The azimuthal asymmetries in ρ^0 production in UPCs

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based on papers: JHEP10(2020)064, PRD104, 094021 (2021)

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Ultraperipheral collisions(UPCs)

relativistically moving ions will introduce electromagnetic field.

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

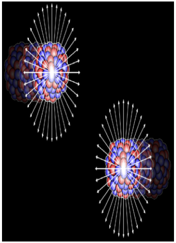
$$n(\omega) = \frac{4Z^2\alpha_e}{\omega}\int \frac{d^2k_\perp}{(2\pi)^2}k_\perp^2\left[\frac{F(k_\perp^2+\omega^2/\gamma^2)}{(k_\perp^2+\omega^2/\gamma^2)}\right]^2$$

$$\sigma^{WW}_{A_1A_2\to A_1A_2X} = \int d\omega_1 d\omega_2 n_{A_1}(\omega_1)n_{A_2}(\omega_2)\sigma_{\gamma\gamma\to X}(\omega_1,\omega_2)$$

$\gamma-\gamma$: $d\sigma \propto Z^4$
$\gamma-A$: $d\sigma \propto Z^2$

But! strong interaction dominant in center collisions

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



pic from Peter Steinberg's talk, Mon
clean background

Photon TMD

photons can be formulated in the context of TMD factorization:

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

Mulders, Rodrigues, PRD63(2001)

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

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

coherent photons are linearly polarized

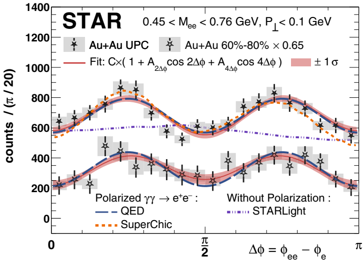
how to probe: azimuthal asymmetry see e.g., Boer, Mulders, Pisano, PRD 80 (2009) 094017

dilepton production in UPCs

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

	Measured	QED calculation
Tagged UPC	16.8%$\pm$2.5%	16.5%
60%-80%	27%$\pm$6%	34.5%

C. Li, J. Zhou and YZ, 2020



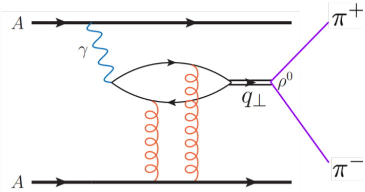
STAR collaboration, PRL127, 052302 (2021), arXiv:1910.12400

coherent photons are linearly polarized is verified by STAR

Motivation

- The fact that the coherent photons in UPCs are highly linearly polarized can be used as a probe to study QCD phenomenology.
- Significant $\cos 2\phi$ and $\cos 4\phi$ asymmetries for ρ^0 meson production in UPCs have been observed by STAR collaboration.
- Huge amounts of data for ρ^0 at STAR and LHC.

ρ production in UPC: illustration diagram



$\phi = p_\perp^\pi \wedge q_\perp$

$q_\perp$: ρ^0 transverse momentum

$p_\perp^\pi$: π's transverse momentum.

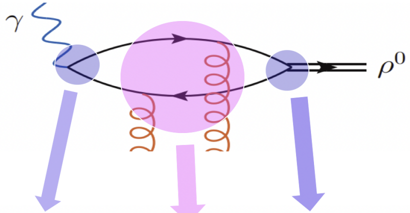
observable:

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

scattering amplitude

Use color dipole model to calculate the scattering amplitude

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

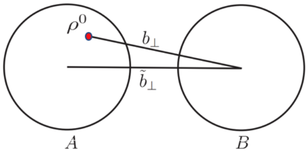


$$\mathcal{A}(\Delta_\perp) = i\int d^2b_\perp e^{i\Delta_\perp\cdot b_\perp}\int\frac{d^2r_\perp}{4\pi}\int_0^1 dz\, \boxed{\Psi^{\gamma\to q\bar{q}}(r_\perp, z, \epsilon_\perp^\gamma)}\boxed{N(r_\perp, b_\perp)}\boxed{\Psi^{V\to q\bar{q}*}(r_\perp, z, \epsilon_\perp^V)},$$

photon (vector meson) wave function, calculated in light-cone perturbation theory. polarization dependent.

