Successes and Failures of AdS/QCD "beyond supergravity"

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Outline

1. Motivation
2. AdS/QCD and the hard wall model
3. A more complete framework
4. Results

AdS/QCD

- Higher dimensional dual models, inspired by AdS/CFT
- Powerful method for tackling strongly coupled QCD
- Reproduce part of the low-lying meson spectrum and decay constants (within ~15%)
- Relatively few tunable parameters*
- Naturally incorporate features of existing models (hidden local symmetry, vector meson dominance, etc.)

Problems with AdS/QCD

- Do not consistently include all modes and interactions relevant to QCD and present in the *string* dual description

meson	J	P	C	I	m in MeV
$\pi^{\pm}/\pi^0$	0	-1	$-1/+1$	1	$140/135$
ρ	1	-1	-1	1	775
b_1	1	$+1$	-1	1	1230
a_1	1	$+1$	$+1$	1	1230

- Rho spectrum matches poorly:

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- Rho spectrum matches poorly:

h.w.: $$m_\rho^{(n)} = 832 \text{ MeV}, \; 1910 \text{ MeV}, \; 2994 \text{ MeV} \; \ldots$$

expt: $$m_\rho^{(n)} = 775.49 \text{ MeV}, \; 1465 \text{ MeV}, \; 1720 \text{ MeV} \; \ldots$$

Problems with AdS/QCD

- In other words: large N, large λ is not QCD

AdS | QCD

AdS radius of curvature

$$\frac{\ell^4}{\alpha'^2} = N_c g_{YM}^2 = \lambda_{'tHooft}$$

Yang-Mills coupling

g_s corrections $\longleftrightarrow$ $1/N_C$ corrections

α' corrections $\longleftrightarrow$ $1/\lambda$ corrections

- Sugra limit: Regge trajectories have zero slope
- QCD: Regge trajectories have slope 0.88 GeV^{-2}

Our goals

SKD, J. Harvey, A. Royston [1101.3315;1210.651]

- Extend AdS/QCD (hard wall)
  - to be complete up to a1 mass (including b1)
  - to improve matching to higher ϱ excitations
  - to include all dimension 3 operators

To (boldly) go beyond supergravity:
what can we learn about AdS/QCD (and QCD)
by addressing these issues?

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Approaches to AdS/QCD

- "Top-down" models
    - sugra dual (usually with D-branes) from 10d string theory [Sakai & Sugimoto; Myers & Thompson; Sonnenschein & Kuperstein; ...]
    - fewer free parameters; guaranteed field theory dual
- "Bottom-up" models [Erlich, Katz, Son, Stephanov 2005; da Rold, Pomarol 2005; Karch, Katz, Son, Stephanov 2006]
    - pick confining background
    - include operators relevant to low-energy phenomena
    - toy model to go beyond supergravity approximation

Hard-wall Model

[Erlich, Katz, Son, Stephanov; Da Rold, Pomarol]

- Bottom-up model
- Gravity background: AdS truncated at finite radius

$$ds^2 = \frac{\ell^2}{z^2}\left(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2\right) \quad \text{with} \quad z \in (\underset{\text{UV}}{\epsilon}, \underset{\text{IR}}{z_0})$$

- ℓ : AdS radius
- z : (roughly) energy scale with $\Lambda_{QCD} \sim z_0^{-1}$
- Truncated radial coordinate : discrete spectrum

Operator/Field Content

QCD Operator	naive Δ		AdS Field	$m^2 l^2$
$J^a_{R\mu} = \bar{q}_R \gamma^\mu T^a q_R$	3	$\longleftrightarrow$	$A^a_{R\mu}(x,z)$	0
$J^a_{L\mu} = \bar{q}_L \gamma^\mu T^a q_L$	3	$\longleftrightarrow$	$A^a_{L\mu}(x,z)$	0
$\bar{q}^\alpha_R q^\beta_L$	3	$\longleftrightarrow$	$X(x,z)$	-3

$U(N_f)$
generator

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$U(N_f)$ generator

...often work in terms of $V^a_\mu = \frac{1}{2}\left(A^a_{L\mu} + A^a_{R\mu}\right)$ and $A^a_\mu = \frac{1}{2}\left(A^a_{L\mu} - A^a_{R\mu}\right)$

