Laboratory "Elementary Particle Theory" - Annual Report 2017

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The science research in the Laboratory is focused on various major actively developing research areas in modern theoretical and mathematical physics.The research is conducted within the framework of a broad 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 2017 the members of the Laboratory (co)authored **47 scientific works** altogether, among them - 36 published and 11 pending publication papers in international journals and international conference series. Throughout 2017 scientific papers of Laboratory's members have received **562 independent citations** in international science journals and conference proceedings worldwide.

In 2017 members of the Laboratory have organized the **10-th International Symposium *"Quantum Theory and Symmetries"* incorporating 12-th International Workshop *"Lie Theory and Its Applications in Physics",*** in Varna.

Throughout 2017 the members of the Laboratory have participated in several large projects funded by Bulgarian National Science Foundation (DFNI T02/6 – successfully completed, and the new projects DN-08/3, DN-18/1 and DN-18/3) and Bulgarian Ministry of Science and Education, as well as participated in various prestigious internationally funded projects - supported through bi-national academic cooperation agreements and/or funded by the European Commission programs, among them **COST action MP-1210, COST action MP-1304, COST action MP-1405, COST action CA15117** and **COST action CA16104**.

Principal Research Areas

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

Wess–Zumino–Novikov–Witten (WZNW) models over compact Lie groups constitute the best studied class of two dimensional (2D) rational conformal field theories (RCFTs). The internal (gauge) symmetry that governs the corresponding fusion rules remains however unclear. Our approach is based on the properties of some quantum matrix algebras (zero modes) carrying the internal symmetry in a logarithmic extension of the chiral model. Combining left and right zero modes, one obtains a specific dynamical quantum group. Its Fock representation provides a generalization of the axiomatic approach to gauge theories in which a "restricted" quantum group at a root of 1 serves as a gauge symmetry of the 2D model (L.Hadjiivanov).

The spinor representations of the orthosymplectic Lie superalgebras osp(m|n) are considered and constructed. These are infinite-dimensional irreducible representations, of which the superdimension coincides with the dimension of the spinor representation of so(m-n). The self dual tensor representations of osp(m|n) and their generalizations are also considered. The character of these representations is determined, and a superdimension formula is deduced. From this, it follows that also for these representations the osp(m|n) ~ so(m-n) correspondence holds (*N.Stoilova*).

Feynman amplitudes in perturbative quantum field theory are being expressed in terms of an algebra of functions, extending the familiar logarithms, and associated numbers – *periods.* The study of these functions (including hyperlogarithms) and numbers (like the multiple zeta values), that dates back to Leibniz and Euler, has attracted anew the interest of algebraic geometers and

number theorists during the last decades. The two originally independent developments are recently coming together in an unlikely collaboration between particle physics and what were regarded as the most abstruse branches of mathematics (*I.Todorov*).

A new generalized notion of differential operators is introduced that captures the problem of "taking derivatives of a function at its poles". The residues of an analytic function are particular examples of this new class of operators. The generalized differential operators can be composed and they lead to a generalization of the associative algebras with derivations to a new class of algebras, which are precisely the Operator Product Expansion (OPE) algebras in Quantum Field Theory. We considered the notion of analytic residue of Feynman amplitude in the context of the Nikolov-Stora-Todorov renormalization prescription. This resulted in a new recursive procedure for analytic renormalization in position space (*N.Nikolov, D.Nedanovski*).

We have found recently a relation between parastatistics algebras and the combinatorial algebra known as the plactic monoid: the states in the parastatistics Fock space turned out to be in bijection with the Young tableaux. We have explored the pseudo-plactic algebra defined by Krob and Thibon and found a surprising connection with the numbers of alternating permutations and their generalizations (called "snakes" by V.I. Arnold) related to the topology of bifurcation diagrams in catastrophe theory. This suggests that the combinatorial pseudo-plactic algebra contains information about invariants of plane curves (*T.Popov*).

Area 2: Conformal and Superconformal Symmetry in Gauge, Field and String Theory
(*V.K. Dobrev, V.B. Petkova, L.K. Anguelova, M. Stanishkov, S. Stoimenov, K.P. Hristov, S.G. Mikhov, O. Stoychev,*)

(2a) Strongly-interacting gauge fields (*L.Anguelova, K. Hristov*)

L.A. continued the study of strongly coupled gauge theories via holographic methods. More specifically, she developed further the gauge/gravity duality setup necessary for building models of composite inflation. In such models, the inflaton is not a fundamental scalar, but a composite state in a strongly coupled gauge sector. Previous work in this area had led only to finding solutions, which are dual descriptions of a so called "ultra-slow roll" inflationary regime. The new results show that in principle there are solutions that are dual to the phenomenologically more interesting "slow-roll" inflation. Further, investigating systematically a modification of ultra-slow roll, known as "constant roll", showed that, in parts of the parameter space of these models, one can obtain inflationary expansion that is both stable and compatible with the observational constraint on the scalar spectral index. This establishes the constant roll regime as a phenomenologically viable alternative to the standard slow-roll inflation.

