Measuring Gluon Orbital Angular Momentum at the Electron-Ion Collider

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X. Ji, F. Yuan and Y.Z., arXiv:1612.02438

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Outline

- Gluon OAM and Wigner distribution
- Experimental observable

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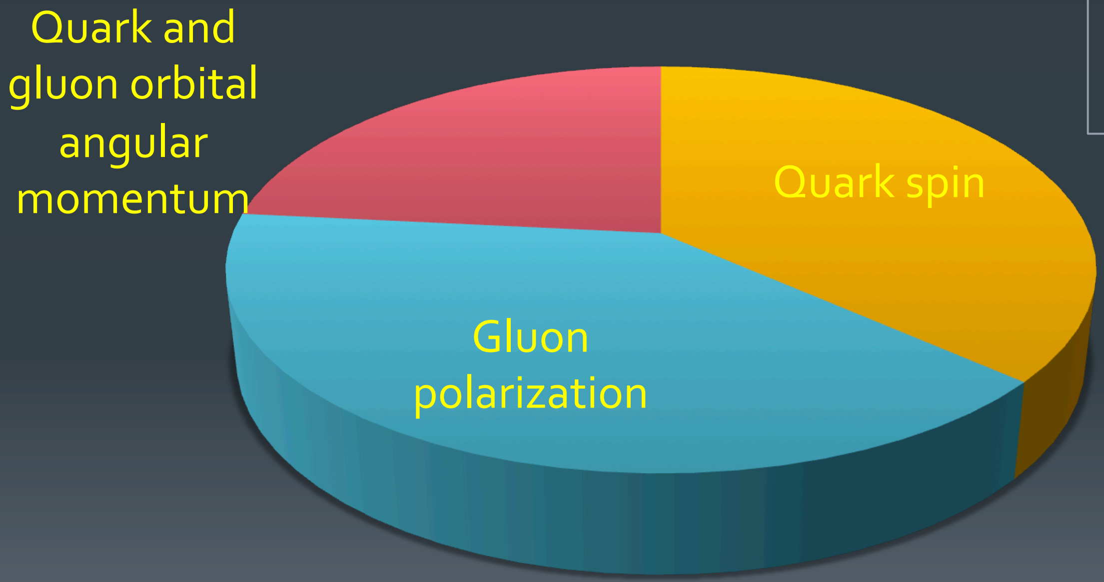
The longitudinal nucleon spin structure



$\Delta\Sigma(Q^2=10\ \mathrm{GeV}^2) = 0.366,$
de Florian et al., 2009

SLAC
HERMES (DESY)
COMPASS (CERN)
JLab
RHIC

Naïve spin sum rule:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + l_q^z + l_g^z$$

$\Delta G(Q^2=10\ \mathrm{GeV}^2) \sim 0.2,$
de Florian et al., 2014
Yang, Liu, Y.Z., et al., 2016

Orbital angular momentum

- OAM in Ji sum rule (Ji, 1997):
  - Measureable through twist-2 GPD in deeply virtual Compton scattering (DVCS)
  - Parton density interpretation not clear
- OAM in Jaffe-Manohar sum rule (Jaffe and Manohar, 1989):
  - Clear partonic interpretation;
  - Related to a TMD (pretzelosity) in model (She, Zhu, and Ma, 2009; H. Avakian et al., 2009, 2010), accessible through SIDIS (Lefky and Prokudin, 2015);
  - Direct measurement not known.

The gluon orbital angular momentum (OAM) and Wigner distribution

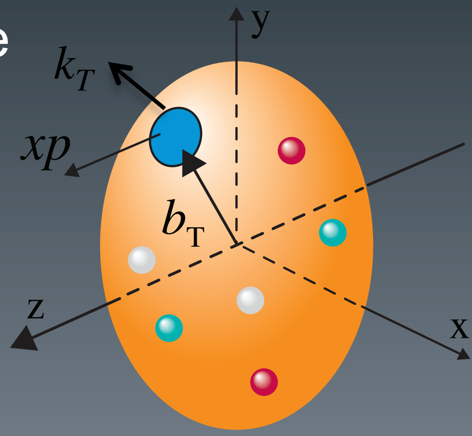
- Moment of a phase space Wigner distribution

$$l_g = \int_0^1 dx\, L_g(x)$$
$$= \int_0^1 dx \int db_\perp^2 d^2k_\perp (b_\perp \times k_\perp) W_{LC}^g(x,0,k_\perp,b_\perp)$$

Belitsky, Ji, and Yuan, 2004;
Meissner, Metz and Schlegel, 2009;
Lorce and Pasquini, 2011;
Lorce et al., 2012;
Y. Hatta, 2012;
Ji, Xiong, and Yuan, 2012.