dipole scattering amplitude. color dipole from nucleus A multi re-scattered with the CGC gluon in nucleus B

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

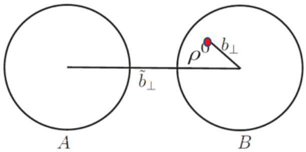


γ from B produce a pair of quarks (dipole), interact with the CGC gluon in A, produce ρ^0 (inside A due to color confinement)

set the center of nucleus B as the zero point,

$\tilde{b}_\perp$: impact parameter, the relative position of the two nuclei in the transverse plane

$b_\perp$: the position of the produced ρ^0 ($\lambda_\rho \ll R_A$)



γ from A produce a pair of quarks (dipole), interact with the CGC gluon in B, produce ρ^0 (inside B due to color confinement) coherent production amplitude:

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

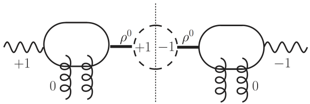
Fourier transform $b_\perp \to q_\perp$,

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

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

Double slit like interference effect

ρ^0 production cross section



$$
\begin{aligned}
\frac{d\sigma}{d^2q_\perp dY d^2\tilde{b}_\perp} = \; & \frac{1}{(2\pi)^4}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp+\Delta_\perp-q_\perp)(\epsilon_\perp^{V*}\cdot\hat{k}_\perp)(\epsilon_\perp^{V}\cdot\hat{k}'_\perp)\Big\{\int d^2b_\perp \\
\times\; & e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\Big[T_A(b_\perp)\mathcal{A}_{in}(Y,\Delta_\perp)\mathcal{A}^*_{in}(Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp)+(A\leftrightarrow B)\Big] \\
+\; & \Big[e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp)\Big] \\
+\; & \Big[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-\Delta_\perp)}\mathcal{A}_{co}(-Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\Big] \\
+\; & \Big[\boxed{e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-k_\perp)}}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\Big] \\
+\; & \Big[\boxed{e^{i\tilde{b}_\perp\cdot(k'_\perp-\Delta_\perp)}}\mathcal{A}_{co}(-Y,\Delta_\perp)\mathcal{A}^*_{co}(Y,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(Y,k'_\perp)\Big]\Big\},
\end{aligned}
$$

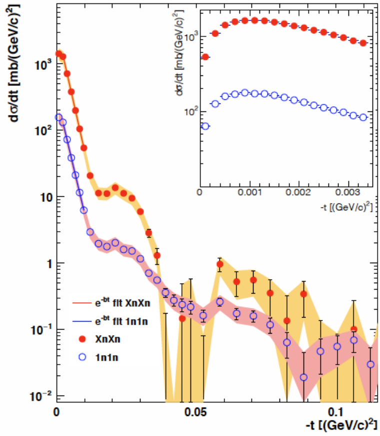
the interference terms ensure the perfect peak and valley structure

$$(\epsilon_\perp^{V*}\cdot\hat{k}_\perp)(\epsilon_\perp^{V}\cdot\hat{k}'_\perp)\to\Big[(\hat{k}_\perp\cdot\hat{k}'_\perp)+\cos(2\phi)\Big(2(\hat{k}_\perp\cdot\hat{q}_\perp)(\hat{k}'_\perp\cdot\hat{q}_\perp)-\hat{k}_\perp\cdot\hat{k}'_\perp\Big)\Big],$$

