Applications of the gauge/gravity duality to hadron physics

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Outline

1. Introduction to holographic QCD

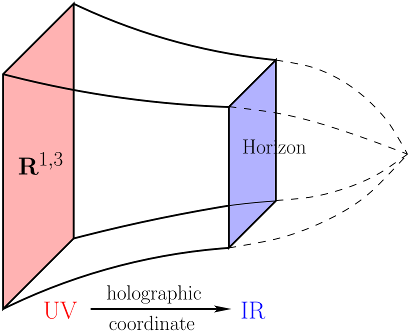
Gauge/gravity duality

- Gauge/gravity duality: at large N_c, strongly coupled field theory $\leftrightarrow$ classical higher dimensional gravity
- Well known example: $\mathcal{N} = 4$ Super Yang-Mills
  $\leftrightarrow$ type IIB supergravity on $AdS_5 \times S^5$ ("AdS/CFT")
- Relatively easy classical analysis of strongly coupled phenomena $\Rightarrow$ apply to QCD?
- There are possible issues (QCD not conformal, no SUSY, and $N_c = 3$ is not that large ...) but since solving QCD is hard, it's worth trying – and it turns out to work quite nicely!

Gauge/gravity duality for QCD

Basic features:

- Geometrization of RG flow: running of the gauge coupling in QCD $\leftrightarrow$ non-AdS geometry
- $\Rightarrow$ confinement scale, broken conformal symmetry
- Thermodynamics of QCD $\leftrightarrow$ thermodynamics of a planar bulk black hole



- Operators $O_i(x^\mu) \leftrightarrow$ classical bulk fields $\phi_i(x^\mu, r)$

$$Z_{\text{grav}}(\phi_i|_{\text{bdry}} = J_i(x^\mu)) = \int \mathcal{D}\phi_i e^{iS_{QCD} + i\int d^4x J^i(x^\mu) O_i(x^\mu)}$$

  - E.g. $\bar{\psi}^j \psi^i \leftrightarrow \phi^{ij}$ $\quad T_{\mu\nu} \leftrightarrow g_{\mu\nu}$ $\quad J_\mu \leftrightarrow A_\mu$
- Condensates in QCD $\langle O_i \rangle \leftrightarrow$ nontrivial extrema $\phi_i(r)$ in the bulk, e.g. black hole "hair"

Gauge/gravity duality for QCD: approaches

Top-down: models directly based on string theory

- Concrete, fixed string models in 10/11 d with brane configurations
- Control on what dual field theory is (it's not QCD though)
- E.g., $D3$-$D7$ models and Witten-Sakai-Sugimoto model: $D4$-$D8$-$\overline{D8}$

Bottom-up: models constructed "by hand"

- Follow generic ideas of holography, inspiration from top-down
- Introduce fields for most important operators (marginal)
- Lots of freedom $\rightarrow$ effective 5d description, no link to specific dual theory, comparison with QCD data essential
- Either a fixed geometry (AdS) or dynamical gravity
- Examples: hard/soft wall models, light-front holography

This talk: rich bottom-up models; lots of input from string theory

- Lots of parameters to be fitted from data
- Goal: mimic QCD as closely as possible

Improved Holographic QCD

"Improved holographic QCD" (IHQCD): string-inspired bottom-up model for pure Yang-Mills
[Review: Gursoy, Kiritsis, Mazzanti, Michalogiorgakis, Nitti arXiv:1006.5461]

$$\mathcal{S}_{\mathsf{IHQCD}} = M^3 N_c^2 \int d^5x \sqrt{g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$

- $\lambda = e^{\phi} \leftrightarrow \mathrm{Tr}(F^2)$
- Near UV bdry, $\lambda \approx$ 't Hooft coupling $g^2 N_c$
- $g_{\mu\nu} \ \leftrightarrow \ T_{\mu\nu}$

The only non-trivial input V_g needs to be determined by comparing to QCD physics

- Strong coupling (IR) physics: qualitative properties of QCD
- Weak coupling (UV) physics: perturbation theory
- Remaining degrees of freedom: lattice data (thermodynamics and glueball spectra)

Adding quarks (V-QCD)

