The limits of the strong CP problem

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Phys.Lett.B 822 (2021) 136616
2001.07152 [hep-th]

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The aim:

Challenge the conventional view of the strong CP problem by showing that a careful **infinite 4d volume** limit implies that **QCD does not violate CP** regardless of the value of the θ **angle**

The plan:

Fundamentals of the strong CP problem

Fermion correlators from cluster decomposition and the index theorem

Fundamentals of the strong CP problem

The QCD θ angle

$$S_{\rm QCD} = \int \mathrm{d}^4x \left[-\frac{1}{4g^2} F^a_{\mu\nu} F^a_{\mu\nu} + \frac{g^2\theta}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} F^a_{\mu\nu} F^a_{\rho\sigma} + \sum_{i=1}^{N_f} \overline{\psi}_i \left(i\gamma^\mu D_\mu - m_i e^{i\alpha_i \gamma_5} \right) \psi_i \right] .$$

~~CP~~ ~~CP~~

θ-term is a total derivative and thus corresponds to a **boundary term**

it can never contribute in perturbation theory:

effects of θ are nonperturbative

S_θ is **CP-odd!**

Yet no CP violation has been observed in the strong interactions: **Strong CP problem**

$$|d_n| < 1.8 \times 10^{-26} e \cdot cm$$ [nEDM collaboration 2020]

What do we need for CP violation?

Need **interfering contributions** to amplitudes with **misaligned phases** (otherwise one could redefine all phases away)

- **Phases** of **perturbative** contributions fixed by α_i
- θ **naively expected to give additional phases** $\exp(-S^{\mathrm{E}}_{\mathrm{QCD}}) \propto \exp(\mathrm{i}\Delta n\theta)$

- **We need to compute correlators and see if they depend on both types of CP-odd phases (α_i and θ) or not**

Towards correlators: vacuum path integral

$$\int_{\phi_i,\phi_f,T} \left(\prod \mathcal{D}\phi\right) e^{\mathrm{i}S_T} = \langle\phi_f|e^{-\mathrm{i}HT}|\phi_i\rangle = \sum_n e^{-\mathrm{i}E_nT}\langle\phi_f|n\rangle\langle n|\phi_i\rangle$$

To get a **vacuum transition amplitude** we can take the **infinite *T* limit,**

$$Z = \lim_{T\to\infty e^{-i0+}} \int_T \left(\prod \mathcal{D}\phi\right) e^{\mathrm{i}S_T} \sim \lim_{T\to\infty e^{-i0+}} \langle 0|e^{-\mathrm{i}HT}|0\rangle$$

To recover the vacuum amplitude for **finite *T***, one would **need to know the wave functional of the vacuum**

$$\langle 0|e^{-iHT}|0\rangle = \int [\mathcal{D}\phi_f]_{T/2}[\mathcal{D}\phi_i]_{-T/2}\langle 0|\phi_f\rangle\langle\phi_f|e^{-iHT}|\phi_i\rangle\langle\phi_i|0\rangle$$

$$= \int [\mathcal{D}\phi_f]_{T/2}[\mathcal{D}\phi_i]_{-T/2}\langle 0|\phi_f\rangle\langle\phi_i|0\rangle \int_{\phi_i,\phi_f,T} \left(\prod \mathcal{D}\phi\right) e^{\mathrm{i}S}$$

▶ **To ensure projection into vacuum, we use the Euclidean path integral for infinite V *T***

Finite action constraints and topology

Euclidean path integral receives contributions from fluctuations around **finite action saddles**

- In **infinite spacetime, gauge** fields at saddles must be **pure gauge transf. at ∞**
- Fields fall into **homotopy classes** with **integer topological charge** Δn

Atiyah-Singer's index theorem:

$$\Delta n = \#(\text{Right-handed zero modes of } D) - \#(\text{Left-handed zero modes of } D)$$

$$\not{D}\psi_R = 0 \qquad \not{D}\psi_L = 0$$

The **θ-term** is related to the **topological charge!** $-S^E_\theta = i\theta\Delta n$

The θ-term is only guaranteed to be $\propto$ to an integer in an infinite spacetime

Spurious chiral symmetry

The partition function changes under **chiral field redefinitions** due to **masses** and **anomaly**

