SPIN2021 The 24th International Spin Symposium

Matsue, Japan

Explore double slit interference effect with linearly polarized photons in UPCs

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Based on papers:

1903.10084 and 1911.00237; Cong Li, ZJ and Ya-jin Zhou
2003.06352; Bo-wen Xiao, Feng Yuan and ZJ
2006.06206; Hong-xi Xing, Cheng Zhang, ZJ and Ya-jin Zhou
2106.13466; Yoshikazu Hagiwara, Cheng Zhang, ZJ and Ya-jin Zhou

Oct. 18-22, 2021, Matsue, Shimane Prefecture, Japan

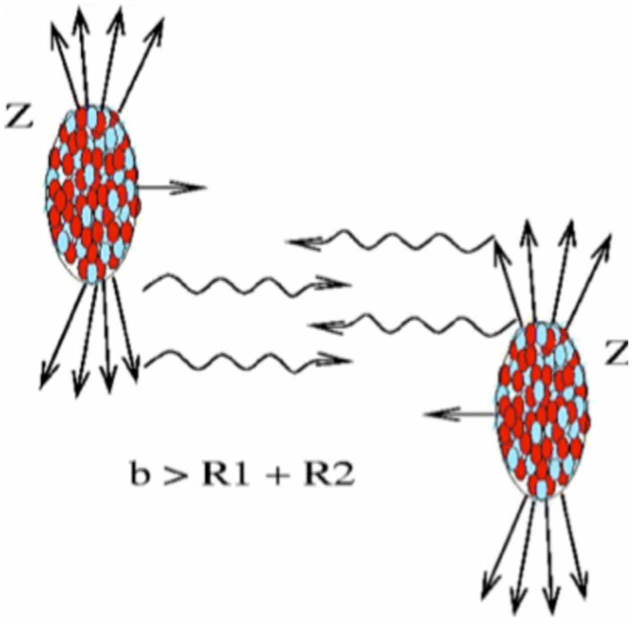
Outline

- Linearly polarized photon distribution
- Cos2ϕ in rho production
- Cos4ϕ in di-pion production
- Summary and Outlook

"Spin Polarization Effects in (peripheral /central) Heavy Ion Collisions",
yesterday's talk by Zuo-tang Liang.

We focus on ultraperipheral collisions.

