Spin physics at the EIC

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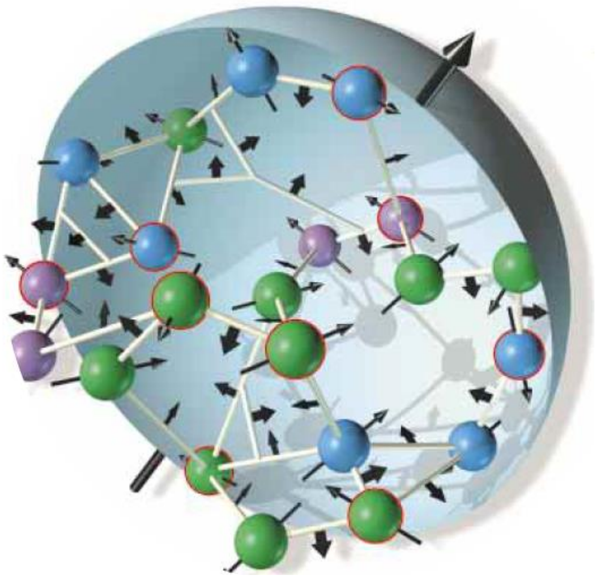
BNL/RIKEN BNL

RHIC-AGS user's meeting, Aug.1-4, 2023

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

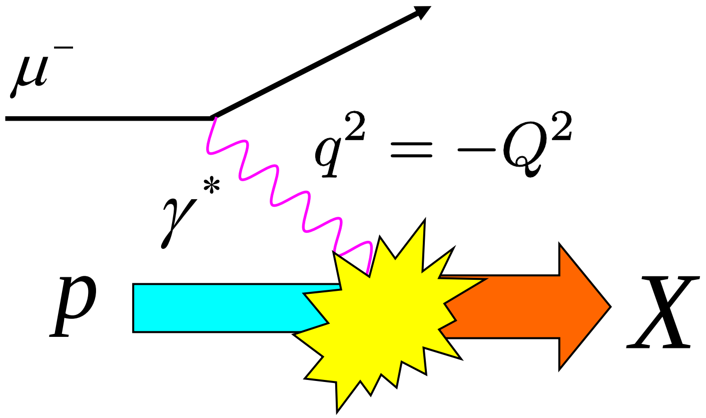
$$= \frac{1}{2}\Delta\Sigma + L^q_{kin} + J_g$$ Ji sum rule

