Annex 3.

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

APPROVED

JINR DIRECTOR

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PROJECT PROPOSAL FORM

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

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

1.1 Theme code - 02-2-1081-2009

1.2 Project code – 02-2-1081-1-2010/2025, 02-1-1081-2-2013/2025

1.3 Laboratory – DLNP, VBLHEP, MLIT, FLNP, BLTP

1.4 Scientific field – High energy physics of elementary particles and heavy ions

1.5 Title of the project/LRIP subproject – ATLAS. Detector upgrade and physics at LHC

1.6 Project/LRIP subproject leader(s) – Bednyakov V.A.

1.7 Project/LRIP subproject deputy leader(s) (scientific supervisor(s)) – Yeletskikh I.V., Cheplakov A.P.

2 Scientific case and project organization

2.1 Annotation

The primary goal of the ATLAS experiment is to explore proton-proton collisions at record-breaking energies (7 – 14 TeV in c.m.f.) at Large Hadron Collider (LHC). The physics program of the experiment includes precision measurements of the Standard model (SM) parameters, investigating limits of its applicability and aims at addressing the fundamental questions of the modern physics such as nucleon structure, top-quark physics, existence of the dark matter particles, possible manifestations of quantum-gravity effects and additional space dimensions, observations of new properties of the known fundamental interactions.

JINR scientists (as in previous years) plan to obtain and publish new results related to all major parts of the ATLAS physics program. New data that are going be collected in collisions of proton beams of high luminosity will allow performing high-precision observations and measurements of rare processes, obtain inputs for improving simulation of the studied processes, extend sensitivity to processes beyond SM. Studies of heavy hadron properties, such as CP-violation in *B*-meson decays, search for new hadronic states in decay spectra, measurements of exotic tatraquark and pentaquark states; top-quark physics, proton structure and modeling of the charm and beauty hadron production are planned. Within the Higgs physics program the studies of its production in association with top-quarks and vector bosons as well as new measurements of Higgs-boson couplings to SM particles will be performed. Searches for beyond SM physics such as manifestations of quantum black holes at TeV scale in pp-collisions are going to continue.

JINR plans to continue active participation in ATLAS software (SW) development and support. These activities, in particular, include development and support of databases for the experiment, trigger system software, support for the event reconstruction and simulation performance in all detector subsystems.

The High-Luminosity LHC (HL-LHC) physics program will be crucial for deepening our understanding of fundamental physics, enabling in particular precision studies of the Higgs sector and enhancing sensitivity to rare processes and potential new physics signals. With unprecedented integrated luminosity, it will offer a unique opportunity to probe the Standard Model (SM) with extreme accuracy and explore connections to open questions in particle physics, astroparticle physics, and cosmology. The HL-LHC legacy measurements of many SM parameters are expected to remain relevant for decades, even during the operation of a next future collider. Until then, our understanding of key SM sectors will rely on the ultimate precision achieved by the HL-LHC experiments.

The HL-LHC conditions require unprecedented detector technologies in terms of radiation hardness, high detection granularity and resolution, precision track timing, and powerful triggers. To meet these challenges, ATLAS pursues an ambitious upgrade program. The JINR group is actively engaged in upgrading several subsystems of the ATLAS detector, making significant contributions to the modernization of the muon spectrometer, liquid argon calorimeter and construction of a novel High-Granularity Timing Detector (HGTD).

2.2 Scientific case

JINR participation in ATLAS physics program

The iternational ATLAS collaboration has been founded over 30 years ago to design and construct the new-generation multi-purpose facility aiming at investigations of the fundamental properties of matter in pp-collisions with energies up to 14TeV at LHC. Currently the ATLAS collaboration involve 2632 authors and overall around 6000 participants from 187 institutions in 42 countries. Since it’s foundation the collaboration designed, produced and tested the highly complex experimental equipments, the unprecedented precision of detector simulation and physics processes in it have been achieved. This led to the discovery of a new Standard Model particle—the Higgs boson—in 2012 and the measurements of its crucial properties. In 2025, the participants of the ALICE, ATLAS, CMS, and LHCb experiments were awarded the Breakthrough Prize in Fundamental Physics for "precise measurements of the Higgs boson's properties confirming the symmetry-breaking mechanism of mass generation, the discovery of new strongly interacting particles, the study of rare processes and matter-antimatter asymmetry, as well as the exploration of nature at the smallest scales and most extreme conditions at CERN's Large Hadron Collider."

A list of works and studies conducted at JINR made a decisive contribution to the results obtained by the collaboration. This list includes:

1. Production, installation and setup of all main detector subsystems including works within detector upgrade
   1.1. Elements of the muon spectrometer
   1.2. Elements of the liquid argon calorimeter and central part of tile calorimeter
   1.3. Calibration of ATLAS calorimeters and their preparation to data taking
   1.4. Contribution to data acquisition and trigger systems development
   1.5. Partcipation in development and production of the High Granularity Timing Detector (HGTD)
2. Development and support of several important ATLAS software componets:

2.1. Development of the distributed computing system at JINR and development and support for detector conditions databases and event databeses;
2.2. Development of the trigger software;
2.3. Development and support of the reconstruction and simulation software for the different detector subsystems, including configuration software, fast calorimeter simulation, tuning of calorimeter simulation using test beam facilities, etc.;

3. Studies within the physics program of the experiment and their implementation during all periods of data taking:

3.1. Higgs boson physics studies, including measurements of cross sections of Higgs boson produced in association with gauge vector bosons (F.Ahmadov, EPJC 81 (2021) 178, JHEP 04 (2025) 075); contribution of JINR scientists to these studies consisted in processing experimental data, validation of new methods for heavy jets identification, participation in development and optimization of machine learning approaches that are used in event selection. Measurements of Higgs boson couplings to heavy quarks in this channel show results consistent with Standard Model (Fig. 1, left). The value of Higgs boson coupling to charm quarks is limited from above at 11.5 times that predicted by SM (Fig.1, right). Besides these, the differential cross sections of the Higgs boson produced in association with gauge weak bosons depending on the transverse momentum of gauge boson have been measured. These results are also in good agreement with SM prediction.

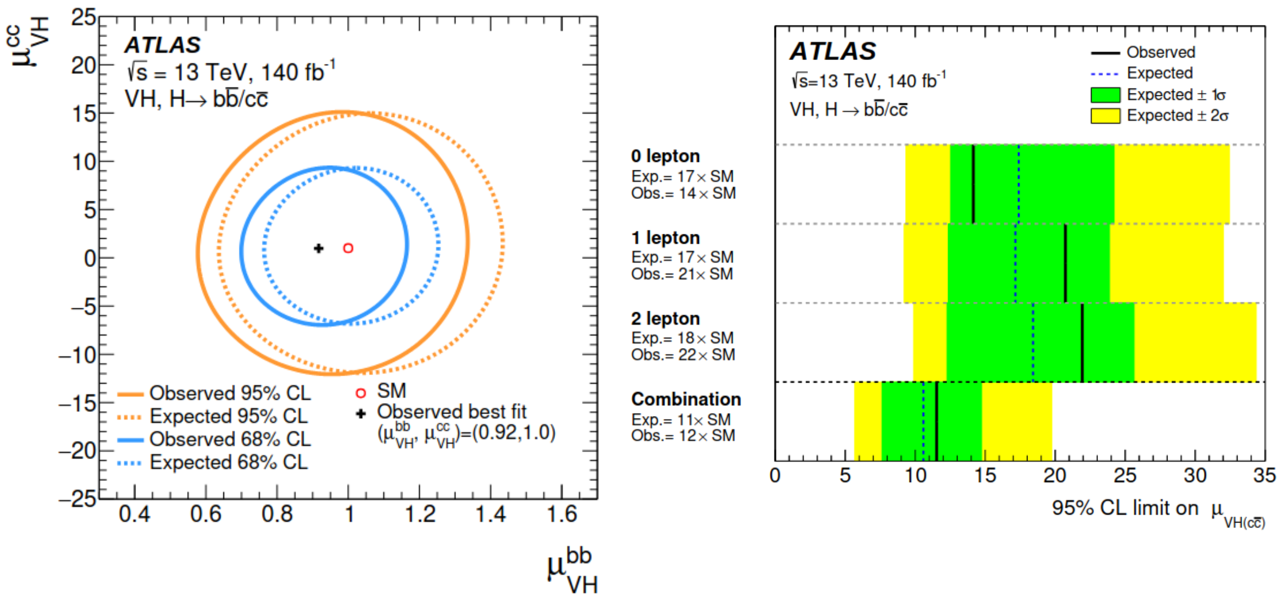


Fig.1. Results of the Higgs couplings to charm and beauty quarks in the production channel with gauge bosons. Left plot shows result of simultaneous fit of there values with one and two standard deviation contours. Right plot demonstrates upper limits on Higgs bosons coupling to charm quarks.

3.2. Studies of Higgs boson produced via gluon-gluon fusion processes associated with W-bosons (E.Ramakoti, Phys. Rev. D 108 (2023) 032005, EPJC-25-04-101). The contribution of JINR physicists to these studies involved optimizing event selection based on kinematic variables for the vector boson fusion channel, comparing the performance of jet reconstruction using different algorithms, and investigating the impact of pile-up on jet reconstruction in the forward region. Figure 2 shows the results of the cross-section measurements for these processes. The obtained values are in agreement with the predictions of the Standard Model.

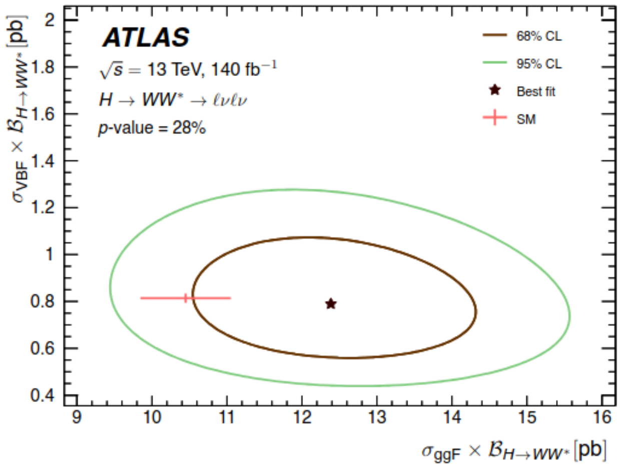


Fig. 2. Results of measurements of Higgs boson production cross sections via vector boson fusion (VBF) and gluon-gluon fusion (ggF). The combined measurement uncertainty is presented (contours showing one and two standard deviations), along with a comparison to the Standard Model (SM) predictions for these cross sections.

3.3. Exploration of top-quark Yukawa coupling via Higgs-boson + top-quarks production processes (I.Boyko, I.Yeletskikh, A.Didenko, O.Dolovova, A.Tropina, *Phys. Part. Nuclei Lett.* **21**, 481–488 (2024), *Phys. Part. Nuclei Lett.* **21**, 615–618 (2024)); researchers at JINR have proposed a set of new kinematic variables that allow for enhancement of the efficiency of *tH* signal selection in the Higgs boson decay channel into two *b*-jets. In addition, deep learning models have been applied for event selection, and a number of new optimization methods for these algorithms have been developed. Modeling of signal and background processes and application of machine learning for event classification conducted at JINR, have demonstrated that the expected tH signal significance in the experiment can be increased by a factor of 2–5 compared to conventional kinematic variable-based (Cut&Count) event selection methods. Furthermore, JINR scientists have developed a new evolutionary algorithm for optimizing hyperparameters of the deep networks used in these studies.

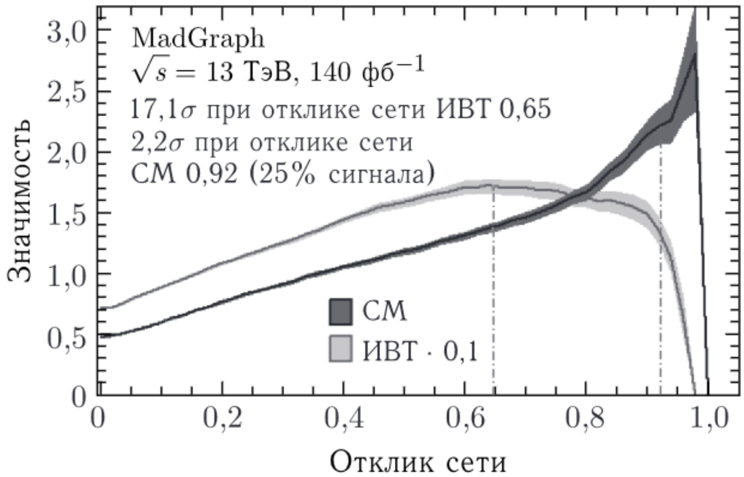


Fig. 3. The expected significance of the Higgs boson signal in the channel of associated production with single top-quark using deep learning for the Standard Model signal and the «inverted top coupling» model (ITC). The expected significance without applying machine learning corresponds to selection with a network response that is equal to 0.

3.4. Development of theoretical models of heavy gauge bosons with masses of the order of few TeV and the search for their signals in dilepton final states (M. Chizhov, V. Bednyakov, I. Yeletskikh, *JHEP* **10** (2017) 182). JINR scientists developed theoretical models of heavy gauge bosons Z* that extend the Standard Model and feature a "tensor-like" interaction with Standard Model particles. Alongside other models of heavy bosons, JINR scientists derived constraints on the parameters of these new models in decay channels involving two muons or two electrons. The study included data analysis, simulation of signal and background events, investigation of contributions from various systematic uncertainties, and statistical analysis of the observed mass spectra.

3.5. Participation in the search for heavy bosons decaying into a W/Z/H boson and a photon (E. Khramov, *Phys. Rev. Lett.* **125** (2020) 251802, *JHEP* **07** (2023) 125). The contribution of JINR physicists to these studies included: data processing, development of software for data analysis, evaluation of systematic uncertainties, statistical analysis of data, deriving new constraints on the parameters of the studied models.

