Pomeron and Odderon Regge Trajectories from AdS/QCD holographic models

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Strings and Dunes
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Work done in collaboration with:
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With previous work with
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Summary of the talk:

- The Pomeron, the Odderon and Glueballs
- Brief Review: AdS/CFT correspondence and AdS/QCD Models
- Glueballs and the Hardwall Model
- Glueballs in AdS/QCD Softwall Model
- A Dynamical Softwall Model
- A Truncated Analytical Softwall Model
- Some other Results
- Conclusions

Regge Trajectories

Strongly interacting particles (Hadrons) obey approximate relations between Angular Momentum (J) and quadratic masses (m^2)

$$J(m^2) \approx \alpha_0 + \alpha' m^2 \ ,$$

where α_0 and α' are constants

The Pomeron

Experimental Regge trajectories from proton proton scattering

$$J(m^2) \approx 1.08 + 0.25\, m^2 \ ,$$

Masses *m* in GeV (P. V. Landshoff, "Pomerons," hep-ph/0108156.)

The Pomeron

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The Pomeron is related to Glueball states $2^{++}, 4^{++}, 6^{++}, 8^{++}, \ldots$
and may be to 0^{++}

The Odderon

F. J. Llanes-Estrada, P. Bicudo, and S. R. Cotanch, Phys. Rev. Lett. 96, 081601 (2006).

Relativistic many-body model (RMB)

$$J_{\rm RMB}(m^2) = -0.88 + 0.23m^2,$$

Non-relativistic constituent model (NRCM)

$$J_{\rm NRCM}(m^2) = 0.25 + 0.18m^2.$$

The Odderon

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Non-relativistic constituent model (NRCM)

$$J_{\rm NRCM}(m^2) = 0.25 + 0.18m^2.$$

The Odderon is related to Glueball states $, 3^{--}, 5^{--}, 7^{--}$, ...

and may be $1^{--},$

Experimental signs of the Odderon

The best experimental evidence for the odderon occurred in 1985 at ISR CERN. A difference between differential cross sections for pp and $p\bar{p}$ in the dip-shoulder region $1.1 < |t| < 1.5$ GeV^2 at $\sqrt{s} = 52.8$ GeV was measured, but these results were not confirmed [14].

There are two more evidences related to the nonperturbative odderon, that is, the change of shape in the polarization in $\pi^- p \to \pi^0 n$ from $p_L = 5$ GeV/c [16,17] to $p_L = 40$ GeV/c [18] and a strange structure seen in the $UA4/2$ dN/dt data for pp scattering at $\sqrt{s} = 541$ GeV, namely a bump centered at $|t| = 2 \times 10^{-3}$ GeV^2 [19].

[14] R. Avila, P. Gauronm, and B. Nicolescu, Eur. Phys. J. C **49**, 581 (2007).
[15] Z.-H. Hu, L.-J. Zhou, and W.-X. Ma, Commun. Theor. Phys. **49**, 729 (2008).
[16] D. Hill *et al.*, Phys. Rev. Lett. **30**, 239 (1973).
[17] P. Bonamy *et al.*, Nucl. Phys. **B52**, 392 (1973).
[18] V.D. Apokin *et al.*, AIP Conf. Proc. **95**, 118 (2008).
[19] C. Augier *et al.* (UA4/2 Collaboration), Phys. Lett. B **316**, 448 (1993).

Experimental signs of the Odderon

LCH new results?

Some groups are looking for the Odderon…

AdS/CFT correspondence

(Maldacena, 1997)

String theory in $AdS_5 \times S^5$ (10 dimensions) is equivalent to *N=4* super-Yang-Mills SU(N) theory for large N in 4 dimensions

AdS_5 = 5 dim. Anti-de Sitter space = space with negative constant curvature

S^5 = 5 dim. hypersphere

N=4 extended supersymmetric conformal gauge theory

Other versions of the Correspondence

M-theory in $AdS_4 \times S^7$ (11 dimensions) is equivalent to super-Yang-Mills SU(N) conformal gauge theory with large N in 3 dimensions.

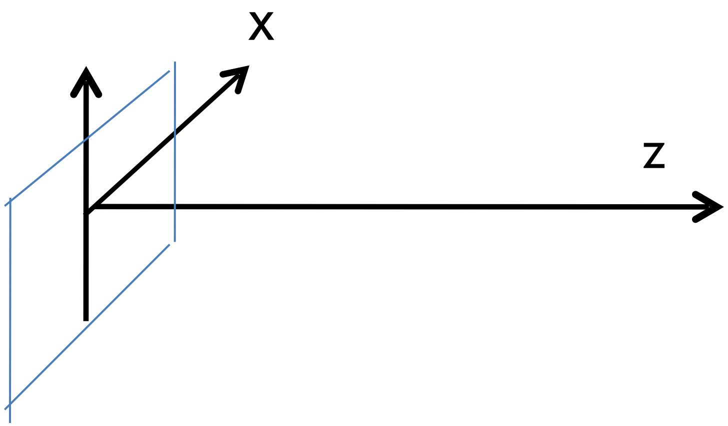
M-theory in $AdS_7 \times S^4$ (11 dimensions) is equivalent to super-Yang-Mills SU(N) conformal gauge theory with large N in 6 dimensions.

Holography in String theory

AdS Space in Poincaré coordinates

$$ds^2 = \frac{R^2}{(z)^2}(dz^2 + (d\vec{x})^2 - dt^2)$$

The 4-dim boundary is at z = 0



Fifth dimension z ~ 1 / E where E = Energy in 4-dim boundary

Hard-wall Model

Polchinski & Strassler 2001/2002

Scattering of Glueballs using the AdS/CFT correspondence

Finite region in AdS space $0 < z < z_{max}$

$z_{max} \sim 1 / E$ where E is the Energy scale in boundary theory

HBF & Braga JHEP 2003, EPJC 2004

Masses of Glueball states 0++ and its radial excited states 0++*, 0++**, 0++***, ...

Brodsky, Teramond PRL 2005, 2006; Erlich, Katz, Son, Stephanov PRL 2005.

Extension to Mesons and Baryons

Scalar Glueballs in the Hard-wall model

Accordingly to the AdS/CFT dictionary a massive field in AdS is related to a p-form with conformal dimension

$$m_5^2 R^2 = (\Delta - p)(\Delta + p - 4),$$

So, for a scalar field on the boundary

$$M_5^2 R^2 = \Delta(\Delta - 4) \cdot$$

For normalizable modes

$$\Delta = 2 + \sqrt{4 + (\mu R)^2}.$$

Scalar Glueballs in the Hard-wall model

In particular for scalar Glueballs related to a massless field in AdS_5 we have a boundary operator

$$\mathcal{O}_4 = Tr(F^2) = Tr(F^{\mu\nu} F_{\mu\nu})$$

with

$$\Delta = 4 \, .$$

4d Glueball states are described in AdS(5) by Bessel functions which satisfy some boundary condition at z=z_max.

Glueballs in the Hard-wall model and the Pomeron (*J++*) *P=C=+1*, *J=(0),2,4,…*

4d Glueball states are described in AdS(5) by Bessel functions which satisfy some boundary condition at z=z_max.
For massive scalar fields in AdS_5:

$$\left[z^3\partial_z\frac{1}{z^3}\partial_z+\eta^{\mu\nu}\partial_\mu\partial_\nu-\frac{(\mu R)^2}{z^2}\right]\phi=0.$$

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$$\phi(x,z)=C_{\nu,k}e^{-iP.x}z^2J_\nu(u_{\nu,k}z),$$

$$\Delta=2+\sqrt{4+(\mu R)^2}.$$

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$$\phi(x,z) = C_{\nu,k}e^{-iP.x}z^2 J_\nu(u_{\nu,k}z),$$

Boundary operator:

spin $\ell = J.$

$$\mathcal{O}_{4+\ell} = FD_{\{\mu_1}\ldots D_{\mu_\ell\}}F$$

$$\Delta = 4 + \ell.$$

$\Delta = 2 + \sqrt{4 + (\mu R)^2}.$ $\quad (\mu R)^2 = \ell(\ell + 4).$ $\quad \nu = 2 + \ell$

Glueballs in the Hard-wall model and the Pomeron (J++) *P=C=+1, J=(0),2,4,...*

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$$(\mu R)^2 = \ell(\ell + 4).$$

$$\nu = 2 + \ell$$

Dirichlet boundary conditions

$$u_{\nu,k} = \frac{\chi_{\nu,k}}{z_{\max}} = \chi_{\nu,k}\Lambda_{\text{QCD}}; \qquad J_\nu(\chi_{\nu,k}) = 0.$$

The zeros of the Bessel functions give the masses of the Glueballs

Dirichlet boundary conditions

TABLE I. Masses of glueball states J^{PC} with even J expressed in GeV, estimated using the sliced $AdS_5 \times S^5$ space with Dirichlet boundary conditions. The mass of 0^{++} is an input from lattice results [38,39].

