Strategy for Long Range Program in Particle Physics

Executive Summary

JINR is a multidisciplinary international research institute deeply involved in international science, especially in Particle Physics. It made important hardware contributions to scientific and technical infrastructures within and beyond JINR, and took an active part in the harvesting of scientific results in data analysis. The JINR Particle Physics Program intends to stay well integrated into the European and worldwide Particle Physics Strategies.

The JINR strategy is based on a balance between home and international experiments. Both of them must be scientifically solid, well defined, and expand new frontiers in our understanding of physical laws that govern the Universe. Especially in Particle Physics, researchers from all the JINR Member States should be able to participate in a stimulating research at the facilities like the LHC at CERN, exploiting at the same time the potential of the unique JINR infrastructure, which some university groups of its Member States do not often enjoy.

Thus, a scientific program with several research directions, to be carried out at JINR in Particle Physics, is presented in this report for the mid-term (2024-2030) and long-term (2031-2037) periods.

The main directions of research for the medium and long terms are related to:

- Precision exploration of strongly interacting states, including proton structure, QCD phases, like quark-gluon plasma, new hadronic states, including exotic states.
- Electro-weak and flavor physics.
- Studies for better understanding of the evolution of the Universe through high energy hadron-hadron collisions, as well as through searches for dark matter and dark sectors at colliders and in non-accelerator experiments.
- Experimental and theoretical determination of a model, beyond the Standard Model (SM), free from the SM shortages.
- Accelerator Science and technology.

Many if not all of these directions are interwoven and interconnected. There is a strong synergy between these branches of research, as well as between the expertise of the JINR various laboratories. A solid research program for the next two decades is shortly reviewed below and in greater detail in the main text.

Accelerator Based Physics and Accelerator Technologies

JINR is a standing member of both the ATLAS and CMS collaborations for over 25 years, and remains one of the key participants with great investments into these projects. The major discovery of both experiments was the observation of the Higgs boson production and its decay.

About halfway within the mid-term period of the JINR Strategy LRP - from 2023 till 2026 - the LHC will be upgraded to increase the luminosity by a factor of 5 to 7.5, reaching the record 3000 inverse femtobarn and 14 TeV beam center-of-mass energy by the end of its Run 5. By 2038 the integrated luminosity will be 20 times larger than all currently accumulated statistics, which will open a door to new insights and discoveries.

JINR plans to invest further in ATLAS about **4M USD** for the production of 32 quadruplets of NSW and upgrade of RPC of the Muon System, upgrade of electronics of LAr EM Calorimeter, Tile Hadronic Calorimeter, TDAQ System and production of the HGTD, and about **3M USD** in CMS for the upgrade of the endcap muon system, based on precision Cathode Strip Chambers, and construction of the High Granularity Hadron Calorimeters. In total, JINR envisages to invest about **22-26M** USD in ATLAS and CMS till 2037.

In the long-term period, after the HL-LHC upgrade, JINR should play a leading role in physics analyses like precision measurements within the SM, searches for BSM Physics, including dark matter, supersymmetry and exotics, studies of the hadron structure.

JINR has made substantial contributions to both LHC experiments and plans to continue doing so. Based on its scientific expertise and technical infrastructure, JINR intends to play an important role in the LHC physics and specifically in these two flagship experiments, that a single JINR member state cannot achieve.

The worldwide accelerator community explores different scenarios of pushing the energy and luminosity frontiers even further for the post HL-LHC era. The current considerations include proton, electron and proton-electron colliders with possible sites at CERN (CLIC, LHeC, FCC, HE-LHC), Japan (ILC) and China (CepC, SppC), where various new ideas of accelerator technologies are to be explored.

The JINR researchers will join in these efforts and gain the necessary expertise whenever required to play a leading role in these investigations. As in the past years, when JINR was internationally recognized as a potential site for the ILC, a new young generation of JINR's scientists is going to look out for feasible large-scale contributions of JINR to these global projects.

Since the planning horizon extends beyond 2040, when new generations of scientists play a crucial role, JINR will develop a dedicated, clear-cut and elaborate educational program to guarantee a smooth know-how transfer and constant growth of new knowledge.

Detector Technologies and Training

JINR is internationally recognized for its advancement of detector technologies. This expertise will be deepened henceforth by using modern high-tech standards and pushing further the frontiers. Yet, a considerable amount of knowledge must be acquired in modern electronics, robotics and precision mechanics. JINR will take all the necessary measures to attract to JINR world-level experts to lead perspective directions within detector technologies.

Finally, it is well recognized that an elaborate educational program at JINR must be developed to guarantee new highly trained generations of researchers. Moreover, JINR intends to develop a strong, innovative and bright outreach program meeting the world-class standards in this new field of communication. An outreach service that provides accurate and appealing information about the institutes research activities to a wide audience is understood today as of highest importance and a responsibility of scientists towards the society.