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

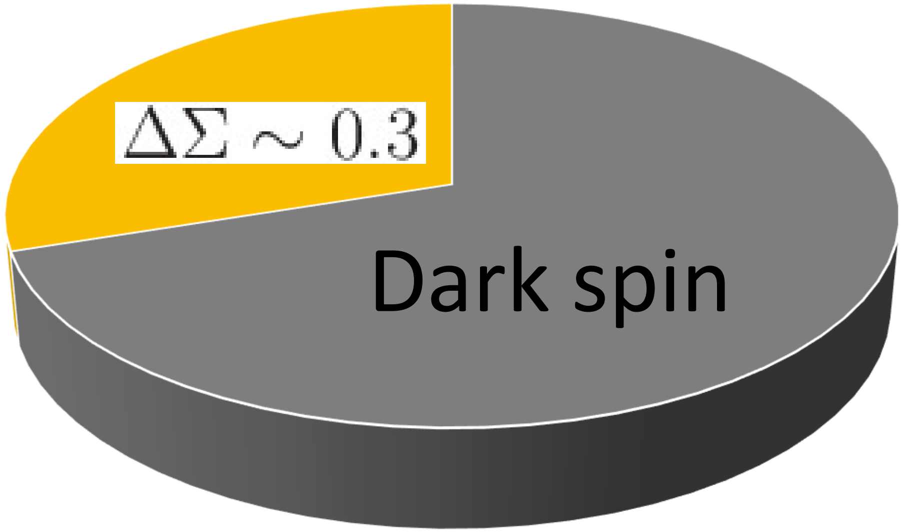
$\Delta\Sigma$ from polarized DIS

Longitudinal double spin asymmetry in polarized DIS

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



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



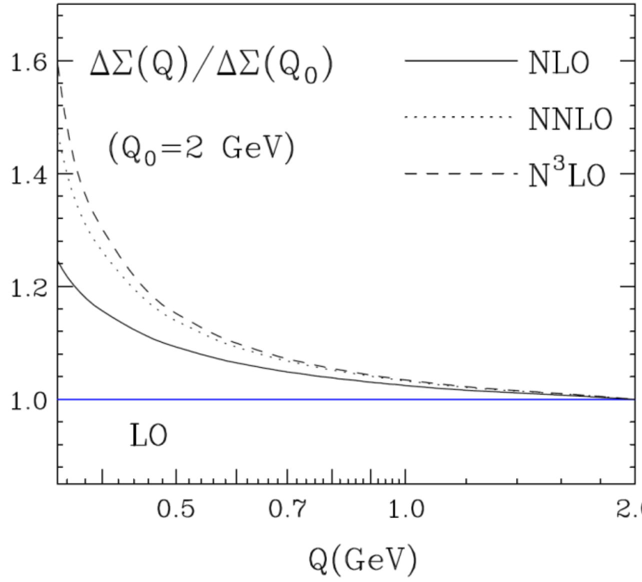
Helicity pQCD precision frontier

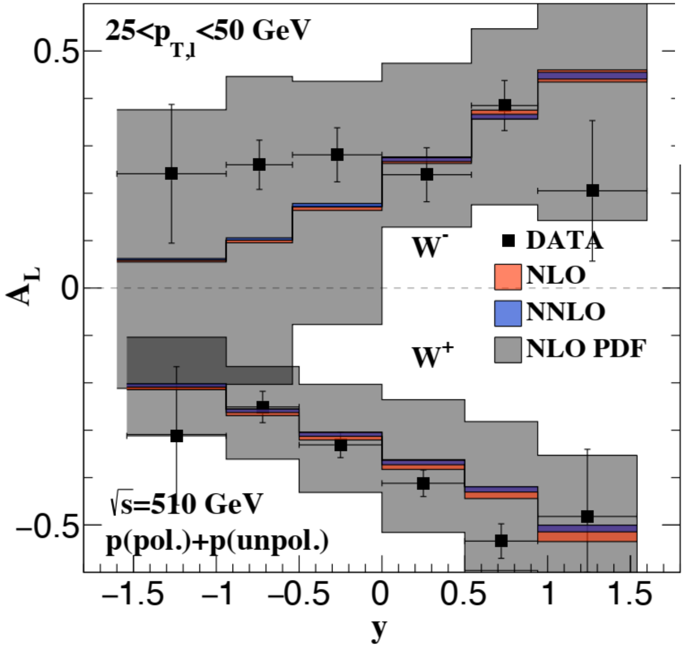
4-loop evolution of $\Delta\Sigma$
De Florian, Vogelsang (2019)

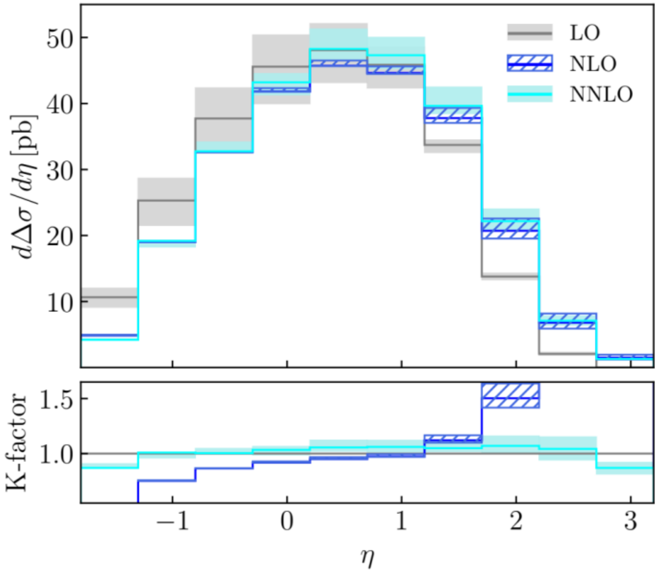
NNLO jet production in polarized DIS
Borsa, de Florian, Pedron (2020)

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)







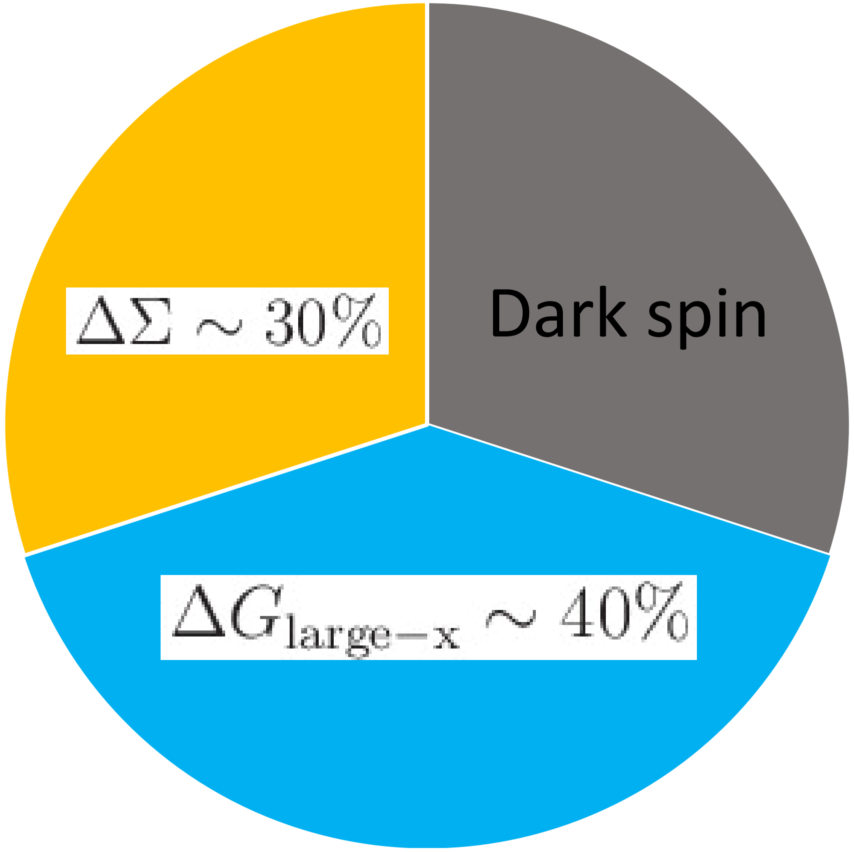
Evidence of nonzero gluon helicity $\Delta G = \int_0^1 dx \Delta G(x)$

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

Does the remaining spin (~30%) come from the small-x region of $\Delta G(x)$?

