Azimuthal correlations in UPCs

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Based on papers:

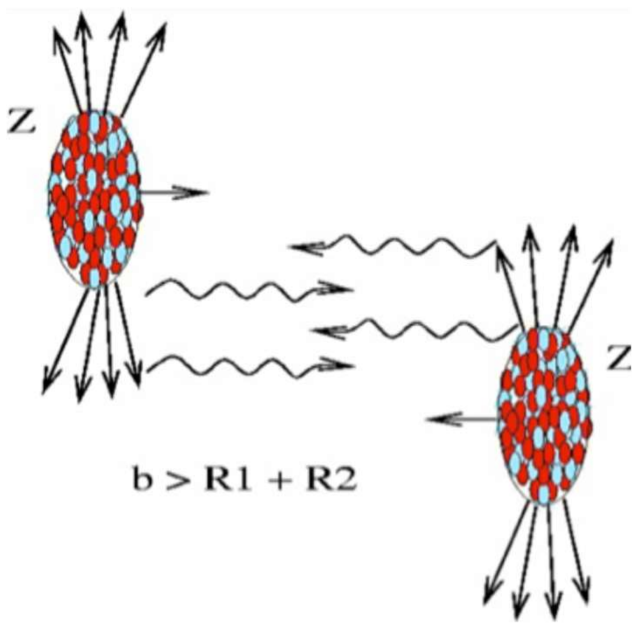
1903.10084 and 1911.00237; Cong Li, ZJ and Ya-jin Zhou
2003.06352; Bo-wen Xiao, Feng Yuan and ZJ
2006.06206; Hong-xi Xing, Cheng Zhang, ZJ and Ya-jin Zhou
2011.13151; Yoshikazu Hagiwara, Cheng Zhang, ZJ and Ya-jin Zhou

Open questions in photon-induced interactions-from Relativistic Nuclear collisions to the Future EIC, 26-28 April, 2021.

Outline

- Linearly polarized photon distribution
- Cos4ϕ in di-lepton production
- Cos2ϕ in rho production
- Cosϕ and Cos3ϕ in di-pion production
- Summary and Outlook

