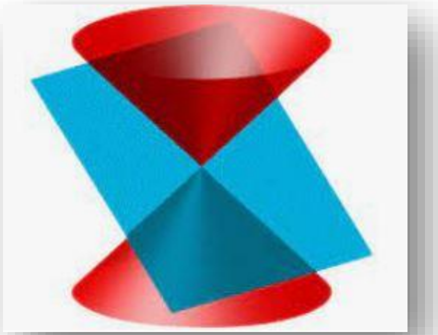
Signature(s) of gluon OAM



Light cone 2022: Physics of Hadrons on the Light Front

Shohini Bhattacharya

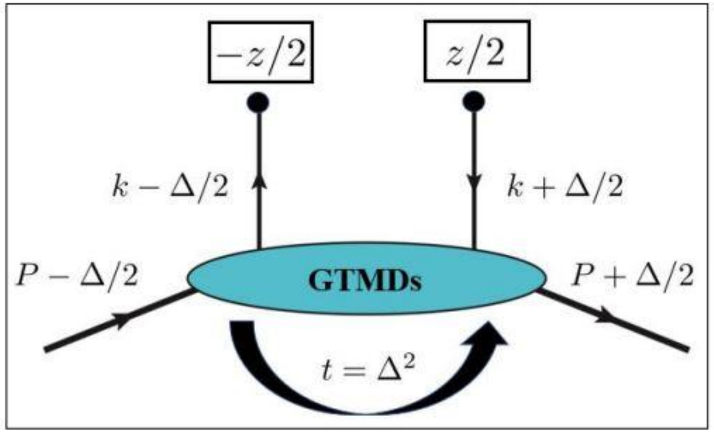
BNL

21 September 2022

Outline

- **Generalized TMDs (GTMDs)**
- **Wigner functions**
- **Observables for GTMDs: State of the art**
- **Summary**

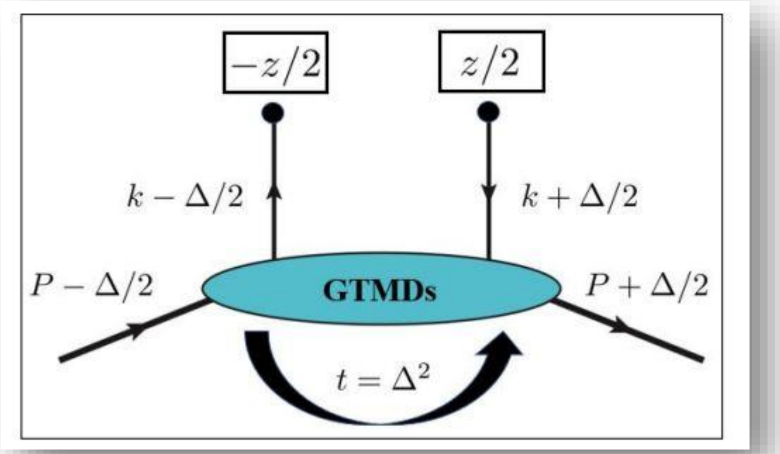
Generalized **T**ransverse **M**omentum dependent **D**istributions (GTMDs)



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)



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Parameterization of correlator through GTMDs:

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

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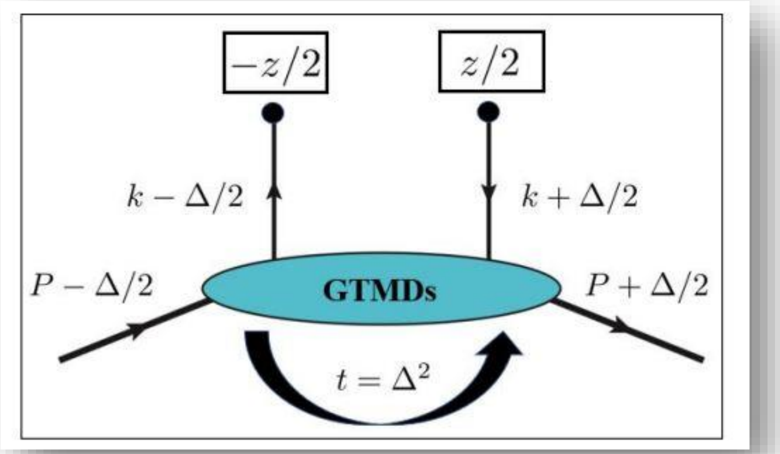

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x : "average" longitudinal momentum fraction of quark

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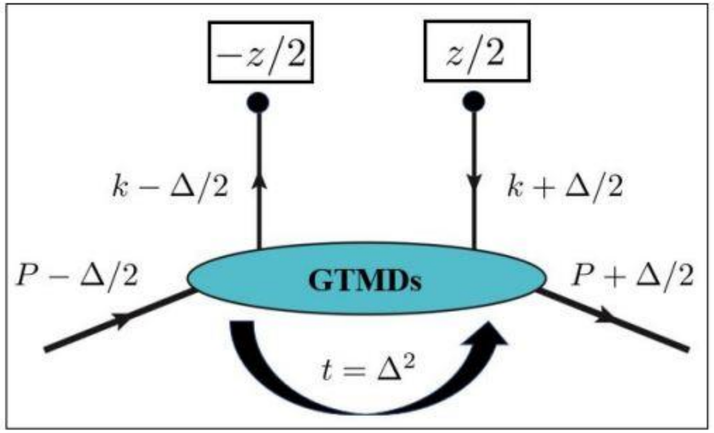

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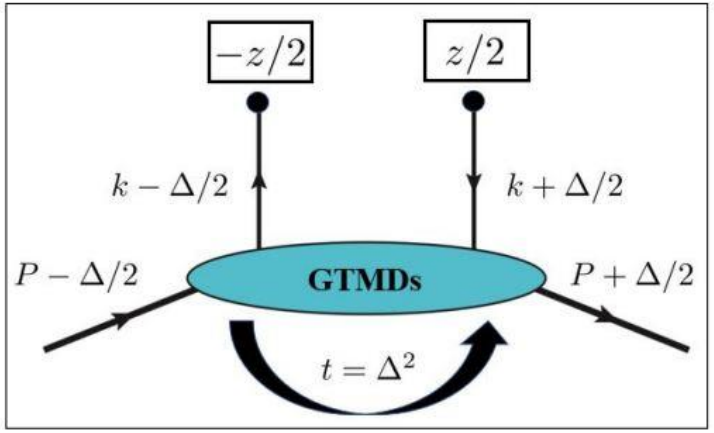

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$\Delta_\perp$: transverse momentum transfer to nucleon

x : "average" longitudinal momentum fraction of quark

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

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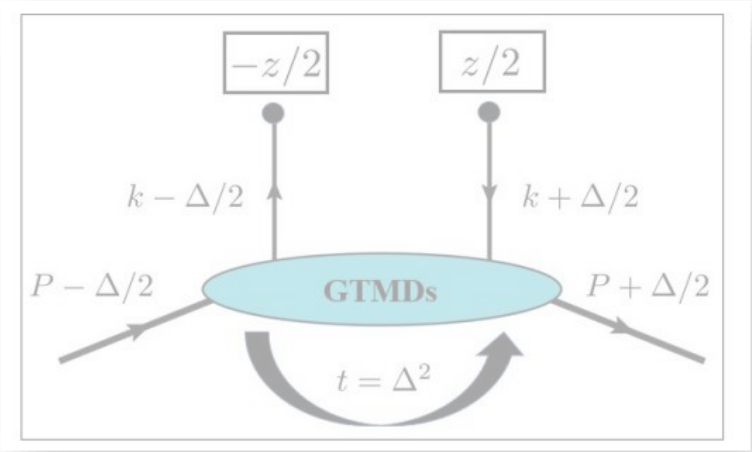
Generalized Transverse Momentum dependent Distributions (GTMDs)



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General results:

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

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

iii. **GTMDs are complex functions**

Why are GTMDs interesting?

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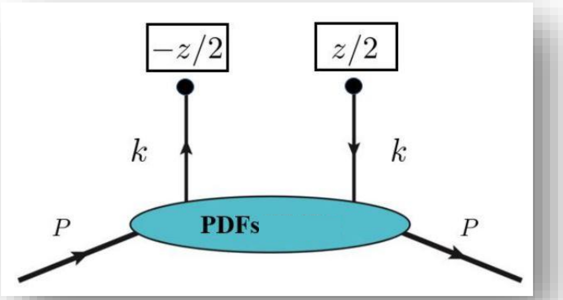
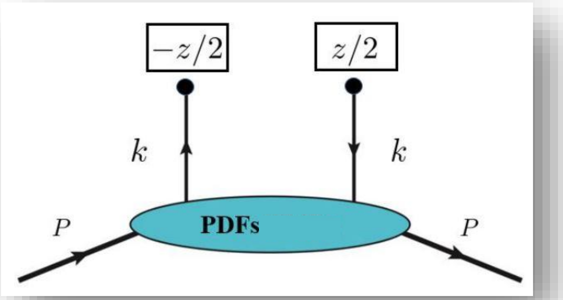
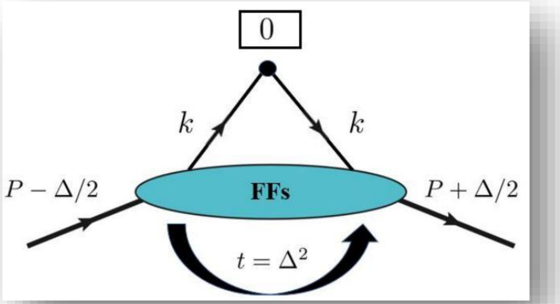


PDFs (x)

Why are GTMDs interesting?



PDFs (x) **FFs** (Δ)



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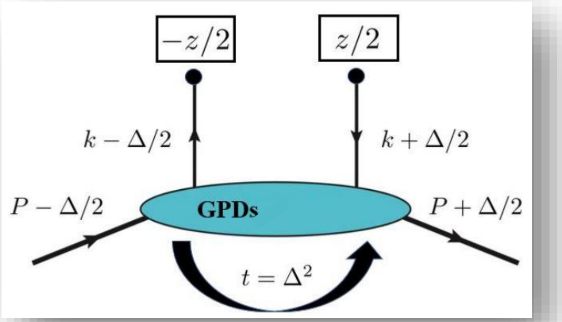
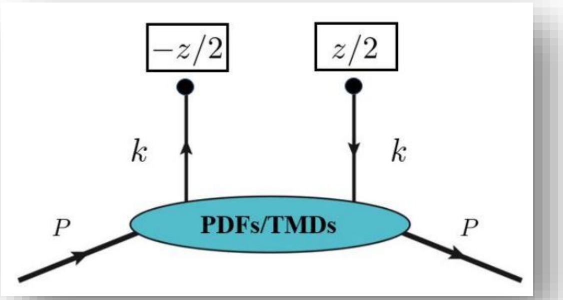




TMDs $(x, \vec{k}_\perp)$

GPDs (x, Δ)

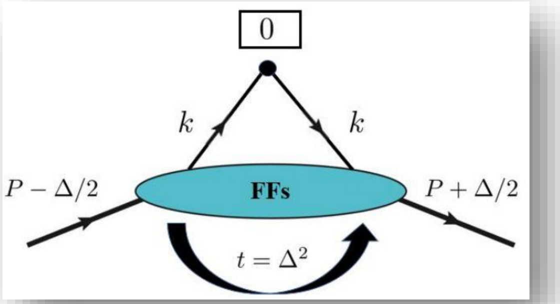
$\int d^2\vec{k}_\perp$

$\Delta = 0$

$\int dx$

PDFs (x)

FFs (Δ)



Why are GTMDs interesting?

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

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

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

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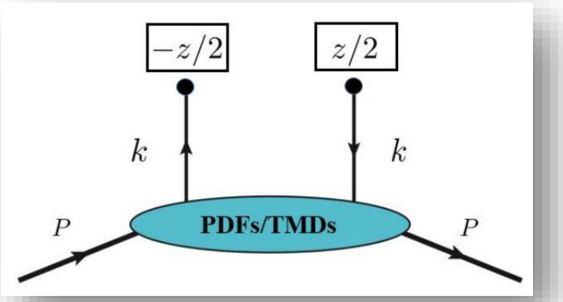
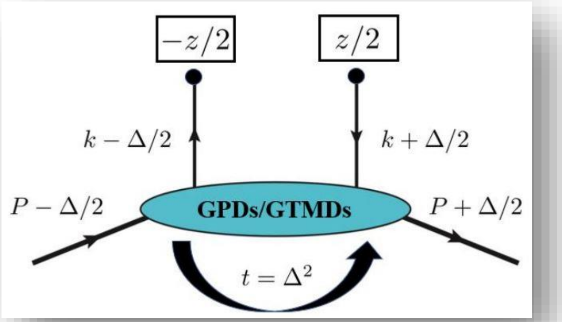
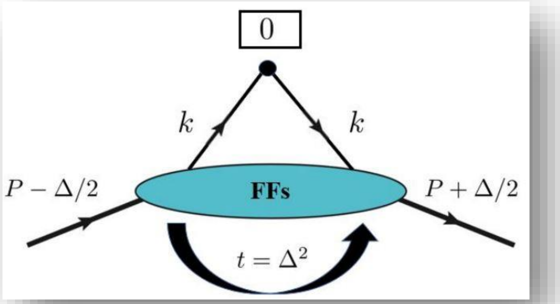






Why are GTMDs interesting?

