INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY

FNP Foundation for Polish Science

EUROPEAN UNION
EUROPEAN REGIONAL
DEVELOPMENT FUND

International PhD studies in Fundamental Problems of Quantum Gravity and Quantum Field Theory

First Recruitment

Description of individual PhD thesis projects:

I. **Hadron light-front wave functions based on AdS/QCD duality,** ***supervised by prof. Stanisław D. Głazek, University of Warsaw***

Outline of the project: Structure and interaction of hadrons are known at the probability level. A deeper understanding at the level of amplitude is required for conceptually clear and quantitatively precise description of processes that involve hadrons, such as collisions of protons or their interaction with electrons and photons. This project aims at construction of the renormalized wave functions of hadrons using insights from AdS/QCD duality and light-front holography. Since cross-sections in processes that involve hadrons can be expressed in terms of their generalized parton distributions and form factors, the graduate student would be expected to compute the relevant observables using the derived wave functions. Two main results provide foundation for this project. The general theoretical framework in the study will be the similarity renormalization group procedure for Hamiltonians that was originally formulated by Głazek and Wilson and subsequently developed by Głazek and his students in the University of Warsaw in application to QCD. This framework is a natural candidate for incorporating the vast amount of information from the phenomenology of hadronic wave functions developed by Brodsky and his collaborators, based on the development of AdS/QCD correspondence and light-front holography.
Stays abroad: Stanford Linear Accelerator Center (SLAC), at least 6 months, likely extension to 12 months.

II. **Relativistic description of gluons in hadrons,** *supervised by prof. Stanisław D. Głazek, University of Warsaw*

Outline of the project: QCD suggests that wave functions of hadrons should have significant gluon components. The energy upgrade plan for JLab is focused on the international effort to search for exotic hadrons in which the gluon components carry quantum numbers that quarks alone cannot have. One way of constructing relevant wave functions theoretically is based on the Coulomb gauge formulation of QCD developed by Szczepaniak and his collaborators. Relativistic theory of quark wave functions in general is also being developed by Hoyer, whose basic approach incorporates a number of required high-energy features. This project aims at a boost invariant description of hadrons with significant gluon components using light-front formulation of QCD and similarity renormalization group procedure for effective particles developed by Głazek. The goal is to establish if the approaches of Szczepaniak and

Hoyer can be unified in a systematic way using the renormalized light-front Hamiltonian formulation of QCD. In particular, the key question is what spatial configurations of quarks and gluons should be searched for experimentally and what signatures for different such configurations can be established, if any, on the basis of a relativistic theory.
Stays abroad: Indiana University -9 months, University of Helsinki - 3 months

III. Similarity renormalization group study of few-body systems, *supervised by prof. Stanisław D. Głazek, University of Warsaw*

Outline of the project: Coulomb and phenomenological AMO forces are important examples of interactions that require precise quantitative understanding in realistic systems. They can be studied in the most general context using new similarity renormalization group (SRG) techniques invented by Głazek and Wilson and developed by Perry: initially in particle physics, then in nuclear physics, and recently in the case of limit cycles that may lead to measurable effects in atomic physics, such as very cold systems. These systems develop three-body forces, which may exhibit cyclic SRG behavior that can be studied already in few-body systems. But few-body Hamiltonians are well approximated by finite matrices that yield bound state and scattering dynamics to high, controllable precision. The key question of the project is how one can achieve machine precision with matrices that are as small as possible. Kinetic energy can be non-relativistic or relativistic. Interactions can be local or non-local (i.e., diagonal in position representation or not), short range (with universality classes emerging from point-like interactions) or long range. Thus, it is worthwhile to study broad classes of Hamiltonians, using a wide variety of SRG transformations. Discovering and characterizing relevant universality classes would be the main outcome of the whole project and the student collaborating with Głazek and Perry could contribute to the development of important theoretical tools for many interdisciplinary applications ranging from particle to nuclear to atomic and molecular dynamics. One can imagine setting up and solving many simple few-body SRG problems, for gaining experience. Even the restriction to few-body Hamiltonians should be eventually lifted, but the problems and techniques required as one allows more than just three particles drastically complicate calculations and are best thought of as something to add as a second stage.
Stays abroad: Ohio State University 1 year, with possible extension