Coherent photon distributions



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

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

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

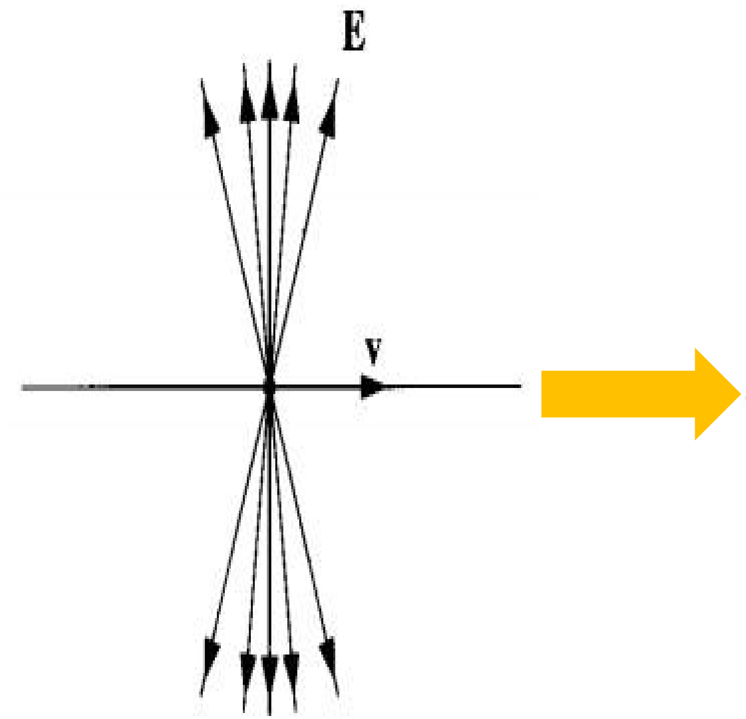
4 million times

$\mathbf{K_T} \leq \mathbf{1}/R_A$

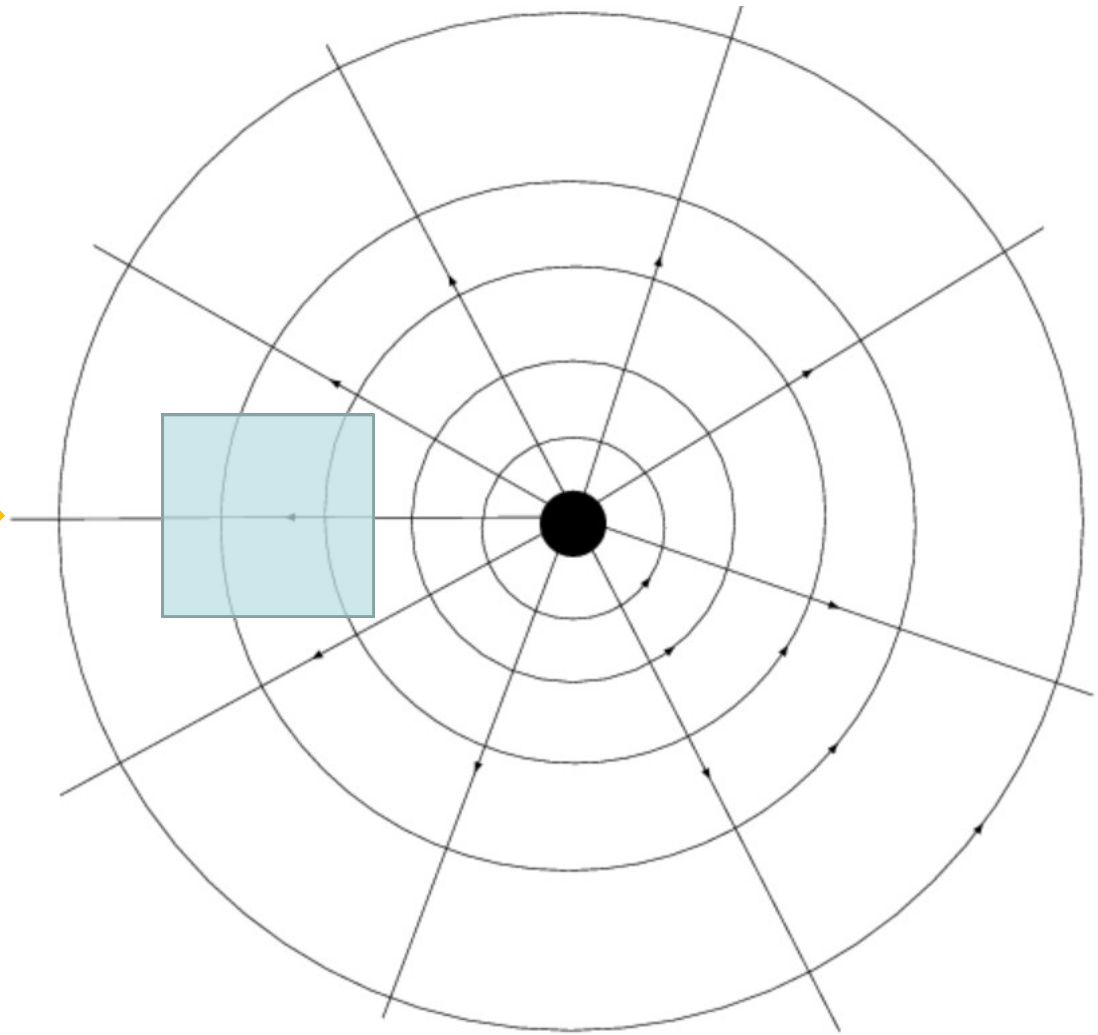
$d\sigma \propto Z^4$
clean background

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

The boosted Coulomb potential

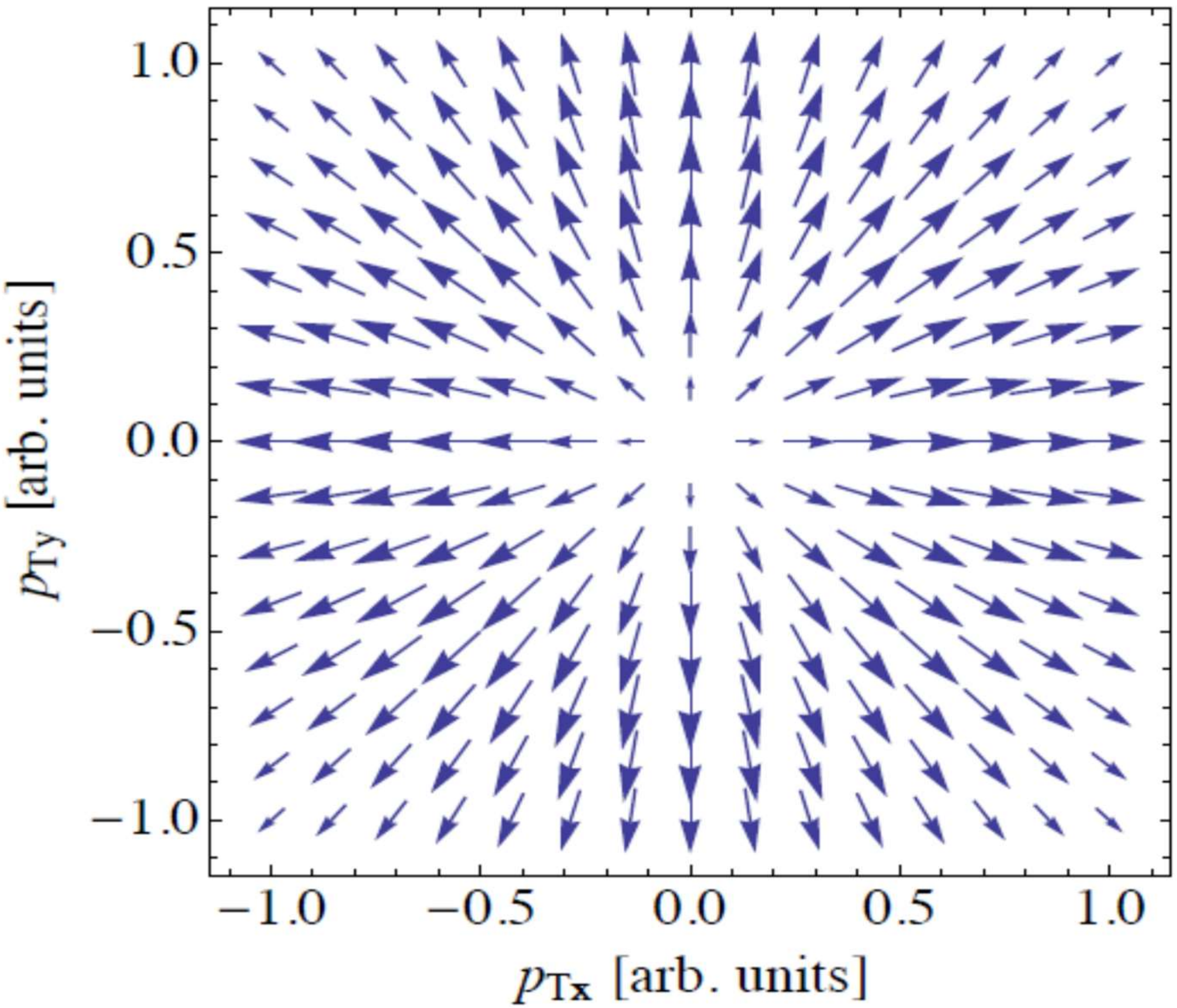


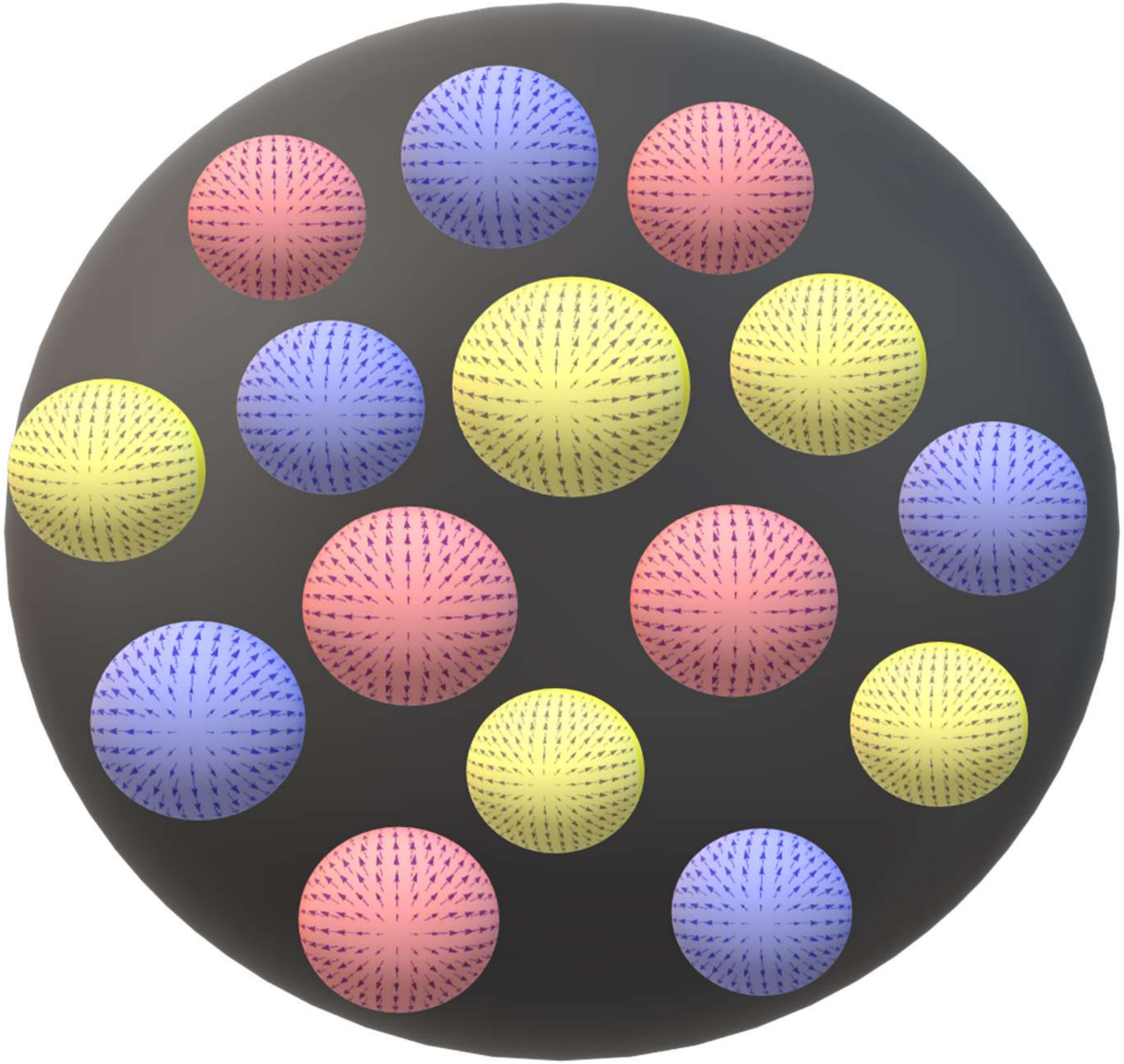
Side view



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

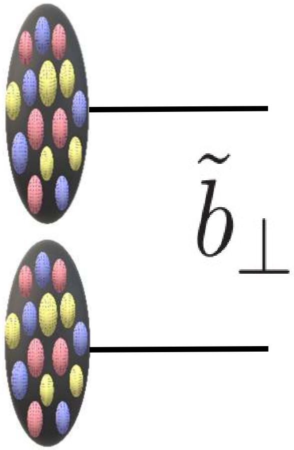
