Polarisation-dependent studies of exclusive J/ψ production in hadron-hadron and lepton-hadron interactions

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PRD 106, 074008 (2022)

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Ultraperipheral collisions(UPCs)

relativistically moving ions will introduce electromagnetic field.

UPC:

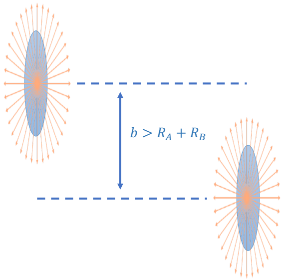
Two nuclei physically miss each other, interact (only) electromagnetically

Equivalent photon approximation(EPA)
1924, Fermi;
Weizäscker and Williams, 1930's;

$$xf_1^{\gamma}(x, k_\perp^2) = \frac{Z^2\alpha_e}{\pi^2} k_\perp^2 \left[\frac{F(k_\perp^2 + x^2 M_p^2)}{(k_\perp^2 + x^2 M_p^2)} \right]^2$$

Woods-Saxon form factor,

$$F(\vec{k}^2) = \int d^3 r e^{i\vec{k}\cdot\vec{r}} \frac{\rho^0}{1 + \exp\left[(r - R_{WS})/d\right]}$$



But! strong interaction dominant in center collisions

clean background

see also Farid Salazar and Valery Pozdnyakov's talk

gluon/photon TMD

gluon/photon TMD factorization:

$$\int \frac{2dy^- d^2y_\perp}{xP^+(2\pi)^3} e^{ik\cdot y} \langle P|F_+^\mu(0)F_+^\nu(y)|P\rangle\Big|_{y^+=0}$$
$$= \delta_\perp^{\mu\nu} f_1(x,k_\perp^2) + \left(\frac{2k_\perp^\mu k_\perp^\nu}{k_\perp^2} - \delta_\perp^{\mu\nu}\right) h_1^\perp(x,k_\perp^2),$$

Mulders, Rodrigues, PRD63(2001)

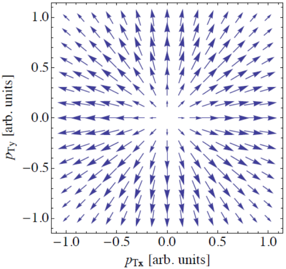
A nucleus moves along P^+, A^+ dominant, $F_+^\mu \propto k_\perp^\mu A^+$, implies

$$\boxed{f_1(x,k_\perp^2) = h_1^\perp(x,k_\perp^2)}$$

small-x photons/gluons are linearly polarized

A. Metz and J. Zhou, 2011, C. Li, J. Zhou and YZ, 2019

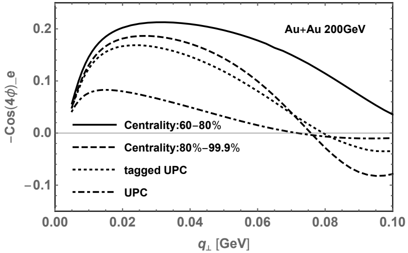
EM field in $k_\perp$ space, beam view



$\epsilon_\perp // k_\perp$

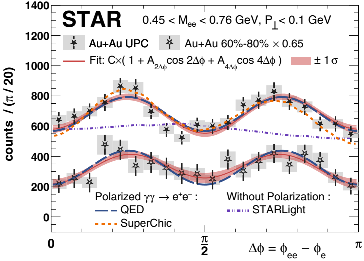
Linearly polarized photon verified by STAR collaboration

Azimuthal asymmetries in $\gamma\gamma \to e^+e^-$



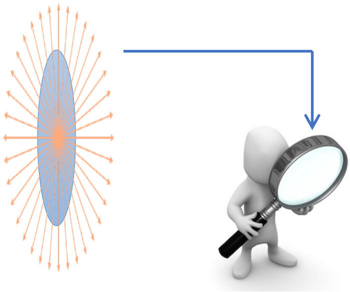
	Measured	QED calculation
Tagged UPC	16.8%±2.5%	16.5%
60%-80%	27%±6%	34.5%

