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Participation of JINR in the Physics Research Programme at the BEPCII/BESIII

BESIII/JINR

02-2-1123-2023/2025

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PROJECT APPROVAL LIST

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at the BEPCII/BESIII

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I. DENISENKO

APPROVED BY THE JINR DIRECTOR

AGREED

JINR VICE-DIRECTOR

CHIEF SCIENTIFIC SECRETARY

CHIEF ENGINEER

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Contents

Abstract

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 leading in the research of exotic XYZ states discovered during the last two decades.

The JINR group is 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; studies of $\pi^+\pi^-\eta$ production in e^+e^- collisions.

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 75 kUSD for 2023-2025.

Аннотация проекта

Эксперимент BESIII на электрон-позитронном коллайдере BEPCII работает в ИФВЭ АН КНР (Пекин, Китай) начиная с 2008 года. В основные задачи эксперимента входят исследования в области спектроскопии адронов, проверка предсказаний квантовой хромодинамики, изучение распадов очарованных частиц, а также проверка предсказаний Стандартной модели и поиски "новой физики" за ее пределами. На сегодняшний день эксперимент BESIII играет ключевую роль в исследованиях чармония, очарованных частиц и тау-лептонов и является лидером в изучении экзотических XYZ-состояний, открытых за последние десятилетия.

Группа сотрудников ОИЯИ участвует в эксперименте BESIII с 2005 года. Данный проект нацелен на продолжение участия группы ОИЯИ в анализе данных BESIII для получения новых результатов в следующих областях: адронной спектроскопии и поиске экзотических адронов; изучении свойств рождения и распада состояний чармония и чармониеподобных структур; изучению функций фрагментации c-кварка в области низких энергий. В частности, предлагается следующее: проанализировать ряд каналов радиационных распадов J/ψ и ψ(2S) для подтверждения полученных ранее указаний на рождение скалярного скалярного глюбола; опубликовать полученные результаты измерения инклюзивного сечения прямого рождения состояний чармония в электрон-позитронной аннигиляции с энергией выше 4 ГэВ; изучить структуру распада J/ψ путем измерения разности фаз между амплитудами сильного и электромагнитного взаимодействия в ряде эксклюзивных процессов; изучить систему $\pi^+\pi^-\eta$ в электрон-позитронной аннигиляции.

В настоящее время группа ОИЯИ является одним из ведущих разработчиков программного обеспечения в коллаборации BESIII. В рамках данного проекта будут продолжены работы по поддержке программных пакетов, разработанных ранее группой ОИЯИ. Также запланированы исследование и разработка алгоритмов машинного обучения для их последующего применения как в рамках эксперимента BESIII, так и в рамках других экспериментов.

Бюджет проекта составляет 75 тыс. долларов США на 2023-2025 год.

Introduction

The BESIII experiment at the electron-positron collider BEPCII started its operation in the Institute of High Energy Physics (Beijing, China) in 2008. BEPCII is an electron-positron collider designed to operate in the c-tau region. The Beijing Spectrometer III (BESIII) is a highly precise general-purpose detector designed for high luminosity e^+e^- collisions in the tau-charm energy region. The main tasks of the experiment are the studies of charmonium physics, physics of charmed mesons, tau leptons and light hadron spectroscopy.

The physics data taking was started in March of 2009. Based on the analysis of collected unique data sets more than 350 papers has been published making great contributions to hadron spectroscopy, tests of various aspects of QCD, charmed hadron decays, and precision test of the Standard Model (SM), as well as the probes of new physics beyond the SM. Nowadays, the BESIII experiment is the world leader of researches in the tau-charm energy domain and one of pioneers in studies of exotic XYZ states discovered during the last two decades.

JINR group is participating in the BESIII experiment since 2005. An important results in the field of light meson spectroscopy, charmonia production, D-meson decays and other topics has been obtained. This project is aimed at a continuation of BESIII data analysis by the JINR group, focusing on the search for scalar and tensor glueballs, measurements of charmonia production properties at the collision energies above 4 GeV, on 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, and probing the c-quark fragmentation functions at low energies.

Software development is the main technical contribution of the JINR group to the BESIII experiment. Currently, the JINR group is one of the leading developers of the core software, distributed computing and physics analysis tools. Besides the maintenance of software packages, developed earlier by JINR group, 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 experience and results obtained by the JINR group in BESIII will be essential for the further participation in the Super-c-tau factory project in Sarov.

