Azimuthal modulation in diffractive vector meson production in ultraperipheral collisions

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XXXVII International Workshop on High Energy Physics
“Diffraction of hadrons: Experiment, Theory, Phenomenology”

Outline

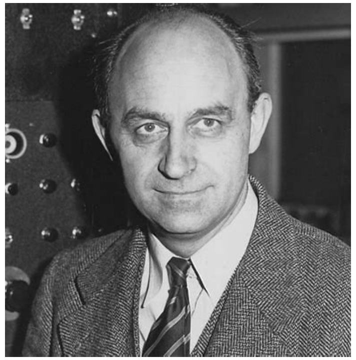
- Introduction to UPC and linearly polarized photon
- Probe nucleon structure in photon-induced diffractive process by using linearly polarized photon in UPC and EICs

Equivalent photon approximation (EPA)

Over 100 years

1. *1924, Fermi;* "…consider that when a charged particle passes near a point, it produces, at that point, a variable electric field. If we decompose this field, via a Fourier transform, into its harmonic components we find that it is equivalent to the electric field at the same point if it were struck by light with an appropriate continuous distribution of frequencies.

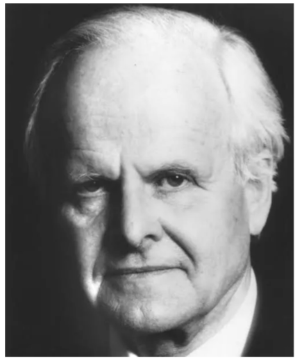
arXiv:hep-th/0205086, Persico remarks that this was one of Fermi's favorite ideas and that he often used it in later life.



2. *1930's, Weizäscker and Williams (individually);*

developed to relativistic charged particles,
method of virtual quanta

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



Ultraperipheral collision (UPC) in heavy-ion collisions

cross section in γ–γ processes in heavy-ion collisions:

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

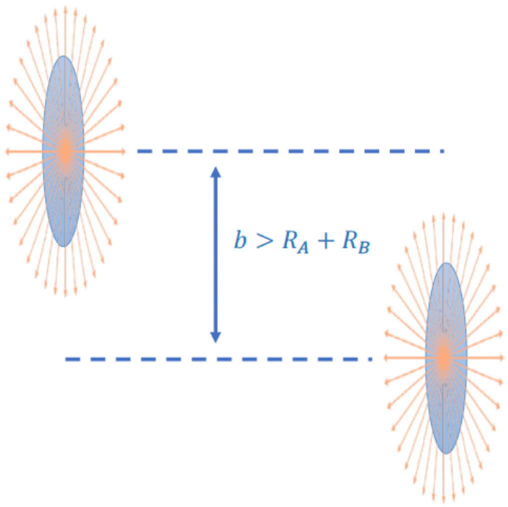
$\gamma-\gamma$: $d\sigma \propto Z^4$ e.g. Au, 79^4=3.9*10^7

$\gamma-A$: $d\sigma \propto Z^2$

But! strong interaction dominant in center collisions

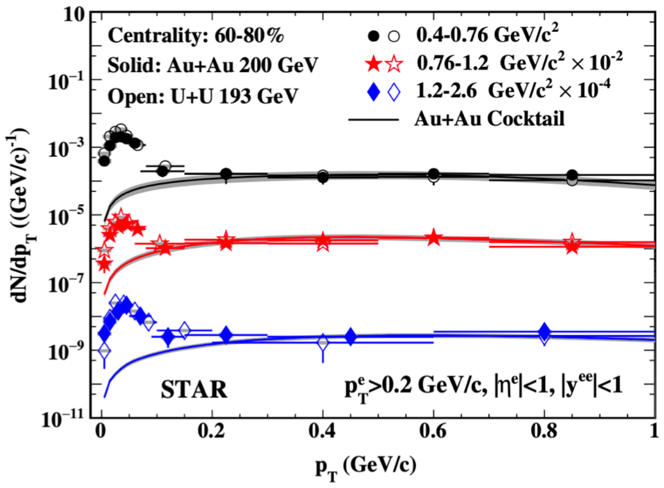
- UPC

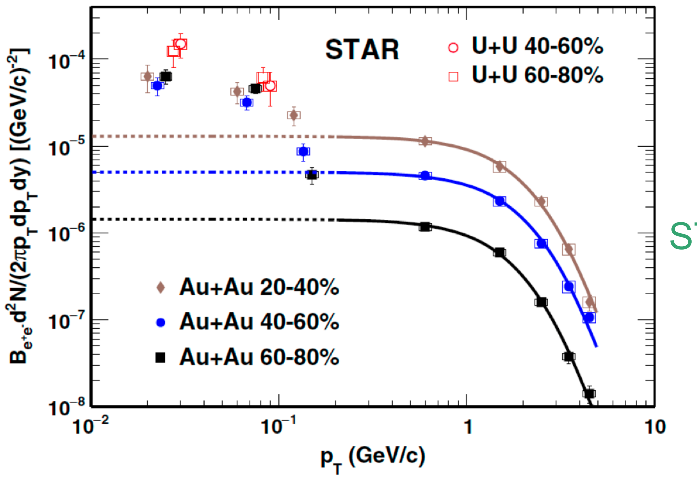
Two nuclei physically miss each other, interact (only) electromagnetically



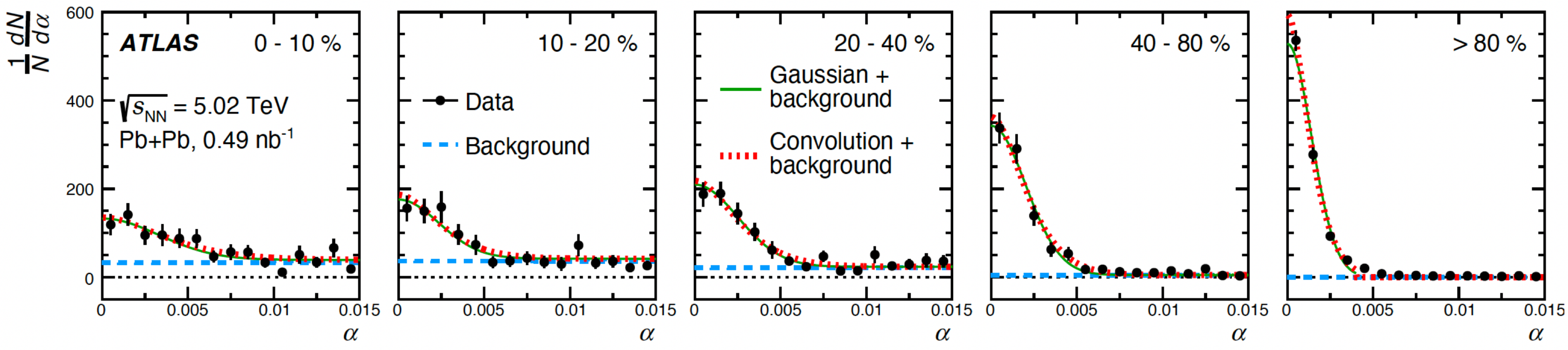
Clean background

Measurements of dilepton in UPC at STAR and ATLAS





STAR Collaboration, PRL123, 132302 (2019)



ATLAS Collaboration, PRL **121**, 212301 (2018)

Linearly polarized photon

Low electron energy, Sommerfeld, 1931

relativistic energies, May, Wick, 1951

ANNALEN DER PHYSIK

5. FOLGE, 1931, BAND 11, HEFT 3

Über die Beugung und Bremsung der Elektronen

Von A. Sommerfeld

(Mit 12 Figuren)

Übersicht: Der I. Teil bildet eine systematische Einleitung zu der Behandlung des kontinuierlichen Röntgenspektrums im II. Teil. Der I. Teil geht nur in der Methode, nicht in den Resultaten über die Arbeiten von Gordon, Mott, Temple hinaus. Der II. Teil setzt, im Gegensatz zu Arbeiten von Oppenheimer und Sugiura den Endzustand des gebremsten Elektrons als ebene, durch Beugung modifizierte Welle an. Polarisation und Intensität im kontinuierlichen Spektrum werden nach der Methode der Matrixelemente berechnet. Um die azimutale Verteilung der Intensität, insbesondere die Voreilung des Maximums zu erhalten, muß die Rechenmethode verfeinert werden durch Berücksichtigung der Retardierung. Die Resultate werden mit Messungen von Kulenkampff verglichen.

Detection of Gamma-Ray Polarization by Pair Production*

G. C. Wick
Radiation Laboratory, University of Californ
December 12, 1950

IT has been pointed out by Yang,[1] th
provide a method for detecting the p
the high energy range: $h\nu \gg mc^2$ (*m* be
where the usual Compton recoil method b
idea is to utilize the azimuthal dependenc
cross section $d\sigma$, the azimuth ϕ being
direction **k** of the incident quantum an
taining **k** and the electric polarization ve

On the Production of Polarized High Energy X-Rays

M. May and G. C. Wick
Department of Physics, University of California, Berkeley, California
December 12, 1950

THE purpose of this note is to examine the possibility of experiments with *polarized* x-rays of high energy, the polarization being obtained by using only a portion of the x-ray beam emitted (by a betatron, synchrotron, or linear-accelerator target) at an angle θ to the direction of the electron beam. The optimum angle,

PHYSICAL REVIEW VOLUME 84, NUMBER 2 OCTOBER 15, 1951

On the Polarization of High Energy Bremsstrahlung and of High Energy Pairs

Michael M. May
Physics Department, University of California, Berkeley, California

(Received July 2, 1951)

The polarization of bremsstrahlung due to electrons with initial energies much larger than $137Z^{-\frac{1}{3}}\,mc^2$ is calculated under relativistic, small angles approximations. The cross section for photons polarized normally to the plane containing the initial direction of the electron and the direction of the photon is found to be larger than for photons polarized in that plane. A similar calculation shows that the plane containing one of a pair produced by a polarized photon together with the direction of that photon tends to lie parallel to the plane of polarization rather than normal to it, except for one special case. The effect of the deviation due to multiple scattering of electrons in the target upon the angular dependence of the polarization is considered.

Linearly polarized photon

- EPA photons induced by relativistically moving charged particles are linearly polarized due to their transverse momentum

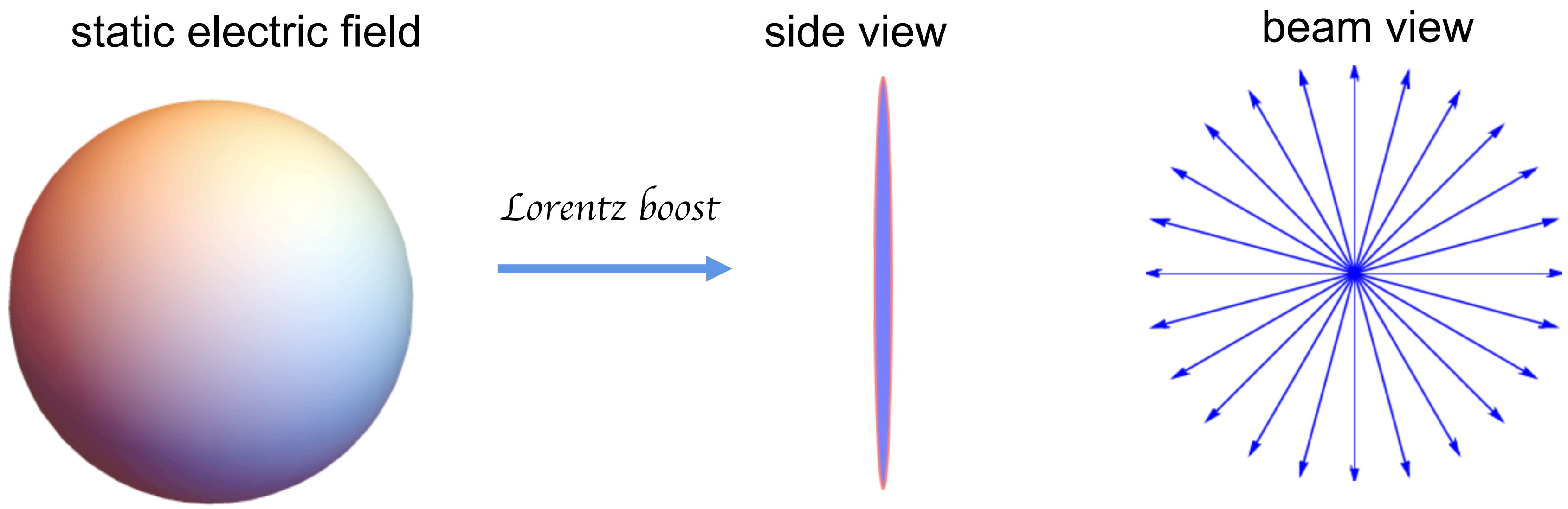
In position space

static electric field

Linearly polarized photon

- EPA photons induced by relativistically moving charged particles are linearly polarized due to their transverse momentum

In position space



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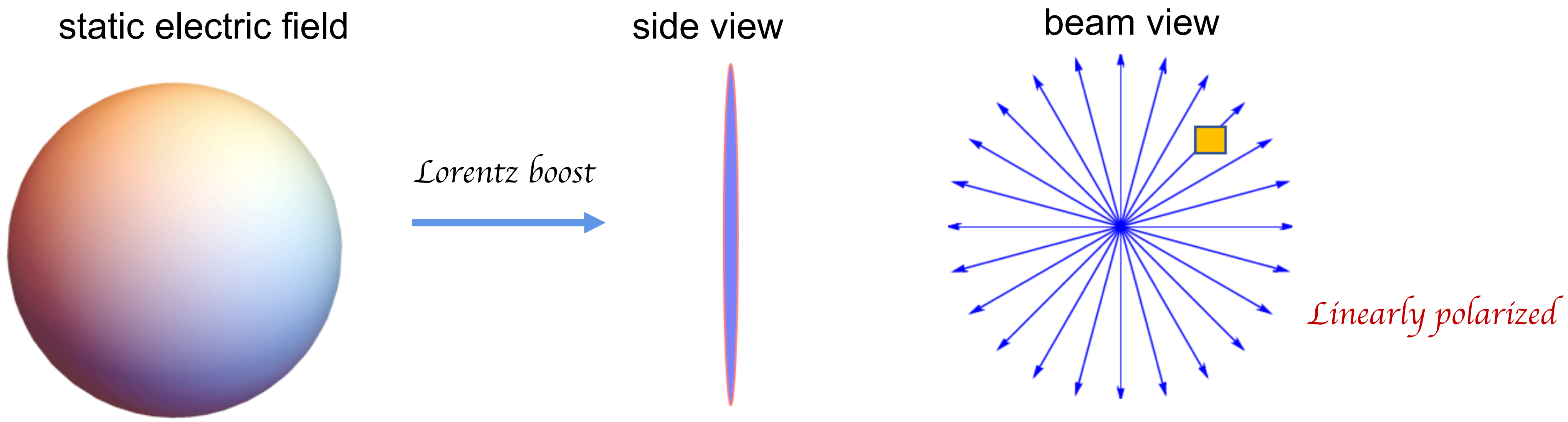
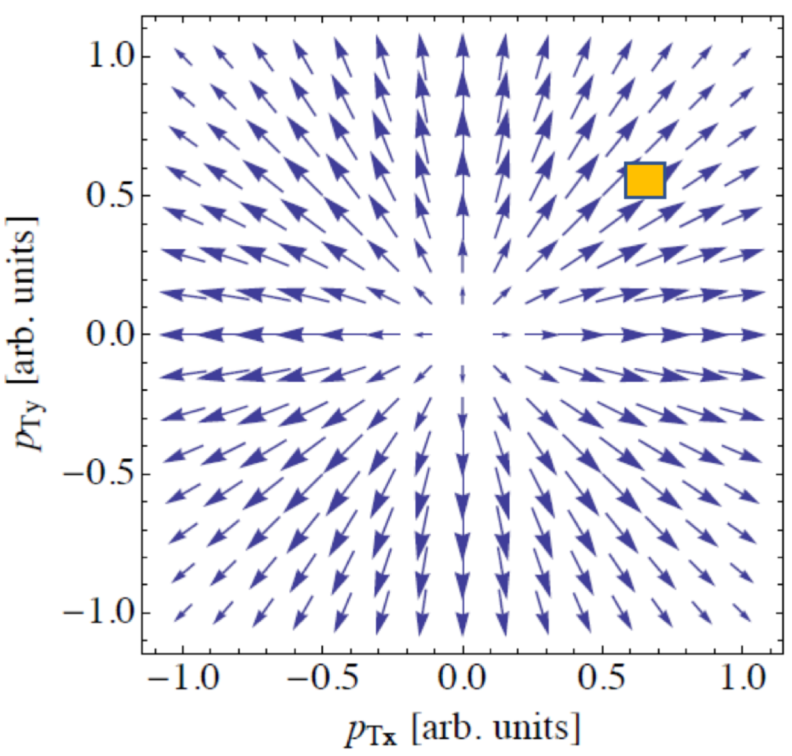