3.6. Participation in the search for observable manifestations of supersymmetry (V.A. Bednyakov, D.I. Kazakov, A.V. Gladyshev, Yu.A. Budagov, D.I. Khubua, E.V. Khramov, S.N. Karpov, A. Soloshenko, *Eur. Phys. J. C* 76 (2016) 565). Within this work, JINR scientists conducted a series of theoretical studies of models incorporating supersymmetry of elementary particles, proposed several directions for possible experimental searches, and carried out work on preparation and analysis of experimental data, estimation of systematic uncertainties, derivation of new experimental constraints on the parameters of the studied models (squarks and gluinos) in decay channels involving leptons, jets, and missing transverse momentum.

3.7. Search for quantum black holes in proton-proton collisions (S.N. Karpov, Z.M. Karpova, Phys. Rev. D 109 (2024) 032010). Researchers at JINR conducted work on the preparation and selection of experimental data in the lepton-plus-jet channel, optimization of search regions, control and validation regions, calculating systematic uncertainties, modeling of signal and background events, tuning of simulation parameters, and statistical analysis of the data. The observed spectra show good agreement with Standard Model predictions. New constraints on the cross-sections and masses of quantum black holes were obtained in the theoretical frameworks of the Arkani-Hamed–Dimopoulos–Dvali (ADD) and Randall–Sundrum (RS) models. The lower limits on the allowed masses are approximately 9 TeV and 7 TeV, respectively (Fig. 4).

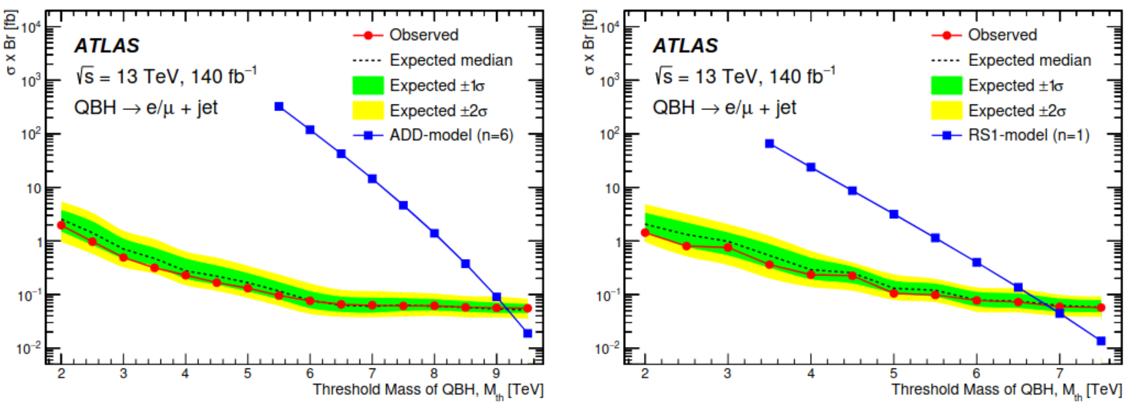
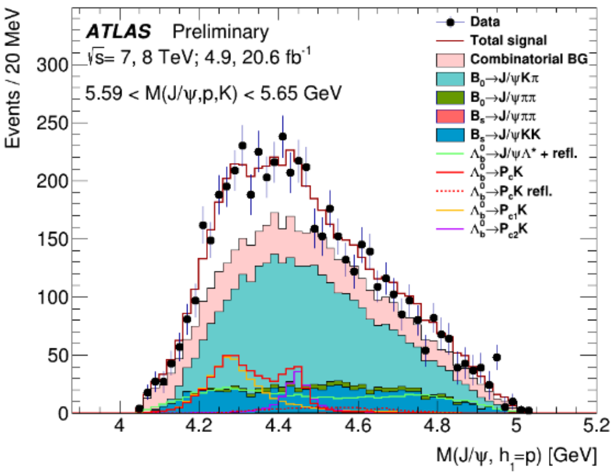


Fig. 4. Limits on masses and cross sections of the Quantum Black Holes in the ADD (left) and RS (right) models.

3.8. Study of the proton structure, including the Intrinsic Charm contribution and the Transverse Momentum Dependent gluon density (G. Lykasov, V. Bednyakov, A. Lipatov, *Phys. Part. Nuclei* **55**, 941–949 (2024); *Phys. Rev. D* **107**, 014022). Theoretical studies of the proton structure at LHC energies have been conducted by researchers at JINR. In particular, new estimates have been obtained for the possible contribution of so-called "intrinsic charm" to the parton distribution functions, as well as the dependence of the gluon contribution on transverse momentum (gluon TMD). A set of experimental measurements with the highest sensitivity to the parameters of these theoretical models has been proposed.

3.9. Study of the properties and spectra of beauty hadrons and light states, including the search for and measurement of properties of pentaquark and tetraquark states (L. Gladilin, A. Vasyukov, I. Eletskikh, doi.org/10.22323/1.377.0010). JINR physicists prepared data, optimized selection of signal event candidates, developed the amplitude analysis method in which simulated events of the phase-space of decays are weighted by analytical matrix elements obtained within the helicity amplitude formalism. Studies were conducted on the possibility of identifying hadronic tracks with momenta of several GeV in ATLAS, systematic uncertainties were evaluated, statistical data analysis was performed, and the parameters of two pentaquark states (P_c(4380), P_c(4450)) were measured in $\Lambda_b^0 \rightarrow J/\Psi Kp$ decays (Fig. 5). A number of new data analysis methods were proposed to enhance sensitivity to the parameters of exotic states, and directions for further research on exotic hadrons at the ATLAS facility were outlined.



Parameter	Value	LHCb value [5]
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ rad	–
$m(P_{c1})$	$4282^{+33}_{-26}(\text{stat})^{+28}_{-7}(\text{syst})$ MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	140^{+77}_{-50} (stat)$^{+41}_{-33}$ (syst) MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	4449^{+20}_{-29} (stat)$^{+18}_{-10}$ (syst) MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	51^{+59}_{-48} (stat)$^{+14}_{-46}$ (syst) MeV	$39 \pm 5 \pm 19$ MeV

Fig. 5. Sugnals of pentaquark states observed in mass spectrum of J/Ψ and a proton in $\Lambda_b^0 \rightarrow J/\Psi kp$ decays (left). Parameters of pentaquark states obtained from ATLAS data and their comparison to LHCb results (right).

3.10. Study of resonant production of the pairs of hidden-charm mesons (I. Yeletskikh, A. Didenko, L. Gladilin, *Phys. Rev. Lett.* 131 (2023) 151902). The ATLAS experiment (alongside LHCb and CMS) observed spectrum of new resonances in the invariant mass of *J/ψ*-meson pairs, as well as in the *J/ψ-ψ(2S)* meson system. These resonances are consistent with the hypothesis of fully charmed tetraquark states. Researchers from JINR proposed an amplitude analysis approach for the observed resonances in *J/ψ*-meson pair production and the *J/ψ-ψ(2S)* system. Analytical matrix elements for the decays were derived, observed spectra of invariant masses and angular variables were analyzed.

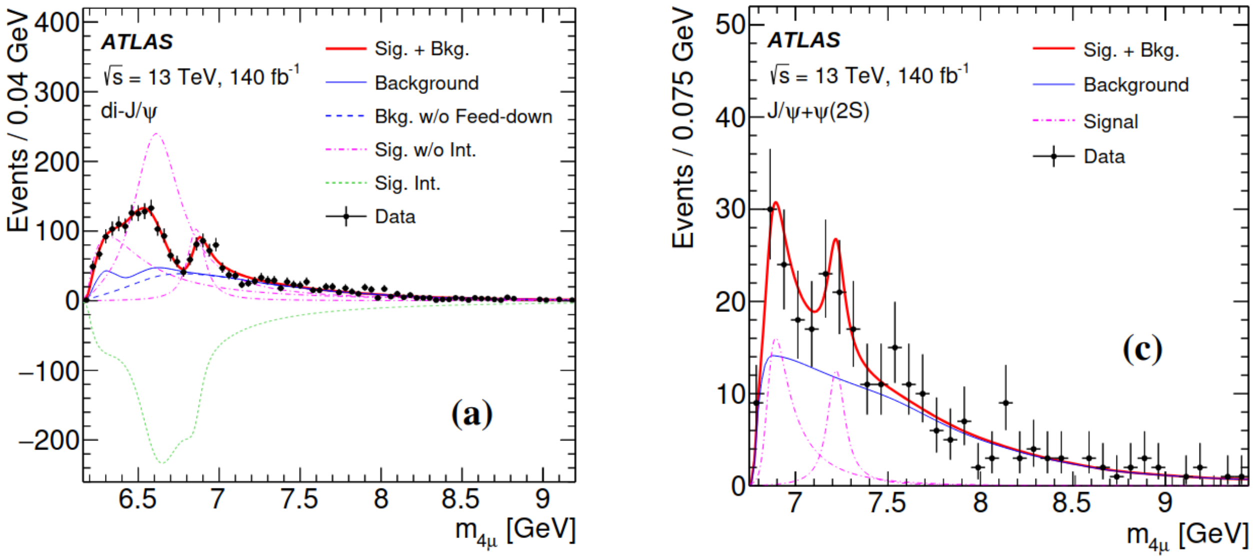


Fig. 6. Spectra of *J/ψ*-meson pair invariant mass (left) and invariant mass of *J/ψ-ψ(2S)* *system (right). Signals of new resonances are shown with masses ~6.6, 6.9, 7.2 GeV.*

3.11. Study of B_c-meson decays (L. Gladilin, T. Lyubushkina, *JHEP* 08 (2022) 087). Data preparation and selection were performed, systematic uncertainties were evaluated, and the ratios of the decay probabilities of Bc mesons in the J/ψ Ds and J/ψ π channels were measured at 0.70 ± 0.11.

3.12. Measurement of associated production of *Z*-bosons and heavy hadronic jets (S. Turchikhin, *JHEP* 07 (2020) 44). The contribution of JINR researchers included data preparation and analysis, evaluation of reconstruction efficiency and heavy jet identification, simulation of the studied processes and fitting of the observed data distributions.

3.13. Measurement of Bose-Einstein correlations in high-multiplicity track events (Yu. Kulchitsky, P. Tereshko, E. Plotnikova, *Eur. Phys. J. C* 82 (2022) 608; *Phys. Lett. B* 758 (2016) 67). JINR researchers conducted an analysis of high-multiplicity track events and minimum-bias (MinBias) events, obtained distributions of Bose-Einstein correlation parameters as functions of charged track multiplicity and performed comparisons with other model predictions. As multiplicity increases a saturation effect in the distributions is observed (Fig. 7.).

3.14. Participation in measurements of total and differential cross-sections of associated W-boson and top-quark pair production (A. Maslennikov, JHEP 05 (2024) 131). The contribution of JINR researchers included supervising students participating in this analysis and validating the quality of the simulated processes under study.

3.15. Participation in data quality control and measurements of reconstruction quality for various detector objects (muons, electrons, photons, hadronic jets) (S. Turchikhin, E. Soldatov, JINST 15 (2020) P04003, JINST 15 (2020) P09015, JHEP 05 (2024) 162)

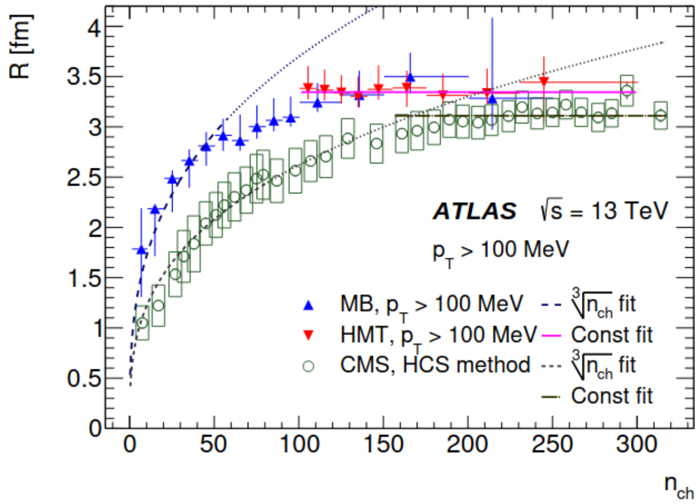


Fig. 7. Dependence of the effective radius of Bose-Eistein correlations on the charged track multiplicity in the event. Comparison between ATLAS and CMS results is presented.

3.15. Development of Monte Carlo generators (SANC, ReneSANCe) and theoretical description of experimentally observed processes (L. Kalinovskaya, E. Dydyshko, V. Ermolchik, S. Bondarenko).

The motivation for continuing work and research within the ATLAS collaboration is based on the key provisions of the long-term development plan of JINR (the JINR Roadmap). In particular, this plan includes the main directions of modern particle physics and the most topical challenges in this field today. Despite the Standard Model's ability to describe experimentally observed phenomena with high precision, even up to TeV energy scales, it is clear that it is not a complete theory. Rather, it represents only a low-energy approximation of a more general theory that incorporates gravitational interaction and provides a description of physical phenomena up to Planck mass energies. The most crucial questions that cannot be resolved within Standard Model have to be addressed by physics research of the nearest future:

1. Are there new fundamental phenomena in the energy range between the electroweak unification scale (a few hundred GeV) and the Planck scale that determine the limits of the Standard Model's applicability? Is there an energy scale for the unification of fundamental interactions, and what is it?
2. What is the source of masses of elementary particles and what causes their hierarchy in the Standard model? Is there a ‘fine tuning’ of the Standard Model parameters?
3. What is the nature of dark matter and dark energy? Is it possible to explore them at particle colliders?
4. What is the source of baryonic asymmetry in the universe?
5. Are there extra spacial dimensions and fundamental forces and symmetries related to them?

