Annex 3.

Form of opening (renewal) for Project / Sub-project of LRIP

APPROVED

JINR DIRECTOR

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SCIENTIFIC AND TECHNICAL REASONING FOR THE OPENING / RENEWAL OF PROJECT/SUB-PROJECT OF LARGE RESEARCH INFRASTRUCTURE PROJECT IN RESEARCH AREA WITHIN THE TOPICAL PLAN FOR JINR RESEARCH

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

1.1 Theme code / LRIP (for renewable themes) - *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.*

02-0-1085-2009

1.2 Project/sub-project of a MIP code (for renewed themes)

0

1.3 Laboratory
DLNP

1.4 Scientific field
Elementary Particle Physics and Relativistic Nuclear Physics

1.5 The name of the Project/subproject of the LRIP

BESIII

1.6 Project/ sub-project of the LRIP Leader(s)
Igor Denisenko

1.7 Project/sub-project of the LRIP Deputy Leader(s) (scientific supervisor of the project/sub-project of the LRIP)
Alexey Zhemchugov

2 Scientific rationale and organizational structure

2.1 Annotation

The BESIII experiment at the electron-positron collider BEPCII is running at the Institute of High Energy Physics (Beijing, China) since 2008. The experiment is aimed at studies of hadron and charmonium spectroscopy, tests of various aspects of QCD, charmed hadron decays, and precision test of the Standard Model, as well as the probes of new physics beyond the Standard Model. Nowadays, the BESIII experiment is playing the leading role in the world in the τ-charm domain and is one of the leading experiments in the research of exotic XYZ states discovered during the last two decades.

The JINR group has been participating in the BESIII experiment since 2005. This project is aimed at a continuation of BESIII data analysis by the JINR group, focused on the light hadron spectroscopy and search for glueball states, the physics of charmonium production and decays and the search and study of exotic charmonia and charmonium-like structures and probing of the c-quark fragmentation functions in the low-energy region. Specifically, the project goals include the analysis of the selected channels of radiative J/ψ and ψ(2S) decays to confirm previously published evidence for the scalar glueball production; publication of the performed measurement of the inclusive prompt production of charmonia at the collision energy above 4 GeV and further studies of charmonia production; the study of the J/ψ decay structure by determination of the phase between amplitudes of strong and electromagnetic interactions in the number of exclusive processes.

Currently, the JINR group is one of the leading software developers in the BESIII collaboration. In the scope of the project, the maintenance of software packages developed earlier by the group will be continued. The research and development of machine learning algorithms for the event reconstruction, is planned with the prospect to apply these algorithms in BESIII and other experiments.

The requested project budget is 175 kUSD for 2024-2028.

2.2 Scientific justification (purpose, relevance and scientific novelty, methods and approaches, methodologies, expected results, risks)

Purpose and objectives of the project

The purpose of the project is to explore hadron spectra in QCD and search for exotic exotic states, study the charmonium production and decays, to search for and study the exotic charmonia and charmonium-like structures, and to determination of c-quark fragmentation functions using the BESIII data. To achieve this purpose, the data analysis of the BESIII experiment must be continued with the following objectives.

Light hadron spectroscopy and search for scalar and tensor glueballs

Existence of quark-less particles, glueballs, was suggested nearly 50 years ago and at present they are predicted in a number of non-perturbative approaches to QCD, including lattice QCD and dual (AdS/QCD) models (see PLB 816,136227 (2021) for a mini-review and references). At the same time, such states have never been reliably identified experimentally. The question of their existence is fundamental for understanding QCD in the strong coupling regime. The radiative J/ψ decays provide an ideal gluon-rich environment for formation of glueballs.

According to the recent unquenched lattice QCD results, the lightest glueball state has quantum numbers of scalar mesons and a mass about 1.8 GeV. Its identification is complicated due to possible mixing with conventional mesons. Thus, it requires detailed information on the production and decay properties of scalar mesons. The most appropriate approach for that is a combined analysis of radiative J/ψ decays in the framework of K-matrix or N/D approach. Such analysis has been performed with the leading participation of JINR BESIII group [PLB 816,136227 (2021)], evidence of scalar glueball production has been reported. The analysis lacked data on multimeson (four meson and more) radiative J/ψ decays and used rough BESII data on $J/\psi \to \gamma 4\pi$. The partial-wave analysis of such decays, especially $J/\psi \to \gamma 4\pi^0$, would be crucial to confirm the reported observations.

