2020

JOINT INSTITUTE FOR NUCLEAR RESEARCH

JINR

JOINT INSTITUTE FOR NUCLEAR RESEARCH

DUBNA

VEKSLER AND BALDIN LABORATORY OF HIGH ENERGY PHYSICS

In 2020, the activity of the Veksler and Baldin Laboratory of High Energy Physics was aimed at construction, development and commissioning of separate units of the accelerator complex “Nuclotron–NICA” and MPD, BM@N and SPD experimental facilities. Experiments were also continued at external accelerators.

THE MOST IMPORTANT RESULTS IN THE DEVELOPMENT OF THE NICA COMPLEX

Nuclotron–NICA Project. ***Booster and Beam Transport Channels.*** On November 20, 2020, the Prime Minister of the Russian Federation M. Mishustin made a technological launch of one of the main units of the megascience project “NICA Complex” — a superconducting booster synchrotron, the Booster. By that moment the assembly of the Booster magnet cryostat system had been completed. All subsystems were installed and tested, the power supply system for the magnets was tested and tuned under operation at an equivalent load, the HILAc–Booster beam transport channel was constructed, adjusted and tested. By the end of the year, the initial commissioning tests and full-scale measurements aimed at testing and tuning of all systems when working with the He^{1+} ion beam had been performed. Work with the beam began on December 19, according to the approved schedule.

During the run, the following work was sequentially performed:

- the assembly and testing of the vacuum system were completed;
- the ACS of the Booster was launched, a monitoring system designed to monitor the process of cryostatting was put into operation, the magnet cryostat system was cooled to a temperature of 4.5 K;
- the quench detection and protection system was adjusted and put into operation, the energy dump system was tested, the system of cycle setting and the power supply system for the Booster magnets were tuned;
- the heavy-ion accelerator HILAc and the beam transport channel from HILAc to the Booster were adjusted, the injection system units were tuned to the design parameters;
- the beam was injected onto the magnetic field plateau corresponding to the injection energy, a circulating He^{1+} beam was obtained;
- the main systems for diagnostics of the circulating beam and the closed orbit correction system were consistently tested, the intensity of the circulating beam is ensured close to the design one;
- the high-frequency system was tuned, the adiabatic beam capture mode was tested in the acceleration mode, the acceleration of ions up to energy of 100 MeV/nucleon was ensured;
- the electron cooling system was switched on and tested;
- magnet power systems, cryogenic and magnet cryostat systems were tested when operating in a magnetic field cycle with design parameters.

The beam circulation mode was obtained without switching on the magnetic field error correction system, while the deviations of the beam orbit from the nominal position in the horizontal plane did not exceed ± 15 mm (a few more in the vertical plane). This is a direct confirmation that the quality of production and assembly of the system elements meets the design requirements. During the run, there was a stable operation of the magnet cryostat system with a magnetic field cycle of about 400 h.

The use of the orbit correction system together with the tuning of the beam transport channel from HILAc to the Booster and the tuning of the injection system units made it possible to achieve the beam intensity at the level of $7 \cdot 10^{10}$ of circulating He^{1+} ions (Fig. 1), which is equivalent in current to 10^9 Au^{31+} ions.

The characteristic lifetime of ions due to recombination with molecules and atoms of the residual gas was approximately 1.9 s (Fig. 1). Taking into account the cross sections of the recharging processes, this value corresponds to the residual gas pressure in the beam chambers at the level of $(3–6) \cdot 10^{-8}$ Pa, which corresponds to the readings of vacuum gauges and to the design value with the starting configuration of the pump-out system.

During three shifts, work was carried out to test the electron cooling system (ECS). At the injection energy using the ECS dipole magnets and the Booster correction magnets, the orbit of the circulating beam was corrected under the field of the solenoid of the cooling section up to 0.07 T. In this field, a stable mode of energy recovery of the electron beam with an electron current of up to 150 mA was ensured. The effect of interaction between the electron and circulating ion beams was observed using an ionization profilometer. A decrease in the ion lifetime due to recombination with electrons in the cooling section, which depends on the electron energy, was reliably recorded. The optimum electron energy (the potential of the electron gun cathode) is in the range of 1.74–1.82 keV, which corresponds to the calculated value.

At the end of the run, a comprehensive testing of the magnet power systems, cryogenic and magnet cryostat systems was carried out during operation in a magnetic field cycle with the maximum consistently achievable parameters. As a result, a cycle with two “plateaus” corresponding to the injection energy and the energy of electron cooling was set in the area of the increasing field. A field of 1.8 T was achieved on the upper “plateau”, and a rate of field change of 1.2 T/s was ensured in the areas of increase and decrease of the field (Fig. 2), which fully corresponds to the design parameters of the cycle.

All tasks of the run were fully completed. For all Booster systems the necessary information was obtained for their further development during the preparation for the run to accelerate heavy ions.

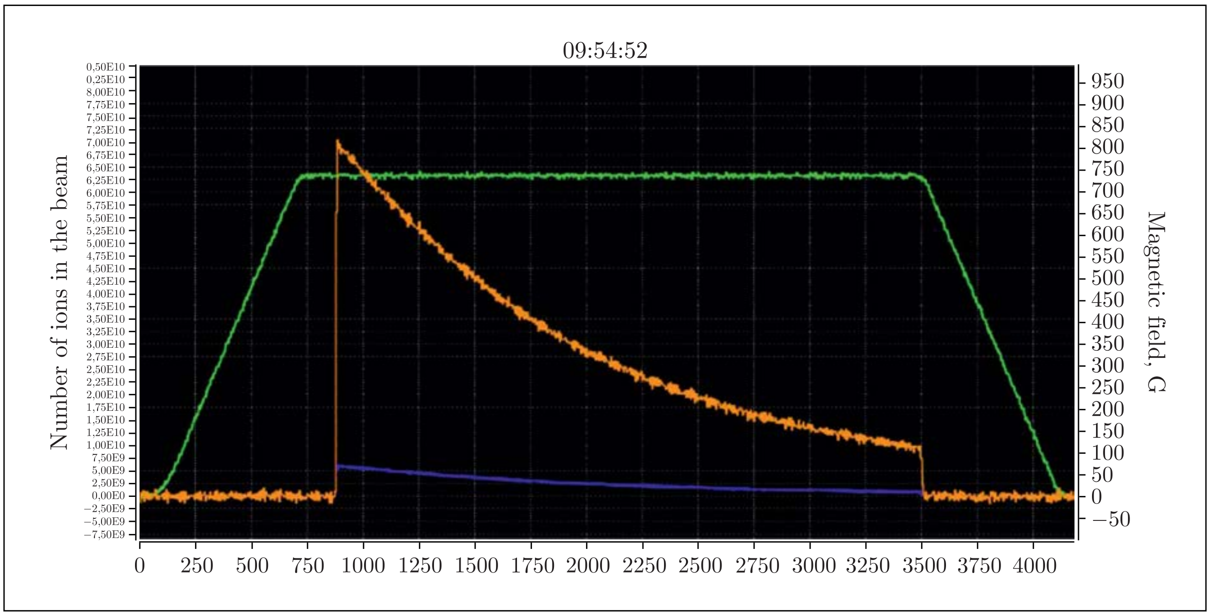

Fig. 1. Results of measuring the intensity of the circulating beam using a parametric power transformer (PPT) with optimum tuning of all systems. The green curve is the magnitude of the magnetic field in G, the blue curve is the PPT signal, and the orange curve is the number of circulating particles. Time along the horizontal axis is given in ms