C. Li, J. Zhou and YZ, 2020

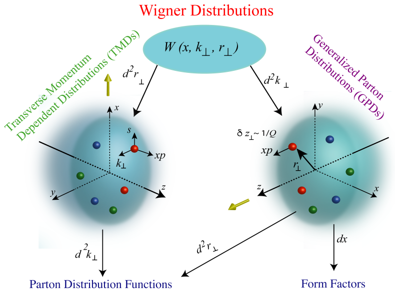


STAR collaboration, PRL127, 052302 (2021)

UPC: an ideal platform to “see” nucleus

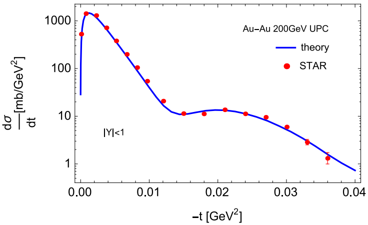


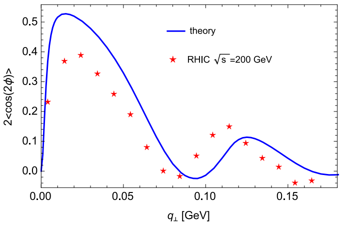
- linearly polarized photon
- high luminosity
- clean background
- ...



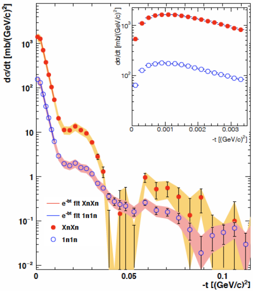
How? photo-nuclear diffractive production of vector mesons, di-jets...

ρ^0 production at RHIC STAR

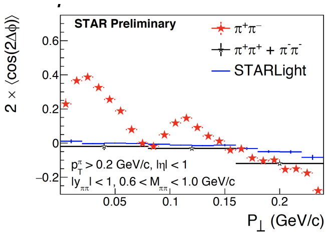




H.X. Xing, C. Zhang, J. Zhou and YZ, JHEP10(2020)064

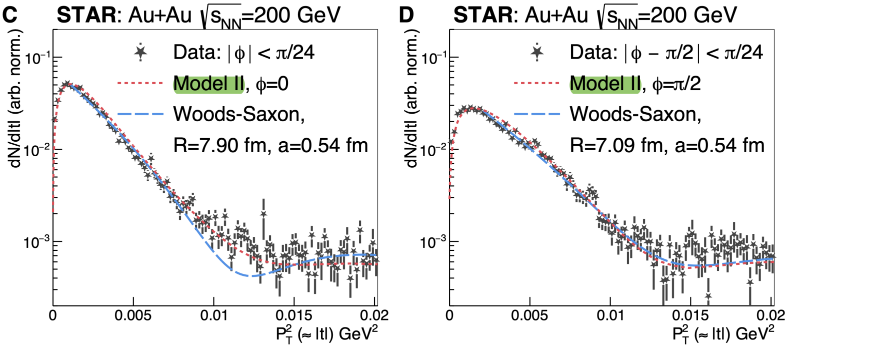


STAR, Phys.Rev.C 96 (2017) 5, 054904



Daniel Brandenburg, QM 2019

ρ^0 production at RHIC STAR



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

Model II: H.X. Xing, C. Zhang, J. Zhou and YZ, JHEP10(2020)064

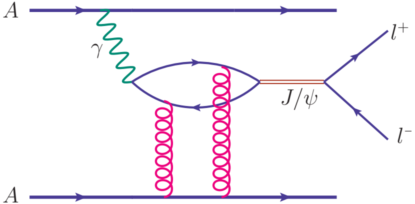
Polarisation dependent diffractive J/ψ production in AA and eA collisions

- The mass is appropriate
  - m_c is heavy enough: perturbative calculation reliable
  - m_c is not too heavy: prevents access to the saturation regime
- Large cross section, and easy to be identified experimentally
- Experimental interest in UPC process at RHIC and LHC.
- Interference effect in AA collisions but not in eA collisions, azimuthal azymmetries different shape.
- Sensitive to nuclear geometry, provide a complementary way to extract transverse spatial gluon distribution.