Direct Photons Point to Positive Gluon Polarization

Results from 'golden measurement' at RHIC's PHENIX experiment show the spins of gluons align with the spin of the proton they're in

June 21, 2023

Helicity evolution at small-x

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

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

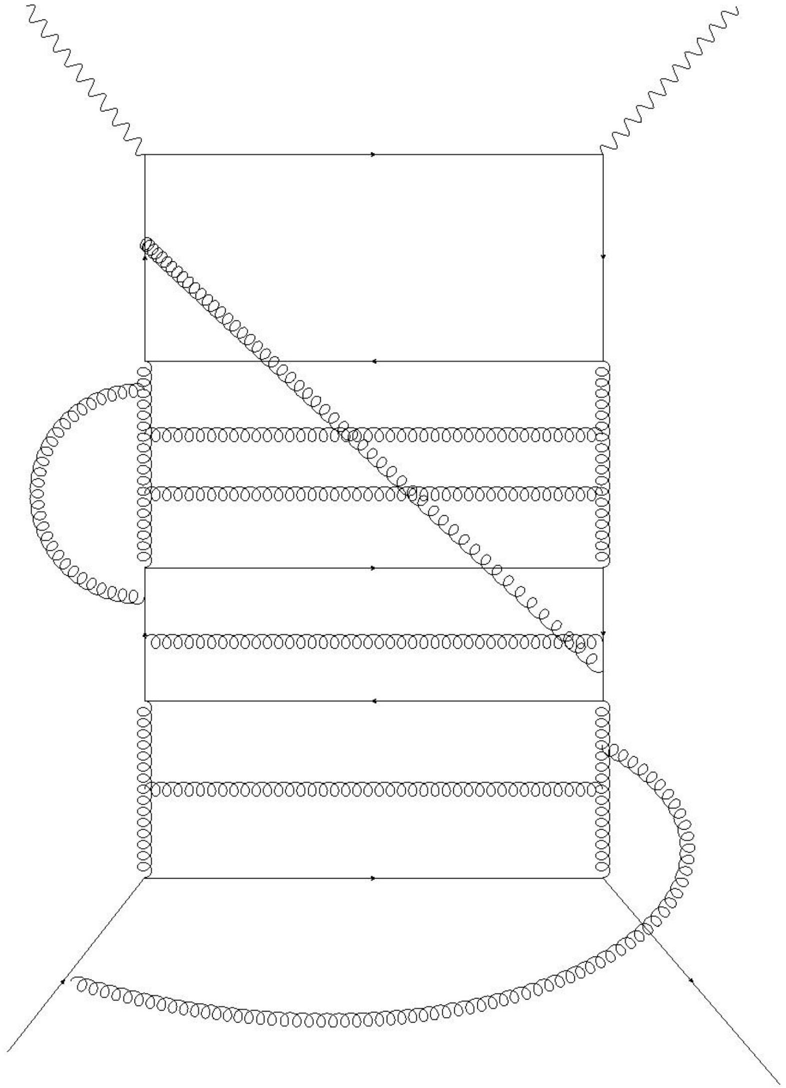
Unlike BFKL, we need to include quark ladders
Unlike BFKL, we need to include non-ladder diagrams

Resummation very hard, but can be done!

Bartels, Ermolaev, Ryskin (1996)

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

$$\alpha \approx 3.664 \sqrt{\frac{\alpha_s N_c}{2\pi}}$$



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)

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

Based on Cougoulic, Kovchegov, Tarasov, Tawabutr (2022)

Discrepancy at 4-loops!

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

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

An elephant in the room: Orbital angular momentum

It's an undeniable fact that experimentally we know nothing about OAM.

Of course, this doesn't mean that OAM is unimportant.

At small-x, helicity and OAM cancel.