Introduction

Particle Physics Challenges

A vast variety of elementary particles and their interactions are best described by the Standard Model of Particle Physics. The SM is a quantum field theory (QFT) model with the $SU(3)_C xSU(2)_L xU(1)$ gauge group founded theoretically and experimentally in the 1960s-1970s. Although the SM is believed to be theoretically self-consistent and considered to provide a tremendous amount of successful experimental predictions, it fails to fully explain the baryon asymmetry, it lacks a viable candidate for a dark matter particle and it cannot incorporate the general theory of relativity or account for accelerating expansion of the Universe, hypothetically explained nowadays by the dark energy impact.

Yet, the SM can accommodate but cannot explain hierarchical masses of quarks and leptons and patterns of their weak mixing matrices. Neither does it address the particular gauge symmetry in nature, nor the number of fermion families, nor the origin of CP-violation. Therefore, it is believed that there must be a model beyond the SM capable to get rid of shortages of the SM. There are basically three directions of a search for physics beyond the SM:

1. Identifying phenomena diverging from the SM expectations at high energies.
2. Looking for specific predictions of new models.
3. Increasing the measurement precision to test further the SM predictions. These are the decays of particles that are usually examined in finest details. Such studies correspond to low energies.

Since the most challenging problems (baryon asymmetry, dark matter and dark energy) of the SM come from cosmological and astrophysical observations, nowadays it is believed that studying the evolution of the Universe could provide deeper insights into Elementary Particle Physics.

Among various observation channels we highlight the following ones, which are expected to assure a breakthrough in resolving some of the puzzles of the Universe:

1. Search for sources of ultra-high energy photons and neutrinos in the cosmic radiation.
2. Multi-Messenger Astronomy.
3. Relic neutrino observation.
4. Diffuse neutrino observation.
5. Gravitational waves observation.

It is reasonable to be optimistic about this scientific program which not only balances the above-mentioned research directions, but also has every likelihood of bringing us towards some future pioneering philosophy within both Particle Physics and Astrophysics.

Past Research Projects

In this section we will briefly review the most remarkable results in Particle Physics achieved with a decisive role of the JINR scientists over the last seven years. These attainments are to be considered separately in Physics and technologies. Below we will summarize all the JINR contributions to both groups of these results.

Discoveries in Physics.

1. **Higgs boson discovery.** This result was obtained by ATLAS [1] and CMS [2] collaborations. DLNP and VBLHEP contributed mostly to ATLAS and CMS, respectively.
2. **Discovery of a family of exotic charmonium-like particles containing four quarks.** The discovery was done by the scientists from the BES-III [3] and BELLE [4], LHCb [5] experiments.
3. **Discovery of the direct CP-violation in the K0 system (NA48).**

JINR’s contributions to the above-mentioned discoveries are briefly summarized in some details below.

ATLAS and CMS Experiments at the LHC at CERN.

JINR is a standing member of both the ATLAS and CMS collaborations for over 25 years, and remains one of the key participants with great investments into these projects. In compliance with its responsibilities, JINR performed for the ATLAS experiment:

- Design, production and commissioning of the detector modules for the Muon Spectrometer, Liquid argon and Tile Calorimeters, and for the Inner Tracker.
- Calibration of the ATLAS calorimeters and preparation for data-taking.
- Participation in the development of the ATLAS Trigger DAQ (TDAQ).
- Creation of the ATLAS GRID at JINR (one of the best in Russia).
- Modelling and optimization of the ATLAS magnet system.
- Design, production and assembly of the elements of the ATLAS magnet system.

It should be mentioned that only Italy, the USA, CERN and JINR have contributed to all main subsystems (TileCal, Muon, LAr, ID, TDAQ) of the ATLAS detector.

JINR and its Member States, participating in the CMS experiment within Russia and Dubna Member States CMS Collaboration (RDMS CMS Collaboration), contributed to CMS and to the physics data analyses.

- Full responsibility for design, construction, maintenance and operation of the Endcap Hadron Calorimeters (by VBLHEP and RDMS).
- Full responsibility for design, construction, maintenance and operation of the First Forward Muon Stations (ME1/1) (by VBLHEP and RDMS).
- Participation in design and construction of the Preshower for the Endcap Electromagnetic calorimeters (by VBLHEP and RDMS).
- Computing based on the GRID technology, including CMS Tier-1 and Tier-2, connected with some physics tasks.
- Participation in the detector operation and data taking shifts, including the fast detector monitoring, monitoring of data, taking and data quality certification (by VBLHEP, LIT).

The key and decisive commitment to the discovery of the Higgs boson of the RDMS scientists from the JINR Member States was honoured with the commendation by the CMS Spokesperson Joe Incandela in his letter addressed to the RDMS authors of the discovery on 31 July 2012.

