Probing gluon Orbital Angular Momentum through Exclusive dijet production at the EIC

QCD with Electron Ion Collider (QEIC) 11

Shohini Bhattacharya

Brookhaven National Laboratory

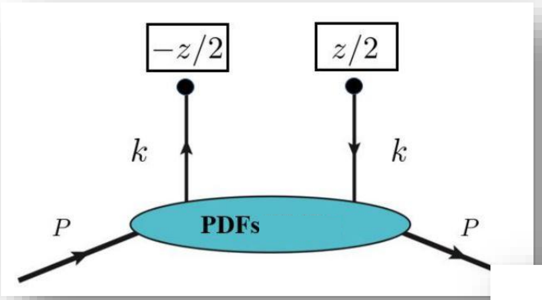
19 December 2022

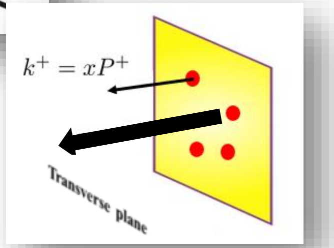
Quantum Chromodynamics (QCD): Non-perturbative functions

Parton motion

Nucleon motion

Snapshots of the nucleons





Parton Distribution Functions

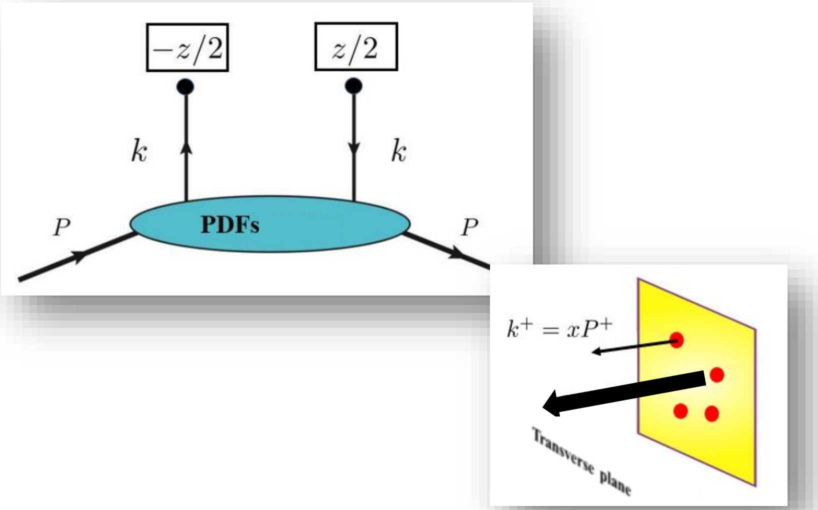
PDFs (x)

Quantum Chromodynamics (QCD): Non-perturbative functions

Parton motion

Nucleon motion

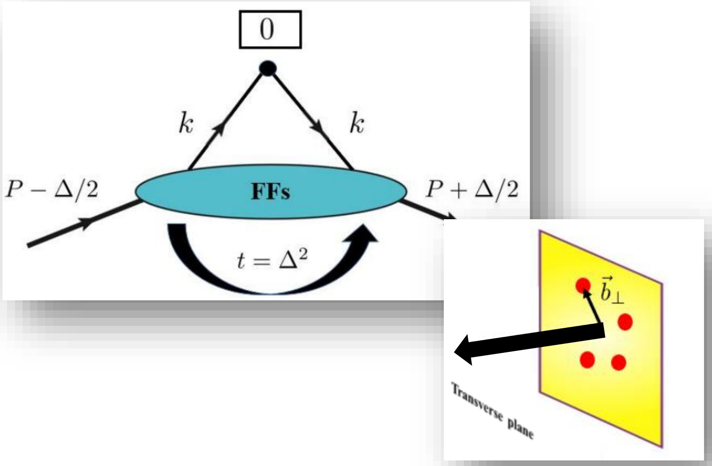
Snapshots of the nucleons



Form Factors

PDFs (x)

FFs (Δ)



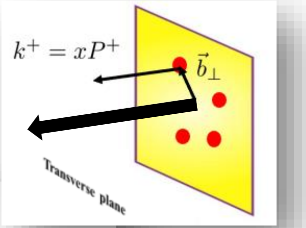
Quantum Chromodynamics (QCD): Non-perturbative functions

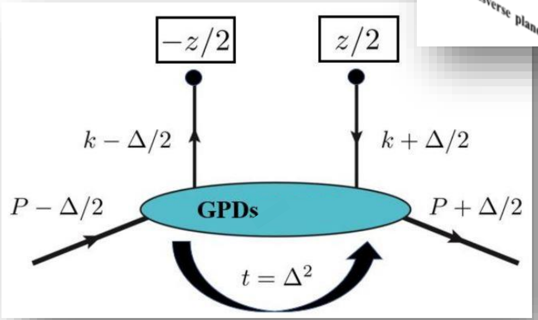
Parton motion

Nucleon motion

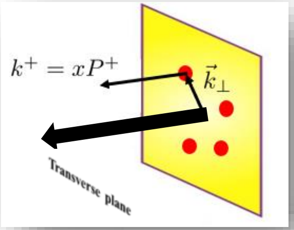
Snapshots of the nucleons

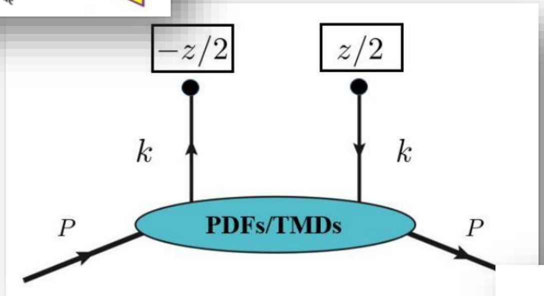
Generalized Parton Distributions

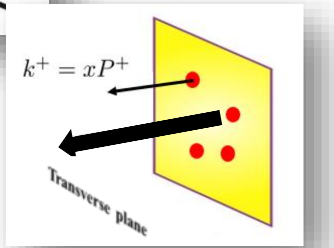




Transverse Momentum-dependent Distributions







TMDs $(x, \vec{k}_\perp)$

GPDs (x, Δ)

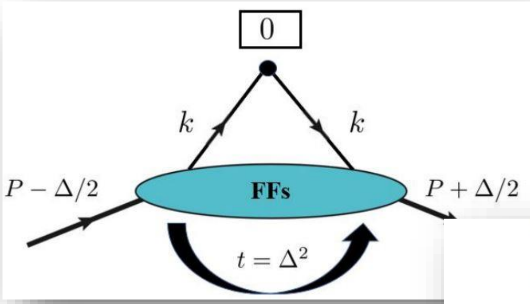
$\int d^2\vec{k}_\perp$

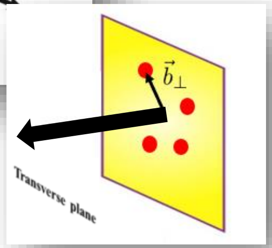
$\Delta = 0$

$\int dx$

PDFs (x)

FFs (Δ)





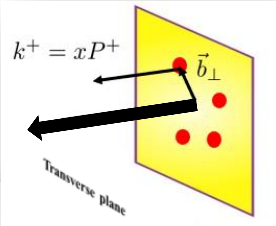
Quantum Chromodynamics (QCD): Non-perturbative functions

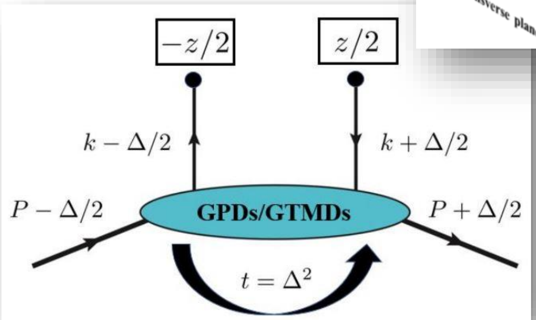
Parton motion

Nucleon motion

Snapshots of the nucleons

Generalized Transverse Momentum-dependent Distributions





GTMDs $(x, \vec{k}_\perp, \Delta)$

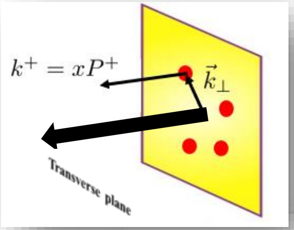
$\Delta = 0$ → **TMDs** $(x, \vec{k}_\perp)$

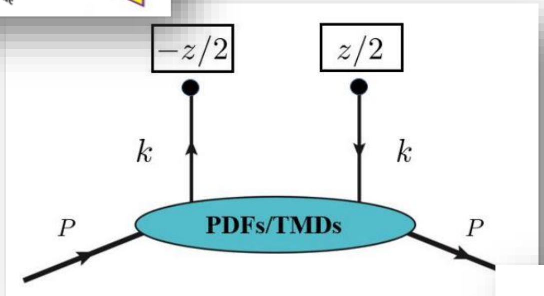
$\int d^2\vec{k}_\perp$ → **GPDs** (x, Δ)

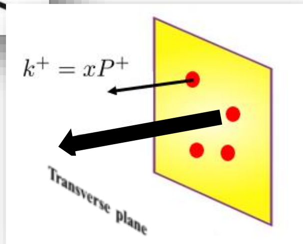
TMDs $(x, \vec{k}_\perp)$ → $\int d^2\vec{k}_\perp$ → **PDFs** (x)

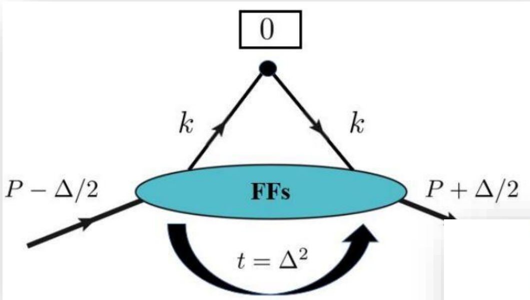
GPDs (x, Δ) → $\Delta = 0$ → **PDFs** (x)

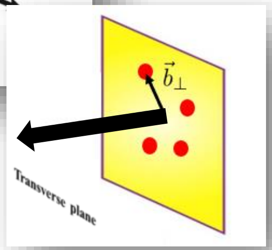
GPDs (x, Δ) → $\int dx$ → **FFs** (Δ)





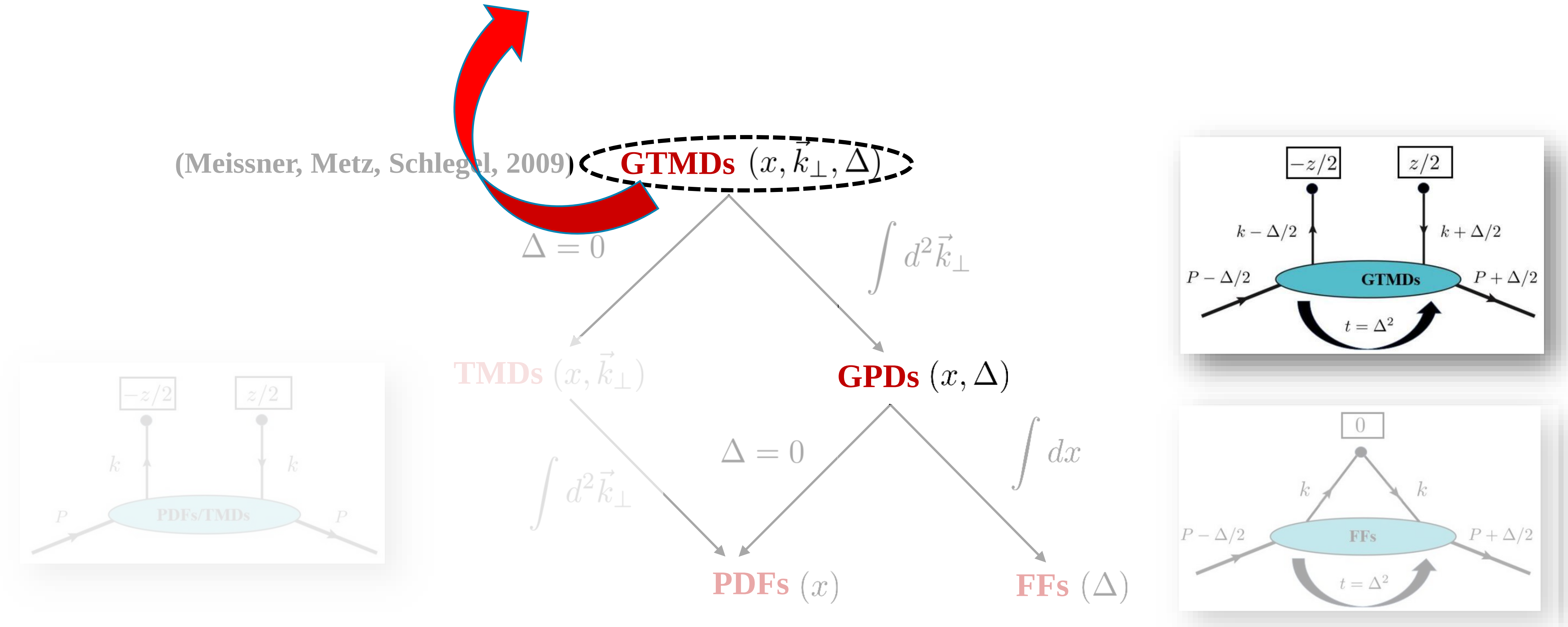






Outline

1. **Progress in the last 6 years**



Outline

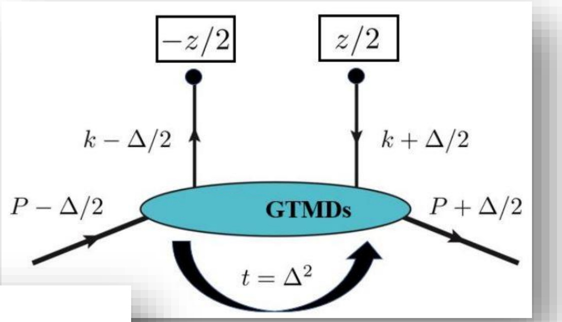
1. **Progress in the last 6 years**

2. **Accessing Orbital Angular Momentum (OAM) through GTMDs**

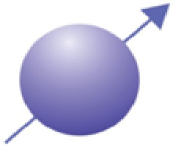
(Meissner, Metz, Schlegel, 2009) **GTMDs** $(x, \vec{k}_\perp, \Delta)$

$\Delta = 0$ $\int d^2\vec{k}_\perp$

$\Delta = 0$



An incomplete story:

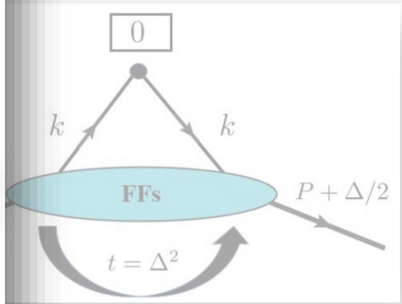


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

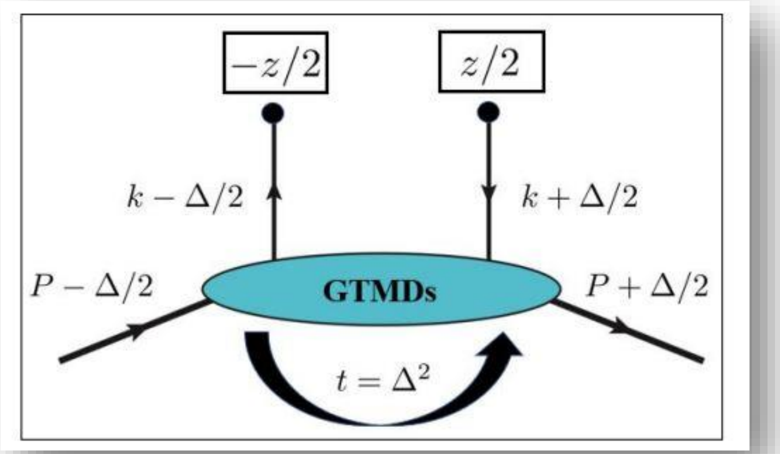
Best known | How well do we know? | ?? | Another major scientific goal of the EIC

Quark helicity | **Gluon helicity** | **OAM of quarks & gluons**

s s



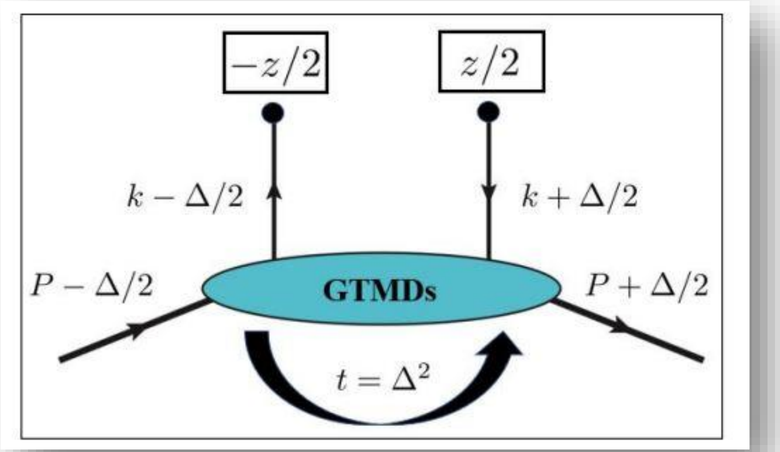
Generalized Transverse Momentum dependent Distributions (GTMDs)



Definition of a (quark) GTMD correlator:

$$W^{q[\Gamma]}_{\lambda,\lambda'} = \frac{1}{2}\int \frac{dz^- d^2\vec{z}_\perp}{(2\pi)^3}\, e^{ik.z} < p', \lambda' | \bar{\psi}^q(-\tfrac{z}{2})\,\Gamma\,\mathcal{W}(-\tfrac{z}{2},\tfrac{z}{2})\psi^q(\tfrac{z}{2})|p,\lambda > \Big|_{z^+=0}$$

Generalized Transverse Momentum dependent Distributions (GTMDs)



Definition of a (quark) GTMD correlator:

$$W^{q[\Gamma]}_{\lambda,\lambda'} = \frac{1}{2}\int \frac{dz^- d^2\vec{z}_\perp}{(2\pi)^3}\, e^{ik.z} < p', \lambda' | \bar{\psi}^q(-\tfrac{z}{2})\,\Gamma\, \mathcal{W}(-\tfrac{z}{2}, \tfrac{z}{2})\psi^q(\tfrac{z}{2})|p, \lambda > \Big|_{z^+=0}$$

Parameterization of correlator through GTMDs:

$$\boxed{X^q(x, \xi, \vec{k}^2_\perp, \vec{\Delta}^2_\perp, \vec{k}_\perp \cdot \vec{\Delta}_\perp)}$$

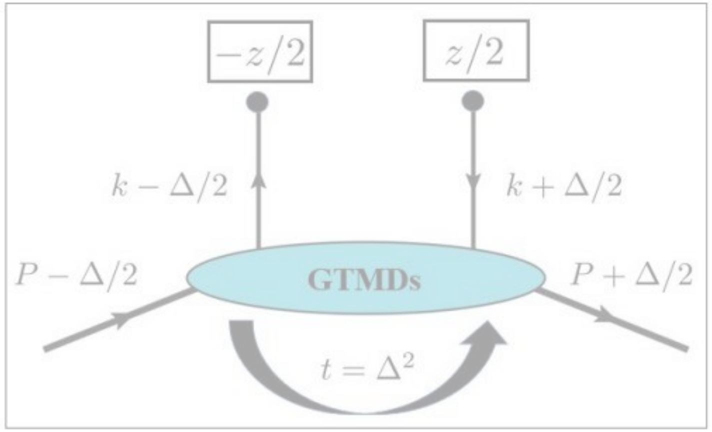
$\Delta_\perp$: **transverse momentum transfer to nucleon**

x : **"average" longitudinal momentum fraction of quark**

$\vec{k}_\perp$: **"average" transverse momentum of quark**

$\xi = \frac{p^+ - p'^+}{p^+ + p'^+} = -\frac{\Delta^+}{2P^+}$: **longitudinal momentum transfer to nucleon**

Generalized Transverse Momentum dependent Distributions (GTMDs)



Definition of a (quark) GTMD correlator:

$$W^{q[\Gamma]}_{\lambda,\lambda'} = \frac{1}{2}\int \frac{dz^- d^2\vec{z}_\perp}{(2\pi)^3}\, e^{ik.z} < p', \lambda' | \bar{\psi}^q(-\tfrac{z}{2})\,\Gamma\,\mathcal{W}(-\tfrac{z}{2}, \tfrac{z}{2})\psi^q(\tfrac{z}{2})|p,\lambda > \Big|_{z^+=0}$$

General results:

i. **<u>16</u> leading-twist GTMDs for quarks (Meissner, Metz, Schlegel, arXiv: 0906.5323)**

ii. **<u>16</u> leading-twist GTMDs for gluons (Lorcé, Pasquini, arXiv: 1307.4497)**

iii. **GTMDs are complex functions**

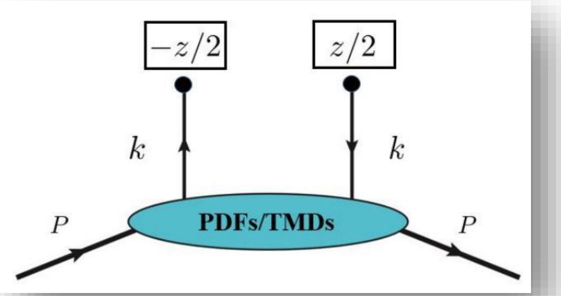
Why are GTMDs interesting?

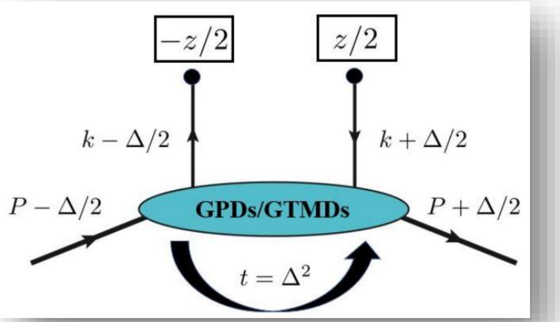
Why are GTMDs interesting?

