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

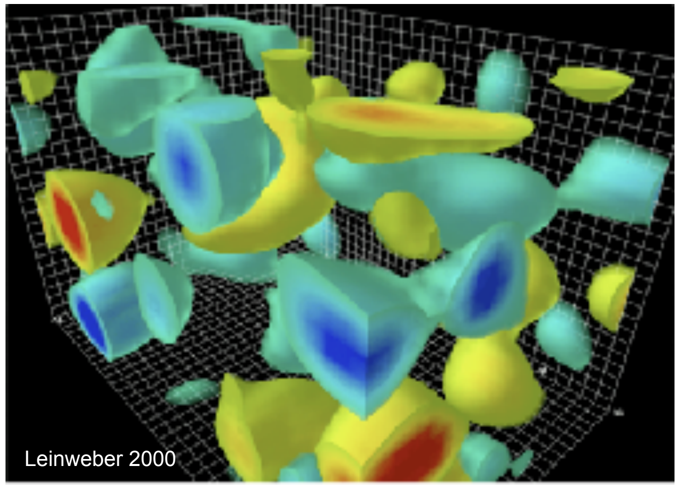
C. Weiss (Jefferson Lab), SPIN2021, Session "Fundamental Symmetries and Spin Physics Beyond the Standard Model", Matsue, Japan, 18-22 Oct 2021 [Webpage]

Purpose: Calculate nucleon matrix element of dimension-6 CP-odd gluon operator $f^{abc}\tilde{F}^a_{\mu\nu}F^b_{\mu\rho}F^c_{\nu\rho}$ (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 $\tilde{F}^a_{\mu\nu}F^a_{\mu\nu}$. Insights in magnitude and chiral properties of neutron EDM

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



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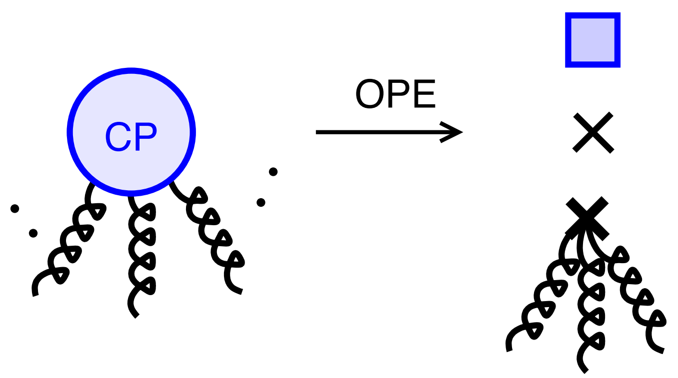
Context: CP-violation and gluon operators



Gluon operators from CP-violation

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

Dim-4 $\tilde{F}^a_{\mu\nu} F^a_{\mu\nu}$

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

Dim-6 $f^{abc} \tilde{F}^a_{\mu\nu} F^b_{\mu\rho} F^c_{\nu\rho}$

Dim-6: Alternative scenario proposed by Weinberg 1989 ←

Hadronic matrix elements

$$\langle N(p') \,|\, \ldots \,|\, N(p) \rangle$$

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?

