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# Measurement of the Rare Decay $K^+ \to \pi^+ \nu\nu$ at the CERN SPS

**NA62 Project (**Collaboration **NA62)** *Prologation for 2019-2021*

Theme 02-1-1096-2010/2019

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DATE OF SUBMISSION OF PROPOSAL OF PROJECT TO SOD 2018

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Form № 25

Sheet of the Project Approvals

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Theme number: 02 - 1 -1096- 2010/2019

Theme leaders: V.D.Kekelidze, Yu.K.Potrebenikov
Project leaders: V.D.Kekelidze, Yu.K.Potrebenikov

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| **APPROVED BY JINR DIRECTOR** | ____________ (Signature) | «___»_________**2018.** (Date) |
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| **JINR VICE-DIRECTOR** | ____________ | «___»_________**2018.** |
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| **TEAM LEADER** | [signature] | «12» 03 **2018.** |
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**List of contents**

**Abstract**

The proposed project is a continuation of the three stages of NA62 project, implemented in VBLHEP JINR in 2010 - 2018. The goal of all stages of the project is the participation in realization of the NA62 experiment at SPS CERN, where a measurement of the very rare kaon decay $K^+ \to \pi^+ \nu\nu$ is planned to make a decisive test of the Standard Model (SM) by means of the 10%-precision measurement of the Cabibbo-Kobayashi-Maskawa (CKM) matrix parameter $V_{td}$.

Additionally, a series of precision measurements may be performed for the kaon rare leptonic decay modes in order to check the validity of the Chiral perturbation theory (ChPT) that provides a low energy approximation for the strong interactions description. Apart from that, there is a plan to search for the Goldstone fermion superpartner – pseudoscalar sgoldstino.

The strategy of the ongoing NA62 experiment is based on the measurement of the high energy $K^+$ decays in flight. In this case, the kaons production cross section is optimized as a function of the proton energy, and the photons detection is efficient due to their high energies in the laboratory system.

The JINR NA62 team consists of experienced physicists and young scientists. Prof. V. Kekelidze and D. Madigozhin possess the Doctor of Science degree. Yu. Potrebenikov, S. Gevorkian, E. Goudzovski, L. Glonti, T. Enik, N. Molokanova, S. Movchan and I. Polenkevich possess the PhD degrees. All of them have a vast experience obtained in other experiments on the kaon decay properties, including the NA48, NA48/1 and NA48/2. A. Korotkova, M. Misheva and S. Shkarovsky participated in the data analysis for NA48/2 experiment and work currently on their PhD theses based on the corresponding results. A. Baeva, D. Baigarashev and D. Emelyanov are young employees actively involved into the project, and they plan to prepare PhD theses based on the NA62 data.

The volume of the necessary funding for the years 2019-2021 from the JINR budget is **$380k**.

## Introduction

The proposed project is a continuation of the three stages of NA62 project, implemented in VBLHEP JINR in 2010 - 2018. The goal of all stages of the project is the participation in realization of the NA62 experiment at SPS CERN, where a measurement of the very rare kaon decay $K^+\to\pi^+\nu\bar{\nu}$ is planned to make a decisive test of the Standard Model (SM) by means of the 10%-precision measurement of the Cabibbo-Kobayashi-Maskawa (CKM) matrix parameter $V_{td}$.

Using the Wolfenstein notation of CKM, the relationship between the parameters ρ and η may be represented by the unitarity triangle shown in Figure 1. The “golden modes” $K^0\to\pi^0\nu\bar{\nu}$ and $K^+\to\pi^+\nu\bar{\nu}$ give an opportunity to make a very sensitive tests of SM, as their probabilities are directly related to $\eta^2$ (height of triangle) and $(\rho - 1.4)^2 + \eta^2$. The SM predictions for these two decay rates have accuracy to 2% and 8% respectively, and if significant deviations from the predictions will be observed, it will undoubtedly be the evidence of the phenomenon beyond the SM.

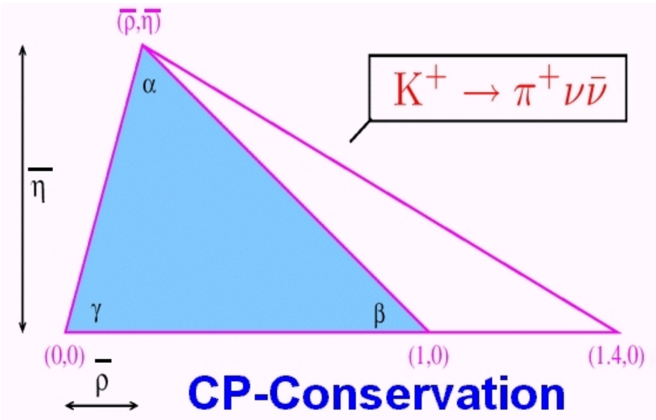



*Figure 1. The decay $K^+\to\pi^+\nu\nu$ is represented by the right segment of the triangle.*

The purpose of the NA62 experiment, a detailed description of which is given in [1,2,3,4], is to register about 100 events of $K^+\to\pi^+\nu\bar{\nu}$ decay and to keep the total systematic uncertainty small. It will be a considerable improvement with respect to the currently available E787 and E949 result [5] based on just 7 golden mode events.

To this purpose, at least $2\times10^{13}$ $K^+$ decays are required, assuming a 10% signal acceptance and the branching ratio of $10^{-10}$. Small systematic uncertainty requires a rejection factor for generic kaon decays at the order of $10^{12}$, and the possibility to measure registration efficiencies and background suppression factors directly from the data. The possibility to work in an intense kaon beam, reliability of signal extraction and background suppression are the main criteria of success in preparation and carrying out of the NA62 experiment.

