Towards a holographic description of QCD

Stefano Nicotri

Dipartimento Interateneo di Fisica "M. Merlin", Università degli Studi di Bari, & INFN Sezione di Bari

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Introduction

QCD: a difficult theory to deal with

Two regimes of QCD and tools for theoretical analysis

Perturbative

- Perturbation theory

Non-Perturbative

- Lattice
- QCD sum rules
- ...

Old dream: "QCD: a solvable theory"

Holographic QCD $\longrightarrow$ new way of approaching QCD $\longrightarrow$ new powerful tool

What is holography?
How to construct a holographic description of QCD?

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AdS/CFT correspondence

- AdS_5 symmetry group isomorphic to four dimensional conformal group

Duality (J. Maldacena, E. Witten, I. Klebanov)

Large N limit of a strongly coupled $SU(N)$ $\mathcal{N}=4$ SYM in $\mathcal{M}_4$ $\rightleftarrows$ Supergravity Theory in $\mathrm{AdS}_5 \times \mathrm{S}^5$

Conjecture

Defined:

- $\mathcal{O} \longrightarrow$ operator in strong coupled $\mathcal{N}=4$ SYM
- φ_0 its source in the CFT generating functional $\left\langle \exp \int \varphi_0 \mathcal{O} \right\rangle_{\mathrm{CFT}}$
- φ the field dual to $\mathcal{O}$ in the string theory
- $Z(\varphi)$ the partition function of the string theory $\sim$ $\exp(-iS_{eff}(\varphi))$ in SUGRA limit
- z the *holographic* coordinate

$$\left\langle \exp \int \varphi_0 \mathcal{O} \right\rangle_{\mathrm{CFT}} = Z(\varphi) \sim \exp(-iS_{eff}(\varphi))$$

with "boundary condition":

$$\varphi(x,z) = \int d^4x' \, K(x-x',z)\, \varphi_0(x') \qquad K(x-x',z) \xrightarrow[z\to 0]{} \delta^4(x-x')$$

where $K(x-x',z)$ is a bulk-to-boundary evolution operator

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Link to QCD

Problems with QCD

- $\mathcal{N} = 4$ SYM is a conformal field theory while QCD is not
- $\mathcal{N} = 4$ SYM is a supersymmetric theory while QCD is not
- $\mathcal{N} = 4$ SYM has no S-matrix while QCD has

Proposals

QCD "nearly conformal" when all $m = 0$ and when α_s does not run
Supposing the existence of a "gravity dual" of QCD:

Top-to-bottom approach

- Starting by string theory
- Trying to reproduce QCD

Bottom-to-top approach

- Starting by QCD
- Trying to construct the dual theory

Results

- Masses & decay constants
- Condensates
- Correlation functions
- Heavy Quark potential

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Powerful tool

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Bottom-to-top approach: hard wall model

Framework (J. Polchinski, M. Strassler)

Bulk $= \mathrm{AdS}_5$ cut at $z = z_m \sim 1/\Lambda_{QCD}$ $\Leftrightarrow$ $ds^2 = \frac{1}{z^2}(\eta_{\mu\nu} dx^\mu dx^\nu + dz^2) \quad 0 \leqslant z \leqslant z_m$

QCD lives on the boundary $z = 0$

How to construct the action

- QCD operator $\mathcal{O}_{\mu\nu\ldots\beta}$ of order p and dim Δ $\leftrightarrow$ free field in the bulk $B_{\mu\nu\ldots\beta}$
- $m_5^2 = (\Delta - p)(\Delta + p - 4)$
- Global symmetry in the boundary $\leftrightarrow$ local (gauge) symmetry in the bulk
- QFT in the boundary $\leftrightarrow$ classical theory in the bulk

Example: Scalar operator $\mathcal{O}$

Action & EOM:

$$S = -\frac{1}{2k} \int d^5x \sqrt{|g|} \left(g^{MN} \partial_M X \, \partial_N X + m_5^2 X^2 \right)$$

$$\partial_M \left[\sqrt{|g|} \, g^{MN} \partial_N X(x,z) \right] - m_5^2 X(x,z) = 0$$

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Bottom-to-top approach: soft wall - dilaton model

Framework (A. Karch, E. Katz, D. Son, M. Stephanov)

Bulk = asymptotically AdS_5 with a background "dilaton" field $\phi(z)$

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With:

- $\phi - A \xrightarrow[z\to\infty]{} c^2 z^2$
- $\phi - A \xrightarrow[z\to 0]{} -\ln z$
- $A(z)$ cannot contain powers z^β with $\beta \geqslant 2$

Simplest choice:

- $\phi = c^2 z^2$
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This model reproduces Regge behaviour of vector-mesons: $m_n^2 \sim n$

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Example of a calculation: glueball masses

0^+ glueball

QCD

- Described by $tr(G^2) = Tr(G_{\mu\nu} G^{\mu\nu})$
- Dimension $\Delta = 4$
- Scalar ($p = 0$)

AdS_5

- Described by a scalar field $X(x, z)$
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Massless free scalar field

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How to compute masses?

- 4-dim Fourier transformation of the field: $X(x, z) = \int d^4x\, e^{iq\cdot x} \tilde{X}(q, z)$
- Fields on shell $\rightarrow q^2 = -m^2$

Eigenvalues m_n^2 of the EOM $\rightarrow$ 0^+ glueball spectrum

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- Described by $Tr(G(DG)G)$
- Dimension $\Delta = 7$
- Vector $(p = 1)$

AdS$_5$

- Described by a vector field $V_M(x, z)$
- Mass $m_5^2 = (\Delta - p)(\Delta + p - 4) = 24$

Massive free vector field

Action & EOM:

$$S = -\frac{1}{2k}\int d^5x\sqrt{|g|}\, e^{-\phi(z)}\left(\frac{1}{2}g^{MN}g^{ST}F_{MS}F_{NT} + 24g^{ST}V_S V_T\right)$$

$$\partial_M\left[\sqrt{|g|}\, e^{-\phi(z)}g^{MN}g^{ST}F_{MS}(x,z)\right] - 24\sqrt{|g|}\, e^{-\phi(z)}g^{ST}V_S(x,z) = 0$$

where:

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Masses

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2. Modification of the standard AdS/CFT correspondence $\longrightarrow$ QCD
3. Different approaches
4. In Dilaton approach:
   - 0^{+} glueball mass spectrum
   - 1^{--} glueball mass spectrum

AdS/QCD seems to be very interesting and powerful in investigating QCD

but there is still a lot of work to do

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