Gluon tomography with UPCs

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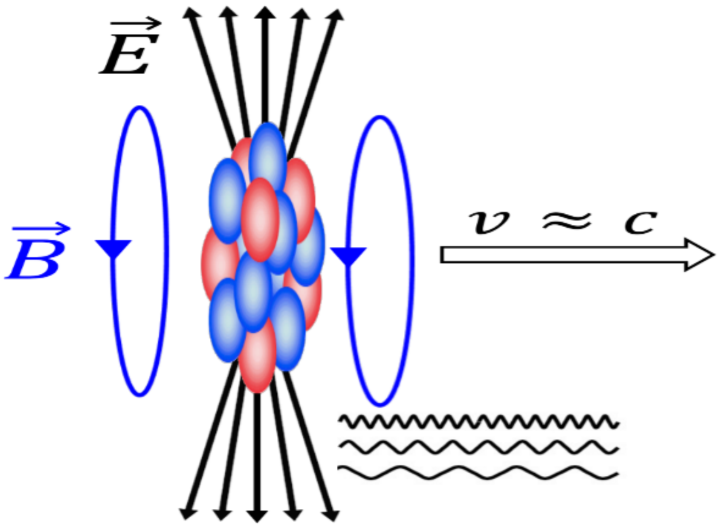
Outline

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

Experimental aspects, Shuai's talk

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

Linear polarization of photons at small x

- In the context of TMD factorization:

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

Mulders-Rodrigues， 2001

$$F_+^\mu = \partial_+ A^\mu - \partial^\mu A_+ \longrightarrow F_+^\mu \propto k_+ A^\mu - k_\perp^\mu A_+ \longrightarrow F_{+\nu} \propto -k_\perp A_+$$

- For given nuclear charge form factor:

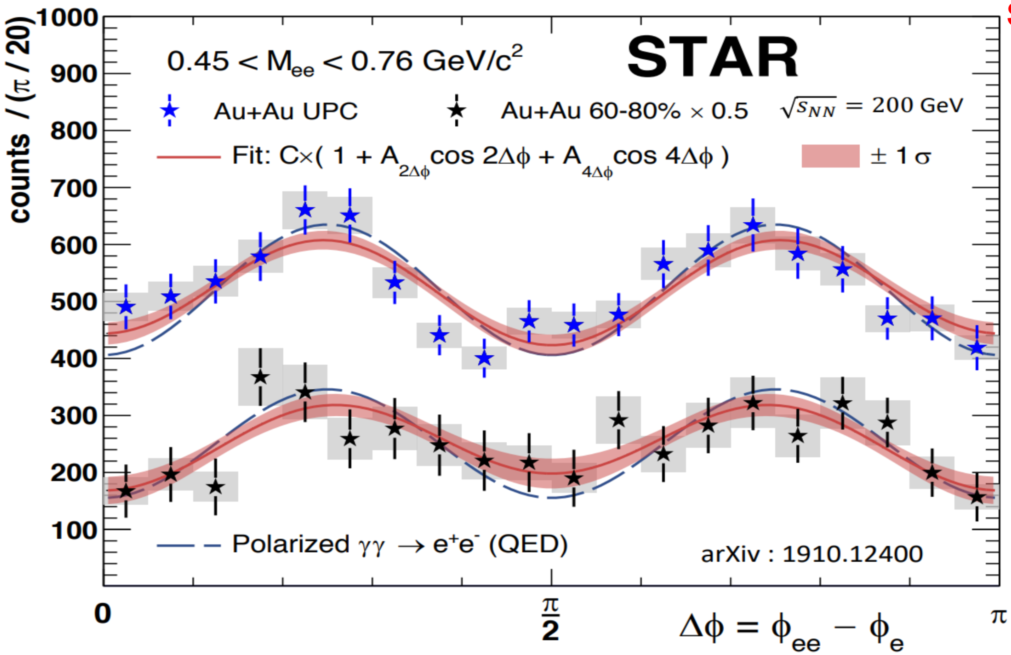
$$x f_1^\gamma(x,k_\perp^2) = x h_1^{\perp\gamma}(x,k_\perp^2) = \frac{Z^2\alpha_e}{\pi^2} k_\perp^2 \left[\frac{F(k_\perp^2 + x^2 M_p^2)}{(k_\perp^2 + x^2 M_p^2)}\right]^2$$

- Common feature of gauge bosons: CGC is linearly polarized **A. Metz, ZJ; 2011**