J_V conserved

J_A not conserved

$\bar{q}^\alpha_R q^\beta_L$	3	$\longleftrightarrow$	$X(x,z)$	-3

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mesons		$\longleftrightarrow$	normalizable modes	

Hard-wall action

- Hard wall action:

$$S_{hw} = \int d^4x dz \sqrt{g}\, \mathrm{Tr}\left[-\frac{1}{2\ell g_5^2}\left(F^{(V)2} + F^{(A)2}\right) + |DX|^2 - \frac{m_X^2}{\ell^2}|X|^2\right]$$

- m_X and scaling dimension related by $\Delta(\Delta - 4) = m_X^2 \ell^2$

- Chiral symmetry broken when X takes on a vev:

$$X_0 = \mathbf{1} \cdot \frac{1}{2\ell^{3/2}}\left(m_q \ell^{\Delta-3} z^{4-\Delta} + \frac{\sigma \ell^{3-\Delta}}{2(\Delta - 2)} z^{\Delta}\right)$$

non-normalizable

normalizable

- Free parameters: $g_5,\ m_X,\ z_0,\ m_q,\ \sigma$

- Original hard wall: fix g_5 and m_X from perturbative QCD

- Nice results for lowest resonances!

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Our goals

- Motivated by phenomenology extend the hard wall
  - b_1 states
  - better fit for heavier rhos
- Include all (naive) dimension 3 QCD operators
- Add interactions
  - break chiral symmetry
  - break degeneracy of 1^{--} and 1^{+-}

The Missing Mode

[Imoto, Sakai, Sugimoto; Cappiello, Cata, D'Ambrosio; SKD, J. Harvey, A. Royston]

- Naive dimension 3 operators in QCD:

$$\bar{q}T^a q \qquad \bar{q}T^a\gamma^5 q \qquad \bar{q}T^a\gamma^\mu q \qquad \bar{q}T^a\gamma^\mu\gamma^5 q \qquad \bar{q}T^a\sigma^{\mu\nu} q$$

- $O^T_{\mu\nu} \equiv \bar{q}T^a\sigma^{\mu\nu}q$ can create both 1^{--} and 1^{+-} resonances [Chizhov; Shifman; Glozman]:

$$\langle 0|O^T_{\mu\nu}|b_1^{(n)}(k)\rangle = \frac{i}{\sqrt{2}} f_b^{(n)}\ \epsilon_{\mu\nu\alpha\beta}\ \varepsilon^{\alpha}_{(b)}k^\beta$$

$$\langle 0|O^T_{\mu\nu}|\rho^{(n)}(k)\rangle = \frac{i}{\sqrt{2}} f_{\rho T}^{(n)}\ (\varepsilon_{(\rho)\mu}k_\nu - \varepsilon_{(\rho)\nu}k_\mu)$$

- New type of ϱ^T meson in different rep. of flavor group than ϱ generated by J_V: they mix when χsb

How do we realize this operator in (bottom-up) holography?

1. Identify the dual field with appropriate degrees of freedom, scaling dimension, transformation properties (e.g. global symmetry in field theory gives gauge symmetry in dual)

2. Write down the Lagrangian (will include some arbitrary parameters)

3. Identify appropriate boundary conditions at IR boundary (issue specific to hard-wall)

4. Add interactions (to implement χsb)

5. Make predictions, fix undetermined parameters: how do we do?

Dual Field

- Source O^T with a two-form field in **bifundamental** of **flavor** symmetry group: b_{MN}
    - Must be **complex**
- Must yield total of 3+3=6 physical degrees of freedom
- Naively b_{MN} has **twice** the number of d.o.f. we need!

$$20 - 8 = 12$$

generic complex two-form

Proca-like condition

First order action

- NO tensor gauge invariance needed (doesn't work anyway)
- Known solution from IIB sugra on $AdS_5 \times S^5$: first order action

$$S_{b0} = -\frac{i\,\mathrm{sgn}(\mu)}{2\ell g_b^2} \int_{\mathcal{M}} \mathrm{Tr}\left[\bar{b} \wedge \left(D - i\frac{\mu}{\ell}\star\right) b - b \wedge \left(D + i\frac{\mu}{\ell}\star\right) \bar{b}\right] + S_{\partial\mathcal{M}}$$

