

Successes and Failures of AdS/QCD “beyond supergravity”

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U. of Crete, April 25 2013

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 $\sim 15\%$)
- 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
π^\pm / π^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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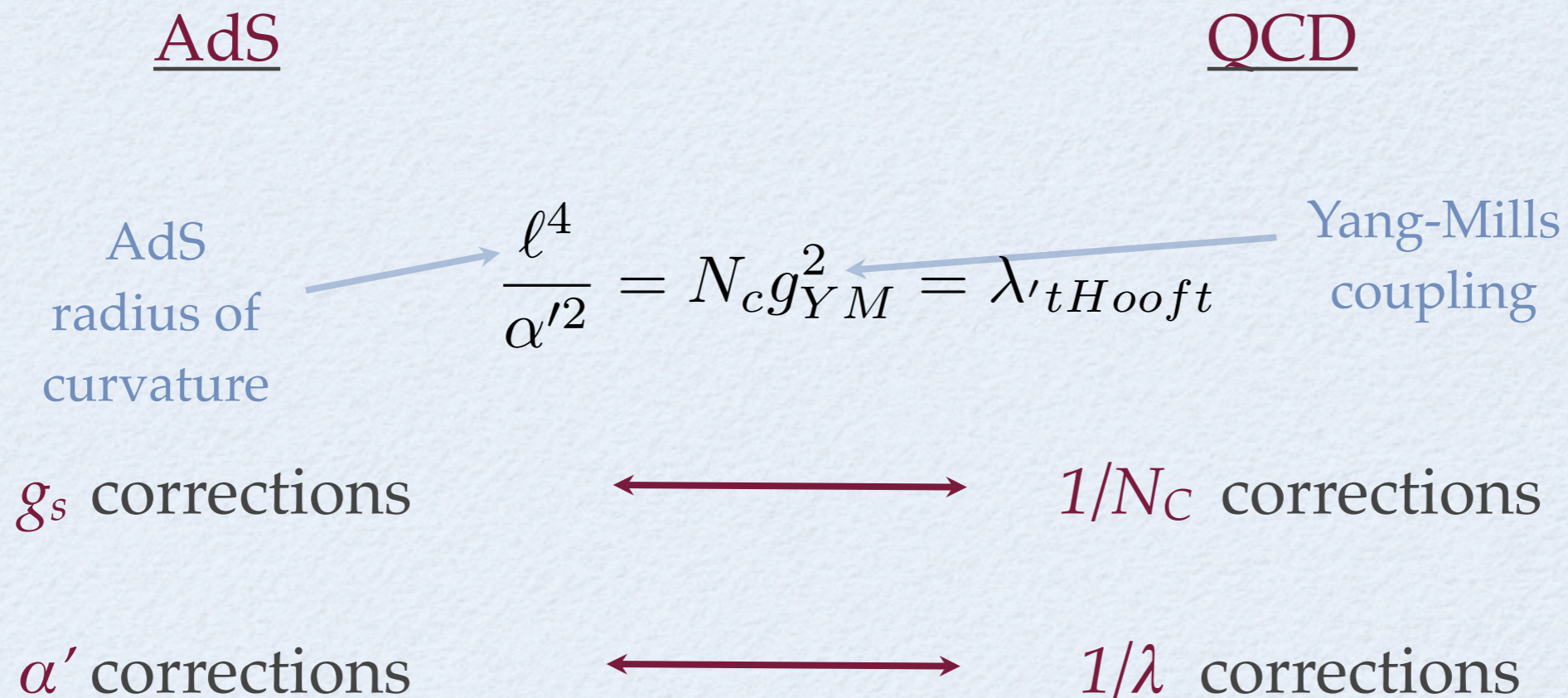
- Rho spectrum matches poorly:

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

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

Problems with AdS/QCD

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



- 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 a_1 mass (including b_1)
 - to improve matching to higher q 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**