Linearly polarized photon

- EPA photons induced by relativistically moving charged particles are linearly polarized due to their transverse momentum

In momentum space

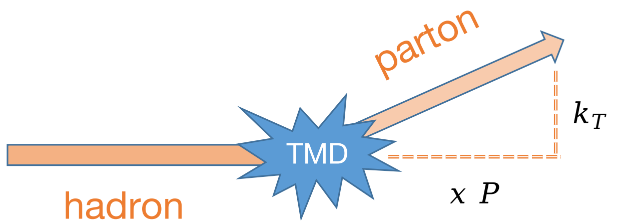


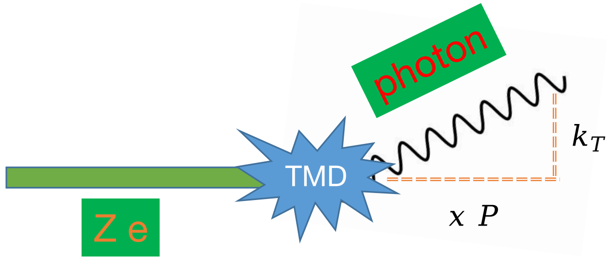
$\epsilon_\perp // k_\perp$

Linearly polarized

Linearly polarized photon/gluon, formalism in the framework of TMD (transverse-momentum-dependent) factorization

- gluon/photon TMD factorization:





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

P. Mulders, J. Rodrigues, PRD63(2001)

the numbers of gluons with opposite circular polarizations in a longitudinally (transversely) polarized nucleon. The off-diagonal function $H^\perp$ also is a difference of densities, but in this case of linearly polarized gluons in an unpolarized hadron. Using the circular polarizations, $H^\perp$ flips the polarization.

- Small x (dipole) gluons/photons are highly linearly polarized

A. Metz, J. Zhou, PRD84(2011)

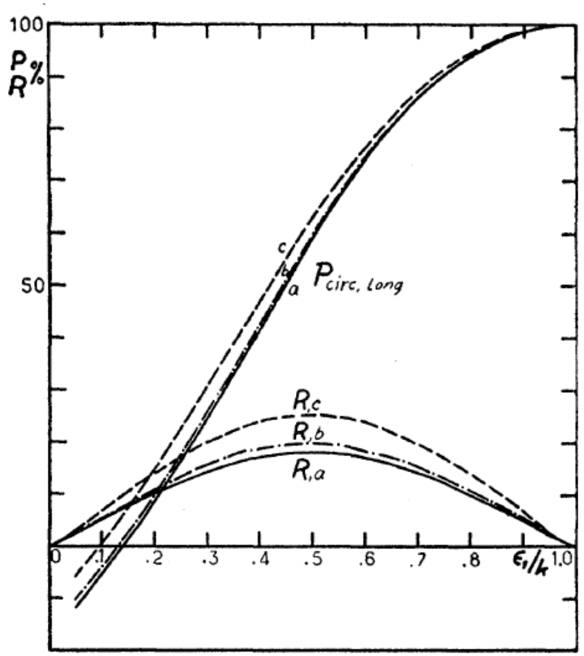
C. Li, J. Zhou, YZ, PLB795(2019)

$$f_1(x,k_\perp^2) = h_1^\perp(x,k_\perp^2)$$

How to probe linearly polarized photon/gluon, examples

Early studies about linearly polarized photon

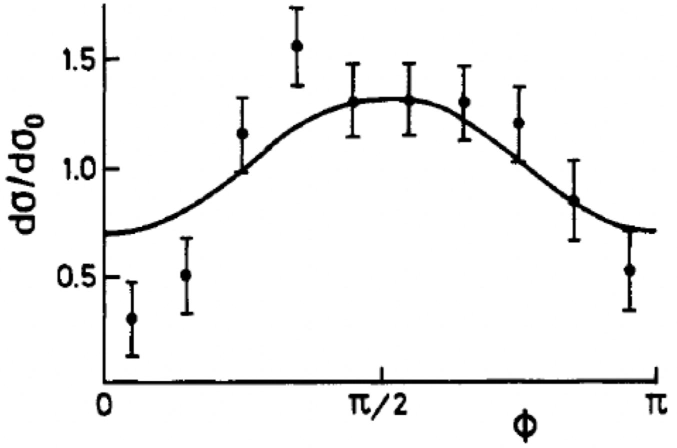
$$R=\frac{d\sigma(\hat{u}=\mathbf{e})-d\sigma(\hat{u}\cdot\mathbf{e}=0)}{d\sigma(\hat{u}=\mathbf{e})+d\sigma(\hat{u}\cdot\mathbf{e}=0)}$$



H.Olsen, L.C. Maximon, Phys.Rev. 114 (1959) 887-904

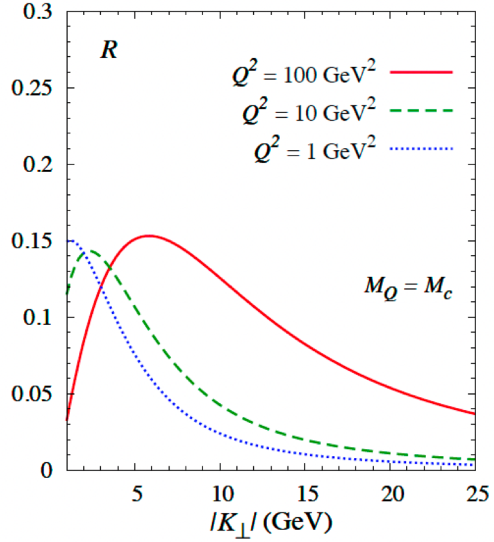
azimuthal modulations induced by linearly polarized gluon

$$pp \rightarrow pp\pi^+\pi^-$$



T. Jacobsen, H. Olsen, Phys.Scripta 42(1990)

$$e(\ell)+h(P)\rightarrow e(\ell')+Q(K_1)+\bar{Q}(K_2)+X$$



$$R=\left|\frac{\int d^2q_T\, q_T^2\, \cos 2(\phi_T-\phi_\perp)\, d\sigma}{\int d^2q_T\, q_T^2\, d\sigma}\right|$$

D.Boer, S. Brodsky, P. Mulders, C. Pisano, SLAC-PUB-14359 (2010)

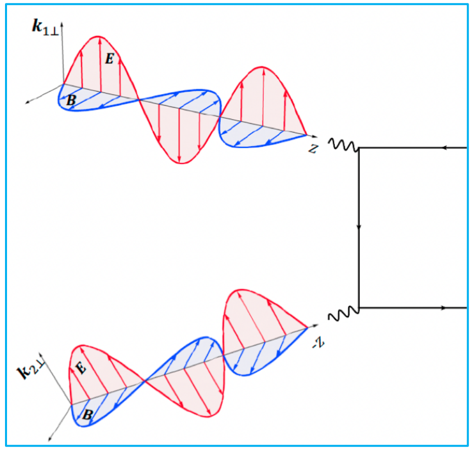
• • • • • •

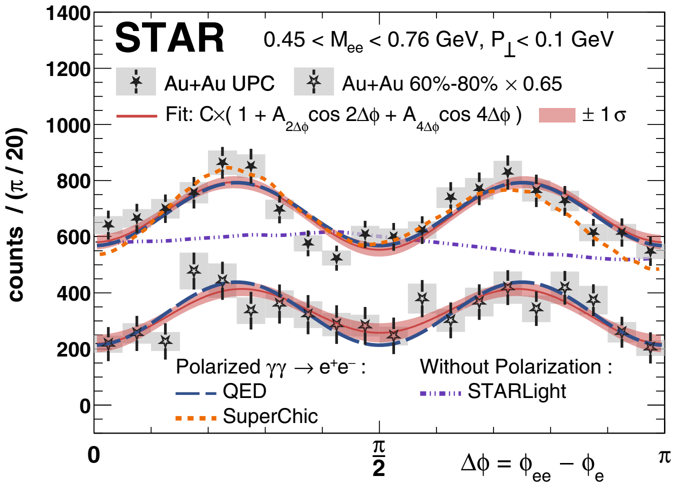
Azimuthal asymmetry in dilepton production in UPC

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

$$\frac{d\sigma}{d^2\mathbf{p}_{1\perp} d^2\mathbf{p}_{2\perp} dy_1 dy_2} = \frac{2\alpha_e^2}{Q^4}[\mathcal{A} + \mathcal{B}\cos 2\phi + \mathcal{C}\cos 4\phi]$$

$f_1^\gamma(x_1, k_{1\perp}^2) h_1^{\perp\gamma}(x_2, k_{2\perp}^2)$ $\qquad$ $h_1^{\perp\gamma}(x_1, k_{1\perp}^2) h_1^{\perp\gamma}(x_2, k_{2\perp}^2)$





STAR collaboration, PRL127, 052302 (2021)

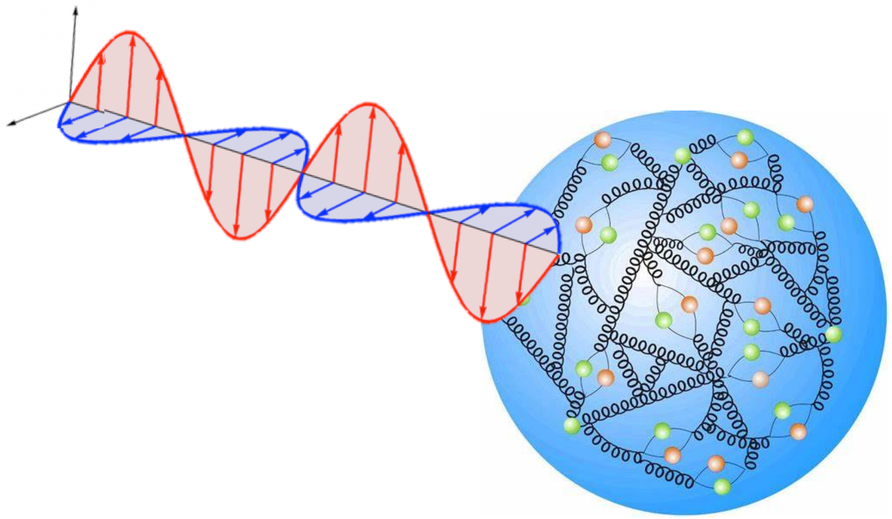
	Measured	QED calculation
Tagged UPC	16.8%±2.5%	16.5%
60%-80%	27%±6%	34.5%

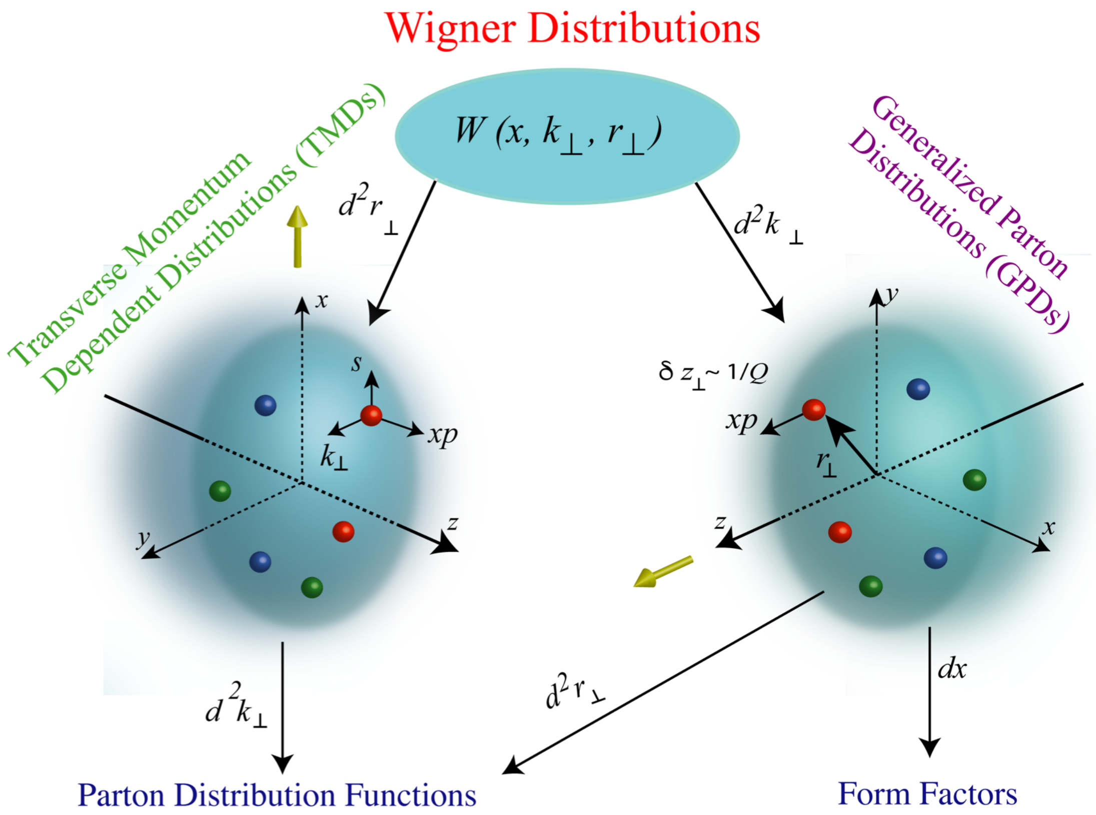
C. Li, J. Zhou and YZ, PLB795, 576(2019)

C. Li, J. Zhou and YZ, PRD101, 034015(2020)

We predicted the azimuthal asymmetries in dilepton@UPC, later verified by STAR

UPC: an ideal platform to “see” nucleus





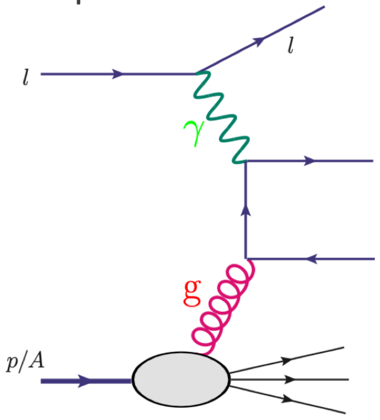
- ✓ linearly polarized photon
- ✓ high luminosity
- ✓ clean background
- ✓ ...