Verified by STAR experiment

➢ Cos 4ϕ asymmetry in EM dilepton production

STAR collaboration, PRL 127, 2021

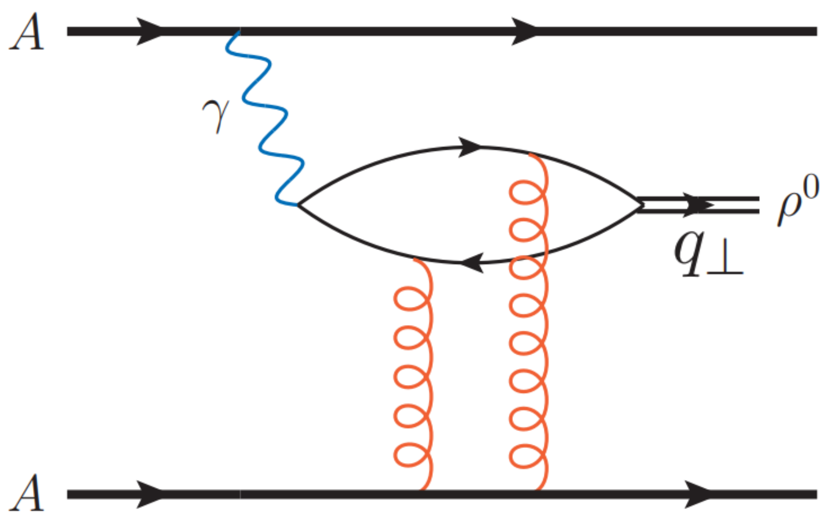


$0.45GeV^2<Q^2<0.76GeV^2$
$P_t>200MeV$, $|y|<1, q_t<100MeV$

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%

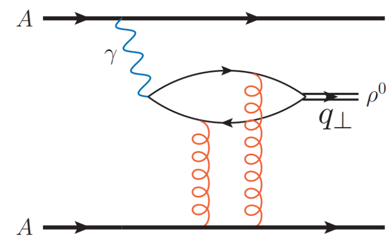
Polarization dependent Vector meson diffractive production



Diffractive vector production

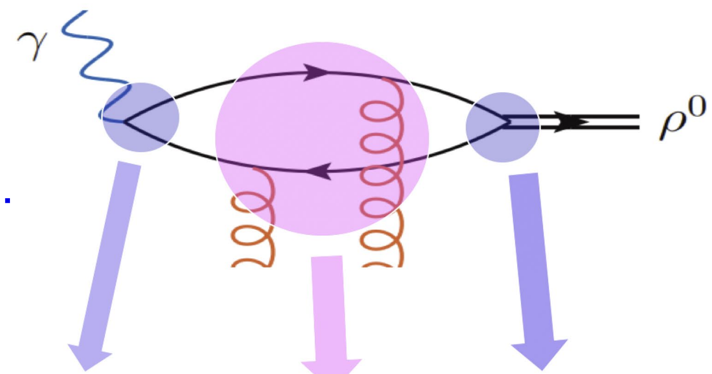
Motivations:

- ➢ Studying the saturation effect
- ➢ Transverse spatial imaging of gluons



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

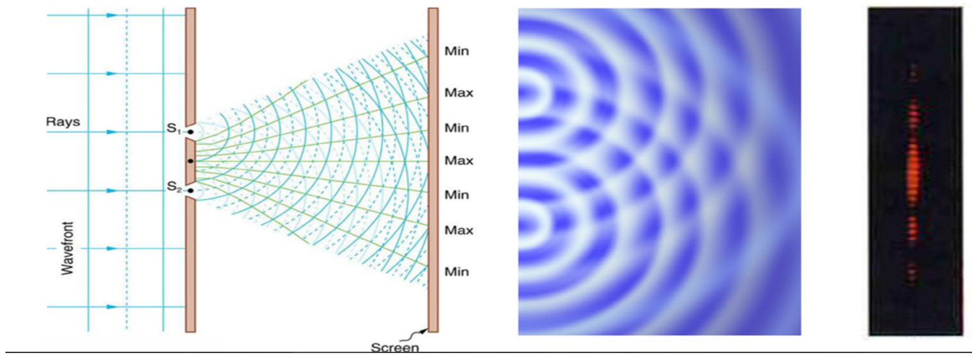
◆ Small x formalism:
dipole model, CGC, Glauber model…



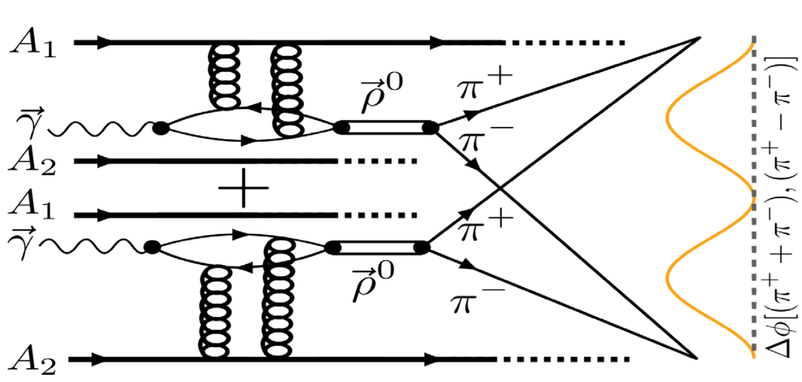
$$\mathcal{A}(\Delta_\perp) = i\int d^2b_\perp e^{i\Delta_\perp\cdot b_\perp}\int\frac{d^2r_\perp}{4\pi}\int_0^1 dz\, \Psi^{\gamma\to q\bar{q}}(r_\perp,z,\epsilon_\perp^\gamma) N(r_\perp,b_\perp) \Psi^{V\to q\bar{q}*}(r_\perp,z,\epsilon_\perp^V)$$

