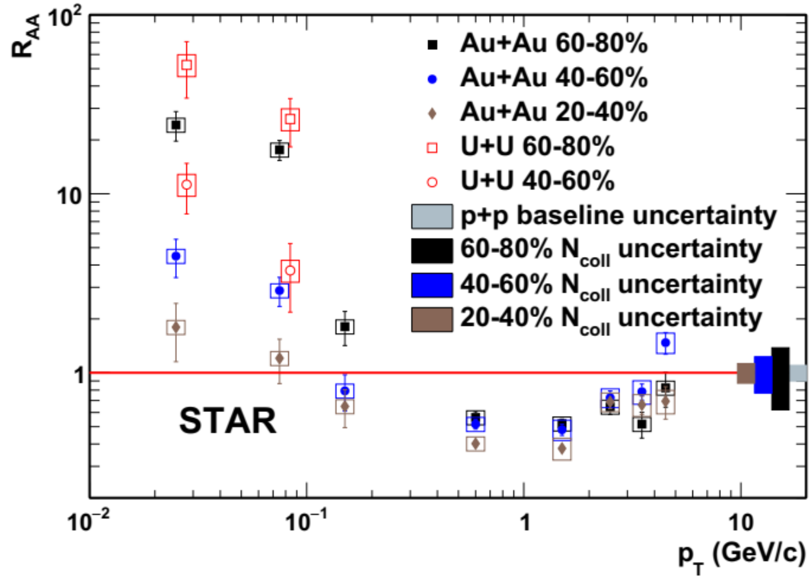


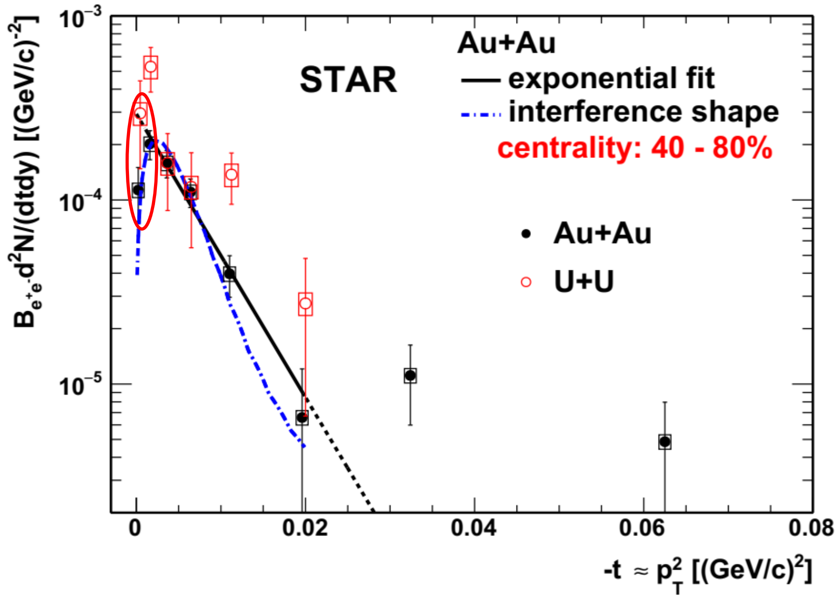
- Significant enhancement of J/ψ yield observed in p_T interval 0 – 0.3 GeV/c for peripheral collisions (50 – 90%).
- Can not be described by hadronic production modified by the hot medium or cold nuclear matter effects!

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

The observations at STAR

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





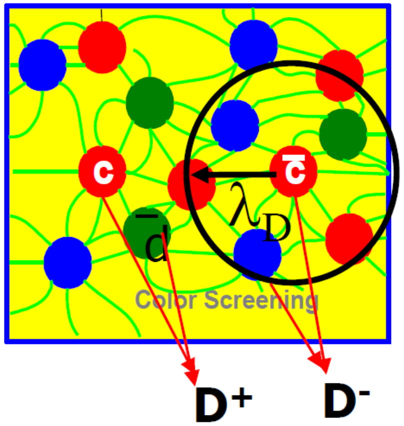
- Significant enhancement of J/ψ yield observed at p_T interval 0 – 0.2 GeV/c for peripheral collisions.
- No significant difference between Au+Au and U+U collisions.