How? photo-nuclear diffractive production of vector mesons, di-jets...

Probing gluon tomography using photon

- semi-inclusive processes

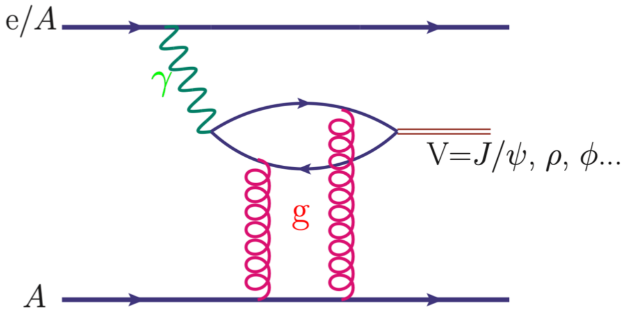
e.g.



Probe gluon TMD (transverse momentum dependent distributions)

- exclusive processes

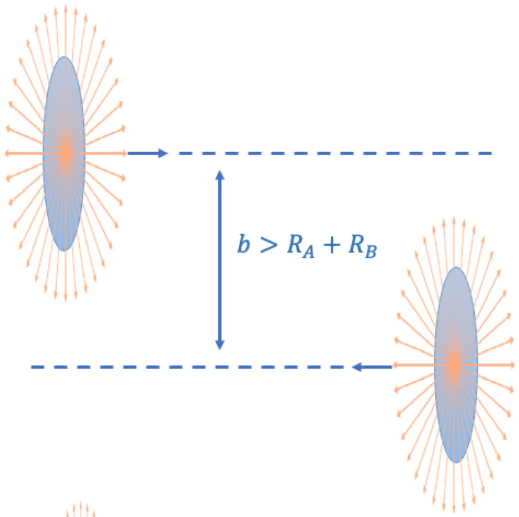
e.g.



Probe gluon Wigner distributions, GPD (transverse spatial distributions)

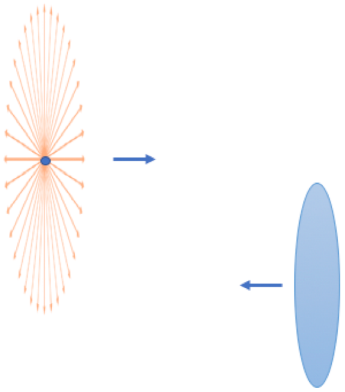
Two platforms to probe gluon tomography in diffractive photoproduction processes

- Ultra-peripheral collisions (UPCs)



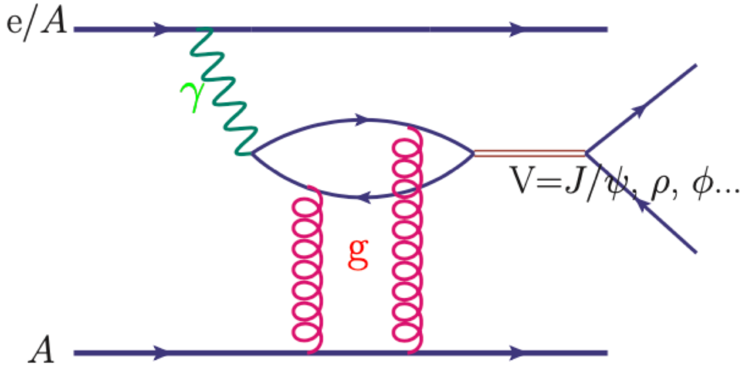
Double-slit interference

- EICs

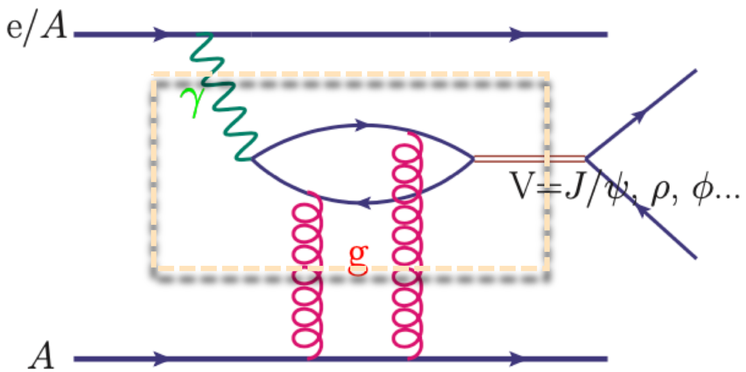


One-slit interference

Diffractive Vector meson photoproduction in UPCs and EICs



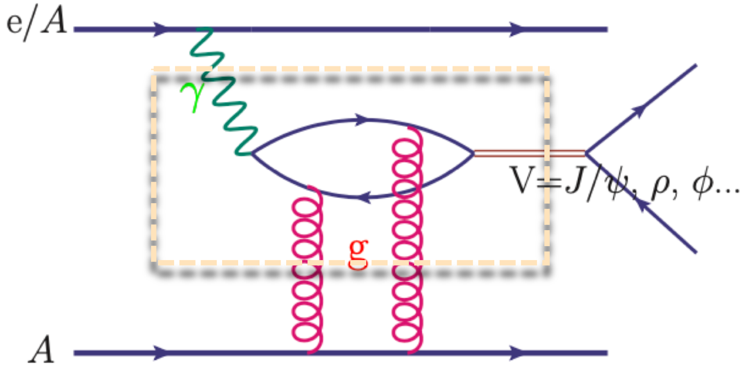
Diffractive Vector meson photoproduction in UPCs and EICs



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

For polarization averaged calculation, see: M. G. Ryskin, 93; S. J. Brodsky, L. Frankfurt, J. F. Gunion, A. H. Mueller and M. Strikman, 94

Diffractive Vector meson photoproduction in UPCs and EICs



$\epsilon_\perp^\gamma \to \epsilon_\perp^V$, unique observables :

$$\langle \cos(n\phi) \rangle = \frac{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} \cos(n\phi)\, d\mathcal{P}.\mathcal{S}.}{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} d\mathcal{P}.\mathcal{S}.}$$

where $\phi = q_\perp \wedge p_\perp^l$

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

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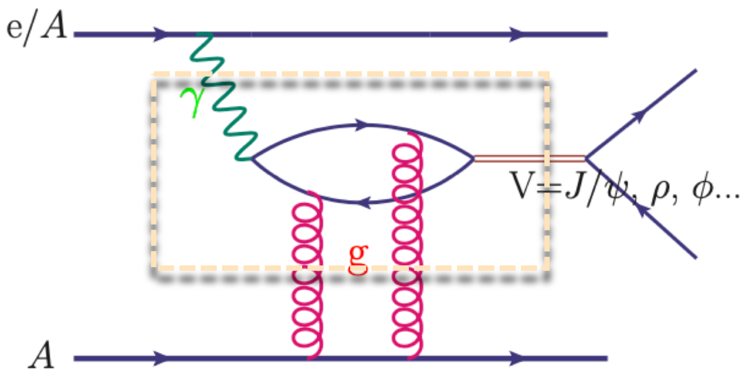
Diffractive Vector meson photoproduction in UPCs and EICs



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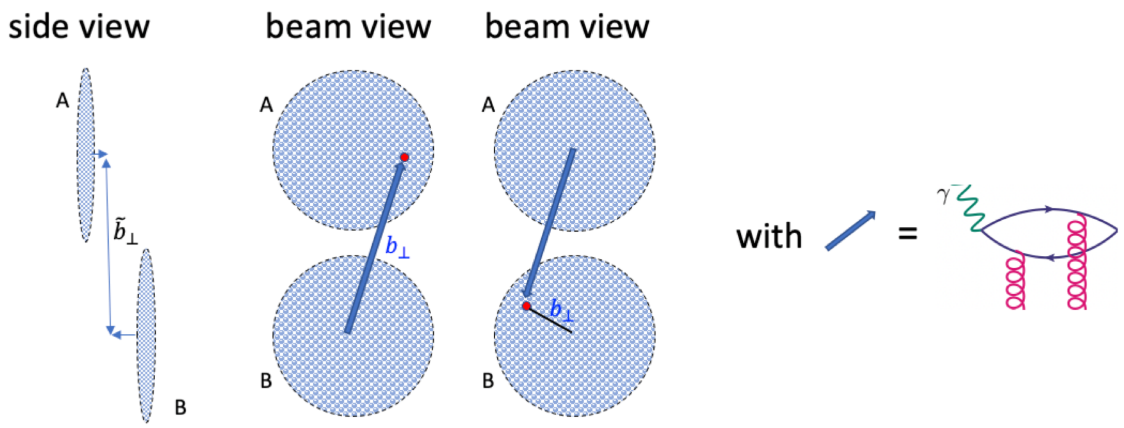
where $\phi = q_\perp \wedge p_\perp^l$

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

For polarization averaged calculation, see: M. G. Ryskin, 93; S. J. Brodsky, L. Frankfurt, J. F. Gunion, A. H. Mueller and M. Strikman, 94

dipole amplitude

Joint $\tilde{b}_\perp$ and $q_\perp$ picture



A,B take turns to be the source of color dipole

$\tilde{b}_\perp$: impact parameter
$b_\perp$: the position of the produced V $(\lambda_{J/\psi} \ll R_A)$
$b_\perp \leftrightarrow q_\perp$

Coherent cs: summing up amplitudes → squaring it

Incoherent cs: squaring the amplitude → summing up

coherent dominant at low $k_\perp$ $(\leq\sim \frac{1}{R_A}, \sim$ 30 MeV for Au and Pb) coherent production amplitude:

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

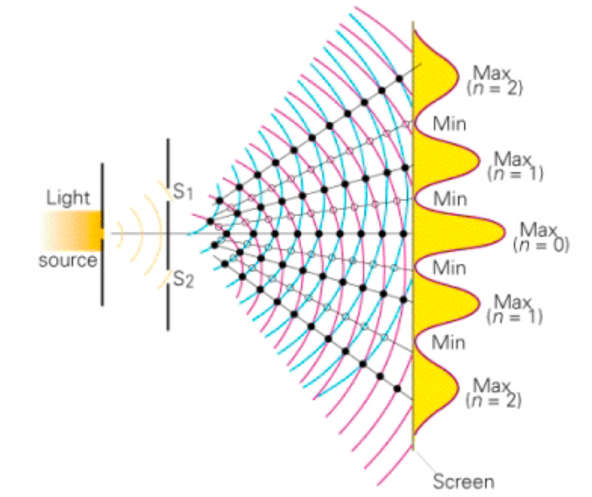
Fourier transform $b_\perp \to q_\perp$,

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

$$\left\{F_B(Y,k_\perp)N_A(Y,\Delta_\perp)\boxed{e^{-i\tilde{b}_\perp\cdot k_\perp}}+F_A(-Y,k_\perp)N_B(-Y,\Delta_\perp)\boxed{e^{-i\tilde{b}_\perp\cdot\Delta_\perp}}\right\},$$

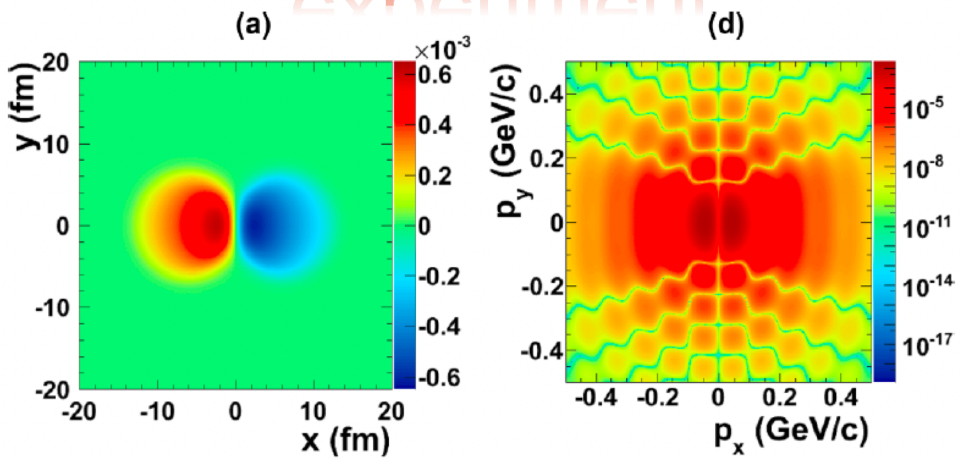
Double slit like interference effect

Classical:

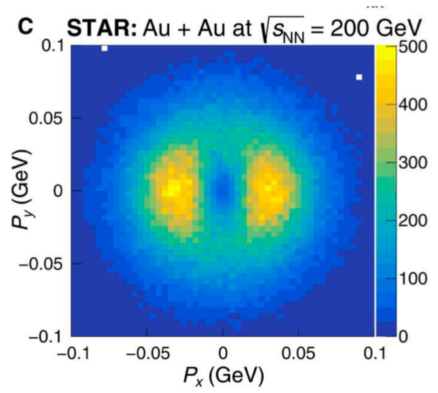


interference effect

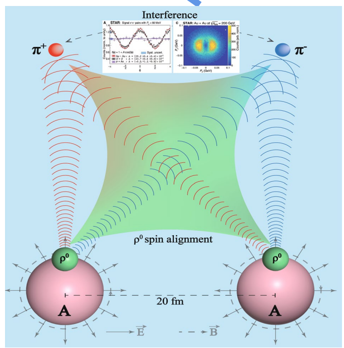
experiment



W. Zha, L. Ruan, Z. Tang, Z. Xu, S. Yang, PRC 99, 061901 (2019)



STAR collaboration, Sci.Adv. 9, eabq3903 (2023)



