Il Colle di Galileo

Higher Spins, Strings and Dualities

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Abstract. This workshop program brought together experts and young researchers from all over the world with the aim of fostering exchange on a number of topics that lie at the interface between String Theory, considered to be a promising candidate for a unified theory of fundamental interactions, and the theory of higher-spin fields. Key problems addressed included issues related to the roots of String Theory, the AdS/CFT correspondence, the underlying higher spin geometry and symmetries, the consistency of interacting Higher Spin Field Theory, black holes, modern trends in classical and quantum gravity and other topics.

Keywords. Gauge fields, gravity, higher spins, string theory, geometry, algebras.

Scientific background and motivation from historical perspective

Experimentally observed particles and fields that are believed to be fundamental constituents of nature carry spins from 0 to 2. For instance, the Higgs particle recently discovered at CERN in Geneva has spin 0, the electron has spin ½, the photon has spin 1 and the graviton (the still hypothetical quantum of the gravitational field) has spin 2. The particles (and fields) that carry spins greater than 2 are called higher-spin (HS for short) particles. To date only composite strongly interacting and short-lived massive particles (resonances) with spin up to 15/2 have been observed experimentally. They were first discovered in the 1960s.

However, higher spins made their first appearance in Field Theory as far back as the 1930s, first in the work of Majorana (1932), who extended Dirac's theory of the electron in a way that ended up describing infinitely many higher spins, and then in the more popular works of Dirac (1936), and Fierz and Pauli (1939) who formulated mass-shell constraints on the dynamics of HS fields and identified certain difficulties of minimal coupling of these fields to the electro-magnetic field.

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A further boost to research in this area was provided in the 1960s by the experimental discovery of strongly interacting resonances carrying higher spins. Their Regge properties (spin-mass dependence) were instrumental in the original discovery of String Theory, the quantum spectrum of which includes an infinite tower of massive HS excitations. The formulation of ten–dimensional superstrings in the 80s was an exciting development, but field theory ideas and methods drawn from supergravity were then resurrected and proved essential to elucidate the dualities between them about ten years later. Despite these remarkable developments, the very nature of String Theory still remains largely elusive. This fact now constitutes an important motivation to look more closely at HS string modes, which clearly underlie the most cherished properties of string amplitudes, including (non-)planar duality, modular invariance or the open-closed duality that is at the heart of the AdS/CFT correspondence.

In the 1960s, most of the activity on higher spins was along the lines of S-matrix theory. Key results of the time include Weinberg's 1964 work on soft emissions, the Coleman-Mandula theorem and the Velo-Zwanziger argument, classical no-go results that in retrospect encode extremely important information on HS interactions but ended up discouraging at length broader efforts in the field, which was developed only by a few enthusiasts inspired by the construction of free massless HS gauge theories in flat and (Anti) de Sitter (AdS) spaces by Fronsdal and collaborators. No-go results were bypassed to some extent in the early 1980s, in Sweden and the Netherlands, where examples of cubic HS couplings were first constructed, and then in Russia, where Fradkin and Vasiliev showed how standard-looking HS couplings to gravity would not face obstructions in the presence of a cosmological term.

This line of research culminated, starting from the early 90s, in Vasiliev's *unfolded formulation* of classically consistent non-linear equations for infinitely many symmetric HS gauge fields. This construction combines an appropriate extension of the "tangent space" formulation of gravity with free-differential algebras, which first appeared in mathematical literature in the 1960s and, independently, in the work of D'Auria and Fré on supergravity in the early 1980s. The resulting first-derivative equations involving infinitely many auxiliary fields still lack a satisfactory action principle, but nonetheless the approach has already provided unexpected new windows for the AdS/CFT correspondence, making it possible to probe it beyond the case of strongly coupled boundary modes.

In the late 1990s it was discovered that certain large-N Yang-Mills theories with large 't Hooft coupling are dual to String Theory on weakly curved AdS backgrounds. Supergravity has thus provided a window on strongly coupled gauge theory. This correspondence has been subjected to many precise tests. However, the string description becomes much more complicated as the large 't Hooft coupling gets reduced and the curvature increases. Luckily, in the extreme limit of vanishingly small 't Hooft coupling the theory simplifies again. On the gauge theory side the theory becomes free, and admits infinitely many conserved HS currents. Since the AdS/CFT duality maps them into massless HS gauge fields in the bulk, the dual descriptions of such free large *N* field theories naturally include interacting higher–spin gauge theories in AdS. Thus, just like supergravity theories, massless HS gauge theories play an important role on the gravitational side of the AdS/CFT duality. Conversely, given the complexity of HS gauge theories, their dual descriptions via weakly coupled models provide useful tools for their exploration.

