Spin physics at the EIC

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BNL/RIKEN BNL

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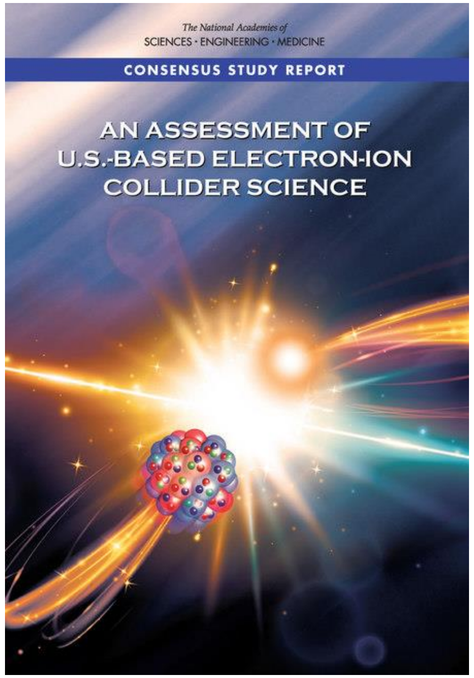
- BSM connections

An Assessment of U.S.-Based Electron-Ion Collider Science

NAS report
07/24/2018



Committee on U.S.-Based Electron-Ion Collider Science Assessment

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

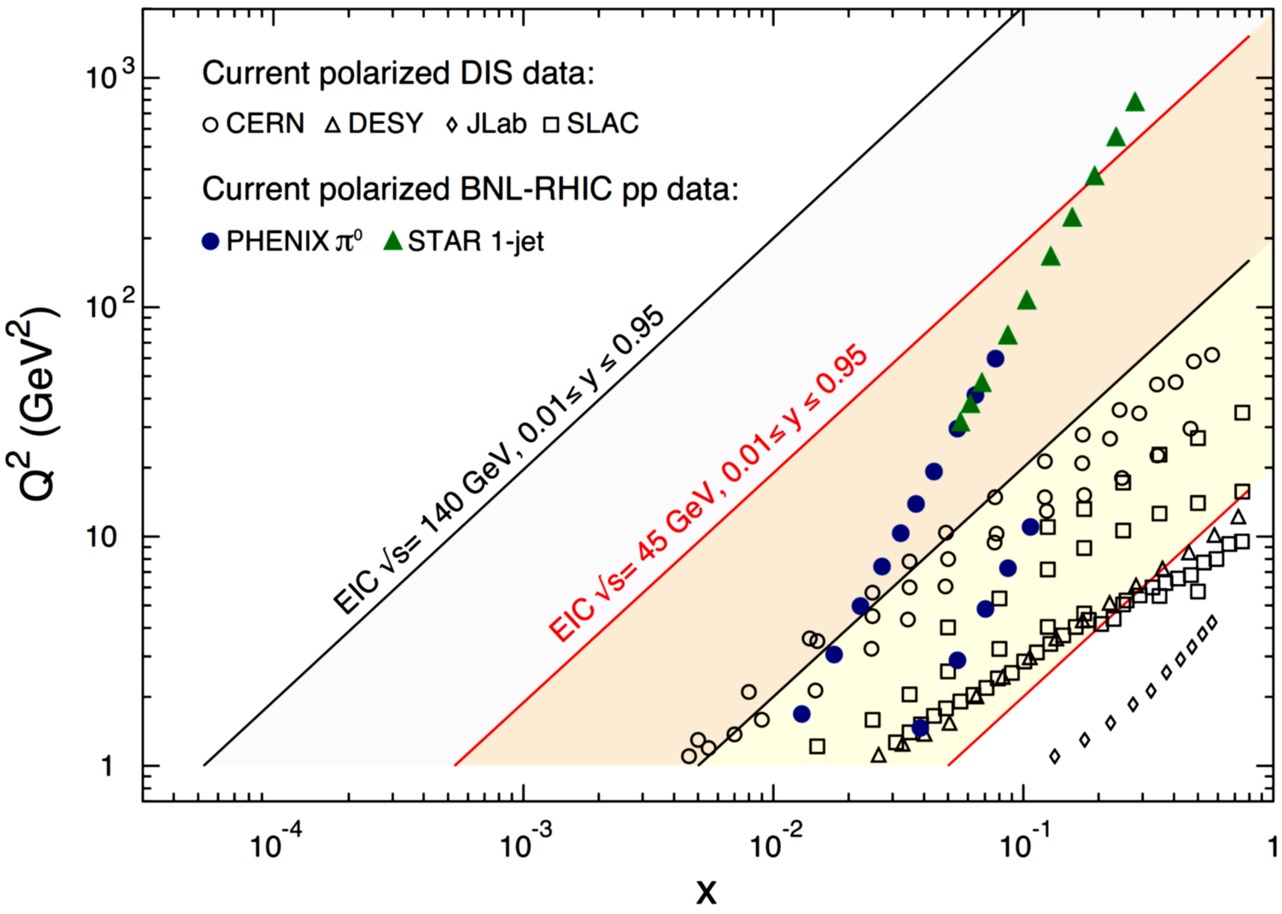
A Consensus Study Report of

The National Academies of
SCIENCES · ENGINEERING · MEDICIN

Finding 1: An EIC can uniquely address three profound questions about nucleons-protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

EIC: the world's first polarized ep collider



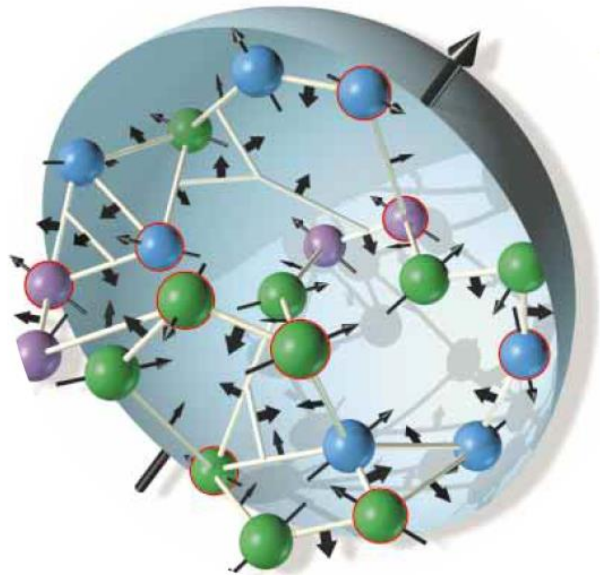
Unprecedented coverage in kinematics, very high luminosity

Tremendous physics opportunities for spin-related topics, both in QCD and BSM physics

Light ions can also be polarized.

Longitudinal spin

The proton spin problem



The proton has spin ½.

The proton is not an elementary particle.

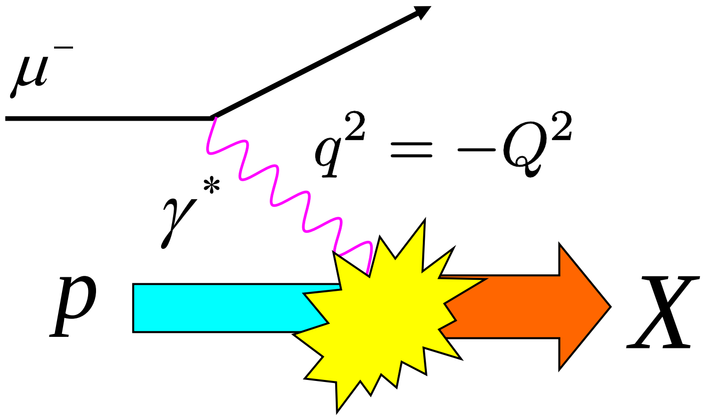
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$ Jaffe-Manohar sum rule

$$= \frac{1}{2}\Delta\Sigma + L^q_{kin} + J_g$$ Ji sum rule

$\Delta\Sigma = 1$ in the naïve quark model

$\Delta\Sigma$ from polarized DIS

Longitudinal double spin asymmetry in polarized DIS



$$A_{LL} = \frac{\mu^\uparrow p^\downarrow - \mu^\uparrow p^\uparrow}{\mu^\uparrow p^\uparrow + \mu^\uparrow p^\downarrow} \sim \left(1 + \frac{\sigma_L}{\sigma_T}\right) \frac{2x g_1}{F_2}$$

$$\int_0^1 dx g_1(x) = \frac{1}{9}(\Delta u + \Delta d + \Delta s) + \frac{1}{12}(\Delta u - \Delta d) + \frac{1}{36}(\Delta u + \Delta d - 2\Delta s) + \mathcal{O}(\alpha_s)$$

isovector axial charge

$$\Delta u - \Delta d = g_A \approx 1.2$$

octet axial charge, can be estimated from hyperon semileptonic decay

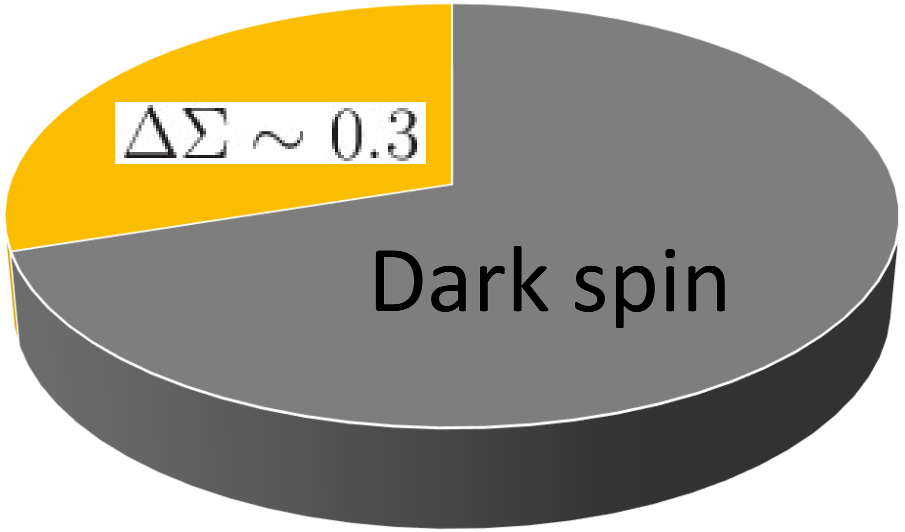
`Spin crisis'

