Measuring Gluon Orbital Angular Momentum at the Electron-Ion Collider

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Outline

- Proton spin structure from DIS
- Gluon OAM and Wigner distribution
- Experimental observable

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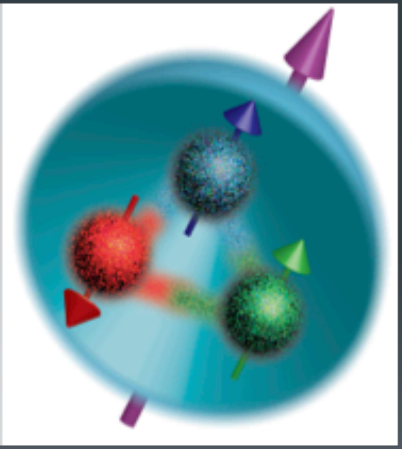
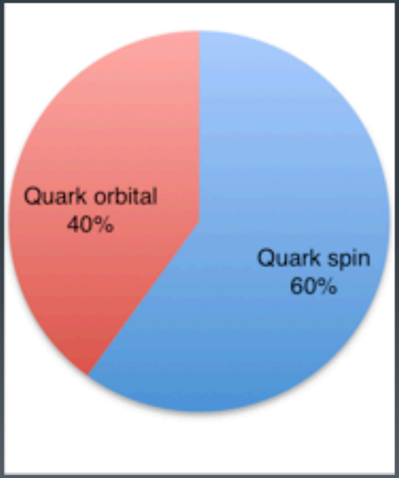
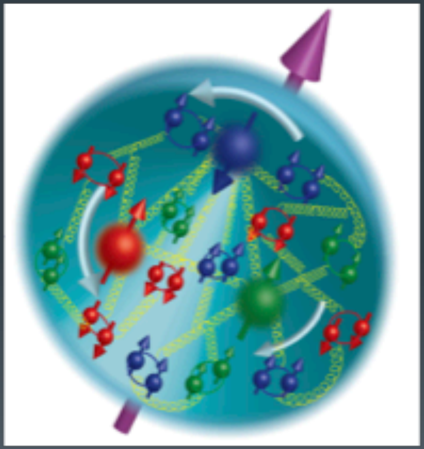
Proton, a platform where the gluon is indispensable

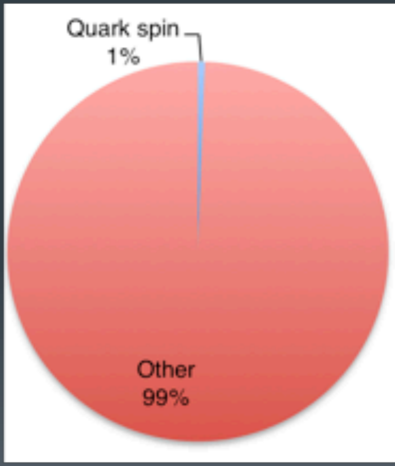
Quark Model Prediction:





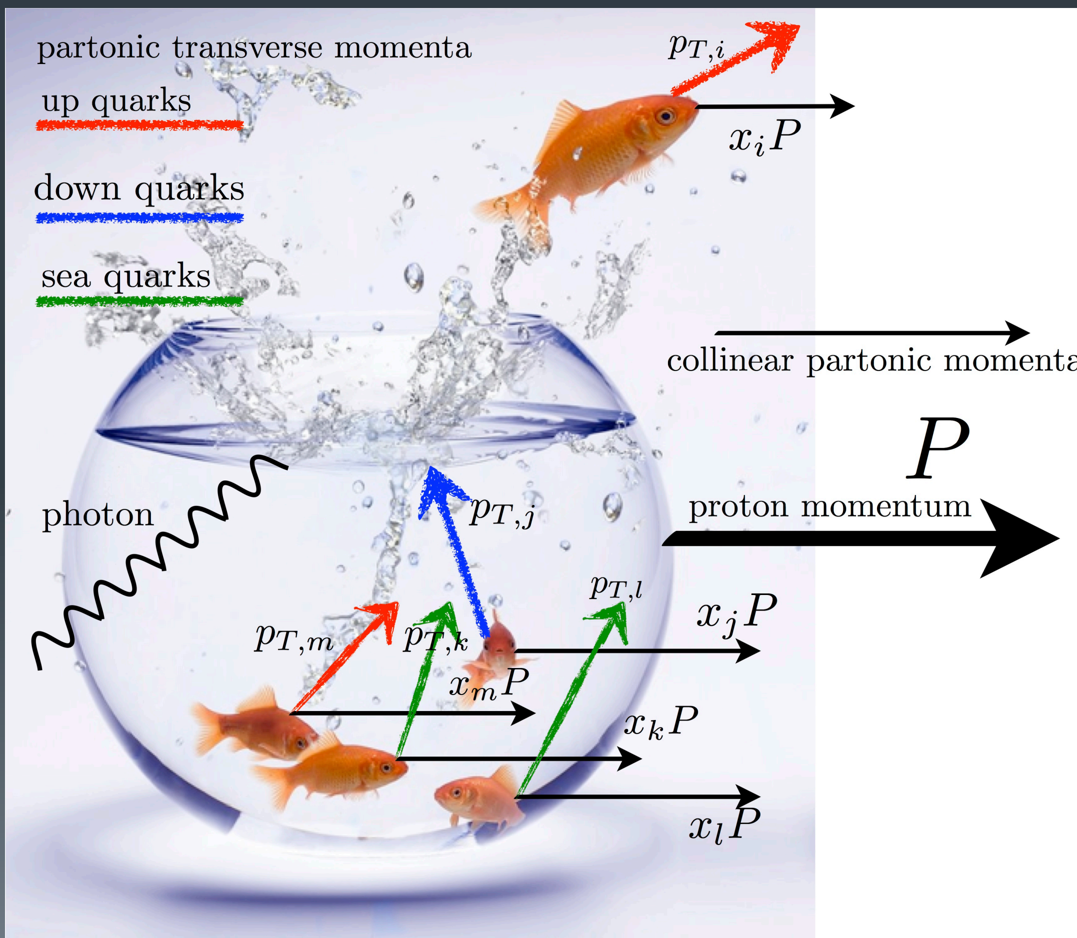
EMC Measurement (1987):





