Nucleons and vector mesons in holographic QCD

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Summary

1. Confinement in Einstein-dilaton holography
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1. Confinement in Einstein-dilaton holography

Einstein-dilaton gravity in 5d:

$$S = \sigma \int d^5x \sqrt{-g} \left[R - \frac{4}{3} (\partial_m \Phi)^2 + V(\Phi) \right]$$

5d ansatz in holographic QCD:

$$ds^2 = \frac{1}{\zeta(z)^2} \left[-dt^2 + d\vec{x}^2 + dz^2 \right] \quad , \qquad \Phi = \Phi(z)$$

Independent field equations:

$$\zeta'' - \frac{4}{9} \zeta \Phi'^2 = 0$$

$$V - \zeta^5 \left(\zeta^{-3} \right)'' = 0$$

Warp factor in the Einstein frame

$$A(z) = -ln\, \zeta$$

Linear confinement is guaranteed by a quadratic dilaton asymptotic behaviour

$$\Phi(z \to \infty) = kz^2$$

Karch-Katz-Son-Stephanov 2006, Gursoy-Kiritsis-Nitti 2007

In this work we consider the following **analytical solutions:**

$$\Phi_I = kz^2 \quad , \qquad \zeta_I(z) = \Gamma\left(\frac{5}{4}\right)\left(\frac{3}{k}\right)^{1/4} \sqrt{z}\, I_{\frac{1}{4}}\left(\frac{2}{3}kz^2\right) \qquad \text{(model I)}$$

$$\Phi_{II} = \frac{1}{2}\sqrt{k}\, z\sqrt{9+4kz^2} + \frac{9}{4}\sinh^{-1}\left(\frac{2}{3}\sqrt{k}z\right) \quad , \qquad \zeta_{II}(z) = z\, exp\left(\frac{2}{3}kz^2\right) \qquad \text{(model II)}$$

Both models leads to a quadratic dilaton at large z and AdS asymptotics at small z

Warp factor in the string frame:

$$A_s(z) = -ln\,\zeta + \frac{2}{3}\Phi$$

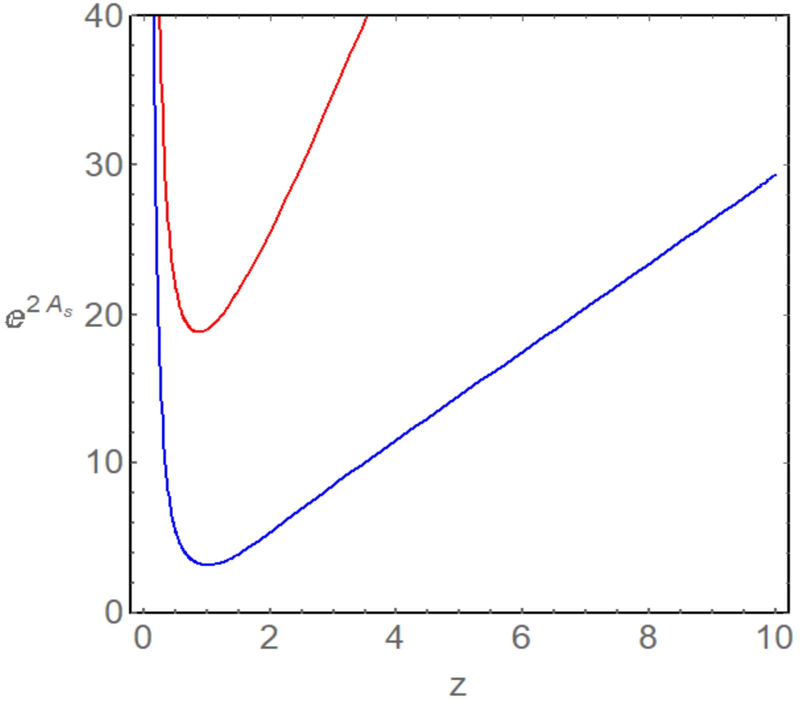
Confinement criterion

The function $f(z)=\sqrt{g_{tt}g_{xx}}$ defined in the string frame should have a minimum $f(z^{*})>0$