Another puzzle is related to the tensor glueball (JPC=2++), which is also unambiguously predicted in lattice calculations with the mass about 2.2 – 2.6 GeV. The mentioned evidence for scalar glueball production are consistent with lattice calculations for the partial width of the $J/\psi \to \gamma G$ decay. At the same time, the sum of partial widths of J/ψ decays to tensor mesons in the mass range between 2.2 and 2.6 GeV is approximately 3-4 times smaller than predicted by lattice QCD for the tensor glueball. This discrepancy motivates studies of final states in radiative J/ψ decays not analyzed before, as well as investigation of higher masses in radiative $\psi(2S)$ decays to $\pi^0\pi^0$, K_SK_S, $\eta\eta$, 4π, and other final states. The latter should be possible with the new $\psi(2S)$ data recently collected by the BESIII Collaboration.

Study of inclusive charmonia production

Charmonia production is one of the main probes of hadron gluon structure to be used in the SPD experiment (arXiv:1904.04779 – SPD CDR), the suggested fixed target program at LHC [Phys.Rept.911,1(2021)], and the EIC project (arXiv:1212.1701 – EIC White Book). The relevant process is gluon fusion to the cc pair and its non-perturbative hadronization to charmonia states. Experimentally, the $J/\psi \to \mu^+\mu^-$ decay provides a clean and distinct signal, which can be also used for reconstruction of heavier charmonia states. The main disadvantage of this approach is lack of understanding of the cc pair hadronization process. There are other issues related to usage of the proper QCD factorization, which is especially important for the energy range of the SPD experiment [PPNP119,103858(2021)].

The e^+e^- collisions provide a clean environment to study charmonia production mechanisms, which is not affected by uncertainties caused by initial hadron states. Such data on inclusive J/ψ from B-factories are used in the global fits [PoS ICHEP2012,278 (2013)]. It is shown that there is a significant tension to describe the data from B-factories, photoproduction data, differential cross sections and polarization data from collider experiments within the most rigorous now nonrelativistic QCD approach to charmonia production [PRD 51, 1125 (1995)]. The BESIII experiment has collected unique large data sets with the collision energy up to 4.95 GeV (about 5 fb^{-1} above 4.6 GeV). New measurements of inclusive charmonia state production cross section, their relative strength, and, most importantly, the charmonia polarization away from resonance peaks at these energies will provide an important input for development of theoretical models and approaches, as well as testing their universality. Apart from observables for J/ψ and $\psi(2S)$, the BESIII potential measurements with χ_c and especially η_c are of extreme importance, as for now only scarce information on production properties of these particles is available.

At the same time, the behavior of the inclusive production cross section for J/ψ and $\psi(2S)$ and polarization of the produced charmonia wide energy range (above 3.8 GeV) as a function of the collision energy could be sensitive to production and decay of known and unknown exotic charmonium-like states. The direct comparison of the measured cross-section of the inclusive prompt J/ψ and $\psi(2S)$ production with the sum of known cross-sections for exclusive channels could put an upper limit for possible hidden channels of e^+e^- annihilation.

The publication draft of inclusive direct J/ψ production in the collision energy range 3.81 – 4.95 GeV performed with the JINR BESIII group undergoes internal referring. The suggested studies can be based on the obtained experience.

Study of c-quark fragmentation function

The fragmentation function $D^h_q(z)$ describes the probability of a hadron h to be found among the fragmentation products of a quark q carrying the fraction z of the quark energy. Due to its non-perturbative nature, the fragmentation function can not be deduced from the first principles, but can be extracted from experimental data (see for example Rev.Mod.Phys.82,2489(2010)).

While the fragmentation functions of the light quarks have been measured with a reasonable precision, the information on the c-quark fragmentation function (CFF) is scarce. There is virtually no experimental data on CFF below the energy of the B-factories. Such information is vital for the charm program of the SPD experiment at the NICA collider. The Pythia8 simulation shows that essentially all events are expected to be produced in the region where the fragmentation function is not known.