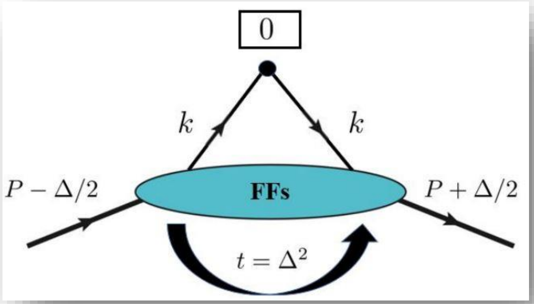
1) GTMDs are the "Mother Functions"

(Meissner, Metz, Schlegel, 2009)

$$
\begin{tikzcd}
 & & \textbf{GTMDs}\ (x, \vec{k}_\perp, \Delta) \arrow[dl, "\Delta = 0"'] \arrow[dr, "\int d^2\vec{k}_\perp"] & & \\
 & \textbf{TMDs}\ (x, \vec{k}_\perp) \arrow[dr, "\int d^2\vec{k}_\perp"'] & & \textbf{GPDs}\ (x, \Delta) \arrow[dl, "\Delta = 0"'] \arrow[dr, "\int dx"] & \\
 & & \textbf{PDFs}\ (x) & & \textbf{FFs}\ (\Delta)
\end{tikzcd}
$$







Why are GTMDs interesting?

1) **GTMDs are the "Mother Functions"**

2) **GTMDs contain physics beyond TMDs & GPDs**

(Meissner, Metz, Schlegel, 2009)

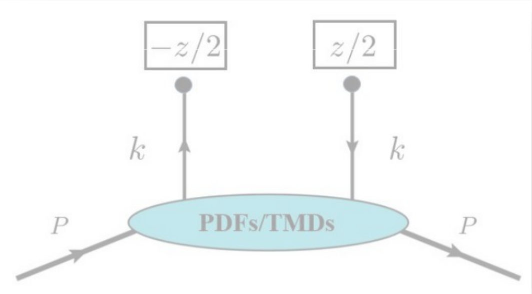
GTMDs $(x, \vec{k}_\perp, \Delta)$

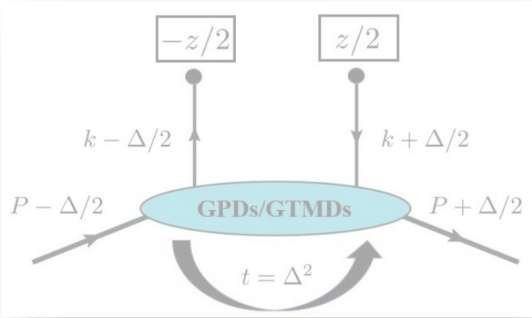
$\Delta = 0$ $\qquad$ $\int d^2\vec{k}_\perp$

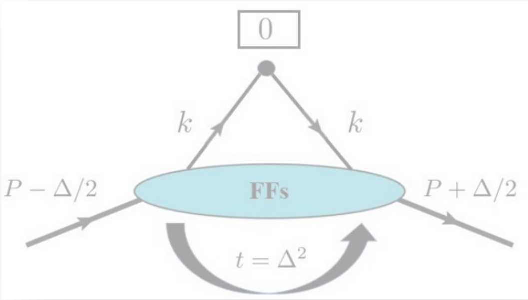
TMDs $(x, \vec{k}_\perp)$ $\qquad$ **GPDs** (x, Δ)

$\int d^2\vec{k}_\perp$ $\qquad$ $\Delta = 0$ $\qquad$ $\int dx$

PDFs (x) $\qquad$ **FFs** (Δ)







Why are GTMDs interesting?

3) Connection to Wigner functions **Wigner Distribution** $(x, \vec{k}_\perp, \vec{b}_\perp)$ **(Belitsky, Ji, Yuan, 2003)**

2-D Fourier Transform $(\vec{\Delta}_\perp)$ $\uparrow$ $\xi = 0$

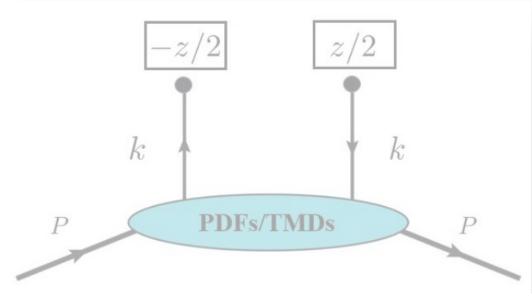
(Meissner, Metz, Schlegel, 2009) **GTMDs** $(x, \vec{k}_\perp, \Delta)$

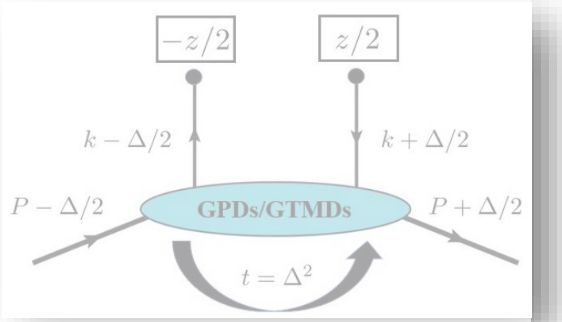
$\Delta = 0$ $\int d^2\vec{k}_\perp$

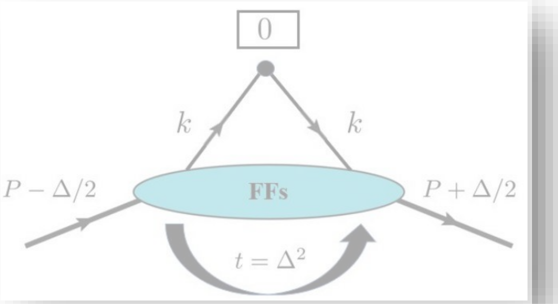
TMDs $(x, \vec{k}_\perp)$ **GPDs** (x, Δ)

$\int d^2\vec{k}_\perp$ $\Delta = 0$ $\int dx$

PDFs (x) **FFs** (Δ)







Why are GTMDs interesting?

3) Connection to Wigner functions

Wigner Distribution $(x, \vec{k}_\perp, \vec{b}_\perp)$ **(Belitsky, Ji, Yuan, 2003)**

Wigner distributions in NRQM
(Wigner, 1932)

- **Calculate from wave-functions:**

$$W(x,k) = \int \frac{dx'}{2\pi} e^{-ikx'} \psi(x + \frac{x'}{2})\, \psi^*(x - \frac{x'}{2})$$

- **Connection with probability densities & observables:**

- **Position-space probability:**

$$|\psi(x)|^2 = \int dk\, W(x,k)$$

- **Expectation value of observables:**

$$< O > = \int dx \int dk\; O(x,k)\, W(x,k)$$

r Transform

$\perp)$

$\xi = 0$

GTMDs $(x, \vec{k}_\perp, \Delta)$

$= 0$

$\int d^2\vec{k}_\perp$

$c, \vec{k}_\perp)$

GPDs (x, Δ)

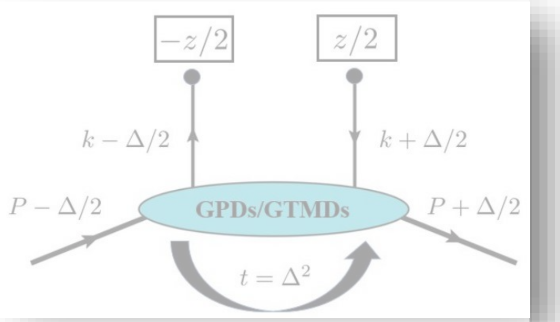
$\Delta = 0$

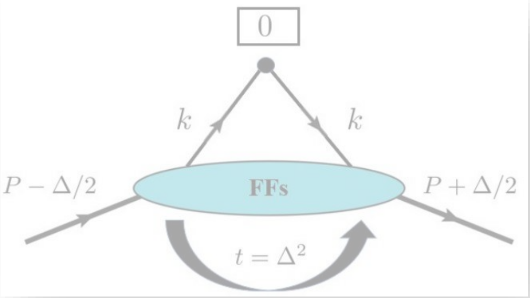
$\int dx$

$d^2\vec{k}_\perp$

PDFs (x)

FFs (Δ)





Why are GTMDs interesting?

3) **Connection to Wigner functions** **Wigner Distribution** $(x, \vec{k}_\perp, \vec{b}_\perp)$ **(Belitsky, Ji, Yuan, 2003)**

Wigner distributions in NRQM
(Wigner, 1932)

❑ **Calculate from wave-functions:**

$$W(x,k) = \int \frac{dx'}{2\pi} e^{-ikx'} \psi(x + \frac{x'}{2})\, \psi^*(x - \frac{x'}{2})$$

❑ **Connection with probability densities & observables:**

- **Position-space probability:**

$$|\psi(x)|^2 = \int dk\, W(x,k)$$

- **Expectation value of observables:**

$$< O > = \int dx \int dk\; O(x,k)\, W(x,k)$$

r Transform

$\perp)$

$\xi = 0$

GTMDs $(x, \vec{k}_\perp, \Delta)$

$= 0$

$x, \vec{k}_\perp)$

GP

$\Delta = 0$

$d^2\vec{k}_\perp$

PDFs (x)

Wigner distributions in parton physics
(Belitsky, Ji, Yuan, 2003)

❑ **Defined through F.T. of GTMD correlator:**

$$W^{[\Gamma]}(x, \vec{k}_\perp, \vec{b}_\perp)$$

❑ **Application:**

Orbital Angular Momentum (OAM)

Intuitive definition of OAM

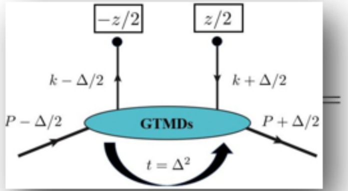
$$< L_z^q > = \int dx \int d^2\vec{k}_\perp \int d^2\vec{b}_\perp (\vec{b}_\perp \times \vec{k}_\perp)\Big|_z\, W_L^{q[\gamma^+]}(x, \vec{k}_\perp, \vec{b}_\perp)$$

(Lorcé, Pasquini, 2011 / Hatta, 2011 / Ji, Xiong, Yuan, 2012)

Why are GTMDs interesting?

3) Connection

Parameterization of a GTMD correlator (Meissner, Metz, Schlegel, arXiv: 0906.5323):



$$= \frac{1}{2M}\,\bar{u}(p',\lambda')\left[F_{1,1} + \frac{i\sigma^{i+}k_\perp^i}{P^+}F_{1,2} + \frac{i\sigma^{i+}\Delta_\perp^i}{P^+}F_{1,3} + \frac{i\sigma^{ij}k_\perp^i\Delta_\perp^j}{M^2}F_{1,4}\right]u(p,\lambda)$$

…uan, 2003)

Wigner distr…
(Wign…

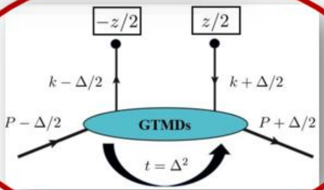
…istributio…s in parton physics
…elitsky, … Yuan, 2003)

…lator:

❑ Calculate from wave-functions:

$$W(x,k) = \int \frac{dx'}{2\pi} e^{-ikx'}\,\psi(x+\frac{x'}{2})\,\psi^*(x-\frac{x'}{2}$$

$$L_z^q = \int dx \int d^2k_\perp d^2b_\perp (\vec{b}_\perp \times \vec{k}_\perp)_z \left\{ \int e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} \right.$$



❑ Connection with probability densities & observables:

- **Position-space probability:**

$$|\psi(x)|^2 = \int dk\, W(x,k)$$

- **Expectation value of observables:**

$$< O > = \int dx \int dk\; O(x,k)\, W(x,k)$$

$x, \vec{k}_\perp)$

GP…

$d^2\vec{k}_\perp$

$\Delta = 0$

PDFs (x)

Orbital Angular Momentum (OAM)

Intuitive definition … OAM

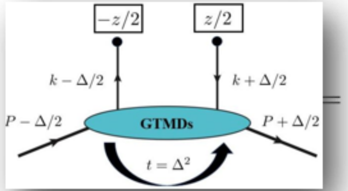
$$< L_z^q > = \int dx \int d^2\vec{k}_\perp \int d^2\vec{b}_\perp (\vec{b}_\perp \times \vec{k}_\perp)\Big|_z\; W_L^{q[\gamma^+]}(x,\vec{k}_\perp,\vec{b}_\perp)$$

(Lorcé, Pasquini, 2011 / Hatta, 2011 /
Ji, Xiong, Yuan, 2012)

Why are GTMDs interesting?

3) Connection

Parameterization of a GTMD correlator (Meissner, Metz, Schlegel, arXiv: 0906.5323):



$$= \frac{1}{2M}\,\bar{u}(p',\lambda')\left[F_{1,1} + \frac{i\sigma^{i+}k_\perp^i}{P^+}F_{1,2} + \frac{i\sigma^{i+}\Delta_\perp^i}{P^+}F_{1,3} + \frac{i\sigma^{ij}k_\perp^i\Delta_\perp^j}{M^2}F_{1,4}\right]u(p,\lambda)$$

...uan, 2003)

Wigner distr...

(W...

...istributio s in parton physics

...elitsky, ... Yuan, 2003)

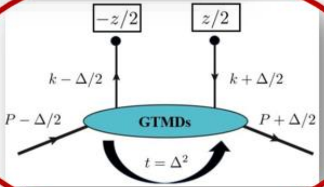
...lator:

❑ Calc...e from wave-functions:

$$W(x,k) = \int \frac{dx'}{2\pi} e^{-ikx'}\,\psi(x+\frac{x'}{2})\,\psi^*(x-\frac{x'}{2}$$

❑ Co...ection with probability densities & obs...bles:

$$L_z^q = \int dx \int d^2k_\perp d^2b_\perp (\vec{b}_\perp \times \vec{k}_\perp)_z \left\{ \int e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} \right\}$$



Orbital Angular Momentum (OAM)

Intuitive definitio... OAM

$$(\vec{b}_\perp \times \vec{k}_\perp)\Big|_z W_L^{q[\gamma^+]}(x,\vec{k}_\perp,\vec{b}_\perp)$$

$$L_z^{q,g} = -\int dx \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{M^2} F_{1,4}^{q,g}(x,\vec{k}_\perp^2)$$

Relation between GTMD $F_{1,4}^{q,g}$ & OAM

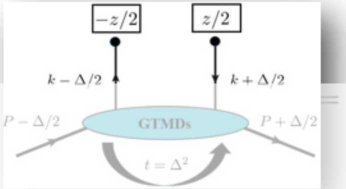
...latta, 2011 / Ji, Xiong, Yuan, 2012)

PDFs (x)

Why are GTMDs interesting?

3) Connection

Parameterization of a GTMD correlator (Meissner, Metz, Schlegel, arXiv: 0906.5323):



$$= \frac{1}{2M}\bar{u}(p',\lambda')\left[F_{1,1} + \frac{i\sigma^{i+}k_\perp^i}{P^+}F_{1,2} + \frac{i\sigma^{i+}\Delta_\perp^i}{P^+}F_{1,3} + \frac{i\sigma^{ij}k_\perp^i\Delta_\perp^j}{M^2}F_{1,4}\right]u(p,\lambda)$$

...an, 2003)

Wigner distr...

...istributio...s in parton physics

...elitsky, ... Yuan, 2003)

Calc... from wave-functions:

$W(x,k) = \int \frac{d...}{2...}$

...lator:

Co...ection with obs...bles:

Big question: Is this measurable?

$$L_z^{q,g} = -\int dx \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{M^2} F_{1,4}^{q,g}(x,\vec{k}_\perp^2)$$

Relation between GTMD $F_{1,4}^{q,g}$ & OAM

Intuitive definition ... OAM

$(\vec{b}_\perp \times \vec{k}_\perp)\Big|_z W_L^{q[\gamma^+]}(x,\vec{k}_\perp,\vec{b}_\perp)$

...latta, 2011 /

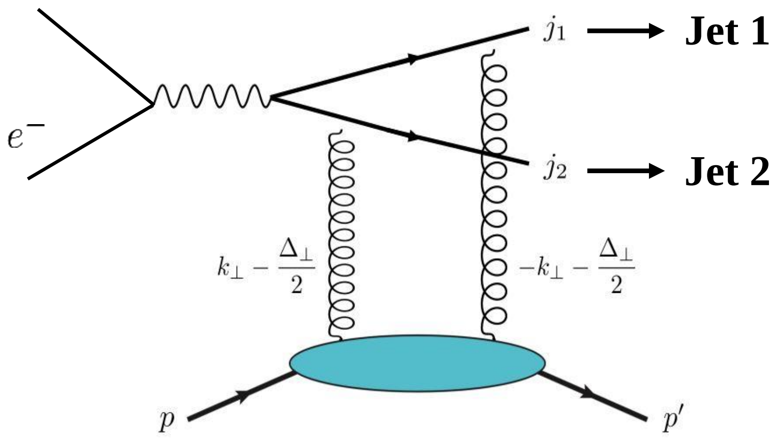
Ji, Xiong, Yuan, 2012)

PDFs (x)

Observables for GTMDs: State of the art

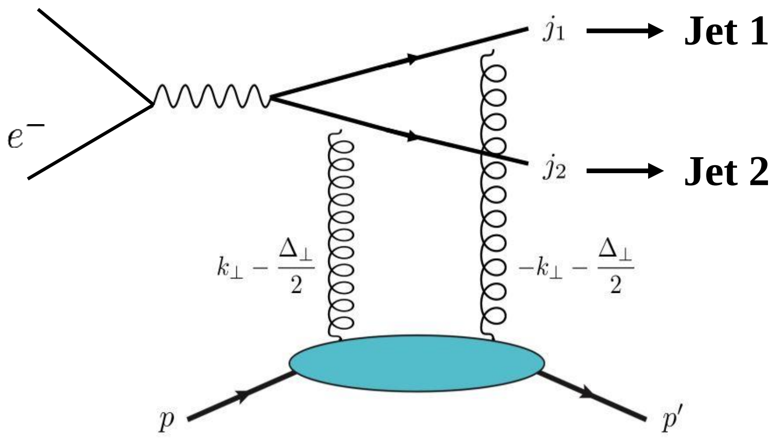
Observables for GTMDs

Exclusive dijet production in lepton-ion collisions at small-x (Hatta, Xiao, Yuan, arXiv: 1601.01585)



Observables for GTMDs

Exclusive dijet production in lepton-ion collisions at small-x (Hatta, Xiao, Yuan, arXiv: 1601.01585)



"Elliptic" Wigner distribution:

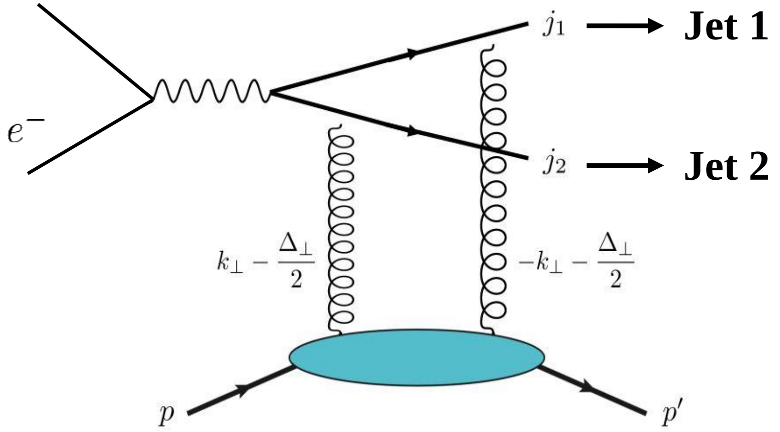
Symmetric part

$$W(x, \vec{k}_\perp, \vec{b}_\perp) \approx W_0(x, |\vec{k}_\perp|, |\vec{b}_\perp|) + 2\cos 2\,(\phi_k - \phi_b)\, W_1(x, |\vec{k}_\perp|, |\vec{b}_\perp|)$$

Elliptic part

Observables for GTMDs

Exclusive dijet production in lepton-ion collisions at small-x (Hatta, Xiao, Yuan, arXiv: 1601.01585)



"Elliptic" Wigner distribution:

$$W(x, \vec{k}_\perp, \vec{b}_\perp) \approx W_0(x, |\vec{k}_\perp|, |\vec{b}_\perp|) + 2\cos 2(\phi_k - \phi_b)\, W_1(x, |\vec{k}_\perp|, |\vec{b}_\perp|)$$

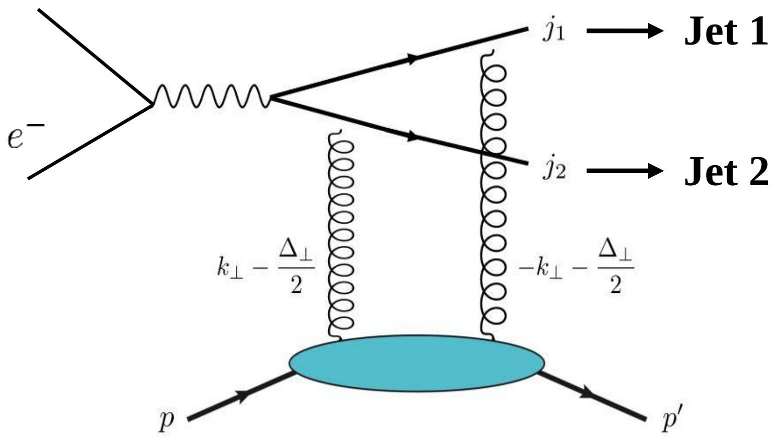
Main result:

$$\frac{d\sigma}{dy_1 dy_2 d^2\vec{\Delta}_\perp d^2\vec{P}_\perp} \propto z(1-z)[z^2 + (1-z)^2] \int d^2k_\perp d^2k'_\perp S(k_\perp, \Delta_\perp) S(k'_\perp, \Delta_\perp) \times \left[\frac{\vec{P}_\perp}{P_\perp^2 + \epsilon^2} - \frac{\vec{P}_\perp - \vec{k}_\perp}{(P_\perp - k_\perp)^2 + \epsilon^2}\right] \cdot \left[\frac{\vec{P}_\perp}{P_\perp^2 + \epsilon^2} - \frac{\vec{P}_\perp - \vec{k}'_\perp}{(P_\perp - k'_\perp)^2 + \epsilon^2}\right]$$

$$\approx d\sigma_0 + 2\cos 2(\phi_{P_\perp} - \phi_{\Delta_\perp}) d\tilde{\sigma}$$

Observables for GTMDs

Exclusive dijet production in lepton-ion collisions at small-x (Hatta, Xiao, Yuan, arXiv: 1601.01585)



“Elliptic” Wigner distribution:

$$W(x, \vec{k}_\perp, \vec{b}_\perp) \approx W_0(x, |\vec{k}_\perp|, |\vec{b}_\perp|) + 2\cos 2(\phi_k - \phi_b)\, W_1(x, |\vec{k}_\perp|, |\vec{b}_\perp|)$$

