Holographic QCD

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- Dilaton flow QCD
- Confinement
- Chiral symmetry breaking
- High temp. phase

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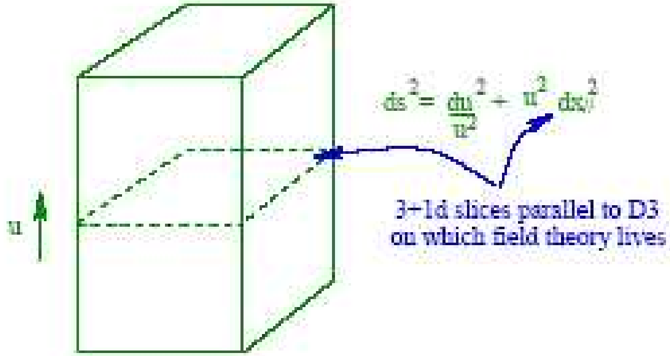
AdS/CFT Correspondence

Maldacena, Witten...

4d strongly coupled $\mathcal{N}$=4 SYM = IIB strings on $AdS_5 \times S^5$
(conformal)

Pretty well established by this point!



u corresponds to energy (RG) scale in field theory

The SUGRA fields act as sources

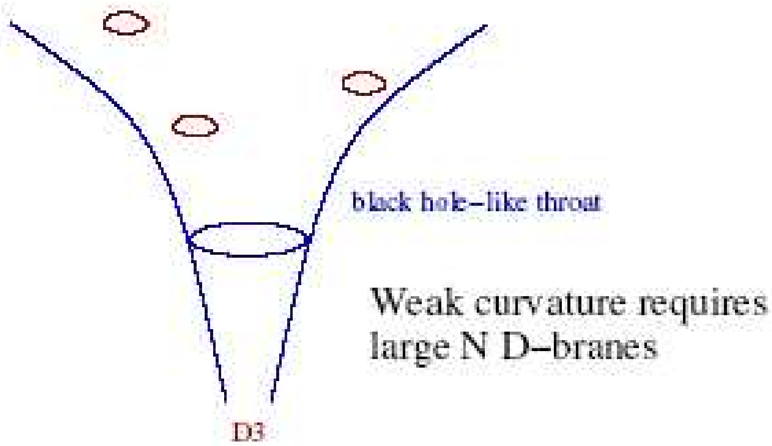
$$\int d^4x \; \Phi_{SUGRA}(u_0)\lambda\lambda$$

eg asymptotic solution ($u \to \infty$) of scalar

$$\varphi \simeq \frac{m}{u} + \frac{\langle\lambda\lambda\rangle}{u^3}$$

Brane Construction

A large N stack of D3 branes generates curvature like a black hole:



The Tension $\to \infty$ limit blows up the throat

$$ds^2 = u^2 dx_{//}^2 + \frac{du^2}{u^2} + d\Omega_5^2$$

This is $AdS_5 \times S^5$

In this limit higher dimension operators linking the gauge theory on brane and gravity fluctuations off are suppressed - the two descriptions decouple.

Towards Real QCD

4d strongly coupled $\mathcal{N}$=4 SYM = IIB strings on $AdS_5 \times S^5$

Technology:

- Deform - break conformal invariance, running coupling
- Deform - break supersymmetry
- Add quarks - D7 probes

The simplest deformation is to add in SO(6) preserving scalar masses:

$$m^2(\varphi_1^2 + \varphi_2^2 + \varphi_3^2 + \varphi_4^2 + \varphi_5^2 + \varphi_6^2)$$

You can not decouple superpartners so this is as close as you can get to QCD!