$$\gamma(x_1 P + k_{1\perp}) + \gamma(x_2 \bar{P} + k_{2\perp}) \to l^+(p_1) + l^-(p_2)$$

$$\langle \cos(4\phi) \rangle \qquad \phi = P_\perp \wedge q_\perp$$

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

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

Impact parameter dependence



See also Bowen and Wangmei's talk

- $\tilde{b}_\perp$ dependent formula established(unpolarized cross section)

M. Vidovic, M. Greiner, C. Best and G. Soff; 93

- Successfully describes dilepton qt broadening effect

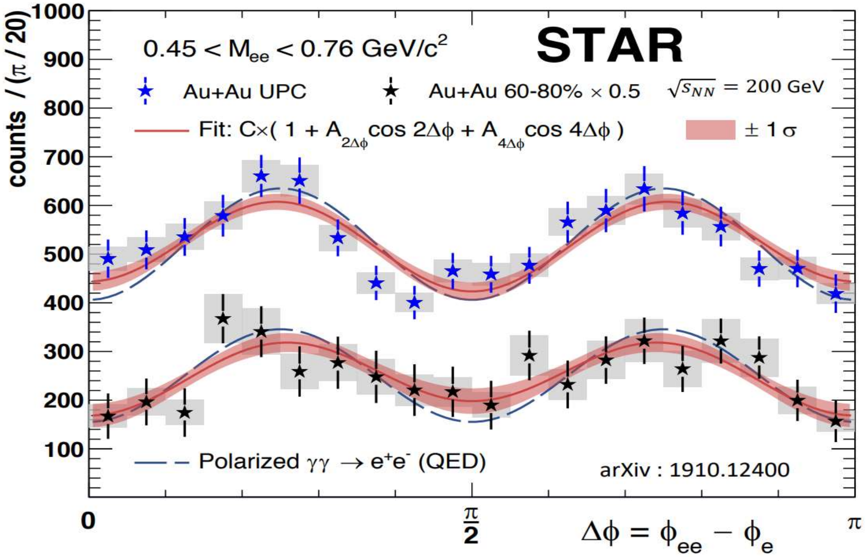
W. Zha, J. D. Brandenburg, Z. Tang and Z. Xu, 2019