Main result:

$$\frac{d\sigma}{dy_1 dy_2 d^2\vec{\Delta}_\perp d^2\vec{P}_\perp} \propto z(1-z)[z^2 + (1-z)^2] \int d^2k_\perp d^2k'_\perp S(k_\perp, \Delta_\perp) S(k'_\perp, \Delta_\perp)$$

$$\left[\frac{\vec{P}_\perp}{P_\perp^2 + \epsilon^2} - \frac{\vec{P}_\perp - \vec{k}_\perp}{(P_\perp - k_\perp)^2 + \epsilon^2}\right] \cdot \left[\frac{\vec{P}_\perp}{P_\perp^2 + \epsilon^2} - \frac{\vec{P}_\perp - \vec{k}'_\perp}{(P_\perp - k'_\perp)^2 + \epsilon^2}\right]$$

Cosine angular modulation

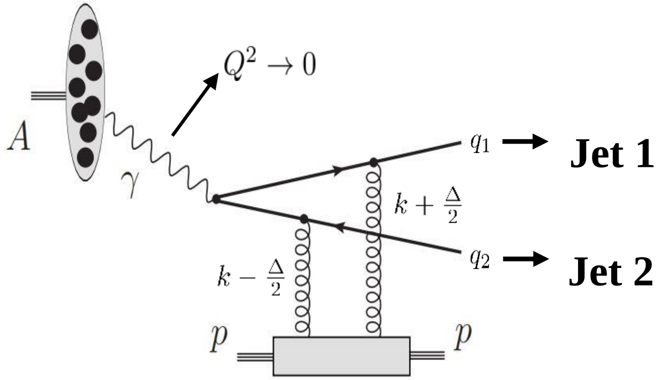
$$\vec{P}_\perp = \frac{1}{2}(\vec{j}_{2\perp} - \vec{j}_{1\perp})$$

$$\approx d\sigma_0 + 2\cos 2(\phi_{P_\perp} - \phi_{\Delta_\perp})\, d\tilde{\sigma}$$

Observables for GTMDs

Exclusive dijet production in lepton-ion collisions at small-x (Hatta, Xiao, Yuan, arXiv: 1601.01585)

Exclusive dijet production in ultra-peripheral collisions at small-x (Hagiwara et al., arXiv: 1706.01765)



Same cosine angular correlation observed in UPC

Main result:

$$\frac{d\sigma}{dy_1 dy_2 d^2\vec{\Delta}_\perp d^2\vec{P}_\perp} \propto z(1-z)[z^2+(1-z)^2]\int d^2k_\perp d^2k'_\perp S(k_\perp,\Delta_\perp)S(k'_\perp,\Delta_\perp)$$

$$\left[\frac{\vec{P}_\perp}{P_\perp^2+\epsilon^2} - \frac{\vec{P}_\perp-\vec{k}_\perp}{(P_\perp-k_\perp)^2+\epsilon^2}\right]\cdot\left[\frac{\vec{P}_\perp}{P_\perp^2+\epsilon^2} - \frac{\vec{P}_\perp-\vec{k}'_\perp}{(P_\perp-k'_\perp)^2+\epsilon^2}\right]$$

$$\approx d\sigma_0 + 2\cos 2\,(\phi_{P_\perp} - \phi_{\Delta_\perp})\,d\tilde{\sigma}$$

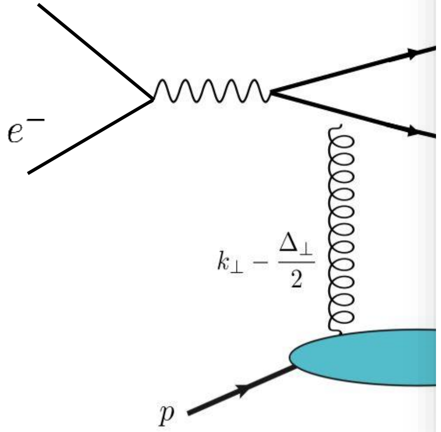
Cosine angular modulation

$$\vec{P}_\perp = \frac{1}{2}(\vec{j}_{2\perp} - \vec{j}_{1\perp})$$

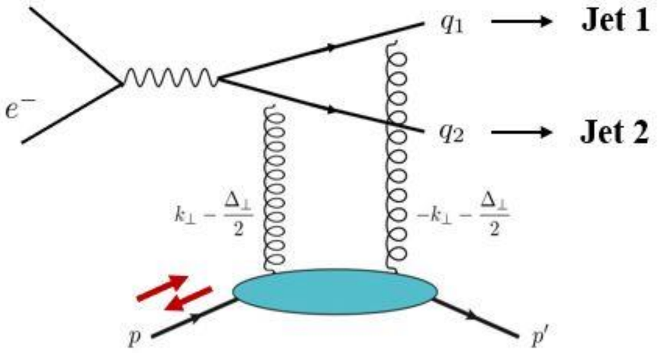
Observables for GTMDs

Coming up:

Exclusiv[...] lepton-ion collisions at small-x (Hatta, Xiao, Yuan, arXiv: 1601.01585)



What happens if target is polarized?



arXiv: 1612.02438 (2016)

Hunting the Gluon Orbital Angular Momentum at the Electron-Ion Collider

Xiangdong Ji,[1,2] Feng Yuan,[3] and Yong Zhao[1,3]

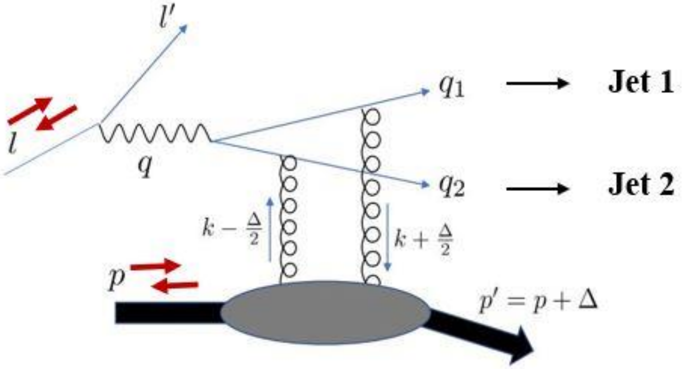
Main result:

$$\frac{d\sigma}{dy_1 dy_2 d^2\vec{\Delta}_\perp d^2\vec{P}_\perp} \propto z(1 - \ldots$$

$$\approx d\sigma_0 \ldots$$

Cosine angula[...]

What happens if in addition lepton is polarized?



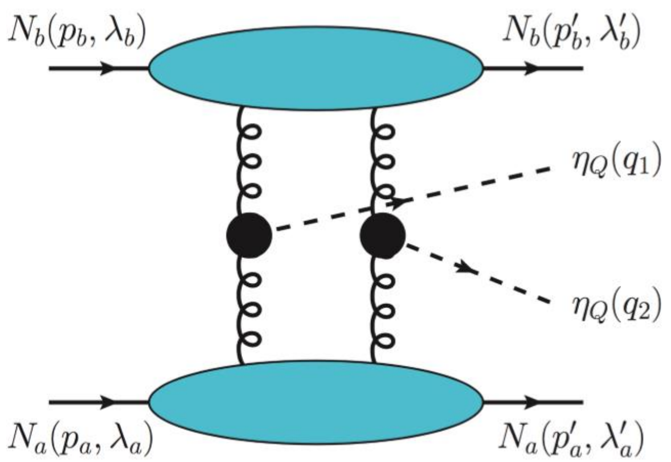
arXiv: 2201.08709 (2022)

Signature of the gluon orbital angular momentum

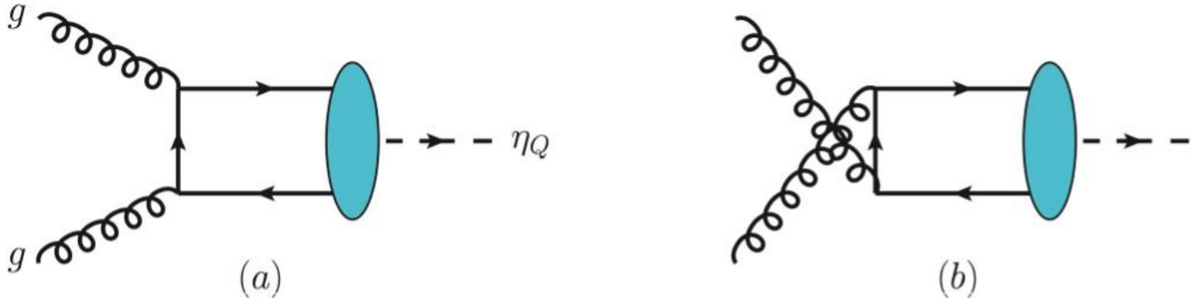
Shohini Bhattacharya,[1,*] Renaud Boussarie,[2,†] and Yoshitaka Hatta[1,3,‡]

Observables for GTMDs

Exclusive double quarkonium production (SB, Metz, Ojha, Tsai, Zhou, arXiv: 1802.10550)



Color Singlet Model: (Kuhn et. al., 1979, …)

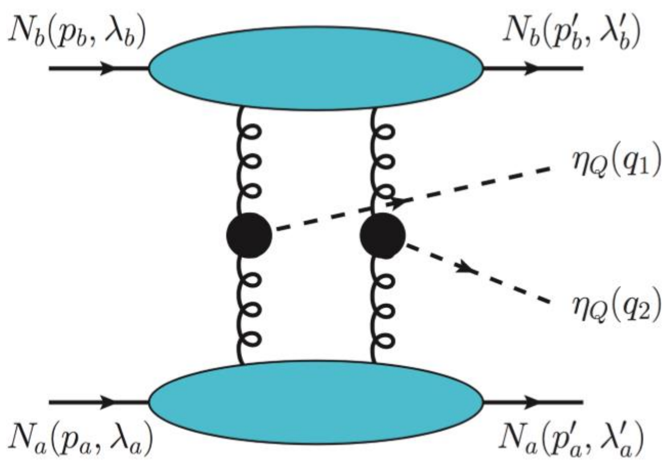


Main result:

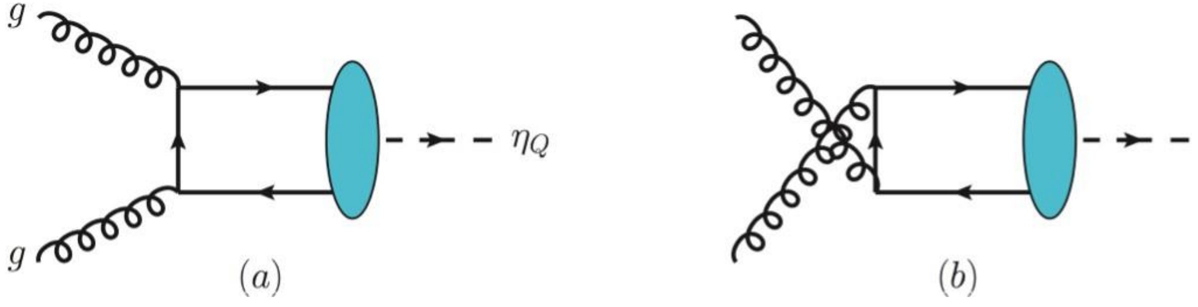
$$\frac{1}{2}\left(\tau_{XY} - \tau_{YX}\right) \approx 2\,\mathrm{Re.}\left\{ -\frac{\varepsilon_\perp^{ij}\Delta_{a\perp}^j}{M}\, C\left[\frac{k_{a\perp}^i}{M} F_{1,4}(x_a, \vec{k}_{a\perp})\, F_{1,1}(x_b, \vec{k}_{b\perp})\right] C\left[F_{1,1}^*(x_a, \vec{p}_{a\perp})\, F_{1,1}^*(x_b, \vec{p}_{b\perp})\right]\right\}$$

Observables for GTMDs

Exclusive double quarkonium production (SB, Metz, Ojha, Tsai, Zhou, arXiv: 1802.10550)



Color Singlet Model: (Kuhn et. al., 1979, …)



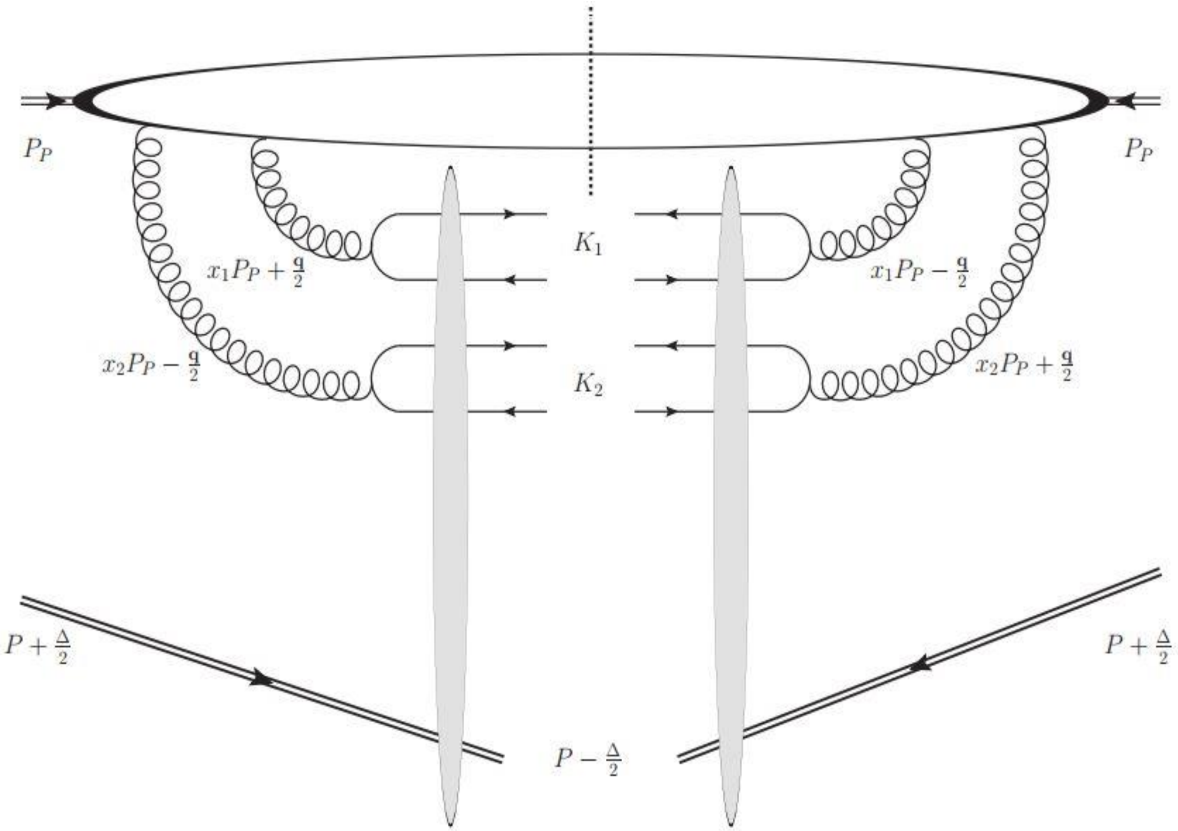
Main result:

$$\frac{1}{2}(\tau_{XY}-\tau_{YX}) \approx 2\,\mathrm{Re.}\left\{ -\frac{\varepsilon_\perp^{ij}\Delta_{a\perp}^j}{M}\, C\left[\frac{k_{a\perp}^i}{M} F_{1,4}(x_a,\vec{k}_{a\perp})\, F_{1,1}(x_b,\vec{k}_{b\perp})\right] C\left[F_{1,1}^*(x_a,\vec{p}_{a\perp})\, F_{1,1}^*(x_b,\vec{p}_{b\perp})\right]\right\}$$

This linear combination of polarization observables is sensitive to gluon OAM

Observables for GTMDs

Single-exclusive pp collisions (Boussarie, Hatta, Xiao, Yuan, arXiv: 1807.08697)



Main result:

Access Weiszacker-Williams gluon GTMD

<u>Example</u>: Result for $\chi_1 \, \chi_1$ production

Double PDF

$$d\sigma \approx F(x_1, x_2) \times \left(G_1(\vec{K}_\perp, \vec{\Delta}_\perp) + \frac{\vec{K}_\perp^2}{2M^2} G_2(\vec{K}_\perp, \vec{\Delta}_\perp) \right)^2$$

Unpolarized & Linearly-polarized GTMDs

More developments …

$$Im.\, \boldsymbol{F_{1,2}}\Big|_{\Delta=0} = -f_{1T}^{\perp}$$

arXiv: 1912.08182 (2019)

Probing the gluon Sivers function with an unpolarized target: GTMD distributions and the Odderons

Renaud Boussarie,[1] Yoshitaka Hatta,[1] Lech Szymanowski,[2] and Samuel Wallon[3,4]

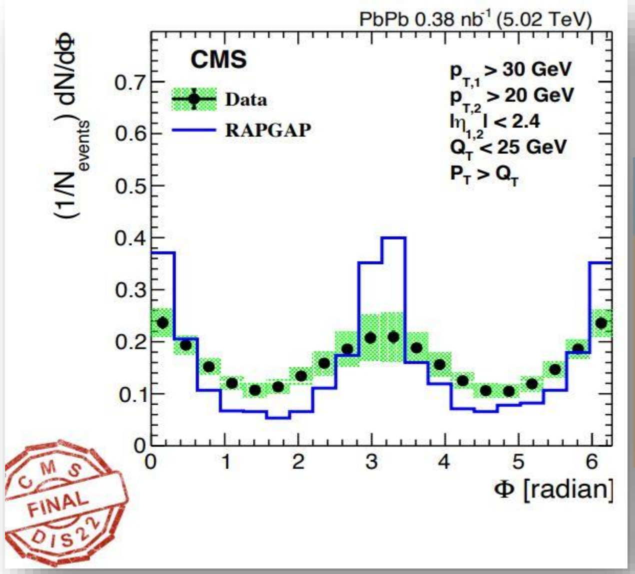
More developments …

$$Im.\, \boldsymbol{F_{1,2}}\Big|_{\Delta=0} = -f_{1T}^{\perp}$$

arXiv: 1912.08182 (2019)

Probing the gluon Sivers function with an unpolarized target: GTMD distributions and the Odderons

Renaud Boussarie,[1] Yoshitaka Hatta,[1] Lech Szymanowski,[2] and Samuel Wallon[3,4]



The CMS Collaboration **Michael Murray's talk, DIS 2022**

Angular correlations in exclusive dijet photoproduction in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

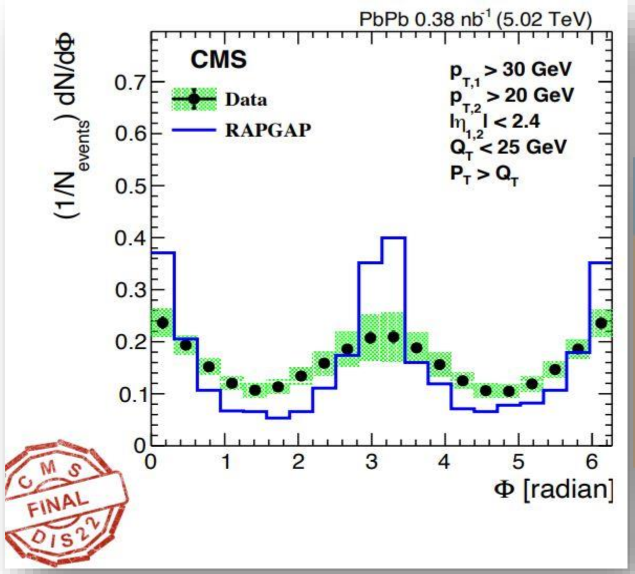
More developments …

$$Im.\, \boldsymbol{F_{1,2}}\Big|_{\Delta=0} = -f_{1T}^{\perp}$$

arXiv: 1912.08182 (2019)

Probing the gluon Sivers function with an unpolarized target: GTMD distributions and the Odderons

Renaud Boussarie,[1] Yoshitaka Hatta,[1] Lech Szymanowski,[2] and Samuel Wallon[3, 4]



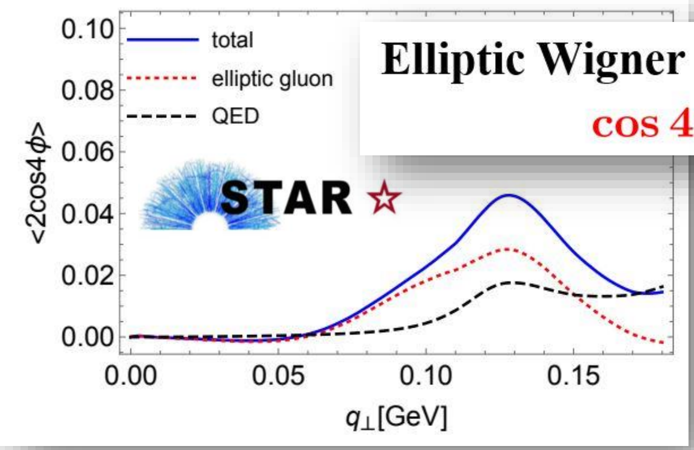
The CMS Collaboration **Michael Murray's talk, DIS 2022**

Angular correlations in exclusive dijet photoproduction in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

arXiv: 2106.13466 (2021)

Probing the gluon tomography in photoproduction of di-pions

Yoshikazu Hagiwara, Cheng Zhang, Jian Zhou, and Ya-jin Zhou



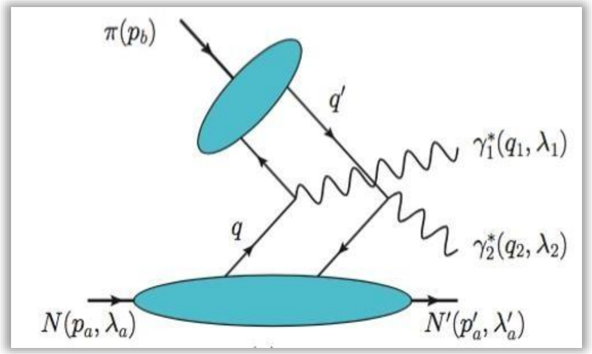
Elliptic Wigner distribution contributes to $\cos 4\phi$ asymmetry

More developments …

arXiv: 1702.04387 (2017)

Generalized TMDs and the exclusive double Drell-Yan process

Shohini Bhattacharya,[1] Andreas Metz,[1] and Jian Zhou[2]



First & only process sensitive to quark GTMDs

More developments …

arXiv: 1702.04387 (2017)

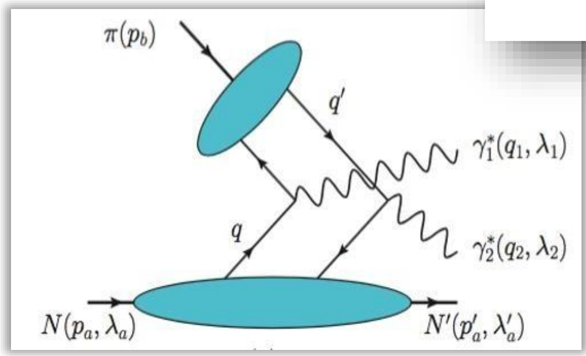
Generalized TMDs and the exclusive dou

Shohini Bhattacharya,[1] Andreas Metz,[1] a

Example of an observable

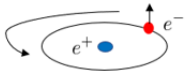
$$\frac{1}{2}(\tau_{XY}-\tau_{YX}) = \frac{4}{M_a^2}(\varepsilon_\perp^{ij}\Delta q_\perp^i \Delta_{a\perp}^j)\boxed{\mathrm{Re.}}\Big\{C^{(-)}\big[F_{1,1}\,\phi_\pi\big]C^{(+)}\big[\vec{\beta}_\perp\cdot\vec{k}_{a\perp}\,F^*_{1,4}\,\phi^*_\pi\big] - C^{(+)}\big[G_{1,4}\,\phi_\pi\big]C^{(-)}\big[\vec{\beta}_\perp\cdot\vec{p}_{a\perp}\,G^*_{1,1}\,\phi^*_\pi\big]\Big\}$$

This observable is sensitive to OAM & spin-orbit correlation



GTMDs related to strength of spin-orbit correlation
(Lorcé, Pasquini, 2011 / Lorcé, 2014)

Recall Spin-Orbit coupling in H atom!



