$\cos(2\phi)$ azimuthal asymmetry in ρ^0 photoproduction in UPCs

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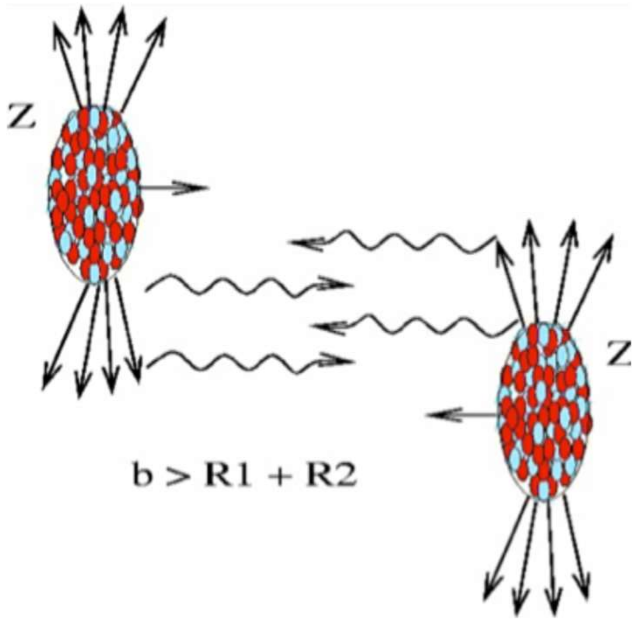
Based on papers: arXiv:2006.06206, arXiv:1903.10084, arXiv:1911.00237

My collaborators: Cong Li, Yajing Zhou, Chen Zhang, Hongxi, Xing

Outline

- Linearly polarized photon distribution
- Joint $\tilde{b}_\perp$ and $q_\perp$ dependent cross section for diffractive vector meson production
- Numerical results
- Summary and Outlook

Coherent photon distributions



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

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

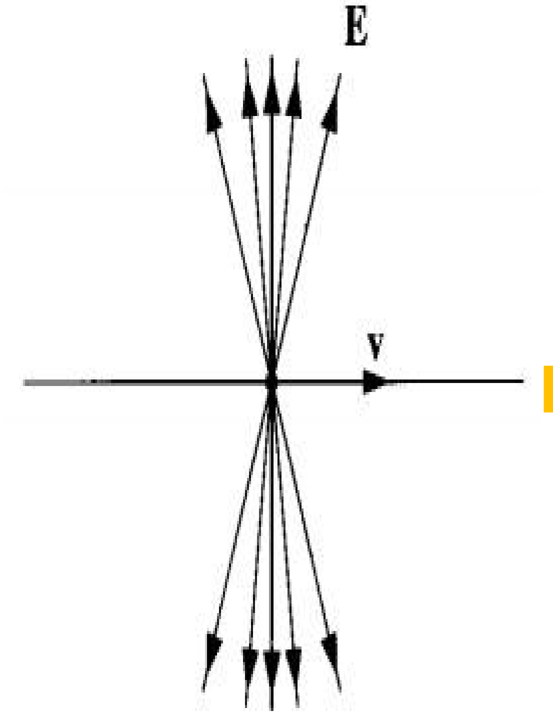
$$\sigma^{WW}_{A_1A_2\to A_1A_2X} = \int d\omega_1 d\omega_2 n_{A_1}(\omega_1) n_{A_2}(\omega_2)\sigma_{\gamma\gamma\to X}(\omega_1,\omega_2)$$

