Hadron scattering as string scattering in holographic QCD

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Based on work with J. Sonnenschein [several papers]
M. Bianchi, M. Firrotta, J.S. [**JHEP 05 (2022) 058**]
A. Armoni, B. Pyszkowski, S. Sugimoto [upcoming].

Veneziano amplitude

In the beginning, there was the Veneziano amplitude

$$A(s,t) = \frac{\Gamma\big(-\alpha(s)\big)\Gamma\big(-\alpha(t)\big)}{\Gamma\big(-\alpha(s)-\alpha(t)\big)} \tag{1}$$

with linear Regge trajectories

$$\alpha(s) = \alpha' s + \alpha_0 \tag{2}$$

There are two interesting high energy limits:

- Fixed angle: $s \to \infty$, $t \to -\infty$ with fixed $\frac{t}{s} = -\frac{1}{2}(1-\cos\theta_s)$.
- Regge limit: $s \to \infty$ with t fixed ($\theta_s \to 0$).

The Veneziano amplitude was written as a $s \leftrightarrow t$ dual amplitude that has the correct behavior for hadron physics in the Regge limit, where

$$A \to (-\alpha(s))^{\alpha(t)} \tag{3}$$

Hard versus soft scattering

However, in the fixed angle limit the Veneziano amplitude is exponentially suppressed ("soft"):

$$A \to (F(\theta))^{-\alpha' s} \tag{4}$$

In QCD it is not too difficult to show, on dimensional grounds, that the expected behavior is a power law ("hard"):

$$A(s,t) \sim f(\theta)\, s^{2-\frac{N}{2}} \tag{5}$$

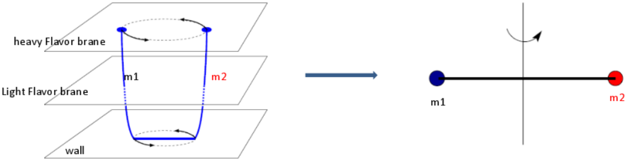
where N is the total number of constituent partons.
[**Matveev-Muradyan-Tavkhelidze 1972**][**Brodsky-Farrar 1973**].
The behavior of Veneziano amplitude is completely incompatible, but eventually it was realized that hard scattering can be achieved in holography [**Polchinski-Strassler 2001**].

Strings as hadrons

There are two ways to relate QCD to strings:

- Holographic QCD: In the spirit of the AdS/CFT duality we look for a string theory dual of QCD.
- Effective string theory: the flux tubes of QCD can be described as strings.

In the holography inspired stringy hadron (HISH), the effective string is itself a limit of strings in a curved, confining background:



Rotating holographic string

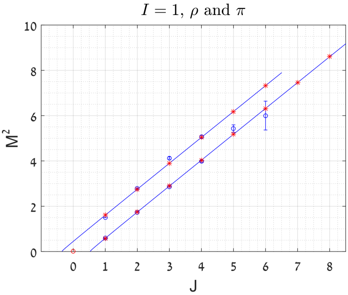
Rotating sting in flat space-time with massive endpoints

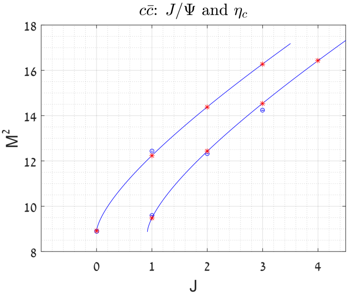
Regge trajectories

We can still achieve much in hadron phenomenology using strings in flat spacetime (see e.g. [**Eur.Phys.J.C 79 (2019)**] for a summary of our work).
Using endpoint masses we can go beyond linear Regge trajectories to describe also hadrons made up of heavy *c* and *b* quarks:

$$\alpha' = 0.88\text{GeV}^{-2}$$

$$m_{u/d} = 60\text{MeV}\,, \quad m_s = 400\text{MeV}\,, \quad m_c = 1490\text{MeV}\,, \quad m_b = 4.7\text{GeV}$$



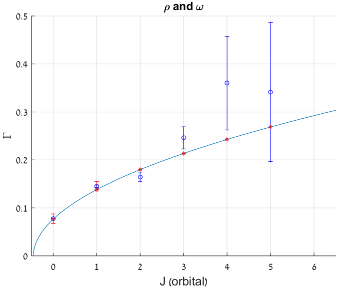


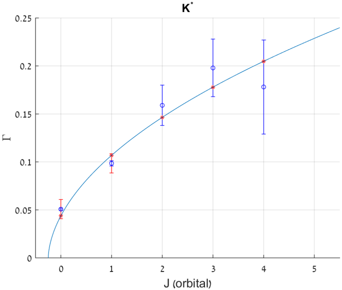
Decay widths

Another basic prediction is that the decay width of a hadron is proportional to the string length:

$$\Gamma = \frac{\pi}{2} ATL$$

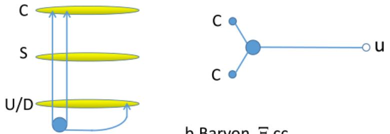
with $A \approx 0.1$ found to be more or less universal.



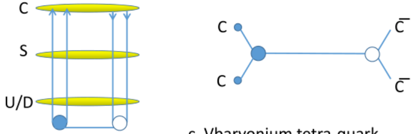


Baryons and exotics

Baryons and tetraquarks can be described by including baryonic vertices in the holography side, or massive diquarks on the string endpoints in the flat spacetime description.



b.Baryon Ξ cc



c. Vbaryonium tetra-quark

Hadron scattering as string scattering

Scattering processes are more interesting than static properties.
As a way to approximate the scattering amplitude of strings in a curved background, we write, following Polchinski & Strassler:

$$A_4(s,t) = \int dz \sqrt{-g} \times A_{10}\big(\tilde{s}(z), \tilde{t}(z)\big) \times \prod_{i=1}^{4} \psi_i(z) \tag{6}$$

In the simplest model, the background is hard wall AdS_5:

$$ds^2 = \frac{\eta_{\mu\nu} dx^\mu dx^\nu + dz^2}{z^2} \tag{7}$$

where $0 < z < z_{IR} \sim \frac{1}{M_{QCD}}$, then

$$\tilde{s} = z^2 s\,, \qquad \tilde{t} = z^2 t \tag{8}$$

Hard scattering from a curved space

If the wave functions behave as $\psi_i \sim z^{\Delta_i}$, and denoting $\Delta = \sum_i \Delta_i$,

$$A_4(s,t) = \int dz\, z^{\Delta-5} \times A_{10}\left(z^2 s, z^2 t\right) \tag{9}$$

then can just change the variables, take the leading s-dependence out of the integral, and get:

$$A_4(s,t) \sim s^{2-\frac{\Delta}{2}} \tag{10}$$

which is the expected QCD result with the identification $N = \Delta$.

Summary

1. Strings are still the easiest way to describe some phenomena of hadron physics.
2. Regge trajectories, decay widths, are easy to calculate and there is good agreement with data.
3. We have a way of describing hadron scattering that has the correct behavior at high energy. What other data can be extracted from it?