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**Annex 1.**

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

***Large Research Infrastructure Project***

**APPROVED**

**JINR Vice-Director**

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**THEME PROPOSAL FORM**

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

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

**1.1. Theme code / LRIP** (for extended themes) ***01-3-1135-2019/2023***

**1.2. Laboratory** BLTP

**1.3. Scientific field Theoretical Physics**

**1.4.** **The title of the Theme / LRIP Fundamental interactions of fields and particles**

**1.5. Theme / LRIP Leader(s) D.I. Kazakov, O.V. Teryaev**

**1.6. Theme / LRIP Deputy Leader(s)**

**2. Scientific case and theme organization**

**2.1. Annotation**

Scientific research on Fundamental interactions of fields and particles focuses on the study of current problems of the modern theory of fundamental interactions, the development of methods of quantum field theory, their application to the description of elementary particle physics within the Standard Model and beyond, theoretical support for existing and planned experiments.

All research is carried out in line with current trends in world science in cooperation with scientists from leading world centers.

Within the framework of the Standard Model, efforts will be focused on the development of multiloop computing methods and their applications to processes at the Large Hadron Collider, the development of new approaches to hadron physics, including heavy quark physics.

In physics beyond the standard model, the search for Dark matter, manifestations of supersymmetry and other possible new physical phenomena is of particular interest. Theoretical support for the search for new physics in accelerator experiments will be combined with research and analysis of astrophysical data.

Developments in neutrino physics, including the field-theoretic description of neutrino oscillations and the processes of neutrino-nucleon interactions with nuclear matter, in particular in connection with the Baikal-GVD experiment, will continue to be of constant concern.

 Special attention will be paid to the theoretical support of other key elements of the JINR experimental program. By studying QCD methods, various approaches to the description of the structure of hadrons and quark-gluon matter in the specific conditions of the NICA complex will be developed and applied. The development of the theory of quark-gluon matter includes methods of quantum field theory, statistical physics, hydrodynamics and even the theory of gravity. This forms the interdisciplinary nature of research within the theme, implemented in cooperation with other themes of BLTP, as well as VBLHEP and DLNP.

**2.2. Projects in the Theme / LRIP subprojects**

**1. Quantum field theory and physics beyond Standard Model**

**D.I. Kazakov, A.V. Bednyakov**

**2. QCD and hadron structure**

**I.V. Anikin, O.V. Teryaev, S.V. Mikhailov**

**3. Phenomenology of strong interactions and precision physics**

**M.A. Ivanov, V.I. Korobov**

**4. Theory of hadronic matter at extreme conditions**

**ЕЕ. Kolomeitsev, V.V. Braguta, S.N. Nedelko**

**5. Theory of electroweak interactions and neutrino physics**

**A.B. Arbuzov, V.A. Naumov**

**2.3. Scientific case** (no more than 20 pages)

(aim, relevance and scientific novelty, methods and approaches, techniques, expected results, risks).

The main aim of the theme is to develop the quantum field theories of Standard Model, to solve the problems in their various applications as well as to construct and study particle physics models beyond the Standard Model.

The relevance and scientific novelty is provided by the established role of Standard Model as fundamental theory of particle physics and importance of its new development and extensions.

The used methods and approaches combine the development of modern perturbative analytical methods with their modifications and use non-perturbative and numerical ones, with special emphasis on lattice simulations.

The techniques and expected results in various directions of investigations may be described as follows.