A proton spin crisis? A naive spin sum rule: $\boxed{\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + l_q + l_g}$

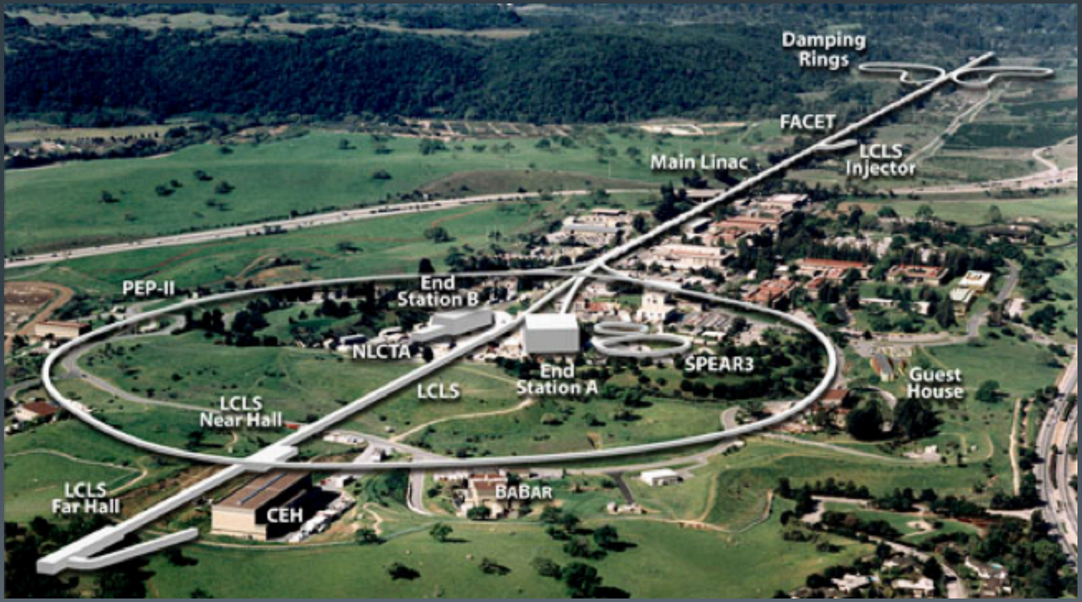
How to probe the nucleon spin structure?



To look into the proton? Smash it first!