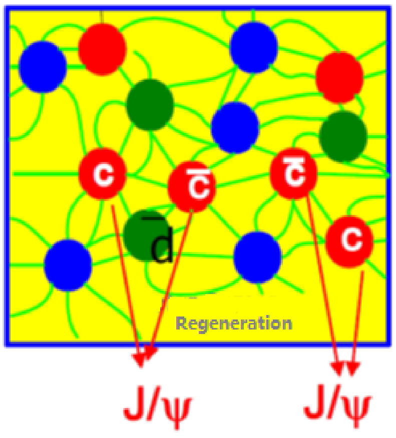
- Similar structure to that in UPC case!
- Indication of interference!
  - ✓ Interference shape from calculation PRC **97** (2018) 044910
- Similar slope parameter!
  - ✓ Slope from STARLIGHT prediction in UPC case – 196 (GeV/c)$^{-2}$
  - ✓ Slope w/o the first point: 177 $\pm$ 23(GeV/c)$^{-2}$ χ^2/NDF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

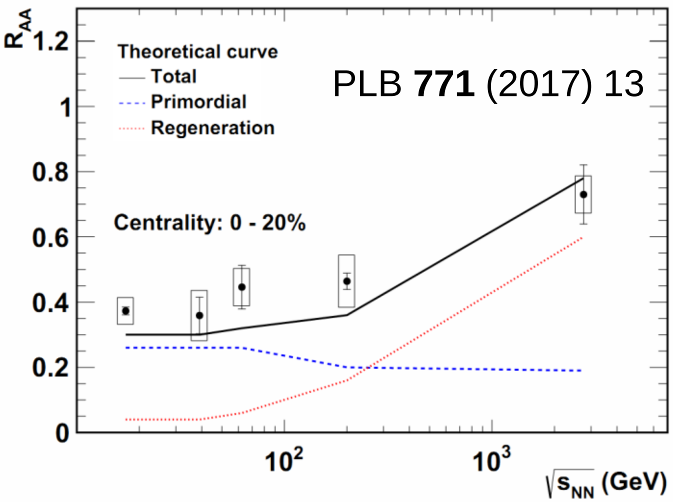
A novel probe for QGP?

- 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
  - ✓…

The baseline?

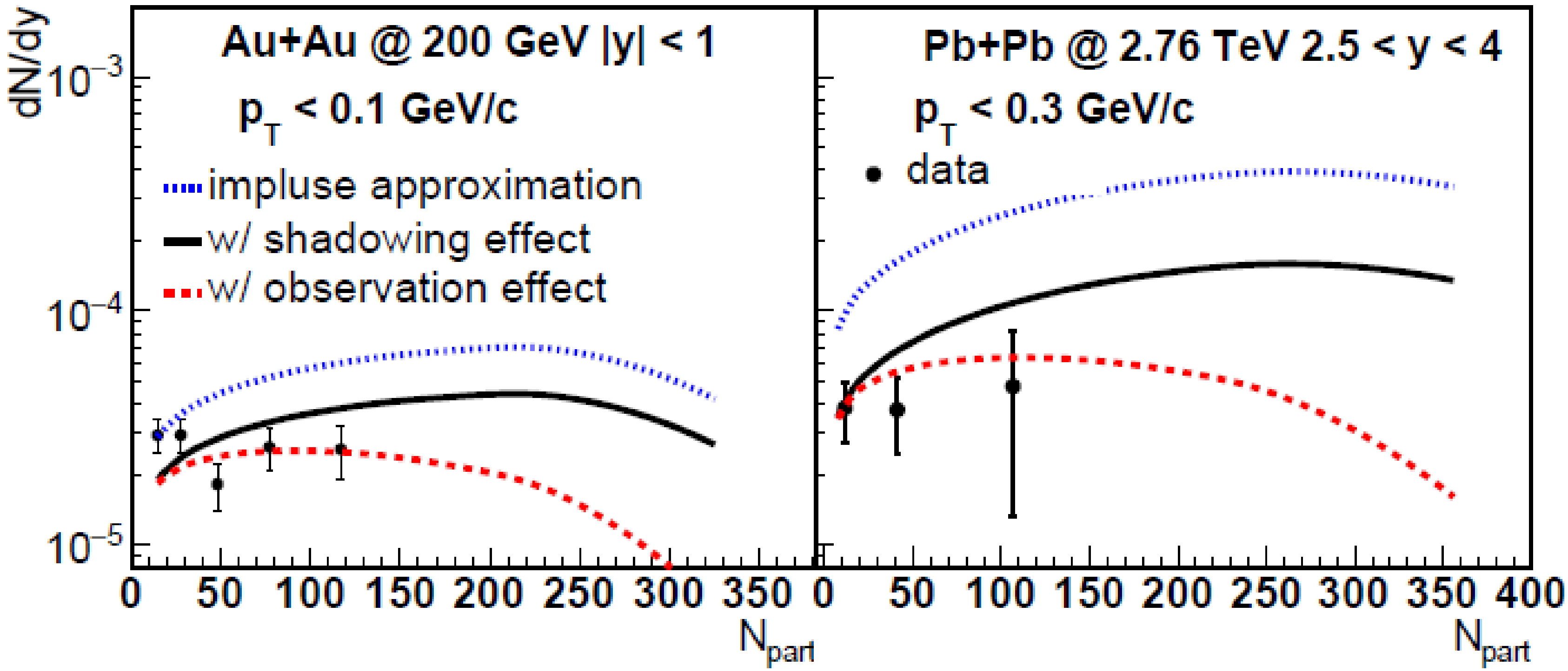






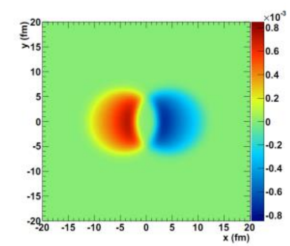
A cleaner probe of color screening?