The Standard Model (SM) of particle physics, formulated about 50 years ago, forms the basis of our understanding of fundamental interactions. The SM as a quantum field theory describes how the basic constituents of matter (quarks and leptons) interact at the microscopic level through weak, strong and electromagnetic forces. Although all data from ground-based laboratory experiments are consistent with the SM predictions, perhaps, apart from some exceptions that will be commented on later, there is some indirect evidence obtained from cosmological observations that the model is not complete: this model cannot explain the baryon asymmetry of the Universe, dark matter and dark energy. All these phenomena could naturally find their explanation in the field of elementary particle physics or, in a more general sense, in QFT. There are also internal problems of the SM itself, such as the problem of the mass hierarchy, the absence of a path to quantum gravity. In addition, nonvanishing neutrino masses cannot be explained in terms of the classical version of the SM, which contains only left-handed neutrinos and only renormalizable interactions. To solve these problems, a large number of new theories beyond the Standard Model (BSM) have been created. These include supersymmetric models, models with composite Higgs sectors, and/or composite quarks and leptons. These models have new particles and interactions, typically at energies above the Fermi scale. They were created to explain some facts that cannot be explained in the SM, such as the quantization of electric charge, the hierarchical structure of generations of quarks and leptons, the possible unification of interactions, etc. Unfortunately, many predictions of such models either do not agree with the data , or are not verifiable using existing or planned experimental devices.

After the discovery of the Higgs boson in 2012 at the Large Hadron Collider (LHC), precision tests 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 procession 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.

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.

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 consider 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 obtaining new exact answers 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, and this method will be investigated in applications to realistic gauge theories.

Another important field of perturbative calculations is the precision spectroscopy of light atoms and molecules being one of the rapidly developing areas of modern physics. Modern methods of sympathetic cooling of atoms, molecules, and ions in traps, methods of quantum logic and quantum information create unique possibilities for high precision measurements of their spectra (with a relative precision of 10–11–10–12). From a theoretical point of view, the most suitable platform for such accurate calculations of spectra is nonrelativistic quantum electrodynamics (NRQED), since the nonrelativistic Schrödinger equation already determines the dynamics of light atoms and molecules with good precision. At the same time, the methods of quantum field theory implemented in NRQED make it possible to construct a rigorous perturbation theory for calculating higher-order corrections in terms of the parameters *v/c~Zα*, *β=m/M*, where *v* is the velocity of electrons (muons) in atoms, *m/M* is the ratio masses of light particles to heavy ones in the molecular system. At the moment, the most accurate calculations of physical transitions have been obtained by our group at BLTP together with the scientists from the Castler-Brossel laboratory, ENS-Sorbonne Université (Paris). Thus, for molecular hydrogen ions H2+ and HD+, the values of vibrational transitions, which are measured in the experiment, have reached a relative accuracy of 7.5×10−12. Compared with recent experiments in Düsseldorf and Amsterdam, these calculations have become one of the most accurate tests of quantum electrodynamics.

It is planned to further develop the methods of NRQED as well as the possibility of using a combined approach, when part of the contributions to the energy of a bound system is considered within the framework of QED, a total sum over all terms in powers of *α* or Z*α*. It is planned to include new terms in the general NRQED scheme, which will allow taking into account the contributions of light-by-light scattering, nontrivial centipede diagrams for one- and two-loop self-energy diagrams, and many others necessary to calculate corrections of the order of m*α*7 and higher.

An important point is the inclusion in the developed model of the phenomenological contributions associated with the effects of the finite size of the nucleus (nucleons, mesons), the polarizability of complex particles. From a technical point of view, an important point is the development of precision methods for calculating a non-relativistic problem as a zero approximation. It is planned to further study various options for choosing and generating test functions, testing their effectiveness when applied to the nonrelativistic Schrödinger equation for bound states and to the Dirac equation of a bound electron in an external field.

Another important task 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. We plan 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, we 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. 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.

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 obtained.

Because of the tremendous progress in observational and experimental capabilities, astronomical data today provide new insights into the physics of elementary particles. Thus, observations of the gravitational-wave signal by the LIGO-Virgo-KAGRA collaboration allowed not only to detect binary black holes and to detect gravitational waves, but also to limit the graviton mass (in recent years, theories of massive gravity have been proposed, which have no ghosts).We intend to find out how new astronomical and experimental data (in particular, data expected from the JWST space telescope launch) can be used to obtain new constraints on the properties of elementary particles (for example, on the graviton mass), as well as to study the distribution of dark matter in the Universe on a qualitatively new level. Another task will be to obtain correlations for the size of shadows for models of galactic centers other than Kerr black holes.