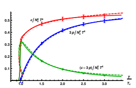
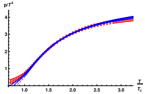
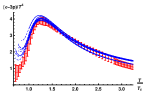
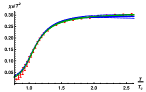
Two bulk scalars: $\lambda \leftrightarrow \mathrm{Tr}(F^2)$, $\quad \tau \leftrightarrow \bar{\psi}\psi$
Gauge field(s) $A_\mu \leftrightarrow \bar{\psi}\gamma_\mu\psi$

- Motivated by a brane setup
- Duals for all operators with $D \leqslant 4$

$$\mathcal{S}_{\mathrm{V-QCD}} = N_c^2 M^3 \int d^5x \sqrt{g} \left[R - \frac{4}{3}\frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$
$$- N_f N_c M^3 \int d^5x \; V_{f0}(\lambda) e^{-\tau^2}$$
$$\times \sqrt{-\det(g_{ab} + \kappa(\lambda)\partial_a\tau\partial_b\tau + w(\lambda)F_{ab})}$$

- Chiral symmetry breaking $\leftrightarrow$ condensation of τ in the bulk

Similar approach to pure glue, but more degrees of freedom: additional asymptotics constraints, more data ...

[Review: MJ arXiv:2110.08281]

2. Regge theory in holographic QCD

Pomeron and Deep Inelastic Scattering

(Soft) Pomeron: Regge trajectory with vacuum quantum numbers

- Dominates elastic pp scattering at high s and small angles:
  $\mathcal{A}(s,t) \sim s^{\alpha(t)} \qquad \alpha(t) \approx 1.08 + 0.25t$
- Total QCD cross section $\sigma \sim \frac{1}{s}\mathrm{Im}\mathcal{A}(s,0) \sim s^{\alpha(0)-1}$
- QCD origin: nonperturbative exchange of soft gluons

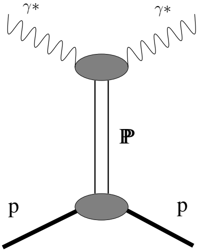
Pomeron in Deep Inelastic Scattering: take large s and soft photon virtuality $Q^2 \sim \mathrm{GeV}^2$

$\Rightarrow$ parton momentum fraction $x = \frac{Q^2}{s} \ll 1$

- Regime where gluon parton distributions dominate

  Data : $\sigma(x, Q^2) \sim x^{1-\alpha(t=0,Q^2)}$

- Observed Q^2 dependence due to multiple Regge trajectories? Soft+hard Pomeron?

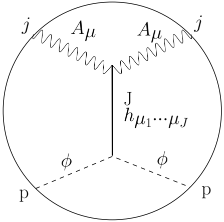


Soft physics, difficult in QCD, open questions – maybe holography can shed light on this?

Pomeron in holographic QCD

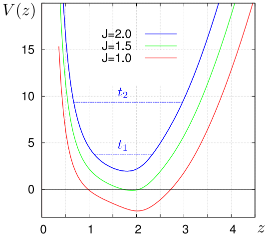
Evaluate hadronic tensor $\sim \langle p' | T\{j(x)j(0)\} | p\rangle$ following dictionary

- Witten diagram – dominated by bulk "graviton" trajectory – high spin J cousins of the 5D graviton



Holographic QCD: choose the IHQCD model

- High J fields need to be added – Ansatz with 5 parameters to be fitted
- Details of proton unimportant in Regge limit
  - Reduces to proton-graviton couplings
  - Enough to use scalar fields



Holographic Regge physics:

- Schrödinger problem in the bulk

$$\left[-\partial_z^2 + V_J(z)\right] h^{(n)}_{\mu_1 \cdots \mu_J} = 0$$

- Summing over J, Sommerfeld-Watson transformation $\Rightarrow$

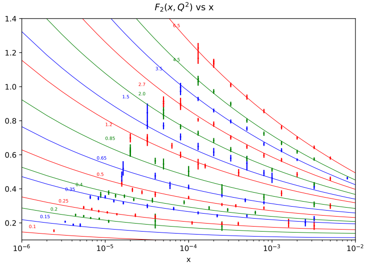
  Regge trajectories $\leftrightarrow$ eigenmodes