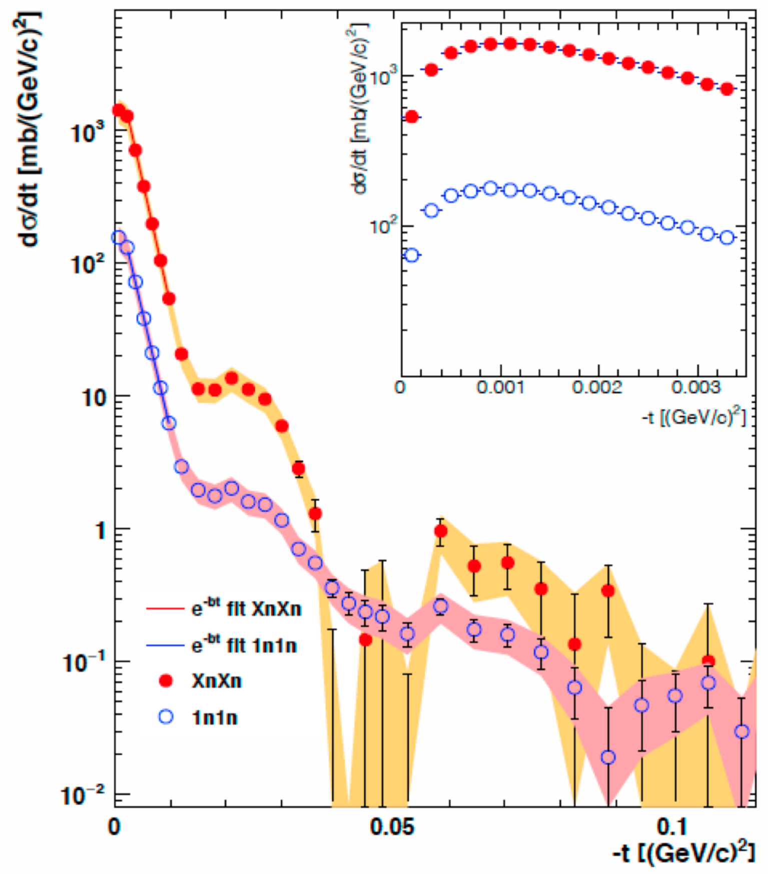
Y.G. Ma, Nucl. Sci. Tech. 34, 16 (2023)

theory

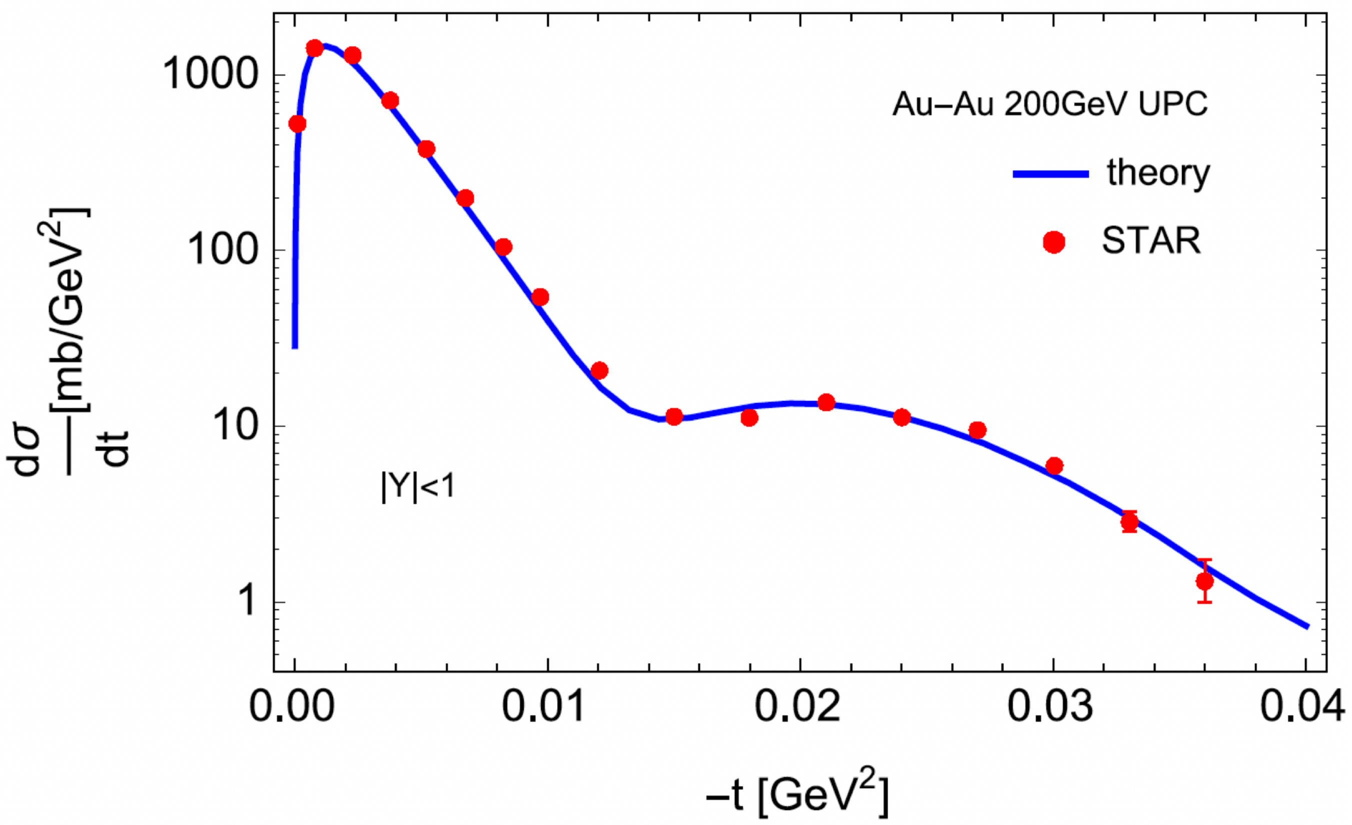
$$
\begin{aligned}
\frac{d\sigma}{d^2q_\perp dY d^2\tilde{b}_\perp} =& \frac{1}{(2\pi)^4}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp+\Delta_\perp-q_\perp)(\epsilon_\perp^{V*}\cdot\hat{k}_\perp)(\epsilon_\perp^{V}\cdot\hat{k}'_\perp)\Big\{\int d^2b_\perp \\
&\times e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\left[T_A(b_\perp)\mathcal{A}_{in}(Y,\D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

H.X. Xing, C. Zhang, J. Zhou and YZ, JHEP10(2020)064

see also W. Zha, J. D. Brandenburg, L.J. Ruan and Z.B. Tang PRD103, 033007(2021)



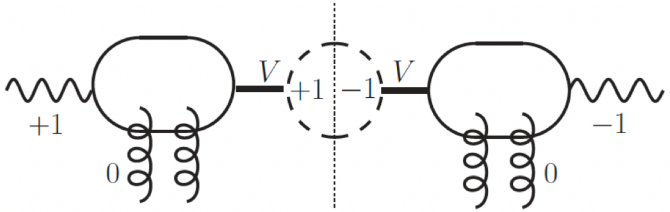
STAR, Phys.Rev.C 96 (2017) 5, 054904



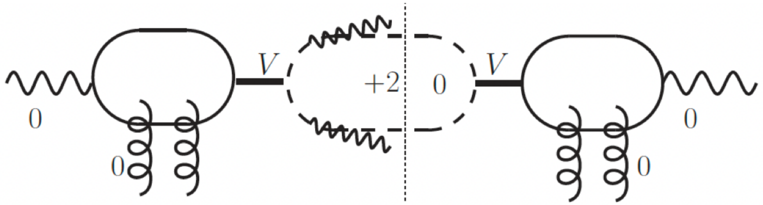
H.X. Xing, C. Zhang, J. Zhou and YZ, JHEP10(2020)064

Azimuthal modulations in diffractive vector meson production in UPC

- Cos2ϕ asymmetry

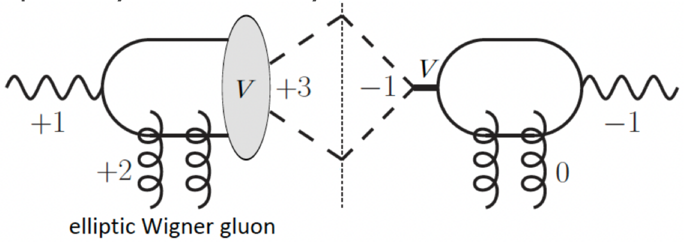


$\langle +1 | -1 \rangle \sim \cos 2\phi$

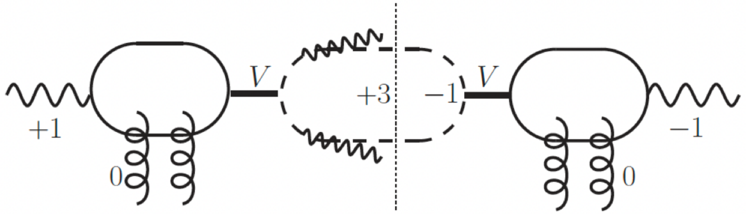


$\langle +2 | 0 \rangle \sim \cos 2\phi$

- Cos4ϕ asymmetry

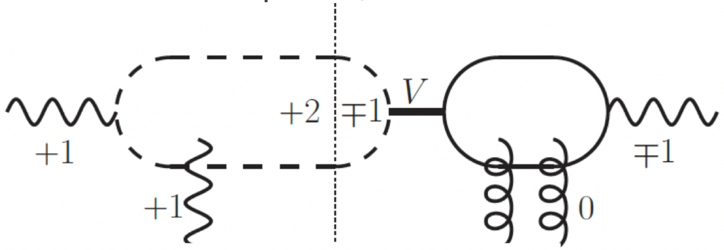


$\langle +3 | -1 \rangle \sim \cos 4\phi$



$\langle +3 | -1 \rangle \sim \cos 4\phi$

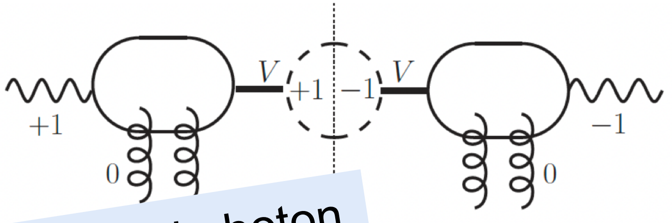
- Cosϕ and Cos3ϕ asymmetries



$\langle +2 | \mp 1 \rangle \sim \cos 3\phi / \cos \phi$

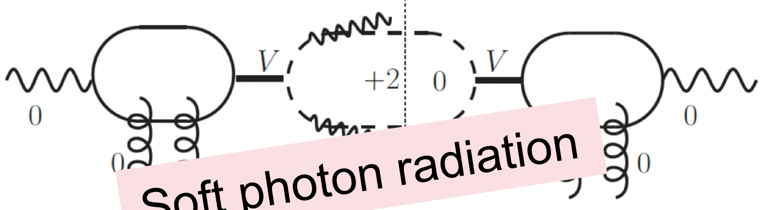
Azimuthal modulations in diffractive vector meson production in UPC

- Cos2ϕ asymmetry



Linearly polarized photon

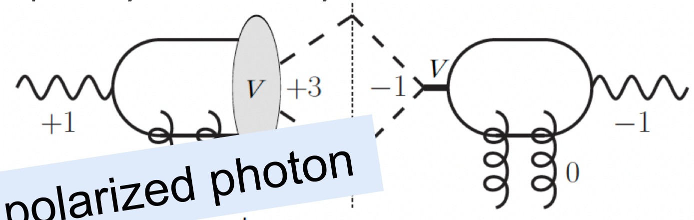
$\ldots 1\rangle \sim \cos 2\phi$



Soft photon radiation

$\langle +2|0\rangle \sim \cos 2\phi$

- Cos4ϕ asymmetry

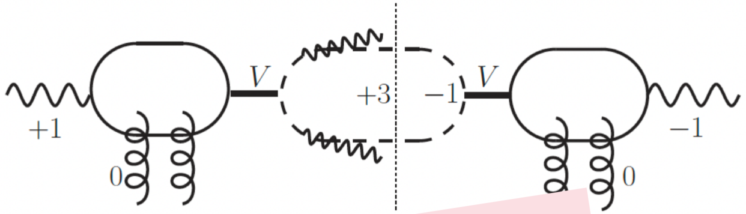


Linearly polarized photon

...ptic Wigner gluon

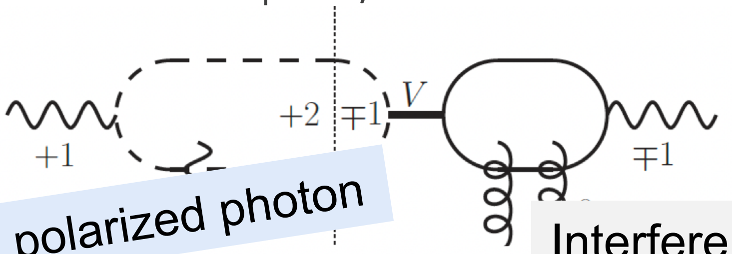
Elliptic Wigner gluon

$\rangle \sim \cos 4\phi$



Soft photon radiation

- Cosϕ and Cos3ϕ asymmetries



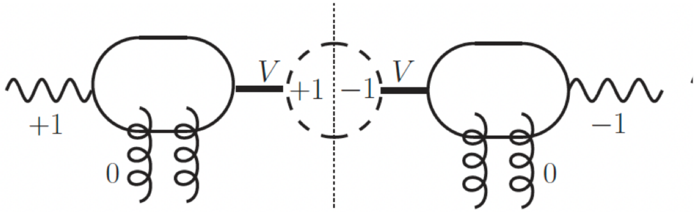
Linearly polarized photon

Interference between diffractive $\rho^0 \to \pi\pi$ and direct $\pi\pi$ production

$\langle +2| \mp 1\rangle \sim \cos 3\phi / \cos\phi$

Azimuthal modulations in diffractive vector meson production in UPC

- Cos2ϕ asymmetry

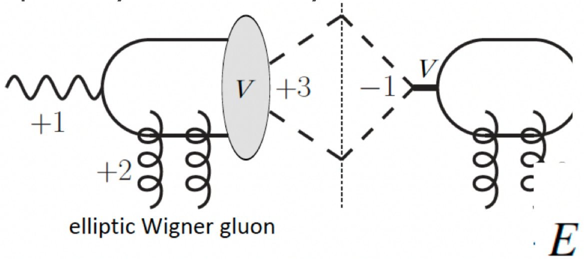


$$\langle +1 | -1 \rangle \sim \cos 2\phi$$

$$N(b_\perp, r_\perp) = 1 - e^{-2\pi B_p A T_A(b_\perp) \mathcal{N}(r_\perp)}$$

$$\mathcal{N}(r_\perp) = 1 - \exp\left[-r_\perp^2 G(x_g, r_\perp)\right]$$

- Cos4ϕ asymmetry

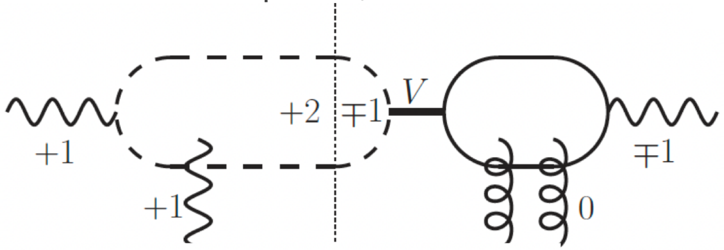


$$\langle +3 | -1 \rangle \sim \cos 4\phi$$

$$N(b_\perp, r_\perp) \approx 1 - \exp\left[-Q_s^2\left(b_\perp^2\right) r_\perp^2/4\right] + E\left(b_\perp^2, r_\perp^2\right) 2 \boxed{\cos(2\phi_b - 2\phi_r)} \frac{Q_s^2\left(b_\perp^2\right) r_\perp^2}{4} e^{-\frac{Q_s^2\left(b_\perp^2\right) r_\perp^2}{4}}$$

Elliptic Wigner gluon

- Cosϕ and Cos3ϕ asymmetries



$$\langle +2 | \mp 1 \rangle \sim \cos 3\phi / \cos\phi$$

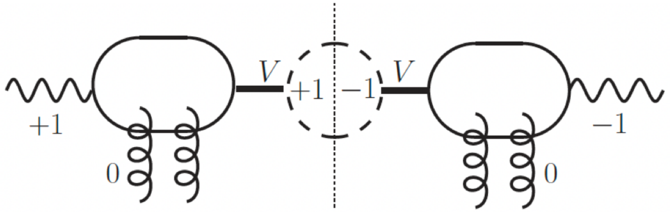
sensitive to nuclear geometry, provide an alternative method to extract transverse spatial gluon distribution.