- Add boundary action for consistent variational principle [c.f. Arutynov & Frolov, 1998]

$$S_{\partial\mathcal{M}} = -\frac{1}{4\ell g_b^2} \int_{\partial\mathcal{M}} \mathrm{Tr}\, \bar{b}_{\mu\nu} b^{\mu\nu}$$

- in pure $AdS_5 \times S^5$ (i.e. CFT): $\Delta_T = 2 + |\mu| \quad \rightarrow \quad \mu = \pm 1$

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to be determined

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Free equations of Motion

$$\boxed{\left(d - i\frac{\mu}{\ell}\star\right) b = 0}$$

- $b_{\mu z}$ is a Lagrange multiplier
- Project on (anti) self-dual parts of b: $\quad b^{\pm}_{\mu\nu} = \pm\frac{i}{2}\epsilon_{\mu\nu}{}^{\rho\sigma} b^{\pm}_{\rho\sigma}$
- Independent second order equations for $b^{\pm}$

$$\left[z^2\partial_z^2 - z\partial_z + k^2 z^2 - \mu(\mu \pm 2)\right] b^{\pm}_{\mu\nu} = 0$$

4d transverse/
longitudinal projectors

- But related by

$$b^{\mp}_{\mu\nu} = \frac{2}{k^2 z^2}\left(\pm\partial_z + \mu^2 - \frac{1}{2}k^2 z^2\right)\left[\left(P^{\perp} - P^{\parallel}\right) b^{\pm}\right]_{\mu\nu}$$

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Total of 6 d.o.f.

IR boundary conditions (part I)

- No obvious hint from QCD
- (z=z_0) boundary condition: restrict to having normalizable and non-normalizable polarizations proportional to each other
  - any other choice explicitly breaks Lorentz invariance

to be determined from IR data

$$b^{+}_{\mu\nu}(k,z) = \tilde{S}_{\mu\nu}(k)\left[zJ_{-\mu-1}(kz) - \boxed{c_b(k,z_0)}\,zJ_{\mu+1}(kz)\right] \equiv \tilde{S}_{\mu\nu}(k)B^{+}(k,z)$$
$$b^{-}_{\mu\nu}(k,z) = \tilde{A}_{\mu\nu}(k)\left[zJ_{-\mu+1}(kz) - \boxed{c_b(k,z_0)}\,zJ_{\mu-1}(kz)\right] \equiv \tilde{A}_{\mu\nu}(k)B^{-}(k,z)$$

Two-point function and IR Boundary Conditions (part II)

- Two-point function:

to be determined from IR data

$$\Pi^{T,T\perp}_{(\mu>0)}(k) = \begin{cases} -\frac{\mathrm{sgn}(\mu)\Gamma(-\mu)}{2^{2\mu-2}g_b^2\ell^2\Gamma(\mu)}\boxed{c_b(k,z_0)}(k\ell)^{2\mu-2} & (\mu \text{ non-integer}) \\ -\frac{\mathrm{sgn}(\mu)}{2^{2\mu-2}g_b^2\ell^2\mu!(\mu-1)!}\left[\log\left(k^2\ell^2\right)+\pi\boxed{c_b(k,z_0)}\right](k\ell)^{2\mu-2} & (\mu \text{ integer}) \end{cases}$$

- Use *k=0* limit to determine physically consistent IR boundary conditions

- Spectrum says: no massless pole!

IR boundary condition

- Two options: $b^{+}(z_0)=0$ or $b^{-}(z_0)=0$ (neglecting additional IR boundary terms)

$$c_b(k,z_0) = \begin{cases} \frac{J_{-\mu-1}(kz_0)}{J_{\mu+1}(kz_0)} & b^+(z_0)=0 \\ \\ \frac{J_{-\mu+1}(kz_0)}{J_{\mu-1}(kz_0)} & b^-(z_0)=0 \end{cases}$$

- Need $\Pi^{TT} \sim \mathcal{O}(1)$ to avoid zero-momentum pole

- $k=0$ limit:

$$\lim_{k\to 0} \Pi^{TT}(k) \sim c_b(k,z_0)(k\ell)^{2\mu-2} = \begin{cases} \mathcal{O}(k^{-4}) & b^+(z_0)=0 \\ \mathcal{O}(k^0) & b^-(z_0)=0 \end{cases}$$

IR boundary condition

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...so $b^-(z_0)=0$ is the only choice!

