# Spin overview

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BNL/RIKEN BNL

Polarized-ion meeting, March 10-12, 2024, CFNS

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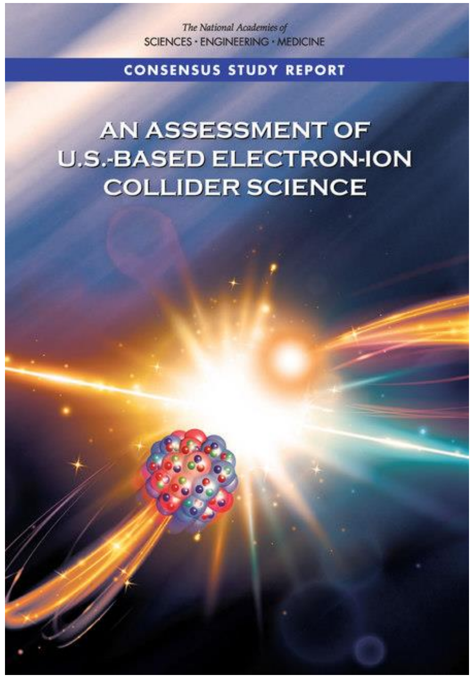
- Longitudinal spin
- Transverse spin
- GPD
- BSM connections

# 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

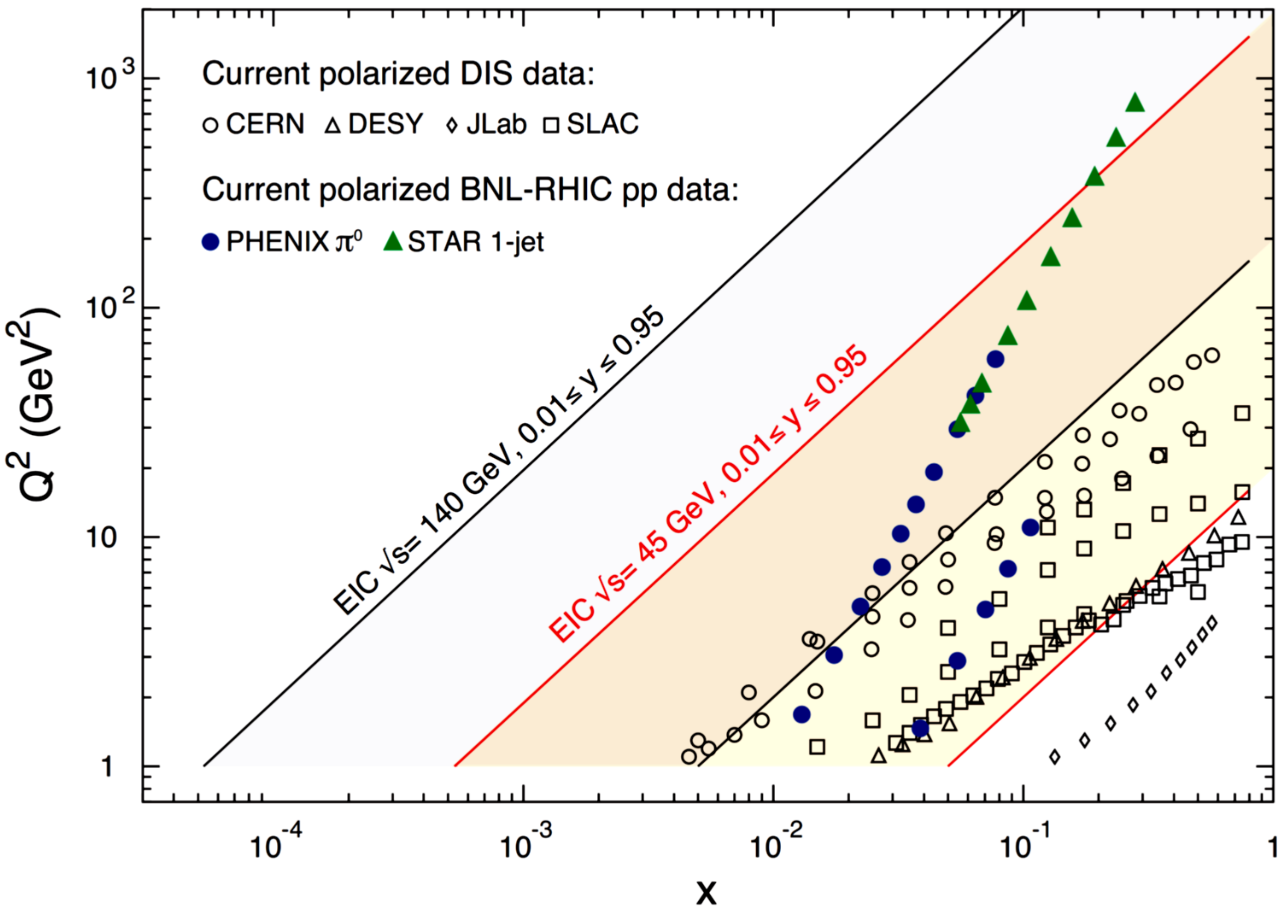
A Consensus Study Report of

*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?
- $\boxed{\text{How does the spin of the nucleon arise?}}$
- What are the emergent properties of dense systems of gluons?

# EIC: the world's first polarized ep collider




Unprecedented kinematical coverage for polarized DIS.

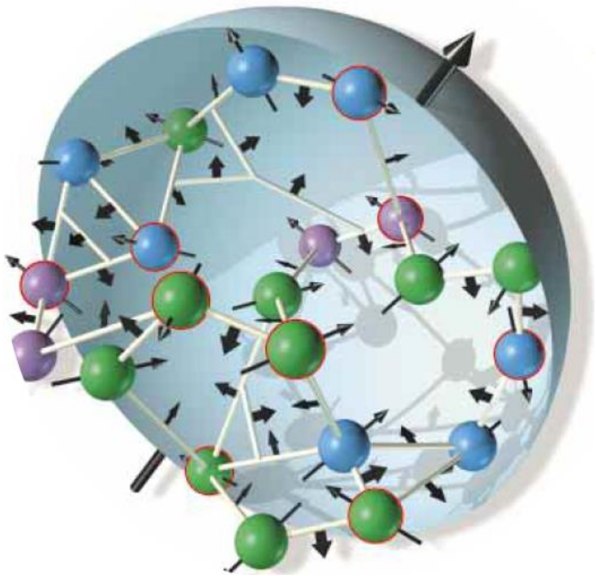
High luminosity, high polarization

Tremendous physics opportunities for spin-related topics

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

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

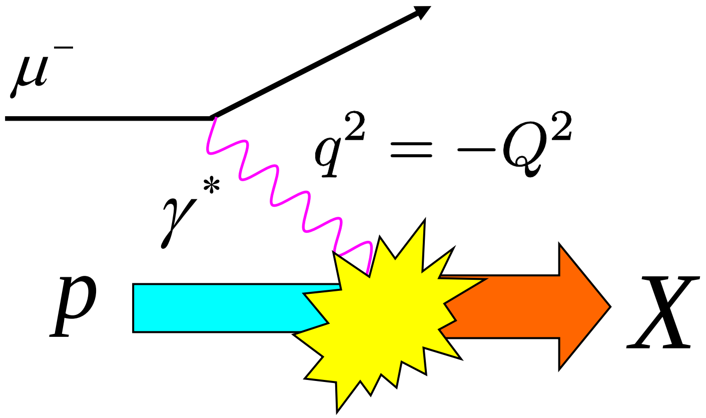
Ji sum rule

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

# $\Delta\Sigma$ from polarized DIS

Longitudinal double spin asymmetry in polarized DIS

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




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

isovector axial charge

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

octet axial charge, can be estimated from hyperon semileptonic decay

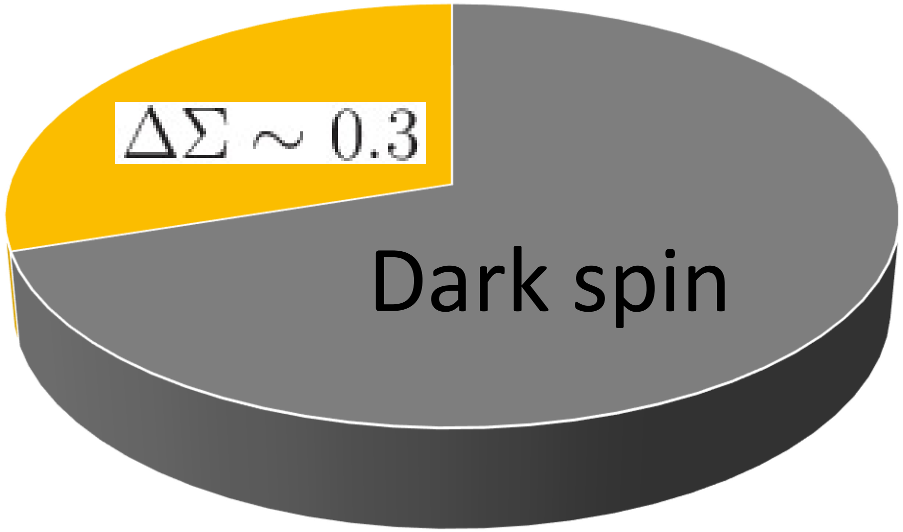
# `Spin crisis'

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

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



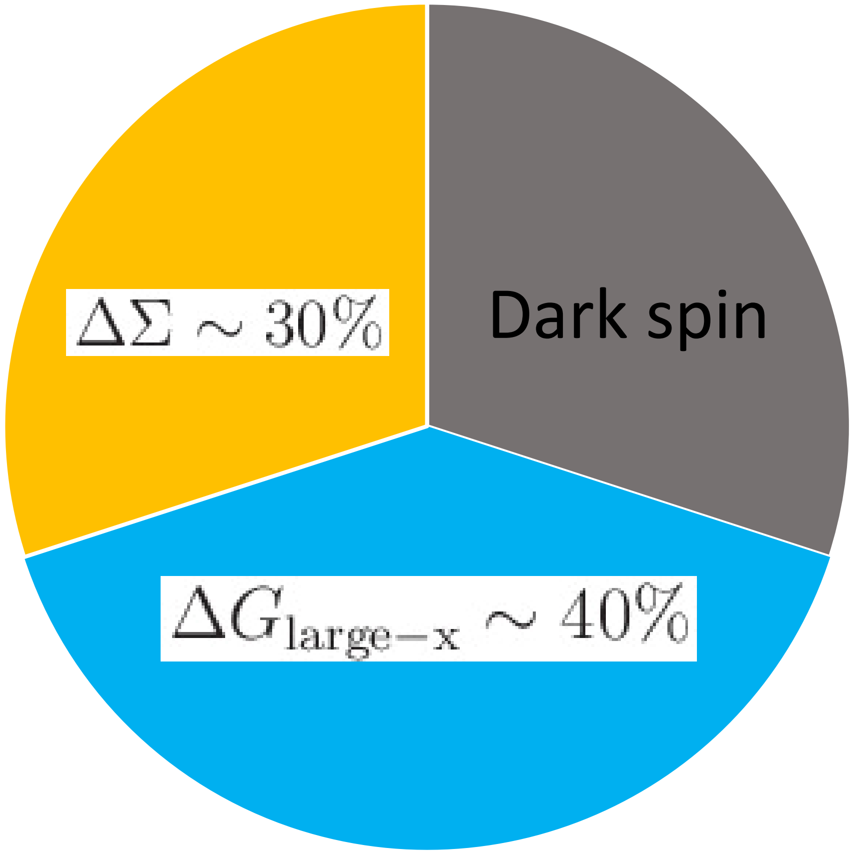
# Evidence of nonzero gluon helicity $\Delta G = \int_0^1 dx \Delta G(x)$

