Referee Report on the project
"JINR participation in the STAR experiment at RHIC"

The experimental results of the STAR collaboration on the study of nuclear matter under extreme conditions, the study of spin-dependent quark and gluon structure functions, the measurement of the polarization of sea quarks in processes with the W-bosons production, the study of nuclear matter in the processes with the production of heavy quarks are well known to the scientific community and have brought a contribution to the formation of modern knowledge in this area of physics. An essential contribution to the creation of the STAR facility and the implementation of the experimental program was also made by the JINR group, where physicists from the JINR Member States, including Slovakia, are actively participating.

The ability to carry out experiments at the RHIC collider with longitudinally and transversely polarized protons, various colliding nuclei (*d*, He, Cu, Au, U) over a wide energy range (from 7 to 200 GeV/nucleon), simultaneously with the development of detecting systems of the STAR facility, allows for many years to successfully solve a wide range of problems in the study of the quark-gluon structure of matter.

The main and significant contribution of JINR to the STAR experiment was the creation of the Endcap Electromagnetic Calorimeter (EEMC). The creation of this detector and its stable operation in data taking made it possible to successfully perform a physical program with polarized protons (measuring the asymmetries of the production of pions, jets, W-bosons with longitudinally and transversely polarized protons) and obtain new information on the spin-dependent gluon and quark (valence and sea) distributions of various flavors.

Throughout the entire period of its participation in the STAR experiment, the JINR group was engaged in the development of new data processing algorithms for studying nucleus-nucleus collisions and processes with jet production in experiments with polarized protons. An original method of data analysis (z-scaling) is proposed and further developed based on general fundamental physical principles such as universality, self-similarity, locality, and fractality of hadron interactions at the constituent level. The approach based on the z-scaling theory may turn out to be an adequate tool for searching for signatures of phase transitions and critical points in the hadronic and nuclear matter.

During the period 2019–2021, the JINR group in the STAR experiment made a significant contribution to obtaining new world-class physical results:

1. In the STAR experiment in nucleus-nucleus interactions, the first verification of CPT invariance in the sector of hypernuclear matter, where (anti-) strange quarks play an essential role in the formation of these nuclei was carried out. The relative difference in mass between hypertriton and antihypertriton is $[1.1 \pm 1.0 \text{ (stat.)} \pm 0.5 \text{ (syst.)}]\cdot 10^{-4}$. This indicates the absence of violations of CPT symmetry ("Measurement of the mass difference and the binding energy of the hypertriton and antihypertriton", Nature Physics 16, 409–412 (2020)).
2. Within the framework of the BES-I energy scan program, fluctuations in the number of net-protons were measured. This data will provide more detailed information about the region in which energy dependence of net-baryon fluctuations may undergo significant changes (non-monotonic variations in kurtosis × variance of the net-proton number distribution as a function of $\sqrt{s_{NN}}$ with 3.0σ significance for central gold-gold collisions) ("Net-proton number fluctuations and the Quantum Chromodynamic critical point", e-Print arXiv (2001.02852)).
3. In collisions of polarized protons at the energy of 510 GeV, the single-spin longitudinal asymmetry of W-boson production was measured and the asymmetry of spin-dependent sea *u* and *d* quark distributions in the proton was established (Phys. Rev. D 99 (2019) 051102).
4. In experiments with longitudinally polarized protons at the energy of 510 GeV, the double-spin asymmetry of jet production was measured for the first time and a positive integral contribution of gluons to the proton spin was found (Phys. Rev. D 100 (2019) 052005).

5. In collisions of gold nuclei at the energy of 200 GeV, the nuclear modification factor for mesons and baryons containing heavy quarks was measured, and a significant (more than 50 %) suppression of hadron yields at transverse momenta of more than 4 GeV/c was established (Phys. Rev. C 99 (2019) 034908).

The main experimental program at the STAR facility in 2019–2021 is the energy scan program. In the ongoing 2021 experiment, the planned measurements have already been carried out at five collider energies (7.7, 9.1, 11.5, 14.6, and 19.6 GeV). Measurements were also performed in experiments with a fixed target, which extends the range of energy scan to lower energies (7.7, 6.2, 5.2, 4.5, 3.94, 3.5 GeV).

Experimental data are being processed and new original methods and algorithms for the analysis of nucleus-nucleus and proton-proton collisions are being developed in the STAR group at JINR.