Kinar, Schreiber and Sonnenschein 1998

In terms of the warp factor we have $$f(z)=exp(2A_s)$$

As shown in the figure, both models satisfy the confinement criterion



2. Vector mesons in confining holographic QCD

Pioneer works in the bottom-up approach:

Erlich-Katz-Son-Stephanov 2005, Grigoryan-Radyushkin 2007

Consider the vectorial currents associated with $SU(2)$ isospin symmetry

$$< J^{\mu,c} > = < \bar{q}(x)\gamma^{\mu}T^{c}q(x) > =< J_R^{\mu,c} >+< J_L^{\mu,c} >$$

Holographic QCD maps the 4d currents to 5d non-Abelian gauge fields described by the action

$$S = -\frac{1}{4g_5^2}\int d^4x\, dz\, \sqrt{-g}e^{-\Phi}\mathrm{Tr}\left({F_{mn}^{R}}^2 + {F_{mn}^{L}}^2\right)$$

Expanding this action at second order in the perturbations, we find in the **vectorial sector**

$$S_V = -\frac{1}{4g_5^2}\int d^4x\, dz\, \sqrt{-g}e^{-\Phi}{v_{mn}^{c}}^2 = -\frac{1}{4g_5^2}\int d^4x\, dz\, e^{A_s-\Phi}{v_{\hat{m}\hat{n}}^{c}}^2$$

where $v_{\hat{m}\hat{n}}^{c} = \partial_{\hat{m}}V_{\hat{n}}^{c} - \partial_{\hat{n}}V_{\hat{m}}^{c}$ and $\hat{m},\hat{n}$ are contracted with a 5d Minkowski metric

The 5d gauge coupling can be fixed as $$\boldsymbol{g_5^2 = \frac{12\pi^2}{N_c}}$$ with $N_c = 3$

to reproduce the perturbative result for the current correlator at large energies

Varying the 5d action one finds the field equation

$$\boldsymbol{\partial_m\left(e^{A_s-\Phi} v_c^{\hat{m}\hat{n}}\right) = 0}$$

and the surface term $$\boldsymbol{\delta S_V = -\frac{1}{g_5^2}\int d^4x\, dz\, \partial_{\hat{m}}(e^{A_s-\Phi} v_c^{\hat{m}\hat{n}}\, \delta V_{\hat{n}}^c)}$$

The 5d vectorial field is decomposed as

$$\boldsymbol{V_{\hat{m}}^c = \left(V_{\hat{z}}^c, V_{\hat{\mu}}^c\right) \quad , \quad V_{\hat{\mu},c} = V_{\hat{\mu},c}^{\perp} + \partial_{\hat{\mu}}\xi^c}$$

We use gauge symmetry to fix $\boldsymbol{V_z^c = 0}$ and it turns out that $\boldsymbol{\xi^c = 0}$

The equation for the transverse sector takes the form (in momentum space)

$$[(\partial_z + A_s' - \Phi')\partial_z - q^2]V_{\perp}^{\hat{\mu},c} = 0$$

Taking the ansatz

$$V_{\perp}^{\hat{\mu},c}(q,z) = e^{-B_V(z)}\eta^{\hat{\mu}}\psi_V(q,z) \quad , \qquad B_V = \frac{1}{2}(A_s - \Phi)$$

the equation takes the Schrödinger form

$$[\partial_z^2 - q^2 - V_V]\psi_V = 0$$

with $V_V = B_V'' + B_V'^2$

The **VEV of the current operator** can be obtained from the surface term in the on-shell action

$$< J^{\hat{\mu},c}(x) > = \frac{\delta S_V}{\delta V_{\hat{\mu},c}^{\perp,0}(x)} = \frac{1}{g_5^2}\left[e^{A_s-\Phi}\partial_z V_{\perp}^{\hat{\mu},c}\right]_{z=\epsilon}$$

and we have introduced a UV regulator $z = \epsilon$ for the AdS boundary

The bulk to boundary propagator and the current correlator

The field in 5 dimensions is mapped to the 4d source using the **bulk to boundary propagator**

$$V^{\perp}_{\hat{\mu},c}(z,x) = \int d^4y\, K^{cd}_{\hat{\mu}\hat{\nu}}(z,x;y) V^{\hat{\nu},d}_{\perp,0}(y)$$

