Laboratory “Elementary Particle Theory” - Annual Report 2018

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The main studies in the Laboratory is focused on various major actively developing research areas in modern theoretical and mathematical physics. Our research is conducted within the framework of an extensive international collaboration with world renown science centers such as CERN (Geneva), ICTP and SISSA (Trieste), JINR (Dubna), as well as with numerous leading universities and academic research institutions from abroad

In 2018 the members of the Laboratory (co)authored **51 scientific works** altogether, among them - 35 published and 16 pending publication papers in international journals (many of them in the Q1-rank category) and in international conference series. Members of the Laboratory participated in numerous advanced international workshops and conferences with **17 invited talks**. Throughout 2018 the scientific papers of Laboratory's members have received **651 independent citations** in international science journals and conference proceedings worldwide.

The most significant contribution to the scientific achievements and the international prestige of our Laboratory has been provided by **Dr. Daniela Doneva** via her 11 papers, most of them published in Q1-rank leading international scientific journals. Most remarkably, she was awarded with the highly prestigious Emmy Noether Prize, as well as with the highest Bulgarian National Prize “Pithagoras” for young scientists.

Throughout 2018 the members of the Laboratory have participated in 7 large projects funded by Bulgarian National Science Foundation (among them projects DN-08/3, DN-18/1 and DN-18/3); 3 international projects within bilateral agreements of Bulgarian Academy of Sciences, as well as participated in various other prestigious internationally funded projects - supported through bi-national academic cooperation agreements and/or funded by the European Commission programs, among them - **COST action MP-1405, COST action CA15117, COST action CA16104 and COST action CA18108**.

Principal Research Areas

Area 1: Algebraic and geometric methods in quantum theory. Quantum informatics (*N. Nikolov, L. Hadjiivanov, I. Todorov, A. Ganchev, L. Georgiev, T. Popov, D. Nedanovski)*

(i) The study of the 27-dimensional exceptional Jordan algebra J as (part of) the finite-dimensional quantum algebra in an almost classical space-time approach to particle physics is continued in a series of 3 papers by *I. Todorov* and collaborators. Along with reviewing known properties of J and of the associated exceptional Lie groups it is argued that the symmetry of the model can be deduced from the Borel-de Siebenthal theory of maximal connected subgroups of simple compact Lie groups.

(ii) The story of the rise of the four-fermion theory of the universal weak interaction and its experimental confirmation, with a special emphasis on the problems related to parity violation, has been reviewed in a paper by *L. Hadjiiavnov* prepared for publication. This is part of an ongoing joint project with *I. Todorov* on the algebraic structure and the symmetry properties of the Standard Model.

(iii) A symmetric operad was suggested for the renormalization group by *N. Nikolov* in a paper prepared for publication.

(iv) It was shown in a conference proceedings paper by *T. Popov* that the causal automorphisms of the Minkowski space-time and the dynamical group of the hydrogen atom both stem from the Tits-Kantor-Koecher conformal construction for a Jordan algebra.

(v) In an IHES Bures-sur-Yvette preprint *I. Todorov* reviewed how, a quarter of a millennium later, some special numbers Euler played with (prototypes of those known in modern mathematics as "periods") have reappeared in the analytic calculation of the anomalous magnetic moment of the electron, one of the most precisely computed and measured physical quantities.

Area 2: Conformal and superconformal symmetry in gauge, field and string models. Noncanonical quantization (*N. Stoilova, T. Palev, V.K. Dobrev, V.B. Petkova, L.K. Anguelova, M. Stanishkov, S. Stoimenov, K Hristov*)

(i) *V. Petkova* and collaborators studied a class of four-point functions of heavily charged and particularly polarized BPS operators in the planar N = 4 SYM theory for any value of the coupling constant. It was found that at weak coupling this class is given in terms of functions evaluating ladder integrals and can be furthermore reorganized as a determinant of a semi-infinite matrix with entries given by linear combinations of such functions.

(ii) *N.Stoilova* and collaborators have shown that the Fock spaces of a set of m parafermions and n parabosons with relative paraboson relations are certain infinite-dimensional lowest weight representations of a new $Z_2 \times Z_2$-graded Lie superalgebra, denoted by $pso(2m+1|2m)$. The subalgebra structure of $pso(2m+1|2m)$ and its root space decomposition was unraveled. Basis vectors of the $pso(2m+1|2n)$ Fock representations were introduced and the explicit actions of the para-operators on these basis vectors of the pso(2m+1|2n) Fock spaces were computed. The analysis is a great step forward in understanding these new $Z_2 \times Z_2$-graded algebras and their representations, and solves some of the mystery that was associated with the new parastatistics algebra.

