1 PROJECT AND AIM OF THE VISIT

The purpose of my visit was to collaborate with the local group formed by Ioannis Iatrakis, Matti Jarvinen and Elias Kiritsis in an ongoing project to study the spectrum of mesons and glueballs of QCD in the Veneziano limit.

1.1 Holographic models of QCD in the Veneziano limit

An interesting mild generalization of QCD involves $SU(N_c)$ YM coupled to N_f Dirac fermions transforming in the fundamental representation (that we will still call quarks). This is a theory that can be studied in the (N_c, N_f) plane. As usual, simplifications arise in the large-N_c limit. The standard 't Hooft large-N_c limit [1] lets $N_c \to \infty$ keeping N_f and $\lambda = g_{\rm YM}^2 N_c$ finite. In this limit the effect of the quarks is suppressed by powers of $\frac{N_f}{N_c} \to 0$, and therefore it corresponds to the "quenched" limit. In particular, interesting dynamical effects as the conformal window, and exotic phases at finite density, driven by the presence of the quarks, are not expected to be visible in the 't Hooft large-N_c limit. In [2] Veneziano introduced an alternative large-N_c limit in which

$$N_c \to \infty \quad , \quad N_f \to \infty \quad , \quad \frac{N_f}{N_c} = x \quad \text{fixed} \quad , \quad \lambda = g_{\rm YM}^2 N_c \quad \text{fixed} \tag{1}$$

in order to make the chiral U(1) anomaly visible to leading order in the $1/N_c$ expansion. There are several interesting issues that are accessible in the Veneziano limit.

- The "conformal window" with an IR fixed point. The window extends from $x = \frac{11}{2}$ to smaller values of x, and includes the Banks-Zaks (BZ) weakly-coupled region as $x \to \frac{11}{2}$ [3].
- The phase transition at a critical $x = x_c$ from the conformal window to theories with chiral symmetry breaking in the IR.
- A transition region near and below x_c, where the theory is expected to exhibit "walking behavior". The theory flows towards the IR fixed point but misses it ending up with chiral symmetry breaking, so that the coupling constant varies slowly over a long range of energies.
- New phenomena at finite density, involving color superconductivity [4] and flavor-color locking [5].

We will work in the hybrid holographic model for QCD developed in [6, 7] which is basically a 5d Einstein-dilaton theory with a phenomenologically motivated potential which permits the model to reproduce properties of large-N_c YM including confinement, a mas gap, asymptotic linear trajectories and realistic glueball spectra at zero temperature. Flavors are introduced in this picture by means of overlapping brane-antibrane pairs. The system contains now an open-string tachyon T dual to the quark-antiquark bilinear and whose condensation breaks the chiral symmetry [8]. With these ingredients, a holographic model of QCD in the Veneziano limit has been recently constructed in [9]. The bulk action of that setup is

$$S = S_g + S_f \,, \qquad S_g = M^3 N_c^2 \int d^5x \sqrt{g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right] , \tag{2}$$

with λ the 't Hooft coupling (exponential of the dilaton Φ) and the flavor action is given by

$$S_f = -xM^3N_c^2 \int d^5x\, V_f(\lambda, T)\sqrt{\det(g_{\mu\nu} + h(\lambda)\partial_\mu T \partial_\nu T^\dagger)}\,. \tag{3}$$

The pure glue potential V_g has been determined in previous studies [7] and the tachyon potential $V_f(\lambda, T)$ was chosen such that general properties of tachyons in string theory and of the dual theory are reproduced (see [9] for details).

The study of this model at zero temperature was performed in [9]. A critical $x = x_c$ where the conformal window ends was found. For the different scenarios considered in [9] it turns out that $3.7 \lesssim x_c \lesssim 4.2$ which is in good agreement with previous estimates. The phase diagram of the system as a function of x was thoroughly studied in [9]

As expected, near and below x_c the model exhibits "walking behavior": the theory flows towards the IR fixed point but misses it ending up with chiral symmetry breaking. Hence the coupling constant varies slowly over a long range of energies making these theories good candidates for models of walking technicolor. Moreover, the dimension of the chiral condensate at the IR fixed point approaches two (and the anomalous dimension approaches unity) as $x \to x_c$ which is in line with the standard expectation from field theory approaches [10, 11].

Technicolor has been used as a generic name for non-perturbative electroweak symmetry breaking mimicking the one induced by QCD, [12]. Although non-perturbative effects in a new strongly coupled gauge theory can induce electroweak symmetry breaking, generating the quark and lepton masses is an extra problem. A new interaction (extended technicolor) is usually invoked to generate the requisite couplings. However their magnitude (and therefore the Standard model masses) are controlled by the dimension of the scalar operator that breaks the electroweak symmetry. In free field theory its dimension is 3, as it is a fermion bilinear. However, for the SM masses to have realistic values the dimension must be reduced to at least around 2, i.e., the anomalous dimension of the operator should be at least one. This is indeed expected to be generated by a "walking" theory [10, 11]. Notice that coupling between the technicolor sector and the standard model may decrease the dimension substantially [13].