IV. F-theory unification and its implications to the LHC physics, *supervised by prof. UW dr hab. Jacek Pawełczyk, University of Warsaw*

Outline of the project: Data from LHC (Large Hadron Collider in CERN, Geneva) experiments are expected to provide numerous hints for the structure of unification theory of all fundamental forces. Among the most attractive possibilities are the so-called Grand Unified Theory (GUT) models and their recently revived string theory version, i.e. F-theory GUT’s. The aim of the project is to study properties of the F-theory GUT’s as the candidate for the unification model. This will involve analysis of the structure of the F-theory GUT's and its ability to solve some theoretical problems of the particle physics such as supersymmetry breaking and generation of scales for various terms of the effective low energy supersymmetry theory. Besides the theoretical issues the project aims to find preliminary answers to some phenomenological consequences for the LHC physics. This includes searching for, e.g., exotic matter, possible new gauge interaction, and supersymmetric particles. Some issues relating particle physics and cosmology (e.g. searching for dark matter candidates) are also planned to study. Members of our research team have a proper background in theoretical issues of string model building for the unification program

as well as good background in phenomenological aspects of these models. Emilian Dudas is a world recognized expert in string theory and its application to particle physics and unification. During the stay at Ecole Polytechnique a student will learn advanced methods of both theoretical and phenomenological analysis of the string unification models.
Stays abroad: Ecole Polytechnique, 2x4 = 8 months

V. **Knots as possible excitations of quantum Yang-Mills fields,** *supervised by prof. Jerzy Lewandowski, University of Warsaw*

Outline of the project: Faddeev described a model where knot-like structure of a solution guarantees its stability. It is a type of nonlinear sigma-model where the nonlinear field takes values in two-dimensional sphere. The solutions are minimizing energy functional proposed by Faddeev. It is a linear combination of traditional sigma-model Hamiltonian and Maxwell energy of magnetic field. Using this model, Faddeev has recently pointed out that there could be a connection between knotted solitons and quantum Yang-Mills field. He stated the hypothesis that particles of Yang-Mills field could be knot-like solitons. This project is aimed to develop the idea proposed by Faddeev. It is of great importance to particle physics and to mathematical physics, it may shed some light on the "Mass-Gap" problem, one of the famous Clay Millenium Problems. The research will involve constant cooperation with St. Petersburg Department of Steklov Mathematical Institute. During four stays lasting 6 months each, a student will: learn the quantum theory of solitons and consult the project with Professor Faddeev in Steklov Mathematical Institute.
Professor Ludwig D. Faddeev, a mathematical physicist is famous for the discovery of Faddeev-Popov ghosts and Faddeev equations. His work led to the invention of quantum groups.
Stays abroad: St. Petersburg Department of Steklov Mathematical Insitute 4x6=24 months.

VI. **Effective low-energy theories from the Randall-Sundrum model with soft branes,** *upervised by prof. Bohdan Grządkowski, University of Warsaw*

Outline of the project: The Standard Model (SM) of electroweak and strong interactions has been verified up to an impressive precision by many experiments. Nevertheless, it is commonly believed that it is only an effective low-energy approximation of some unknown, more fundamental theory. The model suffers from a number of basic drawbacks:

- the hierarchy problem,
- lack of a dark matter (DM) candidate,
- the strong CP problem,
- no explanation for dark energy.

Some of the above problems could be attacked assuming the existence of 5-dimensional space-time with 5th dimension smoothly compactified. The goal of this project is to investigate 5-dimensional models with both gravity and multiple scalar fields propagating in the 5-dim bulk, such that classical (background) solutions of field equations would describe kink-like periodic functions while the metric tensor would have Randall-Sundrum (RS) type warping towards the 5th dimension. Kinks corresponding to localized energy are suppose to constitute branes necessary within the standard RS setup. In that scenario singularities (caused by infinitely thin branes) appearing in the RS model would be replaced by smooth soft branes made of scalar fields.
The following specific issues could be investigated within this project:

- Determination of potentials for scalar fields for which kink-like periodic solutions (scalar background) exist in the presence of non-minimal couplings to gravity.