The on-shell action takes the form

$$S_V^{o-s} = \frac{1}{2g_5^2}\int d^4x \int d^4y\, V^{\hat{\mu},c}_{\perp,0}(x)\left[e^{A_s-\Phi}\partial_z\, K^{cd}_{\hat{\mu}\hat{\nu}}(z,x;y)\right] V^{\hat{\nu},d}_{\perp,0}(y)$$

Using the AdS/CFT dictionary we obtain the **current correlator**

$$G^{cd}_{\hat{\mu}\hat{\nu}}(x-y) = < J_{\hat{\mu},c}(x) J_{\hat{\nu},d}(y) >$$
$$= \frac{\delta S_V^{o-s}}{\delta V^{\hat{\mu},c}_{\perp,0}(x)\,\delta V^{\hat{\nu},d}_{\perp,0}(y)} = \frac{1}{g_5^2}\left[e^{A_s-\Phi}\partial_z\, K^{cd}_{\hat{\mu}\hat{\nu}}(z,x;y)\right]$$

The Sturm-Liouville equation and the spectral decomposition

The bulk to boundary propagator can be written in momentum space as

$$K^{cd}_{\hat{\mu}\hat{\nu}}(z,q) = \left(\eta_{\hat{\mu}\hat{\nu}} - \frac{q_{\hat{\mu}} q_{\hat{\nu}}}{q^2}\right) \delta^{cd} V(z,q)$$

The field $V(z,q)$ satisfy the differential equation

$$\left[(\partial_z + A_s' - \Phi')\partial_z - q^2\right] V(z,q) = 0$$

which can be written in **the Sturm-Liouville form**

$$[\partial_z(p(z)\partial_z) - s(z) + \lambda\, r(z)]V(z,q) = 0$$

where

$$p(z) = r(z) = e^{A_s - \Phi}\ , \qquad s(z) = 0\,, \qquad \lambda = -q^2$$

We define the Green's function by

$$[\partial_z(p(z)\partial_z) - s(z) + \lambda\, r(z)]G(z;z') = \delta(z - z')$$

Following Sturm-Liouville theory we obtain

$$G(z;z') = -\sum_n \frac{v^n(z)v^n(z')}{q^2 + m_{v^n}^2}$$

where the Sturm-Liouville modes satisfy

$$[(\partial_z + A_s' - \Phi')\partial_z + m_{v_n}^2]v^n(z) = 0$$

and are normalised as

$$\int dz\, e^{A_s - \Phi} v^m(z) v^n(z) = \delta^{mn}$$

The bulk to boundary propagator takes the form

$$V(z',q) = -\left[e^{A_s-\Phi}\partial_z G(z;z')\right]_{z=\epsilon} = -\sum_n \frac{\left[e^{A_s-\Phi}\partial_z\, v^n(z)\right]_{z=\epsilon} v^n(z')}{q^2 + m_{v\_n}^2}$$

and the current correlator becomes

$$G_{\mu\nu}^{cd}(q) = \left(\eta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right)\delta^{cd}\sum_n \frac{F_{v_n}^2}{q^2 + m_{v_n}^2}\ , \qquad F_{v^n} = \frac{1}{g_5}\left[e^{A_s-\Phi}\partial_z v^n(z)\right]_{z=\epsilon}$$

The coefficients F_{v^n} **are the vector meson decay constants**

consistent with large N_c QCD

3. Nucleons in confining holographic QCD

Pioneer works in the bottom-up approach:

Brodsky-Teramond 2005, Hong-Inami-Yee 2006, Abidin-Carlson 2009

Nucleons are usually described by interpolating fields. For a proton we use the Ioffe operator

$$< O(x) > = < \epsilon_{abc} \left(u_a^T(x) C \gamma_\mu u_b(x) \right) \gamma_5 \gamma^\mu d_c(x) >$$

Ioffe 1981

In holographic QCD we start with a 5d Dirac spinor described by the action

$$S_F = G_F \int d^4x\, dz \sqrt{-g_s} e^{-\Phi} \left(\frac{i}{2} \bar{\psi}\, \Gamma^n D_n \psi + c.c. - i\, \tilde{m}\, \bar{\psi} \psi \right)$$

where $\Gamma^n = e^n_{\hat{a}} \Gamma^{\hat{a}}$, $D_n = \partial_n + \frac{1}{8} \omega_n^{\hat{a}\hat{b}} [\Gamma_{\hat{a}}, \Gamma_{\hat{b}}]$