Coherent photon distributions



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

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

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

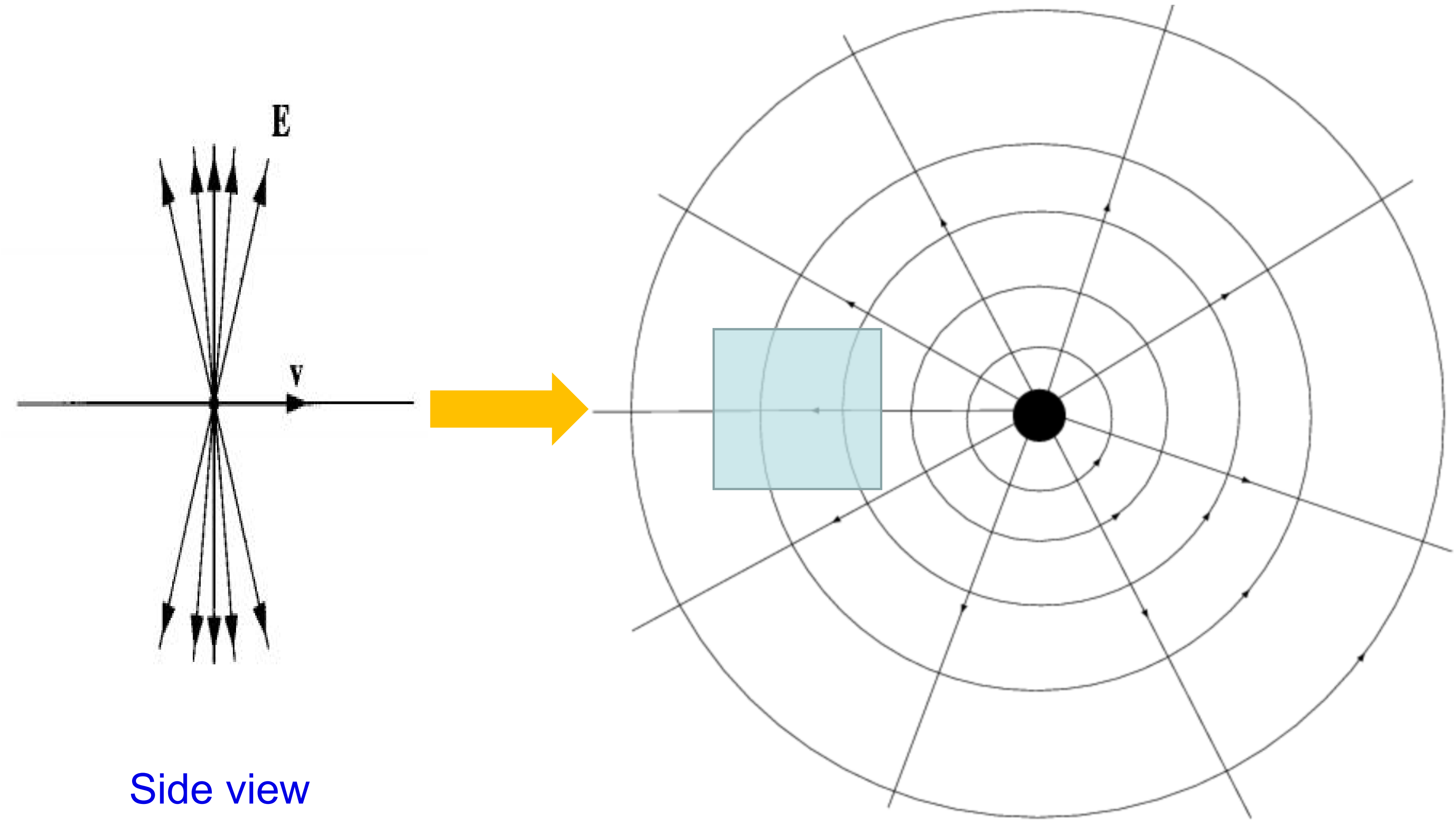
4 million times

$K_T \leq 1/R_A$

$d\sigma \propto Z^4$
clean background

$\gamma - \gamma$
$\gamma - \mathbf{A}$

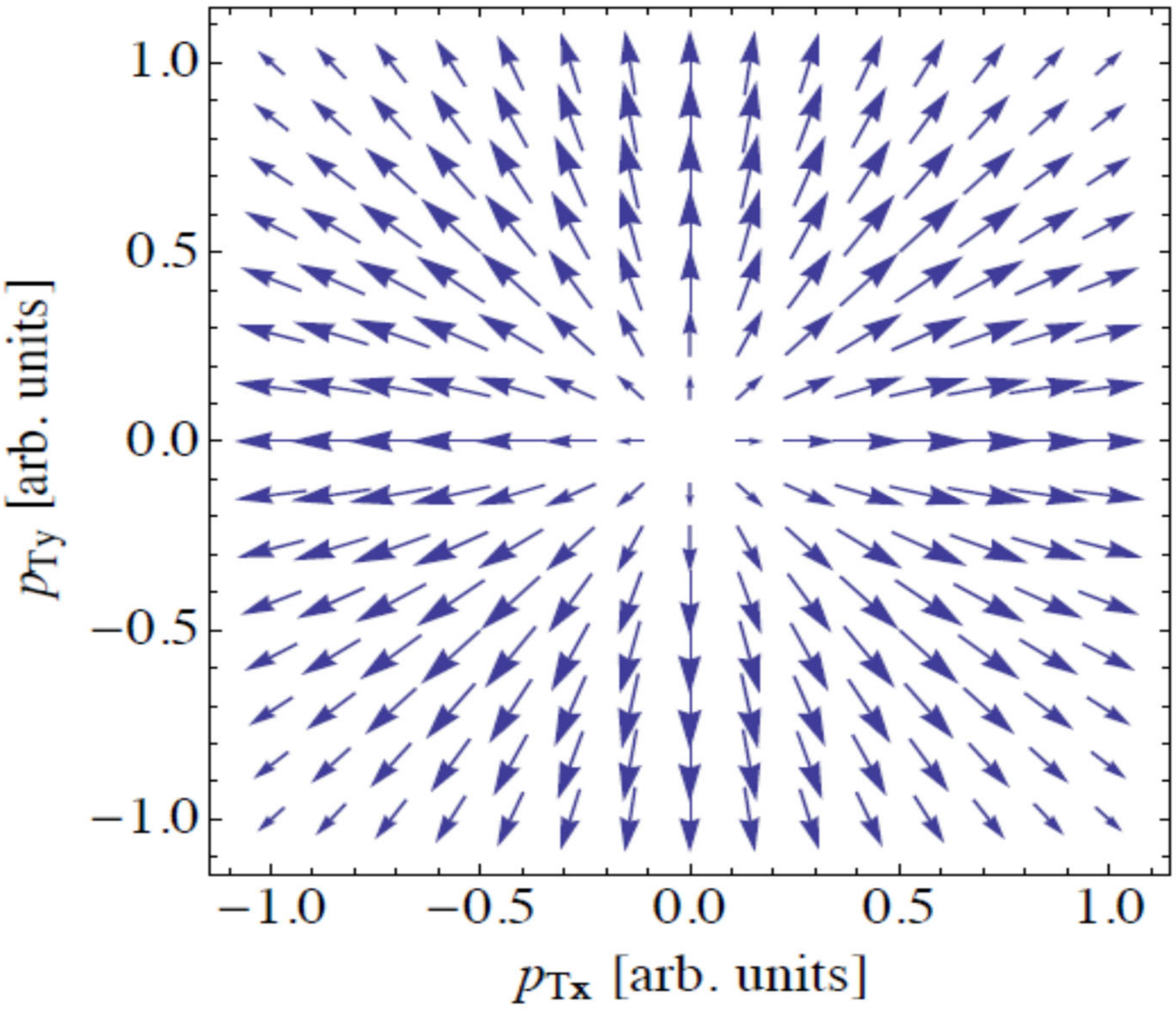
The boosted Coulomb potential

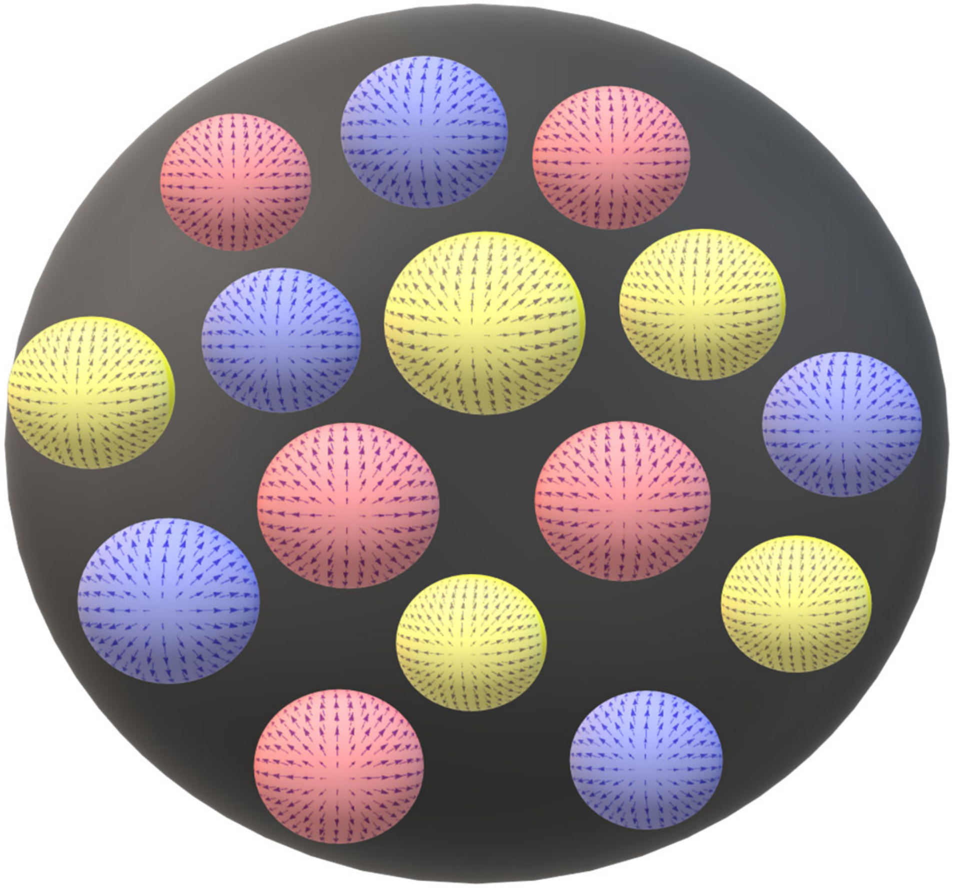


Side view

Head on view

Transverse momentum phase space





CGC is highly linearly polarized state as well.

Metz & Zhou, 2011

How to probe it?

