**Annex 3.**

***Form of opening (renewal) for Project /***

***Sub-project of LRIP***

 **APPROVED**

 **JINR DIRECTOR**

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**PROJECT PROPOSAL FORM**

Opening/renewal of a research project/subproject of the large research infrastructure project within the Topical plan of JINR

**1. General information on the research project of the theme/subproject of the large research infrastructure project (hereinafter LRIP subproject)**

* 1. **Theme code / LRIP** (for extended projects) - *the theme code includes the opening date, the closing date is not given, as it is determined by the completion dates of the projects in the topic.*

**1.2 Project/LRIP subproject code** (for extended projects)

**1.3 Laboratory** BLTP

**1.4 Scientific field** Theoretical physics

**1.5 Title of the project/LRIP subproject**

Quantum Field Theory and Physics beyond the Standard Model

**1.6 Project/LRIP subproject leader(s)**

Kazakov D.I., Bednyakov A.V.

**1.7 Project/LRIP subproject deputy leader(s) (scientific supervisor(s))**

**2 Scientific case and project organization**

**2.1 Annotation**

Quantum Field Theory (QFT) is a widely recognized "language" used to describe the properties of elementary particles and their interactions. It is well known that the triumph of the Standard Model (SM) of particle physics would have been impossible without comparing experimental data obtained from accelerators such as LEP (CERN), HERA (DESY), Tevatron (Fermilab), and LHC (CERN) with high-precision calculations performed using QFT methods. Many years have passed since the construction of the SM, and all these years scientists were searching for New Physics. The problem of dark matter in the universe is an obvious argument for such searches. Unfortunately, experiments have not yet provided a definitive answer as to whether there is some New Physics and what its nature is. Due to this, the problem of increasing the accuracy of theoretical predictions obtained both within the framework of the SM and beyond remains relevant. Since the complexity of calculations in QFT increases significantly with the order of perturbation theory (PT) and the number of characteristic energy scales, there is a need to develop new methods and approaches for calculation and summation of Feynman diagrams - the main elements of the standard PT series. Another important problem is related to the construction of models of New Physics and the study of possible phenomenological consequences of these models. In particular, models that not only explain existing small deviations from SM predictions in some experimental data (so-called "anomalies") but also provide indications of where else to look for manifestations of New Physics are highly appreciated. The proposed project is dedicated to solving these fundamental problems.

**2.2 Scientific case** (aim, relevance and scientific novelty, methods and approaches, techniques, expected results, risks)

The main aim of the Project is to develop the quantum field formalism of gauge and supersymmetric theories, as well as to construct and study particle physics models beyond the Standard Model.

After the discovery of the Higgs boson in 2012 at the Large Hadron Collider (LHC), precision testing of the Standard Model and searches for signals of New Physics, in the existence of which we believe due to cosmological and astrophysical data, became very important.

The precision of theoretical calculations plays a significant role in addressing these issues. The necessity to take into account radiative corrections when comparing with experiments was realized during the work of LEP, and data analysis at LHC is impossible without taking into account higher orders of perturbation theory.

Within the Project, it is planned to use existing experience and continue research on a wide range of issues related to the theoretical description of high-precision observables in the Standard Model. In particular, one of the current tasks is to explain the existing difference between the theoretical prediction and the experimental measurement of the value of the muon anomalous magnetic moment. Standard quantum field theory methods will be used in studies on this topic, as well as non-perturbative methods, such as the dispersion approach in quantum chromodynamics.

In the standard approach, the problem of calculating quantum corrections is divided into several stages, one of which involves reducing the Feynman integrals that arise in the problem to a finite set of master integrals using integration-by-parts (IBP) relations, which can be relatively easily algorithmized.

The problem of computing the master integrals is most easily solved by constructing a convenient basis, the elements of which satisfy a system of differential equations (DEs). As the order of perturbation theory and the number of independent kinematic invariants increase, the number and complexity of master integrals also increase, requiring automation and optimization of different stages of the problem. In particular, within the Project, to obtain initial DEs for master integrals using IBP, the modular arithmetic will be used for systems of linear equations with coefficients dependent on kinematic invariants, masses, and the dimensional regularization parameter ε, followed by reconstruction of rational functions of these variables. This task requires massive parallelization of calculations, using both multi-core CPUs and graphics accelerators.