In 1987, EMC (European Muon Collaboration) announced a very small value consistent with zero

$$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14 \quad !?$$

Recent value from NLO QCD global analysis

$$\Delta\Sigma = 0.25 \sim 0.3$$



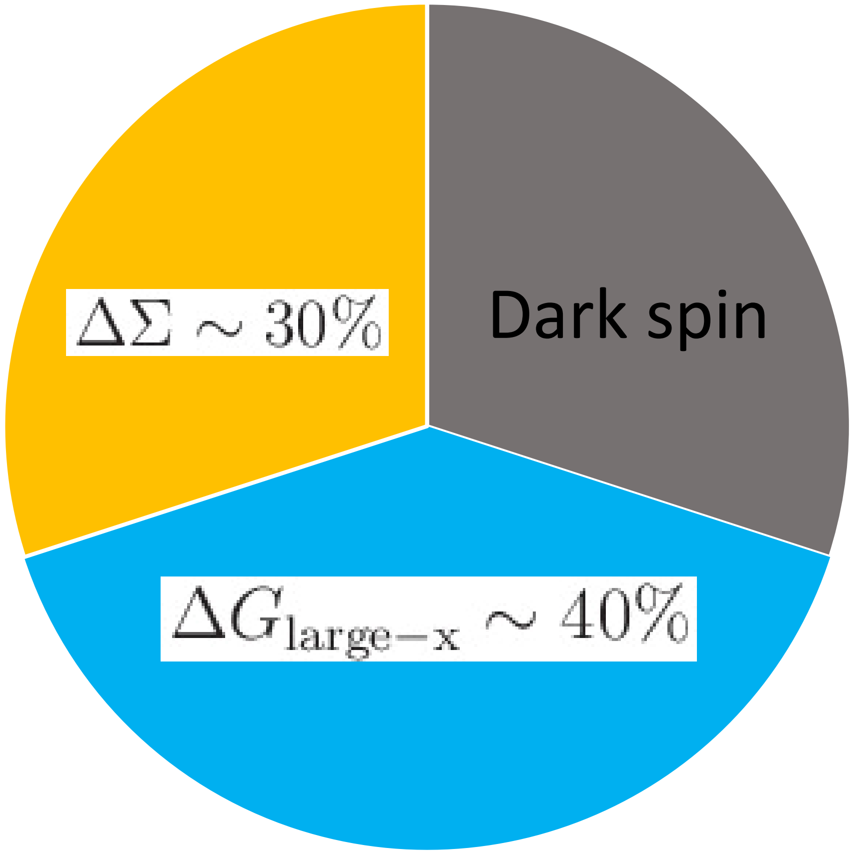
Evidence of nonzero gluon helicity $\Delta G = \int_0^1 dx \Delta G(x)$

A major achievement of the RHIC spin program!

$$\int_{0.05}^{1} dx \Delta G(x, Q^2 = 10\text{GeV}^2) = 0.20^{+.06}_{-.07}$$ DSSV

$$\int_{0.05}^{0.2} dx \Delta G(x, Q^2 = 10\text{GeV}^2) = 0.17 \pm 0.06$$ NNPDF

$$\int_{0.05}^{1} dx \Delta G(x, Q^2 = 10\text{GeV}^2) = 0.23 \pm 0.03$$ JAM



Huge uncertainty from the small-x region → EIC
Renewed interest in the small-x resummation of helicity PDFs

Helicity evolution at small-x

All-order resummation of small-x double logarithms for helicity PDFs

$$(\alpha_s \ln^2 1/x)^n$$

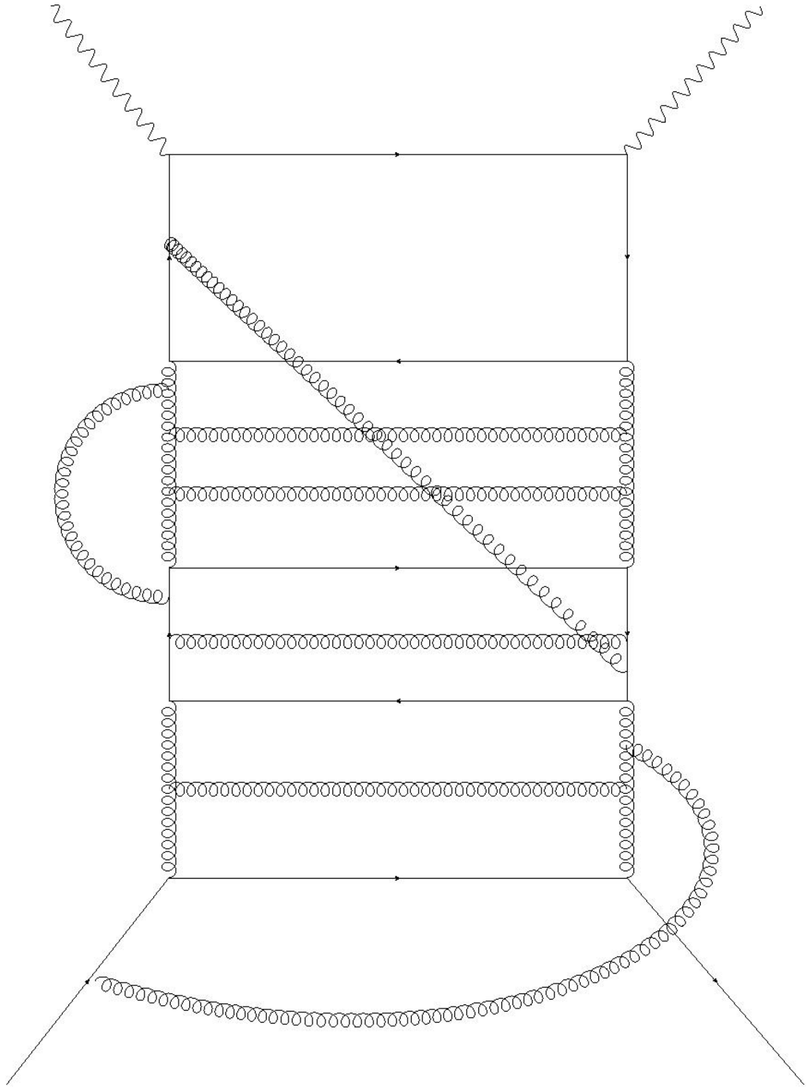
…in contrast to single logarithmic resummation (BFKL) for unpol PDFs

$$(\alpha_s \ln 1/x)^n$$

Unlike BFKL, we need to include quark ladders
Unlike BFKL, we need to include non-ladder diagrams

Resummation very hard, but can be done!

Kirschner Lipatov (1983)
Bartels, Ermolaev, Ryskin (1996)
Kovchegov et al. (2015~)



Regge intercept at small-x, revisited

Bartels, Ermolaev, Ryskin (1996)

$$\Delta\gamma_{GG}^{BER}(\omega) = \frac{4\,\bar{\alpha}_s}{\omega} + \frac{8\,\bar{\alpha}_s^2}{\omega^3} + \frac{56\,\bar{\alpha}_s^3}{\omega^5} + \frac{504\,\bar{\alpha}_s^4}{\omega^7} + \ldots$$

Borden, Kovchegov (2023)

$$\Delta\gamma_{GG}^{us}(\omega) = \frac{4\,\bar{\alpha}_s}{\omega} + \frac{8\,\bar{\alpha}_s^2}{\omega^3} + \frac{56\,\bar{\alpha}_s^3}{\omega^5} + \frac{496\,\bar{\alpha}_s^4}{\omega^7} + \ldots$$

Discrepancy at 4-loops!

$$\Delta q(x), \Delta G(x) \sim \frac{1}{x^\alpha}$$

$$\alpha_{BER} \approx 3.664\sqrt{\frac{\alpha_s N_c}{2\pi}} \qquad \alpha_{BK} \approx 3.661\sqrt{\frac{\alpha_s N_c}{2\pi}}$$