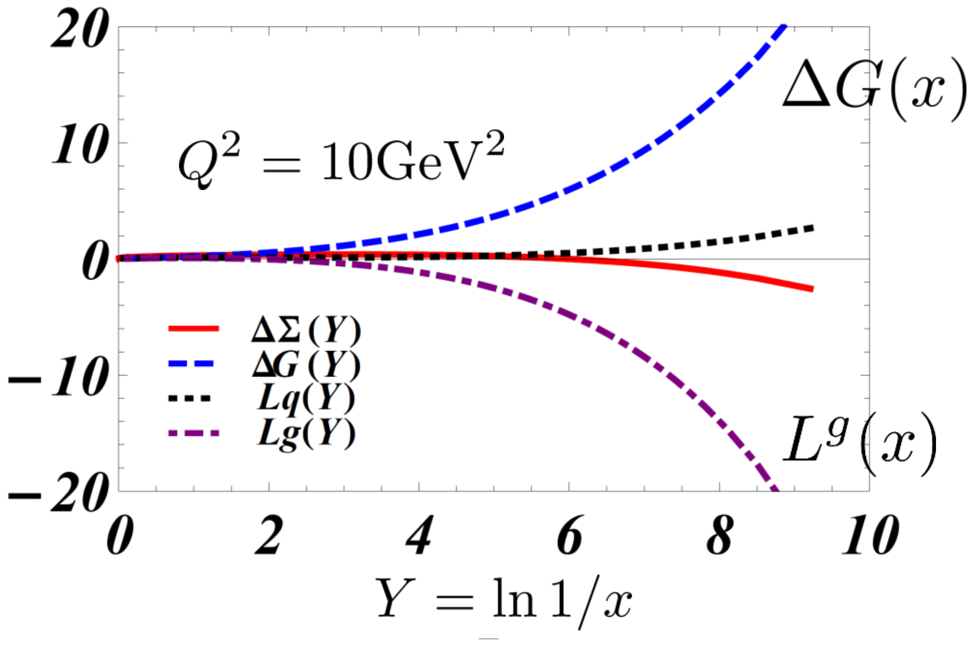
$$\frac{d}{d\ln Q^2} L_g(x) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\left(-2C_F + \cdots\right)\Delta q(x/z)$$

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

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)

YH, Yang (2018)



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.

Helicity is only half of the story.
Can EIC seriously address OAM?

OAM and the Wigner distribution

Wigner/GTMD distribution

Phase space distribution of partons in QCD

Belitsky, Ji, Yuan (2004);

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

Define

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

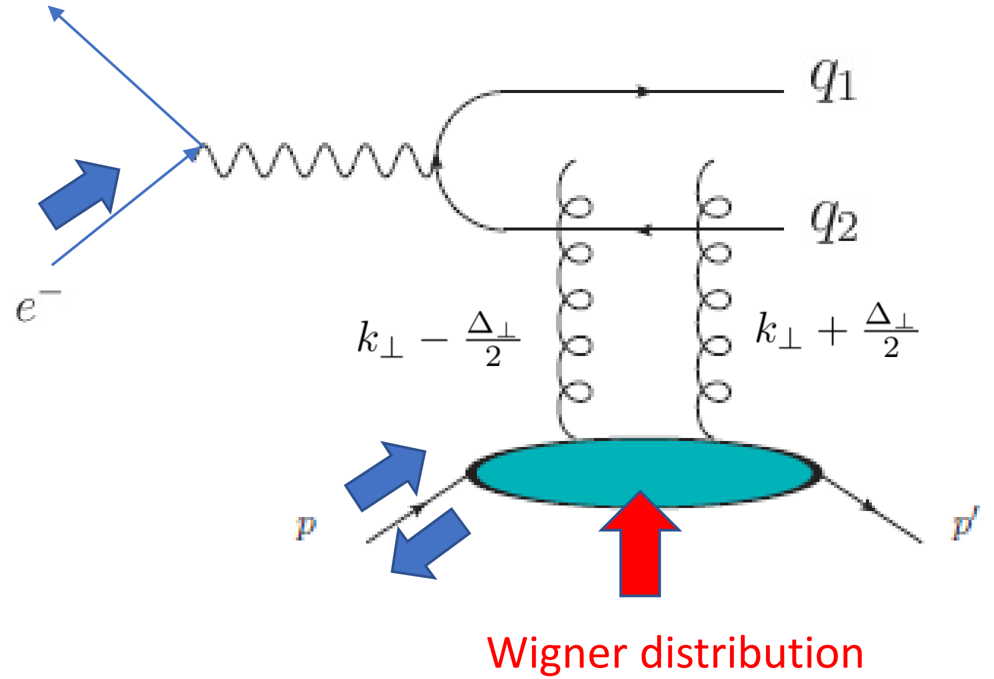
Lorce, Pasquini (2011);
YH (2011);
Ji, Xiong, Yuan (2012)

5D tomography encoded in the Wigner distribution—Holy grail of the nucleon structure

Can we probe it at the EIC?