In addition, the study of proton structure at LHC energies remains highly relevant. These unique energies make research on known Standard Model particles, especially massive ones like the top quark and the Higgs boson, a particularly significant direction. A thorough investigation of these objects will not only refine their key properties but also pave the way beyond the Standard Model.

Answers to these and a number of related questions are the primary objectives of elementary particle physics in the nearest future. The most promising research directions are associated, on the one hand, with accelerator physics (including increasing energies, as well as improving reconstruction accuracy and accelerator luminosities) and, on the other hand, with observational astrophysics. Increasing accelerator energies up to hundreds of TeV will enable direct searches for new physics at corresponding scales. Boosting the luminosity of existing accelerators and improving the precision of reconstructed processes will allow searches for manifestations of new physics through corrections to observed phenomena—such as coupling constants and phases between particles.

JINR plans for partcicpation in physics analysis during 2026-2030

During the next five years the major planned directions of JINR team participation in ATLAS collaboration (aside of detector upgrade) are the following:

1. Contributions to detector exploitation and management (M&O, Shifts, Common Operation Tasks);
2. Physics studies (data preparation and processing, experimental analyses, modeling, theoretical support);
3. Participation in software development and support;

JINR participation in detector exploitation and management

JINR staff will continue to participate in the operation of the ATLAS experimental facility. These activities include shifts at control and monitoring stations, on-call expert shifts, data quality control tasks, and more.

1. Hadronic Scintillator Calorimeter Operation:
   JINR plans to continue its involvement in managing the operation of the hadronic scintillator calorimeter (I. Minashvili);
2. Liquid Argon Calorimeter Operation:
   JINR will maintain its participation in the operational tasks of the liquid argon calorimeter. The institute's responsibilities include the repair and recommissioning of electronics modules, monitoring readout channel quality, and taking part in on-call expert shifts;
3. Distributed Computing Support for ATLAS:
   In the coming years, JINR staff will continue to support distributed computing for the ATLAS experiment;
4. Safety Operations at the detector:
   JINR intends to remain involved in safety-related operations at the facility. JINR staff (V. Batusov, I. Kostyukhina, M. Shiyakova) will continue to serve as Shift Leaders in Matters of Safety (SLIMOS). Additionally, they will oversee radiation safety and manage access control in the ATLAS cavern;

JINR participation in physics research

In the coming years JINR team plans to continue its participation in all major areas of the ATLAS physics program. The analysis of data collected by the detector in 2022–2025, as well as data expected to be collected in the future, will significantly enhance sensitivity to observable parameters or set new limits on their values in a range of physics studies. The main research directions are as follows:

1. Search for Higgs boson production in association with top quarks (N. Guseynov, I. Boyko, A. Didenko, O. Dolovova, A. Tropina, et al.) in the Higgs boson decay channel to a pair of b-jets. This study aims to obtain and analyze data directly sensitive to the magnitude and phase of the Higgs boson-top quark coupling constant. The Standard Model (SM) predicts a phase difference between the *WH* and *tH* coupling constants, leading to destructive interference among various contributions to the Higgs boson production in association with top quarks and a suppression of the cross-section. Possible beyond-the-SM (BSM) corrections to this phase

difference could increase the observed cross-section by several times. The ATLAS Run 3 data is expected to fully exclude models of "inverted *tH* interaction" and significantly improve (in combination with other experimental channels) the precision of measuring the relative phase of the *WH* and *tH* coupling constants. JINR researchers will perform simulations of the signal process ($pp \rightarrow tH$) and background processes ($pp \rightarrow ttH$, $pp \rightarrow ttbb$, $pp \rightarrow ttZ$, etc.). A detailed study and comparison of their physical properties will help identify kinematic parameters, reconstructed by the experimental setup, that enhance the sensitivity to the signal in data selected based on these characteristics. A key part of this work will involve investigating systematic uncertainties in simulations, which directly affect the accuracy and reliability of the results. Active efforts are underway and will continue in developing and applying machine learning (ML) methods for $pp \rightarrow tH$ signal analysis. Previous JINR publications have shown that approaches like boosted decision trees and deep neural networks (DNNs) can improve the expected statistical significance of the $pp \rightarrow tH$ signal by several times compared to conventional data selection methods. However, it was also understood that existing ML applications require further optimization for experimental data analysis. A critical aspect is the proper tuning of hyperparameters (e.g., the number of hidden layers, neurons, synapse structure, training algorithm settings, input variables, etc.). Planned developments include stochastic optimization methods for hyperparameter tuning. The proposed deep learning models will account for variable input dimensions and (in some cases) negative event weights. Unlike conventional loss functions (e.g., cross-entropy), the optimal efficiency criterion for ML may be an experimentally observable quantity, such as the maximum achievable signal significance. New neural network training methods will be developed, capable of handling such criteria without relying on gradient-based approaches (e.g., backpropagation) or requiring network differentiability. Novel overfitting control criteria will be introduced, based on comparing experimental observables between training and test datasets, enabling direct estimation of systematic uncertainties related to ML methods.

2. Study of Higgs boson production via gluon and vector boson fusion (E. Ramakoti). As with other Higgs property measurements, this study is an important SM test and sensitive to potential BSM deviations. JINR's contribution will focus on optimizing event selection via kinematic variables and investigating ML methods for this analysis.
3. Measurements of Higgs boson production cross-sections in gauge boson-associated channels (F. Akhmadov). New data are expected to significantly refine previous measurements, particularly in improving the precision of Higgs boson coupling constants with beauty and charm quarks. Planned JINR contribution consists in studies of heavy jet tagging efficiencies, data processing and validation, optimization of machine-learning models hyper-parameters w.r.t. the signal and background selection efficiencies.
4. Search for manifestations of BSM physics models, particularly quantum black hole (QBH) production in the lepton+jet channel (S. Karpov, Z. Karpova). Analyzing new data in this channel will provide new constraints on QBH model parameters and represent an important test of both the Standard Model's validity at multi-TeV energies and the quality of existing simulation methods. It is planned that JINR physicists will work on optimizing data selection in decay channels with electron + jet and muon + jet, modeling background and signal processes in the Arkani-Hamed–Dimopoulos–Dvali (ADD) and Randall–Sundrum (RS) models, fitting free parameters of the simulated spectra in control kinematic regions, validating the results in validation regions, estimating systematic uncertainties of the modeling, performing statistical data analysis, and deriving new limits on the cross-sections and masses of the predicted signals.

5. Investigation of excited B_c-meson properties and spectra (T. Lyubushkina) is of significant interest for understanding different heavy quark flavour interactions and their bound states. Using existing and future data from the ATLAS experiment, a search will be conducted to identify and measure the parameters of such states in the mass range m(B^*_c)-m(B_c) = 0-150 МэВ. This search requires reconstruction of soft photons in the decays $B^*_c \rightarrow B_c\gamma$, detected via their conversion into electron-positron pairs in the detector material. To accomplish this task, the following steps are planned: application of the Event Picking Service databases and related services, developed and maintained by JINR scientists, development of dedicated algorithms for reconstructing soft photons in selected events, validation of these algorithms and analysis of associated systematic uncertainties. JINR researchers will simulate signal and background events, process the data and optimize event selection criteria, develop code for fitting the observed spectra, evaluate systematic uncertainties related to track reconstruction efficiency, momentum measurement accuracy, detector trigger efficiency, muon reconstruction and identification efficiency, accuracy of $B_c \rightarrow J/\Psi\mu X$ decay modeling, etc.
6. Measurement of the CP-violating phase in Bs-meson decays (V. Lyubushkin). CP violation in $B_s \rightarrow J/\Psi\varphi$ decays arises from interference between direct decay and decay with B_s–*anti*-B_s oscillations. The Standard Model predicts a small phase (φs ~ -0.04), determined by Cabibbo-Kobayashi-Maskawa mixing angles. BSM effects could substantially alter this phase. Current experimental measurements of *φs* show discrepancies, which requires further precise measurements. JINR physicists will participate in fitting observed spectra aiming at determinition of B_s and anti-B_s mesons mixing, systematic uncertainties estimation in the analysis. One of the important parts of this study is the identification (tagging) of B_s and anti-B_s mesons. It is planned that JINR team will take part in development of new tagging algorithms to increase sensitivity to the parameters under measurement.
7. Study of tetraquark and pentaquark states in B-meson decays (A. Vasyukov, I. Yeletskikh). Recent experimental efforts focus on hidden-charm tetraquarks (Z_c, Z_{cs}) and pentaquarks (P_c, P_{cs}). Pentaquark contributions to Λ_b-baryon decay chains were first observed in 2015 by LHCb and confirmed by ATLAS. Since 2014, several experimental collaborations have been investigating the Z_c and Z_{cs} states. Currently, the main objectives of these experimental studies are: precision measurements of their parameters, reliable determination of their spins and parities, discovery of new decay channels and states in their spectra. These studies could shed light on the internal structure of pentaquarks and tetraquarks, as well as the interactions defining their spectra. The complexity of these studies arises from the complexity of background processes, the need to account for interference effects between signal and background decay chains, a significant contribution from combinatorial background, requiring careful estimation, the kinematic proximity of different exotic (tetraquark or pentaquark) states, making their separation difficult. To address these challenges, the following approaches will be developed: multidimensional amplitude analysis, data-driven methods for combinatorial background estimation, analysis of partially reconstructed decay chains, etc. Decays such as $B_0 \rightarrow J/\Psi K\pi$, $B_s \rightarrow J/\Psi KK$, $\Lambda_0 \rightarrow J/\Psi Kp$ will be modeled, including known intermediate resonances (K^*, f, φ, Λ^*) representing background, new tetraquark and pentaquark resonances as signal processes in different spin-parity hypotheses. JINR researchers will generate phase-space MC events and weight them according to the derived matrix elements. Data selection will be optimized based on signal process properties. A new «kinematic transfer» method will be developed, extrapolating background-dominated events into the signal region. A dedicated study will be performed for events with J/ψ and three hadronic tracks, representing one of the

sources of combinatorial background. A new fitting framework will be implemented implementing new approaches mentioned above. Systematic uncertainties will be evaluated, including simulation inaccuracies, theoretical uncertainties, event reconstruction inefficiencies. Due to the large number of free parameters in the decay model, scans of parameter-space profile will be used for robust error estimation.

8. Investigation of double charmonium production and fully charmed tetraquark states (I. Yeletskikh, A. Didenko). In 2021–2022, three major LHC experiments reported the observation of a spectrum of resonances near the production thresholds of J/ψ-meson pair and J/ψ-$\psi(2S)$ system with masses around 6.6, 6.9, and 7.2 GeV. The existence of these states is consistent with the hypothesis of fully-charmed tetraquarks. Refining the study of these states requires improved modeling of their spectra, angular distribution analysis to determine their quantum numbers (spin-parity). Since precision of these measurements is dominated by statistics of the selected J/ψ-pairs and J/ψ-$\psi(2S)$ candidates, the analysis of new ATLAS data will significantly enhance sensitivity to parameters of new resonances. JINR scientists will derive analytical matrix elements for decays of fully-charmed tetraquarks to J/ψ-pairs and J/ψ-$\psi(2S)$ system in different spin-parity hypotheses, develop data selection and analysis frameworks, perform modeling of J/ψ-pair and J/ψ-$\psi(2S)$ production via single-parton and double-parton interactions in proton-proton collisions, simulate spectra of dominant background processes, evaluate systematics for both signal and background distributions. It is planned to perform amplitude analysis of selected events based on multidimensional fits of mass/angular spectra, extract resonance parameters with improved precision, address production mechanisms and internal structure of the tetraquark candidates.
9. Measurement of production cross-sections and branching ratios for heavy hadrons in various decay channels, search for new decay channels of hadrons and gauge bosons (e.g., $W \rightarrow J/\Psi\pi$). This is an important task for understanding the production and hadronization mechanisms of heavy hadrons. JINR physicists are expected to participate in data preparation and selection, estimation of systematic uncertainties, simulation and fitting of observed spectra, and statistical data analysis.
10. Study of the Proton Structure at LHC Energies (G. Lykasov), in particular, investigations of the intrinsic charm contribution to parton distribution functions (PDF) as well as studies of the transverse momentum dependent gluon distribution in proton (TMD). Measurements of differential production spectra of electroweak vector bosons in association with heavy jets, angular distributions in the production of heavy beauty and charm hadrons, as well as heavy jets, will help extract parameters of theoretical models describing the proton structure. The contribution of JINR researchers consists in the development of theoretical models for the proton structure, comparing the predictions of these models with data from various experiments, predicting observable effects that may be detected in different experimental channels at the ATLAS experiment.
11. New measurements of differential cross sections for single and paired Z-boson production in decay channels into neutrinos and photons $(Z \rightarrow \nu\nu\gamma)$ or neutrinos and charged leptons $(ZZ \rightarrow \nu\nu\ell\ell)$ (E. Soldatov). The planned contribution of JINR physicists involves modeling «Triple Gauge Coupling» (TGC) processes, statistical data analysis, and deriving limits on anomalous and neutral TGC parameters.
12. Participation of JINR scientists in data quality control and quality control for different object reconstruction in detector will continue.