[Ballon-Bayona, Carcassés Quevedo, Costa, Djurić 1508.00008]
[Ballon-Bayona, Carcassés Quevedo, Costa 1704.08280]

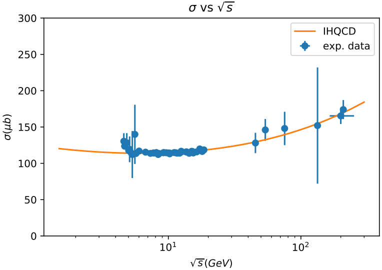
Fitting the DIS data

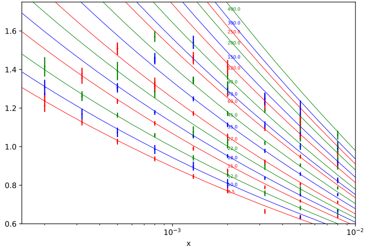
Fit with lowest 4 trajectories

- 5 (graviton model) +
  4 (proton coupling) parameters
- 358 data points, $\chi^2_{d.o.f} \approx 1.4$



$\sigma(\gamma p \to X)$





[Ballon-Bayona, Carcassés Quevedo, Costa 1704.08280]

[Amorim, Costa 2006.05299]

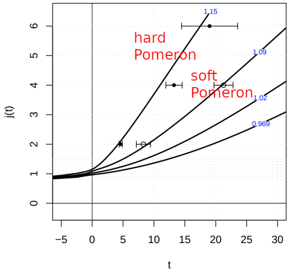
Results, checks and predictions

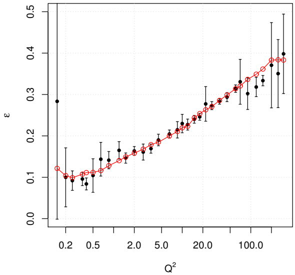
Regge trajectories from the fit:

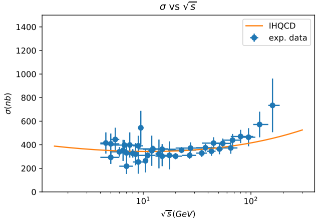
- Two leading trajectories: hard and soft Pomeron
- Reproduce the exponent in $\sigma(x, Q^2) \sim x^{-\epsilon(Q^2)}$

Further checks and predictions:

- $\gamma^*\gamma \to X$ can be fitted by the same Pomeron kernel
- Similar approach works (with minor adjustments) for deeply virtual Compton scattering







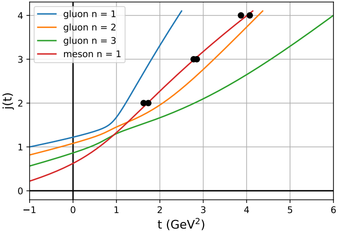
[Amorim, Carcassés Quevedo, Costa 2106.09439]

Extending to meson trajectories

Meson trajectories also expected to be important $\Rightarrow$ extend the model to include quarks $\Rightarrow$ use V-QCD

- First task: fit the model properly to meson masses
- Regge physics: both gluonic (closed string) and mesonic (open string) trajectories