For outstanding contributions in the CMS and ATLAS experiments resulting in the discovery of the Higgs boson, the leader of the Russian team in ATLAS A.M. Zaitsev (IHEP) and the RDMS CMS Spokesperson I.A. Golutvin (JINR) were awarded the P.A. Cherenkov Prize of RAS in 2014.

BES-III Experiment.

The JINR group participated since long in the **Beijing Spectrometer III** (BES III) experiment at the Beijing Electron–Positron Collider II (BEPC II) at the Institute of High Energy Physics (IHEP). BES-III is designed to study the physics of charm, charmonium, and light hadron decays. It also performs studies of the tau lepton, tests of QCD, and searches for physics beyond the Standard Model.

JIR group has participated in:

- Development of the offline software and analysis tools, in particular used in the discovery of exotic charmonium-like particles.
- Design and development of the distributed computing system.
- Data taking and data analysis (light hadron spectroscopy, Charm and Charmonium Physics).

Technological Breakthroughs achieved by JINR Particle Physics groups

1. **Precision Laser Inclinometer (PLI).** The DLNP researchers invented a brand-new instrument to measure the surface inclination angle. The precision reached the record 2.4 10^{-11} rad/$Hz^{1/2}$ in the frequency range of 10^{-6} to 12.5 Hz. This device is indispensable to the particle beams improvement at CERN, earthquake monitoring, applications in gravitational wave detectors (PLI installation at Virgo is displayed in Fig.1) and elsewhere. The DLNP researchers created the concept of the instrument, performed necessary R&D activities, obtained several patents.
2. **SiPM in calorimetry.** The first large-scale application of SiPM for electromagnetic calorimetry with a large dynamic range in Particle Physics (COMPASS experiment at CERN and MPD project at NICA), extensive use of SiPM in hadron calorimetry (CMS experiment upgrade at CERN).
3. **Development of advanced pixel detectors based on a Medipix chip and GaAs sensors for synchrotron radiation sources and for applied research.** The first hybrid pixel detectors based on GaAs:Cr sensor and Medipix chip were developed in collaboration with CERN and the National Research Tomsk State University (TSU). The large area detectors Hexa and Double-Hexa were produced in collaboration with TSUand DESY, with the financial support of the Ministry of Education and Science of the Russian Federation. The GaAsPix detector network was designed and installed at CERN in the ATLAS cavern to monitor the radiation background. The semiconductor detector characterization lab and microCT lab were established at JINR.
4. **R&D of the large-area Micromegas chamber detector for the ATLAS upgrade.** The technology of mass production of large-area Micromegas chambers for New Small Wheels of the ATLAS Muon Spectrometer was developed in the framework of the ATLAS upgrade project. The production site was set up at DLNP JINR and the detector construction is underway.
5. **R&D of bulk Micromegas detectors.** The new laboratory for R&D of MPGD detectors was founded at DLNP. Every step of the technology to produce bulk Micromegas detectors, inspired by original development by CERN and CEA Saclay, was carefully reconsidered and elaborated to adapt for tools and equipment existing at DLNP. In contrast to the technological line which provides production and testing of Micromegas chambers for the outer part of large sectors of NSW ATLAS (type LM2), where component materials supplied from CERN in a centralized fashion for all participants of the project (INFN and German clusters, CEA Saclay, AUTh, JINR), this new line provides the complete production cycle. Thus, JINR became the third research centre in the world, after CERN and CEA Saclay, that possesses the full technological chain of equipment and is capable to produce bulk Micromegas detectors.
6. **Development of the straw tube methodology**. A straw tube with 5 mm in diameter and wall thickness of 12 micron was produced at DLNP for the COMET experiment (a ready-made straw tube is shown in Fig. 2). Tests show that straw tubes meet all the required specifications.