S. Klein, A. H. Mueller, B.W. Xiao and F. Yuan, 2020

- Formulation in terms of photon Wigner distribution

S. Klein, A. H. Mueller, B.W. Xiao and F. Yuan, 2020
M. K. Gawenda, W. Schafer and A. Szcurek, 2020

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



Daniel Brandenburg, QM 2019

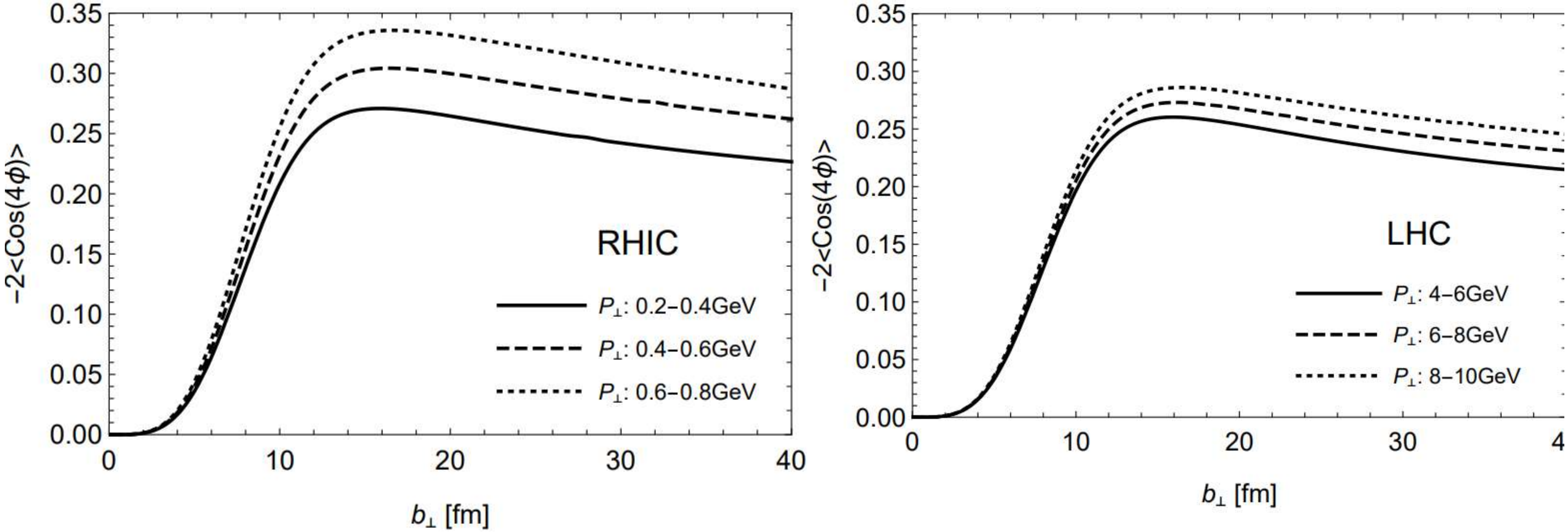
$0.45GeV^2<Q^2<0.76GeV^2$

$P_t>200MeV$, $|y|<1, q_t<100MeV$

C. Li, JZ and Y. Zhou, 2020

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

Cos4ϕ: the correlation bt and Pt in PCs



$$P_\perp \wedge \tilde{b}_\perp$$

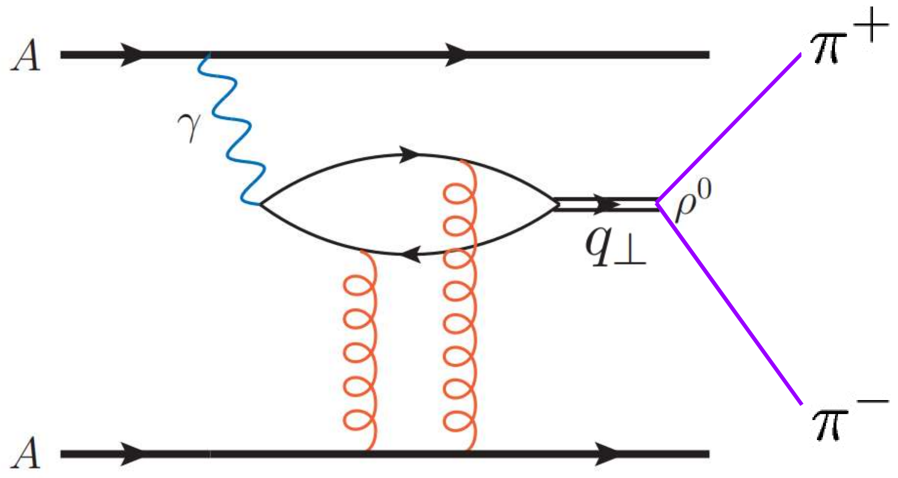
B.W. Xiao, F. Yuan and ZJ, 2020

See also Bowen's talk

The manifestation of the linear polarization of photons in another way.

Cos2ϕ in ρ production

As a probe to study novel QCD phenomenology



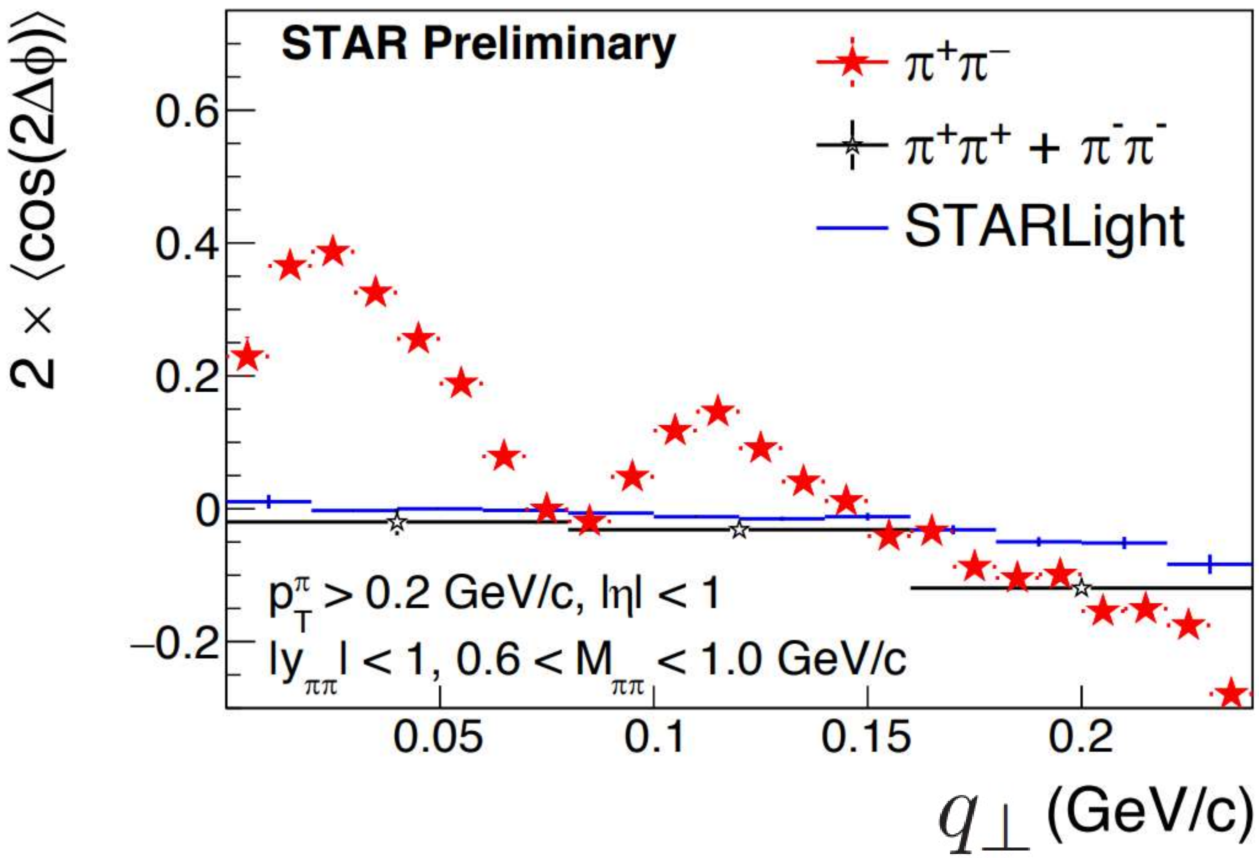
A $\cos(2\phi)$ azimuthal asymmetry is induced by linearly polarized photons.

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, QM 2019

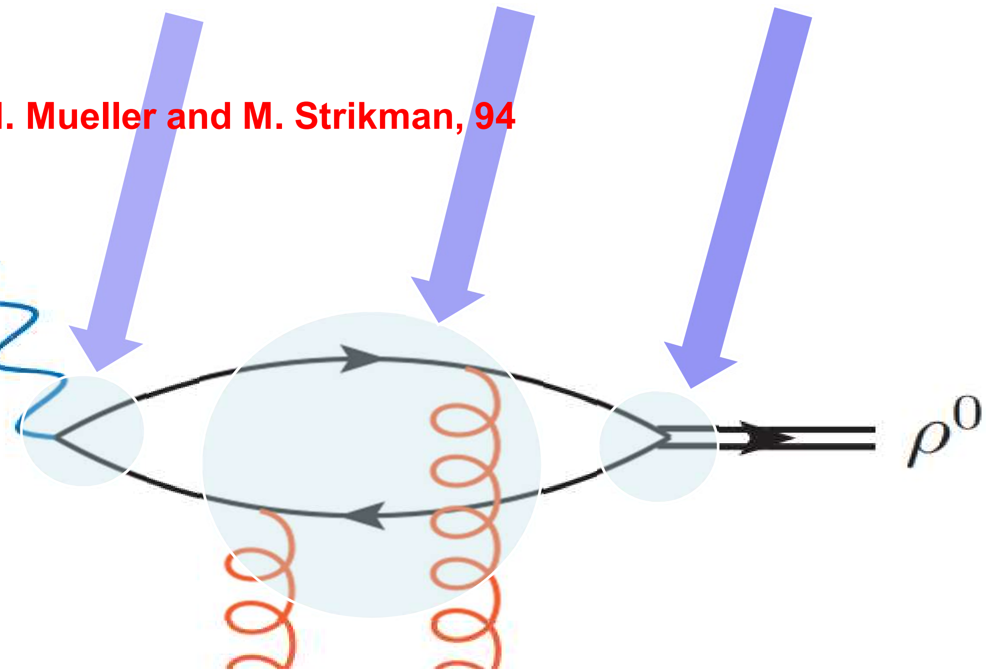
Dipole model calculation

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

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

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

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

Photon transverse momentum

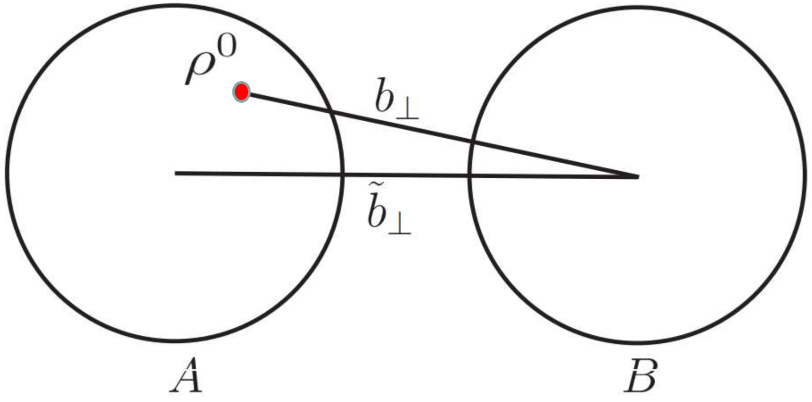
$$2(k_\perp^{\gamma}\cdot\epsilon_\perp^{V*})^2-1$$

