重离子超边缘碰撞中的光-核反应过程

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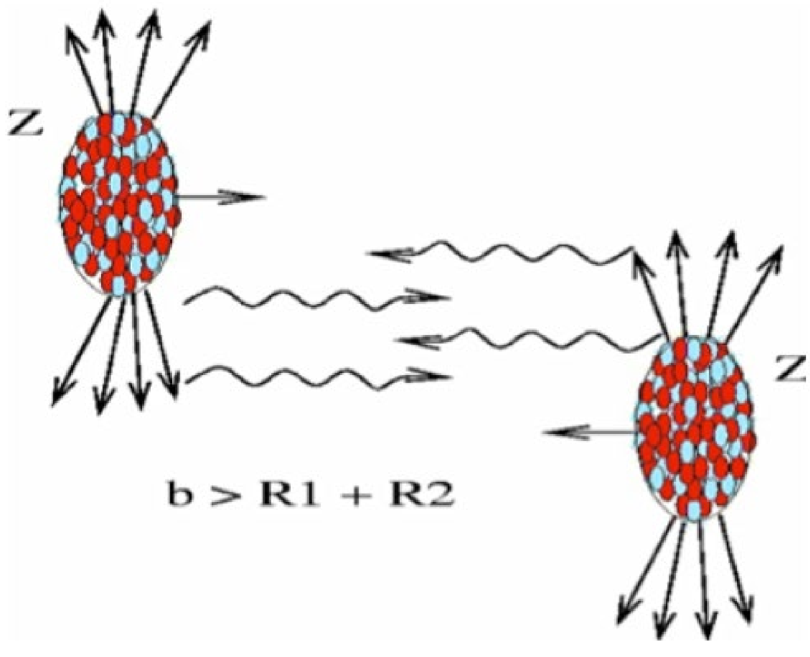
Outline

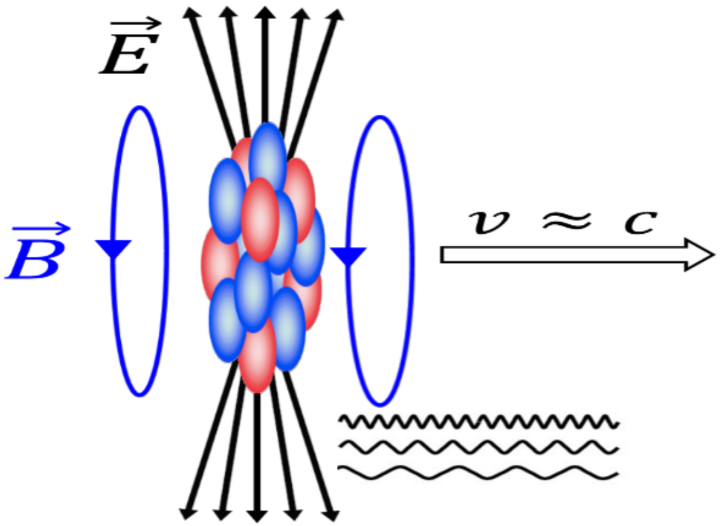
- Background
- Unpolarized diffractive ρ^0 production in UPCs
- Cosϕ ,Cos2ϕ, Cos3ϕ, Cos4ϕ azimuthal asymmetries in ρ^0 production
- Summary

What is UPC

Two nuclei physically miss each other,



Weizascker--Williams approximation



Can be treated as a flux of quasi-photons

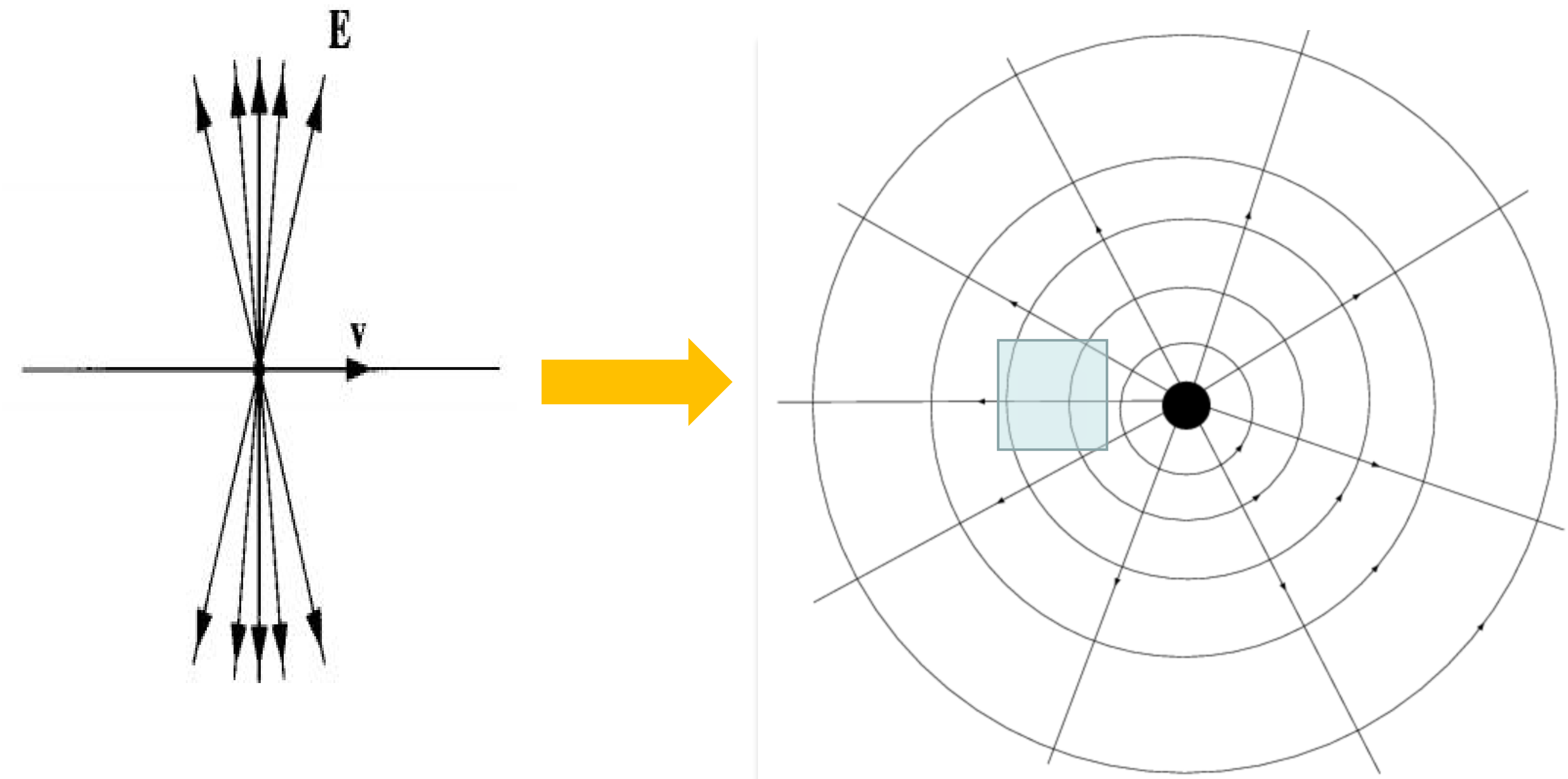
When photon wave length is larger than R, Kt<30MeV, enhance by Z^2

Relativistic heavy ion is extremely **bright!**

Two type interactions:

- photon-photon collisions
- photon-nuclear interactions

The boosted Coulomb potential

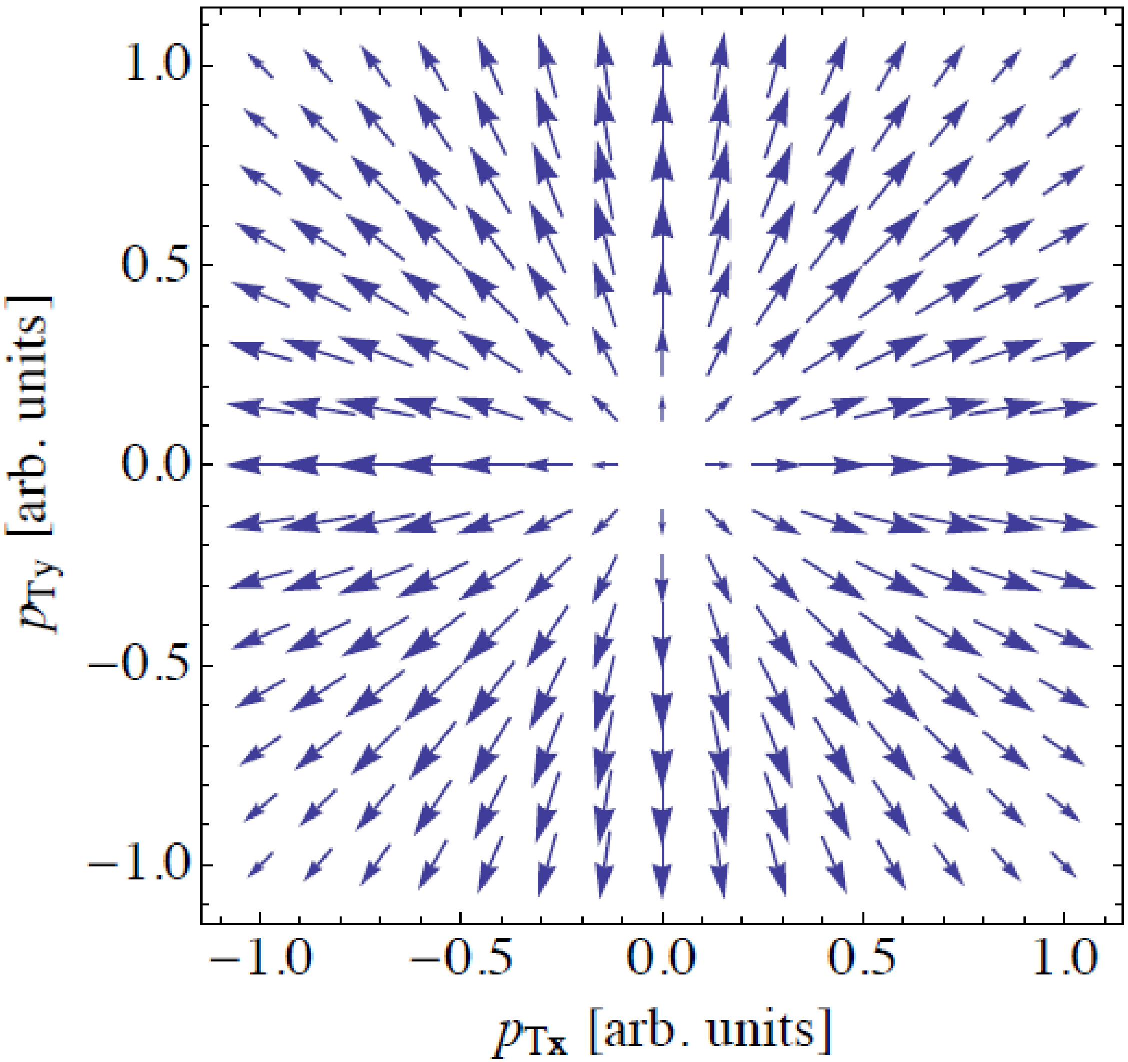


Side view

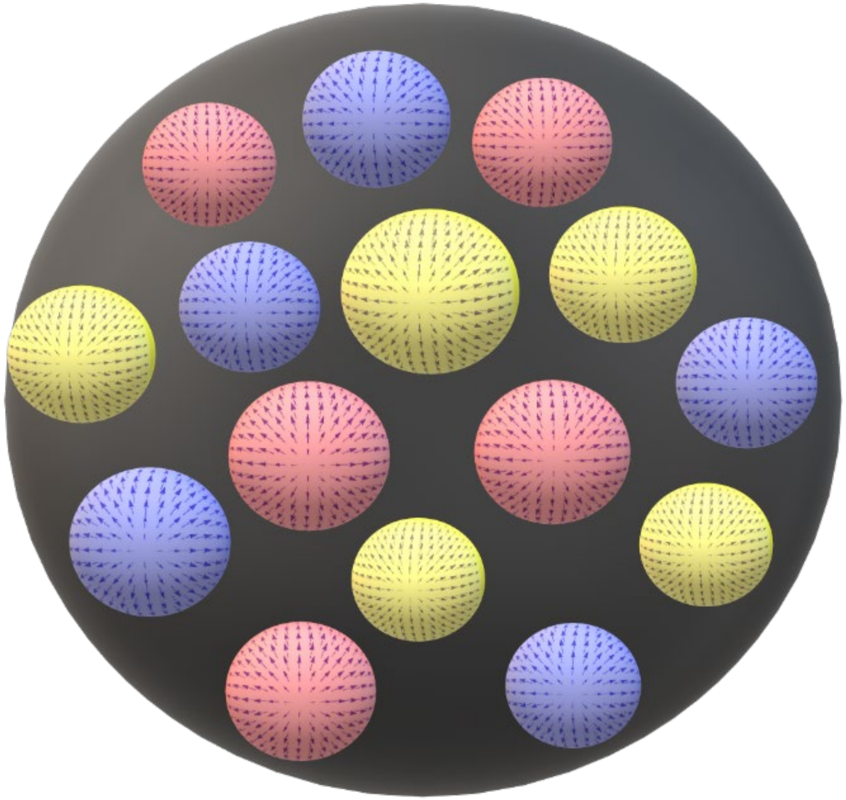
Head on view

Linear polarization of coherent photons

Transverse momentum phase space



Linear polarization of gluons at small x



CGC is linearly polarized A. Metz, ZJ; 2011

Cos 4ϕ asymmetry in EM dilepton production

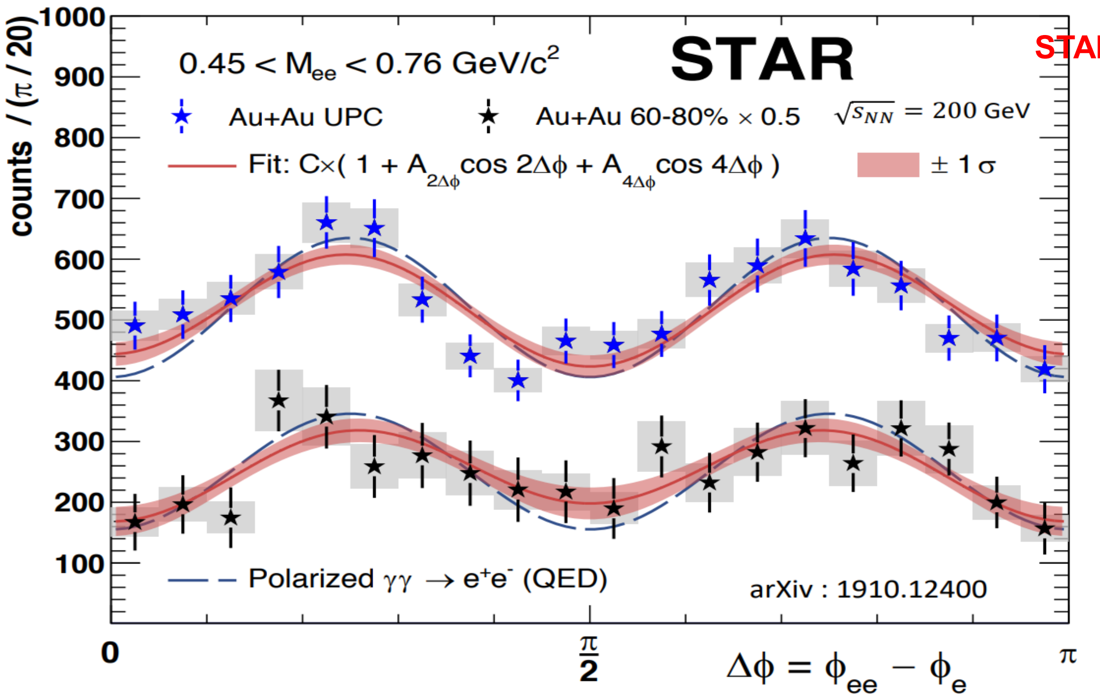
$$\gamma(x_1 P + k_{1\perp}) + \gamma(x_2 \bar{P} + k_{2\perp}) \to l^+(p_1) + l^-(p_2)$$