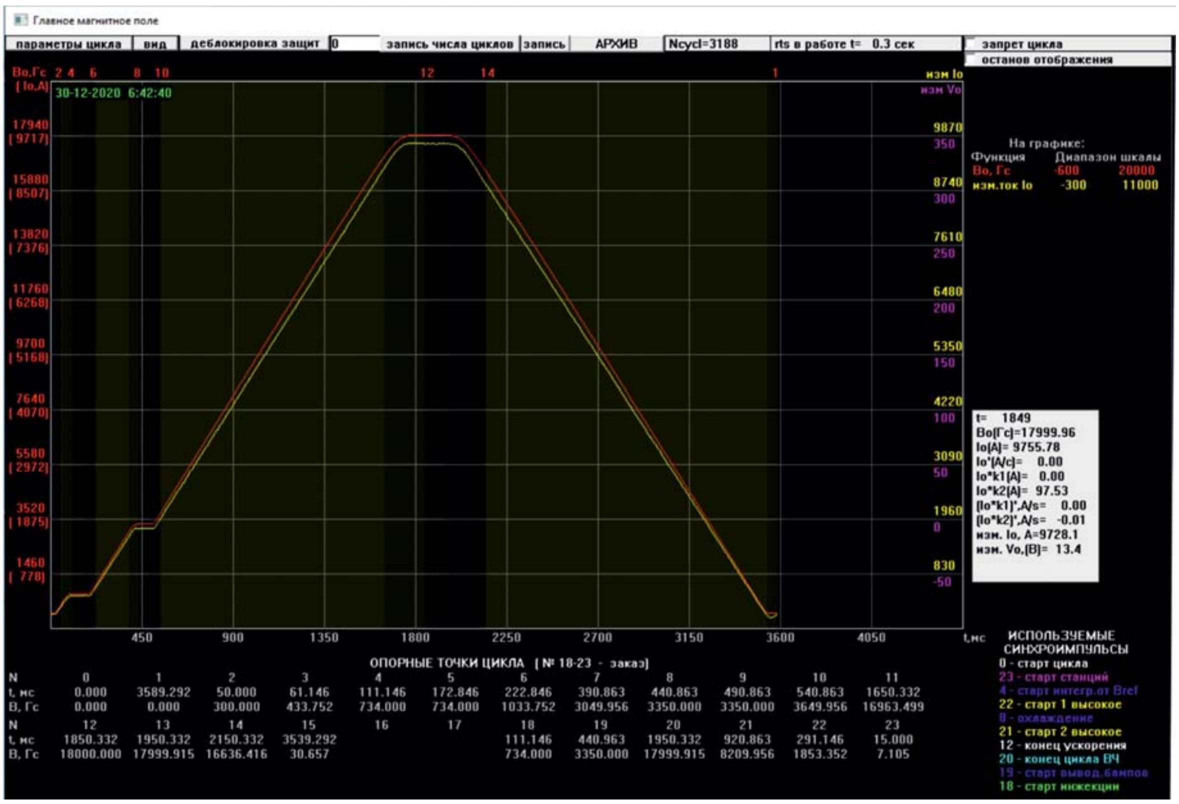

Fig. 2. Design cycle of the magnetic field

Collider. The NICA collider complex is located in building 17. The operation state of the building by the end of 2020 was as follows:

- piles (100%);
- concrete structures (99%);
- metal structure installation (99%);
- facades installation (47%);
- roofs (70%);
- earth works and temporary roads (98%);
- brick and foam block partition walls (63%);
- load-bearing floors (70%);
- finishing works (28%);
- wall drainage system (100%);
- displacement of water supply networks (90%);
- installation of household and storm sewer (15%);
- installation of individual heating units (20%).

A general view of the construction site is shown in Fig. 3. According to the civil works schedule, the deadline for completion of building 17 is December 2021. These terms are primarily due to a significant (50%) increase in construction volume at the stage of project implementation. The coronavirus pandemic has also affected meeting the contract deadlines.

In 2020, the production and testing of equipment for the collider subsystems continued. 80% of the collider's dipole and 10% of the quadrupole magnets have been already produced and tested on the high-technology line for assembling and testing of superconducting magnets.

Fig. 3. General view of the construction site of the collider complex (November 2020)

Cryogenic Complex. The new cryogenic compressor station, for the installation of which a separate building is being built, is one of the key elements of the upgraded cryogenic NICA complex. Civil works are in progress at a high pace and the terms of the contract should be met by mid-2021.

In general, at the end of 2020, the amount of work performed to develop the design configuration of the NICA complex was about 70%.

MPD Project. In 2020, the formation of the MPD collaboration, which numbered over 500 specialists from 39 institutes and 11 countries, was completed. Six collaboration meetings were held to discuss the progress of the project. The agreement process of Memoranda of Understanding documenting the rights and obligations of the participating institutes to construct the facility, including contributions to the general MPD fund, is being continued.

The MPD detector will be installed in a special pavilion in the main building 17 of the NICA complex. Works on the pavilion are mostly completed, and the installation of the incoming equipment has already started. Together with these works, electrical networks (1.2 MV) and their laying, ventilation system, water cooling and heating systems are being installed, technical documentation is being written for the laying of gas lines for MPD detectors and cryogenic lines (gaseous and liquid nitrogen and helium) for the Solenoid. Server units are installed.

Solenoid Magnet. In July 2020, the main parts of the magnet yoke (28 plates and 2 support rings) arrived in Dubna from the Czech Republic after the test assembly performed at the HM Vitkovice production plant. In the shortest time possible, 13 plates and support rings were assembled with the same high accuracy as that one at the plant: deviations of most of the measured geometric dimensions from the control parameters did not exceed 0.2 mm, with rare exception they were 0.5 mm, taking into account a magnetic circuit length of 8970 mm and a diameter of 6670 mm. After long discussions with specialists from the Italian company ASG Superconductors, which is responsible for the quality of the magnetic field in the MPD detector, the "go-ahead" was received to continue the assembly, and on December 25, 2020, the last 28th plate was installed. The final measurements of the geometry of the magnetic circuit again showed the high accuracy of the production of plates and support rings and their assembly into a single whole (Fig. 4).

In November 2020, a complex logistics operation for the transportation of the MPD superconducting solenoid magnet produced by ASG Superconductors company was successfully completed. The valuable cargo was delivered by sea and river to Dubna and placed in the MPD pavilion. In 2021, the magnetic circuit will be partially disassembled to the level of 13 plates, the Solenoid will be installed, and the magnetic circuit with a total weight of about 900 t will be completely re-assembled. After connecting the necessary communications, the Solenoid will be cooled. By the end of April, it is planned to cool it to the temperature of liquid nitrogen, and by September 2021 — to the temperature of liquid helium. After that, a measuring station with 32 Hall sensors will be installed to measure the uniformity of the magnetic field. To obtain the required field uniformity of $3 \cdot 10^{-4}$, it is planned to adjust the currents in the correction coils. After each adjustment it will be necessary to measure the 3D map of the field. At the end of 2021, the installation process of MPD detectors will start.

Time Projection Chamber. Time Projection Chamber (TPC) is the main tracking detector of the MPD experiment. In 2020, the outer TPC cylinder consisting of C3–C4 shells with a

