Nucleon EDM from polarized DIS

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Based on 2009.03657 (PRD),
2012.01865 (PLB)

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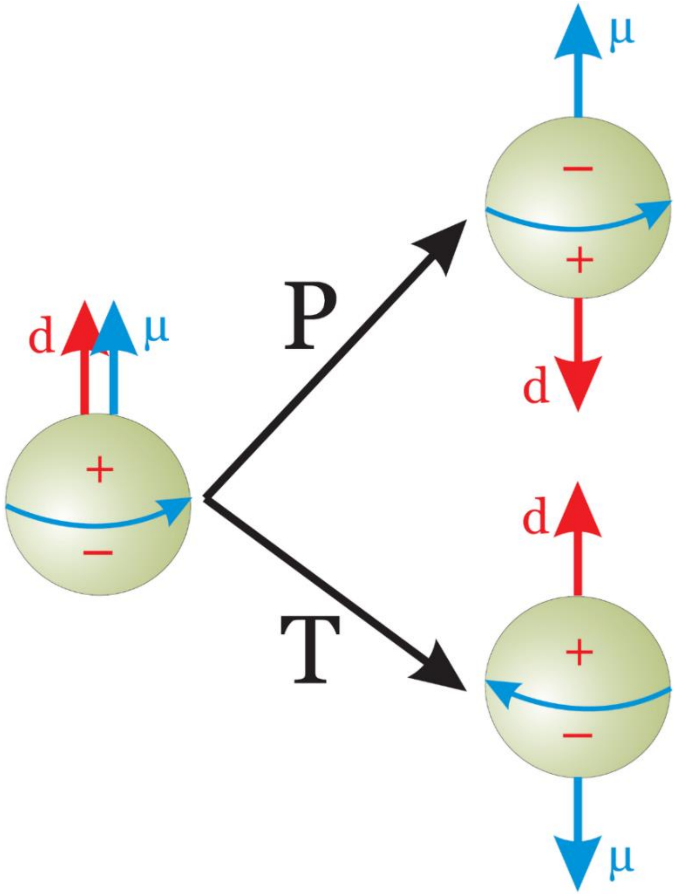
Nucleon electric dipole moment (EDM)

If nonvanishing, CP is violated.
EDM is a vector, must be proportional to nucleon spin

CKM mechanism gives too small values of nucleon EDM, much smaller than the current experimental upper bound

→ CP violation from BSM physics?



Can high energy ep colliders help, especially the Electron-Ion Collider(EIC)?

Chromoelectric 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

$$e + p \to e' + \pi^+ + \pi^- + X$$

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

Third moment may be related to Quark chromomagnetic dipole moment

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

→ CP-violating nucleon-pion couplings

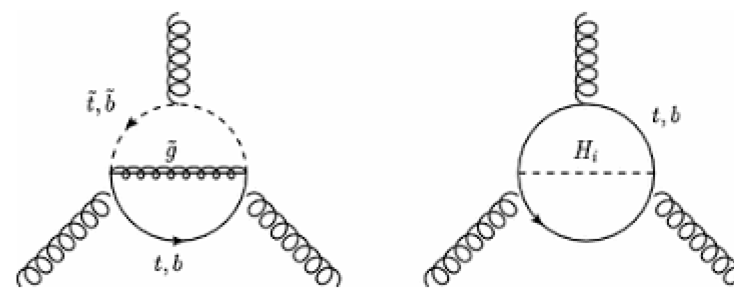
Weinberg operator (1989)

$$\mathcal{O}_W = g f_{abc} \tilde{F}^a_{\mu\nu} F^{\mu\alpha}_b F^{\nu}_{c\alpha}.$$

CP-odd, dimension-6, scalar gluonic operator.