Comparison with model calculation



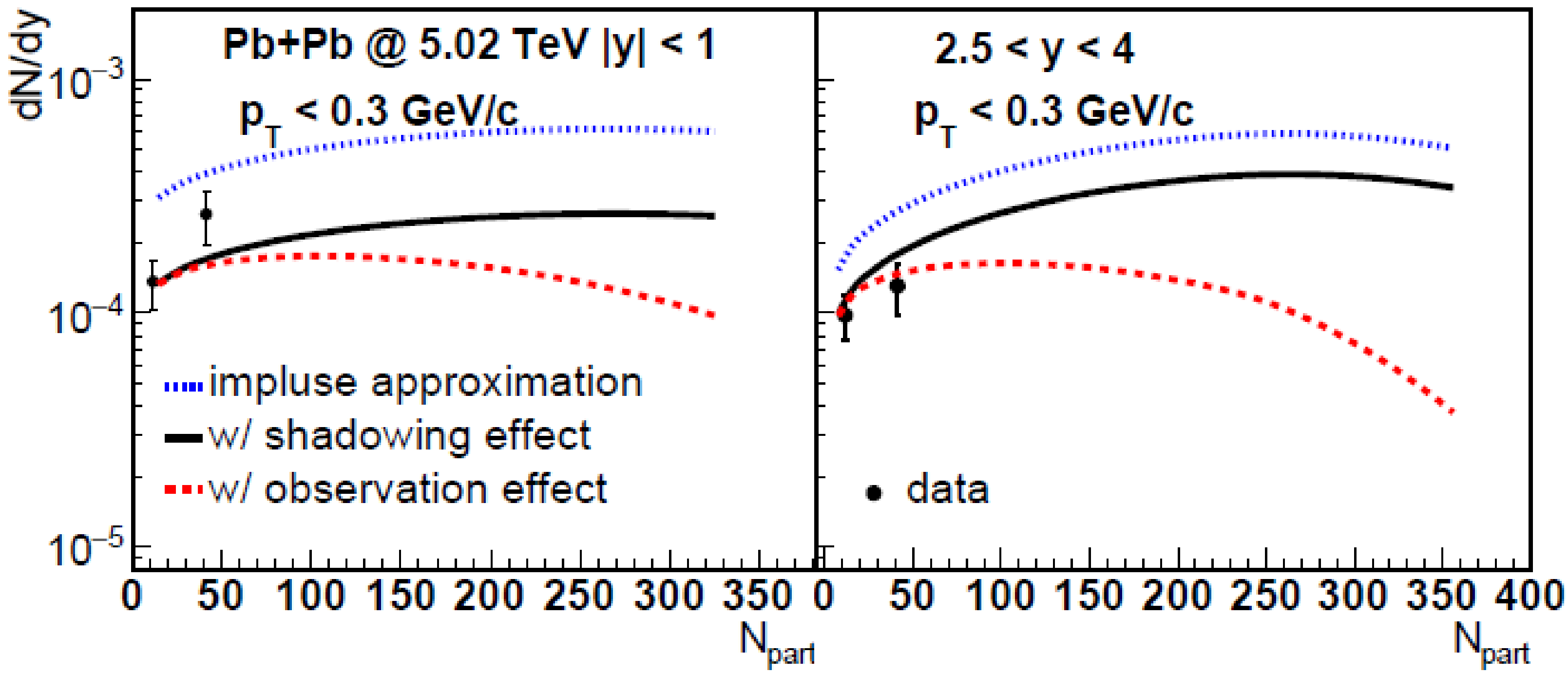
- Well described by the coherent photoproduction mechanism for peripheral collisions
- Hint of disruption from the medium
  - ✓ The observation effect
  - ✓ The QGP swallowing