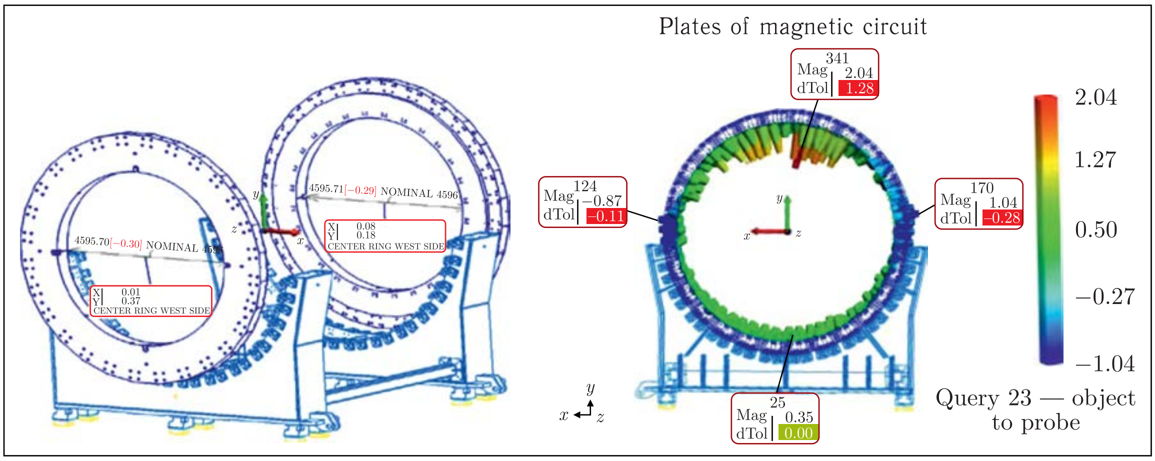

Fig. 4. Measurement results for magnetic circuit assembly

diameter of about 2.8 m and a length of 3.4 m was assembled, the work on the installation of a mechanical structure for fixing thermal shields was completed on the C4 shell. The main elements of the TPC, such as high-voltage electrode, flanges, rods, etc., are ready for assembly; all 24 readout chambers are produced and tested. 113 sets (8%) of front-end electronic cards are produced. The gas system for the TPC is ready. Special ultraviolet lasers and a laser beam distribution system at a small radius have been supplied to JINR, the purchase of units for low-voltage and high-voltage TPC systems developed at CAEN has begun. Cooling system, slow control system, DAQ, tools for installing the TPC into the MPD facility are being developed. The assembly of the TPC will be completed in early 2021, followed by testing the detector using cosmic rays.

Time-of-Flight System. MPD Time-of-Flight (TOF) system is based on multigap resistive plate chambers (mRPC), 40% of mRPCs have already been produced. The assembly of TOF modules and their testing with cosmic rays are underway. All test bench equipment matches the system that will be used in MPD. A part of assembly and installation equipment is being produced. A basic device for transferring and adjusting the TOF modules inside MPD is currently under development. The purchase of devices and subsystem components is almost completed. TOF gas system is already in operation in the test bench.

FHCal. Each of the two arms of the forward MPD detector includes 44 modules with dimensions of $150 \times 150 \times 1100$ cm, which are 42 alternating layers of lead and scintillator assembled in seven longitudinal segments. FHCal modules and readout electronics are ready for operation and are being tested with cosmic rays. The design of the FHCal support platform has been completed and a tender has been announced for its production.

ECal. The uniqueness and complexity of the ECal is in the projection geometry of the detecting modules. At two sites ("Tensor" Dubna and Protvino) in Russia, work on the production of modules for an electromagnetic calorimeter is going according to the plan. One fourth of all modules should be produced in China. In 2020, the PRC government financed the construction of modules that will be produced by several universities in China, headed by Tsinghua University. The entire infrastructure for mass production has already been prepared and work has started. The central part of the ECal consists of 38 400 "towers" with a cross section of 4×4 cm, the assembly of 16 "towers" forms one module. Currently, 300 modules have been produced. This is enough to construct three ECal sectors. By the middle of the year, modules for another three sectors will be produced in Russia, and colleagues from the PRC have planned to produce eight sectors by the end of 2021.

Milestones of the MPD Assembling. Milestones of the MPD assembling are described in the table.

Stage of assembly	Deadline
Preparing to switch on the solenoid magnet (cryogenics, power supply, etc.)	January–September 2021
Magnetic field measurements	October–November 2021
Preparing for installation of detector subsystems	December 2021
Installation of TOF, TPC, electronics platform, cabling	January–June 2022
Installation of a beam tube, FHCal, cosmic ray test system	July 2022
Facility tests on cosmic rays	July–December 2022
Commissioning	December 2022
Beam operation	March 2023

MC Simulation and Data Analysis. Preparation for physical analysis is carried out in five physics working groups of the MPD project. In recent months, large-scale Monte Carlo simulations have been performed at the "Govorun" supercomputer at JINR LIT, each including several million events. A procedure for validating Monte Carlo data has been developed. The NICA special computing cluster at VBLHEP is also regularly used by members of the MPD collaboration to analyze this data and evaluate the performance of the MPD facility. This allowed one to prepare several dozen scientific reports from the MPD collaboration for international scientific conferences in 2020.

BM@N Experiment. The BM@N collaboration includes 250 physicists and engineers from 20 institutes and 10 countries. The aim of the experiment is to study the dynamics of reactions and the properties of hadrons in dense nuclear matter, to investigate the production of strange hyperons close to the threshold and search for hypernuclei in interactions of the extracted beams of the Nuclotron with fixed targets. The project also studies the structure of nuclei at small internucleon distances.

Data Analysis. In 2020, an analysis of the experimental data recorded in the interactions of argon nuclei with kinetic energy of 3.2A GeV with the nuclei of Al, Cu, Sn, and Pb targets was performed. In these interactions the signal of Λ hyperons was obtained in the spectrum of effective masses of (p, π^-) pairs (Fig. 5).

Charged π^+, K^+ mesons, as well as protons and light nuclear fragments ^{3}He, d/^{4}He (Fig. 6), were identified according to the data of the central and external tracking systems and the time-of-flight system. The analysis of the yield of these particles is carried out depending on the kinematic variables.

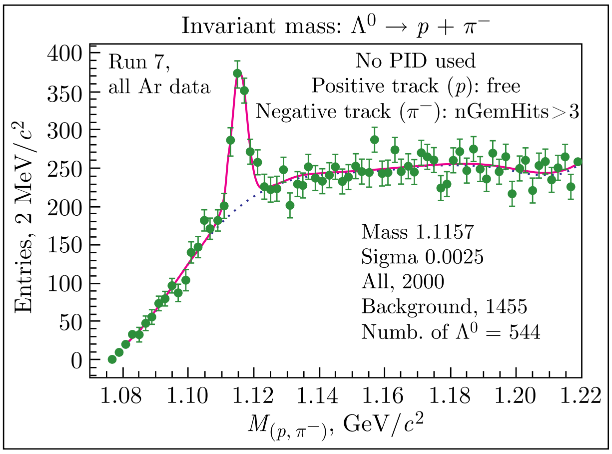

Fig. 5. Signal of Λ hyperons in the spectrum of effective masses of (p, π^-) pairs in interactions of an argon beam with energy of 3.2A GeV with various targets

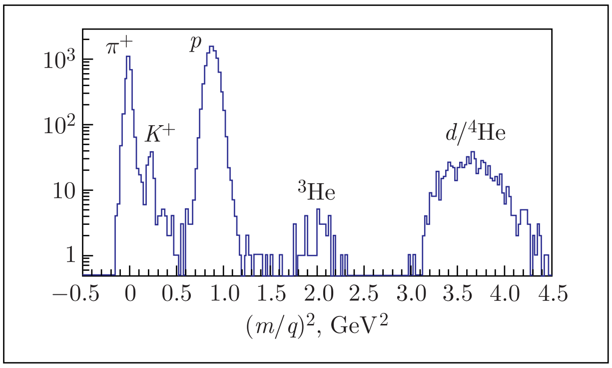

Fig. 6. Identification of π^+, K^+, p, ^{3}He and d/^{4}He by the TOF-700 system in interactions of Ar nuclei with energy of 3.2A GeV with different targets: the square of the mass distribution of identified particles normalized to charge value

A complete analysis of data in the studied interactions of carbon nuclei with a liquid hydrogen target was carried out using the program for studying nucleon correlations. Based on the results of the study, a paper "The Transparent Nucleus: Unperturbed Inverse Kinematics Nucleon Knockout Measurements with a 48 GeV/c Carbon Beam" was prepared and accepted for publication in *Nature Physics*. The quasi-elastic exclusive process $^{12}\text{C} + p \to 2p + {}^{11}\text{B}$ with the registration of all reaction products (Fig. 7) was measured, and the events of proton scattering by correlated nucleon pairs in the carbon nucleus in reactions like $^{12}\text{C} + p \to 2p + {}^{10}\text{B}/{}^{10}\text{Be} + (n/p)$ were identified.