In this Project we propose to perform a first measurement of the inclusive D-meson production in e^+e^- collisions in the energy domain between charmonium and bottomonium. So far, the BESIII experiment has collected a unique data sample of about 5 fb^{-1} integrated luminosity at energies from 4.60 to 4.95 GeV. At the first stage, an inclusive cross-section of D-meson pair production will be measured using these data samples. To provide the information on the unpolarized c-quark fragmentation function, momentum spectra of D-mesons will be measured. Information on the fragmentation of the transversely polarized c-quark can be extracted from the Collins asymmetry. The latter is measured from the distribution of the azimuthal angle φ_0 between the two planes: the first one containing momenta of both D-mesons and the second one containing a momentum of one of the D-mesons and the beam axis.

The event selection will be based on exclusive reconstruction of two D-mesons and at least one additional charged particle not assigned to any of the D-mesons. To minimize a combinatorial background, D-mesons must be reconstructed via the decays of simplest topology: not more than 3 charged particles and not more than one π^0 or η. About 15% of all decays can be reconstructed in this way. This corresponds to several thousands of events per BESIII energy point.

Research and development of algorithms for reconstruction of events in the BESIII detector using machine learning methods

In recent years, methods of deep learning have gained increasing popularity due to their ability to detect hidden nonlinear dependencies in data and to parallelize the linear algebra operations underlying these methods. The prospect of using deep learning methods for neural networks in the task of event reconstruction lies in the problem of creating effective algorithms for “deep tracking” that surpass classical algorithms in speed.

Two new approaches to tracking problem were developed in scope of the joint RFBR-NSFC project No. 19-57-53002 and have already been successfully used for track recognition in the BESIII experiment [Nikolskaia A. et al. Local strategy of particle tracking with TrackNETv2 on the BES-III CGEM inner detector, AIP Conference Proceedings (2021) - Vol. 2377. - No. 1. - pp. 060004; Shchavelev E. et al. Global strategy of tracking on the basis of graph neural network for BES-III CGEM inner detector, AIP Conference Proceedings (2021) - Vol. 2377. - No. 1. - pp. 060001; Goncharov P. et al. BM@N Tracking with Novel Deep Learning Methods, EPJ Web of Conferences (2020) Vol. 226. - P. 03009].

The first approach, TrackNetv3, relies on the use of a recurrent neural network (RNN), which allows you to combine track extrapolation with testing the hypothesis that a set of points belongs to a true track and is compatible with a smooth curve, that is, essentially reproduces the idea of a Kalman filter with the difference that the physical parameters describing the track are approximated by a neural network using synaptic weights determined during its training. The second approach, RDGraphNet, uses a graph network and allows to implement global search for tracks in an event, which is especially attractive when analyzing events with a large multiplicity. During the project, these approaches will be adapted to search and recover particle tracks in the main BESIII tracker. The main difficulty is the adaptation of neural networks to recover tracks in drift detectors, which requires solving the "left-right" ambiguity. To prototype neural networks and study the quality of their work, the Ariadne software package will be used [Goncharov P. et al. Ariadne: PyTorch library for particle track reconstruction using deep learning, AIP Conference Proceedings (2021) Vol. 2377. - No. 1. - pp. 040004].

Algorithms based on convolutional networks will also be developed to search for clusters in the BESIII electromagnetic calorimeter.

Another application of machine learning methods is vertex finding. The LOOT program was applied to solve the problem of primary vertex finding in the BESIII inner tracking detector. This program is based on the deep convolutional neural network that processes all event hits at once, like a three-dimensional image. Due to improvement of the network loss function and applying an appropriate metric, the authors of [E. Rezvaya, P. Goncharov, Y. Nefedov, G. Ososkov, A. Zhemchugov, Improvements of the LOOT model for primary vertex finding based on the analysis of development results, http://ceur-ws.org/Vol-3041/138-142-paper-25.pdf] obtained an estimate of the event vertex coordinates with an accuracy acceptable to physicists.

Existing well-established event reconstruction of the BESIII experiment based on classical algorithms allows to study the performance of new, deep learning algorithms in the very detail, to investigate stability of these methods against noise and other data imperfections, and to elaborate methods for effective estimation of the systematic uncertainty connected with the use of the machine learning tools. These results will be useful not only for BESIII, but also for any other collider experiment including the ones of the NICA project.