1) GTMDs are the "Mother Functions"

(Meissner, Metz, Schlegel, 2009)

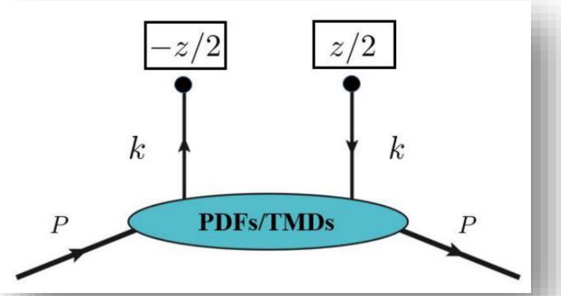
GTMDs $(x, \vec{k}_\perp, \Delta)$

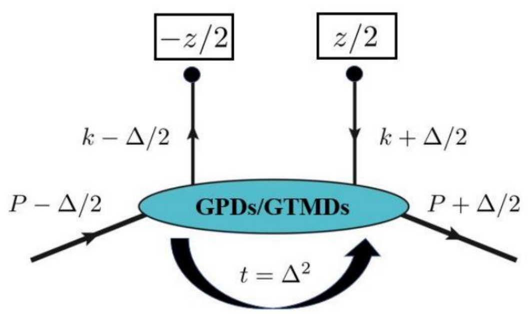
$\Delta = 0$ $\qquad$ $\int d^2\vec{k}_\perp$

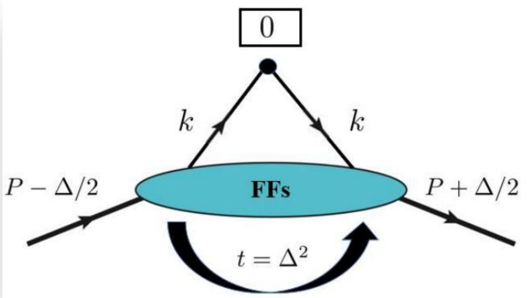
TMDs $(x, \vec{k}_\perp)$ $\qquad$ **GPDs** (x, Δ)

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

PDFs (x) $\qquad$ **FFs** (Δ)







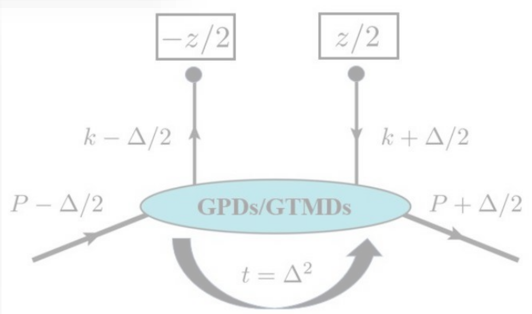
Why are GTMDs interesting?

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

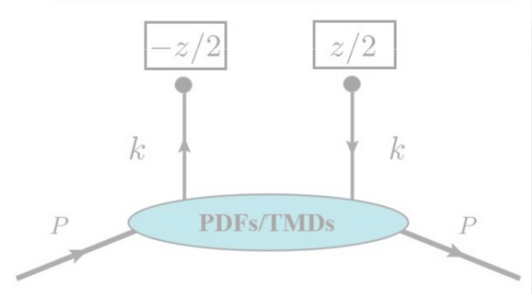
2) **GTMDs contain physics beyond TMDs & GPDs**

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

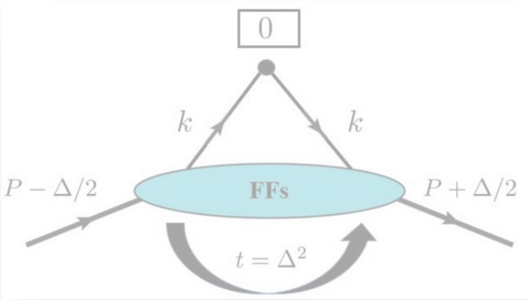
$\Delta = 0$ $\int d^2\vec{k}_\perp$



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)**

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)

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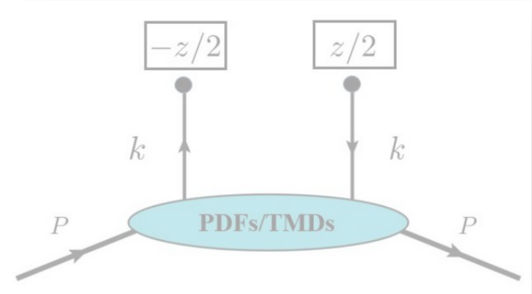
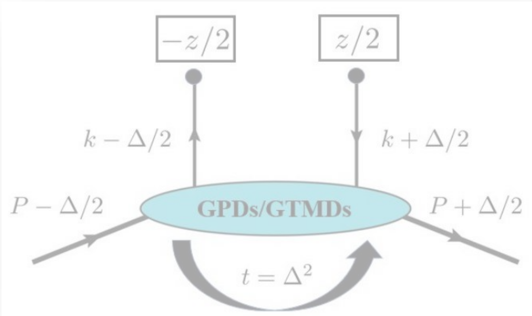
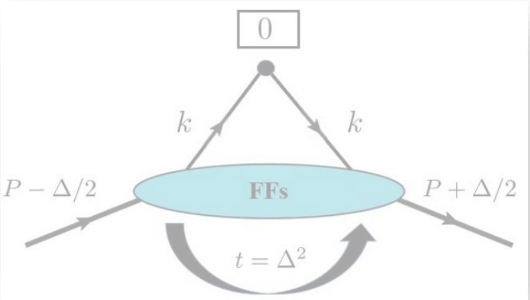
PDFs (x) **FFs** (Δ)







Why are GTMDs interesting?

Application

Wigner functions

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Wigner functions

- **Recap from NRQM:**

  Expectation value of observables $\langle \mathcal{O} \rangle = \int dx \int dk \mathcal{O}(x,k) W(x,k)$

Why are GTMDs interesting?

Application

Wigner functions & connection to parton Orbital Angular Momentum

- **Recap from NRQM:**

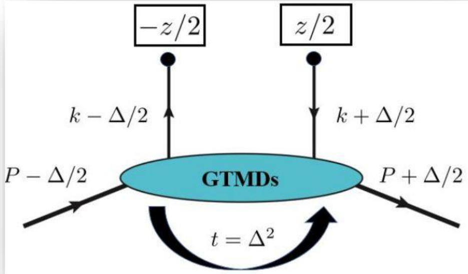
Expectation value of observables $\langle \mathcal{O} \rangle = \int dx \int dk \mathcal{O}(x,k) W(x,k)$

- **OAM as a moment of Wigner distribution** : **(Lorcé, Pasquini, 2011 / Hatta, 2011 / Ji, Xiong, Yuan, 2012)**

$$L_z^q = \int dx \int d^2k_\perp d^2b_\perp (\vec{b}_\perp \times \vec{k}_\perp)_z \, W^q \ (x, \vec{b}_\perp, \vec{k}_\perp)$$

Intuitive definition of OAM

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



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

- **OAM as a moment of Wigner distribution/GTMD: (Lorcé, Pasquini, 2011 / Hatta, 2011 / Ji, Xiong, Yuan, 2012)**

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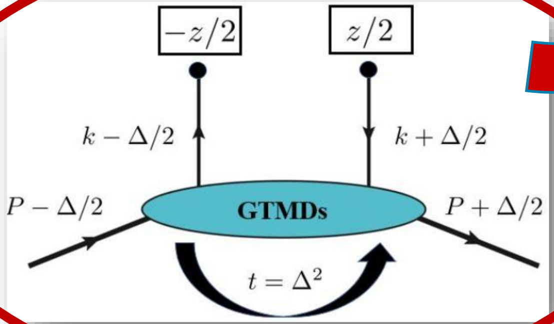

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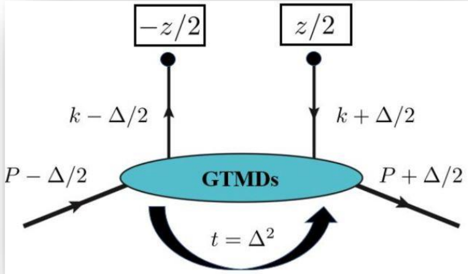

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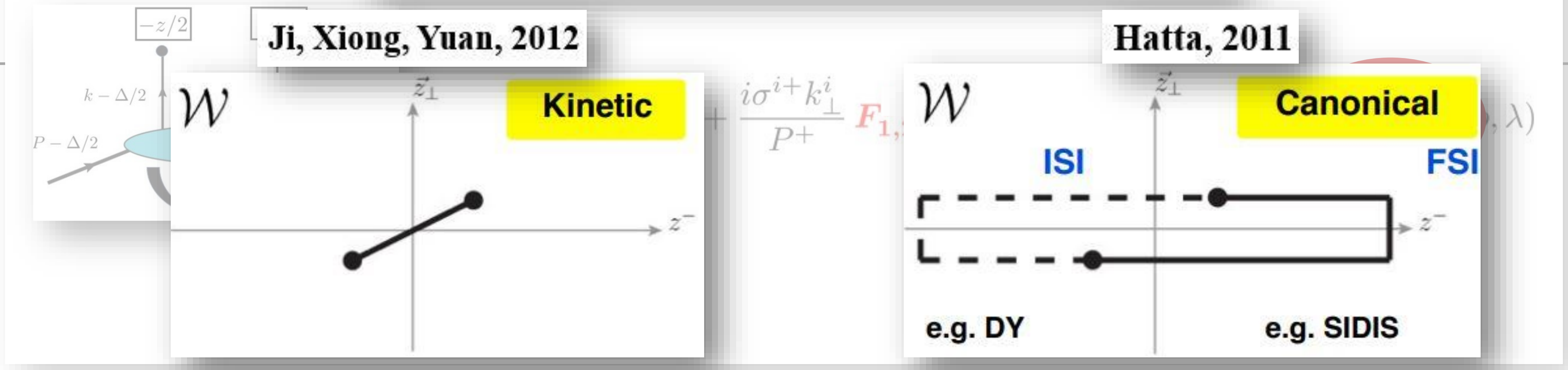
- **OAM as a moment of Wigner distribution/GTMD: (Lorcé, Pasquini, 2011 / Hatta, 2011 / Ji, Xiong, Yuan, 2012)**

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

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

Same equation holds for gluons (Hatta, 1111.3547)

Gauge-invariant extension



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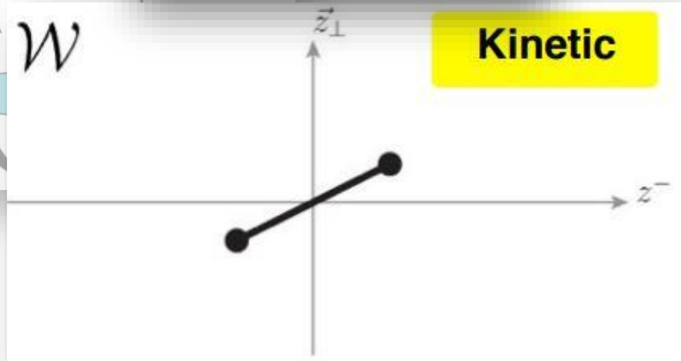
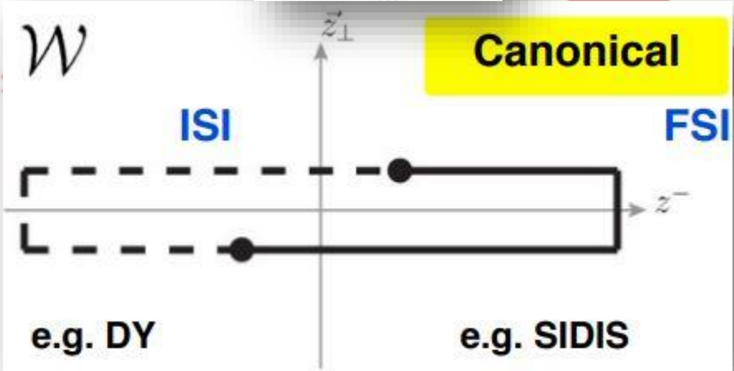
Parameterization of a ... 23):

Ji, Xiong, Yuan, 2012

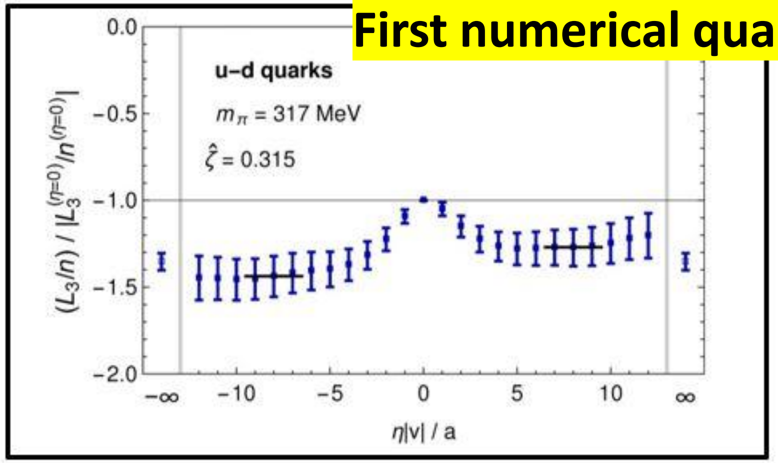


Hatta, 2011



• O ... Xiong, Yuan, 2012)

