Non-perturbative dynamical origin of the nucleon spin

PacificSPIN 2026

Jun-Young Kim

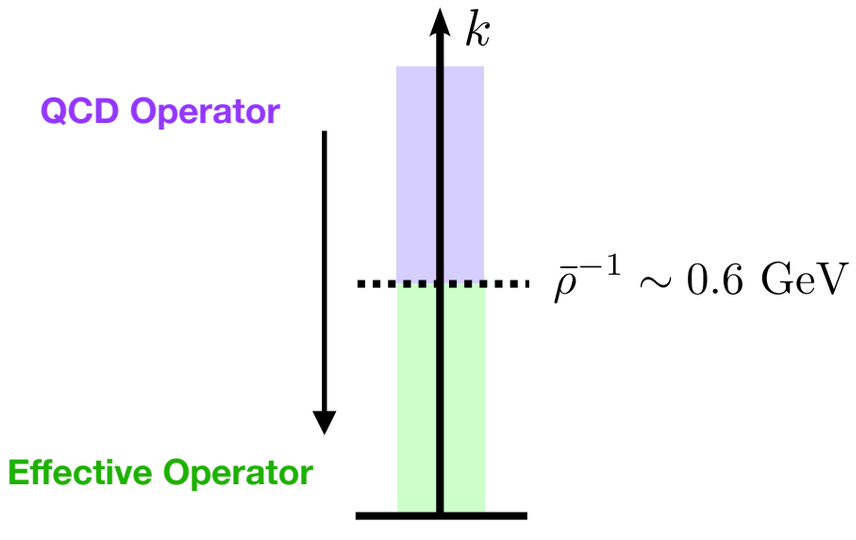
In collaboration with C. Weiss, H.-Ch. Kim, H. Y. Won

October 30 2026

The 13th Circum-Pan-Pacific Symposium on High Energy Spin Physics

QCD operators: Twist-3

$$O_q^{\mu\nu} = \bar{\psi}\Gamma\tau\psi$$



$$(O_{\text{eff}})_q^{\mu\nu} = \quad ?$$

$$\nabla := \partial - iA$$

$$O_q^{\mu\nu} = \bar{\psi}\gamma^{[\mu} i\nabla^{\nu]}\tau\psi$$

$$= -\frac{1}{4}\epsilon^{\mu\nu\alpha\beta}\partial_\alpha[\bar{\psi}\gamma_\beta\gamma_5\tau\psi]$$

Non-perturbative effects on gluon field

[JYKim ,C. Weiss PLB (2024)]

Conserved QCD operators → response of the chiral Lagrangian to the symmetry transformation. No dynamical information is needed.

- Vector current, energy-momentum tensor current

Non-conserved QCD operators → Derivation of the effective operator requires dynamical information beyond the chiral Lagrangian

- Quark/gluon operators characterizing the parton structures
- Most non-perturbative models cannot treat gluon fields in a systematic and controllable way. $\nabla := \partial - iA$

Twist-3 QCD operator $J = S^q + L^q + J^g$

Twist-3 spin-1 local operator [antisymmetrized EMT current]

Nucleon matrix element = moments of twist-3 PDF/GPD [Ji's relation]

QCD equation of motion → total derivative of the axial-vector current

Gauge-dependent part plays an essential role

Program

Construct description of QCD vacuum based on “Instanton vacuum” [Diakonov, Petrov (1984)/ Shuryak (1982)]

Derive effective theory (dynamics) from chiral symmetry breaking [Diakonov, Petrov, Pobylitsa (1986)]

Derive effective operators resulting from twist-3 QCD operator

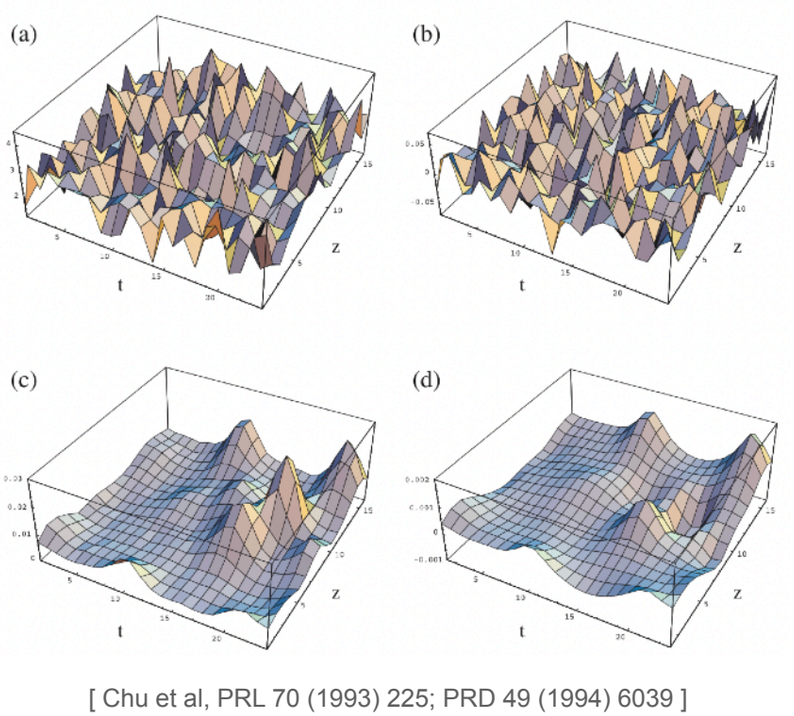
- Use parametric approximation: diluteness of instantons, $1/N_c$ [Diakonov et al, (1996) /J. Balla, M.V. Polyakov, C. Weiss (1999)]
- Obtain effective operators consistent with effective dynamics
- Satisfy QCD relation [J.-Y. Kim, C. Weiss, PLB (2024)]