Azimuthal modulations in diffractive vector meson production in UPC

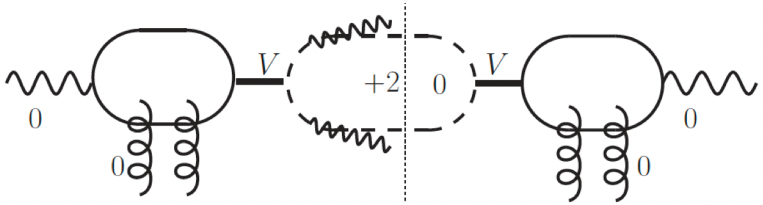
- Cos2ϕ asymmetry, in ρ^0 production, and J/ψ production

H.X. Xing, C. Zhang, J. Zhou and YZ, 2020,JHEP

J. D. Brandenburg, Z. Xu, W. Zha, C. Zhang, J. Zhou,YZ, PRD 106, 074008 (2022)

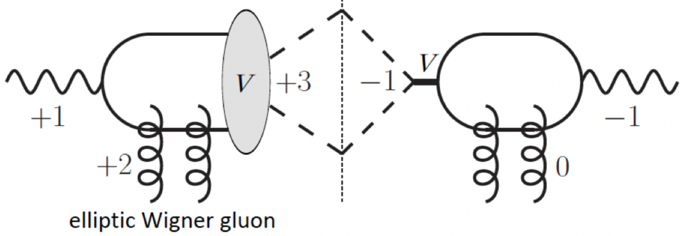


$\langle +1|-1\rangle \sim \cos 2\phi$

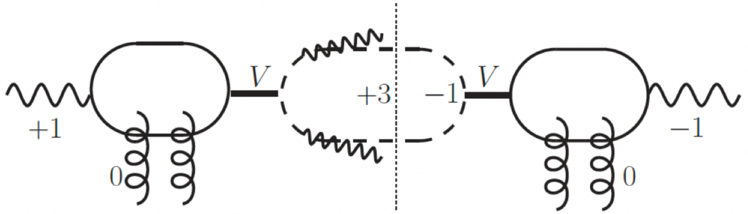


$\langle +2|0\rangle \sim \cos 2\phi$

- Cos4ϕ asymmetry , in ρ^0 production



$\langle +3|-1\rangle \sim \cos 4\phi$

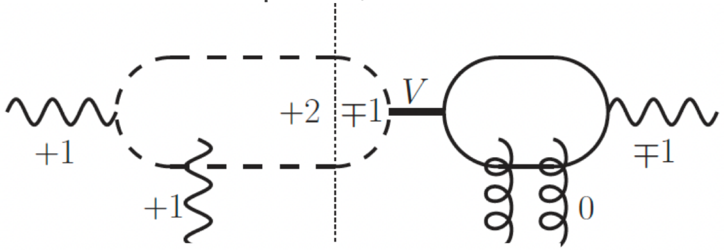


$\langle +3|-1\rangle \sim \cos 4\phi$

Y. Hagiwara, C. Zhang, J. Zhou and YZ, PRD.104, 094021(2021)

- Cosϕ and Cos3ϕ asymmetries, , in diffractive ρ^0 and direct $\pi\pi$ production

Y. Hagiwara, C. Zhang, J. Zhou and YZ, PRD103.074013(2021)

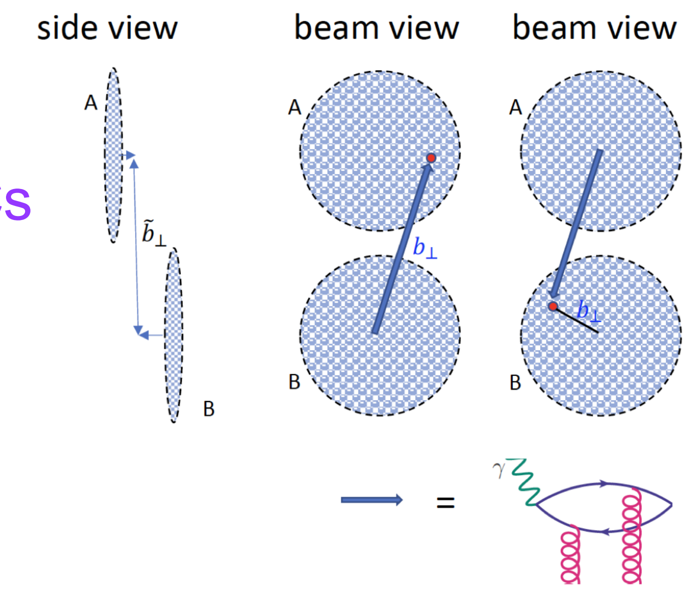


$\langle +2|\mp 1\rangle \sim \cos 3\phi/\cos\phi$

sensitive to nuclear geometry, provide an alternative method to extract transverse spatial gluon distribution.

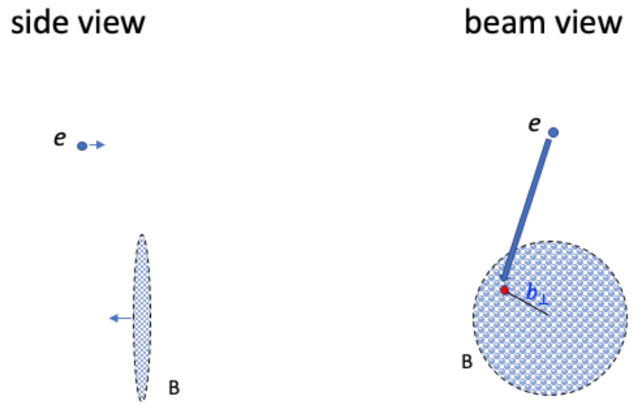
Difference between UPCs and EICs

In UPCs



A,B take turns to be the source of color dipole
double-slit interference in UPCs

In EICs



electron provide the photon,
one-slit interference

Cos2ϕ asymmetry in J/ψ production

In UPCs

$$\frac{d\sigma}{d^2 p_{1\perp} d^2 p_{2\perp} dy_1 dy_2 d^2\tilde{b}_\perp}$$
$$= \frac{\mathcal{C}}{2(2\pi)^7} \frac{24 e^4 e_q^2}{(Q^2 - M^2)^2 + M^2\Gamma^2} \frac{|\phi(0)|^2}{M} \int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp + \Delta_\perp - q_\perp) \left[\hat{k}'_\perp \cdot \hat{k}_\perp - \frac{4(P_\perp \cdot \hat{k}_\perp)(P_\perp \cdot \hat{k}'_\perp)}{M^2} \right]$$
$$\times \left\{ \int d^2 b_\perp e^{i\tilde{b}_\perp \cdot (k'_\perp - k_\perp)} [T_A(b_\perp) \mathcal{A}_{\rm in}(x_2, \Delta_\perp) \mathcal{A}^*_{\rm in}(x_2, \Delta'_\perp) \mathcal{F}(x_1, k_\perp) \mathcal{F}(x_1, k'_\perp) + (A \leftrightarrow B)] \right.$$
$$+ [e^{i\tilde{b}_\perp \cdot (k'_\perp - k_\perp)} \mathcal{A}_{\rm co}(x_2, \Delta_\perp) \mathcal{A}^*_{\rm co}(x_2, \Delta'_\perp) \mathcal{F}(x_1, k_\perp) \mathcal{F}(x_1, k'_\perp)] + [e^{i\tilde{b}_\perp \cdot (\Delta'_\perp - \Delta_\perp)} \mathcal{A}_{\rm co}(x_1, \Delta_\perp) \mathcal{A}^*_{\rm co}(x_1, \Delta'_\perp) \mathcal{F}(x_2, k_\perp) \mathcal{F}(x_2, k'_\perp)]$$
$$\left. + [e^{i\tilde{b}_\perp \cdot (\Delta'_\perp - k_\perp)} \mathcal{A}_{\rm co}(x_2, \Delta_\perp) \mathcal{A}^*_{\rm co}(x_1, \Delta'_\perp) \mathcal{F}(x_1, k_\perp) \mathcal{F}(x_2, k'_\perp)] + [e^{i\tilde{b}_\perp \cdot (k'_\perp - \Delta_\perp)} \mathcal{A}_{\rm co}(x_1, \Delta_\perp) \mathcal{A}^*_{\rm co}(x_2, \Delta'_\perp) \mathcal{F}(x_2, k_\perp) \mathcal{F}(x_1, k'_\perp)] \right\}$$

J. D. Brandenburg, Z. Xu, W. Zha, C. Zhang, J. Zhou and YZ, 2022

Cos2ϕ asymmetry in J/ψ production

In UPCs

the spin correlation between γ and J/ψ result in the azimuthal asymmetry

$$\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2\tilde{b}_\perp}$$
$$=\frac{\mathcal{C}}{2(2\pi)^7}\frac{24e^4e_q^2}{(Q^2-M^2)^2+M^2\Gamma^2}\frac{|\phi(0)|^2}{M}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp\delta^2(k_\perp+\Delta_\perp-q_\perp)\left[\hat{k}'_\perp\cdot\hat{k}_\perp-\frac{4(P_\perp\cdot\hat{k}_\perp)(P_\perp\cdot\hat{k}'_\perp)}{M^2}\right]$$
$$\times\left\{\int d^2b_\perp e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}[T_A(b_\perp)\mathcal{A}_{\rm in}(x_2,\Delta_\perp)\mathcal{A}^*_{\rm in}(x_2,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_1,k'_\perp)+(A\leftrightarrow B)]\right.$$
$$+[e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\mathcal{A}_{\rm co}(x_2,\Delta_\perp)\mathcal{A}^*_{\rm co}(x_2,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_1,k'_\perp)]+[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-\Delta_\perp)}\mathcal{A}_{\rm co}(x_1,\Delta_\perp)\mathcal{A}^*_{\rm co}(x_1,\Delta'_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_2,k'_\perp)]$$
$$\left.+[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-k_\perp)}\mathcal{A}_{\rm co}(x_2,\Delta_\perp)\mathcal{A}^*_{\rm co}(x_1,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_2,k'_\perp)]+[e^{i\tilde{b}_\perp\cdot(k'_\perp-\Delta_\perp)}\mathcal{A}_{\rm co}(x_1,\Delta_\perp)\mathcal{A}^*_{\rm co}(x_2,\Delta'_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_1,k'_\perp)]\right\}$$

J. D. Brandenburg, Z. Xu, W. Zha, C. Zhang, J. Zhou and YZ, 2022

Cos2ϕ asymmetry in J/ψ production

In UPCs

the spin correlation between γ and J/ψ result in the azimuthal asymmetry

$$\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2\tilde{b}_\perp}$$

$$=\frac{\mathcal{C}}{2(2\pi)^7}\frac{24e^4e_q^2}{(Q^2-M^2)^2+M^2\Gamma^2}\frac{|\phi(0)|^2}{M}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp\delta^2(k_\perp+\Delta_\perp-q_\perp)\left[\hat{k}'_\perp\cdot\hat{k}_\perp-\frac{4(P_\perp\cdot\hat{k}_\perp)(P_\perp\cdot\hat{k}'_\perp)}{M^2}\right]$$

$$\times\left\{\int d^2b_\perp e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}[T_A(b_\perp)\mathcal{A}_{\rm in}(x_2,\Delta_\perp)\mathcal{A}^*_{\rm in}(x_2,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_1,k'_\perp)+(A\leftrightarrow B)]\right.$$

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

$$\left.+[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-k_\perp)}\mathcal{A}_{\rm co}(x_2,\Delta_\perp)\mathcal{A}^*_{\rm co}(x_1,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_2,k'_\perp)]+[e^{i\tilde{b}_\perp\cdot(k'_\perp-\Delta_\perp)}\mathcal{A}_{\rm co}(x_1,\Delta_\perp)\mathcal{A}^*_{\rm co}(x_2,\Delta'_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_1,k'_\perp)]\right\}$$

the interference terms ensure the perfect peak and valley structure

J. D. Brandenburg, Z. Xu, W. Zha, C. Zhang, J. Zhou and **YZ**, 2022

Cos2ϕ asymmetry in J/ψ production

In EICs

the spin correlation between γ and J/ψ result in the azimuthal asymmetry

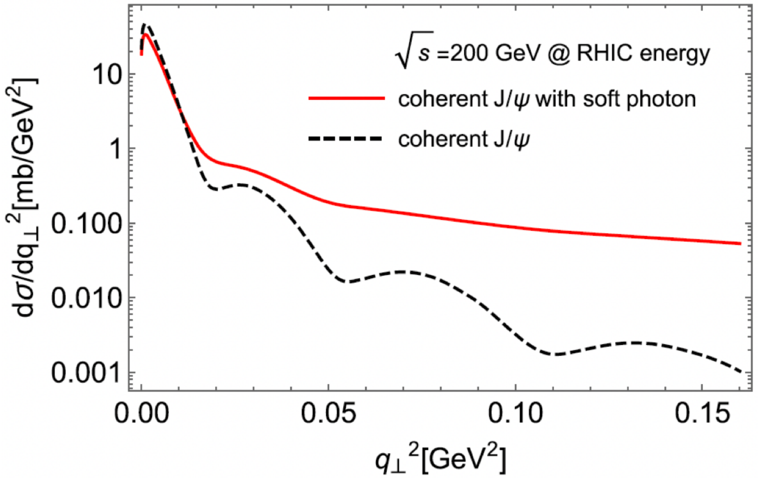
$$\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2\tilde{b}_\perp}$$
$$=\frac{\mathcal{C}}{2(2\pi)^7}\frac{24e^4e_q^2}{(Q^2-M^2)^2+M^2\Gamma^2}\frac{|\phi(0)|^2}{M}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp\delta^2(k_\perp+\Delta_\perp-q_\perp)\left[\hat{k}'_\perp\cdot\hat{k}_\perp-\frac{4(P_\perp\cdot\hat{k}_\perp)(P_\perp\cdot\hat{k}'_\perp)}{M^2}\right]$$
$$\times\left\{\int d^2b_\perp e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}[T_A(b_\perp)\mathcal{A}_{\rm in}(x_2,\Delta_\perp)\mathcal{A}^*_{\rm in}(x_2,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_1,k'_\perp)+(A\leftrightarrow B)]\right.$$
$$+[e^{i\tilde{b}_\perp\cdot(k'_\perp-k_\perp)}\mathcal{A}_{\rm co}(x_2,\Delta_\perp)\mathcal{A}^*_{\rm co}(x_2,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_1,k'_\perp)]+[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-\Delta_\perp)}\mathcal{A}_{\rm co}(x_1,\Delta_\perp)\mathcal{A}^*_{\rm co}(x_1,\Delta'_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_2,k'_\perp)]$$
$$\left.+[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp-k_\perp)}\mathcal{A}_{\rm co}(x_2,\Delta_\perp)\mathcal{A}^*_{\rm co}(x_1,\Delta'_\perp)\mathcal{F}(x_1,k_\perp)\mathcal{F}(x_2,k'_\perp)]+[e^{i\tilde{b}_\perp\cdot(k'_\perp-\Delta_\perp)}\mathcal{A}_{\rm co}(x_1,\Delta_\perp)\mathcal{A}^*_{\rm co}(x_2,\Delta'_\perp)\mathcal{F}(x_2,k_\perp)\mathcal{F}(x_1,k'_\perp)]\right\}$$

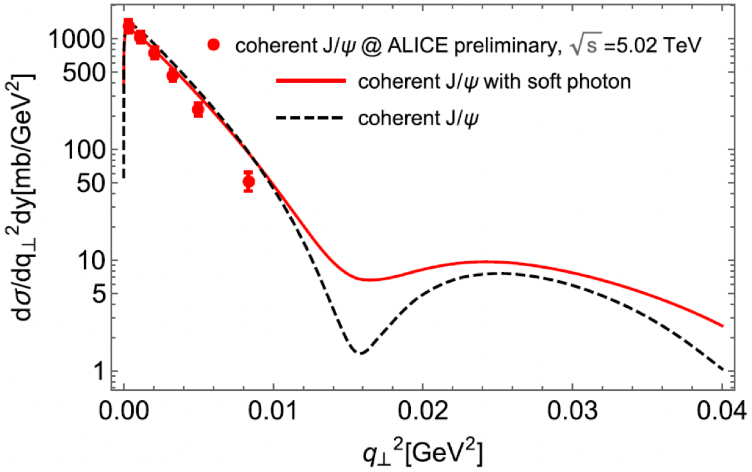
the behavior will differ from that in UPC