W. Zha etal., PRC **99**, 061901 (2019)



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

The transverse linearly polarized photons

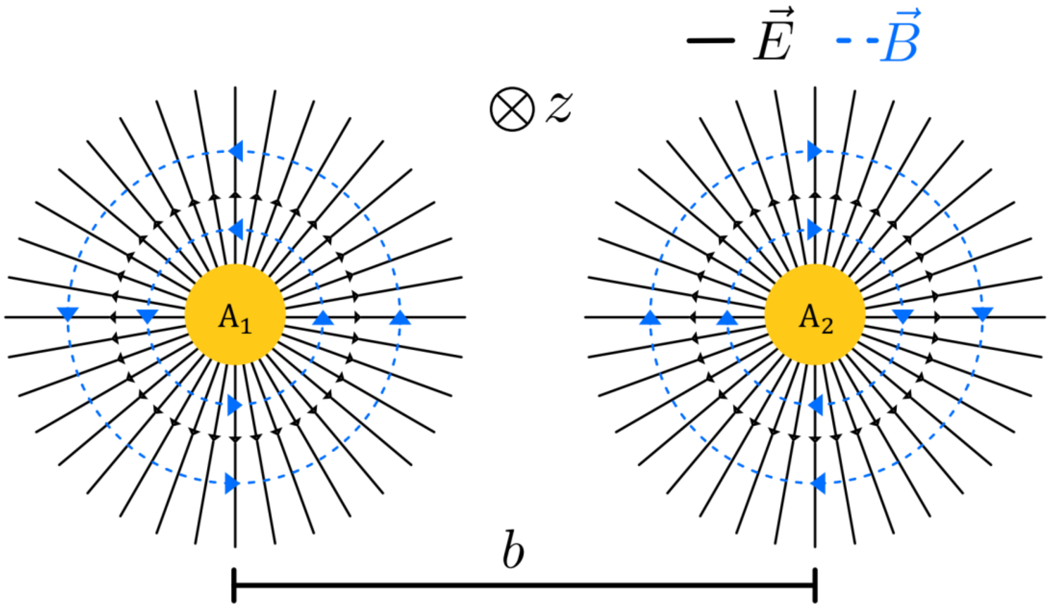
Extreme Lorentz contraction of EM fields $\vec{E} \perp \vec{B} \perp z$

✓ Linearly polarized in transverse plane

Polarization vector: follows the electrical vector of photons

Well defined in the position and momentum eigenstates

Aligned radially with the "emitting" source



The transverse linearly polarized photons

Extreme Lorentz contraction of EM fields $\vec{E} \perp \vec{B} \perp z$

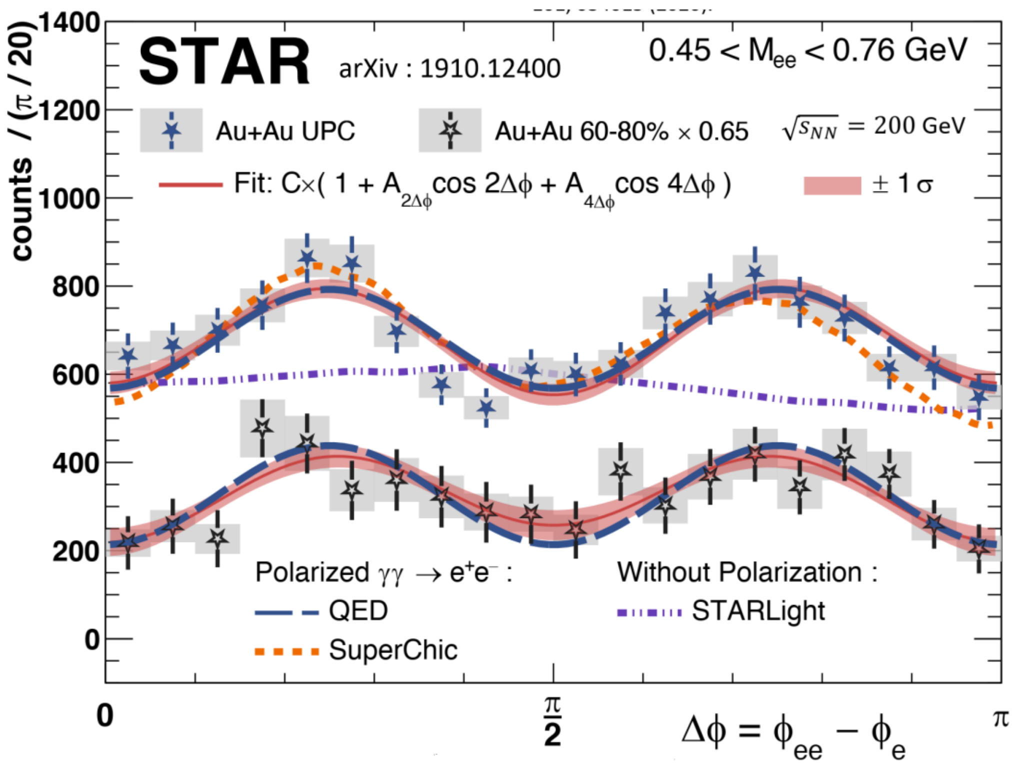
✓ Linearly polarized in transverse plane