First numerical quantification of differences between Ji & JM OAM



First lattice calculation of L_{JM} vs. L_{Ji} (Engelhardt, 1701.01536)

i. Figure shows $L^{u-d}_{\text{JM}}/L^{u-d}_{\text{Ji}}$

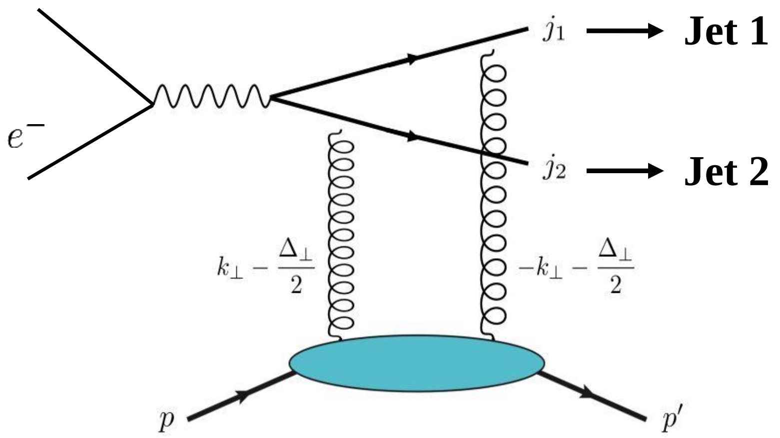
ii. Significant numerical differences between L_{JM} & L_{Ji}

OAM

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)



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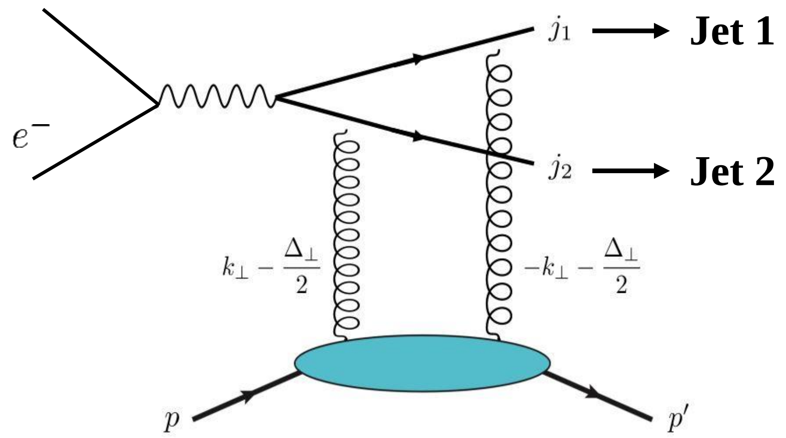

"Elliptic" Wigner distribution:

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

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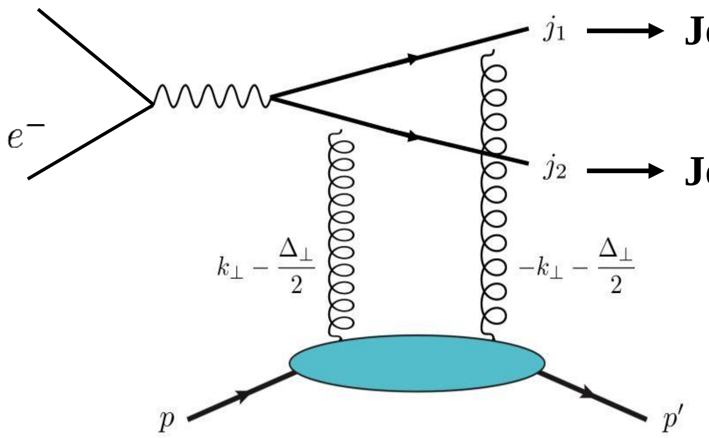

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Main result:

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

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

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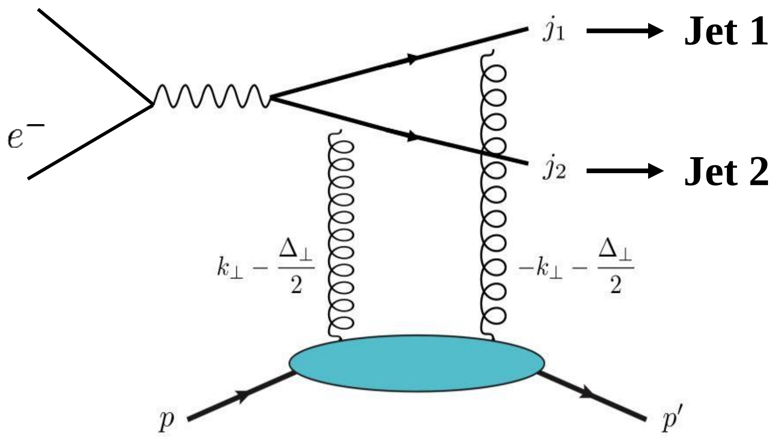

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Cosine angular modulation

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

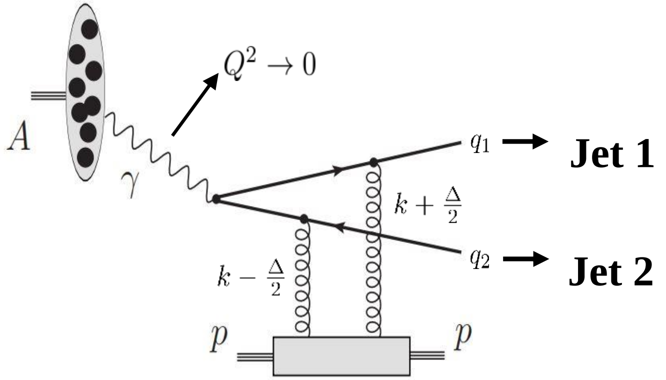
$$\approx d\sigma_0 + 2\cos 2(\phi_{P_\perp} - \phi_{\Delta_\perp}) d\tilde{\sigma}$$

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

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:

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

Cosine angular modulation

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

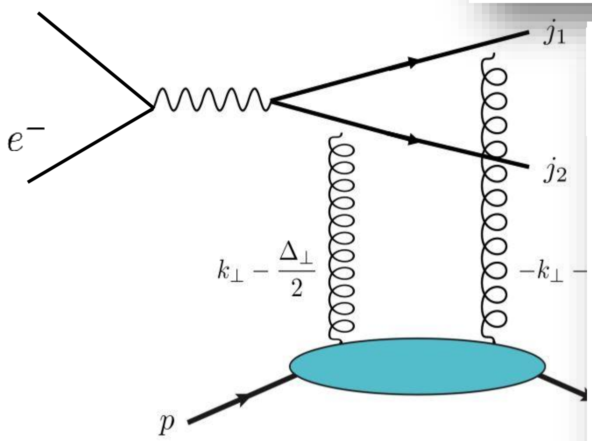
$$\vec{P}_\perp = \frac{1}{2}(\vec{j}_{2\perp}-\vec{j}_{1\perp})$$

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

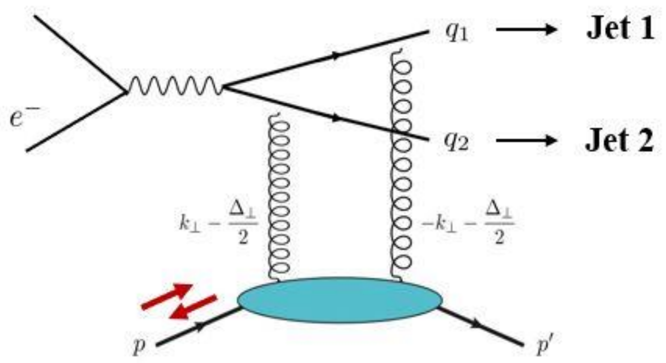
Observables for GTMDs

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

Coming up:



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:

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

Cosine angular modulation

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

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

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Observables for GTMDs

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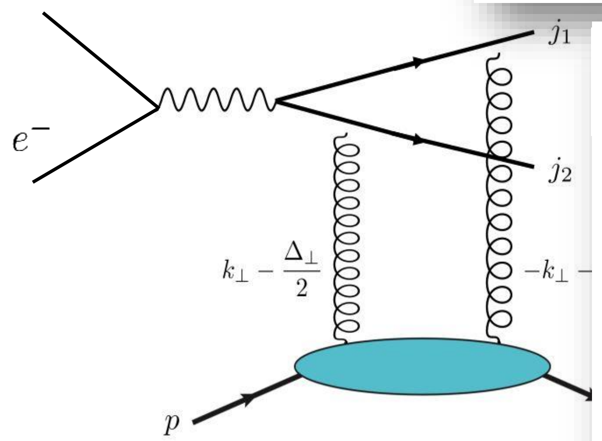


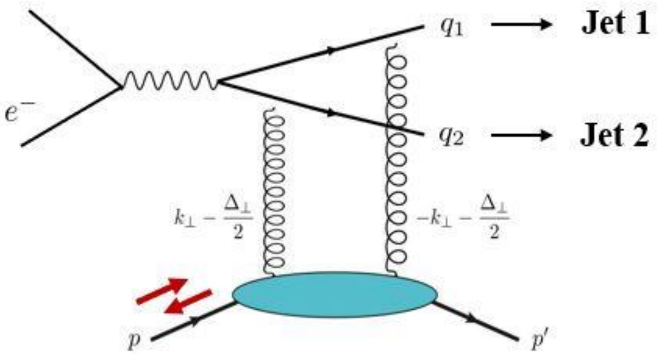
Main result:

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

$$\approx d\sigma_0$$

Cosine angul

What happens if target is polarized?



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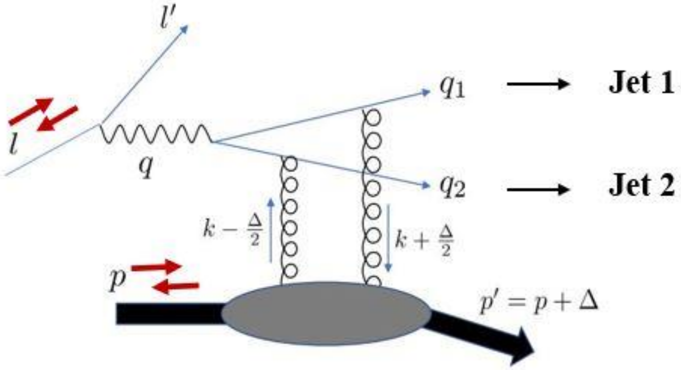
Hunting the Gluon Orbital Angular Momentum at the Electron-Ion Collider

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

What happens if in addition lepton is polarized?



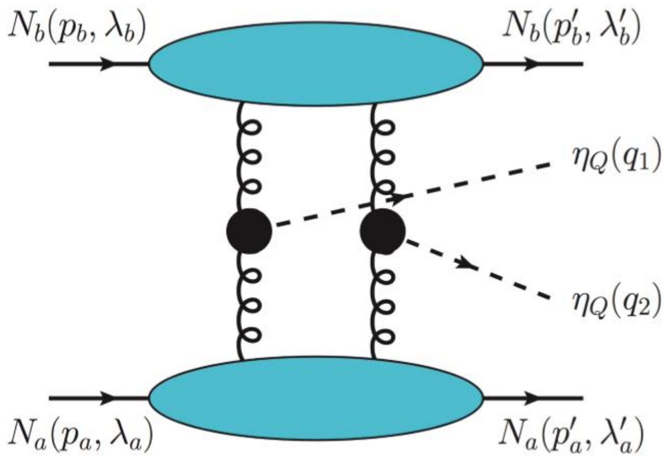
arXiv: 2201.08709 (2022)

Signature of the gluon orbital angular momentum

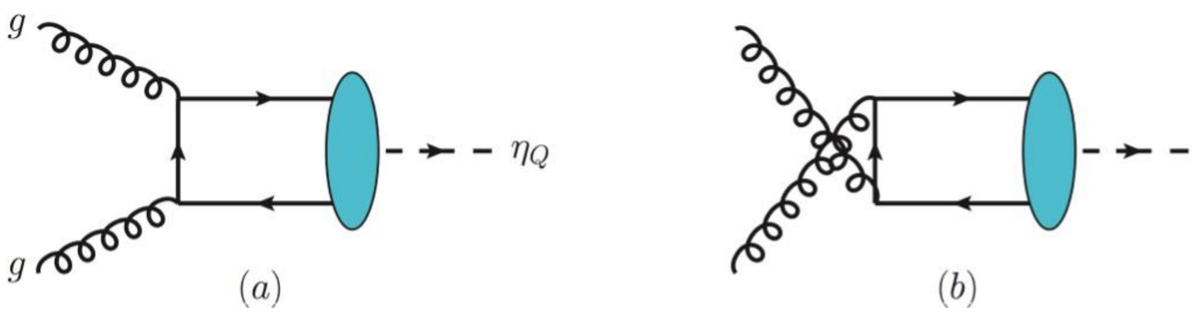
Shohini Bhattacharya,[1,*] Renaud Boussarie,[2,†] and Yoshitaka Hatta[1,3,‡]

Observables for GTMDs

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



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

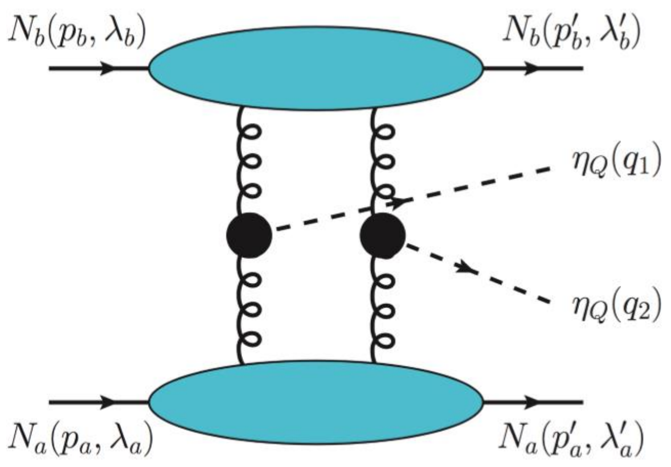


Main result:

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

Observables for GTMDs

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



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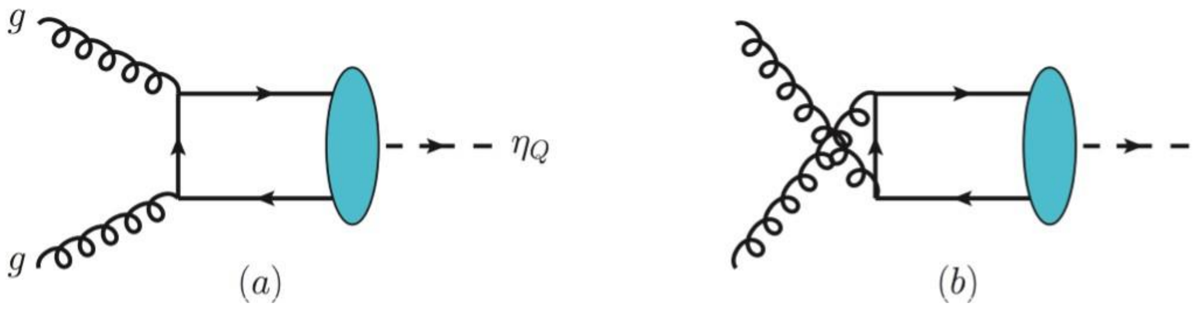

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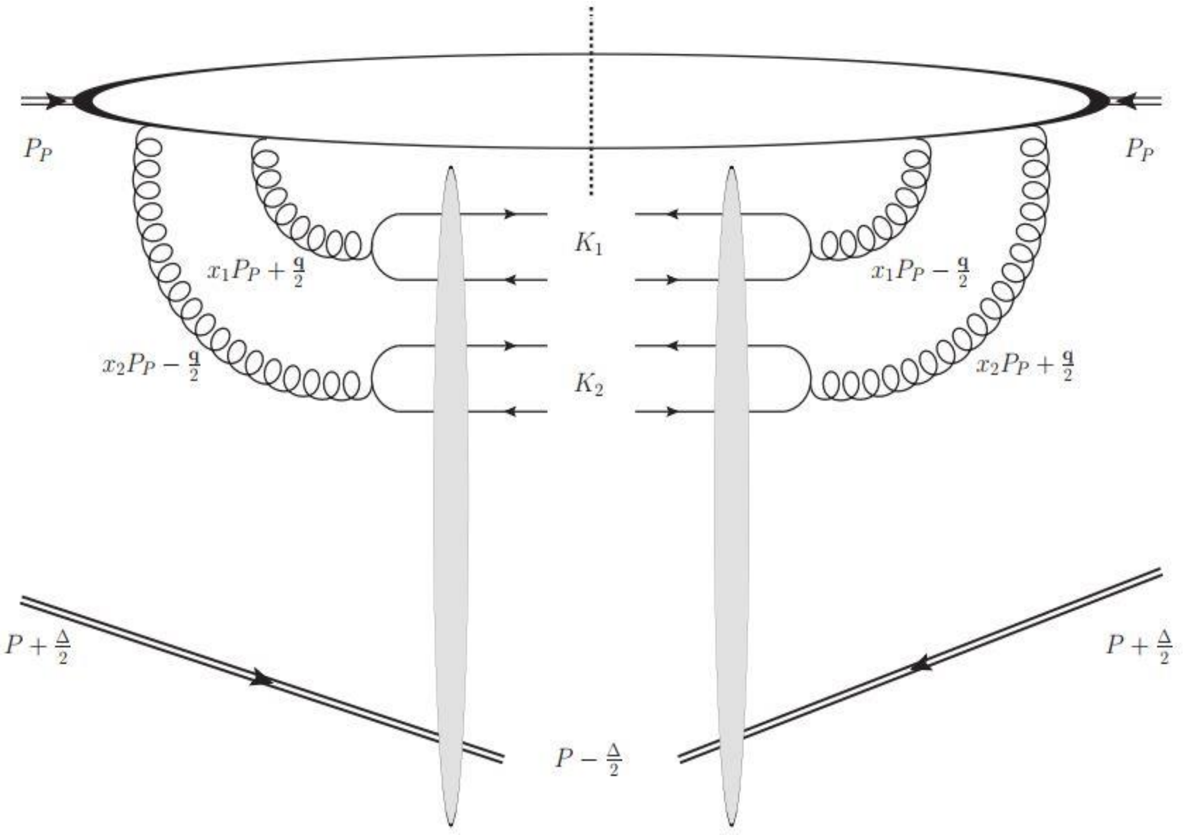
This linear combination of polarization observables is sensitive to gluon OAM

Observables for GTMDs

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



Main result:

Access Weiszacker-Williams gluon GTMD

Example: 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]

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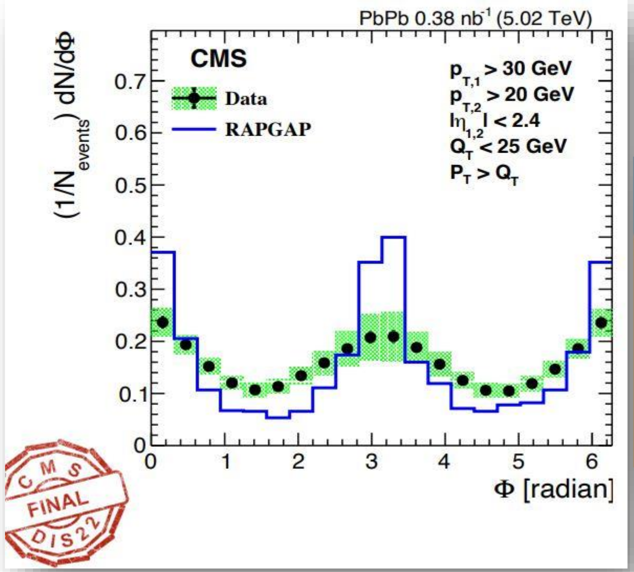

The CMS Collaboration

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 …

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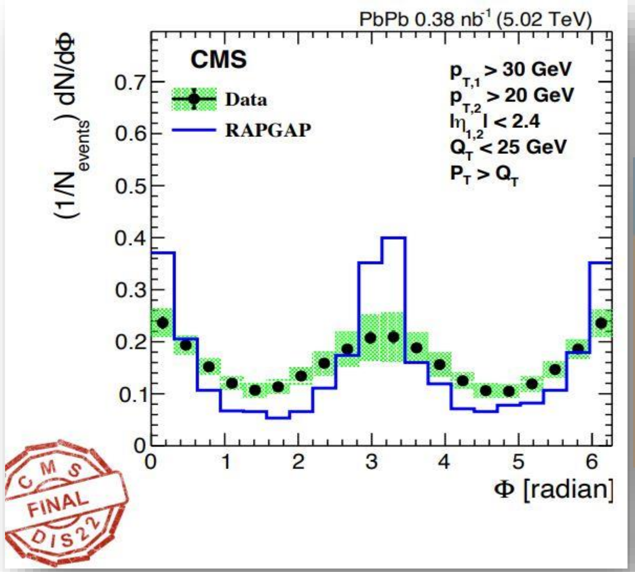

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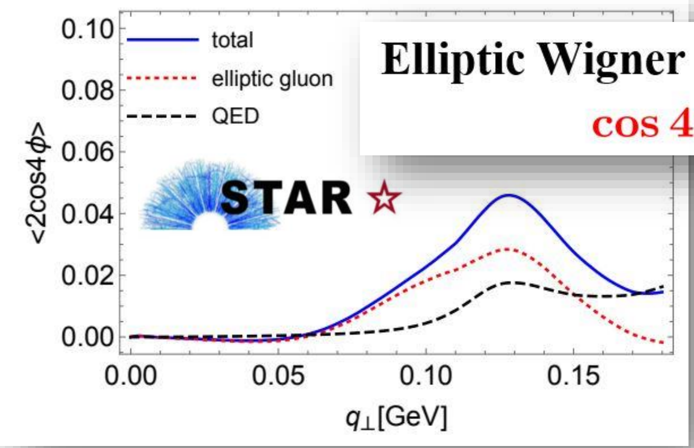
Angular correlations in exclusive dijet photoproduction in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

arXiv: 2106.13466 (2021)

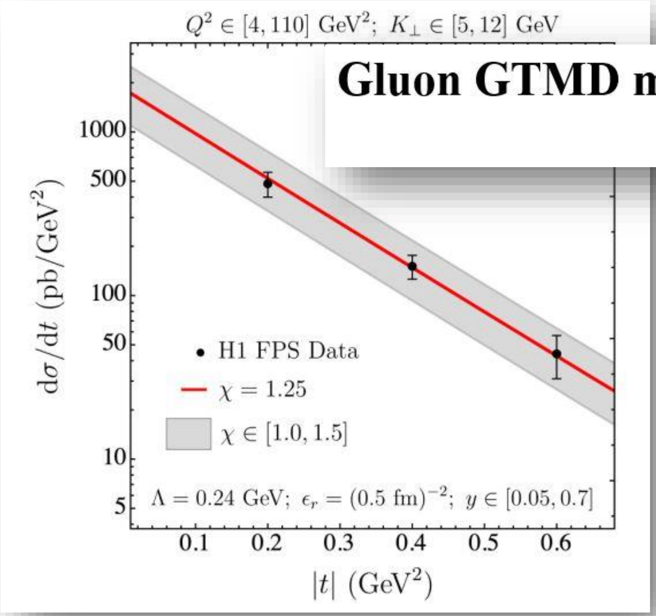
Probing the gluon tomography in photoproduction of di-pions

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



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

More developments …



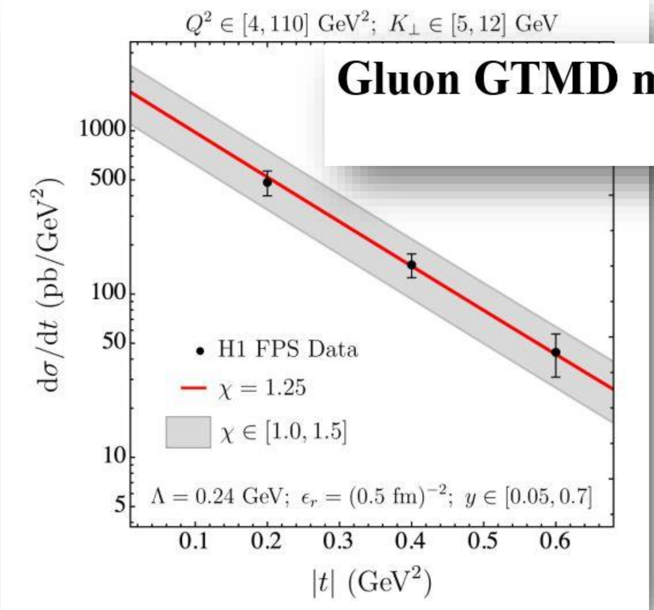
Gluon GTMD model based on MV model can describe HERA-H1 data

arXiv: 2106.15148 (2021)

GTMD model predictions for diffractive dijet production at EIC

Daniël Boer[1,*] and Chalis Setyadi[1,2,†]

More developments …



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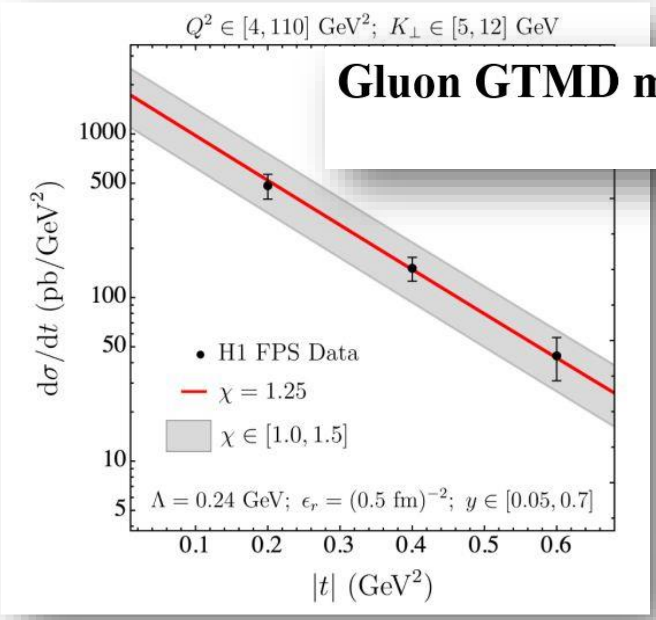
Impact of JIMWLK evolution: See Mantysaari, Mueller, Schenke, 1902.05087

More developments …



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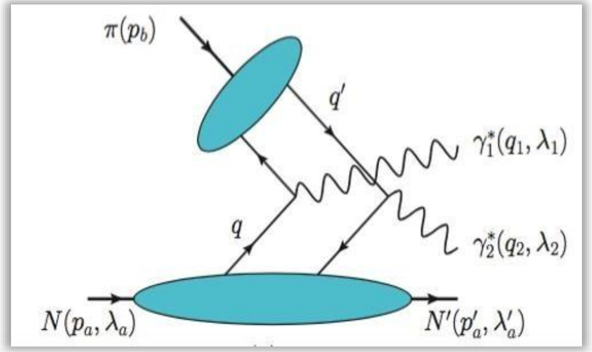