Large kaon flux makes it possible to search for other rare kaon decays and to study their characteristics, including a check of the prediction [6] about the existence of Goldstone fermion superpartners - pseudoscalar sgoldstino P and to improve the probability limits set by HyperCP [7] and ISTRA [8]. Apart from that, a series of precision measurements may be performed for the kaon rare decay modes in order to check the validity of the Chiral perturbation theory (ChPT). A search for the rare decays, that are forbidden or extremely suppressed in the frameworks of SM opens a possibility to discover a new physics or to set a new limits on the validity of SM and some its extensions. It includes the search for the light candidates to the dark matter that may be generated in rare kaon decays, for example – heavy neutral lepton [9].

Physical motivation is presented in more details in Chapter 2 of the Proposal of the experiment [1] and in Chapter 3 of the report [4].

**State-of-the-art of the science case proposed**

The most precise experimental results have been obtained by the E787 and E949 experiments at BNL by studying of the stopped kaon decays [5]: $B(K^+\to\pi^+\nu\nu) = (1.73^{+1.15}_{-1.05})\times10^{-10}$. Apart from the NA62 experiment described below, no other measurements of this mode are currently conducted or planned. Existing gap between the theoretical precision and the large experimental error motivates a strong experimental effort. Significant new constraints can be obtained with a measurement of the rate of this reaction at the level of 10% or better.

The strategy of the ongoing NA62 experiment is based on the measurement of the high energy $K^+$ decays in flight. In this case, the kaons production cross section is optimized as a function of the proton energy, and the photons detection is efficient due to their high energies in the laboratory system. As a result, the $\pi^+\nu\bar{\nu}$ signal acceptance is expected to be about 20 times higher than in the stopped kaon BNL experiments. The NA62 experimental setup is shown in the Figure 2.

Charged products of the studied $K^+$ decay are registered primarily by the straw tracker which allows one to register a single track and to measure the corresponding momentum with a good accuracy. In order to extract the signal, the distribution of the missing mass square for $K^+$ and positively charged track is analyzed in assumption that the track is produced by $\pi^+$. The missing mass distribution without experimental resolution for the $K^+\to\pi^+\nu\bar{\nu}$ decay is shown in the left diagram of the Figure 3 by solid red line. The NA62 signal acceptance areas are chosen taking into account the resolution of the setup (Region I and Region II in the Figure 3). The left diagram shows the distributions of background decays, which can be separated from the signal by means of kinematics, and the right one shows kinematically inseparable background.

To suppress the background of the two-particle decays, both the kinematic cuts and the particle identification (PID) are necessary. Backgrounds from $K^+$ three- and four-body decays are also considerable, that assumes a detailed analysis of their properties and implementation of specific rejection techniques to each of them. The $K^+$ decay modes with the largest probabilities are listed in Table 1 with the methods of the corresponding background suppression.

