MPP Project Review

String Theory and Applications to Elementary Particle Physics

Johanna Erdmenger

Max Planck–Institut für Physik, München

Outline

1. String Theory at the MPP
2. String Theory and QCD
3. Future Prospects

Of great interest to string theory:

Possible experimental discovery of supersymmetry at colliders

Some research topics at Max Planck Institute

1. Deriving the Standard Model from String Theory,

   Vacuum Structure of String Theory

   Blumenhagen, Lüst, Honecker, Gmeiner, Weigand, Akerblom, Jeschek, Plauschinn, Moster ...

2. Cosmology and Supergravity

   Zagermann ...

3. QCD and String Theory

   Erdmenger, Apreda, Park, Sieg, Große, Höhne, Kaminski, Rust ...

Tsimpis, Sochichiu, Schmidt ....

QCD and String Theory

Aim:

To describe non-perturbative features of QCD

Using a new duality which originates from string theory

Chiral symmetry breaking, meson spectra, QCD at finite temperature

The AdS/CFT correspondence

(Maldacena 1997, AdS: Anti de Sitter space, CFT: conformal field theory)

- Duality Quantum Field Theory $\Leftrightarrow$ Gravity Theory
- Arises from String Theory in a particular low-energy limit
- Duality: Quantum field theory at weak coupling

  $\Leftrightarrow$ Gravity theory at strong coupling (and vice versa)

Conformal field theory in four dimensions

$\Leftrightarrow$ Supergravity Theory on $AdS_5 \times S^5$

Conformal field theory

Quantum field theory in which

the fields transform covariantly under conformal transformations

Conformal coordinate transformations: preserve angles locally

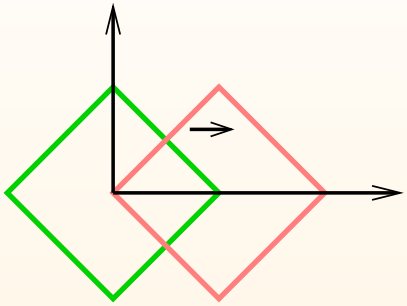
$\Rightarrow$ Correlation functions are determined up to a small number of parameters

$\beta = 0$

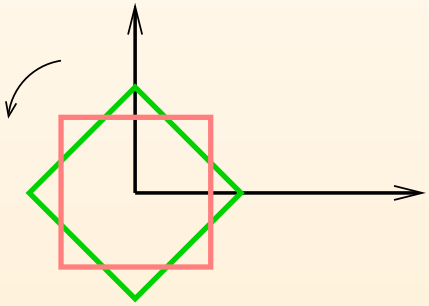
Confinement and conformal symmetry are incompatible!

