

CP-violating gluon operators and neutron EDM from the instanton vacuum

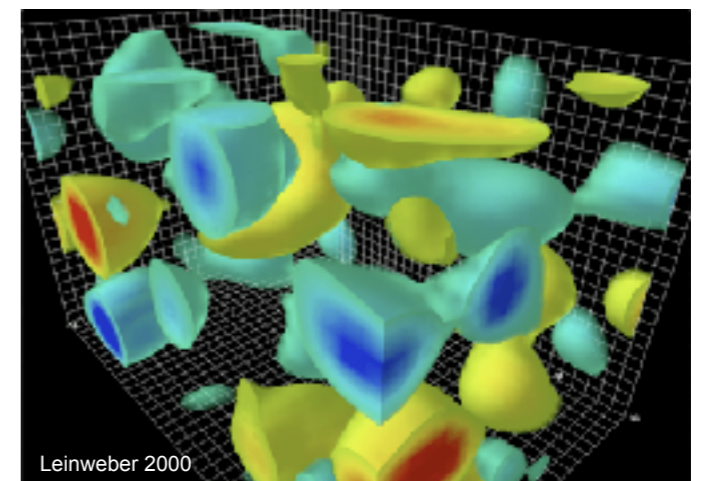
C. Weiss (Jefferson Lab), Mini-Symposium BSM Searches in Fundamental Symmetries, 2021 APS DNP Fall Meeting [Webpage]

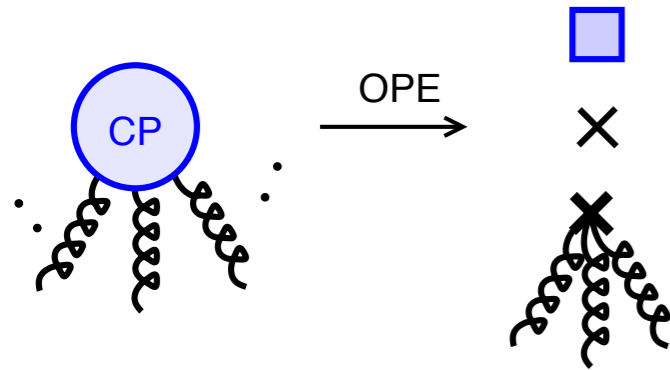
Purpose: Calculate nucleon matrix element of dimension-6 CP-odd gluon operator $f^{abc} \tilde{F}_{\mu\nu}^a F_{\mu\rho}^b F_{\nu\rho}^c$ (Weinberg operator) and estimate induced neutron EDM

Method: Instanton picture of QCD vacuum: Analytic description abstracted from LQCD simulations, based on topological fluctuations of gauge fields, chiral symmetry breaking

Results: Large nucleon matrix element of dimension-6 gluon operator. Connection with topological charge $\tilde{F}_{\mu\nu}^a F_{\mu\nu}^a$. Insights in magnitude and chiral properties of neutron EDM

C. Weiss, Phys. Lett. B 819 (2021) 136447 [INSPIRE]





Gluon operators from CP-violation

CP-violating processes at EW scale → OPE expansion
 → QCD operators at hadronic scale → Observables

Dim-4

$$\tilde{F}_{\mu\nu}^a F_{\mu\nu}^a$$

Dim-4: Topological charge density operator, connected with chiral symmetry, creates “strong CP problem”

Dim-6

$$f^{abc} \tilde{F}_{\mu\nu}^a F_{\mu\rho}^b F_{\nu\rho}^c$$

Dim-6: Alternative scenario proposed by Weinberg 1989 ←

$$\langle N' | \dots | N \rangle$$

Hadronic matrix elements

Dim-6 operator — challenging problem

LQCD: Higher-dim operators mix with lower-dim ones with power-divergent coefficients, non-perturbative treatment