J. D. Brandenburg, Z. Xu, W. Zha, C. Zhang, J. Zhou and YZ, 2022

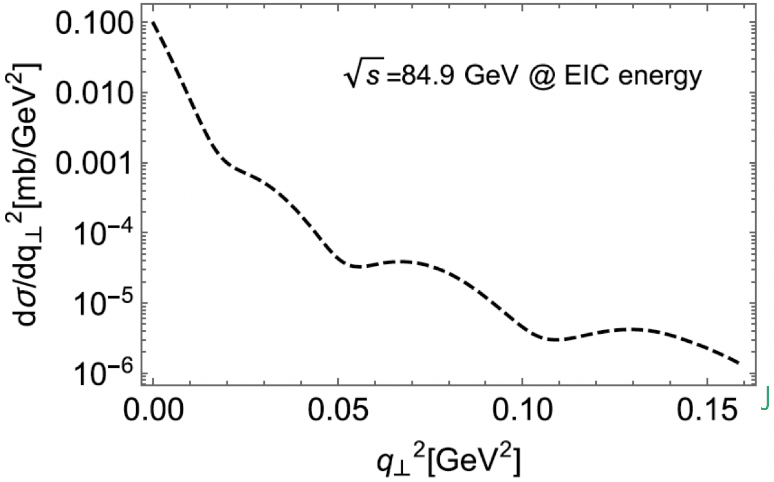
Cross section in J/ψ production

In UPCs





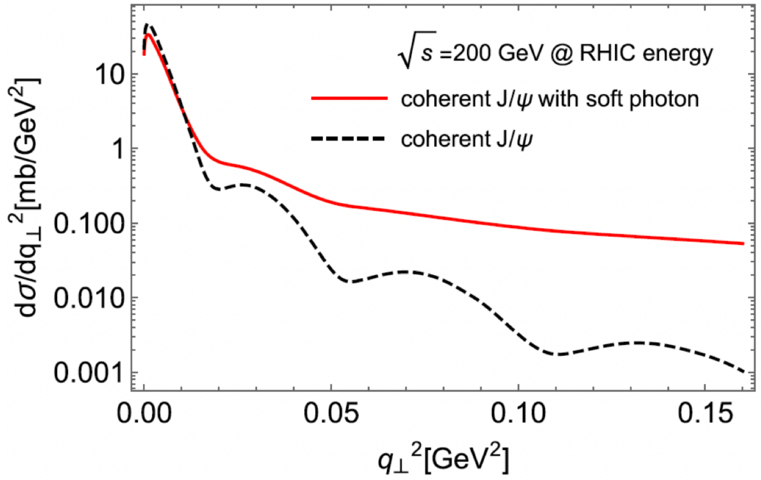
In EICs

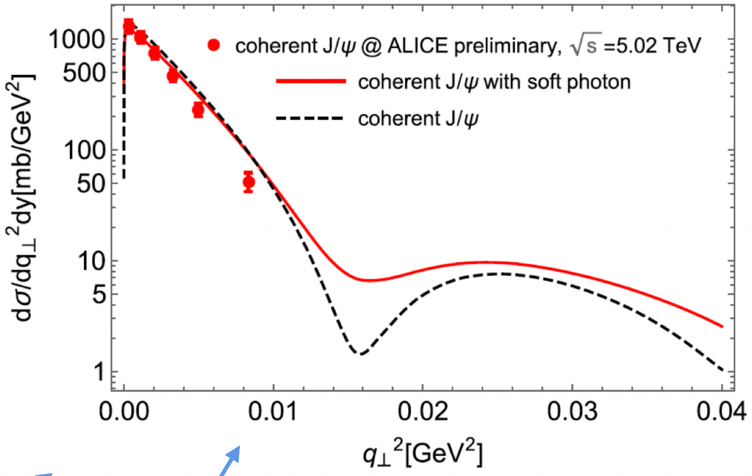


J. D. Brandenburg, Z. Xu, W. Zha, C. Zhang, J. Zhou and YZ, 2022

Cross section in J/ψ production

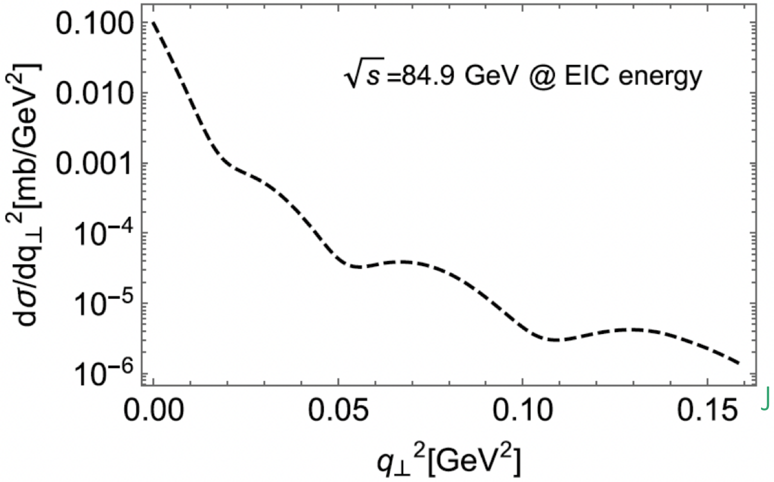
In UPCs





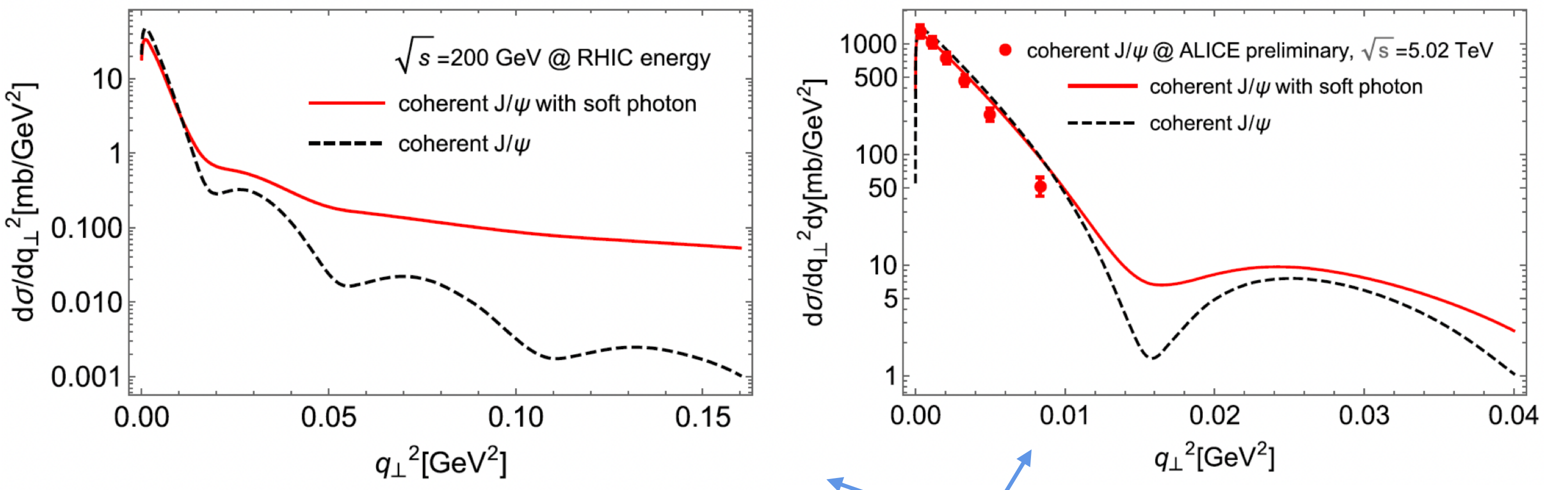
Double-slit interference

In EICs



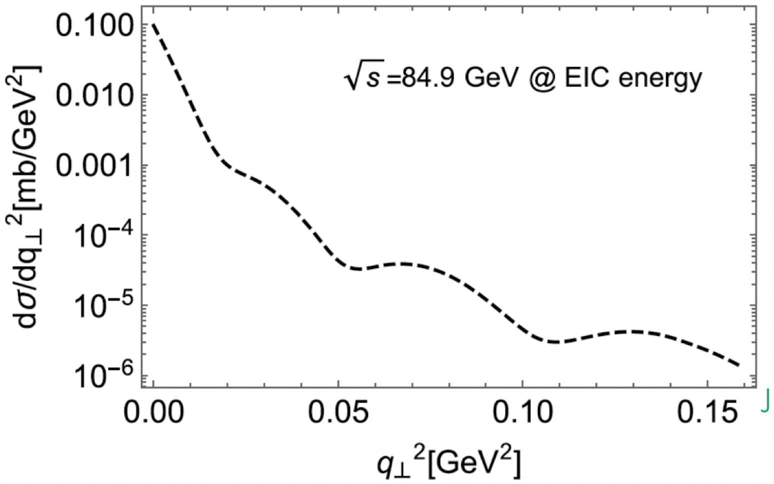
J. D. Brandenburg, Z. Xu, W. Zha, C. Zhang, J. Zhou and YZ, 2022