$\boxed{\mathrm{Re.}}\,F_{1,4}^{q/g}$	$\vec{L}_{q/g}\cdot\vec{S}_N$	Nucleon
$\boxed{\mathrm{Re.}}\,G_{1,1}^{q/g}$	$\vec{L}_{q/g}\cdot\vec{S}_{q/g}$	Quark & Gluon

First & only process sensitive to quark GTMDs

More developments …

arXiv: 1702.04387 (2017)

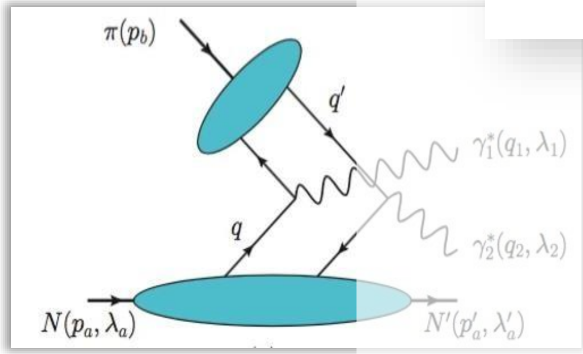
Example of an observable

Generalized TMDs and the exclusive dou

Shohini Bhattacharya,[1] Andreas Metz,[1] a

$$\frac{1}{2}(\tau_{XY}-\tau_{YX}) = \frac{4}{M_a^2}(\varepsilon_\perp^{ij}\Delta q_\perp^i \Delta_{a\perp}^j)\boxed{\text{Re.}}\Big\{C^{(-)}\big[F_{1,1}\,\phi_\pi\big]C^{(+)}\big[\vec{\beta}_\perp\cdot\vec{k}_{a\perp}\,F_{1,4}^*\,\phi_\pi^*\big]$$
$$-\,C^{(+)}\big[G_{1,4}\,\phi_\pi\big]C^{(-)}\big[\vec{\beta}_\perp\cdot\vec{p}_{a\perp}\,G_{1,1}^*\,\phi_\pi^*\big]\Big\}$$

This o



arXiv: 2208.00021 (2022)

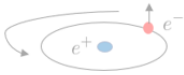
First proof of factorization

GTMDs and the factorization of exclusive double Drell-Yan

Miguel G. Echevarria[a,b], Patricia A. Gutierrez Garcia[c], Ignazio Scimemi[c]

(Lorce, Pasquini, 2011 / Lorce, 2014)

Recall Spin-Orbit coupling in H atom!



$\boxed{\text{Re.}}\,F_{1,4}^{q/g}$ — $\vec{L}_{q/g}\cdot\vec{S}_N$ — Nucleon

$\boxed{\text{Re.}}\,G_{1,1}^{q/g}$ — $\vec{L}_{q/g}\cdot\vec{S}_{q/g}$ — Quark & Gluon

First & only process sensitive to quark GTMDs

Our recent work

Signature of the gluon orbital angular momentum

Shohini Bhattacharya,[1,*] Renaud Boussarie,[2,†] and Yoshitaka Hatta[1,3,‡]

In Collaboration with:

Renaud Boussarie (CPHT, CNRS)

Yoshitaka Hatta (BNL)

Based on:

PRL 128, 182002 (arXiv: 2201.08709)

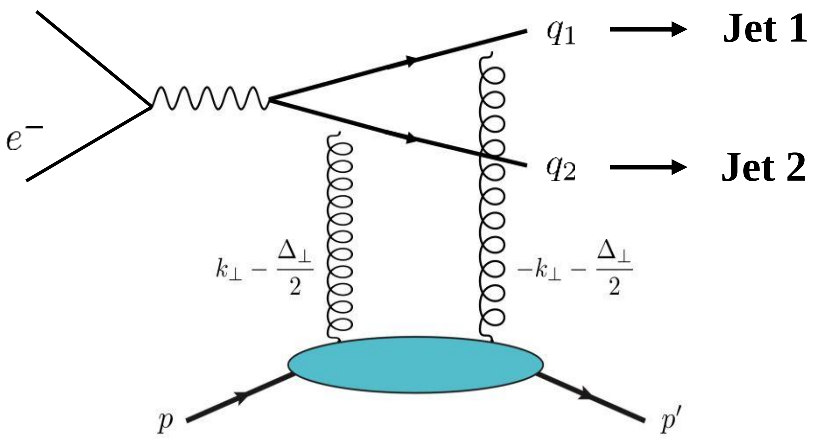
Probing gluon OAM through exclusive dijet production

Inspiration

arXiv: 1612.02438 (2016)

Hunting the Gluon Orbital Angular Momentum at the Electron-Ion Collider

Xiangdong Ji,[1,2] Feng Yuan,[3] and Yong Zhao[1,3]



We took a fresh look at this 2016 paper

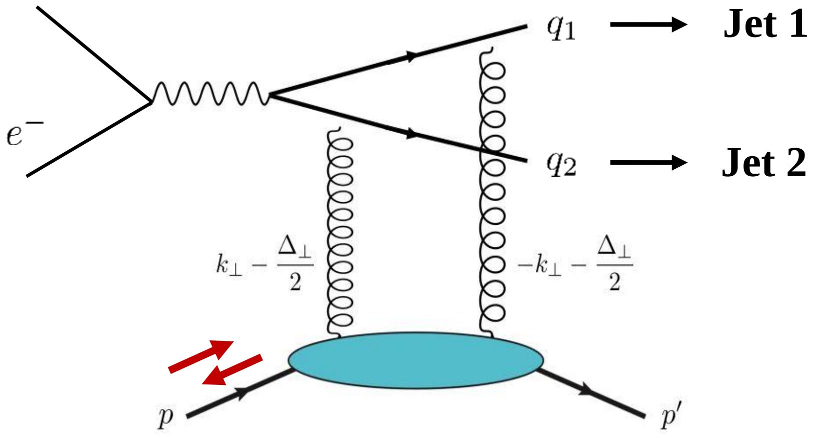
Probing gluon OAM through exclusive dijet production

Summary of the 2016 paper

arXiv: 1612.02438 (2016)

Hunting the Gluon Orbital Angular Momentum at the Electron-Ion Collider

Xiangdong Ji,[1,2] Feng Yuan,[3] and Yong Zhao[1,3]

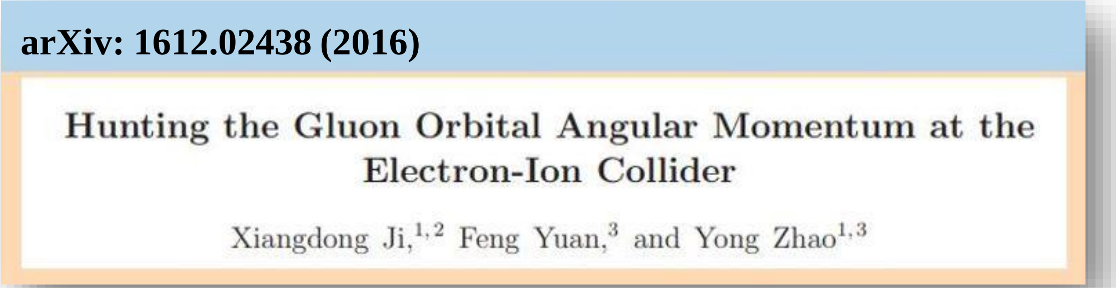


Longitudinal single spin asymmetry (SSA):

$$\frac{d\Delta\sigma}{dydQ^2d\Omega} = \sigma_0 h_p \frac{2(\bar{z}-z)(q_\perp \times \Delta_\perp)}{q_\perp^2 + \mu^2}\Big[16\beta(1-y)\mathfrak{Im}[F_g^* + 4\xi^2\bar{\beta}F_g'^*][\mathcal{L}_g + 8\xi^2\bar{\beta}\mathcal{L}_g'] + (1+(1-y)^2)\,\mathfrak{Im}[F_g^* + 2\xi^2(1-2\beta)F_g'^*][\mathcal{L}_g + 2\bar{\beta}(1/z\bar{z}-2)(\mathcal{L}_g + 4\xi^2(1-2\beta)\mathcal{L}_g')]\Big]$$

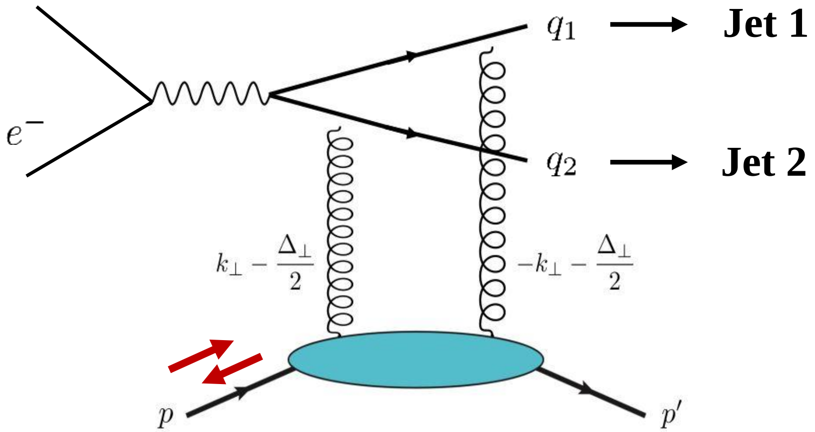
Probing gluon OAM through exclusive dijet production

Summary of the 2016 paper


arXiv: 1612.02438 (2016)

Hunting the Gluon Orbital Angular Momentum at the Electron-Ion Collider

Xiangdong Ji,[1,2] Feng Yuan,[3] and Yong Zhao[1,3]



Schematic structure of SSA (oversimplified):

$$\boxed{\frac{d\sigma}{dy\,dQ^2\,d\Omega} \sim \sigma_0 h_p \sin(\phi_{q_\perp} - \phi_{\Delta_\perp})\,(\bar{z} - z)\left[\mathfrak{Im}\Big(F_g^*(\xi)\mathcal{L}_g(\xi)\Big)\right]}$$

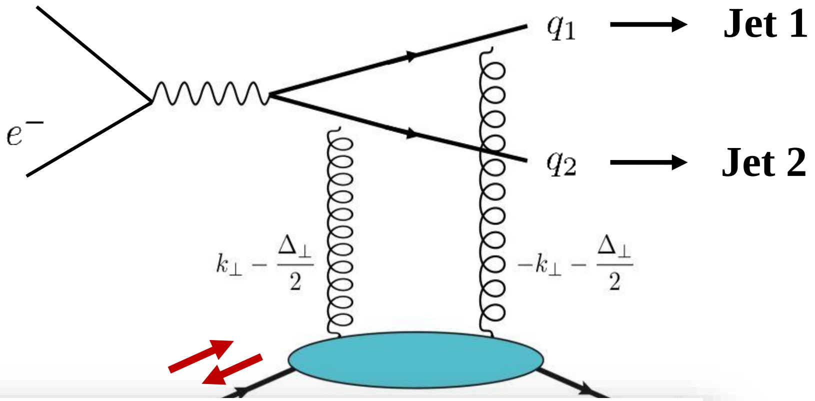
Probing gluon OAM through exclusive dijet production

Summary of the 2016 paper

arXiv: 1612.02438 (2016)

Hunting the Gluon Orbital Angular Momentum at the Electron-Ion Collider

Xiangdong Ji,[1,2] Feng Yuan,[3] and Yong Zhao[1,3]



Signature of OAM is sinusoidal angular modulation

Longitudinal single spin asymmetry (SSA):

$$q_\perp = q_{1\perp} - q_{2\perp}$$

Moment of GPD

$$\boxed{\frac{d\sigma}{dy dQ^2 d\Omega} \sim \sigma_0 h_p \sin(\phi_{q_\perp} - \phi_{\Delta_\perp})(\bar{z} - z)\left[\Im\mathfrak{m}\left(F_g^*(\xi)\mathcal{L}_g(\xi)\right)\right]}$$

Moment of OAM

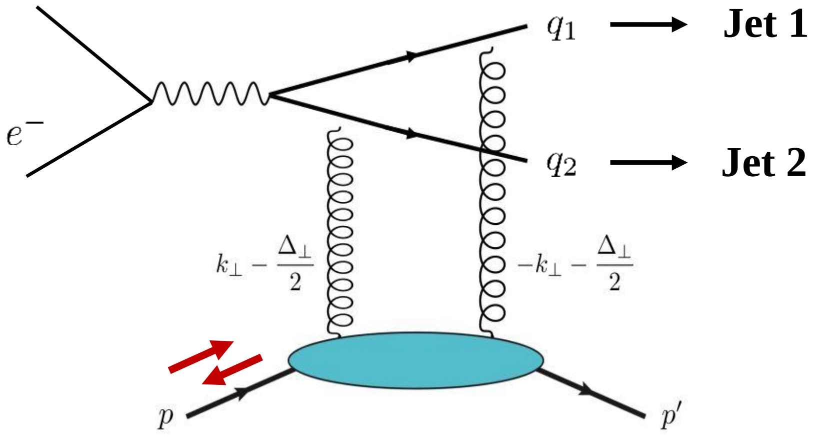
Probing gluon OAM through exclusive dijet production

Summary of the 2016 paper

arXiv: 1612.02438 (2016)

Hunting the Gluon Orbital Angular Momentum at the Electron-Ion Collider

Xiangdong Ji,[1,2] Feng Yuan,[3] and Yong Zhao[1,3]



Issues with SSA:

$$q_\perp = q_{1\perp} - q_{2\perp}$$

$$\boxed{\frac{d\sigma}{dy dQ^2 d\Omega} \sim \sigma_0 h_p \sin(\phi_{q_\perp} - \phi_{\Delta_\perp})\,(\bar{z} - z)\left[\mathfrak{Im}\Big(F_g^*(\xi)\mathcal{L}_g(\xi)\Big)\right]}$$

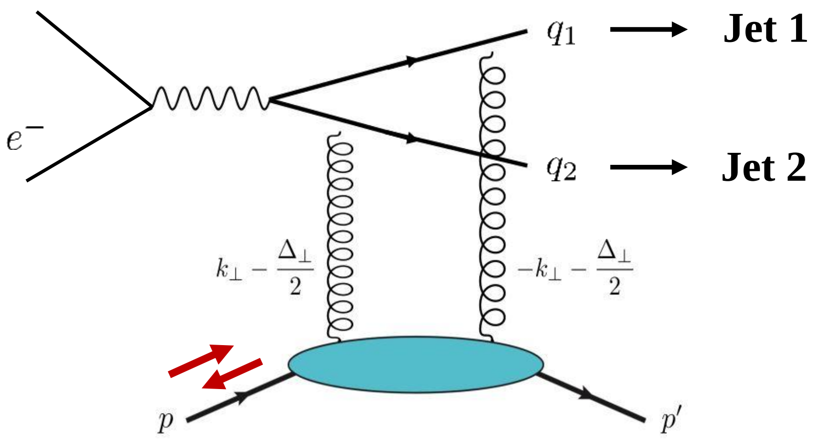
Probing gluon OAM through exclusive dijet production

Summary of the 2016 paper

arXiv: 1612.02438 (2016)

Hunting the Gluon Orbital Angular Momentum at the Electron-Ion Collider

Xiangdong Ji,[1,2] Feng Yuan,[3] and Yong Zhao[1,3]



Issues with SSA:

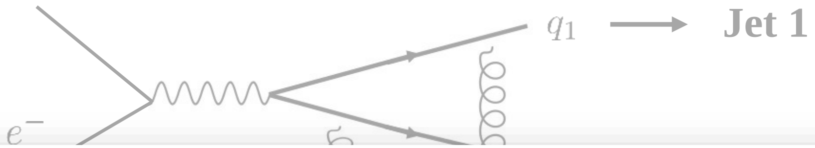
$$q_\perp = q_{1\perp} - q_{2\perp}$$

$$\frac{d\sigma}{dydQ^2d\Omega} \sim \sigma_0 h_p \sin(\phi_{q_\perp} - \phi_{\Delta_\perp})(\bar{z} - z)\left[\Im m\left(F_g^*(\xi)\mathcal{L}_g(\xi)\right)\right]$$

SSA vanishes for symmetric jet configurations $z = \bar{z} = \frac{1}{2}$

Probing gluon OAM through exclusive dijet production

Summary of the 2016 paper



arXiv: 1612.02438 (2016)

Hunting the Gluon Orbital Angular Momentum
Electron-Ion Collider

Xiangdong Ji,[1,2] Feng Yuan,[3] and Yong Zhao[1,3]

"Compton Form Factor":

$$\boxed{\mathcal{L}_g(\xi) = \int dx \frac{x^2 \xi L_g(x,\xi)}{(x^2 - \xi^2 + i\xi\epsilon)^3}}$$

Third pole at $x = \pm\xi$ ⟶ potentially dangerous for collinear factorization

(See Cui, Hu, Ma, 1804.05293)

Issues with SSA:

$$q_\perp = q_{1\perp} - q_{2\perp}$$

$$\frac{d\sigma}{dy dQ^2 d\Omega} \sim \sigma_0 h_p \sin(\phi_{q_\perp} - \phi_{\Delta_\perp})(\bar{z} - z)\left[\Im m\left(F_g^*(\xi)\mathcal{L}_g(\xi)\right)\right]$$

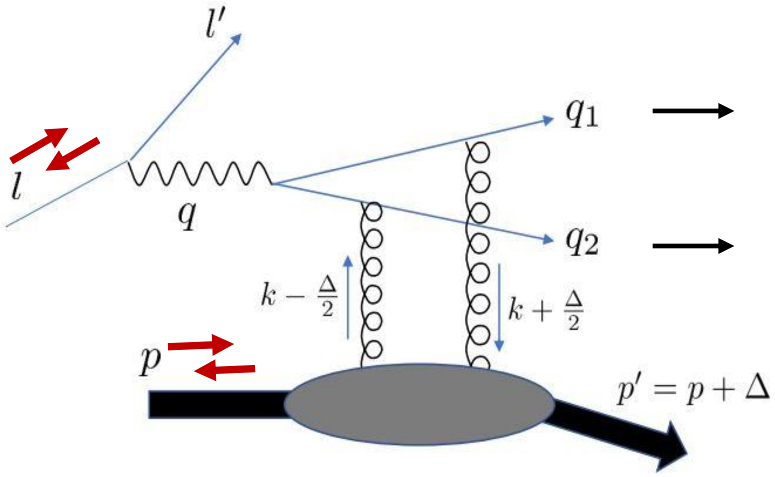
SSA vanishes for symmetric jet configurations $z = \bar{z} = \frac{1}{2}$

Probing gluon OAM through exclusive dijet production

Our work

Signature of the gluon orbital angular momentum

Shohini Bhattacharya,[1,*] Renaud Boussarie,[2,†] and Yoshitaka Hatta[1,3,‡]



q_1 ⟶ **Jet 1**

q_2 ⟶ **Jet 2**

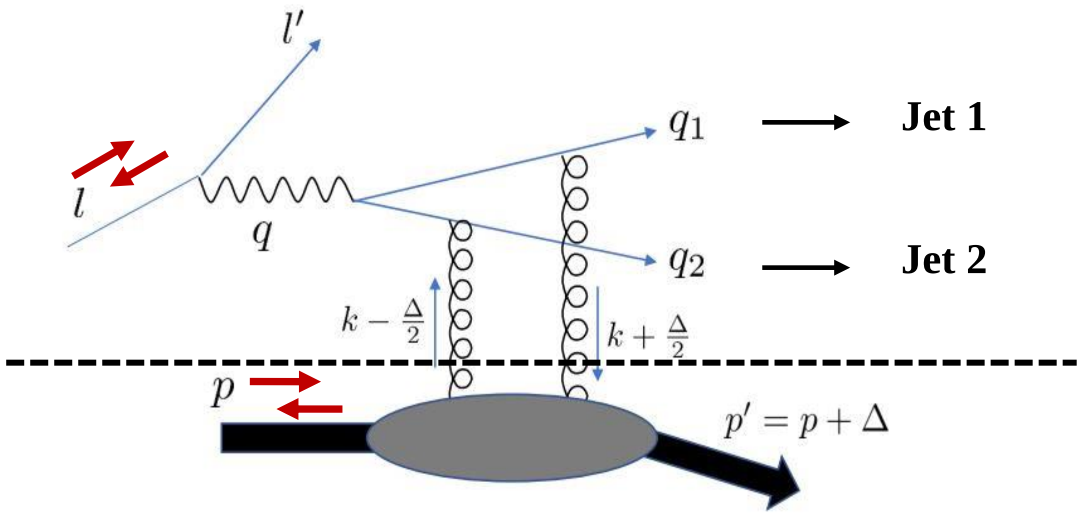
Distinct feature in our work

Double spin asymmetry (DSA):-

Both electron & incoming proton are longitudinally polarized

Probing gluon OAM through exclusive dijet production

Scattering amplitude



- **6 leading-order Feynman diagrams**
- **Scattering amplitude:**

$$\boxed{A \propto \int dx \int d^2k_\perp \, \underset{\text{Hard part}}{\mathcal{H}(x,\xi,q_\perp,k_\perp,\Delta_\perp)} \, \underset{\text{Soft part}}{x f_g(x,\xi,k_\perp,\Delta_\perp)}}$$