Summary so far

- Added two-form to hard wall model
  - two towers of (degenerate) 1^{+-} and 1^{--} states
- First-order action
- Fixed IR boundary conditions with physical considerations
- How do we do?
  - $\mu = \mu_{pert} = 1$ gives $m_1 \sim 800\ MeV$ (ouch!)
  - fixing μ with b_1 mass gives $\mu \sim 1.8$
- No chiral symmetry-breaking effects included yet
- μ should flow with RG!

Chiral Symmetry Breaking

- Most experimental data from quadratic order in fields
- Include terms leading order in 5d dimension
  - cubic interaction that gives quadratic contributions when χsb (“Higgs” effect)
    - mix ϱ^T and ϱ^V
    - produce observed decay $b_1 \to \pi + \omega$
- Organizing principles: flavor C, P-invariant; leading in 5d dimension
- For consistency in dimension counting, add other terms as well

Chiral symmetry-breaking

- Roughly of the form bVX
  - when $X=X_0$ mixes b and V modes at quadratic order
  - gives interaction between pion, b, V at cubic order
- Unique dimension 11/2 term P, C, $U(N_f)_L \times U(N_f)_R$ invariant

$$S_{g_1} = g_1 g_b g_5 \int d^5x \sqrt{g}\ \mathrm{Tr}\left\{\hat{b}_{MN}\hat{F}_R^{MN} X^\dagger + X^\dagger \hat{F}_L^{MN}\hat{b}_{MN} + X\hat{F}_R^{MN}\hat{b}^\dagger_{MN} + \hat{b}^\dagger_{MN}\hat{F}_L^{MN} X\right\}$$

- When $X=X_0$:

$$S^{(2)}_{g_1} = 2 g_1 g_b g_5 \int d^5x \sqrt{g}\ X_0(z)\ \mathrm{Tr}\left[(\hat{b}+\hat{b}^\dagger)_{MN}\hat{F}_V^{MN}\right]$$

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...mixes ρ^V and ρ^T!

Complete model* (in 5d dimension)

- Dimension 11/2: contribution to b decay

$$S_{g_3} = i g_3 g_b^2 g_5 \int \sqrt{g}\ \mathrm{Tr}(\bar{b}_{MN} F_{(L)}^{NP} b_P^M + b_{MN} F_{(R)}^{NP} \bar{b}_P^M)$$

- Dimension 6: contribution to b quadratic action

$$S_{g2} = g_2 g_b^2 \ell \int \sqrt{g}\ \mathrm{Tr}\left\{ \hat{b}_{MN} X^\dagger \hat{b}^{MN} X^\dagger + \hat{b}^\dagger_{MN} X \hat{b}^{\dagger MN} X \right\}$$

  - mass splitting for parity 1 and -1 towers in b

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Free Parameters and How to Fit Them

hard wall: $z_0 \quad g_5 \quad m_q \quad \sigma \quad \Delta$

extension: $\mu \quad \cancel{g_b} \quad g_1 \quad g_2 \quad \cancel{g_3}$

- Common approach: fix parameters by matching to perturbative QCD (correlators, scaling dimensions, etc)
  - fewer free parameters, more predictive models
  - Erlich, Katz, Son, Stephanov (in original hard wall)
    - only 3 free parameters, good results
  - Alvarez, Hoyos, Karch (in extended hard wall)
    - no new free parameters, correlators produce expected large Q behavior

Free Parameters and How to Fit Them

- But...
  - UV of hard wall is not UV of QCD (or IR is not IR)
  - everything not protected by symmetry should flow with RG
  - Alvarez, Hoyos, Karch: 1^{--} states heavier than 1^{++} or 1^{+-}
    - or ok spectrum but tiny pion decay constant

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Our approach: forget predictive model, do global fit: does it work?