In UPCs



Double-slit interference

In EICs

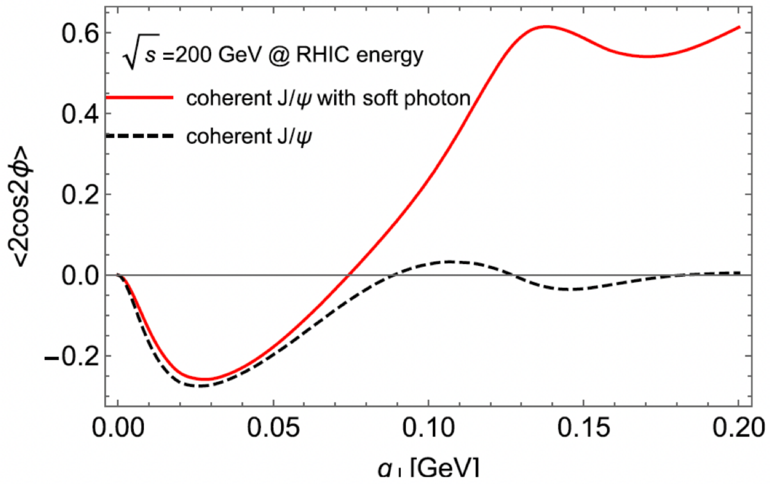


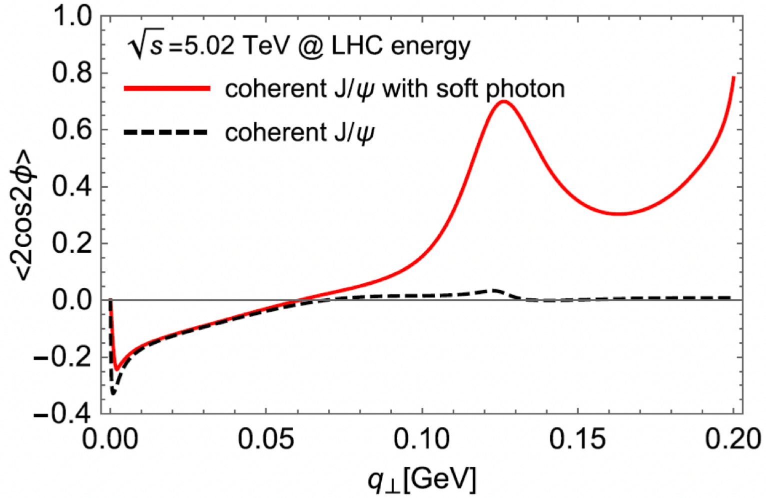
One-slit interference

J. D. Brandenburg, Z. Xu, W. Zha, C. Zhang, J. Zhou and YZ, 2022

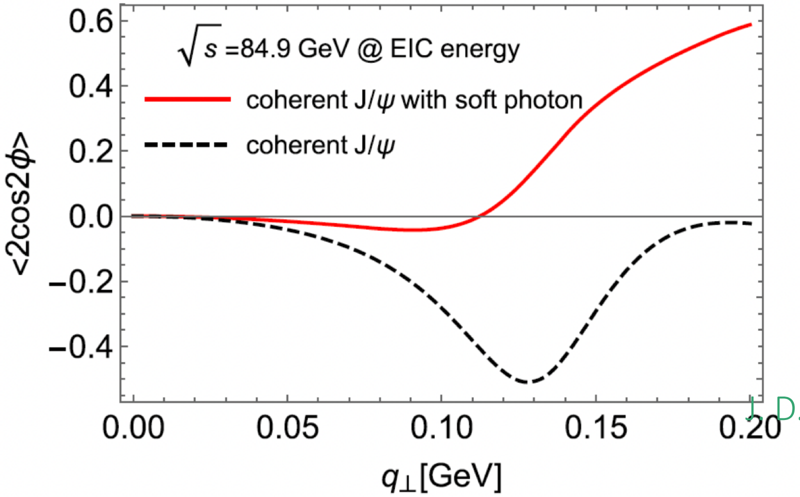
Cos2ϕ asymmetry in J/ψ production

In UPCs





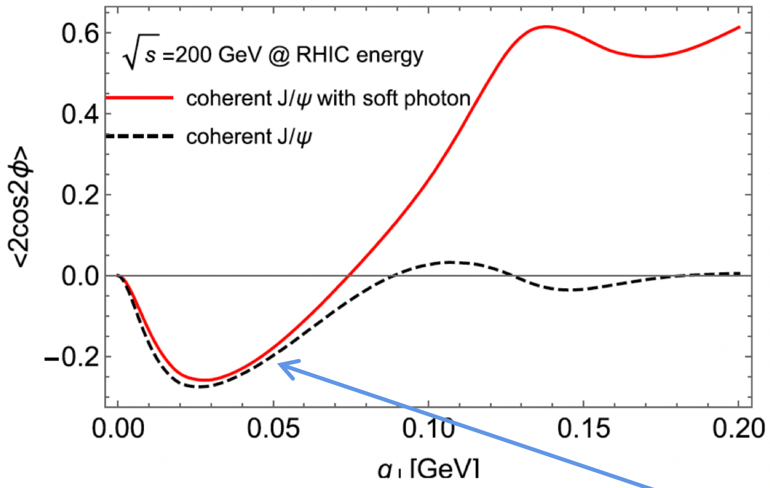
In EICs

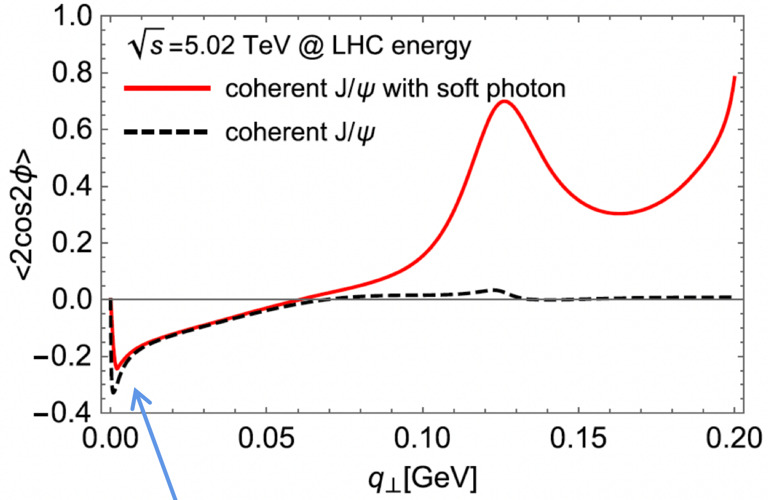


J. D. Brandenburg, Z. Xu, W. Zha, C. Zhang, J. Zhou and YZ, 2022

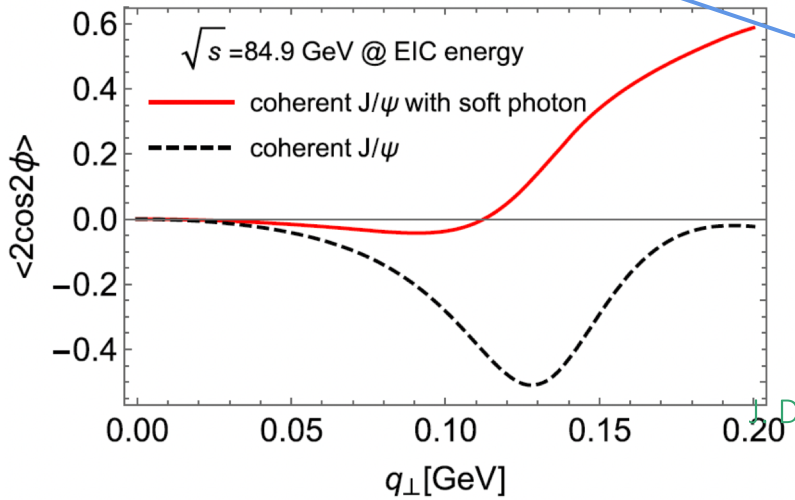
Cos2ϕ asymmetry in J/ψ production

In UPCs





In EICs



Double-slit interference effect

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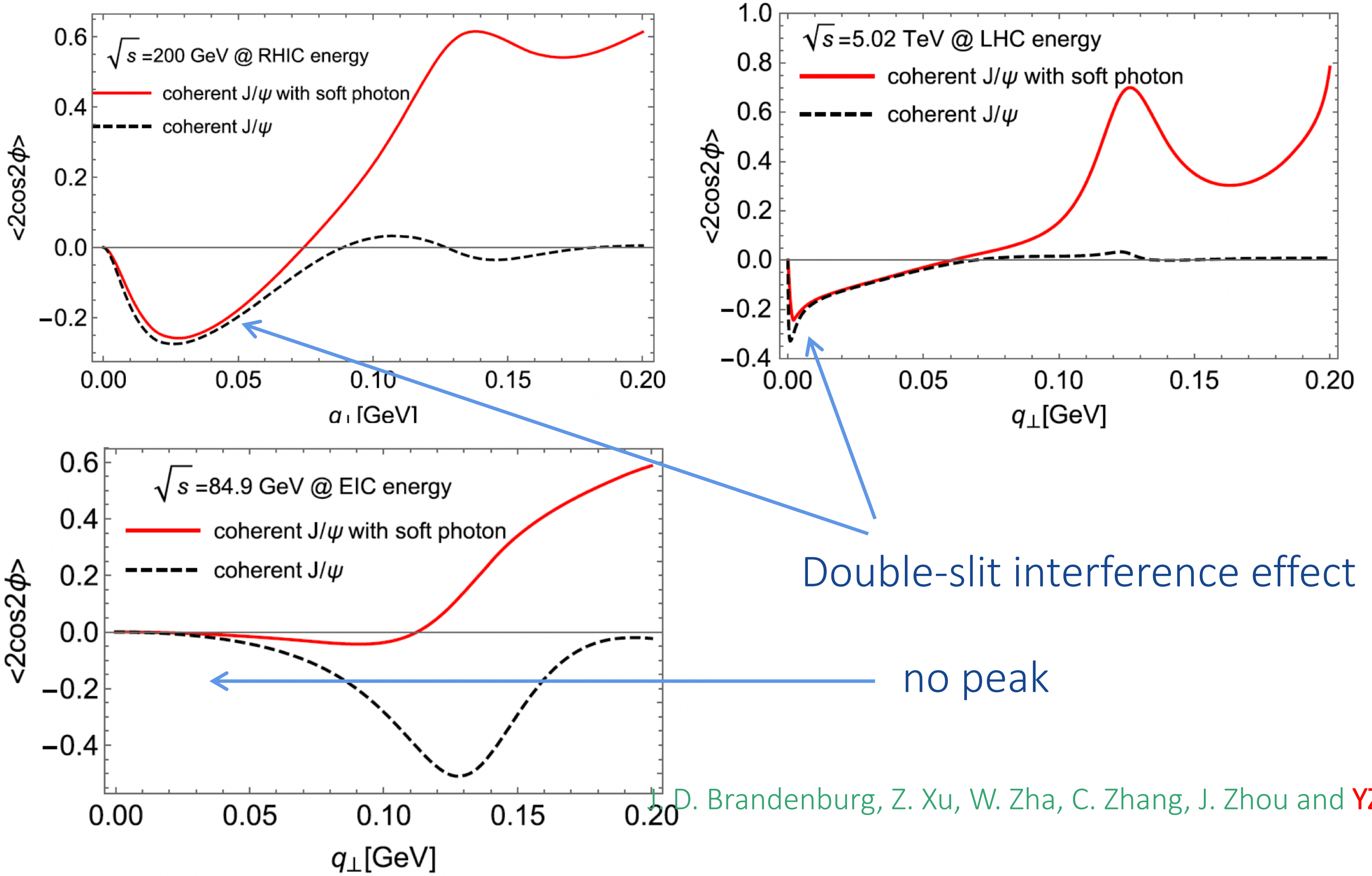
Cos2ϕ asymmetry in J/ψ production

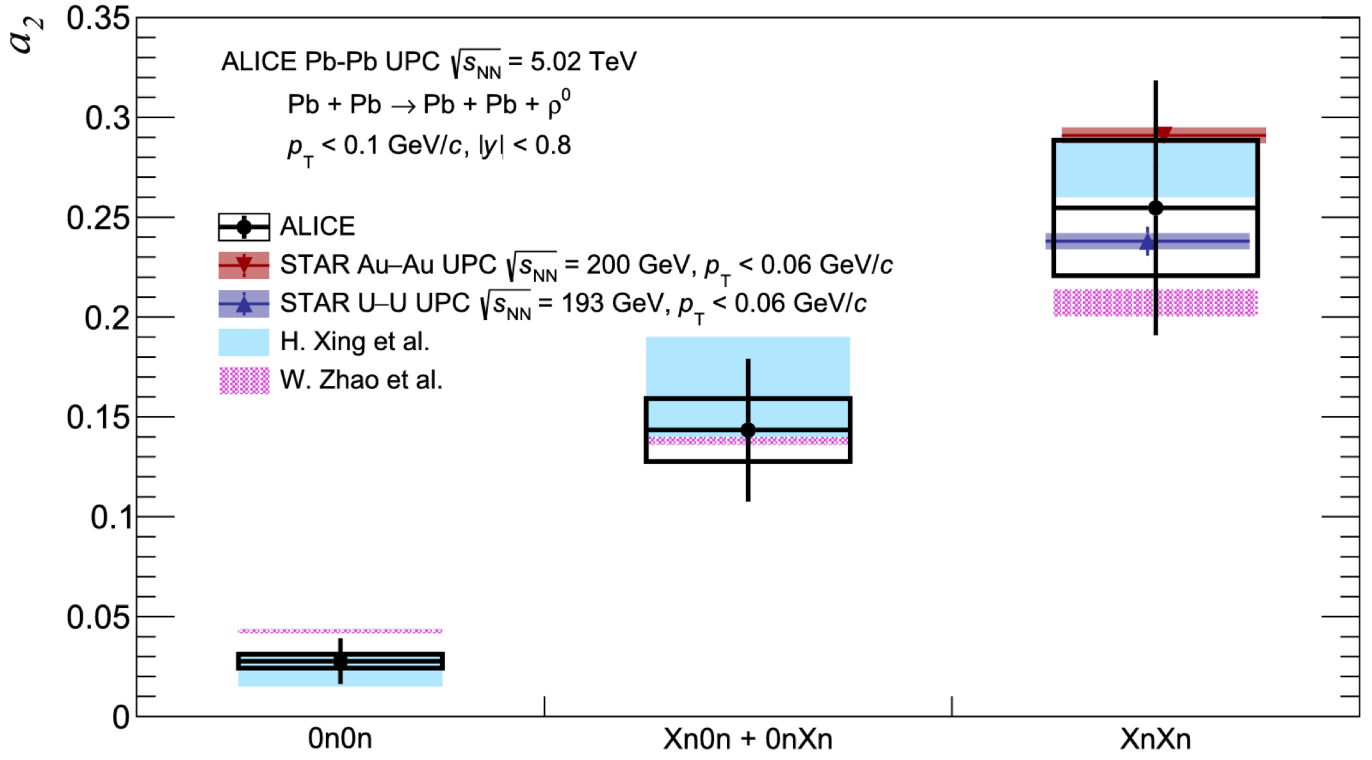
In UPCs

In EICs



J. D. Brandenburg, Z. Xu, W. Zha, C. Zhang, J. Zhou and YZ, 2022

cos2ϕ asymmetry in ρ production, ALICE measurement vs. theory

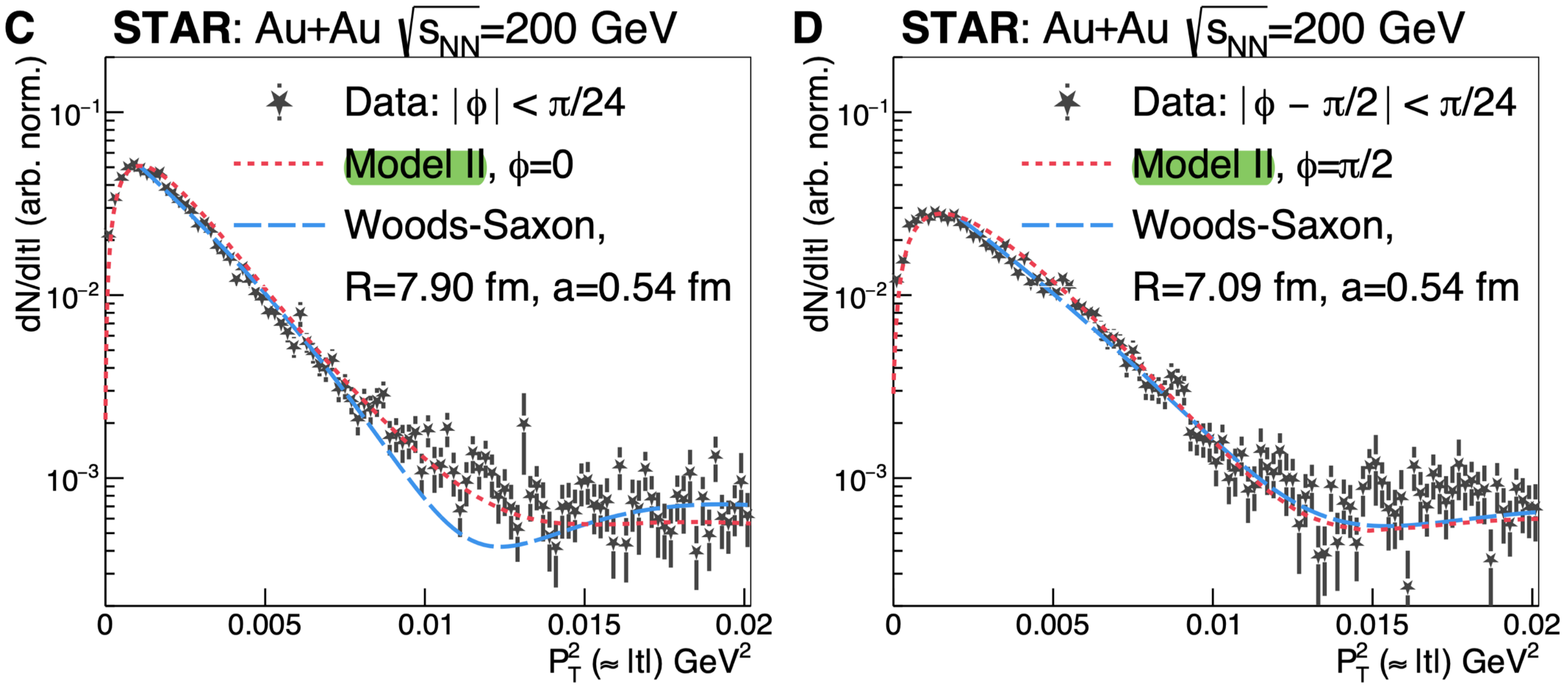


ALICE: PLB 858 (2024) 139017

SDU-SCNU group: Hongxi Xing, Cheng Zhang, Jian Zhou, Ya-Jin Zhou *JHEP* 10 (2020) 064

BNL group: Heikki Mäntysaari, Farid Salazar, Björn Schenke, Chun Shen, Wenbin Zhao *Phys.Rev.C* 109 (2024) 2, 024908

cos2ϕ asymmetry in ρ production, STAR measurement vs. theory

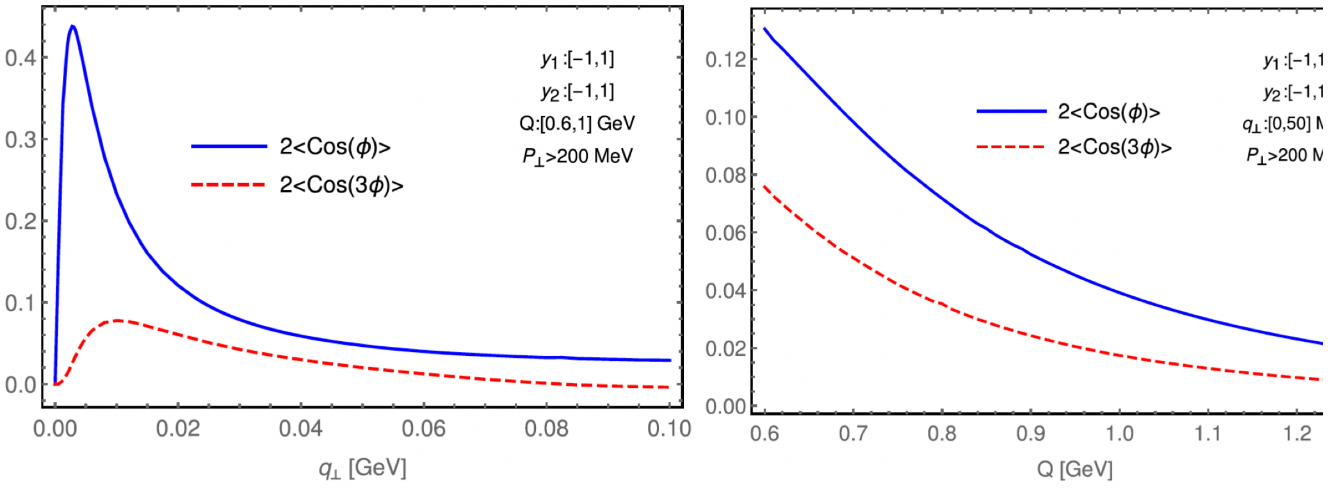


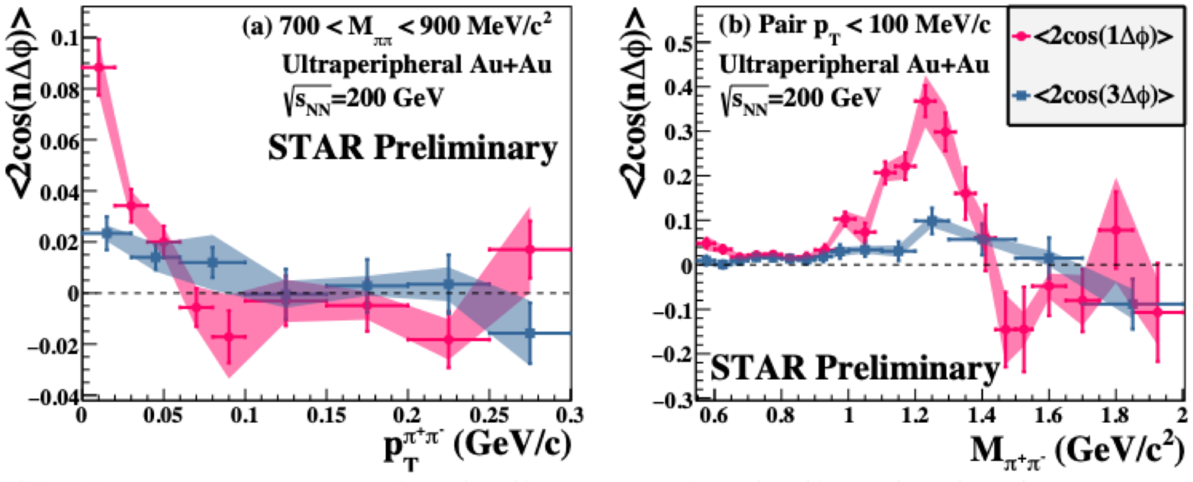
STAR, Sci.Adv. 9, eabq3903 (2023)