Dirichlet glueballs	lightest state	1st excited state	2nd excited state
0^{++}	1.63	2.67	3.69
2^{++}	2.41	3.51	4.56
4^{++}	3.15	4.31	5.40
6^{++}	3.88	5.85	6.21
8^{++}	4.59	5.85	7.00
10^{++}	5.30	6.60	7.77

HBF, Braga, Carrion, PRD 2006

Our result for the ratio of masses $M_{2^{++}}/M_{0^{++}} = 1.48$ is in good agreement with lattice |

Morningstar, Peardon, PRD 1997, 1999; Teper hep-lat/9711011.

Neumann boundary conditions

$$u_{\nu,k} = \frac{\xi_{\nu,k}}{z_{\max}} = \xi_{\nu,k}\Lambda_{\rm QCD} \qquad (2-\nu)J_\nu(\xi_{\nu,k}) + \xi_{\nu,k}J_{\nu-1}(\xi_{\nu,k}) = 0.$$

TABLE II. Masses of glueball states J^{PC} with even J expressed in GeV, estimated using the sliced $AdS_5 \times S^5$ space with Neumann boundary conditions. The mass of 0^{++} is an input from lattice results [38,39].

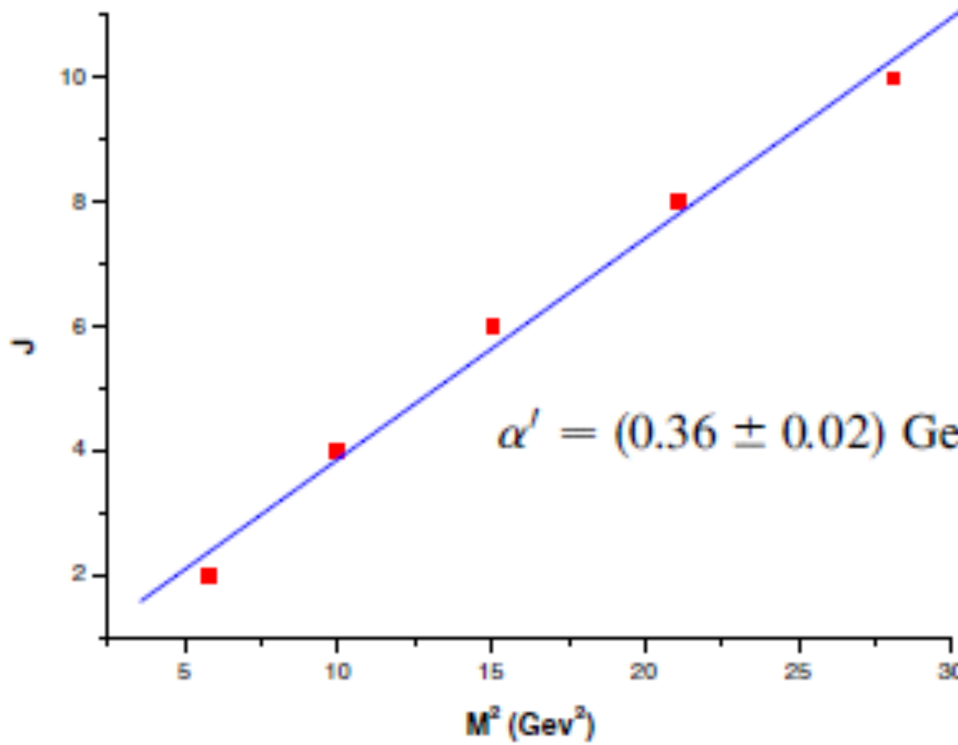
Neumann glueballs	lightest state	1st excited state	2nd excited state
0^{++}	1.63	2.98	4.33
2^{++}	2.54	4.06	5.47
4^{++}	3.45	5.09	6.56
6^{++}	4.34	6.09	7.62
8^{++}	5.23	7.08	8.66
10^{++}	6.12	8.05	9.68

$\frac{M_{2^{++}}}{M_{0^{++}}} = 1.56$; $\frac{M_{0^{++*}}}{M_{0^{++}}} = 1.83$ very good agreement with lattice

REGGE TRAJECTORIES

Dirichlet

$$J = \alpha(t = M^2) = \alpha_0 + \alpha' M^2.$$



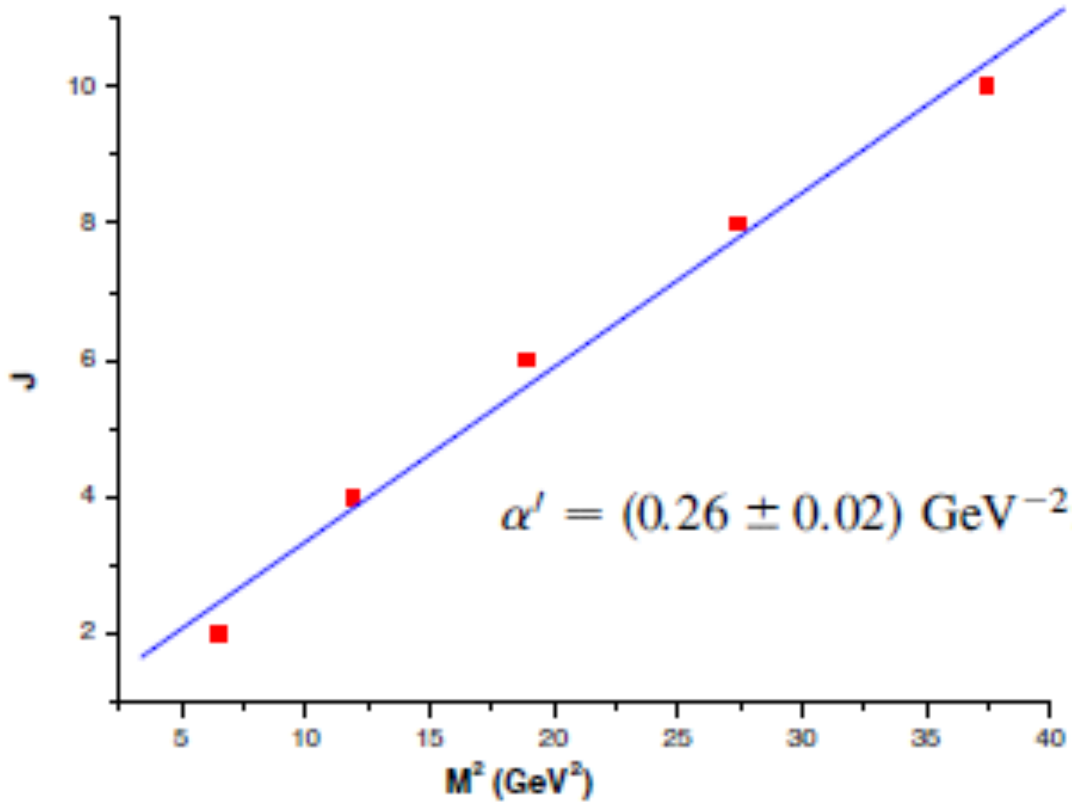
$\alpha' = (0.36 \pm 0.02)\ \mathrm{GeV}^{-2}$; $\alpha_0 = 0.32 \pm 0.36.$

FIG. 2 (color online). Approximate linear Regge trajectory for Dirichlet Boundary condition for the states $2^{++}, 4^{++}, 6^{++}, 8^{++}, 10^{++}$.

REGGE TRAJECTORIES

Neumann

$$J = \alpha(t = M^2) = \alpha_0 + \alpha' M^2.$$



$$\alpha' = (0.26 \pm 0.02)\ \text{GeV}^{-2}; \qquad \alpha_0 = 0.80 \pm 0.40$$

FIG. 1 (color online). Approximate linear Regge trajectory for Neumann Boundary condition for the states $2^{++}, 4^{++}, 6^{++}, 8^{++}, 10^{++}$.

Comparison with the Pomeron

$$J(m^2) \approx 1.08 + 0.25\, m^2\ ,$$

The Hard-wall Regge trajectories for Glueballs with Neumann boundary conditions

$$\alpha' = (0.26 \pm 0.02)\ \mathrm{GeV}^{-2}; \qquad \alpha_0 = 0.80 \pm 0.40$$

are in good agreement.