JINR's Contribution to ATLAS Software Development and Theoretical Support

In recent years, JINR's involvement in ATLAS software development and support has expanded considerably. The efficiency of reconstruction, simulation, triggering, event selection, and analysis software directly impacts physics results. For 2025–2029, JINR plans to continue and expand its contributions in key areas:

1. Development of the ReneSANCe Monte Carlo generator, including calculations of radiative corrections and refined modeling of LHC physics processes, such as polarized *W*-boson production in proton-proton collisions.
2. Theoretical studies of proton structure at LHC energies, including intrinsic charm and transversely polarized gluon contributions to observable processes, e.g., calculations of angular asymmetries in *D*-meson pair production.
3. Development and maintenance of the EventIndex database, critical for analyses requiring non-standard reconstruction (e.g., excited B_c-meson studies). Tasks include data integrity checks, duplicated event handling, registered by different triggers.
4. Support for ATLAS calorimeter software, including response simulation, calibration, and detector condition database maintenance.
5. ATLAS trigger system software support.
6. Development of statistical analysis tools, such as a pseudo-data generator for multidimensional kinematic spectrum analysis.
7. Creation and testing of multivariate analysis software, including custom mathematical models, machine learning algorithms, and neural network training tailored to high-energy physics data.

This comprehensive program ensures JINR's continued leadership in ATLAS physics and software contributions.

JINR participation in ATLAS upgrade program

The ATLAS and CMS experiments at LHC are unique drivers of fundamental understanding of nature at the energy frontier. With a collected luminosity of $3ab^{-1}$ per experiment, ATLAS and CMS can achieve, in particular *[ATL-PHYS-PUB-2025-018, CMS-HIG-25-002]:*

1. The observation of the $H \rightarrow \mu^{+}\mu^{-}$ and $H \rightarrow Z\gamma$ rare processes and the determination of the corresponding couplings with a precision of 3% and 7%;
2. The measurement of the other main Higgs boson couplings to fermions and vector bosons with a precision between 1.6% and 3.6%;
3. The observation of the SM di-Higgs-boson production with a significance exceeding 7σ;
4. The measurement of the Higgs boson trilinear self-coupling λ_3 with a precision better than 30%;
5. The measurements of extremely rare processes, such as simultaneous four-top-quark production, with a precision of 6%;
6. Constraints on anomalous interactions between the top quark and the Z boson, probing new physics at energy scales up to 2 TeV, etc.

To achieve such accuracies, a large statistical sample of experimental data is required, so efforts are being made to increase the LHC luminosity, which necessitates the modernization of the detectors and elements of the CERN accelerator complex. The first stage of the detector modernization (Phase 1) was carried out during the second Long Shutdown of the LHC (LS2), when instantaneous luminosity of the LHC more than doubled (Fig. 8); after LS3 and completion of the Phase-II of the LHC and detector upgrades, the luminosity will increase fivefold compared to the nominal value of 10^{34} cm^{-2} s^{-1}.

<u>Phase-I of the ATLAS detector upgrade</u>

The preliminary schedule for the LHC project, updated in March 2025, is presented in Figure 1.

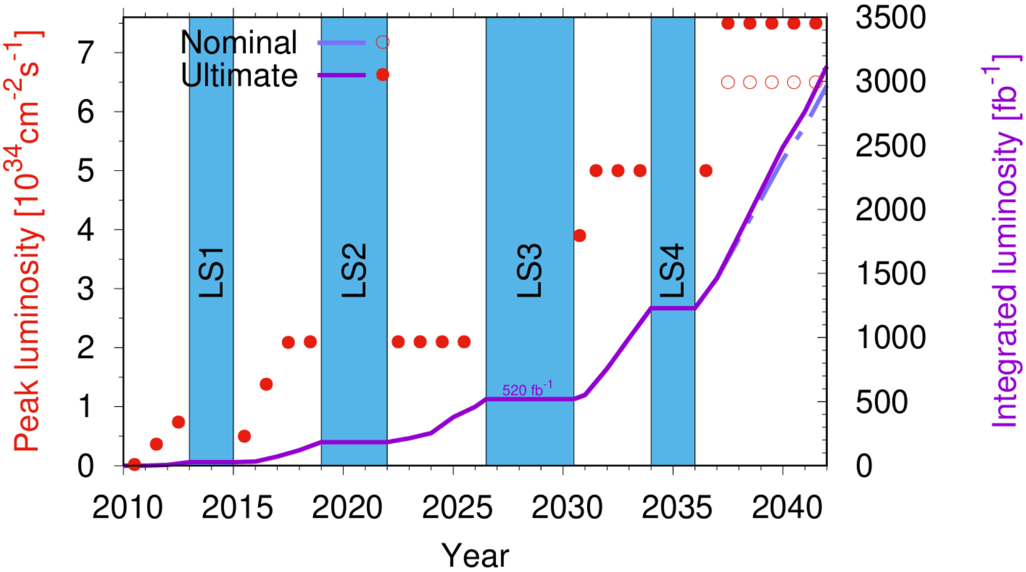


Fig. 8: A preliminary schedule showing the delivered peak (integrated) luminosity in red (purple) as a function of year. The periods of long shutdown are shown by the blue bands. The nominal scenario (light purple, open red circle) in Run 5 corresponds to an average number of *pp* interactions per bunch crossing (pileup) of about 173, and the ultimate scenario (dark purple, solid red circle) corresponds to a pileup of 200. Both Run 5 scenarios include heavy ion data taking.

The Phase-I of the ATLAS detector upgrade was completed by the end of 2022. The JINR team played important role in realization of the New Small Wheel (NSW) project for the Muon spectrometer, we made contributions in development of the Demonstrator for the Tile calorimeter readout electronics. For the Tile subsystem we also performed radiation tests of new scintillators and contributed to the production and assembly of the new modules. Our engineers designed baseplane for readout crates and designed preshaper board for the LAr trigger electronics. The radiation tests were done for readout boards, cables and optical patch-cords at the IBR-2m pulsed neutron reactor.

Muon spectrometer (Phase-I)

The most significant contribution of the JINR within the Phase-I of the ATLAS Upgrade project was made for the upgrade of the Muon spectrometer. The JINR group was responsible for the fabrication and testing of Micromegas modules for the outer part of the large sectors of the NSW - LM2 (see Fig. 9). All 64 (plus 4 additional spares) readout panels with a total area of 384 m^2 out of 1200 m^2 NSW were manufactured and tested at JINR. Using drift panels produced at Aristotle University of Thessaloniki, Greece (AUTh), the group also produced and tested 32 Micromegas modules (plus 1 spare module).

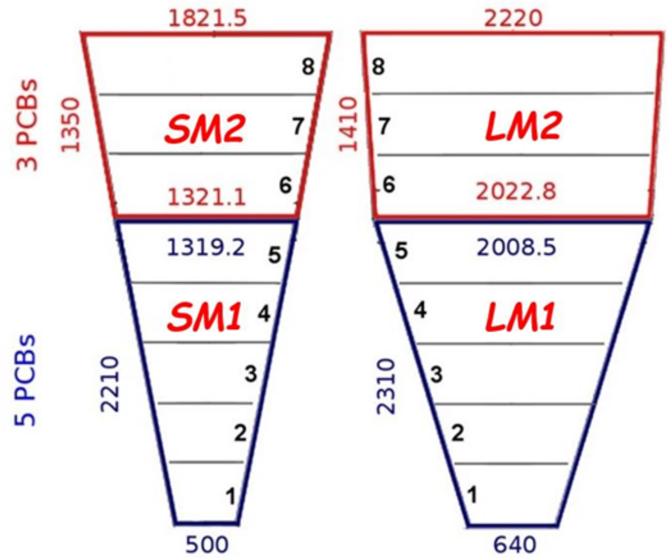


Fig. 9. Schematic view of small and large sector wedges of NSW. Dimensions are given in mm.

To fulfill these obligations two specialized workshops were built in the Dzhelepov Laboratory for Nuclear Physics (Fig. 10). The first line was used to produce and test MM chambers/quadruplets for NSW of the ATLAS Muon Spectrometer, the second line is the Micromegas full production cycle line used for R&D and production of small batches of MM detectors for various applications (Fig. 11).

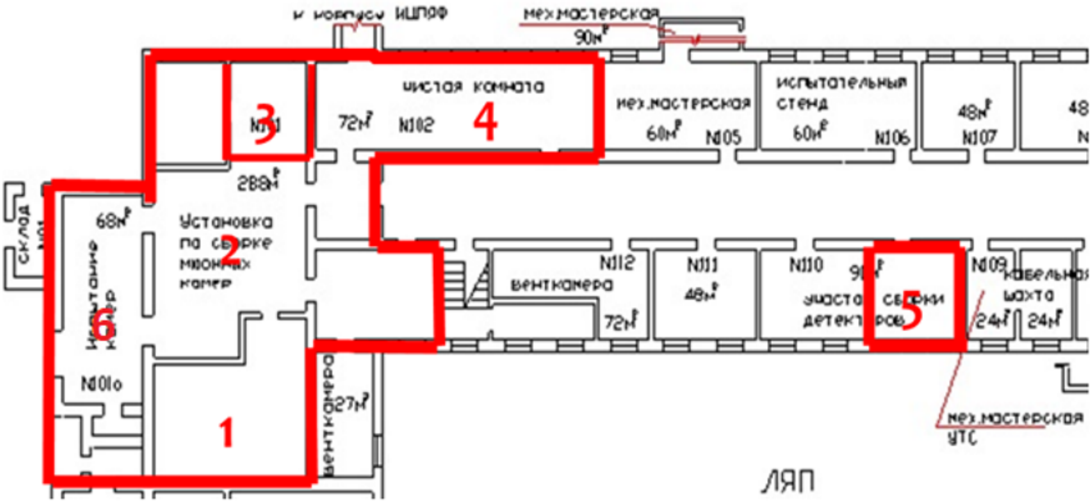


Fig. 10. MM production lines: 1 – panel production, 2 – cosmic stand, 3 – gas leak tests, 4 – quadruplets assembly and testing, 5 – room for panel washing, 6 – “Dubna bulk lab”.

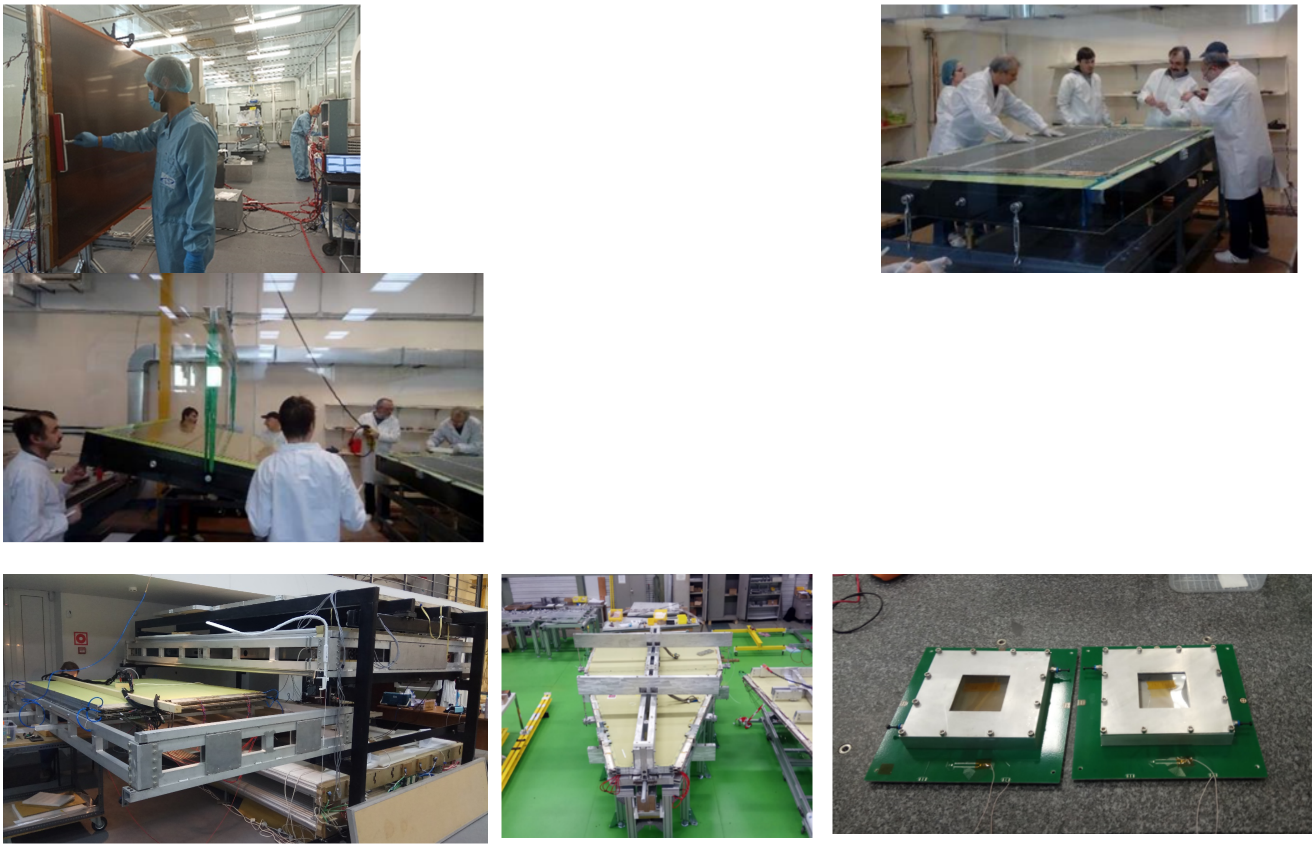


Fig. 11. Various stages of the RO panels and modules production and testing, and the new prototypes.

After production and testing, the MM modules were shipped to CERN, where they were tested, integrated into the NSW structures and commissioned by DLNP JINR group (Fig. 12). Currently, the MM modules are successfully operating in the ATLAS muon spectrometer. By May 2024, the MM trigger was fully integrated, achieving >95% efficiency across all NSW sectors and reducing fake rates further. Fake MM trigger segments are now at sub-% levels.