Another issue deeply related to DM and beyond Standard Model physics is neutrino physics.

To analyze the results of current (NOνA, T2K) and future (DUNE, Hyper-Kamiokande, etc.) accelerator experiments, precise knowledge of neutrino scattering cross sections on nuclei at intermediate energies (~0.5–20 GeV) is required. As part of the work on the further development of the superscaling model with effective nucleon mass (SuSAM\*), which has successfully proven itself in describing the quasielastic scattering of electrons on nuclei, we plan to adjust the model parameters (effective nucleon masses and Fermi momenta in nuclei, scaling function parameters) using all available modern data on quasielastic electron-nucleus scattering. The next stage will be to study the possibility of applying the refined model to predict the nucleon momentum distributions in nuclei, as well as to check in detail the predictive ability of the SuSAM\* model to describe quasielastic neutrino scattering on nuclei. Our plans include the further development of resonance single-pion (1π) production models – essential ingredients of all modern Monte-Carlo neutrino generators. This includes a generalization of the Rein and Kabirnezhad (RK) formalism, based on the SU(6) relativistic quark model by Feynman, Kislinger, and Ravndal and accounting for final-state pion dynamics, as well as tuning the RK model parameters using existing data on 1π neutrinoproduction on hydrogen and deuterium targets. The model takes into account the mass and polarization of the final-state leptons and includes all families of baryon and nucleon resonances with masses below 2 GeV, as well as the non-resonance background interfering with the main contribution. The results will be implemented in the neutrino generator GENIE and used to predict event rates in the DUNE near detectors under construction.  
  
Accurate phenomenological models of the nucleon electromagnetic form factors are necessary for calculating cross sections of quasielastic interactions of leptons with nucleons and nuclei, a crucial component of planning and processing the results of any neutrino experiment. We plan to re-tune the parameters of the most popular models based on a global statistical analysis of current data on differential electron scattering cross sections on hydrogen and deuterium, avoiding the form factor extraction stage and thus its attendant uncertainties . The improved form factor models will be implemented in the neutrino generator GENIE.  
With the development of the instrumental base of high-energy neutrino astrophysics and neutrino tomography (underground and deep underwater/underice neutrino telescopes, working and designed radio, acoustic and orbital fluorescence detectors) it becomes necessary to develop effective methods for calculating neutrino propagation through matter which take into account the combined effect of elastic forward scattering (refraction) and inelastic reactions on flavor neutrino oscillations (including transitions to hypothetical sterile states). During the planned period will be studied methodologically important special case – the transport through the Sun of neutrinos generated by galactic cosmic rays in the solar atmosphere.  
  
The hypothesis explaining the hierarchy of masses of light leptons and the characteristic scale of the electroweak interaction, based on the assumption of the existence of the superheavy Majorana neutrino (Fukugita, Yanagita), allows to explain the observed baryon asymmetry of the Universe due to the non-conservation of the total lepton number and subsequent electroweak processes at lowering the temperature of the primary cosmological plasma. It is of interest to study the possible connection between the magnitude and sign of the CP invariance violation in the decays of the superheavy neutrinos and the CP violation phase in the mixing matrix of light neutrinos. The study of the contribution of ultra-high energy neutrinos arising in a multidimensional modification of gravity, and a comparison of theoretical expectations with observations on the Cherenkov neutrino telescopes Baikal GVD and IceCube will establish a possible mechanism for the generation of ultra-high energy cosmic rays.  
  
The theory of strong interactions, quantum chromodynamics (QCD), is one of the most interesting and complex theories in modern theoretical physics. The complexity of QCD is related to the strong interaction between elementary excitations (quarks and gluons) at low energies, which leads to a significant change in the properties of these excitations. For this reason, QCD belongs to the class of strongly correlated systems that cannot be studied analytically based on the first principles.

