AdS/CFT and QCD

15 January 2007

Magdalena Larfors

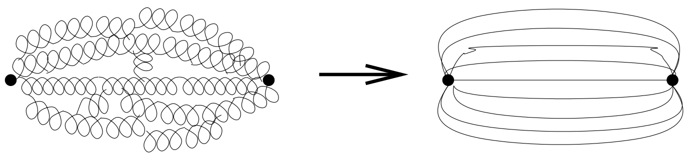
Outline

- Motivation from QCD.
- AdS/CFT in general.
- What string theory corresponds to QCD?
- Using AdS/CFT to understand QCD.
- Experimental evidence of AdS/QCD?

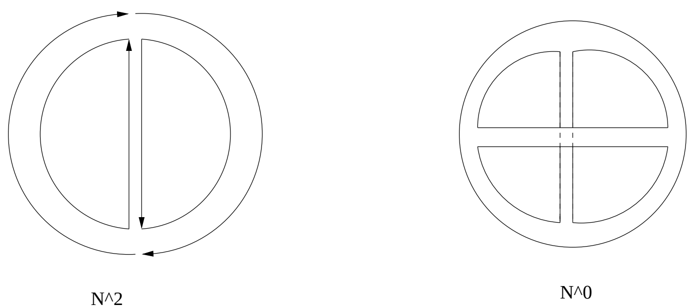
Motivation

• Regge behaviour of lightest hadrons of a given spin:
$m \sim TJ^2 + const. \to$ relativistic string.

• Lund string model description of hadronisation.



• 't Hooft limit of $SU(N)$: $N \to \infty$, $\lambda = g_{YM}^2 N$ fixed. Expansion in $1/N$?
Only planar diagrams contribute $\sim$ tree-level world-sheet of string! Identify $g_s = 1/N$



AdS/CFT correspondence: general idea

(some)CFT on d-dim flat space-time

is dual to

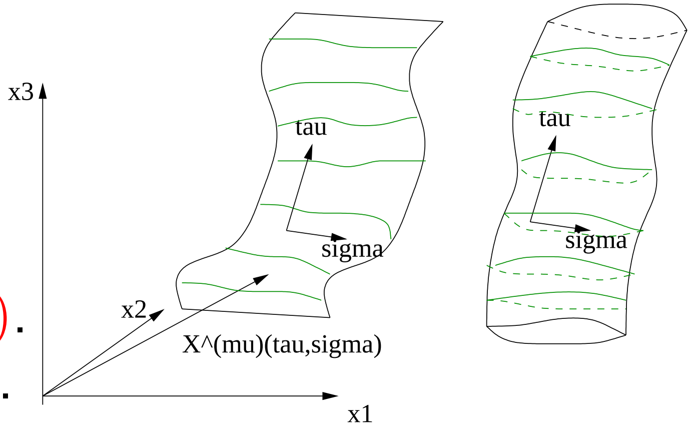
(some) string theory on (at least) d+1-dim AdS space-time.

- Strong/weak coupling duality
- Holography: CFT lives on boundary of 'string space-time'.

AdS/CFT correspondence: different sides

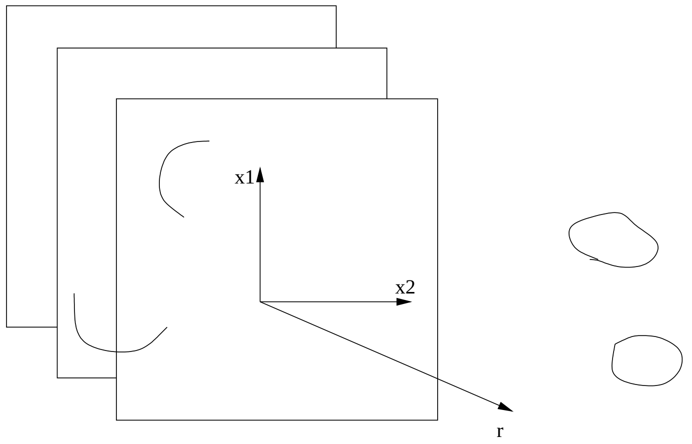
CFT: conformal field theory $\rightarrow$ scale-invariant (cf. QCD).
Prototypical example: $SU(N)$ SYM.
Field content: $A_\mu, \phi_i, \lambda_\alpha$.
Parameters: coupling g_{YM}, n:o of colours N, 't Hooft coupling $\lambda = g_{YM}^2 N$.
Symmetries: R-symmetry SO(6), Conformal symmetry SO(2,4), SUSY.

String theory: 1-dim objects, open or closed.
Oscillation modes $\sim$ Particle types.
World-sheet $(\tau, \sigma) \rightarrow X^\mu(\tau, \sigma)$.
Action (bosonic): $S = T \int d\tau d\sigma \partial_a X^\mu \partial^a X^\nu g_{\mu\nu}$
Parameters: coupling g_S (really a field), tension $T(\sim 1/\alpha')$.
5 string theories with fermions. SUSY. 10-dim space-time.



Let $g_{\mu\nu}$ be AdS$_5$ $\times$ S^5.
$ds^2 = r^2/R^2(-dt^2 + \sum_{i=1}^3 dx_i^2) + R^2 dr^2/r^2 + R^2 d\Omega_5^2$, R radius of AdS$_5$ and S^5.
Symmetries: AdS$_5$: SO(2,4), S^5: SO(6).

