Laboratory "Elementary Particle Theory"

Institute for Nuclear Research and Nuclear Energy

Bulgarian Academy of Sciences

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I. Principal Current Research Topics and International Collaboration

The principal research activities of the members of the Laboratory embrace a broad range of world-wide actively developing research topics of modern theoretical and mathematical physics:

(a) *Applications of conformal symmetry to quantum field theory and statistical physics.*
(b) *Conformal and superconformal symmetry in field and string models*.
(c) *Group-Theoretical Methods and Applications in Quantum Physics.*
(d) *Non-canonical Quantum Statistics, Representations of (Super-)Algebras and Supermanifolds*.
(e) *Modern Aspects in Gravity and String Theories: Study of Higher-Dimensional Extended Objects - Strings and p-Branes, Anti-de-Sitter/Conformal-Field-Theory Duality and Integrability in M-Theory; Cosmology and Black Hole Physics*.
(f) *Particle Physics Phenomenology: Partonic spin content of the nucleon and QCD, Physics beyond the Standard Model.*
(g) *Generalized functions of Colombeau and Applications*.
(h) *Multidisciplinary Research - Supercomputer simulations of bio-molecules and systems.*

The research in above areas is carried out within a wide international collaboration, financed under bilateral research grants, with scientists from several leading world-renown institutions in various countries around the globe, whose current partial list icludes:

(1) *Austria* – Erwin Schroedinger Institute for Mathematical Physics (ESI), Institute on High Energy Physics and University of Vienna;
(2) *Belgium* – University of Ghent;
(3) *Brazil* – Institute for Theoretical Physics (Sao Paulo);
(4) *Finnland* – Finnland Academy of Science;
(5) *France* – C.E.A. Saclay (including "Rila" project of CNRS "**Random geometry, quantum gravity and conformal theories**"), Université de Paris-Sud (Orsay), Ecole Polytechnique, (Palaiseau), L.A.P.P. Annecy, Université Paul Sabatier (Toulouse); Université Henri Poincaré (Nancy);
(6) *Germany* – Institute for Theoretical Physics (University of Göttingen), Technical University of Clausthal; Max-Planck Institut für Mathematik, Leipzig;
(7) *Hungary* – K.F.K.I. (Budapest);
(8) *Israel* – Ben-Gurion University (Beer-Sheva);
(9) *Italy* – I.C.T.P. and S.I.S.S.A. (Trieste), University of Trieste; Rome University "Tor Vergata";
(10) *Republic of Korea* - Ewha University (Seoul);
(11) *Russia* – J.I.N.R. (Dubna);
(12) Switzerland - Theory Group of C.E.R.N., Geneva; University of Geneva;
(13) *United Kingdom* – Imperial and Kings Colleges of University of London, University of York, University of Northumbria at Newcastle;
(14) *United States of America* – University of Delaware (Newark); Michigan University (Ann

Arbor); Pennsylvania State University (Abington); North Carolina State University (Raleigh).

Members of the Laboratory have been participating as network nodes in two large networks financed by the European Commision as well as in other international multipartner projects:

(a) ***"Tools and Precision Calculations for Physics Discoveries at Colliders"*** – FP6 Marie Curie Research Training Network, HEPTools, **MRTN-CT-2006-03550;**

(b) TMD network ***"Mapping out the Transverse Structure of the Nucleon"*** of the FP7 Hadron Physics2 Project;

(c) 3-node network (Clausthal-Leipzig-Sofia Cooperation), financed by the Alexander von Humboldt Foundation ***"Quantum systems related to noncommutative geometries, their symmetries and evolution equations"***;

(d) ***"Exploring the unknown transverse spin structure of the nucleon"*** - N7 Transversity network (I3HP Project).