7. **Development of Si strip detectors**. Based on the Dubna silicon program, silicon coarse strip Preshower detectors for the CMS endcap electromagnetic calorimeters were widely applied in HEP for the first time (18 m^2, 144,000 channels in CMS), as well as the Silicon Option for the Endcap HCAL invented for CMS LoI in 1992 (I.A. Golutvin et al. RD35: "Silicon Hadron Calorimeter module for LHC", CERN/DRDC/91-54, DRDC/P34, January 13th 1992). Today, 25 years later, the idea of Si tracking calorimetry accepted by CMS at the modern level as a High Granularity Calorimeter for HL-LHC.
8. **Development of Cathode Strip Chambers. The** first wide application of CSC was proposed by JINR for the CMS Endcap Muon System. The innermost ME1/1 stations of the Endcap muon system located in a 4 Tesla solenoid was developed by JINR in cooperation with Minsk. Other endcap stations were built by the US institutes in cooperation with Gatchina.
9. **Plastic scintillators with embedded WLS fibers**, so-called sigma tiles, proposed for Hadron calorimetry. CMS Endcap calorimeters were developed by RDMS in cooperation with the Rosatom State Corporation and MZOR, Minsk. 600 tons of brass absorber were made of military shells.
10. **Bending beam of particles.** The technology of the accelerator beam extraction using crystal bent channelling was developed and realized at the leading world accelerator centres.
11. **Gas Electron Multiplier (GEM) technology.** A wide-aperture central tracking system of the BM@N experiment is based on large-area triple Gas Electron Multipliers (GEM) produced at the CERN PH DT and MPT workshop in cooperation with LHEP JINR. The detectors are operational at high radiation loadings and in strong magnetic fields, have high spatial resolution and high geometrical efficiency. BM@N GEM chambers with the size of 1632×450 mm2 are the biggest GEM detectors presently produced in the world.
12. **Time of Flight detectors.** A ToF detector with excellent time resolution of better than 50 psec was designed by JINR in collaboration with CERN and some China's universities.
13. **Film-free gas-discharge detectors.** The VBLHEP groups developed and realized the method of the production of film-free gas-discharge detectors: wire chambers (realized at the Synchrophasotron and U-70), large-aperture proportional chambers for the NA-4 experiment at CERN, drift tube chambers based on the straw tube technologies. These detectors are used in the COMPASS, CBM, NA-62, NA-64, OKA, COMET, MPD, SPD, Thermalization and ATLAS (TRT) experiments.
14. **Record polarized nuclear target.** The DLNP researchers designed and constructed polarized proton and deuterium targets operating at 15-30 mK. The targets are currently in use in Mainz.

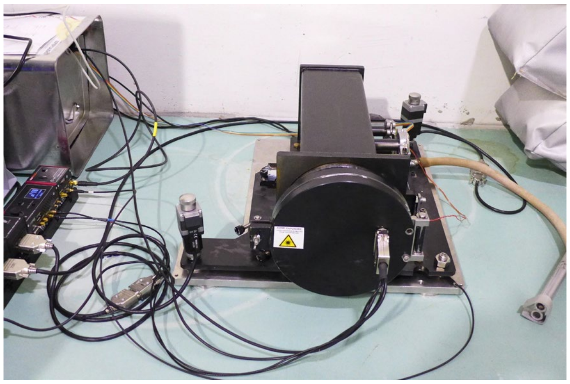

Fig. 1 Precision Laser Inclinometer by DLNP installed as a part of VIRGO detector.

Image credit: Yu. A. Budagov, M.V. Lyablin.

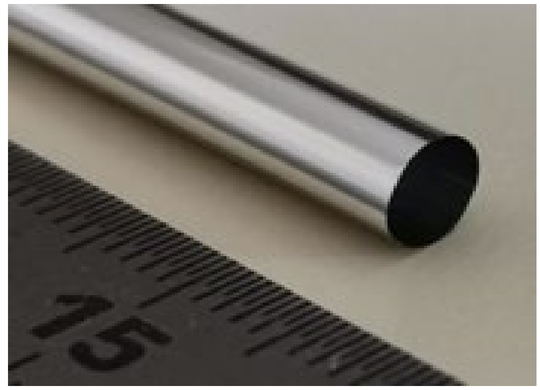

Fig. 2 A straw tube with 5 mm in diameter and wall thickness of 12 micron was produced at DLNP.

Image credit: Z. Tsamalaidze.

Present Research Projects of JINR Particle Physics groups:

The DLNP scientists participate in a number of home and international experiments in Particle Physics.

The experiments in Particle Physics include:

1. **ATLAS.** In total, 29 FTE work in this experiment on both upgrade and physics analyses.
2. **Mu2e.** In total, 10.6 FTE work in this experiment on DAQ and data analysis.
3. **COMET.** In total, 15.4 FTE work in this experiment on R&D of straw tubes and calibration of crystals.
4. **BES-III.** In total, 4.5 FTE work in this experiment on data analysis, software development, MC generator for electron-positron scattering, studies of physics potential of the CLIC project.
5. **PANDA.** In total, 9 FTE work in this experiment on MC generators, a muon detection system prototype.

National and International Networking Context

The VBLHEP scientists participate in a number of international experiments in Particle Physics (Heavy Ion experiments are included in the list since they focus also on Particle Physics):

1. **ATLAS.** In total, 10 FTE work in this experiment on both upgrade and physics analysis.
2. **CMS.** In total, 28 FTE (and 5.9 FTE from other laboratories) work in this experiment on upgrade, physics analysis, and maintenance of detectors within their responsibility.
3. **COMPASS-2.** In total, 9 FTE work in this experiment on data taking, analysis, and maintenance of detectors within their responsibility.
4. **ALICE.** In total, 11 FTE work in this experiment on both upgrade and physics analysis.
5. **PANDA.** In total, 8 FTE work in this experiment on MC generators.
6. **NA-61.** In total, 3 FTE work in this experiment on data taking, data analysis and maintenance of detectors within their responsibility.
7. **NA-62.** In total, 11 FTE work in this experiment on data taking, data analysis, MC, and maintenance of the straw tube-based tracking detector within their responsibility; also, they make necessary theoretical investigations.
8. **NA-64.** In total, 10 FTE work in this experiment on manufacturing and maintenance of the straw tube-based tracker detector, DAQ, MC simulation, online monitor code and analysis software development, data taking and data analysis; theoretical investigations, work on the experiment extension proposal.
9. **STAR.** In total, 22 FTE work in this experiment on data analysis, software development, data taking.
10. **CBM-HADES.** In total, 5 FTE work in this experiment on data taking, analysis, and maintenance of detectors within their responsibility.