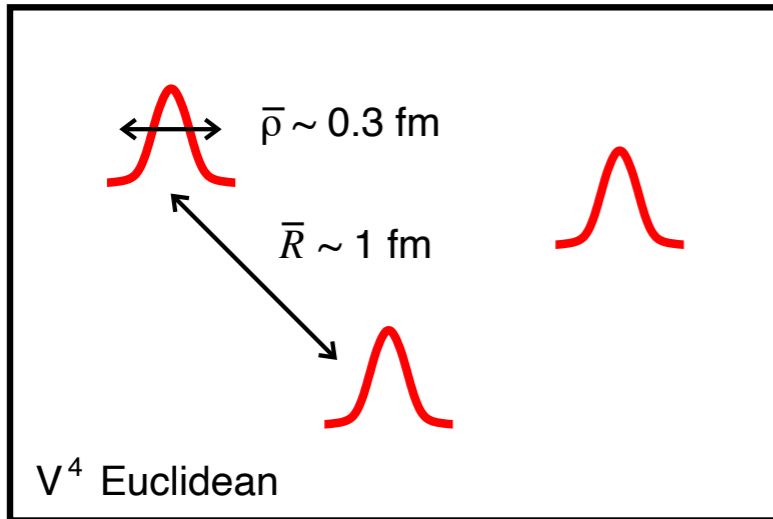
Dynamical models: Non-perturbative gluon fields, correlations, topology?

Vacuum condensates: Bigi, Uraltsev 1991

Quark model: Yamanaka, Hiyama 2000

QCD sum rules: Demir, Pospelov, Ritz 2003; Haisch, Hala 2019

DIS higher-twist operators: Hatta 2000



Topological gauge fields in QCD vacuum

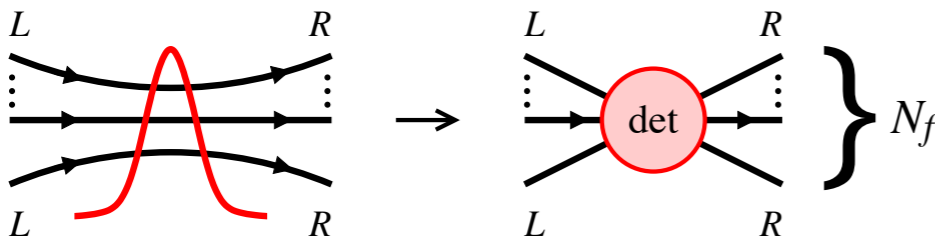
Average size $\bar{\rho} \approx 0.3$ fm, separation $\bar{R} \approx 1$ fm

Strong fields: $(F^2)^{1/4} \approx (32\pi^2/\pi^2\bar{\rho}^4)^{1/4} \approx 1.5$ GeV

Evidence: LQCD cooling, correlation functions

Polikarpov, Veselov 1988; Campostrini et al. 1990; Chu, Negele et al 1993; DeGrand et al 1997; de Forcrand et al 1997, ..., Athenodorou et al 2018

Chiral symmetry breaking



Topological charge \rightarrow fermionic zero modes, chirality flip

Chiral condensate, dynamical quark mass

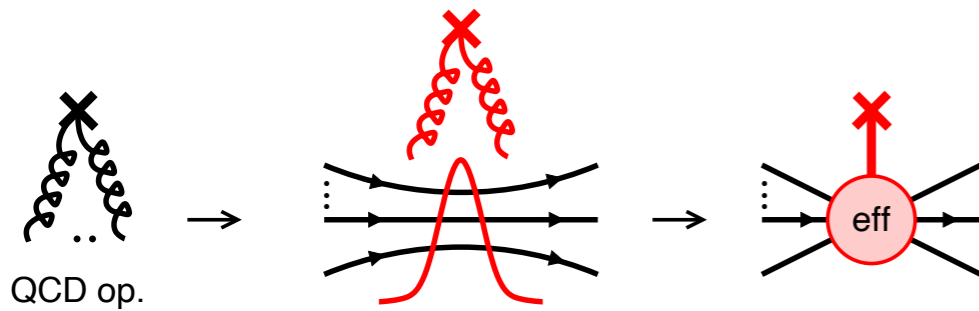
Hadronic correlation functions

Meson/baryon correlators: Masses, form factors, partonic structure, very successful phenomenology

Systematic approach: Parametric expansion in packing fraction $\pi^2\bar{\rho}^4/\bar{R}^4 \approx 0.1$

Effective description of low-energy QCD:
Instanton ensemble + chiral quarks

Shuryak 1982; Diakonov, Petrov 1984/1986; DP + Poblitsa 1988;
Nowak, Verbaarschot, Zahed 1989; Shuryak, Schafer 1993...



Gluon operators in instanton vacuum

Normalized at scale $\mu = \bar{\rho}^{-1} \approx 0.6 \text{ GeV}$

Evaluated in gluon field of single instanton (LO in packing fr.)