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

# 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!

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

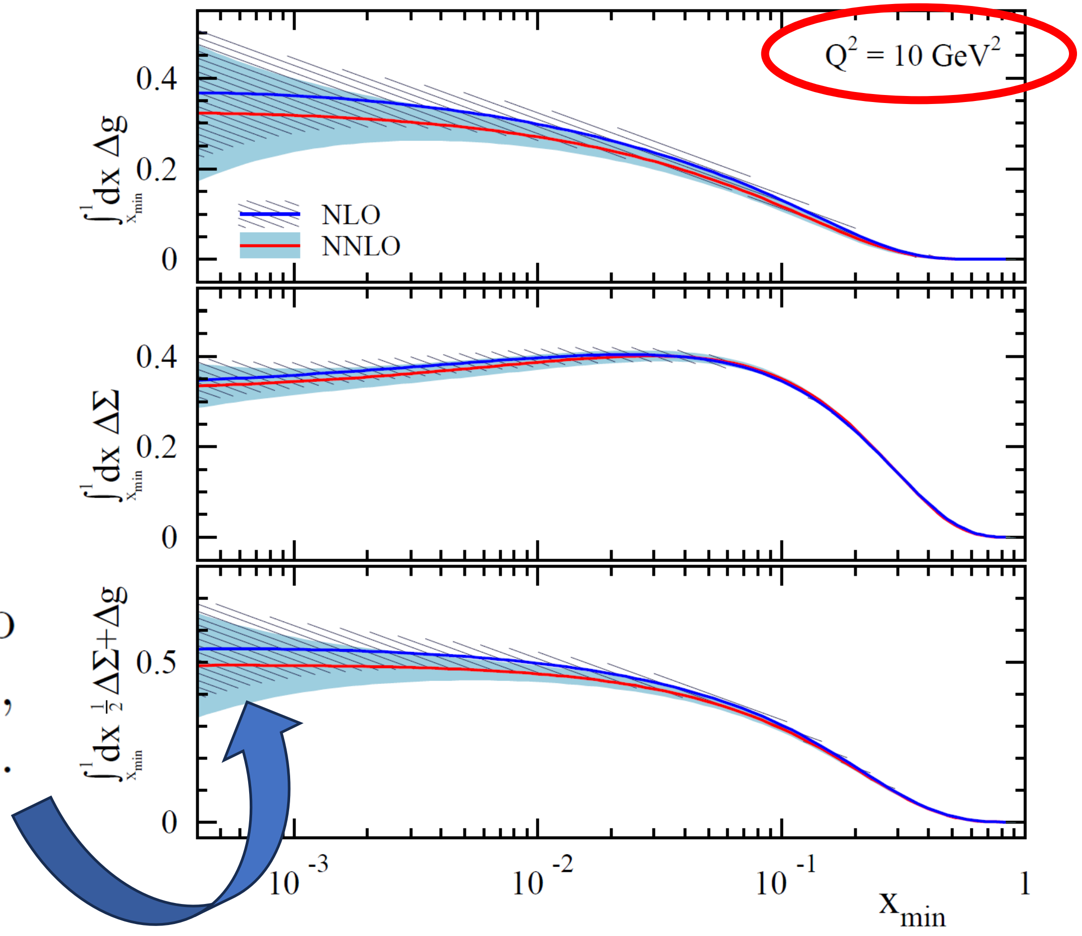
$$\alpha_{BER} \approx 3.664\sqrt{\frac{\alpha_s N_c}{2\pi}} \qquad \alpha_{BK} \approx 3.661\sqrt{\frac{\alpha_s N_c}{2\pi}}$$

# NNLO global analysis for helicity PDF

Borsa, Stratmann, Vogelsang, de Florian, Sassot (2024)

TABLE I. Partial and total $\chi^2$ obtained in the fits

| | Total | DIS | SIDIS | pp-jets | pp-pions | pp-W |
|---|---|---|---|---|---|---|
| NLO | 627.2 | 302.7 | 127.6 | 111.1 | 63.5 | 22.3 |
| NNLO | 607.5 | 294.3 | 122.9 | 104.0 | 66.0 | 20.3 |
| Data points | 673 | 368 | 114 | 91 | 78 | 22 |




of the integrals. Remarkably, when combining the two contributions according to their role for the proton spin, one finds a result approaching 1/2 toward lower $x_{\text{min}}$.

# 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

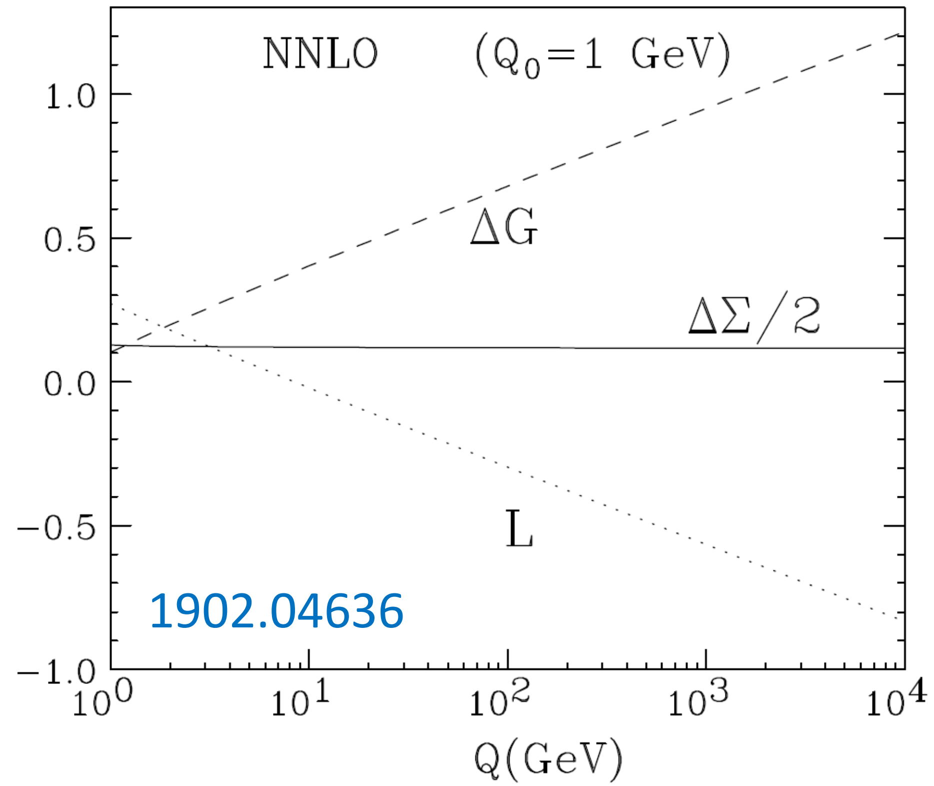
Spin sum rule cannot be complete without understanding OAM

Helicity is not a conserved quantity.

Even if OAM is zero at one scale,

it is nonzero at other 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)

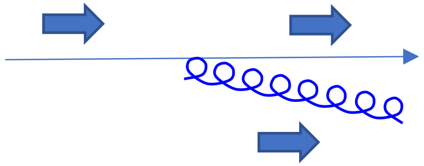
$$\Delta L_q = \frac{1}{2E(2\pi)^3\delta^3(0)} \left\langle p^0_\infty, s^0 \middle| \int d^3x\, i\psi^\dagger (\boldsymbol{x}\times\boldsymbol{\nabla})^3 \psi \middle| p^0_\infty, s^0 \right\rangle,$$

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

Originally formulated in the light-cone gauge

Gauge invariant completion of the Jaffe-Manohar sum rule established. YH (2011)

# 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.

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

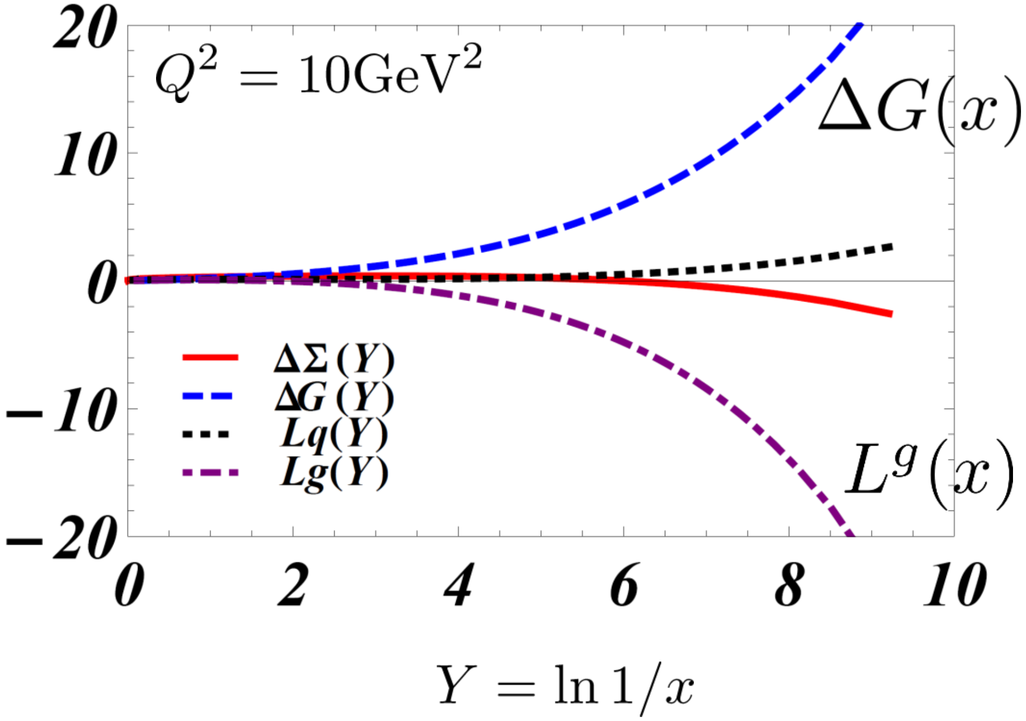
$$\frac{d}{d\ln Q^2} \Delta G(x) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\left(+2C_F + \cdots\right)\Delta q(x/z)$$

# Helicity-OAM cancellation at small-x

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

Boussarie, YH, Yuan (2019)