- Stability of background solutions for a system of several scalar fields coupled to gravity.
- Cosmology with soft branes.
- Localization of fermions in the extra dimension.

The issue no. 1 has been already initiated together with prof. Jose Wudka from University of California Riverside, therefore a student visiting Riverside could easily join the project. A student is expected to spend between 6 and 24 months at both partner institutions (combining time spent at University of California Davis and Riverside). A student will have a chance to work on the research project specified in this application either with the counterpart researchers (J.Gunion and J.Wudka, respectively) or with other faculty members.
Stays abroad: University of California Davis University of California Riverside 6 to 24 months

VII. Multi-singlet extensions of the Standard Model, *supervised by prof. Bohdan Grządkowski, University of Warsaw*

<u>Outline of the project:</u> The goal of this project is to investigate the simplest extensions of the Standard Model (SM) which would ameliorate the hierarchy problem and possibly offer a candidate for DM, while preserving all the successes of the SM. The approach we propose is very pragmatic, so we would extend the SM in a simplest manner which guarantees the cancellation of quadratic divergences at the one-loop level by adding a number of scalars that are singlets under the SM gauge symmetry [see B. Grzadkowski and J. Wudka, Phys. Rev. Lett. 103, 091802 (2009)]. Since higher loop contributions to the quadratic divergence remain non-vanishing, therefore the solution we propose to investigate is applicable only below certain UV cutoff of the order of few TeV. Nevertheless, since the SM cutoff is as low as about 600 GeV, the simple model we propose constitutes a substantial increase of the region of validity for the model. To some extend the multi-singlet scalar extensions are also motivated by so called unparticles, a scenario which recently attracted a lot of attention after being proposed by Georgi. It has been conjectured that unparticles could be "decomposed" into an infinite series of extra degrees of freedom, e.g. gauge singlet scalars, as in our proposal. It turned out that scalar singlets provides candidates for DM. Of course, the scenario considered here requires some amount of fine tuning between parameters, nevertheless the fine tuning is less dramatic than in the SM. If the proposed extension is indeed realized in Nature, some unknown UV completion of the model is required, however its typical scale is of the order of few TeV.
Within this project the following issues could be investigated:

- Leptogenesis in the presence of singlets.
- Cosmological consequences of the presence of singlets.
- Electroweak phase transitions with scalars.
- Existing experimental constraints on multi-scalar extension of the SM.
- LHC tests of the multi-scalar extension of the SM.
- Multi-doublet extensions of the SM.

The 4th issue has been already initiated together with prof. John Gunion from the University of California Davis, therefore a student visiting Davis could easily join the project. A student is expected to spend between 6 and 24 months at both partner institutions (combining time spent at University of California Davis and Riverside). A student will have a chance to work on the research project specified in this application either with the counterpart researchers (J.Gunion and J.Wudka, respectively) or with other faculty members.
Stays abroad: University of California Davis University of California Riverside 6 to 24 months

VIII. Heat kernels in the study of quantum spacetimes, *supervised by prof. Jerzy Kowalski-Glikman, University of Wrocław*

Outline of the project: Doubly-special relativity is one of many theoretical approaches to quantum gravity, initially proposed by Giovanni Amelino-Camelia in 2002. It is based on an assumption, that along with speed of light, there is another physical constant (namely the Planck energy), that on a scale comparable to it the "ordinary" physics breaks down. This poses a need for modification (or "deformation") of the symmetry group of the theory, and the proposed structure of spacetime as well. A well-established mathematical tool to probe this structure is a heat kernel - a fundamental solution to the heat dissipation equation. The exact form of the kernel depends heavily on the space on which the equation is solved and thus may be used to infer key properties of the space. We plan to investigate them for a gamut of quantum spacetimes, with emphasis on the key example of kappa-Minkowski, being the most natural deformation of the ordinary special relativistic Minkowski spacetime. Part of the work will be conducted in the University of Utrecht during six-month-long stays, preferably two or three, depending on actual needs. During these periods the student will learn the theory of Hopf algebras and Hopf spaces and discuss the project with the UU staff. *Stays abroad: Universiteit Utrecht, 3x6=18 months.*