$K_T \leq 1/R_A$

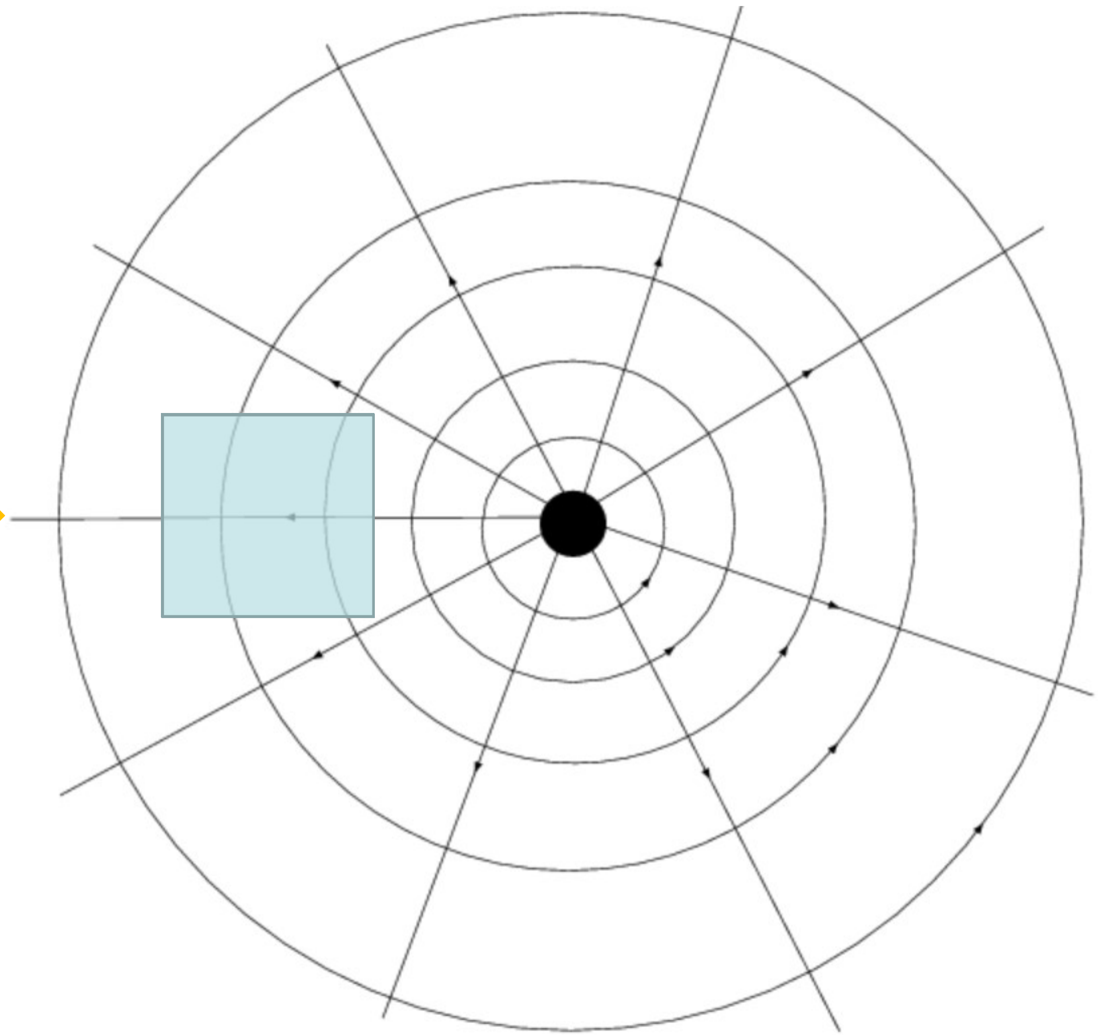
$d\sigma \propto Z^4$
clean background

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

The boosted Coulomb potential

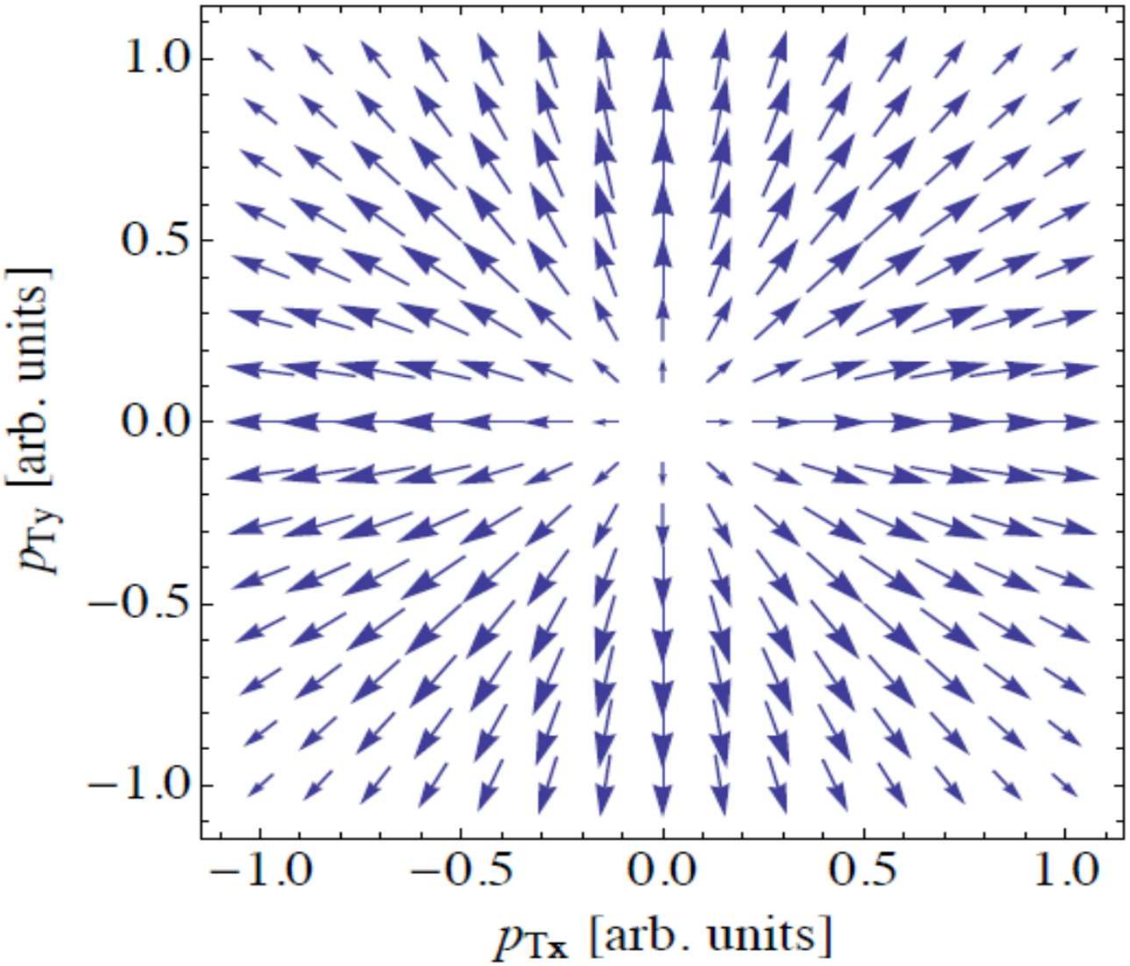


Side view



Head on view

Transverse momentum phase space



CGC is highly linearly polarized state as well. **Metz & Zhou, 2011**

How to probe it?