Odd spin (P=C=-1) Glueballs and the Odderon

Eduardo Capossoli and H. Boschi PRD 2013

Massive scalar fields in AdS_5

$$\left[z^3\partial_z \frac{1}{z^3}\partial_z + \eta^{\alpha\beta}\partial_\alpha\partial_\beta - \frac{m_5^2R^2}{z^2}\right]\phi(x,z) = 0,$$

Boundary operator

$$\mathcal{O}_{6+\ell} = \mathrm{Sym}\,\mathrm{Tr}(\tilde{F}_{\mu\nu}FD_{\{\mu_1}\ldots D_{\mu_\ell\}}F)$$

$$m_5^2R^2 = (\Delta - p)(\Delta + p - 4).$$

(p=0)

conformal dimension $\Delta = 6 + \ell$

spin $\ell = J \geq 1$

$$\phi(x,z) = A_{\nu,k}\exp^{-ip.x}z^2J_\nu(u_{\nu,k}z),$$

$$\nu = \sqrt{4 + m_5^2R^2},$$

$$\nu = 4 + \ell$$

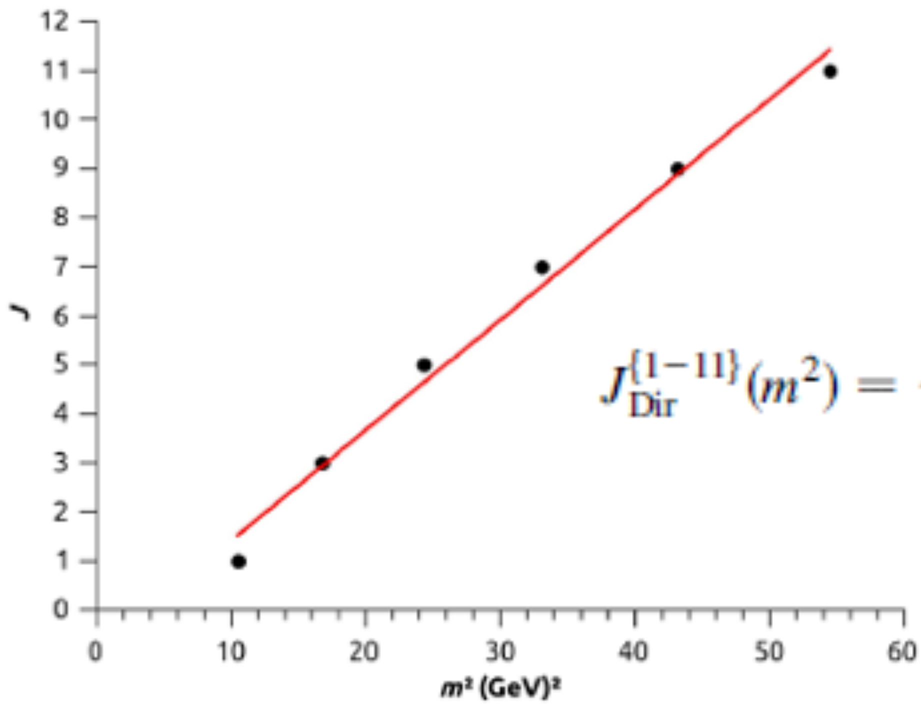
glueball states $1^{--}, 3^{--}, 5^{--}$, etc.

TABLE I. Glueball masses for states J^{PC} expressed in GeV, with odd J estimated using the hardwall model with Dirichlet and Neumann boundary conditions. The mass of 1^{--} is used as an input from the isotropic lattice [36,37]. We also show other results from the literature for comparison.

	Glueball states J^{PC}					
Models used	1^{--}	3^{--}	5^{--}	7^{--}	9^{--}	11^{--}
Hardwall with Dirichlet b.c.	3.24	4.09	4.93	5.75	6.57	7.38
Hardwall with Neumann b.c.	3.24	4.21	5.17	6.13	7.09	8.04
Relativistic many body [1]	3.95	4.15	5.05	5.90		
Nonrelativistic constituent [1]	3.49	3.92	5.15	6.14		
Wilson loop [38]	3.49	4.03				
Vacuum correlator [39]	3.02	3.49	4.18	4.96		
Vacuum correlator [39]	3.32	3.83	4.59	5.25		
Semirelativistic potential [40]	3.99	4.16	5.26			
Anisotropic lattice [41]	3.83	4.20				
Isotropic lattice [36,37]	3.24	4.33				

[36] H. B. Meyer and M. J. Teper, Phys. Lett. B 605, 344 (2005).
[37] H. B. Meyer, arXiv:hep-lat/0508002.

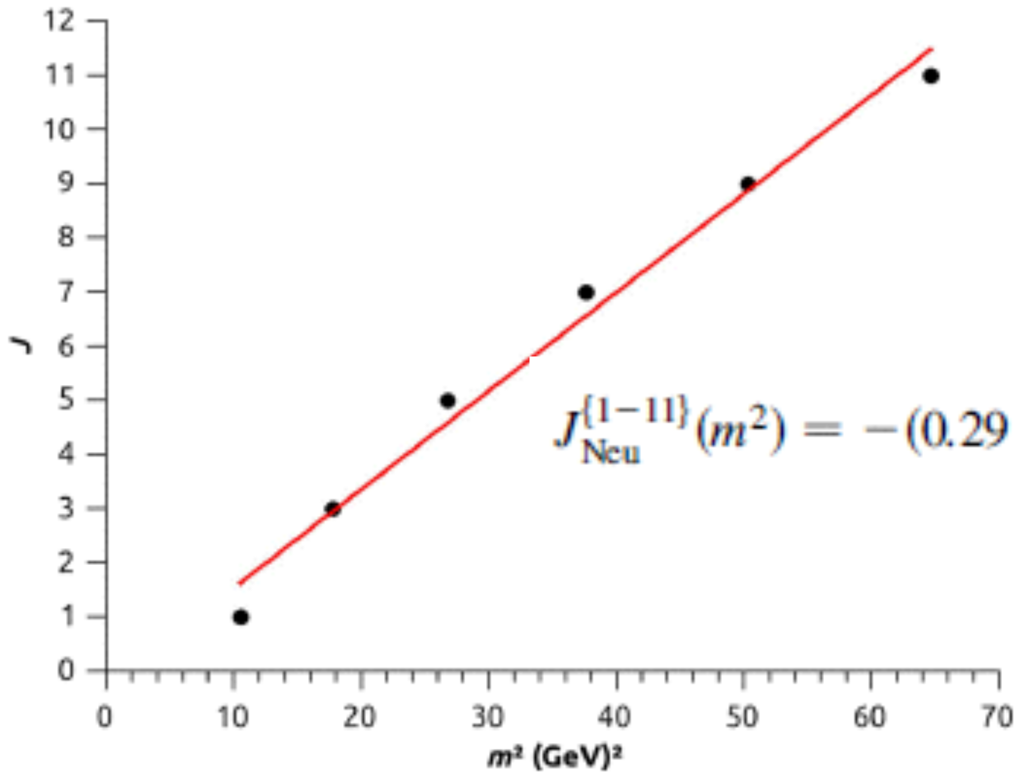
Odd Glueball states in the Hard-wall with Dirichlet Boundary condition



$$J_{\text{Dir}}^{\{1-11\}}(m^2) = -(0.83 \pm 0.40) + (0.22 \pm 0.01)m^2.$$

Good agreement with the Relativistic Many-body Model (RMB)

Odd Glueball states in the Hard-wall with Neumann Boundary condition



$$J_{\rm Neu}^{\{1-11\}}(m^2) = -(0.29 \pm 0.42) + (0.18 \pm 0.01)m^2.$$

Good agreement with the Relativistic Many-body Model (RMB)

Open questions for the Odderon

Experimental confirmation?

The authors

F. J. Llanes-Estrada, P. Bicudo, and S. R. Cotanch, Phys. Rev. Lett. 96, 081601 (2006).

suggest that the state 1^{--} does NOT belong to the Odderon trajectory

Our analysis with the Hard-wall is not conclusive in this regard

Soft-wall AdS/QCD Model

Soft cut off (Karch, Katz, Son, Stephanov PRD 2006)

$$\int d^5x\sqrt{-g}\,\mathcal{L} \quad \Longrightarrow \quad \int d^5x\sqrt{-g}e^{-\Phi}\mathcal{L}\,. \quad ; \quad \Phi(z) = cz^2$$

spectrum of vector mesons $\qquad m_{V_n}^2 = 4c(n+1)\,,$

Glueballs in the soft-wall

[Colangelo, De Fazio, Jugeau, Nicotri PLB(2007)]

The corresponding glueball spectrum is

$$m_{G_n}^2 = 4c(n+2)\,.$$

Softwall Model

1

Colangelo et al 2007 (scalar, vector and tensor glueballs)
Capossoli, HBF 2016 (higher spin glueballs)

$$S = \int d^5x \sqrt{-g} e^{-\Phi(z)} \left[g^{mn} \partial_m \mathcal{G} \partial_n \mathcal{G} + M_5^2 \mathcal{G}^2 \right],$$

$$ds^2 = g_{mn} dx^m dx^n = \frac{R^2}{z^2} (dz^2 + \eta_{\mu\nu} dy^\mu dy^\nu) \,,$$

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

$$\partial_m [\sqrt{-g} \, e^{-\Phi(z)} g^{mn} \partial_n \mathcal{G}] - \sqrt{-g} e^{-\Phi(z)} M_5^2 \mathcal{G} = 0 \,,$$

