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Theta dependence in Holographic QCD

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- *FB, Aldo L. Cotrone, Roberto Sisca, JHEP 1508 (2015) 090*
- *Lorenzo Bartolini, FB, Stefano Bolognesi, Aldo L. Cotrone, Andrea Manenti (in progress)*

Plan

- The θ-angle in Yang-Mills and QCD
- Holographic Yang-Mills at finite θ-angle
- Holographic QCD at finite θ-angle

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Effects of the θ parameter interesting but challenging.

The θ-angle in Yang-Mills

- Euclidean Lagrangian

$$\mathcal{L}_\theta = \frac{1}{2g_{YM}^2} \mathrm{Tr} F_{\mu\nu} F^{\mu\nu} - \frac{i}{32\pi^2} \theta \, \epsilon^{\mu\nu\rho\sigma} \, \mathrm{Tr} F_{\mu\nu} F_{\rho\sigma}$$

- θ term breaks P,T and hence CP. Due to instantons: non perturbative.
- θ multiplies topological charge density, whose 4d integral is integer.
- Physics periodic under $\theta \longrightarrow \theta + 2\pi$

- Effects: vacuum structure, CP violating effects in QGP [Kharzeev et al], mass and interactions of η' meson in QCD [Witten-Veneziano], cosmology (axions)

- Challenging on the Lattice (sign problem: imaginary term)
- Can get results only for few terms in expansion around $\theta \approx 0$.

Lattice results

[Pisa Lattice QCD group: Bonati, D'Elia, Vicari et al; years 2006-present]

- Ground state energy density

$$f(\theta) - f(0) = \frac{1}{2}\chi_g \theta^2 \left[1 + \bar{b}_2 \frac{\theta^2}{N_c^2} + \bar{b}_4 \frac{\theta^4}{N_c^4} + \mathcal{O}(\theta^6)\right] \quad \chi_g = f''(\theta)|_{\theta=0} \neq 0 \text{ topological susceptibility}$$

$\bar{b}_2 \approx -0.2$ (from N_c=3,…,6 data) $|b_4| < 0.001$ (N_c=3)

- String tension

$$T_s(\theta) = T_s(0)\left[1 + \bar{s}_2 \frac{\theta^2}{N_c^2} + \mathcal{O}(\theta^4)\right], \quad \bar{s}_2 \approx -0.9 \text{ (from } N_c\text{=3,…,6 data)}$$

- Lowest 0^{++} glueball mass

$$M_{0^{++}}(\theta) = M_{0^{++}}(0)\left[1 + g_2\theta^2 + \mathcal{O}(\theta^4)\right], \quad g_2 \approx -0.06(2), \quad (N_c = 3)$$

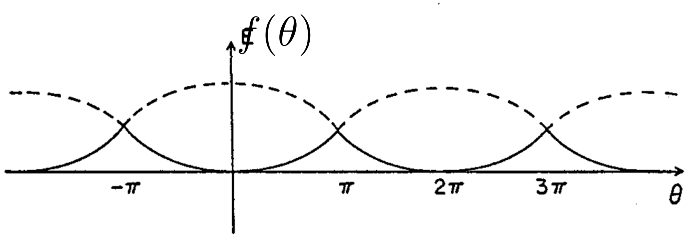
- Deconfinement temperature

$$T_c(\theta) = T_c(0)\left[1 + R_\theta\theta^2 + \mathcal{O}(\theta^4)\right], \quad R_\theta \approx -0.0175(7), \quad (N_c = 3)$$

The θ-angle in large N Yang-Mills

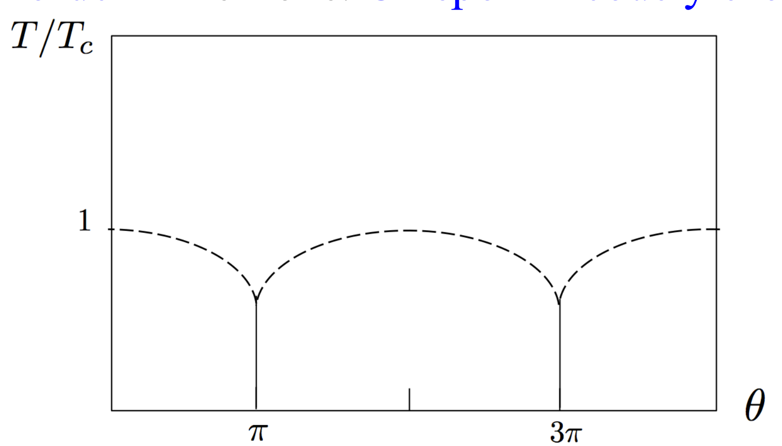
- $$\mathcal{L} = \frac{N_c}{2\lambda}\left[\mathrm{Tr}F^2 - i\frac{\lambda}{8\pi^2}\frac{\theta}{N_c}\mathrm{Tr}F\tilde{F}\right]$$ ‘t Hooft limit: must take θ/N fixed.