Estimate the nucleon matrix element of the derived effective operator within the effective theory using the same parametrical approximation

- Orbital angular momentum / Spin-orbit correlation (twist-3) [J.-Y. Kim, H-Y. Won, C. Weiss PLB (2026)]
- Instanton effects [J.-Y. Kim, H-Y. Won, H.-Ch. Kim , C. Weiss, PRD (2024)]

Effective theory

Instanton vacuum



[Chu et al, PRL 70 (1993) 225; PRD 49 (1994) 6039]

Instanton

Chiral symmetry breaking is caused by topological fluctuations of the gauge fields in the QCD vacuum (instantons)

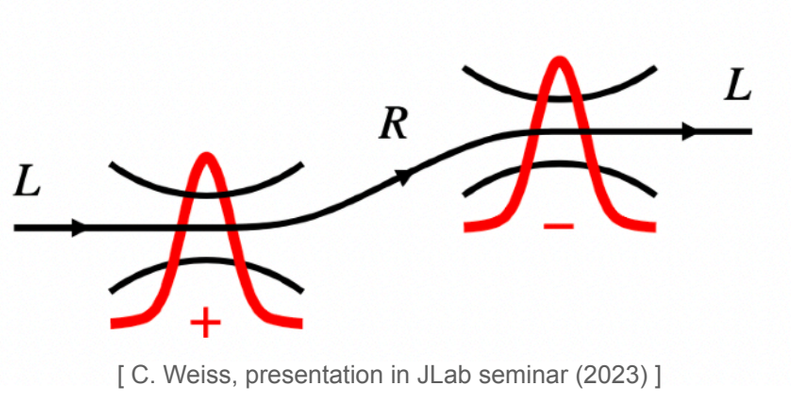
Instantons: Classical solutions of the Yang-Mills equation (self-duality) in Euclidean time

Typical size $\bar{\rho} \sim 0.3$ fm, separation $\bar{R} \sim 1$ fm

Fermion zero modes

Dirac equation (in the presence of the instanton field background) $\rightarrow$ $(i \nabla^{\mu} \gamma_{\mu} + im)\Psi = \lambda \Psi$

Zero mode $\lambda = 0$ (dominant in the low energy regime)



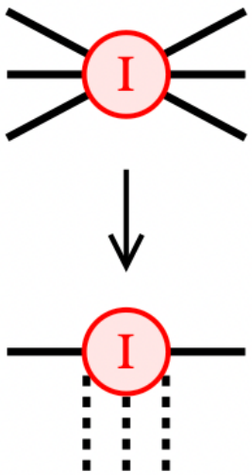
[C. Weiss, presentation in JLab seminar (2023)]

Chiral symmetry breaking

Quarks experience chirality flip $\rightarrow$ order parameter $\langle \bar{\psi} \psi \rangle \neq 0$;

Main outcome: massless bosons $\langle \bar{\psi}^a_L \psi^b_R \rangle \sim U^{ab}$; generation of the dynamical quark mass

Instanton vacuum: Effective theory



[J.Y. Kim, C. Weiss, PLB (2024)]

Effective action

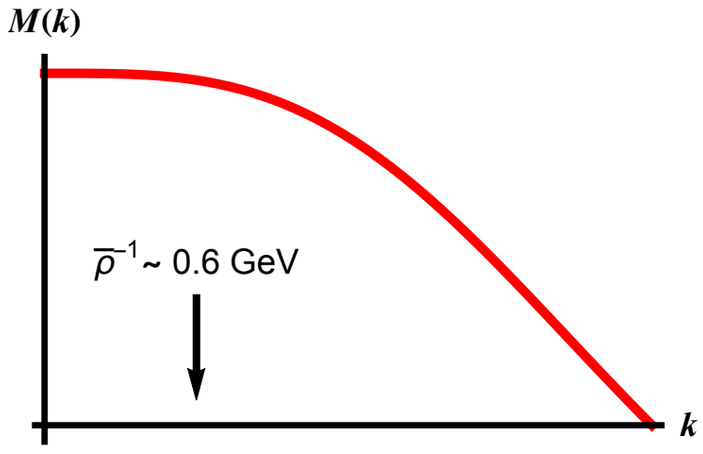
Zero mode induces the multi-fermion interaction (’t Hooft vertex) /
Bosonization $\bar{\psi}^a \psi^b \sim U^{ab}$

Semi-bosonized effective action

Systematic expansions: Diluteness of the instanton ($M\bar{\rho}$), $1/N_c$ expansion

$$S = -\int d^4x \bar{\psi}[i\partial^\mu \gamma_\mu + MU^{\gamma_5}]\psi \qquad U^{\gamma_5}(x) = \frac{1+\gamma_5}{2}U(x) + \frac{1-\gamma_5}{2}U^\dagger(x)$$