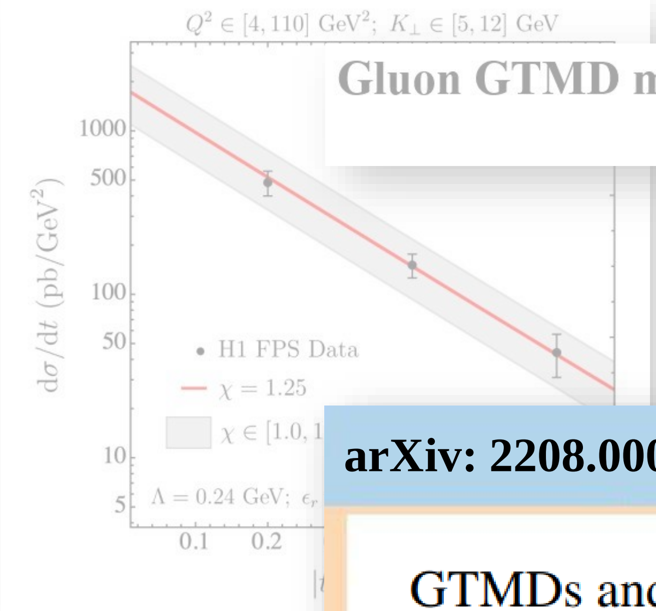
arXiv: 1702.04387 (2017)

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 …



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arXiv: 2106.15148 (2021)

GTMD model predictions for diffractive dijet production at EIC

…ri, Mueller, Schenke, 1902.05087

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]

arXiv: 1702.04387 (2017)

Generalized TMDs and the exclusive double Drell-Yan process

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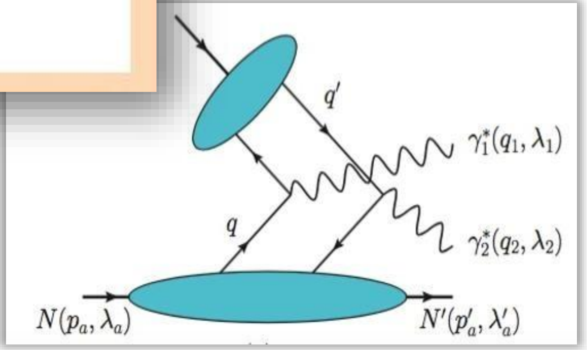


First & only process sensitive to quark GTMDs

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)

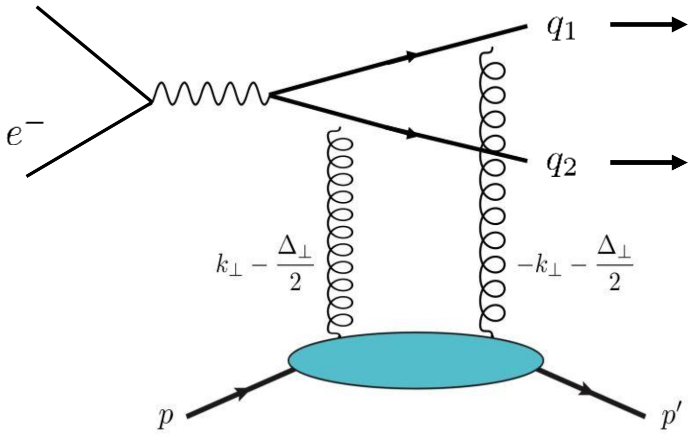
Probing gluon OAM through exclusive dijet production

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]



Jet 1

Jet 2

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)

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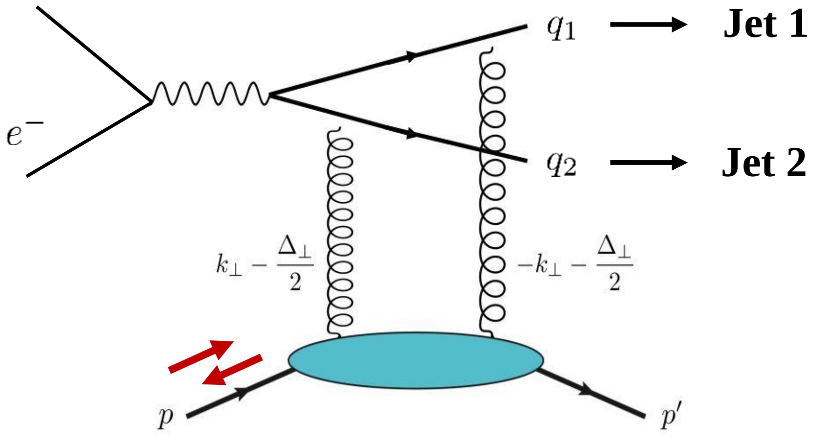

Longitudinal single spin asymmetry (SSA):

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

Probing gluon OAM through exclusive dijet production

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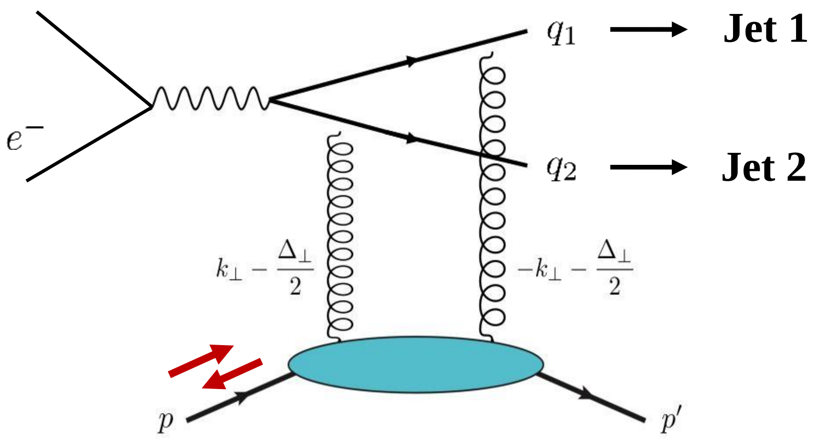

Schematic structure of SSA (oversimplified):

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

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

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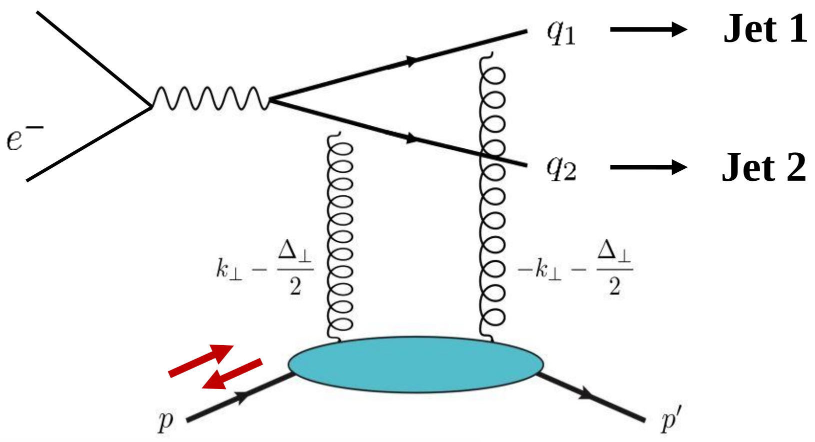


Signature of OAM is sinusoidal angular modulation

Moment of GPD

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

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

Moment of OAM

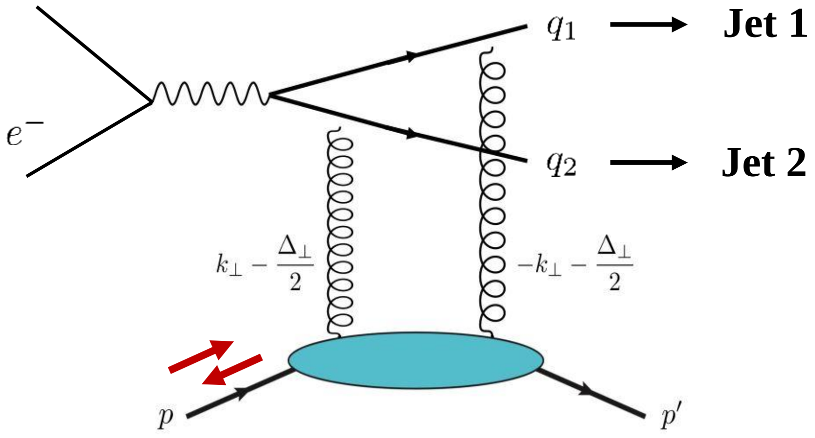
Probing gluon OAM through exclusive dijet production

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:

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

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

Probing gluon OAM through exclusive dijet production

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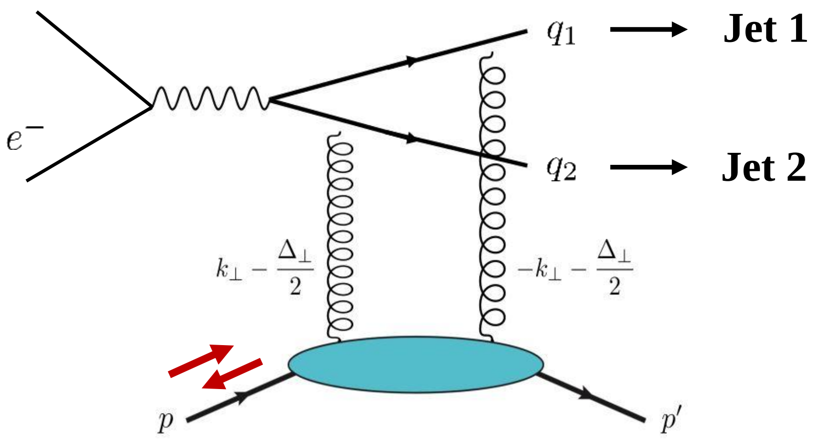


Issues with SSA:

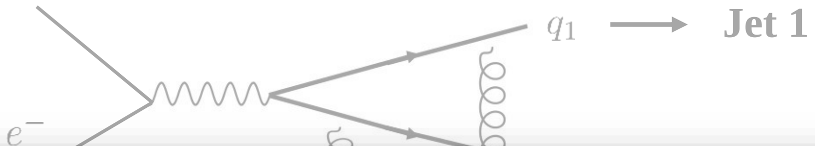
$$q_\perp = q_{1\perp} - q_{2\perp}$$

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

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

Probing gluon OAM through exclusive dijet production

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 $x = \pm\xi$ $\longrightarrow$ potentially dangerous for collinear factorization

(See Cui, Hu, Ma, 1804.05293)

Issues with SSA:

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

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

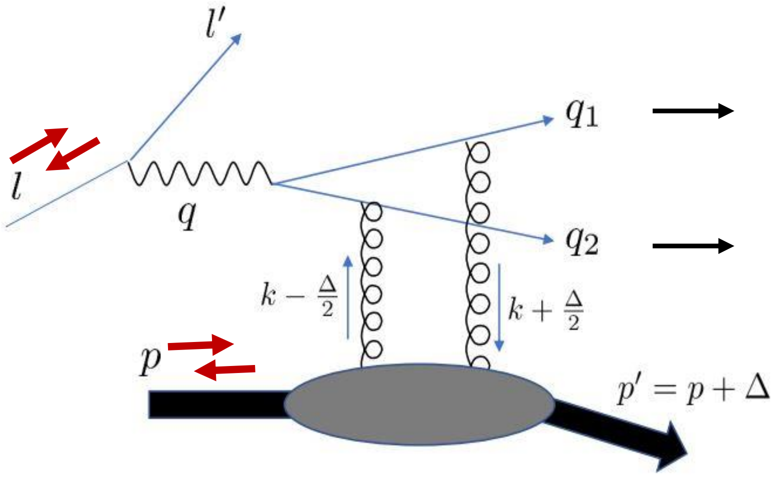
SSA vanishes for symmetric jet configurations $z = \bar{z} = \frac{1}{2}$

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,‡]



$\longrightarrow$ **Jet 1**

$\longrightarrow$ **Jet 2**

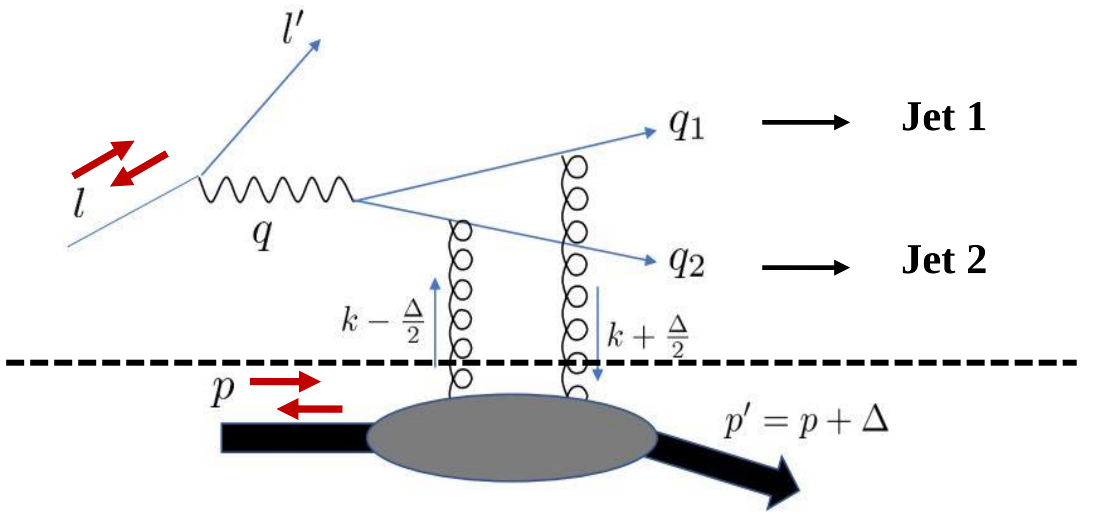
Distinct feature in our work

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:**

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

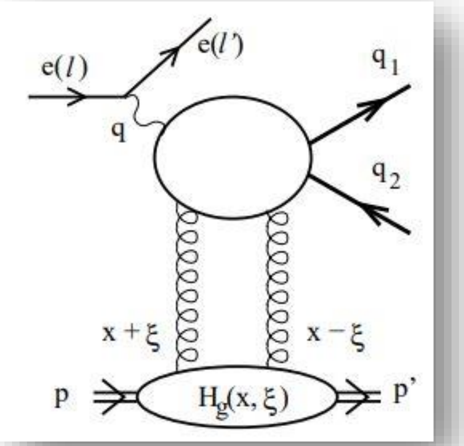
Hard part — Soft part

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Twist expansion:

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



Braun, Ivanov, 0505263

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

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

Probing gluon OAM through exclusive dijet production

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

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

Twist expansion:

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

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

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

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

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Twist expansion:

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

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

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

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Twist expansion:

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

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

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

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

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

Probing gluon OAM through exclusive dijet production

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

(See Radyushkin, 9805342)

Hence, integrals containing third poles are divergent

Twist expansion:

- **Twist-3 amplitude:** Proportio

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

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

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

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Probing gluon OAM through exclusive dijet production

Scattering amplitude

Twist expansion:

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

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

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

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

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

Probing gluon OAM through exclusive dijet production

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

Recall: Not possible in SSA

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

Issues with SSA:

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

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

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

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

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Twist expansion:

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

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

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

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

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

Probing gluon OAM through exclusive dijet production

Scattering amplitude

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

DSA's OAM part:

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

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

Consequence:

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

Probing gluon OAM through exclusive dijet production

Scattering amplitude

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

DSA's OAM part:

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

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":

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

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

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

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

- **Analogous contribution should enter SSA**

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

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

Helicity contributes to the same angular modulation as that of OAM

Probing gluon OAM through exclusive dijet production

Scattering amplitude

Not the end of the story:

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

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

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

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

$$\int dx \frac{H_g(x,\xi)}{(x^2-\xi^2+i\xi\epsilon)^3} \qquad \int dx \frac{x\tilde{H}_g(x,\xi)}{(x^2-\xi^2+i\xi\epsilon)^3}$$

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:

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

Cross section:

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

Study cross section as differential in the skewness variable

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

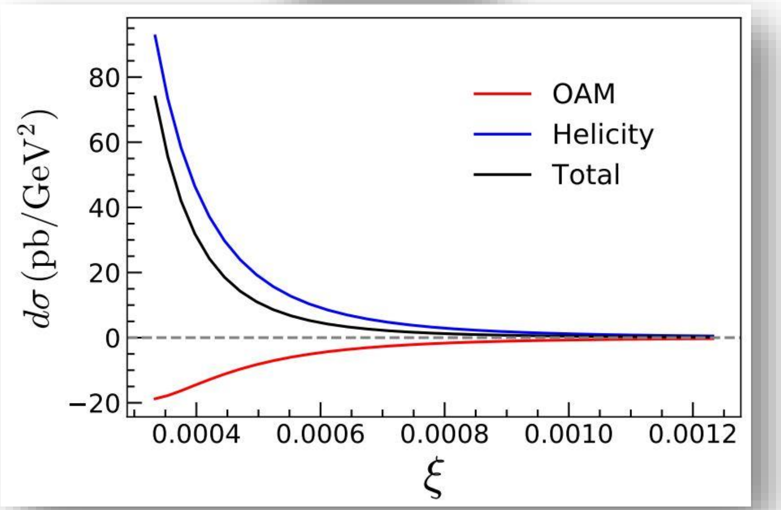
Relation between skewness & jet momenta:

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

Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

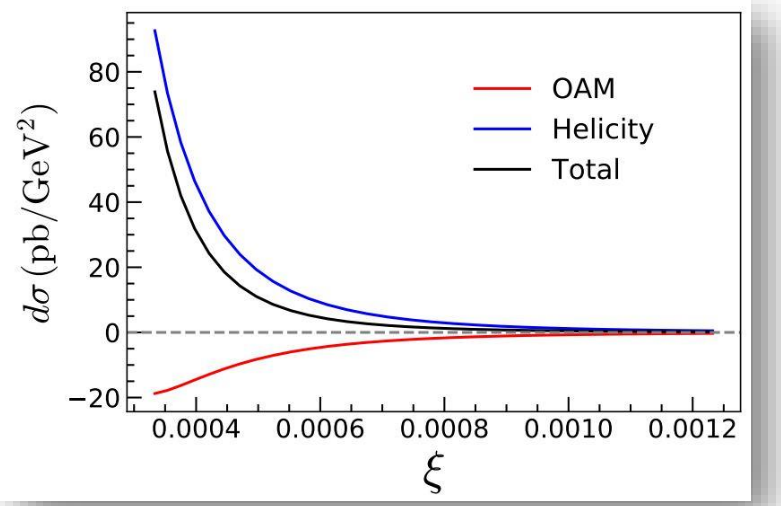
$Q^2 = 2.7$



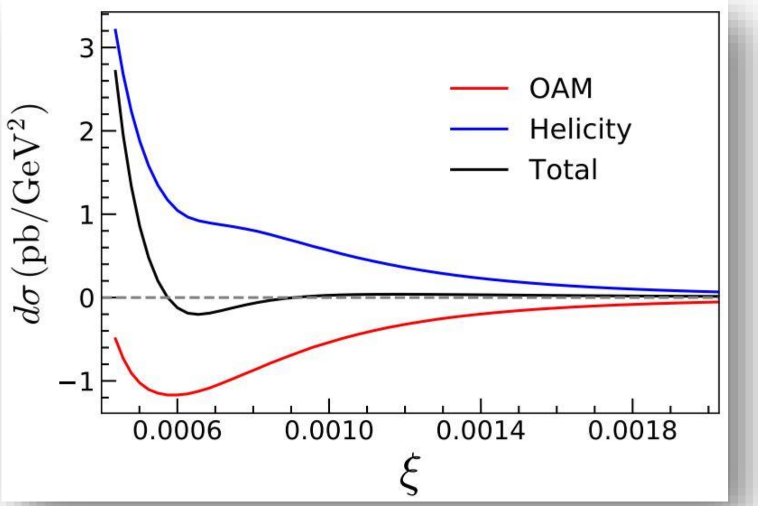
Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

$Q^2 = 2.7$



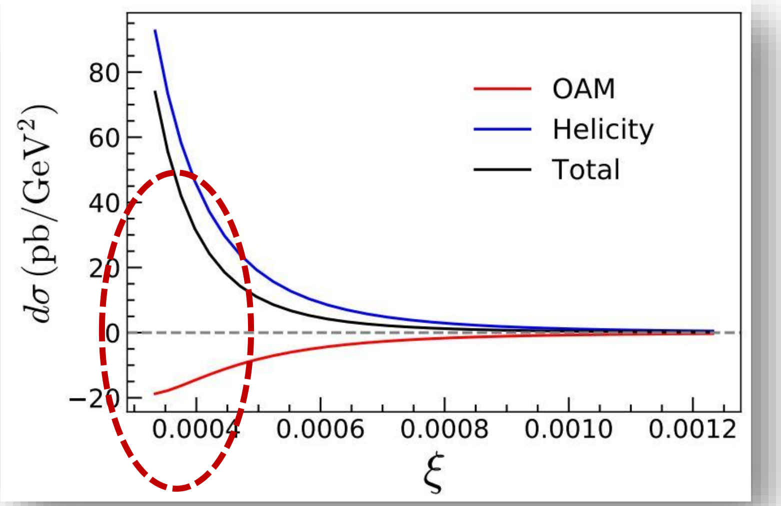
$Q^2 = 4.8$



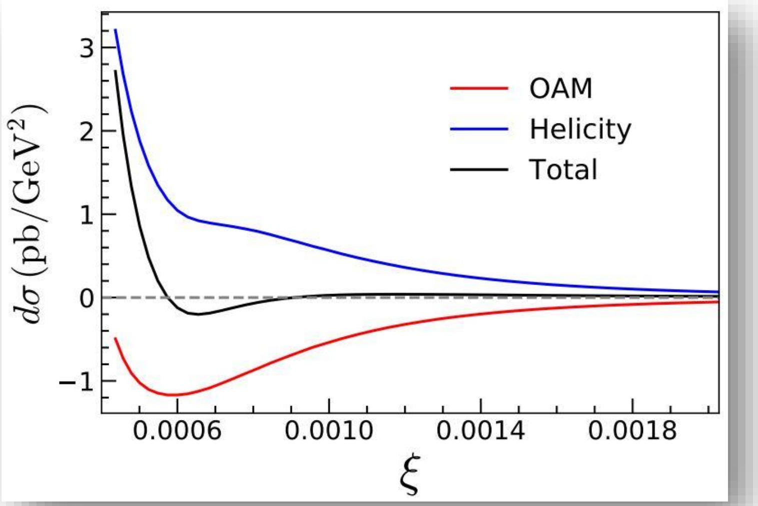
Probing gluon OAM through exclusive dijet production

Numerical estimate of cross section

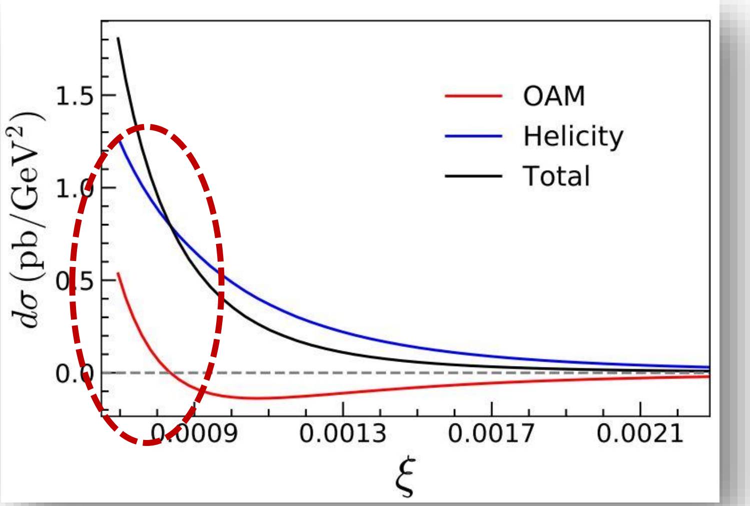
$Q^2 = 2.7$



$Q^2 = 4.8$



$Q^2 = 10$



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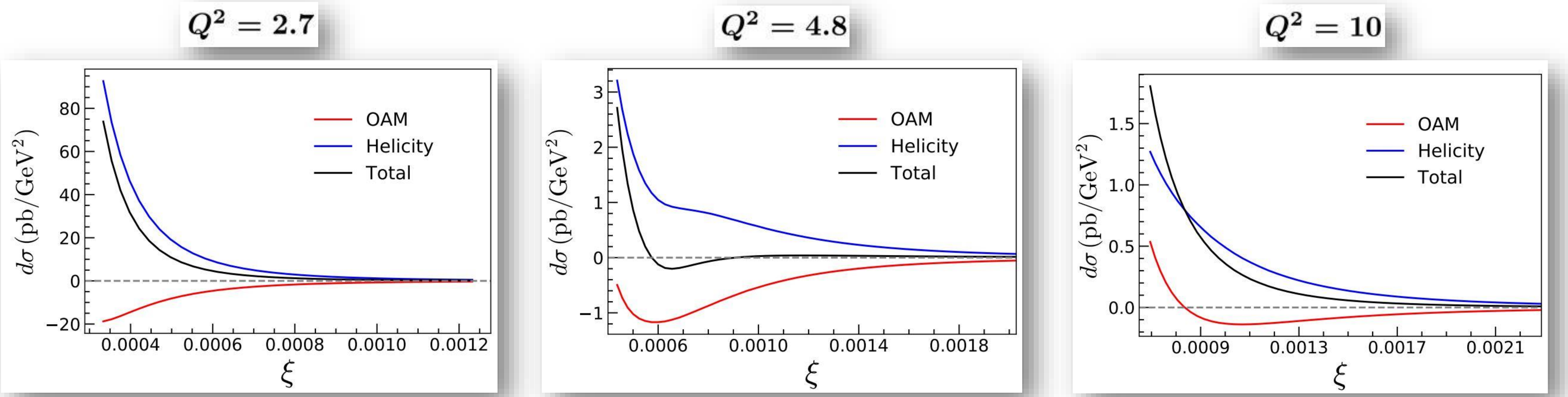
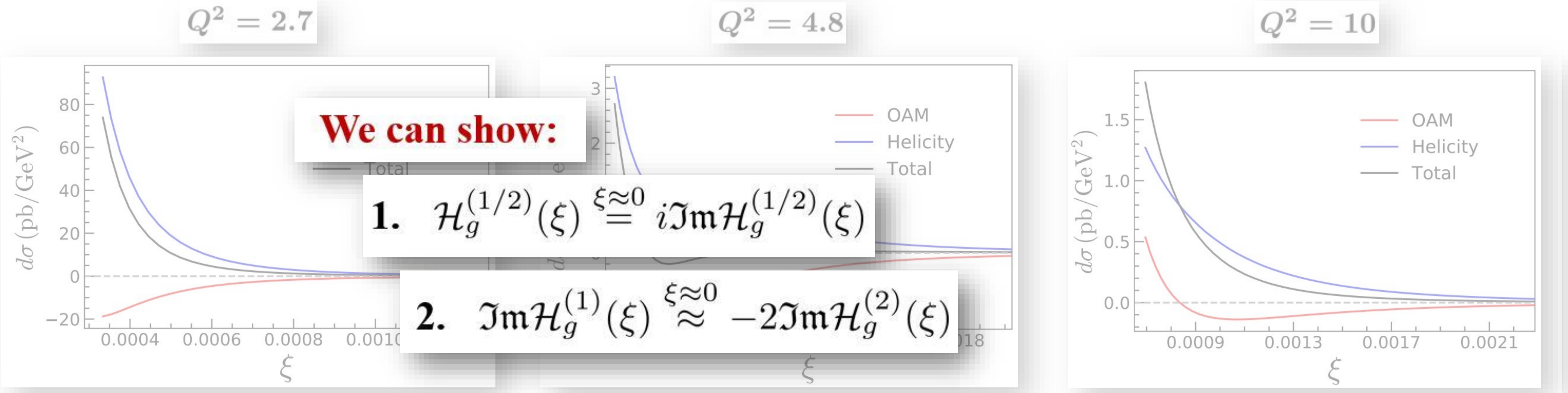
Numerical estimate of cross section