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

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

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

Verified by STAR experiment



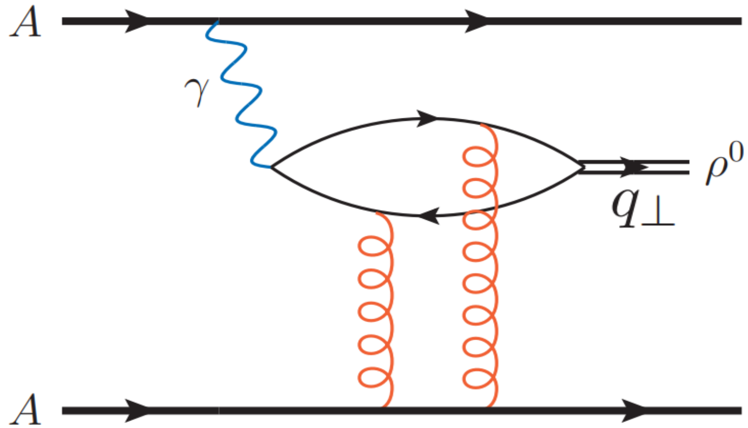
STAR collaboration, PRL 127, 2021

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

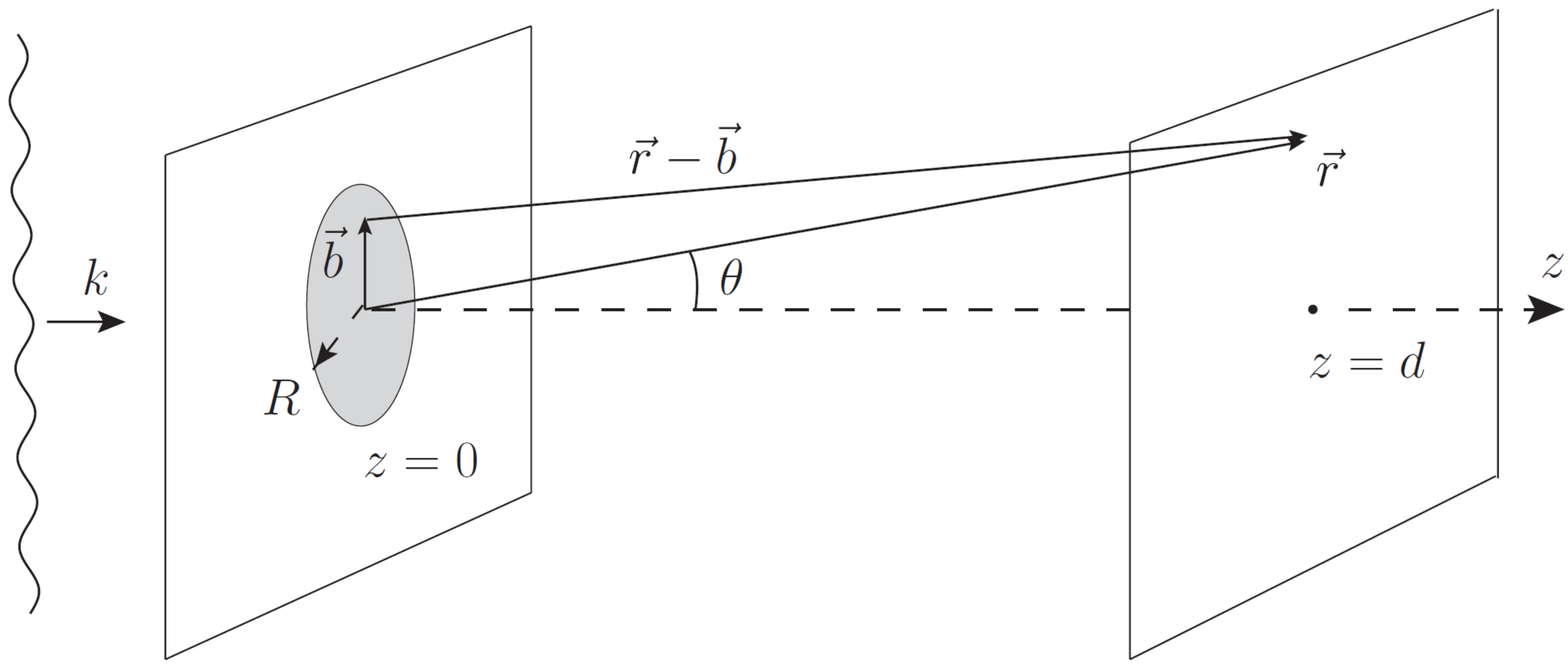
C. Li, JZ and Y. Zhou, 2019，2020

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

Vector meson diffractive production



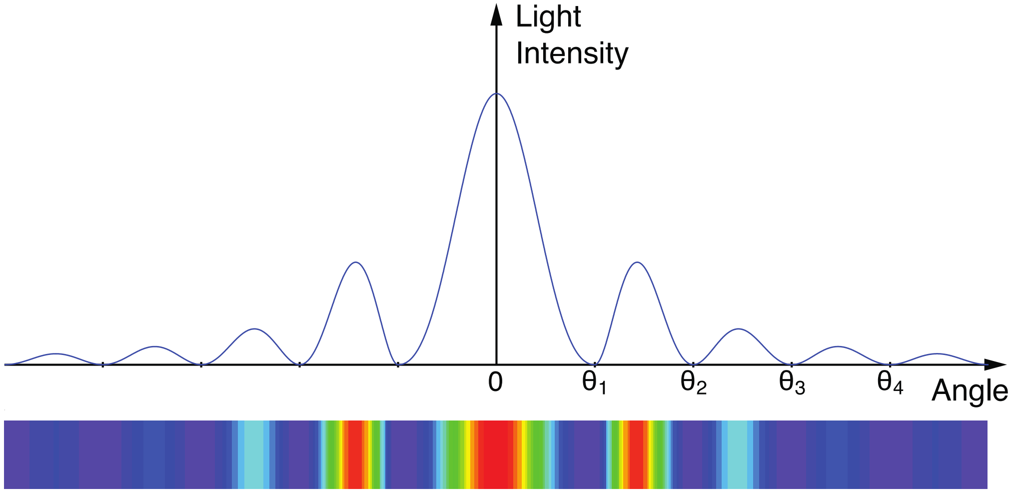
Diffraction in optics

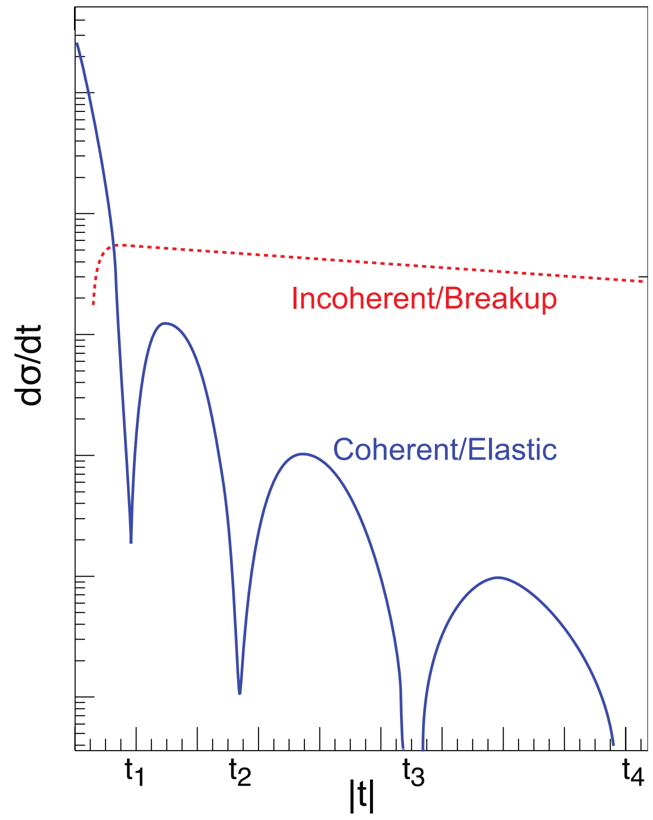


- Reconstruct the size R of the obstacle and the optical "blackness" of the obstacle from the diffractive pattern.

Optical Analogy

Diffraction in high energy scattering is not very different from diffraction in optics: both have diffractive maxima and minima:



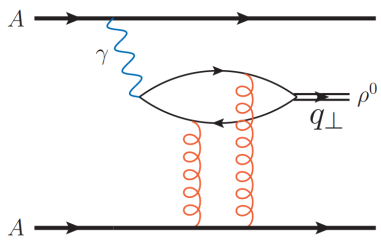


Coherent: target stays intact;
Incoherent: target nucleus breaks up, but nucleons are intact.

Diffractive vector production

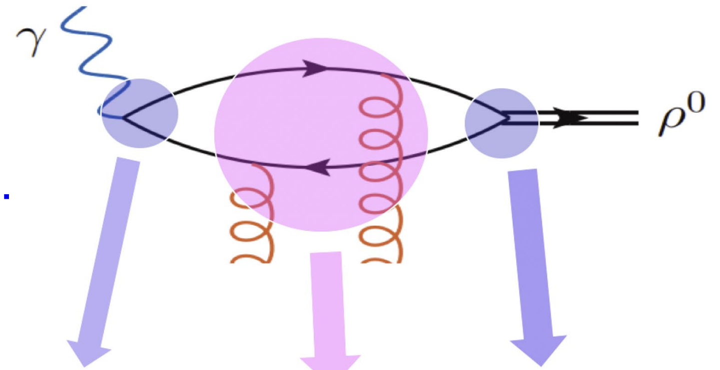
Motivations:

- Studying the saturation effect
- Transverse spatial imaging of gluons



$$\frac{\sigma_{el}^{q\bar{q}A}}{\sigma_{tot}^{q\bar{q}A}} = \frac{\int d^2b\, N^2}{2\int d^2b\, N} \longrightarrow \frac{1}{2}$$

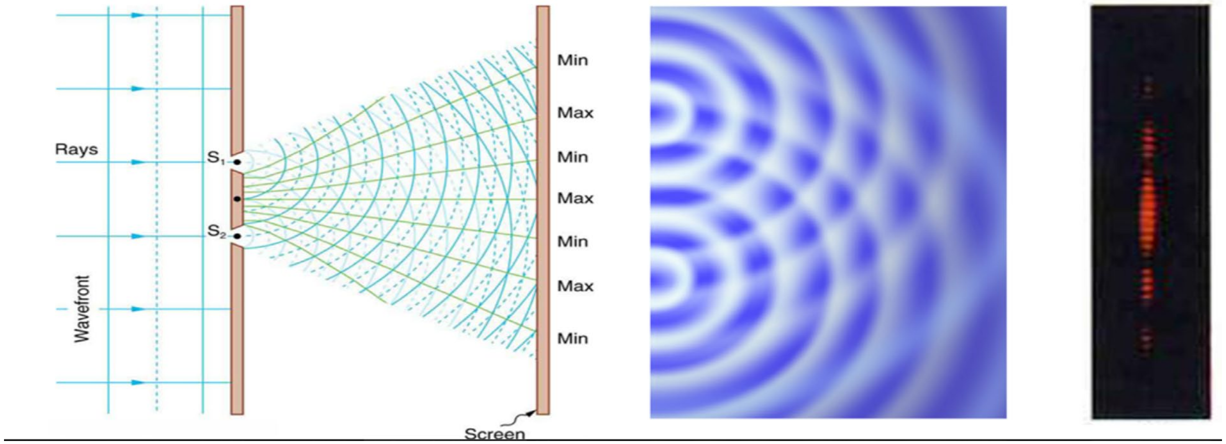
◆ Small x formalism:
dipole model, CGC, Glauber model…