Spurion symmetry: Z invariant under chiral transformations plus "spurion" transf:

$$\psi \to e^{i\beta\gamma_5}\psi$$
$$\bar{\psi} \to \bar{\psi}e^{i\beta\gamma_5}$$

$$\theta \to \theta + 2N_f\beta, \quad \mathfrak{m}_j = m_j e^{\mathrm{i}\alpha_j} \to e^{-2i\beta}\mathfrak{m}_j$$

Effective Lagrangians for QCD should **respect spurion symmetry**

Nonperturbative effects in QCD

Integrating anomaly eq: $\Delta Q_5 = 2N_f \Delta n + \text{mass corrections}$

▶ There are **interactions** that **violate chiral charge** by $2N_f\Delta n$ units

Captured by **effective `t Hooft vertices**

$$\mathcal{L}_{\text{eff}} \supset -\sum_j m_j \bar{\psi}_j (e^{-i\alpha_j} P_L + e^{i\alpha_j} P_R)\psi_j - \Gamma_{N_f} \mathrm{e}^{\mathrm{i}\xi} \prod_{j=1}^{N_f} (\bar{\psi}_j P_{\mathrm{L}} \psi_j) - \Gamma_{N_f} \mathrm{e}^{-\mathrm{i}\xi} \prod_{j=1}^{N_f} (\bar{\psi}_j P_{\mathrm{R}} \psi_j)$$

['t Hooft]

Nonperturbative effects in QCD

$$\mathcal{L}_{\text{eff}} \supset -\sum_j m_j \bar{\psi}_j (e^{-i\alpha_j} P_L + e^{i\alpha_j} P_R)\psi_j - \Gamma_{N_f} \mathrm{e}^{\mathrm{i}\xi} \prod_{j=1}^{N_f} (\bar{\psi}_j P_{\mathrm{L}} \psi_j) - \Gamma_{N_f} \mathrm{e}^{-\mathrm{i}\xi} \prod_{j=1}^{N_f} (\bar{\psi}_j P_{\mathrm{R}} \psi_j)$$

- **2 options compatible with spurion chiral symmetry:**

$\xi = \theta$	CP violation (phases not aligned)
$\xi = -\sum_i \alpha_i \equiv -\alpha$	No CP violation (all phases aligned, can be removed)

How to resolve the ambiguity?

Must **match effective `t Hooft vertices** with **QCD computations**

Only real computation that we know of is **`t Hooft**'s, using **dilute instanton gas** and yielding $\xi = \theta$ **(CP violation)**

We have **recomputed Green's functions in the dilute instanton gas**, in Euclidean and Minkowski spacetime, and found $\xi = -\alpha$ **(no CP violation)**

We also have a **computation which does not rely on instantons**, summarized next

Fermion correlators from cluster decomposition and the index theorem

Strategy

We want a **derivation that does not rely on instantons**

The aim is to **constrain** the **functional dependence** of the partition functions $Z_{\Delta n}$ on $VT \equiv \Omega$, Δn, $\mathfrak{m}_j = m_j e^{i\alpha_j}$

Fermion masses can be understood as **sources** for the integrated fermion correlators [Leutweyler & Smilga]

$$\mathcal{L} \supset \sum_j \left(\bar{\psi}_j (\mathfrak{m}_j^* P_L + \mathfrak{m}_j P_R)\psi_j\right)$$

These correlators should be **sensitive to global CP-violating phases**

$$\frac{\partial}{\partial \mathfrak{m}_i} Z_{\Delta n} = -\int d^4x \, \langle \bar{\psi}_i P_R \psi_i \rangle_\nu, \qquad \frac{\partial}{\partial \mathfrak{m}_i^*} Z_{\Delta n} = -\int d^4x \, \langle \bar{\psi}_i P_L \psi_i \rangle_\nu.$$

Cluster decomposition

$$Z(\Omega) = \sum_{n=-\infty}^{\infty} \int_{\Delta n} \mathcal{D}\phi e^{-S_\Omega[\phi]+i\Delta n\theta} \equiv \sum_{n=-\infty}^{\infty} e^{i\Delta n\theta} \tilde{Z}_{\Delta n}(\Omega)$$