Cos4ϕ in di-lepton production

Cos 4ϕ asymmetry in EM dilepton production

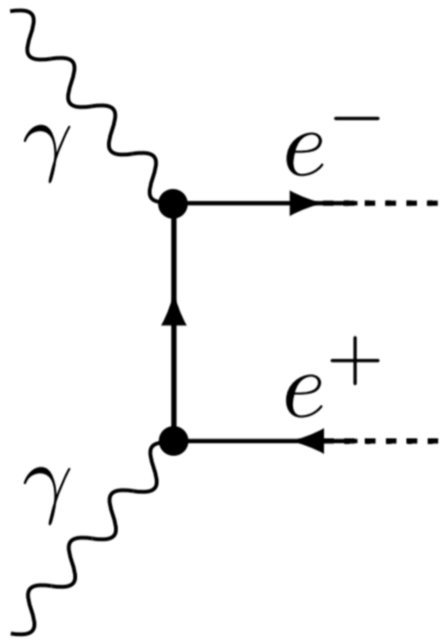
$$\gamma(x_1 P + k_{1\perp}) + \gamma(x_2 \bar{P} + k_{2\perp}) \to l^+(p_1) + l^-(p_2)$$

$$\langle \cos(4\phi) \rangle$$

$$\phi = P_\perp \wedge q_\perp$$

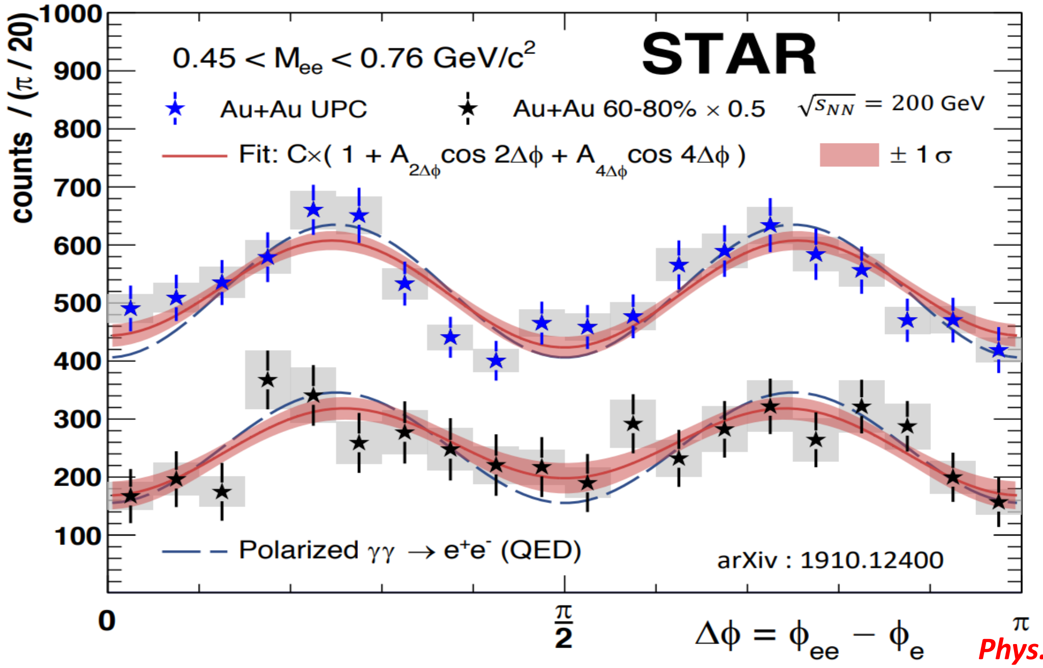
$$P_\perp \equiv (p_{1\perp} - p_{2\perp})/2$$

$$q_\perp \equiv p_{1\perp} + p_{2\perp}$$



correlation limit: $P_\perp \gg q_\perp$

$\tilde{b}_\perp$ dependent $\langle\cos(4\phi)\rangle$ V.S. STAR experiment



Phys.Rev.Lett. 127 (2021) 5, 052302

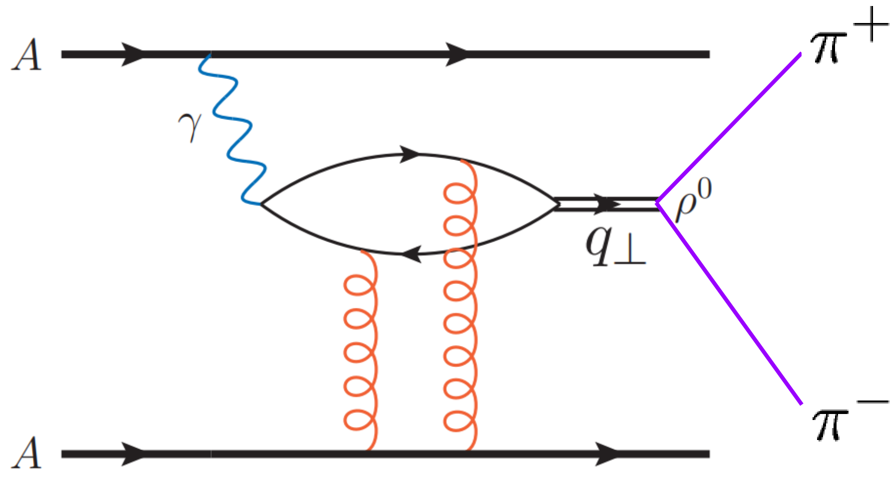
$0.45GeV^2<Q^2<0.76GeV^2$
$P_t>200MeV$, $|y|<1, q_t<100MeV$