Fit: include 3 gluonic and a mesonic trajectory



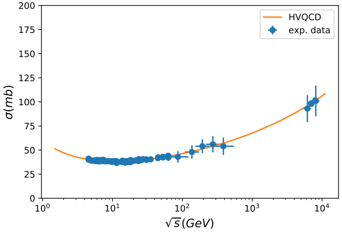
Ratio	$R_{pred.}$	$R_{obs.}$	$\lvert R_{pred.} - R_{obs.}\rvert / R_{obs.}$
$m_{\rho(1450)}/m_\rho$	1.662	1.890	0.121
$m_{\rho(1700)}/m_\rho$	2.141	2.219	0.035
$m_{\rho(2000)}/m_\rho$	2.559	2.580	0.008
$m_{\rho(2270)}/m_\rho$	2.940	2.922	0.006
$m_{\omega(782)}/m_\rho$	1	1.010	0.010
$m_{\omega(1420)}/m_\rho$	1.662	1.832	0.093
$m_{\omega(1650)}/m_\rho$	2.141	2.154	0.006
$m_{\omega(1960)}/m_\rho$	2.559	2.528	0.012
$m_{\omega(2205)}/m_\rho$	2.940	2.844	0.034
$m_{\omega(2290)}/m_\rho$	3.289	2.954	0.127
$m_{\omega(2330)}/m_\rho$	3.610	3.005	0.201
$m_{a_1(1260)}/m_\rho$	1.591	1.587	0.003
$m_{a_1(1930)}/m_\rho$	2.095	2.489	0.158
$m_{a_1(2095)}/m_\rho$	2.523	2.702	0.066
$m_{a_1(2270)}/m_\rho$	2.916	2.928	0.004
$m_{f_1(1285)}/m_\rho$	1.653	1.654	0.001
$m_{f_1(1420)}/m_\rho$	2.128	1.840	0.157
$m_{f_1(1970)}/m_\rho$	2.543	2.542	0.0004
$m_{f_1(2310)}/m_\rho$	2.930	2.980	0.017
m_π/m_ρ	0.1740	0.1741	0.0006
$m_{\pi(1300)}/m_\rho$	1.731	1.677	0.032
$m_{\pi(1800}/m_\rho$	2.337	2.337	5×10^{-5}
$m_{\pi(2070)}/m_\rho$	2.785	2.670	0.043
$m_{\pi(2360)}/m_\rho$	3.173	3.044	0.042
$m_{a_0(1450)}/m_\rho$	0.685	1.901	0.640
$m_{a_0(2020)}/m_\rho$	1.492	2.612	0.429

[Amorim, Costa, MJ 2102.11296]

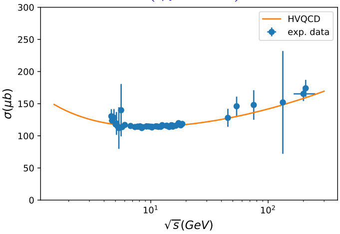
Fit results

- Exchange kernels determined by fixing the Pomeron intercept and high J meson masses
- Couplings of p and γ to the trajectories fitted to σ's
- 8 parameter fit to 199 data points with $\chi^2_{d.o.f} \approx 0.74$

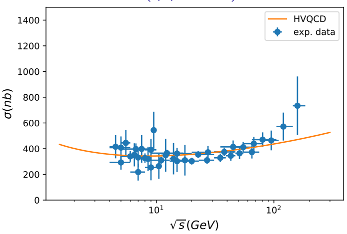
$\sigma(pp \to X)$



$\sigma(\gamma p \to X)$



$\sigma(\gamma\gamma \to X)$



Simultaneous fit of all σ's requires including the meson trajectory!

3. Baryons in holographic QCD

Baryons in large N_c QCD

Baryons are color singlet states of N_c quarks

- Massive, $M \propto N_c$ in the large N_c limit [Witten NPB 160 (1979) 57]
- $\Rightarrow$ Effective description as solitons of the pion field

Baryon = topological soliton solution of the chiral pion Lagrangian (with nontrivial winding number $\pi_3(SU(N_f))$ of the flavor group)

$$\mathcal{L}_\pi = \frac{f_\pi^2}{4}\mathrm{Tr}\{L_\mu L^\mu\} \qquad L_\mu = U^\dagger \partial_\mu U \qquad U = \exp(i\pi^a T^a / f_\pi)$$

carrying a nonzero baryon charge

$$N_B = \frac{1}{24\pi^2}\int d^3x\ \epsilon_{ijk}\mathrm{Tr}\{L^i L^j L^k\}$$

Such solutions exist, but they have zero size at lowest energy...