4D volume

Factorizing path integral a la [Weinberg]

$$\tilde{Z}_{\Delta n}(\Omega = \Omega_1 + \Omega_2) = \int_{\Delta n} \mathcal{D}\phi e^{-S_{\Omega_1+\Omega_2}[\phi]} = \sum_{\Delta n_1} \int_{\Delta n_1} \mathcal{D}\phi e^{-S_{\Omega_1}[\phi]} \int_{\Delta n - \Delta n_1} \mathcal{D}\phi e^{-S_{\Omega_2}[\phi]}$$

$$\tilde{Z}_{\Delta n}(\Omega = \Omega_1 + \Omega_2) = \sum_{\Delta n_1=-\infty}^{\infty} \tilde{Z}_{\Delta n_1}(\Omega_1) \tilde{Z}_{\Delta n - \Delta n_1}(\Omega_2)$$

Taking the clustering argument further

We use **index theorem** to separate complex phases coming from fermion masses

$$\tilde{Z}_{\Delta n}(\Omega) = e^{i\Delta n\alpha} \underbrace{g_{\Delta n}(\Omega)}_{\text{Real}} \Rightarrow g_{\Delta n}(\Omega_1 + \Omega_2) = \sum_{\Delta n_1 = -\infty}^{\infty} g_{\Delta n_1}(\Omega_1) g_{\Delta n - \Delta n_1}(\Omega_2)$$

Ansatz motivated by **parity**

$$g_{\Delta n}(\Omega) = \Omega^{|\Delta n|} f_{|\Delta n|}(\Omega^2), \quad f_{|\Delta n|}(0) \neq 0.$$

Assuming **analiticity** in Ω there is a **unique solution** with free parameter β !

$$f_{\Delta n}(\Omega) = I_{\Delta n}(2\beta\Omega)$$

$$Z_{\Delta n} = \mathrm{e}^{\mathrm{i}\Delta n(\theta+\alpha)} I_{\Delta n}(2\beta\Omega)$$

c.f. [Leutweyler & Smilga]

Mass dependence and correlators

As the $g_{\Delta n}$ are real β can only depend on $\mathfrak{m}_k \mathfrak{m}_k^*$:

$$Z_{\Delta n}(\Omega) = e^{\mathrm{i}\Delta n(\theta - \mathrm{i}/2 \sum_j \log(\mathfrak{m}_j/\mathfrak{m}_j^*))} I_{\Delta n}(2\beta(\mathfrak{m}_k \mathfrak{m}_k^*)\,\Omega)$$

Taking derivatives with respect to $\mathfrak{m}$, $\mathfrak{m}^*$ gives **averaged integrated correlators**

Spurion chiral charge +2

$$\frac{1}{VT}\int d^4x\, \langle \bar{\psi}_i P_R \psi_i \rangle_{\Delta n} = -\, e^{\mathrm{i}\Delta n(\theta + \bar{\alpha})} \Bigg(-\frac{\beta}{2\mathfrak{m}_i} (I_{\Delta n+1}(2\beta\Omega) - I_{\Delta n-1}(2\beta\Omega)) + \mathfrak{m}_i^* (I_{\Delta n+1}(2\beta\Omega) + I_{\Delta n-1}(2\beta\Omega)) \frac{\partial}{\partial(\mathfrak{m}_i \mathfrak{m}_i^*)} \beta(\mathfrak{m}_k \mathfrak{m}_k^*) \Bigg)$$

Summing over topological sectors

$$\frac{1}{VT}\int d^4x\,\langle\bar\psi_i P_R\psi_i\rangle = \lim_{N\to\infty}\lim_{VT\to\infty}\frac{\sum_{\Delta n=-N}^{N}\frac{1}{VT}\int d^4x\,\langle\bar\psi_i P_R\psi_i\rangle_{\Delta n}}{\sum_{\Delta m=-N}^{N} Z_{\Delta m}} = 2\mathfrak{m}_i^*\,\partial_{\mathfrak{m}_i\mathfrak{m}_i^*}\beta(\mathfrak{m}_k\mathfrak{m}_k^*),$$

$$\frac{1}{VT}\int d^4x\,\langle\bar\psi_i P_L\psi_i\rangle = \lim_{N\to\infty}\lim_{VT\to\infty}\frac{\sum_{\Delta n=-N}^{N}\frac{1}{VT}\int d^4x\,\langle\bar\psi_i P_L\psi_i\rangle_{\Delta n}}{\sum_{\Delta m=-N}^{N} Z_{\Delta m}} = 2\mathfrak{m}_i\,\partial_{\mathfrak{m}_i\mathfrak{m}_i^*}\beta(\mathfrak{m}_k\mathfrak{m}_k^*).$$