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

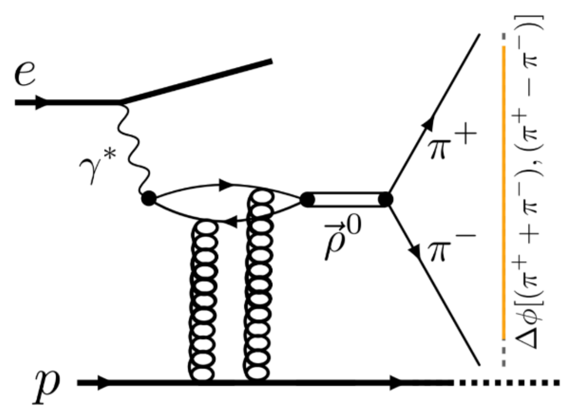


➢ double-slit experiment in UPCs



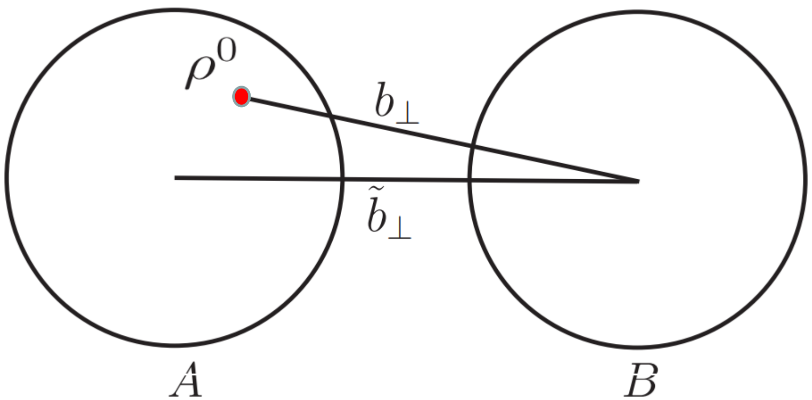
RHIC/LHC

S. Klein. & Nystrand, 1999



EIC

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 $b_\perp$

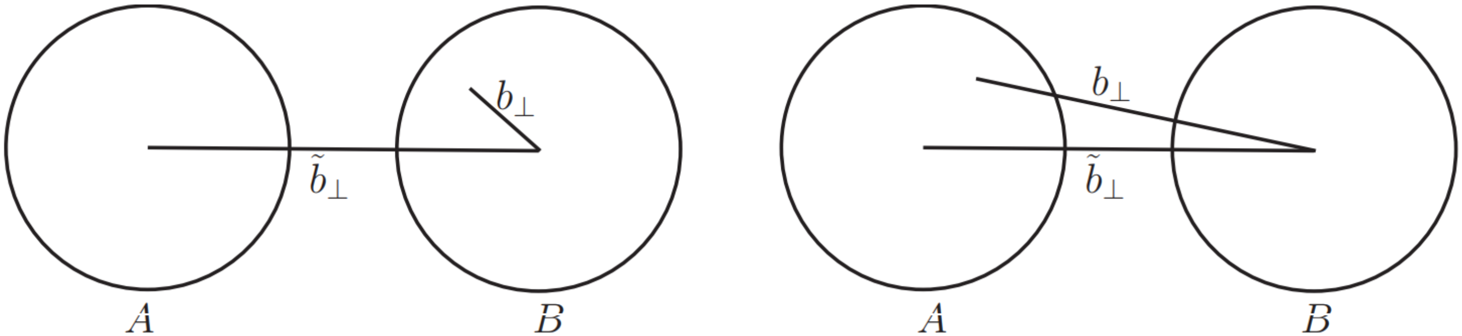
The probability amplitude of producing ρ^0 at position $b_\perp$

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

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:

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

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

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

Some model inputs

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

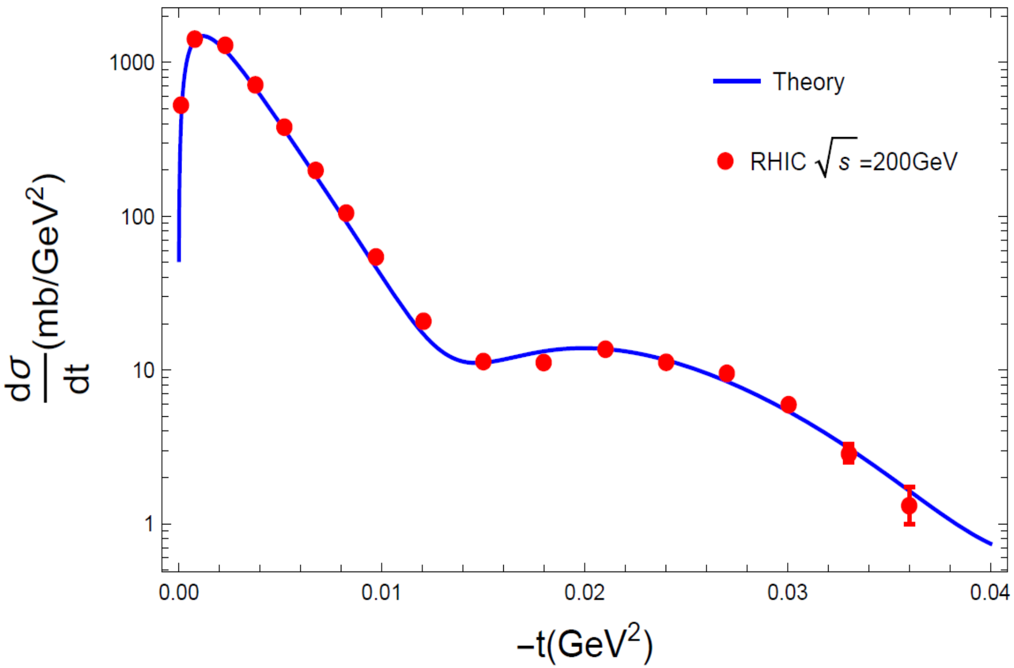
Gold target	Skin depth	Strong interaction radius
Standard value	0.54fm	6.38fm
Fitted to STAR data	0.64fm	6.9fm