Dilaton Flow in 5d Supergravity

5d truncation ignoring the 5-sphere (SO(6) gauge symmetry)

$$S=\frac{1}{4\pi G_5}\int d^5x\sqrt{-g}\left(\frac{1}{4}R-\frac{1}{8}g^{ab}\nabla_a\phi\nabla_b\phi+V\right)$$

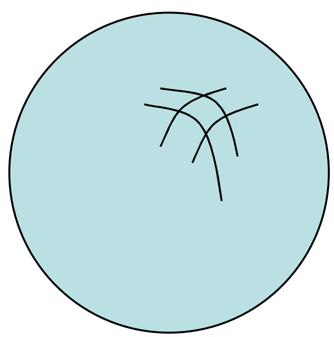
There are 42 scalars - a 20 of SO(6)

- a 10 and $\overline{10}$ of SO(6)

- scalar dilaton-axion, singlets of SO(6) – dual to $\frac{1}{g^2}F^{\mu\nu}F_{\mu\nu}$

$$m^2 Tr(\phi_1^2+...+\phi_6^2)$$

is invisible at supergravity level



These configs are dual to D3 5-balls – Gauss' law gives pure AdS background.

If we break susy though we expect all SO(6) singlets to switch on – there are non-trivial dilaton flows

$$\frac{1}{4}R_{ab} = \frac{1}{8}\partial_a\phi\partial_b\phi - g_{ab}$$
$$\nabla^2\phi = 0$$

$$ds_5^2 = e^{2A}\left(-e^{2B}dt^2 + dx_3^3\right) + dr^2$$

$$e^{4\bar{A}} = \frac{c_4^2 e^{8r} - c_3^2}{2c_4 e^{4r}}$$

$$\bar{B} = \frac{c_2}{4c_3}\ln\left(\frac{c_4 e^{4r} - c_3}{c_4 e^{4r} + c_3}\right) + B_0$$

$$\phi = \frac{c_1}{4c_3}\ln\left(\frac{c_4 e^{4r} + c_3}{c_4 e^{4r} - c_3}\right) + \phi_0$$

Analytic solutions that can be lifted to 10d supergravity

$$ds^2 = e^{\phi/2}\left(\frac{u^2}{L^2}\mathcal{A}^2(u)dx_4^2 + \frac{L^2}{u^2}du^2 + L^2 d\Omega_5^2\right)$$

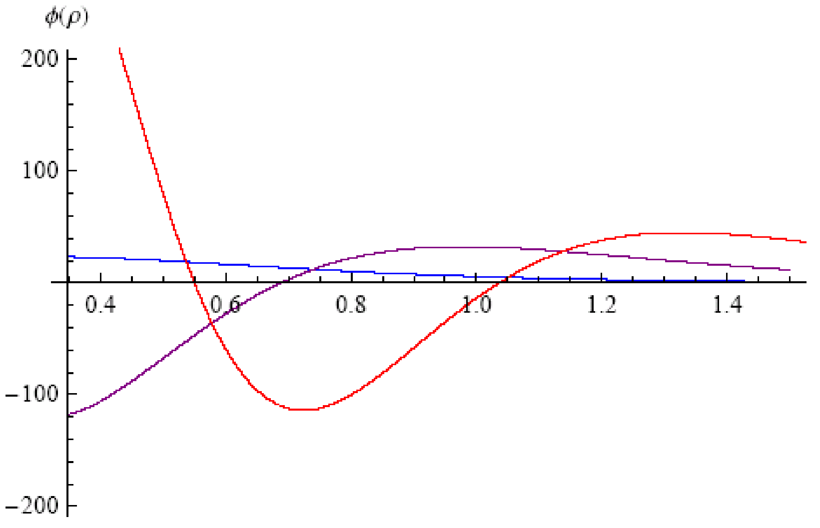
$$\mathcal{A}(u) = \left(1 - (\frac{u_0}{u})^8\right)^{\frac{1}{4}}, \qquad e^{\phi} = \left(\frac{(u/u_0)^4 + 1}{(u/u_0)^4 - 1}\right)^{\sqrt{3/2}}$$

Tr F^2 is non-zero

u_0 **is mass gap (position of D3 ball(?))**

We seek normalizable fluctuations in Tr F ^{2} / dilaton

$$\delta\phi = f(r) e^{-ikx}, \qquad k^2 = -M^2$$

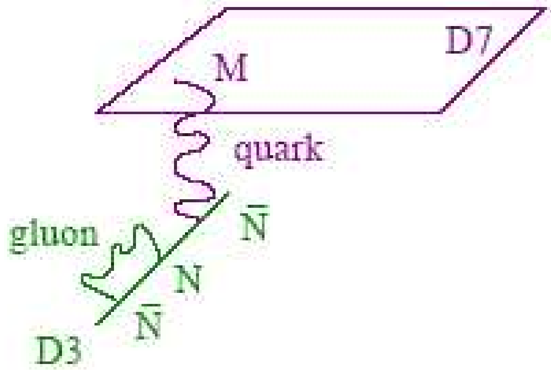


n	1	2	3	4	5
M_n	4.1	7.2	10.2	13.2	16.2

Table I: Lowest five glueball masses in the zero temperature dilaton flow geometry in units of the deformation scale u_0.