Conformal coordinate transformations

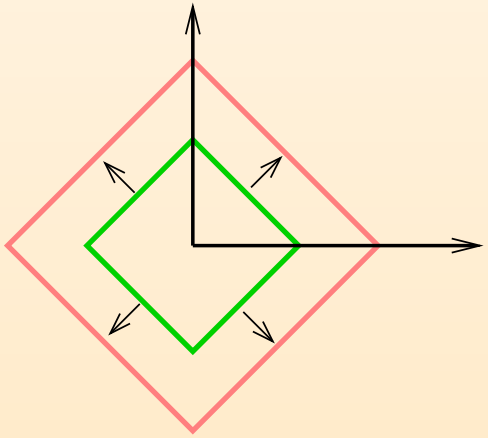
Translation

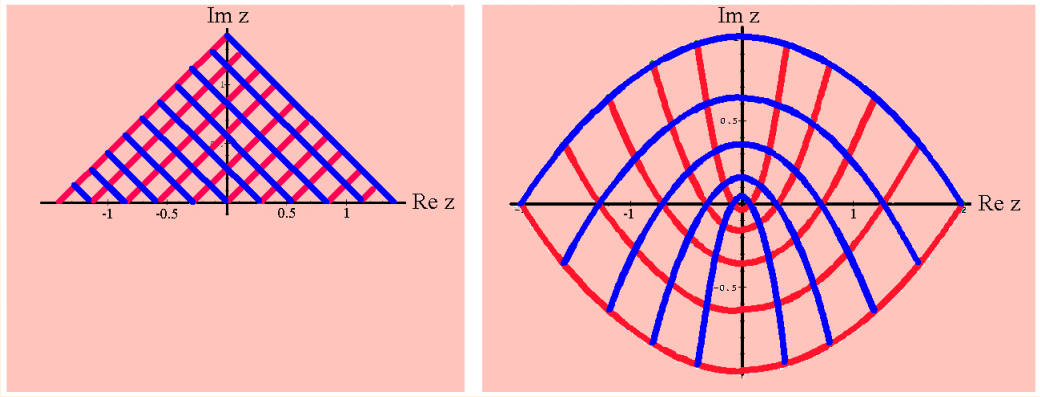


Rotation



Scale transformation

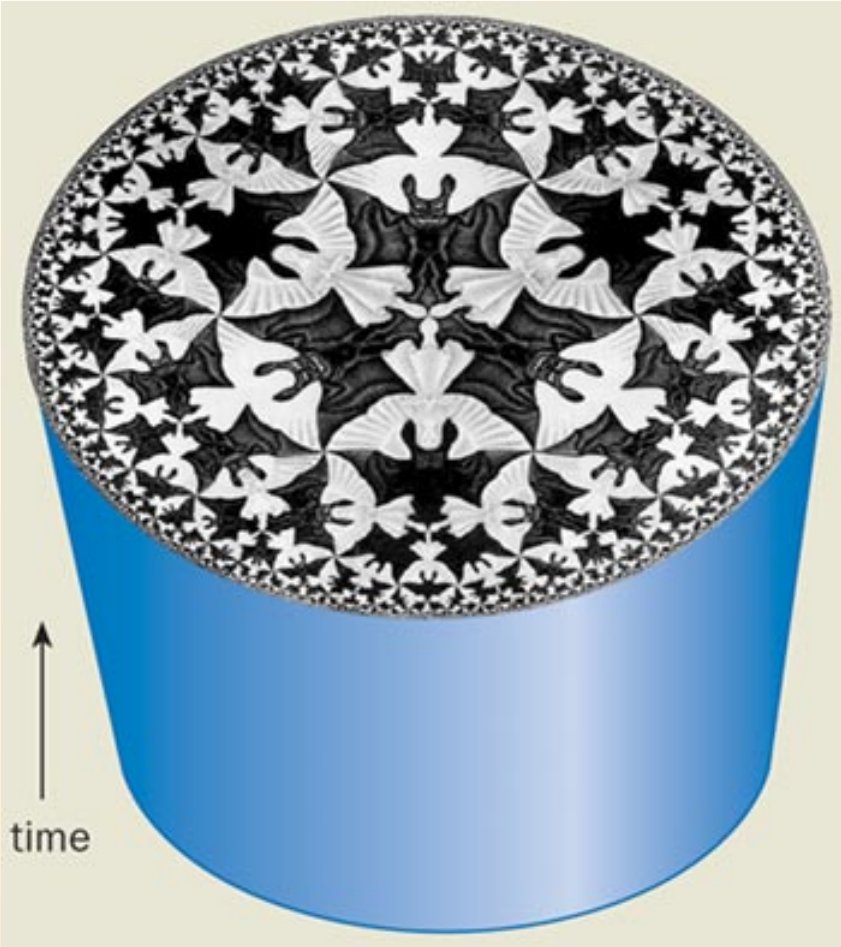




special conformal transformation

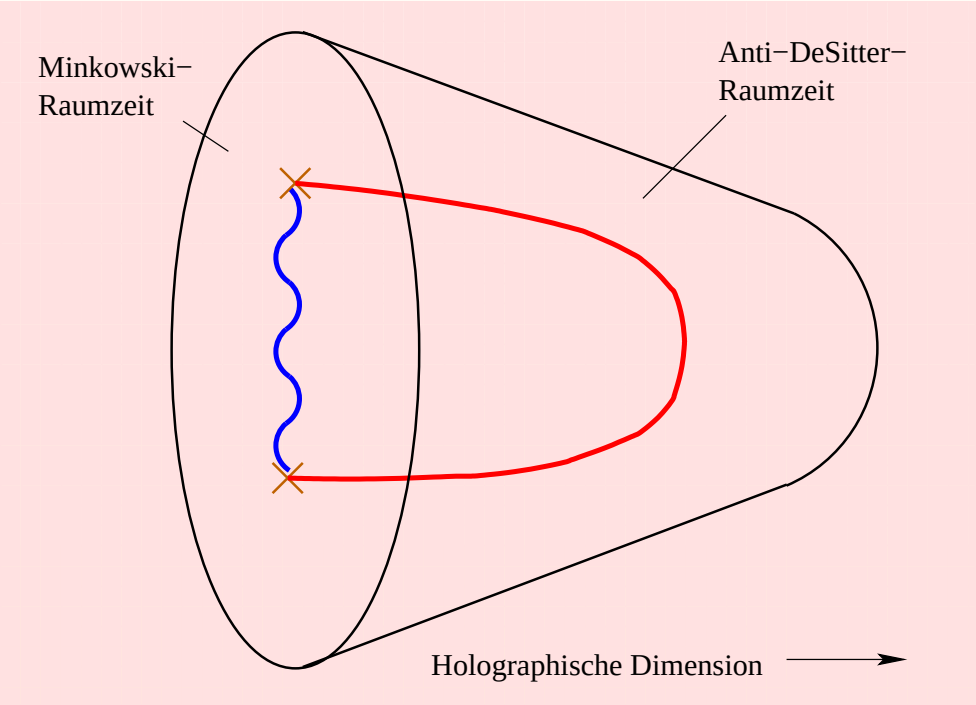
Anti-de Sitter Space