AdS/CFT: Prototypical example



Type IIB superstring theory

+ Stack of N coincident D3-branes.

$ds^2 = H^{-1/2}(-dt^2 + \sum_{i=1}^{3} dx_i^2) + H^{1/2}(dr^2 + r^2 d\Omega_5^2)$
with $H(r) = 1 + R^4/r^4$ and $R^4 = 4\pi g_s N \alpha'$,

Consider low-energy limit $E \ll 1/\sqrt{\alpha'}$: bulk and brane physics decouple.

Geometric/space-time description:
Energy measured at infinity (as in QFT): $E = H^{-1/4} E_r \leq E_r$
Two kinds of low-energy excitations:

- E_r small, r arbitrary $\rightarrow$ Bulk IIB supergravity.
- E_r arbitrary, r small $\rightarrow$ IIB superstring on near-brane geometry: $AdS_5 \times S^5$

String description: closed strings in bulk, open strings on brane.

- massless modes $\rightarrow$ IIB supergravity in 10-dim bulk.
- massless modes $\rightarrow$ $\mathcal{N} = 4$ SYM on 4-dim brane.

Testing the equivalence

Conjecture: $\mathcal{N} = 4$ SYM in flat 4-dim is dual to IIB superstring on $\mathrm{AdS}_5 \times \mathrm{S}^5$.

Dictionary: $g_s \sim g_{YM}^2$, $R^4/\alpha'^2 \sim g_{YM}^2 N$.
Symmetries match.

Perturbative YM: $\lambda = g_{YM}^2 N \ll 1$ (small coupling)
Supergravity: $R^4/\alpha'^2 \gg 1$ (flat space, small string length).
Calculable in non-overlapping regimes - duality.

Comparison problematic:
- CFT at strong coupling?
- String theory in curved space-times?

Test: compute things that are independent of coupling.
Result: string state energies $\leftrightarrow$ scaling dimension of operators.
$\Rightarrow$ String states $\Leftrightarrow$ Local operators.

So what?

This is a QCD course, after all.

- QCD is not conformal, α_s depends on energy scale.
- QCD is not supersymmetric.
- QCD has 3 colours, not infinitely many.

Can we generalise the procedure to find a string theory corresponding to QCD? E.g. introduce branes, compactify space etc.
Or, can we get qualitative QCD behaviour in some limit?
(Or, from string theorists' perspective, can QCD tell us something about strings?)

AdS/QCD correspondence

Gauge theory at large N should have a string theory description.

One way to get AdS/QCD:
Start with a $\mathcal{N} = (2, 0)$ SCFT in flat 6-dim, which is dual to M theory on $AdS_7 \times S^4$.
Compactify on $S^1 \times S^1$ and impose antiperiodic BC for fermions (breaks SUSY).
If $\Lambda_{QCD} \ll 1/R(S^1)$ we get pure QCD (only glue, N colours) on CFT side.

What happens on string theory side?
Compactification + M/string theory dualities $\longrightarrow$ Type IIA string on BH background.
Above: small curvature $\longrightarrow$ supergravity approx. valid.
Here: $R(S^1)$ need to be small.
Weakly coupled theories $\sim$ large curvatures $\Rightarrow$ strings on highly curved spaces?

However, in the the supergravity limit: confinement, mass gap, θ vacua and confinement-deconfinement transition at finite temperature. Seems promising?
Similar to lattice strong coupling expansion but Lorentz invariant.
Other deformations $\longrightarrow$ quarks fundamental representation, chiral symmetry etc.

Using AdS/CFT qualitatively

At momenta $\gg \Lambda_{QCD}$, QCD is almost conformal.
$\Rightarrow$ Study CFTs with AdS duals to learn stuff about QCD.

E.g. look at $\mathcal{N} = 4$ SYM in flat 4-dim. Break SUSY.
At small $\lambda = g_{YM}^2 N$, DIS physics is similar to that of QCD.

• Use OPEs to calculate form factors of hadrons. OK for small and large $\lambda = g_{YM}^2 N$.
• Use the AdS/CFT and recalculate on string theory side (large $\lambda = g_{YM}^2 N$).

Results agree:
• small coupling, few partons with high Bjorken-x. Scattering off pointlike partons.
• small coupling, many partons with very low Bjorken-x. Scattering off parton cloud/whole hadron.
Transition 'understood' from brane transition on string theory side.

Experimental tests of the AdS/QCD correspondence

Can the dual string theory explain experimental observations of low-energy/large-coupling QCD?
E.g. confinement, hadronisation etc.

QGP at RHIC: strongly coupled liquid, not weakly coupled gas.
• measured viscosity-to-entropy ratio ~ 0.1 (pQCD ~ 1).

• AdS/CFT $\Rightarrow$ low viscosity for strongly coupled $\mathcal{N} = 4$ SYM.

Possible interpretation: RHIC process is dual to string theory on AdS space-time with departing BH.

Summary

- AdS/CFT is a (conjectured) correspondence: gauge theories $\Leftrightarrow$ string theories.

- Weak/strong coupling duality.

- String theory side is easy at large N.

- Work in progress for QCD, but qualitative conclusions can be made (and tested with experiments).

References:

Aharony et al, Large N field theories, string theory and gravity. Phys.Rep. 323 (2000) 183-386.
di Vecchia, hep-th/990307.
Frampton, hep-th/0305160.
Maldacena, hep-th/0309246.
Polchinski et al, hep-th/0209211.
Shuryak hep-ph/0608177.