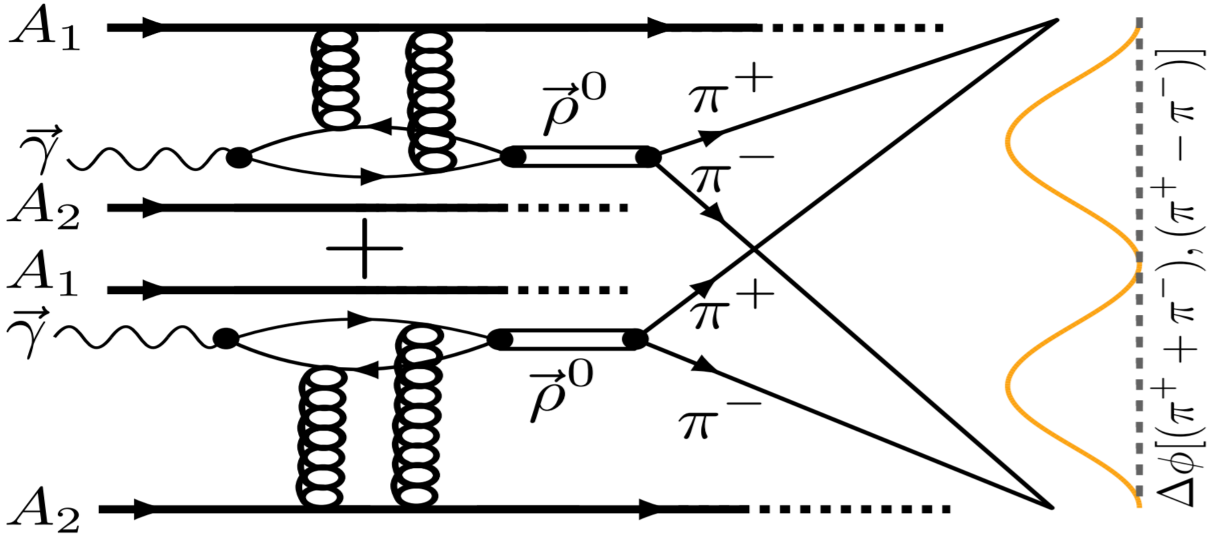
$$\mathcal{A}(\Delta_\perp) = i\int d^2b_\perp e^{i\Delta_\perp\cdot b_\perp}\int\frac{d^2r_\perp}{4\pi}\int_0^1 dz\, \boxed{\Psi^{\gamma\to q\bar{q}}(r_\perp,z,\epsilon_\perp^\gamma)}\boxed{N(r_\perp,b_\perp)}\boxed{\Psi^{V\to q\bar{q}*}(r_\perp,z,\epsilon_\perp^V)}$$

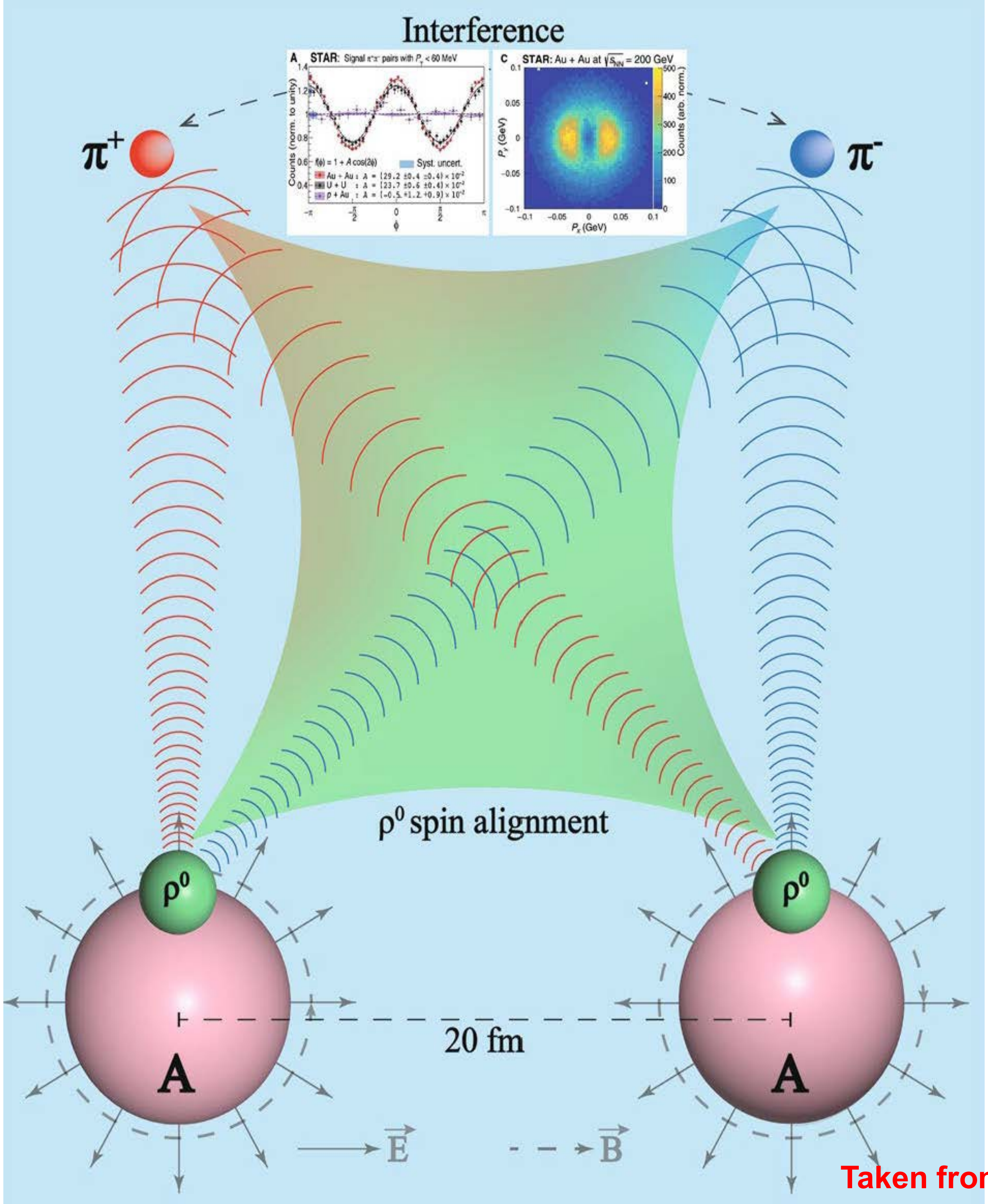
Ryskin, 93; Brodsky, Frankfurt, Gunion, Mueller, Strikman, 94; Klein, Nystrand,1999; Munier, Stasto, Mueller, 2001, Kowalski, Teaney, 2003; Lappi, Mantysaari, 2011; Rezaeian, Siddikov, Klundert, Venugopalan，2013; Guzey, Strikman, Zhalov, 2014, Lansberg, Massacrier, Szymanowski, Wagner, 2019; Mäntysaari, Salazar, Schenke, 2022; and many more…

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



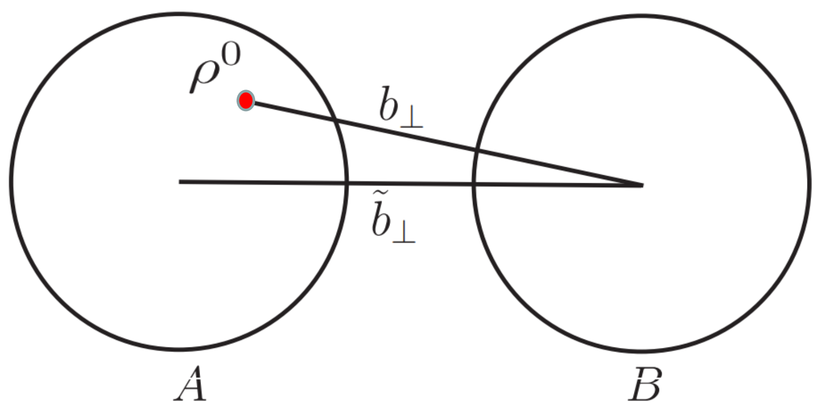
- **double-slit experiment in UPCs**





Taken from Y. G. Ma's review paper.