2.3 Estimated completion date

2029

2.4 Participating JINR laboratories

DLNP, BLTP, LIT

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 - Ribbons	 - -	 - -	 - -	 - -	 - -
Tier 1 (core-hour)	-	-	-	-	-
Tier 2 (core-hour)	120000	120000	120000	120000	120000
SC Talker (core-hour) - CPU - GPU	 - -	 - -	 - -	 - -	 - -
Clouds (CPU cores)	60000	60000	60000	60000	60000

2.5. Participating countries, scientific and educational organizations

Organization	Country	City	Participants	Type of agreement
BESIII Collaboration	China, USA, Germany, Italy, Russia, Netherlands, Sweden, Korea, Japan, India, Pakistan	Beijing	IHEP CAS (the host institution)*	MoU

*The full list of participating institutes is available at the BESIII Collaboration webpage bes3.ihep.ac.cn.

2.6. Co-executing organizations *(those collaborating organizations/partners without whose financial, infrastructural participation the implementation of the research programme is impossible. An example is JINR's participation in the LHC experiments at CERN).*

3. Staffing

3.1. Staffing needs in the first year of implementation

№ № n/a	Category employee	Core staff, Amount of FTE	Associated Personnel Amount of FTE
1.	scientific staff	7.8	0.3
2.	engineers		
3.	professionals		

4.	employees		
5.	workers		
	Total:	**7.8**	**0.3**

3.2. Human resources available
3.2.1. JINR core staff

№ № п/a	Category of employees	NAME	Division	Position	Amount of FTE
1.	scientific staff	Bakina O. Boyko I. Shelkov G. Dedovich D. Denisenko I. Guskov A. Nefedov Y. Egorov P. Pogodin S. Zhemchugov A. Bytyev V. Korenkov V. Ososkov G. Pelevanyuk I.	DLNP DLNP DLNP DLNP DLNP DLNP DLNP DLNP DLNP DLNP BLTP LIT LIT LIT	researcher researcher researcher researcher researcher researcher researcher trainee trainee researcher researcher researcher researcher researcher	
2.	engineers				
3.	professionals				
4.	workers				
	Total:				**7.8**

3.2.2. JINR associated personnel

№ № п/a	Category of employees	Partner organization	Amount of FTE
1.	Scientific employees	NRC «Kurchatov Institute» - PNPI	0.3
2.	engineers		
3.	professionals		
4.	workers		

	Total:		0.3

4. Financial support

4.1 Total estimated cost of the project/sub-project of the LRIP

Forecast of the total estimated cost (specify cumulatively for the whole period, excluding FPC). The details are given in a separate form.
175K USD

4.2 Extrabudgetary funding sources

Estimated funding from co-executors/customers - total.

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Project (sub-project of the LRIP) Leader __________/___________/

Date of submission of the project (sub-project of the LRIP) to DSOA: __________
Date of decision of the laboratory's STC: __________ document number: __________

Year of the project (subproject of the LRIP) opening: _________________

(for renewable projects) -- Project start year: ________

Schedule proposal and resources required for the implementation of the Project / Sub-project of the LRIP

Names of costs, resources, sources of funding			**Cost (thousands of dollars) resource requirements**	**Cost, distribution by year**				
				1st year	2nd year	3rd year	4th year	5th year
		International cooperation (IC)	125	25	25	25	25	25
		Materials						
		Equipment and third-party services (commissioning)	50	10	10	10	10	10
		Commissioning work						
		Services of research organisations						
		Acquisition of software						
		Design/construction						
		Service costs (*planned in case of direct project affiliation)*						
Re	**Nor**	Resources						

sources required	**mo-hours**	– the amount of FTE,	39	7.8	7.8	7.8	7.8	7.8
		– accelerator/installation,						
		– reactor,….						
Sources of funding	**Budgetary resources**	JINR budget *(budget items)*						
	Extrabudgetary (supplementary estimates)	Contributions by co-contractors Funds under contracts with customers Other sources of funding						

Project (sub-project of the LRIP) Leader_________/________________/

Laboratory Economist _________/________________/

APPROVAL SHEET FOR PROJECT / SUBPROJECT OF THE LRIP

NAME OF THE PROJECT/SUBPROJECT OF THE LRIP

DESIGNATION OF THE PROJECT / SUBPROJECT OF THE LRIP

PROJECT/SUBPROJECT OF THE LRIP CODE

THEME / LRIP CODE

NAME OF THE PROJECT/ SUBPROJECT OF THE MIP LEADER

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 / MIP LEADER	SIGNATURE	NAME	DATE
PROJECT / SUBPROJECT OF THE LRIP LEADER	SIGNATURE	NAME	DATE

APPROVED BY THE PAC	SIGNATURE	NAME	DATE