H.X. Xing, C. Zhang, J. Zhou and YZ, 2020,JHEP

cosϕ and cos3ϕ asymmetry in ρ production, STAR measurement vs. theory

- interference between diffractive $\rho^0 \to \pi\pi$ and direct $\pi\pi$ production

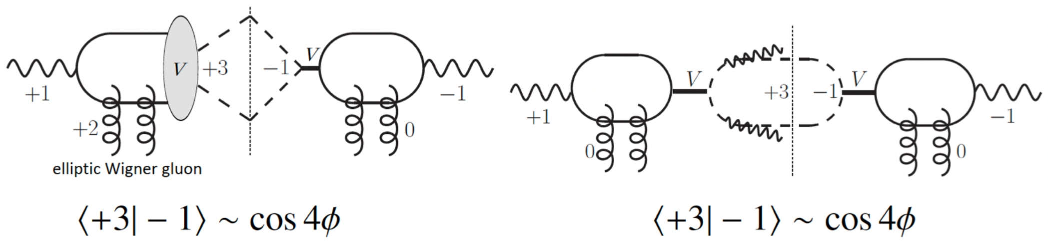


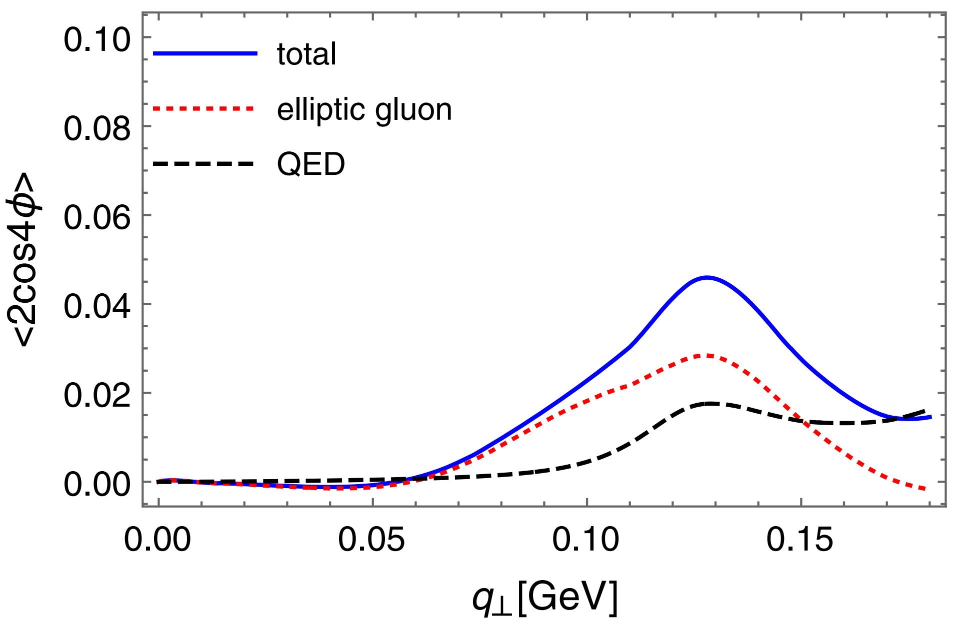


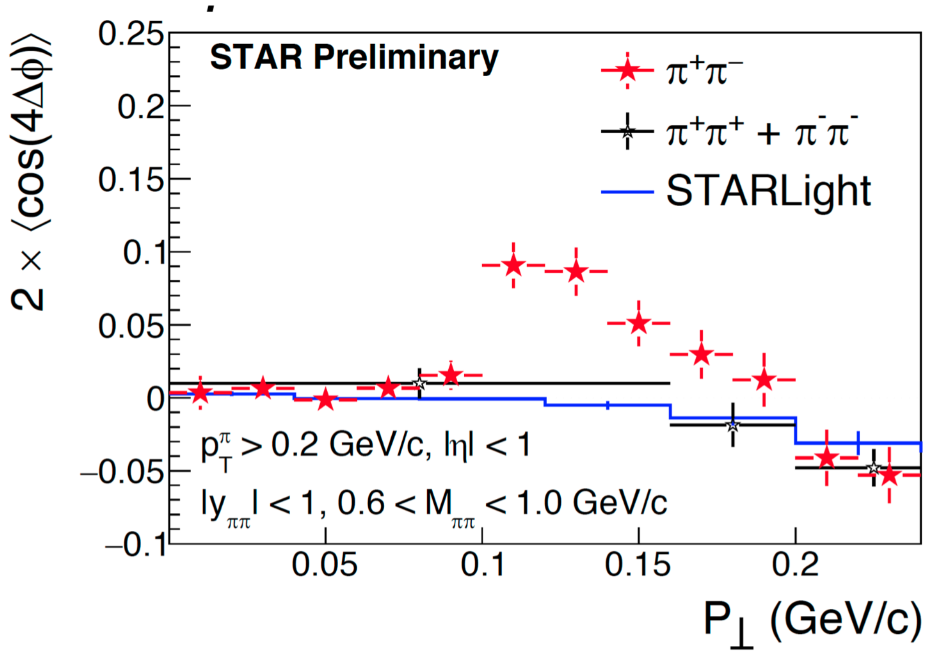
Y. Hagiwara, C. Zhang, J. Zhou and YZ, PRD103.074013(2021)

Chi Yang and Samuel's talk on UPC2025 in Finland

cos4ϕ asymmetry in ρ production, STAR measurement vs. theory







- Both elliptic gluon Wigner distribution and final-state soft photon radiation contribute to cos4ϕ asymmetry.

Summary

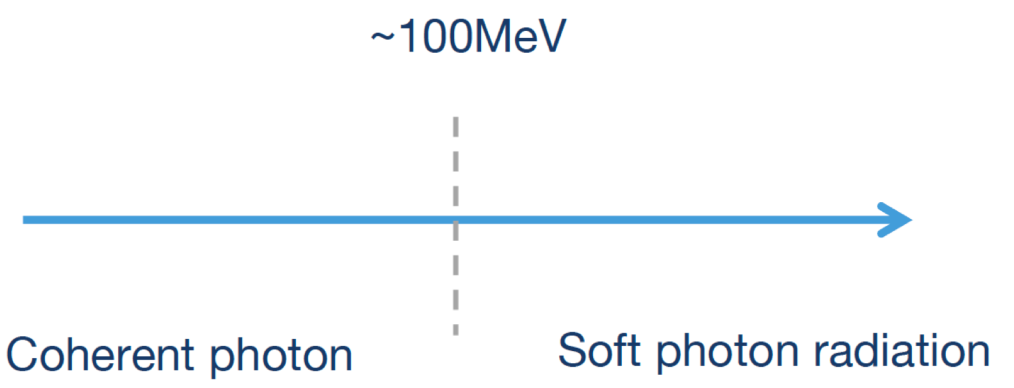
- The EPA photons are linearly polarized, which can be used to probe nuclear structure in diffractive photo-nuclear processes in UPCs and EICs, and provide a method to extract spatial gluon distribution.
- Quite a few measurements at LHC and RHIC have been made, awaiting for the extraction of corresponding gluon distributions.
- The diffractive patterns predicted in UPCs and EICs differ significantly, both in their cross sections and azimuthal asymmetries. Measuring and comparing these observables in UPCs and EICs can provide deeper insights into gluon tomography.

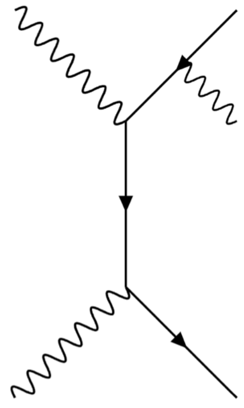
Thank you for your attention!

- backups

Soft photon radiation

the recoiled momentum of the lepton also cause azimuthal anisotropy





~1/R~30MeV

$$\mathrm{Sud}_{1-\mathrm{loop}}(r_\perp) = \frac{\alpha_e}{\pi} ln \frac{Q^2}{m^2} ln \frac{P_\perp^2}{\mu_r^2}$$

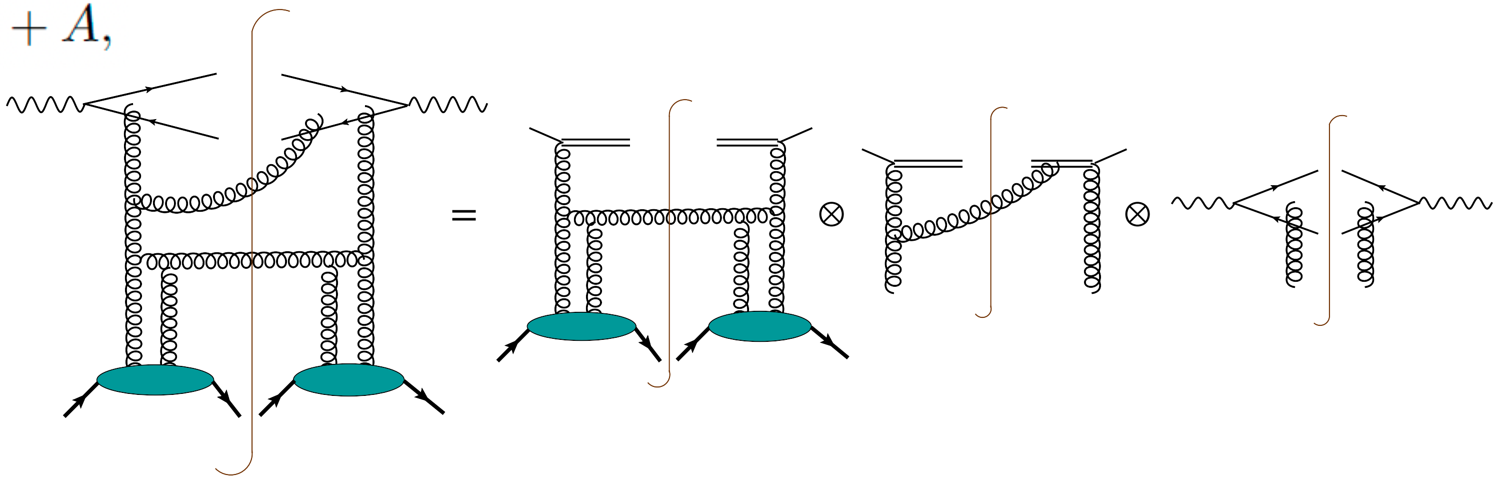
$$\frac{d\sigma(q_\perp)}{d\mathcal{P}.\mathcal{S}.} = \int d^2 q'_\perp \frac{d\sigma_0(q'_\perp)}{d\mathcal{P}.\mathcal{S}.} S(q_\perp - q'_\perp)$$

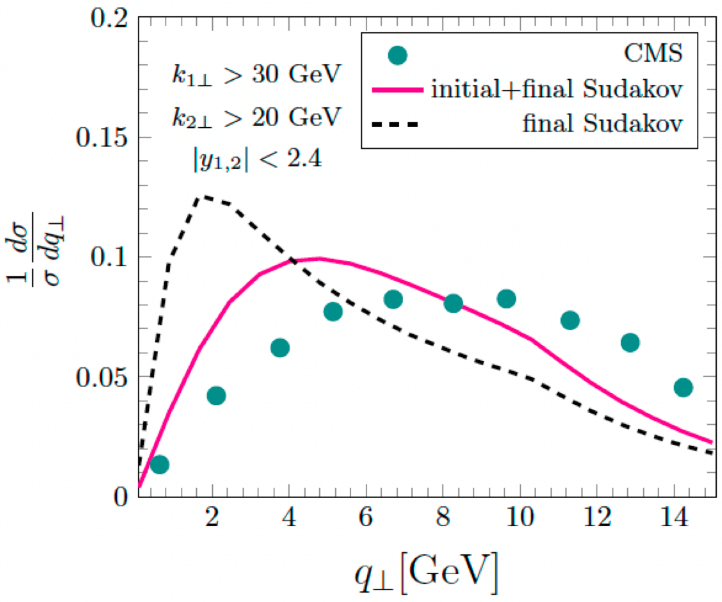
$$S(l_\perp) = \delta(l_\perp) + \frac{\alpha_e}{\pi^2 l_\perp^2} \{c_0 + 2c_2 \boxed{\cos 2\phi} + 2c_4 \boxed{\cos 4\phi} + \ldots\}$$

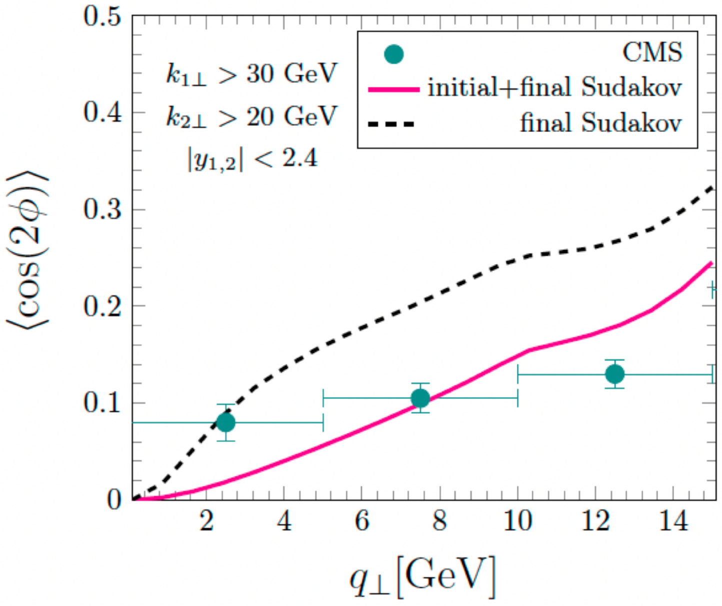
Y. Hatta, B.W. Xiao, F. Yuan and J. Zhou, PRL126, 142001(2021) and PRD104, 054037(2021)

Diffractive di-jet production in UPC

$$\gamma(x_\gamma p) + A \rightarrow q(k_1) + \bar{q}(k_2) + g(l) + A,$$







D.Y. Shao, Y. Shi, C. Zhang, J. Zhou and YZ, JHEP07(2024)189

Initial state radiation reduce the azimuthal asymmetry, could provide novel insights into the mechanisms of diffractive di-jet production