BESIII experiment and its current status

BEPCII is a double ring machine initially designed to collide e^+e^- beams in the energy range of $\sqrt{s}$ = (2 - 4.6) GeV. It is optimized for the center-of-mass energy of 2 × 1.89 GeV and in April 2016 its instantaneous luminosity reached of 1.0 $\times 10^{33}$ $cm^{-2}s^{-1}$ for such collisions. The BEPCII collider was upgraded during summer shutdown in 2019. Its maximum beam energy was increased from 2.3 GeV to 2.47 GeV (thus reaching a collision energy of 4.9 GeV) and a top-up injection was implemented. In collision operation, the latter allowed improving of the integral luminosity during the data taking by (20-30) % at high energies. The next BEPCII upgrade project was approved in July 2021. It will increase the collider luminosity by a factor of 3 at high energies and extend energy reach to 5.6 GeV. The installation of new equipment will start in July 2024 and running is planned for January 2025.

The BESIII detector is placed inside a 1 T superconducting solenoid and the steel structure of its flux return. The coil of the superconducting magnet is located outside of the electromagnetic calorimeter and has a mean radius of 1.482 m and a length of 3.52 m. The multilayer drift chamber (MDC) surrounds the beryllium beam pipe. Two superconducting quadrupoles are inserted in the conically shaped MDC end caps as close as possible to the interaction point. The time-of-flight (TOF) system is located outside of the main drift chamber, consisting of two layers of plastic scintillator counters in the barrel part and of MRPC chambers in the end-cap. The CsI(Tl) electromagnetic calorimeter (EMC) is placed outside of the TOF system and inside the solenoid. The muon identifier (MUC) consists of layers of resistive plate chambers (RPCs) inserted in gaps between steel plates of the flux return yoke. The polar angle coverage of the spectrometer is $21^\circ < \theta < 159^\circ$, and the solid angle coverage is $\Delta\Omega/4\pi = 0.93$. An upgrade of the detector is planned for 2023 with a view to replace the existing inner part of the MDC by the cylindrical GEM tracker (CGEM).

The experiment is run by an international BESIII Collaboration, which currently consists of about 500 members from 16 countries.

The collaboration has collected unprecedentedly large data sets in whole available energy range including 10 billion J/ψ events and 3 billion ψ(2S) events. The current running plan describes data taking from 2020 to 2023. Since 2020 BESIII has accomplished data taking of 1.85 fb^{-1} in the energy range 4.74 – 4.95 GeV and has

collected 2.55 billion ψ(2S) decays. The next goals include 800 pb^{-1} of continuum data below the ψ(2S) peak, and 17 fb^{-1} at the mass of ψ(3770). The proposals for data taking after 2023 are summarized the BESIII White Paper *[Chin.Phys.C 44, 040001 (2020)]*, the actual data taking plan is to be adopted by the BESIII Collaboration in summer 2022.

Since 2019 the BESIII Collaboration has published more than a hundred of papers. The most interesting results are obtained for exotic XYZ states, charm decays and neutron structure. Among all publications the following can be mentioned.

The near-threshold structure is observed in the K^+ recoil mass spectra in $e^+e^- \to K^+ (D_s^- D^{*0} + D_s^{*-} D^0)$ *[PRL126,102001 (2021)]*. The analyzed data sets of 3.7 fb^{-1} are collected at center-of-mass energies from 4.628 to 4.698 GeV. An access of events over known contributions near the $D_s^- D^{*0}$ and $D_s^{*-} D^0$ mass thresholds in K^+ recoil mass is observed at the collision energy of 4.681 GeV. The structure is consistent with a resonance line-shape and its pole mass and width are determined. The statistical significance of the structure is 5.3σ. This is the first candidate for a hidden-charm state with strangeness.

The absolute branching fraction for the $D_s^+ \to \tau^+ \nu_\tau$ decay is measured with the record precision *[PRL127,171801 (2021)]* via $\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$. The analysis is based on the data with integral luminosity of 6.32 fb^{-1} collected at the center-of-mass energies between 4.178 and 4.226 GeV. The branching ratio of this decay is given by the product of f_{Ds+} and $|V_{cs}|$. The former can be calculated from lattice QCD and the obtained measurement thus provides a stringent test on the unitarity of CKM matrix.