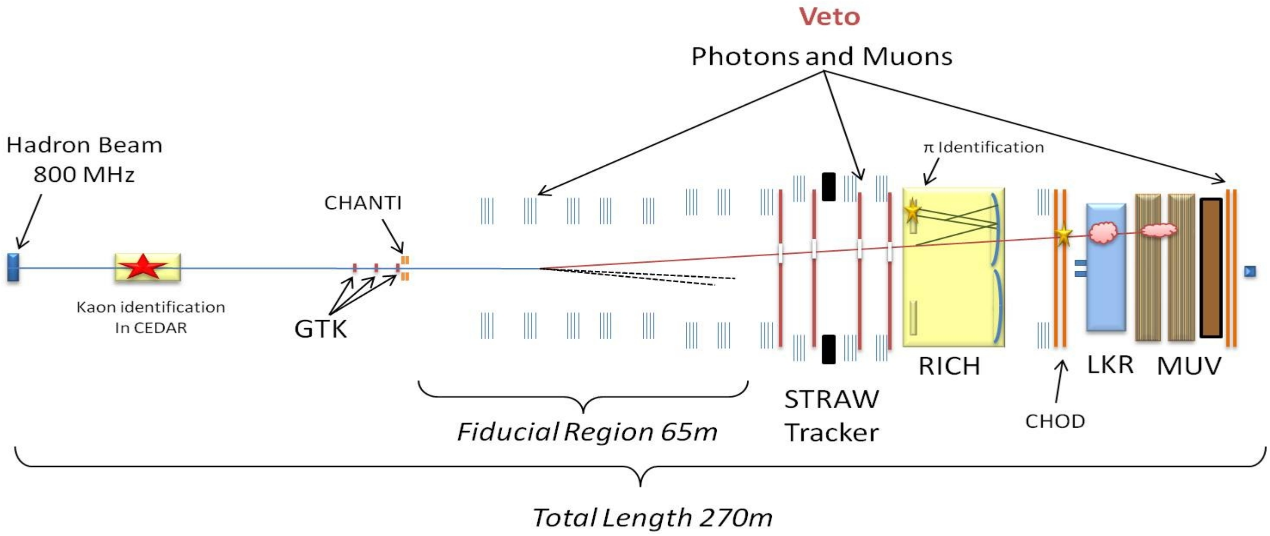



*Figure 2. Schematic view of the NA62 experimental setup.*

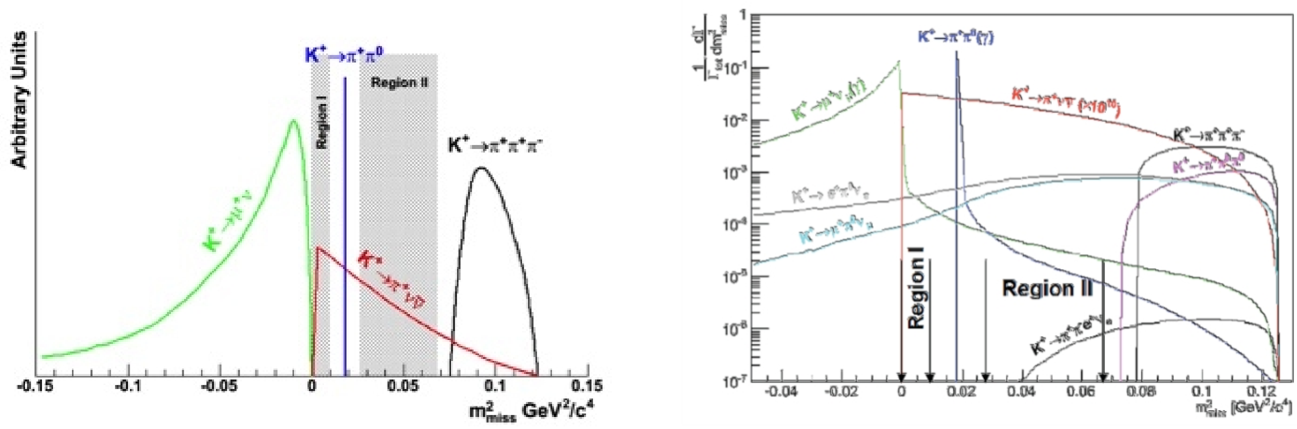



*Figure. 3. Missing mass* $m^2_{miss} = (P_K - P_{track})^2$ *distribution for the signal (red line) and background events. Background decay modes that may be separated from the signal by kinematics are shown on the left plot, while the inseparable background is on the right plot.*

There are also $K^+$ decay modes (with branching ratios > $10^{-5}$), for example, $K_{e4}$ ($K^+ \rightarrow \pi^+\pi^- e^+\nu$), which can have a topology similar to the studied decay in cases when both the negatively charged pion and the charged lepton escape detection. So it is mandatory that the $\pi^-$ be observed and that the detector therefore be rendered hermetic with respect to negatively charged particles of momentum < 60 GeV/c. This is provided by a system with 4 tracking detectors (chambers composed of straw tubes) forming the active elements of the NA62 Magnetic Spectrometer [3].

*Table 1. The most frequent $K^+$ decay modes.*

| Decay Mode | Branching Ratio | Background Rejection method |
|---|---|---|
| $K^+ \to \mu^+\nu$ | 63% (called $K_{\mu2}^+$) | μ PID, Two-Body Kinematics |
| $K^+ \to \pi^+\pi^0$ | 21% | Photon Veto, Two-Body Kinematics |
| $K^+ \to \pi^+\pi^+\pi^-$ | 6% | Charged Particle Veto, Kinematics |
| $K^+ \to \pi^+\pi^0\pi^0$ | 2% | Photon Veto, Kinematics |
| $K^+ \to \pi^0\mu^+\nu$ | 3% (called $K_{\mu3}^+$) | Photon Veto, μ PID |
| $K^+ \to \pi^0 e^+\nu$ | 5% (called $K_{e3}^+$) | Photon veto, *E/p* |

The physical tasks define the NA62 experimental setup design (see Figure 2). The main design idea was the redundant measurement of particle characteristics to control non-Gaussian tails for the precise measurement of event kinematics. NA62 experimental setup includes the following detector systems:

- The **CEDAR** identifies the $K^+$ component in the beam with respect to the other beam particles by employing an upgraded differential Čerenkov counter.
- The Gigatracker **(GTK)** consists of three Si micro-pixel stations measuring time, direction and momentum of the beam particles before entering the decay region.
- The **STRAW tracker** consists of 4 straw chambers. It measures the coordinates and momentum of secondary charged particles originating from the decay region. In order to minimize multiple scattering the chambers are built of ultra-light material and are installed inside the vacuum tank. The four Straw chambers are arranged around a large aperture dipole magnet (MNP33, black at the scheme), providing a vertical B-field of 0.36 T.
- The **RICH detector** consists of 17m long radiator filled with Neon gas at 1 atm. allowing the separation of pions and muons between 15 and 35 GeV/c.
- A system of Photon-Veto detectors provides hermetic coverage of the decay region from zero to large (~50 mrad) angles. This is assured by:

1. the high-resolution Liquid Krypton electromagnetic calorimeter (**LKr**),
2. the Intermediate Ring (**IRC**) and Small-Angle (**SAC**) Calorimeters and,
3. a series of 12 annular photon-veto (**LAV** or **Veto**) detectors for large angles.

- The Muon-Veto detectors (**MUV**) are composed of the two-part hadron calorimeter followed by the additional layer of iron and the transversally segmented hodoscope. This system supplements and provides redundancy with respect to the RICH in the detection and rejection of muons.

These detectors are complemented by “guard-ring” counters (**CHANTI**) surrounding the last GTK station, and the charged-particle hodoscope (**CHOD**), covering the acceptance and located between the RICH and the LKr.

All these detectors are operated and inter-connected with a high-performance **trigger** and **data-acquisition** (**TDAQ**) system. The main detectors are described in details in [1,3].

The usage of a high intensity unseparated $K^+$ beam required several challenging solutions that have been done during the setup design and construction:

- the detector is able to perform charged particle tracking at 1 GHz total rate, ~60 MHz/cm$^2$ with a minimal material and excellent time resolution for the kaon momentum measurement;
- the differential Cerenkov counter for the positive kaons identification (CEDAR) is built;
- hermetic photon vetoes are constructed, they are divided in three angular regions and use three different detection techniques for $\gamma$-rejection;
- $\mu/\pi$ separation is performed by the RICH counter for $\mu$ rejection and for track kinematics reconstruction;
- and finally, the magnetic spectrometer for momentum measurement of kaon decay charged products together with RICH provides a redundancy in missing mass reconstruction to suppress a possible non-gaussian tails.