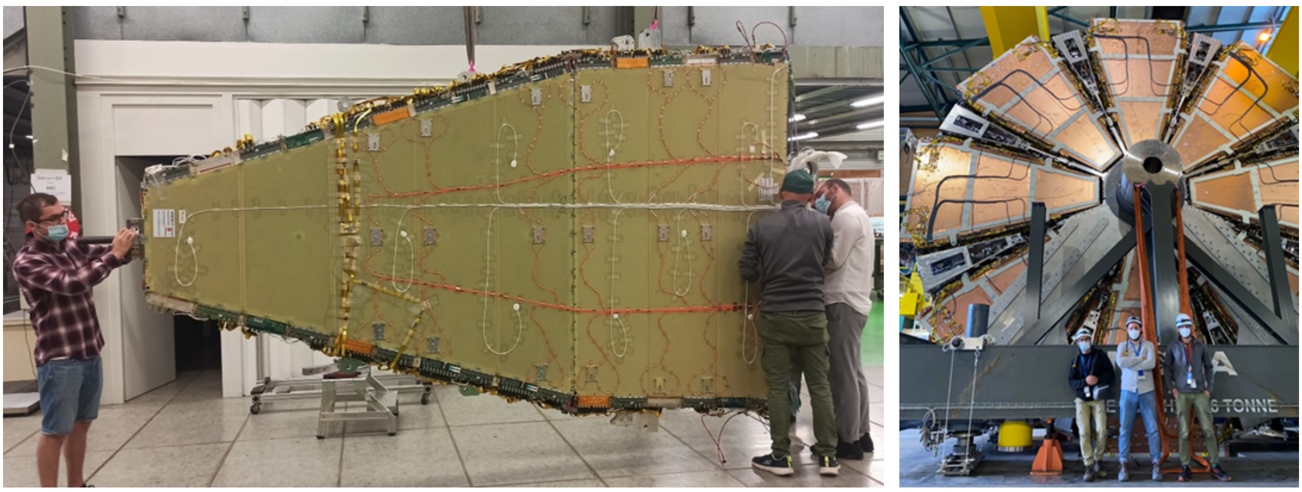


Fig. 12. Members of the DLNP JINR team during the integration of the LM1 and LM2 modules (BB5 area at CERN) and in front of the fully assembled NSW wheel.

This way the modern Micromegas technology was brought to JINR. Nowadays two production lines for Micromegas chambers are used for the ATLAS R&D and provide the institute employees with the opportunity to use the chambers in different physics experiments and in applied studies, including experiments at the NICA complex.

Liquid argon calorimeters (Phase-I)

The scope of the LAr Phase-I upgrade project was to design, build and install new trigger readout electronics. The objective of this upgrade was to provide higher-granularity, higher-resolution and longitudinal shower information from the calorimeter to the Level 1 trigger processors. The 10-fold increase in granularity improved the trigger energy resolution and efficiency for selecting electrons, photons, τ-leptons, jets, and missing transverse momentum, while enhancing discrimination against backgrounds and fakes in an environment with high instantaneous luminosity.

The upgrade to the trigger branch of the LAr system begins with the signal which is produced by the linear mixer in the front-end electronics, as shown in the block diagram in Fig. 13. This signal is sent over the baseplane to the new LAr Trigger Digitizer Board (LTDB), where it undergoes digitization.

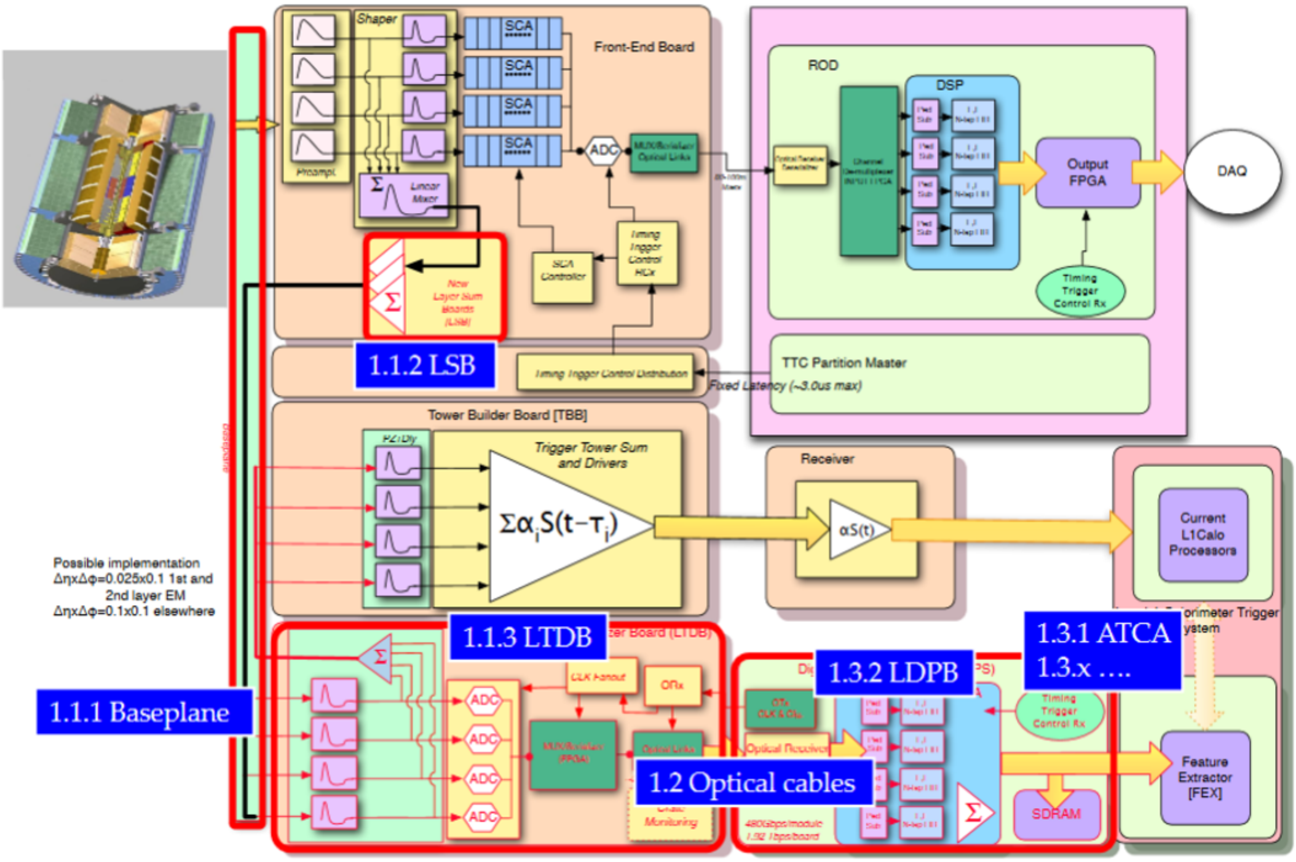


Fig. 13. Schematic block diagram of the Phase-I upgrade LAr trigger readout architecture. The new components are indicated by red outlines and arrows

Baseplane for the Hadronic Endcap Calorimeter (HEC) front-end readout crate was developed by the JINR team and produced in collaboration with colleagues from TRIUMF (Canada). We also proposed design for the prototype of the preshaper of LTDB, it was produced and successfully tested (Fig. 14)

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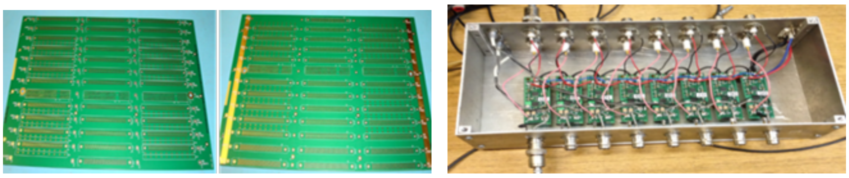

Fig. 14. Baseplane and prehaper prototype and test board for LTDB.

A series of radiation tests of the LAr calorimeter readout boards and cables were conducted at the irradiation channel 3 of the IBR-2 reactor. The JINR group took part in a test beam at SPS CERN to study the effects of space charge with minimodules of the FCal forward calorimeter.

<u>Phase-II of the ATLAS detector upgrade</u>

To fully exploit the discovery potential of the HL-LHC, the ATLAS Collaboration has proposed a Phase-II upgrade programme of the ATLAS Detector, consisting of modifications and replacements of existing sub-systems as well as new additions to the Detector *[CERN-LHCC-2015-020].*

To cope with the demanding conditions at the HL-LHC, the ATLAS collaboration is upgrading its detectors with state-of-the-art instrumentation and technologies. These new detectors need to withstand a much harsher environment with high radiation, high data-rates, larger event sizes, and high-occupancy with up to 200 proton-proton interactions per proton bunch crossing. Key improvements include changes to the trigger and data acquisition system, a completely new all-silicon inner tracker, a new silicon timing detector, as well as upgrades to the calorimeter electronics, additional muon chambers and electronics, and forward detectors as shown in Figure 15.

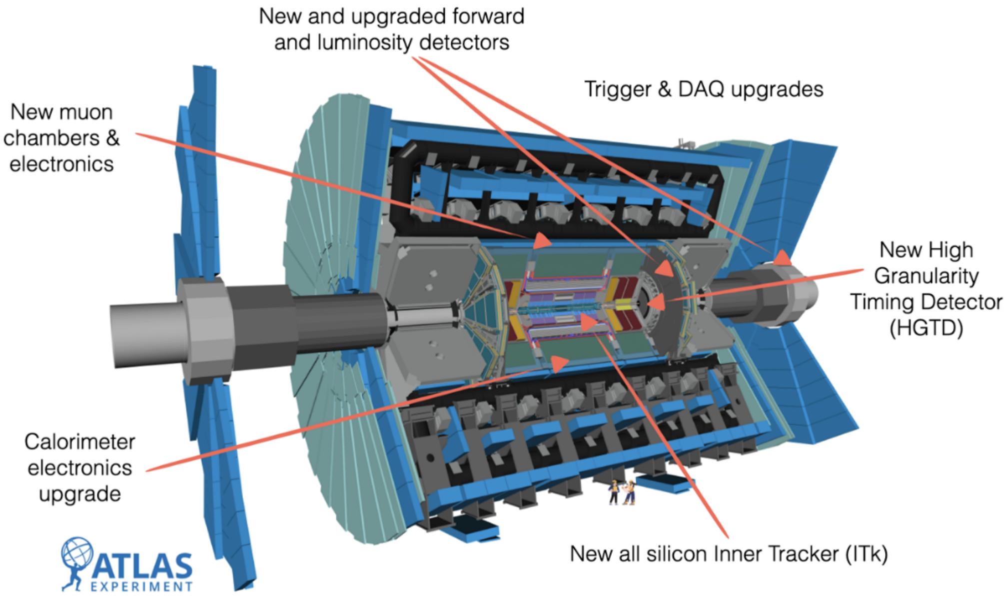

Fig. 15. Schematic of the major upgrades to the ATLAS detector for the HL-LHC era including a trigger and data acquisition (DAQ) upgrades with increased read out rates, a new all-silicon inner tracker (ITk), a new high granularity timing detector (HGTD), calorimeter electronics upgrades, new muon chambers and electronics with improved coverage and new and upgraded forward and luminosity detectors *[JINST 19 (2023) P05063].*

In 2019 the JINR signed several Memoranda of Understanding for Collaboration in the Construction of the ATLAS Detector (Phase-II Upgrade) that define the obligations of the JINR group to participate in the upgrade of the muon spectrometer, LAr calorimeter and construction of the HGTD. In addition, the procurements of parts and hardware components are foreseen for these subdetectors as well as for

TDAQ system. The total CORE[1] cost of all the items is about ~2.7 MCHF. These expenses are foreseen in the Seven Year Plan for the Development of JINR (2024-2030). Our goal is to maximize the JINR in-kind contribution.

Resistive Plate Chambers (RPC) for muon spectrometer (Phase-II)

In accordance with the MoU for the ATLAS Phase-II Upgrade the DLNP ATLAS group is involved in the development and production of the new resistive plate chambers (RPC) for the ATLAS Muon spectrometer. It includes, in particular:

- RPC Singlet assembly and testing;
- Strip panels production and testing;
- Gas system design, production, installation;
- Power distribution design, production and installation;
- Surface commissioning, installation in the pit and final commissioning.

The present ATLAS Resistive Plate Chamber (RPC) system represents the first level trigger in the ATLAS barrel region. It consists of 6 concentric cylindrical layers providing independent space-time measurements along the track with a resolution of 1ns × 1cm. For the HL-LHC programme, this system will undergo a major upgrade, which will consist of installing three additional next-generation full-coverage RPC layers in the inner region of the barrel. This upgrade will increase trigger acceptance (from 78% to 92% and up to 96% by requiring the inner and outer layers to match) and improve time resolution for time-of-flight measurements (0.4 ns for the new thin-gap RPCs and 1.1 ns for the old RPCs). The new thin-gap (1 mm) RPCs will occupy an area of 472 m^2 and will be organized into 306 triplets. A singlet (Fig. 16) is the assembly of a gas volume enclosed between two readout panels with strips parallel to the long side of the chamber. In turn, the gas volume of the resistive plate chamber consists of a gas gap enclosed between two high-pressure laminate (HPL) plates. A layer of graphite is applied to the outer surface of each HPL plate. The total thickness of the gas volume is approximately 4.5 mm.