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 $b_\perp$

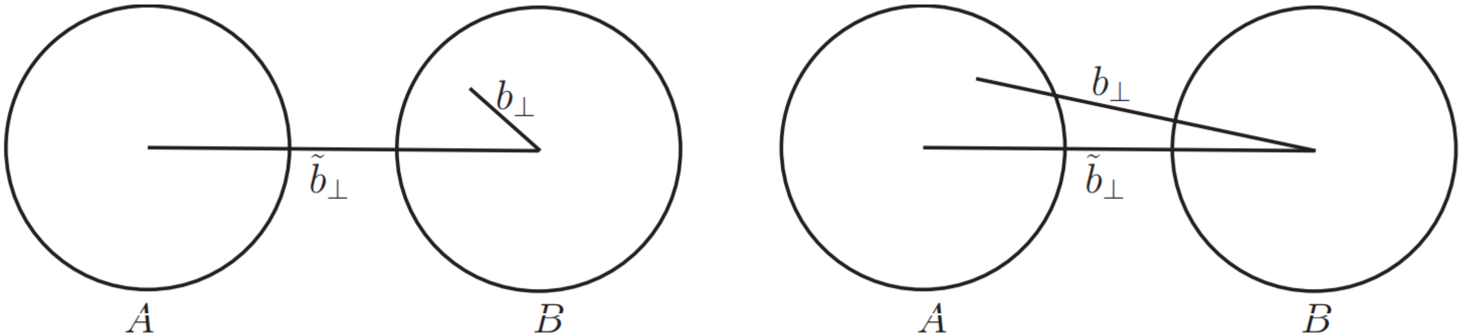
The probability amplitude of producing ρ^0 at position $b_\perp$

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

EM potential induced by B

Gluon density inside A

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



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

Making Fourier transform:

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

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

Xing, Zhang, ZJ, Zhou, 2020

- 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:** $k_\perp + \Delta_\perp = k'_\perp + \Delta'_\perp$

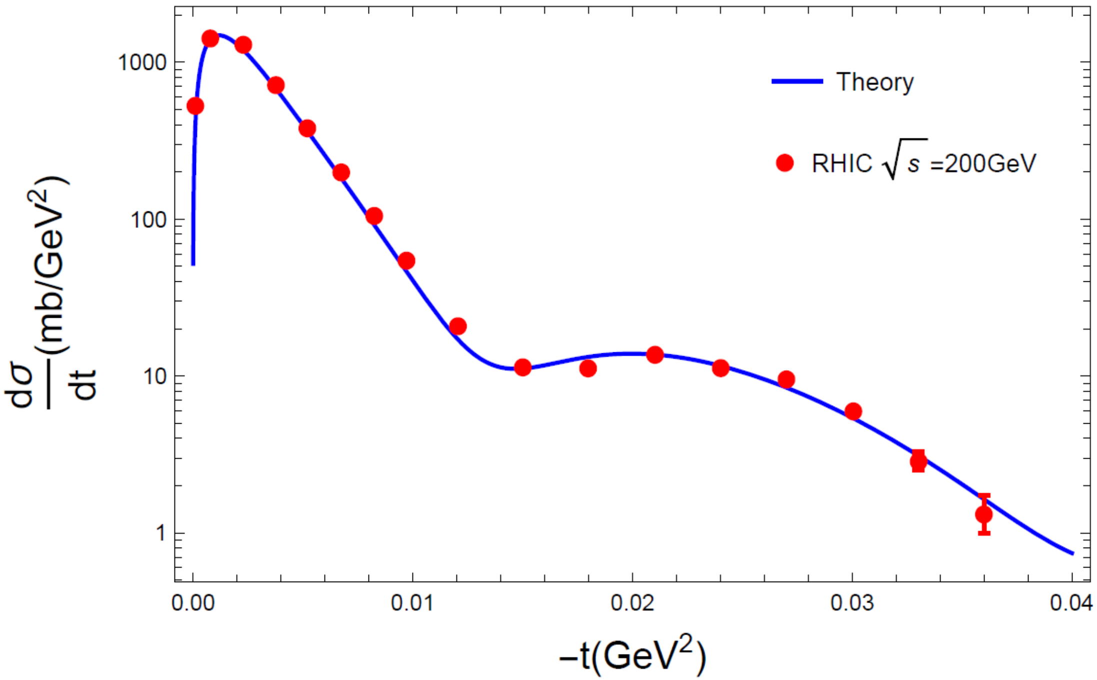
$$
\begin{aligned}
\frac{d\sigma}{d^2q_\perp dY d^2\tilde{b}_\perp} =& \frac{1}{(2\pi)^4}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp+\Delta_\perp-q_\perp)(\epsilon_\perp^{V*}\cdot\hat{k}_\perp)(\epsilon_\perp^{V}\cdot\hat{k}'_\perp)\Big\{\int d^2b_\perp \\
&\times e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\left[T_A(b_\perp)\mathcal{A}_{in}(Y,\D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