Gluon OAM from single/double spin asymmetry in diffractive dijet

Ji, Yuan, Zhao (2016) (single)
Bhattacharya, Boussarie, YH (2022) (double)



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

$$\int d^2k_\perp k_\perp^i W_g(k_\perp, \Delta_\perp) \sim \epsilon^{ij} \Delta_\perp^j L_g$$

$$d\sigma^{h_p h_l} \sim h_p h_l \cos(\phi_{l_\perp} - \phi_{\Delta_\perp}) \mathrm{Re}\, \mathcal{H}_g^{(1)*} \left(\tilde{\mathcal{H}}_g^{(2)} + \frac{q_\perp^2 - \mu^2}{q_\perp^2 + \mu^2} \mathcal{L}_g \right)$$

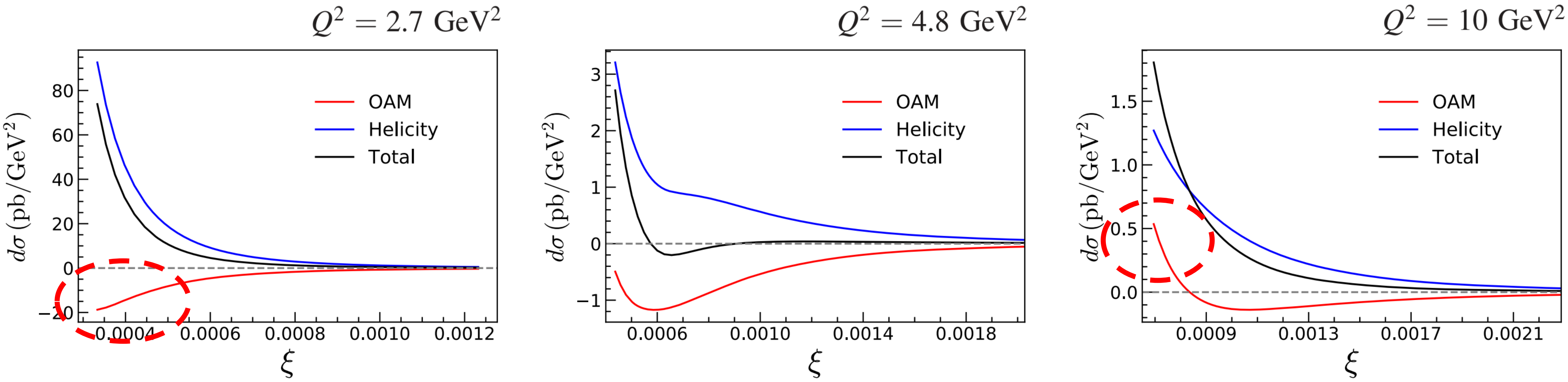
lepton angle

recoil proton angle

Compton form factors of gluon helicity and OAM

Prediction for EIC

Bhattacharya, Boussarie, YH (2022)



Depending on the sign of $q_\perp^2 - \frac{Q^2}{4}$, helicity and OAM add up/cancel.

First-ever quantitative prediction for an observable sensitive to OAM
To extract OAM, we need to know $\Delta G(x)$ precisely at small-x

In practice, jets at low momenta are hard to reconstruct.
Alternative measurement? Bhattacharya, Boussarie, YH, in preparation

Generalized Parton Distribution (GPD)

Off-forward generalization of PDF

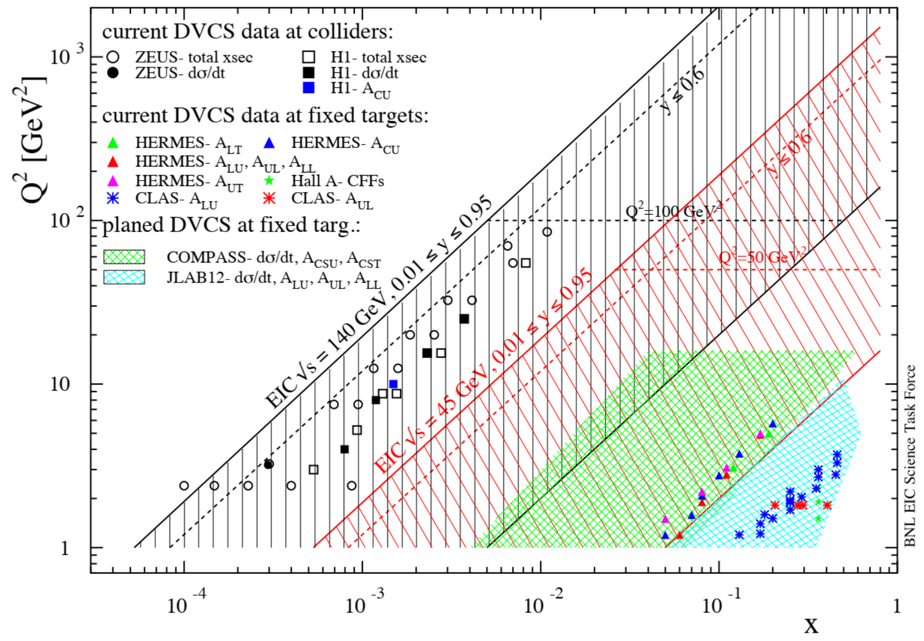
$$P^+ \int \frac{dy^-}{2\pi} e^{ixP^+y^-} \langle P'S'|\bar{\psi}(0)\gamma^\mu\psi(y^-)|PS\rangle$$