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

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 $b_\perp$

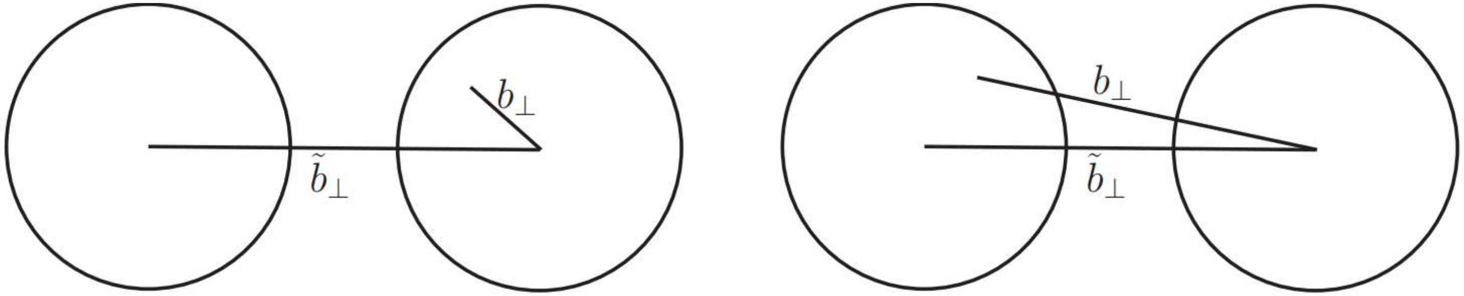
The probability amplitude of producing ρ^0 at position $b_\perp$

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

$\mathcal{F}_B(Y, b_\perp)$: 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



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

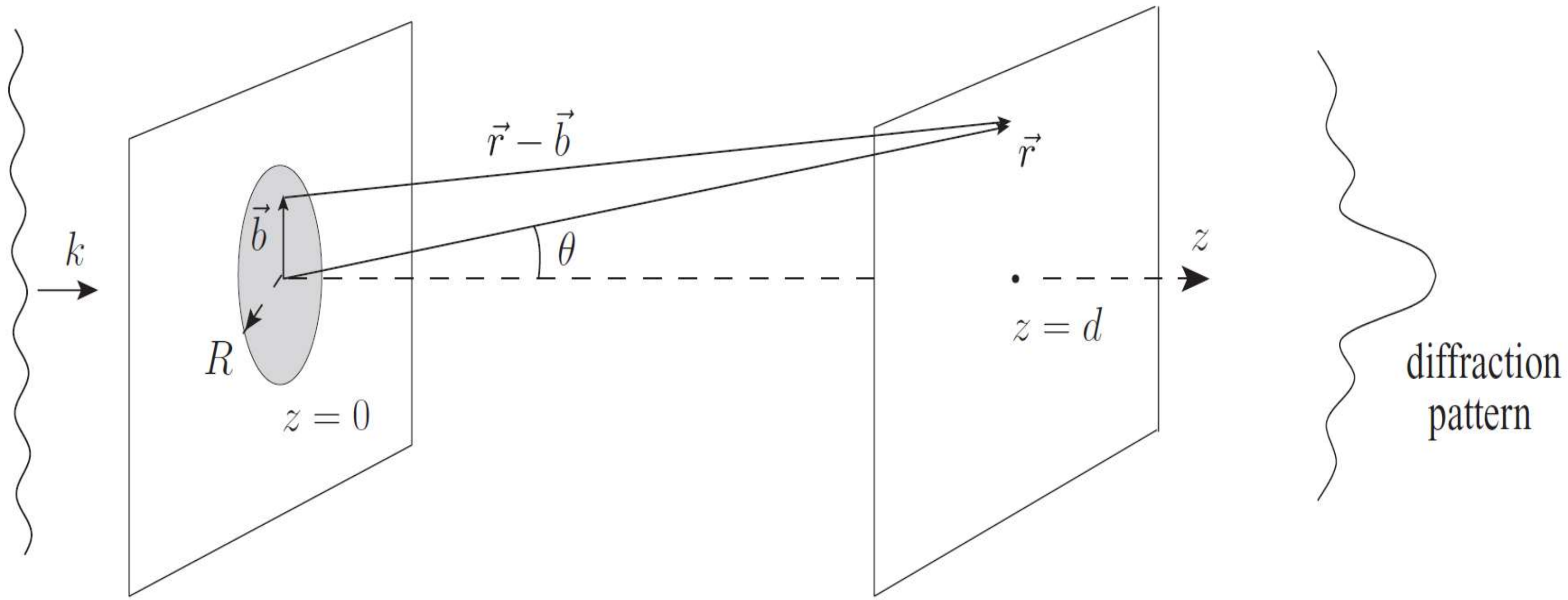
Making Fourier transform:

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

- 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

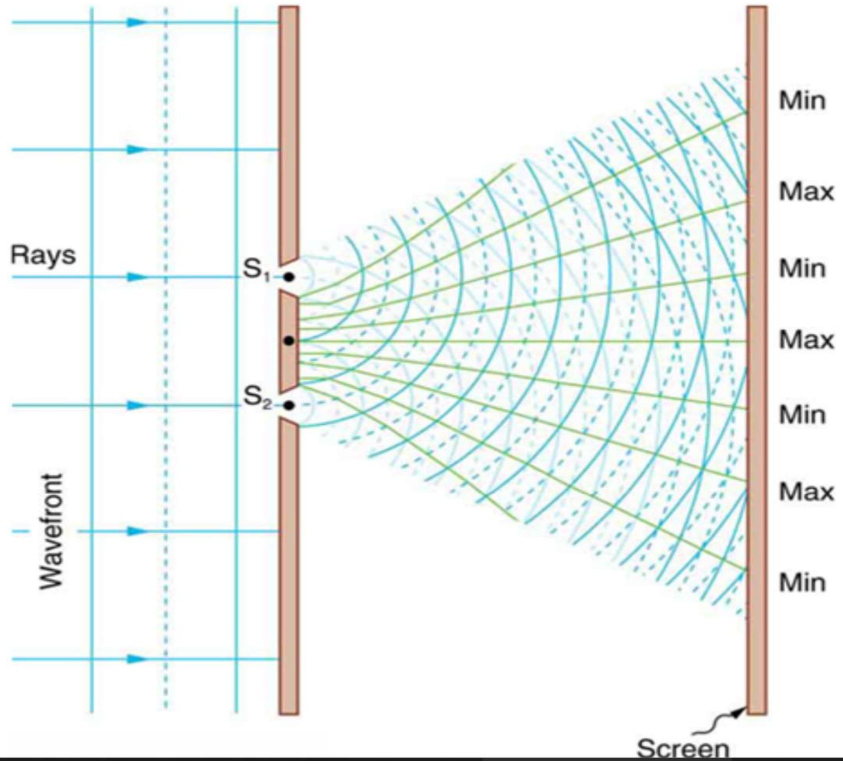
Diffractive pattern

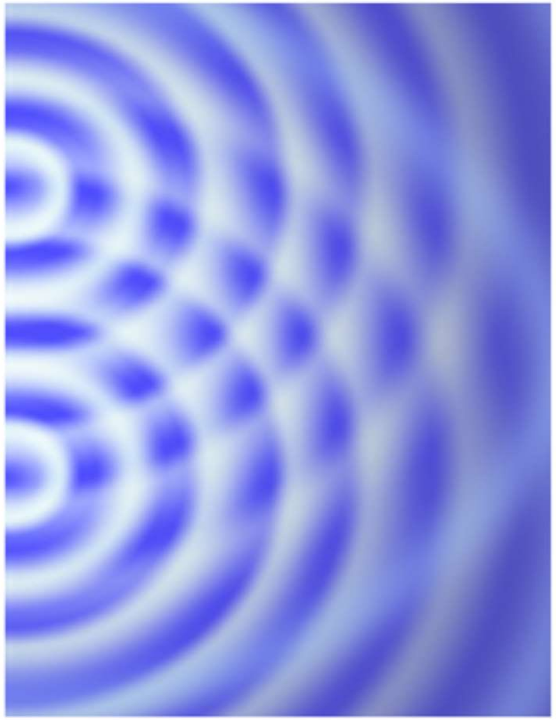


Taken from Yuri's book

$$\frac{d\sigma}{dt} = \pi R^2 \frac{J_1^2\left(\sqrt{|t|}R\right)}{|t|}$$

Young's double-slit experiment in heavy ion collisions





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

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

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

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

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

Two remarks

- Integrate out $\tilde{b}_\perp$, producing $\delta^2(k_\perp - k'_\perp)$ $\delta^2(\Delta_\perp - k'_\perp)$

$$\frac{d\sigma}{d^2 q_\perp dY} = \frac{1}{(2\pi)^4} \int d^2 k_\perp x f(x, k_\perp) \left\{ 1 + \cos 2\phi \left[2(\hat{q}_\perp \cdot \hat{k}_\perp)^2 - 1 \right] \right\}$$
$$\left\{ A_{co}(Y,\Delta_\perp) A^*_{co}(Y,\Delta_\perp) \mathcal{F}(Y,k_\perp) \mathcal{F}(Y,k_\perp) - A_{co}(-Y,\Delta_\perp) A^*_{co}(-Y,\Delta_\perp) \mathcal{F}(-Y,k_\perp) \mathcal{F}(-Y,k_\perp) \right\}$$

  - When $Y = 0$, complete destructive interference.

S. R. Klein and J. Nystrand,2000

- Incoherent production doesn't contribute to the asymmetry

$\Delta_\perp$ distribution is very flat

$$\int d^2 k_\perp x f(x, k_\perp) \left[2(\hat{q}_\perp \cdot \hat{k}_\perp)^2 - 1 \right] = 0$$

Some model inputs

- Gluon distribution/Dipole amplitude: GBW model for a nucleon
- Charge distribution: Woods-Saxon distribution.
- Nucleon distribution inside a nucleus: Modified WS distribution

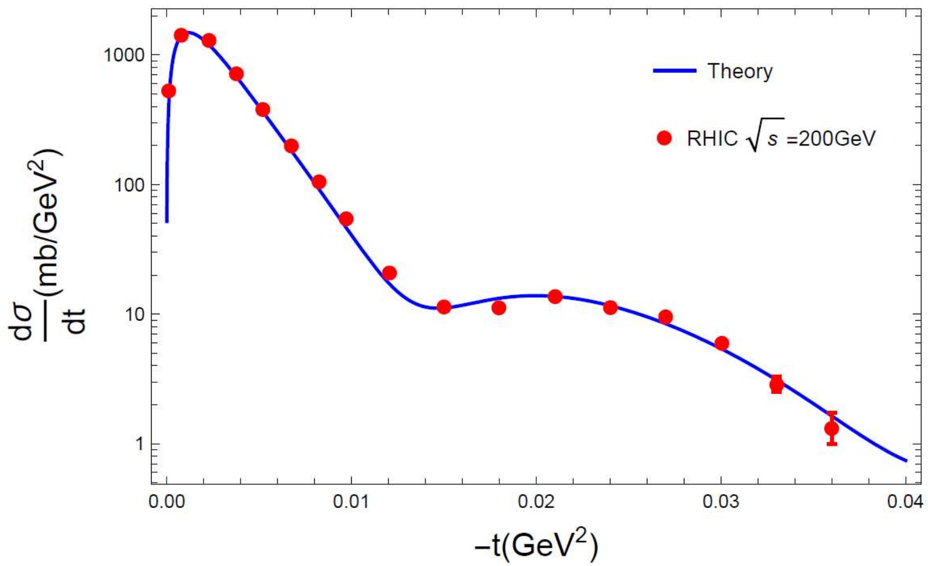
Nuclear strong interaction radius should be slightly larger than
its EM radius due to neturon skin effect and possible pion cloud effect

- Vector meson wave function: taken from H. Kowalski and D. Teaney, 2003
- Quasi-real photon wave function: QED
- Computing "Xn" events with,

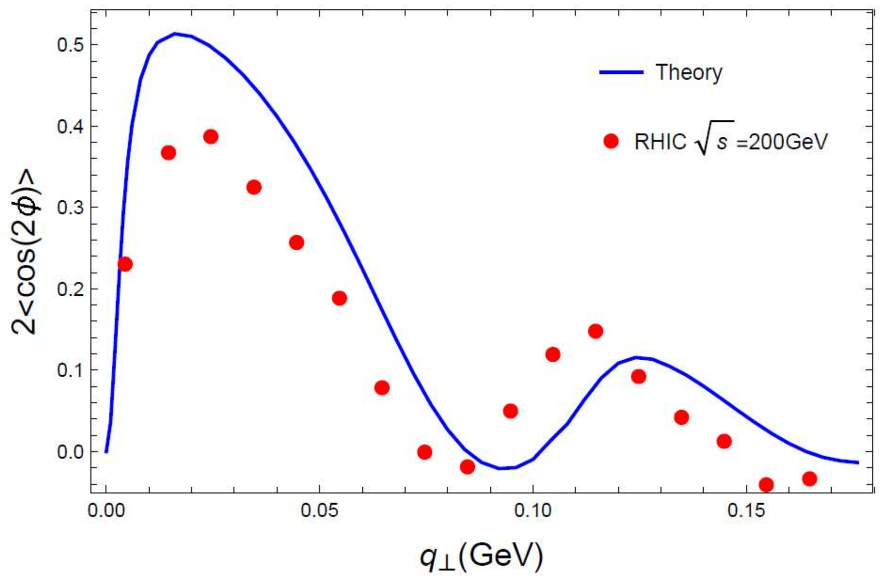
$$2\pi \int_{2R_A}^{\infty} \tilde{b}_\perp d\tilde{b}_\perp P^2(\tilde{b}_\perp) d\sigma(\tilde{b}_\perp, \ ...) \qquad P(\tilde{b}_\perp) = 1 - \exp\left[-P_{1n}(\tilde{b}_\perp)\right]$$