C. Li, JZ and Y. Zhou, 2020

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

Cos2ϕ in ρ production

As a probe to study novel QCD phenomenology



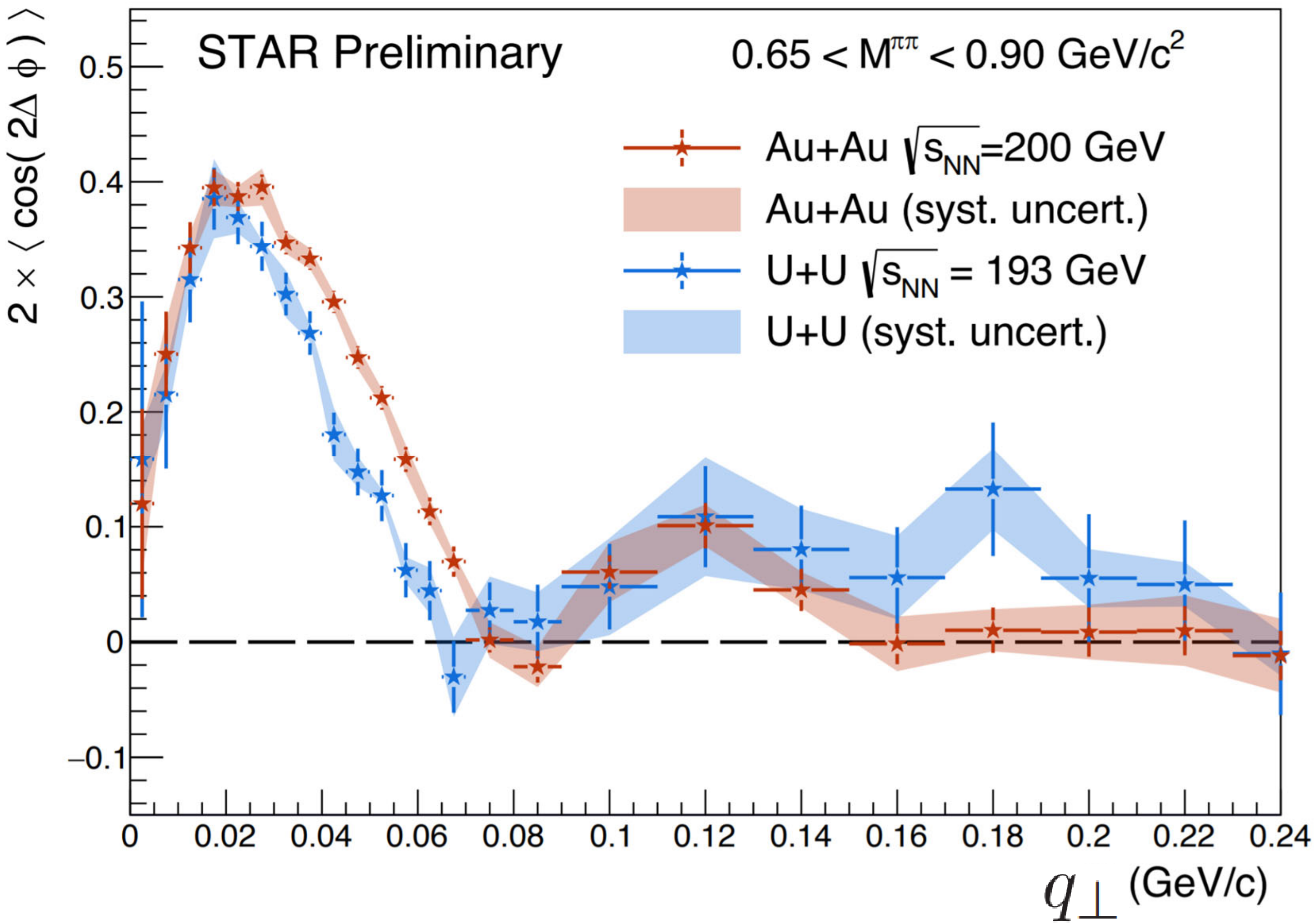
A $\cos(2\phi)$ azimuthal asymmetry is induced by linearly polarized photons.

ϕ is the angle between $q_\perp$ and $p_\perp^\pi$

$q_\perp$: ρ^0 transverse momentum

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

$\cos(2\phi)$ STAR measurement



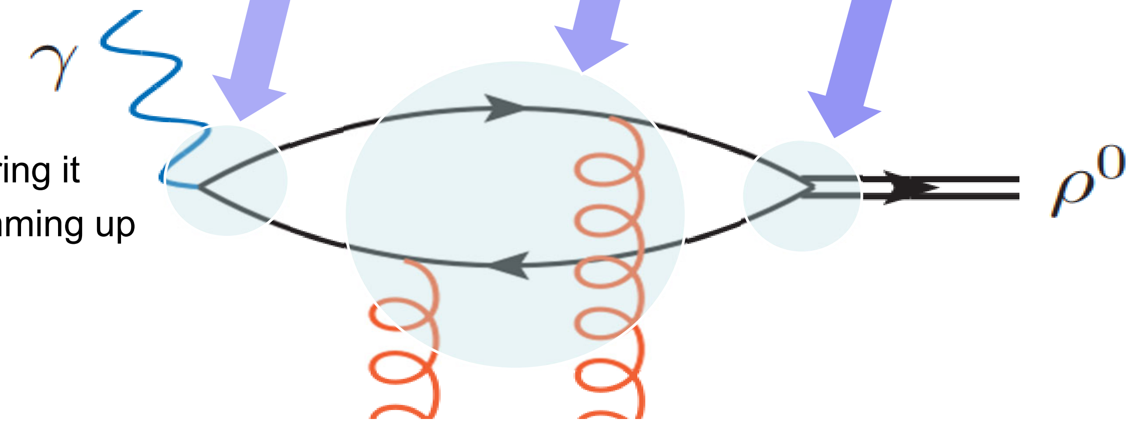
Daniel Brandenburg

Dipole model calculation

Diffractive scattering amplitude(based on dipole model)

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

M. G. Ryskin, 93
S. J. Brodsky, L. Frankfurt, J. F. Gunion, A. H. Mueller and M. Strikman, 94



Coherent: summing up amplitude→squaring it
Incoherent: squaring the amplitude→summing up

Formulated in the Glauber multiple re-scattering model:

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

Spin dependent wave function

$$\sum_{a,a',\sigma,\sigma'} \Psi^{\gamma\to q\bar{q}}\Psi^{V\to q\bar{q}*} = (\epsilon_\perp^{V*}\cdot\epsilon_\perp^{\gamma})\frac{ee_q}{2\pi}2N_c\int\frac{d^2r_\perp}{4\pi}N(r_\perp,b_\perp)\Big\{\left[z^2+(1-z)^2\right]$$
$$\times\frac{\partial\Phi^*(|r_\perp|,z)}{\partial|r_\perp|}\frac{\partial K_0(|r_\perp|e_f)}{\partial|r_\perp|}+m_q^2\Phi^*(|r_\perp|,z)K_0(|r_\perp|e_f)\Big\}$$

Spin correlation: SCHC **Star measurement Phys.Rev.C 77 (2008)**

- Linear polarization of photons implies: $\epsilon_\perp^{\gamma} \; // \; k_\perp$

Photon transverse momentum

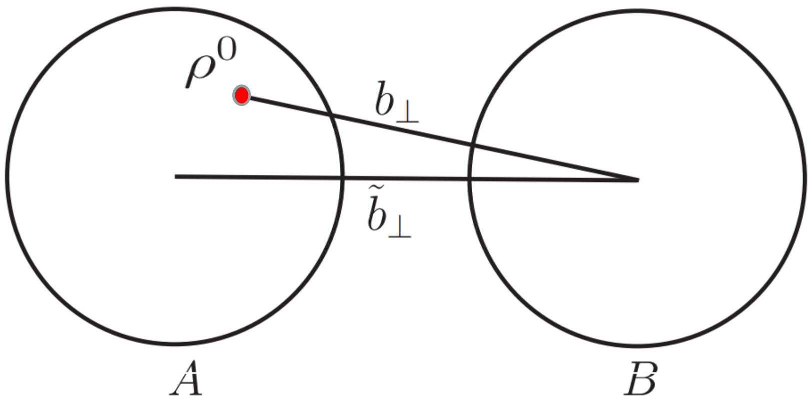
$$2(k_\perp^{\gamma}\cdot\epsilon_\perp^{V*})^2-1$$

$$q_\perp = k_\perp + \Delta_\perp$$

Observed by STAR

$$2(\hat{q}_\perp\cdot\epsilon_\perp^{V*})^2-1 \xrightarrow{\hat{p}_\perp^{\pi}\cdot\epsilon_\perp^{V*}} 2(\hat{q}_\perp\cdot\hat{p}_\perp^{\pi})^2-1$$