Large statistics of kaon decays in NA62 provide us with a possibility to check the prediction [6] about the existence of Goldstone fermion superpartners — pseudoscalar sgoldstino *P* (see Figure 4, left part). The HyperCP experiment [7] has registered 3 decays $\Sigma \rightarrow \pi\mu^+\mu^-$ where the mass of $P \rightarrow \mu^+\mu^-$, if it exists, is 214.3 MeV. In the NA62 experiment the precise measurement of incoming $K^+$ parameters provides a possibility to reconstruct the complete event kinematics even without $\pi^+$ registering for the decay $P \rightarrow \gamma\gamma$.

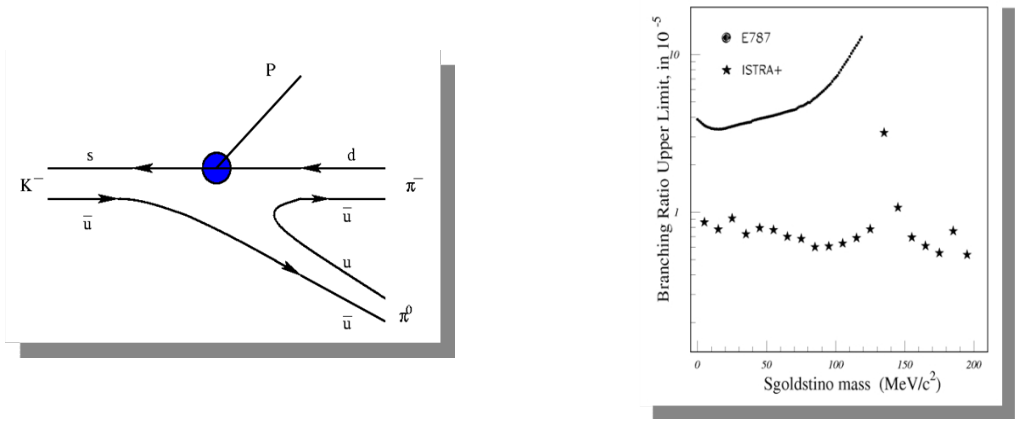



*Figure 4. A diagram of supersimmetric Goldstone fermion partners production (left) and the upper limit of sgoldstino branching ratio from ISTRA experiment [7] (right).*

**<u>Report for the prevoius implementation period of the NA62 project in JINR</u>**

The NA62 experimental setup has been constructed and tested during the autumn 2014 run with CERN SPS beams. Experts from JINR and CERN have provided the construction and installation of the track spectrometer detectors designed and built during the two NA62 project stages completed in JINR earlier (in 2010-2012 and in 2013-2015).

A spectrometer configuration based on the straw tracker has been adopted for the detection and measurement of charged decay products upstream the RICH counter. To minimize the multiple scattering of the outgoing decay products, the spectrometer detectors are installed in vacuum. The straw tracker is designed without internal frames and flanges. The straw tracker consists of 4 chambers based on straw tubes and positioned upstream and downstream the MNP33 spectrometer magnet.

Each chamber consists of four coordinate views - X, Y, U, V. Desirable momentum and angle precision for secondary particles is $\Delta p/p \leq 1\%$ and $\Delta\theta_{\pi K} \leq (50 - 60)$ μrad. These requirements are achieved by means of minimum matter along the particle trajectory and the spatial resolution of the tracker about ~80 μm for a space point.

The main element of the detector is an ultra-light straw tube ~2.4 m long (2.1 m of effective length) and 9.8 mm in diameter. The tubes are manufactured from 36 μm thin polyethylene terephthalate (PET) foils, coated inside the tube with two thin metal layers (0.05 μm of Cu and 0.02 μm of Au) in order to provide electrical conductivity on the cathode and to suppress the straw tube gas diffusion. The anode wire (Ø=30 mm) is made of gold-plated tungsten.

Studies performed with three straw prototypes allowed us to estimate the achievable characteristics of the constructed detectors with different gas mixtures and various read-out electronics, radiation resistance of straw tubes, as well as to design the optimal scheme of straw positioning inside the mechanical framework that allows to achieve a high efficiency of tracks registration by the spectrometer detectors. These works are described in details in the report on the 2010 - 2012 stage of the NA62 project.

After the installation of straw chambers into the NA62 experimental setup in 2014 (see. Fig. 5) their actual position has been measured with respect to the beam axis with an accuracy of 0.3 mm. Vacuum tests of straw detectors have been conducted in real experimental conditions. All the necessary cables and gas communications for the chambers have been laid. The gas supply system with a protection from the effects of a possible straw damage in the vacuum volume has been mounted as well. 4 modules with high-voltage and low-voltage power supplies (MPOD) have been installed for powered straw tracker (see. Fig.6, left). JINR staff members have developed a user-friendly management interface for these modules (Fig.6, right). Integration of the modules into the common "NA62 slow control" system of the NA62 experiment has been carried out as well.

A shape of the experimental leading edge time distribution in a straw tube has been compared with the simulation one. A good agreement of these spectra (see. Fig. 7) allowed one to use the simulated relation between the drift time and the coordinate of a particle in a straw. Time shifts of the track hit $T_0$ for each straw are adjusted with respect to the reference time given by the charged particles hodoscope CHOD of the NA62 set-up.