K.H. continued the study of holographic counting of black hole microstates. In 2017 the programme of holographic microstate counting, initiated in the previous year for a magnetically charged class of asymptotically AdS_4 black holes in M-theory dual to the so-called ABJM theory, was extended to dyonic black holes. Further examples of microstate counting were found for asymptotically AdS_5 black holes in type IIB string theory dual to 4d N=4 super Yang-Mills and for asymptpotically AdS_4 black holes in massive type IIA string theory dual to 3d Chern-Simons coupled super Yang-Mills. Further studies of holographic examples are ongoing.

(2b) Conformal and Superconformal Symmetry in Field and String Theory
(*V.Petkova, M. Stanishkov, O. Stoychev*)

V.P. constructed correlators in the W_4 Toda 2d conformal field theory for a particular class of representations. A relation to the Virasoro theory with different central charge was

demonstrated. The relevance of the classical limits of the constructed 3-point functions and braiding matrices to problems in 4d conformal theories was discussed in detail.
M.S. considered a RG flow in certain 2D coset models perturbed by the least relevant field. Recently, he computed the anomalous dimensions and the mixing coefficients of certain fields in the UV and IR symmetric coset theories. This was further developed for the case of another su(2) coset theory describing the N=2 superconformal model. It was shown that there does not exist a non-trivial IR fixed point up to second order in this case. The results were presented at the International conference "Quantum theory and symmetries" in Varna. ***M.S.*** also successfully defended a thesis for obtaining the degree "Doctor of sciences" ("Doctor habil.") entitled "Symmetries in two dimensional conformal field theories and related integrable models".

(2c) Invariant (Deformed) Differential Equations and Non-Standard Quantum Groups (*V. Dobrev, S. Stoimenov, S. Mikhov*)

V.D. found the classification of conformal representations induced from the maximal cuspidal parabolic, He also found the classification of invariant differential operators for the noncompact group SU(4,4) and the classifiction of the positive energy unitary Irreducible representations of the superalgebra osp(1|8,R). V.D. published the monograph "*Invariant Differential Operators, Volume 2: Quantum Groups*", De Gruyter Studies in Mathematical Physics, vol. 39 (De Gruyter, Berlin, Boston, 2017, ISBN 978-3-11-043543-6, 394 + xii pages.
S.S. constructed meta-conformal transformations of (d+1) space-time as an extension of dynamical scaling with dynamical exponent z=1 and under condition to leave invariant the linear transport equation in d spatial dimensions. The corresponding meta-conformal Lie algebras provides new kind of representations of the conformal Lie algebra for d=1, while for d≠1 they have a different algebraic structure. For d=1 the covariant two-point functions in the form of correlators, relevant for physical applications (without singularities and with correct limits) were derived by an algebraically sound procedure. From them, through a simple contraction a Galilei-conformal correlator can be obtained. For d>2 the representations of meta-conformal algebras are finite-dimensional, however for d=2 an infinite-dimensional extension exist. It is isomorphic to the direct sum of three centreless Virasoro algebras.

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

(3a) ***Generalized Gravity and Nonlinear Gauge Theories with Applications to Elementary Particle Physics and Cosmology*** (E. Nissimov. S. Pacheva, D. Staicova).
Our (*E. Nissimov. S. Pacheva*) main results in 2017 belong to the following closely related and actively developing modern research areas in gravity and cosmology:

(i) Unified ("quintessential") description of the evolution of early and late (modern epoch) Universe based on the earlier developed formalism of non-Riemannian spacetime volume-forms (formalism of *Guendelman-Nissimov-Pacheva*) in extended theories of gravity, in particular, new self-consistent unified description of "dark energy" and "dark matter" as two different manifestations of one single matter source ("darkon" scalar field).

(ii) Exhibiting a fundamental feature of space-time - gravity-assisted generation in the "late" Universe of Higgs-like spontaneous gauge symmetry breaking, while electroweak SU(2)xU(1) remains unbroken in the "early" universe.