In the frame of the NICA project implementation, the VBLHEP scientists participate in the experiments:

11. **BM@N.** In total, 74 FTE work in this experiment on R&D of the detector, its preparation for commissioning, development of corresponding electronics, DAQ, slow control, trigger; development of the scientific program and MC simulation; software development, data taking and data analysis; theoretical investigations.
12. **MPD. I**n total, 113 FTE work in this experiment on R&D and manufacturing of the detector, its preparation for commissioning tests, development of corresponding electronics and DAQ; development of the scientific program and MC simulation; software development; theoretical investigations.
13. **SPD.** In total, 22 FTE work in this experiment on R&D of the detector, its preparation for commissioning tests, development of the scientific program and MC simulation; software development; theoretical investigations.
14. **Nuclotron-NICA.** In total, 485 FTE work in this experiment on development and creation of the accelerators of the NICA complex and corresponding infrastructure.

In-house experiments realized by international collaborations include:

15. **Hyper-NIS.** In total, 17 FTE work in this experiment on its preparation for commissioning tests.
16. **Scan-3.** In total, 10 FTE work in this experiment on its preparation for commissioning tests.
17. **FAZA.** In total, 8 FTE work in this experiment on its preparation for commissioning tests.
18. **DSS.** In total, 10 FTE work in this experiment on data taking and analysis, as well as on its maintenance, preparation for commissioning tests and upgrade.
19. **Alpom-2.** In total, 1 FTE work in this experiment on data analysis.

JINR systematically invests resources in the development of both the national research infrastructure and experimental facilities, allowing present and future generations to work in the top-ranked scientific surroundings.

Staff and Equipment

DLNP and VBLHEP were the first two laboratories - the real founders of JINR back in 1956.

DLNP

Nowadays, the DLNP scientists run a wide range of experimental projects both at home and elsewhere. There is a variety of unique competences accumulated in methodology, detector construction, data analyses.

The scientific program of DLNP includes Particle Physics, accelerator technologies, Neutrino Physics and Astrophysics, Radiation Medicine, Genetics and molecular genetics studies, Radiochemistry and Nuclear Spectroscopy, ultra-cold temperatures as major directions.

From the 727 employees of DLNP, **278** are scientists, **304** are engineers and specialists, **121** are technicians and **24** are from administration. **39** of the scientists have a degree “Doctor of Science”, while **141** have a degree “PhD”.

DLNP has its own Information Technology Division, responsible for computer resources, data storage, internet access and lots of various services, and an Engineering Design Department with about two dozen highly qualified engineers.

The laboratory is equipped with several dozens of machines, including modern numerical CNC machines (SafanDarley, HAAS), 3D-printers and scanners. There is also a proton synchrophasotron, a linear electron accelerator, radiochemical equipment, microelectronics for R&D and production lines, as well as various tools and instruments for R&D of particle detectors.

VBLHEP

The 1207 VBLHEP employees can be broken down into **310** of scientists, **578** engineers and specialists, **260** technicians and **57** working in administration. **60** of the scientists have a degree “Doctor of Science”, while **141** have a degree “PhD”. The VBLHEP management intends to keep the number of FTEs working in Off-Site experiments below 100 in order to fulfil its responsibilities for the NICA project.

Expertise to Be Developed

JINR is determined to develop this currently missing expertise for achieving the research goals presented in this report:

- Application Specific Integrated Circuit (ASIC).
- FPGA Electronics.
- Robotics.
- Quantum Computing.
- General Relativity and Gravitational Interferometry.
- Project management.

ATLAS and CMS

LHC operates at the nominal collision energy of 13–14 TeV and luminosity of 3×10^{34} sm^{-2} s^{-1} and will carry on till the end of 2023 collecting 300 fb^{-1} of integrated luminosity at this stage (The LHC Run 3).

The third LHC long shutdown (Long Stop 3, LS3) is scheduled for 2024-2026 (Fig.1). From 2026 on, the LHC is expected to operate at an increased luminosity of 5×10^{35} cm^{-2} s^{-1} which will allow during the LHC Run 4 and Run 5 to increase the statistics by more than one order of magnitude up to 3000 fb^{-1}.

JINR intends to continue its involvement in the CERN-LHC program by participating in the ATLAS, CMS as well as the ALICE collaborations. An adequate matching of human resources to financial and hardware contributions must be targeted.