Joint $\tilde{b}_\perp$ & $q_\perp$ dependent cross section I



A and B are two incoming nuclei (head on view)

Assuming ρ^0 is locally produced at position $b_\perp$

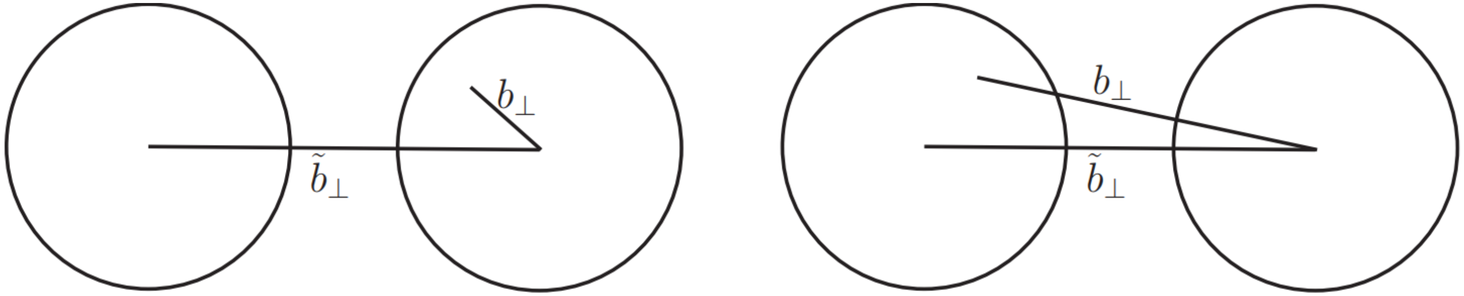
The probability amplitude of producing ρ^0 at position $b_\perp$

$$\mathcal{M}(Y, \tilde{b}_\perp, b_\perp) \propto \mathcal{F}_B(Y, b_\perp) N_A(Y, b_\perp - \tilde{b}_\perp)$$

$\mathcal{F}_B(Y, b_\perp)$: EM potential induced by B

$N_A(Y, b_\perp - \tilde{b}_\perp)$: Gluon density inside A

Joint $\tilde{b}_\perp$ & $q_\perp$ dependent cross section II



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

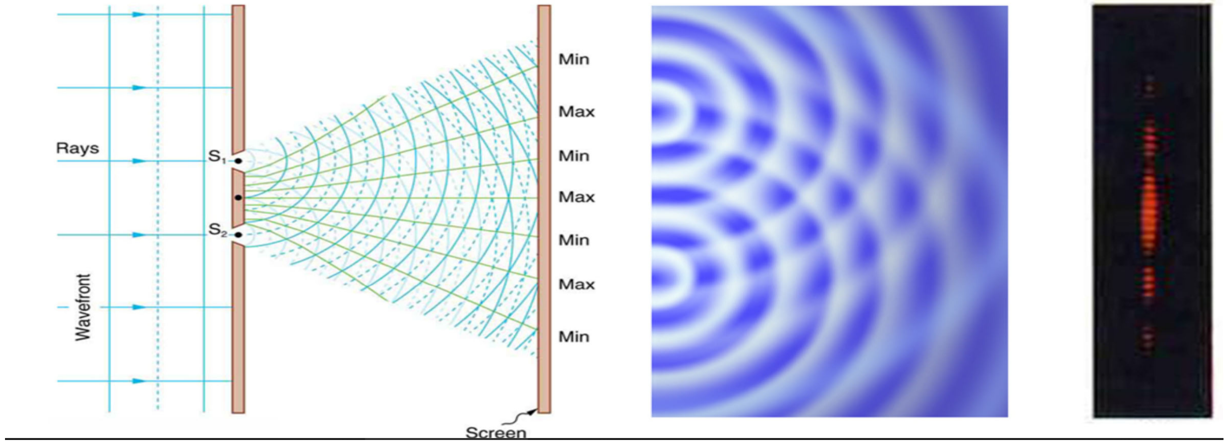
Making Fourier transform:

$$\mathcal{M}(Y,\tilde{b}_\perp,q_\perp) \propto \int d^2k_\perp d^2\Delta_\perp \delta^2(q_\perp-\Delta_\perp-k_\perp)$$
$$\times\left\{\mathcal{F}_B(Y,k_\perp)N_A(Y,\Delta_\perp)e^{-i\tilde{b}_\perp\cdot k_\perp}+\mathcal{F}_A(-Y,k_\perp)N_B(-Y,\Delta_\perp)e^{-i\tilde{b}_\perp\cdot\Delta_\perp}\right\}$$

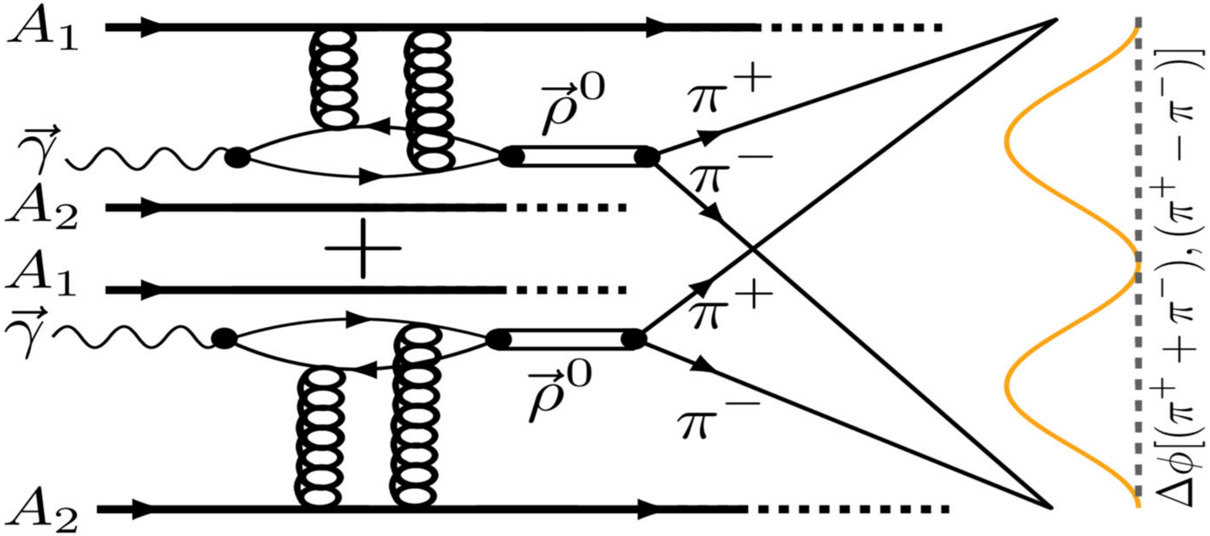
- The $\tilde{b}_\perp$ dependence enters via the phase.
- The relative phase leads to the destructive interference effect.