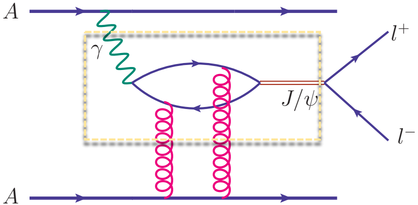
Key ingredients

- Color dipole model
- Gluon distribution
- Linearly polarized photon
- Joint impact parameter and transverse momentum dependent cross section
- Interference effect
- Soft photon radiation

vector meson production in UPCs, color dipole model



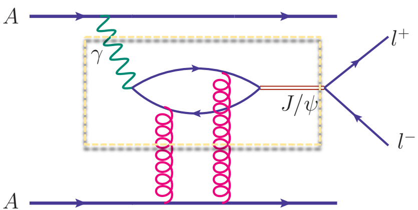
vector meson production in UPCs, color dipole model



$$\mathcal{A}(\Delta_\perp) = i\int d^2b_\perp e^{i\Delta_\perp\cdot b_\perp}\int\frac{d^2r_\perp}{4\pi}\int_0^1 dz\, \Psi^{\gamma\to q\bar{q}}(r_\perp, z, \epsilon_\perp^\gamma) N(r_\perp, b_\perp) \Psi^{V\to q\bar{q}*}(r_\perp, z, \epsilon_\perp^V),$$

For polarization averaged calculation, see: M. G. Ryskin, 93; S. J. Brodsky, L. Frankfurt, J. F. Gunion, A. H. Mueller and M. Strikman, 94

vector meson production in UPCs, color dipole model



$\epsilon_\perp^\gamma \to \epsilon_\perp^V$, unique observables :

$$\langle\cos(n\phi)\rangle = \frac{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} \cos(n\phi)\, d\mathcal{P}.\mathcal{S}.}{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} d\mathcal{P}.\mathcal{S}.}$$

where $\phi = q_\perp \wedge p_\perp^l$

$$\mathcal{A}(\Delta_\perp) = i\int d^2b_\perp e^{i\Delta_\perp\cdot b_\perp}\int\frac{d^2r_\perp}{4\pi}\int_0^1 dz\, \Psi^{\gamma\to q\bar{q}}(r_\perp, z, \epsilon_\perp^\gamma) N(r_\perp, b_\perp) \Psi^{V\to q\bar{q}*}(r_\perp, z, \epsilon_\perp^V),$$

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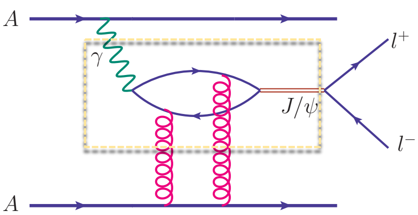

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For polarization averaged calculation, see: M. G. Ryskin, 93; S. J. Brodsky, L. Frankfurt, J. F. Gunion, A. H. Mueller and M. Strikman, 94

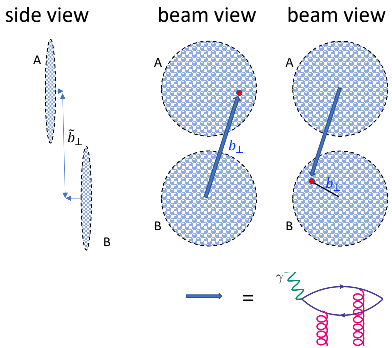
- dipole amplitude calculation:

$$N(b_\perp, r_\perp) = 1 - e^{-2\pi B_p A T_A(b_\perp)\mathcal{N}(r_\perp)}$$

$\mathcal{N}(r_\perp) = 1 - \exp\left[-r_\perp^2 G(x_g, r_\perp)\right]$: dipole-nucleon scattering amplitude