IX. Observable algebras arising from gauge field theories and their analysis in terms of gauge invariants, *supervised by prof. Jerzy Kijowski, Polish Academy of Sciences Center for Theoretical Physics*

Outline of the project: There have been recently several attempts to construct quantum theory of gauge fields in a non-perturbative way, based on appropriate lattice approximations. Important examples of such an approach are provided by the "Lattice gauge theory" in Quantum Chromodynamics and the so called "Loop theory" of gravity. There are serious arguments for choosing the following strategy here: "first solve constraints and then quantize the true observables (i.e. gauge invariants) only". The opposite strategy: "first quantize everything and then try to impose constraints on the quantum level" is often unpracticable because of high nonlinearity of constraints. The observable algebras obtained this way have a very interesting structure and lead to novel, highly non trivial quantum systems which were obtained by quantizing classical stratified phase spaces.

Partial results of that type have been obtained in simplest case of the SU(2)-gauge. Results concerning the SU(3)-gauge are only preliminary. We plan to investigate deeply these structures and extend a similar approach to gravity. In particular, possibility of using matter fields (like e.g. hydrodynamical or elastic matter) as possible gauge-fixing tools in Quantum Gravity will be investigated.
Stays abroad: University of Leipzig, 3x6=18 months

X. Applications of the spin networks and Spin Foam Models in Quantum Field Theory and quantum gravity, *supervised by prof. Jerzy Lewandowski, University of Warsaw*

Outline of the project: Spin networks and spin foam models are new tools of modern quantum theory. The quantum states of gauge potential can be represented by Penrose's spin networks. After Ponzano-Regge and Rovelli, we understand that a time evolution of those quantum

states should be characterized by a suitable spin foam model. Those models are known in the cases of the Chern-Simons theory and the lower dimensional gravity. However a correct model describing 4-dimensional quantum gravity has not been found yet. The aim of this project is to investigate the applications of spin networks and spin foams in the quantum theory of gravity with special attention to cosmological models. The research includes quantum gravity in terms of the Ashtekar variables. The research will involve constant cooperation with Université de la Méditerranée Centre de Physique Théorique in Marseille, France. During three stays lasting 3 months each, a student will: learn the Spin Foam Models methods at Centre de Physique Théorique in Marseille. Prof. Jerzy Lewandowski is one of the main contributors to formulation and development of Loop Quantum Gravity. Prof. Rovelli is one of the leaders of quantum gravity and pioneers in Loop Quantum Gravity.
Stays abroad: Université de la Méditerranée Centre de Physique Théorique, Institut Universitaire de France 3x3=9 months.

Foreign partner institutions:

- National Accelerator Laboratory, Stanford University, California, USA, coordinator Prof. S. J. Brodsky
- Indiana University, Bloomington, Department of Physics and NTC, coordinator Prof. A. P. Szczepaniak
- Physics Department, University of Helsinki, and the Helsinki Institute of Physics, coordinator Prof. P. Hoyer
- Ecole Polytechnique, Centre de Physique Theorique (CphT), Palaiseau Cedex, France, coordinator Prof. E. Dudas
- The Ohio State University, Department of Physics, coordinator Prof. R. J. Perry
- St. Petersburg Department of Steklov Mathematical Insitute, coordinator Prof. L.D. Faddeev
- University of California Davis, coordinator Prof. J.Gunion
- University of California Riverside, coordinator Prof. J. Wudka
- Université de la Méditerranée Centre de Physique Théorique, Institut Universitaire de France, Marseille, coordinator: Prof. C. Rovelli
- Universiteit Utrecht (the Netherlands), coordinator: Dr. M. Arzano
- University of Leipzig, coordinator: Prof. G. Rudolph