Experimental Facility Status. According to the development programme of the facility for studying the interactions of heavy nuclei, detectors for the complete BM@N configuration were developed (Fig. 8). Tests with cosmic muons of seven GEM detectors with an active region of 163×39 cm have been carried out, and readout electronics for these detectors based on chips by IDEAS company (Norway) have been produced.

The design was developed and silicon microstrip detectors were produced for three planes of the forward tracking detectors FwdSi, which will be installed immediately after the target; readout electronics based on chips by IDEAS company are being produced.

Silicon detectors have been produced for three Si beam trackers and two Si beam profilers, which will be installed before the target to measure the beam track and focus the beam on the target; the design of the detectors was developed, the readout electronics are being produced; a trigger detector is being produced based on azimuthal silicon segments.

A wide-aperture tracking system consisting of four planes of microstrip silicon STS detectors is being developed together with the CBM collaboration members; fast electronics for reading and receiving data for these detectors are being developed; a hybrid tracking system based on FwdSi/STS and GEM detectors has been simulated to determine the detection efficiency of cascade decays of hyperons and hypernuclei in interactions of heavy nuclei.

Three CSC cathode strip chambers of 133×107 cm have been produced in addition to the one already operating for recording tracks for the TOF-400 system; the design of two large

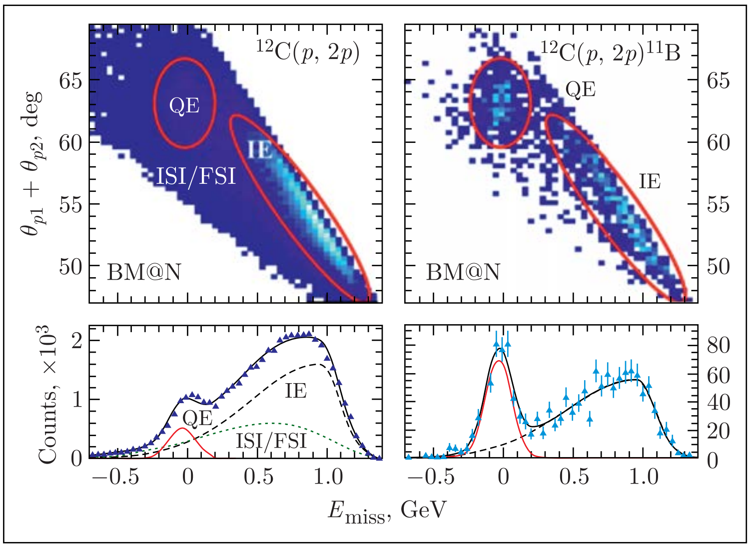

Fig. 7. Quasi-elastic events (QE) identified by the correlation between the missing $E_{\rm miss}$ energy in the ^{12}C rest frame and the angle between two scattered protons in the laboratory frame. The contribution of background events of inelastic interactions (IE) and secondary interactions in the initial and final states (ISI, FSI) is also shown

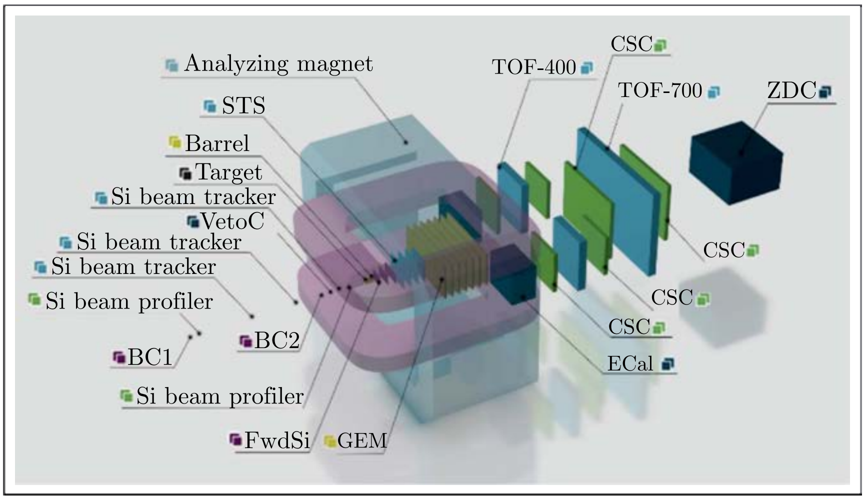

Fig. 8. Complete configuration of the BM@N detectors for studying heavy nucleus interactions

CSC cathode chambers of 219 × 145 cm for the TOF-700 system has been developed. Prospective fast readout electronics for GEM and CSC detectors based on VMM3a chips for high-intensity ion beams (2 MHz) are being developed.

A beam transport channel in the BM@N experimental zone up to the target has been produced and installed; a beam transport channel from thin carbon fiber inside the installation from the target to the ZDC hadron calorimeter to suppress interactions of heavy ions with air is being manufactured; a vacuum target station with several targets has been produced.

In addition to the FHCal calorimeter for measuring the centrality of interactions, a quartz hodoscope has been produced to register nuclear fragments in the region of high-intensity heavy ion beams.

In 2021, it is planned to resume research in the BM@N experiment, and in late autumn, an experiment is planned to be conducted under the research programme for nucleon correlations at short distances using a carbon ion beam.

SPD Project. In 2020, SPD CDR, which met the requirements of the updated physics programme and external conditions, was prepared for consideration by the PAC for Particle Physics. The expected performance of the facility was estimated using Monte Carlo simulation methods.

The following prototypes of detectors have been constructed and tested. A 16-layer prototype of the SPD muon system has been developed, electromagnetic calculations for the magnetic system have been performed. A prototype of the coordinate module of 63 × 63 mm vertex detector was developed based on the use of double-sided silicon microstrip detectors and a flat polyimide cable. The prototypes of the heterogeneous calorimeter were tested using cosmic rays. The first tests with a radioactive source of the VMM3a readout chip for the straw tracker prototype were carried out. A prototype detector based on microchannel plates for the inside part of SPD BBC (Beam–Beam Counter) has been successfully tested under ultrahigh vacuum conditions up to 10^{-10} Pa. The first version of the prototype of readout electronics with the Time-over-Threshold (ToT) option for the external scintillation unit of the BBC has been tested.

A miniSPD stand has been constructed for simultaneous irradiation of various SPD detectors with cosmic muons, which is also used for testing and tuning of systems of data acquisition, slow control, gas distribution, low-voltage and high-voltage power supplies. For the SPD test zone two target stations were developed and produced to locate targets and detectors in the common volume of vacuum of the extracted beam channel, two control rooms were constructed. Work is underway to produce detecting and metrological equipment for a low-energy channel, and simulation is being performed for a high-energy channel.

Three remote workshops of the SPD proto-collaboration were held for the preparation of the CDR and the physical programme; the draft of the SPD constitution was formulated, the formation of the Collaboration continues.

ALPOM-2 Project. The research under the ALPOM-2 project was aimed at finding the analyzing power in inclusive nucleon scattering. Three new approaches to the development of polarimetry — switching on a calorimeter to select high-energy nucleons in the final state using a charge exchange reaction and replacing a hydrogen-rich light target with heavier nuclei — open the way to simpler and more efficient measurements of nucleon polarization in the GeV energy range.

Figure 9 shows the analyzing power as function of the transverse momentum and different thresholds of energy deposit in the hadron calorimeter. It can be seen that the analyzing power increases by a factor of about 2 when the particles with low-energy deposit are suppressed. The new data and their interpretation [1] were highly appreciated at the Jefferson Laboratory (USA), where, on this basis, at the CEBAF complex at JLAB an experiment was approved to measure the ratio of the electromagnetic form factors of the neutron.