S. R. Klein and J. Nystrand,2000

- **Young's double-slit experiment**



- **double-slit experiment in UPCs**



Courtesy of Daniel Brandenburg

Joint $\tilde{b}_\perp$ & $q_\perp$ dependent cross section III

- Full cross section: $k_\perp + \Delta_\perp = k'_\perp + \Delta'_\perp$

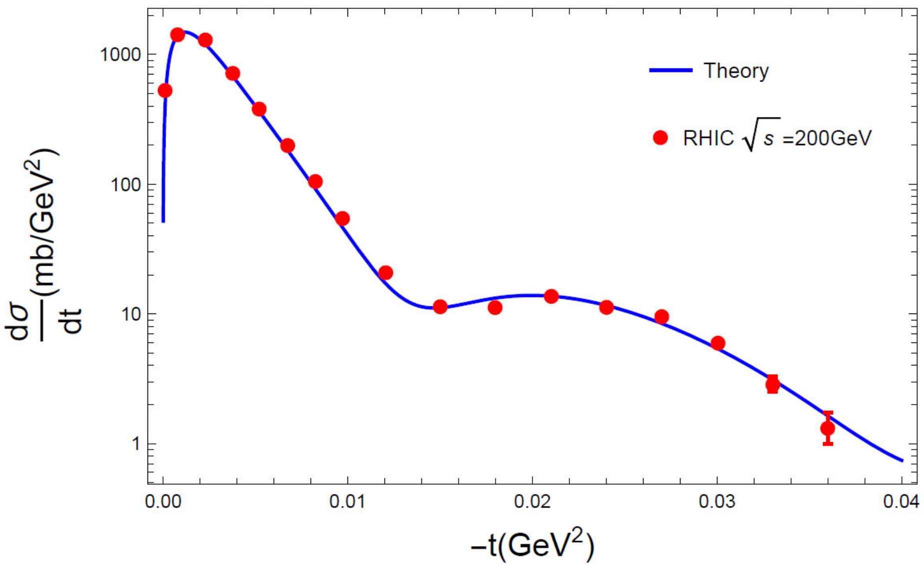
$$\frac{d\sigma}{d^2q_\perp dY d^2\tilde{b}_\perp} = \frac{1}{(2\pi)^4}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp + \Delta_\perp - q_\perp)(\epsilon_\perp^{V*}\cdot\hat{k}_\perp)(\epsilon_\perp^V\cdot\hat{k}'_\perp)\Big\{\int d^2b_\perp$$
$$\times e^{i\tilde{b}_\perp\cdot(k'_\perp - k_\perp)}\left[T_A(b_\perp)\mathcal{A}_{in}(Y,\Delta_\perp)\mathcal{A}^*_{in}(Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp) + (A\leftrightarrow B)\right]$$
$$+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp - k_\perp)}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp)\right]$$
$$+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp - \Delta_\perp)}\mathcal{A}_{co}(-Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right]$$
$$+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp - k_\perp)}\mathcal{A}_{co}(Y,\Delta_\perp)\mathcal{A}^*_{co}(-Y,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right]$$
$$+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp - \Delta_\perp)}\mathcal{A}_{co}(-Y,\Delta_\perp)\mathcal{A}^*_{co}(Y,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(Y,k'_\perp)\right]\Big\}, \quad (2.14)$$

H.X. Xing, Z. Zhang, ZJ, Y.J. Zhou, 2020

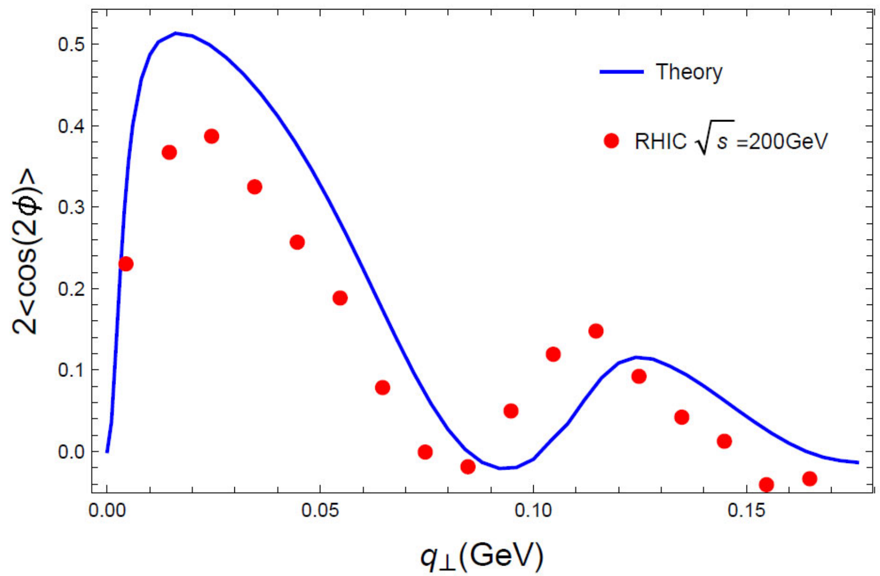
- EM potential: $\mathcal{F}(Y,k_\perp) = \frac{Z\sqrt{\alpha_e}}{\pi}|k_\perp|\frac{F(k_\perp^2 + x^2M_p^2)}{(k_\perp^2 + x^2M_p^2)}$