Besides its intrinsic interest and its connections with Statistical Mechanics, the conjectured equivalence between these models expands the range of AdS_4/CFT_3 and AdS_4/CFT_3 dualities in a way that does not rely on supersymmetry. Recently, various instances of this HS holography were subjected to impressive tests which boosted the growing interest in the subject.

However, profound questions about the geometry of HS fields remain unanswered to date. Important information can be drawn from the comparison with String Theory, in which massive HS excitations have a relatively simple and concrete realization in Minkowski space. The cubic interactions of massless symmetric HS fields are simply encoded in string amplitudes, the limiting behavior of which for vanishing tension makes way for a systematics of conserved HS currents. A deeper understanding of these issues should be of interest also in connection with attempts to simplify the computation of S-matrix amplitudes in field theory and, at a potentially deeper level, could shed some light on the links between String Theory and the breaking of HS symmetries, contemplated at length by many authors but never properly quantified.

Key information on the dynamics of HS fields is encoded in exact solutions of their equations of motion. Recently discovered HS solutions reproduce in the weak-field regime black holes of General Relativity, accompanied by non-vanishing profiles for massless symmetric tensors of all ranks. It has become clear that a thorough study of HS black holes, even in the simpler three-dimensional setting, can affect our present understanding of space-time geometry, and can shed light on key issues such as unitarity in the presence of higher spins and the AdS/CFT interpretation of HS theory.

This cursory look at past and more recent research avenues in the field is intended to offer a glimpse of the timeliness and high potential of this extended brainstorming activity that brought together, at GGI, young researchers and experts on Higher Spins, String Theory and Field Theory.

Workshop Program

The Workshop Program was attended by more than 90 participants from Armenia, Canada, Chile, EU, India, Russia, South Africa, South Korea and the USA. C. Fronsdal (California Uni. Los Angeles, USA) and A. Bengtsson (Boras U. College, Sweden), who pioneered in this field of research, were among the participants.

[The complete lists of participants and seminars can be found on the Program Webpage http://www.ggi.fi.infn.it/index.php?p=events.inc&id=103].

The program started with a School running from March 18 to March 27, which was intended to provide a basic and yet comprehensive introduction to the subjects of the workshop. The School was mainly oriented toward Master and PhD students and non-specialists, but turned out to be very useful even for experts in the field.

The School was attended by 45 participants, including 5 Master students, 12 PhD students, 11 Post Docs and 17 senior scientists. The school program (available at http://www.ggi.fi.infn.it/index.php?p=events.inc&id=116) consisted of a series of lectures on 9 topics given by well-known theorists working in this field: X. Bekaert (Tours U., France), N. Boulanger (Mons U., Belgium), V. Didenko (Lebedev Phys. Inst. Moscow, Russia), D. Francia (SNS Pisa, Italy), S. Fredenhagen and E. Skvortsov (AEI Golm, Germany), S. Giombi (Princeton U., USA), C. Iazeolla (Inst. of Physics AS CR, Prague, Czech Republic), A. Jevicki (Brown U., USA), Y. Zinoviev (IHEP Protvino, Russia).

The timetabling of the lectures was strictly organized in such a way that each lecture provided the key theoretical background for understanding the material of the following lectures. Every afternoon after the lectures there were lively discussion sessions in which participants asked questions and made interesting comments and remarks that were very useful for acquiring further insight into the details of the subject. At the end of the School the organizers asked the participants to fill in a questionnaire about the organization of the School. The overall response was that the School was very well organized, as far as the selection of topics and the schedule were concerned, and the perceived quality of the lectures was very high. There was a useful suggestion for the organization of future school events, namely that the solutions of the exercises proposed during lectures should be dealt with in a separate session from the discussion.

From March 28 to May 5 the program was organized along the lines of long-term workshops, with only 3-4 seminars per week, leaving most of the time for informal discussions and collaborations. The topics included:

- Foundations of Higher Spin Field Theory and different approaches to its description.
- Higher spin algebraic structures and geometry.
- Problems of Higher Spin interactions.
- Higher Spins in String Theory.
- Dualities, Holography and AdS/CFT.
- Black holes, space-time structure and quantum gravity.

The success of this activity is amply reflected in the papers that several participants posted on the arXiv during the Workshop and immediately after it.

The Conference held during the last week (on May 6-9, 2013) summarized the principal recent developments in the field of the Workshop. It was attended by 50 participants. The Conference Program included 28 talks, the list of which is available at http://www.ggi.fi.infn.it/index.php?p=events.inc&id=121.

The number of applications to take part in this activity was very high. It was far beyond the financial and logistic capacities of the GGI, and forced the Organizers to implement certain selection criteria. The financial support and the efficient assistance of the GGI staff provided to the Organizers in running the various events of this Workshop is highly appreciated. It should also be mentioned that the participation of almost all the young researchers from Russia was supported by the Russian "Dynasty" Foundation, which is gratefully acknowledged.