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

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

ρ^0 diffractive pattern

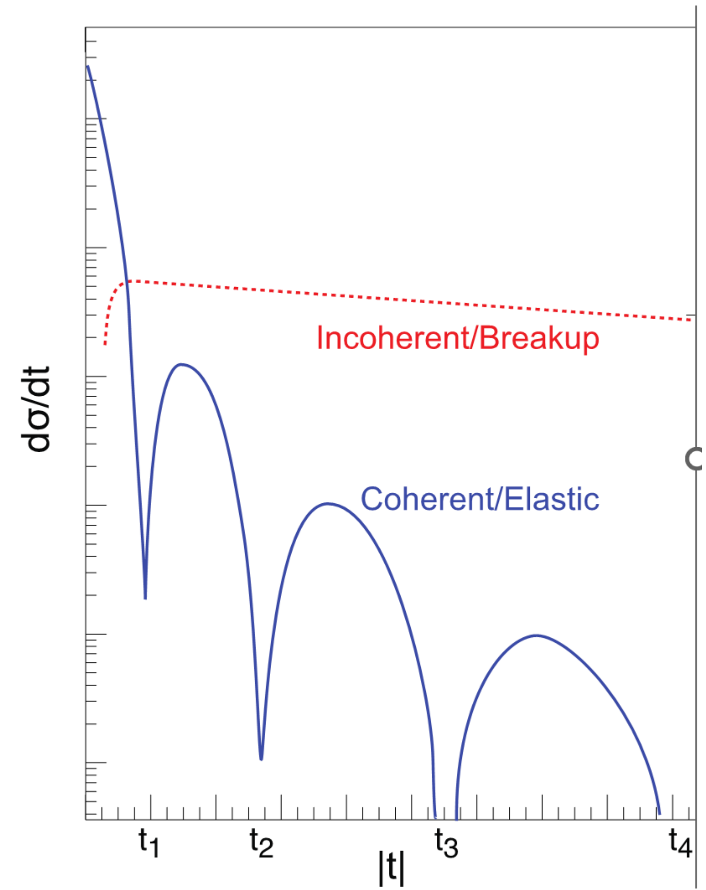
Diffractive VM production in UPC



H.x. Xing, C. Zhang, ZJ, Y.j.Zhou 2020

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

Diffractive VM production in eA



- **One slit interference(black disk limit)**

Azimuthal asymmetries from soft photon radiation

- Soft factor at LO:

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

Hatta, Xiao, Yuan, ZJ, 2021

- Large log:

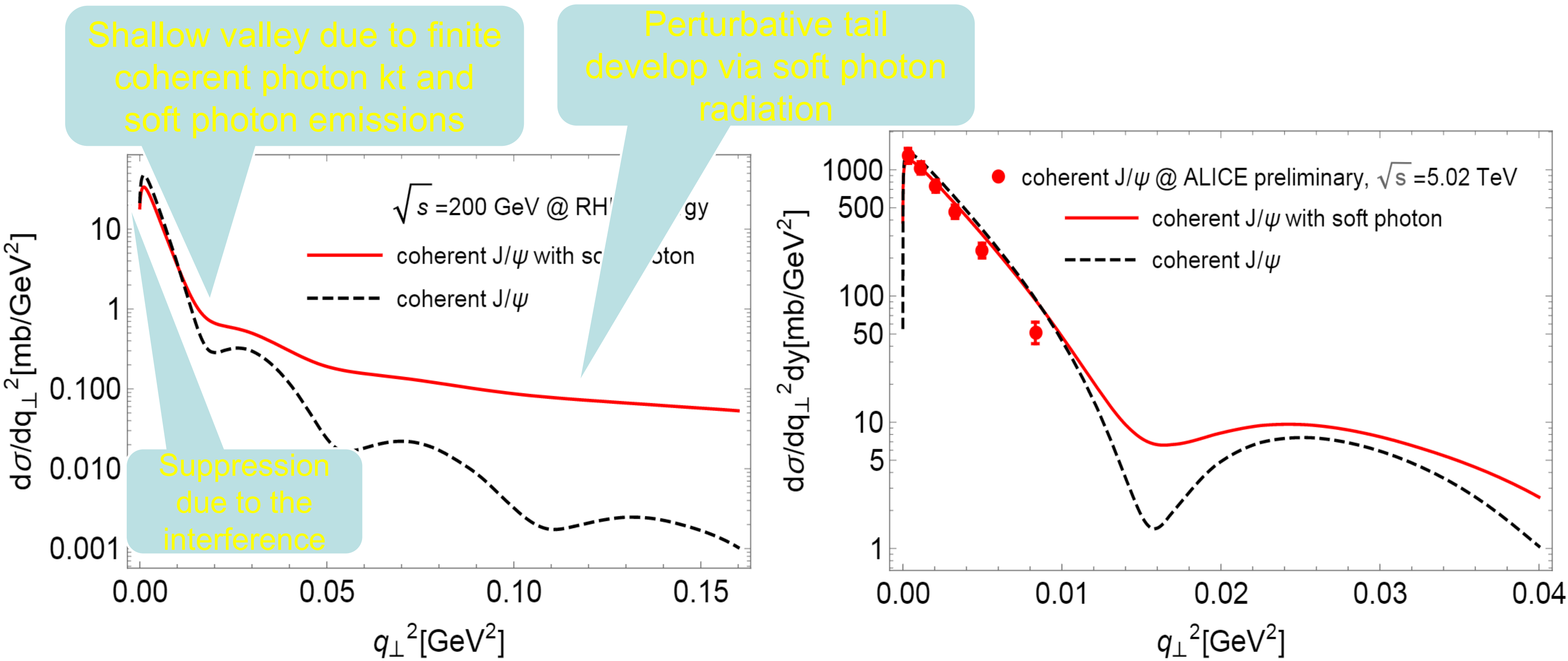
$$\ln \frac{M^2}{m^2}$$

Vector meson mass

Pion or electron mass

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

J/psi diffractive pattern

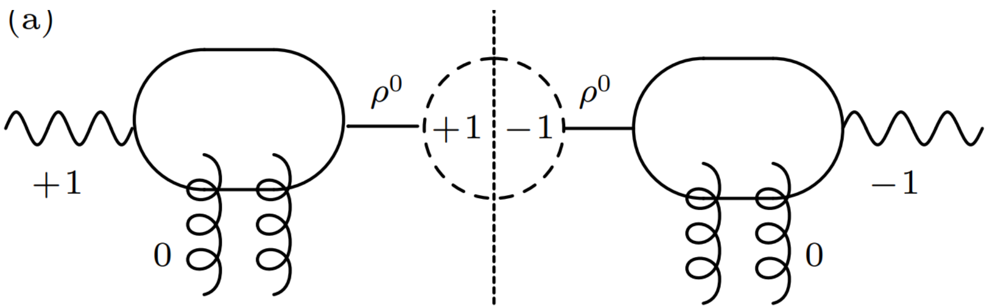


Brandenburg-Xu-Zha-Zhang-ZJ-Zhou, 2022
Mantysaari-Salazar-Schenke, 2022

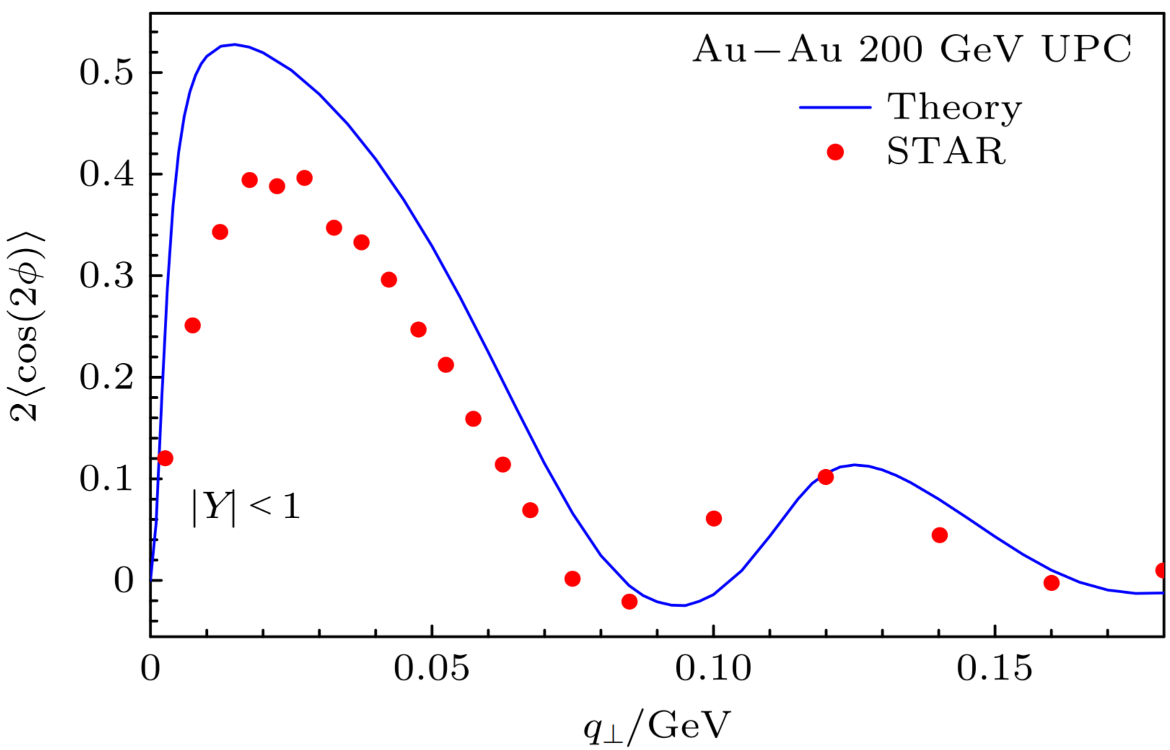
- Hard scale: better justify the perturbative treatment
- Wider separation of scales: stronger soft photon radiation effect