Effective chiral action



Degrees of freedom→Goldstone boson + Massive quark
$(p < \bar{\rho}^{-1} \sim 600\ \mathrm{MeV})$

UV cutoff by zero mode form factor $M(k)$

Typical size of the dynamical quark mass $M(0) \sim 0.3 - 0.4\ \mathrm{GeV}$

Fully bosonized action corresponds to the chiral Lagrangian

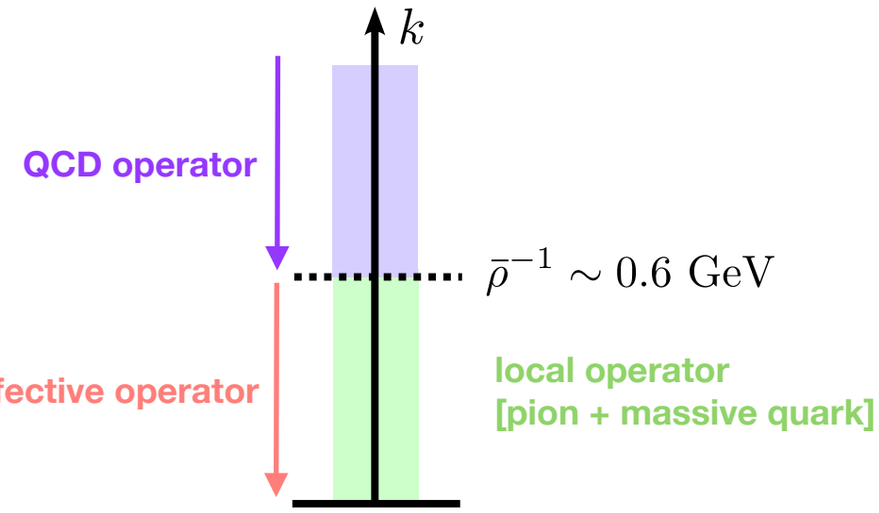
Effective operator

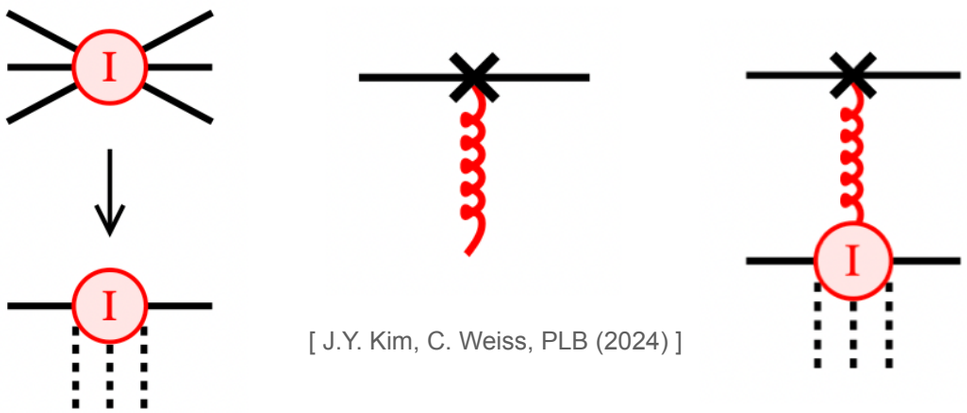
Instanton vacuum: Evaluating QCD operators

QCD operator

QCD operators normalized at scale $\bar{\rho}^{-1} \sim 0.6$ GeV

Use approximations : Diluteness, saddle-point approximation $1/N_c$





[J.Y. Kim, C. Weiss, PLB (2024)]

$$\mathscr{F}[A] = \sum_{I+\bar{I}} \mathscr{F}[A_I] + O(\rho^4/R^4)$$

$$\langle \ldots \mathscr{F}[A] \ldots \rangle_{\text{inst}} \to \langle \ldots \mathscr{F}[\bar{\psi}, \psi] \ldots \rangle_{\text{eff}}$$

[Diakonov et al, (1996) /J. Balla, M.V. Polyakov, C. Weiss (1999)]

Gluon operator in the instanton vacuum

Coupling through the quark zero modes (’t Hooft vertex)

Local QCD gluon operator $\mathscr{F}[A]$

Single-instanton approximation (packing fraction)

Gauge field is converted into the effective fermion operator in the effective theory

Effective operators: Twist-3

Gauge-dependent part $\nabla := \partial - iA \rightarrow$ the additional spin-flavor-dependent term (“potential” term)

QCD relation is also satisfied in the effective theory

EOM in QCD

$$[i\nabla^{\mu}\gamma_{\mu}]\psi = 0$$

↓

EOM in effective theory

$$[i\partial^{\mu}\gamma_{\mu} - MU^{\gamma_5}]\psi = 0$$

Angular momentum decomposition [JYKim ,C. Weiss PLB (2024)]