Redefining the Dirac field as $\psi \to e^{\Phi/2} \psi$

the action becomes $$S_F = G_F \int d^4x\, dz \sqrt{-g_s} \left(\frac{i}{2} \bar{\psi}\, \Gamma^n D_n \psi + c.c. - i\, \tilde{m}\, \bar{\psi} \psi \right)$$

The 5d gauge coupling can be fixed as $G_F = 2\,\pi^{-4}$

to reproduce the perturbative QCD result for the nucleon correlator at large energies

In holographic QCD the vielbein takes the form $e^n_{\hat{a}} = e^{-A_s}\delta^n_{\hat{a}}$

and the non-vanishing components of the spin connection are $\omega^{\hat{z}\hat{\nu}}_{\hat{\mu}} = -\omega^{\hat{\nu}\hat{z}}_{\hat{\mu}} = -A_s'\,\delta^{\hat{\nu}}_{\hat{\mu}}$

The Dirac action becomes

$$S_F = G_F \int d^4x\, dz\, e^{4A_s}\left(\frac{i}{2}\bar{\psi}\,\Gamma^{\hat{a}}\partial_{\hat{a}}\psi - \frac{i}{2}(\partial_{\hat{a}}\bar{\psi})\Gamma^{\hat{a}}\psi. - i\, e^{A_s}\tilde{m}\,\bar{\psi}\psi\right)$$

Varying this action we obtain the field equations

$$\left(\Gamma^{\hat{a}}\partial_{\hat{a}} + 2A_s'\Gamma^{\hat{z}} - e^{A_s}\tilde{m}\right)\psi = 0$$

$$\bar{\psi}\left(\overleftarrow{\partial_{\hat{a}}}\Gamma^{\hat{a}} + 2A_s'\Gamma^{\hat{z}} + e^{A_s}\tilde{m}\right) = 0$$

and the surface term

$$\delta S_F = G_F \int d^4x \left(\frac{i}{2}e^{4A_s}\delta\bar{\psi}\,\Gamma^{\hat{z}}\psi\right)_{z=\epsilon} + c.c.$$

Left and right decomposition: $$\psi = \psi_R + \psi_L$$

where $$\psi_{R/L} = P_{R/L}\psi \qquad \bar{\psi}_{R/L} = \bar{\psi} P_{L/R} \qquad P_{R/L} = \frac{1}{2}\left(1 \pm \Gamma^{\hat{z}}\right)$$

The Dirac equation decomposes as

$$\Gamma^{\hat{\mu}} \partial_{\hat{\mu}} \psi_{R/L} = \pm\left(\partial_z + 2A_s' \pm e^{A_s} \tilde{m}\right) \psi_{L/R}$$

and the surface term becomes

$$\delta S_F = G_F \int d^4x \left(\frac{i}{2} e^{4A_s} \delta\bar{\psi}_L \, \psi_R - \frac{i}{2} e^{4A_s} \delta\bar{\psi}_R \, \psi_L \right)_{z=\epsilon} + c.c.$$

Since ψ_R and ψ_L are not independent we need to correct the Dirac action as

$$S_F' = S_F + G_F \int d^4x \left(\sqrt{-\gamma} \frac{i}{2} \bar{\psi}\psi \right)_{z=\epsilon} = S_F + G_F \int d^4x \left(\frac{i}{2} e^{4A_s} (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L) \right)_{z=\epsilon}$$

so that $$\delta S_F' = G_F \int d^4x \left(\frac{i}{2} e^{4A_s} \delta\bar{\psi}_L \psi_R \right)_{z=\epsilon} + c.c.$$

At small z (near the boundary) we find the asymptotic behaviour

$$\psi_L(x,z) = \alpha_L(x) z^{2-m} + \cdots + \beta_L(x) z^{3+m} + \ \ldots$$
$$\psi_R(x,z) = \alpha_R(x) z^{3-m} + \cdots + \beta_R(x) z^{2+m} + \ \ldots$$