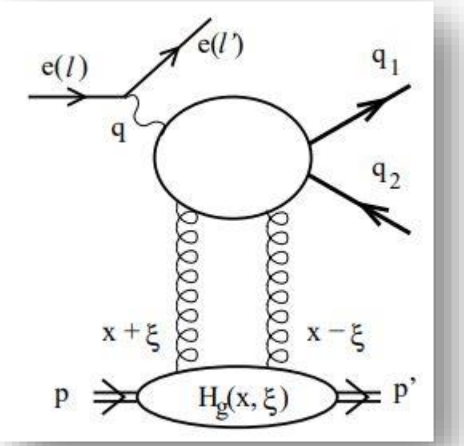
Hard part Soft part

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Twist expansion:

- **Twist-2 amplitude:** **Proportional to gluon GPD**



Braun, Ivanov, 0505263

$$A_T^2 = \frac{ig_s^2 e_{em} e_q}{N_c} \frac{1}{q_\perp^2 + \mu^2} \left(\bar{u}(q_1) \not{\epsilon}_\perp v(q_2)\right) \int dx \frac{1}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)} \times \left(1 + \frac{2\xi^2(1-2\beta)}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)}\right) \boxed{\int d^2k_\perp x f_g(x,\xi,k_\perp,\Delta_\perp)}$$

$$A_L^2 = \frac{ig_s^2 e_{em} e_q}{N_c} \frac{1}{(q_\perp^2 + \mu^2)^2} 4\xi z\bar{z} QW \left(\bar{u}(q_1)\gamma^- v(q_2)\right) \int dx \frac{1}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)} \times \left(1 + \frac{4\xi^2\bar{\beta}}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)}\right) \boxed{\int d^2k_\perp x f_g(x,\xi,k_\perp,\Delta_\perp)}$$

$$L_z^{q,g} = -\int dx \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{M^2} F_{1,4}^{q,g}(x, \vec{k}_\perp^2)$$

Relation between GTMD $F_{1,4}^{q,g}$ & OAM

gh exclusive dijet production

g amplitude

Twist expansion:

- **Twist-3 amplitude: Proportional to gluon OAM**

$$A_T^3 = -\frac{ig_s^2 e_{em} e_q}{N_c} \frac{2(\bar{z}-z)}{(q_\perp^2+\mu^2)^2} \bar{u}(q_1)\epsilon_\perp \cdot \gamma_\perp v(q_2) \int dx \frac{x}{(x^2-\xi^2+i\xi\varepsilon)^2} \left(2\xi + \frac{(2\xi)^3(1-2\beta)}{(x^2-\xi^2+i\xi\varepsilon)}\right) \boxed{\int d^2k_\perp q_\perp \cdot \boldsymbol{k}_\perp \, x f_g(x,\xi,k_\perp,\Delta_\perp)}$$
$$- \frac{ig_s^2 e_{em} e_q}{N_c} \frac{2(2\xi)^2 z\bar{z} W}{(q_\perp^2+\mu^2)^2} \bar{u}(q_1)\gamma^- v(q_2) \int dx \frac{x}{(x^2-\xi^2+i\xi\varepsilon)^2} \boxed{\int d^2k_\perp \epsilon_\perp \cdot \boldsymbol{k}_\perp \, x f_g(x,\xi,k_\perp,\Delta_\perp)}$$

$$A_L^3 = \frac{ig_s^2 e_{em} e_q}{N_c} \frac{16\xi^2(\bar{z}-z)z\bar{z}QW}{(q_\perp^2+\mu^2)^3} \bar{u}(q_1)\gamma^- v(q_2) \int dx \frac{x}{(x^2-\xi^2+i\xi\varepsilon)^2} \left(1 + \frac{8\xi^2(1-\beta)}{(x^2-\xi^2+i\xi\varepsilon)}\right) \boxed{\int d^2k_\perp q_\perp \cdot \boldsymbol{k}_\perp \, x f_g(x,\xi,k_\perp,\Delta_\perp)}$$

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Twist expansion:

- **Twist-3 amplitude:** Proportional to gluon OAM

$$A_T^3 = -\frac{ig_s^2 e_{em} e_q}{N_c} \frac{2(\bar{z}-z)}{(q_\perp^2+\mu^2)^2} \bar{u}(q_1)\epsilon_\perp \cdot \gamma_\perp v(q_2) \int dx \frac{x}{(x^2-\xi^2+i\xi\varepsilon)^2} \left(2\xi + \frac{(2\xi)^3(1-2\beta)}{(x^2-\xi^2+i\xi\varepsilon)} \right) \int d^2k_\perp q_\perp \cdot \boldsymbol{k}_\perp \, x f_g(x,\xi,k_\perp,\Delta_\perp)$$

$$- \frac{ig_s^2 e_{em} e_q}{N_c} \frac{2(2\xi)^2 z\bar{z}W}{(q_\perp^2+\mu^2)^2} \bar{u}(q_1)\gamma^- v(q_2) \int dx \, x \int d^2k_\perp \epsilon_\perp \cdot \boldsymbol{k}_\perp \, x f_g(x,\xi,k_\perp,\Delta_\perp)$$

Factorization-breaking third poles at $x = \pm\xi$

$$A_L^3 = \frac{ig_s^2 e_{em} e_q}{N_c} \frac{16\xi^2(\bar{z}-z)z\bar{z}QW}{(q_\perp^2+\mu^2)^3} \bar{u}(q_1)\gamma^- v(q_2) \int dx \frac{x}{(x^2-\xi^2+i\xi\varepsilon)^2} \left(1 + \frac{8\xi^2(1-\beta)}{(x^2-\xi^2+i\xi\varepsilon)} \right) \int d^2k_\perp \, q_\perp \cdot \boldsymbol{k}_\perp \, x f_g(x,\xi,k_\perp,\Delta_\perp)$$

Probing gluon OAM through exclusive dijet production

Twist expansion:

- **Twist-3 amplitude:** Proportio

Note: Gluon GPDs may contain $\sim \theta(\xi - |x|)(x^2 - \xi^2)^2$

(See Radyushkin, 9805342)

Hence, integrals containing third poles are divergent

$$A_T^3 = -\frac{ig_s^2 e_{em} e_q}{N_c} \frac{2(\bar{z} - z)}{(q_\perp^2 + \mu^2)^2} \bar{u}(q_1)\epsilon_\perp \cdot \gamma_\perp v(q_2) \int dx \frac{x}{(x^2 - \xi^2 + i\xi\varepsilon)^2} \left(2\xi + \frac{(2\xi)^3(1 - 2\beta)}{(x^2 - \xi^2 + i\xi\varepsilon)} \right) \int d^2k_\perp q_\perp \cdot \boldsymbol{k}_\perp \, x f_g(x, \xi, k_\perp, \Delta_\perp)$$

$$-\frac{ig_s^2 e_{em} e_q}{N_c} \frac{2(2\xi)^2 z\bar{z}W}{(q_\perp^2 + \mu^2)^2} \bar{u}(q_1)\gamma^- v(q_2) \int dx \frac{x}{\cdots} \int d^2k_\perp \epsilon_\perp \cdot \boldsymbol{k}_\perp \, x f_g(x, \xi, k_\perp, \Delta_\perp)$$

Factorization-breaking third poles at $x = \pm\xi$

$$A_L^3 = \frac{ig_s^2 e_{em} e_q}{N_c} \frac{16\xi^2(\bar{z} - z)z\bar{z}QW}{(q_\perp^2 + \mu^2)^3} \bar{u}(q_1)\gamma^- v(q_2) \int dx \frac{x}{(x^2 - \xi^2 + i\xi\varepsilon)^2} \left(1 + \frac{8\xi^2(1 - \beta)}{(x^2 - \xi^2 + i\xi\varepsilon)} \right) \int d^2k_\perp q_\perp \cdot \boldsymbol{k}_\perp \, x f_g(x, \xi, k_\perp, \Delta_\perp)$$

Scattering amplitude

Twist expansion:

Switch off the factorization-breaking third poles by setting $z = \bar{z} = \frac{1}{2}$

$$A_T^3 = -\frac{ig_s^2 e_{em} e_q}{N_c} \boxed{\frac{2(\bar{z}-z)}{(q_\perp^2+\mu^2)^2}} \bar{u}(q_1)\epsilon_\perp \cdot \gamma_\perp v(q_2) \int dx \frac{x}{(x^2-\xi^2+i\xi\varepsilon)^2}\left(2\xi + \frac{(2\xi)^3(1-2\beta)}{(x^2-\xi^2+i\xi\varepsilon)}\right) \int d^2k_\perp q_\perp \cdot \boldsymbol{k}_\perp \, x f_g(x,\xi,k_\perp,\Delta_\perp)$$

$$-\frac{ig_s^2 e_{em} e_q}{N_c} \frac{2(2\xi)^2 z\bar{z}W}{(q_\perp^2+\mu^2)^2} \bar{u}(q_1)\gamma^- v(q_2) \int dx \frac{x}{\ldots} \int d^2k_\perp \epsilon_\perp \cdot \boldsymbol{k}_\perp \, x f_g(x,\xi,k_\perp,\Delta_\perp)$$

Factorization-breaking third poles at $x = \pm\xi$

$$A_L^3 = \frac{ig_s^2 e_{em} e_q}{N_c} \frac{16\xi^2 \boxed{(\bar{z}-z)} z\bar{z}QW}{\boxed{(q_\perp^2+\mu^2)}^3} \bar{u}(q_1)\gamma^- v(q_2) \int dx \frac{x}{(x^2-\xi^2+i\xi\varepsilon)^2}\left(1 + \frac{8\xi^2(1-\beta)}{(x^2-\xi^2+i\xi\varepsilon)}\right) \int d^2k_\perp \, q_\perp \cdot \boldsymbol{k}_\perp \, x f_g(x,\xi,k_\perp,\Delta_\perp)$$

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Twist expansion:

Switch off the factorization-breaking third poles by setting $z = \bar{z} = \frac{1}{2}$

$$A_T^3 = -\frac{ig_s^2 e_{em} e_q}{N_c} \boxed{\frac{2(\bar{z}-z)}{(q_\perp^2+\mu^2)^2}} \bar{u}(q_1)\epsilon_\perp \cdot \gamma_\perp v(q_2) \int dx \frac{x}{(x^2-\xi^2+i\xi\varepsilon)^2}\left(2\xi \cdot \frac{(2\xi)^3(1-2\beta)}{(x^2-\xi^2+i\xi\varepsilon)}\right) \int d^2k_\perp q_\perp \cdot \boldsymbol{k}_\perp x f_g(x,\xi,k_\perp,\Delta_\perp)$$

Recall: Not possible in SSA

Factorization-breaking third poles at $x = \pm\xi$

Issues with SSA:

A_l^3 $q_\perp = q_{1\perp} - q_{2\perp}$

$$\boxed{\frac{d\sigma}{dy dQ^2 d\Omega} \sim \sigma_0 h_p \sin(\phi_{q_\perp} - \phi_{\Delta_\perp})(\bar{z}-z)\left[\mathrm{Im}(F_g^*(\xi)\mathcal{L}_g(\xi))\right]}$$

SSA vanishes for symmetric jet configurations $z = \bar{z} = \frac{1}{2}$

$$\frac{8\xi^2(1-\beta)}{(x^2-\xi^2+i\xi\varepsilon)}\Bigg) \int d^2k_\perp q_\perp \cdot \boldsymbol{k}_\perp x f_g(x,\xi,k_\perp,\Delta_\perp)$$

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Twist expansion:

Switch off the factorization-breaking third poles by setting $z=\bar{z}=\frac{1}{2}$

$$A_T^3 = -\frac{ig_s^2 e_{em} e_q}{N_c}\frac{2(\bar{z}-z)}{(q_\perp^2+\mu^2)^2}\bar{u}(q_1)\epsilon_\perp\cdot\gamma_\perp v(q_2)\int dx\,\frac{x}{(x^2-\xi^2+i\xi\varepsilon)^2}\left(\cdots+\frac{(2\xi)^3(1-2\beta)}{(x^2-\xi^2+i\xi\varepsilon)}\right)\int d^2k_\perp q_\perp\cdot \boldsymbol{k}_\perp\, x f_g(x,\xi,k_\perp,\Delta_\perp)$$

$$\boxed{-\frac{ig_s^2 e_{em} e_q}{N_c}\frac{2(2\xi)^2 z\bar{z}W}{(q_\perp^2+\mu^2)^2}\bar{u}(q_1)\gamma^- v(q_2)\int dx\,\frac{x}{(x^2-\xi^2+i\xi\varepsilon)^2}\int d^2k_\perp \epsilon_\perp\cdot \boldsymbol{k}_\perp\, x f_g(x,\xi,k_\perp,\Delta_\perp)}$$

DSA is sensitive to OAM through an interference between twist-2 amplitude A^2 & twist-3 amplitude A_T^3 (No third pole)

$$A_L^3 = \frac{ig_s^2 e_{em} e_q}{N_c}\frac{16\xi^2(\bar{z}-z)z\bar{z}QW}{(q_\perp^2+\mu^2)^3}\bar{u}(q_1)\gamma^- v(q_2)\int dx\,\frac{x}{(x^2-\xi^2+i\xi\varepsilon)^2}\left(\cdots+\frac{8\xi^2(1-\beta)}{(x^2-\xi^2+i\xi\varepsilon)}\right)\int d^2k_\perp q_\perp\cdot \boldsymbol{k}_\perp\, x f_g(x,\xi,k_\perp,\Delta_\perp)$$

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Main result $(z = 1/2)$**:**

DSA's OAM part:

$$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu = -\frac{2^{10}\pi^4}{N_c} h_l h_p \alpha_s^2 \alpha_{em} e_q^2 \frac{(1+\xi)\xi Q^2}{(q_\perp^2+\mu^2)^2} |l_\perp||\Delta_\perp| \cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$
$$\times \mathfrak{Re}\left[\left\{\mathcal{H}_g^{(1)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\left(\mathcal{H}_g^{(2)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(2)*}\right)\right\}\mathcal{L}_g + \left(\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\mathcal{E}_g^{(2)*}\right)\frac{\mathcal{O}}{2}\right]$$

Probing gluon OAM through exclusive dijet production

Scattering amplitude

DSA does not vanish for symmetric jet configurations $z = \bar{z} = \frac{1}{2}$

Main result $(z = 1/2)$:

Consequence:

Elimination of factorization-breaking third poles at $x = \pm\xi$

DSA's OAM part:

$$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu = -\frac{2^{10}\pi^4}{N_c} h_l h_p \alpha_s^2 \alpha_{em} e_q^2 \frac{(1+\xi)\xi Q^2}{(q_\perp^2+\mu^2)^2} |l_\perp||\Delta_\perp| \cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$
$$\times \mathfrak{Re}\left[\left\{\mathcal{H}_g^{(1)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\left(\mathcal{H}_g^{(2)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(2)*}\right)\right\}\mathcal{L}_g + \left(\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\mathcal{E}_g^{(2)*}\right)\frac{\mathcal{O}}{2}\right]$$

"Compton Form Factors":

$$\mathcal{L}_g(\xi) = \int_{-1}^{1} dx \frac{x^2 L_g(x,\xi)}{(x-\xi+i\epsilon)^2(x+\xi-i\epsilon)^2}$$

$$\mathcal{H}_g^{(1)}(\xi) = \int_{-1}^{1} dx \frac{H_g(x,\xi)}{(x-\xi+i\epsilon)(x+\xi-i\epsilon)} \qquad \mathcal{H}_g^{(2)}(\xi) = \int_{-1}^{1} dx \frac{\xi^2 H_g(x,\xi)}{(x-\xi+i\epsilon)^2(x+\xi-i\epsilon)^2}$$

Scattering amplitude

Main result $(z = 1/2)$**:**

DSA's OAM part:

Scattered lepton angle

$$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu = -\frac{2^{10}\pi^4}{N_c} h_l h_p \alpha_s^2 \alpha_{em} e_q^2 \frac{(1+\xi)\xi Q^2}{(q_\perp^2+\mu^2)^2} |l_\perp||\Delta_\perp| \cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$
$$\times \Re\left[\left\{\mathcal{H}_g^{(1)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\left(\mathcal{H}_g^{(2)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(2)*}\right)\right\}\mathcal{L}_g + \left(\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\mathcal{E}_g^{(2)*}\right)\frac{\mathcal{O}}{2}\right]$$

Signature of gluon OAM is cosine angular modulation

Probing gluon OAM through exclusive dijet production

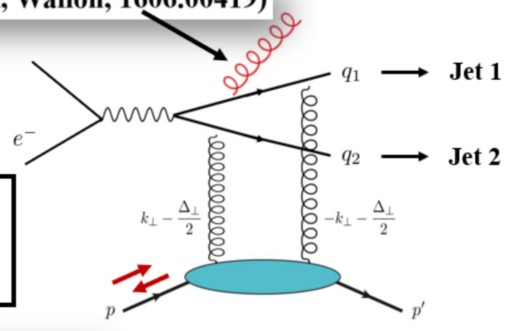
tude

(Boussarie, Grabovsky, Szymanowski, Wallon, 1606.00419)

Schematic structure of SSA (oversimplified):

$$\boxed{\frac{d\sigma}{dydQ^2d\Omega} \sim \sigma_0 h_p \sin(\phi_{q_\perp} - \phi_{\Delta_\perp})(\bar{z} - z)\left[\mathfrak{Im}(F_g^*(\xi)\mathcal{L}_g(\xi))\right]}$$

Jet angle affected by gluon emissions



Scattered lepton angle

$$\boxed{\begin{aligned}\int d\phi_{q_\perp} L^{\mu\nu} A_\mu^* A_\nu = &-\frac{2^{10}\pi^4}{N_c} h_l h_p \alpha_s^2 \alpha_{em} e_q^2 \frac{(1+\xi)\xi Q^2}{(q_\perp^2+\mu^2)^2} |l_\perp||\Delta_\perp| \cos(\phi_{l_\perp} - \phi_{\Delta_\perp}) \\ &\times \mathfrak{Re}\left[\left\{\mathcal{H}_g^{(1)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\left(\mathcal{H}_g^{(2)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(2)*}\right)\right\}\mathcal{L}_g + \left(\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\mathcal{E}_g^{(2)*}\right)\frac{\mathcal{O}}{2}\right]\end{aligned}}$$

Signature of gluon OAM is cosine angular modulation

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Main result $(z = 1/2)$**:**

DSA's OAM part:

$$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu = -\frac{2^{10}\pi^4}{N_c} h_l h_p \alpha_s^2 \alpha_{em} e_q^2 \frac{(1+\xi)\xi Q^2}{(q_\perp^2+\mu^2)^2} |l_\perp||\Delta_\perp| \cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$
$$\times \mathfrak{Re}\left[\left\{\mathcal{H}_g^{(1)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\left(\mathcal{H}_g^{(2)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(2)*}\right)\right\}\mathcal{L}_g + \left(\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\mathcal{E}_g^{(2)*}\right)\frac{\mathcal{O}}{2}\right]$$

"Compton Form Factors":

$$O(x,\xi) \equiv \int d^2\widetilde{k}_\perp \frac{\widetilde{k}_\perp^2}{M^2} F_{1,2}(x,\xi,\widetilde{\Delta}_\perp = 0)$$

$$\mathcal{O}(\xi) = \int_{-1}^{1} dx \frac{xO(x,\xi)}{(x-\xi+i\epsilon)^2(x+\xi-i\epsilon)^2}$$

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Not the end of the story:

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Not the end of the story:

- **Interference between unpolarized & helicity GPD** $(z = 1/2)$**:**

Helicity GPD

$$\boxed{\int d\phi_{q_\perp} L^{\mu\nu} A_\mu A_\nu = \frac{2^{10}\pi^4}{N_c} h_l h_p \alpha_s^2 \alpha_{em} e_q^2 \frac{(1-\xi^2)\xi Q^2}{(q_\perp^2+\mu^2)^2} |l_\perp||\Delta_\perp| \cos(\phi_{l_\perp} - \phi_{\Delta_\perp}) \mathfrak{Re}\left[\left(\mathcal{H}_g^{(1)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(1)*}\right)\left(\tilde{\mathcal{H}}_g^{(2)} - \frac{\xi^2}{1-\xi^2}\tilde{\mathcal{E}}_g^{(2)}\right)\right]}$$

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Not the end of the story:

- **Interference between unpolarized & helicity GPD** $(z = 1/2)$**:**

Helicity GPD

$$\int d\phi_{q_\perp} L^{\mu\nu} A_\mu A_\nu = \frac{2^{10}\pi^4}{N_c} h_l h_p \alpha_s^2 \alpha_{em} e_q^2 \frac{(1-\xi^2)\xi Q^2}{(q_\perp^2+\mu^2)^2} |l_\perp||\Delta_\perp| \cos(\phi_{l_\perp} - \phi_{\Delta_\perp}) \mathfrak{Re}\left[\left(\mathcal{H}_g^{(1)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(1)*}\right)\left(\tilde{\mathcal{H}}_g^{(2)} - \frac{\xi^2}{1-\xi^2}\tilde{\mathcal{E}}_g^{(2)}\right)\right]$$

Helicity contributes to the same angular modulation as that of OAM

DSA is a simultaneous probe of gluon OAM & it's helicity

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

See backup slides for details on how we modelled GPDs and OAM

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

Realistic EIC kinematics

$\sqrt{s}$ [GeV]	Q^2 [GeV^2]	y	ξ
120	2.7	0.7	$\lesssim 10^{-3}$
	4.8		
	10.0		

Focus on:

$$z = \bar{z} = \frac{1}{2}$$

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

Realistic EIC kinematics

$\sqrt{s}$ [GeV]	Q^2 [GeV^2]	y	ξ
120	2.7	0.7	$\lesssim 10^{-3}$
	4.8		
	10.0		

Focus on:

$$z = \bar{z} = \frac{1}{2}$$

Cross section:

$$\boxed{\frac{d\sigma}{dy dQ^2 d\phi_{l_\perp} dz dq_\perp^2 d^2\Delta_\perp} = \frac{\alpha_{em} y}{2^{11}\pi^7 Q^4} \frac{\int d\phi_{q_\perp} L^{\mu\nu} A_\mu^* A_\nu}{(W^2+Q^2)(W^2-M_J^2) z\bar{z}}}$$

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

Realistic EIC kinematics

$\sqrt{s}$ [GeV]	Q^2 [GeV^2]	y	ξ
120	2.7	0.7	$\lesssim 10^{-3}$
	4.8		
	10.0		

Focus on:

$$z = \bar{z} = \frac{1}{2}$$

Study cross section as differential in the skewness variable

$$\frac{d\sigma}{dy\,dQ^2\,dz\,d\xi\,d\delta\phi}$$

Cross section:

$$\boxed{\frac{d\sigma}{dy\,dQ^2\,d\phi_{l_\perp}\,dz\,dq_\perp^2\,d^2\Delta_\perp} = \frac{\alpha_{em}y}{2^{11}\pi^7 Q^4}\,(\ldots}$$