Flavor singlet $(u+d)$: strongly constrained by global symmetry

Flavor non-singlet $(u-d)$: instanton effects play an important role

$$O_q^{\mu\nu} = \bar{\psi}\gamma^{[\mu} i\nabla^{\nu]}\tau\psi = -\frac{1}{4}\epsilon^{\mu\nu\alpha\beta}\partial_{\alpha}[\bar{\psi}\gamma_{\beta}\gamma_5\tau\psi] \longrightarrow (O_{\text{eff}})_q^{\mu\nu} = \bar{\psi}\left(\gamma^{[\mu} i\partial^{\nu]}\tau + \frac{i}{4}\sigma^{\mu\nu}[\tau, MU^{\gamma_5}]\right)\psi = -\frac{1}{4}\epsilon^{\mu\nu\alpha\beta}\partial_{\alpha}[\bar{\psi}\gamma_{\beta}\gamma_5\tau\psi]$$

Spin-orbit correlation

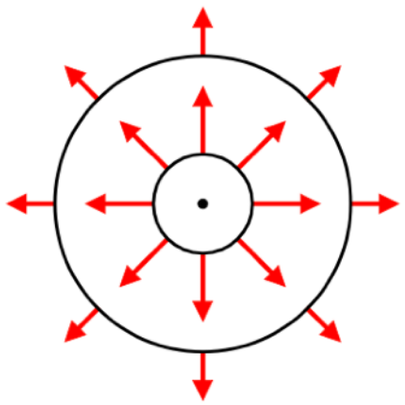
Flavor singlet and non-singlet $(u \pm d)$: instanton effects play an important role

$$O_q^{\mu\nu} = \bar{\psi}\gamma^{[\mu} i\nabla^{\nu]}\gamma_5\tau\psi = -\frac{1}{4}\epsilon^{\mu\nu\alpha\beta}\partial_{\alpha}[\bar{\psi}\gamma_{\beta}\tau\psi] \longrightarrow (O_{\text{eff}})_q^{\mu\nu} = \bar{\psi}\left(\gamma^{[\mu} i\partial^{\nu]}\gamma_5\tau - \frac{i}{4}\sigma^{\mu\nu}\gamma_5\{MU^{\gamma_5}, \tau\}\right)\psi = -\frac{1}{4}\epsilon^{\mu\nu\alpha\beta}\partial_{\alpha}[\bar{\psi}\gamma_{\beta}\tau\psi]$$

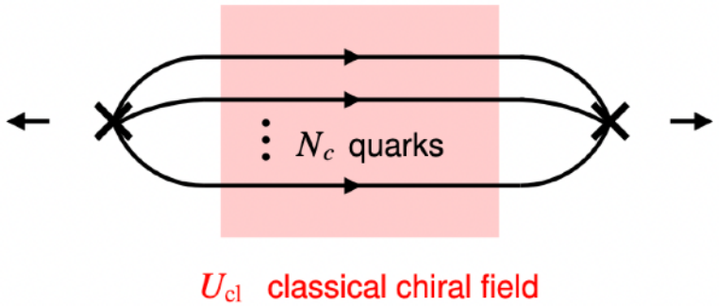
Nucleon matrix element

: How much do instantons contribute to the quark orbital angular momentum in the nucleon?

Instanton vacuum: Correlation function



$U_{\rm cl}(x)$ isospin



$U_{\rm cl}$ classical chiral field

Chiral theory in the large N_c limit of QCD

$$S = -\int d^4x \bar{\psi}[i\partial^\mu\gamma_\mu + MU^{\gamma_5}]\psi$$

Effective action

$$U = e^{iP(r)\hat{\mathbf{r}}\cdot\tau}$$

Hedgehog symmetry → key role in the spin-flavor symmetry

Nucleon correlation function

$$\Pi_N(T) = \int dUF[U]e^{-S_{\rm eff}[U]}$$

Saddle point approximation in $1/N_c$ expansion

$$\lim_{T\to\infty}\Pi_N(T) \sim e^{-M_N T} \qquad \left.\frac{\delta S[U]}{\delta U}\right|_{U=U_{\rm cl}} = 0$$

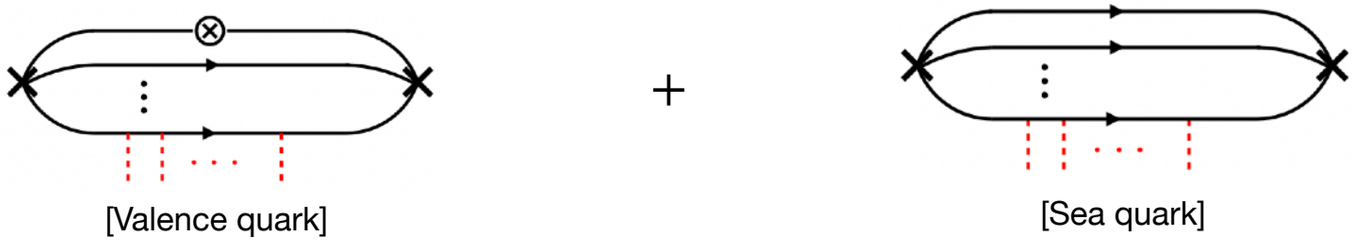
Saddle point equation

Matrix element of the effective operator

$$\langle N'|O^{\mu\nu}_{\rm spin-}{}_n(0)|N\rangle = \lim_{T\to\infty}\frac{1}{Z}\mathcal{N}e^{ip_4\frac{T}{2}-ip'_4\frac{T}{2}}\int d^3x\int d^3y e^{-i\mathbf{p}'\cdot\mathbf{y}+i\mathbf{p}\cdot\mathbf{x}}$$

$$\times\int D\psi D\psi^\dagger DU J_{N'}(\mathbf{y},T/2)O^{\mu\nu}_{\rm spin-}{}_n(0)J^\dagger_N(\mathbf{x},-T/2)\exp[-S]$$