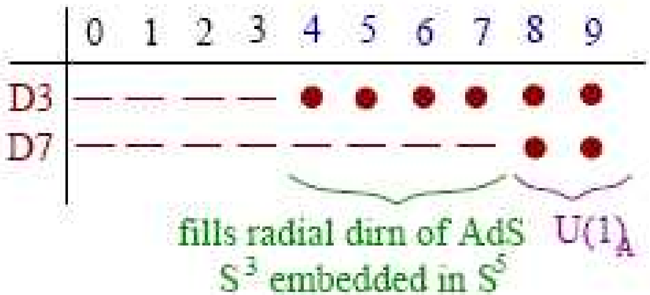
Adding Quarks

Bertolini, DiVecchia...; Polchinski, Grana; Karch, Katz...



Quarks can be introduced via D7 branes in AdS

The brane set up is



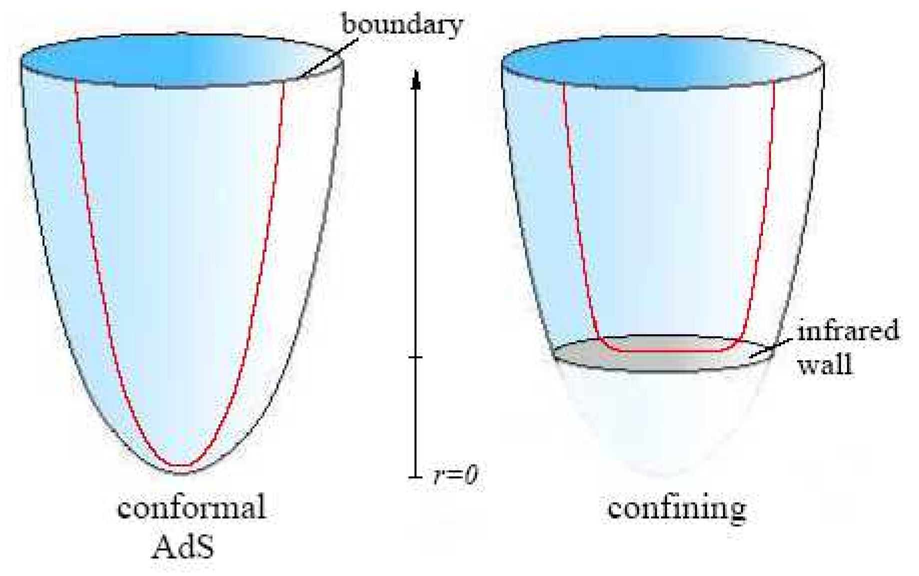
We will treat D7 as a probe - quenching in the gauge theory.

Minimize D7 world volume with DBI action

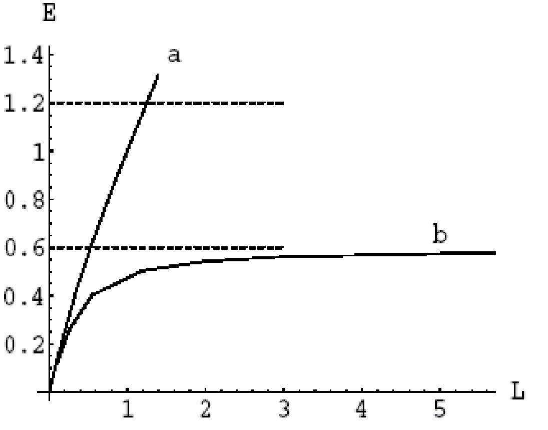
$$S_{D7} = -T_7 \int d\xi^8 \sqrt{P[G_{ab}]}, \qquad P[G_{ab}] = G_{MN} \frac{dx^M}{d\xi^a} \frac{dx^N}{d\xi^b}$$