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 diffractive pattern

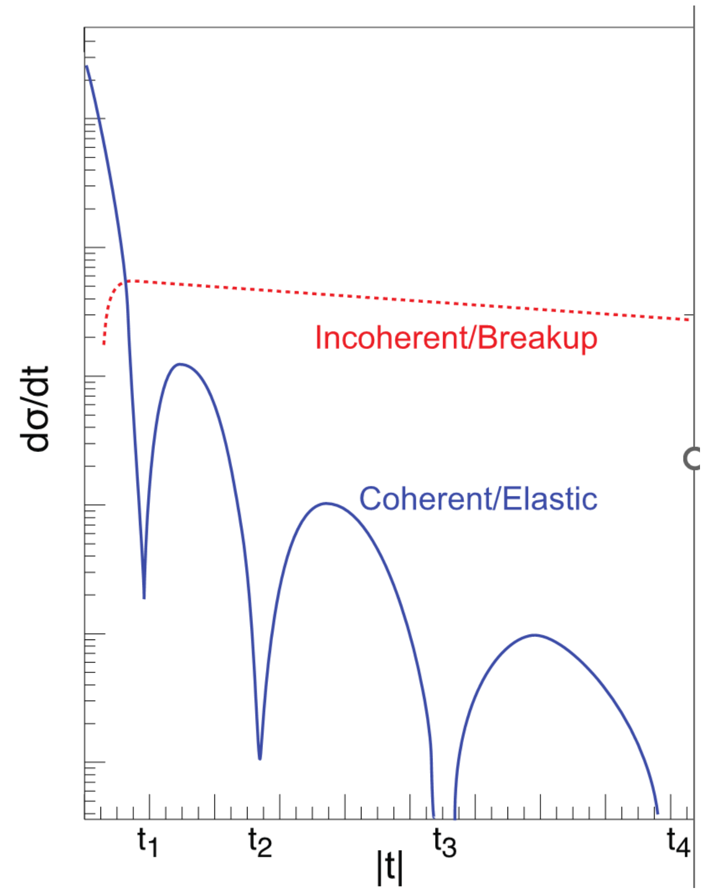
Diffractive VM production in UPC



Xing, Zhang, ZJ, Zhou 2020

- **Double slit interference effect**
- **Smearing caused by finite photon kt**

Diffractive VM production in eA

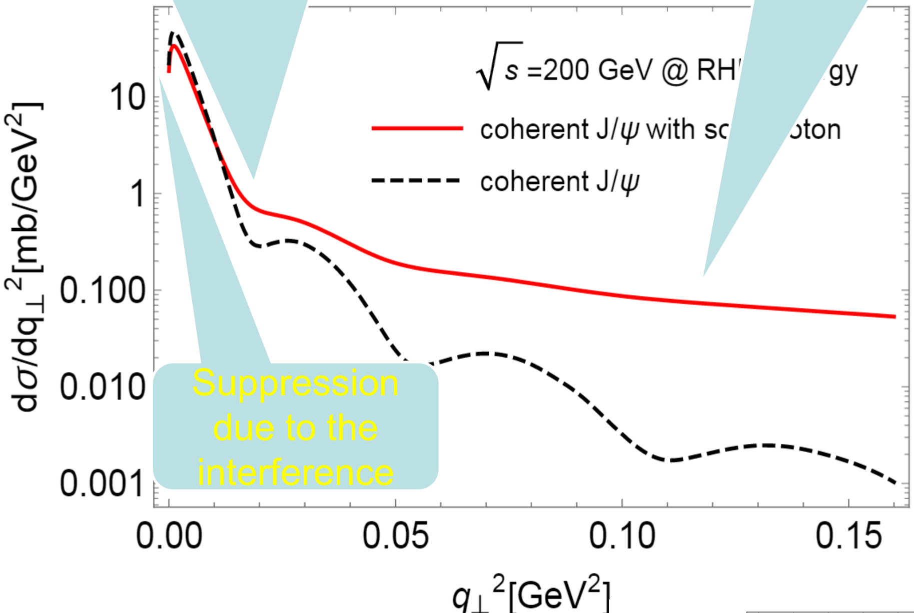


- **One slit interference**

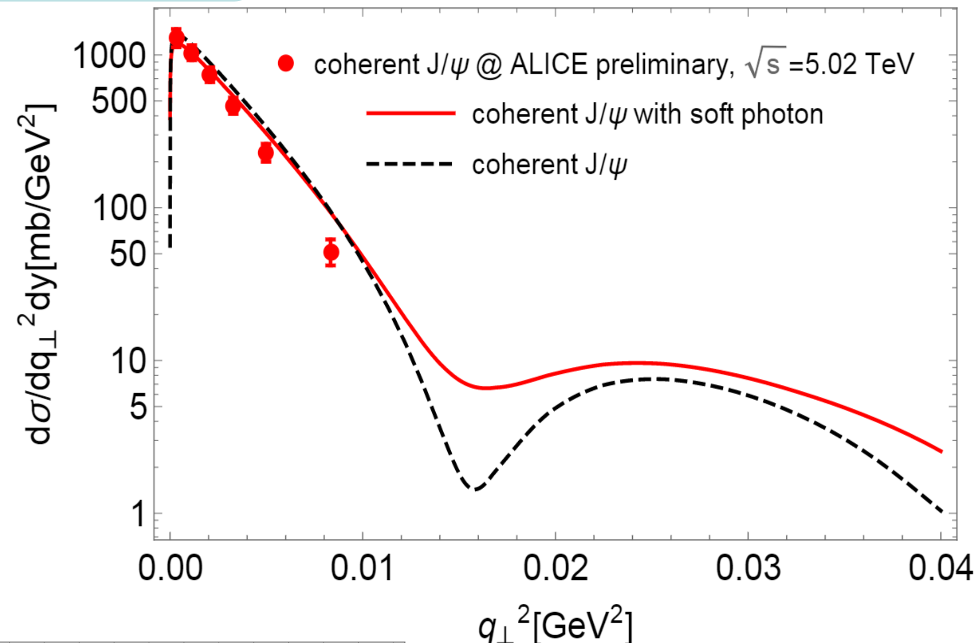
J/psi diffractive pattern

Shallow valley due to finite coherent photon kt and soft photon emissions

Perturbative tail develop via soft photon radiation

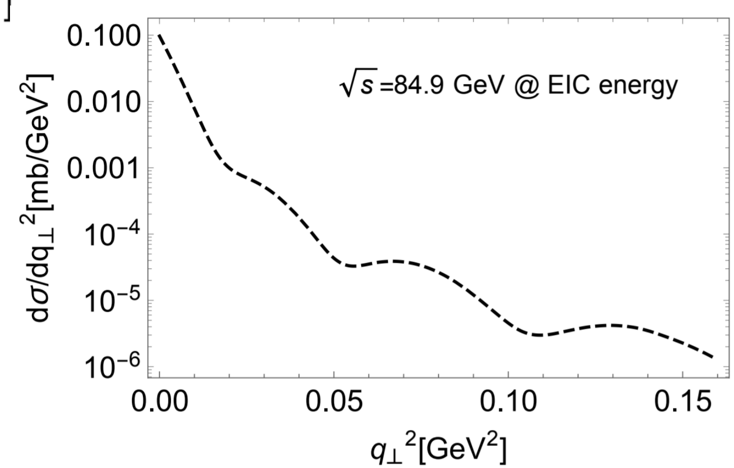


Suppression due to the interference



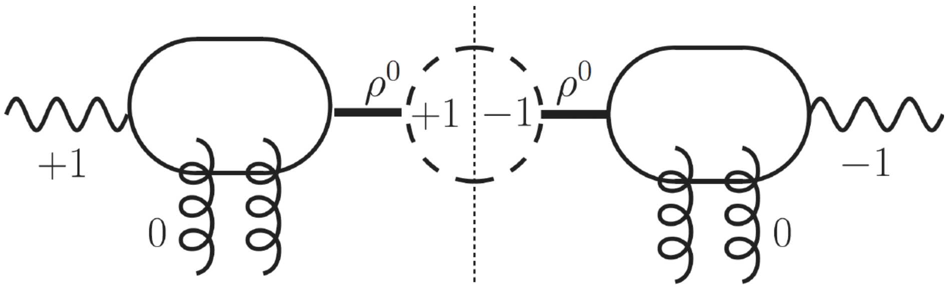
- **At EIC:**

no dip structure

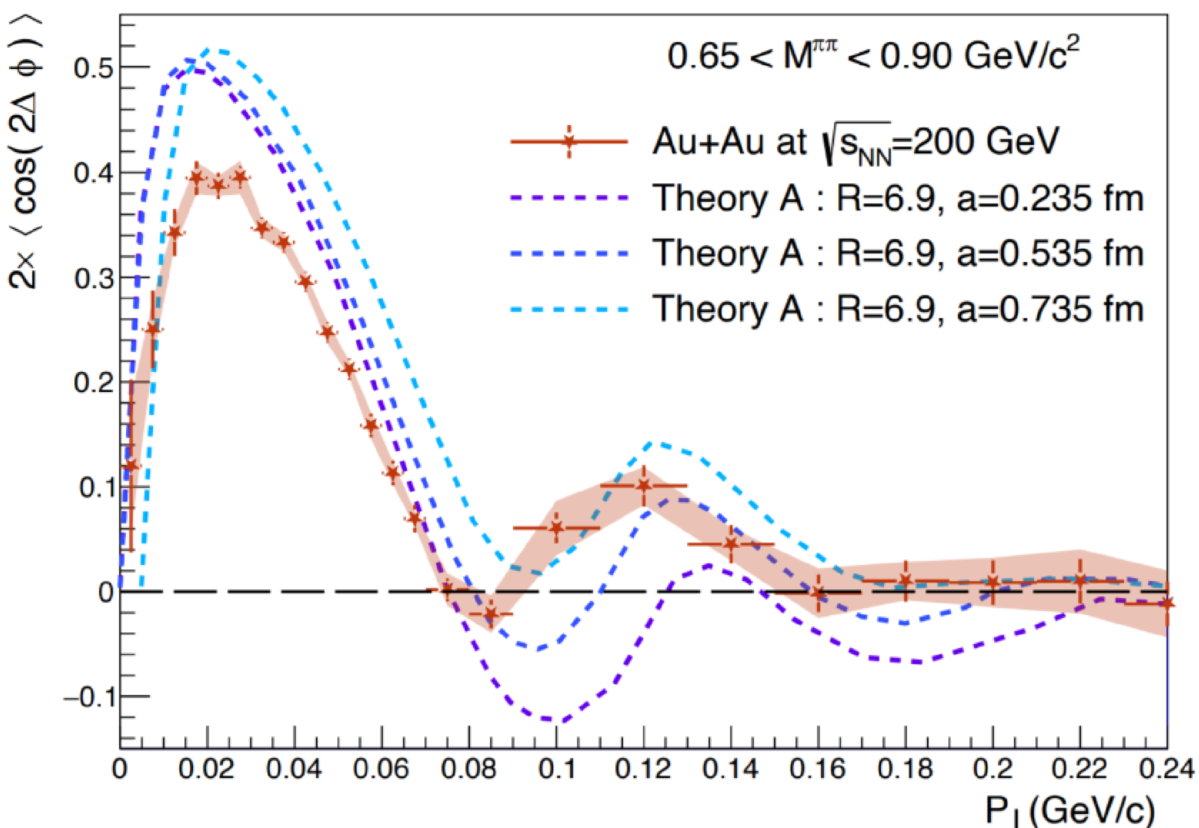


Azimuthal asymmetries in di-pion production

Cos2ϕ in ρ^0 production



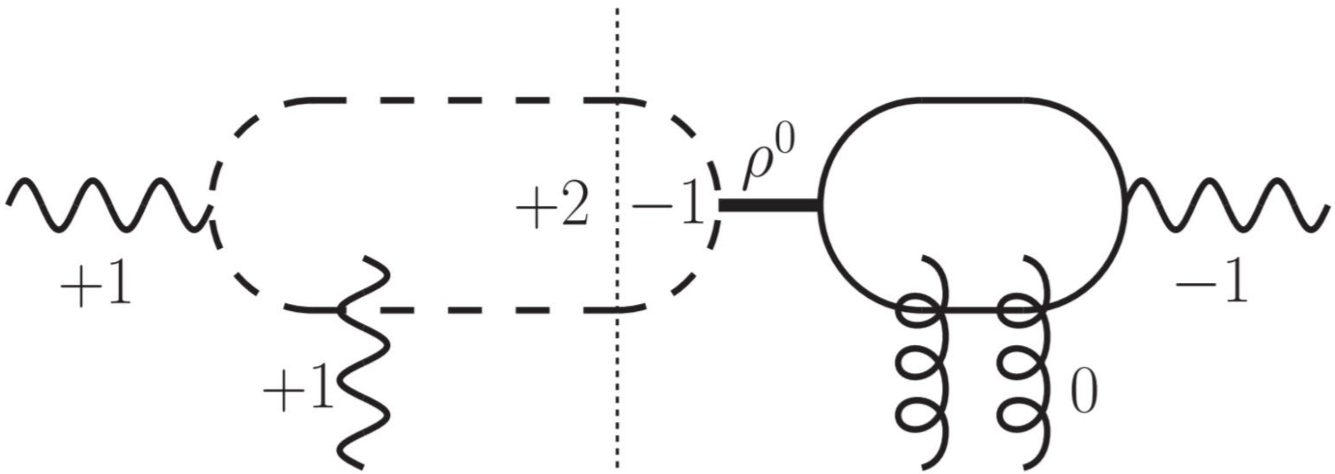
$$\langle +1|-1\rangle \sim \cos 2\phi$$



Xing, Zhang, ZJ, Zhou, 2020;

STAR collaboration, Sci.Adv. 2023

Coulomb nuclear interference



EM production V.S. via ρ decay

EM: 1/t

QCD: nuclear form factor F(t=0)