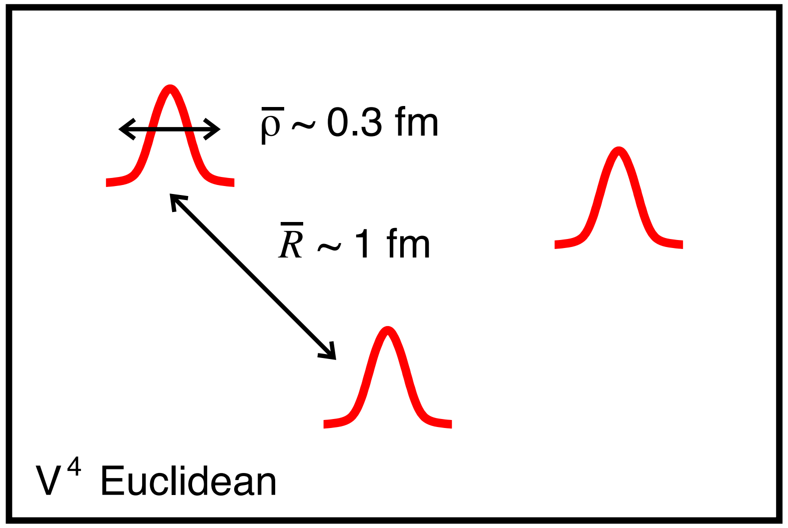
Vacuum condensates: Bigi, Uraltsev 1991

Quark model: Yamanaka, Hiyama 2000

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

DIS higher-twist operators: Hatta 2000

Method: Instanton vacuum



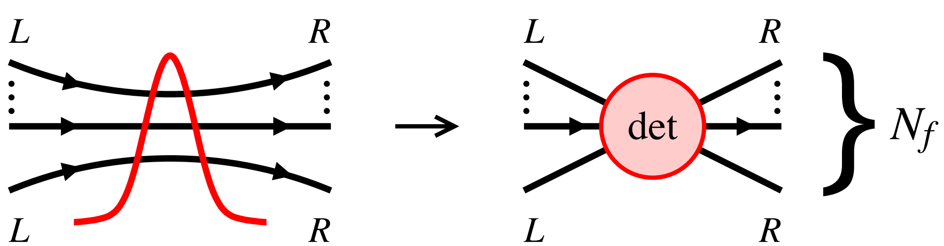
Topological gauge fields in QCD vacuum

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 → fermionic zero modes, chirality flip

Chiral condensate, dynamical quark mass

Hadronic correlation functions

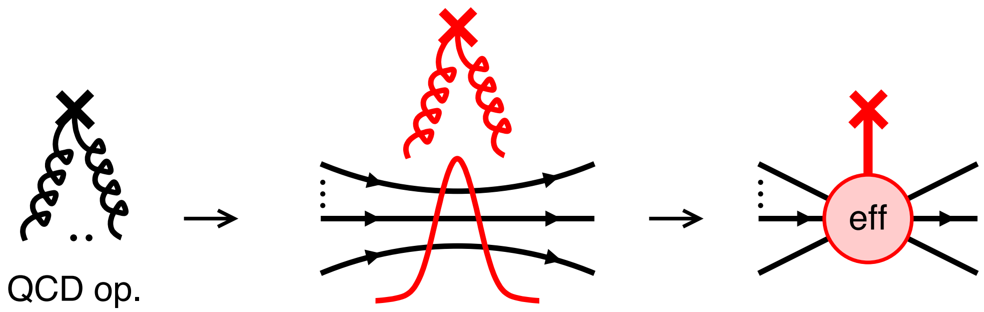
Meson/baryon correlators: Masses, form factors, partonic structure, very successful phenomenology

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 + Pobylitsa 1988; Nowak, Verbaarschot, Zahed 1989; Shuryak, Schafer 1993…

Calculation: Gluon operators



Gluon operators in instanton vacuum

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

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

Converted to effective quark operator → 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
→ 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

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

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

$$\frac{12}{5\bar{\rho}^2} = 0.86\,\text{GeV}^2 = (0.22\,\text{fm})^{-2}$$

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

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

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 $\tilde{F}FF$

Comments: Neutron EDM induced by $\tilde{F}FF$

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

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

EDM as correlation function

Electromagnetic vertex under influence of CP-violation

EDM induced by $\tilde{F}F$

Chirally suppressed, vanishes if $m_f \to 0$

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 $\tilde{F}F$: $|\,d_n\,|\,(\text{dim-6}) \approx 6 \times 10^{-3}\,|\,a_6 \cdot \text{GeV}^2\,|\,e$ 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 $\langle N \,|\, \tilde{F}FF \,|\, N \rangle$

Summary

- 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