Softwall Model

2

$$\mathcal{G}(z, x^{\mu}) = v(z) \exp i q_{\mu} x^{\mu},$$

$$v(z) = \psi(z)(z/R)^{3/2} \exp \tfrac{1}{2}(kz^2),$$

“Schrödinger-like” equation

$$-\psi''(z) + \left[k^2 z^2 + \frac{15}{4z^2} + 2k + \left(\frac{R}{z}\right)^2 M_5^2\right] \psi(z) = -q^2 \psi(z)$$

which has a well known solution:

$$\psi_n(z) = \mathcal{N}_n\, z^{t(M_5)+\frac{1}{2}}\; {}_1F_1(-n; t(M_5)+1, kz^2) \exp\{-kz^2/2\}$$

where $t(M_5) = \sqrt{4 + R^2 M_5^2},$

Softwall Model

3

The corresponding "eigenenergies" $-q^2 = -q_\mu q^\mu$ are identified with the 4-d glueball squared masses

$$m_n^2 = \left[4n + 4 + 2\sqrt{4 + M_5^2 R^2}\right] k; \quad (n = 0, 1, 2, \cdots).$$

$$\Delta = 2 + \sqrt{4 + R^2 M_5^2}$$

scalar glueball state 0^{++} $\qquad$ $\mathcal{O}_4 = Tr(F^2) = Tr(F^{\mu\nu} F_{\mu\nu})$

$(M_5^2 = 0)$ $\qquad$ $\Delta = 4.$

$$m_n^2 = [4n + 8]\, k; \quad (n = 0, 1, 2, \cdots).$$

Higher spin glueballs in the softwall model [1]

Analoglous to the higher spin Glueballs in the Hardwall

$$\Delta = 2 + \sqrt{4 + R^2 M_5^2} \qquad 0^{++},\ 2^{++},\ 4^{++},\ \text{etc.}$$

$$\mathcal{O}_{4+J} = F D_{\{\mu 1 \ldots} D_{\mu J\}} F, \qquad \Delta = 4 + J$$

$$M_5^2 R^2 = J(J+4)\,; \qquad (\text{even } J)\,.$$

$$m_n^2 = \left[4n + 4 + 2\sqrt{4 + J(J+4)}\right] k; \quad (n = 0, 1, 2, \cdots, \text{even } J)\,,$$

Higher spin glueballs in the softwall model 2

Analogous to the higher spin Glueballs in the Hardwall

$$\Delta = 2 + \sqrt{4 + R^2 M_5^2} \qquad 1^{--},\ 3^{--},\ 5^{--},\ \text{etc.}$$

$$\mathcal{O}_{6+J} = SymTr\left(\tilde{F}_{\mu\nu} F D_{\{\mu 1 \ldots} D_{\mu J\}} F\right),$$

$$M_5^2 R^2 = (J+6)(J+2)\,; \qquad (\text{odd } J),$$

$$m_n^2 = \left[4 + 2\sqrt{4 + (J+6)(J+2)}\right] k; \quad (\text{odd } J). \qquad (n=0)$$

Not good when compared with the literature!!!

A Dynamical Softwall Model 1

Li & Huang JHEP 2013 (scalar glueballs)
Capossoli, Li, HBF 2016 (higher spins)

The 5D action for the graviton–dilaton coupling in the string frame is given by:

$$S = \frac{1}{16\pi G_5} \int d^5x \sqrt{-g_s}\, e^{-2\Phi(z)} (R_s + 4\partial_M \Phi \partial^M \Phi - V_G^s(\Phi))$$

The metric tensor has the following form:

$$ds^2 = g^s_{mn} dx^m dx^n = b_s^2(z)(dz^2 + \eta_{\mu\nu} dx^\mu dx^\nu);$$

$$b_s(z) \equiv e^{A_s(z)}$$

A Dynamical Softwall Model 2

Einstein frame and equations of motion

$$g^E_{mn} = g^s_{mn} e^{-\frac{2}{3}\Phi}, \qquad V^E_G = e^{\frac{4}{3}\Phi} V^s_G \,,$$

$$b_E(z) = b_s(z) e^{-\frac{2}{3}\Phi(z)} = e^{A_E(z)}, \qquad A_E(z) = A_s(z) - \frac{2}{3}\Phi(z)\,.$$

$$-A''_E + A'^2_E - \frac{4}{9}\Phi'^2 = 0\,,$$

and

$$\Phi'' + 3A'_E\Phi' - \frac{3}{8} e^{2A_E} \partial_\Phi V^E_G(\Phi) = 0\,.$$

A Dynamical Softwall Model 3

For a quadratic dilaton

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

one finds the solutions

$$A_E(z) = \log\left(\frac{R}{z}\right) - \log\left({}_0F_1(5/4, \frac{\Phi^2}{9})\right)$$

and

$$V_G^E(\Phi) = -\frac{12\,{}_0F_1(1/4, \frac{\Phi^2}{9})^2}{R^2} + \frac{16\,{}_0F_1(5/4, \frac{\Phi^2}{9})^2\Phi^2}{3R^2}$$

A Dynamical Softwall Model 4

Going back to the String frame

$$A_s(z) = \log\left(\frac{R}{z}\right) + \frac{2}{3}\Phi(z) - \log\left[{}_0F_1\left(\frac{5}{4}, \frac{\Phi^2}{9}\right)\right],$$

which means a deformed AdS space

$$ds^2 = g^s_{mn} dx^m dx^n = b_s^2(z)(dz^2 + \eta_{\mu\nu} dx^\mu dx^\nu); \quad b_s(z) \equiv e^{A_s(z)}$$

and a potential

$$V_G^s(\Phi) = \exp\{-\frac{4}{3}\Phi\}\left[-\frac{12\,{}_0F_1(1/4, \frac{\Phi^2}{9})^2}{R^2} + \frac{16\,{}_0F_1(5/4, \frac{\Phi^2}{9})^2 \Phi^2}{3R^2}\right]$$

A Dynamical Softwall Model 5

5D action for Scalar Glueballs in String frame

$$S = \int d^5x \sqrt{-g_s}\,\frac{1}{2} e^{-\Phi(z)} [\partial_M \mathcal{G} \partial^M \mathcal{G} + M_5^2 \mathcal{G}^2],$$

which implies the equations of motion

$$\partial_M [\sqrt{-g_s}\, e^{-\Phi(z)} g^{MN} \partial_N \mathcal{G}] - \sqrt{-g_s} e^{-\Phi(z)} M_5^2 \mathcal{G} = 0\,.$$

as before

$$\mathcal{G}(z, x^\mu) = v(z) e^{iq_\mu x^\mu}\,, \qquad B(z) = \Phi(z) - 3A_s(z)\,, \qquad v(z) = \psi(z) e^{B(z)/2}$$

so that one gets a Schrödinger-like equation:

$$-\psi''(z) + \left[\frac{B'^2(z)}{4} - \frac{B''(z)}{2} + M_5^2 \left(\frac{R}{z}\right)^2 e^{4kz^2/3} \mathcal{A}^{-2} \right] \psi(z)$$

$$= -q^2 \psi(z)\,, \qquad \text{where } \mathcal{A} = {}_0F_1(5/4, \Phi^2/9).$$

A Dynamical Softwall Model 6

Higher spins from AdS/CFT

$$M_5^2 R^2 = \Delta(\Delta - 4) - J \qquad (J = 0, 1, 2, 3, \cdots)$$

which implies an effective potential of the form

$$V_J(z) = k^2 z^2 + \frac{15}{4z^2} - 2k + \frac{\Delta(\Delta - 4) - J}{z^2} e^{4kz^2/3} \mathcal{A}^{-2} \, .$$

A Dynamical Softwall Model 6

Higher spins from AdS/CFT

$$M_5^2 R^2 = \Delta(\Delta - 4) - J \qquad (J = 0, 1, 2, 3, \cdots)$$

which implies an effective potential of the form

$$V_J(z) = k^2 z^2 + \frac{15}{4z^2} - 2k + \frac{\Delta(\Delta - 4) - J}{z^2} e^{4kz^2/3} \mathcal{A}^{-2} .$$