Correlation function



[Valence quark] [Sea quark]

AM decomposition and spin-orbit correlation

AM decomposition [JYKim, H.-Y. Won, C. Weiss PLB 2026]

Ji's relation $[u+d]$

$$S^{u+d}[0.25] + L^{u+d}[0.25] = J^{u+d}[0.5]$$

$$L^{u+d}[\text{kin}] = 0.25, \quad L^{u+d}[\text{pot}] = 0$$

Ji's relation $[u-d]$

$$S^{u-d}[0.47] \; + \; L^{u-d}[-0.22] \; = \; J^{u-d}[0.25]$$

$$L^{u-d}[\text{kin}] = -0.07 \; \ll \; L^{u-d}[\text{pot}] = -0.15$$

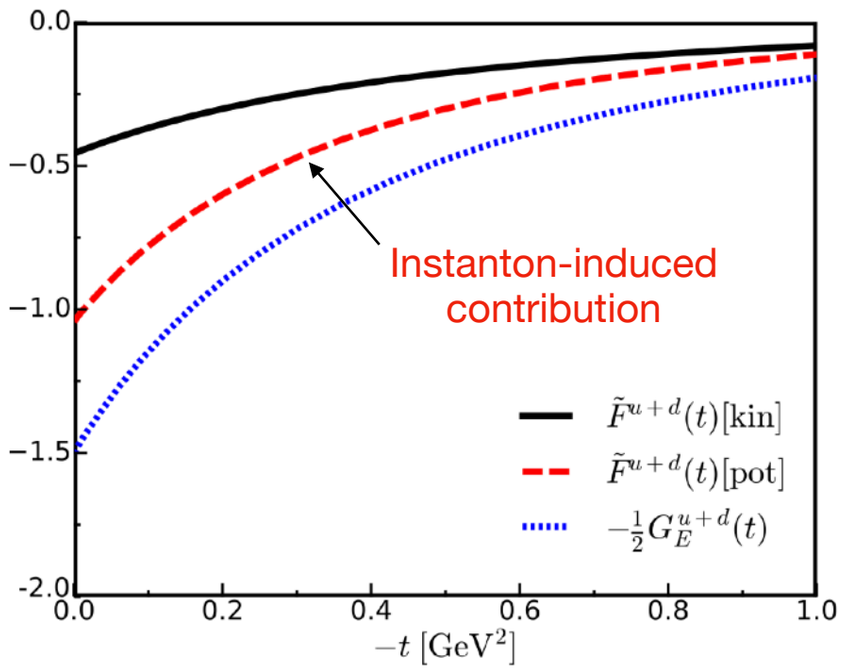
Spin-orbit correlation [JYKim, H.-Y. Won, H.-Ch Kim, C. Weiss (2024)]

Parity counterpart Ji's relation $[u+d]$

$$C_z^{u+d} = -\frac{1}{2} G_E^{u+d} = -\frac{3}{2}$$

$$C_z^{u+d}[\text{kin}] = -0.45 \; \ll \; C_z^{u+d}[\text{pot}] = -1.05$$

Twist-3 generalized form factor $\tilde{F}(t)$



Applications and extensions

Twist-2 [non-local operator]

Chiral-odd GPDs : Spin-flavor structure, Sum rules, polynomiality, and numerical estimation in the chiral theory.

[J-Y Kim, C. Weiss, in preparation]

Twist-3 [second Mellin moment of the twist-3 GPDs]

transverse Spin-orbit correlation / chiral decomposition of the orbital angular momentum

[J.-Y. Kim, C. Weiss, PLB (2024)]

$$\bar{\psi}\nabla^{[\mu}i\sigma^{\nu]\lambda}\psi$$

Second Mellin moment of the chiral-odd twist-3 GPDs

$$\bar{\psi}\overleftrightarrow{\nabla}^{\mu}\psi \to \bar{\psi}(x)\partial^{\mu}\psi(x) + O(1)_{\text{instanton effect}}$$

[J.-Y. Kim, in progress]

Twist-4 [operator in non-forward matrix element]

Separation of $\bar{c}_{q,g}(t)$ into the quark and gluon parts [scheme dependent]

$$\partial_{\mu}T_{q}^{\mu\nu} = \bar{\psi}F^{\mu\nu}\gamma_{\mu}\psi$$

Connection to the trace anomaly in the effective theory

$$T_{\mu\mu} \sim -\frac{b}{32\pi^2}F^2$$

Summary

Main strategy: instanton vacuum, effective theory, $1/N_c$ expansion

- We derive twist-3 effective operators consistent with effective dynamics.
- The effective operator satisfies the operator relations from the QCD equation of motion.
- Instanton effects [gauge-dependent part] on the OAM and the spin-orbit correlation are numerically huge.

$$L^{u-d}[\text{kin}] = -0.07 \ll L^{u-d}[\text{pot}] = -0.15 \qquad C_z^{u+d}[\text{kin}] = -0.45 \ll C_z^{u+d}[\text{pot}] = -1.05$$

Thank you very much!