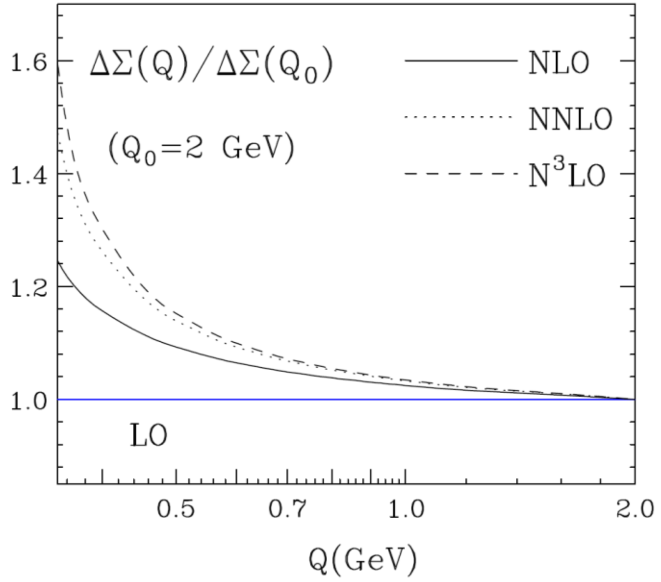
Helicity pQCD precision frontier

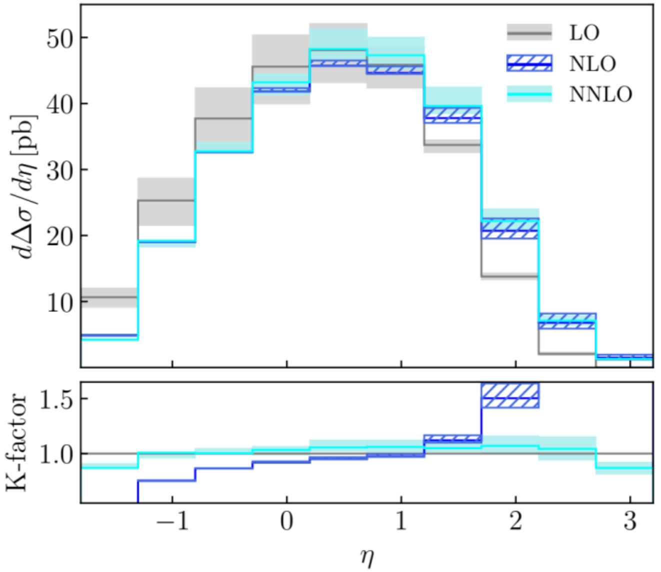
4-loop evolution of $\Delta\Sigma$
De Florian, Vogelsang (2019)

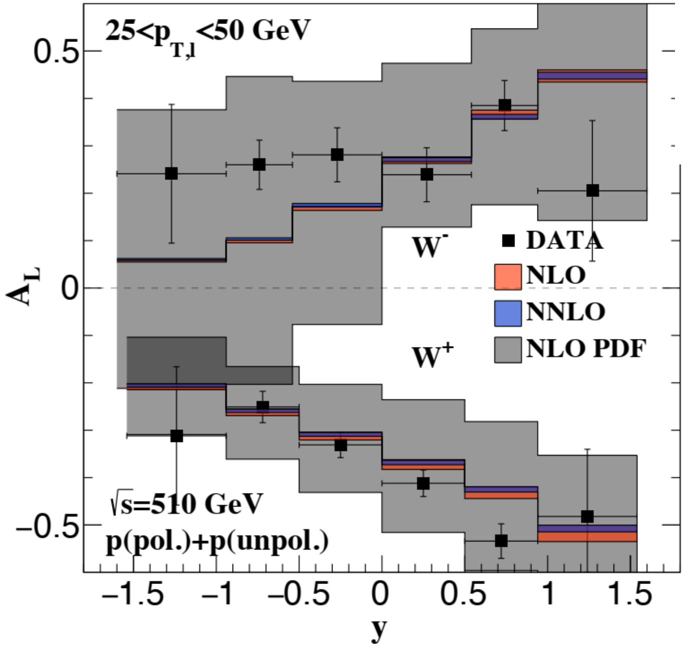
NNLO jet production in polarized DIS
Borsa, de Florian, Pedron (2020)

NNLO longitudinal spin asymmetry of W at RHIC
Boughezal, Li, Petriello (2021)

3-loop Wilson coefficients for $g_1(x)$
Blumlein, Marquard, Schneider, Schonwald (2022)



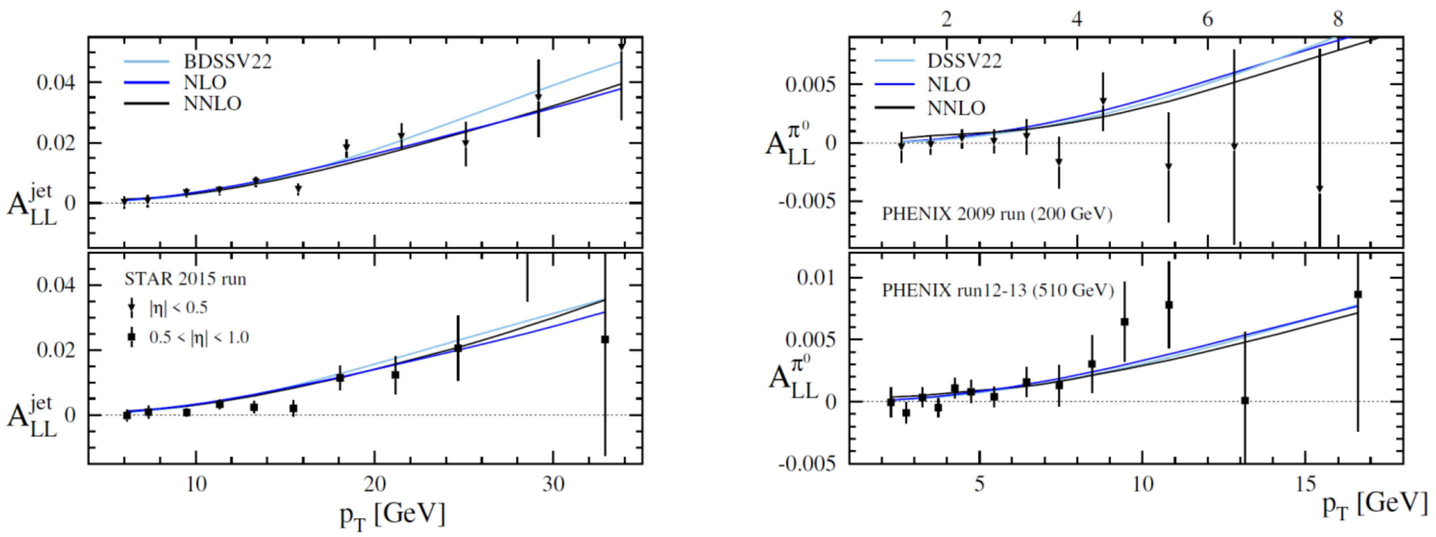




NNLO global analysis for helicity PDF on the way

Vogelsang, talk at SPIN2023

Data:		
DIS:	EMC,SMC,E142,E143,E154,E155, HERMES, COMPASS, HALL-A,CLAS (p,n,d,He)	**378**
SIDIS:	HERMES, COMPASS (p-$\pi^{\pm}$, d-$\pi^{\pm}$)	**80**
PP-JETS:	STAR run 5,6,9,12,13,15 ($\sqrt{s} = 200, 510\, GeV$) (no dijets yet)	**91**
PP-$\pi^0/\pi^{\pm}$:	PHENIX, STAR	**82**
PP $W^{\pm}$:	PHENIX, STAR	**22**
Total:		**653**



Theory developments and future data from the EIC will determine the precise helicity structure of the proton!

An elephant in the room: Orbital angular momentum

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

No experimental measurement of OAM so far

Spin sum rule cannot be complete without understanding OAM

Helicity is not a conserved quantity.
Even if OAM is zero at some scale, it is nonzero at different scales.

$$\frac{d}{d\ln Q^2}\left(\frac{1}{2}\Delta\Sigma(Q^2) + \Delta G(Q^2) + L_q(Q^2) + L_g(Q^2)\right) = 0$$

What exactly is OAM in QCD?

$$L = x \times p$$

canonical momentum $-i\partial^\mu$

kinetic momentum $-iD^\mu$

Canonical OAM Jaffe, Manohar (1990)

$$\Delta L_q = \frac{1}{2E(2\pi)^3\delta^3(0)} \left\langle p_\infty^0, s^0 \middle| \int \mathrm{d}^3x\, i\psi^\dagger (\boldsymbol{x} \times \boldsymbol{\nabla})^3 \psi \middle| p_\infty^0, s^0 \right\rangle,$$

$$\Delta L_g = \frac{1}{2E(2\pi)^3\delta^3(0)} \left\langle p_\infty^0, s^0 \middle| \int \mathrm{d}^3x\, \mathrm{Tr}\{E^k (\boldsymbol{x} \times \boldsymbol{\nabla})^3 A^k\} \middle| p_\infty^0, s^0 \right\rangle.$$

To be understood in the light-cone gauge $A^+ = 0$

Gauge invariant completion available $\partial^\mu \to D^\mu - \frac{i}{D^+} F^{+\mu}$ $A^\mu \to \frac{1}{D^+} F^{+\mu}$ YH (2011)