Furthermore, two groups of scientists from the Laboratory have earned two prestigious grants with significant funding from the Bulgarian National Science Foundation within the framework program "Ideas":

(d) ***"Quantum Structure and Geometric Nature of Fundamental Forces"*** – Bulgarian National Science Foundation (BNSF) Grant DO 02-257 (in collaboration with Departments of Physics and Mathematics of Sofia University);

(e) "***Structure of the nucleon and lepton-nucleon processes***" – BNSF Grant DO 02-288 (in collaboration with Laboratory " Mathematical Modeling in Physics" of the same Institute).

(f) ***"Supercomputer simulations of bio-molecules and systems"*** – within the Center of Excellence "Supercomputer applications", including participants from Bulgarian Academy of Sciences (IPPI, INRNE), University of Sofia "St. Kl. Ohridski" (Faculties of Physics, Mathematics and Informatics, Chemistry), Technical University – Sofia, and Medical University – Sofia. Among the international partners are Los Alamos National Laboratory and Texas A&M University, USA; IBM Research Laboratory and Institute for Scientific Computing, ETH, Zurich, Switzerland; Institute for High-Performance Computing and Networking, CNR, Naples, Italy; University of Oxford, UK.

II. Main Current Research Achievements in the Laboratory

(1) *Applications of conformal symmetry to quantum field theory and statistical physics* (A. Ganchev, L. Georgiev, L. Hadjiivanov, N. Nikolov, T.Popov, I. Todorov)

The research area includes the following main directions of study:

- Models of Quantum Field Theory with conformal symmetry in two and higher dimensions.
- Algebraic aspects of Perturbative Quantum Field theory
- Application of two dimensional conformal field theory models to the description of mesoscopic phenomena in the Quantum Hall effect, and Hall realization of elementary quantum gates ("topological quantum computers")
- Quantum Groups as generalized internal symmetries in two dimensional conformal field theory models
- Hopf structure on Standard Young Tableaux

Here are some of the basic results obtained in 2009 in these directions, together with the names of

the main investigators in each of them.

(*I. Todorov, N. Nikolov*) It is known that there are no local scalar Lie fields in more than two dimensions. Bilocal fields, however, which naturally arise in conformal operator product expansions, do generate infinite Lie algebras. It was demonstrated that these Lie algebras of local observables admit (highly reducible) unitary positive energy representations in a Fock space. The multiplicity of their irreducible components is governed by a compact gauge group. The mutually commuting observable algebra and gauge group form a dual pair in the sense of Howe. In a theory of local scalar fields of conformal dimension 2 in four space-time dimensions the associated dual pairs were constructed and classified.

(*N. Nikolov*) Perturbation theory in QFT is one of the technically most difficult subjects in contemporary theoretical physics. This is, first and foremost, due to the appearance of complicated integrals in higher orders, as well as, to the complexity of the accompanying renormalization. In a series works a new approach is created to renormalization group based on cohomological analysis of renormalization in quantum field theory on configuration space. This approach is developed in both Euclidean and Minkowski space. In this method, the renormalization group action is derived from solutions of certain cohomological equations on configuration spaces. The explicit construction of such solutions requires introducing a new class of polylogarithmic functions depending on vector variables and thus, it is a source of new interesting mathematical structures in algebraic geometry and topology. In this way, this investigation is of interdisciplinary interest: from one hand, for quantum field theory, and from the other hand for number theory and theory of special functions.

(*L. Georgiev*) The braid generators in the Ising-anyon topological quantum computer, which are the elementary building blocks of all topologically protected quantum gates, have been rigorously derived from the multi-anyon Pfaffian wave functions, representing qubits realized in the fractional quantum Hall state with filling factor 5/2, using the operator-product expansions in the Neveu-Schwarz and Ramond sectors. It has been also proven that the two wave-function representations of the braid group B_{2n} are exactly equivalent to the two spinor representations of SO(2n) with definite parity, and the equivalence matrices have been constructed explicitly. On the other hand, it has been demonstrated that the two inequivalent spinnor representations of the braid group are equivalent from the point of view of the topological quantum information processing.