Azimuthal dependent cross section

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

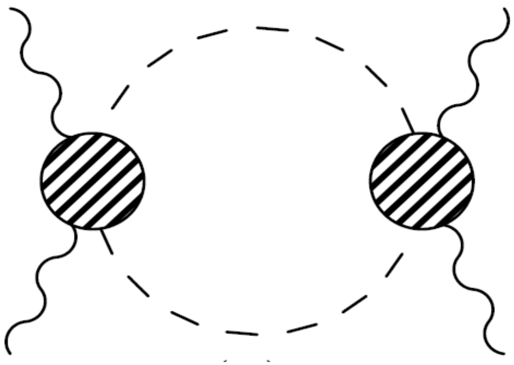
Yoshikazu Hagiwara, Cheng Zhang, ZJ and Ya-jin Zhou, 2020

Interesting observation:

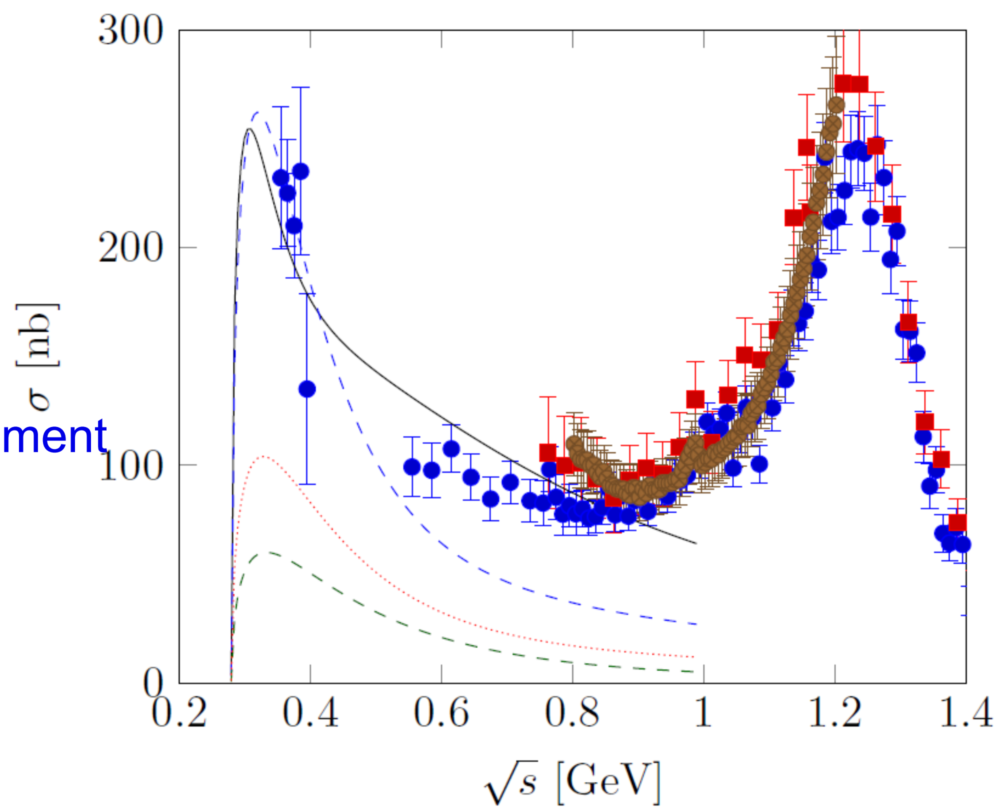
- Interference CS vanishes identically when integrating out ϕ

Hadronic Light-by-light scattering

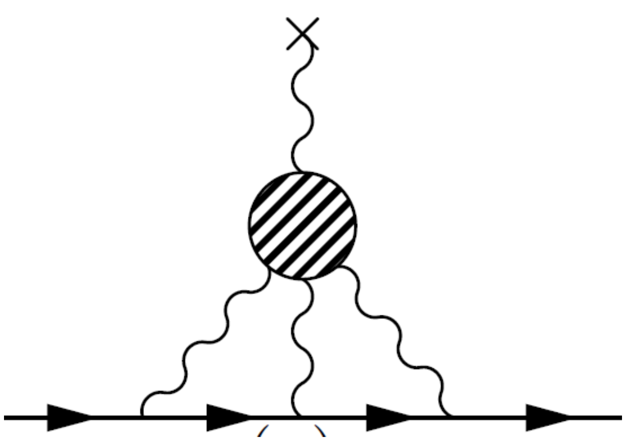
- Related via Optical theorem



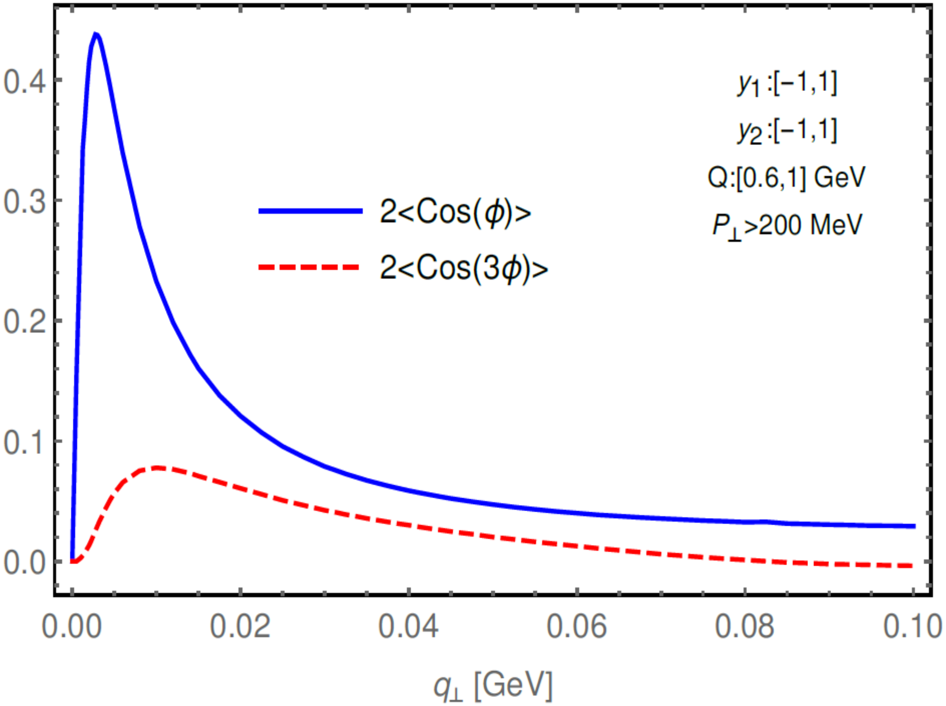
◆ Data point is sparse around ρ^0 mass region