ρ^0 production in UPCs

Unpolarized cross section



Cos2ϕ azimuthal asymmetry

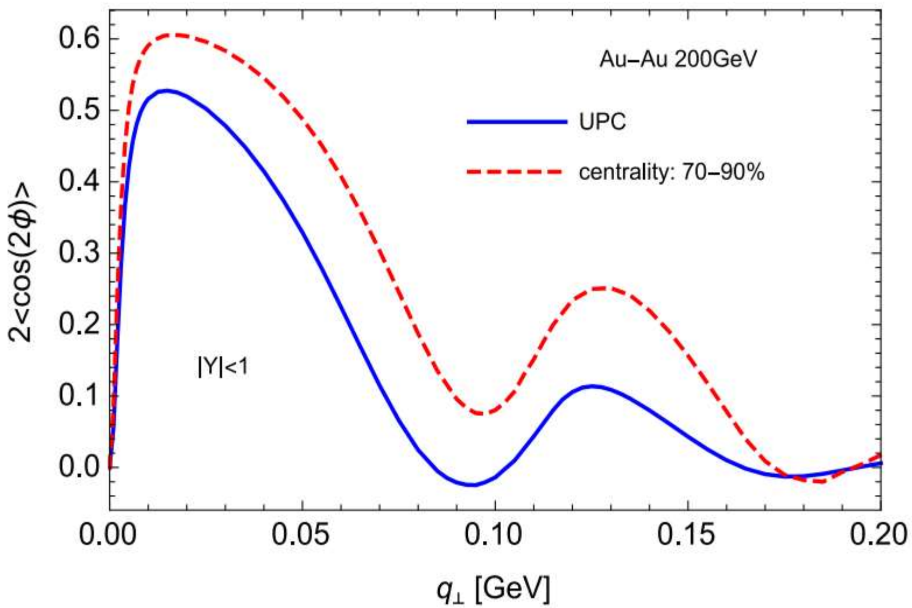


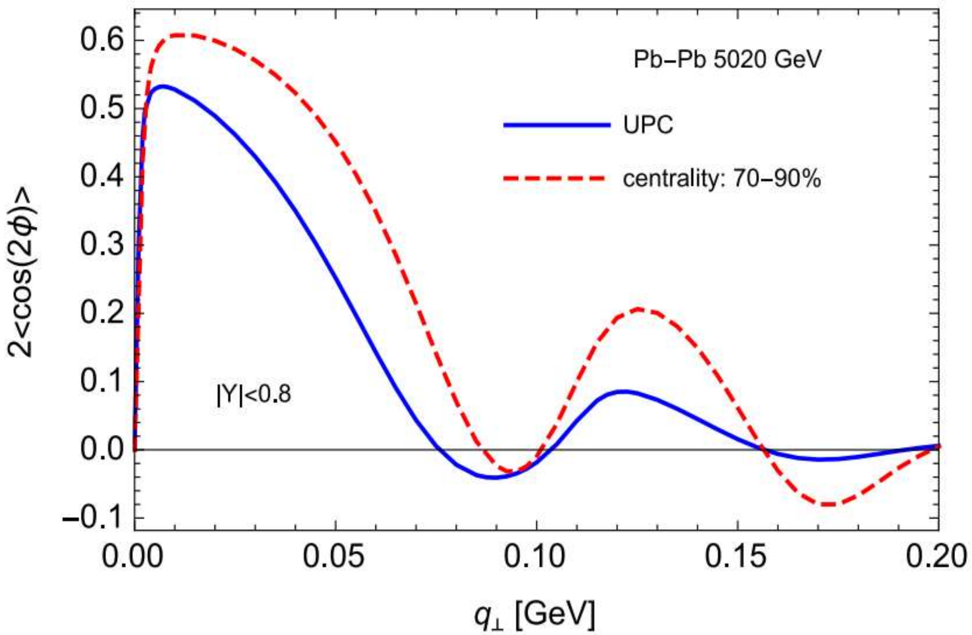
Daniel Brandenburg, QM 2019

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

Predications for PCs at RHIC and LHC energies



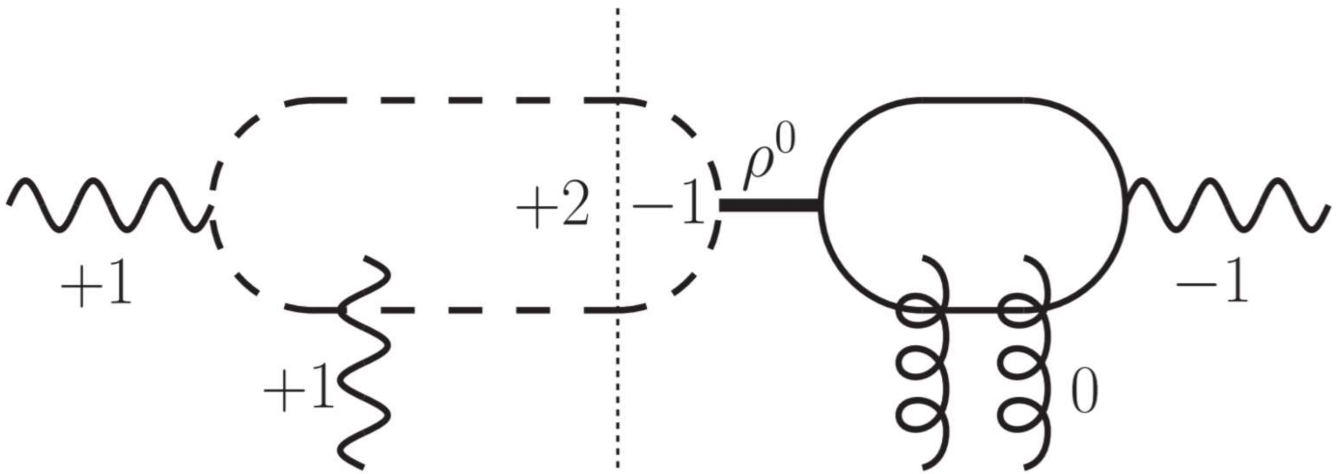


The diffractive shape is sensitive to the distance between two colliding nuclei.