Motivation for continuation of the participation in the ATLLAS and CMS program

ATLAS and CMS are general purpose experiments, designed to study the physics of pp collisions at the Large Hadron Collider (LHC). Their prime goals are to explore physics at the TeV scale and examine the mechanism of electroweak symmetry breaking through the studies of the Higgs particles discovered in 2012 and searches for

- extra Higgs bosons beyond the Standard Model,
- supersymmetric partners of the SM particles,
- extra dimensions at TeV-energy scale,
- hints for unification of all fundamental interactions,
- deviations from the SM predictions.

These experiments will provide precision tests of the SM and measurements of EW and QCD processes.

For the Higgs boson in particular, the coupling constants to the SM particles will be measured with a precision of 5–14% and 2–10% given the integrated luminosities of 300 and 3000 fb^{-1}, respectively. Apart from that, collecting ~1200 fb^{-1} of integrated luminosity will enable observation of rare Higgs-boson decays such as $H \to \mu\mu$. This will also help clarify the problem of the $B^0 \to \mu\mu$ branching ratio which, according to the data of the first LHC run, slightly disagrees with the SM prediction by some 2 standard deviations.

International Context

The ATLAS and CMS international collaborations were established more than 25 years ago to search primarily for the Higgs boson existence with the help of the LHC.

Nowadays, the collaborations include more than 8000 and 5000 participants in ATLAS and CMS, respectively, from more than 200 institutes in about 50 countries.

During these 25 years, very complex ATLAS and CMS detectors were designed, constructed, commissioned, and used to successfully investigate a variety of physics phenomena, including a long-awaited Higgs boson discovery in 2012.

The JINR contribution to this achievement is of fundamental importance. The JINR teams are going to increase their contributions to the ATLAS and CMS physics programs as indicated further in the next section.

Scientists from almost all JINR Member States do work in the ATLAS and CMS experiments as JINR groups.

JINR LHC group program for the mid-term period

The JINR scientists target investigations in the following.

- Studies of the proton structure, hadronization, QCD coupling and of hadron’s spectra.
- Tests of the Standard Model at the LHC energies.
- Searches for Supersymmetry.
- Searches for new heavy particles and new interactions.
- Precision measurements of the properties of elementary particles and heavy baryons.
- Searches for signals predicted by scenarios of low-energy multidimensional gravity, extended gauge models, models with dark matter candidates, and scenarios with fermion flavour violation.

Also, both the ATLAS and CMS teams plan a number of upgrades, maintenance and R&D works in these experiments. Those are highlighted in the next section, indicating also the required resources.

JINR LHC group program for the long-term period

Scientists from JINR are going for new results in such important tasks as:

- Studies of the proton structure and of hadron spectra.
- Tests of the Standard Model at the LHC energies and higher statistics.
- Searches for Supersymmetry.
- Searches for new heavy particles and new interactions
- Measure with greater accuracy the properties of known elementary particles, such as: W and Z bosons, top quark, and heavy baryons.
- The upgrade work in the framework of the ATLAS and CMS Upgrade Projects during the long technical stop LS4 (2030) and LS5 (2034).
- R&D works for the upgrade of the ATLAS and CMS detector systems planned for LS4 (2030) and LS5 (2034).
- Maintenance of the ATLAS and CMS detectors system within the JINR responsibilities.

Required Resources

In the framework of the Phase-II (2017-2027) of the ATLAS upgrade, the JINR group will participate in:

- Production of new sRPC modules and gas system development for the muon spectrometer.
- Development of readout electronics, mass production of patch-cords for optical links and their radiation tests at the IBR-2 reactor for the liquid argon electromagnetic calorimeter.
- Procurement of various components of the TDAQ system, etc.

The CMS team will work on:

- Upgrade in the framework of the CMS Upgrade Project during the long technical stop LS3 (2024-2026).
- R&D for the upgrade of the CMS detector system planned for the LS4 (2030) and the LS5 (2034).
- Maintenance of the CMS detector system within the JINR responsibilities (endcap muon and hadron calorimetry systems).

- Upgrade of the First Forward muon station (ME1/1) and other ME2,3,4/1 muon stations.
- Participation in the construction of new High Granularity Hadron Calorimeters (HGCAL).
- Procurement of various components of the HGCAL, etc.

The MoUs have been signed by the Director of JINR V. A. Matveev. The overall JINR contribution to the Phase-II of the ATLAS upgrade is 3.4 MCHF, including Common Fund. This work will be done by the team that is presently involved in the Phase-I related activities. The overall contribution of JINR to the Phase-II of the CMS upgrade is 2.8 MCHF, including Common Fund. This work will be done by the team that is presently involved in the Phase-I upgrade activities and R&D for Phase-II.

- During the mid-term period JINR expects to invest 3.4M USD to ATLAS and 2.8M USD to CMS.
- During the long-term period JINR expects to invest 3.4M USD to ATLAS and 2.8M USD to CMS.