- Fix: add a higher derivative term

$$\mathcal{L}_\pi = \frac{f_\pi^2}{4}\mathrm{Tr}\{L_\mu L^\mu\} + \frac{1}{32e^2}\mathrm{Tr}\,[L_\mu, L_\nu][L^\mu, L^\nu]$$

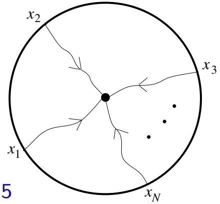
- Now solution stabilized: the skyrmion

The holographic baryon

Holographic description of the baryon may be useful

- To understand the properties and structure of baryons
- To model dense nuclear matter (and neutron stars)
- For use in scattering applications

Recall the standard AdS/CFT duality:
$\mathcal{N}=4$ SYM is dual to IIB sugra on $\mathrm{AdS}_5\times\mathrm{S}^5$



- Baryons are objects where N_c fundamental strings ($\leftrightarrow$ quarks) can end
- Obtained by wrapping a D5 brane over the S^5

[Witten hep-th/9805112]

- For AdS_5, boils down to solitons of 5D gauge fields in the bulk

$$\mathcal{L}_{\mathrm{B}} \sim -\kappa \int d^5x\, \mathrm{Tr} F_{\mu\nu}^2$$

- Similar to the BPST instanton in 4D Yang-Mills
- "Upgrade" of the Skyrmion picture!
- Writing $A_\mu \sim i\partial_\mu U\, U^\dagger$,
  - Effective Skyrmion Lagrangian reproduced at the bdry
  - The topological instanton number maps to the baryon number

Example: solitons in a hard wall model

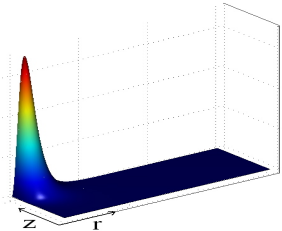
Hard wall model: AdS_5 with "hard" cutoff at $z = z_{\mathrm{IR}}$ with $N_f = 2$

$$S = -M_5^3 \int d^5x \sqrt{-\det g}\left[\left(F_{\mu\nu}^{(L)}\right)^2 + (L \leftrightarrow R)\right] + \\ + \frac{iN_c}{24\pi^2}\int A_L \wedge F^{(L)} \wedge F^{(L)} - (L \leftrightarrow R) + \cdots$$

[Pomarol, Wulzer 0712.3276, 0807.0316]

$$(A_L)_j^a = -(A_R)_j^a = f_1(x)\epsilon_{jak}x_k \\ + f_2(x)(r^2\delta_{aj} - x_a x_j) + f_3(x)x_j x_a$$

$$(A_L)_\mu|_{z_{\mathrm{IR}}} = (A_R)_\mu|_{z_{\mathrm{IR}}}$$



	Experiment	AdS_5	Deviation
m_ρ	775	850	+10%
m_{a_1}	1230	1390	+13%
m_ω	782	850	+9%
F_ρ	153	175	+14%
F_ρ/F_ω	0.88	0.90	+2%
F_π	87	91	+5%
$g_{\rho\pi\pi}$	6.0	5.4	−10%
L_9	$6.9\cdot10^{-3}$	$6.2\cdot10^{-3}$	−10%
L_{10}	$-5.5\cdot10^{-3}$	$-6.2\cdot10^{-3}$	+12%
M_N	940	1180	+25%
$\sqrt{\langle r_{E,S}^2\rangle}$ (fm)	0.79	0.87	+21%
g_A	1.25	0.98	−21%
$\mu_p - \mu_n$	4.7	3.7	−22%
$\Gamma(\omega\to\pi\gamma)$	0.75	0.82	+10%
$\Gamma(\omega\to3\pi)$	7.5	7.1	−6%
$\Gamma(\rho\to\pi\gamma)$	0.068	0.072	+5%
$\Gamma(\omega\to\pi\mu\mu)$	$8.2\cdot10^{-4}$	$7.4\cdot10^{-4}$	−9%
$\Gamma(\omega\to\pi ee)$	$6.5\cdot10^{-3}$	$7.4\cdot10^{-3}$	+14%

[See also: baryons in WSS model]

[Kim, Sin, Zahed arXiv:0708.1469; Hata, Sakai, Sugimoto, Yamato hep-th/0701280]

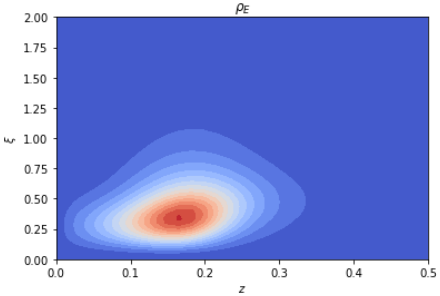
Solitons in V-QCD

Towards a realistic holographic description of baryons

- Use V-QCD: a model with gluons and (dynamical) quarks
- The model is able to (simultaneously) describe both QCD thermodynamics and meson mass spectra
- Solve numerically
  1. The fully backreacted background – quark and gluon sectors simultaneously
  2. The soliton in the probe limit
- Highly technical and challenging problem!

