International Workshop

on

QCD Green's functions, confinement, and phenomenology

A. General considerations and theoretical foundations

Non-Abelian gauge theories have been at the center stage of elementary particle physics for the last four decades, since the establishment of electroweak gauge theory and, a few years later, Quantum Chromodynamics (QCD), the theory describing strong interactions. Unlike quantum electrodynamics (QED), which yields with spectacular success to perturbation theory and Feynman-diagram techniques, only the ultraviolet (high-energy) regime of QCD is amenable to a perturbative treatment, due to the characteristic property of asymptotic freedom. The infrared sector of QCD, on the other hand, is the host of several nonperturbative phenomena, which most famously encompass quark confinement and dynamical mass generation, and powerful methods must be employed for their quantitative treatment.

The basic building blocks of QCD are the Green's (correlation) functions of the fundamental physical degrees of freedom, gluons and quarks, and of the unphysical ghosts. Even though it is well-known that these quantities are not physical, since they depend on the gauge-fixing scheme and parameters used to quantize the theory, it is widely believed that reliable information on their non-perturbative structure is essential for unraveling the infrared dynamics of QCD [1]. In addition to their relevance for phenomenology, the QCD Green's function encode information on confinement, albeit in a rather subtle way.

The two basic non-perturbative tools that permit the exploration of the infrared domain of QCD are (**i**) the lattice, where space-time is discretized and the quantities of interest are evaluated numerically, and (**ii**) the infinite set of integral equations governing the dynamics of the QCD Green's functions, known as Schwinger-Dyson equations (SDE). While the lattice calculations are limited by the lattice size used, the problem of the Gribov copies, and the extrapolation of the numerical results to the continuous limit, the fundamental conceptual difficulty in treating the SDE resides in the need for a self-consistent truncation scheme, *i.e.*, one that does not compromise the gauge-invariance of the quantities studied.

B. Main objectives of the proposed workshop

The objective of the proposed workshop is to bring together QCD experts, in order to discuss the various recent developments in this field, with particular emphasis on the infrared behaviour of Green's functions and the various pictures of confinement.

We propose to focus on the following main topics

i. Strengthen the synergy between the lattice and SDE communities

Given that both the lattice and the SDE aspire to describe essentially the same physics, it would be important to advance their complementarity and strengthen their mutual interplay. The primary objective of the proposed workshop focuses precisely on this possibility: the meanigful and systematic comparison between lattice and SDE results, and their use for obtaining high-quality phenomenology. It would seem that we have reached a historical point where the proposed synergy between lattice and SDE does not constitute wishful thinking but rather a tengible reality. Indeed, the quality of lattice data is steadily improving, as has been recently attested by the results reported on the infrared behavior of the gluon and ghosts propagators using large volumes [2, 3]. On the other hand, due to several recent developments [4], we have at our disposal, for the first time, a manifestly gauge invariant truncation scheme for the Schwinger-Dyson series of QCD.

ii. Understanding the infrared behaviour of gluon and ghost propagators

A great deal of activity has been dedicated recently on the study of the infrared behaviour of gluon and ghost propagators, both on the lattice and with SDE. It it generally accepted by now that the lattice yields an infrared finite gluon propagator in the Landau gauge. This rather characteristic behavior has been firmly established recently, using large-volume lattices both in $SU(2)$ [2] as well as in $SU(3)$ [3]. In addition, the lattice dressing function for the ghost propagator in the same gauge is also infrared finite and, contrary to naive expectations, displays no power-law enhancement. A qualitatively similar picture has been obtained recently from the study of a manifestly gauge invariant set of SDE derived in [5].

Clearly several aspects need to be further investigated such as (i) the dependence of the infrared behavior on the gauge chosen (e.g., Landau vs Feynman gauge); (ii) study on the lattice auxiliary (ghost) Green's functions appearing in the new SDE; (iii) refine the SDE treatment to improve the quantitative agreement with lattice simulations; (iv) study the effect of the Gribov copies on the lattice simulations.

iii. Center vortices and confinement.

From the theoretical point of view, the aforementioned behavior of the propagators can be understood in terms of a dynamically generated, momentum-dependent gluon mass [6]. In this picture the low-energy effective theory of QCD is a non-linear sigma model, known as massive gauge-invariant Yang-Mills, obtained from the generalization of Stuckelbergs con- struction to non-Abelian theories.

This model admits vortex solutions, with a long-range pure gauge term in their potentials, which endows them with a topological quantum number corresponding to the center of the gauge group [Z_N for $SU(N)$], and is, in turn, responsible for quark connement and gluon screening. Specifically, center vortices of thickness $\sim m^{?1}$, where m is the induced mass of the gluon, form a condensate because their entropy (per unit size) is larger than their action. This condensation furnishes an area law to the fundamental representation Wilson loop, thus conning quarks. On the other hand, the adjoint potential shows a roughly linear regime followed by string breaking when the potential energy is about $2m$, corresponding to gluon screening [7].