A new leptonic decay mode of D-mesons, $D^+ \to \tau^+ \nu_\tau$, is reported by the BESIII Collaboration *[PRL123, 211802 (2019)],* the decay signal is observed with a statistical precision of 5.1σ. The measurement is possible due to the world's largest sample of charmed mesons (2.93 $fb^{-1)}$ collected for collisions at 3.773 GeV. The measurement can be combined with the world-average for $D^+ \to \mu^+ \nu_\mu$ to test lepton flavor universality, no evidence for its violation is found.

The BESIII data recorded at the center-of-mass energies between 2.0 and 3.08 GeV allowed the BESIII Collaboration to measure the neutron form factors in the time-like region with unprecedented precision *[Nat.Phys.17,1200 (2021)]*. It is shown that photon-neutron interaction is weaker than photon-proton. This result is in contrast with results of the FENICE experiment, but agrees with many theoretical calculations. Most interestingly, the effective form factor of the neutron shows a periodic behavior, similar to earlier observations of the proton form factor reported by the BaBar Collaboration. The origin of the behavior is to be understood.

Results of the JINR group in 2019-2022

The JINR group worked in 2019-2022 on the following topics.

1) Partial wave analysis of $J/\psi \to K^+K^-\pi^0$.

The analysis performed by the JINR BESIII group is published in *Phys.Rev.D 100, 032004 (2019)*. The analysis reveals contributions from $K^*_2(1430)^\pm$, $K^*_2(1980)^\pm$, $K^*_4(2045)^\pm$ decaying to $K^\pm\pi^0$. The two latter states are observed in J/ψ decays for the first time. The most precise measurements of $K^*(980)^\pm$ and $K^*_2(1430)^\pm$ masses and widths are obtained. Two resonance signals decaying to K^+K^- are also observed, their interpretations are suggested. The total branching ratio, as well as partial widths for decays through individual states, are reported, most of the values are reported for the first time.

2) Scalar isoscalar mesons and the scalar glueball from radiative J/ψ decays.

The BESIII data on radiative J/ψ decays to ππ, KK, ηη, and ωφ constrained by two meson scattering data and data on proton-antiproton annihilation to three mesons are analyzed in the N/D approach *[PLB 816,136227 (2021)]*. The analysis revealed enhancement in the scalar meson production rate in radiative J/ψ decays. The position of the enhancement is consistent with estimations of the scalar glueball mass and the associated partial width is consistent with lattice calculation for its production in radiative J/ψ decays. The enhancement was interpreted as an admixture of scalar glueball in the wave-functions of scalar mesons. This work is performed with the leading participation the JINR BESIII group and is based on its previous experience.

3) Cross-section measurement of the light meson pair production in the energy range of 2-3 GeV and around the J/ψ peak.

We performed a search for the process $e^+e^- \to \pi^+\pi^-\eta$ ($\eta \to \gamma\gamma$ and $\eta \to 3\pi^0$) at 20 energy points in the range from 2.00 to 3.08 GeV. A preliminary estimate of the cross section of this process has been made. The presence of a peak-like behavior of the cross section in the region of 2 GeV requires a more detailed study. We plan to expand our measurements using higher energy data and using the initial state radiation (ISR) method: look for the $e^+e^- \to \gamma(\text{ISR})\ \pi^+\pi^-\eta$ process.

We used BESIII data at 3.686 MeV corresponding to the production of ψ(2S) to study the decay of $\psi(2S) \to \pi^+\pi^- J/\psi$. The number of J/ψ in this process was estimated

with an accuracy better than 0.2%. This allowed us to accurately measure the branching fraction of the decay $J/\psi \to \varphi\eta$ ($\varphi \to K^+K^-$, $\eta \to \gamma\gamma$). The interference between the decays $J/\psi \to \varphi\eta$ and $J/\psi \to$ non-φ $K^+K^-\eta$ was taken into account. We plan to complete this study with a journal publication and later use this result to measure the relative phase between the strong and electromagnetic amplitudes in the analysis of BESIII scan data near the J/ψ peak.