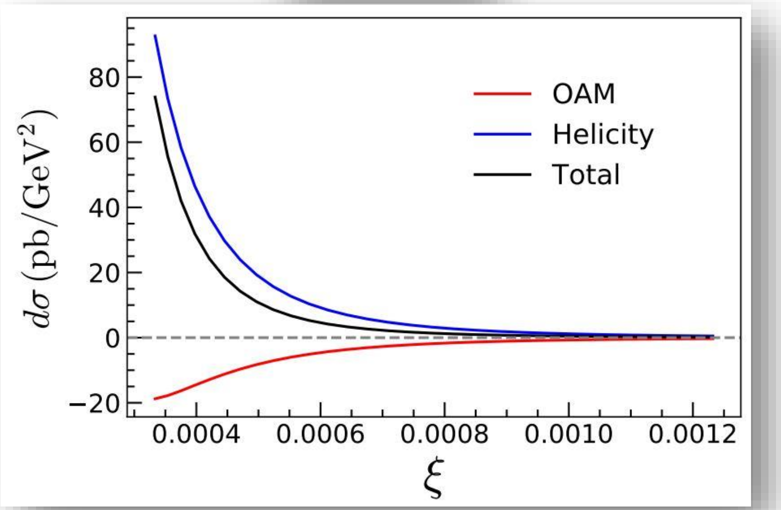
Relation between skewness & jet momenta:

$$\boxed{\xi = \frac{q_\perp^2 + z\bar{z}Q^2}{-q_\perp^2 + z\bar{z}(Q^2 + 2W^2)}}$$

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

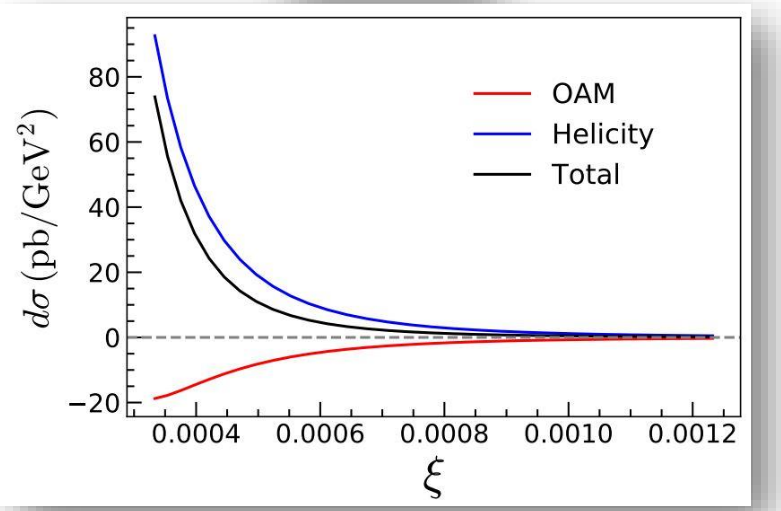
$Q^2 = 2.7$



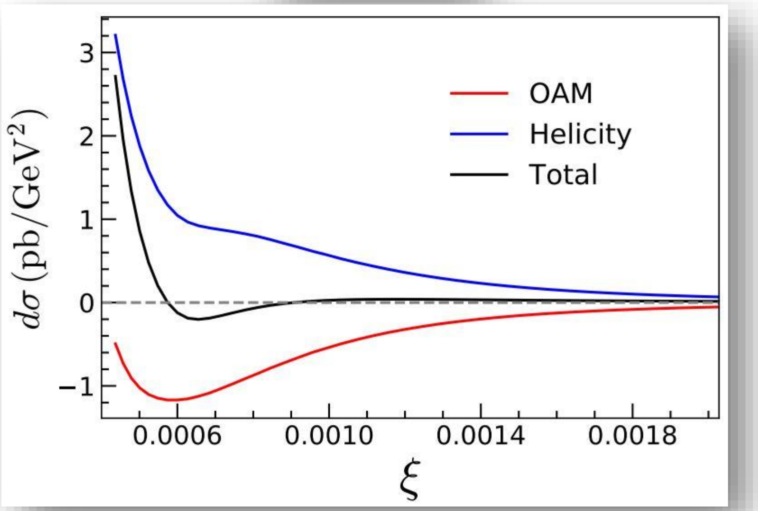
Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

$Q^2 = 2.7$

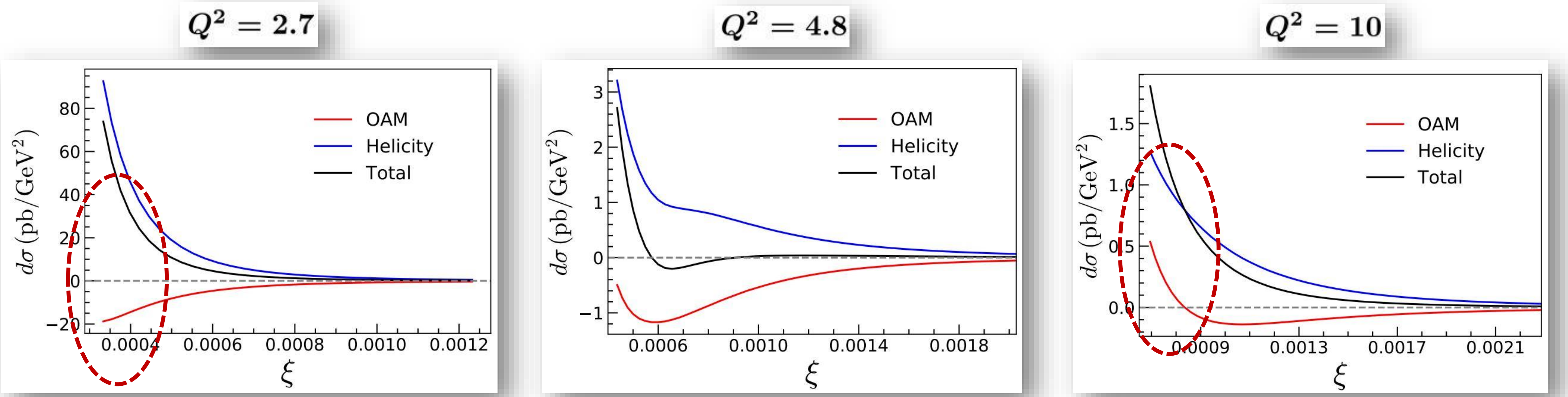


$Q^2 = 4.8$



Probing gluon OAM through exclusive dijet production

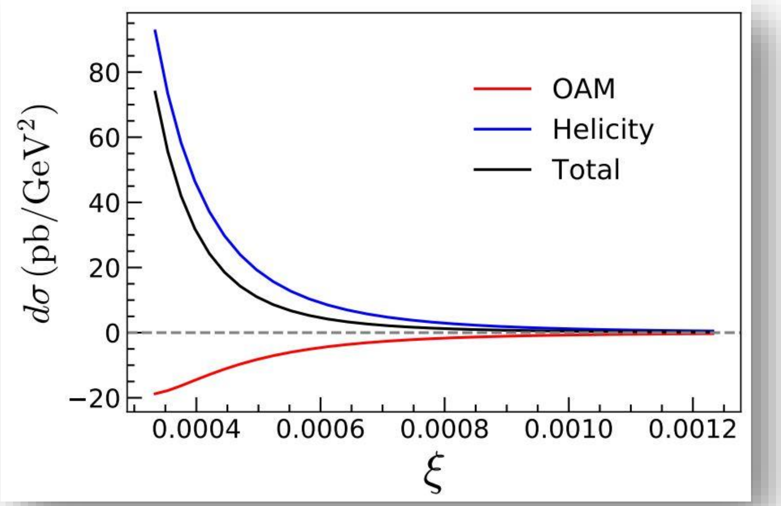
Numerical estimate of cross section



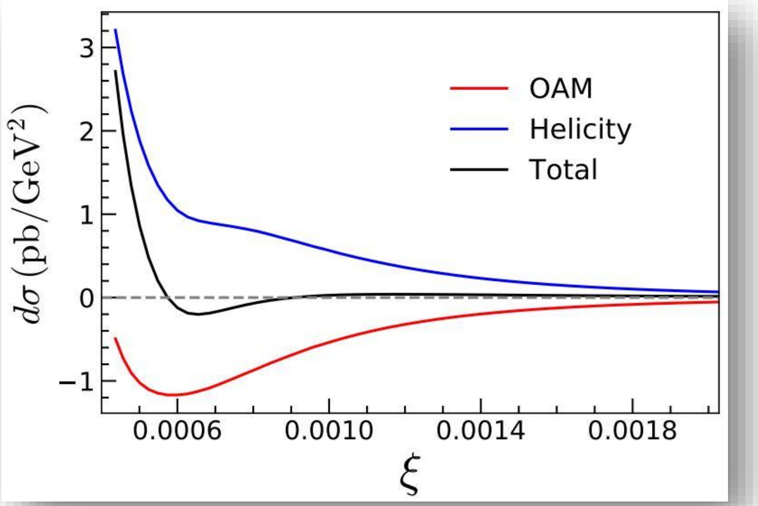
Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

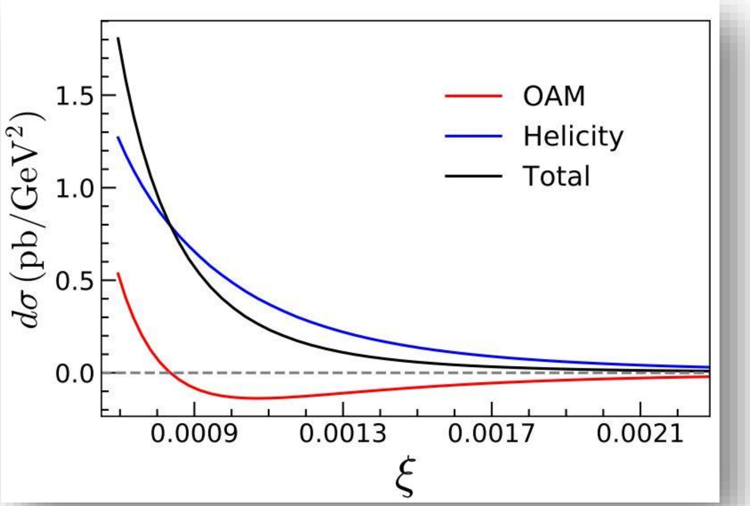
$Q^2 = 2.7$



$Q^2 = 4.8$



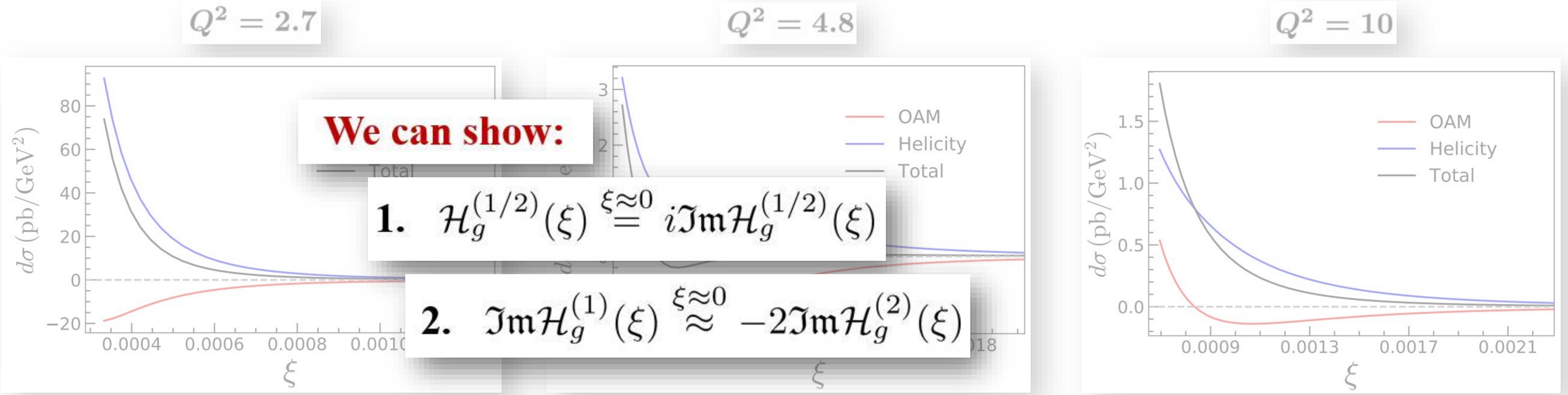
$Q^2 = 10$



DSA: $$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu \Big|_{\delta\phi=0} \sim \mathfrak{Re}\left[\mathcal{H}_g^{(1)*}(\xi)\,\tilde{\mathcal{H}}_g^{(2)}(\xi)\right] - \mathfrak{Re}\left[\left\{\mathcal{H}_g^{(1)*}(\xi) + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\mathcal{H}_g^{(2)*}(\xi)\right\}\mathcal{L}_g(\xi)\right]$$

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section



We can show:

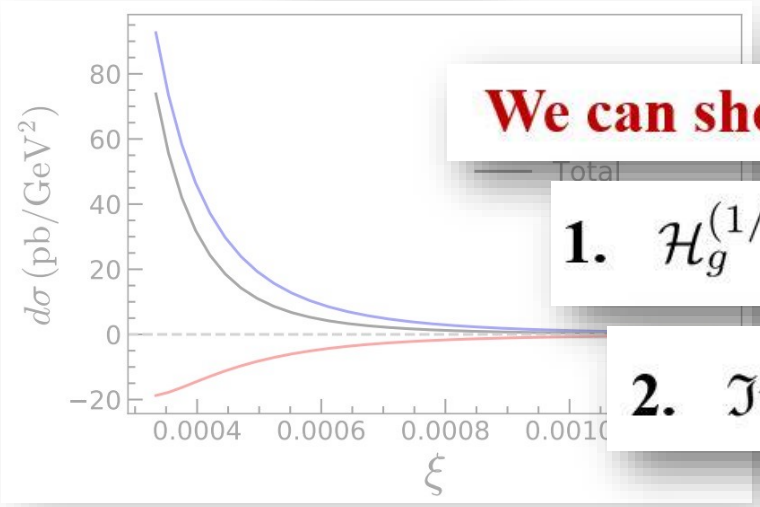
1. $\mathcal{H}_g^{(1/2)}(\xi) \overset{\xi\approx 0}{=} i\mathfrak{Im}\mathcal{H}_g^{(1/2)}(\xi)$

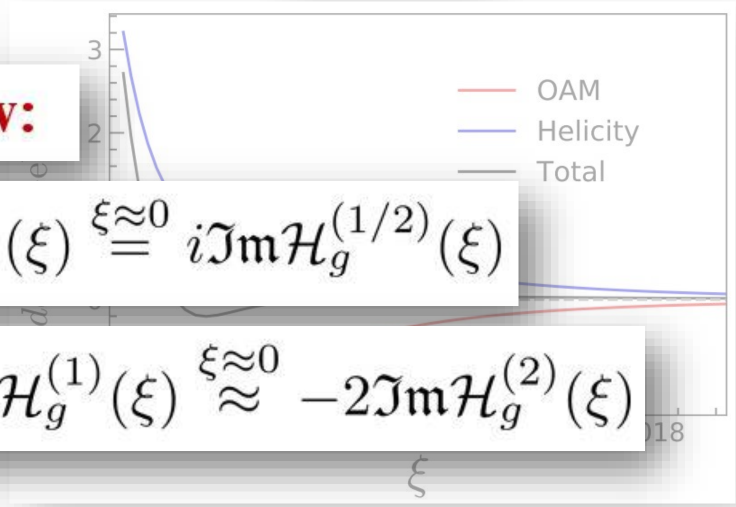
2. $\mathfrak{Im}\mathcal{H}_g^{(1)}(\xi) \overset{\xi\approx 0}{\approx} -2\mathfrak{Im}\mathcal{H}_g^{(2)}(\xi)$

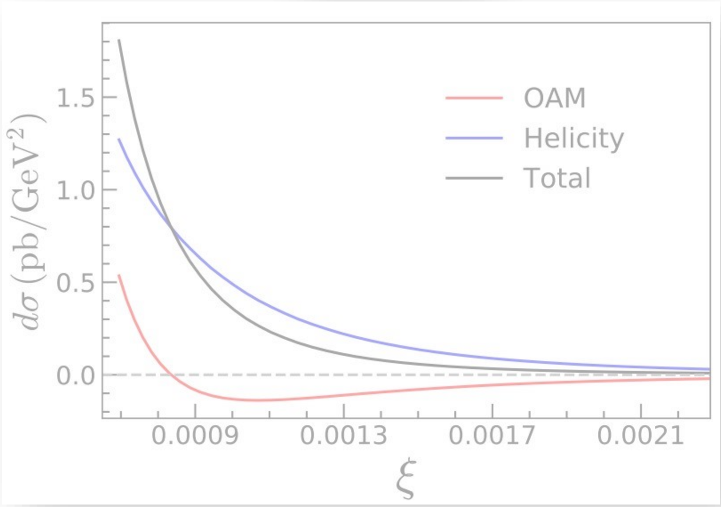
DSA: $$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu\Big|_{\delta\phi=0} \sim \mathfrak{Re}\left[\mathcal{H}_g^{(1)*}(\xi)\,\tilde{\mathcal{H}}_g^{(2)}(\xi)\right] - \mathfrak{Re}\left[\left\{\mathcal{H}_g^{(1)*}(\xi) + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\mathcal{H}_g^{(2)*}(\xi)\right\}\mathcal{L}_g(\xi)\right]$$

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section







We can show:

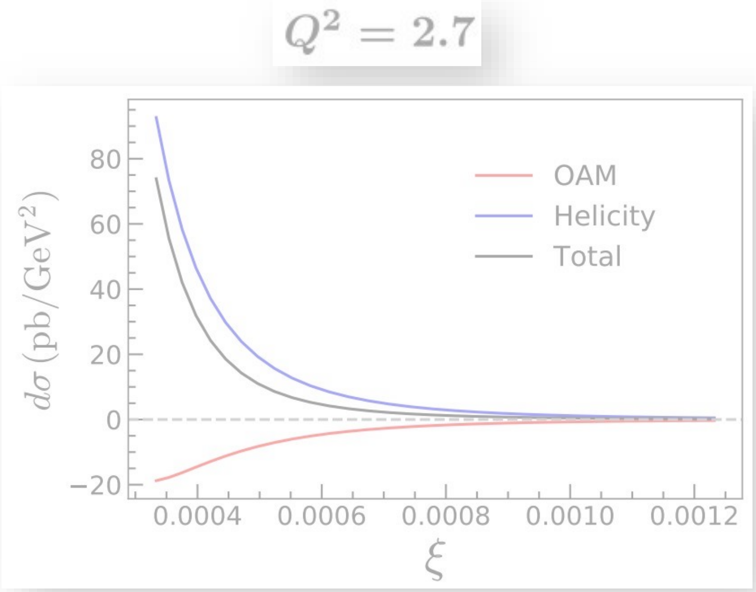
1. $\mathcal{H}_g^{(1/2)}(\xi) \overset{\xi\approx 0}{=} i\,\mathfrak{Im}\mathcal{H}_g^{(1/2)}(\xi)$

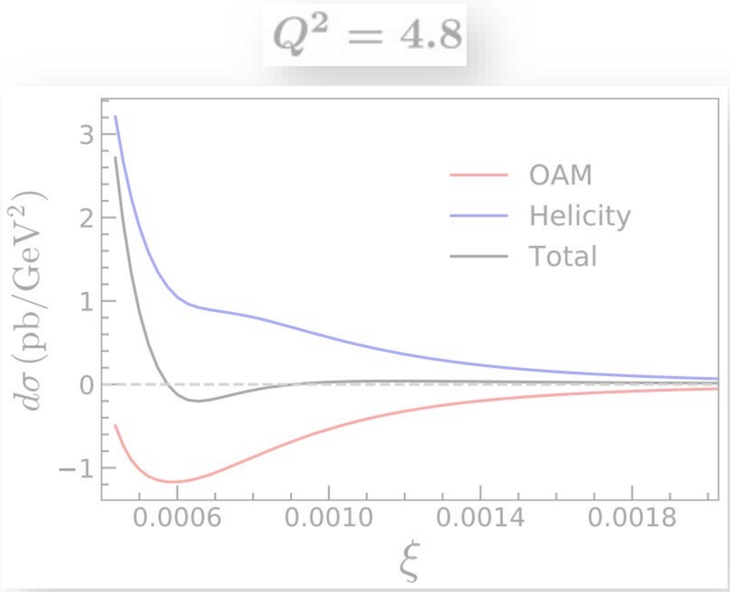
2. $\mathfrak{Im}\mathcal{H}_g^{(1)}(\xi) \overset{\xi\approx 0}{\approx} -2\,\mathfrak{Im}\mathcal{H}_g^{(2)}(\xi)$

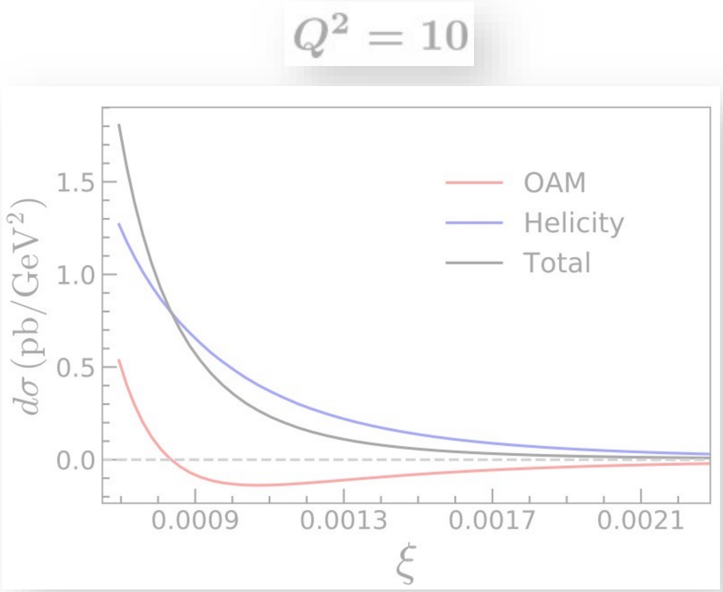
DSA: $$\int d\phi_{q_\perp} L^{\mu\nu} A_\mu^* A_\nu \Big|_{\delta\phi=0} \sim \mathcal{H}_g^{(1)*}(\xi)\left(\tilde{\mathcal{H}}_g^{(2)}(\xi) + \frac{q_\perp^2 - Q^2/4}{q_\perp^2 + Q^2/4}\,\mathcal{L}_g(\xi)\right)$$