Space of constant negative curvature, has a boundary



Quelle: Institute of Physics, Copyright: C. Escher

AdS/CFT Correspondence



AdS/CFT correspondence:

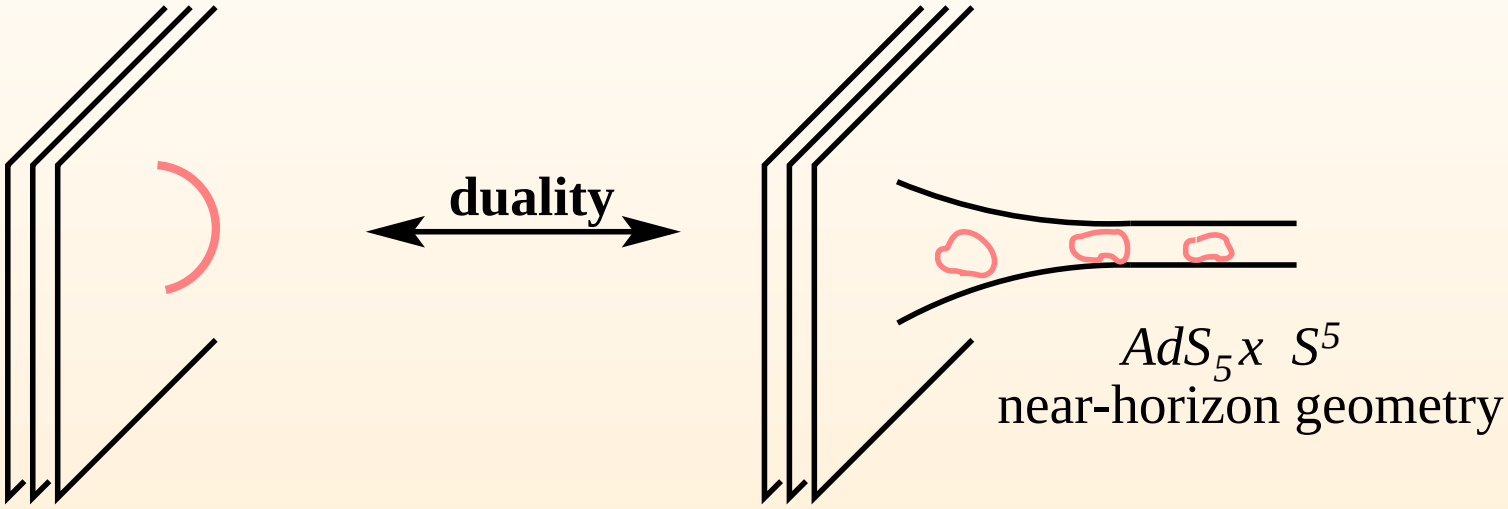
'Dictionary' Gauge invariant operators in field theory $\Leftrightarrow$ Fields in gravity theory