4) Cross-section measurement of the semi-inclusive reaction $e^+e^- \to J/\psi X$ above 4.0 GeV

The inclusive cross-section of prompt J/ψ production is measured at center-of-mass energies from 3.8 to 4.7 GeV using e^+e^- annihilation data corresponding to an integrated luminosity of 20 fb^{-1} collected with the BESIII detector from 2011 to 2020.

As a result of the preliminary review of the analysis performed by the BESIII Charmonium group, the event selection criteria have been optimized, as well as simulation to evaluate the efficiency of the selection procedure has been improved. At the BESIII collaboration meeting, the analysis was approved and entered the internal review stage.

New data up to 5.6 GeV correspond to the main focus of the current research because it could be useful for a test of charmonia production models in the transition region of perturbative and non-perturbative QCD.

5) Search for proton-antiproton bound state in the reaction $e^+e^- \to 2p2\bar{p}$ performed by a graduate student. A bachelor thesis has been prepared in 2020.

Software development is the main technical contribution of the JINR group to the BESIII experiment. Currently, the JINR group is one of the leading developers of the core software and physics analysis tools. Maintenance of software packages, developed earlier by JINR group, including the ROOT-based analysis framework BEAN was continued in 2019-2022. The support of the JINR segment of the BESIII distributed computing system was continued.

The results of the JINR group have been presented in the following reports:

1) I. Denisenko, “Light hadron spectroscopy at BESIII”, 19-th Lomonosov Conference on Elementary Particle Physics, Moscow, 22 - 28, August 2019.
2) Ю. Нефедов, “Обзор эксперимента BESIII”, сессия-конференция СЯФ ОФН РАН, Новосибирск, март 2020.
3) S. Pogodin, “Search for proton-antiproton bound state in the reaction $e^+e^- \to 2p2\bar{p}$ in the BESIII experiment”, BSc thesis, Dubna, 2020.

4) P. Egorov, “Measurement of the cross-section of $e^+e^-\to\eta\pi^+\pi^-$ in energy range 2.00 − 3.08 GeV”, BSc thesis, Dubna, 2020.

5) I. Denisenko, “Partial wave analysis of $J/\psi \to K^+K^-\pi^0$”, 9th International Conference on New Frontiers in Physics (ICNFP 2020), Crete, 4-12 October 2020.

6) I. Denisenko, “Partial wave analysis of $J/\psi \to K^+K^-\pi^0$”, 5-th International Conference on Particle Physics and Astrophysics (ICPPA 2020), Moscow, 5-9 October 2020.

7) I. Denisenko, “Partial wave analysis of $J/\psi \to K^+K^-\pi^0$”, XXIV International Scientific Conference of Young Scientists and Specialists (AYSS-2020), 9-13 November 2020.

8) I. Denisenko, “Light hadron spectroscopy and search for exotic states in the $J/\psi \to K^+K^-\pi^0$ decay and radiative J/ψ decays to two pseudoscalars”, PhD thesis, 2021.

9) O. Bakina, poster “Proposal for the prompt inclusive J/ψ production measurement at future Super c-tau factories”, Workshop on future Super c-tau factories, 15-17 November 2021.

10) O. Bakina, poster "Studies of charmonium decay from BESIII", 30th International Symposium on Lepton Photon Interactions at High Energies, 10-14 January 2022.

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 and to search for and study the exotic charmonia and charmoniumlike structures 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 has never been reliable 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 have been performed with the leading participation of JINR BESIII group *[PLB 816,136227 (2021)]*, evidences of scalar glueball production have 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 ψ(2S) decays to $\pi^0\pi^0$, K_SK_S, ηη, 4π, and other final states. The latter should be possible with the new ψ(2S) data recently collected by the BESIII Collaboration.

Measurement of the cross section of the process $e^+e^- \to \pi^+\pi^-\eta$ in the energy range up to 3 GeV

The cross section of the process $e^+e^- \to \pi^+\pi^-\eta$ is interesting in many respects. As a part of the total hadronic cross section it is used for the calculations of the hadronic contribution to the muon anomalous magnetic moment *[PRD 97,114025(2018)]*. The $e^+e^- \to \pi^+\pi^-\eta$ cross section data can be also used to study the properties of the ρ(1450), ρ(1700) and ρ(2150) resonances.