The interaction energy between a quark and an anti-quark is given by embedding a string in the space:

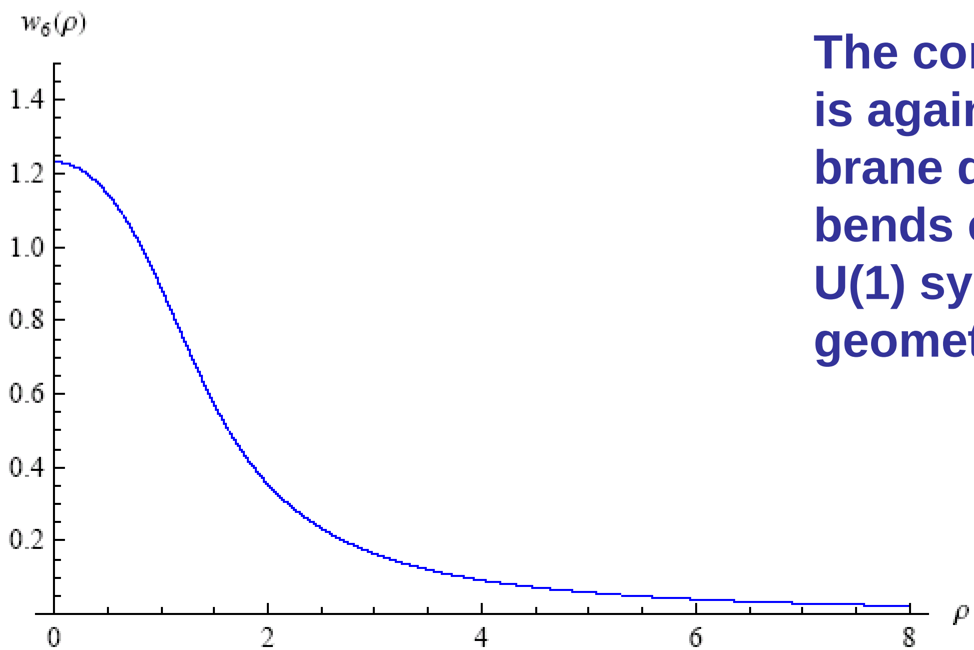
D7



The singularity repels the string and it lies along the wall – a linear potential emerges



This theory has a U(1) symmetry that is dynamically broken by a quark condensate



The core of the geometry is again repulsive - the D7 brane does not lie flat but bends explicitly breaking a U(1) symmetry of the geometry