Solving the obtained DE systems is a separate important task to which significant attention will be paid within the Project. The case where the solution can be expressed in terms of generalized polylogarithms has been well studied, and bases have been constructed to reduce the arising iterative integrals to its elements. At the same time, many calculations require extending the class of functions, for example, by elliptic polylogarithms. The problem of finding the minimum set of functions through which master integrals can be expressed in this case remains open. Within the Project, issues related to the completeness of the basis of elliptic polylogarithms will be studied.

In practice, the most obvious and universal way to find solutions is based on constructing and matching generalized power series. In some cases, the latter can be rewritten as generalized hypergeometric functions of one or more variables, with indices depending on the dimensional regularization parameter ε. To expand them in terms of either generalized polylogarithms or repeated integrals with algebraic kernels, a specialized Mathematica package will be developed. For numerical calculation of the resulting functions, generalized Frobenius solutions for the corresponding automatically generated systems of differential equations will be used. It is important that the proposed numerical method will be both significantly faster and more accurate than, for example, direct numerical integration using sector decomposition. The proposed calculation methods will be used to solve various problems in elementary particle physics.

In some cases related to quantum field theories with higher symmetries, there is an alternative approach to calculating loop integrals. For example, in problems of computation of anomalous dimensions (conformal spectrum) and structural constants (basic elements in the conformal bootstrap program) of theories with extended supersymmetry, such as N=4 SYM and ABJM models, spin chains with long-range interactions play a key role. Development of the methods for solving equations for these chains, including the quantum spectral curve method as one of the most promising at present, is therefore of great interest allowing to find exact solutions to the mentioned quantum field theories. Within this Project, it is planned to continue the development of new methods for solving equations for quantum spectral curves for N=4 SYM and ABJM theories. In particular, systematic solutions of these equations will be considered at large values of Lorentz spin for twist 1 and 2 operators in the weak coupling limit, systematic solutions at strong coupling and fixed spin values, as well as solutions of simplified equations for quantum spectral curves obtained by expanding the original equations at large operator twists.

In addition, the Project will study integrable quantum field theories of the "fishnet" type in various dimensions and their dual models. The spectra of several six-dimensional models, their correlation functions, and amplitudes will be studied.

Furthermore, it is planned to continue studying the properties of formally non-renormalizable theories. While these are usually interpreted as effective models requiring ultraviolet completion, the question whether it is possible to considering such theories as fundamental (e.g., gravity) and carry out self-consistent calculations in perturbation theory remains relevant. In particular, within the previously proposed approach, aspects of the subtraction procedure's scheme dependence will be investigated. Additionally, effective potentials for different interactions will be studied, and the results will be applied to cosmology for the analysis of various inflation models.

Moreover, a recently developed approach allows to obtain new exact results in theories with internal symmetries in the form of an expansion in a large charge. It has been shown that the leading and next-to-leading terms effectively sum certain contributions that arise in standard perturbation theory at all orders. Within the Project, this method will be investigated in applications to realistic gauge theories.

In addition, the Project will address the issue of alternative expansions of observables within the framework of analytic QCD, one of the founders of which was academician D.V. Shirkov. The Project plans to analyze analytical generalizations of the strong coupling constant in higher orders of perturbation theory and their application to studying sum rules and various decays.

Another important task of the Project is to provide theoretical support for modern experiments (in particular, at the Large Hadron Collider) in the search for new physics. The absence of clear signals in direct searches enhances the role of small deviations from the predictions of the Standard Model (SM), arising from virtual corrections from new particles, which in the case of transitions between flavors of the same charge (FCNC transitions) can compete with contributions from known SM particles.

There are many options for new physics discussed in the literature. Therefore, it is necessary to thoroughly and comprehensively investigate each possibility. The Project plans to pay significant attention to the phenomenology of various Beyond-the-SM models. Special attention will be paid to studying the possible properties of dark matter (DM). The analysis is expected to involve close collaboration with experimentalists.