Induced in the QCD Lagrangian by physics beyond the Standard Model (BSM)

$$\mathcal{L}_{eff} = w \int d^4x \mathcal{O}_W(x)$$



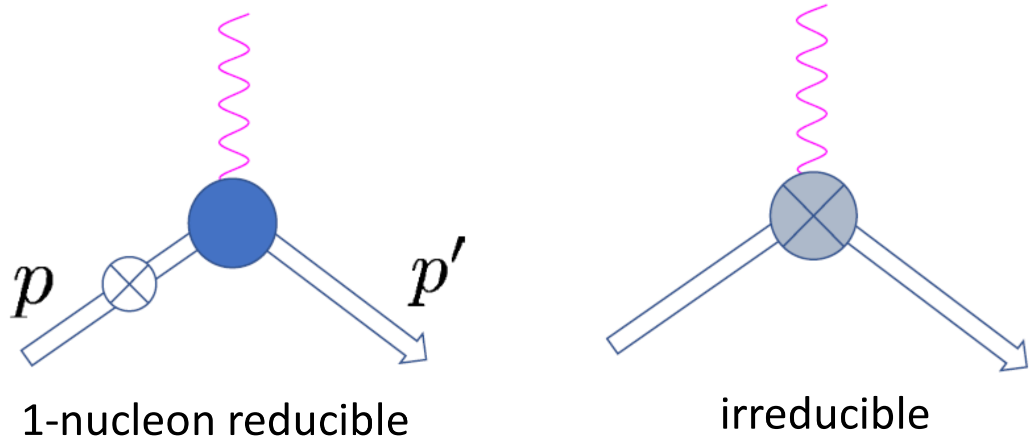
Want to calculate the proportionality constant in nucleon EDM

$$d_{n,p} \propto w$$

Weinberg operator contribution to EDM

There are two types of diagrams,
1-nucleon reducible and irreducible

Bigi, Uraltsev (1991)



Reducible contribution

$$d_n \sim \mu_n \frac{\langle p' | w \mathcal{O}_W | p \rangle}{m_N \bar{u}(p') i\gamma_5 u(p)}$$

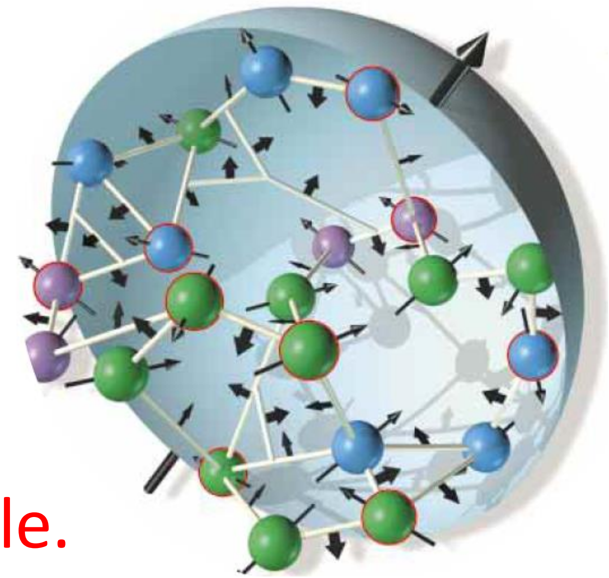
QCD sum rule
Demir, Pospelov, Ritz (2003)
Haisch, Hala (2019)

Connecting to DIS observable
YH (2020) ← this talk

Irreducible contribution

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

The proton spin problem



The proton has spin ½.

The proton is not an elementary particle.

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

Quarks' helicity

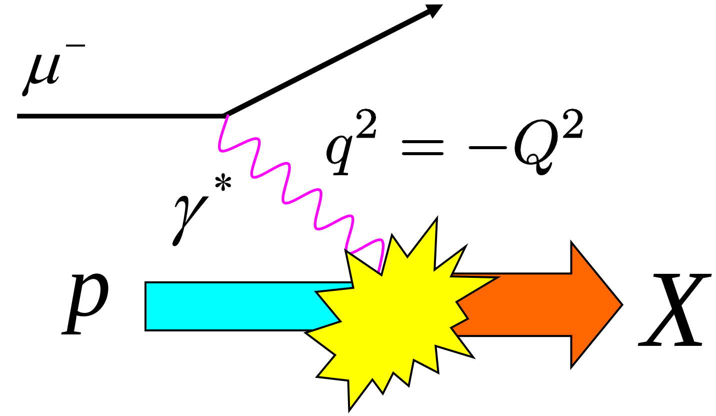
Gluons' helicity

Orbital angular Momentum (OAM)