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

leads to $\cos 4\Delta\phi$ modulation

C. Li, J. Zhou, Y.-j. Zhou, PLB 795, 576 (2019)

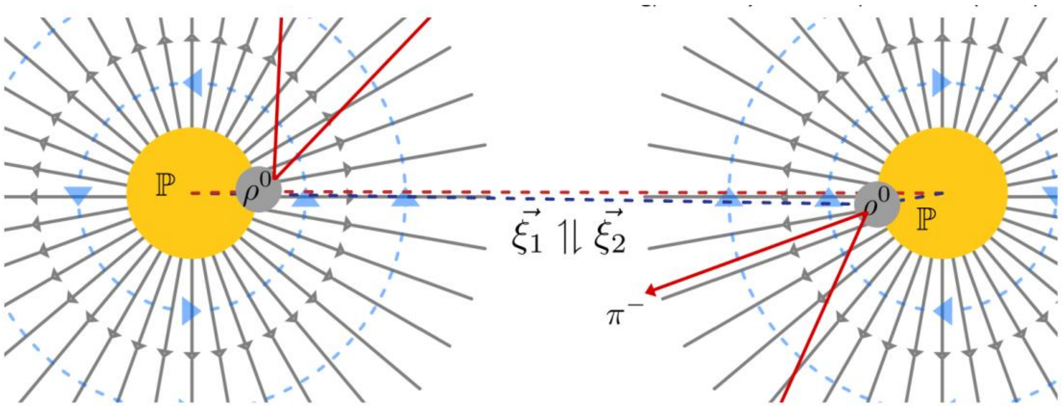
Confirmed by STAR Collaboration!



STAR Collaboration, , Phys. Rev. Lett. 127 (2021) 052302
Li, C., Zhou, J. & Zhou, Y. Phys. Rev. D101, 034015 (2020)

Polarized photon + gluon collisions

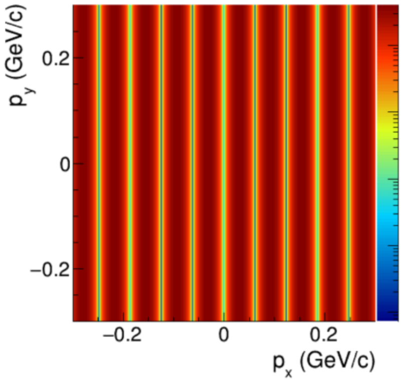
Polarization vector : aligned along the impact parameter



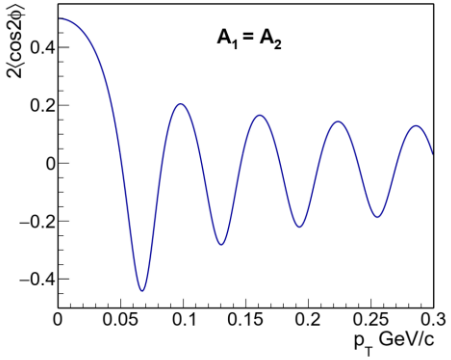
Helicity conservation: the produced vector meson inherits the polarization state of photon

