The neutron electric dipole moment revisited

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Outline

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Dipole moment

θ vacuum

EDM revisited

Conclusions

Objective

- The existence of a non-zero permanent electric dipole moment (EDM) of the neutron would reveal new sources of CP violation and shed light on the origin of the matter–antimatter asymmetry of the Universe

- The most sensitive measurement of the neutron EDM to date, $d_n < 1.8 \times 10^{-26}$ e cm, is compatible with zero. New experiments are designed to improve the sensitivity by an order of magnitude within the next decade. How can this result be understood?

- We distinguish between anomalous and non-anomalous sources of CP violation. Anomalous sources of CP violation can be rotated into the QCD θ term, $S_\theta = i\theta\, Q$, while non-anomalous sources (e.g. CKM, SUSY, etc.) can not.

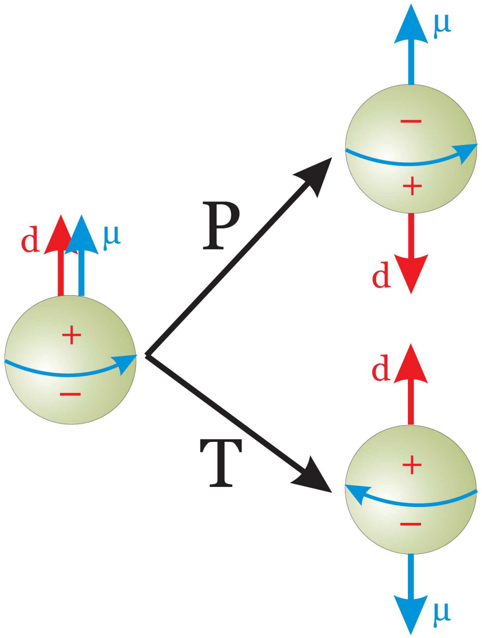
- In this talk we will focus on anomalous CP violation, commonly understood as strong CP violation, which can be reduced to instantons, and show that CP is conserved in the strong interactions at the hadronic level, resulting in $d_n = 0$

Dipole moment

$$\vec{d} = \int d^3x \, \vec{x} \, \rho(x)$$

$$\vec{d} \, \vec{\mu} \;\rightarrow\; - \vec{d} \, \vec{\mu}$$

CP



Nucleon electromagnetic current

$$\langle p', s' | J_\mu | p, s \rangle = \bar{u}(\vec{p}\,', s')\, \mathcal{J}_\mu\, u(\vec{p}, s)$$

$$\mathcal{J}_\mu = \gamma_\mu\, F_1(q^2) + \sigma_{\mu\nu}\, q_\nu\, \frac{F_2(q^2)}{2m_N} + (\gamma q\, q_\mu - \gamma_\mu\, q^2)\, \gamma_5\, F_A(q^2) + \sigma_{\mu\nu}\, q_\nu\, \gamma_5\, \frac{F_3(q^2)}{2m_N}$$

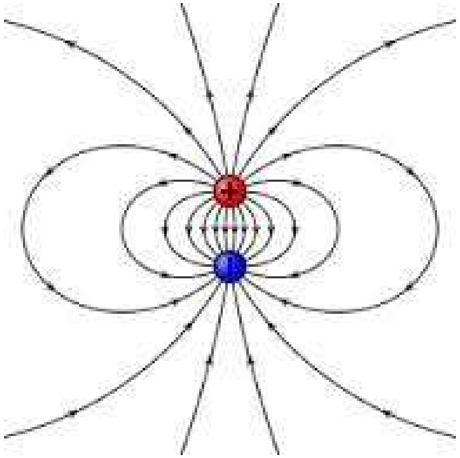
anapole

dipole

Dipole moment

$$d_N = \frac{e\, F_3(0)}{2m_N} \;\propto\; e_q\, \ell$$

$\boxed{\ell \simeq 10^{-13}\,\text{fm}}$



Renormalize θ angle?