- Scaling with θ/N + periodicity in θ: multi-branched energy density f(θ)[Witten, 1980]



$$f(\theta) = b\,N^2 \mathrm{min}_k \left(\frac{\theta + 2k\pi}{N}\right)^2 + O\,(\theta^4/N^4)$$

- At θ=(2k+1)π: expect first order transitions. CP spontaneously broken
- Expected phase diagram



Theta term in QCD

$$\mathcal{L} = \frac{1}{4} F^a_{\mu\nu}(x) F^a_{\mu\nu}(x) + \sum_{f=1}^{N_f} \bar{\psi}_f \left(D + m_f\right) \psi_f$$

a) Massless quarks:

$$\psi \to e^{i\alpha\gamma_5}\, \psi$$

$$[d\psi][d\bar{\psi}] \to \exp\left(\frac{-i\,\alpha\, g^2\, N_f}{32\pi^2} \int d^4x\, \epsilon_{\mu\nu\rho\sigma} F^a_{\mu\nu} F^a_{\rho\sigma}\right) [d\psi][d\bar{\psi}]$$

$$\theta \to \theta - 2\alpha N_f$$

- Theta rotated away by chiral rotation. No theta dependence

b) Massive quarks: $m_f \to e^{2i\alpha}\, m_f$ $\qquad \theta = \theta_q + \arg\det M$

- Neutron Electric Dipole Moment: $d_n \sim \theta \dfrac{e m_f}{m_n^2} \sim \theta \dfrac{e m_\pi^2}{m_n^3} \approx 10^{-16} \theta\, e\, \mathrm{cm}$

- Experiments: $|d_n| < 2.9 \times 10^{-26} e\, \mathrm{cm}$ so $|\theta| < 10^{-10}$. Strong CP problem.

Neutron Electric Dipole Moment in the literature

Compute: $$\vec{D}_{n,s} = \int \mathrm{d}^3x\, \vec{x}\, \langle n, s | J^0_{\mathrm{em}} | n, s \rangle$$

Year	Approach/model	$c = d_n/(\theta \cdot 10^{-16} e \cdot \mathrm{cm})$
1979	bag model	2.7
1980	ChPT	3.6
1981	ChPT	1
1981	ChPT	5.5
1982	ChPT	20
1984	chiral bag model	3.0
1984	soft pion Skyrme model	1.2
1984	single nucleon contribution	11
1990 [20]	Skyrme model $N_f = 3$	2
1991 [19]	Skyrme model $N_f = 2$	1.4
1991	ChPT	3.3(1.8)
1991	ChPT	4.8
1992	ChPT	−7.2, −3.9
1999	sum rules	2.4(1.0)
2000	heavy baryon ChPT	7.5(3.2)
2004	instanton liquid	10(4)
2007	holographic QCD “hard–wall”	1.08
2015	1502.02295 [hep-lat]	- 3.8 (2)