The most precise measurements of $e^+e^- \to \pi^+\pi^-\eta$ cross section have been performed by BABAR collaboration *[PRD 97,052007(2018)]* and by CMD-3 collaboration *[JHEP 2020,112(2020)].* BABAR measured this cross section in the c.m. energy range 1.15-3.05 GeV with the initial state radiation technique. The CMD-3 measured $e^+e^- \to \pi^+\pi^-\eta$ cross section in the c.m. energy range 1.2–2.0 GeV and fit it with two models. One of them includes contributions of the ρ(770) and ρ(1450) intermediate mechanisms while the other one includes also a contribution of the ρ(1700).

We already have preliminary results of measuring the cross section of the process $e^+e^- \to \pi^+\pi^-\eta$ in the data samples at the c.m. energy range 2.00–3.08 GeV. The dominant components are found to be $e^+e^- \to \rho\eta$ and $e^+e^- \to a^{\pm}_2\,\pi^{\mp}$. These data show two resonances near the threshold of 2 GeV. We plan to expand our measurements using higher energy data and using the initial state radiation (ISR) method. Due to the fact that annihilation of e^+e^- is mostly accompanied by emission of one or several photons from the initial state, the high luminosity at the e^+e^- collider experiments allows a complementary approach to the energy scan technique for hadron cross section measurements. We will use events with detected ISR photon which allow us to measure the $e^+e^- \to \pi^+\pi^-\eta$ cross section over a wide range of energies from the process threshold to the c.m. energy.

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 $c\bar{c}$ pair and its non-perturbative hadronization to charmonia states. Experimentally, the $J/\psi \to \mu^+\mu^-$ decay provides 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 $c\bar{c}$ 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 ψ(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 ψ(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 ψ(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 analysis of inclusive direct J/ψ production in the collision energy range 3.81 – 4.70 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.

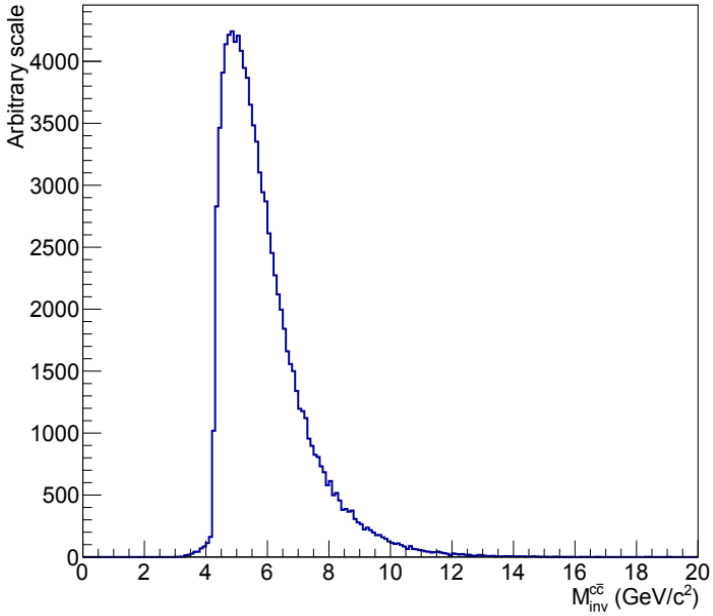

Fig. 1: Invariant mass of $c\bar{c}$ pair in proton-proton collisions at 27 GeV at SPD simulated with Pythia8.

Fig. 1 shows a simulated spectrum of the $c\bar{c}$ invariant mass for 27 GeV NICA collision energy. 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, BESIII experiment has collected a unique data sample of about 5 fb^{-1} integrated luminosity at the 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. An 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 particle 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.

Work plan

In 2023 the following physics results are planned to be obtained:

- Publication of the paper “Measurement of the branching fraction of J/ψ →φη”.
- Study of the $e^+e^- \rightarrow \pi^+\pi^-\eta$ reaction below J/ψ peak via ISR method.
- Publication of the paper on the prompt J/ψ production in the collision energy range 3.81 – 4.70 GeV.
- Preparation of the PhD thesis by O. Bakina.
- Feasibility study of probing fragmentation functions of c-quark from BESIII data.