(*I. Todorov, L. Hadjiivanov*) The book by I. Todorov and L. Hadjiivanov “Quantum Groups and Braid Group Statistics in Conformal Current Algebra Models” (Lecture Notes, UFES, Vitoria, E.S., Brazil 2009) has been completed, submitted and later, accepted for publication. It contains a considerably extended version of a course of lectures delivered by Ivan Todorov during his visit at the Physics Department of the Federal University of Espírito Santo (Vitória, Brazil) in the autumn of 2007. The lectures provide an introduction to quantum groups, braid groups and their applications to 2-dimensional conformal field theory. They acquaint the reader (presumably, a graduate or PhD student, although the content would also be helpful for experienced researchers) with the basic concepts of Hopf algebras, permutation and braid groups, the conformal symmetry in two and higher dimensions and the axiomatic quantum field theory. The exposition contains original recent results of the authors and is accompanied by many examples and exercises, as well as with bibliographic and historical references.

(*T. Popov*) A new family of Hopf structures on the set of Standard Young Tableaux has been constructed in collaboration with Jean-Louis Loday. It was shown that the combinatorial Poirier-Reutenauer Hopf algebra is a distinguished member of the family in question. Another notable member of this family underlies the Fock-like representations of the parastatistics algebra. The connection of the Hopf structures on Standard Young Tableaux with the theory of non-commutative symmetric functions and algebras of rooted decorated trees is under investigation.

(2) *Conformal and superconformal symmetry in field and string models*
(Dobrev, Petkova, Stoytchev, Stanishkov)

The operator product expansion of local operators in the presence of defect lines is considered both in the rational conformal field theory and the $c>25$ Virasoro (Liouville) theory. The duality transformation of the 4-point function with inserted defect operators is explicitly computed. The two channels of the correlator reproduce the expectation values of the Wilson and 't Hooft operators, recently discussed in Liouville theory in relation to the AGT conjecture.

The 3-point tachyon correlators of the open non-critical string theory with ZZ Liouville branes are found. The construction includes the determination of the matter 3-point boundary coefficients for non-degenerate $c<1$ Virasoro representations.

We give a group-theoretic interpretation of non-relativistic holography as equivalence between representations of the Schroedinger algebra describing bulk fields and boundary fields. Our main result is the explicit construction of the boundary-to-bulk operators in the framework of representation theory (without specifying any action). Further we show that these operators and the bulk-to-boundary operators are intertwining operators. In analogy to the relativistic case, we show that each bulk field has two boundary fields with conjugated conformal weights. These fields are related by another intertwining operator given by a two-point function on the boundary. Analogously to the relativistic result of Klebanov-Witten we give the conditions when both boundary fields are physical. Finally, we recover in our formalism earlier non-relativistic results for scalar fields by Son and others.

A simple characterization is given of braids that can be unplaited keeping separately their upper ends and their lower ends tied together. This classical problem has a rather complicated algebraic solution (Shepperd, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Volume 265, Issue 1321, pp. 229-244). Our approach is geometric-topological and uses the link between SO(3) and spherical braids.

We point out that the nontrivial central extension of the superalgebra su(2/2) is related to the some not so well-known Serre relations.

(3) *Group-Theoretical Methods and Applications in Quantum Physics*
(Dobrev, Mihov, Stoimenov)

The symmetries of non-linear Schroedinger equations with power-law non-linearities are investigated. It is shown that Galilei invariance can be extended to Schroedinger invariance if the coupling constant(s) in non-linearity is treated as dimensionful quantity. This is used to find a new non-stationary solutions from given stationary ones.

The singular vectors in Verma modules over the Schroedinger algebra in (n+1) dimensional space-time are found for the case of general representations. Using the singular vector hierarchies of equations invariant under Schroedinger algebras are constructed.

We construct exotic bialgebras that arise from multiparameter 9x9 R-matrices, some of which are new. We also construct the dual bialgebras of two of these exotic bialgebras.