The well established method is the QCD factorization separating the perturbative subprocess and non-perturbative parton distributions describing the hadron structure.

For many years, theoretical and experimental studies of the nucleon structure have been restricted to a

one-dimensional picture along a light-cone direction. Within this one dimensional picture, quark and gluon contents of the nucleus are described by the parton distribution functions (PDFs) which depends on the longitiduinal momentum of the parton inside the hadron.

The last decade have witnessed a tremendous effort to go beyond this one dimensional description of the nucleon. Recent improvements in experimental facilities, such as increased electron beam luminosities and polarization degrees, detector resolution and coverage, and advanced theoretical computation frameworks, such as calculating radiative and power corrections to complementary sets of observables, provide a break through to investigate the multi-dimensional partonic content of the nucleon which is also referred to as hadron tomography.

In this respect, the multi-dimensional parton distribution functions such as transverse-momentum-dependent distribution functions (TMDs) or generalized parton distribution functions (GPDs) have been the key subjects of both experimental and theoretical studies.

With the advent of new generation colliders such as Electron Ion Collider (EIC) in the USA, Large Hadron electron Collider (LHeC) at CERN, the theoretical improvements of these distribution functions are mandatory for a precise comparison with the data. Motivated from this need, we will develop a comprehensive theoretical framework to study the multi-dimensional partonic content of the hadrons by combining various approaches starting from the first principles of QCD.

It is also planned to apply the method of parton distributions (developed in QCD) to describe electrodynamic corrections to processes studied in current and future high energy physics experiments.

Also noteworthy is the huge success of the chiral perturbation theory ChPT (chiral perturbation theory), the oldest effective SM field theory, which has been widely used to obtain precision results for the dynamics of low-energy mesons. It is expected that this search for increasingly higher accuracy, both in theory and experimentally, will continue in the hope of finding deviations from the SM, as indicated by a number of available experimental data.

One of the key characteristics of SM is lepton flavor universatility (LFU ). However, hints of deviations from LFU have been found in a number of heavy meson decays. The emerging experimental possibility of studying the properties of B mesons provided excellent conditions for studying the effects of new physics (NP) both at the theoretical and experimental levels. The BABAR collaboration reported for the first time a discrepancy between the measurements of semileptonic B decays and the SM predictions for the ratios of the partial widths of the decay of a B meson into D mesons and a tauonic pair to the same decay, but with a muon pair in the final state. The Heavy Flavor Averaging Group (HFLAV) recently released the most recent global averages for 2022, analyzed using information from the collaboration between Belle, LHCb and BABAR, showing deviations in the 2-3σ levels. All of these measurements are indicative of a violation of LFU and are usually regarded as anomalies in *b*-*c* decays.

The NP contributions to the *b → c τ ν* transition imply that NP contributions to the *bb̄ → τ τ* transition are unavoidable given the assumption that neutrinos are exclusively left handed. Therefore, the ratio of lepton decays of bottomonium Υ(*bb*) into a tauonic pair to the corresponding decay into a muon (electron) pair can be used to test LFU.

An important aspect of the study of charmed physics is the study of D-meson decays with an open charm. If the decays of such mesons with spin zero are well studied both in theoretical approaches and in experiment (impressive results were obtained by the BES III collaboration), then the decays of vector D\* mesons with spin 1 are very difficult to study experimentally. Since the B\*→Bπ decay is kinematically forbidden, it is impossible to directly measure the interaction constant g(B\*Bπ). However, the D and B systems can be coupled via the universal heavy meson-pion interaction constant, which makes it possible to calculate g(B\*Bπ) , which is necessary for the model-independent extraction of the matrix element of the Cabibbo-Kabayashi-Maskawa matrix |*Vub*|.