Table partially taken from Panagopoulos, Vicari 2008

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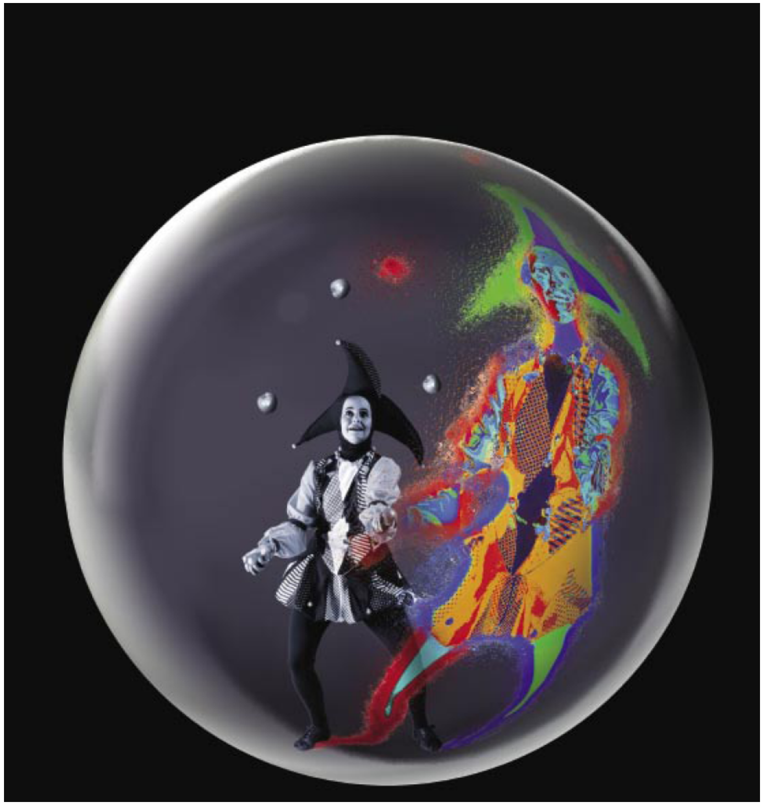
Exact θ-dependence in a large N Yang-Mills model from holography

Holography

[Maldacena, 97; Witten; Gubser, Klebanov, Polyakov, 98]

Quantum field theories in d-dim equivalent to theories of gravity in d+1 dim



Holography

[Maldacena, 97; Witten; Gubser, Klebanov, Polyakov, 98]

Quantum field theories in d-dim equivalent to theories of gravity in d+1 dim

- Hint 1: RG flow in d = foliation in d+1; extra coordinate = RG energy scale.
- Hint 2: quantum gravity is holographic. Area law for black hole entropy.
- Hint 3: Open/closed string duality. Open strings: gauge fields. Closed: gravitons.

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- Works as a duality: large N, strong coupling in QFT = classical gravity
- QFT operator $\leftrightarrow$ gravity field. E.g. $T_{\mu\nu} \leftrightarrow g_{\mu\nu}$; $J_\mu \leftrightarrow A_\mu$; $\mathrm{Tr}\, F^2 \leftrightarrow \phi$
- QFT global symmetry $\leftrightarrow$ Local symmetry in gravity
- QFT partition function, large N, strong coupling $\leftrightarrow$ $\exp[-S_{gravity}]$

Holography

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- One-to-one map if dual pairs are embedded in 10d string theory: top-down approach
- Open strings end on p+1 dim hyperplanes, Dp-branes (D = Dirichelet bound. cond.)
- N D3-branes in IR: $\mathcal{N}$=4 SU(N) susy Yang-Mills: a 3+1 dim conformal FT (CFT)
- Dual description: quantum gravity (closed string theory) on Anti-de-Sitter in 4+1.

Witten’s holographic Yang-Mills [Witten 1998]

- To describe non susy Yang-Mills in 3+1: go beyond AdS/CFT

- Start with a 5d SU(Nc) supersymmetric Yang Mills theory
- (low energy of open strings attached to N_c D4-branes)
- Compactify on circle $S^1{}_{x4}$ of radius $R_4 = 1/M_{KK}$ with antiperiodic fermions.
- (low energy of open strings attached to Nc D4-branes wrapped on $S^1{}_{x4}$)
- Low energy: 4d non-susy $SU(N_c)$ Yang-Mills + adjoint KK modes

- Can add θ term to the model, no sign problem.
- To leading order in θ/N_c done in [Witten 1998].