Even spins and the pomeron

twist 2 trajectory $\Delta = J + 2$

Complex masses for 0++ and 2++ → No Regge trajectory

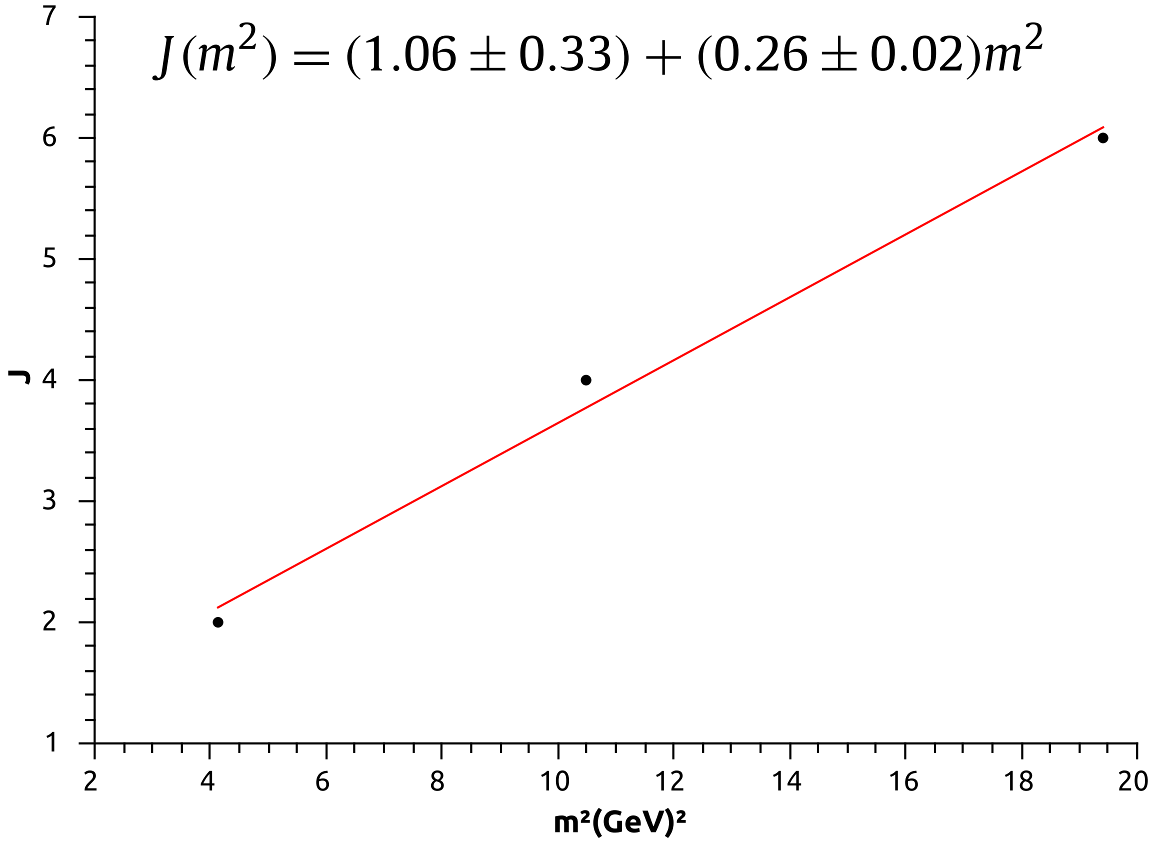
twist 4 trajectory $\Delta = J + 4$

Real masses for 0++ and 2++, etc → Good Regge trajectories

Table 1
Masses m_n expressed in GeV for the glueball states J^{PC} with even J as the eigenstates of Eq. (9) with the potential (12) for $k = 0.10$ GeV^2.

	Glueball states J^{PC}						k
	0^{++}	2^{++}	4^{++}	6^{++}	8^{++}	10^{++}	
m_n	0.51	2.03	3.23	4.40	5.56	6.71	0.10

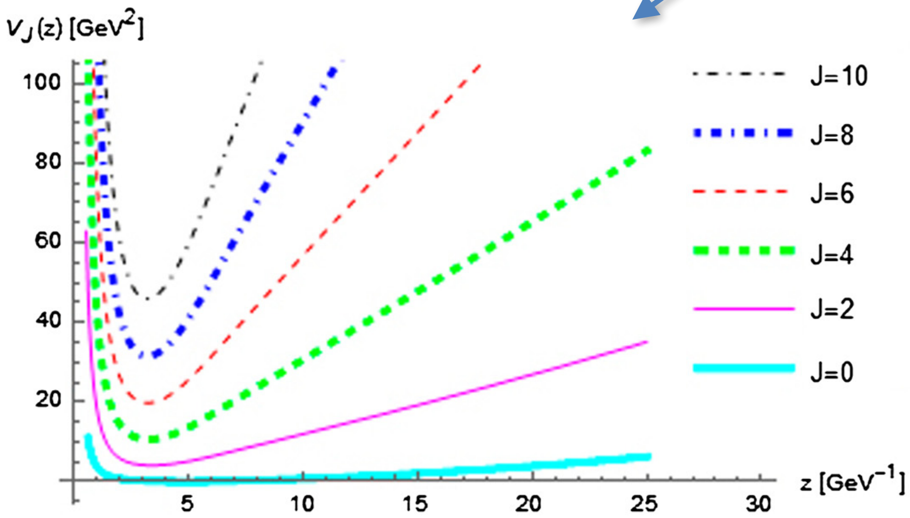
Regge trajectory: glueball states 2^{++}, 4^{++} and 6^{++}

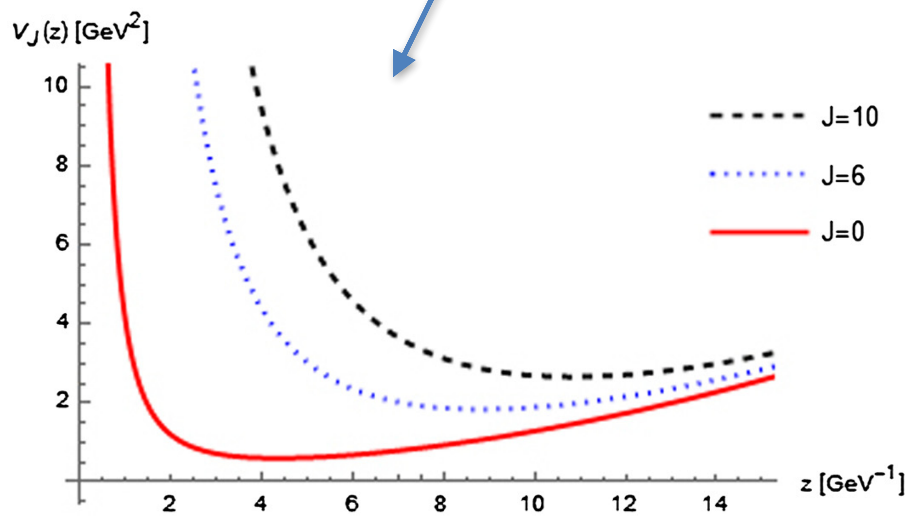


Very good compared to experimental pomeron:

$$J(m^2) \approx 1.08 + 0.25\,\mathrm{m}^2,$$

Effective potentials in the Dynamical Softwall X usual Softwall





Odd spins and the odderon

$$\mathcal{O}_{6+J} = SymTr\left(\tilde{F}_{\mu\nu} F D_{\{\mu 1 \dots} D_{\mu J\}} F\right),$$

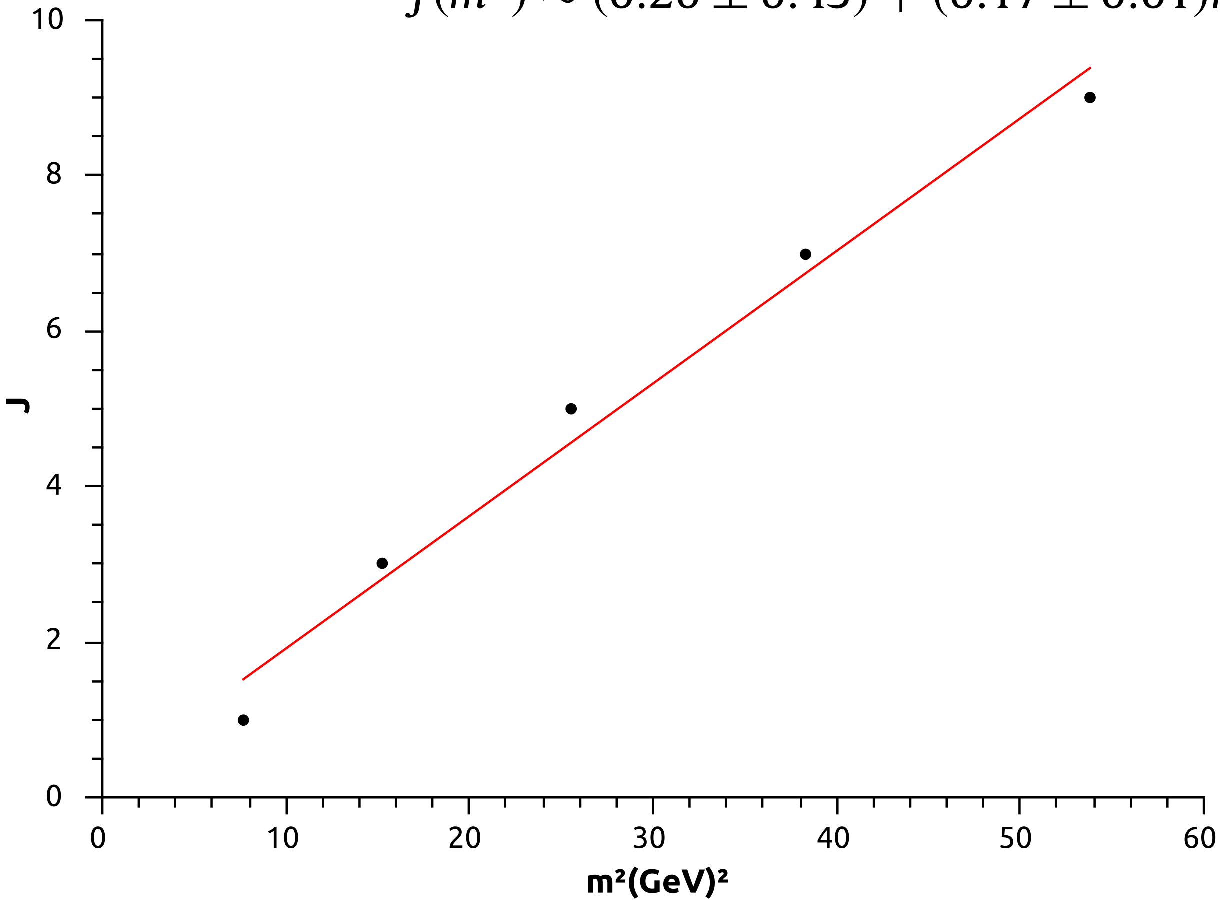
$$\Delta = 6 + J \qquad \text{spin } 1 + J.$$