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

Second moments relevant to Ji sum rule

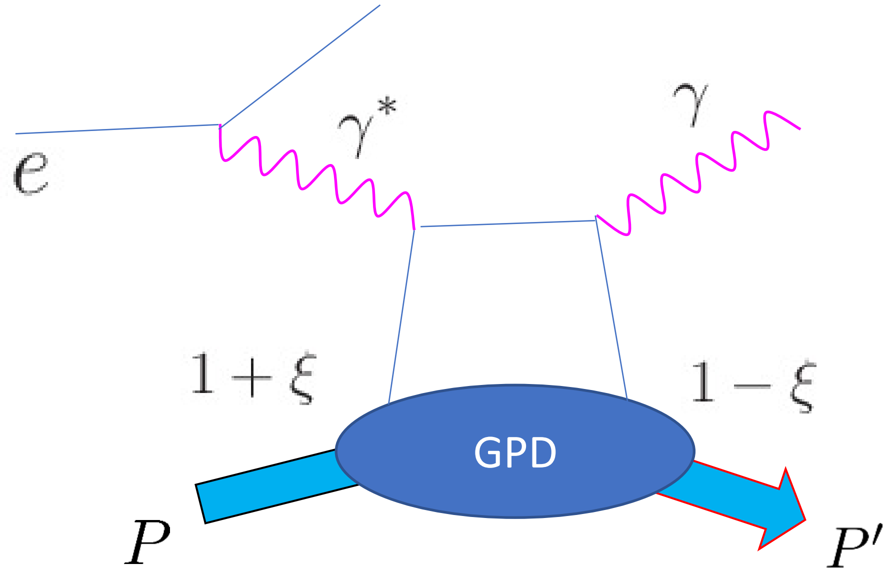
$$J_{q,g} = \frac{1}{2}\int_0^1 dx\, x(H_{q,g}(x) + E_{q,g}(x))$$

EIC offers an unprecedented kinematical coverage for DVCS and other exclusive processes. New era of GPD studies.



Deeply Virtual Compton Scattering

$$i\int d^4y e^{iqy}\langle P'|T\{J^\mu(y)J^\nu(0)\}|P\rangle$$
$$= \frac{g_\perp^{\mu\nu}}{2P^+}\bar{u}(P_2)\left[\gamma^+\mathcal{H} + \frac{i\sigma^{+\nu}\Delta_\nu}{2M}\mathcal{E}\right]u(P_2) + \cdots$$



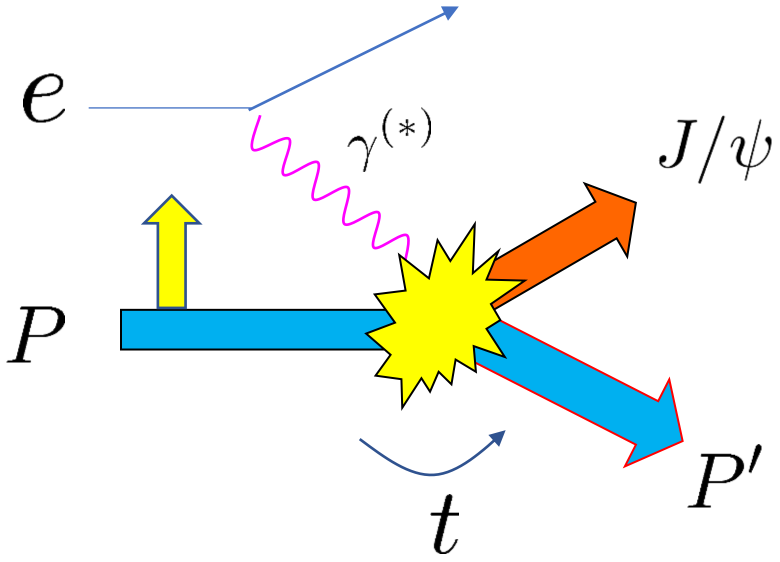
Compton form factors

$$\begin{pmatrix}\mathcal{H}(\xi)\\ \mathcal{E}(\xi)\end{pmatrix} = \int_{-1}^{1} dx C_q(x,\xi)\begin{pmatrix}H_q(x,\xi)\\ E_q(x,\xi)\end{pmatrix} + \alpha_s \int_{-1}^{1} dx C_g(x,\xi)\begin{pmatrix}H_g(x,\xi)\\ E_g(x,\xi)\end{pmatrix} + \cdots$$