1802.02716



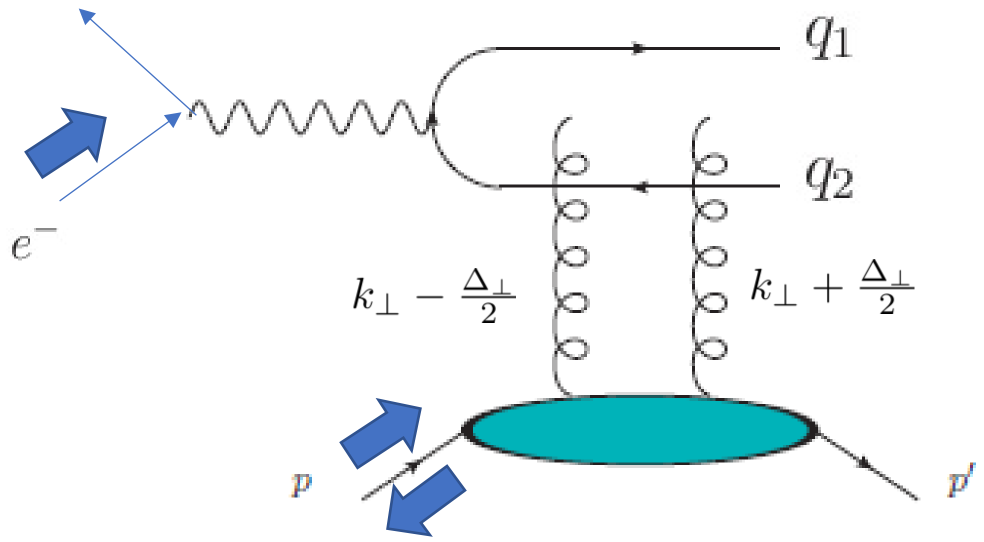

EIC may find a sizable contribution to $\Delta G$ from the small-x region.

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

Can EIC seriously address OAM?

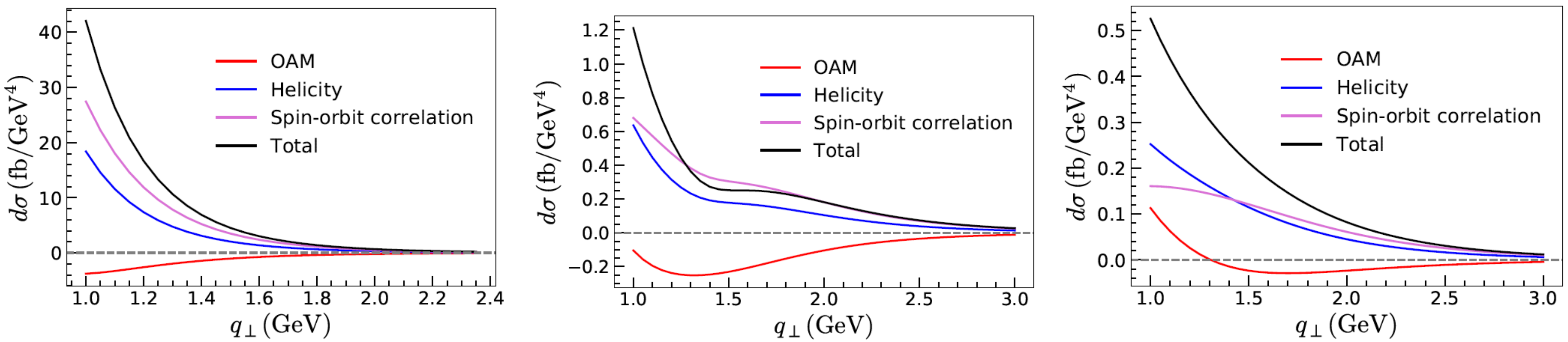
Bhattacharya, Boussarie, YH (2022,2024); Kovchegov, Manley (2024)

# Accessing OAM at the EIC: Longitudinal double spin asymmetry in diffractive dijet




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

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

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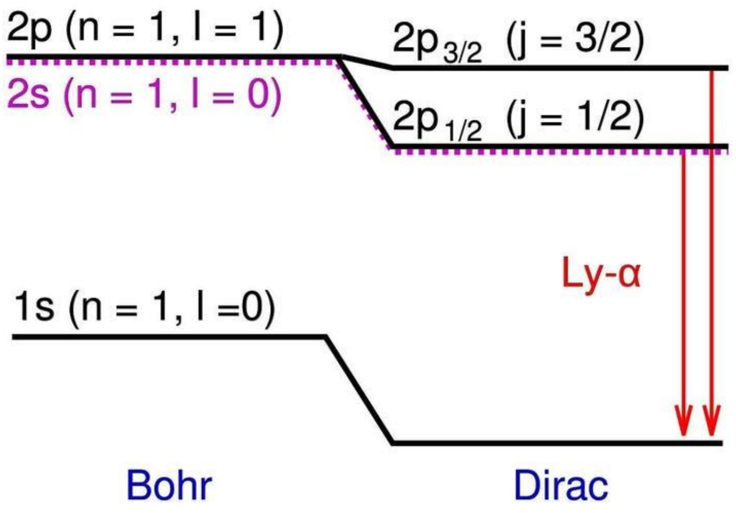
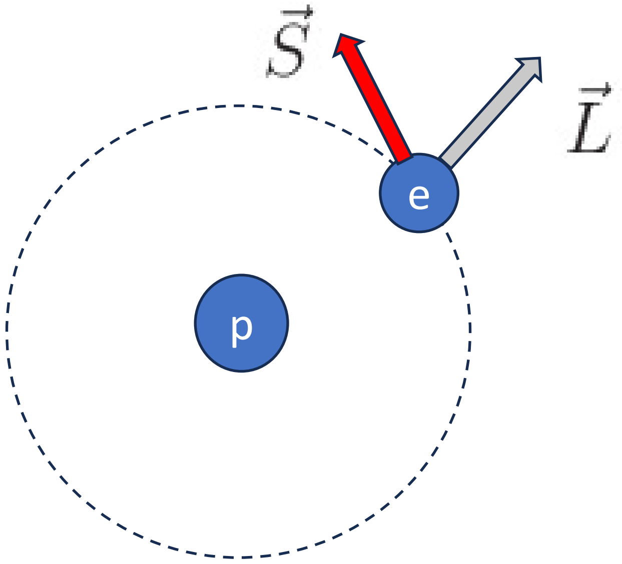
# Spin-orbit coupling

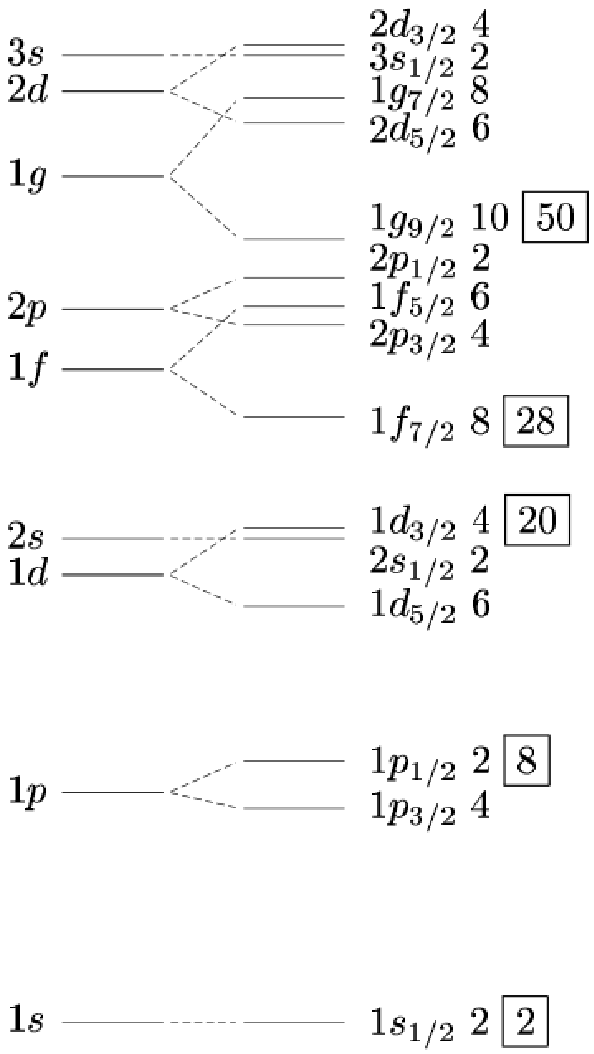
Interaction between the spin and orbital angular momentum of the same particle

$$V = -\frac{\mu_B e}{mc^2 r^3}\vec{S}\cdot\vec{L}$$




Nuclear magic number




Ubiquitous phenomena in subatomic physics

What about in QCD?

# Quark spin-orbit correlation

Polarized quark GTMD

Meissner, Metz, Schlegel (2008)

$$\tilde{f}_q(x,\xi,k_\perp,\Delta_\perp) = \int \frac{d^3z}{2(2\pi)^3} e^{ixP^+z^- - ik_\perp\cdot z_\perp} \langle p's'|\bar{q}(-z/2)W_\pm\gamma^+\gamma_5 q(z/2)|ps\rangle$$

$$= \frac{-i}{2M}\bar{u}(p's')\left[\frac{\epsilon_{ij}k_\perp^i\Delta_\perp^j}{M^2}G_{1,1}^q + \frac{\sigma^{i+}\gamma_5}{P^+}(k_\perp^i G_{1,2}^q + \Delta_\perp^i G_{1,3}^q) + \sigma^{+-}\gamma_5 G_{1,4}^q\right]u(ps)$$

Quark spin-orbit correlation

$$C_q = \int dx \int d^2k_\perp \frac{k_\perp^2}{M^2} G_{1,1}^q(x,k_\perp,0) \sim \langle S^z L^z\rangle$$

Lorce, Pasquini (2011)

$C_q > 0$ if helicity and OAM are aligned, $C_q < 0$ if they are anti-aligned

# Twist structure of spin-orbit correlation

YH, Schoenleber (2024)

Unpol PDF

$$C_q(x) = x\int_x^{\epsilon(x)} \frac{dx'}{x'^2} x'\Delta q(x') - x\int_x^{\epsilon(x)} \frac{dx'}{x'^2} q(x')$$
$$-x\int_x^{\epsilon(x)} dx_1 \int_{-1}^{1} dx_2 \frac{\Psi_{qF}(x_1,x_2)}{x_1-x_2} P\frac{3x_1-x_2}{x_1^2(x_1-x_2)}$$
$$-x\int_x^{\epsilon(x)} dx_1 \int_{-1}^{1} dx_2 \tilde{\Psi}_{qF}(x_1,x_2) P\frac{1}{x_1^2(x_1-x_2)},$$

$$C_g(x) = x\int_x^{\epsilon(x)} \frac{dx'}{x'^2} x'\Delta G(x') - 2x\int_x^{\epsilon(x)} \frac{dx'}{x'^2} G(x') - 4x\sum_q \int_x^{\epsilon(x)} \frac{dx'}{x'^3} \int dX \tilde{\Psi}_{qF}(X,x')$$
$$+4x\int_x^{\epsilon(x)} dx_1 \int dx_2 P\frac{\tilde{N}_F(x_1,x_2)}{x_1^3(x_1-x_2)} + 4x\int_x^{\epsilon(x)} dx_1 \int dx_2 \frac{N_F(x_1,x_2)}{x_1^3(x_1-x_2)} P\frac{2x_1-x_2}{x_1-x_2}$$