In particular, the Project will investigate Higgs "portals" to dark matter, i.e., theoretical models in which new scalars from non-minimal extensions of the Higgs sector of the SM serve as mediators between the dark and visible sectors. Since the simplest constructions of an extended Higgs sector have already been ruled out by combined data from direct observation and collider searches for DM particles, non-minimal Higgs sectors, starting with a two-higgs-doublet model (2HDM) and its further modifications, or models with non-doublet (triplet) representations for Higgs fields containing good candidates for DM particles, need to be used. The so-called scalar (pseudoscalar) deformations of 2HDM will be studied, i.e., 2HDM+s/a models with sufficiently weak coupling between Higgs states from 2HDM and additional (pseudo)scalars. In this case, using analytical methods and computer modeling to scan a wide range of free model parameters, as is usually done in physical analysis in experiments at the LHC, theoretical estimates of the observability of effects for selected specific channels can be obtained as a starting point when selecting preferred areas of the model space based on existing constraints for 2HDM. In the future, this approach can be extended to arbitrary values of mixing parameters in the Higgs sector, using a "global fit" of data from all physically related channels, with the help of neural network methods. This is a task for the perspective of several years, with the involvement of data that will be obtained during RUN 3 LHC.

It is also planned to study the possibility of interaction between the visible and hidden sectors that can arise in modifications 2HDM+ZV' of the two-higgs-doublet model with the additional "dark" gauge group, i.e., essentially assuming the existence of a mixed Higgs-gauge portal. The Project also plans to consider models that predict processes with flavor violation in interactions between the dark and visible sectors, as occurs, in particular, in supersymmetric theories with broken R-parity or in models with an Higgs sector allowing for FCNC.

Furthermore, the Project will study simplified models that can be regarded as effective theories arising at relatively low energies from more fundamental constructions. The advantage of such models is the minimal number of additional parameters, which facilitates comparison with experiment.

To scan the parameter space required for preparing "theoretical templates" to be compared with experimental data, modeling will be carried out using a range of event generators, including Pythia8, QBH, MadGraph5\_aMC@NLO with integrated FeynRules library, and others.

Based on the results of the conducted research and the comparison of the obtained theoretical estimates with experimental data collected at the LHC, indications are expected to be obtained (in the case of fortunate circumstances - discovery) of signals of new physics, or in the absence of such indications, new unique constraints on the model parameter space for the considered scenarios of beyond Standard Model physics and the Higgs sector will be imposed.

The expected results include:

- Improved estimate of the contribution from hadronic vacuum polarization to the anomalous magnetic moment of the muon;

- Investigation of shapes of higher twist contributions in deep inelastic scattering with the resummation of large threshold logarithms;

- Calculation of two-loop diagrams that arise in non-relativistic QED using the effective mass method and investigation of the completeness of basis functions for elliptic polylogarithms;

- Development of a new specialized computer package for the epsilon expansion of generalized hypergeometric functions with one or more variables, whose indices depend on the dimensional regularization parameter, as well as for the numerical calculation of the resulting functions;

- Explicit analytical calculation of multi-point master integrals using differential equations;

- Calculation of two-loop contributions to electron-muon scattering and quarkonia production;

- Calculation of the double spectral density in the problem of sum rules for B-anti-B mixing, which is an important experimental quantity that imposes strict constraints on possible new physics;

- Calculation of three-loop massive form factors and polarization operators in QCD;

- Calculation of multi-loop amplitudes and form factors with a large number of kinematic invariants in theories with extended supersymmetry;

- Derivation of systematic solutions to quantum spectral curve equations for the case of maximally supersymmetric Yang-Mills theory in four dimensions and ABJM theory in three dimensions, both in the weak and strong coupling limits;

- Calculation of spectra, correlation functions, and amplitudes in a number of six-dimensional "fishnet" models;

- Application of the large charge expansion method to gauge theories and analysis of the resulting implications in both particle physics and condensed matter theory;

- Investigation of the scheme dependence of a previously proposed self-consistent subtraction procedure for non-renormalizable theories;

- Calculation of effective potentials for a range of theories of modified gravity and their application to analyze various inflationary models;

- Investigation of the theory and phenomenology of scalar and vector bosonic stars;

- Detailed cosmological and astrophysical analysis of the properties of primary black holes and their connection to the dark matter problem and observable supermassive black holes;