- EIC: one slit; UPCs: two slits

Cosϕ and Cos3ϕ in di-pion production

Coulomb nuclear interference



EM production V.S. via ρ decay

EM: 1/t

QCD: nuclear form factor F(t=0)

EM and QCD amplitudes

Low momentum transfer, pion treated as a point like particle in EM production:

$$\mathcal{M}_{\gamma\gamma\to\pi\pi} = 2e^2\left[\epsilon^{\gamma}_{\perp 1}\cdot\epsilon^{\gamma}_{\perp 2} - \frac{2P_\perp^2}{P_\perp^2+m_\pi^2}(\epsilon^{\gamma}_{\perp 1}\cdot\hat{P}_\perp)(\epsilon^{\gamma}_{\perp 2}\cdot\hat{P}_\perp)\right]$$

QCD amplitude:

$$\mathcal{M}_{\rho\to\pi^+\pi^-} = i\left[\mathcal{A}_{co}(x_g,\Delta_\perp)+\mathcal{A}_{in}(x_g,\Delta_\perp)\right] f_{\rho\pi\pi}\frac{P_\perp\cdot\epsilon^V_\perp}{Q^2-M_\rho^2+iM_\rho\Gamma_\rho}$$

with

$$\mathcal{A}_{co}(x_g,\Delta_\perp) = \int d^2b_\perp e^{-i\Delta_\perp\cdot b_\perp}\int\frac{d^2r_\perp}{4\pi}\,N(r_\perp,b_\perp)[\Phi^*K](r_\perp)$$

$$\mathcal{A}_{in}(x_g,\Delta_\perp) = \sqrt{A}2\pi B_p e^{-B_p\Delta_\perp^2/2}\left[\int\frac{d^2r_\perp}{4\pi}\mathcal{N}(r_\perp)e^{-2\pi(A-1)B_pT_A(b_\perp)\mathcal{N}(r_\perp)}[\Phi^*K](r_\perp)\right]$$

Azimuthal dependent cross section

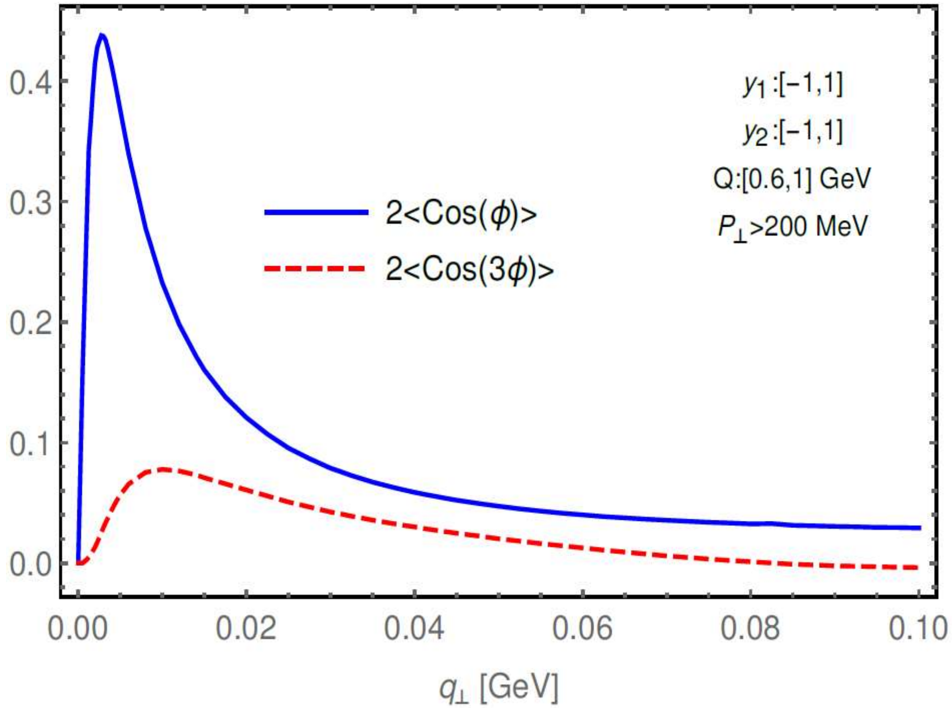
$$\frac{d\sigma_I}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2\tilde{b}_\perp} = \frac{\alpha_e}{Q^2}\frac{1}{(2\pi)^4}\frac{1}{\sqrt{4\pi}}\frac{2M_\rho\Gamma_\rho|P_\perp|f_{\rho\pi\pi}}{(Q^2-M_\rho^2)^2+M_\rho^2\Gamma_\rho^2}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp$$
$$\times\delta^2(k_\perp+\Delta_\perp-q_\perp)\left[\hat{k}_\perp\cdot\hat{\Delta}_\perp-\frac{2P_\perp^2}{P_\perp^2+m_\pi^2}(\hat{k}_\perp\cdot\hat{P}_\perp)(\hat{\Delta}_\perp\cdot\hat{P}_\perp)\right](\hat{P}_\perp\cdot\hat{k}'_\perp)$$
$$\times 2\left\{\left[e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_2,\Delta_\perp)\mathcal{F}(x_1,k'_\perp)\mathcal{A}^*_{co}(x_2,\Delta'_\perp)\right]\right.$$
$$\left.+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-k_\perp)}\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_1,\Delta_\perp)\mathcal{F}(x_2,k'_\perp)\mathcal{A}^*_{co}(x_1,\Delta'_\perp)\right]\right\}$$

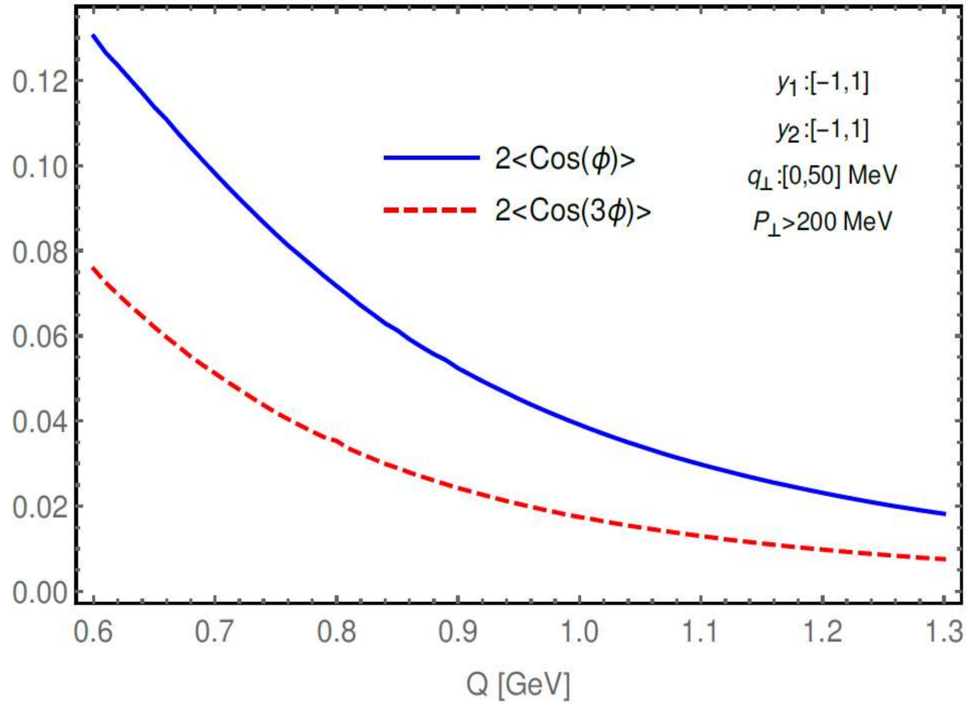
Yoshikazu Hagiwara, Cheng Zhang, ZJ and Ya-jin Zhou, 2020

Interesting observation:

- Interference CS vanishes identically when integrating out ϕ

Numerical results





- Constrain the phase of the dipole amplitude

Summary

- Coherent photons excited by charged heavy ion are linearly polarized
- Rich physics is revealed via azimuthal asymmetries in UPCs
- J/ψ diffractive production….   EIC case…..

Thank you!

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