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:

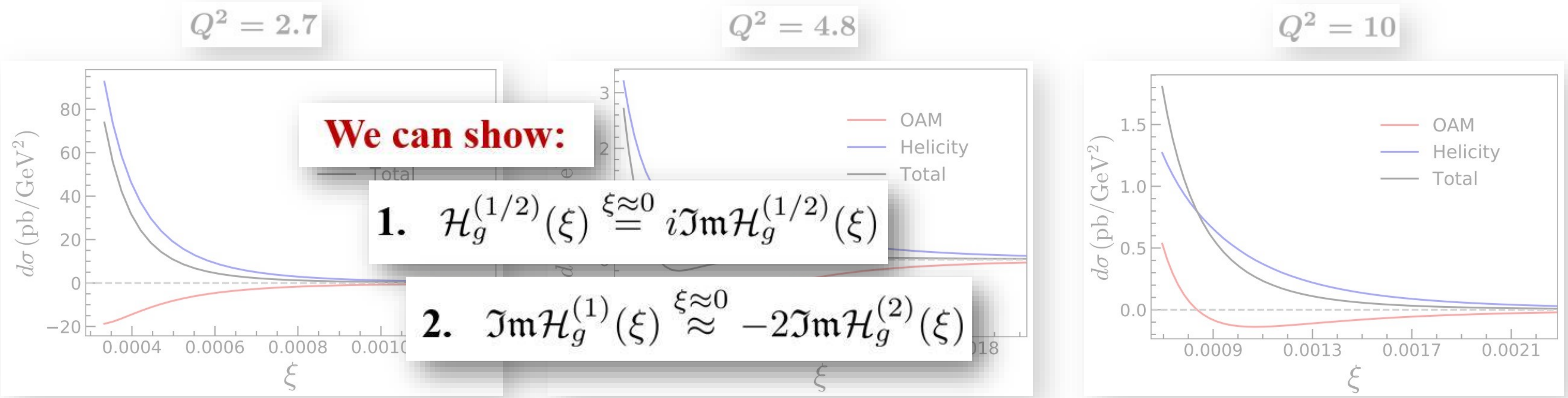
1. $\mathcal{H}_g^{(1/2)}(\xi) \overset{\xi\approx 0}{=} i\,\mathfrak{Im}\mathcal{H}_g^{(1/2)}(\xi)$

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

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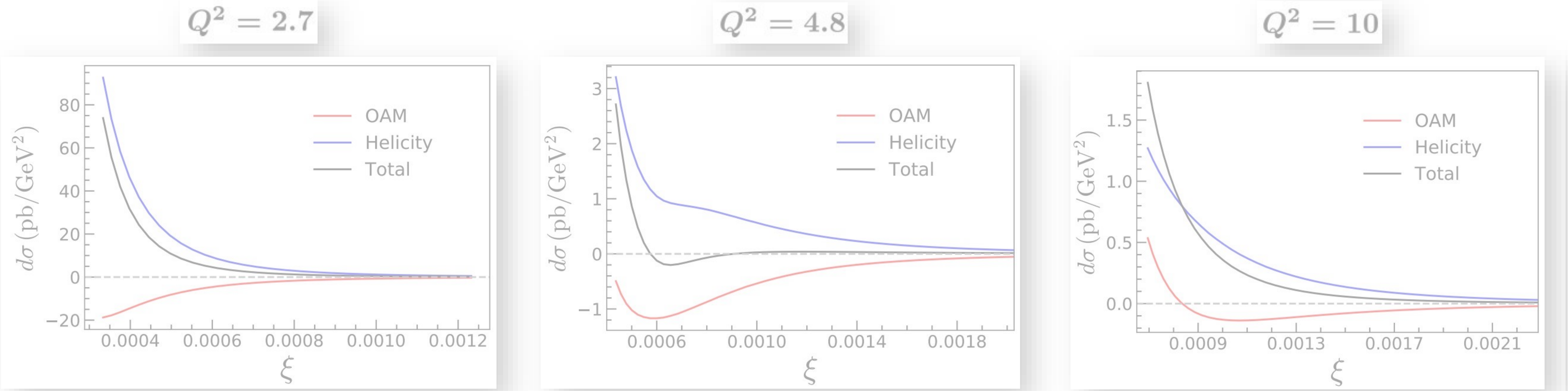


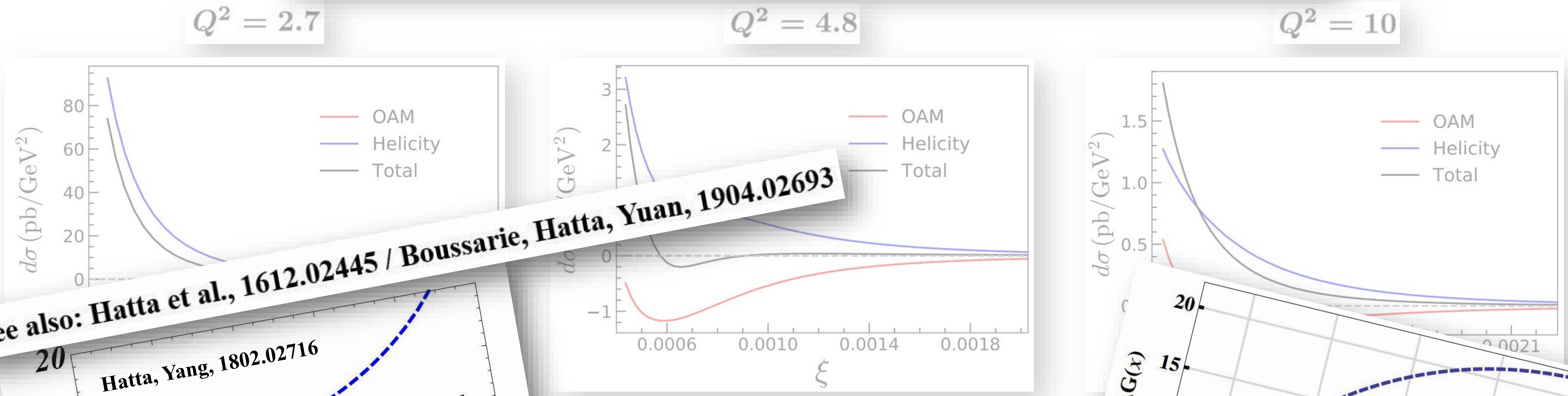
DSA:

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

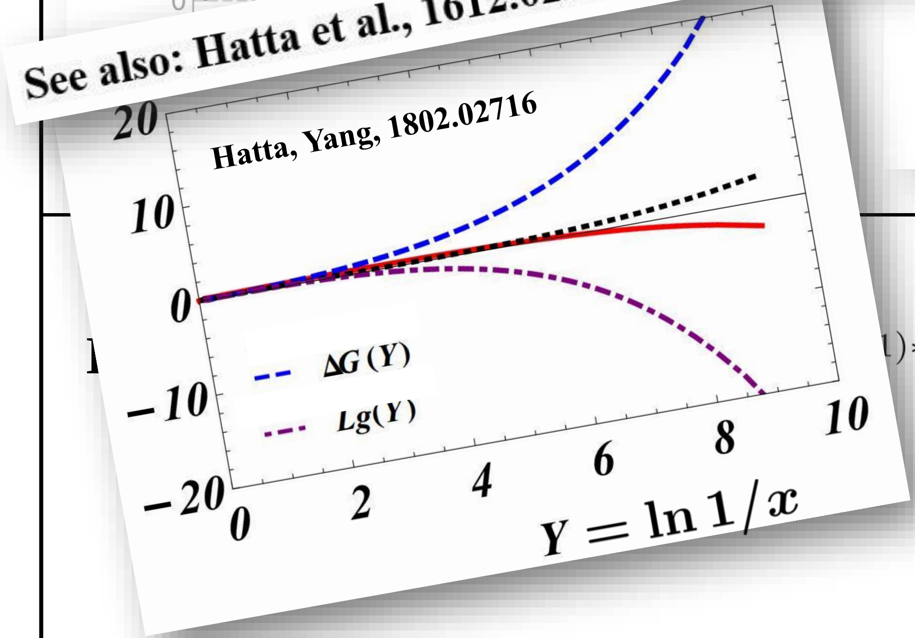
$\tilde{\mathcal{H}}_g^{(2)}$ **&** $\mathcal{L}_g$ **interfere positively/negatively depending upon sign of** $q_\perp^2 - \dfrac{Q^2}{4}$

Cancellation expected between Helicity & OAM at small x

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

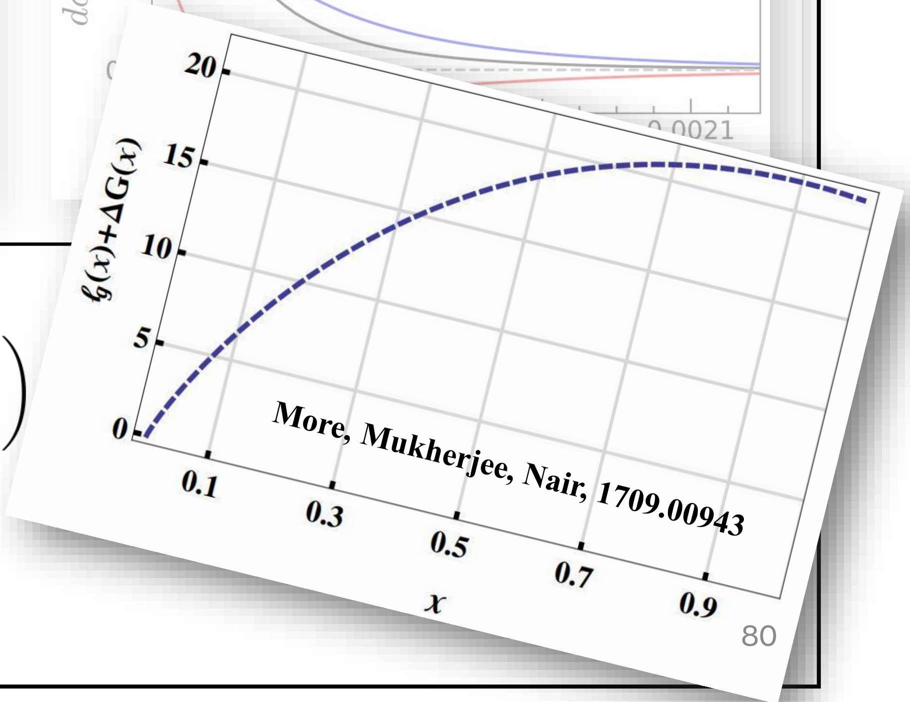


See also: Hatta et al., 1612.02445 / Boussarie, Hatta, Yuan, 1904.02693



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

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



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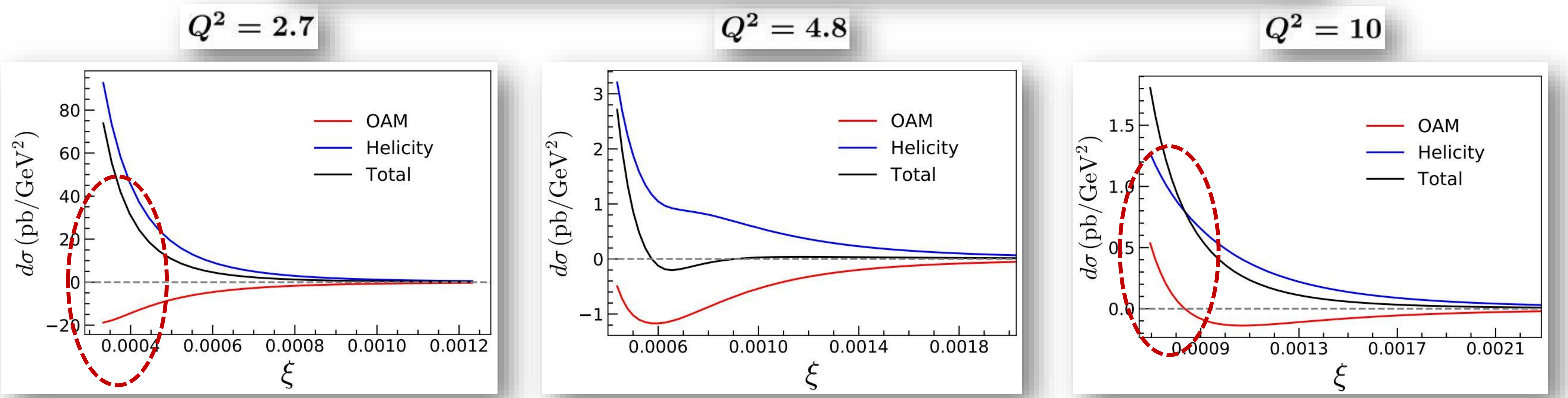