Cos 4ϕ asymmetry in EM dilepton production

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

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

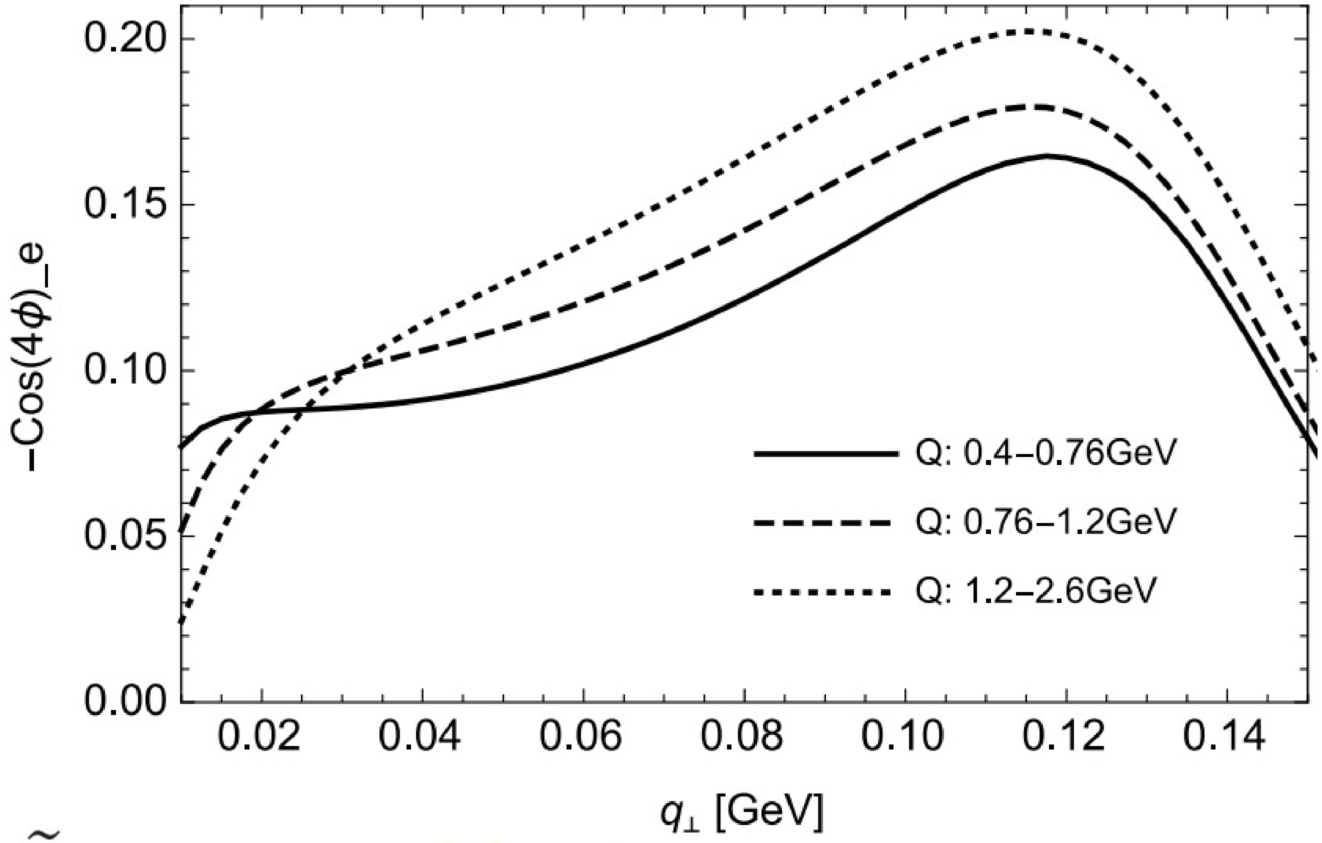
$$P_\perp \equiv (p_{1\perp} - p_{2\perp})/2 \qquad q_\perp \equiv p_{1\perp} + p_{2\perp}$$

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

A different type $\langle \cos(4\phi) \rangle$ asymmetry: $P_\perp \bigwedge \tilde{b}_\perp$

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

$\langle\cos(4\phi)\rangle$ in TMD factorization



- $\tilde{b}_\perp$ integrated [0, ∞] cross section, formulated in the conventional TMD factorization.