$\Delta\Sigma$ from polarized DIS

Longitudinal double spin asymmetry

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



$$\int_0^1 g_1^{p,n}(x, Q^2)dx$$

$$= (\pm\frac{1}{12}g_A + \frac{1}{36}a_8)(1 - \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)) + \frac{1}{9}\Delta\Sigma(1 - \frac{33-8N_f}{33-2N_f}\frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2))$$

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

This is what QCD-spin people are usually interested in.

Last line is called `higher twist' corrections, usually a nuisance when extracting $\Delta\Sigma$

An operator identity

Start from an exact identity YH, 2009.03657

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

$$\overleftrightarrow{D}_\alpha = \frac{D_\alpha - \overleftarrow{D}_\alpha}{2}$$

Take the off-forward matrix element

$$\begin{aligned} \langle p' | \mathcal{O}_W | p \rangle &= -i\Delta^\mu \langle p' | \tilde{F}_{\mu\nu} \overleftrightarrow{D}_\alpha F^{\nu\alpha} | p \rangle + \cdots \\ &\approx i\Delta^\mu \underline{\langle p | \bar{\psi} g \tilde{F}_{\mu\nu} \gamma^\nu \psi | p \rangle} + \cdots \end{aligned}$$

$$\Delta^\mu = p'^\mu - p^\mu$$

This matrix element is familiar to experts of QCD spin!

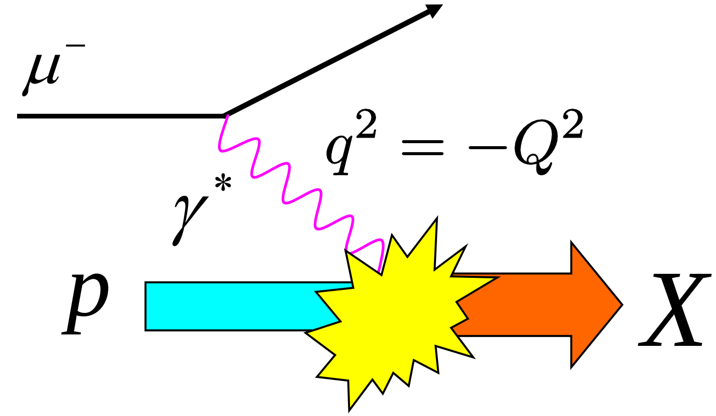
Shuryak, Vainshtein (1982)

$$\langle p | \bar{\psi} g \tilde{F}_{\mu\nu} \gamma^\nu \psi | p \rangle = -f_0 M^2 S^\mu$$

$\Delta\Sigma$ from polarized DIS

Longitudinal double spin asymmetry

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



$$\int_0^1 g_1^{p,n}(x,Q^2)dx \;;$$

$$= (\pm\frac{1}{12}g_A + \frac{1}{36}a_8)(1 - \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)) + \frac{1}{9}\Delta\Sigma(1 - \frac{33-8N_f}{33-2N_f}\frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2))$$

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

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Operator mixing

Choose

$$\mathcal{O}_W = g f_{abc} \tilde{F}^a_{\mu\nu} F^{\mu\alpha}_b F^{\nu}_{c\alpha}$$

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

as the basis of operators and study their mixing under RG.