Future colliders

Motivation

After the discovery of the Higgs boson at LHC, the Standard Model is now a complete theory. However, there remain a number of open questions which cannot be answered within the SM framework. Among them are the problems of hierarchy, fine-tuning, scale of neutrino masses, dark matter and many others. It is widely believed that sooner or later SM will be superseded by a new theory able to answer the fundamental questions of that kind. The development of such theory needs an experimental insight from high-energy collider experiments.

Historically the new particles are often discovered at hadron colliders which are capable to reach very high energies. The discovery is then followed by high-precision measurements of the properties of the new particles. Electron-positron colliders with their clean experimental environment are optimally suited for such precision measurement. For example, W and Z bosons have been discovered at the hadron collider SppS, while their properties were measured down to a permille level at the e^+e^- colliders LEP and SLD. The tiny effects of radiative corrections observed at LEP and SLD allowed to predict the masses of the top quark and Higgs boson, which in turn were discovered at Tevatron and LHC.

It is expected that the New Physics phenomena can be observed at future e^+e^- colliders as tiny deviations from the Standard Model predictions via the measurements of top and Higgs properties at sub-percent level. Another possibility is the extremely precise measurement of W and Z boson properties at the level better than 10^{-4}. A direct discovery of new particles is also possible, since LHC experiments cannot cover the full spectrum of all the possible New Physics signatures.

International Context

Currently, 4 projects of the future electron-positron colliders are being actively developed: CEPC (China), CLIC and FCC (CERN), ILC (Japan). CLIC and ILC are linear colliders, while CEPC and FCC are circular ones, with possible upgrade to proton-proton or electron-proton collisions to provide a significant increase of collision energy. For CEPC and ILC the expected maximum e^+e^- collision energy is 240-250 GeV ("Higgs-factory"). FCC is planned to reach the top-pair threshold (350-360 GeV). CLIC plans to start operation at 380 GeV and then increase the energy up to 3000 GeV, making possible a direct search of New Physics. Additionally, CEPC and FCC are capable to provide an ultra-high luminosity running at 91 GeV ($0.7\text{-}5\cdot10^{12}$ Z bosons, "TeraZ-factory"), which would allow to improve the LEP precision by 2 orders of magnitude.

CLIC and FCC are the international collaborations coordinated by CERN. Both CERN member states and non-member states are actively involved in the projects. ILC is expected to receive the largest single contribution from Japan. However, it is a wide international collaboration, with non-Japanese contribution expected to be more than a half of the total project. CEPC is expected to receive at least 75-80% of its budget from China. However, an international collaboration is currently being formed to attract the contributions of technology and expertise, which is especially important given that no HEP project of comparable scale has been developed in China so far.

It is obvious that all four machines cannot be constructed simultaneously. Most likely, 1 or 2 projects will be chosen out of the 4. The active construction phase is expected to begin in 2028-2030, with first collisions in 2035-2037. It is therefore very important that at the current stage JINR keeps a critical level of involvement in all projects of the future collider.

Proposed Research

JINR physicists have accumulated a vast experience in physics at electron-positron colliders. JINR group participated in DELPHI experiment at LEP in 1987-2005 and in BES-III experiment at BEPCII since then. The ZFITTER program developed in JINR was the standard tool for the LEP data analysis.

Currently a wide R&D program is carried out in the Institute. JINR can provide an important contribution to the design and construction of the future collider and its detectors; data taking, processing and analysis; theoretical calculations for the interpretation of the experimental observables.

The following activities have already been started or are foreseen for both mid- and long-term periods:

- Accelerator technology R&D based on precision laser inclinometer developed in JINR.
- Development of novel particle detectors, in particular compact forward calorimeter developed in the FCAL collaboration, pixel detectors based on GaAs sensors and MPGD detectors (Micromegas, RPC, etc) which are currently developed in JINR.
- Development (and later implementation) of the experimental program of the future colliders in the following fields: precision measurement of the Higgs boson properties;

observation of the triple-Higgs vertex; top quark physics; physics of two-photon collisions; direct searches for the new phenomena at high energies.
- Creation of the theoretical program for complete one-loop calculations of the electron-positron annihilation into different final states including the polarization effects.
- Participation in the GRID computing infrastructure for the decentralized data processing.

Required Resources

The active construction phase is expected to begin around 2030. This stage will require substantial increase of resources.

Since all these top accelerator projects will have a price-tag in the order of many billions of $, JINR member states must have early discussions of how to participate under the JINR umbrella in such a unique World-Wide Facility.

For the R&D in accelerator technology as well as detector design, with prototype construction for both,

- **8M** USD are expected for the mid-term period.
- **35M** USD are expected for the long-term period.