(iii) Stabilization of "late" universe evolution via inflaton coupling to a Gauss-Bonnet topological density generating a stable minimum of the effective inflaton potential. The same mechanism is responsible both for the negligible value of modern epoch's cosmological constant

(vacuum "dark energy" density), as well as for the naturally very small Higgs mass (w.r.t. Planck scale).

(iv) Wheeler-DeWitt quantization of gravity models of unified "dark energy" and "dark matter", in particular, no cosmological singularities ("big bang" or "big crunch") are found in the evolution of the quantum average of the Friedman scale factor.

(v) Thin-shell lightlike wormholes – we extended our previous mathematically correct treatment of the Einstein-Rosen "bridge" as a wormhole generated via a lightlike brane "exotic matter" source occupying the wormhole "throat" (the latter property was missing in the original Einstein-Rosen's paper from 1935). By providing the systematic Kruskal-Penrose description of the full analytically extended wormhole spacetime manifold (in collaboration with *E. Guendelman* and *M. Stoilov*) of the correct Einstein-Rosen "bridge" we explicitly showed its traversability w.r.t. the proper-time of travelling observers, as well as we constructed explicitly closed time-like curves (a generic problem in wormhole physics). The same results were generalized for the case of multi-throat lightlike thin-shell wormholes.

D. Staicova (in collaboration in part with *M.Stoilov*).has studied the application of an extended gravity model with non-Riemannian spacetime volume-forms (the *Guendelman-Nissimov-Pacheva* formulation) in cosmology, where we have explored its parameter-space It was found that in addition to the standard expanding universes, we are able to obtain universes undergoing phase transition. Then, using the so obtained evolutions, we are able to fit the data from Supernova type Ia and we find two one-parametric families of solutions fitting with very good precision the observational data.

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

We compute structure constants in three-point functions of three string states in AdS4×CP3 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). A simple classification, based on two free functions, is given of the anisotropic relativistic stellar models, resembling the one of charged isotropic solutions. On the ground of this database, and taking into account the conditions for physically realistic stellar models, a method is proposed for generating all such solutions. It is based on the energy density and the radial pressure as seeding functions. Different relations between the physical conditions are found and the need for a graphic proof is reduced just to one pair of inequalities. This general formalism is illustrated by an example of a class of models with linear equation of state and simple energy density. It is found that they depend on three free constants and concrete examples are given. Some other popular stellar models are studied with the same method.

(3d) ***Models and dynamics of rapidly rotating neutron stars*** (D. Doneva). We studied the oscillation modes of rapidly rotating neutron stars in scalar-tensor theories of gravity with a particular emphasis on a rotational driven secular instability. The differences with pure general relativity were examined and possible ways to further constrain the scalar-tensor theories of gravity with future gravitational wave observations were identified. We also investigated new classes of black hole and neutron star solutions in a particular class of Gauss-Bonnet theory of gravity that admits spontaneous scalarization. The interesting fact is that in this case the

scalarization is not induced by the presence of matted but instead by the curvature of the spacetime itself.

(3e) ***Non-rotating neutron stars in minimal dilatonic gravity*** (K. Marinov) The minimal dilatonic gravity, also called massive Brans-Dicke model with w=0, is a proper generalization of standard general relativity. We have studied a non-rotating neutron star model with realistic equations of state and the corresponding dark matter and dark energy effects.

Area 4: Theory and Phenomenology of Elementary Particles and Their Bound States - ***Partonic spin content of the nucleon and QCD*** (*E. Christova, D. Stamenov, M. Stoilov*)

At present, enormous efforts are made in JLab, COMPASS (CERN) and HERMESS (DESY) towards measuring the 3-dimentional structure of the nucleon – the transverse momentum dependent (TMD) parton densities. We consider one of them - the Boer-Mulders TMD functions, that describe transversely polarized quarks in an unpolarised nucleon. At present they are extracted using a simplifying model assumption of proportionality between the Boer-Mulders and Sivers functions. We formulated 2 relations for testing this assumption but for the sum of the valence-quark densities. We showed that COMPASS data on semi-inclusive deep inelastic scattering on deuterium are compatible with the suggested tests, but they completely disagree with the used assumption of proportionality for each quark-flavour separately. This implies that present parametrisation for Boer-Mulders functions are not reliable. The results are obtained by *E.Christova* and *M.Stoilov* in collaboration with *Elliot Leader* from Imperial College, London and presented at the workshops DSPIN 2017, JINR, Dubna and Transversity-2017, Frascati, Italy.