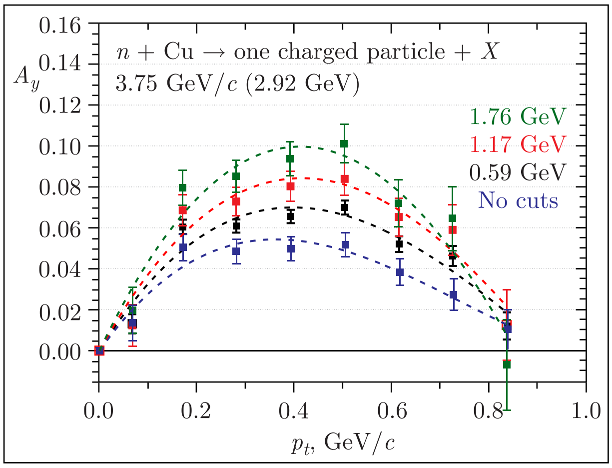

Fig. 9. Analyzing power of A_y in relation to the p_t transverse momentum

PARTICIPATION IN EXPERIMENTS AT EXTERNAL ACCELERATORS

Experiments at the Large Hadron Collider. ***ALICE.*** The main efforts of the JINR group in data analysis and physics simulation were focused on the study of femtoscopic correlations and the production of vector mesons in ultra-peripheral Pb–Pb collisions. In addition, the staff continued to participate in the maintenance and development of the GRID–ALICE analysis at JINR.

The analysis of femtoscopic correlations of K^+K^- pairs for Pb–Pb collisions at 2.76 TeV conducted within the FSI model using a new "Dubna approximation" with traditional parameters for the contributions of the $a_0(980)$ states (Martin, Achasov) and free parameters for $f_0(980)$ has been adjusted and completed [2]. A good correlation was obtained between the experimental data and the model predictions: the values of the $f_0(980)$ meson mass and width,

$M = (990 \pm 20)$ MeV/c^2 and $\Gamma = (39.70 \pm \pm 7.94$ (stat.) ± 11.80 (syst.)) MeV/c^2, correspond to tabular (PDG) data. These results were reported by the JINR group at the ICPPA-2020 conference. The publication is being prepared.

The results of the analysis of femtoscopic correlations for pairs of identical charged kaons in Pb–Pb interactions at 5.02 TeV were compared with the predictions of the EPOS hydrodynamic model. Figure 10 shows the radii of the kaon radiation sources, R_{inv}, depending on the transverse momenta of the pairs, k_T, and the centrality of the events. Solid and dotted lines are model predictions with rescattering of particles in the final state and without it, respectively. It can be seen that the particle rescattering mechanism is important for a correct description of the experimental data. The results were also presented by the JINR group at ICPPA-2020 [3].

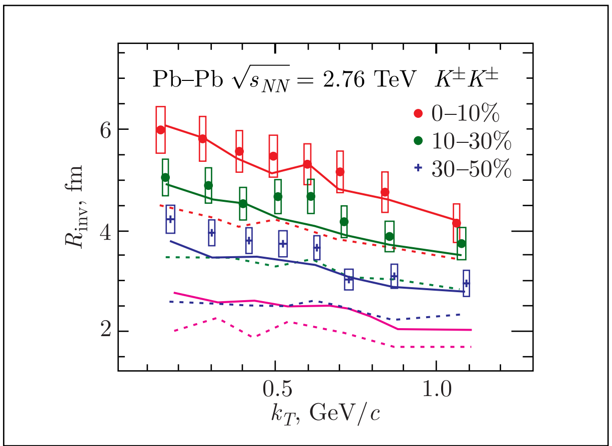

Fig. 10. Radii of sources of pairs of charged kaons depending on the transverse momentum of the pairs. Lines — EPOS model predictions

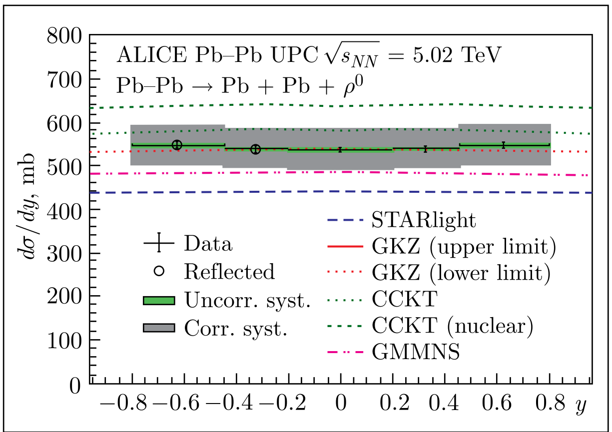

Fig. 11. Comparison of differential cross sections (by rapidity) of coherent production of ρ^0 mesons with predictions of various models

New analysis results of femtoscopic correlations of pairs of identical charged pions and kaons in pp interactions at 13 TeV were obtained separately for spherical ($S_T > 0.7$) and jet-like ($S_T < 0.3$) events (S_T is transverse sphericity). The main result is a decrease in the radii of particle radiation sources with increasing k not only in jet-like but also in spherical events, which indicates a nontrivial collective behavior of particles expected only for nucleus–nucleus collisions with the possible formation of quark–gluon plasma.

The analysis of the coherent production of ρ^0 mesons in ultraperipheral Pb–Pb collisions at 5.02 TeV was completed. Differential cross sections of their production have been determined and comparisons with the predictions of the models have been made (Fig. 11). In addition, the first measurements of the coherent photoproduction of an object similar to a resonant state with a mass of about 1700 MeV/c^2 were made. These results were reported at ICHEP-2020 in Prague and published in JHEP [4].

The JINR group continued active research within the framework of the project on upgrading the ALICE PHOS electromagnetic calorimeter in order to select the optimal photodetector and readout electronics.

ATLAS. Based on the statistics corresponding to the integrated luminosity of 139 fb^{-1} at the LHC at $\sqrt{s} = 13$ TeV, the study of the process of associated production of the Higgs boson with W or Z boson and its decay into a pair of b-quarks was continued, and the signal significance was observed in the channels with W or Z boson of 4.0 and 5.3 standard deviations with expected values of 4.1 and 5.1, respectively. The cross section for the associated Higgs boson production is measured as a function of the transverse momentum of the gauge boson (Fig. 12) [5]. All cross section measurements are in line with the Standard Model expectations, and overall uncertainties range from 30% at large transverse momenta of the gauge boson to 85% at low values. Also, the restrictions have been put on the parameters of the effective Lagrangian sensitive to the modification of the WH and ZH processes, as well as to the decay of the Higgs boson into b-quarks.

Together with colleagues from JINR FLNP, radiation tests of high-speed differential amplifiers were carried out. The results demonstrated good stability up to a neutron fluence value of $\sim 1 \cdot 10^{16}$ cm^{-2}.

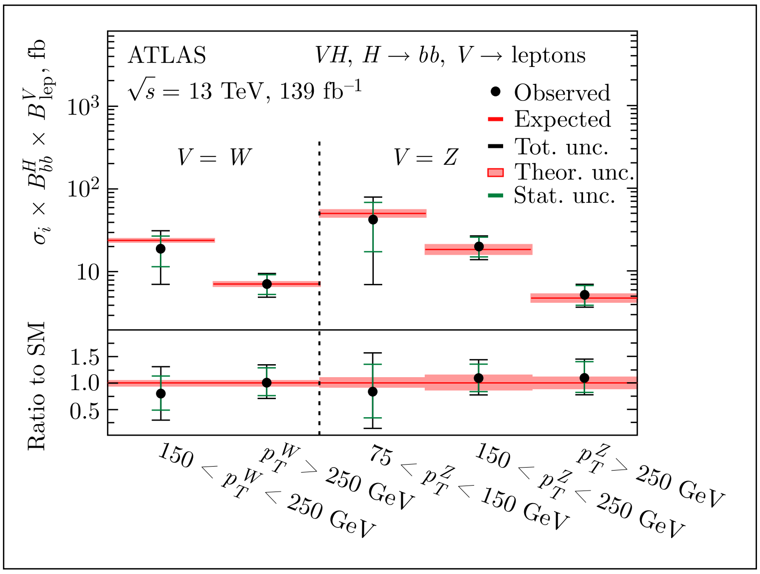

Fig. 12. Measured cross section $VH(bb)$, $V \to$ leptons

CMS. The studies carried out by the JINR group in the CMS experiment in 2020 were aimed at searching for signals of New Physics in a channel with a pair of leptons and multiple production of hard particles, at testing the predictions of extended gauge models with and without lepton flavour violation (LFV), scenarios with additional spatial dimensions, with an extended Higgs sector, as well as at testing simplified descriptions of interactions of dark matter (DM) with SM matter. Precision tests of the Standard Model were carried out in a channel with a pair of muons, as well as in processes of inclusive jet production.