NICA SPD

Being a JINR on-site mega-science project, NICA is reviewed in a separate document. The consideration here concerns mainly DLNP participation in NICA SPD experiment. Due to its polarized beams, NICA will be a forefront facility for spin physics in the World

Motivation

The share of the nucleon spin between spins and orbital momenta of quarks and gluons still remains an open question. Further studies of this phenomena could provide further insights into the QCD structure of hadrons. The measurement of the spin effects related with the transverse motion of partons inside the nucleon is the main goal of the SPD experiment.
NICA SPD is presently working on a conceptual design report (CDR), but the management has decided to construct the SPD hall already in the present construction period.

International Context

Scientists from JINR member-states and abroad are expected to increase their participation, thus establishing a truly international environment in NICA SPD experiment.

Proposed Research

The current considerations deal with the spin structure of hadrons and Transverse Momentum Dependent Parton Distribution Functions. The comprehensive research program is being determined.

The TMD (transverse momentum dependent) PDFs will be accessed via such hard processes like Drell-Yan process, charmonia production and prompt-photon production in the center-of-mass energy interval from 10 to 27 GeV in p-p and d-d collisions with luminosity up to 10^{32} cm^{-2} s^{-1}.

The DLNP team intends to perform the measurement of the transverse single and longitudinal double spin asymmetries in prompt-photon and charmonia production with accuracy on the level of below 2% in order to access the helicity and Sivers PDFs for gluons. Charmonia production mechanisms will also be tested. DLNP also participates actively in the development of the SPD muon system and DAQ system. Preparation of the TDR should be finished till 2023 and the time scale for realization of the project extends beyond 2025.

Required Resources

- For the mid-term period JINR plans to invest 21M USD which break down:
    - R&D, construction and commissioning of data acquisition system: 10M USD.
    - R&D, construction and commissioning of muon system: 10M USD.
    - Travel expenses: 1M USD.
- For the long-term period JINR plans to invest 8M USD for the detector maintenance.

Summary

The proposed long-term Strategy for Elementary Particle Physics and Astrophysics at JINR is based on four pillars: Accelerator Based Physics and Accelerator Technologies, and Detector Technologies, supplemented by a well though educational and outreach program.

This strategy carefully strengthens traditional JINR strong expertise in particle physics, and detector technologies.

Timeline

Tables 1 and 2 provide compact summaries on the timelines of the mid- and long-term experimental activities. The cell colours in tables 1,2 are summarized in what follows.

Cell color	R&D	Construction Commissioning	Data taking	STOP	Decision Point

<table>
<tr><td></td><td colspan="2">24</td><td colspan="2">25</td><td colspan="2">26</td><td colspan="2">27</td><td colspan="2">28</td><td colspan="2">29</td><td colspan="2">30</td><td>Main physics goal
Invest.-Budget, USD</td></tr>
<tr><td rowspan="2">**ATLAS**</td><td colspan="5" rowspan="2">LS3 upgrade</td><td colspan="9">RUN 4</td><td rowspan="2">Beyond the SM, precision EW and QCD
3.4M
+39 FTEs/a</td></tr>
<tr><td colspan="9">LS4, LS5 R&D</td></tr>
<tr><td rowspan="2">**CMS**</td><td colspan="5" rowspan="2">LS3 upgrade</td><td colspan="9">RUN 4</td><td rowspan="2">Beyond the SM, precision EW and QCD
2.8M
+ 28 FTEs/a</td></tr>
<tr><td colspan="9">LS4, LS5 R&D</td></tr>
<tr><td>**Future Colliders**</td><td colspan="3"></td><td colspan="1"></td><td colspan="4"></td><td colspan="6"></td><td>Beyond the SM, precision EW and QCD
8M</td></tr>
<tr><td>**NICA-SPD**</td><td colspan="4"></td><td colspan="10"></td><td>TMD PDF
21M + 50 FTEs/a</td></tr>
</table>

Table 1. Timeline of projects from the mid-term Strategy for elementary particle physics and astrophysics at JINR. *(Full costs of 1 FTE about 50 k$ in 2020 $)*

	31	32	33	34	35	36	37	Main physics goal **Budget, USD**
ATLAS	LS3 upgrade		RUN 4					Beyond the SM, precision EW and QCD **3.4M** **+39 FTEs/a**
			LS4, LS5 R&D					
CMS	LS3 upgrade		RUN 4					Beyond the SM, precision EW and QCD **2.8M** **+ 28 FTEs/a**
			LS4, LS5 R&D					
Future colliders								Beyond the SM, precision EW and QCD **35M**
NICA-SPD								TMD PDF **8M+ 50 FTEs/a**

Table 2. Timeline of projects from the long-term Strategy for elementary particle physics and astrophysics at JINR. *(Full costs of 1 FTE about 50 k$)*

International Context

JINR Strategy for Elementary Particle Physics is a careful balance of home and foreign experiments. All JINR member-states have a unique possibility to enjoy both a rich, modern JINR infrastructure and participation in the world-class leading experiments in the fields of particle physics.

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