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

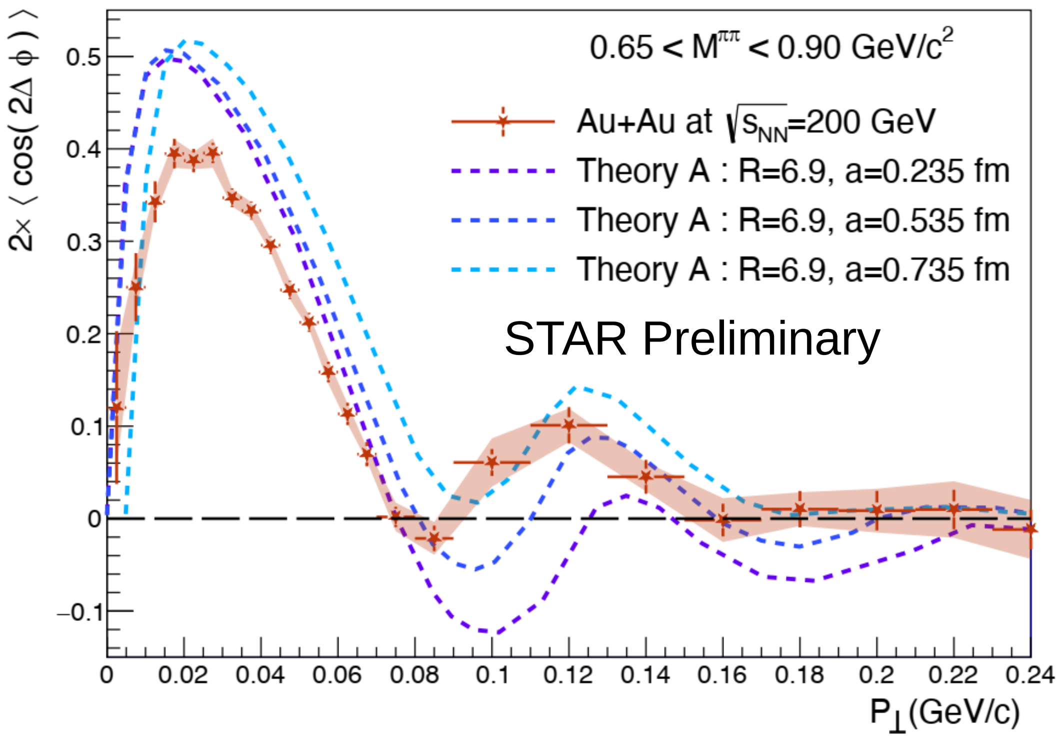
The interference in momentum space



$\cos 2\Delta\phi$ modulation



Polarized photon + gluon collisions



Qualitative description of data

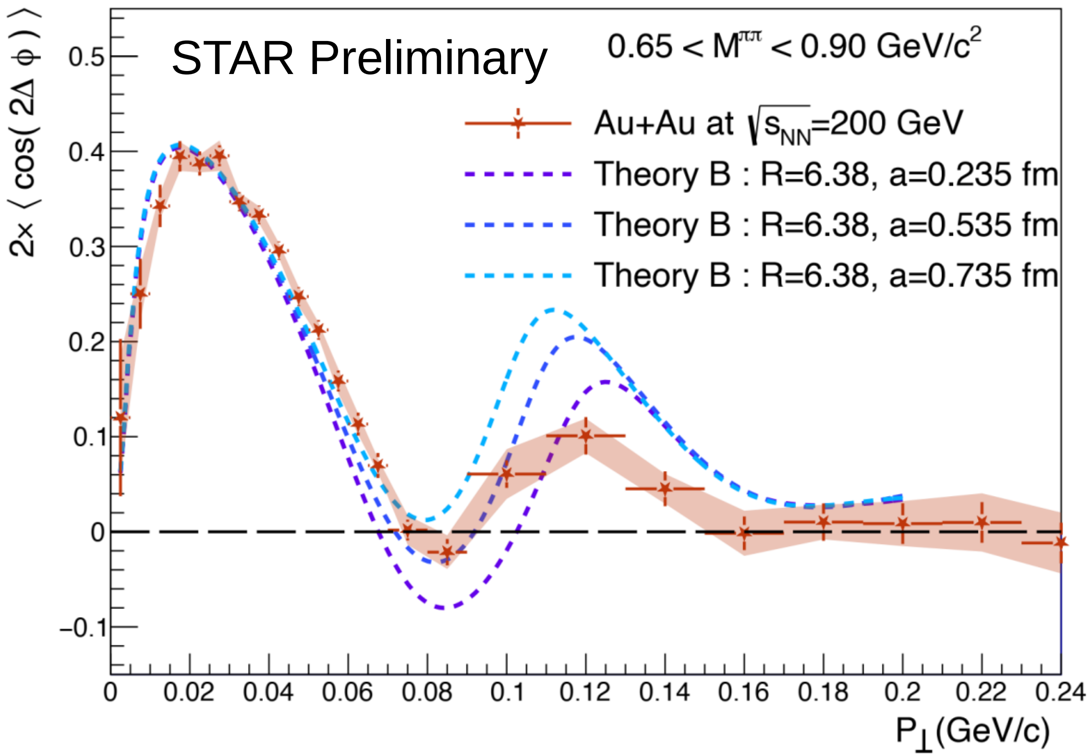
- Large first peak
- Approximate location of second peak

Second peak shows strong dependence on details of nuclear geometry

Xing, H. et.al. JHEP. 2020, 64 (2020)

A two-source interference pattern resulting from quantum spin-momentum correlations

Polarized photon + gluon collisions



Qualitative description of data
- Large first peak
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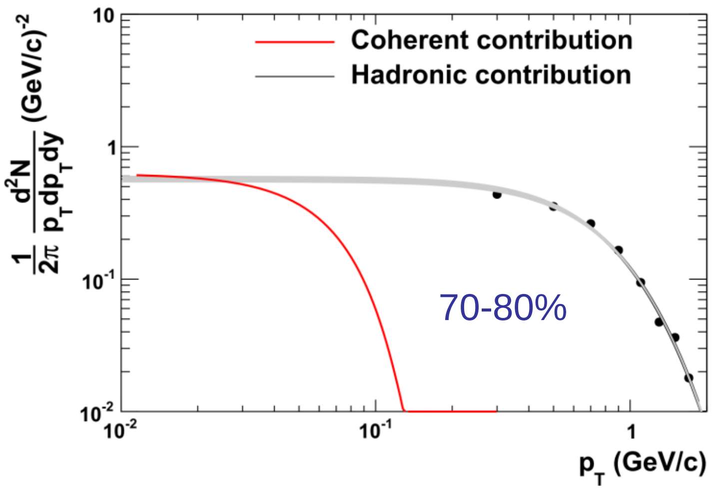
Second peak shows strong dependence on details of nuclear geometry

Zha, W., J.D. Brandenburg, Ruan, L. & Tang, Z. *PRD* **103**, 033007 (2021)

A two-source interference pattern resulting from quantum spin-momentum correlations