$$\phi = m + \frac{c}{r^2} + \ldots$$

$$\langle \bar{q} q \rangle = 1.51 u_0^3$$

Meson Masses

We seek normalizable fluctuations of the D7

$$\delta\phi = f(r)e^{-ikx}, \qquad k^2 = -M^2$$

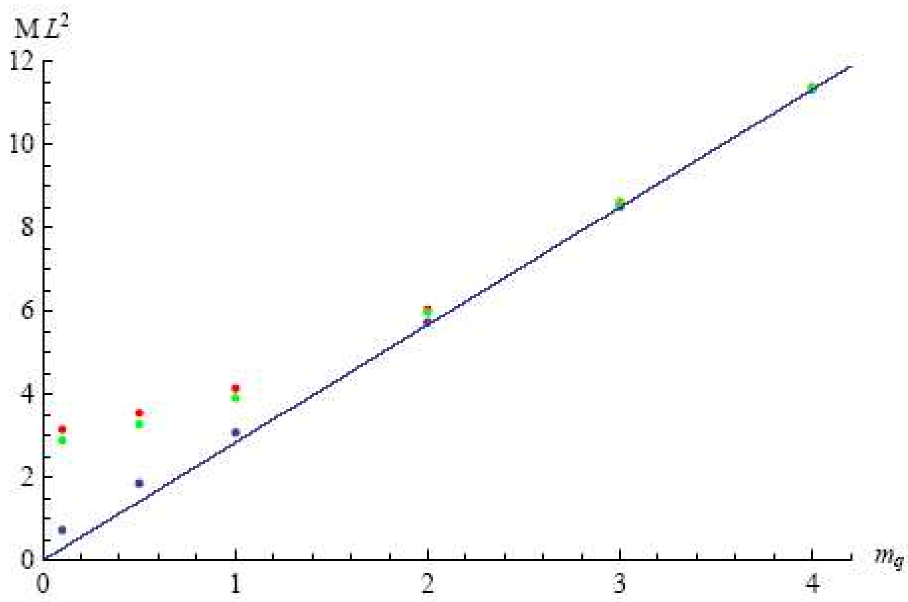


FIG. 1: Pion (blue), sigma (red) and vector (green) masses as a function of quark mass - all in units of u_0. The line shows the large-m_q limit.

Massless Goldstone

Massive sigma and rho mesons

As in all AdS duals these states are tightly bound

m ~ 1/ lambda$^{1/2}$

High Temperature Phase

The duals of high T gauge theories are black holes – their free energy scales like N^2 (Witten)

Analytically can show there is no black hole with dilaton hair – the only black hole in 5d supergravity is AdS-Schwarzchild

$$ds^2 = \frac{K(u)}{L^2} d\tau^2 + L^2 \frac{du^2}{K(u)} + \frac{u^2}{L^2} dx_4^2 + L^2 d\Omega_5^2 \qquad K(u) = u^2 - \frac{u_h^4}{u^2}$$

We conclude that Tr F^2 switches off at high T

Presumably the scalar mass is still there but invisible….

The Thermal Phase Transition

We can compare the free energies of the dilaton flow geometry (with compact Euclidean time) and the black hole

$$S_{DF} = \frac{1}{2G_5 L^2} \int_0^{\frac{\pi L^2}{u_h}\sqrt{1-\frac{u_h^4}{\Lambda^4}}} d\tau \int_{u_0}^{\Lambda} \sqrt{-g}\, dr$$

$$S_{BH} = \frac{1}{2G_5 u_h L^3} \int_{u_h}^{\Lambda} u^3 du = \frac{1}{8G_5 u_h L^3} (\Lambda^4 - u_h^4)$$

$\Lambda \to \infty$ limit

$$S_{BH} - S_{DF} = \frac{1}{16 G_5 u_h L^3} (4u_0^4 - u_h^4)$$

A first order transition

$$T_c = \frac{\sqrt{2} u_0}{\pi L^2}$$

$$T_c \sim 124 \text{ MeV}$$

(fixing the rho mass)

At the supergravity level this non-supersymmetric theory and the N=4 theory share the same supergravity dual

Regular glueball and meson solutions are replaced by in-falling quasi-normal modes… the bound states decay into the thermal bath

(Hoyos.., Myers…, Peeters…)

n	ω_n
1	$\pm$ 2.1988 - 1.7595 i
2	$\pm$ 4.2119 - 3.7749 i
3	$\pm$ 6.2155 - 5.7773 i
4	$\pm$ 8.2172 - 7.7781 i
5	$\pm$ 10.2181- 9.7785 i

Table IV: the scalar mesonic quasinormal frequencies in the high T phase ($m_q = 0$) - in units of $\frac{u_h}{L^2}$.

ratio of viscosity to entropy density $\frac{\eta}{s} = \frac{1}{4\pi}$

(Son, Starinets,Policastro)

Summary

Dilaton Flow QCD is a holographic model with

- **Confinement**
- **Mass gap**
- **A quark condensate**
- **A massless pion & a massive rho**
- **A thermal deconfinement transition**
- **Meson melting at high T**

A review:

arXiv:0711.4467 [hep-th]