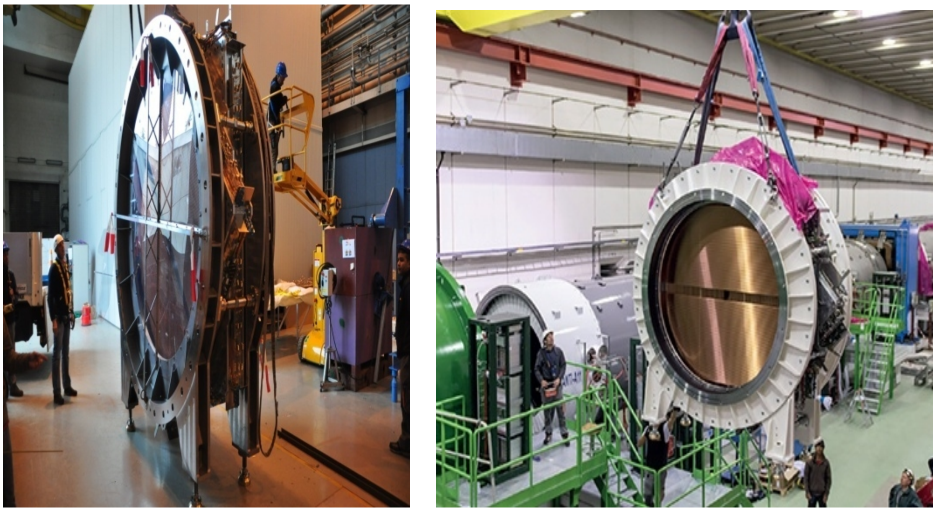


*Figure 5. Straw chamber assembled of 2 modules (left) and its installation into the NA62 experimental setup (right).*

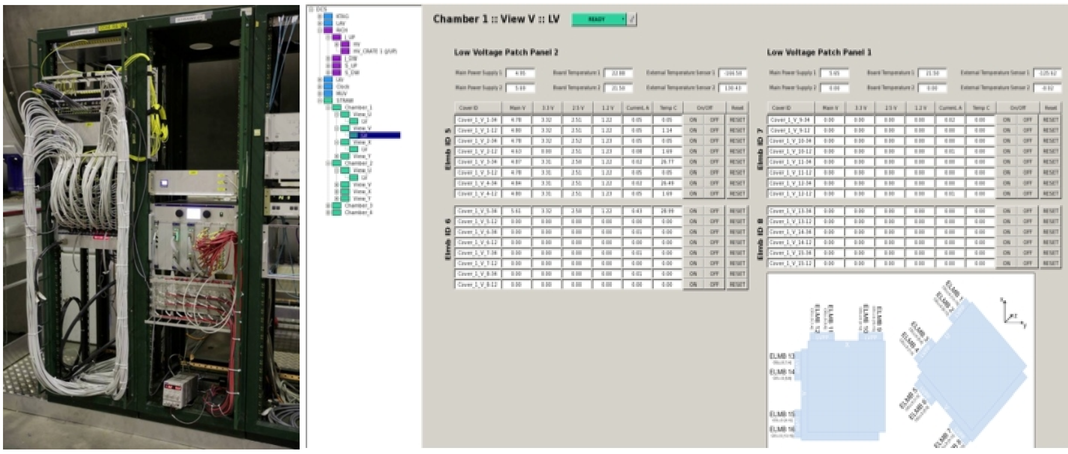



*Figure 6. MPOD module with high- and low-voltage power supplies for one straw chamber (left) and user interface control panel (right).*

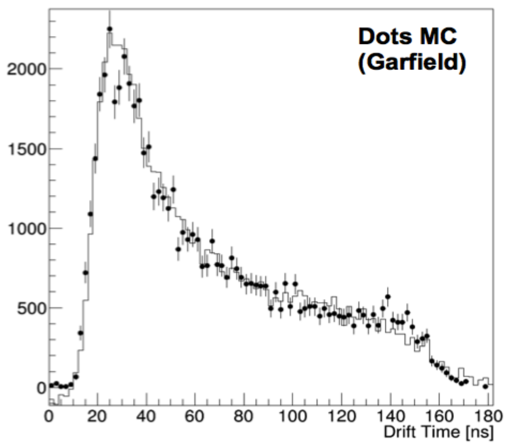



*Figure 7. The typical shape of the leading drift time distribution in the straw tube: points – the simulation results, solid line - the experimental data.*

NA48/2 and NA62 experimental data obtained in 2003 – 2010 were analyzed in parallel with the NA62 data taking:

- On the basis of NA48/2 data, a new upper limit on the rate of the lepton number violating decay $K \rightarrow \pi\mu^{\pm}\mu^{\pm}$ has been obtained: $Br(K \rightarrow \pi\,\mu^{\pm}\mu^{\pm}) < 8.6\times10^{-11}$ at 90% CL [10,32,33]. Searches for two-body resonances have been resulted in the upper limits for the products of branching ratios $Br(K^{\pm} \rightarrow \mu^{\pm} N_4)B(N_4 \rightarrow \pi\mu)$ and $B(K^{\pm} \rightarrow \pi^{\pm} X)B(X \rightarrow \mu^{+}\mu^{-})$. These limits depend on the hypothetical particle lifetime ($10^{-9}$ and $10^{-11}$ for the resonance lifetime below 100 ps).
- On the basis of NA62 data collected in 2007, a measurement of $\pi^0$ electromagnetic transition form factor slope parameter has been measured to be $a=(3.68\pm0.57)\times10^{-2}$ [11]. The obtained result is in good agreement with the theoretical expectations and earlier measurements. It is the most precise experimental determination of the slope in the time-like momentum transfer region.
- A peak search has been performed in the reconstructed missing mass spectrum of $K^{+}\rightarrow\mu^{+}\nu$ decays collected by NA62 experiment in 2007. In the absence of a signal, limits in the range $2\times10^{-6}$ to $10^{-5}$ have been set on the squared matrix element $|U_{\mu4}|^2$ describing the mixing between the muon and heavy neutrino states, for the heavy neutrino masses in the range 300-375 MeV/$c^2$ [12,13].
- The paper on the measurement of form factors of $K_{e3}$ and $K_{\mu3}$ decays based on NA48/2 data is in preparation after the internal reviewing. Preliminary results on the form factors of the semileptonic decays of charged kaons have been presented at the conferences [14]. Dubna group has the responsibility for the final result publishing.
- The analysis of the new rare decay $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}e^{+}e^{-}$ based on NA48/2 data is in its final stage, it is the first experimental evidence of this channel. The preliminary value of the measured branching fraction of this decay $Br(\pi^{\pm}\pi^{0}e^{+}e^{-})=(4.22 \pm 0.06_{stat}\pm0.04_{syst}\pm0.13_{ext})\times10^{-6}$ is obtained [14].
- The study of $K_{\mu4}^{00}$ rare decay on the basis of NA48/2 data is in progress, a preliminary result on the branching ratio is obtained. This decay mode also has not been experimentally observed earlier.
- The analysis of the four-lepton kaon decays is started on the basis of the NA62 data collected in 2016 and 2017 years.