In the channel with a pair of leptons, predictions were made (Fig. 13) for the mass limits of the new heavy boson Z' (resonance with spin 1 in the SSM model) of the extended calibration sector of the SM, which can be achieved when the LHC operates in the high luminosity mode (1000–3000 fb^{-1}) based on the latest CMS data [6]. For the SSM model, the onset of the kinematic limit in the range of 7 TeV/c^2 at energy of 13 TeV was demonstrated, which corresponds to 7–8 TeV/c^2 at 14 TeV.

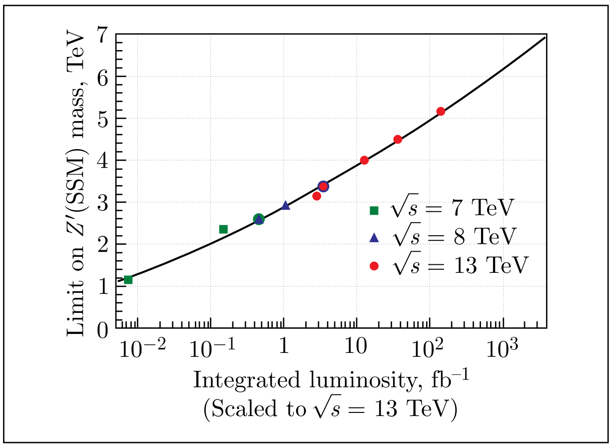

Fig. 13. Observed mass limits for the hypothetical gauge boson Z' in the SSM model at c.m.s. energies of 7, 8, and 13 TeV as function of the integrated luminosity

A generalizing analysis of the results and prospects of searching for multidimensional gravity signals under conditions of limited LHC energy (14 TeV) [7] has been carried out. It has been demonstrated that the LHC has reached the limit of its capability to observe possible signals from quasi-classical multidimensional black holes of RS- and ADD-type.

However, there is still a window of opportunity for the so-called “quantum” black holes (QBH) with a characteristic experimental signature with violation of flavor ($e\mu/e\tau/\mu\tau$). The obtained restrictions on the minimum acceptable values of the QBH mass are from 3.6 to 5.6 TeV/c^2 depending on the model and the number of additional n dimensions (Fig. 14).

In a channel with a pair of oppositely charged leptons, an experimental search for the interaction mediator between the SM fields and the dark matter sector has been carried out. In the absence of a significant excess of the signal over the expected SM background within the simplified DM model (with one DM Dirac particle and one mediator), upper limits on themasses of TM particles and axial-vector and vector mediators have been established [8, 9].

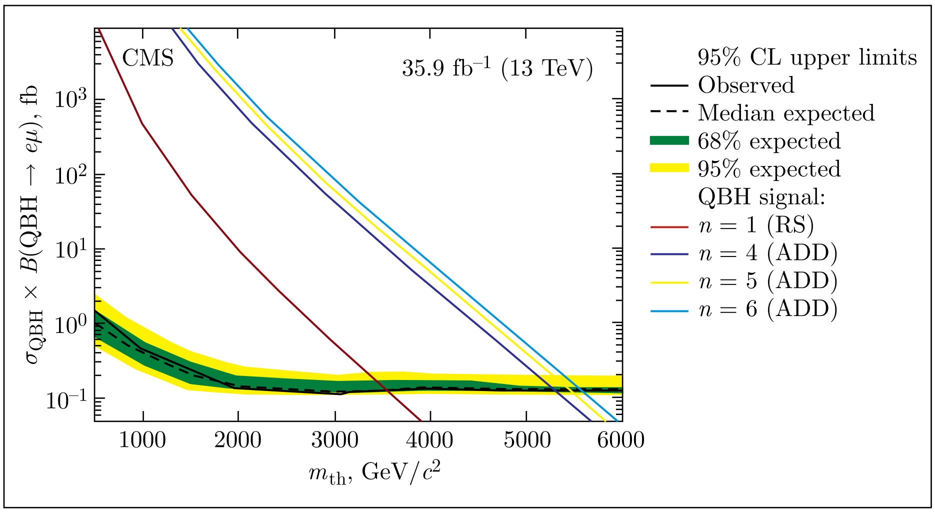

Fig. 14. Upper limits of the cross section for QBH production decaying to the final state $e\mu$ as function of the threshold value of the QBH mass. Predictions are shown for multidimensional QBH models for several choices of the number of extra dimensions: $n = 1$ (RS) and $n = 4$, 5, 6 (ADD)

Within the second phase of the CMS upgrade programme, JINR physicists participated in the refurbishment of the electronics and the CSC cooling system of the ME1/1 muon station. Tests of the assembled chambers were carried out with cosmic rays. An upgraded system of readout electronics of the central hadron calorimeters (HCal) based on silicon photomultipliers (SiPM) was put into operation. A new method for assembling active scintillation elements has been developed and tested on a prototype module of a highly granular end-cap calorimeter (HGCal). Studies were carried out on the radiation hardness of the components and on the optimization of the configuration of this calorimeter.

In 2021, it is planned to utilize the full statistics of the LHC while focusing at finding New Physics and measuring the characteristics of the Drell–Yan process. It is planned to complete the measurement of the forward–backward asymmetry and slopes, as well as to develop a prototype of an automated data quality control system.

Experiments at the CERN Super Proton Synchrotron. *COMPASS.* Measurement of the processes with the production of hadrons in semi-inclusive deep inelastic scattering (SIDIS) of leptons off unpolarized nucleons makes it possible to obtain information on the intrinsic transverse momentum of quarks in a nucleon and on the Boer–Mulders function by measuring the azimuthal modulations of the cross section of these reactions. These modulations have been recently measured in the HERMES experiment at DESY on proton and deuteron targets, as well as in the COMPASS experiment using a CERN SPS muon beam and ^{6}LiD target [10]. In both cases, the amplitudes of modulations $\cos\varphi h$ and $\cos 2\varphi h$ (Fig. 15) demonstrate strong kinematic dependences for both positive and negative charged hadrons. It has been known for some time that the measured hadronic final states in these experiments receive a contribution to SIDIS from exclusive diffraction processes with the production of vector mesons, which is of particular importance at large z values, the fraction of the virtual-photon energy carried by the hadron.

In previous measurements of azimuthal asymmetry, this contribution was not taken into account, since there was no information that it could distort azimuthal modulations. Nowadays a method has been developed for assessing the contribution of exclusive reactions to azimuthal asymmetries. Subtracting this contribution leads to a better understanding of the kinematic effects, and the residual nonzero $\cos 2\varphi h$ modulation gives an indication of the nonzero effect of the Boer–Mulders function.