# 2 spin sum rules, 2 momentum sum rules!

Spin

$$\frac{1}{2} = \frac{1}{2}\sum_q (A_{q+\bar{q}} + B_{q+\bar{q}}) + \frac{1}{2}(A_g + B_g)$$

Ji (1996)

$$= \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Jaffe, Manohar (1990)

Momentum

$$1 = \sum_q A_{q+\bar{q}} + A_g$$

Feynman (1969)

$$= -3C_q^{(2)} - \frac{3}{2}C_g^{(2)} + \frac{3}{2}\int_{-1}^{1} dx dx' \left[\Lambda_q(x,x') + \frac{2x\tilde{\Lambda}_q(x,x') + \tilde{\Lambda}_G(x,x')}{x - x'}\right]$$

YH, Schoenleber (2024)

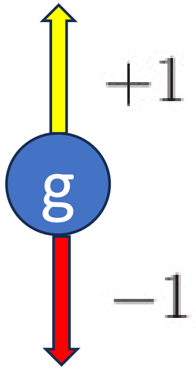
# Spin-orbit correlation at small-x

Bhattacharya, Boussarie, YH (2024)

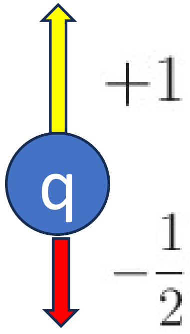
$$\frac{i}{x}\int \frac{d^3z}{(2\pi)^3 P^+} e^{ixP^+z^- - ik_\perp\cdot z_\perp}\langle p'|2\mathrm{Tr}[W_+\tilde{F}^{+\mu}(-z/2)W_\pm F^+_{\ \mu}(z/2)]|p\rangle \;=\; -i\frac{\epsilon_{ij}k^i_\perp\Delta^j_\perp}{M^2}C_g^{[+\pm]}(x,\xi,k_\perp,\Delta_\perp),$$

Approximate $e^{ixP^+z^-} \approx 1$ (eikonal approximation)

$$C_g(x) = -G(x)$$




$$C_q(x) = -\frac{1}{2}q(x)$$



# Quantum entanglement of spin and OAM

Bhattacharya, Boussarie, YH (2024)

$s^z = \pm 1$ qubit (Alice) $l^z = \pm 1$ qubit (Bob)

Perfect spin-orbit anti-correlation at small-x → `Bell states'

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle_s|-\rangle_l + |-\rangle_s|+\rangle_l\right), \qquad |\Psi^-\rangle = \frac{1}{\sqrt{2}i}\left(|+\rangle_s|-\rangle_l - |-\rangle_s|+\rangle_l\right)$$

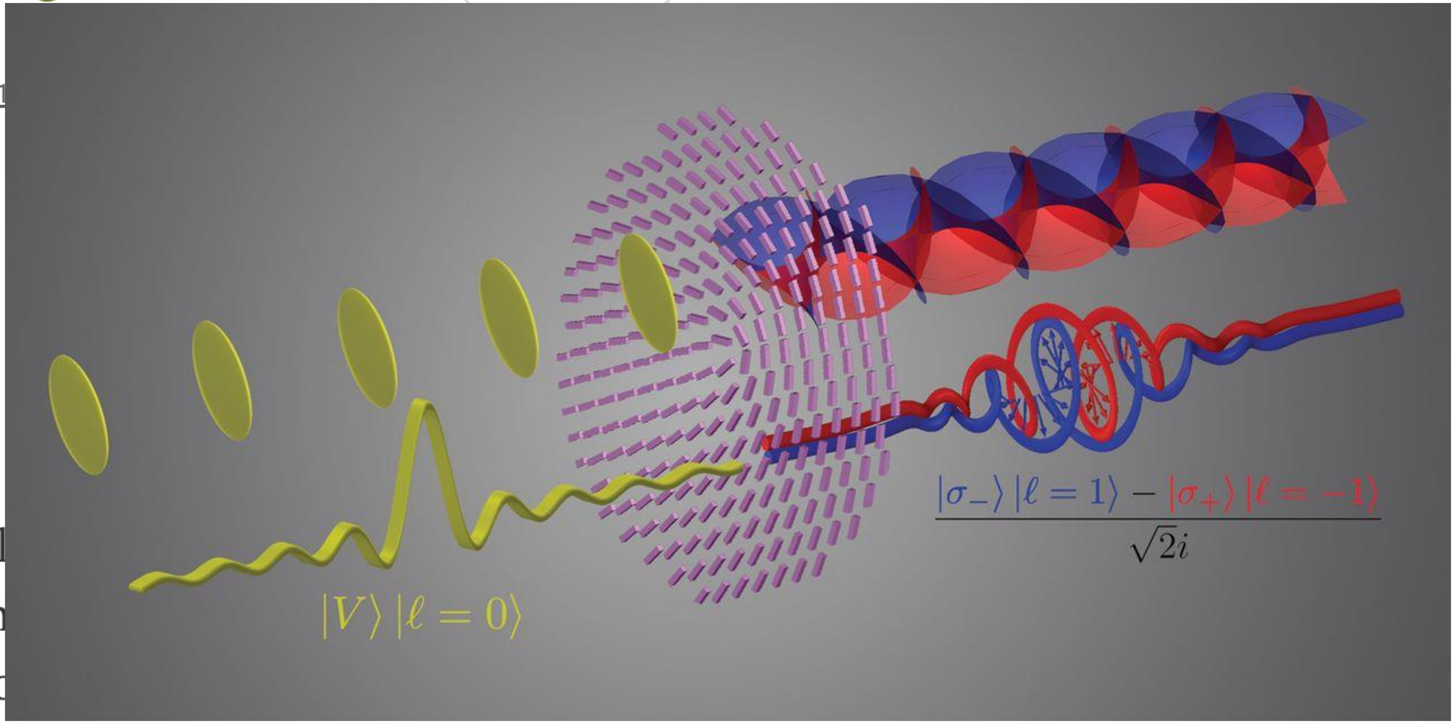
Every single quark and gluon at small-x is a maximally entangled Bell state

$\langle S^z \rangle = \langle L^z \rangle = 0$ but $\langle S^z L^z \rangle = -1$

# Quantum entanglement of the spin and orbital angular momentum of photons using metamaterials

TOMER STAV, ARKADY FAERMAN, ELHANAN MAGUID, DIKLA OREN, [...], AND MORDECHAI SEGEV +2 authors Authors Info & Affiliations

SCIENCE 14 Sep 2018 Vol 361, Issue 6407 pp. 1101-1104 DOI: 10.11



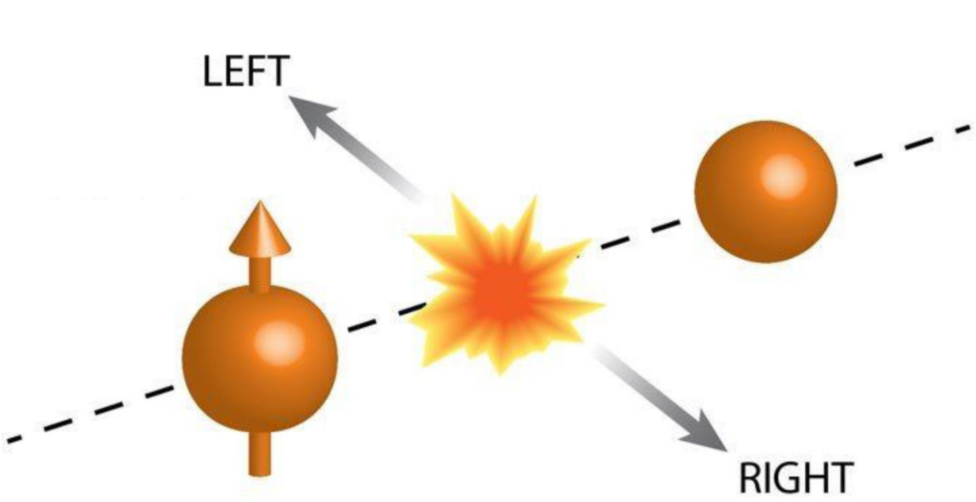

## Abstract

Metamaterials constructed from deep subwavel
phenomena ranging from negative refractive in
eral relativity, and superresolution imaging. Mo
new platform for quantum optics. We present the use of a dielectric metasurface to generate entanglement between the spin and orbital angular momentum of photons. We demonstrate the genera-

In QCD, maximal entanglement is a default property of soft partons!

# Transverse spin

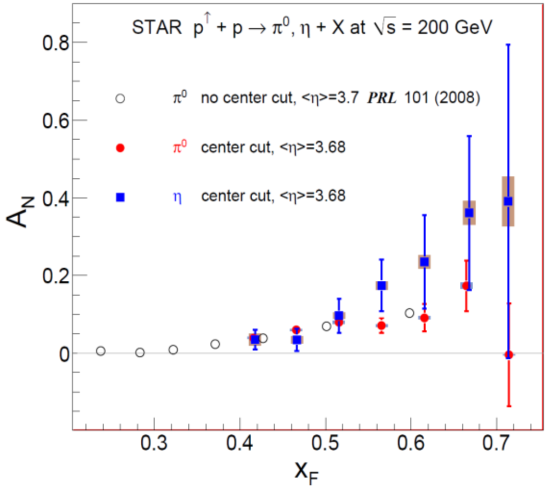
# Transverse Single Spin Asymmetry (SSA)