In parallel with the experimental works the following methodical and theoretical results have been obtained:

- The interactive software tool for the straw spectrometer geometrical, data taking and power supply mapping has been developed for the use in NA62 collaboration.

- The calibration and monitoring tool for the control of the straw time measurement stability on the burst-by-burst basis has been developed. It is implemented for the correction of data collected in 2016 and for the special on-line monitoring during the runs 2017 and 2018.
- The analysis software tool has been developed for the control of the straw wire positions and the tube transverse displacements. It uses the two-dimensional plots of the hit times and the distances between the reconstructed Spectrometer track and the wire where the hit is recorded.
- A review of the kaon decay studies performed by NA48, NA48/1 and NA48/2 collaborations has been prepared and published [15].
- The NA62 drift chamber design has been published [16]. The main features of the chamber and some characteristics of the drift tubes are described.
- The NA62 spectrometer acquisition system has been described in the paper [17]. The front-end and read-out systems of the detector are presented along with the first results of the detector performance.
- For the development of charged particle detectors based on straw tubes operating in vacuum, a special measurement technique is required for the evaluation of their mechanical properties. Equations that govern straw behaviour under internal pressure are reviewed, and a new experimental method of a strained pressurized straw tube study is proposed. The Poisson's ratio of the straw wall, which defines the stability conditions of a built-in tube, is measured for the NA62 spectrometer straw [18].
- It is shown that positions of wires in straws and thus the anode spacing in the drift chambers can be directly determined with a high accuracy (~5–10 μm) using a microscope mounted on a high-precision optical bench. These data are important for decreasing errors during reconstruction of charged particle track coordinates in the drift chambers [19,35].
- A design of the device for fabricating thin-wall (straw) drift tubes using polyethylene terephthalate film 36 μm thick by ultrasonic welding is published as well as the technique for controlling their quality [20,34].
- The interactions of transversely and longitudinally polarized vector mesons with nucleons have been studied theoretically [21,22].
- The production of two-meson electromagnetic bound states and free meson pairs in relativistic collisions has been considered. The amplitude of DMA transition from 1S to 2P state, which is essential for the pionium Lamb shift measurements, has been obtained [23].
- The possibility of difference in interaction of transverse and longitudinally polarized vector mesons with nucleons is discussed [24].

During the NA62 experimental runs in 2016-2018 the JINR group members perform in total about 250 shifts on the experimental setup.

**Description of the proposed research**

Subject of the research and methods

Reasearch activity proposed for the extension of the NA62 Project in JINR will be focused on the reaching the final goal of the ongoing NA62 experiment – nearly 10% precision measurement of the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio. JINR contribution to this result already includes the participation in the Spectrometer creation and maintaining. During the analysis stage, JINR group will take part in the checks and evaluation of rare background sources related to the Spectrometer resolution and efficiency. Additionally, some second priority physical tasks are foreseen for the data analysis.

Apart from the main goal, NA62 collaboration plans to investigate a series of the kaon rare decay modes. JINR group participates in the analysis of the four-lepton decays $K^+ \to e^+\nu\mu^+\mu^-$, $K^+ \to e^+\nu e^+e^-$, $K^+ \to \mu^+\nu e^+e^-$ and $K^+ \to \mu^+\nu\mu^+\mu^-$ (not yet observed) with the branching ratios of the order of $10^{-8}$. Their precision measurement will improve our knowledge of the ChPT parameters and will check its validity. The search for the forbidden modes $K^+ \to e^-\nu\mu^+\mu^+$, $K^+ \to \mu^-\nu e^+e^+$ is also foreseen in order to check the limits of SM.

It is possible to register about 50 $\pi^+\pi^0 P$ decays with sgoldstio P (if it exists) in the final state, similar to $\pi^+\pi^0\pi^0$, even with a trigger, downscaled by a factor of 100 for the upper limit of the branching ratio near $10^{-8}$, that is three orders of magnitude lower, than the limit from ISTRA experiment [8] (see Figure 4, right part).

A search for heavy neutral lepton (HNL) production in charged kaon decays is also foreseen on the basis of NA62 data. For example, Neutrino Minimal Standard Model [9] postulates three HNLs, explaining dark matter and baryon asymmetry of the universe. The idea of the search for HNL in NA62 is based on the missing mass distributions for $K^+ \to e^+$ and $K^+ \to \mu^+$ topologies with the measured kaon and lepton momenta. Heavy neutral lepton production should be visible as the peak on the missing mass distribution at the apriory unknown nonzero value of the mass.