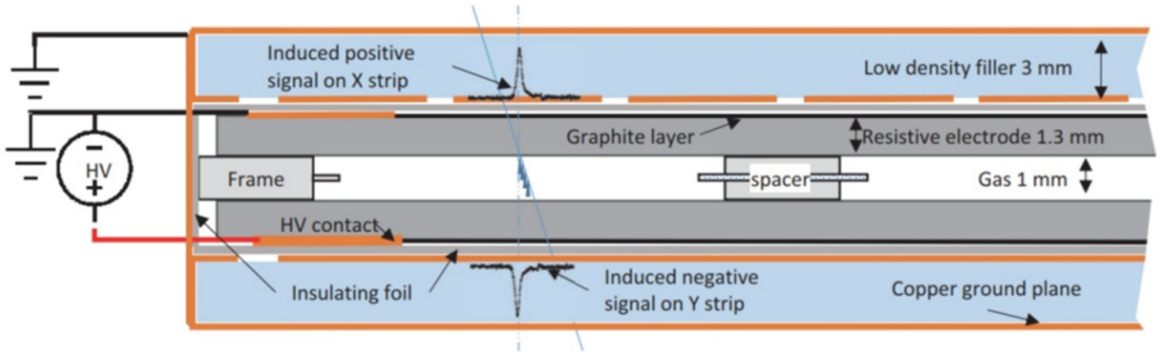

Fig. 16. Schematic view of the RPC Singlet.

The production area of NSW LM2 Micromegas (Phase-I) was adapted for production of BI RPC readout panels. Two vacuum tables technology is used for production. This technology allows gluing both sides of the panels in one pass and the panel thickness does not depend on variation of the material (PCB+Honeycomb) thickness (Fig. 17).

1 * *The CORE (Cost of Resource Exchange) value identifies only the deliverable's direct cost; it excludes associated manpower costs, exchange rate fluctuations, prototyping cost, R&D costs, etc. It includes items such as components, industrial stuff (but not institute staff) for production, outsourced parts of assembly, installation, test and commissioning.*

Fig. 17. Technological stages of the RPC panel production process

Three test readout BIL type panels were produced and tested for geometric characteristics. The tests showed a high quality of production (Fig. 18). All produced panels satisfy requirements with a large margin. Moreover, a 3-axis linear module with a measuring optical probe made it possible to measure the absolute dimensions of the panel and the strips on it and confirmed high quality.

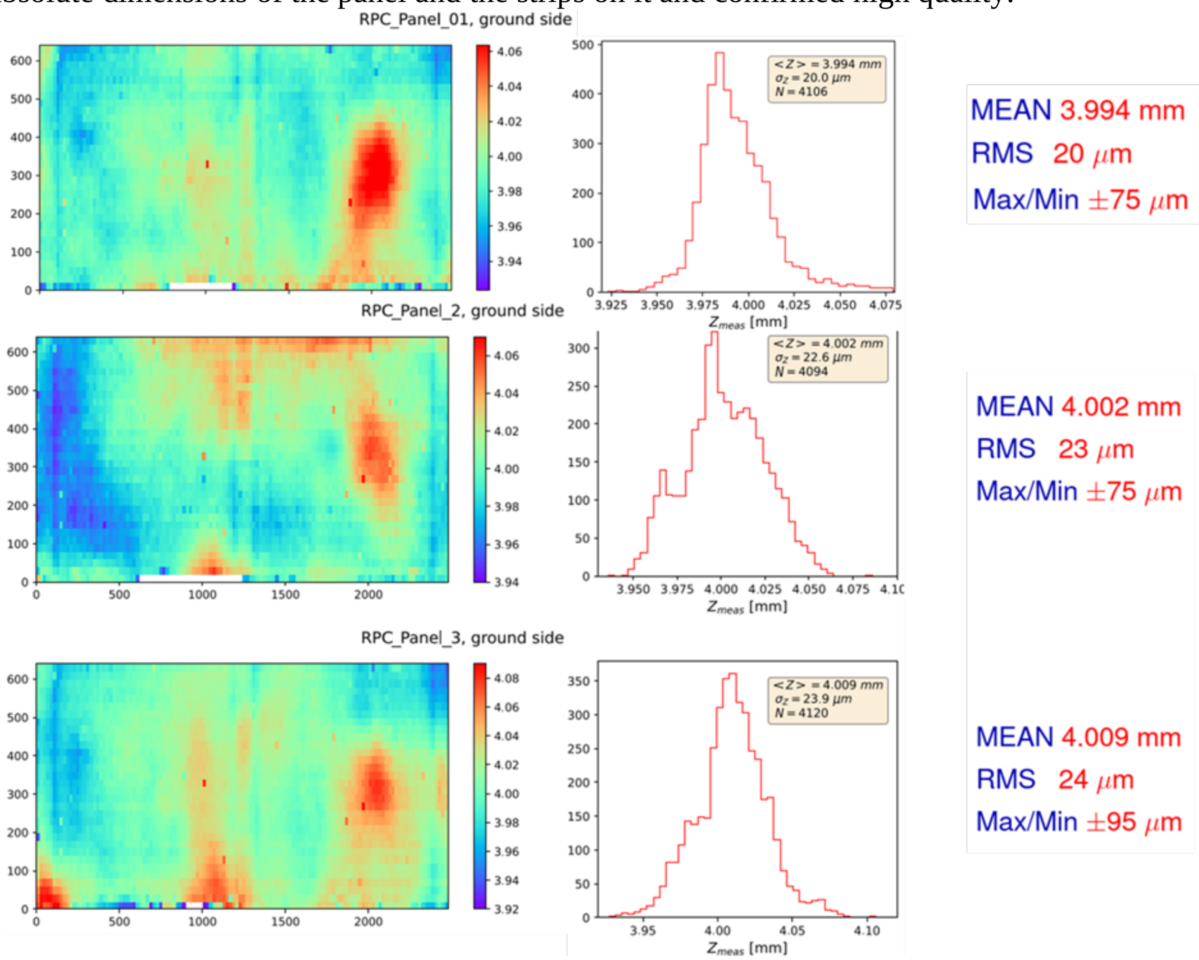

Fig. 18. Results of measuring the geometrical characteristics of the panels.

While realization of the RPC production at JINR remains uncertain, the first full production cycle site in Russia and Eastern Europe for the development and testing of modern Micromegas Micro Pattern Gas Detectors (MPGD) has been established at DLNR JINR. It provides the opportunity to carry out new developments, produce and test prototypes and small batches of detectors, and participate effectively in the implementation of major physics experiments, such as AMBER project at SPS at CERN, MPD and SPD experiments at the NICA accelerator complex.

High-Granularity Timing Detector (Phase-II)

The large increase of pileup interactions is one of the main experimental challenges for the HL-LHC physics programme. A powerful new way to mitigate the effects of pileup is to use high-precision timing information to distinguish between collisions occurring close in space but well-separated in time. A High-Granularity Timing Detector, based on low gain avalanche detector technology, is therefore proposed for the ATLAS Phase-II upgrade (Fig. 19). Covering the pseudorapidity region between 2.4 and 4.0, this device will improve the detector physics performance in the forward region. The typical number of hits per track in the detector was optimized so that the target average time resolution per track for a minimum-ionising particle is 30 ps at the start of lifetime, increasing to 50 ps at the end of HL-LHC operation. The high-precision timing information improves the pileup reduction to improve the forward object reconstruction, complementing the capabilities of the upgraded Inner Tracker (ITk) in the forward regions of ATLAS and leading to an improved performance for both jet and lepton reconstruction.

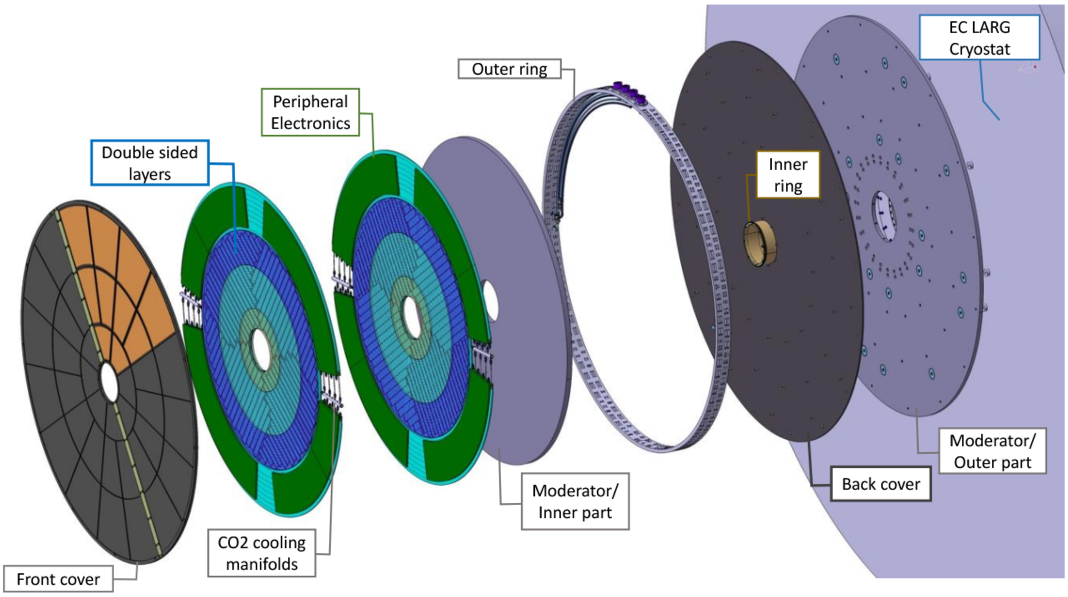

Fig. 19. Global view of the HGTD to be installed on each of two end-cap calorimeters. The various components are shown: hermetic vessel (front and rear covers, inner and outer rings), two instrumented double-sided layers (mounted in two cooling disks with sensors on the front and back of each cooling disk), two moderator pieces placed inside and outside the hermetic vessel.

The JINR group was involved in the HGTD project from the very beginning. Our employees occupy a number of coordinating positions in the collaboration. The official MoU for collaboration in construction of HGTD was signed in 2022. The JINR obligations include:

- Development and production of the DCS system;
- Design, development, production and testing of the half-disk instrumentation stand;
- Design, development, production and testing of tool for half-disk installation;
- Participation in testbeam activities, assembly of components, installation and integration work.

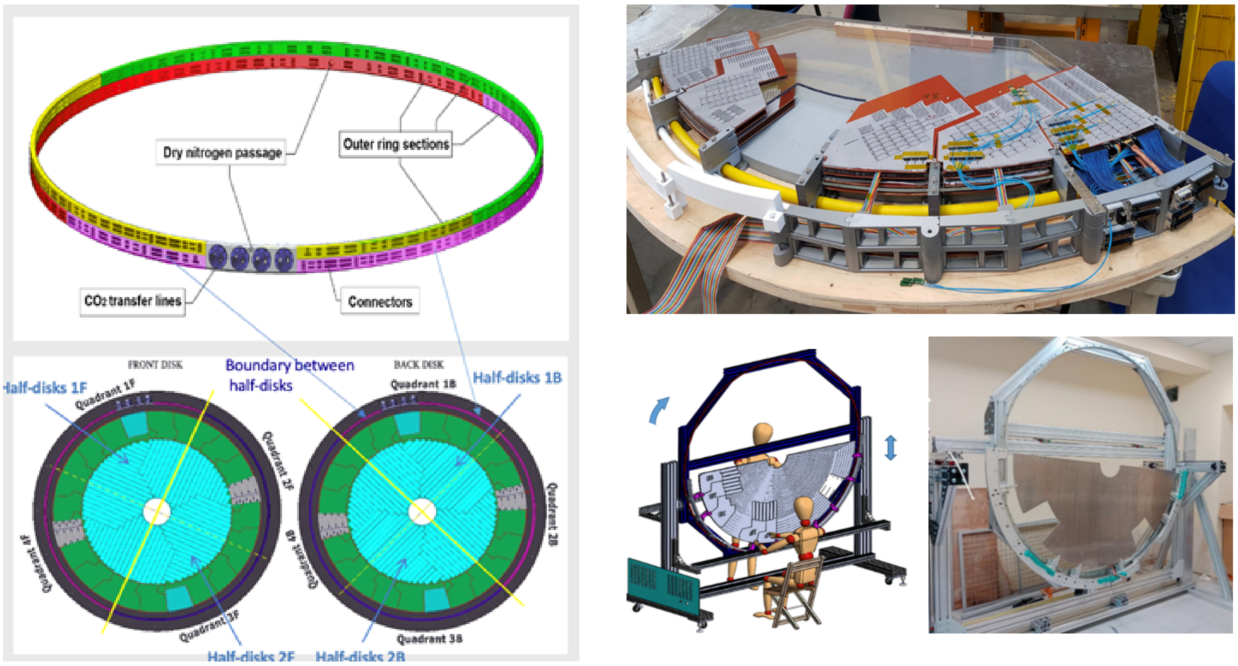

Fig. 20. Details of the HGTD services, the mock-up and prototype of the stand for the HGTD half-disk instrumentation.

The JINR team developed an optimal scheme for the arrangement of the modules and peripheral electronics in order to maximize the number of identical components. A concept for the outer ring of the detector and connecting services was also proposed and realized in a prototype (Fig. 20). The HGTD detector comprises:

- ~300 cables and 40 optical cables connected to each vessel at outer ring
- 281 pigtails + 80 optical fanouts per vessel interconnect peripheral electronics boards with cables
- HV, LV, NTC pigtails all are identical, fanouts are the same length.

To optimize the layout of electrical and optical services inside the HGTD case, 3D model of services inside the detector case was developed and mock-up was constructed. It was used to determine the locations and dimensions of electrical and optical services for their further manufacture.

We proposed the concept and designed a stand for instrumentation of HGTD half-disks. The prototype of the stand was manufactured at JINR and is being prepared for shipment to CERN. The group continues to work on developing DCS control system (hardware and software). We are participating in the development of the HGTD Demonstrator. Module-0 comprises 1 peripheral board with 54 modules (108 ALTIROC ASICs) and other detector systems – mechanics, cooling, HV, LV, etc. Beam tests of the modules are foreseen at the SPS and DESY.

The most significant in-kind contribution of the JINR team in the project will be manufacturing additional stands and mechanical components for HGTD support frame followed by participation in the assembly of HGTD half-disks using stands manufactured in Dubna.