QCD

$$S = S_{\mathrm{QCD}} + S_\theta$$

$$S_\theta = i\theta Q$$

$$Q = -\frac{1}{32\pi^2}\sum_x F^a_{\mu\nu}\tilde{F}^a_{\mu\nu} \in \mathbb{Z}$$

$$\xRightarrow{\text{AWI}}$$

$$S_\theta = -\frac{i}{3}\,\theta\,\hat{m}\sum_x \left(\bar{u}\gamma_5 u + \bar{d}\gamma_5 d + \bar{s}\gamma_5 s\right)$$

$$\hat{m}^{-1} = \frac{1}{3}\left(m_u^{-1} + m_d^{-1} + m_s^{-1}\right)$$

Anomalous CP violation

flavor singlet

$$\chi_t = \frac{\langle Q^2\rangle}{V} \approx (75\,[\mathrm{MeV}])^2$$

$$\theta \; < \; 10^{-10}$$

(in truth has no basis)

Strong CP problem

Entirely due to instantons

$\boldsymbol{\theta}$ vacuum

Assumption so far: No phase transition for $|\theta| < \pi$

Peccei-Quinn (axion) solution, e.g., realized by shift symmetry $\theta \to \theta + \delta$

However

- It is known from the case of the massive Schwinger model that a θ term may change the phase of the system. Callan, Dashen and Gross have claimed that a similar phenomenon will occur in QCD. The statement is that the color fields produced by quarks and gluons will be screened by instantons for $|\theta| > 0$. 't Hooft has shown that due to the joint presence of gluons and monopoles a rich phase structure may emerge as a function of θ

- We are faced with a multi-scale problem, involving the passage from the perturbative CP-invariant regime at short distances to the long-distance confining regime. The gradient flow provides a powerful framework for scale setting, and as such is a particular realization of the coarse-graining step of momentum space RG transformations Lüscher, Suzuki et al.

The gradient flow describes the evolution of fields and physical quantities as a function of flow time t. The flow of SU(3) gauge fields is defined by

$$\partial_t \, B_\mu(t,x) = D_\nu G_{\mu\nu}(t,x) \,, \quad G_{\mu\nu} = \partial_\mu \, B_\nu - \partial_\nu \, B_\mu + [B_\mu, B_\nu]$$

where $B_\mu(t=0,x) = A_\mu(x)$ is the original gauge field of QCD. It thus defines a sequence of gauge fields parameterized by t. The renormalization scale μ is set by the flow time, $\mu = 1/\sqrt{8t}$ for $t \gg 0$.

The expectation value of the energy density $E(t,x) = \frac{1}{4} \, G^a_{\mu\nu}(t,x) \, G^a_{\mu\nu}(t,x)$ defines a renormalized coupling

$$g^2_{GF}(\mu) = \frac{16\pi^2}{3} \, t^2 \langle E(t) \rangle \, \big|_{t=1/8\mu^2}$$

at flow time t in the gradient flow scheme Lüscher

The gradient flow proved a powerful tool for tracing the evolution of gauge fields over successive length scales for any initial coupling and showed its potential for extracting low-energy quantities of the theory. Renormalized quantities are found to be independent of flow time `arXiv:2106.11369`

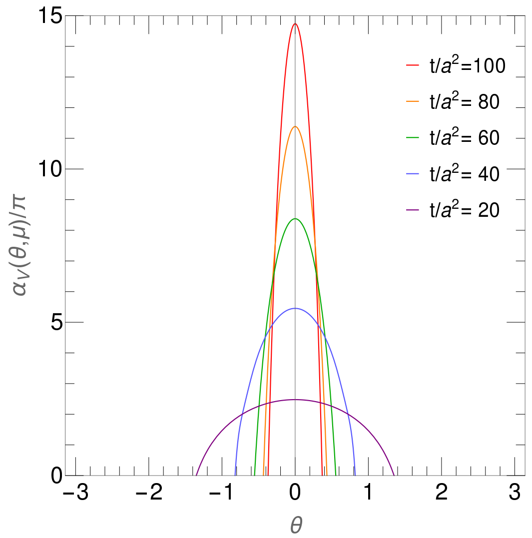
K.U. Can et al. (poster)