Fit Parameters

hard wall					extension		
z_0	g_5	m_q	σ	Δ	μ	$g_1 g_b g_5$	$g_2 g_b^2$
$1.0 z_0$	$1.0 g_5$	$0.7 m_q$	1.0σ	1.1Δ	2.3	0.3	-3.0

original hard wall rms error: ~0.09

rms error: ~0.28

7 observables
3 free parameters

13 observables
8 free parameters

Comparison to hadronic data

quantity	fit	experimental (lattice) result
m_{ρ^0}	781.8 ± 5.0	775.49 ± 0.34
$m_{\rho'}$	1413 ± 6	1465 ± 25
$m_{\rho''}$	1794 ± 12	1720 ± 20
f_ρ	140 ± 1	153 ± 7
m_{b_1}	1121 ± 4	1229.5 ± 3.2
m_{π^0}	138.4 ± 1.1	134.9766 ± 0.0006
m'_{π^0}	1903 ± 15	1300 ± 100
f_π	74.3 ± 0.4	92.4 ± 0.35
m_{a_1}	1119 ± 2	1320 ± 40
f_{a_1}	410 ± 2.4	433 ± 13
$g_{\rho^0\pi\pi}$	5.62 ± 0.02	6.03 ± 0.07
$g_{\rho'\pi\pi}/g_{\rho^0\pi\pi}$	-0.12 ± 0.002	-0.13 ± 0.02
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fix with g_b

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fix with g_b

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$[\Gamma(b_1 \to \omega\pi)$	108^*	$108 \pm 9]$
$[D/S(b_1 \to \omega\pi)$	0.15^*	0.277 ± 0.027]

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quantity	fit	experimental (lattice) result
m_{ρ^0}	781.8 ± 5.0	775.49 ± 0.34
$m_{\rho'}$	1413 ± 6	1465 ± 25
$m_{\rho''}$	1794 ± 12	1720 ± 20
f_ρ	140 ± 1	153 ± 7
$[f_\rho^T$	184^*	$(184 \pm 15)]$
m_{b_1}	1121 ± 4	1229.5 ± 3.2
$[f_{b_1}$	3500^*	$(236 \pm 23)]$
m_{π^0}	138.4 ± 1.1	134.9766 ± 0.0006
m'_{π^0}	1903 ± 15	1300 ± 100
f_π	74.3 ± 0.4	92.4 ± 0.35
m_{a_1}	1119 ± 2	1320 ± 40
f_{a_1}	410 ± 2.4	433 ± 13
$g_{\rho^0\pi\pi}$	5.62 ± 0.02	6.03 ± 0.07
$g_{\rho'\pi\pi}/g_{\rho^0\pi\pi}$	-0.12 ± 0.002	-0.13 ± 0.02
$g_{\rho''\pi\pi}/g_{\rho^0\pi\pi}$	0.031 ± 0.006	0.028 ± 0.02
$[\Gamma(b_1 \to \omega\pi)$	108^*	$108 \pm 9]$
$[D/S(b_1 \to \omega\pi)$	0.15^*	0.277 ± 0.027]

fix with g_b

fix with g_3

Possible problems?

- Large N counting problems

coupling	N_c order	result
$g_1 g_b g_5$	$N_c^{-1/2}$	0.3
$g_3 g_b^2 g_5$	$N_c^{-1/2}$	80
$g_2 g_b^2$	N_c^{-1}	3

- Wrong gravity background?
  - Alvarez et al: better spectrum by changing effective z_0
- 5d dimension counting?
- Inconsistent $\alpha' \neq 0$
  - other $\alpha^{-1/2}$ states? α' corrections to background?

Summary and Conclusions

- Summary:
  - developed consistent (basically) unique way to include b_1,
  - correlators match expected large Q behavior [Alvarez,Hoyos,Karch]
  - 5d dimension counting doesn't work very well
- The future:
  - check other backgrounds, α' effects
  - Original hard wall: unreasonably good!
    - some quantities flow very little from the UV: WHY?

Thanks!