(4) *Non-canonical Quantum Statistics, Representations of (Super-)Algebras and Supermanifolds* (T. Palev, N. Stoilova, V.Molotkov)

It is to shown that the natural statistics of hardcore bosons and hardcore fermions is A-(super)statistics. This may have far going consequences. One of them is that the Hamiltonian of high-temperature superconductivity can be written via creation and annihilation operators of A-statistics, i.e., there are good indications that the A-statistics is the statistics of high-temperature superconductivity.

The Fock spaces of the parafermion and the paraboson algebra, for an infinite set of generators were constructed explicitly. This is equivalent to constructing certain unitary irreducible lowest weight representations of the (infinite rank) Lie algebra so(∞) and of the Lie superalgebra osp(1|∞). These Fock spaces have basis vectors labeled by certain infinite but stable Gelfand-Zetlin patterns, and the transformation of the basis was given explicitly. Alternatively, the basis vectors of the representations can be labeled by semi-standard Young tableaux: the action of a paraboson (or parafermion) creation operator indexed by j then gives rise to an insertion procedure of the number j in the Young tableau.

The question of n-mode coherent states for parabosons, using the constructed osp(1|2n) representations, was investigated. Already for n=2, the problem turned out to be difficult. Two-mode paraboson coherent states, using the explicitly known action in the paraboson Fock spaces were constructed. In appropriate subspaces these coherent states provide a decomposition of unity where the measure, when expressed using the "cat-type" states, is positive definite. Bicoherent states where the mutually commuting lowering operators are diagonalized were also obtained in this context.

Global representation of the functor of supersmooth morphisms is obtained for the wide class of infinite-dimensional supermanifolds --- so called vector supermanifolds. This representation permits one, in particular, to describe explicitly supergroups of automorphisms of N=2 Riemann supersurfaces, which play an important part in N=2 superconformal field theory.

(5) *Modern Aspects in Gravity and String Theories: Study of Higher-Dimensional Extended Objects - Strings and p-Branes, Anti-de-Sitter/Conformal-Field-Theory Duality and Integrability in M-Theory; Cosmology and Black Hole Physics* (E. Nissimov, S. Pacheva, P. Bozhilov, B. Ivanov)

In the last few years the theory of membranes and their higher-dimensional counterparts (*p*-branes) as well as the integrability aspects within Anti-de-Sitter/Conformal-Field-Theory duality became one of our primary research areas in view of their fundamental importance in modern non-perturbative string theory of elementary particles at ultra-high energies and in "string-inspired" cosmology.

(5a) *Lightlike Membranes in Black Hole Physics, Particle Physics and Cosmology* (E. Nissimov, S Pacheva)

In a long series of papers within a joint project with Ben-Gurion University (Israel) we have proposed and systematically studied a substantially new class of *p*-brane theories which are qualitatively distinct from the standard Nambu-Goto type brane models and provide a systematic lagrangian description of *lightlike* branes. As it is well known lightlike branes are of substantial

interest in general relativity as they describe impulsive lightlike signals arising in various violent astrophysical events, e.g., final explosion in cataclysmic processes such as supernovae and collision of neutron stars. Lightlike branes also play important role in the description of various other physically important cosmological and astrophysical phenomena such as the "membrane paradigm" of black hole physics and the thin-wall approach to domain walls coupled to gravity. More recently they became significant also in the context of modern non-perturbative string theory.

In our recent papers on the above subject we have obtained a variety of physically interesting results:

(5a1) The dynamical (variable) tension of a test lightlike brane of codimension one in spherically symmetric or axially symmetric (rotating) gravitational backgrounds evolves exponentially with time - a phenomenon analogous to the famous "mass iflation" effect (matter accululation) around black hole horizons discovered previously by W. Israel and E. Poisson.