The concept of multiquark states consisting of more than three quarks, put forward several decades ago, was first confirmed in 2003 when candidates for multiquark states were measured in the BES, BaBar and Belle experiments. The observed state in the invariant mass spectrum, *π*+ *π*−*J/ψ*, was the first observation of a charmonium-like state X(3872) that did not meet the expectations of existing quark models for any ordinary hadronic particle. The reason was its measured mass of 3872 MeV, which does not fit into the available predictions of spectroscopy models, as well as the difficulty of interpreting it as an excited charmonium *ψ*′: its possible decay into *ρJ/ψ* is strongly suppressed due to isospin violation. In subsequent years, other heavy quarkonia-like states X, Y, Z were discovered, where Y usually denotes an electrically neutral exotic (i.e., non-*c* ̄*c*) charmonium having quantum numbers *JPC* = 1− −, Z is used for charged states, and X denotes any cases other than Y and Z.

In this connection, we plan to Investigate the possibility of violation of lepton universality in lepton decays of charmonium and bottomonium and their radial excitations, obtain bounds on the values of the Wilson coefficients of the Standard Model Effective Theory (SMEFT) operators responsible for breaking the lepton universatility in the tauon sector,

calculate partial widths of strong and electromagnetic decays of vector D-mesons with an open charm, perform analysis of strong decays of the charmonium-like state Y(4230) in order to study the nature of its structure.

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One of the most perspective approach to the theory of strong interactions, is the method of lattice simulation of QCD, which is well recognized in quantum field theory and, without a doubt, the most successful in studying the properties of QCD. The uncertainties of the method well studied, controlled and subject to systematic improvement. Due to the development of computer technology and algorithms, it is possible to study QCD with properties as close as possible to to reality (with dynamical quarks, physical masses of pi-mesons, large physical volumes and small lattice steps).

Thanks to the development of lattice simulation of QCD at zero and nonzero temperature has been well studied.

Another area of ​​the phase diagram that is important to study is QCD with nonzero baryon density. The study of this area is important for understanding of various astrophysical phenomena, as well as descriptions results of the planned NICA and FAIR experiments

It is planned to study the properties of QCD at non-zero baryon density, non-zero temperature and non-zero magnetic field using lattice simulation with an imaginary chemical potential, dynamic u-, d-, and s--quarks and the physical mass of the pi-meson. To conduct such a study, a program written by our group that implements advanced supercomputer technologies and algorithms will be used.

It is expected that quark-gluon matter, which is produced in the process of collision of heavy ions, is not only highly heated, is affected by a strong magnetic field, but and has a non-zero angular velocity of rotation. Therefore, to interpret the results heavy ion collision experiments an important theoretical problem is the study of the properties of rotating quark-gluon matter. In the presented project, we are planning for the first time to study the properties of rotating quark-gluon matter in the framework of lattice simulation.

It is planned to study various issues related to the influence of rotation on the properties of gluodynamics and QCD. In particular, it is planned to study the equation of state of a rotating QCD, the effect of rotation on the confinement/deconfinement phase transitions and the breaking/restoration of chiral symmetry, the effect of rotation on the interaction potential of static quarks, inhomogeneous phases of rotating quark matter. It is also planned to study the simultaneous influence of the magnetic field and the baryon density on the QCD equation of state. In this case, lattice calculations will be carried out with the physical masses of dynamic u-, d-, s-quarks.

The planned studies are important for understanding the results of the NICA experiment, and many of the planned results will be obtained for the first time.