OAM from the Wigner distribution

5D phase space distribution of partons in the nucleon

`staple-shaped' Wilson line

$$W(x,\vec{k}_\perp,\vec{b}_\perp)$$
$$=\int \frac{d^2\Delta_\perp}{(2\pi)^2}\frac{dz^-d^2z_\perp}{16\pi^3}e^{ixP^+z^- -i\vec{k}_\perp\cdot\vec{z}_\perp}\langle P-\frac{\Delta}{2}|\bar{q}(b-z/2)\gamma^+q(b+z/2)|P+\frac{\Delta}{2}\rangle$$

Define

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

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

Twist-3 OAM PDF

YH, Yoshida (2012)

$$L^q_{can}(x) = x\int_x^{\epsilon(x)} \frac{dx'}{x'}(H_q(x')+E_q(x')) - x\int_x^{\epsilon(x)} \frac{dx'}{x'^2}\tilde{H}_q(x')$$

Wandzura-Wilczek part

$$-x\int_x^{\epsilon(x)} dx_1 \int_{-1}^{1} dx_2 \Phi_F(x_1,x_2)\mathcal{P}\frac{3x_1-x_2}{x_1^2(x_1-x_2)^2}$$
$$-x\int_x^{\epsilon(x)} dx_1 \int_{-1}^{1} dx_2 \tilde{\Phi}_F(x_1,x_2)\mathcal{P}\frac{1}{x_1^2(x_1-x_2)}\,.$$

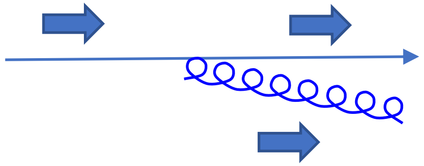
genuine twist-3

$$\Phi_F \sim \langle P'|\bar{\psi}\gamma^+ F^{+i}\psi|P\rangle$$

$$M_F \sim \langle P'|F^{+\mu}F^{+i}F^+_\mu|P\rangle$$

$$L^g_{can}(x) = \frac{x}{2}\int_x^{\epsilon(x)} \frac{dx'}{x'^2}(H_g(x')+E_g(x')) - x\int_x^{\epsilon(x)} \frac{dx'}{x'^2}\Delta G(x')$$
$$+2x\int_x^{\epsilon(x)} \frac{dx'}{x'^3}\int dX\,\Phi_F(X,x') + 2x\int_x^{\epsilon(x)} dx_1 \int_{-1}^{1} dx_2 \tilde{M}_F(x_1,x_2)\mathcal{P}\frac{1}{x_1^3(x_1-x_2)}$$
$$+2x\int_x^{\epsilon(x)} dx_1 \int_{-1}^{1} dx_2 M_F(x_1,x_2)\mathcal{P}\frac{2x_1-x_2}{x_1^3(x_1-x_2)^2}$$

OAM at small-x



$x \ll 1$

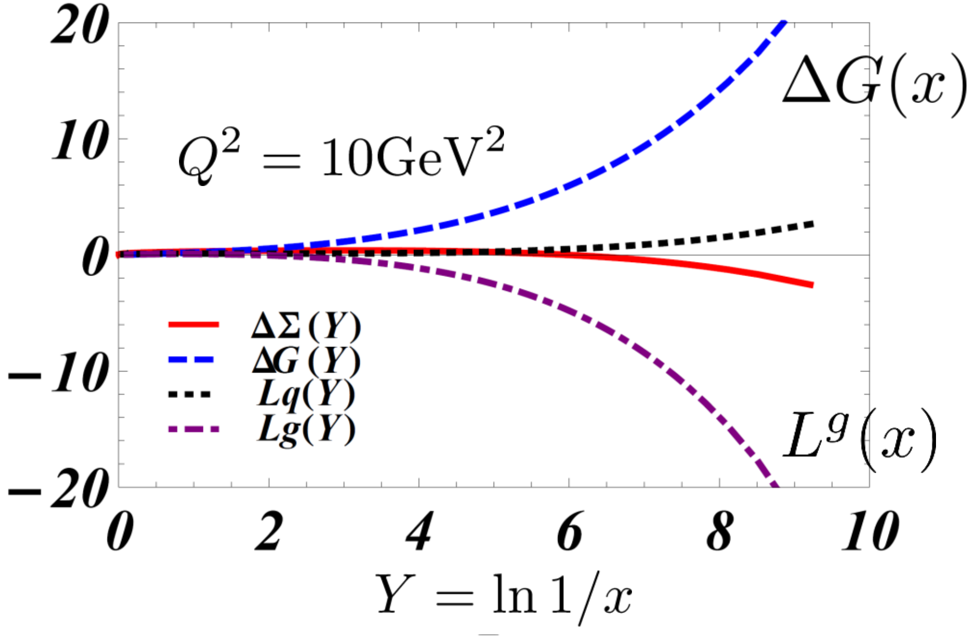
Suppose a quark emits a very soft gluon.
Nothing happens to the quark.
From angular momentum conservation, gluon's helicity and OAM must cancel.

$$\frac{d}{d\ln Q^2} L_g(x) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\left(-2C_F + \cdots\right)\Delta q(x/z)$$

$$\frac{d}{d\ln Q^2} \Delta G(x) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\left(+2C_F + \cdots\right)\Delta q(x/z)$$

Helicity-OAM cancellation at small-x

If $\Delta G(x) \sim \frac{1}{x^{\alpha}}$, then $L_g(x) \approx -\frac{2}{1+\alpha}\Delta G(x)$



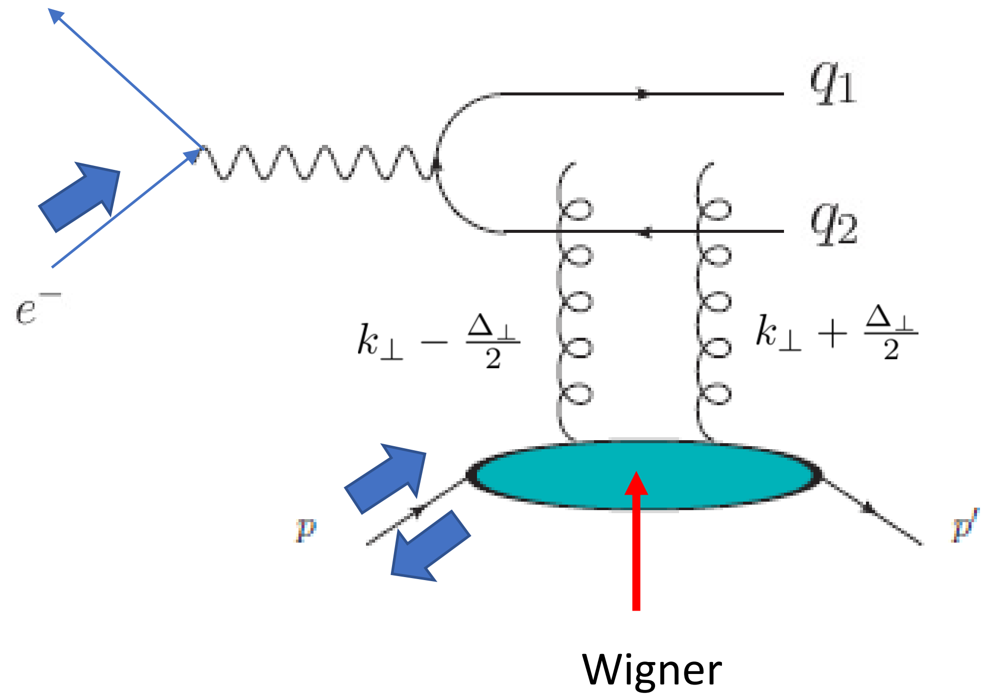
There might be a sizable contribution to ΔG from the small-x region.

If so, there will be even larger L_g from the same x-region with an opposite sign.

Can EIC seriously address OAM?

Longitudinal double spin asymmetry in diffractive dijet production

Inclusive DSA → polarized PDFs
Exclusive DSA → OAM



$$L^z \sim b_\perp \times k_\perp$$

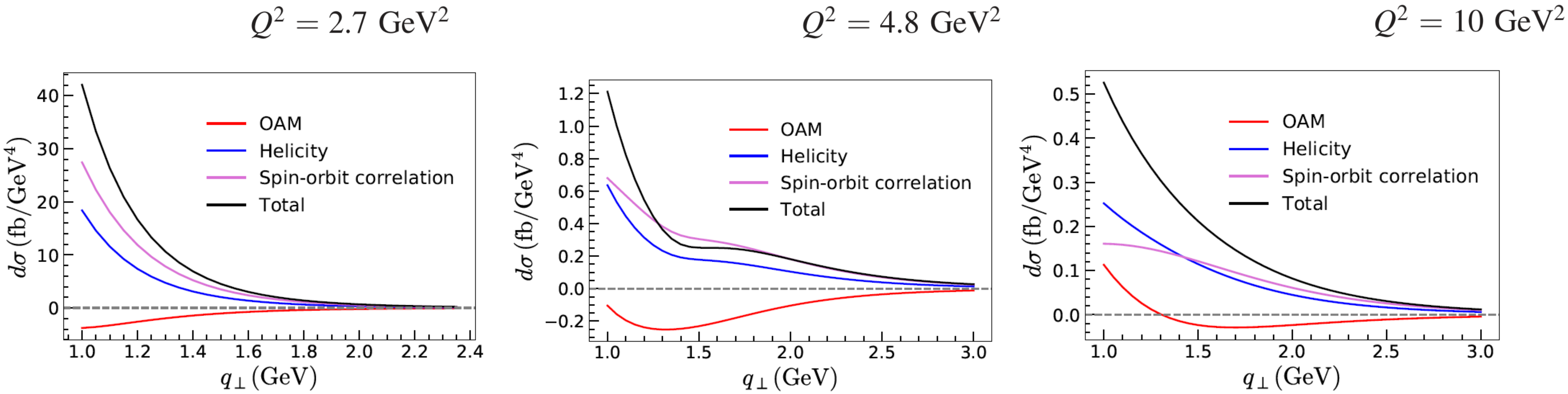
$b_\perp$ conjugate to proton recoil momentum $\Delta_\perp$