The experimental research methods rest upon the NA62 decay-in-flight technique based on the measurement of the high energy kaon decay products as well as on the incoming kaon kinematics registering. Fundamental kinematic relations are used to evaluate the events characteristics, while the statistical interpretation of the results rely upon the established mathematical tools and tested software. NA62 experimental setup described above is built during the previouse stages of the Project, and only its support, tuning and calibration are expected from the JINR group in the future.

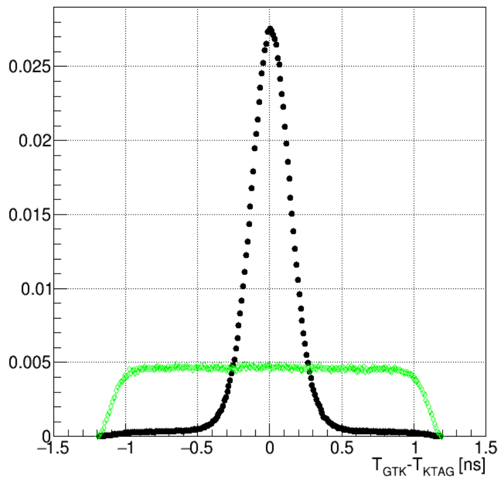
Accomplished groundwork

During the physics NA62 run in 2016 a stable data taking was performed at the intensity of $13 \times 10^{11}$ protons per pulse on the target used for the kaon flux generation (40% of nominal intensity). The intensity was limited by the beam time structure (including 50 Hz variations) that was leading to the increased maximum values of the beam intensity during the burst, that were much higher than it was expected. As a result, the backend electronics of some detectors (including the Spectrometer electronics) was not able to process the data during the peaks of intensity. Nevertheless, about $4 \times 10^{11}$ kaon decays have been collected with a special mixture of trigger conditions useful for the $K^+ \to \pi^+ \nu \bar{\nu}$ mode analysis.

Due to the firmware development, for NA62 run in 2017 the data taking was possible at 60% of nominal intensity, that seems to be a maximum for the given time structure of the beam. During this run nearly $3 \times 10^{12}$ kaon decays have been recorded.

The similar run conditions are expected for the run of 2018. The total expected statistics to be collected in 2016-2018 will correspond to 20 signal events for the SM predicted branching ratio. So there is a preliminary plan to perform the data taking also after the long shutdown scheduled for 2019-2020 in order to complete the $K^+ \to \pi^+ \nu \bar{\nu}$ measurement with the statistics initially foreseen by the experiment Proposal.

The first test results of the main mode analysis are based on the 5% of the 2016 run statistics. The blind analysis strategy is adopted, so the data used for the selection cuts optimization will not participate in the final signal measurement – that is why only a very small part of collected data may be considered at the testing stage of the analysis.



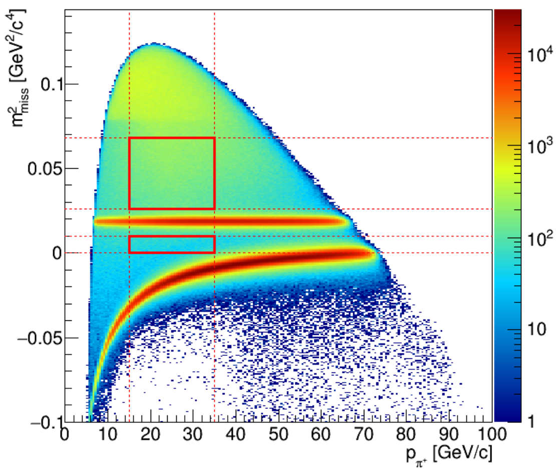




*Figure 8. Left: GTK and KTAG (CEDAR) time difference distributions for the kaons corresponding to the selected* $K^+ \to \pi^+ \pi^+ \pi^-$ *decays (black points) and for the accidental combinations (green points). Right: Missing mass versus the positively charged track momentum for the data collected with a minimum bias trigger in 2016. Red boxes show signal regions.*

Fig. 8 (left plot) demonstrates the time resolution for the two detectors measuring the incoming charged kaon: Gigatracker and KTAG (CEDAR). The time difference peak is formed by the GTK time resolution of ~ 100 ps and KTAG resolution of 80 ps. The probability of accidental kaon mis-tagging is estimated to be 1.7%. The typical closest distance between the kaon and pion tracks forming a physical vertex is ~ 1.5 mm.

The right plot of the Fig. 8 shows the kinematical plots for the minimum bias data. The largest background sources are $K^+ \to \pi^+\pi^+\pi^-$ (dominating above 0.07 $GeV^2/c^4$), $K^+ \to \pi^+\pi^0$ (the peak near 0.02 $GeV^2/c^4$) and $K^+ \to \mu^+\nu$ (the negative missing mass zone). The main backgrounds are detected with the expected characteristics, so their kinematical suppression is expected to be efficient.