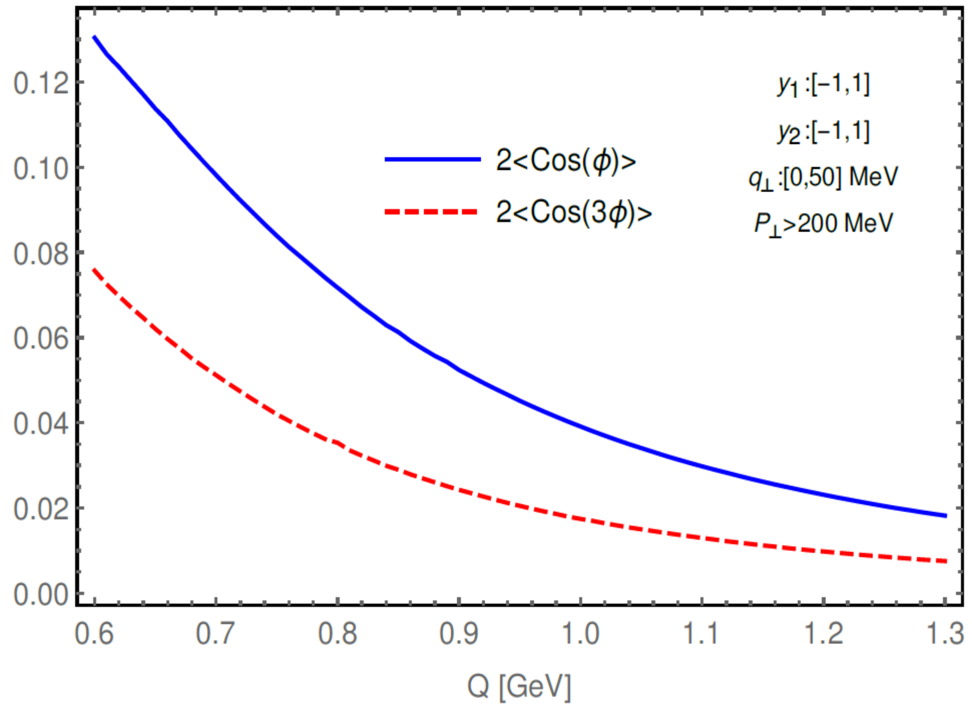


➢ Vital to constrain the hadronic Contribution to anomalous magnetic moment



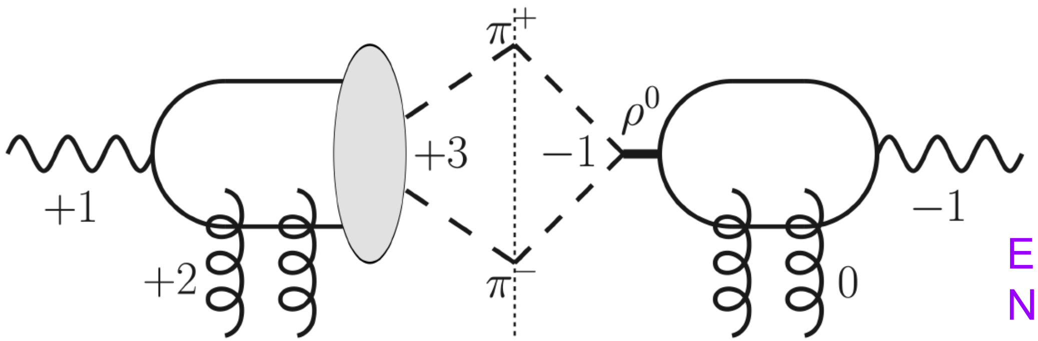
Numerical results





- Constrain the phase of the dipole amplitude

Cos4ϕ in dipion production I

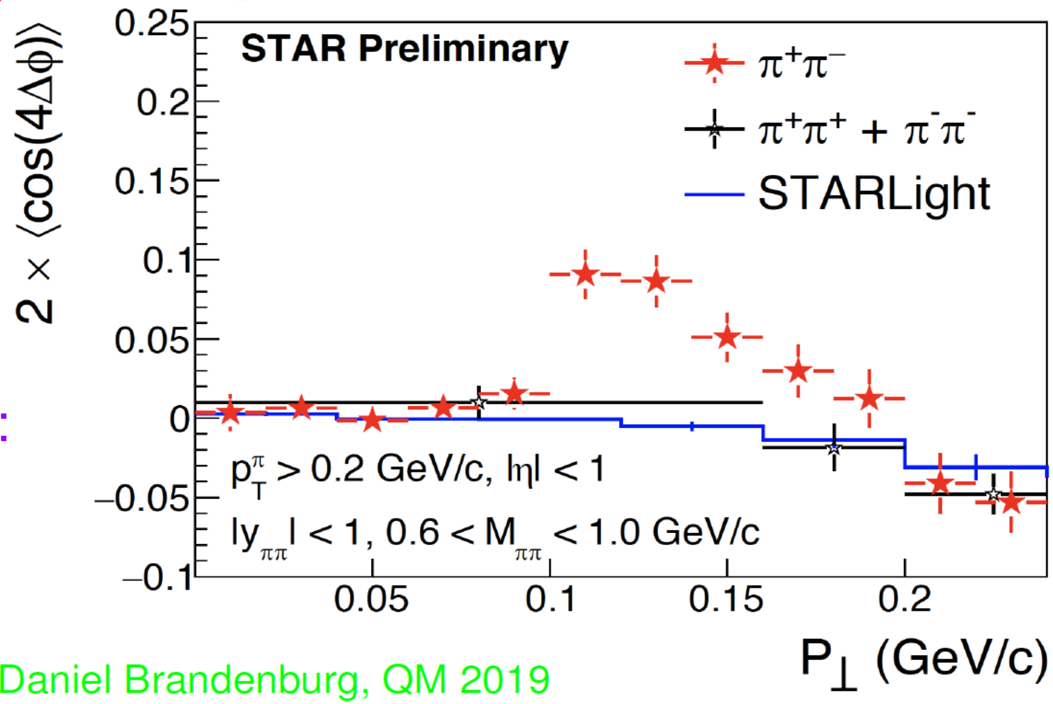


elliptic Wigner gluon

Hatta, Xiao and Yuan, 2016

Elliptic gluon distribution:
Non-trivial correlation between bt and kt

STAR measurement:

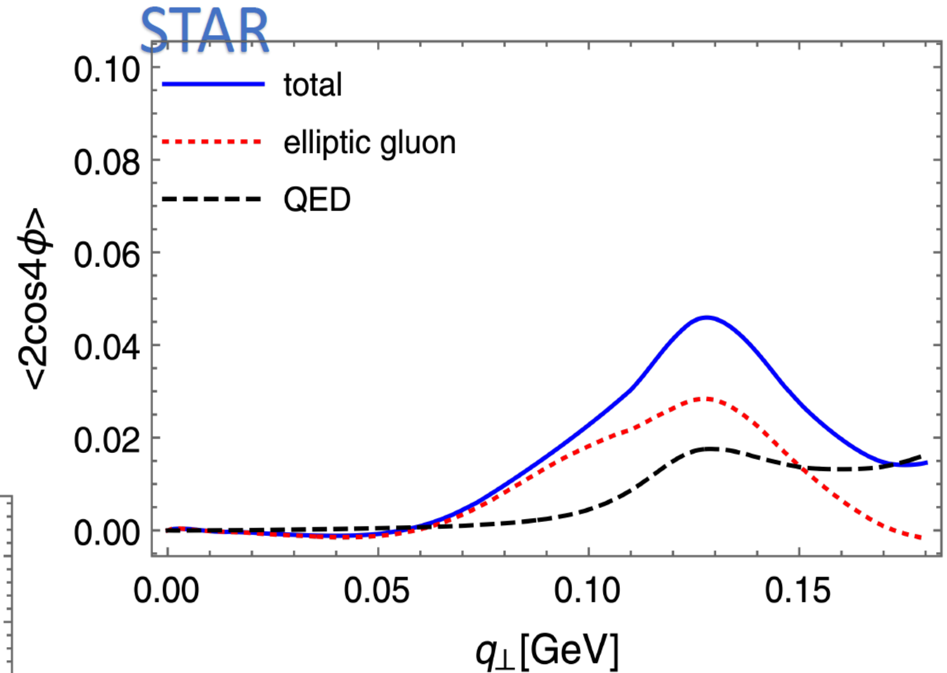


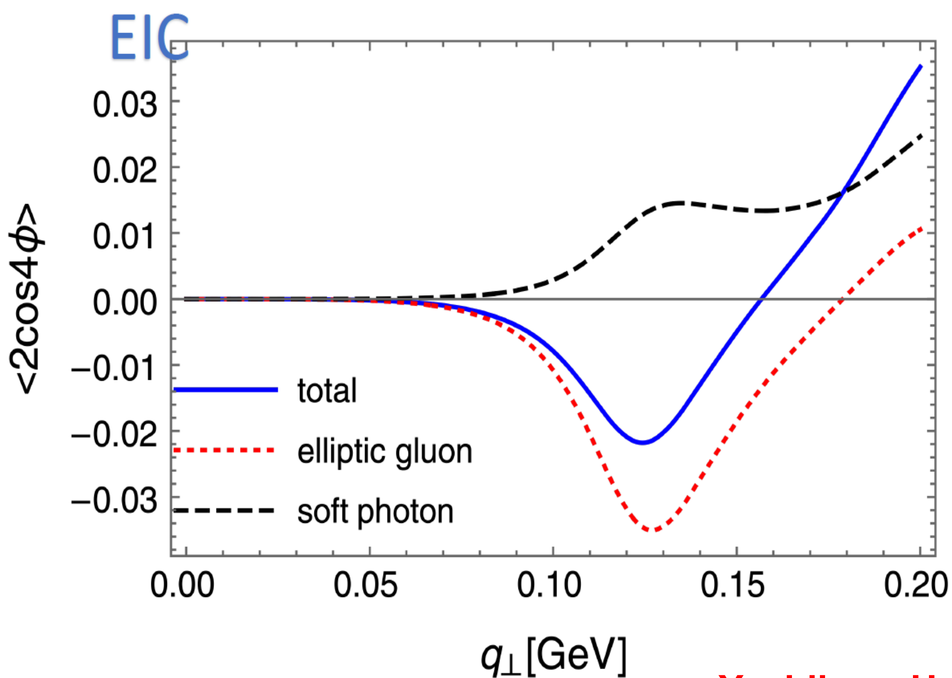
Daniel Brandenburg, QM 2019

Cos4ϕ in dipion production II

QED contribution alone not adequate

contribution from elliptic gluon distribution





- The asymmetry flip sign at EIC

Yoshikazu Hagiwara, Cheng Zhang, ZJ and Ya-jin Zhou, 2021

Summary

- Linear polarization of coherent photons firmly established
- Rich physics is revealed via azimuthal asymmetries in UPCs

- As a tool to explore: BSM physics；Strong field QED

Thank you!

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Gluon GTMD operator definition

$$xG_{DP}(x,q_\perp,\Delta_\perp) \;=\; 2\int \frac{d\xi^- d^2\xi_\perp e^{-iq_\perp\cdot\xi_\perp - ixP^+\xi^-}}{(2\pi)^3 P^+} \times\left\langle P+\frac{\Delta_\perp}{2}\middle| \mathrm{Tr}\left[F^{+i}(\xi/2)U^{[-]\dagger}F^{+i}(-\xi/2)U^{[+]}\right]\middle| P-\frac{\Delta_\perp}{2}\right\rangle$$

In the small x limit:

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

Hatta, Xiao and Yuan, 2016

the correlation limit where $|\Delta_\perp| \ll |q_\perp|$

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

Elliptic gluon GTMD