Symmetry properties coincide

Holography

String theory origin of AdS/CFT correspondence

D3 branes in 10d



$\Downarrow$ Low-energy limit

Supersymmetric $SU(N)$ gauge theory in four dimensions ($N \to \infty$)

Supergravity on $AdS_5 \times S^5$

Generalizations of the AdS/CFT correspondence

$\mathcal{N} = 4$ $SU(N)$ SUSY Gauge theory:

- $N \to \infty$
- Supersymmetry
- Conformal symmetry
- All fields in the adjoint representation of the gauge group

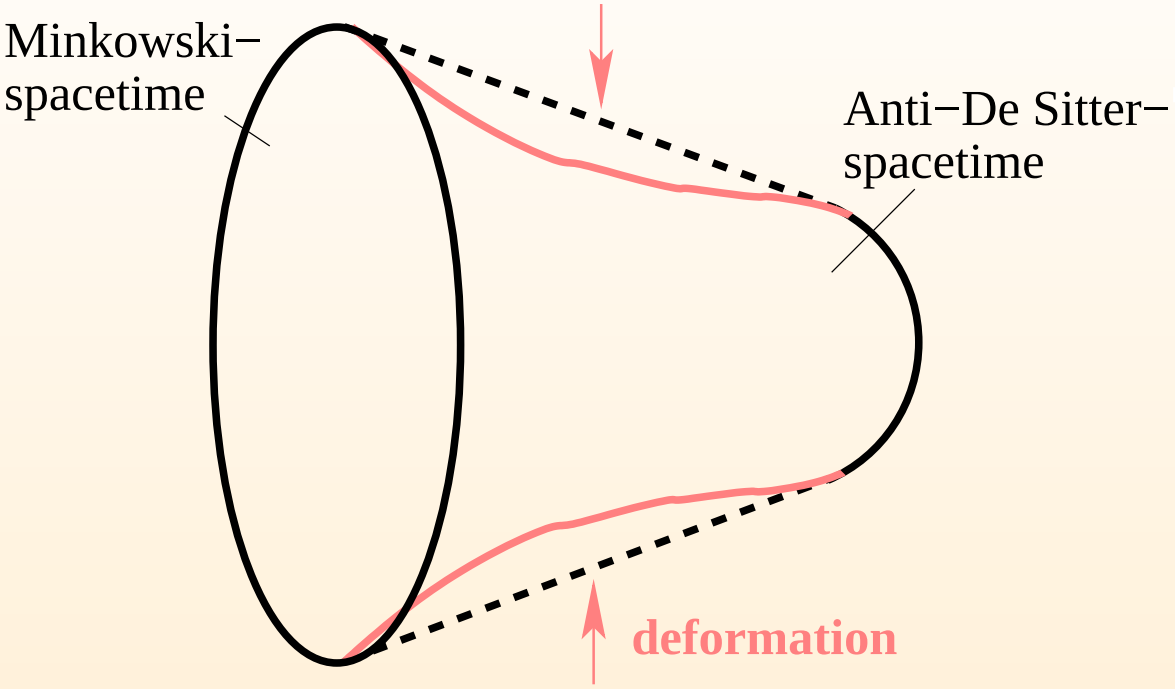
QCD:

- $N = 3$
- No supersymmetry
- Confinement
- Quarks in fundamental representation of the gauge group

Desirable extensions of AdS/CFT:

- Relax $N \to \infty$ limit ($1/N$ corrections) $\Leftrightarrow$ String theory instead of supergravity
- Break SUSY and conformal symmetry $\Leftrightarrow$ Deformation of AdS space
- Add quarks in fundamental representation of gauge group

Deformations of AdS space



Fifth Dimension $\Leftrightarrow$ Energy scale

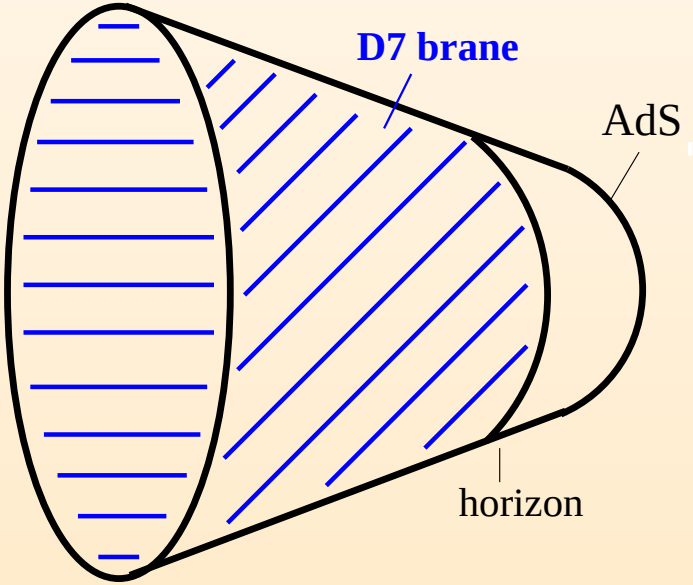
Renormalization group flow from supergravity