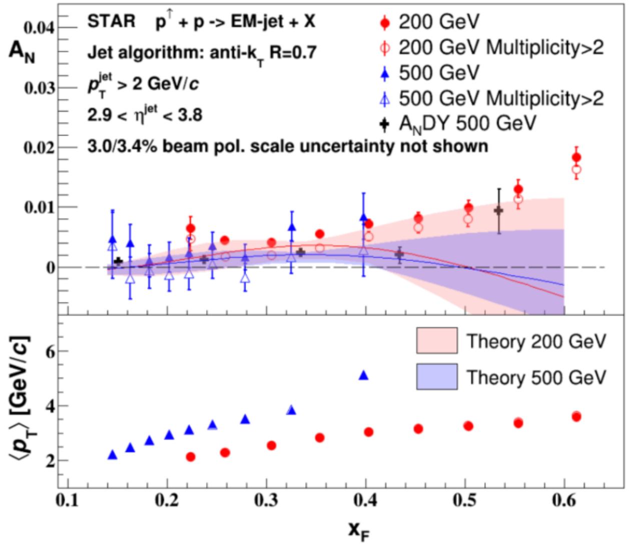


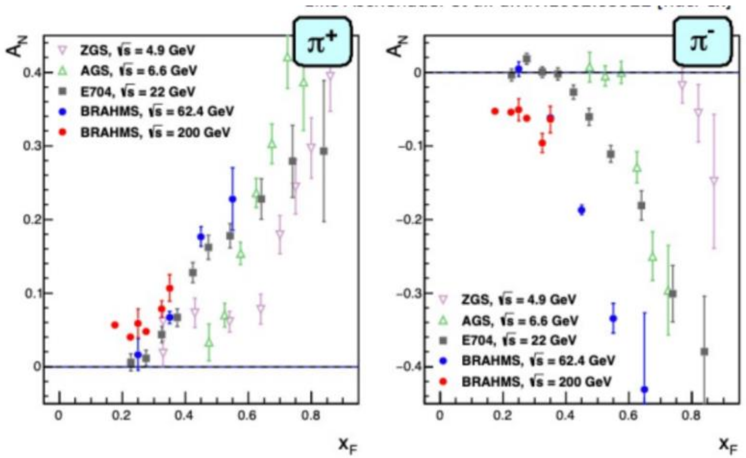

Production of hadrons is left-right asymmetric

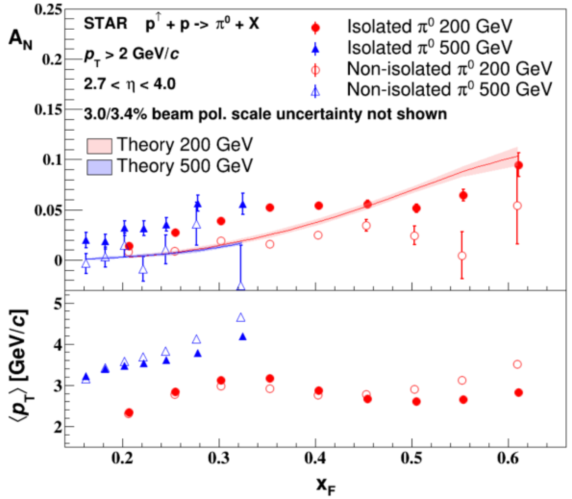
$$d\sigma \sim S_{\perp} \times P_{hT} \sim \sin(\phi_{S_{\perp}} - \phi_{P_{hT}})$$

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



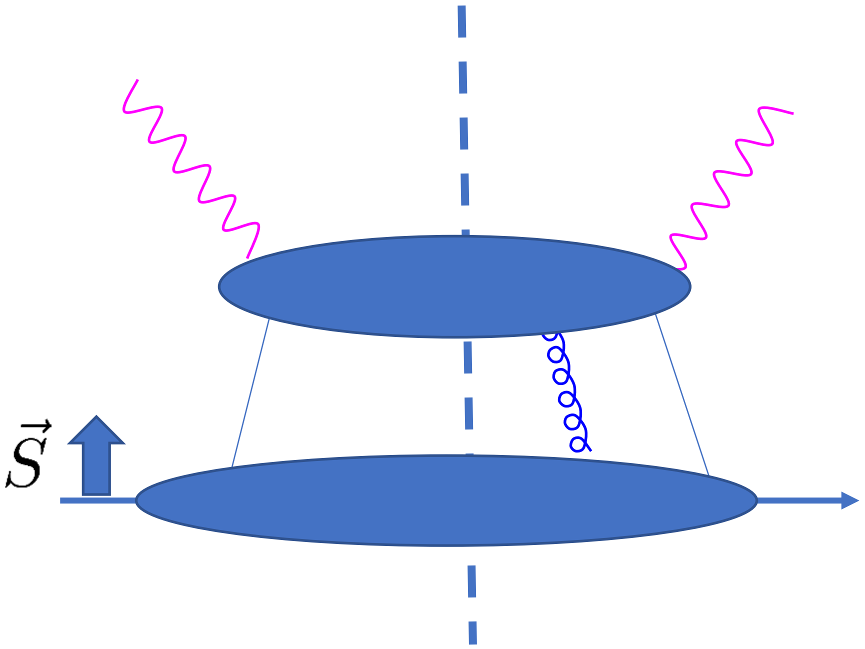




40+ years puzzle in QCD

# 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.

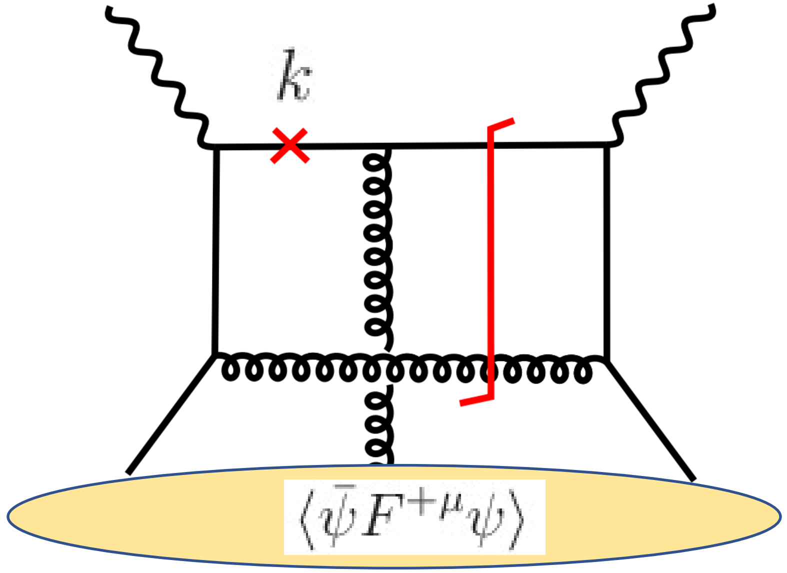
# Origins of SSA

Collinear factorization

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

kt factorization

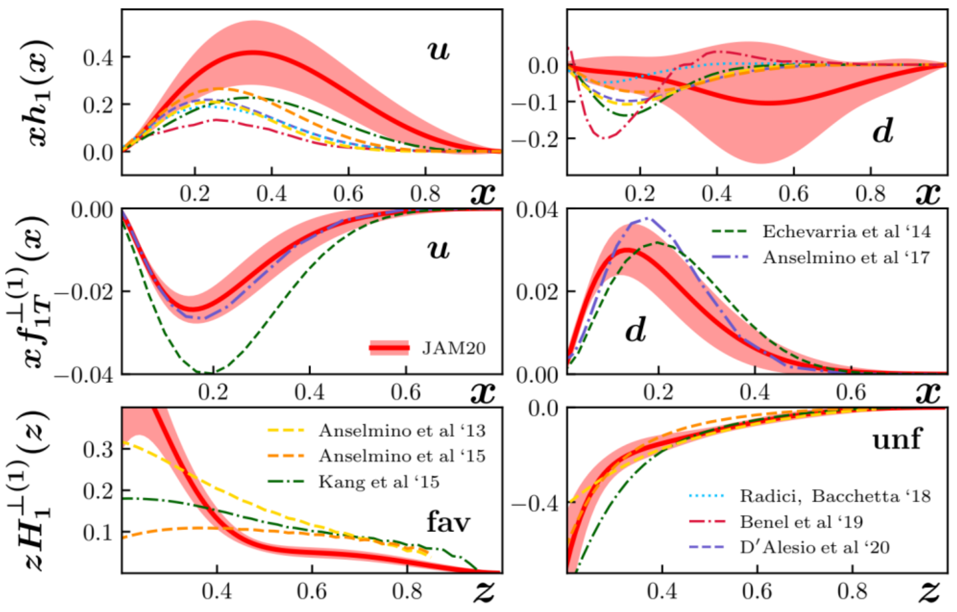
- Sivers function
- Collins function
- ….




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

# Global analysis of SSA

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

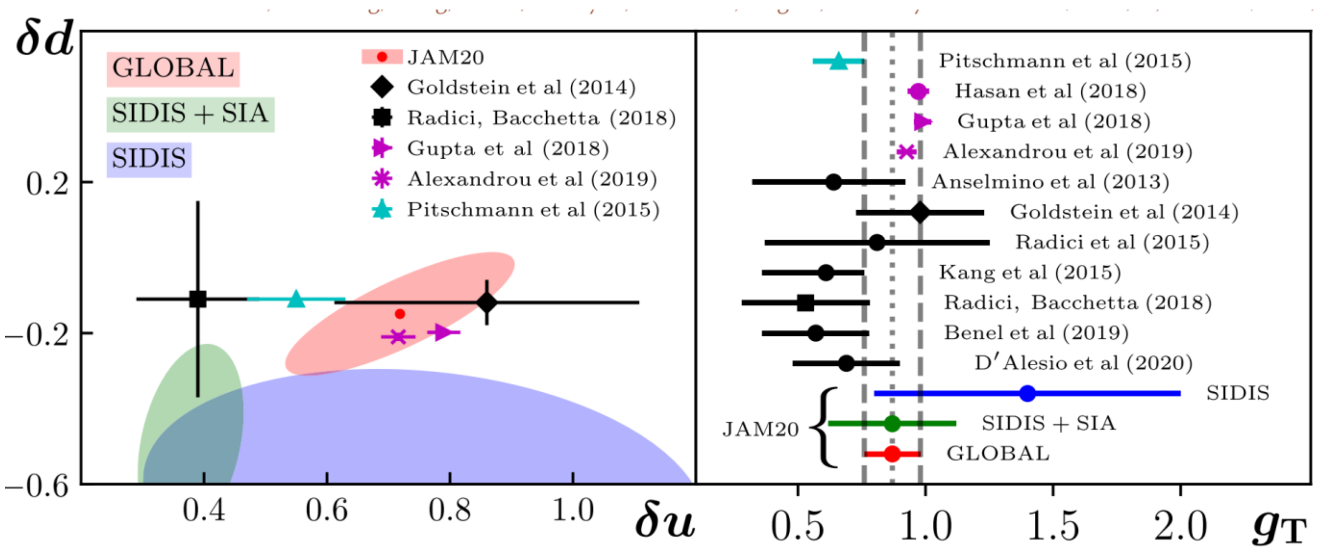



Simultaneous fit of

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.