Also

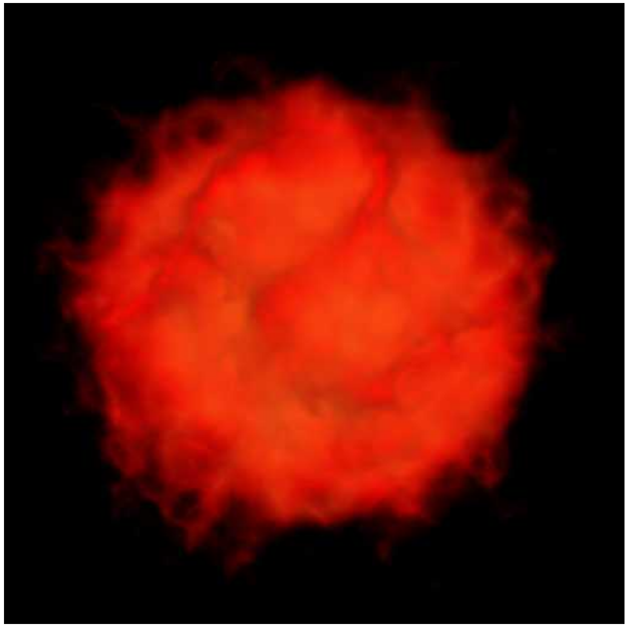
arXiv:0805.0956 [hep-th]

It is derived from the AdS/CFT Correspondence so describes a real gauge theory and contains the DYNAMICS for all this physics (unlike AdS/QCD)

(Sakai-Sugimoto has in addition a non-abelian chiral symmetry but at the expense of being fundamentally five dimensional)

Hadronization

The hadron's emerging in an electron positron collider are not understood from first principles

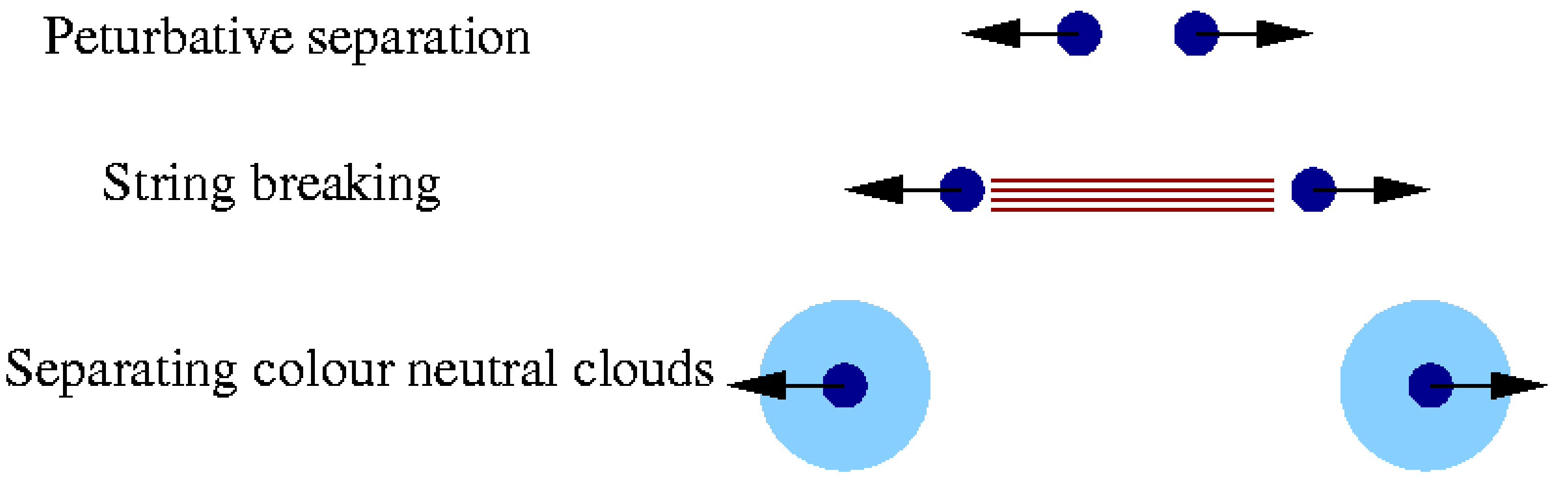


Hadron	Measured
π^+	8.53
π^0	9.18
$K+$	1.18
K^0	1.015
η	0.934
ρ^0	1.21
K^{*+}	0.357
K^{*0}	0.372
η'	0.13
p	0.488
Λ	0.185

Total > 38 particles!

Monte Carlo event generators are tuned to data.