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section







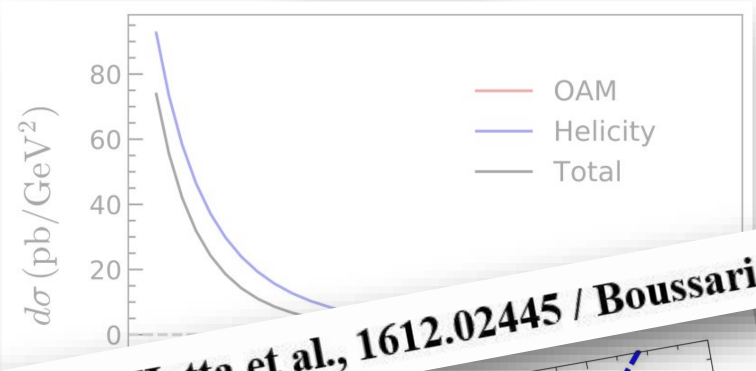
DSA:

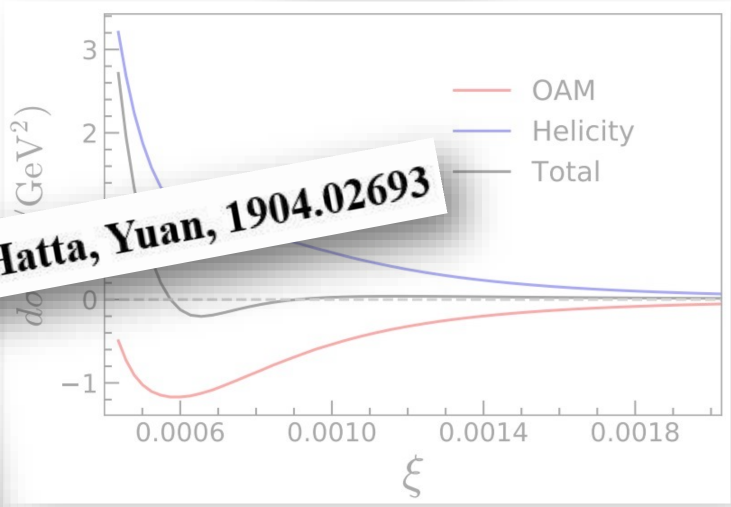
$$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu \Big|_{\delta\phi=0} \sim \mathcal{H}_g^{(1)*}(\xi) \left(\tilde{\mathcal{H}}_g^{(2)}(\xi) + \frac{q_\perp^2 - Q^2/4}{q_\perp^2 + Q^2/4} \mathcal{L}_g(\xi) \right)$$

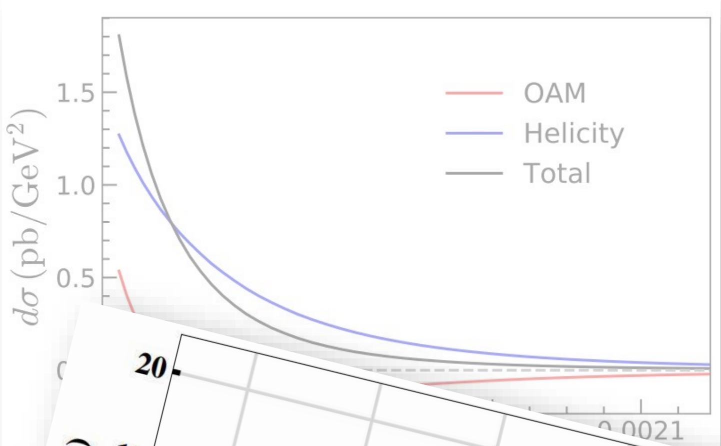
$\tilde{\mathcal{H}}_g^{(2)}$ & $\mathcal{L}_g$ **interfere positively/negatively depending upon sign of** $q_\perp^2 - \dfrac{Q^2}{4}$

Cancellation expected between Helicity & OAM at small x

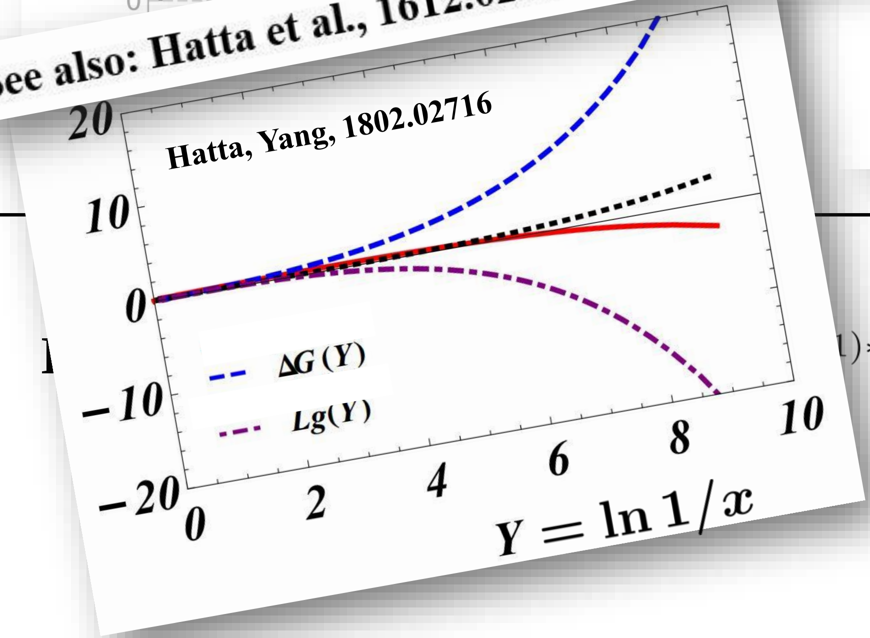
$$\Delta G(x) \approx -L_g(x)$$





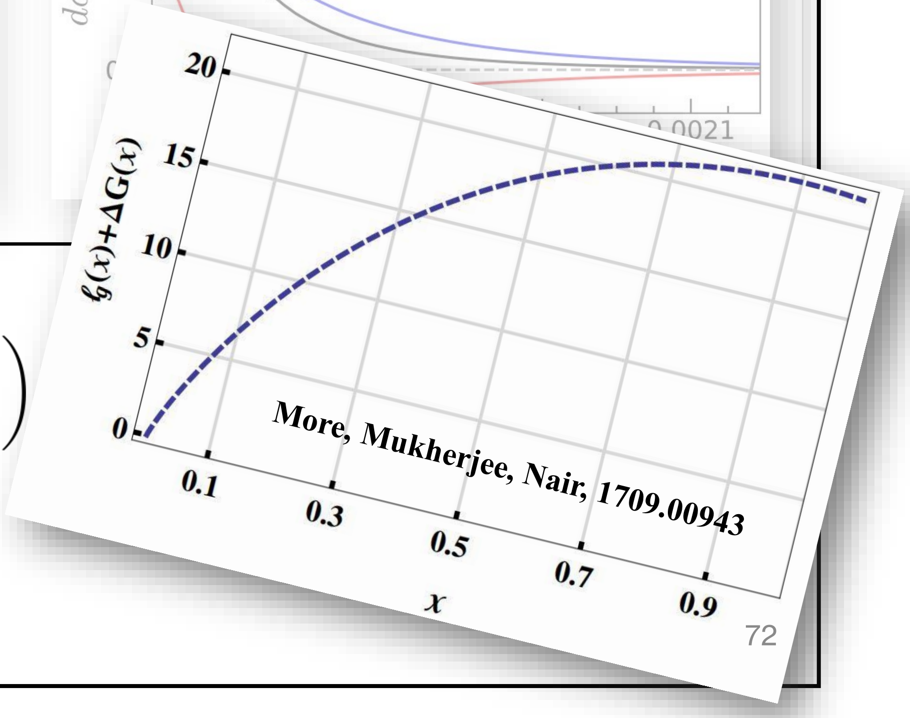


See also: Hatta et al., 1612.02445 / Boussarie, Hatta, Yuan, 1904.02693



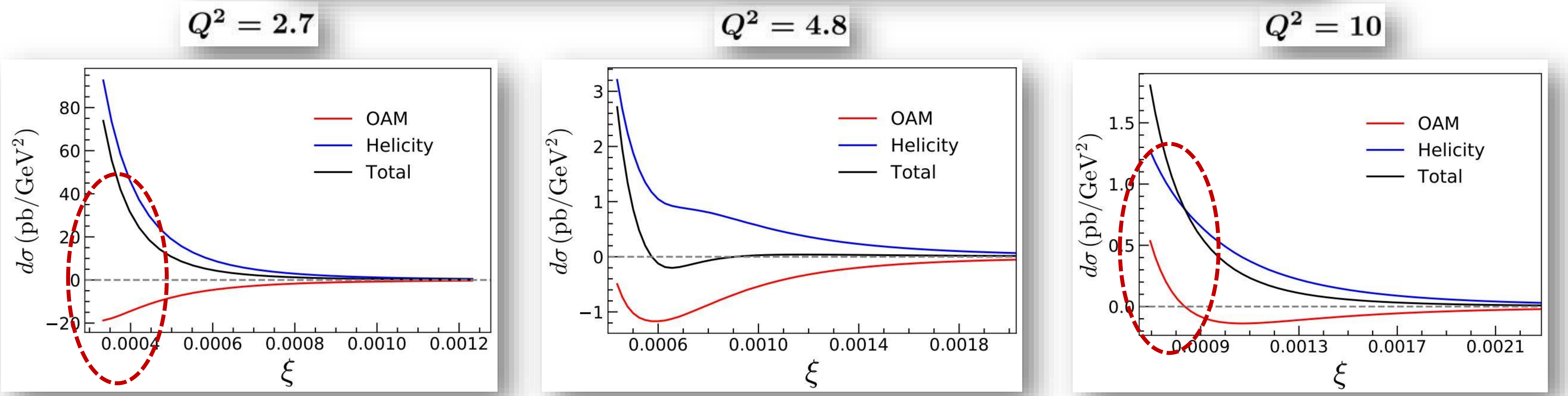
$$\ldots^{)*}(\xi)\left(\tilde{\mathcal{H}}_g^{(2)}(\xi) + \frac{q_\perp^2 - Q^2/4}{q_\perp^2 + Q^2/4}\,\mathcal{L}_g(\xi)\right)$$

$\Delta G(x)$ $\qquad$ $L_g(x)$



Cancellation expected between Helicity & OAM at small x

$$\Delta G(x) \approx -L_g(x)$$



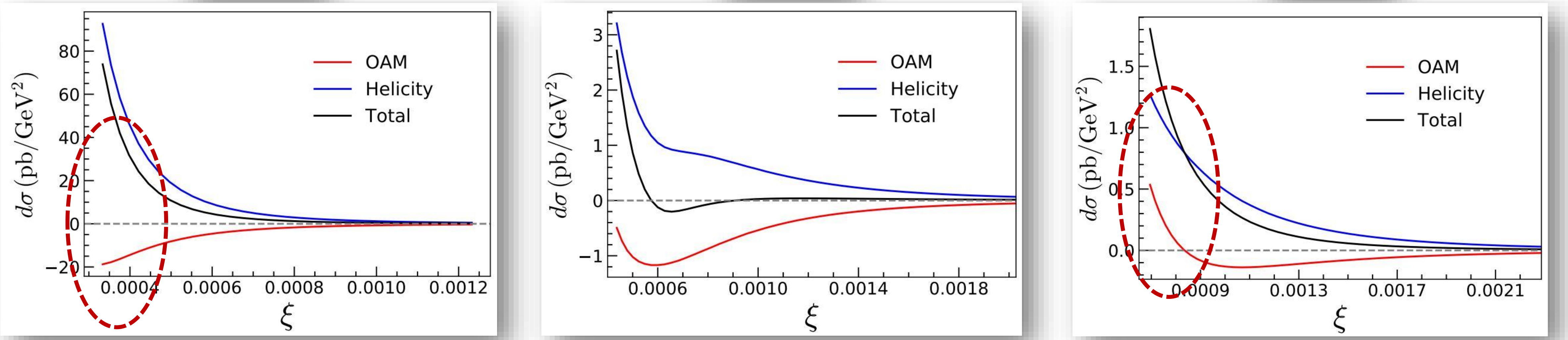
DSA: $$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu \Big|_{\delta\phi=0} \sim \mathcal{H}_g^{(1)*}(\xi) \left(\tilde{\mathcal{H}}_g^{(2)}(\xi) + \frac{q_\perp^2 - Q^2/4}{q_\perp^2 + Q^2/4} \mathcal{L}_g(\xi) \right)$$

$$\tilde{\mathcal{H}}_g^{(2)}(\xi) \downarrow \Delta G(x) \qquad \mathcal{L}_g(\xi) \downarrow L_g(x)$$

Cancellation expected between Helicity & OAM at small x

$$\Delta G(x) \approx -L_g(x)$$

$Q^2 = 2.7$ $\quad$ $Q^2 = 4.8$ $\quad$ $Q^2 = 10$



DSA: $\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu$

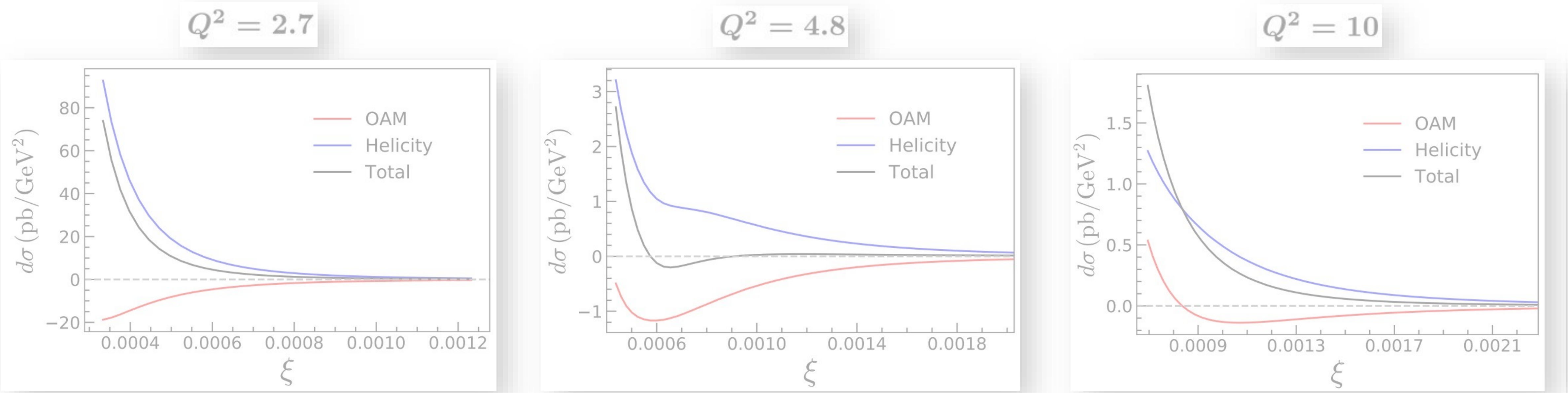
Unique opportunity to study interplay between

$\Delta G(x)$ **&** $L_g(x)$

which has been so far only studied theoretically!

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section



Caveat:

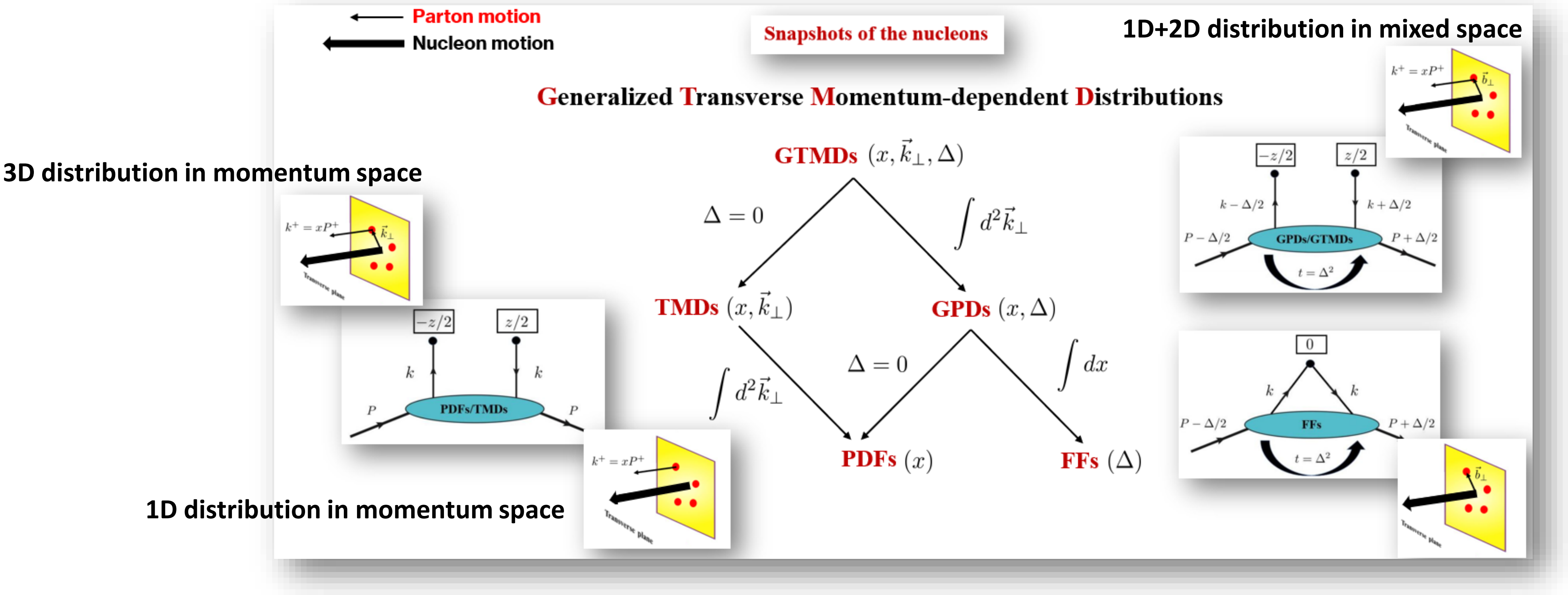
- **In practice, measurements are done in a window in z around $z = 1/2$**

  Corrections of order $\sim (z - 1/2)^2$ should be calculable in k_t -factorization approach

Summary: GTMDs

GTMDs: Big picture

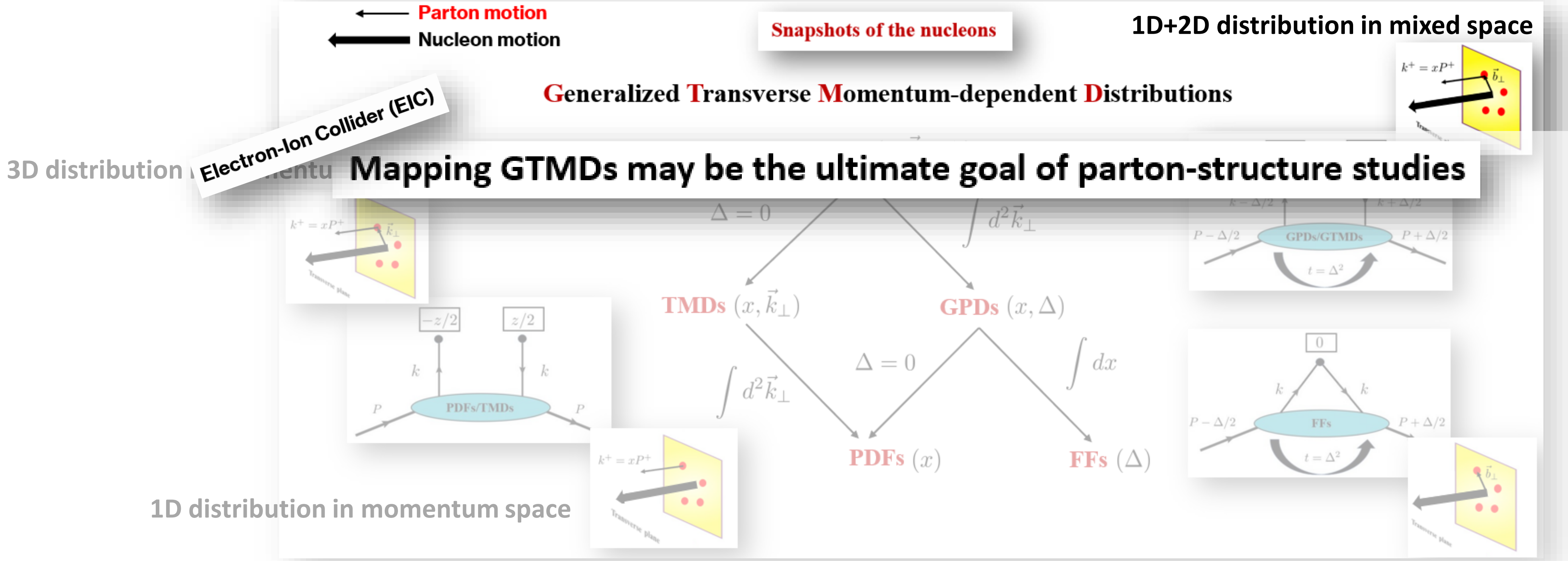
- **GTMDs are the holy grail of spin physics**



Summary: GTMDs

GTMDs: Big picture

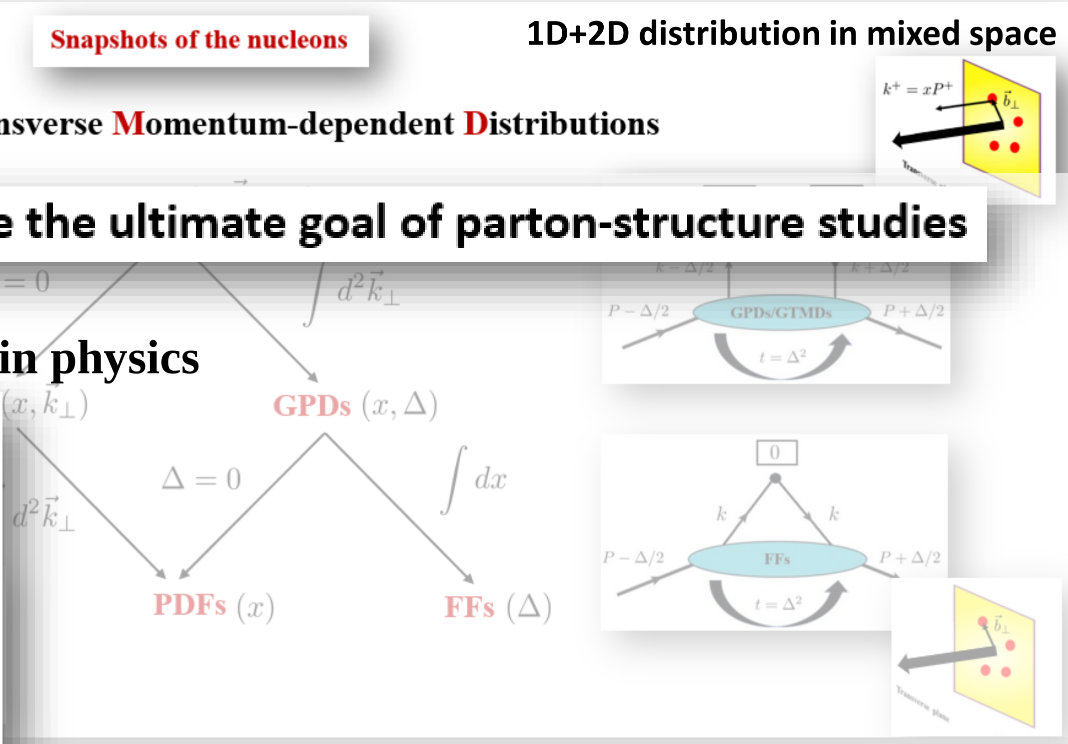
- **GTMDs are the holy grail of spin physics**