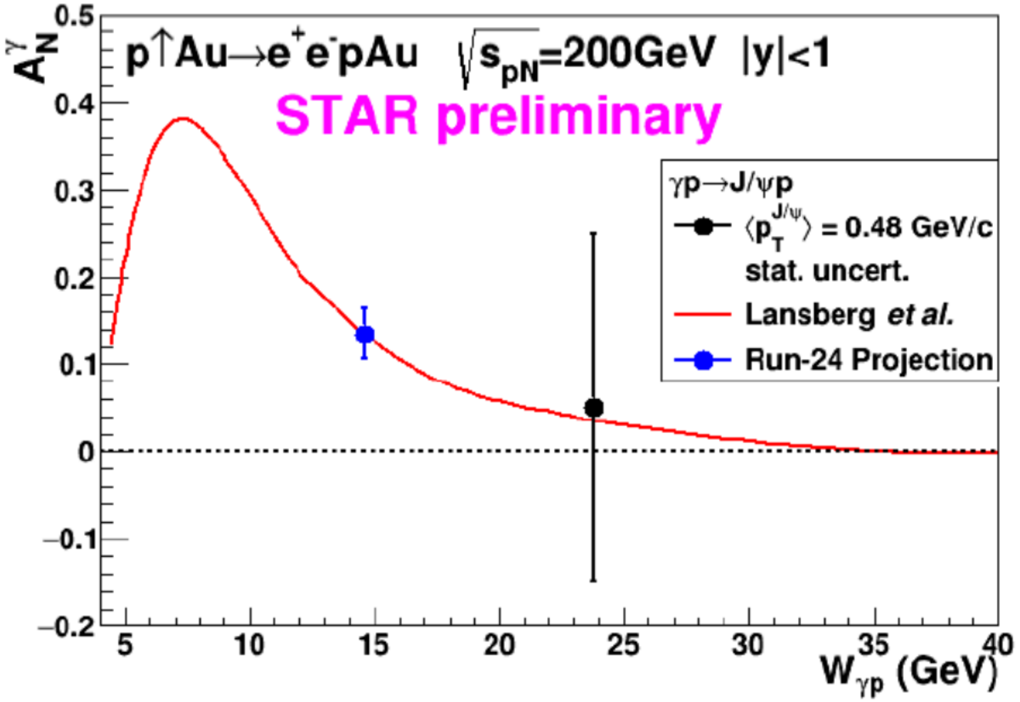
Ingredients for NNLO global analysis ready in near future Braun, Ji, Schoenleber (2023)
In practice, NLO global analysis is already a challenge Kumericki,…
Very hard to access GPD E, especially the gluon one.

GPD E_g from J/ψ 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

Gluon GPD $E_g(x)$ at small-x

YH, Zhou (2022)

Nucleon helicity non-flip

$$xH_g(x) = xG(x) = \int d^2k_\perp \mathcal{G}(x, k_\perp)$$

$$\sim \left(\frac{1}{x}\right)^{4\ln 2\bar{\alpha}_s}$$

BFKL pomeron

Nucleon helicity flip

$$xE_g(x) = \int d^2k_\perp \mathcal{E}(x, k_\perp)$$

$$\sim \left(\frac{1}{x}\right)^{??}$$

Introduce $k_\perp$ -dependence in GPD → GTMD

Recent theory developments in GTMD help solve this problem

Small-x evolution equation for $E_g(x)$

YH, Zhou (2022)

$$\partial_Y \mathcal{E}(k_\perp) = \frac{\bar{\alpha}_s}{\pi} \int \frac{d^2k'_\perp}{(k_\perp - k'_\perp)^2} \left[\mathcal{E}(k'_\perp) - \frac{k_\perp^2}{2k'^2_\perp} \mathcal{E}(k_\perp) \right] - 4\pi^2 \alpha_s^2 \overline{\mathcal{F}}_{1,1}(k_\perp) \mathcal{E}(k_\perp)$$

$Y = \ln 1/x$

$$xE_g(x) \sim xG(x) \propto \left(\frac{1}{x} \right)^{\bar{\alpha}_s 4 \ln 2}$$

BFKL Pomeron behavior, the same as unpol gluon PDF
Eventually reaches gluon saturation.

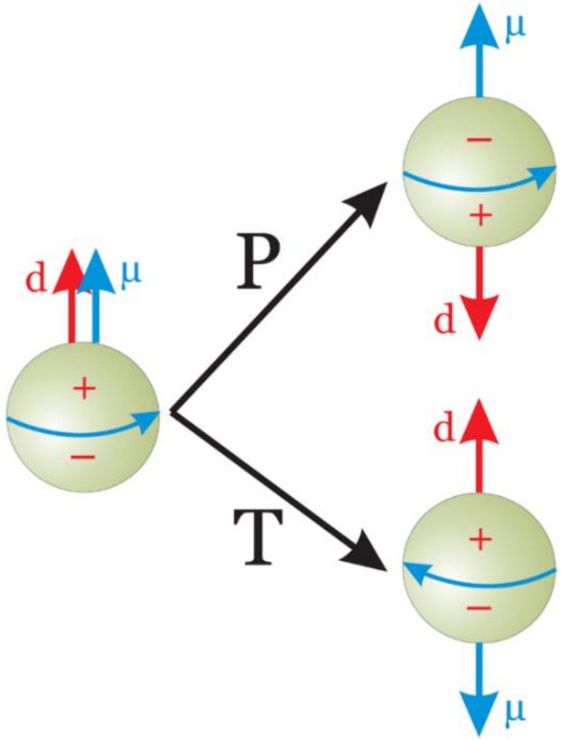
$$J_g = \frac{1}{2} \int_0^1 dx \; x \left[H_g(x,\xi) + E_g(x,\xi) \right]$$