Azimuthal asymmetries in di-pion production

Cos2ϕ in ρ^0 production



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

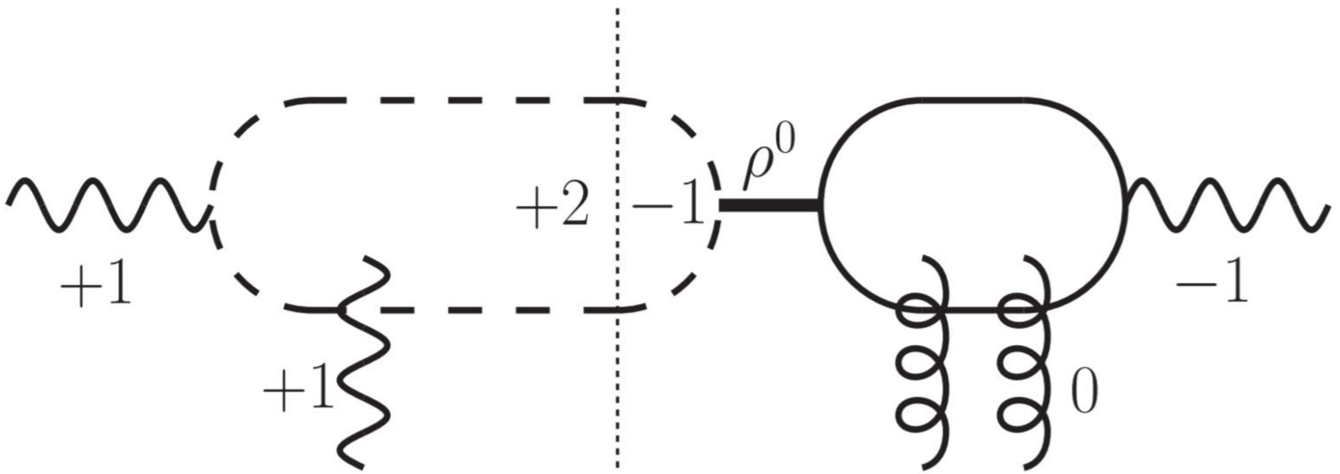


Theory curve taken from
Xing, Zhang, ZJ, Zhou, 2020;

Data points taken from
STAR collaboration, Sci.Adv. 2023

A Glauber model calculation: Zha, Brandenburg, Ruan,Tang, 2021

Coulomb nuclear interference



EM production V.S. via ρ decay

EM: 1/t

QCD: nuclear form factor F(t=0)

Azimuthal dependent cross section

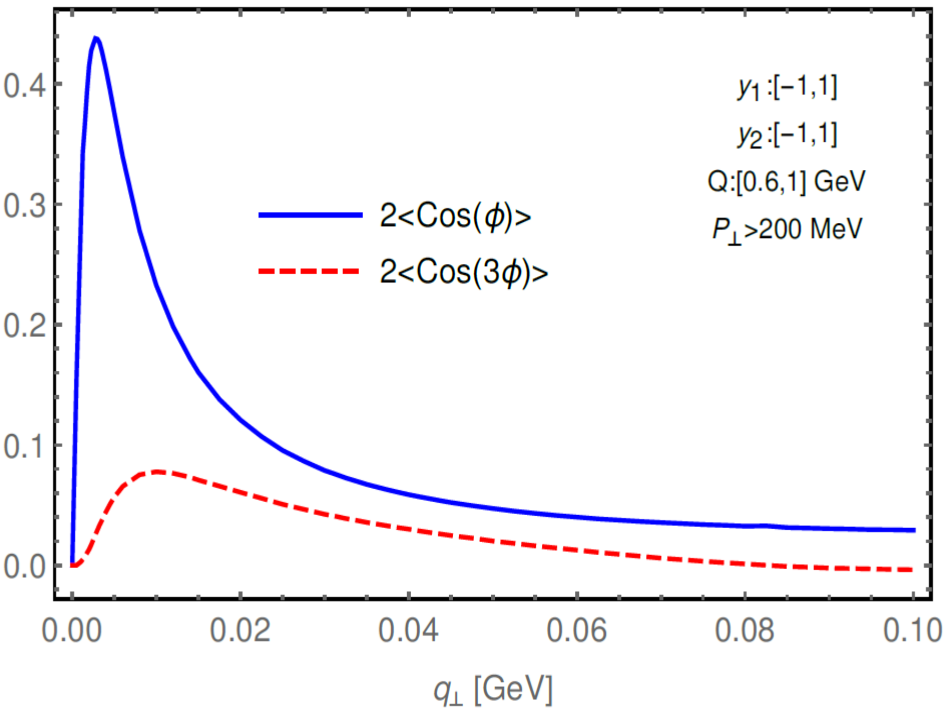
$$\frac{d\sigma_I}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2\tilde{b}_\perp} = \frac{\alpha_e}{Q^2}\frac{1}{(2\pi)^4}\frac{1}{\sqrt{4\pi}}\frac{2M_\rho\Gamma_\rho|P_\perp|f_{\rho\pi\pi}}{(Q^2-M_\rho^2)^2+M_\rho^2\Gamma_\rho^2}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp$$
$$\times\delta^2(k_\perp+\Delta_\perp-q_\perp)\left[\hat{k}_\perp\cdot\hat{\Delta}_\perp-\frac{2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