Upcoming EIC Workshop at Inha University



Title: **International workshop on Electron-Ion Collider Physics**

Tentative datas: **6–10 September 2027**

Venue: Inha University, Incheon, Korea

Invitation plan: Approximately 50–60 researchers

Local organizers

Jun-Young Kim (Inha University)

Hyun-Chul Kim (Inha University)

Jin-Hee Yoon (Inha University)

Nurmukhammad Rakhimov (Inha University)

Hyeon-Dong Son (Inha University)

Ulugbek Yakhshiev (Inha University)

Jung-Keun Ahn (Korea University)

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Yongsun Kim (Sejong University)

Seung-il Nam (Pukyong National University)

Ghil-Seok Yang (Hoseo University)

Hee-Jin Kim (Hoseo University)

Ki-Hoon Hong (Hoseo University)

Yongwoo Choi (Hoseo University)

Samson Clymton (APCTP)

Backup slides

First-quantized representation: Angular momentum

AM decomposition: First-quantized representation

[JYKim, H.-Y. Won, C. Weiss in preparation]

$$J^{u-d} = -\frac{N_c}{12}\int d^3r \sum_{n=\text{occ}} \Phi_n^\dagger(\mathbf{x})\tau^3[2L^3 + 2E_n(\mathbf{r}\times\boldsymbol{\Sigma})^3\gamma_5]\Phi_n(\mathbf{x})$$

$$S^{u-d} = -\frac{N_c}{3}\int d^3x \sum_{n=\text{occ}} \Phi_n^\dagger(\mathbf{x})\left[\tau^3\frac{\Sigma^3}{2}\right]\Phi_n(\mathbf{x})$$

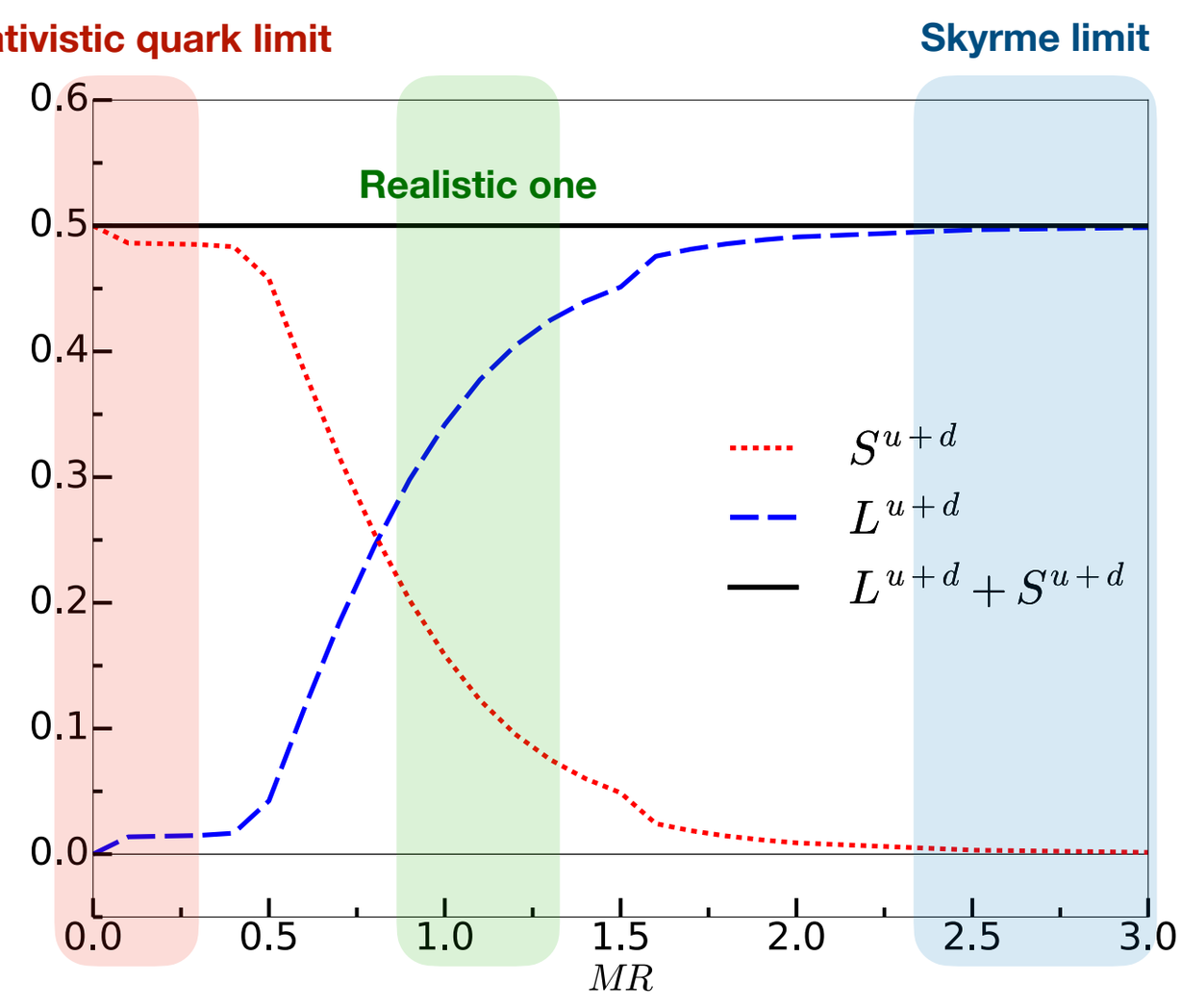
$$L^{u-d} = -\frac{N_c}{3}\int d^3r \sum_{n=\text{occ}} \Phi_n^\dagger(\mathbf{x})\left[\tau^3 L^3\right]\Phi_n(\mathbf{x})$$