Witten's holographic Yang-Mills

- Gravity action (closed string description)

$$S = \frac{1}{2k_0^2}\int d^{10}x\sqrt{-g}\left[e^{-2\phi}\left(\mathcal{R}+4(\partial\phi)^2\right)-\frac{1}{2}|F_4|^2-\frac{1}{2}|F_2|^2\right]$$

- Gauge theory action (open string description, IR)

$$S = \frac{1}{8\pi g_s l_s M_{KK}}\int d^4x\ \mathrm{Tr}F_{\mu\nu}F^{\mu\nu} - \frac{i}{32\pi^2 l_s}\int_{S_{x^4}} C_1 \int d^4x\ \epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}F_{\mu\nu}F_{\rho\sigma}$$

$$\boxed{F_2 = d\,C_1} \qquad \lambda_4 = g_{YM}^2 N_c = 2\pi g_s l_s M_{KK} N_c \qquad \boxed{\theta + 2\pi k = \frac{1}{l_s}\int_{S_{x_4}} C_1}$$

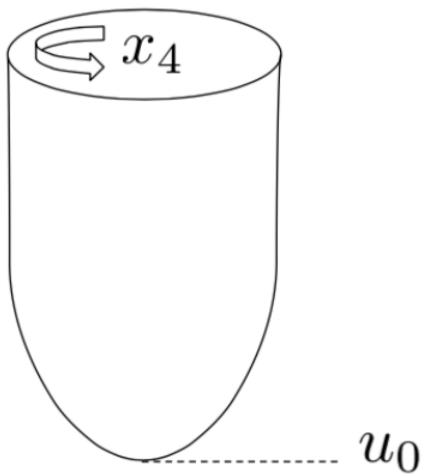
- Holography: gravity picture dual to gauge theory at $\lambda_4 >> 1,\ N_c >> 1$

The gravity solution

[Barbon, Pasquinucci 99; Dubovsky, Lawrence, Roberts 2011] $(x_4 \sim x_4 + 2\pi/M_{KK})$

$$ds^2_{10} = \left(\frac{u}{R}\right)^{3/2}\left[\sqrt{H_0}\, dx_\mu dx^\mu + \frac{f}{\sqrt{H_0}} dx_4^2\right] + \left(\frac{R}{u}\right)^{3/2}\sqrt{H_0}\left[\frac{du^2}{f} + u^2 d\Omega_4^2\right]$$

$$f = 1 - \frac{u_0^3}{u^3}\,, \qquad H_0 = 1 - \frac{u_0^3}{u^3}\frac{\Theta^2}{1+\Theta^2} \qquad \boxed{\Theta \equiv \frac{\lambda_4}{4\pi^2}\left(\frac{\theta + 2k\pi}{N_c}\right)} \qquad \boxed{\theta + 2\pi k = \frac{1}{l_s}\int_{S_{x_4}} C_1}$$



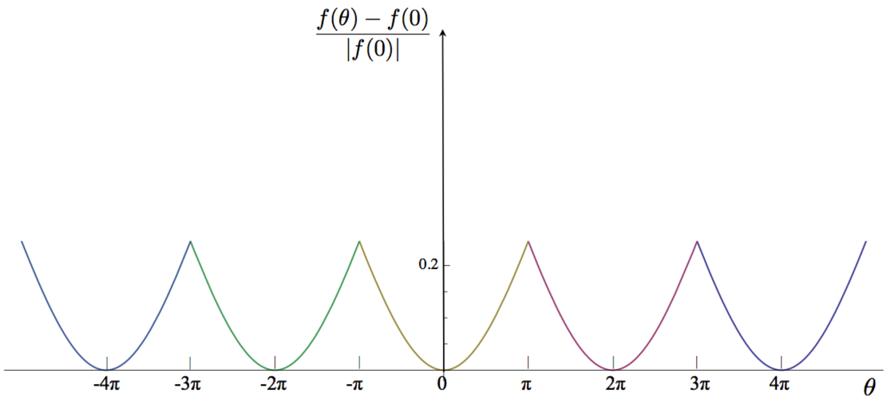
- (u,x_4) subspace is a cigar
- $g_{00}(u_0) \neq 0$ (regular) : confinement
- KK modes NOT decoupled

$$\boxed{u_0 = \frac{4R^3}{9} M_{KK}^2 \frac{1}{1+\Theta^2}}$$

The ground-state energy density

From holographic relation $Z = e^{-V_4 f(\theta)} \approx e^{-S^{\rm ren}_{E\,{\rm on-shell}}}$

$$\boxed{f(\Theta) = -\frac{2N_c^2\lambda_4}{3^7\pi^2}\frac{M_{KK}^4}{(1+\Theta^2)^3}} \qquad \Theta \equiv \frac{\lambda_4}{4\pi^2}\left(\frac{\theta+2k\pi}{N_c}\right) \qquad \boxed{f(\theta) = \min_k f(\Theta)}$$