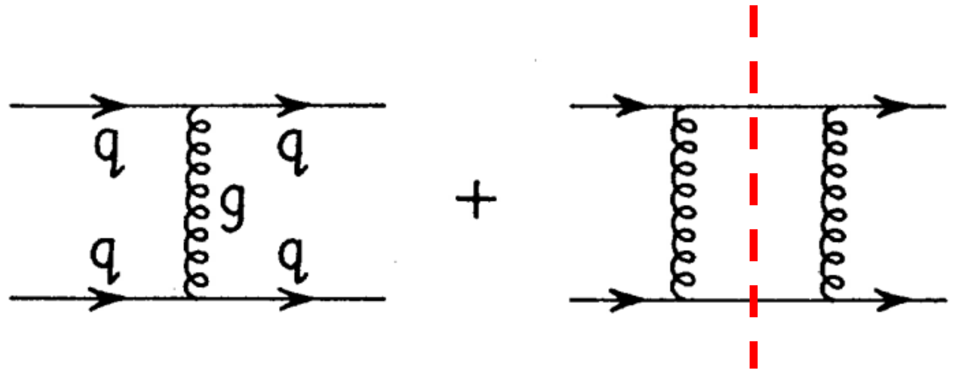
→ Constraints on the nucleon tensor charge. connection to nucleon EDM



# Folklore

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

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

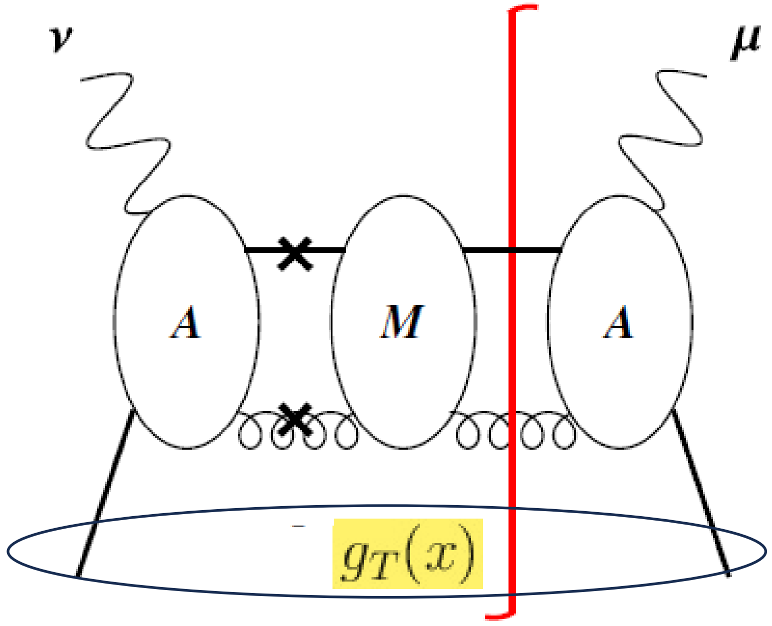



Kane, Pumplin, Repko (1978)

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

# pQCD contribution to SSA at the EIC

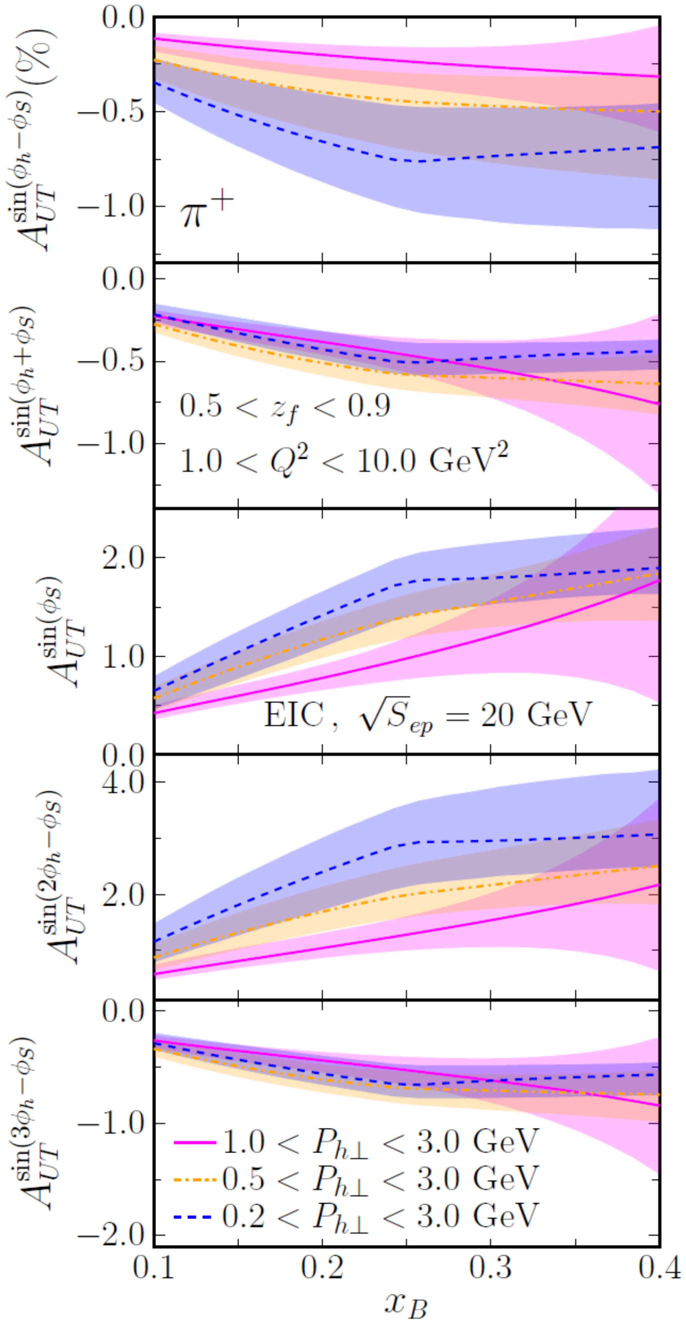
Benic, YH, Kaushik, Li (2021, 2024)




Percent-level asymmetries possible from pQCD alone.

Proton mass!

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



# GPD

# Generalized Parton Distribution (GPD)

Off-forward generalization of PDF Muller, Robaschik, Geyer, Dittes, Horejsi (1994)

$$P^+ \int \frac{dy^-}{2\pi} e^{ixP^+y^-} \langle P'S' | \bar{\psi}(0)\gamma^\mu \psi(y^-) | PS \rangle$$

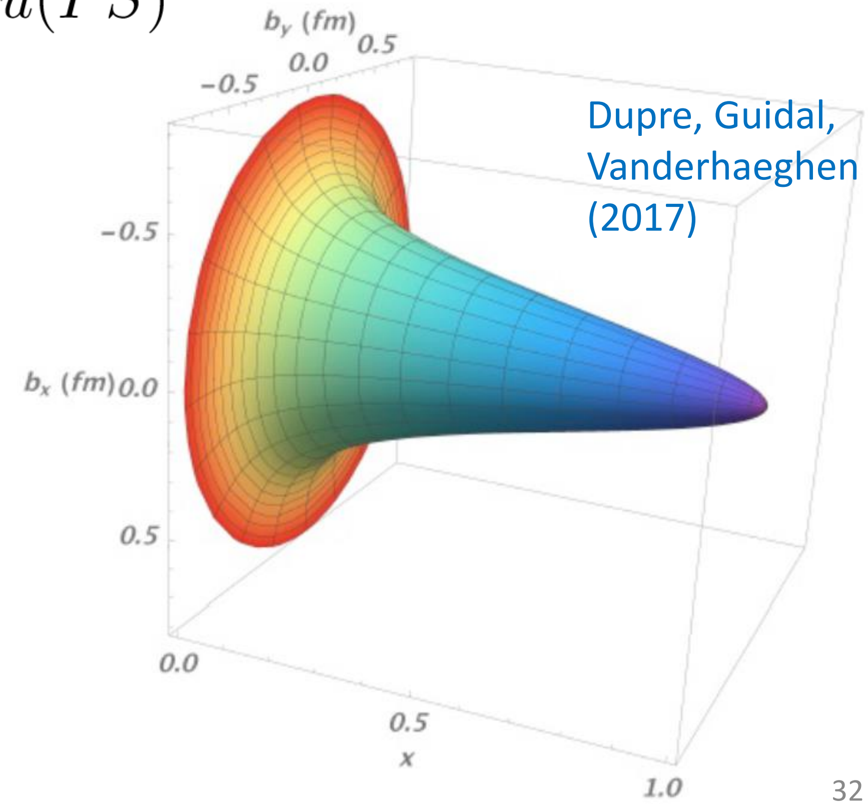
$$= H_q(x,\Delta)\bar{u}(P'S')\gamma^\mu u(PS) + E_q(x,\Delta)\bar{u}(P'S')\frac{i\sigma^{\mu\nu}\Delta_\nu}{2m}u(PS)$$

Integrate over $x$ → elemag form factors $F_{1,2}$

Multiply by $x$ and integrate over $x$ → gravitational form factors

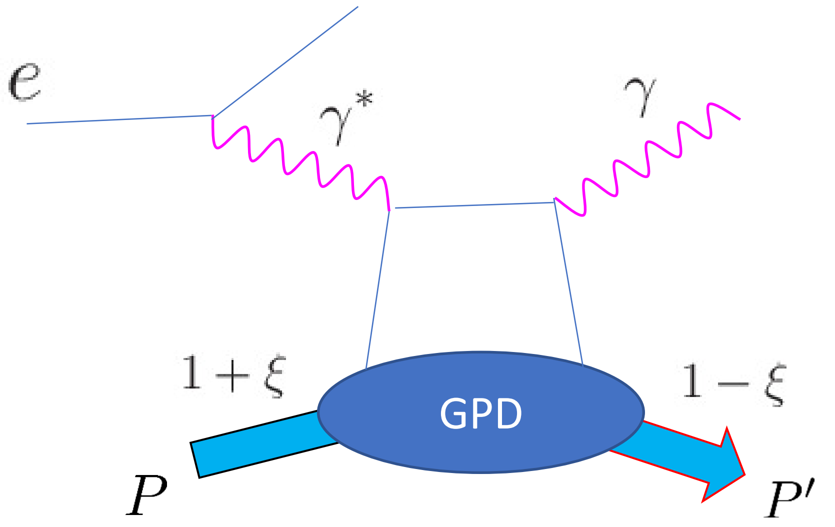
$$\langle P' | \bar{\psi}\gamma^+ iD^+ \psi | P \rangle = \langle T_q^{++} \rangle$$

Fourier transform $\Delta_\perp \leftrightarrow b_\perp$
→ 2D distribution of partons in impact parameter space




Dupre, Guidal, Vanderhaeghen (2017)