C. Li, ZJ, and Y. JZ, 2019

Impact parameter dependence

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

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

- Successfully describes dilepton qt broadening effect

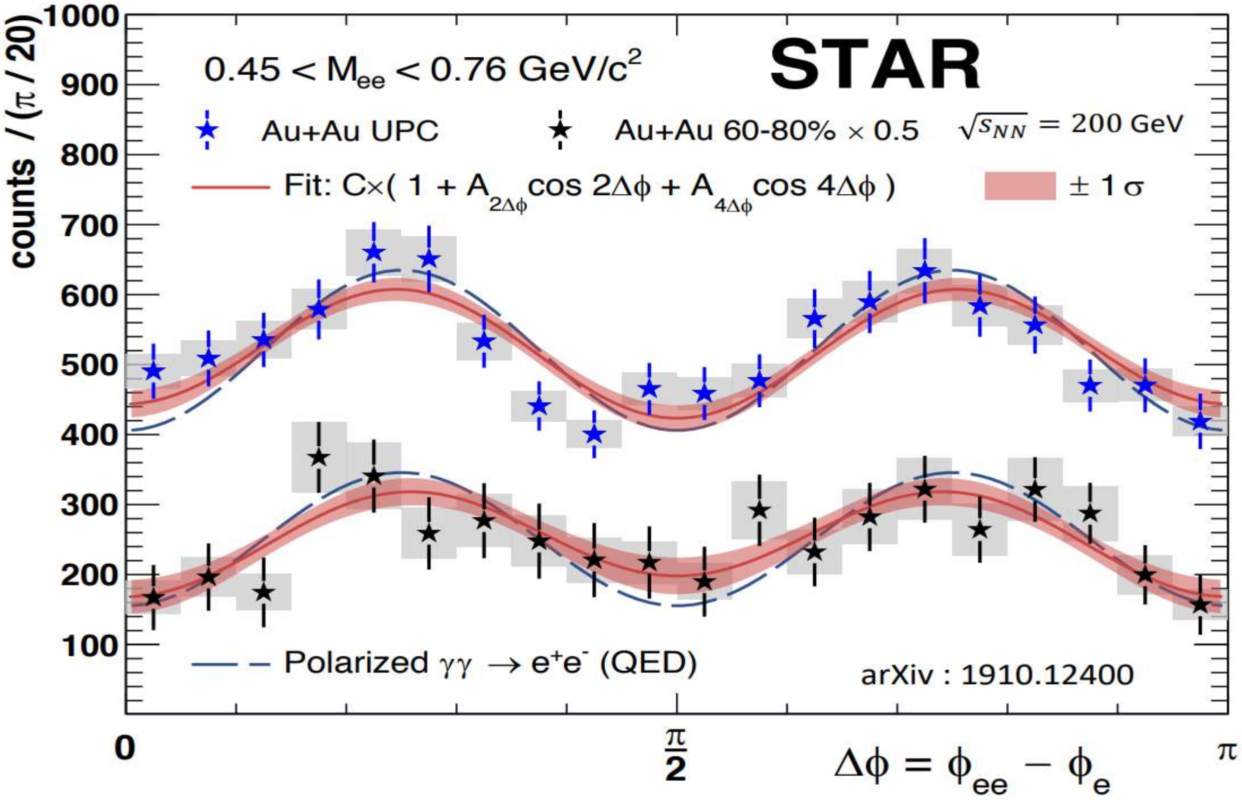
W. Zha, J. D. Brandenburg, Z. Tang and Z. Xu, 2019

- Medium effect could also play a role in causing qt broadening.