Topological classification only **enforced in infinite volume**, which **fixes ordering**

$$\frac{1}{VT}\int d^4x\,\langle\bar\psi_i\psi_i\rangle = 2m_i e^{-i\alpha_i\gamma_5}\partial_{\mathfrak{m}_i\mathfrak{m}_i^*}\beta(\mathfrak{m}_k\mathfrak{m}_k^*)$$

Only a single phase: **no CP violation**

Summing over topological sectors

- Result also valid for more general correlators

- Similar results achieved using dilute instanton gas (like `t Hooft, but with a different ordering of limits)

- Opposite order of limits yields traditional picture of CP-violation

Conclusions

QCD with an arbitrary θ **does not predict CP violation**, as long as the sum over topological sectors is performed at **infinite volume**

This **ordering of limits** is the correct one because the topological classification is only enforced for an infinite volume

Further reading in our paper

- For **local observables** one can recover CP-conserving expectation values from **path integrals in a finite subvolume without θ dependence**
- **No conflict** with nonzero **topological susceptibility** in the lattice and η' **mass**

Thank you!

Additional material

Phase ambiguity in the chiral Lagrangian

The **chiral Lagrangian** at lowest order has the form

$$\mathcal{L} = f_\pi^2 \mathrm{Tr}\partial_\mu U \partial^\mu U^\dagger + a f_\pi^3 \mathrm{Tr} M U + b f_\pi^4 \det U + \text{h.c.}$$

Captures t' Hooft vertices $U \sim \bar{\psi} P_R \psi \sim e^{\mathrm{i}\frac{\Pi^a \sigma^a}{\sqrt{2} f_\pi}}$

There are again **2 options compatible with spurion chiral symmetry**

$b \propto e^{-i\theta}$ $\qquad$ $b \propto e^{i\alpha} = e^{i\sum_j \arg(\mathfrak{m}_j)}$

Usual option, **assumed** by **[Baluni, Crewther et al]** → CP violation

No CP violation!

No CP violation in the chiral Lagrangian

$$\mathcal{L} = f_\pi^2 \mathrm{Tr}\partial_\mu U \partial^\mu U^\dagger + a f_\pi^3 \mathrm{Tr} M U + |b| e^{\mathrm{i}\xi} f_\pi^4 \det U + \mathrm{h.c.}$$

Minimizing the potential for the pions leads to

$$\langle U \rangle = U_0 = \mathrm{diag}\left(\mathrm{e}^{\mathrm{i}\varphi_u}, \mathrm{e}^{\mathrm{i}\varphi_d}, \mathrm{e}^{\mathrm{i}\varphi_s}\right) \, .$$

$$m_i \varphi_i = \frac{m_u m_d m_s (\xi + \alpha_u + \alpha_d + \alpha_s)}{m_u m_d + m_d m_s + m_s m_u} = \tilde{m}(\xi + \alpha_u + \alpha_d + \alpha_s) \, .$$

Adding field *N* containing neutron and proton, the *CP*-violating neutron-pion interactions are of the form

$$\frac{c_+ \tilde{m}(\xi + \alpha_u + \alpha_d + \alpha_s)}{2 f_\pi} \bar{N} \Phi N$$

(ϕ containing $U, U^\dagger$ and gammas) which cancel for $\xi = -\alpha$ → no CP violation

Baluni's CP-violating effective Lagrangian

Baluni's CP-violating Lagrangian (used by [Crewther et al]) is based on searching for field redefinitions that minimize the QCD mass term

$$\mathcal{L}_M(U_{R,L}) = \bar{\psi} U_R^\dagger M U_L \psi_L + \text{h.c.}, \quad U_{R,L} \in SU_{R,L}(3)$$

$$\langle 0|\delta\mathcal{L}|0\rangle = \min_{U_{R,L}} \langle 0|\mathcal{L}_M(U_{R,L})|0\rangle$$

However, there is an **extra assumption**: that the **phase of the fermion condensate is aligned with** θ

$$\langle \bar{\psi}_R \psi_L \rangle = \Delta e^{\mathrm{i}c\theta} \mathbb{I}$$