- Analysis of the prospects for experimental detection of additional Abelian gauge symmetries and an extended Higgs sector in a range of new physics models. Investigation of so-called supersymmetric extensions of the Standard Model;

- Physical analysis of LHC data aimed at detecting manifestations of the "dark sector" in events where either a Higgs boson or a Z boson is produced, accompanied by a significant fraction missing "transverse" energy (MET), presumably carried away by a messenger particle that ultimately decays into the DM particles. The expected outcome is new anomalies in the experimental data (in the fortunate event – the discovery of New Physics), or, in the absence of such signals, new unique constraints on the model parameter space for the considered scenarios of dark matter and Higgs sector;

- Development of new (using neural networks for global scanning) as well as optimization and improvement of existing software for modeling physical processes beyond the Standard Model.

**2.3 Estimated completion date**

**2024-2028**

**2.4 Participating JINR laboratories**

BLTP in collaboration with DLNP, MLIT, and VBLHEP

**2.4.1** **MICC resource requirements**

|  |  |
| --- | --- |
| **Computing resources** | **Distribution by year** |
| 1st year | 2nd year  | 3rd year | 4th year  | 5th year  |
| Data storage (TB)- EOS- Tapes |  |  |  |  |  |
| Tier 1 (CPU core hours) |  |  |  |  |  |
| Tier 2 (CPU core hours) |  |  |  |  |  |
| SC Govorun (CPU core hours)- CPU- GPU |  |  |  |  |  |
| Clouds (CPU cores) |  |  |  |  |  |

**2.5. Participating countries, scientific and educational organizations**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  **Organization** | **Country** | **City** | **Participants** | **Type** **of agreement** |
| GSTU | Belarus | Gomel | Lashkevich V.Chernichenko Y. | collaboration |
| ELTE | Hungary | Budapest | Kärkkäinen T. | collaboration |
| HU | Germany | Hamburg | Kniehl B. | collaboration |
| UR | Germany | Regensburg | Veretin O. | collaboration |
| KIT | Germany | Karlsruhe | Melnikov KPikelner A. | collaboration |
| UoC | Greece | Rethymno | Kousvos S. | collaboration |
| IMP CAS | China | Lanzhou |  Zhang P. | collaboration |
| RBI | Croatia | Zagrab | Antipin O.Panopoulos P. | collaboration |
| INFN, Pisa Uni. | Italy | Pisa | Henriksson J. | collaboration |
| IACS | India | Kolkata | Roy Sourov | collaboration |
| UPMC | France | Paris | Teber S. | collaboration |
| HIP | Finland | Helsinki | Huitu K. | collaboration |

**2.6. Key partners** *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program. An example is JINR's participation in the LHC experiments at CERN).*

**3. Manpower**

**3.1. Manpower needs in the first year of implementation**

|  |  |  |  |
| --- | --- | --- | --- |
| **№№****n/a** | **Category of personnel** | **JINR staff,** **amount of FTE** | **JINR Associated** **Personnel,****amount of FTE** |
| 1. | research scientists | 18 |  |
| 2. | engineers |  |  |
| 3. | specialists |  |  |
| 4. | office workers |  |  |
| 5. | technicians |  |  |
|  | **Total:** | **18** |  |

**3.2. Available manpower**

**3.2.1. JINR staff**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **No.** | **Category of personnel** | **Full name** | **Division** | **Position**  | **Amount** **of FTE** |
| 1. | research scientists | Bednyakov Alexander | BLTP | Head of a sector |  |
| 2 |  | Baushev Anton | BLTP | Leading researcher |  |
| 3 |  | Kotikov Anatoly | BLTP | Leading researcher |  |
| 4 |  | Vladimirov Alexey | BLTP | Senior researcher |  |
| 5 |  | Das Chitta Ranjan | BLTP | Senior researcher |  |
| 6 |  | Nesterenko Alexander | BLTP | Senior researcher |  |
| **7** |  | Onishchenko Andrei | BLTP | Senior researcher |  |
| **8** |  | Savina Maria | BLTP | Senior researcher |  |
| **9** |  | Bezuglov Maxim | BLTP | Junior researcher |  |
| **10** |  | Borlakov Arthur | BLTP | Junior researcher |  |
| **11** |  | Mukhaeva Alfiia | BLTP | Junior researcher |  |
| **12** |  | Tolkachev Denis | BLTP | Junior researcher |  |
| **13** |  | Iakhibbaev Ravil | BLTP | Junior researcher |  |
| **14** |  | Kozlov Gennady  | BLTP | Leading researcher |  |
| **15** |  | Solovtsova Olga | BLTP | Leading researcher |  |
| **16** |  | Gramotkov Nikita | BLTP | Senior laboratory assistant |  |
| **17** |  | Zemlyakov Ivan | BLTP | Senior laboratory assistant |  |
| **18** |  | Volkova Daria | BLTP | Senior laboratory assistant |  |
|  | **Total:**  | **18** |  |  |  |