S. Klein, A. H. Mueller, B.W. Xiao and F. Yuan, 2018, 2020

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

Daniel Brandenburg, QM 2019

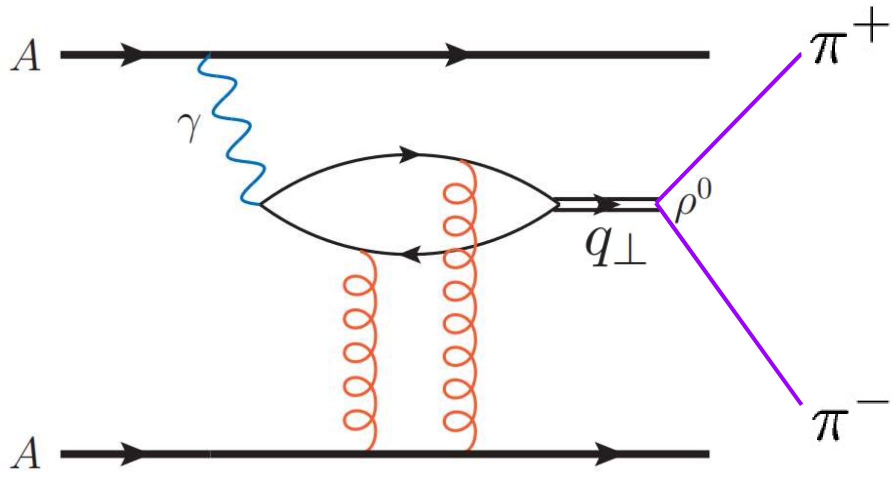


$0.45GeV^2<Q^2<0.76GeV^2$
$P_t>200MeV$, $|y|<1, q_t<100MeV$

C. Li, JZ and Y. Zhou, 2020

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

As a probe to study novel QCD phenomenology



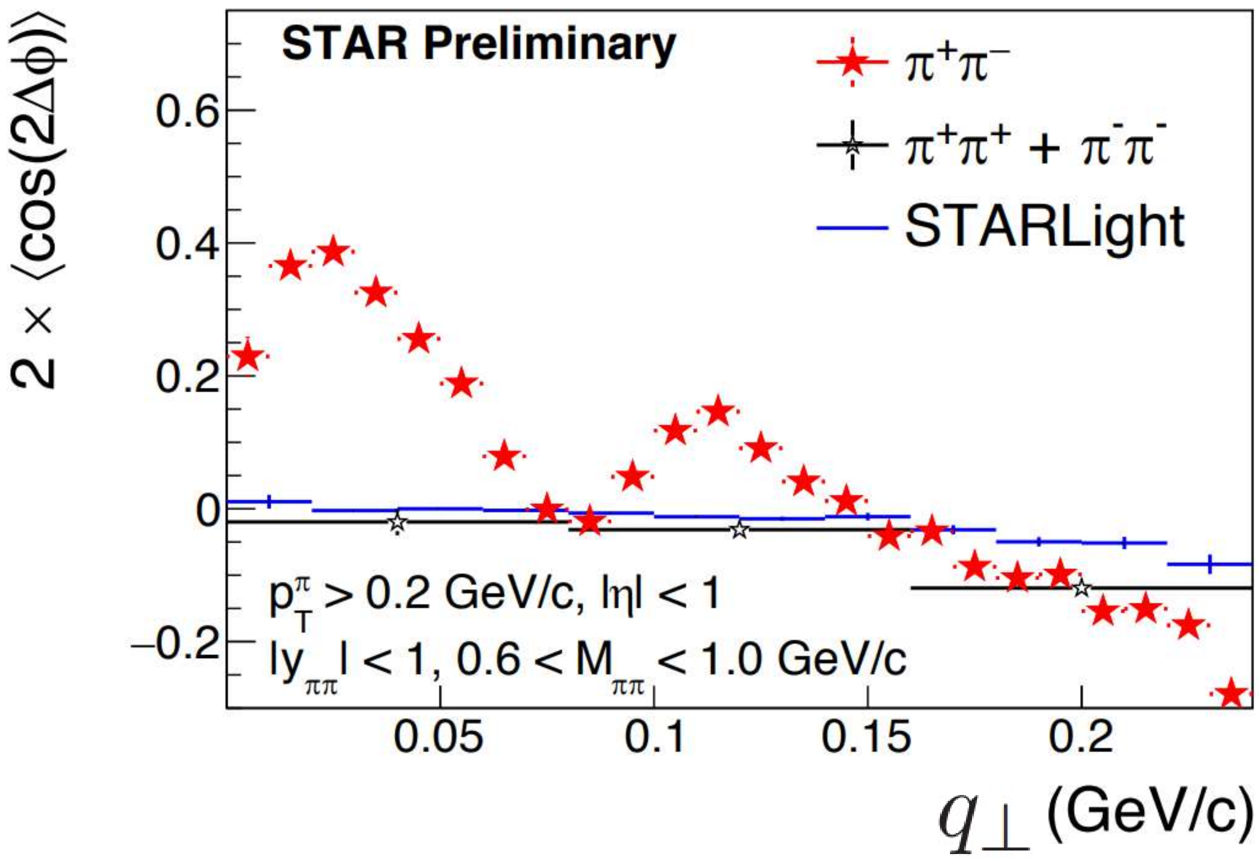
A $\cos(2\phi)$ azimuthal asymmetry is induced by linearly polarized photons.

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



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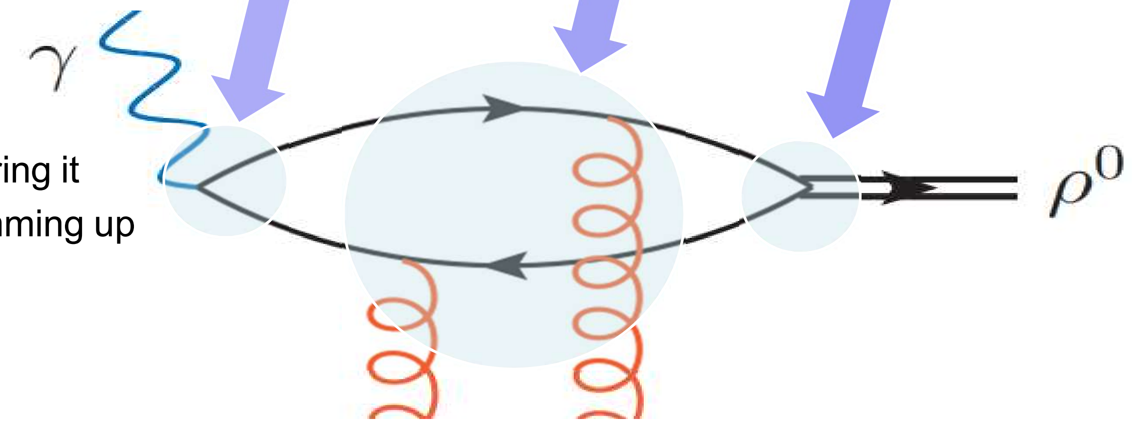
Dipole model calculation

Diffractive scattering amplitude(based on dipole model)

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

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

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

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

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

Photon transverse momentum

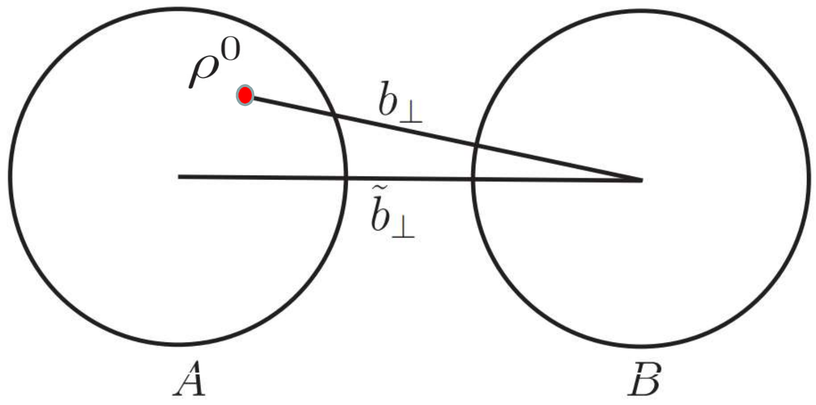
$$2(k_\perp^\gamma\cdot\epsilon_\perp^{V*})^2-1$$