Table 2
Masses m_n expressed in GeV for the glueball states J^{PC} with odd J solving Eq. (9) with the potential (12) for $k = 0.10$ GeV^2.

	Glueball states J^{PC}						k
	1^{--}	3^{--}	5^{--}	7^{--}	9^{--}	11^{--}	
m_n	2.77	3.91	5.05	6.19	7.33	8.47	0.10

Regge trajectories for the odderon

$$J(m^2) \approx (0.20 \pm 0.43) + (0.17 \pm 0.01) m^2$$

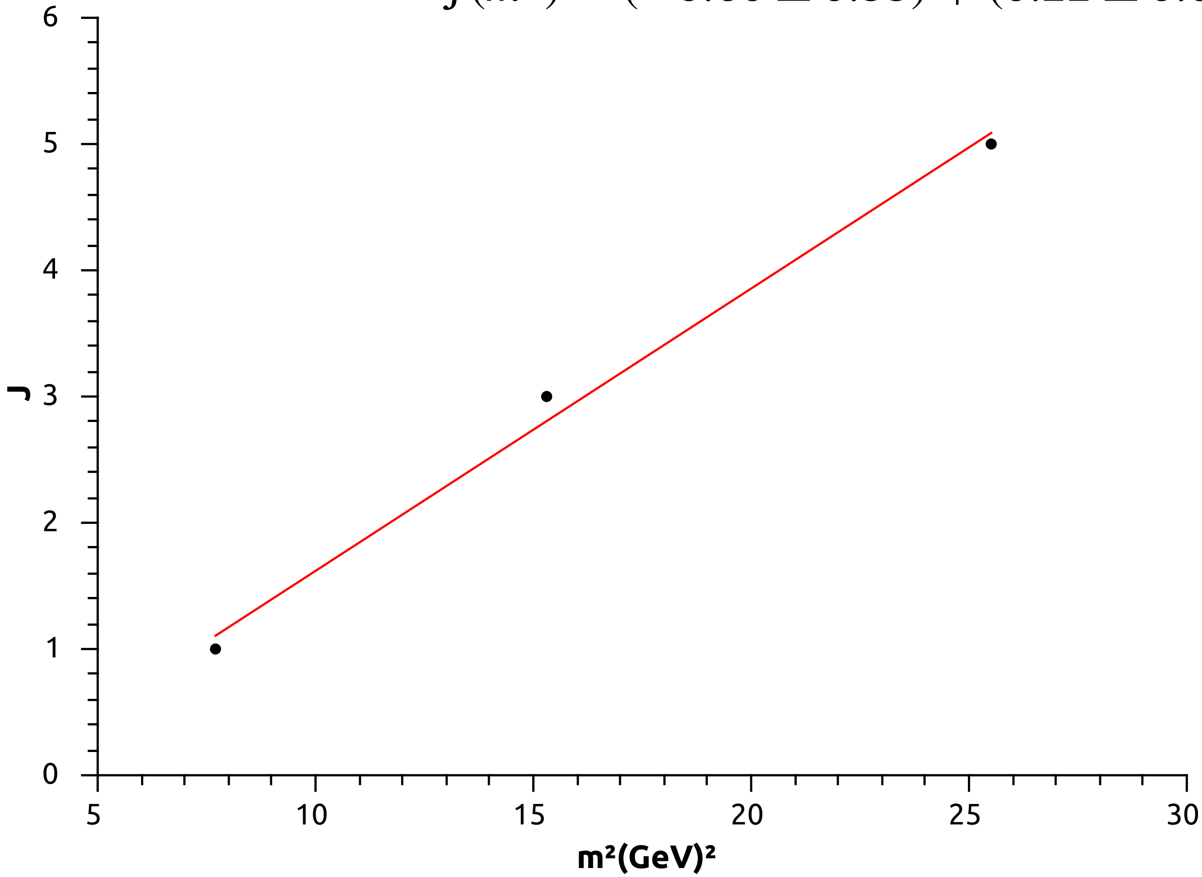


Very good agreement with the non-relativistic model for the odderon:

$$J(m^2) \approx 0.25 + 0.18\,\mathrm{m}^2,$$

Regge trajectories for the odderon

$$J(m^2) = (-0.60 \pm 0.33) + (0.22 \pm 0.01)m^2$$



Very good agreement with the relativistic model for the odderon:

$$J(m^2) \approx -0.88 + 0.23\,\mathrm{m}^2,$$

Finite Temperature AdS/CFT and AdS/QCD

Witten's proposal (1998)

Policastro, Son, Starinets, PRL 2001 (Shear viscosity…)

Finite temperature Yang-Mills theory in 4d dual to a modified AdS(5)xS(5) set up with a **Black Hole** (Schwarzschild AdS (5) x S (5))

The temperature of the Yang-Mills theory is identified with the Hawking temperature of the Black Hole

Soft-wall model at Finite Temperature

AdS black-hole spacetime

$$ds^2 = e^{2A(z)}\left[-f(z)dt^2 + \sum_{i=1}^{3}(dx^i)^2 + f(z)^{-1}dz^2\right],$$

$$A(z) = -\ln(z/L) \qquad f(z) = 1 - (z/z_h)^4.$$

$$z_h = 1/\pi T.$$

Herzog PRL 2007;

Kajantie, Tahkokallio, Yee, JHEP 2007;

Ballon-Bayona, HBF, Braga, Pando Zayas, PRD 2008.

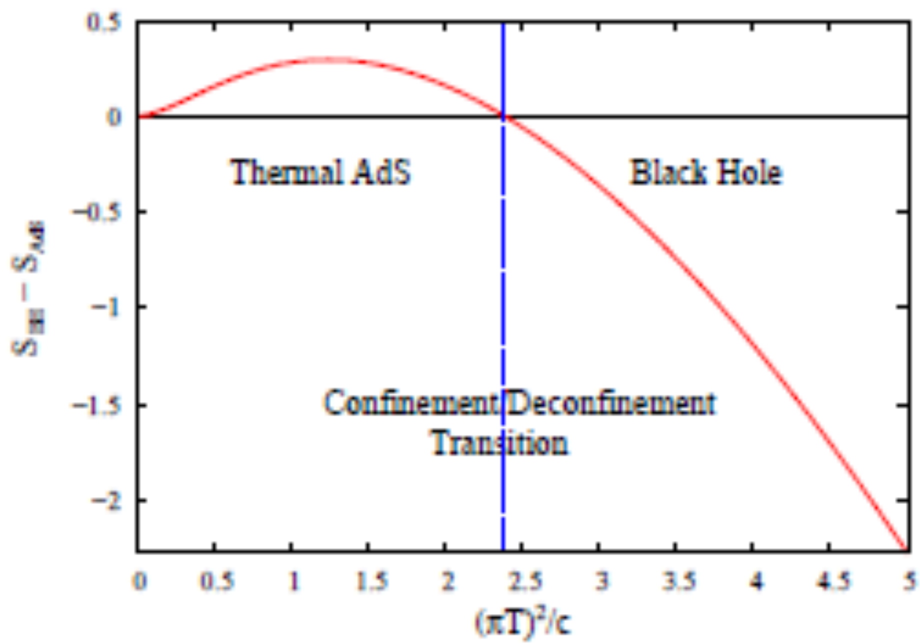
Hard-wall and Soft-wall at Finite Temperature: Confining/deconfining phase transition

Herzog, PRL 2007

Thermal AdS space (low temperature)
(confined phase)