$$+\frac{MN_c}{18}\int d^3x \sum_{n=\text{occ}} \Phi_n^\dagger(\mathbf{x})\left[r\sin P(r)\gamma^0[(\hat{\mathbf{r}}\cdot\tau)(\hat{\mathbf{r}}\cdot\boldsymbol{\Sigma})\right.$$

OAM composed of the kinetic and potential t

Chiral interaction is essential in the effective t

Total angular momentum



$$S^{u-d}[0.47] \quad + \quad L^{u-d}[-0.22] \quad = \quad J^{u-d}[0.25]$$

$$L^{u-d}[\text{kin}] = -0.07 \quad \ll \quad L^{u-d}[\text{pot}] = -0.15$$

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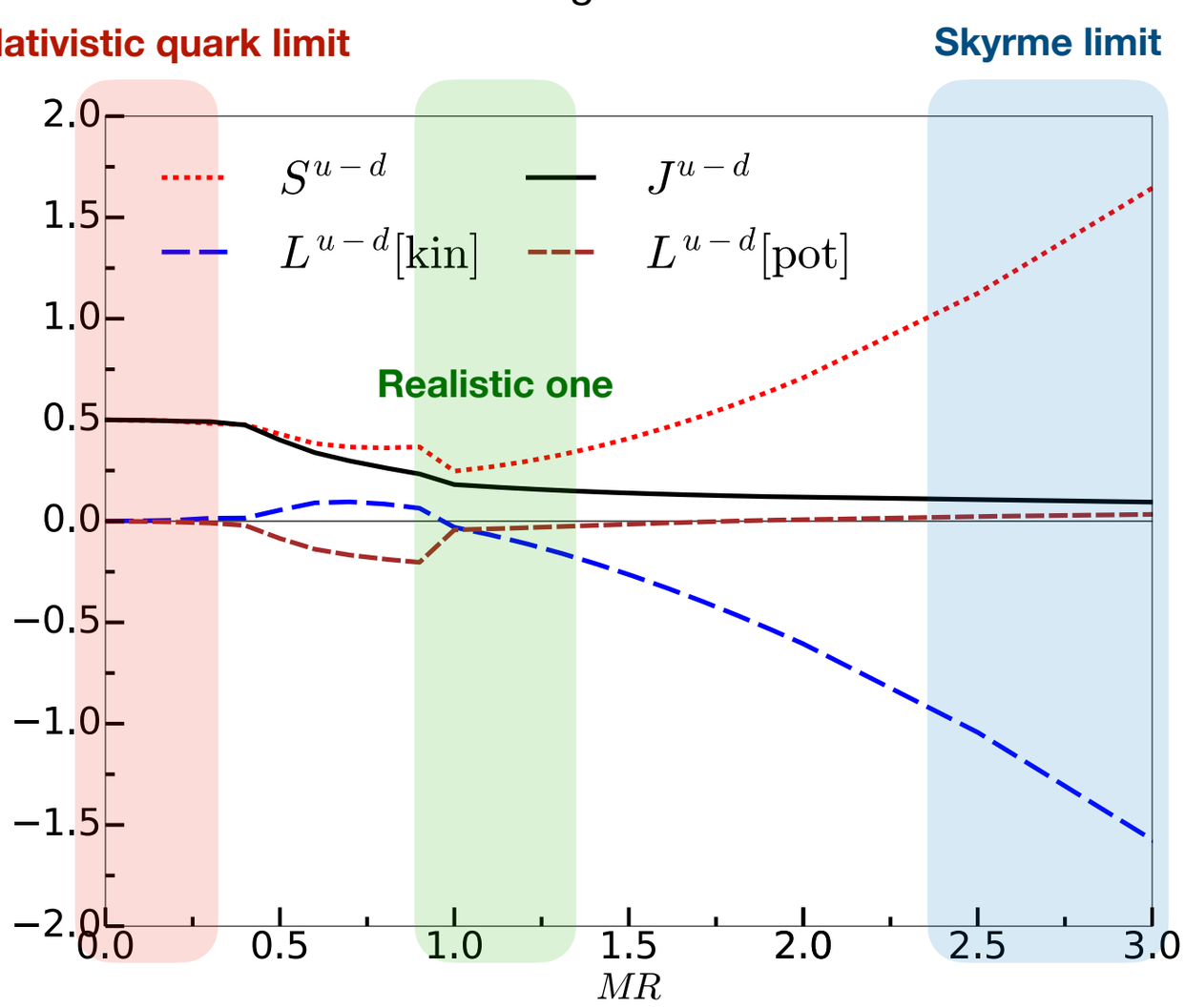
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QCD operators: Twist-2