Expected structure explicitly realized

$$f(\theta) - f(0) = \frac{1}{2}\chi_g\theta^2\left[1 + \bar{b}_2\frac{\theta^2}{N_c^2} + \bar{b}_4\frac{\theta^4}{N_c^4} + \mathcal{O}(\theta^6)\right] \qquad \chi_g = \frac{\lambda_4^3 M_{KK}^4}{4(3\pi)^6} \qquad \bar{b}_2 = -\frac{\lambda_4^2}{8\pi^4}\,, \quad \bar{b}_4 = \frac{5\lambda_4^4}{384\pi^8}$$

- Qualitative agreement with Lattice
- Prediction: $b_4 > 0$ (it would be nice to check it on the lattice)

Other observables

- String tension (from rectangular Wilson loop) $\boxed{T_s = \frac{2\lambda_4}{27\pi} M_{KK}^2 \frac{1}{(1+\Theta^2)^2}}$

$$T_s = \frac{2\lambda_4}{27\pi} M_{KK}^2 \left(1 - \frac{\lambda_4^2}{8\pi^4}\frac{\theta^2}{N_c^2} + \frac{3\lambda_4^4}{256\pi^8}\frac{\theta^4}{N_c^4} + \mathcal{O}(\theta^6)\right)$$

- Light scalar glueball mass $\boxed{M(\Theta) = \frac{M(\Theta=0)}{\sqrt{1+\Theta^2}}}$

$$M(\theta) = M(\theta = 0)\left(1 - \frac{\lambda_4^2}{32\pi^4}\frac{\theta^2}{N_c^2} + \frac{3\lambda_4^4}{2048\pi^8}\frac{\theta^4}{N_c^4} + \mathcal{O}(\theta^6)\right)$$

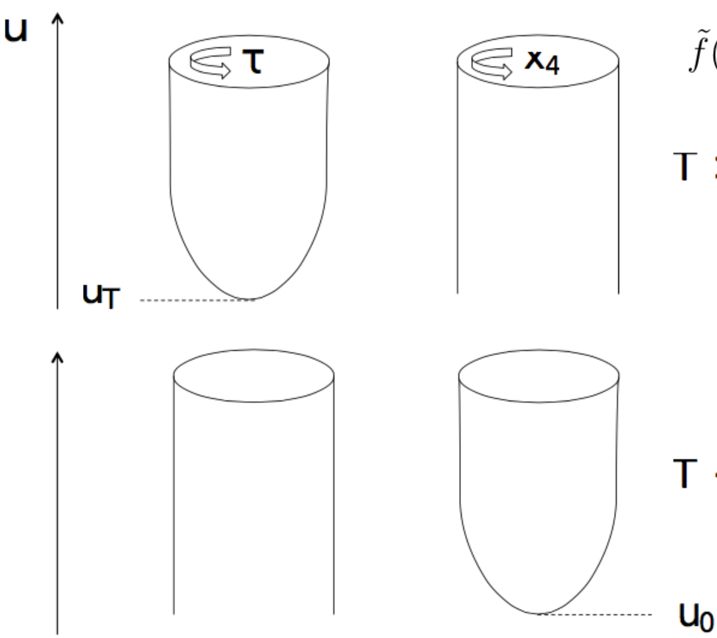
- Again: qualitative agreement with Lattice. Prediction on subleading coefficients

Finite temperature

Two possible gravity solutions, with Euclidean time circle of length 1/T

$$ds^2 = \left(\frac{u}{R}\right)^{3/2} \left[\tilde{f}(u) dx_0^2 + dx_a dx^a + dx_4^2\right] + \left(\frac{u}{R}\right)^{-3/2} \left[\frac{du^2}{\tilde{f}(u)} + u^2 d\Omega_4^2\right] ,$$

$$\tilde{f}(u) = 1 - \frac{u_T^3}{u^3} .$$



$T > T_c$

- black hole solution
- $g_{00}(u_T) = 0$: deconfinement
- no theta dependence

$$\boxed{C_1 \sim \theta dx_4, \;\; F_2 = 0 \quad [(u, x_4) : \text{cylinder}]}$$