Hawking-Page phase transition

AdS Black hole (high temperature)
(deconfined phase)



Quasinormal modes and scalar Glueballs in the Soft-wall at Finite Temperature

Quasinormal modes are formed when a particle/field falls onto a black hole horizon

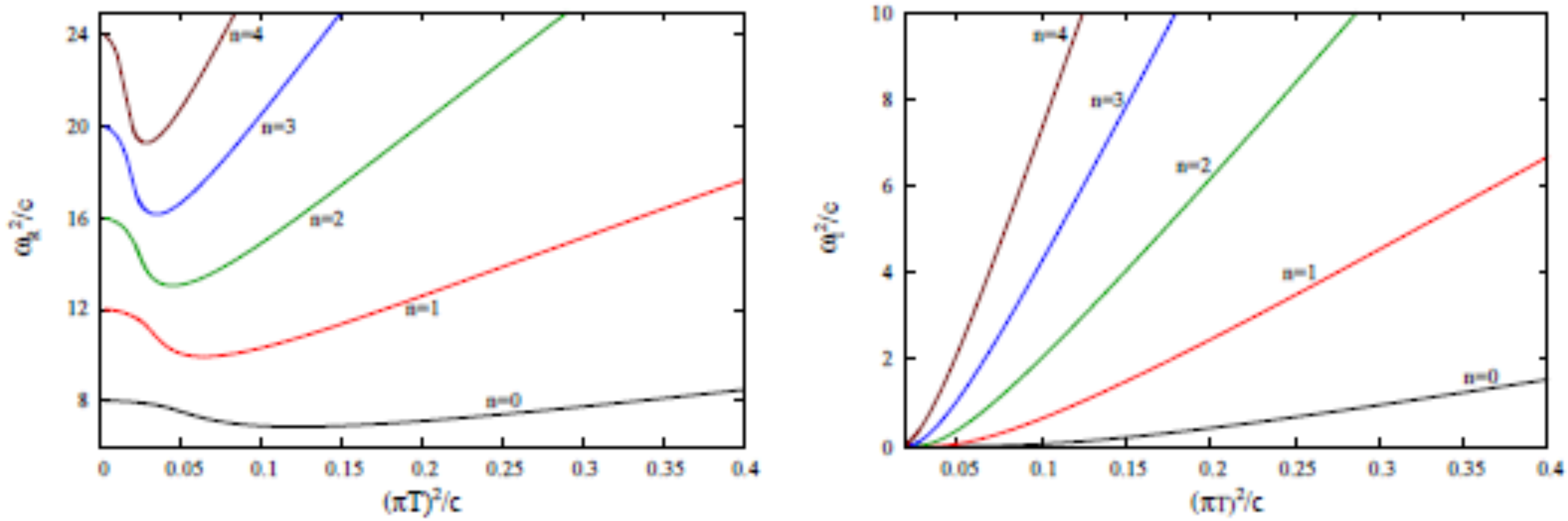


Figure 6. Numerical results for the square of the real and imaginary parts of the QN frequencies, ω_R^2/c and ω_I^2/c, for the first five quasinormal modes $n = 0, 1, \ldots, 4$, with $q = 0$. (zero momentum)

Miranda,Ballon-Bayona, HBF, Braga, JHEP 2009

Quasinormal modes and Vector Mesons in the Soft-wall at Finite Temperature

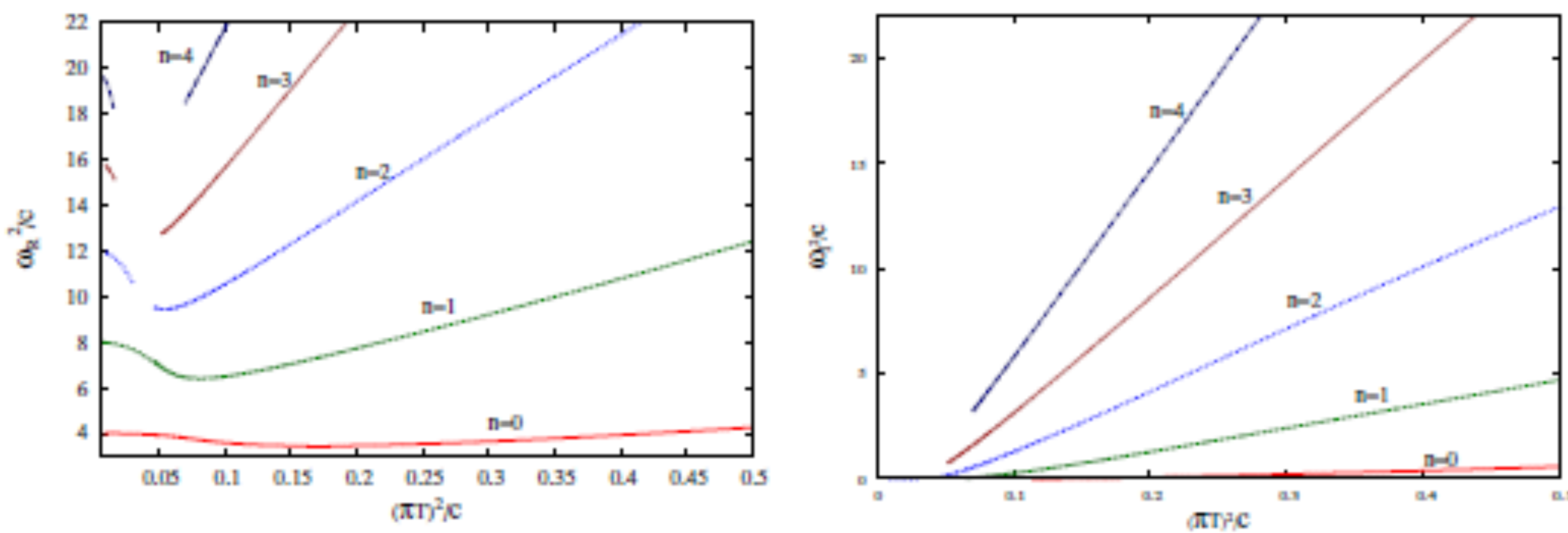
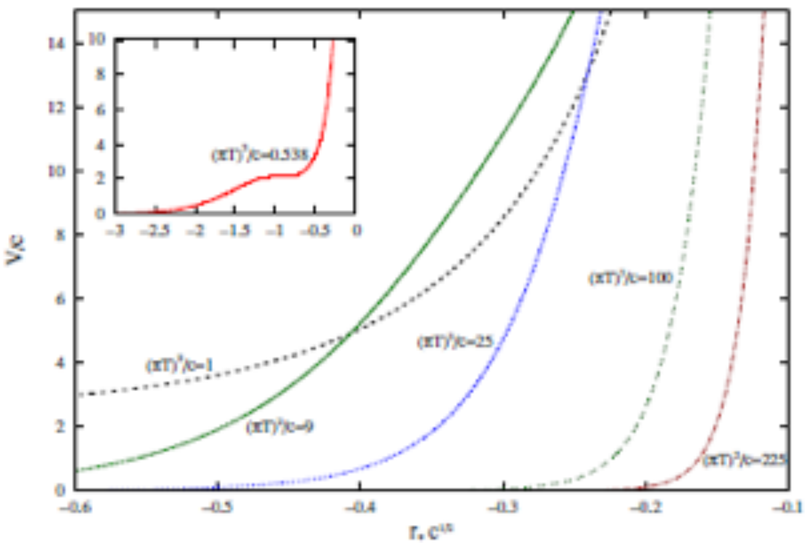


Figure 5. Numerical results for the quasinormal frequencies. On the left panel we show the real part, associated with mass of the vector mesons. On the right panel we show the imaginary part associated with the decay time of the quasiparticle states.

Mamani, Miranda, HBF, Braga, JHEP 2014

Vector Mesons at Finite T in the Soft-wall model

Figure 1. Potential at zero wave number for high temperatures.



the critical value $\widetilde{T}_c^2 = 0.538$ in the detail.

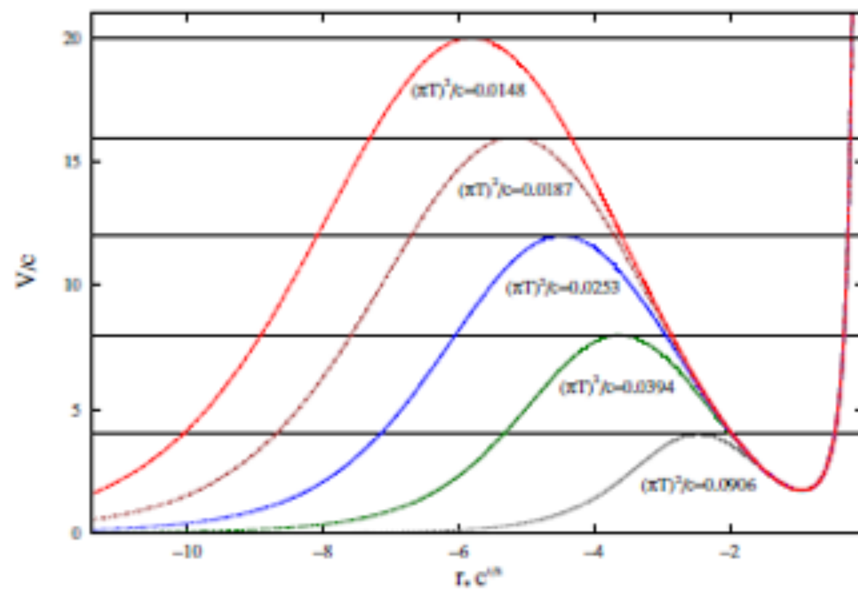


Figure 2. Potential at zero wave number for low temperatures.

