Holographic QCD and its applications

Candidate: Andrea Olzi.
Supervisors: Prof. Francesco Bigazzi, Prof. Aldo Lorenzo Cotrone.

It is known that baryons can be described at low energies, as solitons of the chiral Lagrangian, known as Skyrmions. However, this construction works only for N_f (number of flavors) > 1. In the extreme case $N_f = 1$ the baryon charge cannot be identified, and a macroscopic description of baryons is no longer available. Nevertheless, one-flavored baryons exist and have spin N(number of colors)/2. This reasearch project aims at studying an alternative low energy description of baryons using the holographic correspondence. Holography is a powerful tool to study strongly coupled field theories, like QCD, since it reduces higly-non-trivial computations in quantum field theories to classical computations of general relativity.

Z. Komargodsky in Ref. [1] presented an alternative description of one-flavored baryons for which the Skyrmion picture is inapplicable. The effective low energy description of one-flavored QCD at large N is provided by the theory that describes the dynamics of the η' meson. It can be shown that this theory admits infinitely extended η' configurations, which are $(2+1)$-dimensional objects, called sheets, supporting a Topological Field Theory (TFT). This TFT is the effective field theory that realizes the fractional quantum Hall effect (FQHE). These objects can be interpreted as baryons by coupling the baryon gauge field to the TFT on the sheet. This coupling is precisely like the coupling of the electromagnetic gauge field to the emergent gauge field in the FQHE. If the sheet has a boundary, due to the bulk-boundary correspondence of FQHE, there are edge excitations which carry a conserved baryon number. Moreover, the boundary prevents us to write a smooth configuration of η' everywhere, so we expect it to be a singularity somewhere in the space. Unfortunately, the η' theory has a cusp singularity in the potential. It signals that the theory is incomplete so it is not possible to perform explicit calculations in this framework .

During my master thesis I explored and tested this idea, finding explicit realizations and quantitative results in the framework of the closest holographic top-down model to QCD, the Witten [2]-Sakai-Sugimoto [3] (WSS) model. The flavor degrees of freedom are described by N_f $D8$ probe-branes in the background generated by N $D4$ branes supporting the color degrees of freedom. An important ingredient in this work is the theory living on the $N_f = 1$ flavor brane world-volume which - after a dimensional reduction - is a five-dimensional Maxwell(M)-Chern-Simons(CS) theory in the curved background generated by the color branes. In this framework, the η' meson has a dual string picture in terms of the flavor brane gauge field. The sheet is realized holographically as another probe-brane, a $D6$ brane wrapped on a four-cycle and extended in $(2+1)$ Minkowski directions. I proved that on the world-volume of the $D6$ brane lives the expected TFT that realizes the FQHE. Through the study of the M-CS theory, for which the sheet-brane is a source, I was able to compute the η' profile: the key ingredient in the Hall picture of baryons. I found, for a $D6$-brane infinitely extended along $(2+1)$ Minkowski directions, a smooth profile for η', with both massless and massive quark, as expected. Then, I considered a semi-infinite $D6$-brane, with a straight boundary, which we proved that encodes the singular behavior expected for η'. From the point of view of the five-dimensional M-CS theory, the boundary of the $D6$-brane can be thought as a magnetic linear distribution in a curved background. The problem of infinite magnetic wire in a curved spacetime has been solved semi-analytically, through a series expansion, and numerically. From this solution I extracted the Nambu-Goto action for the transverse fluctuations of the string-like boundary and its tension. Then, I was able to determine the singular profile of the η' field and the depth of this sheet-like configuration.

This research project aims at developing and studying the several future research directions opened by this thesis work. Above all, it is important to investigate, using holographic techniques, the finite size Hall baryon to connect our theoretical construction to QCD phenomenology of $N/2$ spin baryons. Specifically, we want to construct the holographic dual of a disc shaped sheet. This geometry recalls the well known Hall droplet and it allows to use the whole FQHE machinery. Then, we want to quantize the classical results both for the semi-infinite configuration and for the finite size configuration in order to derive the spectrum of baryons. Indeed, these solutions are suitable for the quantization procedure pointed out in [4] for the solitonic Sakai-Sugimoto baryon.

It will be interesting to understand the relation between the Hall picture and the Skyrmion model. Thus, we need to extend our analysis to baryons in the $N_f > 1$ case. We expect that the Hall picture will be more suitable for high-spin baryons, i.e. baryons made out of predominantly one flavor, while for the low-spin baryons the ordinary Skyrmion picture will be more appropriate. Since there is a unique baryon symmetry, there should be a transition between the ordinary Skyrmion and the Hall droplet. It is important to understand how this works in detail.

Moreover, a particularly interesting task for the future will be the study of these novel baryons as dark-matter candidates. Indeed, the WSS model realizes a holographic model of QCD axion [5]. It turns out that adding a single flavor brane in a particular embedding provides the extra flavor needed to implement the composite axion model. Hence, the Hall baryon can be interpreted as dark-matter, and it will be interesting to study its cosmological implications.

References

[1] Z. Komargodsky, *Baryons as Quantum Hall Droplets*, (Dec, 2019), hep-th/ 1812.09253.

[2] E. Witten, *Anti-de Sitter Space, Thermal Phase Transition, And Confinement In Gauge Theories*, Adv.Theor.Math.Phys 1998 no. 2, (Mar, 1998) 505–532, hep-th/9803131v2.

[3] T. Sakai and S. Sugimoto, *Low Energy Hadron Physics in Holographic QCD*, Prog. Theor. Phys. 113 no. 4, (Dec, 2005) 843–882, hep-th/0412141v5.

[4] H. Hata, T. Sakai, S. Sugimoto, and S. Yamato, *Baryons from instantons in holographic QCD*, Prog. Theor. Phys. 117 no. 6, (Mar, 2007) 1157–1180, hep-th/0701280v3.

[5] F. Bigazzi, A. Caddeo, A. L. Cotrone, P. Di Vecchia, A. Marzolla, *The holographic QCD axion*, JHEP 1912 (2019) 056, hep-th/1906.12117.