This assumption **does not hold** for the chiral Lagrangian with $\xi = -\alpha$ as seen in previous slide

The η' mass

Chiral Lagrangian with alignment in the phases of mass terms and anomalous terms still predicts a **nonzero value of the η' mass**

$$\mathcal{L} = f_\pi^2 \mathrm{Tr}\partial_\mu U \partial^\mu U^\dagger + a f_\pi^3 \mathrm{Tr} MU + |b| e^{i \arg \det M} f_\pi^4 \det U + \mathrm{h.c.}$$

$$m_{\eta'}^2 = 8|b|f_\pi^2$$

Can be seen to be **proportional** to the **topological susceptibility** over **finite volumes** of the **pure gauge theory**, in line with [Witten, Di Vecchia & Veneziano]

Classic arguments linking topological susceptibility to CP violation ([Shifman et al]) rely on analytic expansions in θ which **don't apply** with our limiting procedure

Z **becomes non-analytic in θ.** This possibility has been mentioned by [Witten]

[Witten, Nucl. Phys. B 156 (1979)]

the physics is of order e^{-N}, contrary to the basic assumptions of this paper, or else the physics is non-analytic as a function of θ, In the latter case, which is quite plausible, the singularities would probably be at $\theta = \pm\pi$, as Coleman found for the massive Schwinger model [10]. It is also quite plausible that θ is not really an angular variable.)

To write a formal expression for $d^2E/d\theta^2$, let us think of the path integral formulation of the theory:

$$Z = \int dA_\mu \exp i \int \mathrm{Tr}\left[-\tfrac{1}{4}F_{\mu\nu} + \frac{g^2\theta}{16\pi^2 N} F_{\mu\nu}\tilde{F}_{\mu\nu}\right]. \tag{5}$$

Partition function and analiticity

Usual partition function is analytic in θ

$$Z_{\text{usual}} = \lim_{VT\to\infty} \lim_{\substack{N\to\infty \\ N\in N}} \sum_{\Delta n=-N}^{N} Z_{\Delta n} = \mathrm{e}^{2\mathrm{i}\kappa_{N_f} VT \cos(\bar{\alpha}+\theta+N_f\pi)}$$

θ-dependence of observables (giving CP violation) usually relies on θ expansion. e.g.

$$\frac{\langle \Delta n \rangle}{\Omega} = \mathrm{i}\,(\theta-\theta_0)\, \underbrace{\frac{\langle \Delta n^2 \rangle}{\Omega}}_{\text{topological susceptibility}}\Bigg|_{\theta_0} + \mathcal{O}(\theta-\theta_0)^2$$

[Shifman et al]

In our limiting procedure the former is not valid, as Z becomes nonanalytic in θ

$$Z = \lim_{\substack{N\to\infty \\ N\in N}} \lim_{VT\to\infty} \sum_{\Delta n=-N}^{N} Z_{\Delta n} = I_0(2\mathrm{i}\kappa_{N_f} VT) \lim_{\substack{N\to\infty \\ N\in N}} \sum_{|\Delta n|\le N} \mathrm{e}^{\mathrm{i}\Delta n(\bar{\alpha}+\theta+N_f\pi)}$$

θ drops out from observables, there is no CP violation

Finite volumes in an infinite spacetime

Even in an infinite spacetime, we can express expectation values of local observables in terms over **path integration over finite volume**.

This can help make **contact with lattice computations**

Assume **local operator** $\mathcal{O}_1$ with **support** in finite spacetime volume Ω_1

$$\langle \mathcal{O}_1 \rangle_\Omega = \frac{\sum\limits_{\Delta n=-\infty}^{\infty} f(\Delta n) \int\limits_{\Delta n} \mathcal{D}\phi\, \mathcal{O}_1\, \mathrm{e}^{-S_\Omega[\phi]}}{\sum\limits_{\Delta n=-\infty}^{\infty} f(\Delta n) \int\limits_{\Delta n} \mathcal{D}\phi\, \mathrm{e}^{-S_\Omega[\phi]}}$$