Other Results:

Wilson loops in AdS/CFT and AdS/QCD (nonconfining/ confining)

Vector mesons form factors in the D4-D8 model

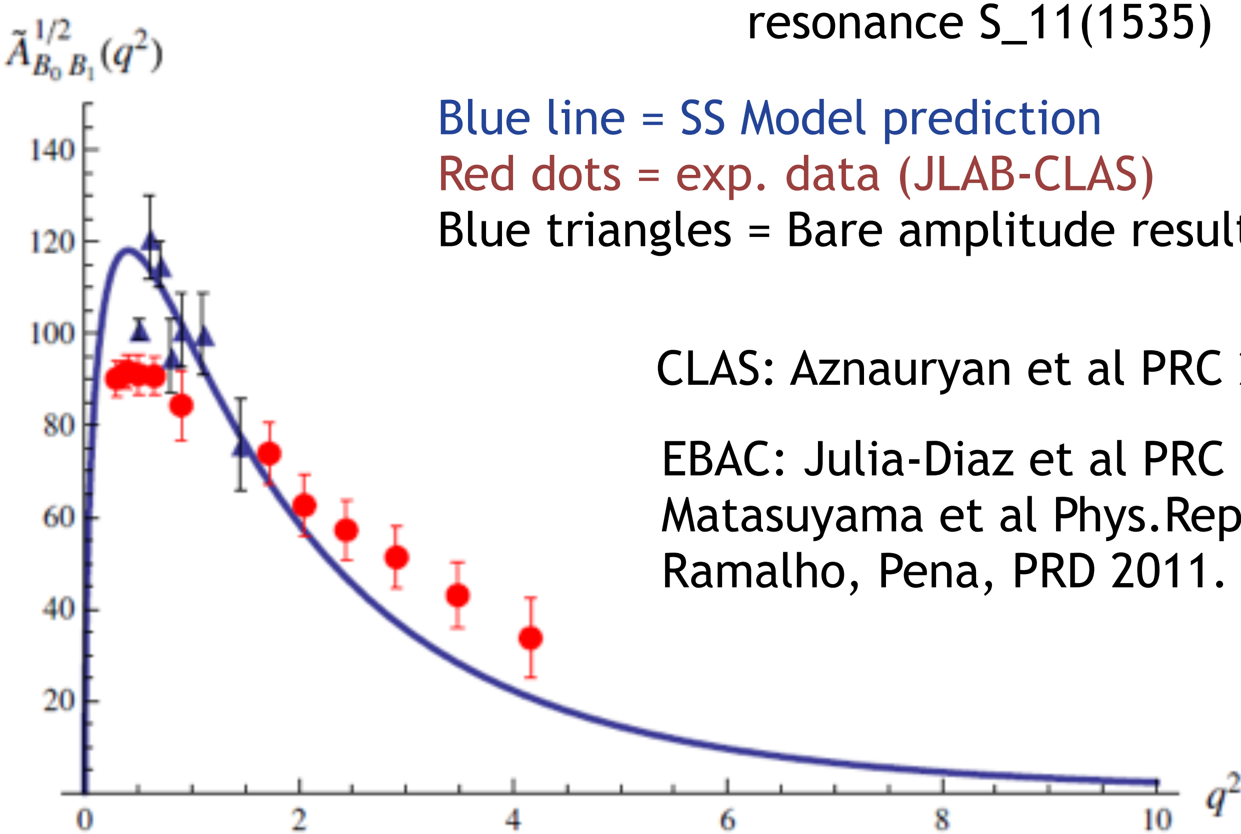
Production of positive and negative parity Baryons in the D4-D8 model

Pion and vector mesons form factors from the Kuperstein-Sonnenschein model

Baryons Form Factors and Proton Structure in the Holographic Sakai-Sugimoto D4-D8 Model

Ballón-Bayona, HBF, Braga, Ihl, Torres, PRD 2012; NPB 2013

Helicity Amplitude $[10^{-3}(\text{GeV})^{-1/2}]$ for the observed negative parity resonance S_11(1535)



$(\text{GeV})^2$

Blue line = SS Model prediction
Red dots = exp. data (JLAB-CLAS)
Blue triangles = Bare amplitude results (EBAC)

CLAS: Aznauryan et al PRC 2009.

EBAC: Julia-Diaz et al PRC 2009;
Matasuyama et al Phys.Rep. 2007;
Ramalho, Pena, PRD 2011.

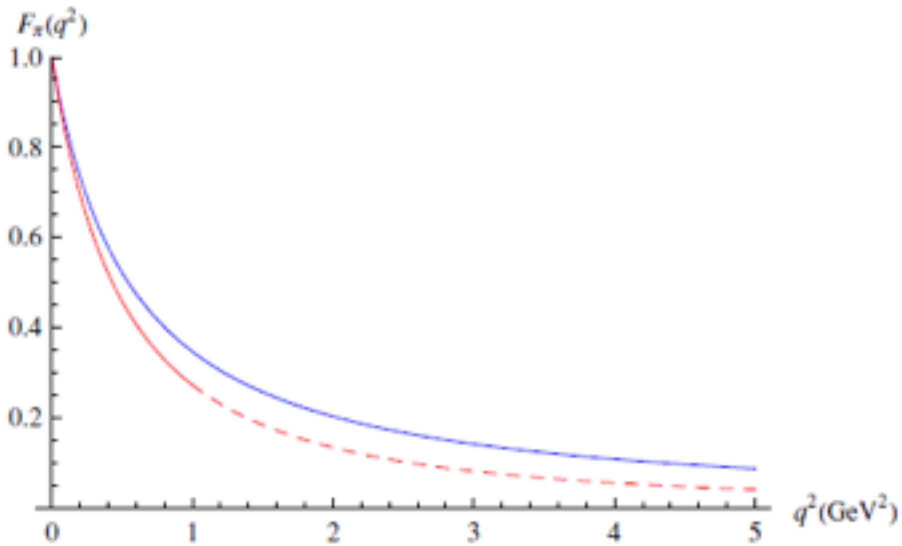
Pion (and vector meson) Form Factors in the Kuperstein-Sonnenschein Holographic model

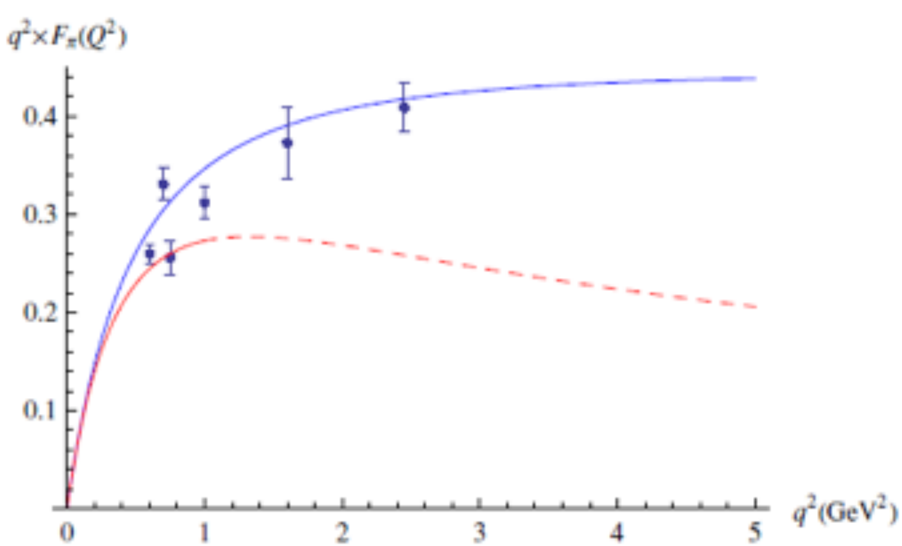
Ballón-Bayona, HBF, Ihl, Torres, JHEP (2010)

D3-brane background
D7-brane profiles

The KS model is based on the $D3$-brane background with a conical singularity in type IIB superstring theory first studied by Klebanov and Witten

Stable, non-supersymmetric, but similar to D4-D8 with VMD





Red = SS model; Blue = KS model
Dots = experimental data (PDG)