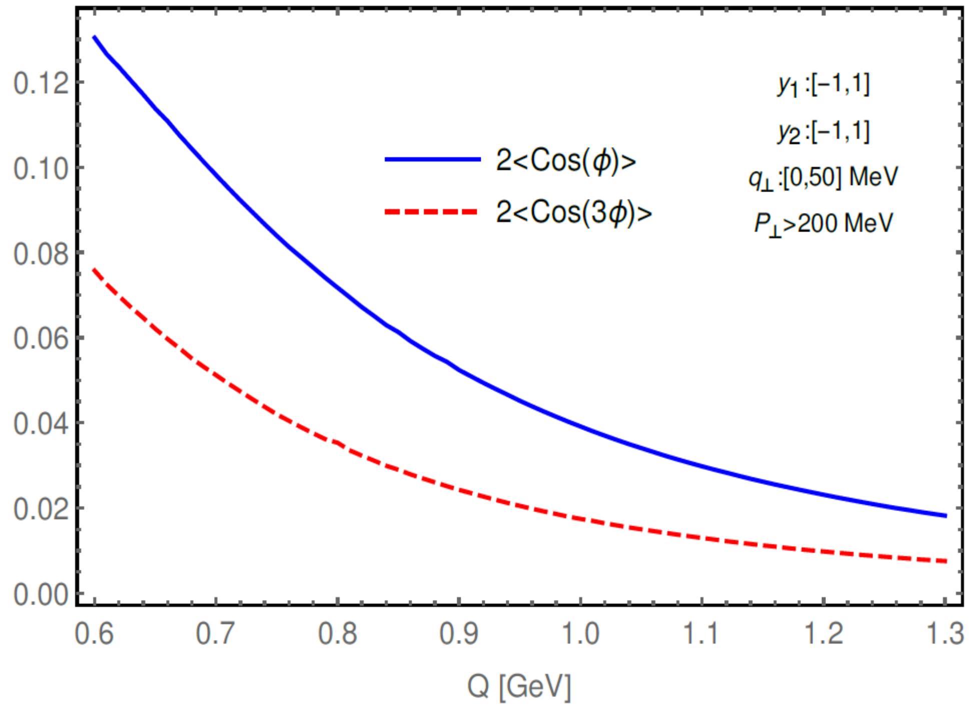
Y. Hagiwara, C. Zhang, ZJ and Y.-j. Zhou, 2020

Interesting observation:

- Interference CS vanishes identically when integrating out ϕ

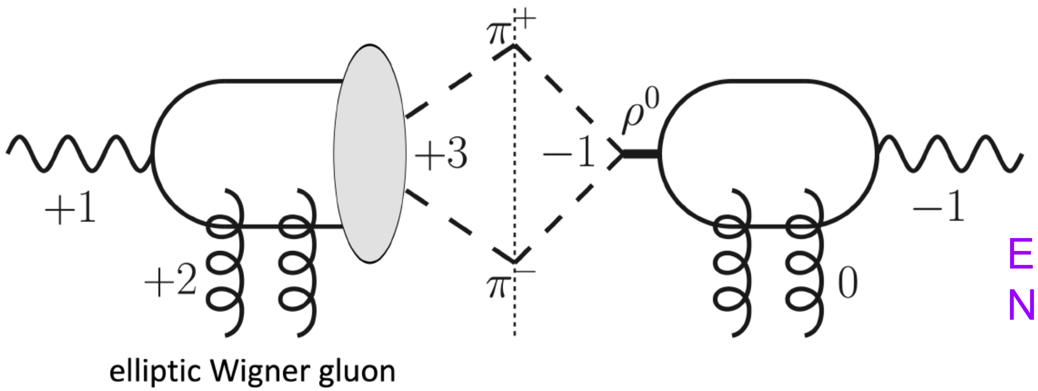
Numerical results





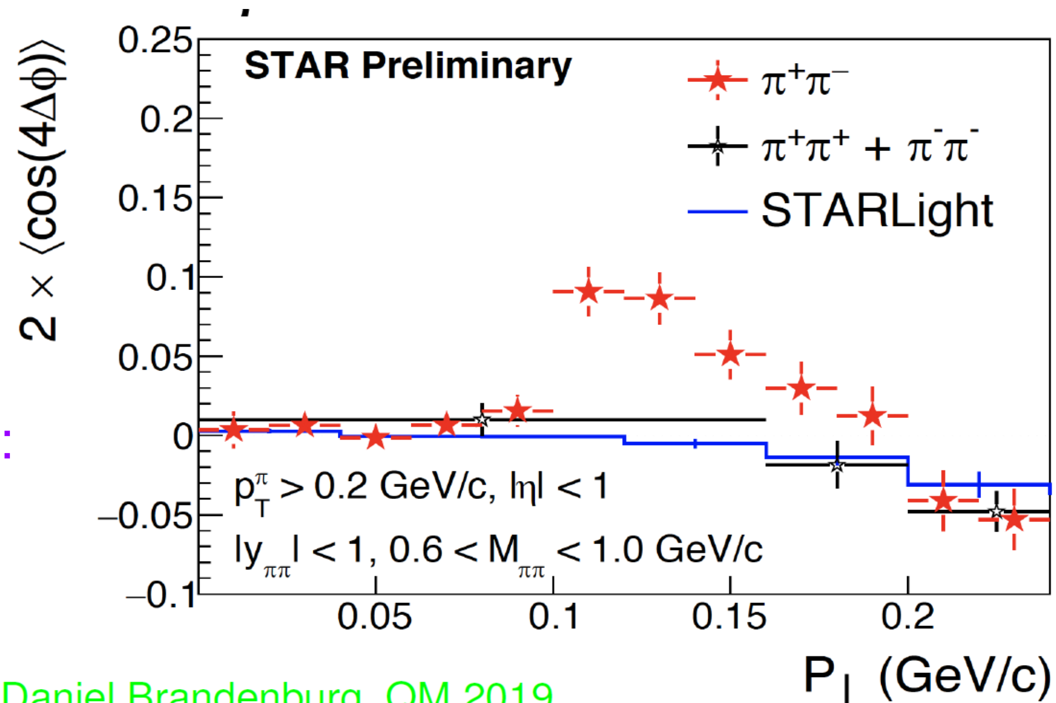
- Constrain the phase of the dipole amplitude