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

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 $b_\perp$

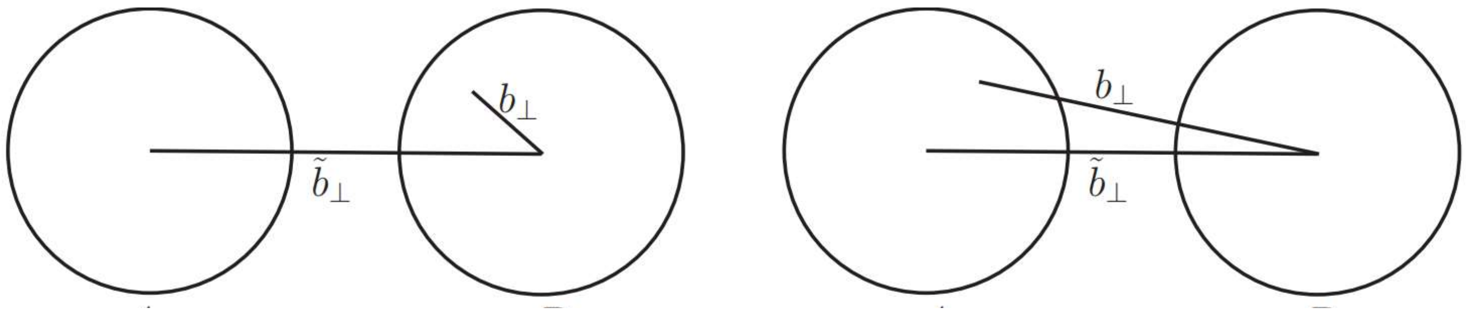
The probability amplitude of producing ρ^0 at position $b_\perp$

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

EM potential induced by B

Gluon density inside A

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



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

S. R. Klein and J. Nystrand,2000

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.

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

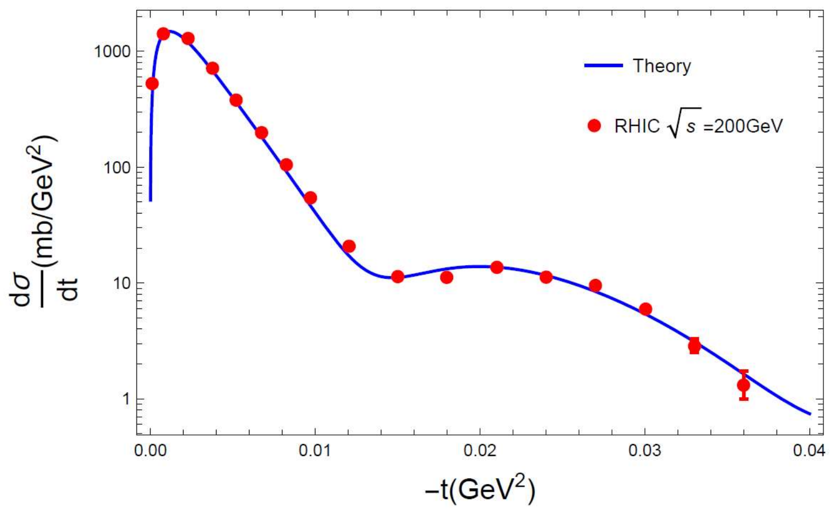
Nuclear strong interaction radius should be slightly larger than
its EM radius due to neturon skin effect and possible pion cloud effect

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

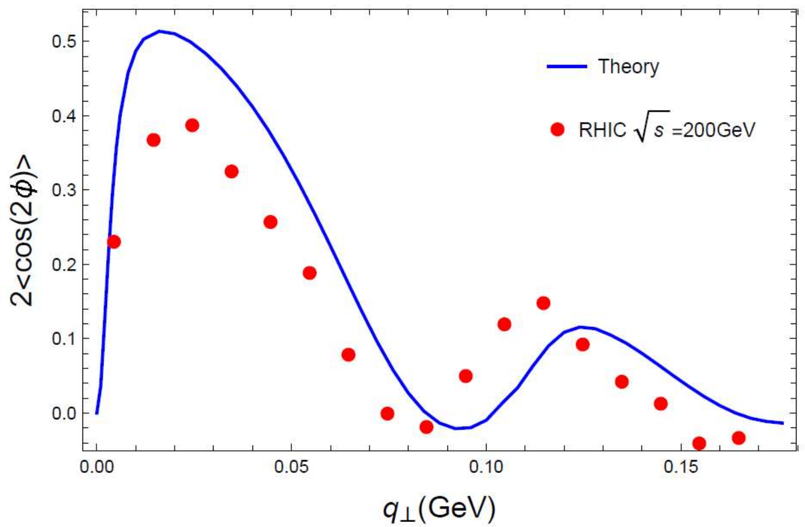
$$2\pi \int_{2R_A}^{\infty} \tilde{b}_\perp d\tilde{b}_\perp P^2(\tilde{b}_\perp) d\sigma(\tilde{b}_\perp, \ ...) \qquad P(\tilde{b}_\perp) = 1 - \exp\left[-P_{1n}(\tilde{b}_\perp)\right]$$