# Proton spin from GPDs

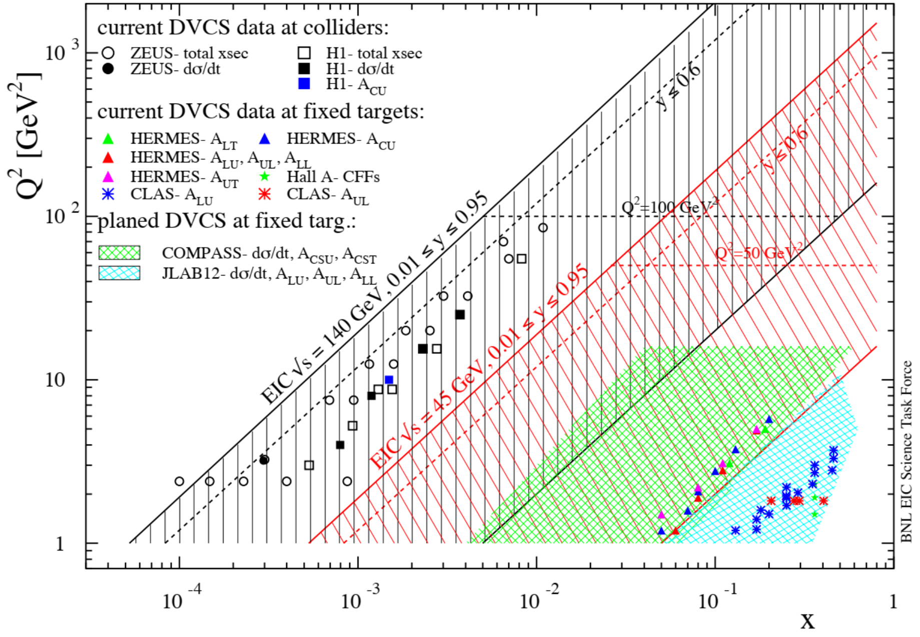



$$J_{q,g} = \frac{1}{2}\int_0^1 dx x(H_{q,g}(x) + E_{q,g}(x))$$

GPD from Deeply Virtual Compton Scattering (DVCS)
and other exclusive processes

$$i\int d^4y e^{iqy}\langle P'|T\{J^\mu(y)J^\nu(0)\}|P\rangle$$

$$= g_\perp^{\mu\nu}\int \frac{dx}{2}\left(\frac{1}{x+\xi-i\epsilon}+\frac{1}{x-\xi+i\epsilon}\right) H_q(x,\xi,\Delta)\bar{u}(P')\gamma^+u(P)+\cdots$$

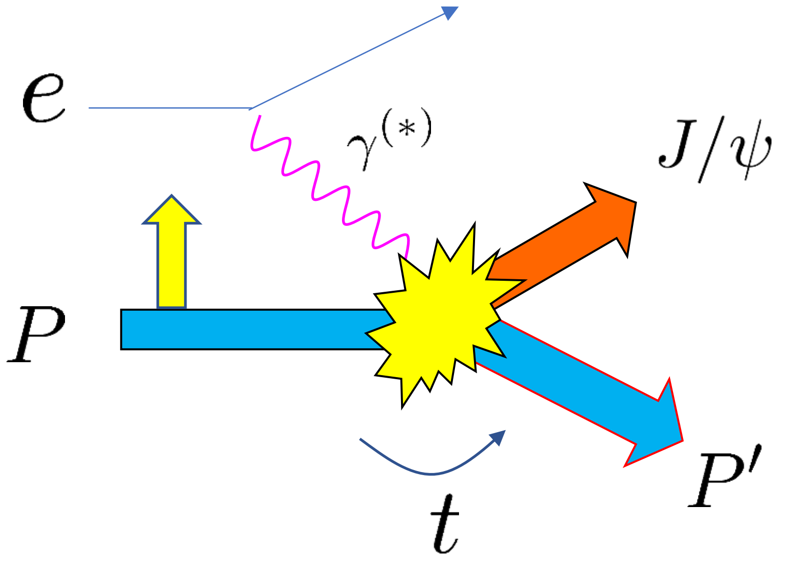



EIC offers an unprecedented kinematical coverage for DVCS.
Rapid theory progress in precision Braun, Schoenleber,…

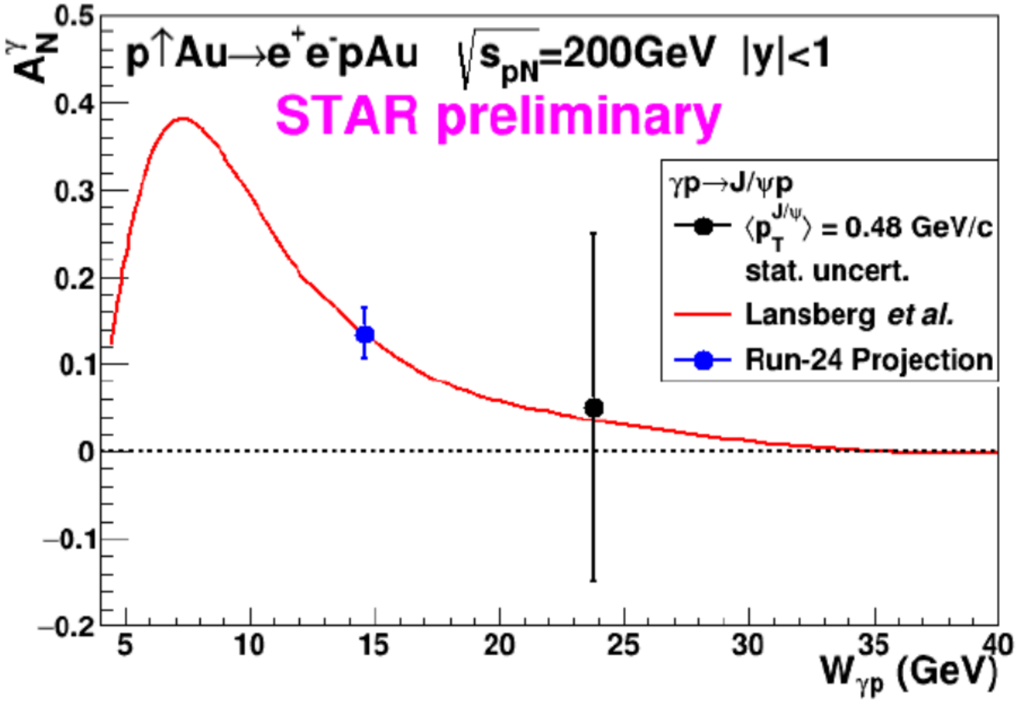
Extraction of GPD E's, especially gluon GPD $E_g(x)$ challenging

# GPD $E_g$ from $J/\psi$ single spin asymmetry

Koempel, Kroll, Metz, Zhou (2012)
Lansberg, Massacrier, Szymanowski, Wagner (2018)




$$A_N \sim \frac{Im(\mathcal{H}_g^* \mathcal{E}_g)}{|\mathcal{H}_g|^2}$$




~~Will be measured by the STAR collaboration in UPC~~
Can be continued at the EIC

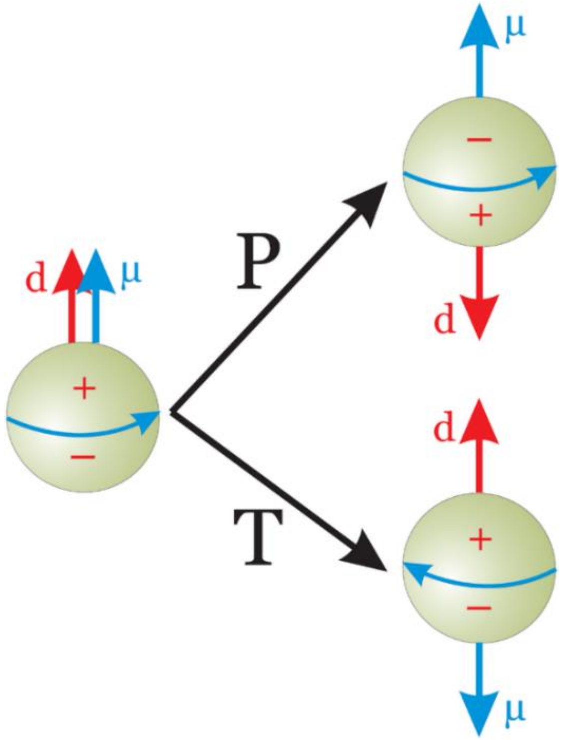
# BSM connections

# 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?

# Lepton electric/magnetic dipole moment from SSA

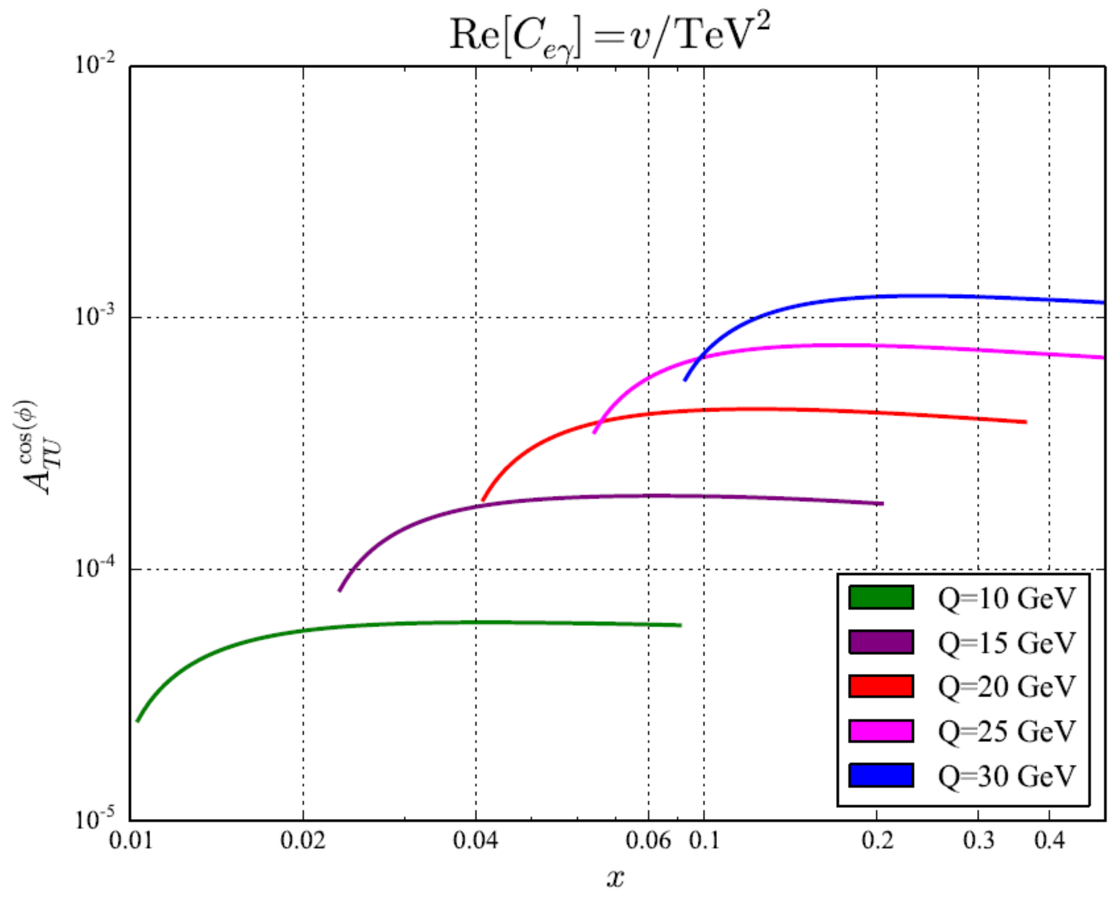
Beam spin asymmetry in $e^{\uparrow}p \to eX$

Boughezal, de Florian, Petriello, Vogelsang (2023)