- Wigner distribution or generalized transeverse momentum distribution (GTMD)

$$W_{LC}^g(x,\xi,k_\perp,b_\perp)$$
$$= \int d^2\Delta_\perp e^{-ib_\perp\cdot\Delta_\perp} f(x,\xi,k_\perp,\Delta_\perp)$$



The gluon orbital angular momentum (OAM) and Wigner distribution

- Parametrization of GTMD

$F^g{}_{1,4}$

$$f_g(x,\xi,k_\perp,\Delta_\perp)=F_g(x,\xi,|k_\perp|,|\Delta_\perp|)+i\frac{\vec{k}_\perp\times\vec{\Delta}_\perp}{2M^2}S^+F_g^{(l)}(x,\xi,|k_\perp|,|\Delta_\perp|)+\cdots$$

- Gluon OAM density as the moment of GTMD

$$L_g(x,\xi,|\Delta_\perp|)=-\int d^2k_\perp\frac{k_\perp^2}{2M^2}F_g^{(l)}(x,\xi,|k_\perp|,|\Delta_\perp|)$$

$$L_g(x)=L_g(x,0,0)$$

Outline

- Gluon OAM and Wigner distribution
- Experimental observable
- Outlook

Experimental Process

$$f_g(x, \xi, k_\perp, \Delta_\perp)$$

Two independent momenta

Momentum transfer of the proton, exclusive process

Consider $\gamma^* p$ scattering:
2->2 process, final state momenta not independent;
2->3 process, one more independent momentum.

Intrinsic transverse momentum k_T, measure dijets!

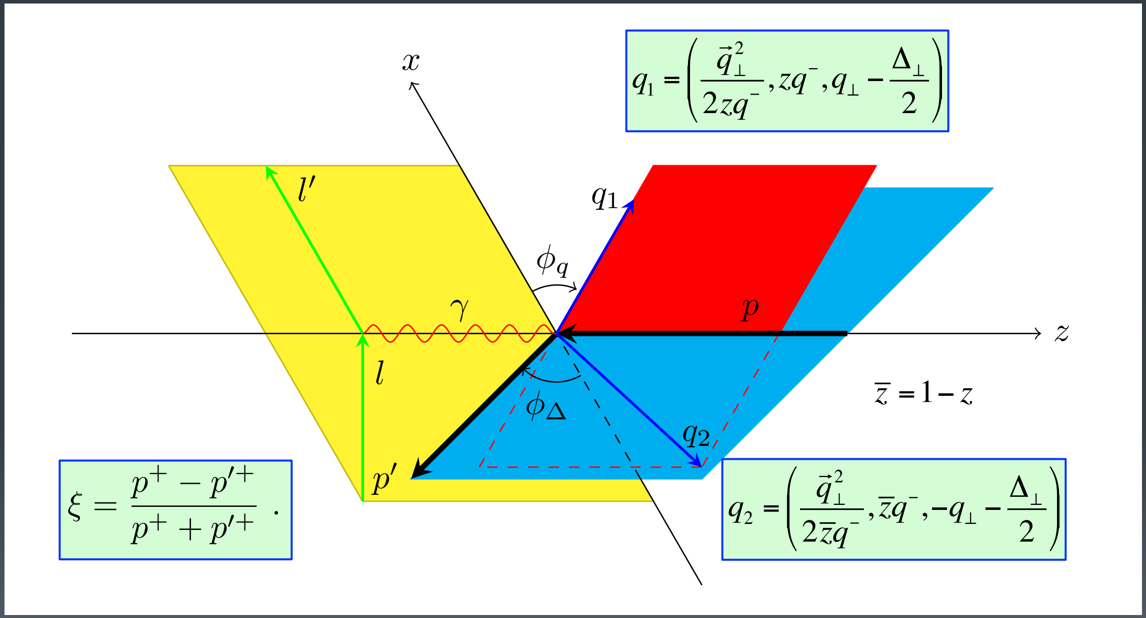
Answer: Exclusive dijet production in l+p scattering ✔