Expand the amplitude to linear order in $k_\perp$ (twist-3 effect)

$$d\sigma^{h_p h_l} \sim h_p h_l \cos(\phi_{l_\perp} - \phi_{\Delta_\perp}) \mathrm{Re}(iA_L^{2*} A_T^{3i} - iA_T^{2i*} A_L^3)$$

Prediction for EIC

Bhattacharya, Boussarie, YH (2022) + paper in preparation



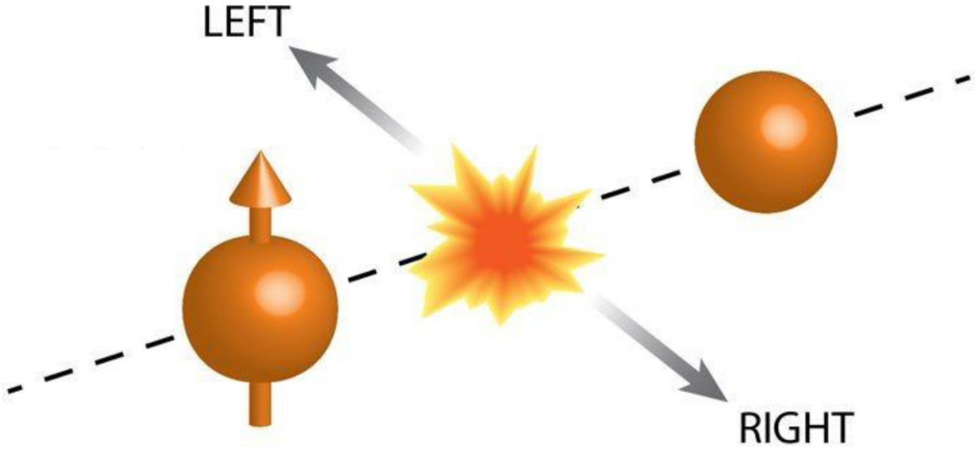
First-ever quantitative prediction for an observable sensitive to OAM

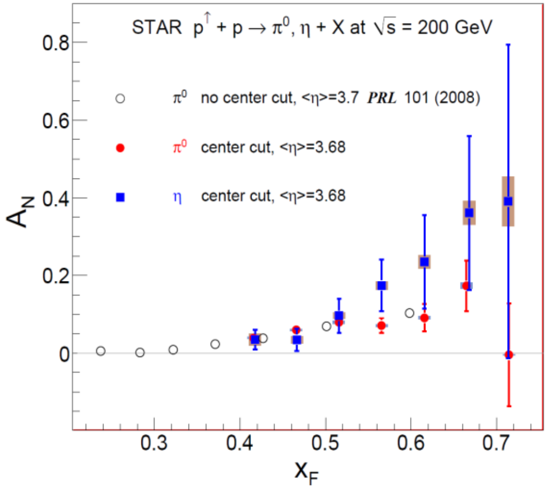
Contamination from helicity and spin-orbit correlation.

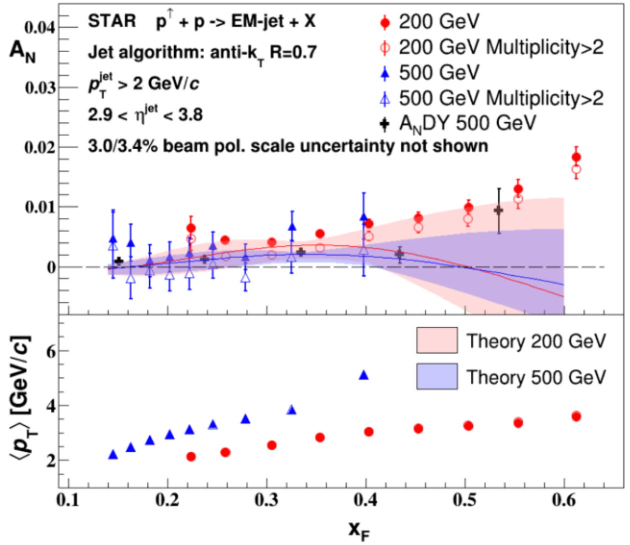
To extract OAM, we need to know $G(x)$, $\Delta G(x)$ precisely at small-x

Transverse spin

Transverse Single Spin Asymmetry (SSA)



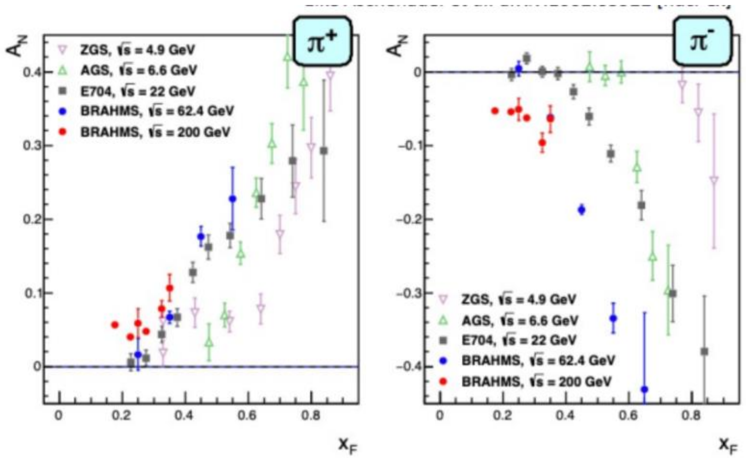


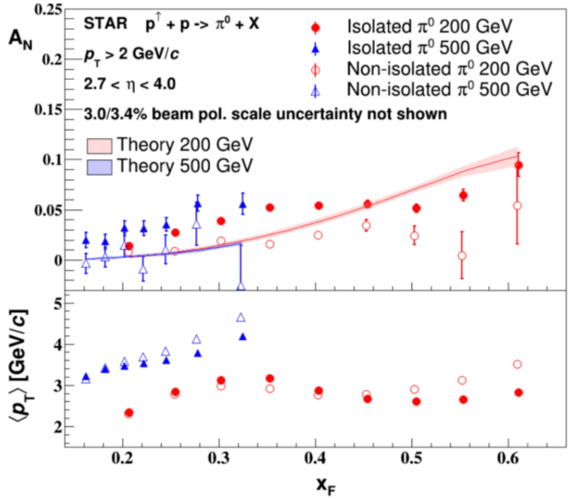


Production of hadrons is left-right asymmetric

$$d\sigma \sim S_\perp \times P_{hT} \sim \sin(\phi_{S_\perp} - \phi_{P_{hT}})$$

$$A_N = \frac{d\sigma_{left} - d\sigma_{right}}{d\sigma_{left} + d\sigma_{right}}$$

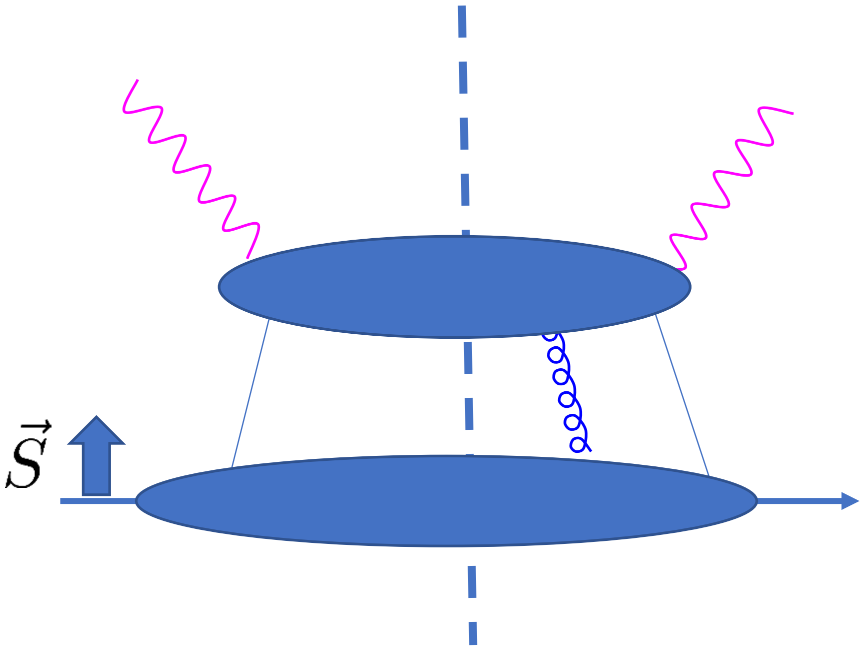




40+ years puzzle in QCD

Quest for a phase

Find part of the cross section linear in spin $\vec{S}$ → interference terms

$$d\sigma \sim$$  $$+ \; c.c.$$

Naively purely imaginary, vanish after adding the c.c. part

An extra factor of i is needed to make the asymmetry nonzero.