$$= \frac{\sum\limits_{\Delta n=-\infty}^{\infty} \sum\limits_{\Delta n_1=-\infty}^{\infty} f(\Delta n) \int\limits_{\Delta n_1} \mathcal{D}\phi\, \mathcal{O}_1\, \mathrm{e}^{-S_{\Omega_1}[\phi]} \int\limits_{\Delta n_2=\Delta n-\Delta n_1} \mathcal{D}\phi\, \mathrm{e}^{-S_{\Omega_2}[\phi]}}{\sum\limits_{\Delta n=-\infty}^{\infty} \sum\limits_{\Delta n_1=-\infty}^{\infty} f(\Delta n) \int\limits_{\Delta n_1} \mathcal{D}\phi\, \mathrm{e}^{-S_{\Omega_1}[\phi]} \int\limits_{\Delta n_2=\Delta n-\Delta n_1} \mathcal{D}\phi\, \mathrm{e}^{-S_{\Omega_2}[\phi]}} \, .$$

Finite volumes in an infinite spacetime

Path integrations over Ω_2 give just the **partition functions** we calculated before

In the **infinite volume** limit the **Bessel functions tend to common value** and dependence on Δn factorizes out and cancels:

$$\langle \mathcal{O}_1 \rangle_\Omega = \frac{\displaystyle\sum_{\Delta n_1 = -\infty}^{\infty} \int_{\Delta n_1} \mathcal{D}\phi \, (-1)^{-N_f \Delta n_1} \mathrm{e}^{-\mathrm{i}\,\alpha \Delta n_1} \mathcal{O}_1 \, \mathrm{e}^{-S_{\Omega_1}[\phi]}}{\displaystyle\sum_{\Delta n_1 = -\infty}^{\infty} \int_{\Delta n_1} \mathcal{D}\phi \, (-1)^{-N_f \Delta n_1} \mathrm{e}^{-\mathrm{i}\,\alpha \Delta n_1} \mathrm{e}^{-S_{\Omega_1}[\phi]}} \,.$$

We recover a **path integration** over a **finite volume, without θ dependence**

Extra phases precisely **cancel those from fermion determinants in** Ω_1

This **removes interferences** between different **topological sectors**

The QCD angle from the vacuum state

Hamiltonian is zero for pure gauge transformations, with integer n_{CS}: Expect **degenerate classical pre-vacua** $|n_{CS}\rangle \equiv |n\rangle$

If the **true vacuum** $|\omega\rangle$ were to be a linear combination of the classical prevacua

$$|\omega\rangle = \sum_n f(n)|n\rangle$$

Demanding **invariance up to a phase** under **gauge transformations** in the Δn class

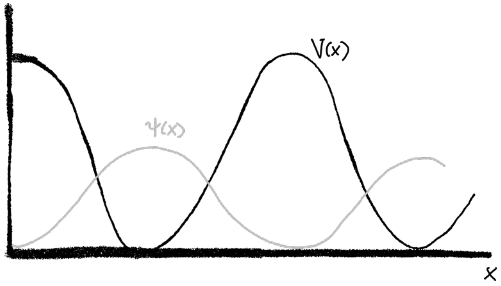
$$U_{\Delta n}|\omega\rangle = \sum_n f(n)|n+\Delta n\rangle = e^{i\Delta n\theta}|\omega\rangle \Rightarrow f(n) = e^{-in\theta}$$

$$Z(\theta) = \langle\omega|e^{-HT}|\omega\rangle = \sum_m\sum_n \langle m|e^{-HT}e^{i\theta(m-n)}|n\rangle = \mathcal{N}\sum_{\Delta n}\langle n+\Delta n|e^{-HT}e^{i\theta\Delta n}|n\rangle$$

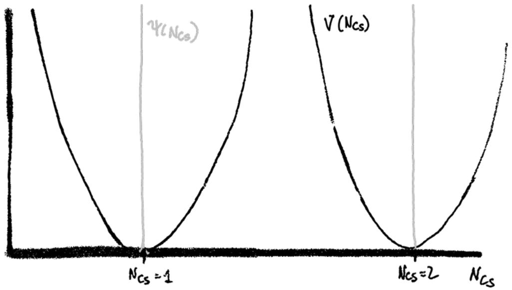
$$= \mathcal{N}\sum_{\Delta n}\int_{\Delta n}\mathcal{D}\phi\, e^{-S_\theta+\dots}$$

Can one use the "θ vacuum" at finite volume?

Bloch wave function in QM:



vs θ vacuum having support only on classical vacua



Too naive! Have to use path integral in infinite 4D volume to project into vacuum