(5a2) We have shown that lightlike branes are the appropriate gravitational sources that provide proper matter energy momentum tensors in the Einstein equations of motion needed to generate traversable wormhole solutions, in particular, self-consistent spherically symmetric and cylindrical rotating wormholes, with the lightlike branes occupying their throats. Here a major role is being played by the dynamical lightlike brane tension. As a particular solution we obtain traversable wormhole with Schwarzschild geometry generated by a lightlike brane positioned at the wormhole throat, which represents the correct consistent realization of the original Einstein-Rosen "bridge" (the explicit presence of lightlike matter at the Einstein-Rosen "bridge" throat has been *overlooked* in the original work of Einstein and Rosen!).

(5a3) With the help of electrically charged lightlike branes we have constructed *regular* black hole solutions of Einstein equations, i.e., black holes possessing event horizons (occupied automatically by the lightlike branes) but with *no* singularity at their center. Similarly, employing electrically neutral lightlike branes we have found a new type of wormhole connecting two non-singular black hole "universes" with the wormhole "throat" being occupied by the lightlike brane. This same wormhole solution can further be transformed into a Kantowski-Sachs "bouncing" cosmology solution.

(5a4) We have found a new physically interesting mechanism of spontaneous compactification of space-time – compactification of some of the space dimensions induced by a lightlike brane. Specifically we have found an exact solution to the Einstein-Maxwell equations of bulk space-time gravity-matter system interacting self-consistently with a lightlike electrically charged brane, where the latter serves as a "bridge" between a "normal" uncompactified universe being the exterior space-time region of a Reissner-Nordstroem black hole beyond the external event horizon, and a Bertotti-Robinson space-time region representing a compactified (tube-like) universe.

(5a5) We also have studied codimenion two (and more) lightlike braneworlds described by lightlike branes of the class discussed above. We have shown that these lightlike braneworlds perform in their ground states non-trivial motions with the speed of light in the extra dimensions (planar circular, spiral winding, etc.) in sharp contrast to standard (Nambu-Goto) braneworlds which occupy some fixed position with respect to the extra dimensions. Lightlike braneworlds provide a natural explanation of the undetectability of (large) extra dimensions from the point of view of an observer confined to the lightlike brane "universe".

(5b) *Integrability and finite- size effects in AdS/CFT* (P. Bozhilov).

We consider finite-size effects for the dyonic giant magnon of the type IIA string theory on

AdS_4 x CP^3 by applying Luescher mu-term formula which is derived from a recently proposed S-matrix for the N=6 super Chern-Simons matter theory. We compute explicitly the effect for the case of a symmetric configuration where the two external bound states, each of A and B particles, have the same momentum p and spin J_2. We compare this with the classical string theory result which we computed by reducing it to the Neumann-Rosochatius
integrable system. The two results match perfectly.

(5c) *General Relativity and Astrophysics* (B.V. Ivanov)

Spherically symmetric perfect fluids and their gravitation have been discussed since the invent of general relativity. Fluids with shear and bulk viscosity, charge and radiation in the form of a heat flow or null radiation have been studied too and are important for star models and gravitational collapse. It is shown that an effective anisotropic spherically symmetric fluid model with heat flow can absorb the addition to a perfect fluid of pressure anisotropy, heat flow, bulk and shear viscosity and null fluid.

(6) *Particle Physics Phenomenology* (E. Christova, D. Stamenov, E. Ginina)

(6a) *Partonic spin content of the nucleon and QCD* (E. Christova, D. Stamenov)

A nucleon spin puzzle inspired by the EMC experiment at CERN and its present status has been examined. A critical assessment of what can be learned from the present data on inclusive polarized deep inelastic lepton-nucleon scattering (DIS) has been presented. In order to test QCD and to extract the polarized parton densities, a next-to-leading order QCD analysis of the world DIS data has been performed. An excellent fit to the data has been found. It has been shown also that while the polarized quark densities are well determined, the gluon polarization is still poorly constrained from the present data. The role of higher twist (non-perturbative QCD) effects in the determination of the polarized parton densities has been studied. It was demonstrated that their account is important for the correct extraction of the polarized parton densities from the data, as well as a good agreement of the data with perturbative and non-perturbative aspects of QCD.