**2.4. Participating JINR laboratories**

**BLTP in collaboration with VBLHEP, DLNP, LIT**

**2.5. Participating countries, scientific and educational organisations:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Organization** | **Country** | **City** | **Participants** | **Type**  **of agreement** |
| Institute for Nuclear Research and Nuclear Energy BAN | Bulgaria | Sofia | D. Bakalov |  |
| Institute of Nuclear Physics | Kazakhstan | Almaty | A.K. Bekbaev |  |
| ENS-Sorbonne Université | France | Paris | Jean-Philippe Karr |  |
| Düsseldorf University | Germany | Düsseldorf | Stephan Schiller |  |
| Hainan University | China | Hainan | Zhen-Xiang Zhong |  |
| Imperial College | United Kingdom | London | Masaki Hori |  |
| Institute of Physics SAS | Slovak Republic | Bratislava | S. Dubnička  A. Liptaj |  |
| Comenius University | Slovak Republic | Bratislava | A. Z. Dubničková |  |
| Universitat Tübingen | Germany | Tübingen | V.E. Lyubovitskij |  |
| Napoli University | Italy | Napoli | P. Santorelli |  |
| University of  Technology | Vietnam | Ho Chi Minh | C.T. Tran |  |
| Novosibirsk State University | Russia | Novosibirsk | A.E. Bondar, A.D. Dolgov, A.S. Rudenko, E.A. Kravchenko, L.A. Panasenko, N.A.Pozdnyakov, 4 students | Joint works |
| University Dubna | Russia | Dubna | E.V. Arbuzova | Joint works |
| Irkutsk State University | Russia | Irkutsk | Collaboration “Taiga” (supervisor N.M. Budnev) | Joint works |
| Belgrade Astronomical Observatory | Serbia | Belgrade | P. Jovanović | Joint works |
| Institute of Nuclear Sciences “Vinča” | Serbia | Belgrade | D. Borka, V. Borka Jovanović | Joint works |
| University of Liverpool | GB | Liverpool | Collaboration “GENIE” (supervisor K. Andreopulos) | Joint works |
| Granada University | Spain | Granada | J.E. Amaro, I.R. Simo | Joint works |
| IHEP | Russia | Protvino | Bornyakov V.G., Rogalev R.N., Kudrov I.E. | Joint works |
| DVFU | Russia | Vladivostok | Molochkov A.V., Goj V.A., Girasimenyuk N.V. | Joint works |

**2.6. Key partners** *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program on the theme. Example – JINR participation in the LHC experiments at CERN).*

**3. Manpower**

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

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Personnel category** | **JINR staff,**  **FTE amount** | **JINR associated personnel,**  **FTE amount** |
| 1. | research scientists | 84 |  |
| 2. | engineers |  |  |
| 3. | specialists |  |  |
|  | **Total:** | **84** |  |

**3.2. Available manpower**

**3.2.1. JINR staff** (total number of participants)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **No.** | **Personnel category** | **Division** | **Position** | **Amount**  **FTE** |
| 1. | research scientists | SDTFI | 84 |  |
| 2. | engineers |  |  |  |
| 3. | specialists |  |  |  |
|  | **Total:** |  | **78** |  |

**3.2.2. JINR associated personnel**

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Personnel category** | **Partner organization** | **Amount of FTE** |
| 1. | research scientists |  |  |
| 2. | engineers |  |  |
|  | **Total:** |  |  |

**4. Financing**

**4.1. Total estimated cost of the theme / LRIP**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **No.** | **Items of expenditure** | **Cost** | **Expenditure per year**  **(thousands of the US dollars)** | | | | | | |
| 1st  year | 2nd  year | 3rd  year | 4th  year | 5th  year | 6tht  year | 7th  year |
| 1. | International cooperation | 1083,7 | 131,6 | 141,4 | 149,7 | 155,9 | 161,9 | 168,3 | 174,9 |
| 2. | Materials |  |  |  |  |  |  |  |  |
| 3. | Equipment, Third-party company services |  |  |  |  |  |  |  |  |
| 4. | Commissioning |  |  |  |  |  |  |  |  |
| 5. | R&D contracts with other research organizations |  |  |  |  |  |  |  |  |
| 6. | Software purchasing |  |  |  |  |  |  |  |  |
| 7. | Design/construction |  |  |  |  |  |  |  |  |
| 8. | Service costs (*planned in case of direct affiliation)* |  |  |  |  |  |  |  |  |
| **TOTAL:** | | **1083,7** |  |  |  |  |  |  |  |

**4.2. Extra funding sources**

Expected extra funding from partners/customers (total for all projects).

