Massive Pions and Baryons in Holographic QCD

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Outline

Introduction

Can we describe low energy QCD in the large-N_c expansion in a simple perturbative way?

What do we know?

QCD at large N_c is described
by a weakly interacting theory of mesons

- towers of mesons
- meson couplings $\sim 1/\sqrt{N_c}$
- meson masses $\sim N_c^0$

Introduction

Describe low-energy QCD at large N_c with extra dimensions

Bottom–up approach guided by holography

[Son, Stephanov (et al.); Da Rold, Pomarol; ...]

Features of the 5D models:

- automatically includes towers of vector and scalar mesons
- very predictive framework
- incorporates calculable Skyrme model [Pomarol, Wulzer]
- valid effective theories: $\Lambda_5/m_\rho \sim N_c^{1/3}$

A 5D Model for QCD

We want to describe QCD with two massive flavors.

We consider a 5D Model $\quad ds^2 = a^2(z)(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2)$

with bulk gauge group $\quad U(2)_L \times U(2)_R$

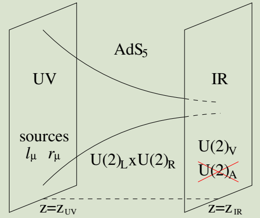
- Chiral symmetry breaking at the IR boundary

$$(L_\mu - R_\mu)|_{z=z_{\rm IR}} = 0$$

$$(L_{\mu 5} + R_{\mu 5})|_{z=z_{\rm IR}} = 0$$

- Dirichlet cond. with "sources" at the UV boundary

$$L_\mu|_{z=z_{\rm UV}} = l_\mu\,, \qquad R_\mu|_{z=z_{\rm UV}} = r_\mu$$



The Quark Masses

The quark masses are incorporated by introducing a 5D scalar field with $U(2)_L \times U(2)_R$ transformations

$$\Phi \to g_L \, \Phi \, g_R^\dagger$$

- Quark masses determine the UV boundary condition

$$\Phi\big|_{z_{\rm UV}} = \left(\frac{z_{\rm UV}}{z_{\rm IR}}\right)^{\Delta} M_q$$

where $\Delta \equiv 2 - \sqrt{4 - M_\Phi^2 L^2}$

- Contribution to the chiral symmetry breaking from the IR

$$\Phi\big|_{z_{\rm IR}} = \xi$$

Mesons from Kaluza–Klein Modes

We can identify the mesons
with the KK modes of the 5D fields

There is a pseudo-Goldstone boson: the pion

- described by the usual χ**PT** Lagrangian
- pion mass: $m_\pi^2 \sim \xi M_q$
- predictions for the decay constant and for $\mathcal{O}(p^4)$ terms in the Lagrangian

The higher KK modes give the massive mesons

- Vector Meson Dominance automatically holds
- Correct N_c scaling for the decay constants and couplings

Fit on the Mesonic Observables (preliminary)

in progress with O. Domenech, A. Pomarol, A. Wulzer

	Experiment (MEV)	AdS_5 (MEV)	Deviation
m_π	135 MeV	134 MeV	0.6%
$m_{\pi(1300)}$	1300 MeV	1230 MeV	5.6%
m_ρ	775 MeV	783 MeV	1.0%
m_ω	782 MeV	783 MeV	0.1%
$m_{a_1(1260)}$	1230 MeV	1320 MeV	7.6%
$m_{a_0(980)}$	980 MeV	1040 MeV	6.5%
$m_{f_0(980)}$	980 MeV	1040 MeV	6.5%
f_π	92 MeV	89 MeV	3.6%
f_ρ	153 MeV	149 MeV	2.7%
f_ω	140 MeV	149 MeV	6.4%
$g_{\rho\pi\pi}$	6.0	4.89	22.7%
$g_{\omega\pi\gamma}$	0.72	0.71	1.1%
$g_{\rho\pi\gamma}$	0.22	0.24	7.9%
$g_{\omega\rho\pi}$	15.0	15.6	3.7%
RMSE			7.7%