Soliton mass $\sim$ 1050 MeV
Work in progress:
stay tuned for
further results...

[MJ, Kiritsis, Nitti, Préau to appear]



Conclusion

Holographic analysis of the Pomeron in DIS and other processes

- Described through higher spin fields in bulk gravity
- "Hard" and "soft" Pomeron arise from the same (graviton, closed string) trajectory in the bulk
- Including a meson trajectory facilitated description of total cross sections at high s

Holographic baryons

- Arise from solitons of gauge fields in the bulk
- Results in simple hard-wall model compare well with experimental data
- Analysis of solitons in a more realistic model (V-QCD) in progress
- Several possible directions to explore in the future!

Backup slides

Constraining the potentials

In the UV ($\lambda \to 0$):

- UV expansions of potentials matched with perturbative QCD beta functions $\Rightarrow$ asymptotic freedom and logarithmic flow of the coupling and quark mass, as in QCD

[Gürsoy, Kiritsis arXiv:0707.1324; MJ, Kiritsis arXiv:1112.1261]

In the IR ($\lambda \to \infty$): various qualitative constraints

- Linear confinement, discrete glueball & meson spectrum, linear radial trajectories
- Existence of a "good" IR singularity
- Correct behavior at large quark masses
- Working potentials often string-inspired power-laws, multiplied by logarithmic corrections (i.e, first guesses usually work!)

[Gürsoy, Kiritsis, Nitti arXiv:0707.1349; MJ, Kiritsis arXiv:1112.1261; Arean, Iatrakis, MJ, Kiritsis arXiv:1309.2286, arXiv:1609.08922; MJ arXiv:1501.07272]

Final task: determine the potentials in the middle, $\lambda = \mathcal{O}(1)$

- Qualitative comparison to lattice/experimental data

Ansatz for potentials, $(x = 1)$

$$V_g(\lambda) = 12\left[1+V_1\lambda+\frac{V_2\lambda^2}{1+\lambda/\lambda_0}+V_{\rm IR}e^{-\lambda_0/\lambda}(\lambda/\lambda_0)^{4/3}\sqrt{\log(1+\lambda/\lambda_0)}\right]$$

$$V_{f0} = W_0 + W_1\lambda + \frac{W_2\lambda^2}{1+\lambda/\lambda_0} + W_{\rm IR}e^{-\lambda_0/\lambda}(\lambda/\lambda_0)^2$$

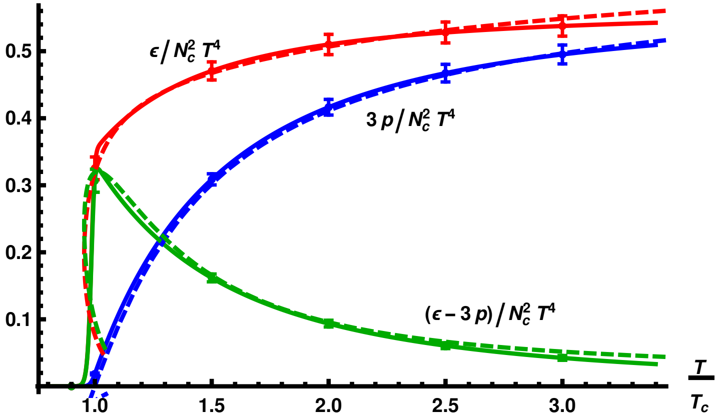
$$\frac{1}{\kappa(\lambda)} = \kappa_0\left[1+\kappa_1\lambda+\bar\kappa_0\left(1+\frac{\bar\kappa_1\lambda_0}{\lambda}\right)e^{-\lambda_0/\lambda}\frac{(\lambda/\lambda_0)^{4/3}}{\sqrt{\log(1+\lambda/\lambda_0)}}\right]$$