Liquid argon calorimeters (Phase-II)

The plans for the JINR group participation in the upgrade of LAr calorimeters included:

- Design and testing of Preamp-Shaper and HEC Preshaper ASICs;
- Production and testing of optical pigtails;
- Development and testing of analog circuit.

In addition to the trigger electronics replaced during Phase-I, the complete replacement of the remaining readout electronics will be completed in Phase-II. Much of the work to upgrade the calorimeter electronics was carried out in parallel with our Phase-I commitments. In particular, the test board for high-frequency operational amplifiers of the analog part of the trigger digitizer LTDB was designed (Fig. 21). The amplifiers demonstrated good linearity up to 8 μA of input current.

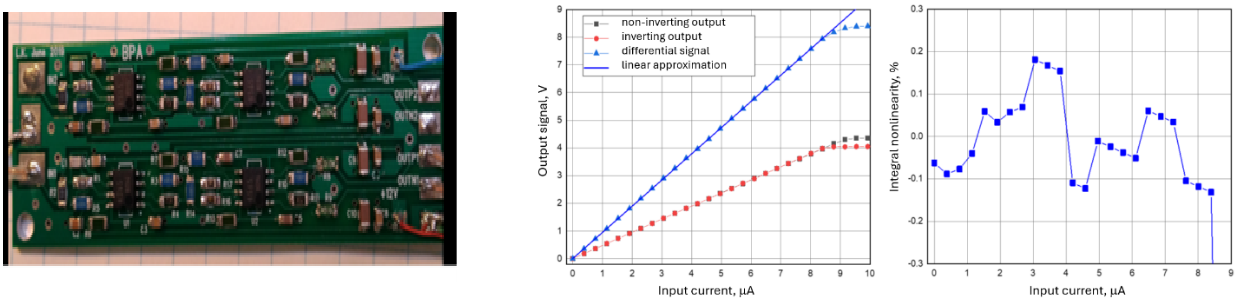

Fig. 21. Test board and results of the linearity measurements.

At the IBR-2 reactor we continued the programme of irradiation tests for the LAr calorimeters. The optical patch-cords were exposed to the fluence of fast neutron $8 \cdot 10^{15}$ n/cm^2. Subsequent analysis of the reflectograms revealed no deviations from the original shape. We have designed and tested a set of patch-cords for the half-crate tests at CERN which are focused on testing the full chain of the LAr readout electronics. These cables were manufactured at the Unicord firm (Moscow) and shipped to CERN.

For the moment, design, testing and mass-production of the optical cables is considered as the main in-kind contribution of our team to the LAr Phase-II upgrade. We also participate in the FCalPulse R&D project.

At the HL-LHC the ATLAS Forward Calorimeter (FCal) energy response will be compromised due to excessive ionization rates. The current pulses will shrink and the shape will distort as a function of the luminosity over the previous few milliseconds and of the location within the module. To assess the degradation in a controlled way, the FCalPulse R&D was proposed. The project employs a single electrode, part of which is subject to constant β radiation to simulate the flux from pileup at the HL-LHC. This electrode, and a control electrode that is not exposed to β's, is then placed in a high-energy electron beam. The response is recorded in a variety of conditions, allowing correction factors to be derived that will recover much of the degradation. We helped our colleagues from Arizona University to manufacture 100 mCi source of Sr-90 in Obninsk and participated in the testbeam.

Testbeam data were collected in the H2 beamline of the CERN North Area in August 2022. The FCal module was exposed to the beam of 180 GeV electrons (Fig. 22).

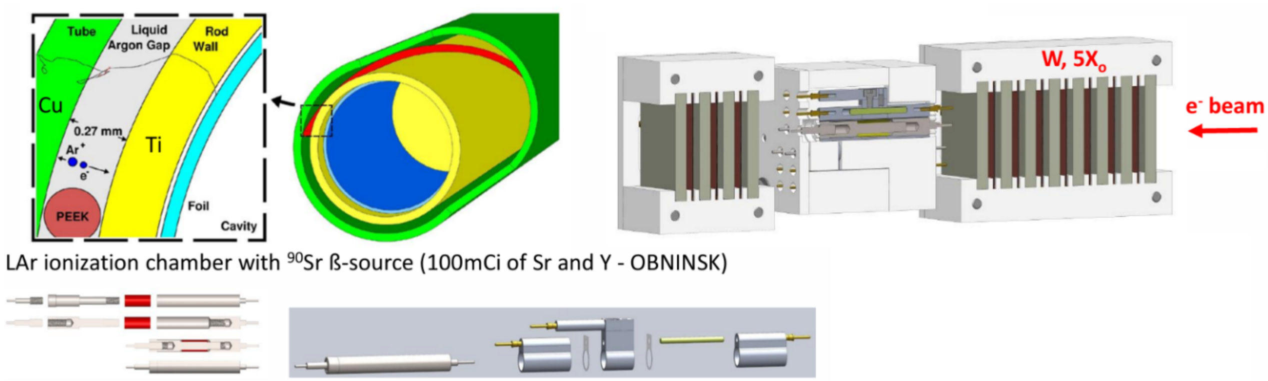

Fig. 22. Details of the FCalPulse testbeam setup.

The JINR group provides GEANT4 simulation of the testbeam. We compared results of our simulation with calculations made in Arizona for the energy deposited in the LAr gap (tube) at various locations of the electron beam for 350 GeV beam energy (Fig. 23).

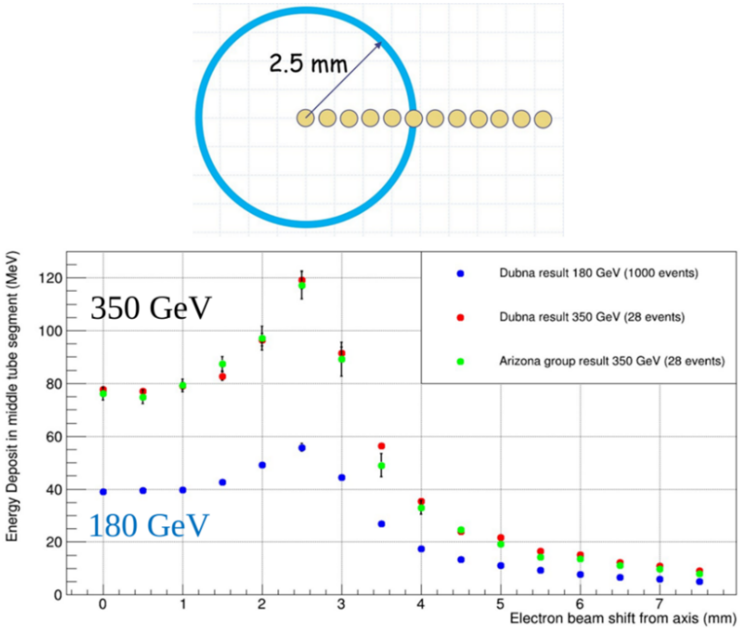

Fig. 23. Deposited energy in LAr volume for various positions of the electron beam of 350 GeV and 180 GeV.

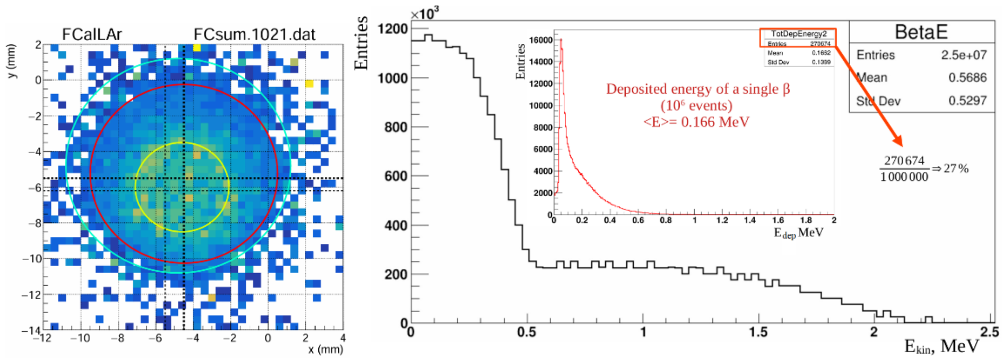

Fig. 24. Testbeam profile and GEANT4 simulation results (initial spectrum of Sr-source and deposited energy).

Monte Carlo simulations are ongoing with real electron beam parameters (Fig. 24). It was shown that about 30% of the β-electrons deposit energy in the LAr gap. The analysis is ongoing with the aim of publication in the near future.

Participation in the NICA project at JINR

Mega-science project of a complex of superconducting rings on colliding beams of heavy ions is a flagship project of the JINR aimed at a study of the nuclear matter in a state of maximum baryonic density, inaccessible to research in other laboratories of the world. The study of the spin structure of the proton and deuteron and the other spin-related phenomena with polarized proton and deuteron beams is one of the main topics of the NICA experimental programme. These ambitious goals will be achieved by conducting experiments using the most modern detector technologies. Many detector technologies adopted in the ATLAS experiment are applicable for use in the NICA experiments.

As part of the future upgrade of the TPC chambers for MPD NICA, the robustness of a new resistive coating (DLC) to discharges has been investigated. The robustness of the detector to electric discharges was demonstrated by accumulating about 10^4 discharge events at a gas gain of 4×10^4 without any visible impact on the operation of the detector.

The JINR team is engaged in the Micromegas-based central tracker (MCT) project for the SPD NICA. The MCT will be located as close as possible to the beam interaction region and will improve pulse resolution and track finding efficiency in the absence of a vertex detector in the initial setup of the SPD. To date, a simulation and gas mixture optimization study has been carried out and the primary and backup solutions have been identified. The discharge resistance of the DLC protective layer has been tested, the technology has been refined, and the first cylindrical prototype has been built (Fig.

25). Several prototypes with different configurations were tested and the main parameters of the future detector were determined.

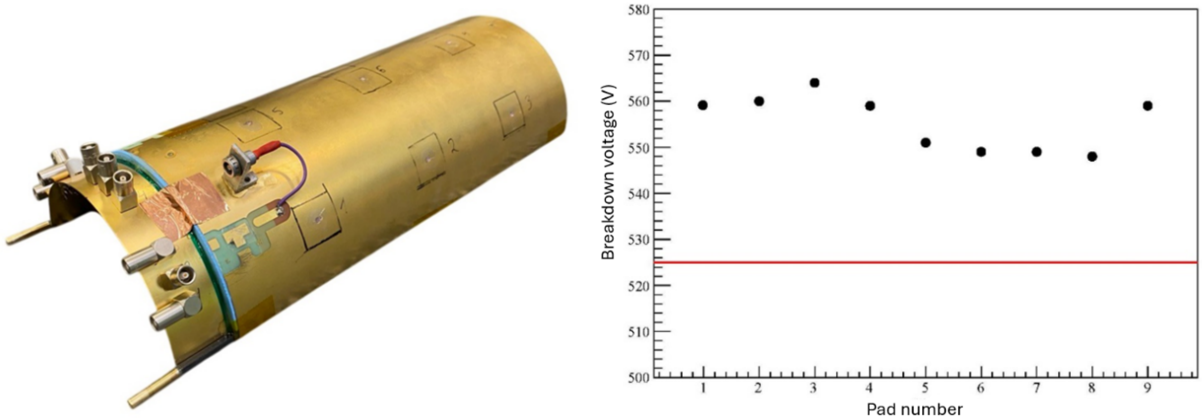

*Fig. 25. General view of semi-cylindrical prototype of the MCT (left) and breakdown voltage(right) measured separately **for all sites**. The red line represents the operating voltage for gas gain of 10^4.*

Four MRPCs were manufactured for prototyping TOF system of the SPD detector. The analog front-end electronics based on the constant fraction discrimination method was designed and optimized for the MRPC timing measurements. The total time resolution of ~40 ps has been achieved for MRPCs with 10 and 12 gaps using cosmic test setup and muon beam at IHEP U-70 accelerator in Protvino (Fig. 26). Obtained result satisfies the requirements of the SPD experiment at NICA (60ps).

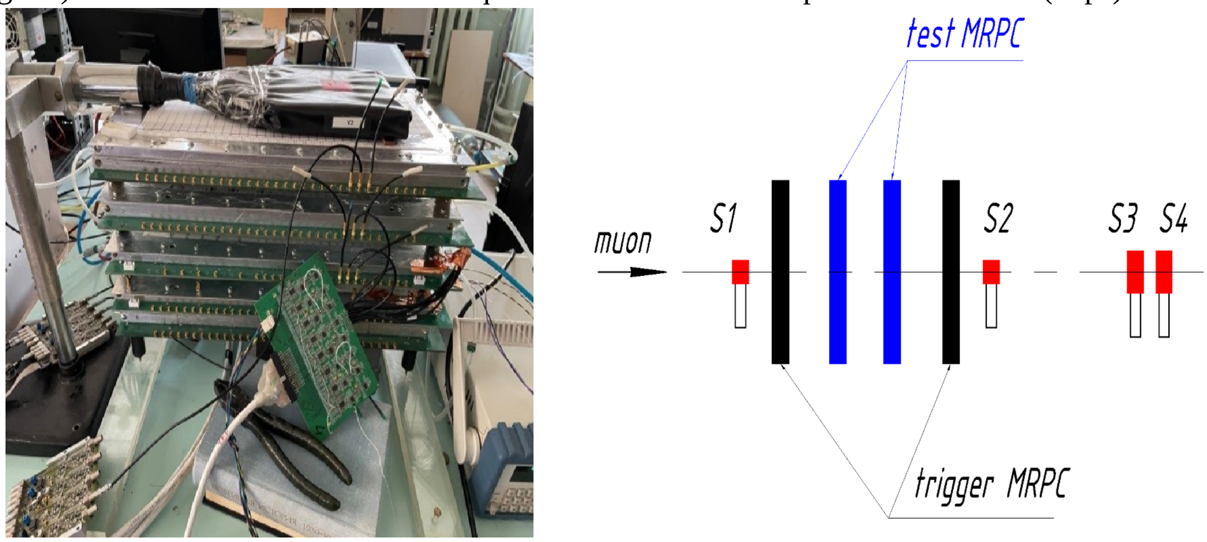

Fig. 26. Cosmic test setup (left) and MRPC test setup (right) at the muon beam at the U-70 accelerator.