The dependence of the polarized parton densities (PDFs) on the method used in the analysis that takes into account or not the kinematic and dynamic $1/Q^2$ corrections to the spin structure function g_1, is demonstrated. It is shown that the precise data in the pre-asymptotic region require a more careful matching of the QCD predictions to the data in order to determine the polarized PDFs correctly.

The results achieved are of importance for understanding the distribution of the nucleon spin among its constituents (quarks and gluons). Using these results, the expected uncertainties for polarized parton densities and higher twist corrections to the nucleon spin-structure function g_1 have been calculated by E. Leader (Imperial College, London), A. Sidorov (JINR, Dubna) and D. Stamenov and became an important part of two Research Proposals which are devoted to the further more precise study of the nucleon structure and were approved to be performed at Jefferson Laboratory (USA) in the near future. Also, FORTRAN packages of the obtained polarized parton densities (known as Leader, Sidorov, Stamenov - LSS polarized PDFs) are presented at the Durham HEPDATA web site http://durpdg.dur.ac.uk/HEPDATA/PDF and are widely used by experimentalists and theorists.

The theoretical interpretation of the new generation of high energy experiments, with the detection of a final hadron *h*, requires an accurate knowledge not only of the parton PDF densities, but also of the fragmentation functions (FFs). The FFs describe the probability for a parton to form a given hadron *h*. Both the PDFs and the FFs are extracted from experiment.

However, different assumptions are inevitably used when obtaining the FFs, which leads to a significant disagreement among the available sets of FFs. It is already clear that the interpretation of the experiments is very sensitive to the used FFs. We (E. Christova and E. Leader) have presented an approach for obtaining model independent information about different non-singlet combinations of FFs in $e^+e^- \to h + X$, in semi-inclusive deep inelastic $e + N \to e + h + X$ scattering and in hadron production $pp \to h + X$, that is independent of any assumptions about the PDFs and FFs, and hold in any order of QCD.

(6b) *Physics beyond the Standard Model* (E. Christova, E. Ginina)

Detecting charged Higgs bosons $H^{\pm}$ at the new colliders would be a clear signal for physics beyond the Standard Model. On the other hand almost all extensions of the Standard Model offer possible new sources of CP violation in order to meet the cosmological requirements. We consider CP violating asymmetries, induced by the Minimal Supersymmetric Standard Model, that relate CP odd observables in H^+ and H^- production and decay processes. Numerical analysis for the expected effects is performed for the LHC. These investigations are fulfilled in collaboration with the SUSY group of the Institute for High Energy Physics, Vienna.

(7) *Generalized functions of Colombeau and Applications* (B. Damyanov)

The modeling of singularities given by distributions or discontinuous functions by means of the generalized functions of Colombeau has proved useful in many problems posed by physical phenomena, such as geodesics for impulsive gravitational waves, jump conditions in hyperbolic systems and others. The algebra $\mathcal{G}$ of generalized Colombeau functions enables modeling and algebraic operations with singularities and by means of the so-called association process – obtaining of results for singular products of Schwartz distributions.

(8) *Supercomputer simulations of bio-molecules and systems* (N. Ilieva)

A computer model of the human interferon gamma (hIFN-γ) binding to its cellular receptor was proposed. The role of the high charge density of hIFN-γ C-termini for the cytokine activity was revealed. The hypothesis for a third participant in the process – the heparin sulphate, was investigated. In order to find a mechanism for inhibition of hIFN-γ biological activity, the possibility to synthesize a mutant form, which does not cause biological response in the cell was investigated. By means of a MD computer model, the alterations in the tertiary structure, caused by mutations of aminoacid residues 86-88 in the molecule of hIFN-γ were investigated. These results were reported at five international conferences and two national workshops.