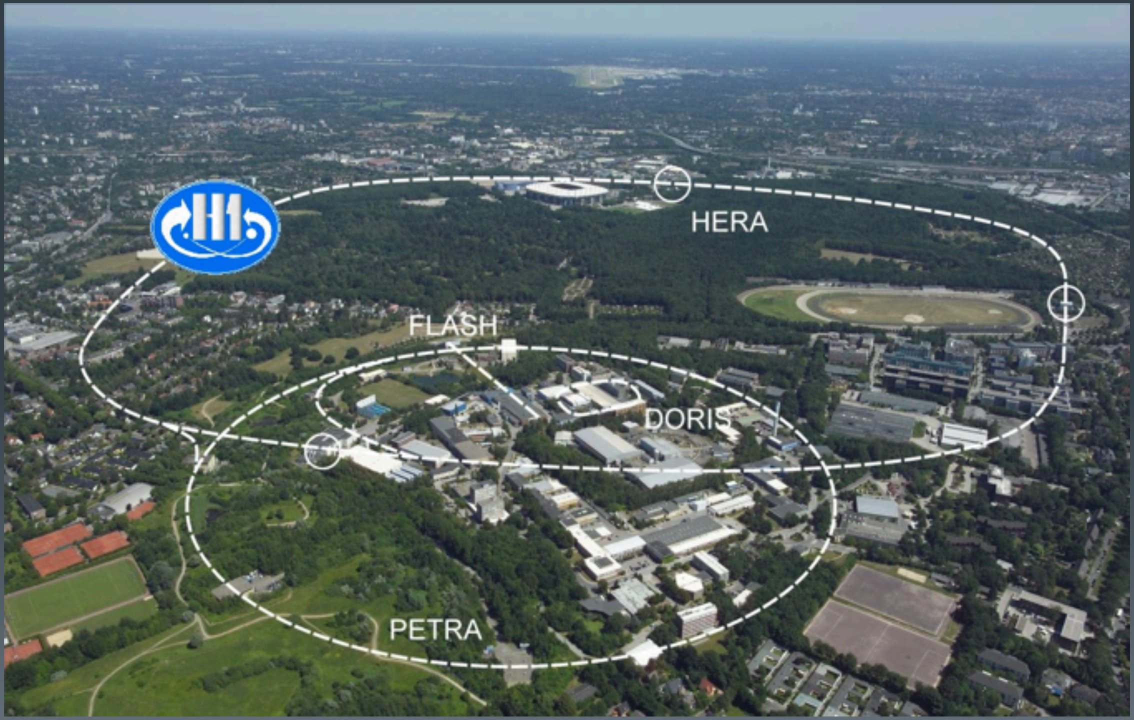
Deep inelastic scattering

State-of-the-art Polarized Deep Inelastic Scattering Experiments



- SLAC
- HERMES @ HERA, DESY
- COMPASS @ SPS, CERN
- CLAS @ Jefferson Lab

State-of-the-art Polarized Deep Inelastic Scattering Experiments



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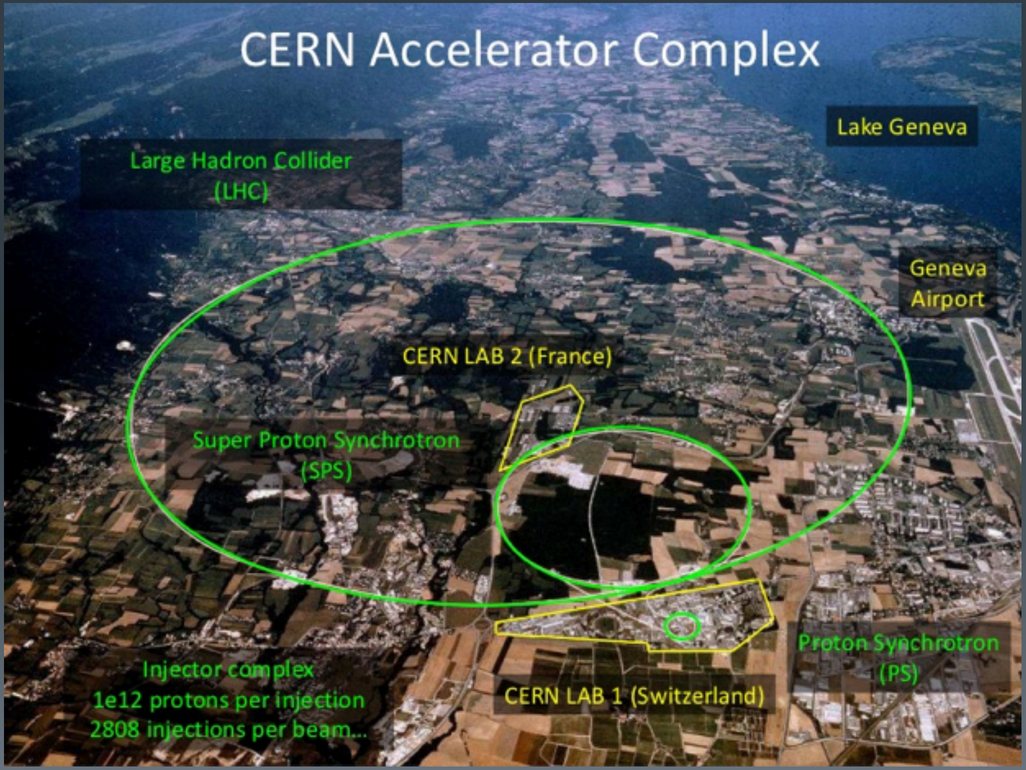

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State-of-the-art Polarized Deep Inelastic Scattering Experiments