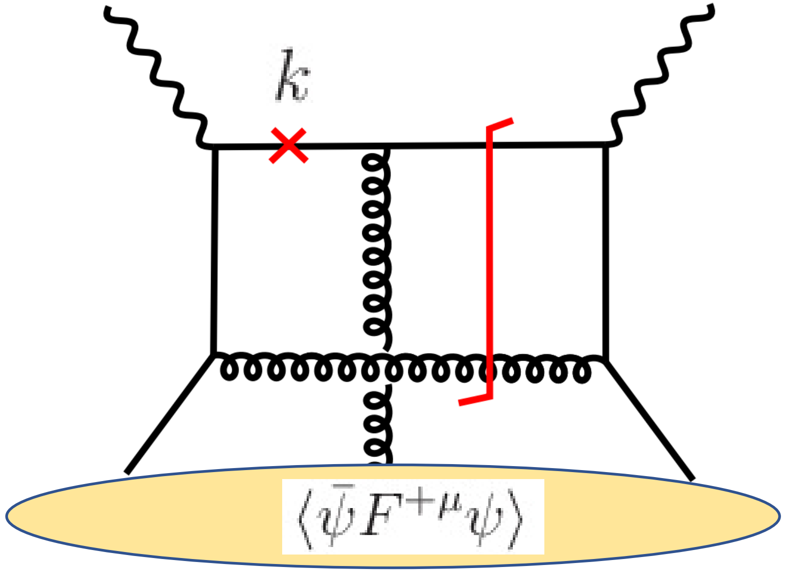
Origins of SSA

Collinear factorization

- Efremov-Teryaev-Qiu-Sterman function
- Twist-three fragmentation functions
- Three-gluon correlator
- ….

kt factorization

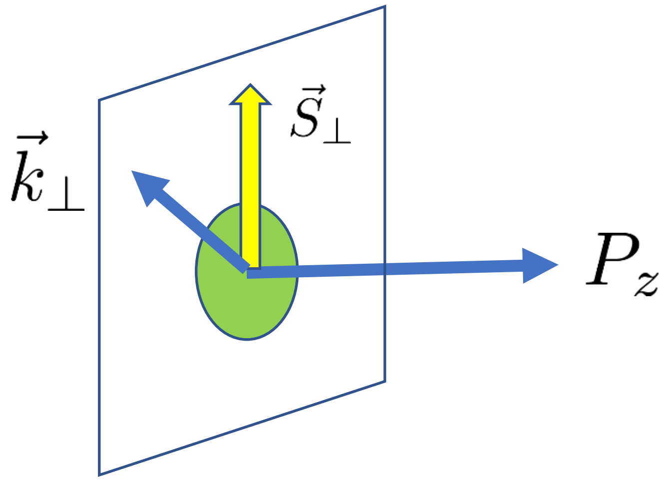
- Sivers function
- Collins function
- ….



$$\frac{1}{k^2 + i\epsilon} = \frac{\mathrm{P}}{k^2} - i\pi\delta(k^2)$$

Universality up to a sign

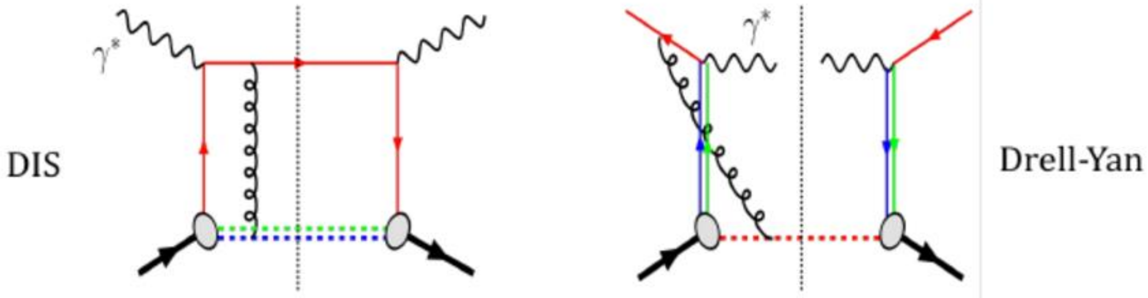
Sivers function for the transversely polarized nucleon



$$\sim \vec{S}_\perp \times \vec{k}_\perp f_{1T}^{\perp}(x, k_\perp)$$

→ Single spin asymmetry

The same function, but with opposite signs in DIS and Drell-Yan. (Collins, 2002)

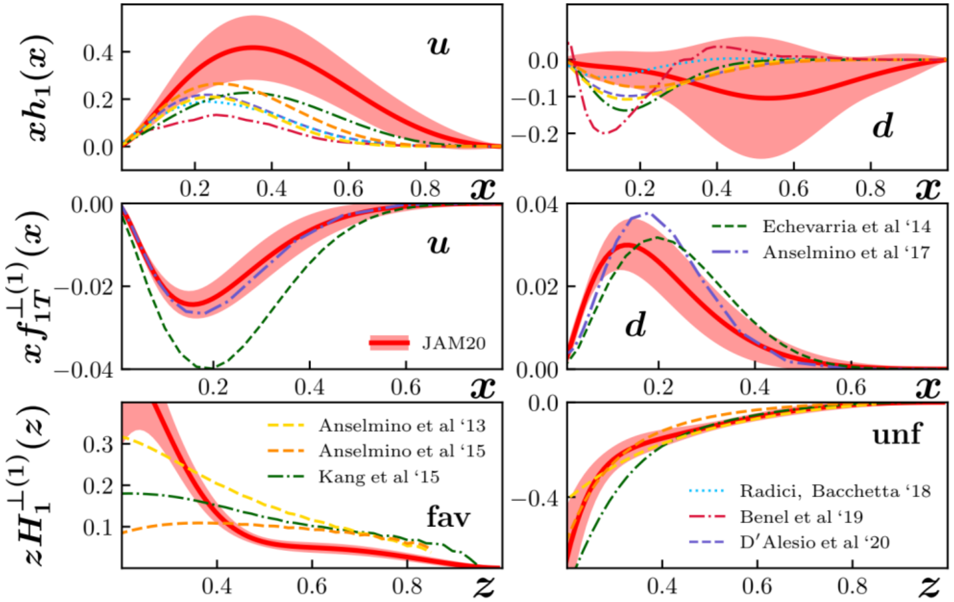


Experimental test (COMPASS)

EIC can also probe gluon Sivers function

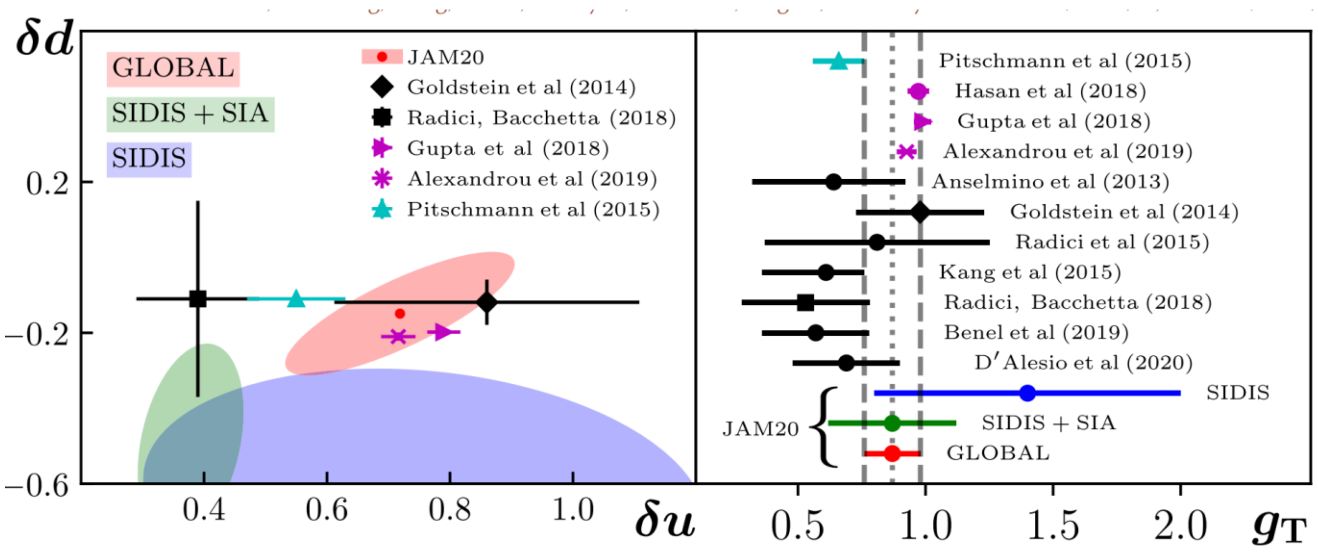
Global analysis of SSA

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)



Simultaneous fit of

e+e- (BELLE, BaBar, BESIII)
SIDIS (COMPASS, HERMES, Jlab) ← input from EIC in future
Drell-Yan (COMPASS, STAR)
pp (STAR, PHENIX, BRAHMS)



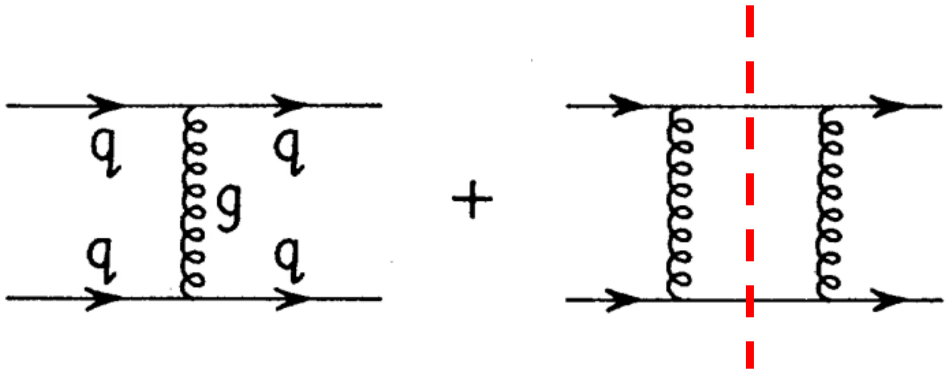
At the moment, the only viable way to generate O(10%) asymmetry seems to be twist-3 FFs convoluted with the transversity distribution.