DSA: $$\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu \Big|_{\delta\phi=0} \sim \mathcal{H}_g^{(1)*}(\xi) \left(\underbrace{\tilde{\mathcal{H}}_g^{(2)}(\xi)}_{\Delta G(x)} + \frac{q_\perp^2 - Q^2/4}{q_\perp^2 + Q^2/4} \underbrace{\mathcal{L}_g(\xi)}_{L_g(x)} \right)$$

Cancellation expected between Helicity & OAM at small x

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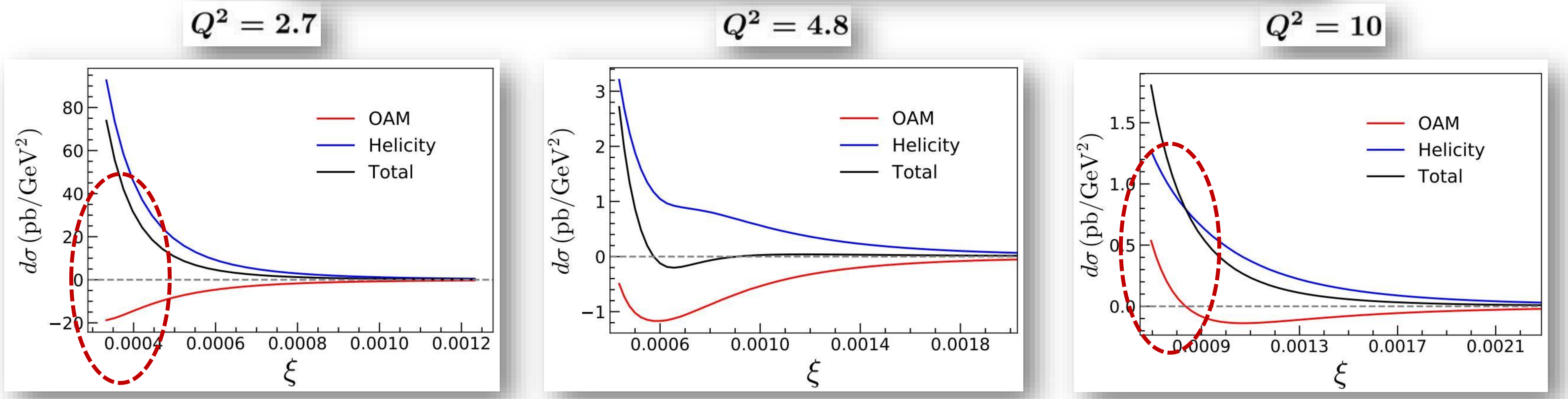

DSA: $\int d\phi_{q_\perp} L^{\mu\nu} A^*_\mu A_\nu$

Unique opportunity to study interplay between

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

which has been so far only studied theoretically!

Summary

Summary of our work

- **Gluon OAM related to the Wigner distribution**

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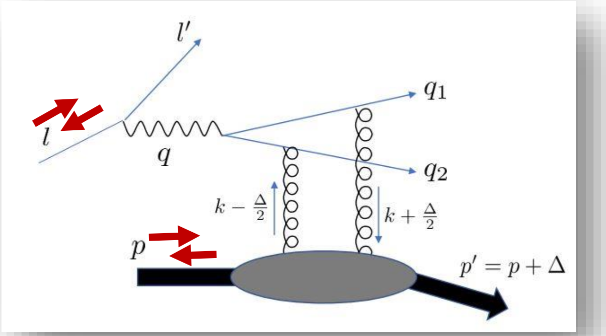
- **DSA in exclusive dijet production is a unique observable to access the gluon OAM @ EIC:**



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

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

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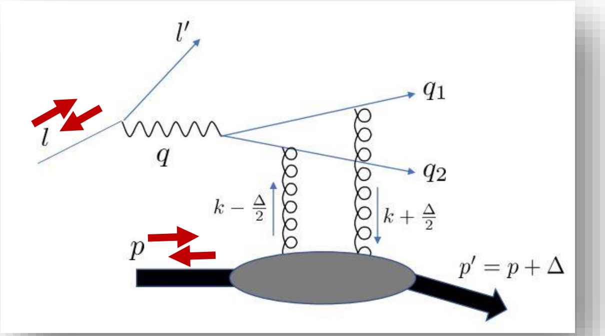

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Signature of gluon OAM is cosine angular modulation

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Summary of our work

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

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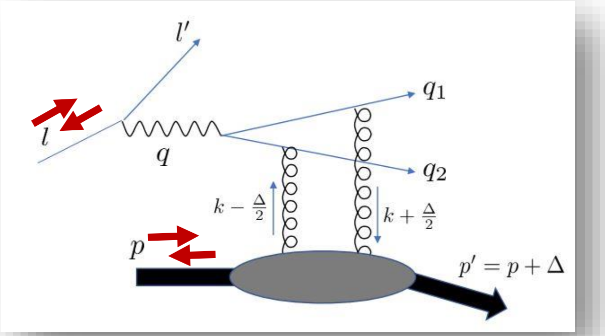

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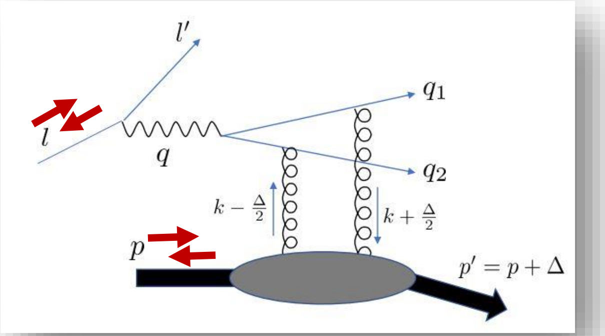
Gluon OAM related to the higher

- DSA in exclusive dijet production is

Consequence:

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



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

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Consequence:

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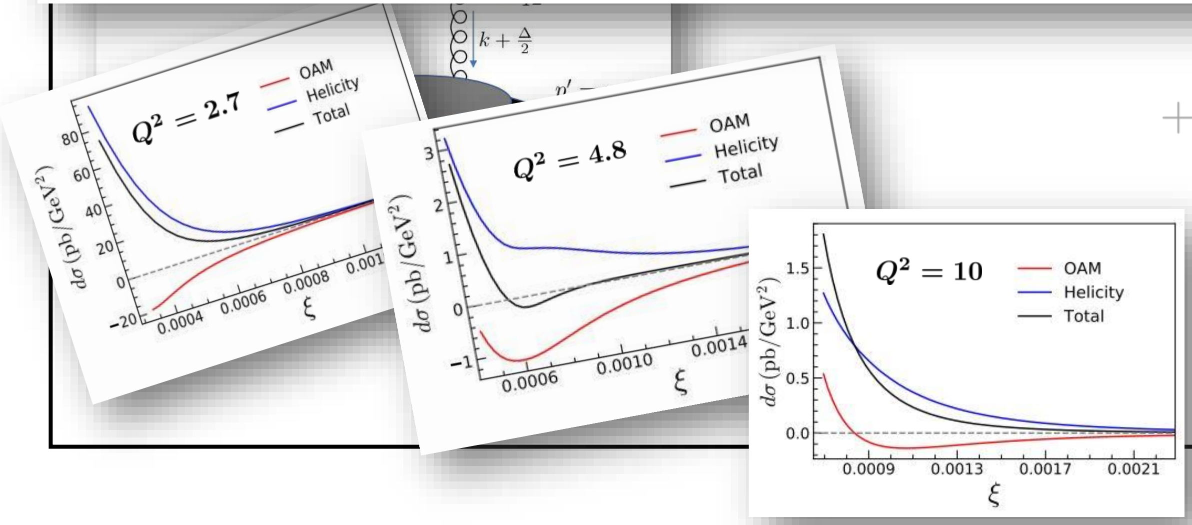
- DSA in exclusive dijet production is

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

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

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

Signature of gluon OAM is cosine angular modulation



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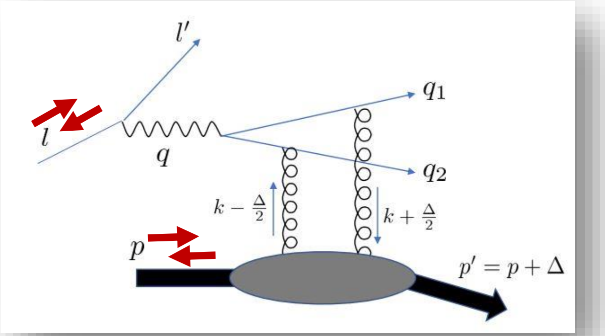
- **Gluon OAM related to the Wigner distribution**
- **DSA in exclusive dijet production is a unique observable to access the gluon OAM @ EIC:**



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- **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

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

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Helicity

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$$\times\, \mathfrak{Re}\left[\left(\mathcal{H}_g^{(1)*} - \frac{\xi^2}{1-\xi^2}\mathcal{E}_g^{(1)*}\right)\left(\tilde{\mathcal{H}}_g^{(2)} - \frac{\xi^2}{1-\xi^2}\tilde{\mathcal{E}}_g^{(2)}\right)\right]$$

Probing gluon OAM through exclusive dijet production

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- **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)**

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

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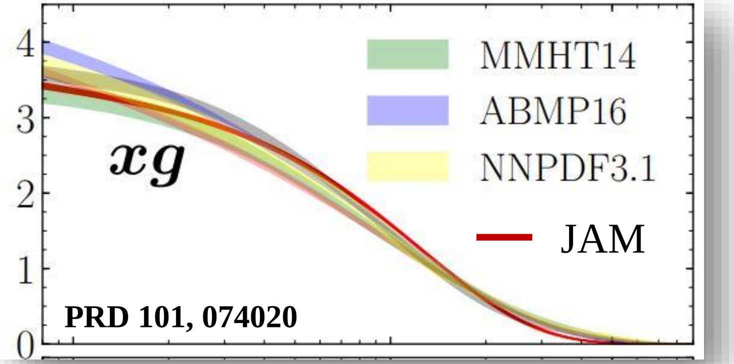
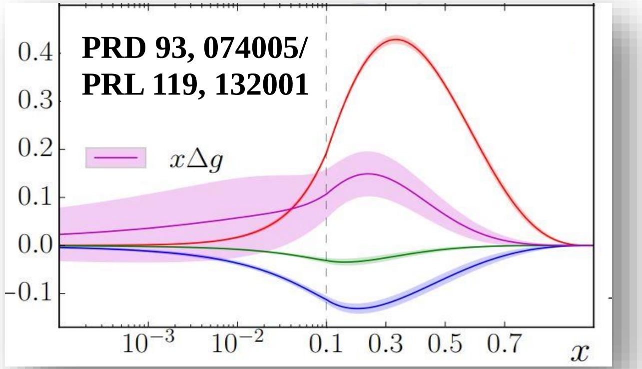
JAM PDFs





Probing gluon OAM through exclusive dijet production

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

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

Probing gluon OAM through exclusive dijet production

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

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

Probing gluon OAM through exclusive dijet production

Cross section

Jet azimuthal angle ($\phi_{q_\perp}$) integrated out

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

Integrate assuming a Gaussian form factor

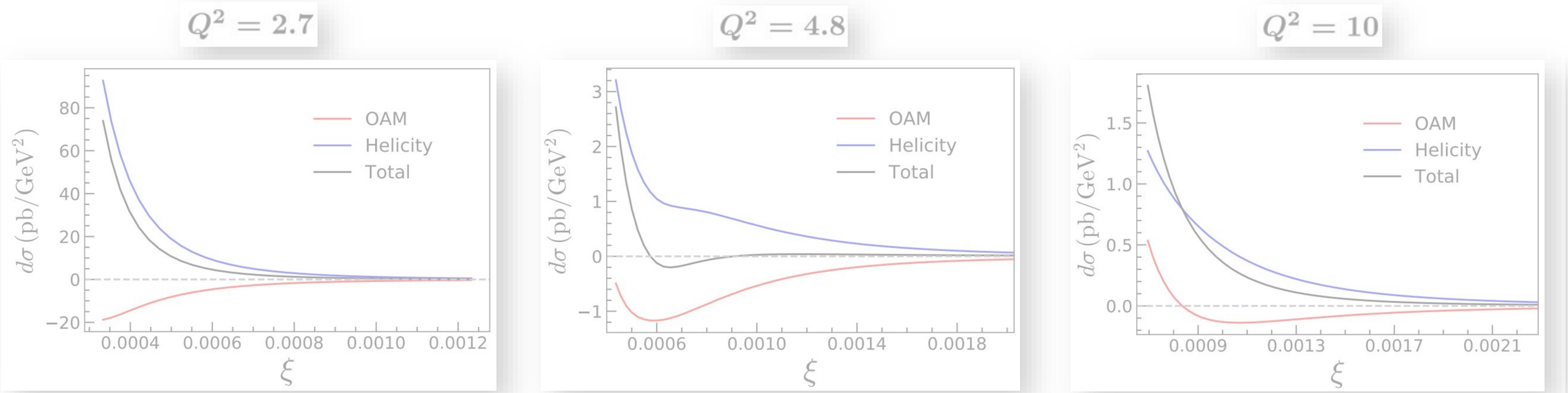
$$\sim e^{-b\Delta_\perp^2}$$

Slope = 5

(See Braun, Ivanov, 0505263)

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