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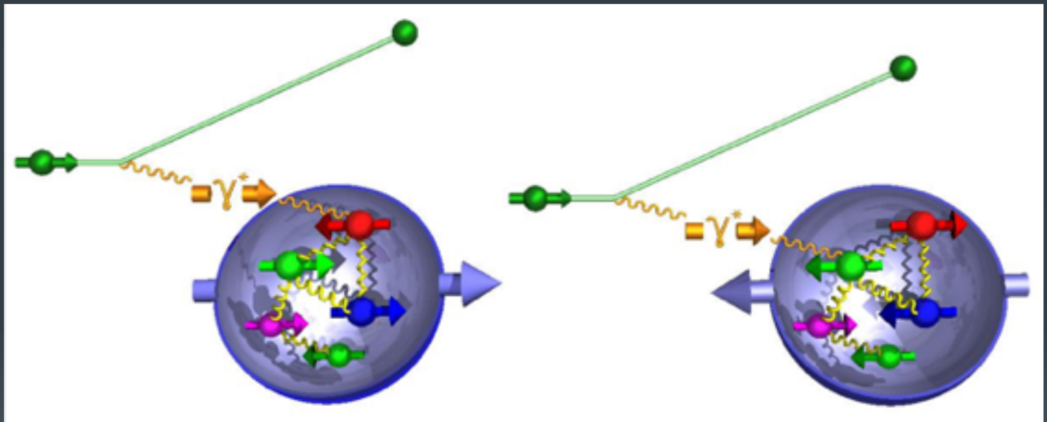
Polarized Lepton Proton Scattering:



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COMPASS @ SPS, CERN

CLAS @ Jefferson Lab

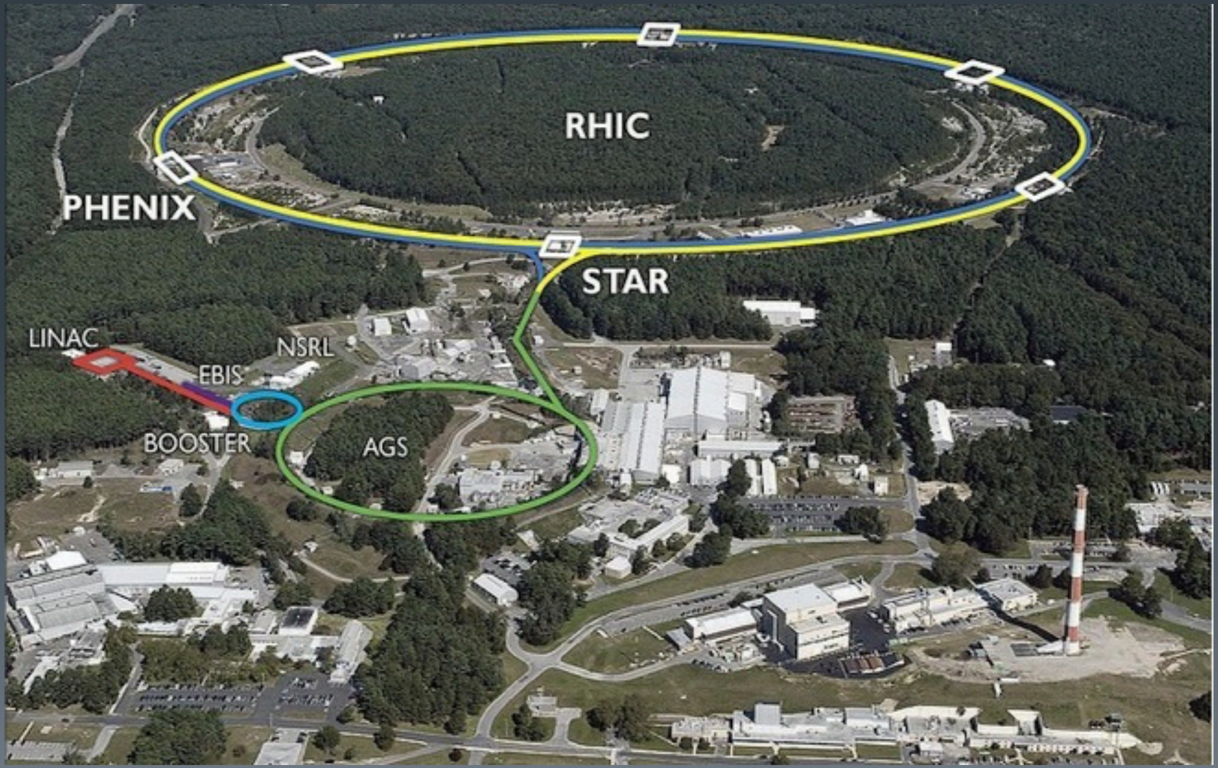
$$\frac{d\sigma_{\uparrow\uparrow} - d\sigma_{\uparrow\downarrow}}{d\sigma_{\uparrow\uparrow} + d\sigma_{\uparrow\downarrow}} \propto \sum_q e_q^{\,2} C_q(x) \otimes \Delta q(x) + C_g(x) \otimes \Delta g(x)$$

$$C_q(x) \sim 1 + O(\alpha_s)$$

$$C_g(x) \sim O(\alpha_s)$$

$$\Delta\Sigma = \int_0^1 dx\ \Delta q(x), \quad \Delta G = \int_0^1 dx\ \Delta g(x)$$