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


The diagram shows two blue arrows pointing upwards towards the interval (ϵ, z_0) in the equation above. The arrow on the left is labeled 'UV' and points to ϵ . The arrow on the right is labeled 'IR' and points to 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	$m^2 l^2$
$J_{R\mu}^a = \bar{q}_R \gamma^\mu T^a q_R$	3	\longleftrightarrow	$A_{R\mu}^a(x, z)$	0
$J_{L\mu}^a = \bar{q}_L \gamma^\mu T^a q_L$	3	\longleftrightarrow	$A_{L\mu}^a(x, z)$	0
$\bar{q}_R^\alpha q_L^\beta$	3	\longleftrightarrow	$X(x, z)$	-3

$U(N_f)$
 generator

Operator/Field Content

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<p>...often work in terms of $V_\mu^a = \frac{1}{2} (A_{L\mu}^a + A_{R\mu}^a)$ and $A_\mu^a = \frac{1}{2} (A_{L\mu}^a - A_{R\mu}^a)$</p> <p>$J_V$ conserved \nearrow J_A not conserved \nearrow</p>				
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Operator/Field Content

QCD
Operator

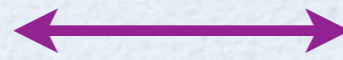
naive
 Δ

AdS
Field

$m^2 l^2$

$$J_{R\mu}^a = \bar{q}_R \gamma^\mu T^a q_R$$

3

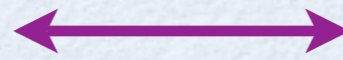


$$A_{R\mu}^a(x, z)$$

0

$$J_{L\mu}^a = \bar{q}_L \gamma^\mu T^a q_L$$

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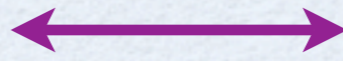
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J_V conserved

J_A not conserved

$$\bar{q}_R^\alpha q_L^\beta$$

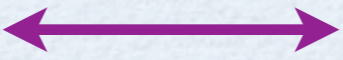
3



$$X(x, z)$$

-3

mesons



normalizable modes

Hard-wall action

- **Hard wall action:**

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

- m_X and **scaling dimension** related by $\Delta(\Delta - 4) = m_X^2 \ell^2$
- **Chiral symmetry broken** when X takes on a vev:

$$X_0 = \mathbf{1} \cdot \frac{1}{2\ell^{3/2}} \left(\underbrace{m_q \ell^{\Delta-3} z^{4-\Delta}}_{\text{non-normalizable}} + \frac{\sigma \ell^{3-\Delta}}{2(\Delta-2)} z^\Delta \right) \underbrace{\hspace{10em}}_{\text{normalizable}}$$

- **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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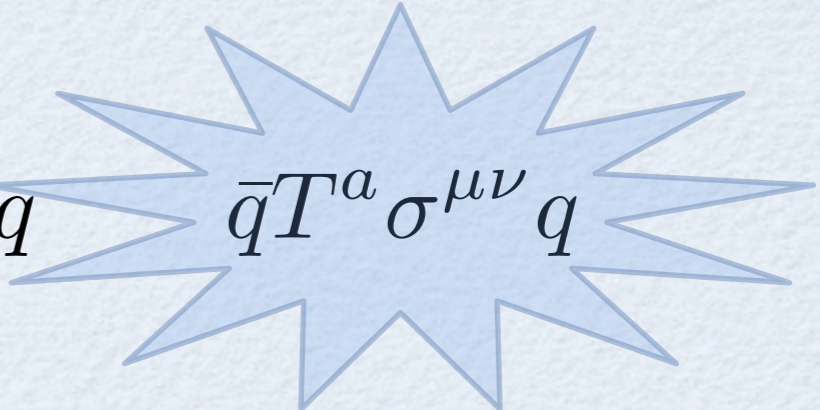
Our goals

- 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:

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


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

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

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

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

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 χ_{sb})
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**

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

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

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

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

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to be determined

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Free equations of Motion

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

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

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

- But related by

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

4d transverse/
longitudinal projectors

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4d transverse/
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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

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

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

- Two-point function:

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

to be determined
from IR data

- 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:

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

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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 $m_1 \sim 800 \text{ MeV}$ (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 χ_{sb} (“Higgs” effect)
 - **mix** ρ^T and ρ^V
 - **produce** observed decay $b_1 \rightarrow \pi + \omega$
- 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

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

- When $X=X_0$:

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

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...mixes q^V and $q^T!$

Complete model* (in 5d dimension)

- Dimension 11/2: contribution to b decay

$$S_{g_3} = ig_3 g_b^2 g_5 \int \sqrt{g} \text{Tr}(\bar{b}_{MN} F_{(L)}^{NP} b_P^M + b_{MN} F_{(R)}^{NP} \bar{b}_P^M)$$

- Dimension 6: contribution to b quadratic action

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

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

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Free Parameters and How to Fit Them

hard wall					extension				
z_0	g_5	m_q	σ	Δ	μ	g_b	g_1	g_2	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**
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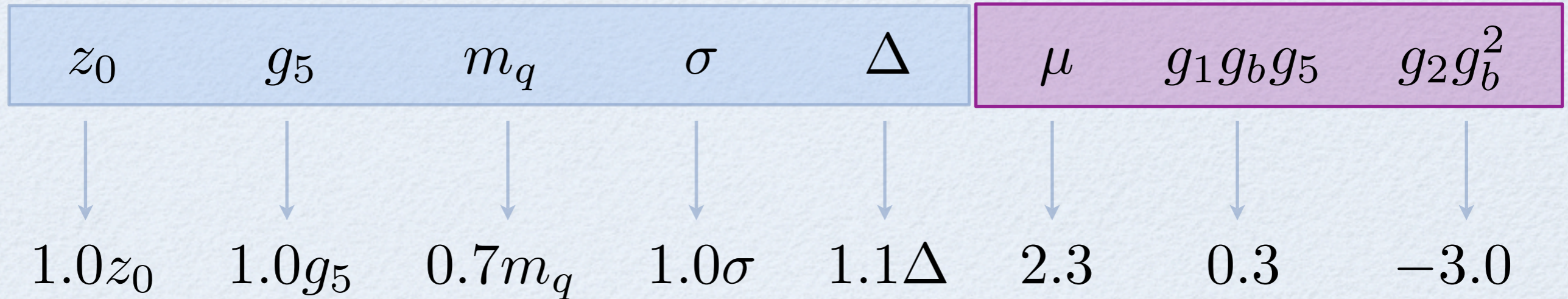
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Our approach: forget predictive model, do global fit: **does it work?**

Fit Parameters

hard wall

extension



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
$g_{\rho'' \pi \pi} / g_{\rho^0 \pi \pi}$	0.031 ± 0.006	0.028 ± 0.02

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$g_{\rho' \pi \pi} / g_{\rho^0 \pi \pi}$	-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

fix
with g_b

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
$[f_{\rho}^T]$	184^*	(184 ± 15)
m_{b_1}	1121 ± 4	1229.5 ± 3.2
$[f_{b_1}]$	3500^*	(236 ± 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
$[\Gamma(b_1 \rightarrow \omega \pi)]$	108^*	108 ± 9
$[D/S(b_1 \rightarrow \omega \pi)]$	0.15^*	0.277 ± 0.027

fix
with g_b

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	quantity	fit	experimental (lattice) result
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	f_π	74.3 ± 0.4	92.4 ± 0.35
fix with g_3	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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	$[\Gamma(b_1 \rightarrow \omega \pi)]$	108^*	108 ± 9
	$[D/S(b_1 \rightarrow \omega \pi)]$	0.15^*	0.277 ± 0.027

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!