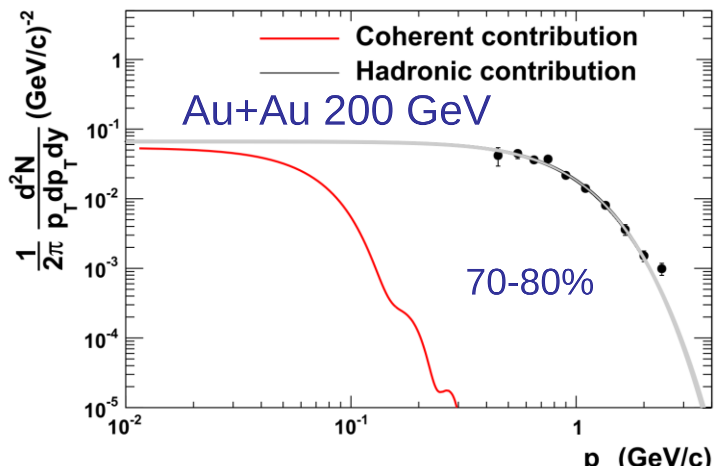
To determine the reaction plane?

ρ photoproduction

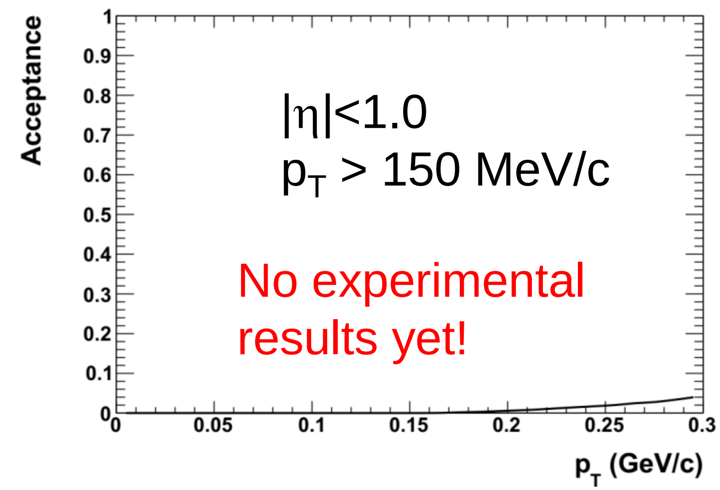


PRL **92** (2004) 092301

ϕ photoproduction

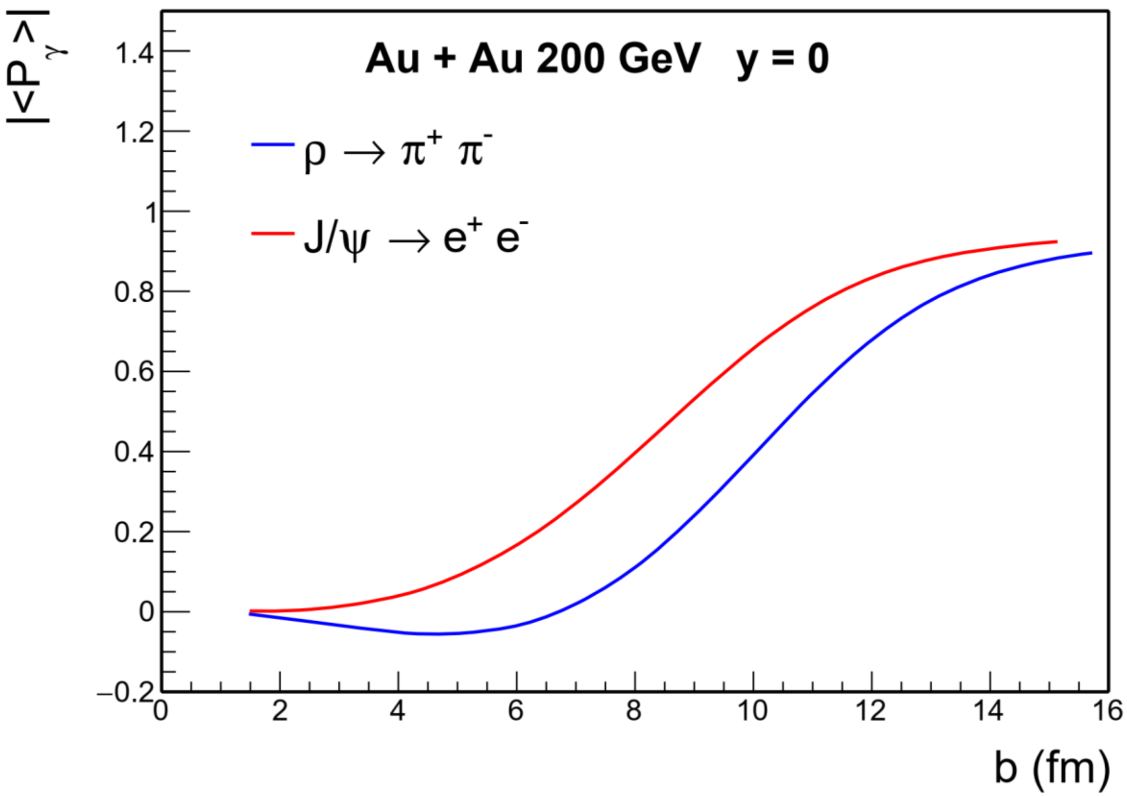


PLB **612** (2005) 181



- Hadronic contribution dominant even at very low p_T for ρ and ϕ
- A dirty probe!