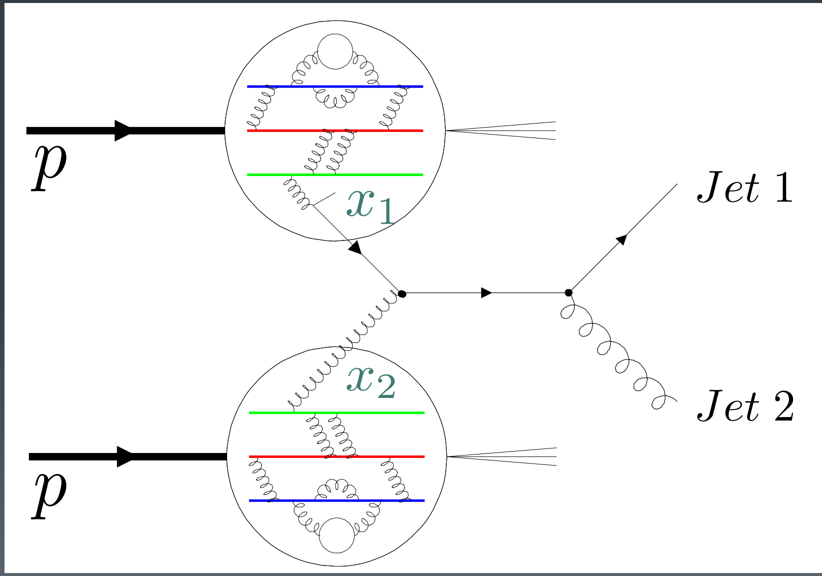
Polarized Proton-Proton Collision Experiment



STAR, PHENIX, BRAHMS @ RHIC, BNL

RHIC has made the most precise measurement of the gluon polarization so far.

Polarized Proton-Proton Collision Experiment



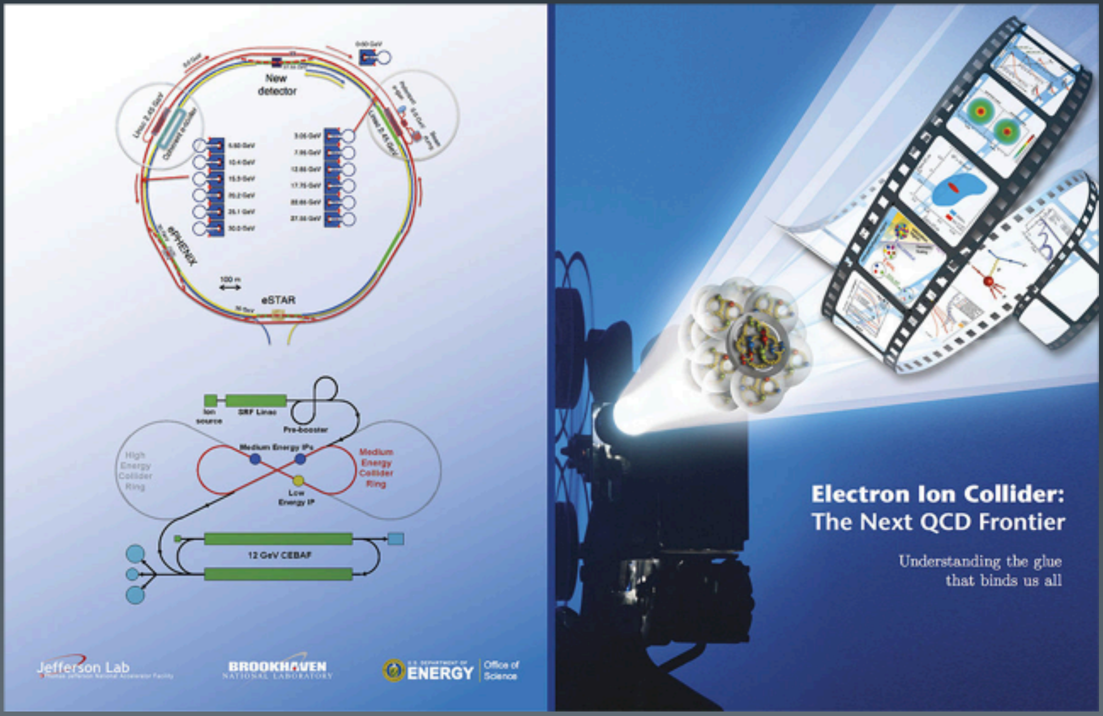
$$\frac{d\sigma_{\uparrow\uparrow} - d\sigma_{\uparrow\downarrow}}{d\sigma_{\uparrow\uparrow} + d\sigma_{\uparrow\downarrow}} \propto \frac{\Delta f_1(x_1) \otimes \Delta f_2(x_2) \otimes \Delta\sigma_{h/J} (\otimes D_f^{\,h})}{f_1(x_1) \otimes f_2(x_2) \otimes \sigma_{h/J} (\otimes D_f^{\,h})}$$