**AGREED:**

**Chief Scientific Secretary Laboratory Director**

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**Head of BEPD Scientific Secretary of the Laboratory**

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**" " 202\_г. " " 202\_г.**

**Head of DSOA Laboratory Economist**

**/\_\_\_\_\_\_\_ / /\_\_\_\_ /**

**" " 202\_ г. " " 202\_г.**

**Head of HRRMD Theme leader**

**/\_\_\_\_\_\_\_ / /\_\_\_\_ /**

**" " 202\_г. " " 202\_г.**

**Project leader (project code) /**

**(LRIP subproject code)**

**/ /**

**“ “ 202\_г.**

**Project leader (project code) /**

**(LRIP subproject code)**

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***Annex 2.***

***Theme / Large Research Infrastructure Project Form***

**APPROVED**

**Director of Laboratory**

**/ /**

**" " 202 г.**

**REPORT ON THEME / LARGE RESEARCH INFRASTRUCTURE PROJECT**

**1. General information on the Theme / LRIP**

**1.1. Theme / LRIP code**

**1.2. Laboratory**

**1.3. Scientific field**

**1.4. Title of the Theme / LRIP**

**1.5. Theme / LRIP Leader**

**1.6. Projects in the Theme / LRIP subprojects**

**2. Scientific report on the Theme / LRIP**

**2.1. Annotation**

During the work on the project, both the fundamental problems of quantum field theory and the applications of the latter to modern problems of particle physics were considered and studied. In particular, an original approach for summation of the contributions of the higher orders of perturbation theory in formally non-renormalizable theories has been developed, a number of non-trivial perturbative calculations have been performed and analyses of modern New Physics models have been carried out.

**2.2. A detailed scientific report**

2.2.1. A description of the work carried out and the results obtained for all projects and activities of the theme.

It was demonstrated how the usual Bogolyubov R-operation can be applied to non-renormalizable theories. The key point of the approach is to replace the multiplicative renormalization used in renormalized theories with an operation in which the renormalization constant depends on the momenta that have to be integrated inside the subgraph. The approach allows to derive generalized renormalization group equations for the amplitude, which have an integro-differential form and re-sum leading asymptotics, as in renormalized theories.

Generalized renormalization group equations describing the leading divergences for any effective potential with for general interactions of scalar fields, including non-renormalizable ones, were constructed. Several important cases were considered for which solutions were obtained. The numerical analysis of the latter was performed.

A complete set of six equations expressing three types of weight functions required for calculating the contributions of the hadronic vacuum polarization function to the anomalous magnetic moment of the muon in terms of each other has been obtained. The results can be used in calculations of the contributions of the hadronic vacuum polarization function to the anomalous magnetic moment of the muon within spacelike methods, particularly lattice calculations.

The higher-order contributions to the anomalous magnetic moments of leptons from vacuum polarization diagrams with lepton loops have been analyzed when the ratio of the lepton mass in the loop to the mass of the external lepton is less than unity. The dependence of the expansion coefficients on the lepton mass ratio has been found and compared with previously known analytical expressions: for real values of lepton masses, the new analytical expressions turn out to be more accurate. Estimates of the order of expansion n\*, from which a particular accuracy is guaranteed for the coefficients have been given.

An approach based on solving differential equations for master integrals in the form of generalized power series has been developed. It was found that for polylogarithmic and some interesting non-polylogarithmic master integrals, first-order nonhomogeneous recurrence relations can be found for the series coefficients. This fact allowed these relations to be solved treating the regularization parameter in perturbation theory or keeping the dependence on it exact. Thus, exact expressions for the master integrals were obtained. The proposed approach was applied to calculate massive non-planar vertices and series of two-loop massive 3- and 4-point diagrams. Exact generalized sum solutions for these integrals can be rewritten in turn through generalized hypergeometric functions and generalized Kampé de Fériet functions.