The JINR group continues to participate in the upgrade and maintenance of superconducting toroids of the ATLAS magnetic system. During the LS3 cryogenic pump replacement, bus-bar upgrades, scaffolding installation and other work in the cavern for the technical coordinator services are planned.

SWOT Analysis

Strength

- Participation in a large and challenging international project in a competitive and high-tech, internationally oriented, research arena.
- Excellent scientific publication and citation records.
- Collaborations with groups at the leading international accelerator center (CERN) and other physics laboratories.
- Great interest from the public and mass-media.

Weaknesses

- The growing age of staff scientists and engineers.

- Difficulties in registration of new people at CERN.

Opportunities

- LHC shows huge discovery potential which attracts scientists at all levels (master students, PhD students, postdocs and staff physicists alike).
- JINR experiments often require completely new and challenging technologies and ATLAS offers our technical departments possibilities and contacts with new research communities. New technology of Micromegas has already been brought to JINR.
- The experience gained in the ATLAS experiment is shared with our colleagues from the NICA project.
- The BiG Grid - e-science grid–project JINR-LCG2 - provides researchers at JINR with state-of-the-art computing services and an opportunity to establish contacts and/or collaborations with many other research disciplines.

Threats

- Expensive and complicated logistics, extremely difficult bank transactions.

In 2024, CERN terminated Cooperation Agreements with institutes from Russia and Belarus, and restrictions were introduced in the Agreement with JINR. Even before that, due to the uncertainty of the situation, the ATLAS Collaboration decided to revise JINR's obligations to participate in Phase-II, some of which were redistributed among other institutes. Negotiations are currently underway to clarify JINR's commitments and prepare a new MoU.

2.3 Estimated completion date – 2030

The start of the long shutdown LS3 for the LHC is now scheduled for early July 2026, seven and a half months later than originally planned. The total duration of the shutdown will increase by approximately four months. Combined, these changes will delay the launch of the High-Luminosity LHC (HL-LHC) (Run 4) by about a year, moving it to June 2030. By that time, the production, assembly, and commissioning of all ATLAS detector subsystems will be completed. In addition to the main tasks, the ATLAS teams are also involved in the experimental program at the NICA facility.

2.4 Participating JINR laboratories

The main participants in the ATLAS physics studies and upgrade program are scientists from the Dzhelepov Laboratory of Nuclear Problems and the Veksler and Baldin Laboratory of High Energy Physics. The project also involves researchers from the Meshcheryakov Laboratory of Information Technologies (responsible for experimental data processing and simulations, including the use of Tier-2-level grid infrastructure) and the Frank Laboratory of Neutron Physics (radiation testing of materials and electronic components). Theoretical support for the project (and related topics) is traditionally provided by the N.N. Bogolyubov Laboratory of Theoretical Physics.

2.4.1 MICC resource requirements

Computing resources	Distribution by year				
	1st year	2nd year	3rd year	4th year	5th year
Data storage (TB) - EOS - Tapes	200	200	200	200	200
Tier 1 (CPU core hours)					
Tier 2 (CPU core hours)	200	200	200	200	200
SC Govorun (CPU core hours) - CPU - GPU					
Clouds (CPU cores)					

2.5. Participating countries, scientific and educational organizations

Organization	Country	City	Participants	Type of agreement
Foundation ANSL	Armenia	Yerevan	G.Akopyan	Collaborative work
IP ANAS	Azerbaijan	Baku	N.Huseynov+5	Collaborative work
SU	Bulgaria	Sofia	M.V.Chizhov	Collaborative work
UdeM	Canada	Montreal	C. Leroy	Collaborative work
TRIUMF	Canada	Vancouve	L.L. Kurchaninov	Collaborative work
CERN	CERN	Geneva	M.Vincter, A.Hoecker, K.Jacobs	Cooperation agreement
CU	Czech Republic	Prague	I.Wilhelm	Collaborative work
LPC	France	Clermont-Ferrand	F. Vasey	Collaborative work
LAL	France	Orsay	D. Fournier	Collaborative work
HEPI-TSU	Georgia	Tbilisi	T. Djobava + 3	Cooperation

				agreement
MPI-P	Germany	Munich	S.Menke	Collaborative work
DESY	Germany	Zeuthen	W.Loman Y.Schrieber	Collaborative work
WIS	Israel	Rehovot	G. Mikenberg	Collaborative work
INFN	Italy	Pisa	T. Del Prete,	Collaborative work
INFN	Italy	Genova	S.Turchikhin	Collaborative work
NIKHEF	Netherlands	Amsterdam	H. Van Der Graaf	Collaborative work
CU	Slovakia	Bratislava	A. Dubnickova, S.Tokar	Collaborative work
IP SAS	Slovakia	Bratislava	S.Dubnicka +3	Collaborative work
IFAE	Spain	Barcelona	M. Cavalli-Sforza	Collaborative work
ANL	USA	Lemont, IL	L. Price	Cooperation agreement
SSU	Uzbekistan	Samarkand	A.Artikov U.Salikhbaev	Collaborative work
BINP	Russia	Novosibirsk	L.Maslennikov, V.Bobrovnikov	Collaborative agreement
MEPhI	Russia	Moscow	E.Soldatov	Collaborative agreement

2.6. Key partners *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program. An example is JINR's participation in the LHC experiments at CERN).*

3. Manpower

3.1. Manpower needs in the first year of implementation

№№ n/a	Category of personnel	JINR staff, amount of FTE	JINR Associated Personnel, amount of FTE
1.	research scientists	29.6	6
2.	engineers	5.3	1
3.	specialists	0.3	

4.	office workers		
5.	technicians	1	
Итого:		**36.2**	**7.0**

3.2. Available manpower
3.2.1. JINR staff

No.	Category of personnel	Full name	Division	Position	Amount of FTE
1.	research scientists	Prof. L.Kalinovskaya	DLNP	Head dep.	0.5
		Y.Dydydshka	DLNP	Sen.scientist	0.4
		V. Yermolchyk	DLNP	Sen.scientist	0.4
		PhD A.Soloshenko	VBLHEP	Head dep.	1
		T.Turtuvshin	VBLHEP	Scientist	1
		Prof. G.Lykasov	DLNP	Chief sc.	0.8
		PhD A.Prokhorov	DLNP	Scientist	1
		PhD V.Lyubushkin	DLNP	Sen.scientist	1
		T.Lyubushkina	DLNP	Scientist	1
		PhD F.Ahmadov	VBLHEP	Sen.scientist	1
		M.Manashova	VBLHEP	Jr.scientist	1
		PhD S.Karpov	DLNP	Sen.scientist	1
		PhD Z.Karpova	DLNP	Sen.scientist	1
		PhD I.Yeletskikh	DLNP	Head dep.	1
		PhD N.Huseynov	DLNP	Sen.scientist	1
		PhD I.Boyko	DLNP	Sen.scientist	0.5
		O.Dolovova	DLNP	Jr.scientist	0.5
		A.Didenko	DLNP	Jr.scientist	1
		A.Vasyukov	DLNP	Jr.scientist	1
		A.Tropina	DLNP	Lab.Assistant	1
		Prof.Y.Kultchitsky	DLNP	Head dep.	1
		P.Tsiareshka	DLNP	Scientist	0.8
		E.Plotnikova	DLNP	Scientist	0.8
		PhD I.Alexandrov	MLIT	Head dep.	0.4
		E.Aleksandrov	MLIT	Scientist	0.2
		A.Kazymov	MLIT	L.programmer	0.2

		M.Mineev	MLIT	Scientist	0.2
		E.Ramakoti	DLNP	Scientist	1
		PhD A. Gongadze	DLNP	Head of sector	0.5
		I. Potrap	DLNP	Scientist	1
		PhD I. Minashvili	DLNP	Jr.scientist	0.5
		PhD A. Cheplakov	VBLHEP	Sc. secretary	0.7
		PhD V. Kukhtin	VBLHEP	Sen scientist	1
		PhD E. Ladygin	VBLHEP	Sen scientist	0.3
		PhD N. Zimin	VBLHEP	Sen scientist	1
		N. Atanov	DLNP	Scientist	0.3
		A. Boikov	DLNP	Jr.scientist	0.2
		PhD Yu. Davydov	DLNP	Head of dept	0.3
		K. Gritsay	DLNP	Scientist	0.4
		S. Malyukov	DLNP	Scientist	1
		V. Moskalenko	DLNP	Jr.scientist	0.3
		S.Bondarenko	BLTP	Prof.	0.4
2.	engineers	I. Gongadze	DLNP	Engineer	0.7
		L. Gongadze	DLNP	Engineer	0.5
		N. Kaurtsev	DLNP	Engineer	0.5
		T. Rudenko	DLNP	Engineer	0.5
		O. Atanova	DLNP	Engineer	0.4
		V. Rogozin	DLNP	Engineer	0.4
		A. Shaikovskii	DLNP	Engineer	0.3
		I. Troeglazov	DLNP	Engineer	1
		S. Mokrenko	DLNP	Engineer	0.4
		I. Fomichev	DLNP	Engineer	0.3
		A. Shutov	DLNP	Engineer	0.3
3.	specialists	N. Ponomarenko	VBLHEP	Specialists	0.3
4.	technicians	M. Serochkin	DLNP	Technician	1
	Total:				**36.2**

3.2.2. JINR associated personnel

No.	Category of personnel	Partner organization	Amount of FTE
1.	research scientists	Budker INP (Novosibirsk) TSU (Tomsk)	3 3
2.	engineers	LPI (Moscow)	1
3.	specialists		
4.	technicians		
	Total:		**7**

4. Financing

4.1 Total estimated cost of the project

Currently, the ATLAS collaboration author list includes 48 JINR staff members and JINR-associated scientists. The institute's commitments consist of approximately 2 FTE (Full-Time Equivalent) for detector shifts and operation, and 9-10 FTE for software support and related tasks. The corresponding expenses for JINR's participation in the collaboration amount to a total of 770 × 5 = 3,810 k$ over the project's five-year implementation period. This includes 300 × 5 = 1,500 k$ in collaboration membership fees. The remaining 470 × 5 = 3,350 k$ covers travel expenses for JINR staff to CERN to fulfill the institute's operational commitments (shifts, detector operation, and software support).

Costs related to participation in the second phase of the detector upgrade include expenses for sending personnel to CERN for test runs of detector systems at CERN accelerators, assembly and installation work, equipment placement in the experimental cavern and other joint activities. These activities will total 1,160 k$. Most of the work will be carried out at JINR, with approximately 900 k$ allocated for material procurement. The corresponding JINR contribution will be around 12 FTE.

Over the project’s duration, its total cost will be 5,040 thousand dollars. A detailed breakdown is provided in a separate form.

4.2 Extra funding sources

Expected funding from partners/customers – a total estimate.

Project (LRIP subproject) Leader __________/___________/

Date of submission of the project (LRIP subproject) to the Chief Scientific Secretary: _________
Date of decision of the laboratory's STC: _________ document number: _________

Year of the project (LRIP subproject) start: ________________

(for extended projects) – Project start year: _______

Proposed schedule and resource request for the Project / LRIP subproject

Expenditures, resources, funding sources			Cost (thousands of US dollars)/ Resource requirements	Cost/Resources, distribution by years				
				1st year	2nd year	3rd year	4th year	5th year
		International cooperation	3810	770	770	770	770	770
		Materials	900	480	270	90	30	30
		Equipment, Third-party company services						
		Commissioning						
		R&D contracts with other research organizations	270	60	60	50	50	50
		Software purchasing	50	10	10	10	10	10
		Design/construction	10	5	5			
		Service costs (*planned in case of direct project affiliation)*						
Resources required	**Standard hours**	Resources						
		- the amount of FTE,	181	36.2	36.2	36.2	36.2	36.2
		- accelerator/installation,						
		- reactor,…	200	200				
Sources of funding	**JINR Budget**	JINR budget *(budget items)*	5040	1325	1115	920	840	840
	Extra fudning (supplementary estimates)	Contributions by partners Funds under contracts with customers Other sources of funding						

Project (LRIP subproject) Leader_______/__________/

Laboratory Economist _______/__________/

APPROVAL SHEET FOR PROJECT / LRIP SUBPROJECT

TITLE OF THE PROJECT/LRIP SUBPROJECT

ATLAS. Detector upgrade and physics studies at LHC

SHORT DESIGNATION OF THE PROJECT / SUBPROJECT OF THE LRIP

ATLAS

PROJECT/LRIP SUBPROJECT CODE

02-2-1081-1-2010/2025

THEME / LRIP CODE

02-2-1081-2009

NAME OF THE PROJECT/ LRIP SUBPROJECT LEADER

Bednyakov V.A.

AGREED

	SIGNATURE	NAME	DATE
JINR VICE-DIRECTOR			
CHIEF SCIENTIFIC SECRETARY			
CHIEF ENGINEER			
LABORATORY DIRECTOR	[signature]	Якушев Е.А.	24.05.25
CHIEF LABORATORY ENGINEER	[signature]	Яковенко С.А.	24.05.25
LABORATORY SCIENTIFIC SECRETARY THEME / LRIP LEADER	[signature]	Simonenko I.	24.05.25
PROJECT / LRIP SUBPROJECT LEADER	[signature]	Bednyakov	13.05.2025

APPROVED BY THE PAC

SIGNATURE	NAME	DATE