L.O. Contribution!

Probing sea quark polarization via W production: J. Zhang's talk

Electron-Ion Collider

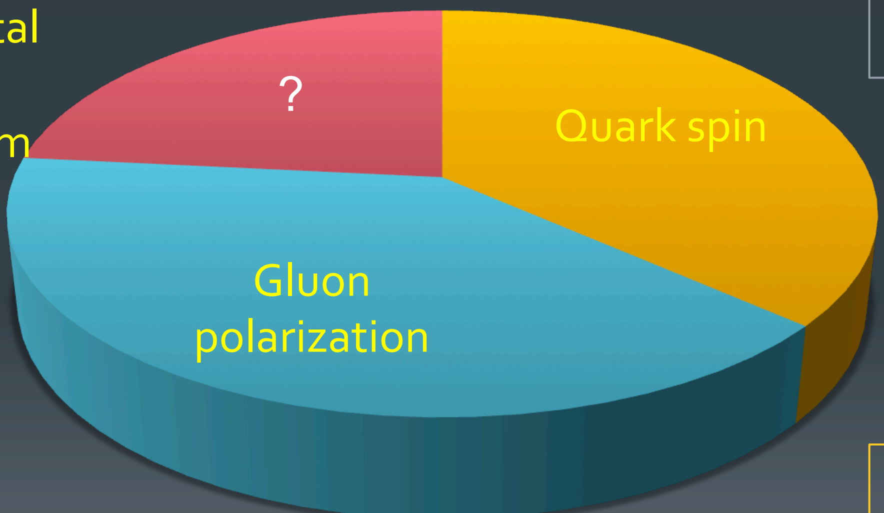
- Highly Polarized Beams
- Large Kinematic Range
- High Collision Luminosity



EIC will be capable of measuring the nucleon spin structure to a more precise level!

A. Accardi et al., arXiv:1212.1701.

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

$\Delta G(Q^2\!=\!10\ \mathrm{GeV}^2) = 0.2\sim0.3$,
de Florian et al., 2014;
E. Nocera et al., 2014;
Lattice QCD: Yang, Suffian, Y.Z., et al., 2016

Naïve spin sum rule: $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + l_q^z + l_g^z$$

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- Proton spin structure from DIS
- Gluon OAM and Wigner distribution
- Experimental observable

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.

$$\frac{1}{2} = J_q + J_g, \quad (L_g = J_g - \Delta G)$$

- OAM in Jaffe-Manohar sum rule (Jaffe and Manohar, 1989):
  - Clear partonic interpretation;
  - Related to a TMD (pretzelosity) in models (She, Zhu, and Ma, 2009; H. Avakian et al., 2009, 2010), accessible through SIDIS (Lefky and Prokudin, 2015; COMPASS, 2017);
  - Model-independent observable not known until recently.

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

The gluon orbital angular momentum (OAM) and Wigner distribution

- Moment of a phase space Wigner distribution

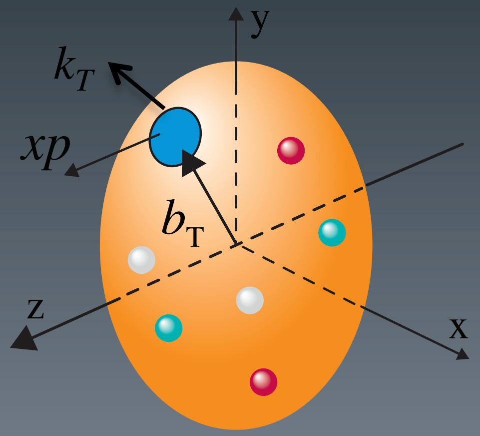
$$L_g(x) = \int db^2{}_\perp d^2k_\perp (b_\perp \times k_\perp) W^g{}_{LC}(x,0,k_\perp,b_\perp)$$

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)

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

$$L_g(x) = \varepsilon_\perp^{\alpha\beta} \left.\frac{\partial}{\partial i\Delta_\perp^\alpha}\right|_{\Delta=0} \int d^2k_\perp k_\perp^\beta f_g(x,\xi,k_\perp,\Delta_\perp)$$



The gluon orbital angular momentum (OAM) and Wigner distribution

- Parametrization of GTMD

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

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

- Gluon OAM density as the moment of GTMD

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

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

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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?