2 WORK CARRIED OUT DURING THE VISIT AND RESULTS OBTAINED: Calculation of the spectrum

The construction of a holographic model for QCD in the Veneziano limit opens the possibility of calculating the spectrum of mesons and glueballs. In the Veneziano limit, mixing is expected between glueballs and mesons to leading order in $1/N_c$. This will affect the 0^{++} glueball that will mix with the 0^{++} flavor-singlet σ-mesons. On the other hand the 2^{++} glueballs, the 1^{--} and 1^{++} vector mesons and the 0^{+-} mesons do not mix, with the exception of the flavor singlet 0^{+-} meson (analogous to η') that will mix with the 0^{+-} glueball due to the axial anomaly. A particularly interesting question here is the behavior of the mass of the lightest 0^{++} state (the technidilaton) as $x \to x_c$.

One needs to compute the fluctuations of both the bulk (2) and flavor (3) actions. For the open string sector, taking into account the worldvolume gauge fields (see [8] for details and notation), (3) is substituted by:

$$S_{DBI} = -x \int d^5x \, \mathrm{SymTr}\left[V_f(\lambda, |T|)\left(\sqrt{-\det \mathbf{A}_L} + \sqrt{-\det \mathbf{A}_R}\right)\right] , \tag{4}$$

where the quantities inside the square roots are

$$\begin{aligned} &\mathbf{A}_{(i)MN} = g_{MN} + \mathfrak{f}(\lambda, T) F^{(i)}_{MN} + \frac{\mathfrak{h}(\lambda, T)}{2}\left((D_M T)^*(D_N T) + (D_N T)^*(D_M T)\right) , \\ &\text{with} \quad D_M T = \left(\partial_M + i A^L_M - i A^R_M\right) T , \end{aligned} \tag{5}$$

where $A^{L,R}_M$ are the ($U(N_f)_{L,R}$) worldvolume gauge fields and the tachyon and its fluctuation reads

$$T = (\tau + s + \mathfrak{s}^a \tau_a) e^{i\theta + i\,\pi^a \tau_a} , \tag{6}$$

where τ corresponds to its (diagonal) background value. The functional form of $\mathfrak{h}$ is discussed in [9] and $\mathfrak{f}$ is not fixed yet.

As for the closed string sector, now see [14] for details and notation, we have the following fluctuations:

$$\begin{aligned} &g_{MN} = g^{(0)}_{MN} + \hat{g}_{MN} , \quad \hat{g}_{MN}\, d\xi^M d\xi^N = e^{2A_s}\left(2\phi\, dz^2 + 2\hat{A}_\mu\, dz\, dx^\mu + h_{\mu\nu}\, dx^\mu\, dx^\nu\right) , \\ &\Phi = \Phi_0 + \chi , \end{aligned} \tag{7}$$

where Φ is the dilaton ($\lambda = e^\Phi$).

One should now expand both the bulk action (2) and the DBI one (4) up to second order in the fluctuations. Then, compute the equations of motion, diagonalize them if needed, and solve them for the backgrounds found in [9].

- As expected, the vector mesons 1^{--} (corresponding to $A^L_\mu + A^R_\mu$) decouple from the rest of the fluctuations. Using numerical methods we are now computing their mass spectrum.

- The axial vector mesons 1^{++} result from the transverse part of $A^L_\mu - A^R_\mu$. They also decouple from the rest of the fluctuations and again running our numerics around the background solutions of [9] we are computing their spectrum.

- The modes coming from θ (see (6)) and the longitudinal part of $A^L_\mu - A^R_\mu$ combine and are dual to the 0^{-+} mesons. They do not mix with other modes and we also compute their spectrum numerically without difficulties.

- The fluctuations of the metric, the traceless part of the modulus of the tachyon (s) and the dilaton (χ) do mix. However, proceeding similarly as in [14] we see that the modes corresponding to the graviton decouple from the rest and realize the 2^{++} glueballs. As for the scalars, the system reduces to two coupled equations for the fluctuations corresponding to the 0^{++} glueball and 0^{++} meson that mix as expected. Again we are working to solve these equations numerically and get the corresponding mass spectra.

- The mixing of the 0^{+-} meson and glueball results from the CP-odd WZ term as discussed in [9].

As described, the expansion of the action, computation of the equations of motion and identification of the relevant modes is under control. We are now applying numerical methods to obtain the mass spectra. Once they are computed we will compare them with QCD results. Of special interest will be the evolution of the masses as x is tuned close to x_c, determining the usefulness of our setup as a model of walking technicolor. Given the progress made in the last month we are confident that we will soon have interesting results to report [15].

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