$G(x_g, r_\perp) = \frac{1}{2\pi B_p}\frac{\pi^2}{2N_c}\alpha_s\left(\mu_0^2 + \frac{C}{r_\perp^2}\right)xf_g\left(x_g, \mu_0^2 + \frac{C}{r_\perp^2}\right)$: gluon distribution (BGBK model)

joint $\tilde{b}_\perp$ and $q_\perp$ dependent picture



A,B take turns to be the source of color dipole

$\tilde{b}_\perp$: impact parameter
$b_\perp$: the position of the produced V ($\lambda_{J/\psi} \ll R_A$)

$$b_\perp \leftrightarrow q_\perp$$

Coherent cs: summing up amplitudes → squaring it

(the nucleus who induced γ is not destroyed, E comes from the superposition of all the electric charge of the nuclei in the nucleus.)

Incoherent cs: squaring the amplitude → summing up

(the nucleus who induced γ is destroyed)

coherent dominant at low $k_\perp$ ($\lesssim \frac{1}{R_A}$, ~ 30 MeV for Au and Pb)

interference effect

coherent production amplitude:

$$\mathcal{M}(Y,\tilde{b}_\perp) \propto \left[F_B(Y,b_\perp-\tilde{b}_\perp)N_A(Y,b_\perp)+N_B(-Y,b_\perp-\tilde{b}_\perp)F_A(-Y,b_\perp)\right]$$

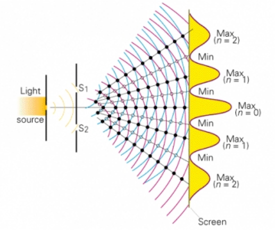
Fourier transform $b_\perp \to q_\perp$,

$$\mathcal{M}(Y,\tilde{b}_\perp) \propto \int d^2k_\perp d^2\Delta_\perp \delta^2(q_\perp-\Delta_\perp-k_\perp)$$

$$\left\{F_B(Y,k_\perp)N_A(Y,\Delta_\perp)\boxed{e^{-i\tilde{b}_\perp\cdot k_\perp}}+F_A(-Y,k_\perp)N_B(-Y,\Delta_\perp)\boxed{e^{-i\tilde{b}_\perp\cdot\Delta_\perp}}\right\},$$

Double slit like interference effect

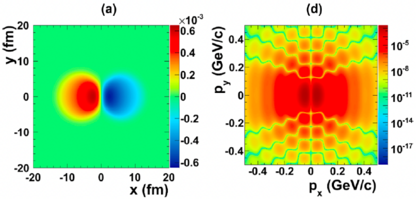
classical:



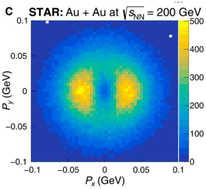
Fermi-scale double-slit interference

experiment

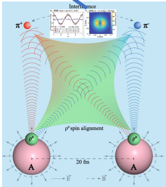
theory



W. Zha, L. Ruan, Z. Tang, Z. Xu, S. Yang, PRC 99, 061901 (2019)



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



Y.G. Ma, Nucl. Sci. Tech. 34, 16 (2023)

New type of double-slit interference experiment at Fermi scale

H.X. Xing, C. Zhang, J. Zhou and YZ, JHEP10(2020)064

W. Zha, J. D. Brandenburg, L.J. Ruan and Z.B. Tang PRD103, 033007(2021)

J/ψ production cross section

$$\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2\tilde{b}_\perp} = \frac{C}{2(2\pi)^7}\frac{24e^4e_q^2}{(Q^2-M^2)^2+M^2\Gamma^2}\frac{|\phi(0)|^2}{M}$$

$$\times\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp\delta^2(k_\perp+\Delta_\perp-q_\perp)\boxed{\left[\hat{k}'_\perp\cdot\hat{k}_\perp-\frac{4(P_\perp\cdot\hat{k}_\perp)(P_\perp\cdot\hat{k}'_\perp)}{M^2}\right]}$$

$$\times\Big\{\int d^2b_\perp e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\left[T_A(b_\perp)\mathcal{A}_{in}(x_2,\Delta_\perp)\mathcal{A}^*_{in}(x_2,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_1,k'_\perp)+(A\leftrightarrow B)\right]$$

$$+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\mathcal{A}_{co}(x_2,\Delta_\perp)\mathcal{A}^*_{co}(x_2,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_1,k'_\perp)\right]$$

$$+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-\Delta_\perp)}\mathcal{A}_{co}(x_1,\Delta_\perp)\mathcal{A}^*_{co}(x_1,\Delta'_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_2,k'_\perp)\right]$$