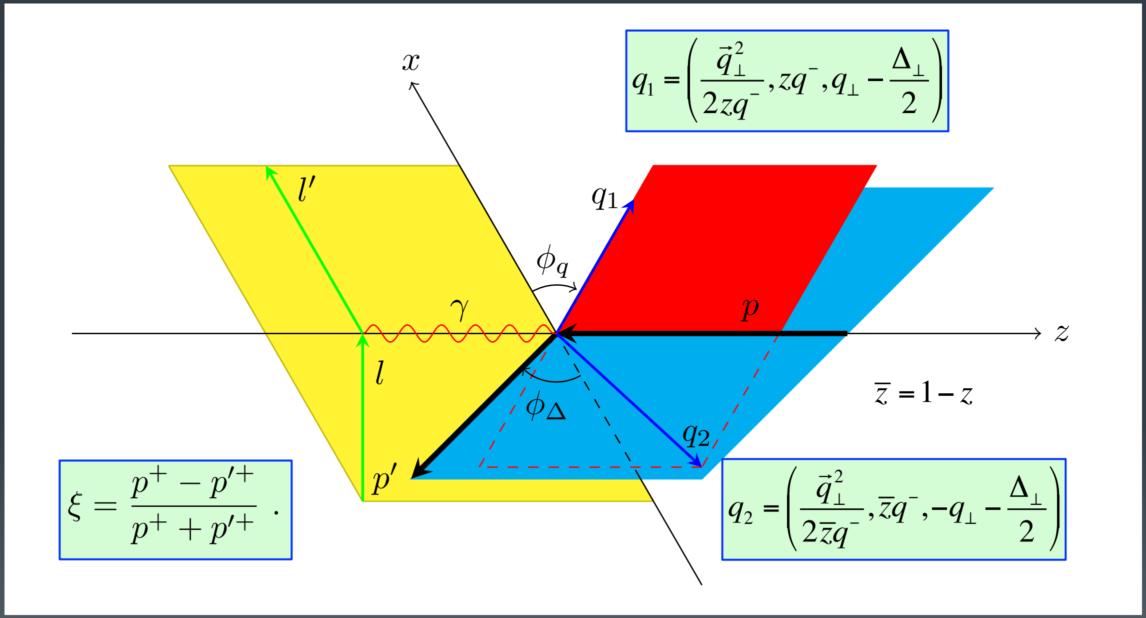
Answer: Exclusive dijet production in $l+p$ scattering ✔

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

Braun and Ivanov, 2005

Hatta, Xiao and Yuan, 2016

Kinematics



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

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

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

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

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

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

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

Scattering Amplitude

Scattering amplitude:

Photon helicity decomposition:

$$g^{\mu\nu} = \sum_{\lambda=L,\perp} \varepsilon_{\lambda}^{*\mu}\varepsilon_{\lambda}^{\nu}$$

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

Leptonic part, averaging initial spins and summing over final spins

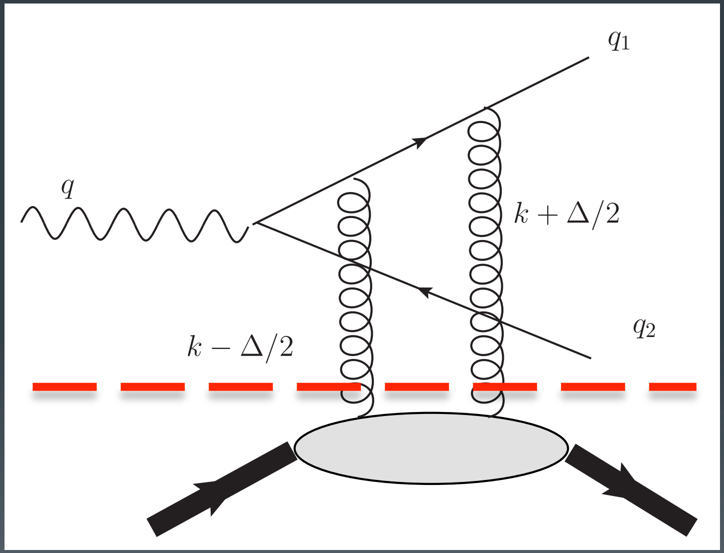
Hadronic part, summing over final state quark spins and color

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

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

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

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

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

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):

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

Differential cross section

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

- Result:

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

$$|q_\perp||\Delta_\perp|\mathrm{Sin}(\phi_q - \phi_\Delta)$$

λ_p Nucleon Polarization

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

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

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: $F(\xi,\pm\xi,t)$, $L(\xi, \pm\xi,t)$.