$$\frac{1}{w(\lambda)} = w_0\left[1+\frac{w_1\lambda/\lambda_0}{1+\lambda/\lambda_0}+\bar w_0 e^{-\lambda_0/\lambda w_s}\frac{(w_s\lambda/\lambda_0)^{4/3}}{\log(1+w_s\lambda/\lambda_0)}\right]$$

$$V_1 = \frac{11}{27\pi^2}\ , \quad V_2 = \frac{4619}{46656\pi^4}\ ; \quad W_1 = \frac{8+3\,W_0}{9\pi^2}$$

$$W_2 = \frac{6488+999\,W_0}{15552\pi^4}\ ; \quad \kappa_0 = \frac{3}{2}-\frac{W_0}{8}\ , \qquad \kappa_1 = \frac{11}{24\pi^2}$$

Fitting: glue sector



- Determine precise form of $V_g(\lambda)$ with UV and IR asymptotics fixed (at $N_f = 0$)
- Follow roughly the strategy in [Gürsoy, Kiritsis, Mazzanti, Nitti arXiv:0903.2859]
- Stiff fit to large N_c YM lattice data [Panero, arXiv:0907.3719]

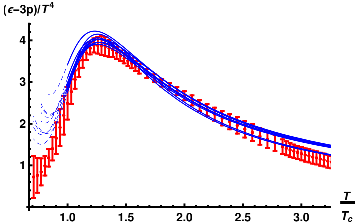
Constraining the flavors at $\mu \approx 0$

Stiff fit to lattice data near $\mu = 0$ (many parameters, but results insensitive to them) [MJ, Jokela, Remes, arXiv:1809.07770]

- Many parameters already fixed by requiring qualitative agreement with QCD
- Good description of lattice data – nontrivial result!

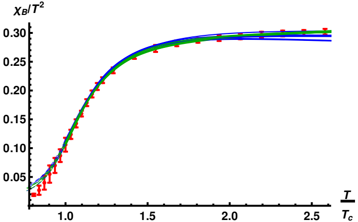
Interaction measure, 2+1 flavors

Lattice data: Borsanyi et al. arXiv:1309.5258



Baryon number susceptibility

Lattice data: Borsanyi et al. arXiv:1112.4416



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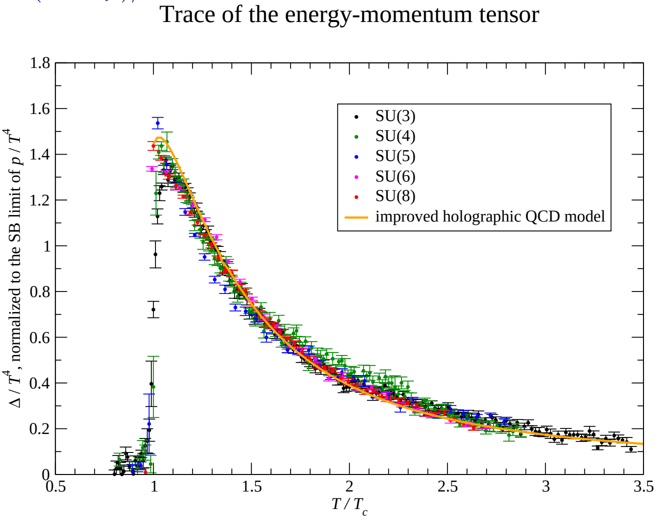
Comparison to lattice QCD

Equation of state from lattice: interaction measure in Yang-Mills
$\Delta/T^4 = (\epsilon - 3p)/T^4$



[Panero]

Glueball spectrum

	IHQCD	Lattice ($N_c = 3$)	Lattice ($N_c = \infty$)
m_{0*++}/m_{0++}	1.61	1.56(11)	1.90(17)
m_{2++}/m_{0++}	1.36	1.40(4)	1.46(11)

And critical temperature

$$\left(\frac{T_c}{m_{0++}}\right)_{\mathrm{IHQCD}} = 0.167, \qquad \left(\frac{T_c}{m_{0++}}\right)_{\mathrm{lattice}} = 0.177(7)$$

[Gürsoy, Kiritsis, Mazzanti, Nitti arXiv:0903.2859]

- Good agreement with both spectrum and finite temperature EoS!