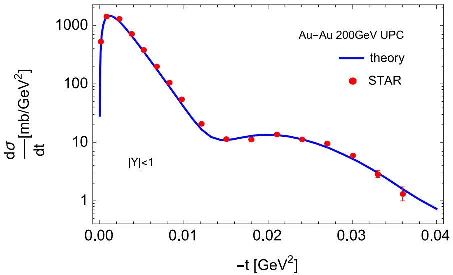
the spin vectors of γ and ρ^0 result in the $\cos 2\phi$ asymmetry

see also W. Zha, J. D. Brandenburg, L.J. Ruan, Z.B. Tang and Z.B. Xu, 2020

coherent ρ^0 production: compare with STAR



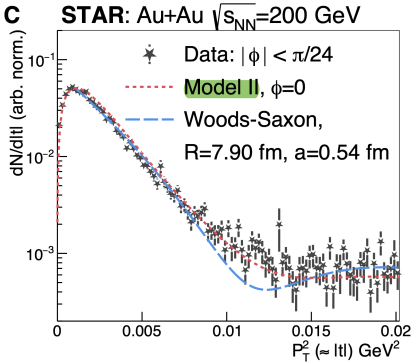
STAR, Phys.Rev.C 96 (2017) 5, 054904



Au	Skin depth	Strong interaction radius
Standard value	0.54fm	6.38fm
Fitted to STAR data	0.64fm	6.9fm

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

coherent ρ^0 production: compare with STAR

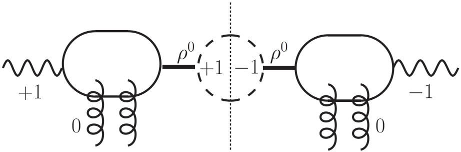


STAR collaboration, arXiv:2204.01625

Isaac Upsal, Wed, WG2

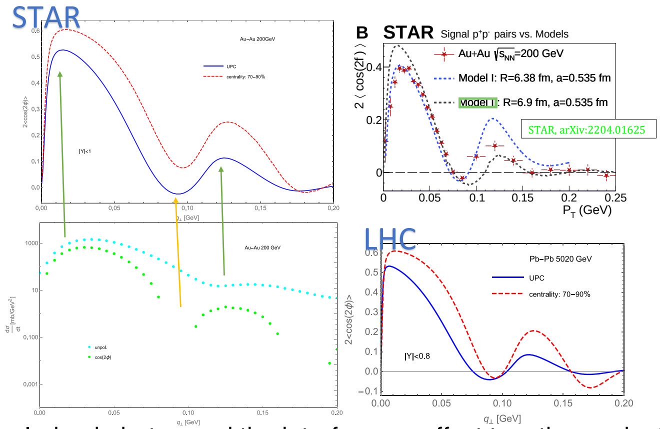
Model II: H.X. Xing, C. Zhang, J. Zhou and YZ, JHEP10(2020)064

$\cos 2\phi$ asymmetry: illustration diagram



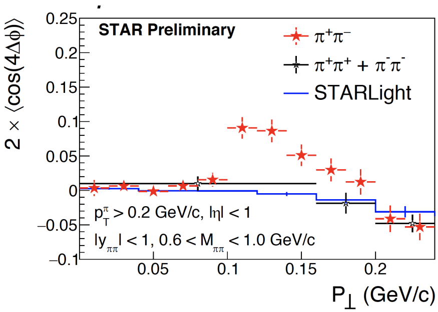
$$\langle +1 | -1 \rangle \sim \cos 2\phi$$

$\cos 2\phi$ asymmetry: numerical results



The linearly polarized photon and the interference effect together make the $< \cos(2\phi) >$ shape.
At pA/EIC, no interference term, the first peak absent.

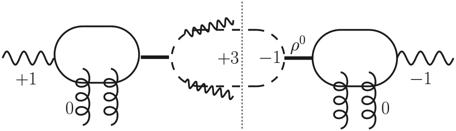
$\cos 4\phi$ asymmetry: STAR experiment



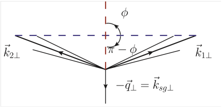
Daniel Brandenburg, QM 2019

$\cos 4\phi$ asymmetry: theory

1. final state soft photon radiation



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



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

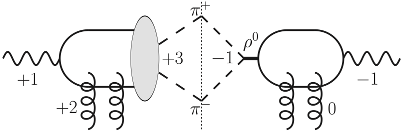
cross section,

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

soft factor at leading order:

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

2. elliptic gluon Wigner distribution



elliptic Wigner gluon

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

dipole amplitude,

$$N(b_\perp, r_\perp) \approx 1 - \exp\left[-Q_s^2\left(b_\perp^2\right) r_\perp^2/4\right] + E\left(b_\perp^2, r_\perp^2\right) 2 \boxed{\cos(2\phi_b - 2\phi_r)} \frac{Q_s^2\left(b_\perp^2\right) r_\perp^2}{4} e^{-\frac{Q_s^2(b_\perp^2) r_\perp^2}{4}}$$

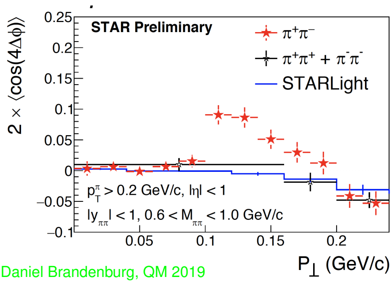
Y. Hatta, B.-W. Xiao, and F. Yuan, PRL (2016).

cross section,

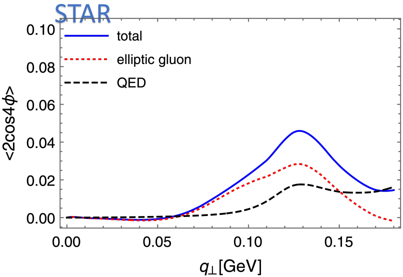
$$\frac{d\sigma_I}{d\mathcal{P.S.}} = \frac{\zeta(1-\zeta)M_\rho\Gamma_\rho|P_\perp|f_{\rho\pi\pi}}{2(2\pi)^7((Q^2-M_\rho^2)^2+M_\rho^2\Gamma_\rho^2)}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp+\Delta_\perp-q_\perp) \boxed{\cos(3\phi_P-\phi_k-2\phi_\Delta)\cos(\phi_P-\phi_{k'})}$$
$$\Big\{e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\mathcal{A}^*(x_2,\Delta'_\perp)\mathcal{E}(x_2,\Delta_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_1,k'_\perp)e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-\Delta_\perp)}\mathcal{A}^*(x_1,\Delta'_\perp)\mathcal{E}(x_1,\Delta_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_2,k'_\perp)$$
$$+e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-k_\perp)}\mathcal{A}^*(x_2,\Delta'_\perp)\mathcal{E}(x_1,\Delta_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_2,k'_\perp)e^{i\tilde{b}_\perp\cdot(k'_\perp-\Delta'_\perp)}\mathcal{A}^*(x_1,\Delta'_\perp)\mathcal{E}(x_2,\Delta_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_1,k'_\perp)\Big\}$$
$$+c.c.$$

for OAM & Wigner distribution study see also Shohini's talk Wed

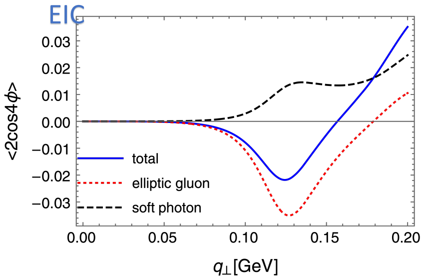
$\cos 4\phi$ asymmetry: numerical results



Daniel Brandenburg, QM 2019



Y. Hagiwara, C. Zhang, J. Zhou, YZ, PRD104, 094021 (2021)



QED alone is not adequate to describe the STAR data, elliptic gluon Wigner distribution also contribute to $\cos(4\phi)$ asymmetry

at EIC, contribution from the elliptic gluon distribution flip sign due to the absence of the double-slit interference

Summary

- The coherent photons in UPCs are highly linearly polarized can be used as a probe to study QCD phenomenology.
- Diffractive ρ production in UPCs induce $\cos 2\phi$ asymmetry, shape like Young's double slit experiment, consistent with STAR experiment.
- QED effect alone severely underestimates the observed $\cos 4\phi$ asymmetry, might signal the very existence of the nontrivial quantum correlation encoded in elliptic gluon distribution.

Thanks!