$$\ell + p \to \ell' + q_1 + q_2 + p'$$

Braun and Ivanov, 2005

Hatta, Xiao and Yuan, 2016

Kinematics



$$q = l - l' \ , \qquad q^2 = -Q^2$$

$$x_{Bj} = \frac{Q^2}{2q \cdot p} \ , \qquad y = \frac{q \cdot p}{l \cdot p} \ ,$$

$$\Delta = p' - p \ , \qquad P = \frac{p + p'}{2} \ ,$$

$$t = \Delta^2 \ , \quad (q + p)^2 = W^2 \ ,$$

$$(q - \Delta)^2 = (q_1 + q_2)^2 = M^2 \ .$$

$$Q^2 \sim W^2 \sim \vec{q}_\perp^{\,2} \gg \Delta_\perp^2$$

$$\mu^2 = z\bar{z}Q^2, \qquad \beta = \frac{\mu^2}{\vec{q}_\perp^{\,2} + \mu^2}$$

Scattering Amplitude

Scattering amplitude:

$$M = \frac{e_{em}}{Q^2} \sum_{\lambda=L,\perp} \bar{u}(l')\not\epsilon_\lambda(q) u(l) \epsilon_{\lambda,\nu} M^{\nu}_{\gamma^*} = \frac{e_{em}}{Q^2} \sum_{\lambda=L,\perp} \bar{u}(l')\not\epsilon_\lambda(q) u(l) \mathcal{A}_\lambda$$

Leptonic part, averaging initial spins and summing over final spins

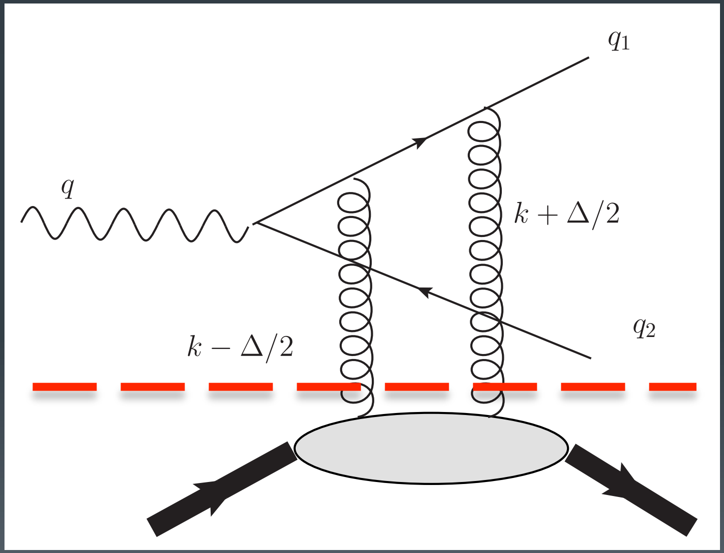
Hadronic part, summing over final state quark spins and color

$$\frac{d\sigma}{dy dQ^2 d\Omega} = \sigma_0 \left[(1-y)|A_L|^2 + \frac{1+(1-y)^2}{2}|A_T|^2 \right]$$

$$\sigma_0 = \frac{\alpha_{em}^2 \alpha_s^2 e_q^2}{16\pi^2 Q^2 y N_c} \frac{4\xi^2 z\bar{z}}{(1-\xi^2)(\vec{q}_\perp^2 + \mu^2)^3}$$

Collinear factorization of hadronic amplitude

- Leading order diagrams (6 in total)



- Collinear Factorization

Hard Part

$$\mathcal{H}(x,\xi,q_\perp,k_\perp,\Delta_\perp)$$

Soft Part

$$xf^g(x,\xi,k_\perp,\Delta_\perp)$$

$$i\mathcal{A}_f \propto \int dx d^2k_\perp \mathcal{H}(x,\xi,q_\perp,k_\perp,\Delta_\perp)\; xf^g(x,\xi,k_\perp,\Delta_\perp)\;,$$

Twist expansion

$$\mathcal{H}(x,\xi,q_\perp,k_\perp,\Delta_\perp) = \mathcal{H}^{(0)}(x,\xi,q_\perp,0,\Delta_\perp) + k_\perp^\alpha \frac{\partial}{\partial k_\perp^\alpha}\mathcal{H}(x,\xi,q_\perp,0,\Delta_\perp) + \cdots \ .$$