**3.2.2. JINR associated personnel**

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Category of personnel**  | **Partner organization** | **Amount of FTE** |
| 1. | research scientists |  |  |
| 2. | engineers |  |  |
| 3. | specialists |  |  |
| 4. | technicians |  |  |
|  | **Total:**  |  |  |

**4. Financing**

The project will be funded through the theme "Fundamental Interactions of Fields and Particles".

**Project (****LRIP subproject) Leader** \_\_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_/

Date of submission of the project (LRIP subproject) to the Chief Scientific Secretary: \_\_\_\_\_\_\_\_\_

Date of decision of the laboratory's STC: 13.04.2023 document number: 14

Year of the project (LRIP subproject) start: 2024

**APPROVAL SHEET FOR PROJECT / LRIP SUBPROJECT**

TITLE OF THE PROJECT

Quantum Field Theory and Physics beyond the Standard Model

SHORT DESIGNATION OF THE PROJECT / SUBPROJECT OF THE LRIP

PROJECT/LRIP SUBPROJECT CODE

THEME / LRIP CODE

NAME OF THE PROJECT LEADER : Kazakov D.I., Bednyakov A.V

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
| AGREED |  |  |  |
| JINR VICE-DIRECTOR  | \_\_\_\_\_\_\_\_\_\_\_SIGNATURE | \_\_\_\_\_\_\_\_\_NAME | \_\_\_\_\_\_\_\_\_DATE |  |
| CHIEF SCIENTIFIC SECRETARY | \_\_\_\_\_\_\_\_\_\_\_SIGNATURE | \_\_\_\_\_\_\_\_\_NAME | \_\_\_\_\_\_\_\_\_DATE |  |
| CHIEF ENGINEER | \_\_\_\_\_\_\_\_\_\_\_SIGNATURE | \_\_\_\_\_\_\_\_\_NAME | \_\_\_\_\_\_\_\_\_DATE |  |
| LABORATORY DIRECTOR | \_\_\_\_\_\_\_\_\_\_\_SIGNATURE | \_\_\_\_\_\_\_\_\_NAME | \_\_\_\_\_\_\_\_\_DATE |  |
| CHIEF LABORATORY ENGINEER | \_\_\_\_\_\_\_\_\_\_\_SIGNATURE | \_\_\_\_\_\_\_\_\_NAME | \_\_\_\_\_\_\_\_\_DATE |  |
| LABORATORY SCIENTIFIC SECRETARY | \_\_\_\_\_\_\_\_\_\_\_ SIGNATURE | \_\_\_\_\_\_\_\_\_NAME | \_\_\_\_\_\_\_DATE |  |
| THEME / LRIP LEADER | \_\_\_\_\_\_\_\_\_\_\_ SIGNATURE | \_\_\_\_\_\_\_\_\_NAME | \_\_\_\_\_\_\_DATE |  |
| PROJECT / LRIP SUBPROJECT LEADER | \_\_\_\_\_\_\_\_\_\_SIGNATURE | \_\_\_\_\_\_\_\_\_NAME | \_\_\_\_\_\_\_\_\_DATE |  |
| APPROVED BY THE PAC  | \_\_\_\_\_\_\_\_\_\_\_SIGNATURE | \_\_\_\_\_\_\_\_\_NAME | \_\_\_\_\_\_\_\_\_ |