(iii) *L. Anguelova* and collaborators investigated multi-field models of cosmological inflation (i.e., models with more than one inflaton field). Such models have generated great interest in the context of recent theoretical developments, regarding the conditions that effective field theories have to satisfy in order to be compatible with quantum gravity. However, since the relevant equations of motion are a very complicated coupled system, most investigations in the literature were numerical. Our new work developed a method for finding analytical solutions, which relies on imposing certain symmetry conditions on the cosmological Lagrangian. Solving these conditions restricts the form of the scalar potential, as well as the field-space metric determining the scalar kinetic terms. Using that, we found the most general scalar potentials, compatible with the presence of a hidden symmetry in two-field models, as well as many exact solutions of the relevant equations of motion, in a special case.

(iv) *K.Hristov* helped in deriving new solutions of a wide class of rotating black holes with zero temperature (generalizations of extremal Kerr-Newman solutions with scalars) in various dimensions (four to seven). All new solutions admit a holographic description via the so-called AdS/CFT correspondence, allowing for a microscopic (i.e. quantum field theoretic) derivation of their degrees of freedom that was shown to match with the semi-classical Beckenstein-Hawking entropy. These results are related to the understanding of the fundamental degrees of freedom of quantum gravity and the black holes as a statistical ensemble.

(v) *S.Stoimenov* and collaborators generalized the meta-conformal algebra meta(1,d), defined as symmetry algebra of ballistic transport equation, for more than one space dimensions. For d>2, the algebra is finite-dimensional, while for d=2 an infinite-dimensional extension exists, given by direct sum of three Virasoro algebras. The explicit form of covariant two-point functions and group transformations are derived as first step toward construction of dynamical meta-conformal filed theory.

(vi) *V.Dobrev* published the monograph "*Invariant Differential Operators, Volume 3: Supersymmetry''*, De Gruyter Studies in Mathematical Physics, vol. 49 (De Gruyter, Berlin, Boston, 2018, ISBN: 978-3-11-052-7490, 218 + viii pages). He considered the multiparameter quantum group deformation of the general linear group GL(n) and constructed its induced representations. Using the case of quantum GL(4) he derived the multiparameter deformation of Minkowski space-time, the multiparameter deformation of Maxwell equations and whole hierarchies of related equations.

(vii) *M. Stanishkov* continued his work on the ADS3/CFT2 correspondence. More precisely, his work was concentrated on the duality between black holes, arising in the D1-D5 brane system and the perturbed symmetric orbifold. Of special interest were specific correlation functions in the latter. Work on this subject is in progress.

Area 3: New Aspects in String Theory and Gravitation (*E. Nissimov, S. Pacheva, B. Ivanov, P. Bozhilov, D. Doneva, D. Staicova, K. Marinov, B. Dimitrov*)

(3a) ***New Approaches in Gravity and Cosmology – Dark Energy, Dark Matter and Gauge Fields*** (*E. Nissimov. S. Pacheva, D. Staicova, K. Marinov*).

The main results in 2018 of *E. Nissimov* and *S. Pacheva* (altogether 9 papers, some published in 2019 or pending publications) belong to the following closely related and actively developing modern research areas in gravity and cosmology:

(i) We apply our earlier developed formalism of non-Riemannian spacetime volume-forms (formalism of *Guendelman-Nissimov-Pacheva*) in extended theories of gravity to construct a new class of "quintessential" inflationary models of gravity coupled to matter incorporating the whole bosonic sector of the standard model of modern elementary particle physics. Thereby we demonstrate the following very interesting features of the space-time physics – gravity-assisted generation in the "late" Universe of spontaneous electroweak symmetry breaking potential of the Higgs-type for the SU(2)xU(1) Higgs-like isodublet scalar field, as well as gravity-assisted generation of confinement of charge particles corresponding to the notorious quark confinement in quantum chromodynamics. On the other hand, we show that in the "early" Universe both spontaneous electroweak symmetry breaking as well as charge confinement are absent – in other words, it is explicitly demonstrated that the material world as we know it today (the fundamental interactions among elementary particles) has been created only in a later phase of Universe' evolution.

(ii) Our previously developed formalism of non-Riemannian spacetime volume-forms achieves a natural description of "dark energy" and "dark matter" in the Universe as a manifestation of a single material entity – a special scalar field "darkon". To this end we have studied the Wheeler-DeWitt quantization of our gravity models of unified "dark energy" and "dark matter", in particular, the WKB approximation of the quantum-mechanical wave function of the Universe. It is shown that the "dark matter" field (the "darkon") plays the role of a "cosmological time", which is one plausible resolution of the notorious problem of the "time arrow" in gravitational theories. No cosmological singularities ("big bang" or "big crunch") are found in the evolution of the quantum average of the Friedman scale factor.