Spin density matrix elements (SDMEs) were measured in the processes of hard exclusive production of ω mesons using polarized μ^+ and μ^- beams of 160 GeV/c directed to a liquid hydrogen target [11]. The measurement covers the range of invariant masses of the final hadronic state $5.0 < W < 17.0$ (GeV/c)^2 with average kinematics $Q^2 = 2.1$ (GeV/c)^2, $W = 7.6$ (GeV/c)^2 and $p_T^2 = 0.16$ (GeV/c)^2. The measured nonzero SDMEs for the transitions of transversely polarized virtual photons to longitudinally polarized vector mesons ($\gamma_T^* \to V_L$)

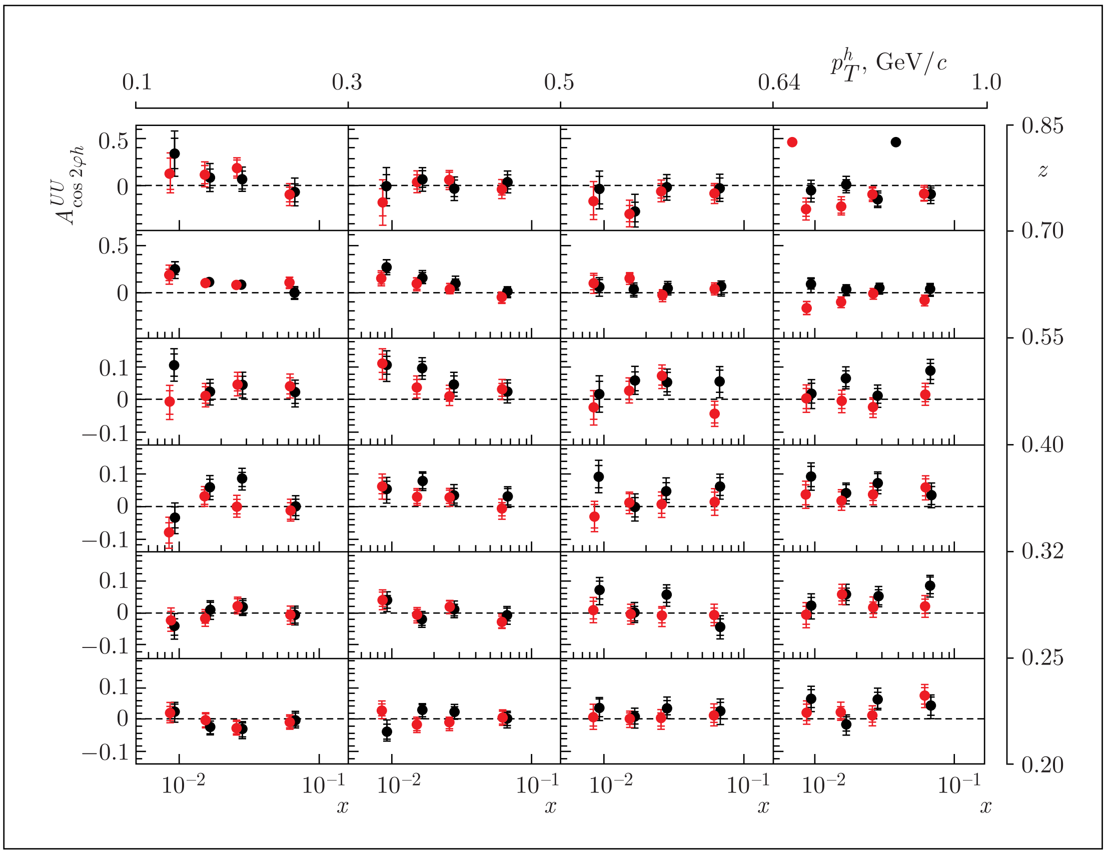

Fig. 15. Semi-inclusive asymmetries $A^{UU}_{\cos 2\varphi h}$ obtained on a ^{6}LiD target

indicate violation of s-channel helicity conservation. A significant contribution of unnatural parity exchange (UPE) transitions is observed, which decreases with increasing of W. The results obtained make it possible to estimate the contribution of the UPE transitions in a model-dependent manner and to evaluate the role of spiral-dependent generalized parton distributions in the processes of exclusive ω-meson production.

NA61/SHINE. The main goal of the NA61 experiment is to study the features of the onset of deconfinement and fireball formation, as well as to find the critical point. The search for the critical point of strongly interacting matter is carried out in the NA61/SHINE experiment by scanning the phase diagram both in temperature and in the baryon chemical potential, which is achieved by measuring at different energies and by studying the dependences on the sizes of colliding systems. The dynamic properties of the energy dependence of the ratio of kaons to pions yields and the slopes of the kaons transverse mass spectra, well known as the "step" and "horn" structures, were studied. In Pb + Pb collisions such structures arise during the formation of a mixed phase of hadronic gas (HG) and quark–gluon plasma (QGP). A fast change of "horn" in the energy dependence of K/π in central Pb + Pb and Au + Au has been found, which is explained as a manifestation of deconfinement in nuclear interactions — the transition from HG to QGP. The NA61/SHINE experiment supplemented these data with new measurements in the $p+p$, Be + Be and Ar + Sc reactions, which showed that the energy dependence of the slope parameter in $p+p$ interactions has the form of a "step" plateau; the data on Be + Be collisions are close to the results for $p+p$ interactions, and the data on Ar + Sc interactions show a dependence on the collision energy qualitatively similar to the data for the $p+p$ reaction, but the plateau is at a much higher level. The results for $p+p$ interactions may indicate the manifestation of deconfinement in small systems.

Due to the plans to increase the intensity of the lead ion beam by more than 10 times, the upgrade of almost all detector systems of this facility has begun at CERN. JINR staff members are upgrading the time-of-flight (TOF) system based on multigap resistive plate chambers (MRPC) with readout strips produced for the

NA61 experiment based on the developments performed at VBLHEP for the NICA project.

NA62 (NA48/2). The NA62 experiment at CERN is aimed at studying the very rare decay of a charged kaon into a charged pion, neutrino and antineutrino. A new result in studying the decay $K^+ \to \pi^+ \nu\nu$ was obtained in the experiment based on data recorded in 2018. Sensitivity to a single event at the level of $1.11 \cdot 10^{-11}$ has been achieved, which corresponds to 7.6 events expected within the Standard Model. Seventeen candidates for signal events with an expected background level of 5.3 events have been experimentally found. Together with the three events previously discovered by the NA62 collaboration in 2016 and 2017 data, this leads to the most accurate measurement of the relative decay probability: $\mathrm{BR}\,(K^+ \to \pi^+ \nu\nu) = (11.0^{+4.0}_{-3.5} \pm 0.3_{\mathrm{syst.}}) \cdot 10^{-11}$, which agrees with the expectations of the Standard Model $(8.4 \pm 0.1) \cdot 10^{-11}$. NA62 will resume registration after a long shutdown of the LHC to achieve the originally planned 10% accuracy.

New results of the analysis of the flavor-changing decay $K^+ \to \pi^+ \mu^+ \mu^-$ were obtained [12]. The preliminary measured values of the form factor parameters are $a = -0.592 \pm 0.015$, $b = -0.699 \pm 0.058$, and the relative probability for the decay $\mathrm{BR}\,(K^+ \to \pi^+ \mu^+ \mu^-) = (9.27 \pm 0.11) \cdot 10^{-8}$. The accuracy achieved in the NA62 experiment significantly improves the available world data on this decay.

The JINR group also takes an active part in the maintenance and development of the facility; adjustment of the production of straw tubes of small diameter and simulation of the efficiency of particle tracks registration are in progress.

NA64. During the reporting period, in the NA64 experiment, which was highlighted in 2019 by the CERN Directorate as one of the most interesting and promising projects from a scientific point of view, the data on the search for the dark photon A' production and decay signals collected in 2016–2018 runs on the SPS CERN e-beam were completely processed and published. The total statistics were composed of $\sim 4 \cdot 10^{11}$ events. The candidates for a signal corresponding to the dark photon signature were not found.

The JINR group is responsible for the development and construction of coordinate detectors based on thin-walled straw tubes for the experiment. The Institute made commitments to produce, equip with electronics and put into operation seven new double-layer chambers made of 6 mm straw tubes with dimensions of 600×1200 mm. In 2020, all planes were produced. Their instrumentation with electronics and testing are underway.