In 2024 the following physics results are planned to be obtained:

- Final results on the phase shift measurement in $e^+e^- \rightarrow \varphi\eta$ and $e^+e^- \rightarrow \omega\eta$.
- Preliminary results from partial wave analysis of $J/\psi \rightarrow \gamma 4\pi^0$ decay.
- Studies of ψ(2S) radiative decays to two pseudoscalar mesons.
- Submission of the paper on $e^+e^- \rightarrow \pi^+\pi^-\eta$ reaction below J/ψ peak via ISR method.
- Measurement of inclusive J/ψ polarization in the energy range above 4 GeV.

In 2025 the following physics results are planned to be obtained:

- Incorporation of $J/\psi \rightarrow \gamma 4\pi^0$ decay and ψ(2S) decays to the global N/D fit. Publication of the results.
- Investigation of the inclusive η_c production.
- Publication on the results of c-quark fragmentation functions analysis from BESIII data (if feasible).

Resources

All works in the scope of the project will be carried out by the staff of the DLNP (5.8 FTE[1]), BLTP (0.5 FTE) and LIT (0.5 FTE). The total project team is 6.8 FTE.

No hardware or material contribution to the experiment is expected from JINR. The project costs are estimated on the base of participation of the JINR group mostly in the BESIII software development and computing equipment, data-taking (shifts), Monte-Carlo simulation and physics analysis and include essentially the travel expenses.

[1]O.Bakina - 1 FTE, I.Boyko - 0.3 FTE, G.Chelkov - 0.1 FTE, D.Dedovich - 0.3 FTE, I.Denisenko - 0.5 FTE, A.Guskov - 0.1 FTE, Yu.Nefedov - 1 FTE, P. Egorov - 1 FTE, S. Pogodin – 1 FTE, A.Zhemchugov - 0.5 FTE.

Short SWOT[2] analysis

Strengths of the project

1. Currently, BESIII offers the world best conditions for studies in tau-charm domain and no competing projects are foreseen in the next 5 years.

2. The JINR group is a member of BESIII collaboration since 2005 and has already the necessary knowledge and skills concerning the experiment conditions, the detector operation, software tools and data processing techniques.

3. The huge amount of data is already available.

Weaknesses of the project

1. The project team needs more MSc and PhD students to be involved into the data analysis.

Opportunities

1. Machine learning algorithms for the event reconstruction and the information on the c-quark fragmentation function will be essential for the SPD experiment at NICA.

2. The Super-ctau factory is being constructed at Sarov now. The experience gained in BESIII experiment will allow the project team to take part in the physics research program development for Super-ctau factory and to continue studies at the new generation of machines.

Threats

No threats are identified.

[2]SWOT – strengths and weaknesses, opportunities, threats

Form №26

Proposed Time-Schedule and Necessary Resources
for implementation of Project
Participation of JINR in the Physics Research Programme

at the BEPCII/BESIII

Parts and systems of set-up, resources and sources of financial support.	**Cost of parts of set-up. Required financial support.**	**Profile proposed by Laboratory.**		
Main parts and equipment (kUSD)				
		2023	**2024**	**2025**
Materials **Equipment** **Travel costs**	**–** **30** **45**	**–** **10** **15**	**–** **10** **15**	**–** **10** **15**
Necessary manpower support (man-hours)				
JINR Central workshop:	–	–	–	–
LNP: - workshop; - design bureau	–	–	–	–
Accelerator, Reactor	–	–	–	–
Computer	–	–	–	–
Maintenance & Operational	–	–	–	–
Sources of financial support (kUSD)				
JINR budget	75	25	25	25
Extra – budgetary (grants, agreements, sponsors etc.)	–-	–	–	–

Project Leader I. Denisenko

Deputy Project Leader A. Zhemchugov

Form №29

Financial Resources Needed for Project realization

Participation of JINR in the Physics Research Programme

at the BEPCII/BESIII

No	TASKS	Total value	2023	2024	2025
	Direct costs of the Project				
1	Accelerator, reactor	–	–	–	–
2	Computer	–	–	–	–
3	Materials	–	–	–	–
4	Equipment	30	10	10	10
5	R&D	–	–	–	–
7	Travel resources				
	a) in non-ruble area	39	13	13	13
	b) in ruble area	6	2	2	2
	Total direct cost:	**75**	**25**	**25**	**25**

Project Leader I. Denisenko

Deputy Project Leader A. Zhemchugov

Director of the Laboratory V.Bednyakov

Main planning engineer of the Laboratory G.Usova