ρ^0 production in UPCs

Unpolarized cross section



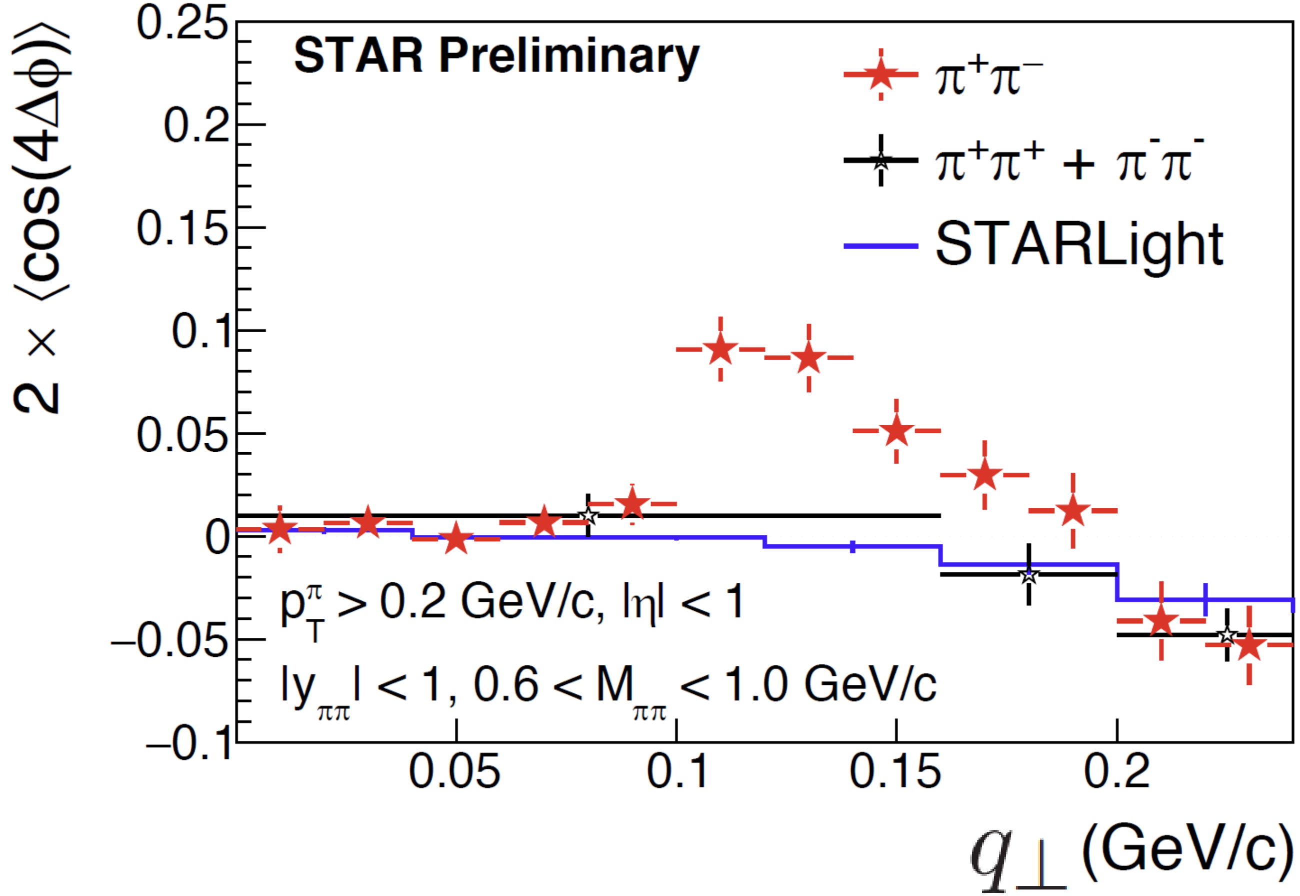
Cos2ϕ azimuthal asymmetry



e-Print: 2006.06206; **H.X. Xing, C. Zhang, J. Zhou and Y. J. Zhou; 2020**

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

Cos4ϕ in di-pion production



Elliptic Gluon GTMD distribution

The operator definition

Y. Hatta, B. W. Xiao and F.Yuan, 2016

$$\int \frac{d^2b_\perp d^2r_\perp}{(2\pi)^4} e^{-iq_\perp\cdot r_\perp - i\Delta_\perp\cdot b_\perp} \frac{1}{N_c}\left\langle \mathrm{Tr}\left[U(b_\perp + \frac{r_\perp}{2})U^\dagger(b_\perp - \frac{r_\perp}{2})\right]\right\rangle$$

$$= \mathcal{F}_x(q_\perp^2, \Delta_\perp^2) + \frac{q_\perp\cdot\Delta_\perp}{|q_\perp||\Delta_\perp|}O_x(q_\perp^2,\Delta_\perp^2) + \left[\frac{(q_\perp\cdot\Delta_\perp)^2}{q_\perp^2\Delta_\perp^2} - \frac{1}{2}\right]\mathcal{F}_x^{\mathcal{E}}(q_\perp^2,\Delta_\perp^2) + \ldots$$