→ Constraints on the nucleon tensor charge. connection to nucleon EDM

Folklore

"Perturbative QCD contribution to SSA is negligible because it's proportional to the quark mass"

$$A_N \sim \alpha_s \frac{m_q}{p_T \text{ or } \sqrt{s}} \sim 10^{-4}$$

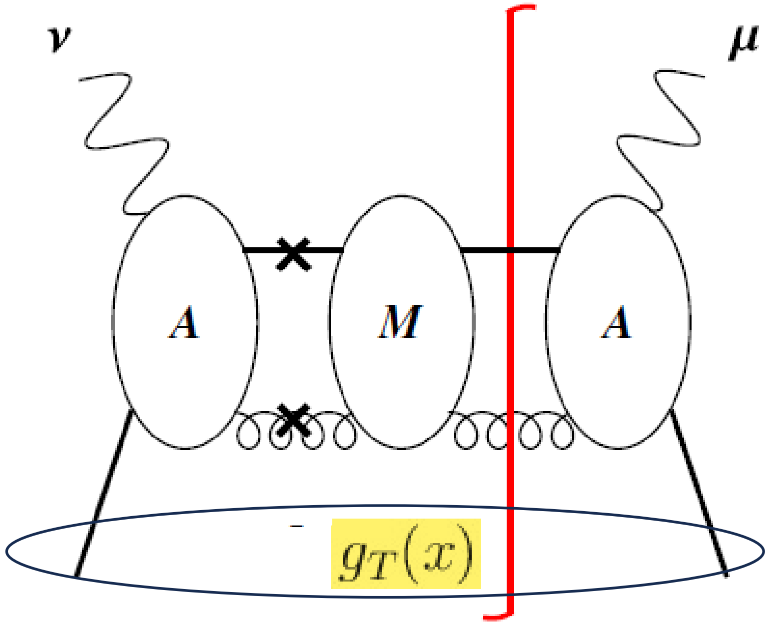


Kane, Pumplin, Repko (1978)

No real pQCD calculation beyond this parametric estimate for 40 years.

pQCD contribution to SSA at the EIC

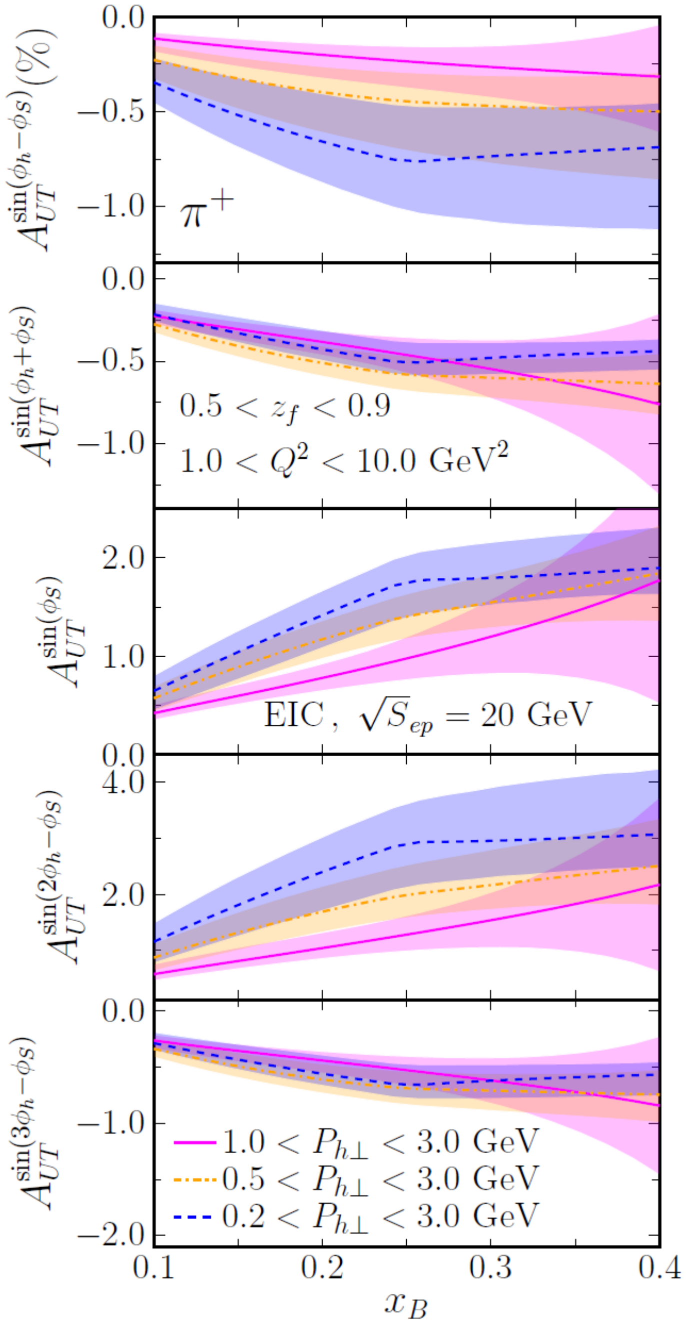
Benic, YH, Kaushik, Li (2021, 2024)



Percent-level asymmetries possible from pQCD alone.

Proton mass!

$$A_N \sim \alpha_s \frac{M_N}{q_T} f\left(\frac{Q}{q_T}, \frac{\sqrt{s}}{q_\perp}\right) \frac{x g_T(x)}{q(x)}$$



BSM connections

Lepton electric/magnetic dipole moment from SSA

Boughezal, de Florian, Petriello, Vogelsang (2023)

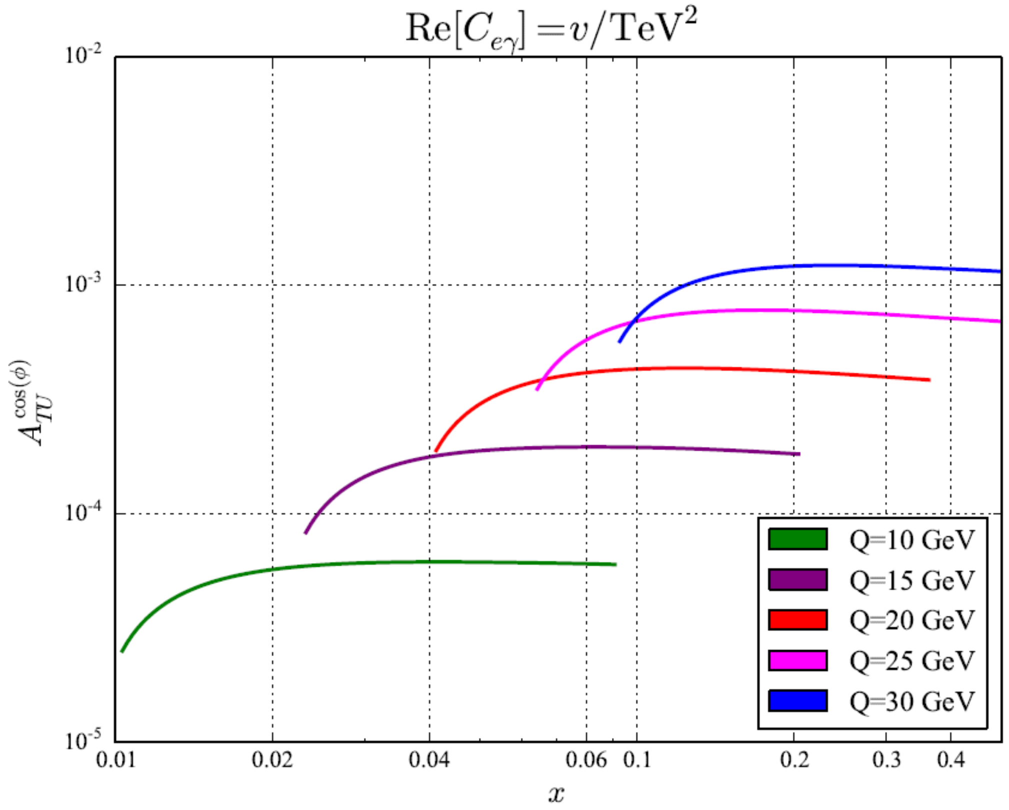
Beam spin asymmetry in $e^{\uparrow}p \to eX$

Very small SM backgrounds

Constraints on SMEFT parameters relevant to electron electric/magnetic dipole moments

$$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu}e)\tau^I\varphi W^I_{\mu\nu},$$
$$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}e)\varphi B_{\mu\nu},$$

Muons at a muon-ion collider?