Converted to effective quark operator \rightarrow correlation fns

Diakonov, Polyakov, Weiss, 1995

CP-violating gluon operators $\tilde{F}F$ and $\tilde{F}FF$

$$\frac{\int d^4x \tilde{F}FF(x)_{I(\bar{I})}}{\int d^4x \tilde{F}F(x)_{I(\bar{I})}} = -\frac{12}{5\bar{\rho}^2}$$

Operators $\tilde{F}FF$ and $\tilde{F}F$ are proportional in field of single instanton \rightarrow effective quark operators also proportional

$$A_{\tilde{F}F}(0) = 32\pi^2 \frac{g_A^{(0)}}{N_f}$$

Nucleon matrix element of $\tilde{F}F$ calculated in instanton vacuum, agrees with $U(1)_A$ anomaly result

Diakonov, Polyakov, Weiss, 1995; Nowak, Verbaarschot, Zahed 1989

$$A_{\tilde{F}FF}(0) = -\frac{12}{5\bar{\rho}^2} \times 32\pi^2 \frac{g_A^{(0)}}{N_f}$$

Nucleon matrix element of $\tilde{F}FF$ inferred from $\tilde{F}F$ and effective operator relation

Weiss 2021

Nucleon matrix element of $\tilde{F}FF$

$$\frac{12}{5\bar{\rho}^2} = 0.86 \text{ GeV}^2 = (0.22 \text{ fm})^{-2} \quad \text{Large numerical value due to localization of instanton field}$$

Instanton vacuum result 7x larger than Bigi Uraltsev 1991 estimate based on vacuum condensates

Comment on estimate based on polarized DIS operators

$$\underbrace{\partial_\mu \left[\bar{\psi} \tilde{F}_{\mu\nu} \gamma_\nu \gamma_5 \psi \right]}_{\text{Twist-4 polarized DIS}} = \tilde{F}_{\mu\nu} F_{\mu\rho} F_{\nu\rho} - \frac{1}{2} \tilde{F}_{\mu\nu} D^2 F_{\mu\nu} \quad \text{Operator relation from QCD equations of motion}$$

Hatta 2020: Nucleon matrix element of $\tilde{F}FF$ estimated assuming all operators have “natural size”

Instanton vacuum: Hierarchical size, strong cancellations between $\tilde{F}FF$ and $\tilde{F}D^2F$, $O(10^2)$ larger result for matrix element of $\tilde{F}FF$

$$d_N \propto i \int d^4x \langle N | T \mathcal{O}(x) J_\mu^{\text{em}}(0) | N \rangle$$

$$\mathcal{O} = \tilde{F}F, \tilde{F}FF$$

EDM as correlation function

Electromagnetic vertex under influence of CP-violation

EDM induced by $\tilde{F}F$

Chirally suppressed, vanishes if $m_f \rightarrow 0$

Crewther, DiVecchia, Veneziano, Witten 1979

Instanton vacuum findings

Weiss 2021

Neutron EDM induced by $\tilde{F}FF$ estimated using instanton relation $\tilde{F}FF \leftrightarrow \tilde{F}F$
and chiral result for EDM induced by $\tilde{F}F$: $|d_n| (\text{dim-6}) \approx 6 \times 10^3 |a_6 \cdot \text{GeV}^2| e \text{ fm}$

Similar order-of-magnitude as estimate of Bigi Uraltsev 1991

Neutron EDM induced by $\tilde{F}FF$ in instanton vacuum appears to be chirally suppressed
in same way as EDM induced by $\tilde{F}F$. Appears paradoxical — general explanation?

Neutron EDM induced by $\tilde{F}FF$ cannot be estimated by saturating correlation function with nucleon
intermediate state, has no direct relation to nucleon matrix element $\langle N | \tilde{F}FF | N \rangle$

- Instanton vacuum enables calculation of hadronic matrix elements of gluon operators. Systematic approach using packing fraction $(\pi^2 \bar{\rho}^4 / \bar{R}^4)$ as small parameter
- Operators $\tilde{F}F$ and $\tilde{F}FF$ proportional in field of instanton, hadronic matrix elements related
- Nucleon matrix element of $\tilde{F}FF$ large because of strong localization of instanton field
- Neutron EDM induced by $\tilde{F}FF$ estimated, same order-of-magnitude as previous estimates. Appears to be chirally suppressed — explanation?

Extensions

- Numerical simulations of $\tilde{F}FF$ correlation functions in instanton ensemble with specific models of instanton interactions

EDM from $\tilde{F}F$: P. Faccioli, D. Guadagnoli and S. Simula 2004

- Hadronic matrix elements of other higher-dimensional QCD operators from BSM physics