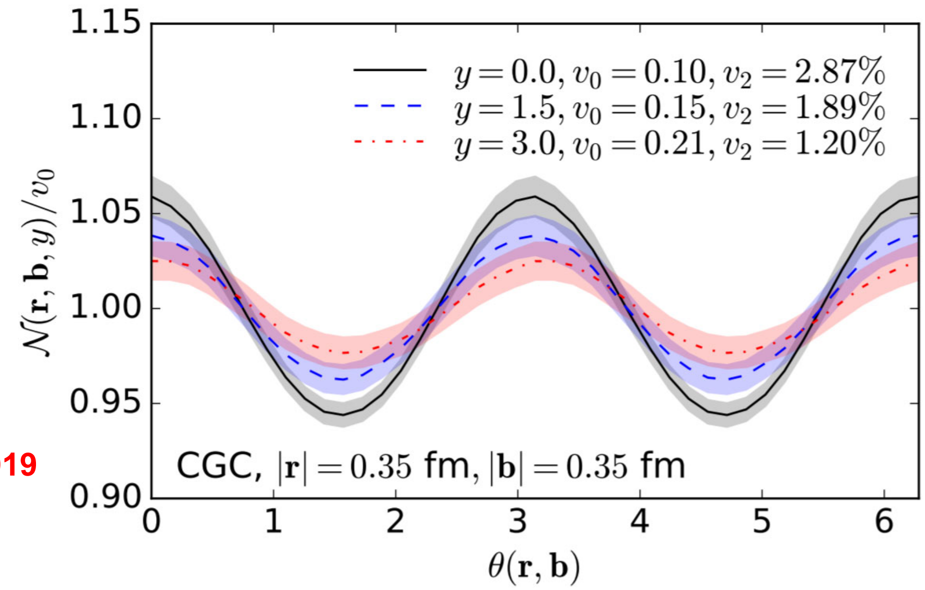
Unpolarized gluon GTMD

Elliptic gluon GTMD

A recent phenomengical study, **D. Boer, C. Setyadi, 2021**

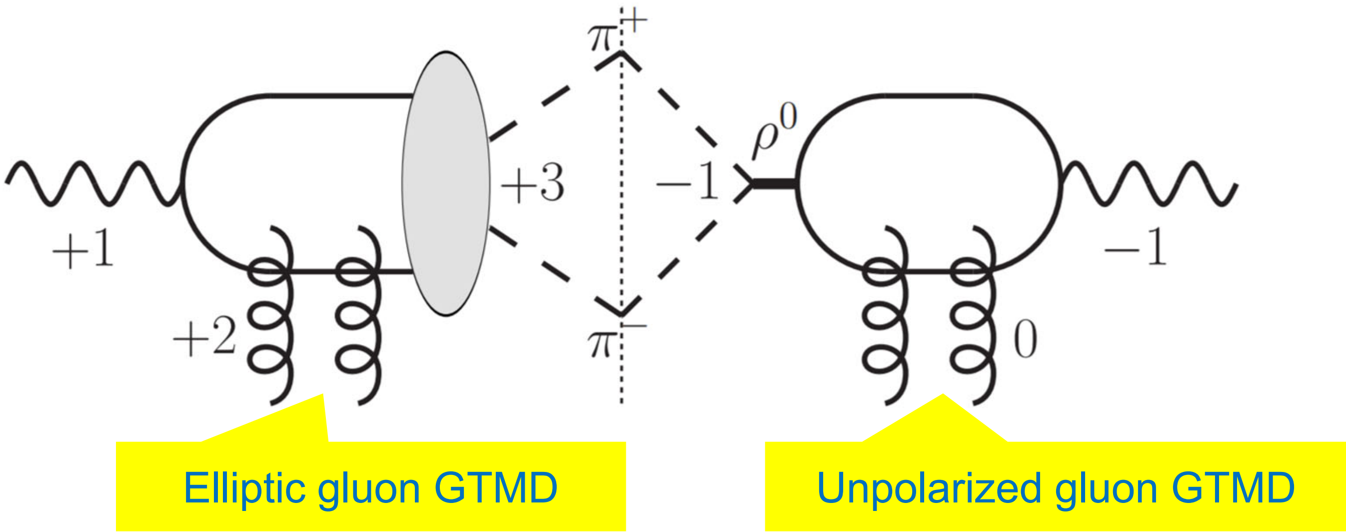
Computed in the MV model, **ZJ 2016**

H. Mantysaari, N. Mueller and B. Schenke, 2019



The interference contribution

direct production via ρ decay



- Elliptic gluon GTMD effectively carries 2 units of OAM!

- The nonperturbative transition from quark pair to di-pion is described by di-pion distribution amplitude

Azimuthal dependent cross section

$$\frac{d\sigma_I}{d\mathcal{P}.\mathcal{S}.} = \frac{\zeta(1-\zeta)M_\rho\Gamma_\rho|P_\perp|f_{\rho\pi\pi}}{2(2\pi)^7((Q^2-M_\rho^2)^2+M_\rho^2\Gamma_\rho^2)}$$

$$\times \int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp + \Delta_\perp - q_\perp)$$

$$\times \cos(3\phi_P - \phi_k - 2\phi_\Delta)\cos(\phi_P - \phi_{k'})\Big\{$$

$$e^{i\tilde{b}_\perp\cdot(k'_\perp - k_\perp)}\mathcal{A}^*(x_2,\Delta'_\perp)\mathcal{E}(x_2,\Delta_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_1,k'_\perp)$$

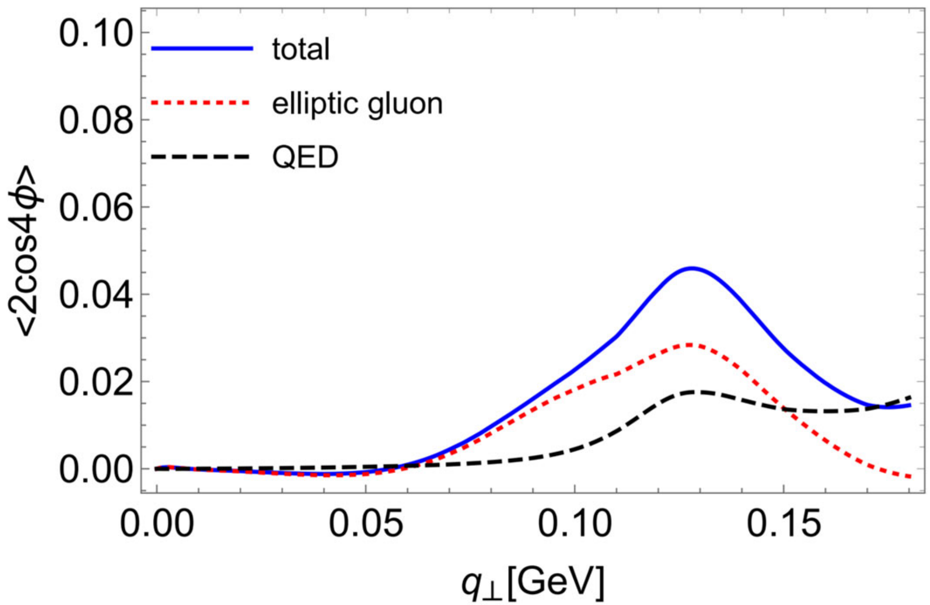
$$+e^{i\tilde{b}_\perp\cdot(\Delta'_\perp - \Delta_\perp)}\mathcal{A}^*(x_1,\Delta'_\perp)\mathcal{E}(x_1,\Delta_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_2,k'_\perp)$$

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

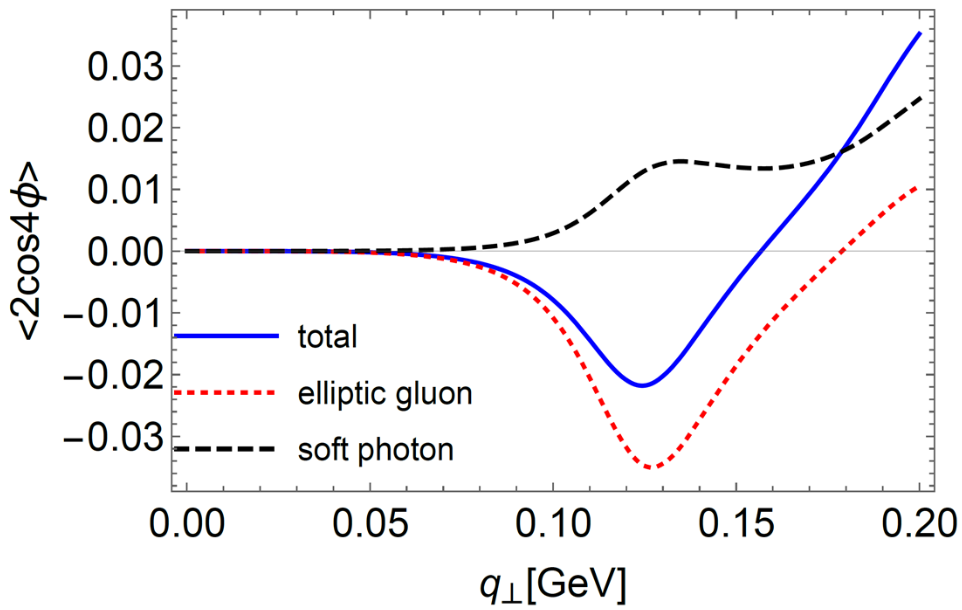
$$+e^{i\tilde{b}_\perp\cdot(k'_\perp - \Delta'_\perp)}\mathcal{A}^*(x_1,\Delta'_\perp)\mathcal{E}(x_2,\Delta_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_1,k'_\perp)\Big\}$$

Numerical results

RHIC



EIC



Remarks:

- Final state soft photon radiations also induce the same cos4ϕ asymmetry
- Elliptic gluon GTMD is a necessary ingredient to describe STAR data
- The difference between RHIC and EIC ➡ double slit interference effect
- Dipion v.s. diffractive dijet **Y. Hatta, B.w. Xiao, F. yuan and ZJ 2020,2021**

Summary

- Coherent photons excited by charged heavy ion are linearly polarized
- Explore novel QCD phenomenology with linearly polarized photons
- cos4ϕ for di-pion is a promising way to access elliptic gluon GTMD

Thank you!