QCD operator

$$O^q_{\alpha_1\ldots\alpha_n} = \bar\psi\gamma_{\{\alpha_1} i\nabla_{\alpha_2}\ldots\nabla_{\alpha_n\}}\psi - \text{traces}$$

$$O^g_{\alpha_1\ldots\alpha_n} = F_{\beta\{\alpha_1} D_{\alpha_2}\ldots D_{\alpha_{n-1}} F_{\alpha_n\}\,\beta} - \text{traces}$$

Twist-2 spin-2 local operator

$\nabla := \partial - iA$ contains gauge potential

Nucleon matrix element = moments of PDF/GPD

Effective operator [Diakonov et al (1996) /J. Balla, M.V. Polyakov, C. Weiss (1999)]

$$(O^q_{\text{eff}})_{\alpha_1\ldots\alpha_n} = \bar\psi\gamma_{\{\alpha_1} i\partial_{\alpha_2}\ldots\partial_{\alpha_n\}}\psi - \text{traces}$$

$$(O^g_{\text{eff}})_{\alpha_1\ldots\alpha_n} = \quad 0 \quad + O(\rho^4/R^4)$$

Gluon operators are suppressed in packing fraction

Use of the pure derivative operator can be justified in the estimation of the effective theory

Without the contributions of the gauge-dependent part, matrix element of the twist-2 non-local operator can be studied safely

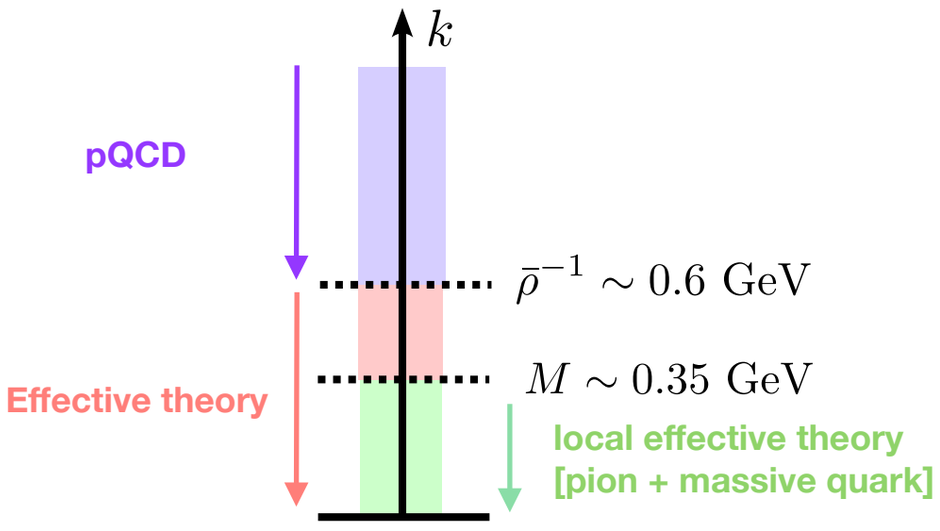
$$(O^q_{\text{eff}})_\alpha = \bar\psi(x)\gamma_\alpha\psi(y)$$

Sum rules of twist-2 GPDs/PDFs are satisfied only by the quark parts

$$\int_{-1}^{1} dx\, f_1^{u+d}(x) = N_c B, \qquad \int_{-1}^{1} dx\, x f_1^{u+d}(x) = 1$$

[Diakonov et al (1996)]

Instanton vacuum: effective theory



Integrating over modes

$$Z = \int [DA]_{\rm low} \int [DA]_{\rm high} \, \exp[-S_{\rm YM}] \quad [\times \text{ fermions}]$$

$$\downarrow$$

$$\rightarrow \int \prod_{I,\bar{I}} dz_I d\rho_I d\mathcal{U}_I \, d_{\rm eff}(\rho_I)$$

$$[\text{fermion}] \sim \int [D\psi^\dagger][D\psi] e^{\int d^4x \psi^\dagger i\gamma_\mu \partial_\mu \psi} V_I$$

(Effective) instanton size distribution $d_{\rm eff}(\rho_I)$

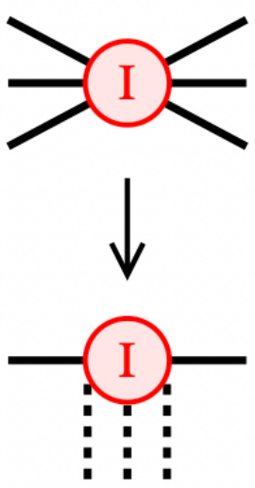
Center of instanton z_I

Color orientation $\mathcal{U}_I$

Instanton size ρ_I

't Hooft vertex $Y_I \propto V_I$

Effective action



[J.Y. Kim, C. Weiss, PLB (2024)]

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Semi-bosonized Effective action

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Effective chiral action