Experiments at RHIC. The VBLHEP employees take an active part in the STAR experiment in Brookhaven to study collisions of relativistic heavy ions. Due to the smallness of the measured difference of relative mass of hypertriton and antihypertriton equal to $(1.1 \pm 1.0\ \text{(stat.)} \pm 0.5\ \text{(syst.)}) \cdot 10^{-4}$, it was concluded that there were no violations of CPT symmetry [13]. The most important scientific priority of the STAR collaboration is the Beam Energy Scan II programme. The goal of the programme is to search for signatures of phase transitions and a critical point in nuclear matter. The planned measurements were performed at five collider energies (7.7, 9.1, 11.5, 14.6 and 19.6 GeV). In 2021, it is proposed to additionally conduct measurements at the sixth energy of 16.7 GeV. Indications that the energy dependence of "net-baryon" fluctuations may undergo significant changes have been obtained. Data analysis is being continued using various models. When studying the plane of the event, a nonzero value of $\nu 1$ was obtained to estimate the magnitude of the direct flow in Au + Au collisions at energy of $\sqrt{s_{NN}} = 27$ GeV.

As part of the preparation of the spin programme at the NICA accelerator complex, the members of the group are developing a ZDC calorimeter prototype based on gallium–gadolinium garnet crystals and absorbers based on W/Cu composite alloys. Prototype assembly and testing with a beam are planned for 2021. In addition, four detectors for a polarimeter based on GaGG crystals with a diameter of 52 mm and a length of 50 mm were designed and produced to be installed at the output of the linear accelerator LU-20.

Experiments at GSI. *HADES.* The main goal of the HADES experiment is to study the properties of dense hadronic matter produced in collisions of heavy ions. The JINR group carried out work on the interpretation of the data obtained in HADES on the production of e^+e^- pairs in the pion–nucleon interaction. The OPER model is being modified to simulate $pp \to pp\pi^+\pi^-$ and $np \to np\pi^+\pi^-$ processes at energies of 3.5 and 4.5 GeV. The employees also participated in the maintenance of the multiwire drift chambers and in the replacement of the recording electronics.

CBM. The CBM experiment will be one of the main experiments at FAIR, which is being constructed. In 2020, the JINR group performed calculations of the magnet with muon detectors of the CBM facility. An estimate of the forces acting on the coils of a superconducting magnet and on a muon detector has been obtained. For the CBM muon system, a trial batch of FEE was produced based on the AST1-1 microcircuit for 50×50 cm straw detector prototype, and radiation tests of the prototype were carried out. A 16-channel board with SiPM readout for a hadron calorimeter was produced and tested.

EVENTS

On April 20–21, the 5th meeting of the BM@N collaboration was held in Dubna. Over 40 reports were presented, and recent results on interactions of carbon and argon nuclei with fixed targets were discussed.

On April 23–24, the 5th meeting of the MPD collaboration was held in a video conference format. Twenty-seven reports were presented on the development of the MPD detector systems and the results of physics analyses.

On August 26, the JINR delegation took part in the solemn opening ceremony of the Years of Russian–Chinese Cooperation in Science, Technology, and Innovation scheduled for 2020 and 2021. An Agreement between the Ministry of Science and Technology of the People's Republic of China and the Joint Institute for Nuclear Research was signed at the event on the participation of China in the construction and operation of the NICA accelerator complex.

On September 15–16, the second meeting of the NICA Cost and Schedule Review Committee (CSRC) was held. The Committee emerged on the decision of the Committee of Plenipotentiaries of the governments of the JINR Member States. The Committee noted considerable progress in the implementation of the NICA project since its last meeting in February and congratulated the team and management on their achievements. The Committee paid special attention to the progress in construction (the MPD hall is almost completed and will soon be ready for magnetic testing) as well as the completion of installation of the Booster and the start of a comprehensive commissioning process.

On October 20–23, VBLHEP hosted an international conference "RFBR Grants for NICA", where the grant holders reported on the results of their studies during the first two years of their work on grants. In addition, the first day of the conference was full of review lectures by leading theorists, presentations by NICA project leaders, by MPD, BM@N and SPD experiment leaders and reports by the representatives of experiments at the FAIR, LHC and RHIC accelerator facilities. The conference programme is available at https://indico.jinr.ru/event/1469.

On October 26–27, the 6th meeting of the BM@N collaboration was held in Dubna. Some of the reports were presented in person and some of them — via video conference. More than 25 out of 40 reports were presented by young employees at parallel sections.

On October 28–30, the 6th meeting of the MPD collaboration was held in a video conference format with 151 participants. Forty reports were presented.

REFERENCES

1. *Basilev S. et al.* Measurement of Neutron and Proton Analyzing Powers on C, CH, CH_2 and Cu Targets in the Momentum Region 3–4.2 GeV/c // Eur. Phys. J. A. 2020. V. 56. P. 26.
2. *Mikhaylov K. (on behalf of the ALICE Collab.).* K^+K^- Correlations in Pb–Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV by ALICE at the LHC // 5th Intern. Conf. on Particle Physics and Astrophysics "ICPPA-2020", Moscow, Oct. 7, 2020.
3. *Rogochaya E., Batyunya B., Malinina L., Mikhaylov K., Romanenko G., Verner K.* Pion and Kaon Femtoscopy in Pb–Pb Collisions at 2.76 TeV in Comparison with EPOS 3 Model Prediction // 5th Intern. Conf. on Particle Physics and Astrophysics "ICPPA-2020", Moscow, Oct. 5–9, 2020.
4. *Pozdnyakov V. (on behalf of the ALICE Collab.).* Vector Meson Photoproduction in Ultra-Peripheral Pb–Pb Collisions at the LHC with ALICE // 40th Intern. Conf. on High Energy Physics "ICHEP 2020", Prague, July 28–Aug. 6;
   ALICE Collab. Coherent ρ^0 Photoproduction in Ultra-Peripheral Pb–Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV // JHEP. 2020. V. 06. P. 035.
5. *ATLAS Collab.* Measurements of WH and ZH Production in the $H \to bb$ Decay Chan-

nel in *pp* Collisions at 13 TeV with the ATLAS Detector. arXiv:2007.02873v1; Eur. Phys. J. C (submitted).

6. *Zarubin A. V., Lanyov A. V., Savina M. V., Shmatov S. V.* Physics with Heavy Dimuons // Articles on Modern Particle Physics / Gen. ed. V. A. Matveev, I. A. Golutvin. Dubna: JINR, 2020. P. 290–317.
7. *Savina M. V., Seitova D.* Program of CMS Experiment to Search for Signals of Multidimensional Low-Energy Gravitation at LHC // Phys. Atom. Nucl. 2021. V. 84, No. 2. P. 149–155.
8. *Zhizin I. A., Lanyov A. V., Shmatov S. V.* Search for New Physics in Dilepton Channel in CMS Experiment at LHC // Phys. Atom. Nucl. 2021. V. 84, No. 2. P. 143–148.
9. *Zhizin I. A., Lanyov A. V., Shmatov S. V.* Search for Heavy Neutral Gauge Bosons in Dilepton Channel in CMS Experiment at LHC // Nucl. Phys. Engineering. 2020 (in press).
10. *COMPASS Collab.* Contribution of Exclusive Diffractive Processes to the Measured Azimuthal Asymmetries in SIDIS // Nucl. Phys. B. 2020. V. 956. P. 115039.
11. *COMPASS Collab.* Spin Density Matrix Elements in Exclusive ω Meson Muoproduction. CERN-EP-2020-169; Eur. Phys. J. C (submitted).
12. *Madigozhin D.* New Measurement of the $K^+ \to \pi^+\mu^+\mu^-$ Decay at NA62 // 9th Intern. Conf. on New Frontiers in Physics "ICNFP 2020", Kolimvary, Crete, Greece (virtual), Sept. 4 – Oct. 2, 2020.
13. *STAR Collab.* Measurement of the Mass Difference and the Binding Energy of the Hypertriton and Antihypertriton // Nature Phys. 2020. V. 16. P. 409.