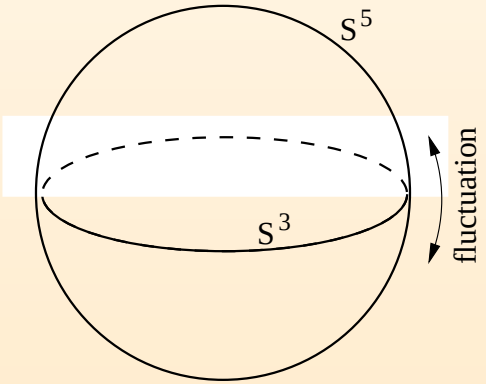
SUSY broken by deformation of S^5

Quarks (fundamental fields) within the AdS/CFT correspondence

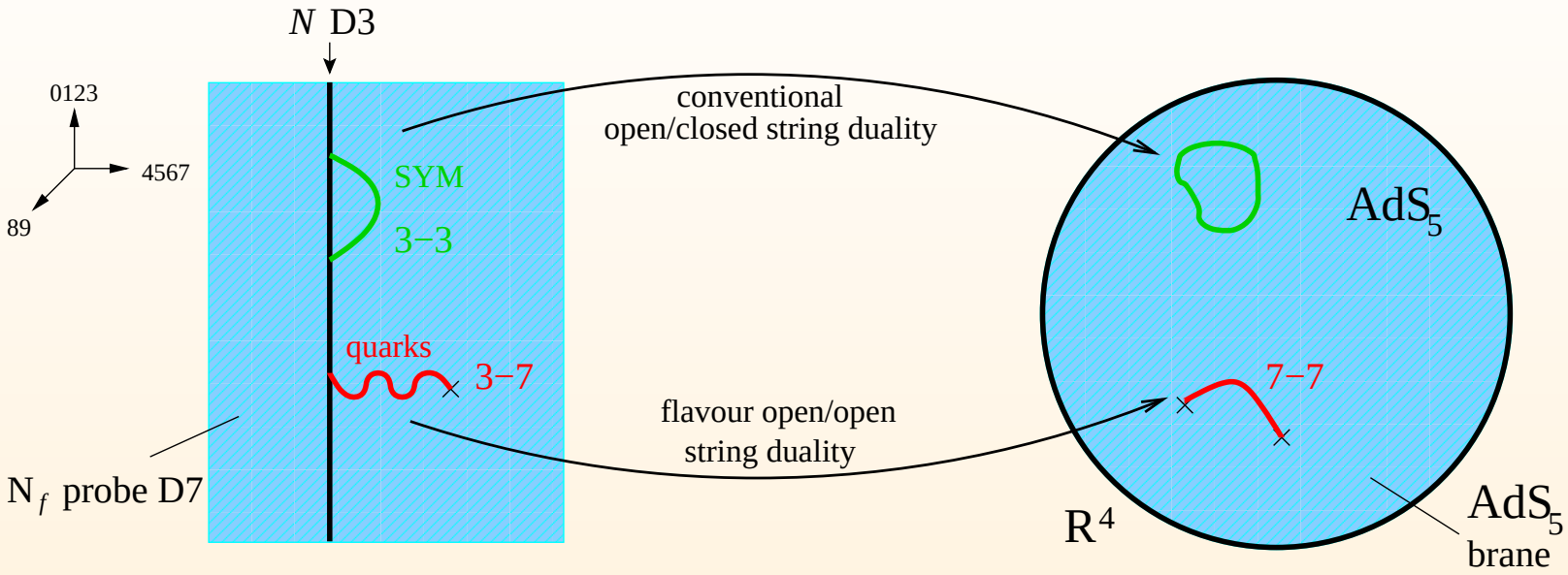
D7 brane probe:

	0	1	2	3	4	5	6	7	8	9
D3	X	X	X	X						
D7	X	X	X	X	X	X	X	X		





Quarks (fundamental fields) from brane probes



$N \to \infty$, N_f small (probe limit))

duality acts twice:

4d $\mathcal{N} = 4$ SU(N) SUSY gauge theory coupled to fundamental multiplet

$\longleftrightarrow$

Supergravity on $AdS_5 \times S^5$ + Dynamics of the probe brane on $AdS_5 \times S^3$

Quarks and Mesons

Quarks are introduced into AdS/CFT via the addition of brane probes

$N_f \ll N_c$, ($N_f = 1$ on our case)

Brane probes: Open strings between D3 branes and brane probe
$\Leftrightarrow$ Fundamental degrees of freedom in the field theory

Field theory described:

$$\mathcal{L} = \tfrac{1}{4} Tr\, F^{\mu\nu} F_{\mu\nu} + \tfrac{1}{2} \bar{\psi} \not{D} \psi$$

gauge group $SU(N)$

$U(1)_A$ symmetry: two Dirac fermions ψ_L, ψ_R; $\psi = \psi_L + \psi_R$

$$\psi_L \rightarrow e^{i\alpha} \psi_L \, , \psi_R \rightarrow e^{-i\alpha} \psi_R$$

chiral symmetry broken by condensate $\langle \bar{\psi} \psi \rangle$

Chiral symmetry breaking within generalized AdS/CFT

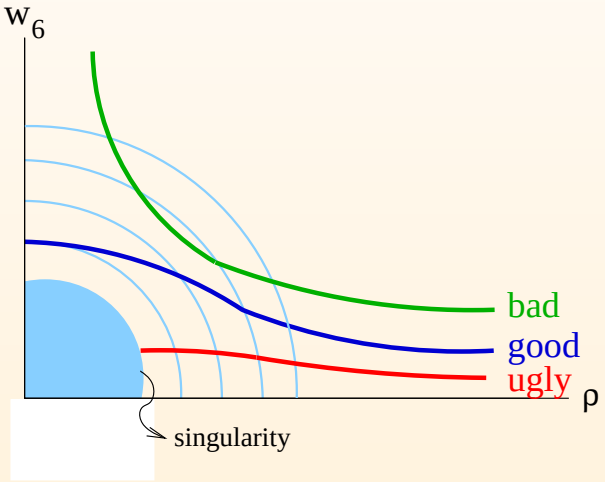
Combine the deformation of the supergravity metric

with the addition of brane probes:

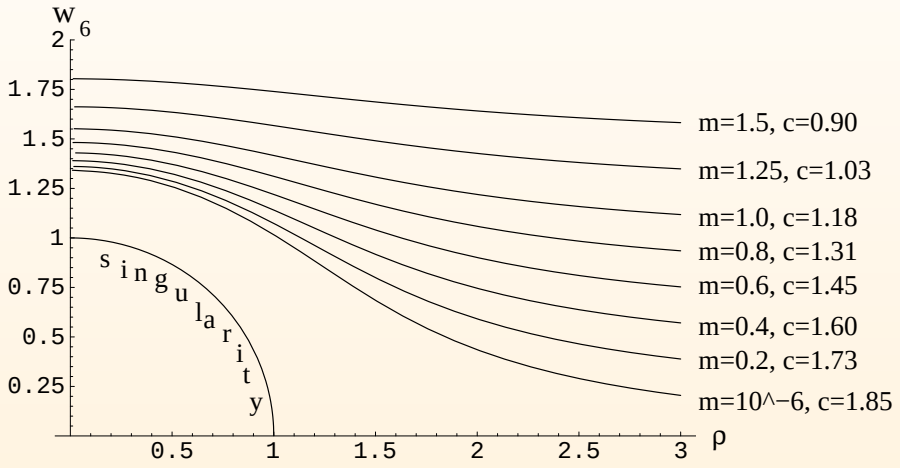
Dual gravity description of chiral symmetry breaking and Goldstone bosons

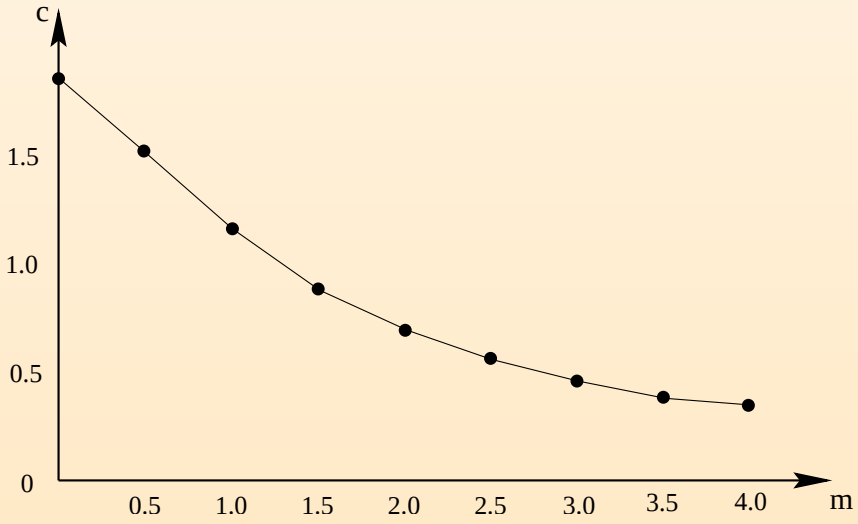
Chiral symmetry breaking

Solution of equation of motion for probe brane



Numerical Result:





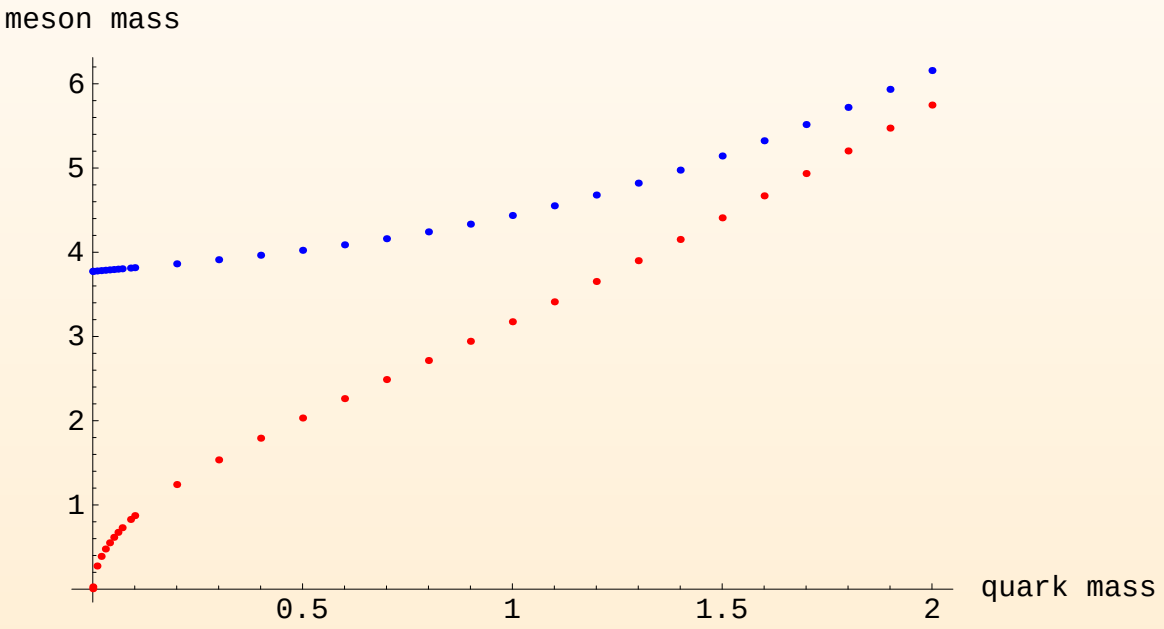
Result:

Screening effect: Regular solutions do not reach the singularity

Spontaneous breaking of $U(1)_A$ symmetry: For $m \to 0$ we have $c \equiv \langle \bar{\psi}\psi \rangle \neq 0$

Meson spectrum

From fluctuations of the probe brane



Goldstone boson (η')

Gell-Mann-Oakes-Renner relation: $M_{Meson} \propto \sqrt{m_{Quark}}$

Comparison to Experiment

$D4/D8/\bar{D}8$ brane model — Sakai+Sugimoto 12/2004

Vector and axial vector mesons ρ und a_1

(from gauge field fluctuations on the probe brane)

Meson mass ratio:

Experiment:

$$\frac{m_{a_1}^2}{m_\rho^2} = \frac{(1230MeV)^2}{(776MeV)^2} = 2.51$$

In string theory model:

$$\frac{m_{a_1}^2}{m_\rho^2} = 2.4$$

Comparison to Experiment

Current algebra result (Weinberg 1968):

$$\frac{m_{a_1}^2}{m_\rho^2} = 2.0$$

Conclusions

AdS/CFT correspondence: New and interesting relation between

quantum field theory and gravity .

Original version:

Strongly coupled supersymmetric conformal field theory in four dimensions

$\Leftrightarrow$

Weakly coupled Anti-de Sitter supergravity in five dimensions

The correspondence has been generalized to less symmetric theories:

RG flows to non-supersymmetric theories (at large N)

Conclusions

Addition of brane probes: Non-perturbative gravitational description of

- Fundamental matter (quarks)
- Spontaneous chiral symmetry breaking
- Goldstone theorem
- Light mesons

- Finite-temperature field theory

Outlook:

- Separation of SUSY breaking scale and Λ_{QCD}
- Fluxes
- Quark-gluon plasma
- B mesons
- Stringy version of composite Higgs model

Workshop ‘QCD and String Theory’, Ringberg Castle, July 2nd-8th 2006