1. A preliminary analysis of the BES-II data was carried out and transverse momentum spectra of charged hadrons produced in Au + Au collisions over the energy range from 7.7 to 54 GeV as a function of centrality were studied. Within the framework of the original method for the analysis of experimental data (z-scaling) developed in the JINR group, the scaling regularities in the production of particles at energies of 7.7 and 9.2 GeV were verified. The parton energy losses depending on the energy and centrality of the collision and transverse momentum of the inclusive particle were estimated.
2. The JINR group has developed a method of fractal analysis of events. The method is based on the property of self-similarity at different levels of resolution in the investigated space (for example, transverse momenta). For each level, the coverage is determined and an equation is drawn up to find the fractal dimension. The equality of dimensions for all equations of the system determines an object called a fractal. The algorithm for reconstruction of fractals was developed, the software package was tested on a wide class of fractals, and the effectiveness of the method was estimated. The JINR group obtained preliminary results of analysis using about 1 million events of different centrality: the optimal parameters of the method were determined, the distributions of events in fractal dimension were obtained, a comparison was performed with different p_T distributions of particles (power-law, exponential, random), classes of events were identified, the p_T distributions of which differ significantly from each other, additional criteria for selecting events are developed in order to significantly suppress the background and getting a cleaner set of fractal events.
3. The JINR group, when analyzing the STAR BES-I data, for the first time obtained spectra on the cumulative particle production in collisions of gold nuclei in the collider mode at energies $\sqrt{s_{NN}}$ = 7.7 and 9.2 GeV. In this region, the smooth behavior of the scaling function and other quantities (momentum fractions, recoil mass), which characterize the microscopic mechanism of hadron production, was found.

The research results of the JINR group have been published in peer-reviewed journals and reported at various international conferences, in particular, at the 2020 Rochester Conference in Prague, Czech Republic.

Experiments at the STAR facility for 2022–2025 are proposed in a new project. The experimental program for this time period includes the following tasks:

1. Completion of research on the BES-II program in the collider mode and in experiments with a fixed target. Measurements of 2021 with high statistics at minimum collider energy of 7.7 GeV and minimum beam energy of 3 GeV in experiments with a fixed target are especially important for calibrations and comparison with planned measurements at the NICA/MPD and BM@N facilities. Measurements at the RHIC are important for JINR since they will provide preliminary information on physical processes in the energy range of the NICA collider, which will have a higher luminosity during measurements.

2. It is necessary to carry out the experiments planned in the project on the collision of light oxygen nuclei, along with heavy ions, to solve an important scientific problem to study the phase diagram of nuclear matter and determine the equation of state.
3. The planned measurements in 2022 and 2024 in the framework of the Cold QCD Physics program with transversely polarized protons at energies of 510 and 200 GeV in proton-proton and proton-nucleus interactions are of great scientific importance. We note that the program of these measurements includes the study Sivers (transfers momentum distribution – TMD) and Efremov-Teryaev-Qui-Sterman (twist-3 collinear distribution) Functions.
4. The Hot QCD Physics program for 2023 and 2025 for the study of the microstructure of QGP in Au + Au collisions at 200 GeV is of considerable scientific interest. This part of the project is aimed at solving the two most important problems – detailing the QCD phase diagram and determining the properties of QGP on small scales.
5. The project formulates several problems on the use of the method of correlation femtoscopy for the systematic study of the space-time parameters of particle production during energy scan, considering various fluctuations.

In the new project, as in the previous stages of research, it is assumed that the members of the JINR group will participate in preparation of data taking runs, in run shifts, working groups on data processing and data analysis, analysis of experimental data using MuDST and PicoDST at JINR, preparation of reports at conferences and publications in peer-reviewed journals, including as principal authors.

As a referee, I recommend actively involving young scientists from JINR in the processing and analysis of experimental data, since the experience they have acquired can be directly used in the upcoming processing of experimental data that will be obtained in the nearest future at the NICA accelerator complex. I note that over the past two years, 8 university students from the JINR member-states have already been attracted to the STAR group at JINR to prepare qualification papers. Each of them is offered a research topic based on the materials of the STAR experiment.

In general, the physics program proposed in the project is well-motivated, and its implementation is beyond doubt.

One of the important achievements of the authors of the project is the possibility of using GRID technology to process events from the STAR facility on the JINR computer cluster, which they have realized jointly with LIT staff. If necessary, this will make it possible to produce sets of experimental data required for priority research for JINR and for the implementation of project tasks.

It should be noted that JINR's participation in the STAR experiment at RHIC is included in the JINR Seven-Year Program for 2018–2023.

Taking into account the successful previous experience of JINR participation in the STAR experiment, there is no doubt about the implementation of the tasks proposed in the new project for 2022–2024.

The funding requested by the authors of the project corresponds to the tasks being solved. I note that this request corresponds to the level of funding that was allocated to the authors of the project at the previous stages.

I recommend to endorse the project of JINR's participation in the STAR experiment in 2022–2024 with the first priority, provide the resources requested by the authors in full, and present the Project at the JINR PAC.

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