Based on calculations of propagator-type master integrals in the low-energy effective theory of heavy quarks (HQET), an analytical four-loop expression for the so-called cusp anomalous dimension in QCD was obtained for the first time. The expression is presented in the form of an expansion in a small angle. In addition, it is shown that using the principle of maximum transcendentality, an expression for the four-loop Bremsstrahlung function in N = 4 Super Yang-Mills theory can be obtained, which coincides with the known all-loop result.

The most general expressions for four- and three-loop renormalization group functions of gauge and Yukawa couplings, respectively, were found in an arbitrary renormalizable quantum field theory in four dimensions. In the case of scalar theories without gauge and Yukawa interactions, a similar result was obtained in the six-loop approximation. These expressions were used for calculations in specific models, both in particle physics and condensed matter theory.

Six-loop anomalous dimensions of operators ϕQ with arbitrary fixed charge Q were calculated in the scalar O(N) model. The calculation was based on a combination of known non-perturbative results obtained by expanding at large Q and explicit perturbative calculations of diagrams for operators with Q=1,...,5. At the fixed point, resummed critical dimensions in three-dimensional space were compared with Monte Carlo simulations and expansions at large N.

An analysis of possible deviations from Standard Model predictions in the observables related to B → Kvv and B → K\*vv processes was conducted within the framework of the weak effective theory, in which vector operators with light left- and right-handed neutrinos were added. The latter can arise in a number of SM extensions, including the supersymmetric extension with an additional Z' boson.

The problem of vacuum stability at the two-loop level was investigated within the SMASH (Standard Model - Axion - Seesaw - Higgs portal inflation) model. Special attention was paid to corrections to the trilinear higgs self-coupling and the problem of generating lepton and baryon asymmetry.

It was shown that the gravitational field of our galaxy and other nearby cosmic objects changes the flavor composition of the relic neutrino background near the Solar System, resulting in an enrichment of tauonic and especially muonic relic neutrinos, while electron relic neutrinos are the rarest for terrestrial observers.

2.2.2. Key publications (list of bibliographic references).

2.2.3. A complete list of publications on the theme (electronic annex).

2.2.4. List of talks presented at international conferences and meetings (electronic annex).

2.2.5. Patent activity (if any).

**2.3 Results of related activities**

2.3.1. Scientific and educational activities. List of theses defended.

2.3.2. JINR grants (scholarships) received.

2.3.3. Awards and prizes.

2.3.4. Other results (expert investigations, organizational, outreach activities).

**3. International scientific and technical cooperation**

The countries, institutions and organizations actually involved.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Organization** | **Country** | **City** | **Participants** | **Type**  **of agreement** |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |

**4. Analysis of planed vs actually used resources: manpower (including associated personnel), financial, IT, infrastructure**

**4** **.1. Manpower (actual at the time of reporting)**

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Personnel category** | **JINR staff,**  **FTE amount** | **JINR associated personnel,**  **FTE amount** |
| 1. | research scientists |  |  |
| 2. | engineers |  |  |
| 3. | specialists |  |  |
|  | **Total:** |  |  |

**4.2. Actual cost of the Theme / LRIP**

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Items of expenditure** | **Full cost**  **(thousands of US** **dollars)** | **Expenditure for the last year,**  **(thousands of US dollars)** |
| 1. | International cooperation |  |  |
| 2. | Materials |  |  |
| 3. | Equipment, Third-party company services |  |  |
| 4. | Commissioning |  |  |
| 5. | R&D contracts with other research organizations |  |  |
| 6. | Software purchasing |  |  |
| 7. | Design/construction |  |  |
| 8. | Service costs (*planned in case of direct project affiliation)* |  |  |
| **TOTAL:** | |  |  |

**4.3. Other resources**

**5. Conclusion**

**6. Proposed reviewers**

**Theme leader**

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**" " 202\_г.**

**Project /LRIP subproject leader (project code)**

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**Project / LRIP subproject leader (project code)**

(in case of several projects)

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**" " 202\_г.**

**Laboratory Economist**

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**" " 202\_ г.**