The source $\alpha_L(x)$ couples to the operator O_R and we find

$$< O_R > = \frac{\delta S_F'}{\delta \bar{\alpha}_L} = i G_F \left(z^{2-m} e^{4A_s} \psi_R \right)_{z=\epsilon} = i G_F \frac{\Gamma^{\hat{\mu}} \partial_{\hat{\mu}}}{\partial^2} \left(z^{2-m} e^{4A_s} \left(\partial_z + 2A_s' + e^{A_s} \tilde{m} \right) \psi_L \right)_{z=\epsilon}$$

Combining the left and right coupled spinor equations we obtain

$$\left[\left(\partial_z + 2A_s' \pm e^{A_s} \tilde{m} \right) \left(\partial_z + 2A_s' \mp e^{A_s} \tilde{m} \right) + \partial^2 \right] \psi_{R/L} = 0$$

We expand in the x directions using a plane-wave basis

$$\psi_{R/L}(x,z) = \int d^4 q \, e^{iq\cdot x} F_{R/L}(q,z) \alpha_{R/L}(q)$$

and we obtain

$$\left[\left(\partial_z + 2A_s' \pm e^{A_s} \tilde{m} \right) \left(\partial_z + 2A_s' \mp e^{A_s} \tilde{m} \right) + Q^2 \right] F_{R/L} = 0$$

with $Q = \sqrt{-q^2}$

The Schrödinger equation

Using a Bogoliubov transformation

$$F_{R/L}(q,z) = e^{-2A_s(z)}\xi_{R/L}(q,z)$$

we obtain the Schrödinger equations

$$[\partial_z^2 + Q^2 - V_{R/L}]\xi_{R/L} = 0$$

with

$$V_{R/L} = \pm\partial_z(e^{A_s}\tilde{m}) + (e^{A_s}\tilde{m})^2$$

We propose the following ansatz for the mass term:

$$\tilde{m} = e^{-A_s}\left(-mA_s' + \frac{1}{2}\Phi'\right)$$

The bulk to boundary propagator and the nucleon correlator

Introducing the bulk to boundary propagator by

$$\psi_L(z,x) = \int d^4y\, F_L(z,x;y)\alpha_L(y)$$

the on-shell action takes the form

$$S_F'^{o-s} = G_F \int d^4x \int d^4y \frac{\Gamma^{\hat{\mu}}\partial_{\hat{\mu}}}{\partial^2}\left(\frac{i}{2}\bar{\alpha}_L(x)\left(z^{2-m}e^{4A_s}(\partial_z + 2\,A_s' + e^{A_s}\tilde{m})F_L(z,x;y)\right)_{z=\epsilon}\alpha_L(y) + c.c.\right)$$

where $\partial_{\hat{\mu}} = \partial/\partial(x-y)^{\hat{\mu}}$

The 2-point nucleon correlator takes the form

$$\Gamma_R(x-y) =< O_R(x)\bar{O}_R(y) \succ \; = iG_F P_R \frac{\Gamma^{\hat{\mu}}\partial_{\hat{\mu}}}{\partial^2}\Big(z^{2-m} e^{4A_s}\big(\partial_z + 2\,A_s' + e^{A_s}\tilde{m}\big)F_L(z, \mathrm{x}; \mathrm{y})\Big)_{z=\epsilon}$$

The bulk to boundary propagator, in momentum space, satisfies the differential equation

$$\left[(\partial_z + 4A_s')\partial_z + \Theta_{\mathrm{L}} + Q^2\right]F_L(z,q) = 0$$

where $$\theta_L(z) = 2A_s'' + 4A_s'^2 + \partial_Z\left(e^{A_s}\tilde{m}\right) - e^{2A_s}\tilde{m}^2$$

The equation can be written in the Sturm-Liouville form

$$[\partial_Z(p(z)\partial_Z) - s(z) + \lambda\, r(z)]F_L(z,q) = 0$$

where $$p(z) = r(z) = e^{4A_s}, \qquad s(z) = -e^{4A_s}\Theta_L\,, \qquad \lambda = Q^2$$