$T < T_c$

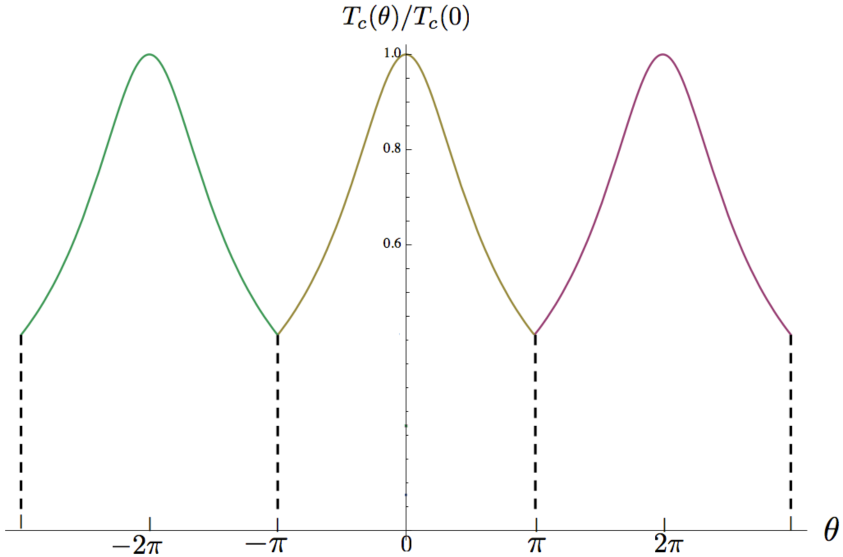
- Euclidean version of T=0 one
- Theta-dependence
- Confinement

Deconfinement temperature

Compare the free energy densities of confined and deconfined phase

$$f = -p = -\frac{2N_c^2\lambda_4}{3^7\pi^2}\frac{M_{KK}^4}{(1+\Theta^2)^3} \equiv \frac{f(0)}{(1+\Theta^2)^3} \qquad f_{dec} = -p_{dec} = -\frac{1}{6}\frac{256 N_c^2 \pi^4 \lambda_4}{729 M_{KK}^2} T^6$$

$$\boxed{T_c(\Theta) = \frac{M_{KK}}{2\pi}\frac{1}{\sqrt{1+\Theta^2}}} \qquad T_c(\theta) = \frac{M_{KK}}{2\pi}\left[1 - \frac{\lambda_4^2}{32\pi^4}\frac{\theta^2}{N_c^2} + \frac{3\lambda_4^4}{2048\pi^8}\frac{\theta^4}{N_c^4} + \mathcal{O}(\theta^6)\right]$$



$$T_c(\theta)_{lat} = T_c(0)_{lat}\left[1 - R_\theta \theta^2 + \mathcal{O}(\theta^4)\right] \ , \quad R_\theta = 0.0175(7)$$

Cusps: tri-critical points
Colored: deconf. first order transition
Dashed: CP-breaking first order transition

Phase diagram as expected

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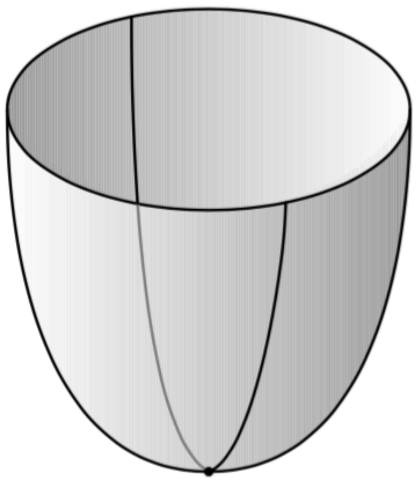
Work in progress

θ-dependence in Witten's model + quarks: Witten-Sakai-Sugimoto model

Holographic computation of Neutron Electric Dipole Moment

Theta term in Witten-Sakai-Sugimoto



Quenched flavors: Nf probe D8-anti-D8-branes
On D8-anti-D8 branes: U(Nf) x U(Nf) gauge theory
This corresponds to QFT chiral symmetry
Chiral symm. breaking = joining of the two branches
Flavors are massless

Gauge field on D8 gives meson tower:

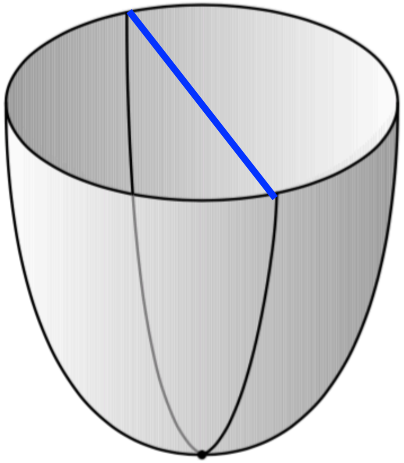
- A_z : Goldstone bosons
- Aμ : (axial) vector mesons

F_2 mixes with $U(1)_A$ gauge field on D8

$$\widetilde{F}_{(2)} = \mathrm{d}C_{(1)} + \mathrm{Tr}\,(\mathcal{A}) \wedge \delta(y)\mathrm{d}y \qquad \delta_\Lambda C_{(1)} = \mathrm{Tr}\,(\Lambda)\delta(y)\mathrm{d}y\ , \qquad \delta_\Lambda \mathcal{A} = i[\Lambda, \mathcal{A}] - \mathrm{d}\Lambda$$

Corresponds to $\theta \to \theta - 2\alpha N_f$ under $\psi \to e^{i\alpha\gamma_5}\,\psi$ No θ dependence.

Mass term in Witten-Sakai-Sugimoto



$U_{\rm KK} \equiv U_0$

Worldsheet instanton

[Aharony-Kutasov; Hashimoto –Hirayama-Lin_hee 2008]

$$S_{\rm mass} = c \int d^4x \,{\rm Tr}\, \mathcal{P} \left[M \exp\left(-i \int_{-\infty}^{\infty} \mathcal{A}_z dz \right) + {\rm c.c.} \right]$$

$$c = \frac{1}{3^{9/2}\pi^3} g_{\rm YM}^3 N_c^{3/2} M_{\rm KK}^3 \mathcal{N}^{-1} \qquad \mathcal{A} = \widehat{A} \frac{\mathbb{1}}{\sqrt{2N_f}} + A^a T^a$$

- Vacuum solution: $\int \hat{A}_z dz \sim \theta, \text{ for } M = m_q \mathbf{1}$
- Ground-state energy density (from on-shell action)

$$F(\theta) - F(0) = N_f m_q \Sigma \left[1 - \cos(\theta/N_f) \right] \;, \quad \Sigma = \frac{\langle \bar\psi \psi \rangle}{N_f}$$

- Same result as from chiral Lagrangian since

$$\mathcal{L}_{mass} \sim \Sigma\, {\rm Tr}[e^{i\theta/N_f} M U + c.c.] \,, \; U \sim \exp\left(-i \int \mathcal{A}_z dz \right)$$

Baryons in Witten-Sakai-Sugimoto

- At large N, baryons as solitons of chiral Lagrangian (M≈N): Skyrmions
- In holographic setup, much in the same way, they are instantons on D8-branes action

[Hata,Sakai,Sugimoto,Yamato. 2007]

$$S_{\text{bulk+D8}} = -\kappa \int \mathrm{d}^4x\mathrm{d}z \left(\frac{1}{2}h(z)\,\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu} + k(z)\mathrm{Tr}\,F_{\mu z}F^{\mu}{}_{z}\right) + \\ -\frac{\kappa}{2}\int \mathrm{d}^4x\mathrm{d}z \left(\frac{1}{2}h(z)\,\widehat{F}_{\mu\nu}\widehat{F}^{\mu\nu} + k(z)\widehat{F}_{\mu z}\widehat{F}^{\mu}{}_{z}\right) + \\ +\frac{N_c}{24\pi^2}\int\left[\omega_5^{SU(N_f)}(A) + \frac{3}{\sqrt{2N_f}}\widehat{A}\,\mathrm{Tr}\,F^2 + \frac{1}{2\sqrt{2N_f}}\widehat{A}\,\widehat{F}^2\right]$$