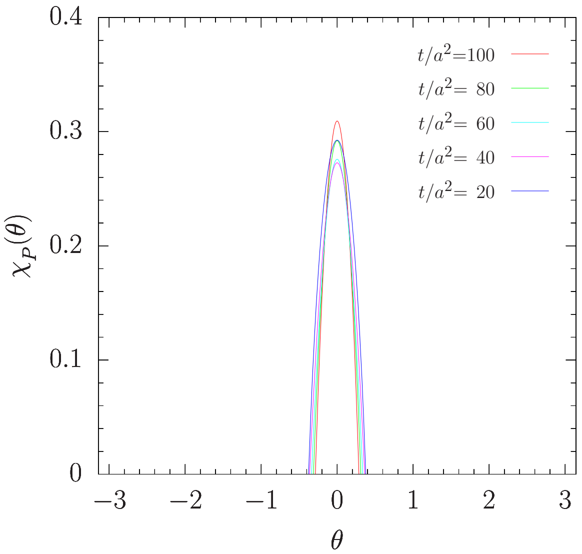
Phase structure in the presence of a θ term

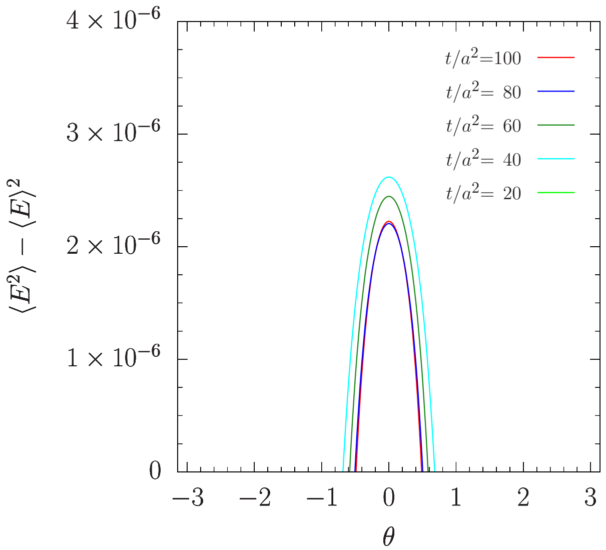
`arXiv:2106.11369`

SU(3) YM

Preliminary







∞ IR slavery: $V(r) = \sigma\, r$

$\uparrow$

$\alpha_V(\theta,\mu)$

Polyakov loop susceptibility

Correlation length ξ^2

Conclusion: Color fields produced by quarks and gluons are screened for vacuum angles $|\theta| > 0$ in the infrared. Thus CP is conserved in the confining phase of the theory