ρ^0 production in UPCs

Unpolarized cross section



Cos2ϕ azimuthal asymmetry



Daniel Brandenburg, QM 2019

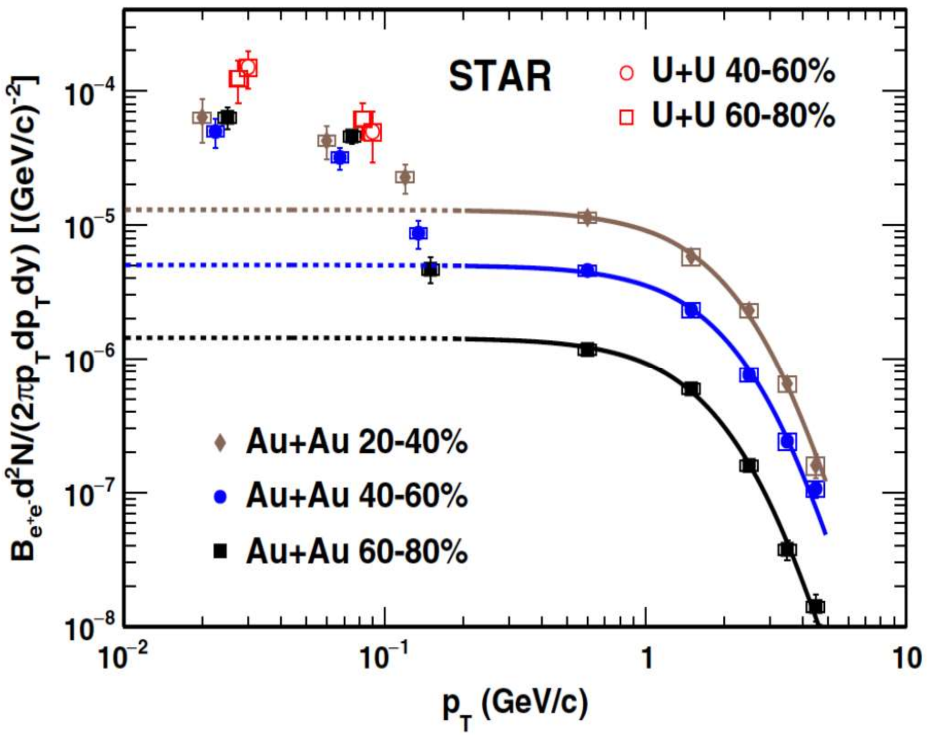
e-Print: 2006.06206; **H.X. Xing, C. Zhang, J. Zhou and Y. J. Zhou; 2020**

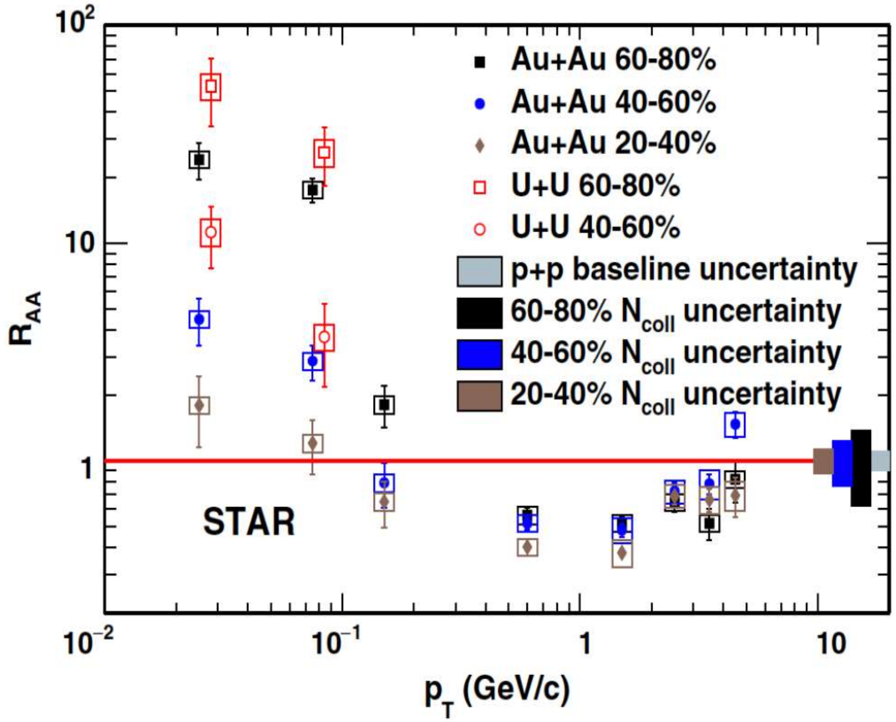
Gold target	Skin depth	Strong interaction radius
Standard value	0.54fm	6.38fm
Fitted to STAR data	0.64fm	6.9fm

The similar result was also obtained by: **W. Zha, J. D. Brandenburg, L.J. Ruan, Z.B. Tang and Z.B. Xu, 2020**

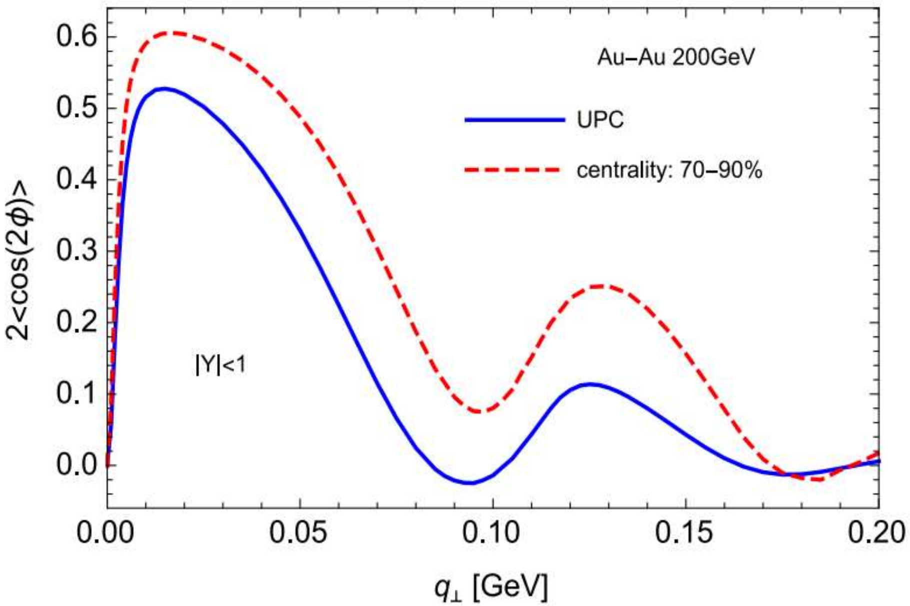
Coherent photon initiated processes in PCs and UPCs