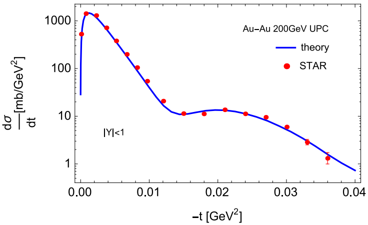
$$+\left[\boxed{e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-k_\perp)}}\mathcal{A}_{co}(x_2,\Delta_\perp)\mathcal{A}^*_{co}(x_1,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_2,k'_\perp)\right]$$

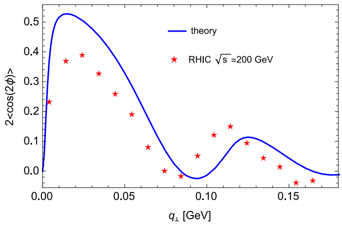
$$+\left[\boxed{e^{i\tilde{b}_\perp\cdot(k'_\perp-\Delta_\perp)}}\mathcal{A}_{co}(x_1,\Delta_\perp)\mathcal{A}^*_{co}(x_2,\Delta'_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_1,k'_\perp)\right]\Big\}$$

the interference terms ensure the perfect peak and valley structure

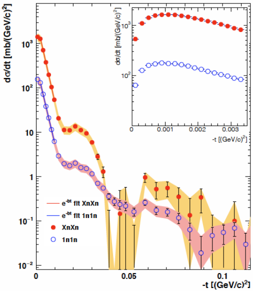
the spin correlation between γ and J/ψ result in the azimuthal asymmetry

ρ^0 production at RHIC STAR

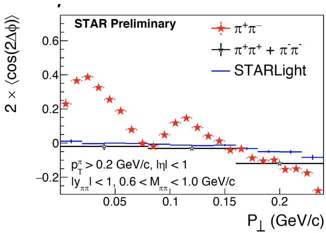




H.X. Xing, C. Zhang, J. Zhou and YZ, JHEP10(2020)064



STAR, Phys.Rev.C 96 (2017) 5, 054904



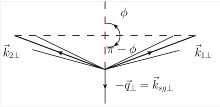
Daniel Brandenburg, QM 2019

soft photon radiation

At relatively high $q_\perp$, final state soft photon radiation dominant.
($\sim >$ 100 MeV)

cross section,

$$\frac{d\sigma(q_\perp)}{d\mathcal{P}.\mathcal{S}.} = \int d^2 q'_\perp \frac{d\sigma_0(q'_\perp)}{d\mathcal{P}.\mathcal{S}.} S(q_\perp - q'_\perp)$$



soft factor at leading order:

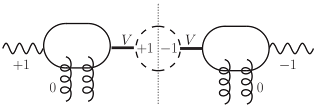
$$S(l_\perp) = \delta(l_\perp) + \frac{\alpha_e}{\pi^2 l_\perp^2} \left\{ c_0 + 2c_2 \boxed{\cos 2\phi} + 2c_4 \boxed{\cos 4\phi} + ... \right\}$$

Y. Hatta, B.W. Xiao, F. Yuan and J. Zhou, PRL(2021) and PRD(2021)

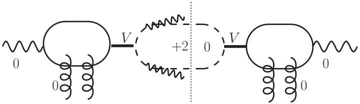
$$\mathrm{Sud}_{1-\mathrm{loop}}(r_\perp) = \frac{\alpha_e}{\pi} \ln \frac{Q^2}{m^2} \ln \frac{P_\perp^2}{\mu_r^2}$$

cartoon illustrations of the azimuthal asymmetries in vector boson production in UPCs