Philosophy



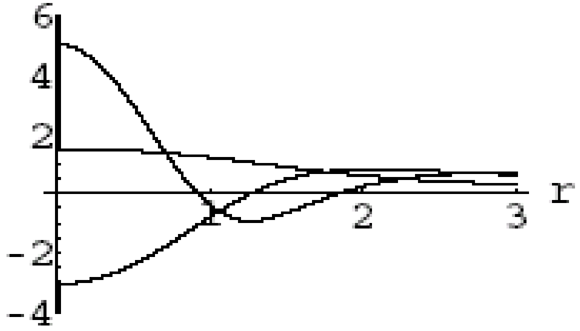
Our model will come down to matching conditions at the point of hadronization… we will argue a simple ansatz does a good job of matching the data

We will dump energy into the holographic model's stress energy tensor and see how it evolves into hadrons

We will assume all hadronic species are equally accessible to production

Rho production

The rho is described by a gauge field in 5d. There are a set of orthogonal functions $g_n(r)e^{ik_nx}$



Hadron	Experiment (MeV)	AdS/QCD (MeV)
ρ	776	776
ρ^*	1459	**1742**
ρ^{**}	1720	**2533**
ρ^{***}	1900	**3305**
ρ^{****}	2150	**4059**

If we expand a Gaussian (centred on r=0, width 300MeV) initial condition in terms of these basis functions

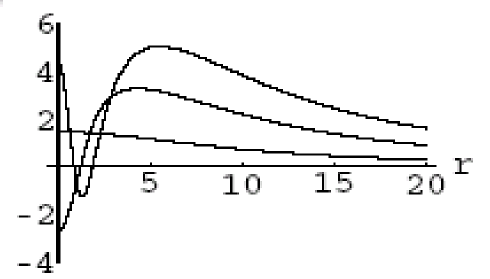
$$c_n = \int_0^\infty \Psi(r)\, w(r) g_n(r) dr$$

We obtain the yields (c_n^2): rho 15 rho* 3 rho 0….**

A Complete Toy

We have basis functions

for pseudo-Goldstones…



To do the whole QCD spectra (127 pts with mass below 1.7 GeV) we rescale r coordinate by m_{hadron} $/m_{rho}$ – the Gaussian does not stretch and we see a suppressed yield.

Spin factor of (2J+1) on production rates

Fit parameters

Gaussian Width

Gaussian Height

The stress energy tensor contributions (rho vs pion) in our holographic model depends on the 'tHooft coupling (AdS radius R) – we fit it.

Decay in Transit

Most of these will decay in transit to the detector…. We use branching ratios from experiment (pdg via HERWIG) to get final yields

EG

The average results from a phi (1020) decay….

	phi
	1020
	0
pi0	0.0443
pi+	0.07
pi-	0.07
K+	0.48947
K-	0.48947
K0	0.34
Kbar0	0.34
eta	0.0126
rho0	0.043
rho+	0.043
rho-	0.043
omega	0
f0(600)	0
K*+	0
K*-	0
K*0	0
K*bar0	0

Final LEP Yields

Parameters

Width = 150 MeV

γ_s **= 0.97**

R = 2.6

Average E = 5.0 GeV

Hadron	Model	Expt
π^+	5.95	8.5
π^0	6.43	9.2
K^+	1.09	1.2
K^0	1.09	1.0
η	1.06	0.93
ρ^0	1.33	1.2
K^{*+}	0.387	0.36
K^{*0}	0.385	0.37
η'	0.042	0.13
p	0.41	0.406
ϕ	0.03	0.1
Λ	0.172	0.19
$\frac{\Sigma^{*+}+\Sigma^{*-}}{2}$	0.0120	0.0094
Ξ^-	0.012	0.012
Ξ^{*0}	0.0040	0.0033
Ω	0.0011	0.0014

Decent match across orders of magnitude in production rates..

RMS of fit 37%

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Holographic duals of gauge theories with

- **Confinement**
- **Mass gap**
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- **A massless pion & a massive rho**
- **A thermal deconfinement transition**
- **Meson melting at high T**

A review:

arXiv:0711.4467 [hep-th]

Also

arXiv:0805.0956 [hep-th]

We seem to shed some light on hadronization multiplicities….

arXiv:0711.0300 [hep-ph]