Using Sturm-Liouville theory we obtain the spectral decomposition

$$G(z;z') = -\sum_n \frac{f_{L,n}(z) f_{L,n}(z')}{q^2 + m_n^2}$$

where the Sturm-Liouville modes satisfy $$\left[(\partial_z + 4A_s')\partial_z + \Theta_L + m_n^2\right] f_{L,n}(z) = 0$$

and are normalised as $$\int dz\, e^{4A_s}\, f_{L,m}(z) f_{L,n}(z) = \delta^{mn}$$

The bulk to boundary propagator takes the form

$$F_L(q,z') = -\left[e^{4A_s}\left(F_L(z)\partial_z G_L(z;z') - G_L(z;z')\partial_z F_L(z)\right)\right]_{z=\epsilon} = \sum_n \frac{f_n m_n f_{L,n}(z')}{q^2 + m_n^2}$$

Using the AdS/CFT dictionary we obtain for the nucleon correlator

$$\Gamma_R(q) = -P_R \Gamma^\mu q_\mu \left(\frac{1}{Q^2}\sum_n \lambda_n^2 + \sum_n \frac{\lambda_n^2}{q^2 + m_n^2}\right) , \qquad \lambda_n = \sqrt{G_F} f_n \;\; , \;\; f_n = \left[z^{-2-m} f_{R,n}(z)\right]_{z=\epsilon}$$

consistent with large N_c QCD

The coefficients λ_n are the nucleon “decay constants”

The first term is a UV divergence that can be subtracted using holographic renormalisation

4. Results

Spectrum of vector mesons

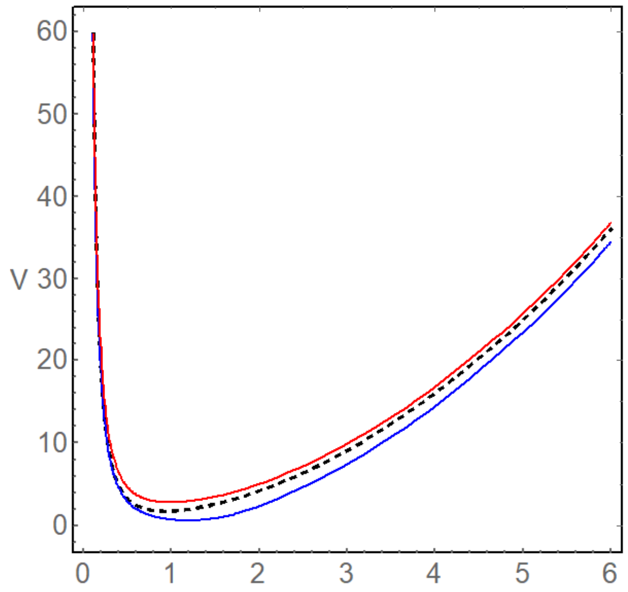
Conformal dimension $\Delta = 3$ for the vectorial current

We solve the Schrödinger equation for the normalisable modes

In the figure we show the Schrödinger potentials for model I (blue), model II (red) and the soft wall model (black dashed)

The infrared parameter k **is the only parameter in the model**

Mass ratios are independent of the choice of k



Ratio	Einstein-dilaton I	Einstein-dilaton II	Soft wall	Hard wall	Experimental
m_{ρ_1}/m_{ρ_0}	1.591	1.34	1.414	2.295	1.652 ± 0.048
m_{ρ_2}/m_{ρ_0}	2.015	1.611	1.732	3.598	1.888 ± 0.032
m_{ρ_3}/m_{ρ_0}	2.365	1.843	2	4.903	2.216 ± 0.026
m_{ρ_4}/m_{ρ_0}	2.67	2.049	2.236	6.209	2.46 ± 0.039
m_{ρ_5}/m_{ρ_0}	2.944	2.236	2.45	7.514	2.769 ± 0.022

Spectrum of nucleons

We consider two possible values for the conformal dimension: $\boldsymbol{\Delta = 7/2}$ and $\boldsymbol{\Delta = 9/2}$