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
- ✓ Strongly aligned to reaction plane
- ✓ No event-event fluctuation
  -Good-Walker paradigm

Phys. Rev. D94, 034042 (2016)

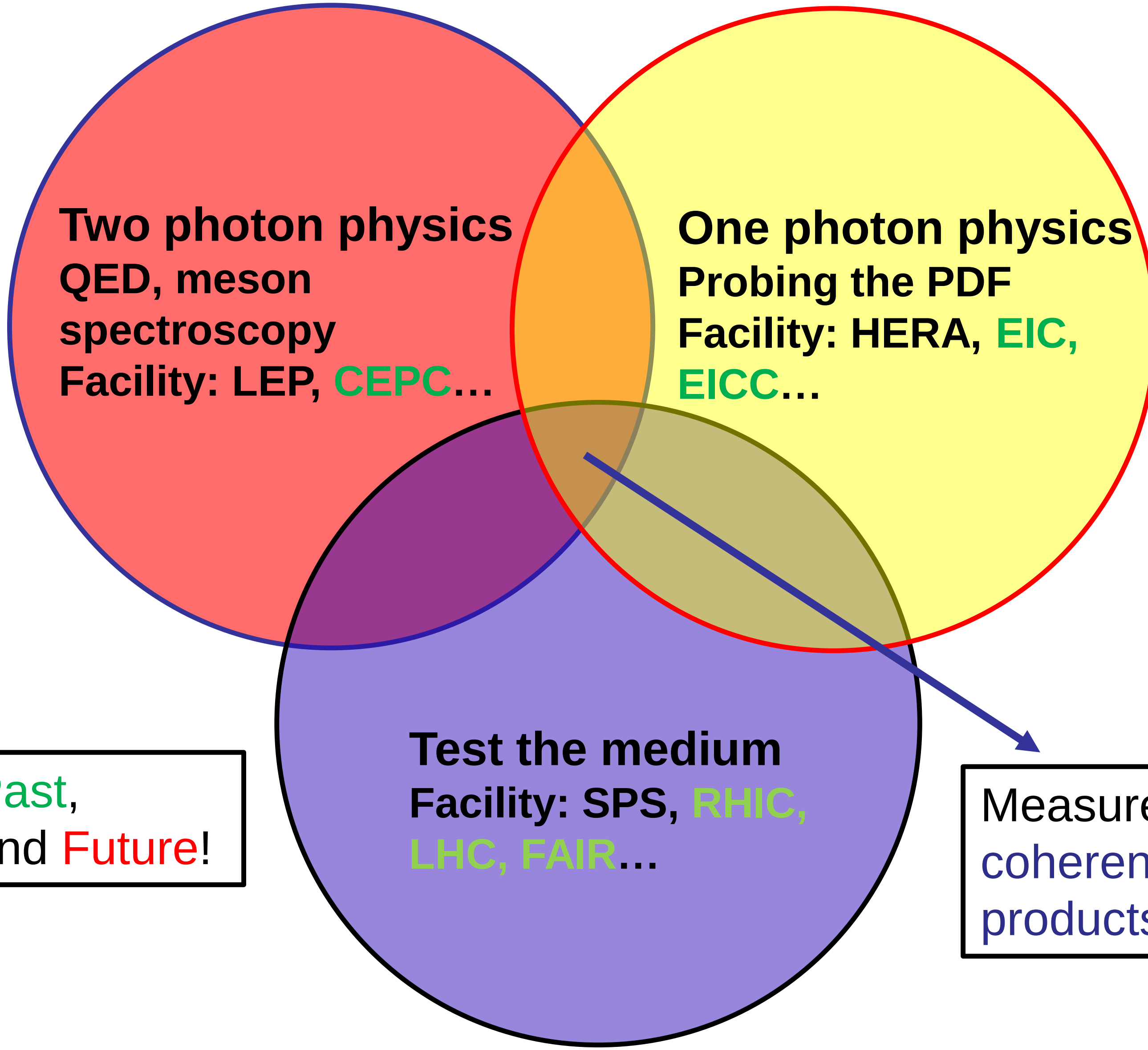
Could directly link the final flow to initial geometry!

Summary

- The vector meson photoproduction in UPCs
  - ✓ Significant shadowing effect
  - ✓ The interference effect in spin-momentum correlation

- Excess of J/ψ production at very low p_T in peripheral A+A collisions
  - ✓ Existence of coherent photoproduction in non UPCs
  - ✓ Novel probe for QGP?
  - ✓ Determine the initial geometry (reaction plane)?

Outlook



Link the Past, Present and Future!

Measurements of coherent photon products in **HHIC**!