- the model has only 5 parameters

Baryons as 5D Skyrmions

[Pomarol, Wulzer; G. P., Wulzer]

Baryons arise as solitons at large N_c [Witten]

The 5D model admits non-trivial static solutions with conserved topological charge B identified with the baryon number

$$B = \frac{1}{32\pi^2} \int d^3x \int dz \, \varepsilon_{\hat{\mu}\hat{\nu}\hat{\rho}\hat{\sigma}} \mathrm{Tr} \left[L^{\hat{\mu}\hat{\nu}} L^{\hat{\rho}\hat{\sigma}} - R^{\hat{\mu}\hat{\nu}} R^{\hat{\rho}\hat{\sigma}} \right]$$

where $\hat{\mu}$, $\hat{\nu}$, ... label the four spatial coordinates

The theory is perturbative: $\Lambda_5 \rho \simeq \Lambda_5 L \sim 2N_c^{1/3}$

- Not the case in the original Skyrme model $\Lambda_4 \rho \simeq 1$!

Static Properties of the Nucleons (very preliminary)

in progress with O. Domenech, A. Pomarol, A. Wulzer

	Experiment	AdS_5	Deviation
M_N	940 MeV	$\sim$ 1070 MeV	$\sim$ 14%
μ_S	0.44	0.38	16%
μ_V	2.35	$\sim$ 1.2	$\sim$ 100%
g_A	1.25	$\sim$ 0.6	$\sim$ 100%
$\sqrt{\langle r^2_{E,S}\rangle}$	0.79 fm	0.82 fm	4%
$\sqrt{\langle r^2_{E,V}\rangle}$	0.93 fm	0.97 fm	4%
$\sqrt{\langle r^2_{M,S}\rangle}$	0.82 fm	0.84 fm	3%
$\sqrt{\langle r^2_{M,V}\rangle}$	0.87 fm	0.87 fm	0.5%
$\sqrt{\langle r^2_{A}\rangle}$	0.68 fm	$\sim$ 0.6 fm	$\sim$ 13%

- parameters fixed by the meson fit

Conclusions and Outlook

Holographic QCD models capture many features of large-N_c QCD in a perturbative framework

- towers of mesons as KK modes of the 5D fields
- highly predictive model (only 5 parameters)

Baryons automatically arise as stable soliton solutions

- calculable and insensitive to the UV cut-off

Future directions:

- Inclusion of the $U(1)_A$ anomaly and the η' mass

(some ideas with A. Wulzer)

The 5D Lagrangian: Gauge Sector

The bulk Lagrangian for the gauge fields is

$$S_g = -\int d^5x\, a(z)\frac{M_5}{2}\left\{\mathrm{Tr}\left[L_{MN}L^{MN}\right] + \frac{1}{2}\widehat{L}_{MN}\widehat{L}^{MN} + \{L \to R\}\right\}$$

- We must also introduce a Chern–Simons term

$$S_{CS} = -i\frac{N_c}{24\pi^2}\int d^5x\{\omega_5(L) - \omega_5(R)\}\,,$$

where

$$\omega_5(A) = \frac{3}{2}\widehat{A}\mathrm{Tr}\left[F^2\right] + \frac{1}{4}\widehat{A}\left(d\widehat{A}\right)^2\,.$$

  - required to reproduce the Adler–Bardeen anomaly.

The 5D Lagrangian: Scalar Sector

The bulk Lagrangian for the scalar field is

$$S_\Phi = M_5 \int d^5x \, a^3(z) \left\{ \mathrm{Tr} \left[(D_M\Phi)^\dagger D^M \Phi \right] - a^2(z) \, M_\Phi^2 \, \mathrm{Tr}[\Phi^\dagger \Phi] \right\}$$

where the covariant derivative is

$$D_M\Phi \equiv \partial_M \Phi - i L_M \Phi + i \Phi R_M$$