Twist 2 (Target-spin independent):

Braun and Ivanov, 2005

$$i\mathcal{A}_f^{(0)} \propto \int dx \mathcal{H}^{(0)}(x,\xi,q_\perp,0,0)\ xF_g(x,\xi,\Delta_\perp)$$

Gluon GPD

Twist 3 (Target-spin dependent):

$$\int d^2k_\perp(\vec{q}_\perp\cdot\vec{k}_\perp)xf^g(x,\xi,k_\perp,\Delta_\perp) = -iS^+(\vec{q}_\perp\times\vec{\Delta}_\perp)xL_g(x,\xi,\Delta_\perp) + \cdots \ ,$$

Differential cross section

$$\Delta\sigma = (\sigma(S^+) - \sigma(-S^+))/2$$

- Result:

$$\frac{d\Delta\sigma}{dy dQ^2 d\Omega} = \sigma_0 \lambda_p \frac{2(\bar{z}-z)(\vec{q}_\perp \times \vec{\Delta}_\perp)}{\vec{q}_\perp^2 + \mu^2}\left[(1-y)A_{fL} + \frac{1+(1-y)^2}{2}A_{fT}\right]$$

λ_p Nucleon Polarization

$$A_{fL} = 16\beta \, \mathrm{Im}\left(\left[\mathcal{F}_g^* + 4\xi^2\bar{\beta}\mathcal{F}_g'^*\right]\left[\mathcal{L}_g + 8\xi^2\bar{\beta}\mathcal{L}_g'\right]\right) ,$$

$$A_{fT} = 2 \, \mathrm{Im}\left(\left[\mathcal{F}_g^* + 2\xi^2(1-2\beta)\mathcal{F}_g'^*\right]\left[\mathcal{L}_g + 2\bar{\beta}\left(\frac{1}{z\bar{z}} - 2\right)\left(\mathcal{L}_g + 4\xi^2(1-2\beta)\mathcal{L}_g'\right)\right]\right)$$

Generalized Compton Form Factors

- Definition:

$$\mathcal{F}_g(\xi,t) = \int dx \frac{1}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)} F_g(x,\xi,t) \ ,$$
$$\mathcal{F}'_g(\xi,t) = \int dx \frac{1}{(x+\xi-i\varepsilon)^2(x-\xi+i\varepsilon)^2} F_g(x,\xi,t) \ .$$

$$\mathcal{L}_g(\xi,t) = \int dx \frac{x\xi}{(x+\xi-i\varepsilon)^2(x-\xi+i\varepsilon)^2} \ xL_g(x,\xi,t) \ ,$$
$$\mathcal{L}'_g(\xi,t) = \int dx \frac{x\xi}{(x+\xi-i\varepsilon)^3(x-\xi+i\varepsilon)^3} \ xL_g(x,\xi,t) \ .$$

- x-dependence cannot be measured:

  Needs modelling of the GPD and GTMD;

  Real part: principle value integration. Imaginary part: $F(\xi, \pm\xi, t)$, $L(\xi, \pm\xi, t)$.

Single longitudinal target-spin asymmetry

- Definition:

$$A_{\sin(\phi_q-\phi_\Delta)} = \int d\phi_q d\phi_\Delta \, \frac{d\sigma_\uparrow - d\sigma_\downarrow}{d\phi_q d\phi_\Delta} \sin(\phi_q - \phi_\Delta) \Big/ \int d\phi_q d\phi_\Delta \, \frac{d\sigma_\uparrow + d\sigma_\downarrow}{d\phi_q d\phi_\Delta}$$

$$A_{\sin(\phi_q-\phi_\Delta)} \propto \frac{(\bar{z}-z)|\vec{q}_\perp||\vec{\Delta}_\perp|}{\vec{q}_\perp^{\,2} + \mu^2}$$

- Feature:

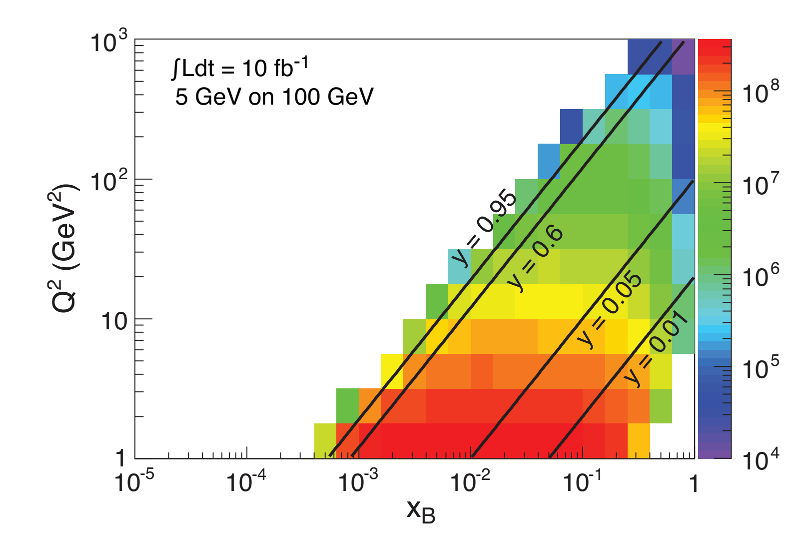
  Asymmetric jets

  Suppressed effect $O(\Delta_T/Q)$

Similar observable in the same process at small x:
Hatta, Nakagawa, Yuan and Y.Z., 2016
double exclusive Drell-Yan:
Bhattacharya, Metz, and Zhou, 2017
Hatta, Bhattacharya's talks

Measurement at EIC

- Key measurements:
  - Dijet momenta
  - Final state nucleon momentum
- Kinematics:
  - Large Bjorken x, high Q^2;
  - Nucleon deflection angle (determines t and ξ).



A. Accardi et al., arXiv: 1212.1701

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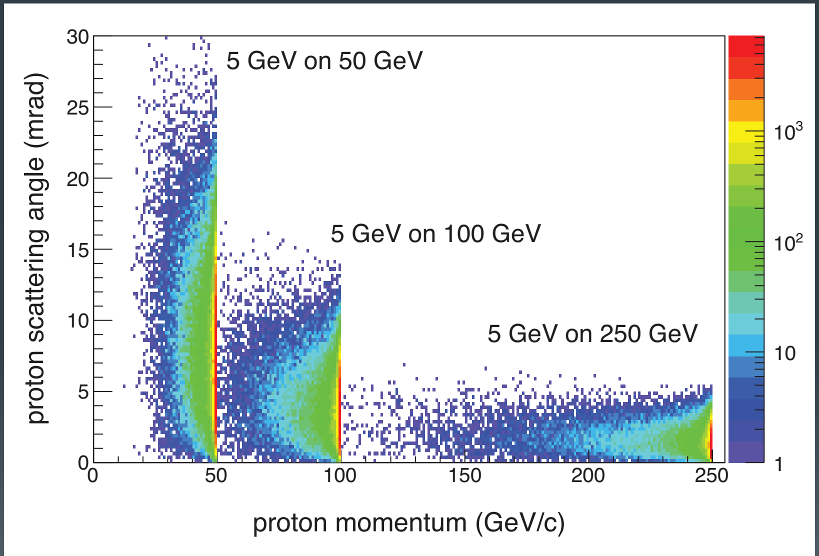

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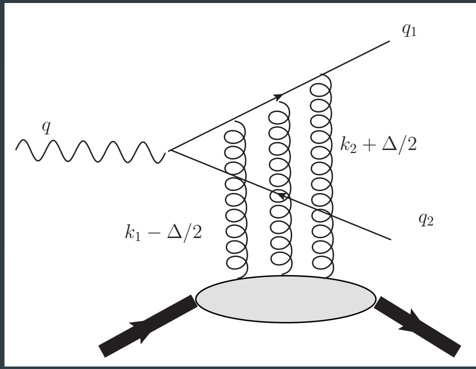
Outlook



Remaining issues:

- Include genuinely twist-three diagrams;
- One-loop radiative corrections, test validity of collinear factorization

After all, the leading contribution to the single target-spin asymmetry is strongly sensitive to the gluon OAM!

Summary

- Gluon OAM in the Jaffe-Manohar sum rule can be measured through the Wigner distribution;
- The leading contribution to the single longitudinal target-spin asymmetry in exclusive dijet production from ep scattering is strongly sensitive to the gluon OAM.
- Differential cross section formula has been derived for the experimental observable.