RG equation*

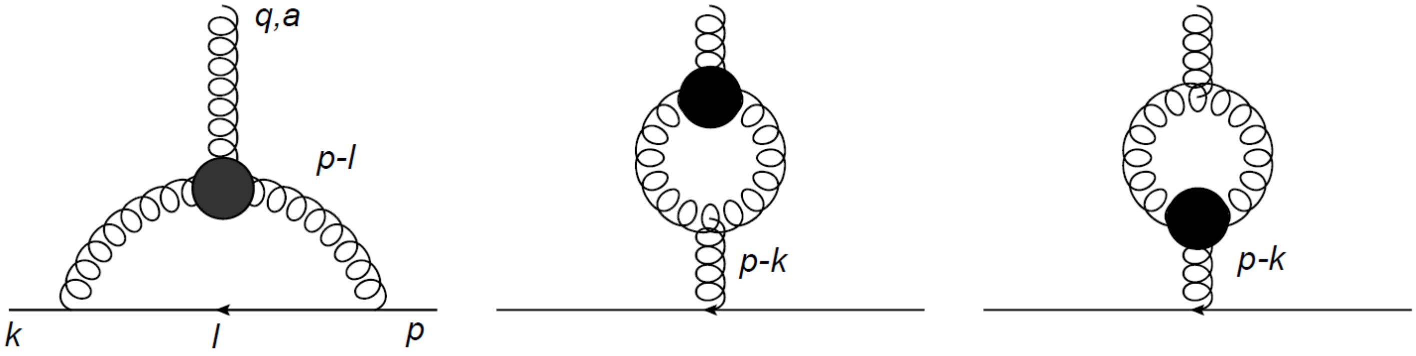
$$\frac{d}{d\ln\mu^2} \begin{pmatrix} \mathcal{O}_W \\ \mathcal{O}_4 \end{pmatrix} = -\frac{\alpha_s}{4\pi} \begin{pmatrix} \gamma_W & \gamma_{12} \\ 0 & \gamma_4 \end{pmatrix} \begin{pmatrix} \mathcal{O}_W \\ \mathcal{O}_4 \end{pmatrix}$$

$$\gamma_W = \frac{N_c}{2} + n_f + \frac{\beta_0}{2} = \frac{7}{3} N_c + \frac{2}{3} n_f$$ Morozov (1983)

$$\gamma_4 = \frac{8}{3} C_F + \frac{2}{3} n_f.$$ Shuryak, Vainshtein (1982)

* Here I neglect the mixing with the chromoelectric operator $m\bar{\psi} g F_{\mu\nu} \sigma^{\mu\nu} \gamma_5 \psi$

Off-diagonal component



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

YH, 2009.03657

Eigenvector of RG-evolution

$$\mathcal{O}_W + \frac{\gamma_{12}}{\gamma_W - \gamma_4}\mathcal{O}_4 = \mathcal{O}_W - \frac{9N_c^2}{3N_c^2+4}\mathcal{O}_4$$

At large RG scales, $\langle \mathcal{O}_W \rangle \approx \frac{9N_c^2}{3N_c^2+4}\langle \mathcal{O}_4 \rangle \approx 1.31\langle \mathcal{O}_4 \rangle$

approaching this limit from below

An estimate of EDM

YH, 2012.01865

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

↑ **total** magnetic moment

Define $\langle p'|\mathcal{O}_W|p\rangle = 4m^3 E\bar{u}(p')i\gamma_5\bar{u}(p)$

Vary E in the window

$$0.5 f_0 < E < 1.3 f_0$$

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

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

Factor 4~5 smaller than an estimate based on QCD sum rule Haisch, Hala (2019)

$$d_p = -109(1 \pm 0.5)\,e\,\mathrm{MeV}, \qquad d_n = 74(1 \pm 0.5)\,e\,\mathrm{MeV}.$$

Comparable to the contribution from irreducible diagrams Yamanaka, Hiyama (2020)

Measuring f_0 at the future Electron-Ion Collider

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

+ target mass corrections

Exploit the large Q^2 leverage at the EIC to isolate the $1/Q^2$ (twist-4) terms.

f_3 can be eliminated by taking the flavor singlet combination.

Separating f_0 from f_8 will be hard in practice. One may estimate f_8 by other means.

Conclusions

- Novel connection between high energy QCD spin and BSM physics.
- A nice addition to the already rich spin program at the future Electron-Ion Collider (EIC). Make the most of EIC's unique capabilities.