(iii) We have proposed a new version of the extended Einstein-Gauss-Bonnet gravity, where unlike the standard approach we avoid the necessity of directly coupling of the 4-dimensional Gauss-Bonnet topological term to matter fields. We achieve this again upon using our formalism of non-Riemannian spacetime volume-forms. In this way we obtain a number of physically interesting effects such as: (a) explicit solutions for the Hubble parameter and the Friedmann scale factor predicting linear growth immediately after the "Big-Bang" ("coasting" universe); (b) analytic derivation of the appearance and the magnitude of the "dark energy" in the late Universe. Furthermore, when studying explicit static spherically symmetric solutions in our new Einstein-Gauss-Bonnet gravity we obtain a rich family of physically interesting solutions including black holes, domain walls and Kantowski-Sachs-type universes with or without physical spacetime singularities.

(iv) *D. Doneva* and *E. Nissimov* are coauthors in the highly acclaimed extensive research and review article of the COST network CA16104 "*Black holes, gravitational waves and fundamental physics: a roadmap*", subsequently published in "Classical and Quantum Gravity".

(v) *D. Staicova* has studied the properties of the effective potential of the modified gravity-matter model in the Guendelman-Nissimov-Pacheva formulation . An analysis of the limits of applicability of the effective potential has showed that during most of the Universe' evolution, the effective potential is a very good approximation of the actual potential term. There is, however, a deviation between the two occurring in the earliest moments of the evolution, which has an important impact on the behavior of the inflaton scalar field. In the studied cases, during this initial time, the inflaton is increasing in absolute value, which seems consistent with "climbing up" the effective potential. Using numerical investigation, we find that during the early stage of the evolution the shape of the numerical potential is very different from that of the effective one and instead of a left plateau followed by steep slope, one observes only a slope with additional local maximum and minimum.

(3b) ***Gauge/gravity duality and integrability in string theory relevant for the Anti-de-Sitter/conformal-field-theory correspondence*** (P. Bozhilov).

(i) We have found a classical giant magnon-like solution with both infinite and finite angular momentum moving in Sch_5 x S^5 with B-field, which is believed to be dual to dipole-deformed N=4 super Yang-Mills theory. This string state propagates as a point particle in non-trivial subspace of the Sch_5 space but shows a giant magnon-like property in the S^2 subspace. We derive the energy-momentum dispersion relations and their finite-size correction for the case of finite but large angular momentum.

(ii) We compute structure constants in three-point functions of three string states in AdS_4 x CP^3 in the framework of the semiclassical approach. We consider HHL correlation functions where two of the states are "heavy" string states of finite-size giant magnons carrying one or two angular momenta and the other one corresponds to such "light" states as dilaton operators with non-zero momentum, primary scalar operators, and singlet scalar operators with higher string levels.

(3c) ***Relativistic gravity and astrophysics – exact solutions of Einstein's equations*** (*B. Ivanov, B. Dimitrov*).

(i) A physically realistic stellar model with a simple expession for the energy density and conformally flat interior is studied (*B. Ivanov*). The conditions for being physically realistic are satisfied by constraining the free parameters of the model and using the relations between the different conditions, found in 2017 by the same author. This is done in a purely algebraic way without graphic proofs. The model may represent a real pulsar. The results are published in *European Physical Journal C* and have accumulated around 90 independent citations so far.

(ii) The problem of two null gravitational cones in the theory of GPS-intersatellite communications between two moving satellites has been thoroughly investigated (*B. Dimitrov*). The physical and mathematical theory of the space-time interval and the geodesic distance on intersecting null cones has been developed in great detail, and the results have been published in two papers – one ArXiv.org preprint pending publication and in the Proceedings of 10-th Balkan Physical Union (Sofia, 2018).

(3d) *Models of scalarized black holes and dynamics of rotating neutron stars* (*D. Doneva*). One of the main discoveries in 2018 was the scalarized black holes in Gauss-Bonnet gravity, that is a destabilization of the Schwarzschild black hole below certain mass and the appearance of new black hole solutions with nontrivial scalar field. Our main paper on the subject was published in Physical Review Letters and the results were later extended to include scalarization of neutron stars and charged black holes as well as a stability study of the obtained solutions. In addition, we have introduced a model of neutron stars in scalar-tensor theories with self-interacting scalar field that attracted considerable interest in the community, and we studied certain universal relation between the neutron star parameters in this case. The first differentially rotating neutron star models in alternative theories of gravity were obtained as well and we studied their astrophysical applications.

(3e) *Non-rotating neutron stars in minimal dilatonic gravity* (*K. Marinov*).
Neutron stars are studied in the model of minimal dilatonic gravity, also called massive Brans-Dicke model with w=0, which is a proper generalization of general relativity. We performed numerical calculations to express the relations between cosmological pressure and dilatonic pressure in the center of the star and on the surface, as they represent the effects connected with dark energy and dark matter respectively.