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

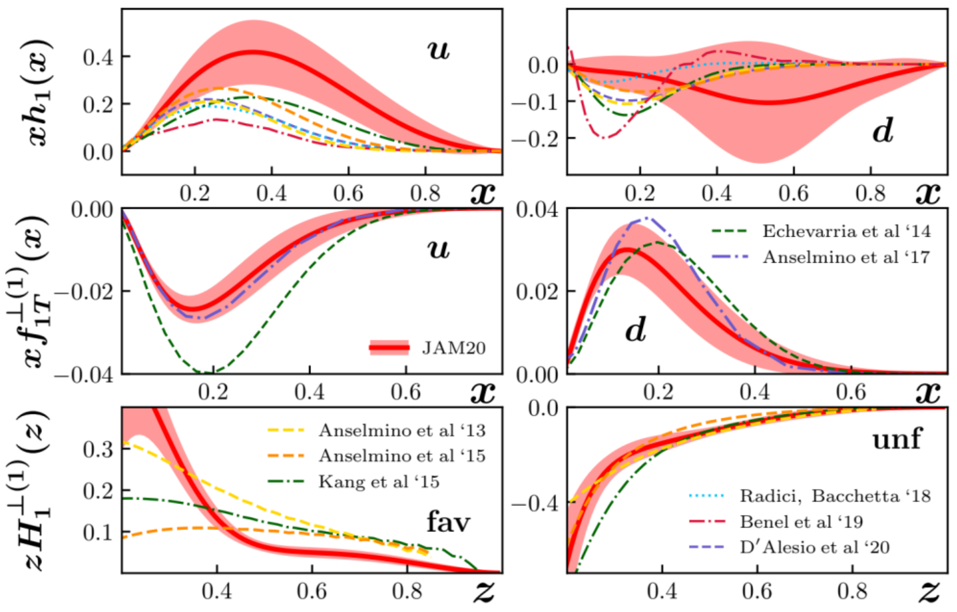
- Theta term $\frac{\theta\alpha_s}{8\pi}F\tilde{F}$
- Quark EDM operator $m_q\bar{\psi}_q F^{\mu\nu}\sigma_{\mu\nu}i\gamma_5\psi_q$
- Weinberg operator $f_{abc}\tilde{F}^a_{\mu\nu}F^{\mu\rho}_b F^{\nu}_{c\rho}$
- …



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

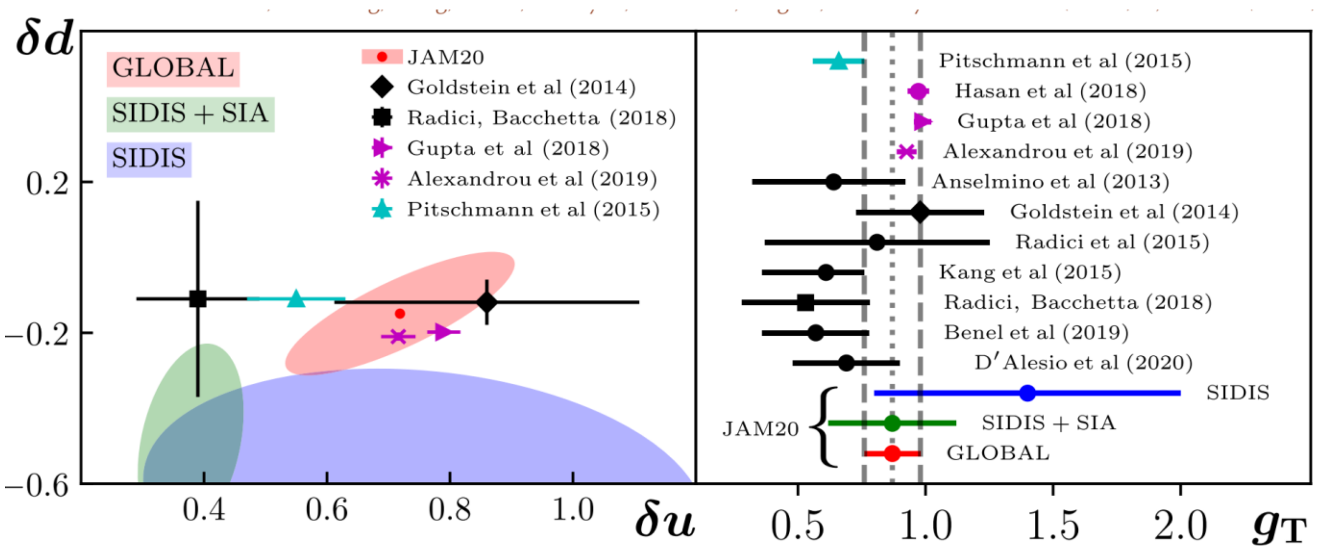
Global analysis of SSA

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.
→ Constraints on the quark EDM operator

Connecting Weinberg operator to higher-twist effect in polarized DIS

YH (2020)

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

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

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

First moment of g1

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

An estimate of EDM

YH (2021)

`One-nucleon reducible' contribution to EDM   Bigi, Uraltsev (1990)

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

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)

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

Can we measure f_0 at the EIC?
New connection between EIC spin and BSM physics

Summary

- Spin is one of the core science cases of EIC
- OAM is the key to fulfill the JM spin sum rule. Lagging far behind in both theory and experiment, but a glimmer of hope.
- EIC offers great opportunities for GPD studies. From spin physics perspective, extraction of GPD E is a major challenge.