We solve the Schrödinger equation for the normalisable modes

Mass ratios presented below are independent of the choice of $\boldsymbol{k}$

$\Delta = 7/2$

Ratio	Einstein-dilaton I	Einstein-dilaton II	Soft wall	Hard wall	Experimental
m_{N_0}/m_{ρ_0}	0.987	0.988	1.414	1.593	1.209 ± 0.002
m_{N_1}/m_{ρ_0}	1.623	1.339	1.732	2.917	1.856 ± 0.039
m_{N_2}/m_{ρ_0}	2.053	1.613	2	4.23	2.204 ± 0.039
m_{N_3}/m_{ρ_0}	2.403	1.847	2.236	5.54	2.423 ± 0.065
m_{N_4}/m_{ρ_0}	2.707	2.054	2.449	6.849	2.706 ± 0.065

$\Delta = 9/2$

Ratio	Einstein-dilaton I	Einstein-dilaton II	Soft wall	Hard wall	Experimental
m_{N_0}/m_{ρ_0}	0.896	0.952	1.732	2.136	1.209 ± 0.002
m_{N_1}/m_{ρ_0}	1.593	1.314	2	3.5	1.856 ± 0.039
m_{N_2}/m_{ρ_0}	2.04	1.595	2.236	4.832	2.204 ± 0.039
m_{N_3}/m_{ρ_0}	2.399	1.833	2.449	6.153	2.423 ± 0.065
m_{N_4}/m_{ρ_0}	2.708	2.043	2.646	7.468	2.706 ± 0.065

Vector meson decay constants

Ratio	Einstein-dilaton I	Einstein-dilaton II	Soft wall	Hard wall	Experimental
$\sqrt{F_{\rho_0}}/m_{\rho_0}$	0.3719	0.283	0.3355	0.4246	0.446 ± 0.0019
$\sqrt{F_{\rho_1}}/m_{\rho_0}$	0.4704	0.3407	0.3989	0.7946	0.5588 ± 0.017
$\sqrt{F_{\rho_2}}/m_{\rho_0}$	0.5298	0.3798	0.4415	1.114	-
$\sqrt{F_{\rho_3}}/m_{\rho_0}$	0.5741	0.41	0.4744	1.405	-
$\sqrt{F_{\rho_4}}/m_{\rho_0}$	0.61	0.4351	0.5017	1.677	-

Nucleon "decay constants" $\left(\alpha = \Delta - \frac{3}{2}\right)$

Ratio	Einstein-dilaton I	Einstein-dilaton II	Soft wall	Hard wall
$\lambda_{N_0}/m_{\rho_0}^{\alpha}$	0.1108	0.09835	0.0507	0.1667
$\lambda_{N_1}/m_{\rho_0}^{\alpha}$	0.1302	0.1158	0.0716	0.4096
$\lambda_{N_2}/m_{\rho_0}^{\alpha}$	0.1519	0.1284	0.0877	0.7138
$\lambda_{N_3}/m_{\rho_0}^{\alpha}$	0.1708	0.1388	0.1013	1.069
$\lambda_{N_4}/m_{\rho_0}^{\alpha}$	0.1878	0.1478	0.1133	1.469

$\Delta = 7/2$

Ratio	Einstein-dilaton I	Einstein-dilaton II	Soft wall	Hard wall	Lattice QCD
$\lambda_{N_0}/m_{\rho_0}^{\alpha}$	0.1055	0.158	0.01791	0.1414	0.05778 ± 0.0107
$\lambda_{N_1}/m_{\rho_0}^{\alpha}$	0.1201	0.1906	0.03102	0.4755	-
$\lambda_{N_2}/m_{\rho_0}^{\alpha}$	0.1462	0.2172	0.04387	1.058	-
$\lambda_{N_3}/m_{\rho_0}^{\alpha}$	0.172	0.2409	0.05664	1.931	-
$\lambda_{N_4}/m_{\rho_0}^{\alpha}$	0.1973	0.2627	0.06937	3.129	-

$\Delta = 9/2$

5. Conclusions

- We presented a minimal holographic QCD model that describes vector mesons and nucleons in a single fashion
- The model contains only one free parameter associated with hadron mass generation and confinement.
- Comparison to experimental data is better for the higher excited states (light states require the addition of chiral symmetry breaking)

Next steps

- Calculate strong couplings between vector mesons and nucleons and find the electromagnetic and gravitational form factors
- Turn on the temperature and investigate the transition to deconfinement, chiral symmetry restoration and the "melting" of hadrons in the quark-gluon plasma