- $\cos 2\phi$ asymmetry

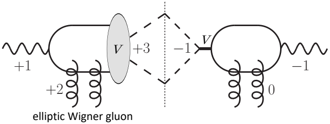


$$\langle +1 | -1 \rangle \sim \cos 2\phi$$

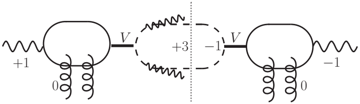


$$\langle +2 | 0 \rangle \sim \cos 2\phi$$

- $\cos 4\phi$ asymmetry

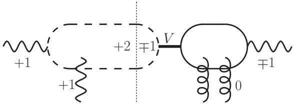


$$\langle +3 | -1 \rangle \sim \cos 4\phi$$



$$\langle +3 | -1 \rangle \sim \cos 4\phi$$

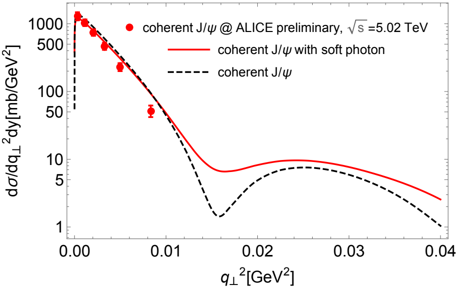
- $\cos \phi$ and $\cos 3\phi$ asymmetries



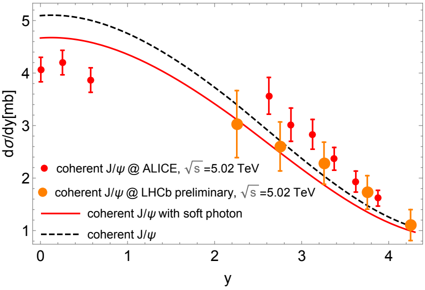
$$\langle +2 | \mp 1 \rangle \sim \cos 3\phi / \cos \phi$$

for azimuthal asymmetries in ρ^0 production see:
H.X. Xing, C. Zhang, J. Zhou and YZ, JHEP10(2020)064, Y. Hagiwara, C. Zhang, J. Zhou and YZ, PRD103, 074013 (2021) and PRD104, 094021 (2021)

Numberical results: J/ψ cross section

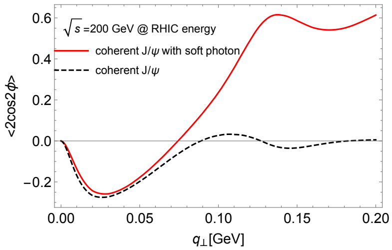


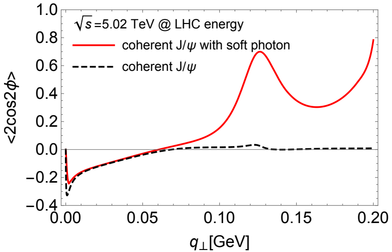
y [-0.8,0.8]

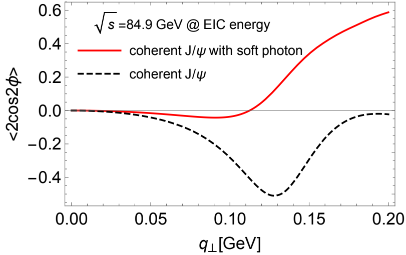


$q_\perp[0, 0.2]$

Numberical results: $J/\psi \cos 2\phi$ asymmetry







The $< \cos(2\phi) >$ shape come from:

- linearly polarized photon
- interference effect
- soft photon effect

At pA/EIC, no interference term, the first peak absent.

Summary

- Linearly polarized coherent photons in UPCs can be used to study nuclear structure, while double-slit like interference effect and final state photon radiation also play important roles in UPC physics.
- For J/ψ exclusive production:
  - cross section estimations consistent with LHC measurements;
  - large $\cos 2\phi$ asymmetries are predicted in UPCs at RHIC and LHC, and at EIC.
- May provide a method to extract spatial gluon distribution.
- Due to the interference effect, the shape of the azimuthal asymmetry curves are different at AA and eA/pA collisions, which is interesting to be tested in the future.

Thanks!