Cos4ϕ in dipion production I



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

STAR measurement:



Daniel Brandenburg, QM 2019

Gluon GTMD operator definition

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

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

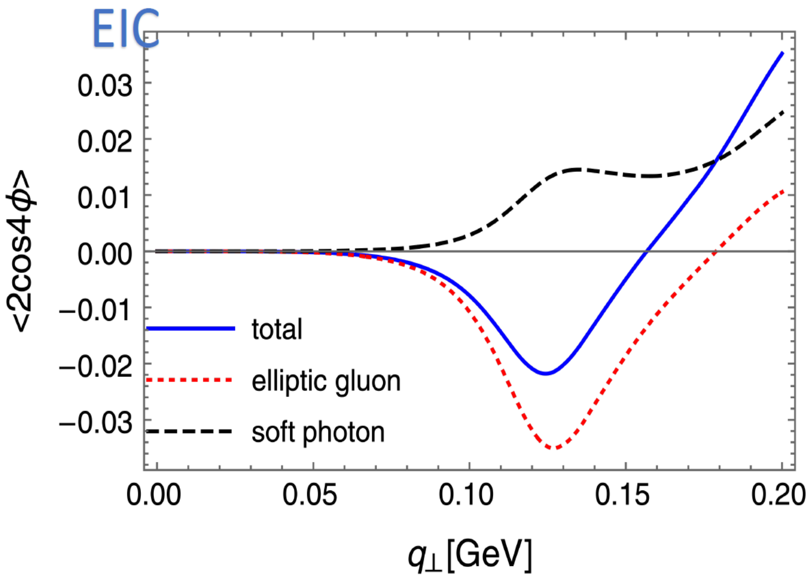
- Attract a lot of attentions:

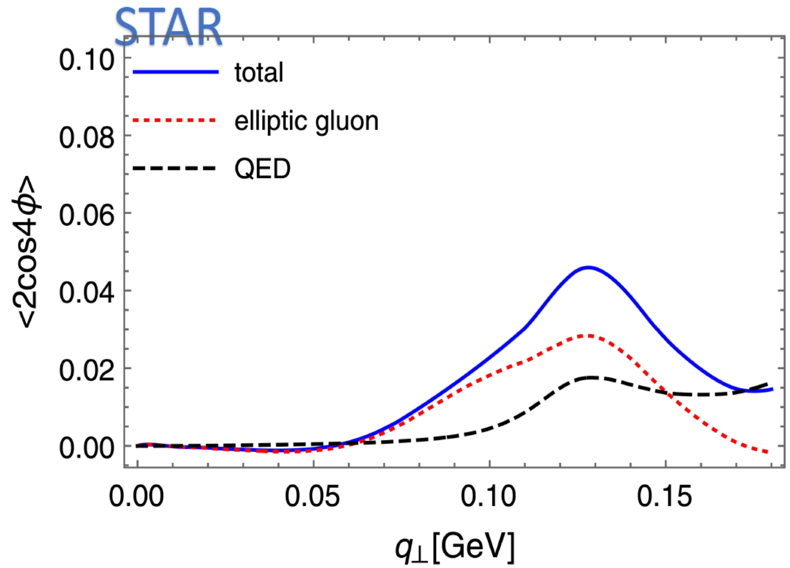
J. Zhou, 2016
R. Boussarie, Y. Hatta, B.-W. Xiao, F. Yuan, 2018
H. Mäntysaari, N. Mueller, F. Salazar, B. Schenke,2020
H. Mäntysaari, K. Roy, F. Salazar, B. Schenke,2021
……

Cos4ϕ in dipion production II

QED contribution alone not adequate

contribution from elliptic gluon distribution





◆ The asymmetry flips sign at EIC

Y. Hagiwara, C. Zhang, ZJ and Y.-j. Zhou, 2021

➢ Universal nonperturbative function describing the transition from a quark anti-quark pair to a di-pion system.
Electron production(large Q^2), more reliable perturbative treatment

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!

山东大学(青岛)
SHANDONG UNIVERSITY，QINGDAO