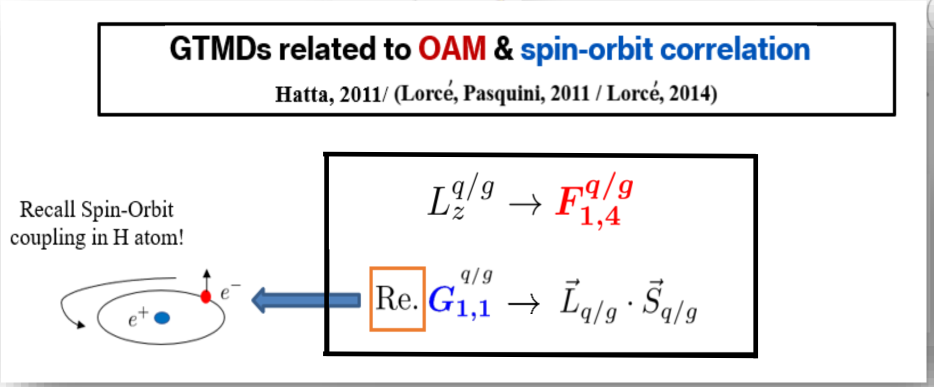
Summary: GTMDs

GTMDs: Big picture

- **GTMDs are the holy grail of spin physics**



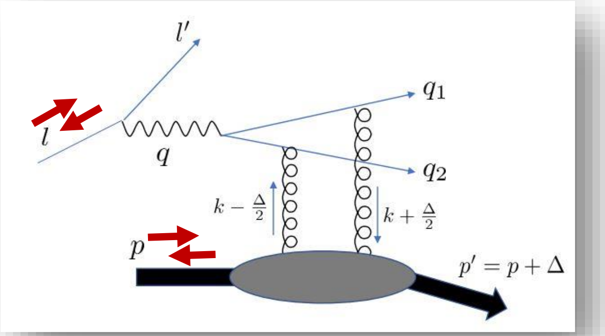
- **Interesting connection between GTMDs & spin physics**



Summary: GTMDs & OAM

Summary of our work

- **GTMDs are the holy grail of spin physics**
- **DSA in exclusive dijet production is a unique observable to access the gluon OAM @ EIC:**



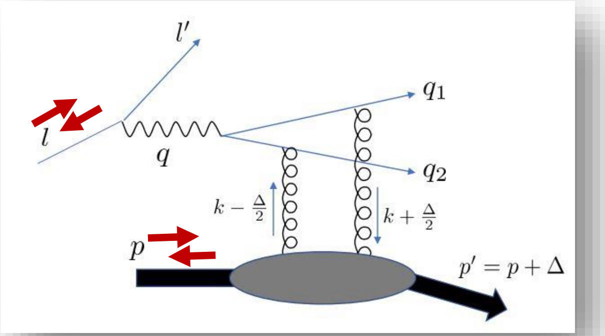
$$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu \sim -\,\mathfrak{Re}\left[\left\{\mathcal{H}_g^{(1)*}(\xi) + \frac{4q_\perp^2}{q_\perp^2 + \mu^2}\mathcal{H}_g^{(2)*}(\xi)\right\}\mathcal{L}_g(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

$$+\,\mathfrak{Re}\left[\mathcal{H}_g^{(1)*}(\xi)\,\tilde{\mathcal{H}}_g^{(2)}(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

Summary: GTMDs & OAM

Summary of our work

- **GTMDs are the holy grail of spin physics**
- **DSA in exclusive dijet production is a unique observable to access the gluon OAM @ EIC:**



$$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu \sim -\,\mathfrak{Re}\left[\left\{\mathcal{H}_g^{(1)*}(\xi) + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\mathcal{H}_g^{(2)*}(\xi)\right\}\mathcal{L}_g(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

$$+\,\mathfrak{Re}\left[\mathcal{H}_g^{(1)*}(\xi)\,\tilde{\mathcal{H}}_g^{(2)}(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

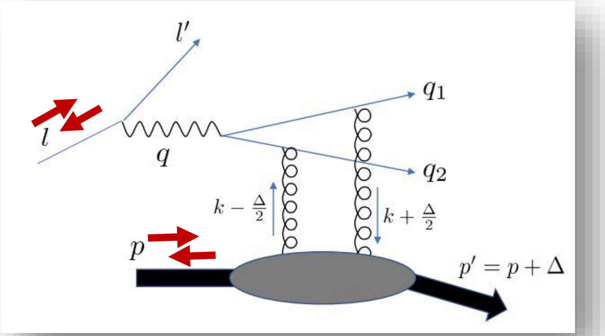
Signature of gluon OAM is cosine angular modulation

Summary: GTMDs & OAM

Summary of our work

DSA does not vanish for symmetric jet configurations $z = \bar{z} = \dfrac{1}{2}$

- **DSA in exclusive dijet production is a unique observable to access the gluon OAM @ EIC:**



$$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu \sim -\,\mathfrak{Re}\left[\left\{\mathcal{H}_g^{(1)*}(\xi) + \frac{4q_\perp^2}{q_\perp^2 + \mu^2}\mathcal{H}_g^{(2)*}(\xi)\right\}\mathcal{L}_g(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

$$+\,\mathfrak{Re}\left[\mathcal{H}_g^{(1)*}(\xi)\,\tilde{\mathcal{H}}_g^{(2)}(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

Signature of gluon OAM is cosine angular modulation

Summary: GTMDs & OAM

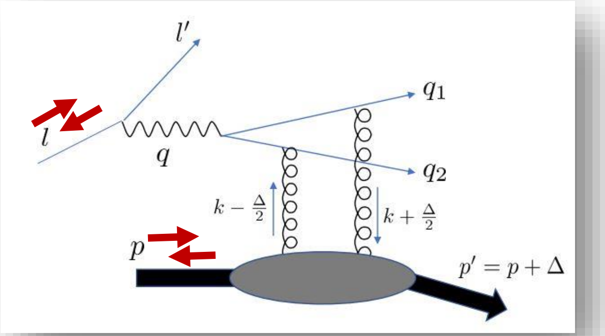
Summary of our work

DSA does not vanish for symmetric jet configurations $z = \bar{z} = \frac{1}{2}$

Consequence:

Elimination of factorization-breaking third poles at $x = \pm\xi$

- DSA in exclusive dijet production is



$$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu \sim -\,\mathfrak{Re}\left[\left\{\mathcal{H}_g^{(1)*}(\xi) + \frac{4q_\perp^2}{q_\perp^2 + \mu^2}\mathcal{H}_g^{(2)*}(\xi)\right\}\mathcal{L}_g(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

$$+\,\mathfrak{Re}\left[\mathcal{H}_g^{(1)*}(\xi)\tilde{\mathcal{H}}_g^{(2)}(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

Signature of gluon OAM is cosine angular modulation

Summary: GTMDs & OAM

Summary of our work

DSA does not vanish for symmetric jet configurations $z = \bar{z} = \dfrac{1}{2}$

GTMDs are the holy grail of spin pl…

Consequence:

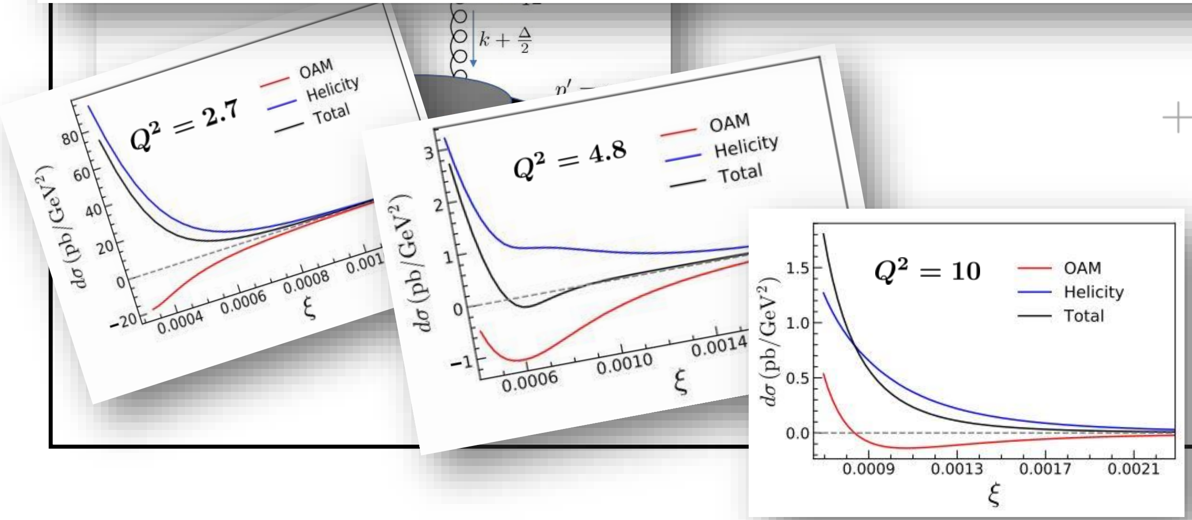
Elimination of factorization-breaking third poles at $x = \pm\xi$

- DSA in exclusive dijet production is

DSA is a unique observable to study interplay between gluon OAM & helicity

$$\Big\}\mathcal{L}_g(\xi)\Big]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

$$+\,\Re\mathrm{e}\left[\mathcal{H}_g^{(1)*}(\xi)\,\tilde{\mathcal{H}}_g^{(2)}(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$



Signature of gluon OAM is cosine angular modulation

Summary: GTMDs & OAM

Summary of our work

DSA does not vanish for symmetric jet configurations $z = \bar{z} = \frac{1}{2}$

Consequence:

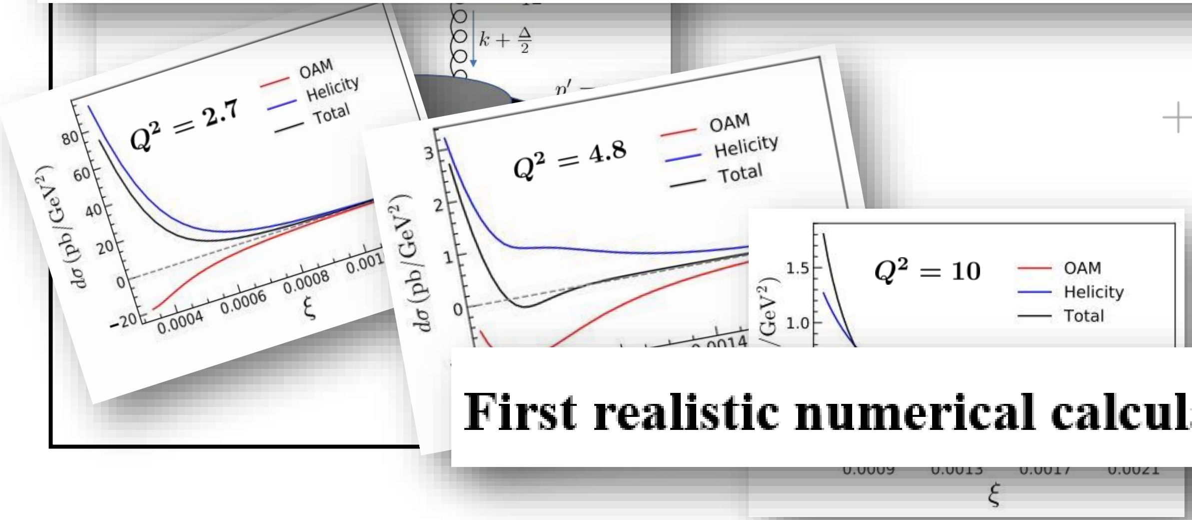
Elimination of factorization-breaking third poles at $x = \pm\xi$

- DSA in exclusive dijet production is

DSA is a unique observable to study interplay between gluon OAM & helicity

$$\Big\}\mathcal{L}_g(\xi)\Big]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

$$+\,\Re e\Big[\mathcal{H}_g^{(1)*}(\xi)\,\tilde{\mathcal{H}}_g^{(2)}(\xi)\Big]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$



Signature of gluon OAM is cosine angular modulation

First realistic numerical calculation of observable sensitive to OAM @ EIC

Backup slides

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

Ingredients for non-perturbative functions

OAM

$$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu = -\frac{2^{10}\pi^4}{N_c} h_l h_p \alpha_s^2 \alpha_{em} e_q^2 \frac{(1+\xi)\xi Q^2}{(q_\perp^2+\mu^2)^2} |l_\perp||\Delta_\perp| \cos(\phi_{l_\perp} - \phi_{\Delta_\perp}) \times \mathfrak{Re}\left[\left\{\mathcal{H}_g^{(1)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\left(\mathcal{H}_g^{(2)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(2)*}\right)\right\}\mathcal{L}_g + \left(\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\mathcal{E}_g^{(2)*}\right)\frac{\mathcal{O}}{2}\right]$$

Helicity

$$\int d\phi_{q_\perp} L^{\mu\nu} A_\mu A_\nu = \frac{2^{10}\pi^4}{N_c} h_l h_p \alpha_s^2 \alpha_{em} e_q^2 \frac{(1-\xi^2)\xi Q^2}{(q_\perp^2+\mu^2)^2} |l_\perp||\Delta_\perp| \cos(\phi_{l_\perp} - \phi_{\Delta_\perp}) \times \mathfrak{Re}\left[\left(\mathcal{H}_g^{(1)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(1)*}\right)\left(\tilde{\mathcal{H}}_g^{(2)} - \frac{\xi^2}{1-\xi^2}\tilde{\mathcal{E}}_g^{(2)}\right)\right]$$

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

Ingredients for non-perturbative functions

- **Neglect contributions from** $(E_g,\, \tilde{E}_g)\,,\, F_{1,2}$ $\longrightarrow$ **Very simple formula**

OAM

$$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu = -\frac{2^{10}\pi^4}{N_c} h_l h_p \alpha_s^2 \alpha_{em} e_q^2 \frac{(1+\xi)\xi Q^2}{(q_\perp^2+\mu^2)^2} |l_\perp||\Delta_\perp| \cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$
$$\times \mathfrak{Re}\left[\left\{\mathcal{H}_g^{(1)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\left(\mathcal{H}_g^{(2)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(2)*}\right)\right\}\mathcal{L}_g + \left(\mathcal{E}_g^{(1)*} + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\mathcal{E}_g^{(2)*}\right)\frac{\mathcal{O}}{2}\right]$$

Helicity

$$\int d\phi_{q_\perp} L^{\mu\nu} A_\mu A_\nu = \frac{2^{10}\pi^4}{N_c} h_l h_p \alpha_s^2 \alpha_{em} e_q^2 \frac{(1-\xi^2)\xi Q^2}{(q_\perp^2+\mu^2)^2} |l_\perp||\Delta_\perp| \cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$
$$\times \mathfrak{Re}\left[\left(\mathcal{H}_g^{(1)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(1)*}\right)\left(\tilde{\mathcal{H}}_g^{(2)} - \frac{\xi^2}{1-\xi^2}\tilde{\mathcal{E}}_g^{(2)}\right)\right]$$

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

Ingredients for non-perturbative functions

- **Neglect contributions from** $(E_g,\, \tilde{E}_g)\,,\, F_{1,2}$ $\longrightarrow$ **Very simple formula**

- **Model** $(H_g,\, \tilde{H}_g)$ **according to the Double distribution approach (see for instance Radyushkin, 9805342)**

$$\boxed{\begin{pmatrix} H_g(x,\xi) \\ \tilde{H}_g(x,\xi) \end{pmatrix} = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(\beta+\xi\alpha-x) \times \frac{15}{16}\frac{[(1-|\beta|)^2-\alpha^2]^2}{(1-|\beta|)^5} \times \begin{cases} \beta\, G(\beta) \\ \beta\, \Delta G(\beta) \end{cases}}$$

Probing gluon OAM through exclusive dijet production

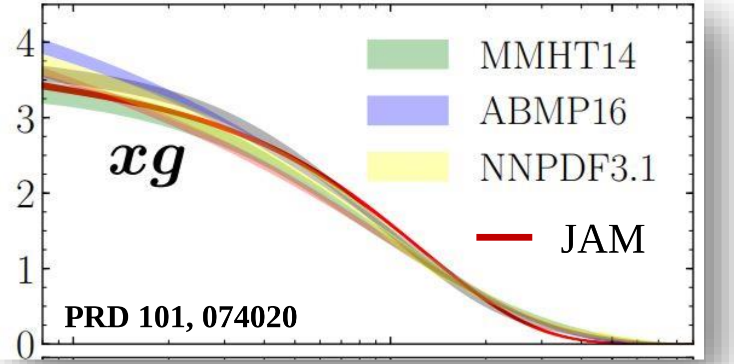
Numerical estimate of cross section

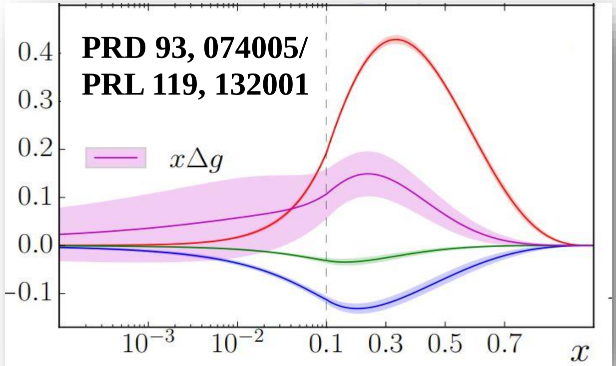
Ingredients for non-perturbative functions

- **Neglect contributions from** $(E_g,\ \tilde{E}_g)\ ,\ F_{1,2}$ $\longrightarrow$ **Very simple formula**
- **Model** $(H_g,\ \tilde{H}_g)$ **according to the Double distribution approach (see for instance Radyushkin, 9805342)**

$$\begin{pmatrix} H_g(x,\xi) \\ \tilde{H}_g(x,\xi) \end{pmatrix} = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(\beta + \xi\alpha - x) \times \frac{15}{16} \frac{[(1-|\beta|)^2 - \alpha^2]^2}{(1-|\beta|)^5} \times \begin{cases} \beta\, G(\beta) \\ \beta\, \Delta G(\beta) \end{cases}$$

JAM PDFs





Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

Ingredients for non-perturbative functions

- **Neglect contributions from** $(E_g,\, \tilde{E}_g)\,,\, F_{1,2}$ $\longrightarrow$ **Very simple formula**
- **Model** $(H_g,\, \tilde{H}_g)$ **according to the Double distribution approach (see for instance Radyushkin, 9805342)**
- **Model for OAM:**

1. "OAM density": (Hatta, Yoshida, 1207.5332)

$$L^g_{can}(\boldsymbol{x}) \;=\; x\int_x^1 \frac{dx'}{x'^2}\big(H_g(x')+E_g(x')\big) \;-\; 2x\int_x^1 \frac{dx'}{x'^2}\Delta G(x') + \text{ genuine twist-three}$$

Numerical estimate of cross section

Ingredients for non-perturbative functions

- **Neglect contributions from** $(E_g,\, \tilde{E}_g)\,,\, F_{1,2}$ $\longrightarrow$ **Very simple formula**
- **Model** $(H_g,\, \tilde{H}_g)$ **according to the Double distribution approach (see for instance Radyushkin, 9805342)**
- **Model for OAM:**

  1. "OAM density": (Hatta, Yoshida, 1207.5332)

$$\boxed{L^g_{can}(x) \overset{\text{WW approx}}{\approx} x \int_x^1 \frac{dx'}{x'^2}(H_g(x') + E_g(x')) - 2x \int_x^1 \frac{dx'}{x'^2} \Delta G(x') + \cancel{\text{genuine twist-three}}}$$

$$H_g(x') = x' G(x')$$

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

Ingredients for non-perturbative functions

- **Neglect contributions from** $(E_g,\ \tilde{E}_g)\ ,\ F_{1,2} \longrightarrow$ **Very simple formula**
- **Model** $(H_g,\ \tilde{H}_g)$ **according to the Double distribution approach (see for instance Radyushkin, 9805342)**

arXiv: 2207.03378 (2022)

Small-x evolution of the gluon GPD E_g

Yoshitaka Hatta[1,2] and Jian Zhou[3]

22)

$$E_g(x) \propto H_g(x)$$

WW approx

$$L^g_{can}(\boldsymbol{x}) \approx x\int_x^1 \frac{dx'}{x'^2}\big(H_g(x') + E_g(x')\big) - 2x\int_x^1 \frac{dx'}{x'^2}\Delta G(x') + \cancel{\text{genuine twist-three}}$$

$$H_g(x') = x'G(x') \qquad \text{Neglect } E_g$$

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

Ingredients for non-perturbative functions

- **Neglect contributions from** $(E_g,\ \tilde{E}_g)\ ,\ F_{1,2}$ $\longrightarrow$ **Very simple formula**

- **Model** $(H_g,\ \tilde{H}_g)$ **according to the Double distribution approach (see for instance Radyushkin, 9805342)**

- **Model for OAM:**

  1. "OAM density": (Hatta, Yoshida, 1207.5332)

$$\boxed{L^g_{can}(\boldsymbol{x}) \overset{\text{WW approx}}{\approx} x\int_x^1 \frac{dx'}{x'^2}\left(H_g(x') + E_g(x')\right) - 2x\int_x^1 \frac{dx'}{x'^2}\Delta G(x') + \cancel{\text{genuine twist-three}}}$$

  2. Use the Double distribution approach to construct $xL_g(x,\boldsymbol{\xi})$ from $xL_g(x)$ (GPD-like approach)