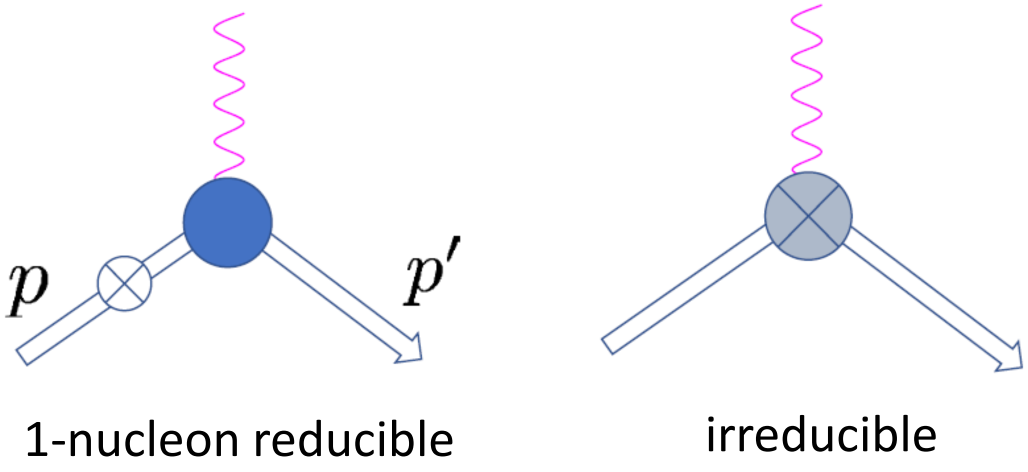
Very small SM backgrounds

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

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



# Weinberg operator $f_{abc}\tilde{F}^a_{\mu\nu}F^{\mu\rho}_b F^\nu_{c\rho}$ contribution to EDM




Bigi, Uraltsev (1991)

Reducible contribution

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

# Connecting Weinberg operator to higher-twist effect in polarized DIS

YH (2021)

Exact identity

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

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

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

First moment of g1

$$\int_0^1 g_1^{p,n}(x,Q^2)dx = (\pm\frac{1}{12}g_A + \frac{1}{36}a_8)(1-\frac{\alpha_s}{\pi}+\mathcal{O}(\alpha_s^2)) + \frac{1}{9}\Delta\Sigma(1-\frac{33-8N_f}{33-2N_f}\frac{\alpha_s}{\pi}+\mathcal{O}(\alpha_s^2))$$
$$-\frac{8}{9Q^2}\left[\{\pm\frac{1}{12}f_3+\frac{1}{36}f_8\}\left(\frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)}\right)^{-\frac{\gamma^0_{NS}}{2\beta_0}} + \frac{1}{9}f_0\left(\frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)}\right)^{-\frac{1}{2\beta_0}(\gamma^0_{NS}+\frac{4}{3}N_f)}\right],$$

# An estimate of EDM

YH (2021)

reducible contribution $$d \sim \mu \frac{\langle p'|w\mathcal{O}_W|p\rangle}{m_N \bar{u}(p')i\gamma_5 u(p)}$$

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

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

Can we extract $f_0$ at the EIC?

New physics may be hidden in higher twist effects

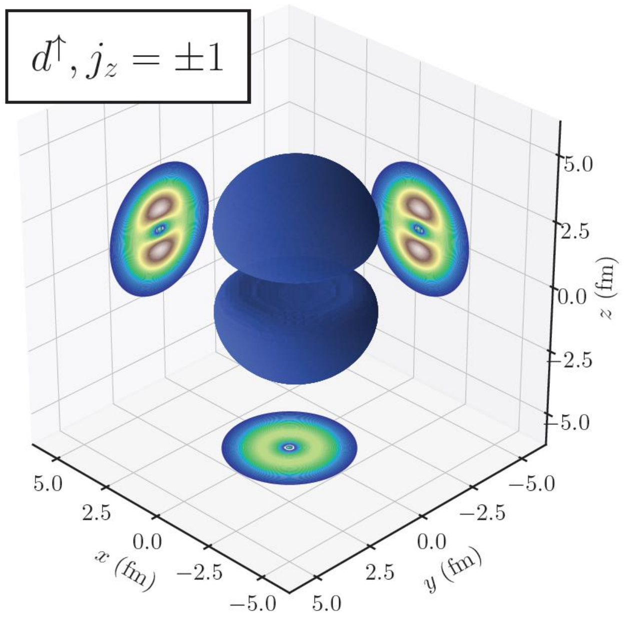
# Polarized Ion opportunities

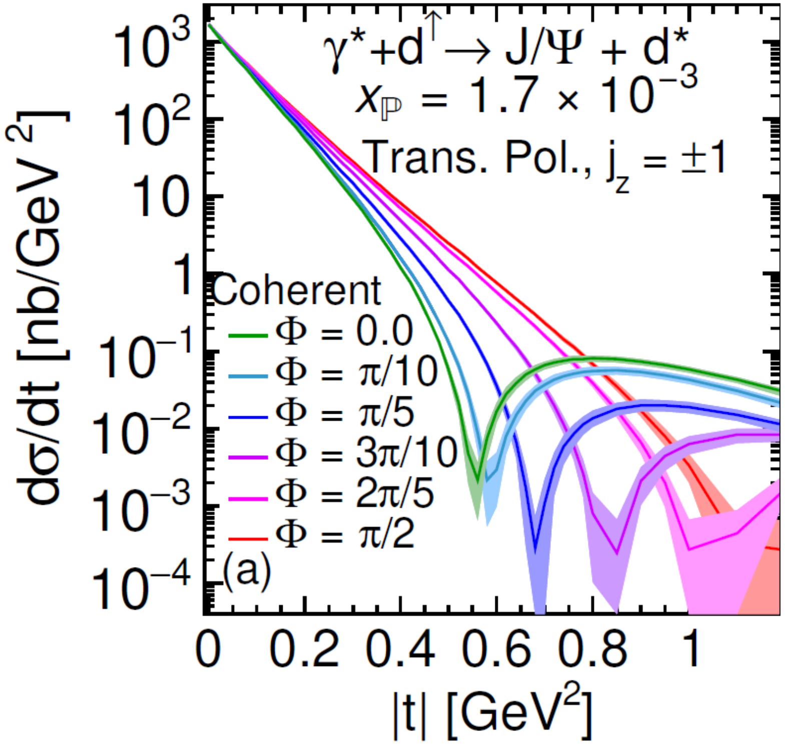
→ Talk by Ian

- Polarized EMC effect
- New PDFs for spin-1 nuclei $b_1(x)$
- Spatial imaging

$\cos(2\Phi)$ asymmetry in exclusive J/psi production

Mantysaari, Salazar, Schenke, Shen, Zhao (2024)



# 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
- Even richer physics with polarized nuclei

# Backup

# Physical meaning of the new momentum sum rule

YH, Schoenleber (2024)

$$1 = \underbrace{-3C_q^{(2)} - \frac{3}{2}C_g^{(2)}}_{\text{kinetic energy}} + \underbrace{\frac{3}{2}\int_{-1}^{1} dx dx' \left[\Lambda_q(x,x') + \frac{2x\tilde{\Lambda}_q(x,x') + \tilde{\Lambda}_G(x,x')}{x-x'}\right]}_{\text{potential energy}}$$

$$\langle p'|\bar{q}\gamma^+ F^{+i} q|p\rangle \approx i\Delta^i \int dx dx' \Lambda_q(x,x')$$

# Transverse force & potential

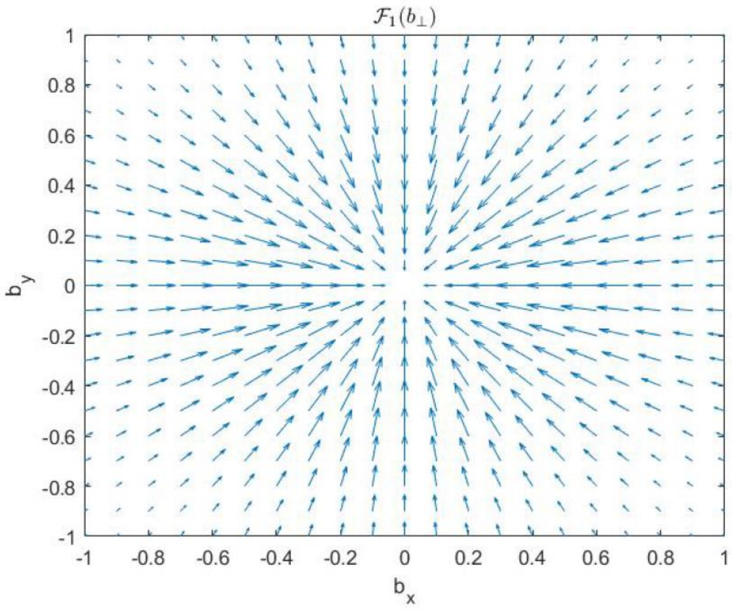
$$F_a^{+i} = \frac{1}{\sqrt{2}}(\vec{E} + \vec{v} \times \vec{B})_a^i$$

color Lorentz force

Burkardt (2008)

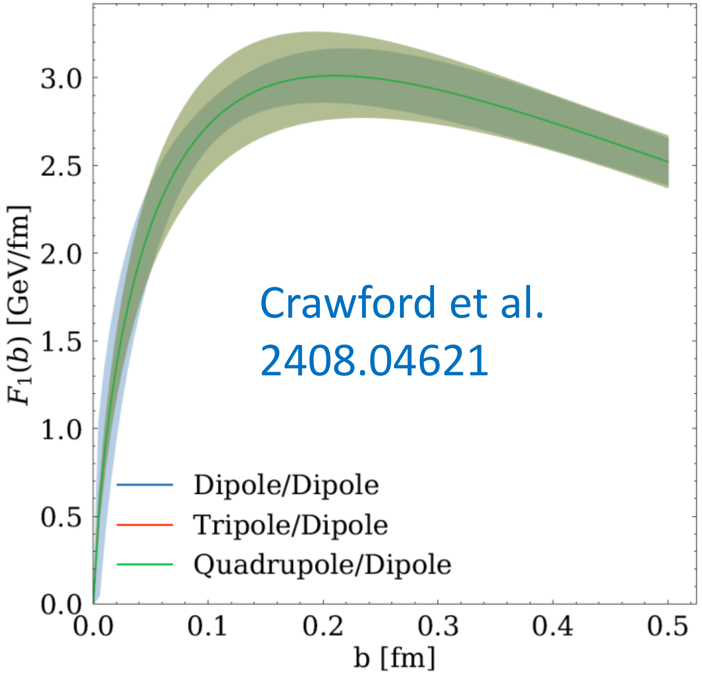
$$\tilde{F}_a^{+i} = -\frac{1}{\sqrt{2}}(\vec{B} - \vec{v} \times \vec{E})_a^i$$

dual color Lorentz force




Aslan, Burkardt, Schlegel (2019)

Force → gradient of a potential $\mathcal{F}_q^i(b_\perp) \equiv -\dfrac{\partial}{\partial b^i} V_q(b_\perp)$




Crawford et al. 2408.04621

$$\frac{3}{2}\int dx dx' \Lambda_q(x, x') = \int d^2 b_\perp V_q(b_\perp)$$