$$\frac{1}{x+\xi-i\varepsilon} = \frac{1}{x+\xi} + i\pi\delta(x+\xi)$$

Single longitudinal target-spin asymmetry

- Definition:

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

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

- Feature:

  Asymmetric jets

  Suppressed effect $O(\Delta_T/Q)$

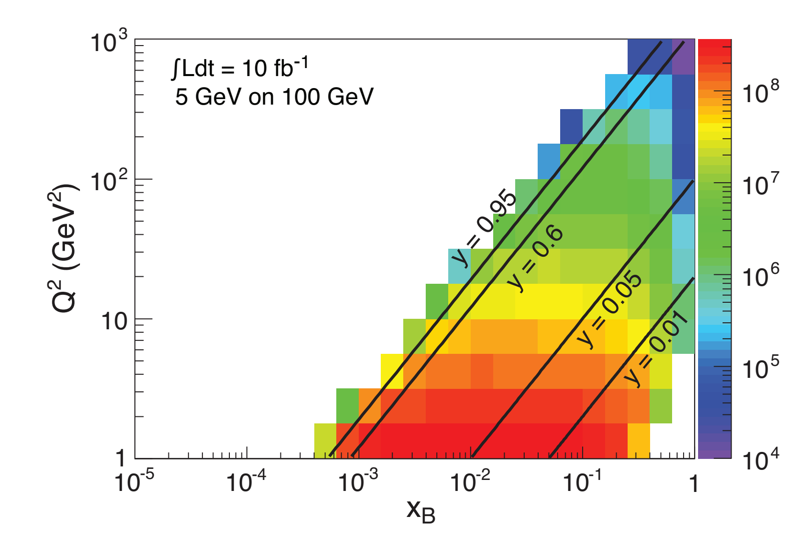
X. Ji, F. Yuan and Y.Z.,
Phys. Rev. Lett. 118(2017) no.19, 192004

The same process at small *x*:
Hatta, Nakagawa, Yuan and Y.Z., 2016
Double exclusive Drell-Yan πp->pγ*γ*:
Bhattacharya, Metz, and Zhou, 2017

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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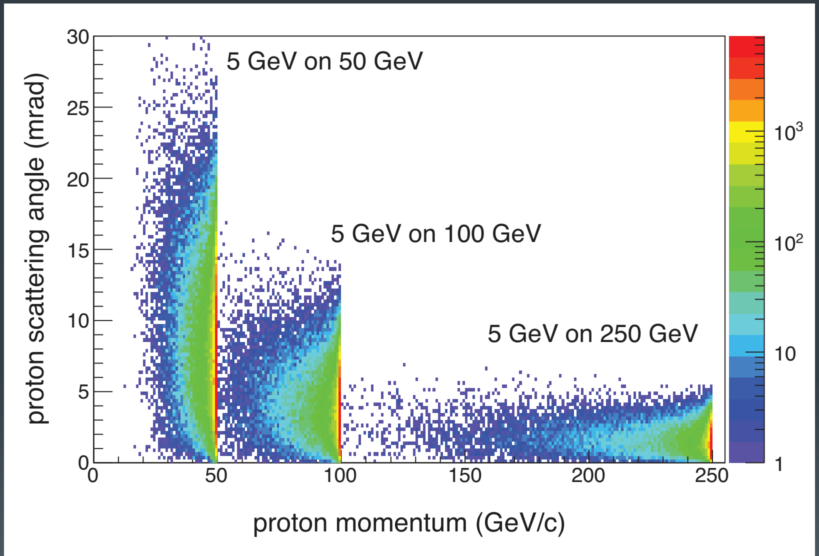
  Dijet momenta
  Final state nucleon momentum

- Kinematics:
  - Large Bjorken x, high Q^2;
  - Nucleon deflection angle (determines t and ξ).

$$E_p = 50\text{GeV}, \quad \theta = 10 mrad$$

$$\xi \sim \frac{1-\cos\theta}{3+\cos\theta} \sim 0.0000125, \ t \sim 0.25\text{GeV}^2.$$



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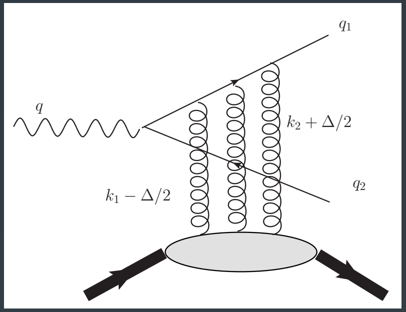
Outlook



- Include genuinely twist-three diagrams (undergoing);
- One-loop radiative corrections, test validity of collinear factorization;
- Simulations.

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.
- The differential cross section formula has been derived for the experimental observable at leading order.