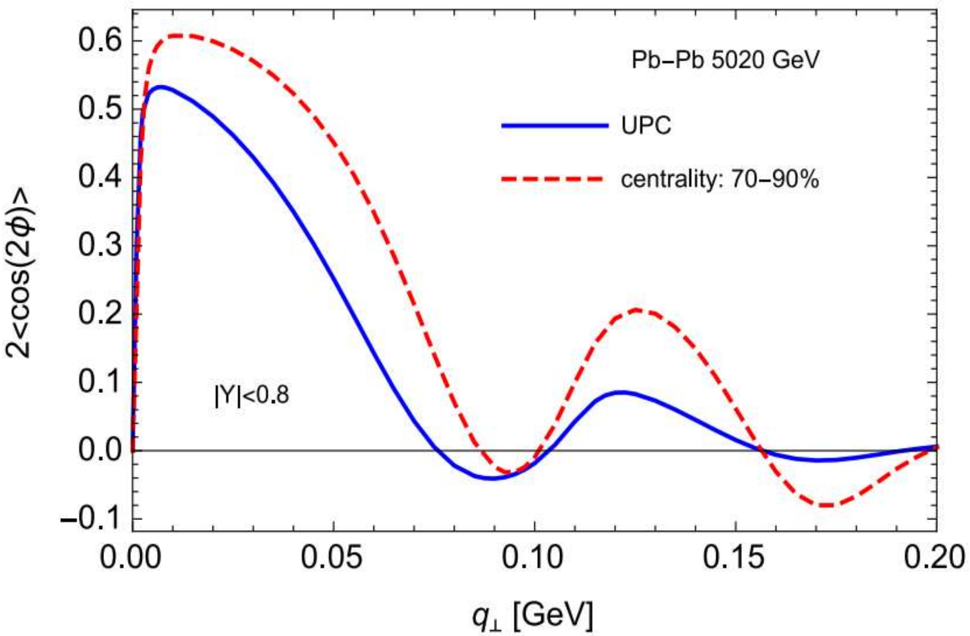
STAR measurement:





Predications for PCs at RHIC and LHC energies





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

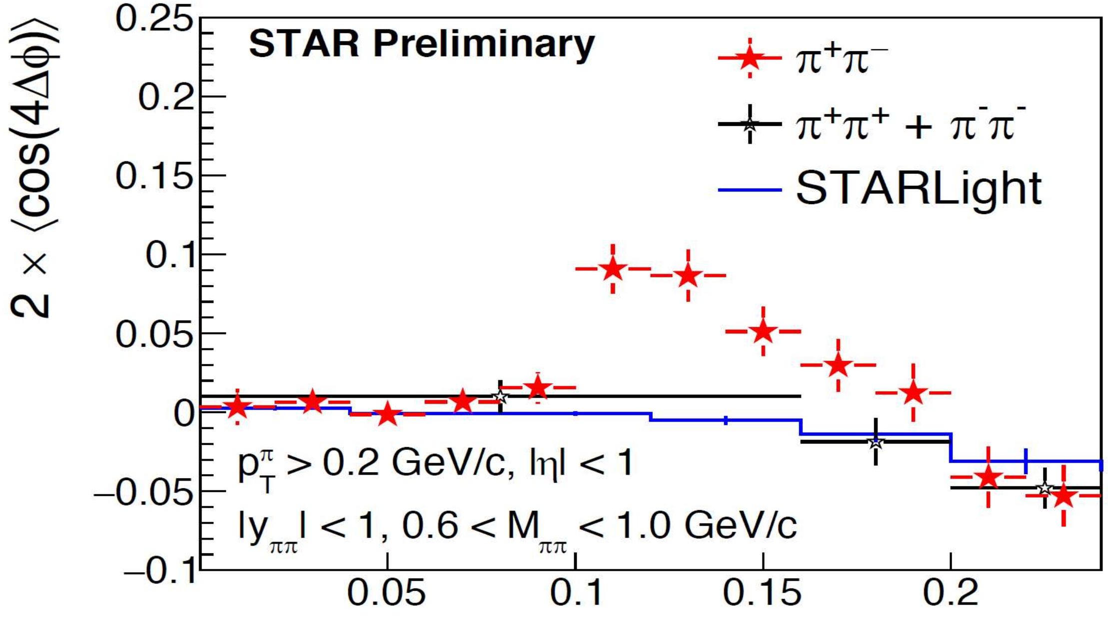
Summary

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

  reliable way to extract nuclear geometry information in UPCs
- Cos2ϕ generated by coherent photon's linear polarization
- Double slit experiment at Fermi scale→ clear demonstration of

  particle-wave duality of rho meson.

Outlook: Cos4ϕ azimuthal asymmetry



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- The true physical origin of Cos4ϕ asymmetry remains mysterious.
- Potential access to gluon Wigner distribution/GTMD?

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