The relevance of center vortices for confinement has been extensively studied on the lattice in recent years [1]. It would be important to (i) review the state-of-the-art on the subject, (ii) study in more details the connection between confinement, center vortices and chiral symmetry breaking both in the fundamental and in the adjoint representations.

iv. Finite temperature effects

At zero temperature non-Abelian gauge theories confine quarks and break chiral symmetry spontaneously. However at finite temperature neither property is present, thus signaling that two phase transitions occur in the intermediate temperature regime. Lattice simulations show that for quarks in the fundamental representation the two temperatures are very close to each other, whereas they differ significantly for adjoint quarks. These results strongly suggest a deep connection between confinement and chiral symmetry breaking which however needs further scrutiny, both at the lattice level as well as in SDE. In particular, it would be useful to understand this connection in the latter context, extending zero temperature formalism in the finite temperature regime.

v. Aspects of QCD phenomenology

There is a number of hadronic processes that are sensitive to the form of the gluon propagator in the deep infrared and the intermediate region around the QCD mass-scale [8]. Thus, under certain assumptions, one may use experimental data for such processes in order to check the self-consistency of the results obtained from the lattices, and discriminate between the possible scenaria for the gluon propagator. Such phenomenological studies may involve the pion form factor, τ-lepton decay rate into non-strange hadrons, heavy quarkonia decays involving the J/ψ and Υ mesons, Pomeron model for pp scattering, and B-decays, to mention a few.

C. Duration and dates

The workshop is expected to last one-week, and would be preferably scheduled in the week going from the 7th to the 11th of September.

D. Organizers

∗ Arlene C. Aguilar, University of Valencia, Spain

∗ Daniele Binosi, ECT* Trento, Italy (co-ordinator)

∗ John M. Cornwall, University of California at Los Angeles, US

∗ Joannis Papavassiliou, University of Valencia, Spain

E. Key participants (expected to attend)

1. J. P. Blaizot (Saclay, France)

2. S. J. Brodsky (SLAC, US)

3. A. Cucchieri (University of Sao Paulo, Brasil)
4. D. Diakonov (N.P. Institute Petersburg, Russia)
5. P. de Forcrand (ETH, Zurich)
6. J. P. Greensite (San Francisco State University, US)
7. U. Heller (American Physics Society, US)
8. E. M. Ilgenfritz (University of Graz, Austria)
9. G. P. Lepage (Cornell University, US)
10. L. McLerran (Brookhaven National Laboratory, US)
11. T. Mendes (University of Sao Paulo, Brasil)
12. M. Muller-Preussker (Humboldt University Berlin, Germany)
13. A. A. Natale (IFT, Sao Paulo, Brasil)
14. S. Olejnik (Bratislava Institute of physics, Slovakia)
15. O. Pene (University of Paris Sud XI)
16. H. Reinhardt (Tubingen University, Germany)
17. C. Roberts (Argonne National Laboratory)
18. Y. Simonov (ITEP, Russia)
19. S. P. Sorella (Rio de Janeiro State University, Brasil)
20. H. Verschelde (Gent University, Belgium)
21. W. Weise (TU Munich, Germany)
22. C. Wetterich (Heidelberg University)

F. Tentative program

We plan to have a five day (Monday to Friday) meeting with roughly forty talks of an approximate duration of forty minutes each (four talks in the morning session and four talks in the afternoon, with the standard coffee and lunch breaks.) A very preliminary program would be the following

- *Day 1*
  - Morning: **Aspects of confinement**
    Speakers: J. M. Cornwall, J. P. Greensite, C. Wetterich,...
  - Afternoon: **Center vortices**
    Speakers: U. Heller, S. Olejnik, H. Reinhardt,...
- *Day 2*
  - Morning: **Infrared behavior of ghost and gluon propagators: lattice results**
    Speakers: O. Boucaud, A. Cucchieri, P. de Forcrand, E. M. Ilgenfritz, T. Mendes,...
  - Afternoon: **Infrared behavior of ghost and gluon propagators: SDE results**
    Speakers: D. Binosi, J. Papavassiliou, O. Pene,...
- *Day 3*
  - Morning: **Gribov horizon and mass generation**
    Speakers: D. Dudal, S. P. Sorella, H. Verschelde,...
  - Afternoon: **Background field method**
    Speakers: G. P. Lepage, A. Pilaftsis, Y. Simonov,...
- *Day 4*
  - Morning: **Chiral symmetry breaking**
    Speakers: A. C. Aguilar, D. Diakonov,...

- Afternoon: **Finite temperatures effects**

  Speakers: J. P. Blaizot, L. McLerran, W. Weise,...

- *Day 5*

  - **Morning: Phenomenological studies**

    Speakers: A. Natale, S. J. Brodsky,...

  - Afternoon: **Bound states, glueballs and Bethe-Salpeter equation**

    Speakers: P. Bicudo, C. Roberts, V. Vento,...

G. Prospects for outside funding

No outside funding is foreseen for the present workshop.

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[1] See, for example, J. Greensite, Prog. Part. Nucl. Phys. **51**, 1 (2003), and references therein.

[2] A. Cucchieri and T. Mendes, arXiv:0710.0412 [hep-lat];

[3] I. L. Bogolubsky, E. M. Ilgenfritz, M. Muller-Preussker and A. Sternbeck, arXiv:0710.1968 [hep-lat]. P. O. Bowman *et al.*, in full Phys. Rev. D **76**, 094505 (2007).

[4] D. Binosi and J. Papavassiliou, Phys. Rev. D **77**, 061702 (2008) [arXiv:0712.2707 [hep-ph]].

[5] A. C. Aguilar, D. Binosi and J. Papavassiliou, Phys. Rev. **78**, 025010 (2008).

[6] J. M. Cornwall, Phys. Rev. D **26**, 1453 (1982).

[7] J. M. Cornwall, Phys. Rev. D **57**, 7589 (1998)

[8] See, e.g., A. C. Aguilar, A. A. Natale and P. S. Rodrigues da Silva, Phys. Rev. Lett. **90**, 152001 (2003); A. C. Aguilar, A. Mihara and A. A. Natale, Phys. Rev. D **65**, 054011 (2002).