EDM revisited

arXiv:1502.02295

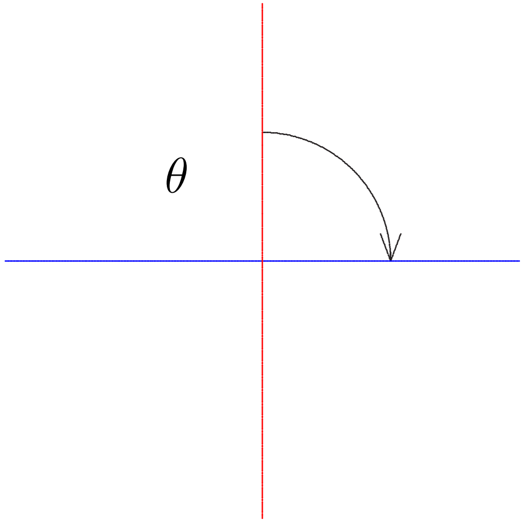
Aoki

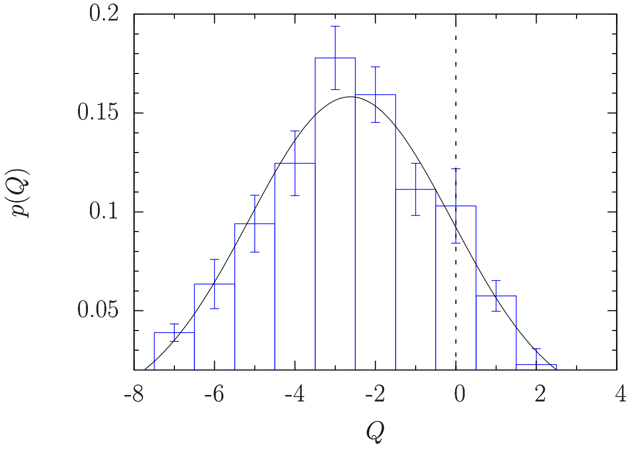
~~Aoki~~

According to Vafa-Witten the theory is analytic at $\theta = 0$. Hence, we may continue θ to imaginary $\bar{\theta} = -i\,\theta$. This leads to the action

$$S_\theta = \frac{1}{3}\bar{\theta}\hat{m}\sum_x (\bar{u}\gamma_5 u + \bar{d}\gamma_5 d + \bar{s}\gamma_5 s)$$

which is amenable to numerical simulations. At the end of the calculation the results are rotated back to real θ



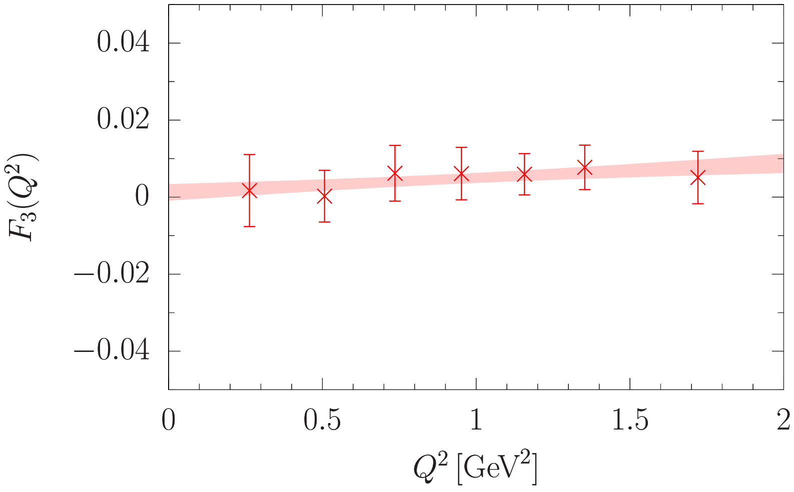


- $e^{i\theta Q}\,P_{\theta=0}(Q) = P_\theta(Q)$, which is reassuring
- The big advantage is that the calculation is done on a non-trivial topological background
- Tricky point: How can one show that the EDM vanishes for $|\theta| > 0$? Hadron radius $\ll$ screening length?

We expect the EDM of the neutron to be largest for heavy quarks, as it will vanish trivially in the chiral limit, $d_n \propto m_u m_d/(m_u + m_d)$

At the SU(3) flavor symmetric point, $m_\pi = m_K = 410$ MeV arXiv:1102.5200

$32^3 \times 64$



$|\theta| \approx 0.4$

This leads to

$$d_n = 0.00028(30)\ [\text{e fm}\ \theta]$$

which is compatible with zero, as expected

Similar results have been reported for reweighting in

arXiv:1701.07792
arXiv:2011.01084
arXiv:2101.07230

Conclusions

- The vacuum of QCD has an incredibly rich structure at the nonperturbative level, which is intimately connected with the topology of gauge fields. It has long been argued that QCD undergoes a phase transition from a confining phase at $\theta = 0$ to a Higgs or Coulomb phase at $|\theta| > 0$. The gradient flow proved a powerful tool for isolating the long-distance modes in the functional integral measure and tracing it over successive length scales

- The novel result is that color charges are screened for $|\theta| > 0$ due to nonperturbative vacuum effects, limiting the vacuum angle to $\theta = 0$ at macroscopic distances, which rules out any strong CP violation at the hadronic level

- The electric dipole moment was found to be zero within the errorbars, $d_n = 0.00028(30)$ [e fm θ], at $\mu \sim 1/a$, as expected. Calculations at smaller quark masses (along the $\bar{m} =$ constant line) and on larger lattices are in progress