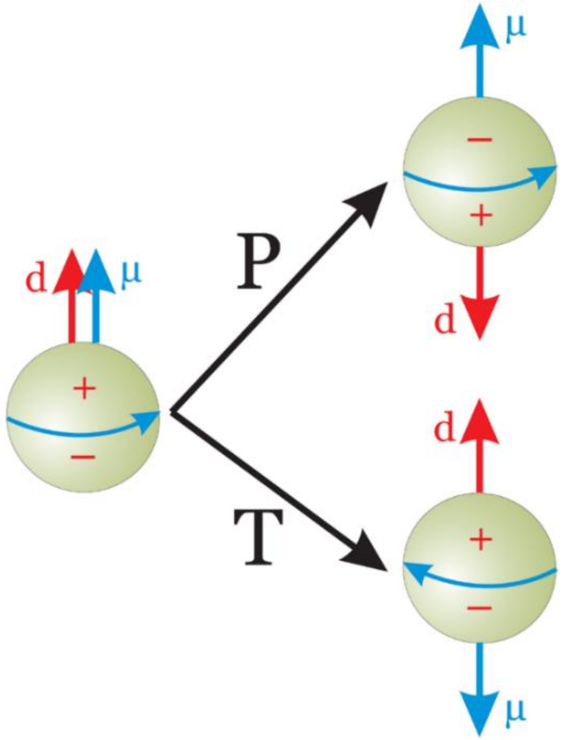


Nucleon electric dipole moment (EDM)

If nonvanishing, both P and CP are violated.
CKM mechanism gives a too small value of nucleon EDM,

CP violation from BSM physics?
Various CP-violating operators studied

- Theta term $\frac{\theta\alpha_s}{8\pi}F\tilde{F}$
- Quark EDM operator $m_q\bar{\psi}_q F^{\mu\nu}\sigma_{\mu\nu}i\gamma_5\psi_q$
- Weinberg operator $f_{abc}\tilde{F}^a_{\mu\nu}F^{\mu\rho}_b F^{\nu}_{c\rho}$
- …



EDM is a vector, must be proportional to nucleon spin
Any connection to high energy QCD spin physics at EIC?

Chromomagnetic dipole moment from higher-twist PDF

Seng (2018)

Chiral-odd twist-three parton distribution function (PDF)

$$e(x) = \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle P|\bar{\psi}(0)\psi(z^-)|P\rangle$$

Accessible in DIS, beam spin asymmetry in $e + p \to e' + \pi^+ + \pi^- + X$ → EIC

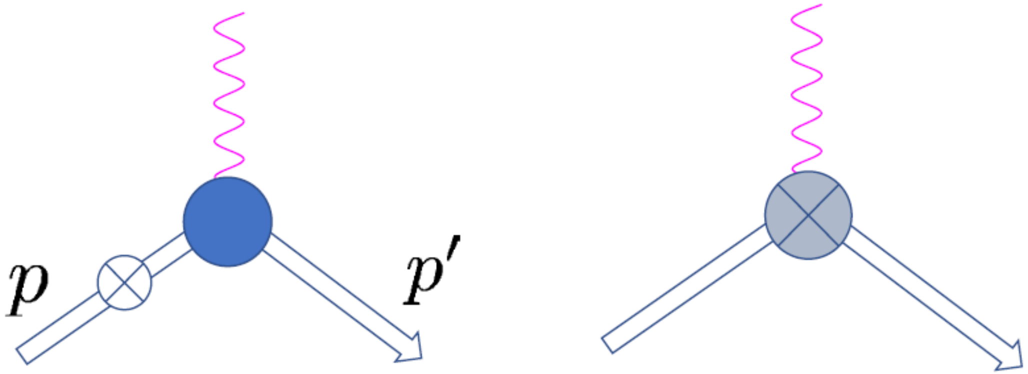
First moment = Nucleon sigma-term $\langle P|\bar{\psi}\psi|P\rangle$ → Dark matter coupling, nucleon mass decomposition

Third moment may be related to quark chromomagnetic dipole moment

$$\langle P|\bar{\psi}F^{\mu\nu}\sigma_{\mu\nu}\psi|P\rangle$$

which in turn is related to CP-odd low-energy pion-nucleon interactions.

Weinberg operator contribution to EDM



1-nucleon reducible　　　irreducible

Bigi, Uraltsev (1991)

Reducible contribution

$$d_{p,n} \sim \mu_{p,n} \frac{\langle p' | w\mathcal{O}_W | p \rangle}{m_N \bar{u}(p') i\gamma_5 u(p)}$$

QCD sum rule
Demir, Pospelov, Ritz (2003)
Haisch, Hala (2019)

Connection to polarized DIS
YH (2021)

Irreducible contribution

Quark model　Yamanaka, Hiyama (2020)
Instanton　Weiss (2021)

Connecting Weinberg operator to higher-twist effect in polarized DIS

Exact identity

$$g f_{abc} \tilde{F}^a_{\mu\nu} F_b^{\mu\alpha} F^\nu_{c\alpha} = -\partial^\mu (\tilde{F}_{\mu\nu} \overleftrightarrow{D}_\alpha F^{\nu\alpha}) - \frac{1}{2} \tilde{F}_{\mu\nu} \overleftrightarrow{D}^2 F^{\mu\nu}$$

$$\langle p' | \mathcal{O}_W | p \rangle \approx i \Delta^\mu \langle p | \bar{\psi} g \tilde{F}_{\mu\nu} \gamma^\nu \psi | p \rangle + \cdots$$

This matrix element enters the twist-4 correction in polarized DIS Shuryak, Vainshtein (1982)

First moment of g1

$$\int_0^1 g_1^{p,n}(x, Q^2) dx = (\pm \frac{1}{12} g_A + \frac{1}{36} a_8)(1 - \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)) + \frac{1}{9} \Delta\Sigma (1 - \frac{33 - 8N_f}{33 - 2N_f} \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2))$$

$$- \frac{8}{9Q^2} \left[\{\pm \frac{1}{12} f_3 + \frac{1}{36} f_8\} \left(\frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)} \right)^{-\frac{\gamma^0_{NS}}{2\beta_0}} + \frac{1}{9} f_0 \left(\frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)} \right)^{-\frac{1}{2\beta_0}(\gamma^0_{NS} + \frac{4}{3} N_f)} \right],$$

Operator mixing

RG equation

$$\frac{d}{d\ln\mu^2}\begin{pmatrix}\mathcal{O}_W\\ \mathcal{O}_4\end{pmatrix} = -\frac{\alpha_s}{4\pi}\begin{pmatrix}\gamma_W & \gamma_{12}\\ 0 & \gamma_4\end{pmatrix}\begin{pmatrix}\mathcal{O}_W\\ \mathcal{O}_4\end{pmatrix}$$

$$\mathcal{O}_4 = -\partial^\mu(\tilde{F}_{\mu\nu}\overleftrightarrow{D}_\alpha F^{\nu\alpha}) \approx \partial^\mu(\bar{\psi}g\tilde{F}_{\mu\nu}\gamma^\nu\psi)$$

$$\gamma_W = \frac{N_c}{2} + n_f + \frac{\beta_0}{2} = \frac{7}{3}N_c + \frac{2}{3}n_f$$

Morozov (1983)

Recently calculated to 3-loops De Vries, Falcioni, Herzog, Ruijl (2020)

$$\gamma_4 = \frac{8}{3}C_F + \frac{2}{3}n_f.$$

Shuryak, Vainshtein (1982)

$$\gamma_{12} = -3N_c$$

Asymptotically, $\langle\mathcal{O}_W\rangle \approx \frac{9N_c^2}{3N_c^2+4}\langle\mathcal{O}_4\rangle$

An estimate of EDM

YH (2021)

reducible contribution

$$d \sim \mu \frac{\langle p'|w\mathcal{O}_W|p\rangle}{m_N \bar{u}(p')i\gamma_5 u(p)} \equiv 4\mu m_N^2 E$$

total magnetic moment

Vary E in the window $0.5 f_0 < E < 1.3 f_0$

f_0 from instanton model. Balla, Polyakov, Weiss (1998)

$$-12w' \, e \, \text{MeV} < d_p < -32w' \, e \, \text{MeV} \qquad 22w' \, e \, \text{MeV} < d_n < 8.4w' \, e \, \text{MeV}$$

Can we extract f_0 at the EIC?
New physics may be hidden in higher twist effects

Summary

- Spin is one of the core science cases of EIC
- Impressive progress in precision calculations with helicity PDFs.
- OAM is the key to complete the spin sum rule. Lagging far behind in both theory and experiment. Real challenge at the EIC.
- Unique opportunities for BSM physics sensitive to spin

  (EDM, anomalous magnetic moment,…)