$\kappa \approx \lambda N_c$

- BPST-like instanton (Nf=2)

$$A_M^{\mathrm{cl}} = -if(\xi)g\partial_M g^{-1}\,, \quad \widehat{A}_0^{\mathrm{cl}} = \frac{1}{8\pi^2 a}\frac{1}{\xi^2}\left[1 - \frac{\rho^4}{(\rho^2+\xi^2)^2}\right]\,, \quad A_0^{\mathrm{cl}} = \widehat{A}_M = 0$$

$$f(\xi) = \frac{\xi^2}{\xi^2+\rho^2}\,, \quad g(x) = \frac{(z-Z)\mathbb{1} - i(\vec{x}-\vec{X})\cdot\vec{\tau}}{\xi}$$

- Small size: $\rho^2 \sim 1/\lambda$
- Spectrum (baryon states) from quantization of collective coordinates
- Quantizing SU(2)xSU(2) global parameters get spin and isospin
- Neutron: state with s=1/2, I=-1/2.

Baryons in Witten-Sakai-Sugimoto

Adding mass and theta term

$$S_{\text{mass}} = c \int \mathrm{d}^4x \, \mathrm{Tr}\, \mathcal{P} \left[M \exp\left(-i \int_{-\infty}^{\infty} \mathcal{A}_z \mathrm{d}z \right) + \text{c.c.} \right]$$

$$S_{\text{kin}} = -\frac{\chi_g}{2} \int \mathrm{d}^4x \left(\theta + \sqrt{\frac{N_f}{2}} \int_{-\infty}^{\infty} \mathrm{d}z \, \widehat{A}_z \right)^2$$

- To first order in mass, baryon states do not receive O(θ) corrections
- New instanton solution to leading order in mass and theta

$$\boxed{\widehat{A}_z^{\text{mass}} = \frac{1}{1+z^2} u(r)}$$

$$u(r) = \frac{c m_q \theta}{\kappa} \int_0^{\infty} \mathrm{d}r' \, u_G(r, r') \left(1 + \cos \frac{\pi}{\sqrt{1 + \rho^2 / r'^2}} \right)$$

$$\boxed{A^0_{\text{mass}} = W(r,z)(\vec{x} - \vec{X}) \cdot \vec{\tau}}$$

$$h(z) \left(\partial_r^2 W(r,z) + \frac{4}{r} \partial_r W(r,z) + \frac{8\rho^2}{(\xi^2+\rho^2)^2} W(r,z) \right) + \partial_z (k(z) \partial_z W(r,z)) =$$
$$= \frac{27\pi}{\lambda} \frac{\rho^2}{(\xi^2+\rho^2)^2} \frac{1}{r} \frac{u'(r)}{1+z^2} \equiv \mathscr{F}(r,z)$$

NEDM in Witten-Sakai-Sugimoto

$J^0_{em} \sim F^{0z}|_{boundary}$

$$\vec{D}_{n,s} = \int \mathrm{d}^3x\, \vec{x}\, \langle n,s|J^0_{\mathrm{em}}|n,s\rangle$$

$$\vec{\mathcal{D}}_{n,s} = \frac{8\pi}{9}\int_0^\infty \mathrm{d}r\, r^4\, \kappa[k(z)\,\partial_z W(r,z)]_{z\to-\infty}^{z\to\infty}\,\langle s|\vec{\sigma}|s\rangle = -\vec{\mathcal{D}}_{p,s}$$

$$d_n = \frac{8\pi}{9}\int_0^\infty \mathrm{d}r\, r^4\, \kappa[k(z)\,\partial_z W(r,z)]_{z\to-\infty}^{z\to\infty}$$

- Fitting parameters with f_π = 92 MeV, m_π= 135 MeV, m_ρ=776 MeV yields

d_n= 0.74 10^{-16} θ e cm

- Fitting with M_N= 940 MeV instead than with m_ρ yields

d_n= 0.72 10^{-16} θ e cm

- Holographic result takes into account contribution from whole meson tower

Conclusions and perspectives

- Theta dependence in large N Yang-Mills and QCD from holography
- Qualitative agreement with Lattice Yang-Mills at small theta
- Predictions for generic theta
- Yang-Mills phase diagram shows qualitative agreement with expected one
- Also computed: entanglement entropy, ‘t Hooft loop (oblique confinement)
- Derived theta dependence of energy density for QCD model with massive flavors
- Computed Neutron Electric Dipole Moment.
- Also computed: CP-breaking nucleon-nucleon-pion coupling.
- Future: Consider m_u-m_d corrections. Study the model with Nf = 2+1 flavors

Thank you