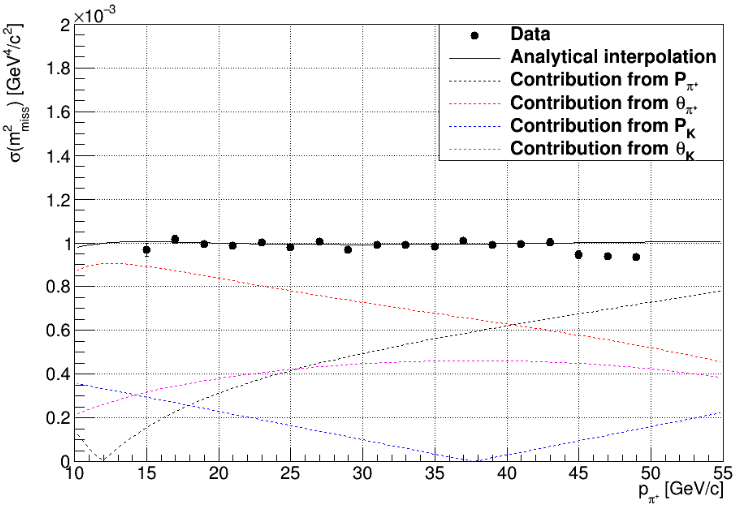



*Figure 9. Resolution of the missing mass measured from the $K^+ \to \pi^+\pi^0$ data (black dots) shown with the separate contributions from different sources estimated from MC simulation.*

Fig. 9 shows the reached resolution of the missing mass with respect to the design level corresponding to 1. One can see, that the design level is well reproduced, so the contributions from the Spectrometer side (listed on the plot as pion-related values) do not exceed the expected values. The measured kinematical suppression is ~ $6\times10^{-4}$ for $\pi^+\pi^0$ and ~ $3\times10^{-4}$ for $\mu^+\nu$ decay, that corresponds to the expectations of the experimental design.

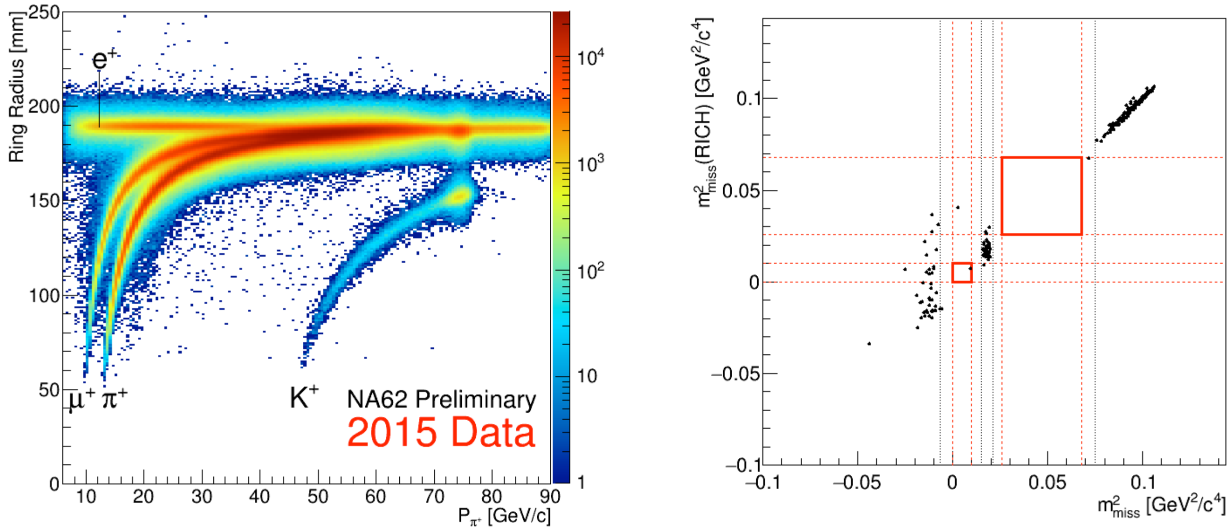



*Figure 10. Left: RICH ring radius vs the track momentum (data collected in 2015). Right: the signal extraction result from 5% of 2016 data set. The missing mass values for the two definitions are plotted: track missing mass and RICH one.*

Fig. 10 illustrates the efficiency of the particles identification by means of RICH data that is used for the separation between the charged pions and muons. For the signal region of pion momentum (< 35 GeV) muons efficiency is below 0.01 for the pions detection efficiency of 80%. But the combined identification performance using RICH together with calorimeters ensures the muons suppression at the level < $10^{-7}$.

The NA62 calorimeters (Lkr, LAV, IRC and SAC) are used for the photons suppression. The $K^+ \to \pi^+\pi^0$ efficiency measured from data with the photons suppression applied is $(1.2 \pm 0.2)\times10^{-7}$, while the expected accidental loss of the signal is ~15%.

The expected amount of signal events in the first 5% of 2016 data set ($2.3 \times 10^{10}$ kaon decays) is much less than one, and no events in the signal region have been found (see the right plot of Fig. 10).

In March of 2018, the collaboration have presented a first result based on the full statistics collected in 2016 ($1.21 \times 10^{11}$ kaon decays). For this data sample the average expected number of $\pi^+\nu\bar{\nu}$ events is about 0.28 with an expected background of 0.15 events. After un-blinding the signal regions, one event is found. The corresponding upper limit for the branching ratio is:

$$Br(K^+ \to \pi^+ \nu\nu) < 14 \times 10^{-10} \text{ @ } 95\% \text{ CL}$$

This result is achieved with just a 1% of total expected statistics of NA62 and demonstrates the validity of the implemented experimental technique.

JINR contribution to the NA62 past and ongoing activities is rather essential. From the very beginning of the project, JINR group together with CERN was responsible for the key detector creation – the NA62 Spectrometer installed in 2014. JINR contribution to the Spectrometer is defining in many aspects: R&D, MC simulation for design stage, straws geometry choise, frames design, straws production (more than 7000 in JINR), Spectrometer modules assembling.

In 2016-2018, the following results related to NA62 have been achieved by the JINR group:

- Software tools for NA62 collaboration have been created: interactive straw map, straw timing stability monitor, straw wires and tubes positioning control.
- NA62 drift chamber design and acquisition system are described in journal papers.
- Straw stability under internal pressure is studied and a technique of its prediction is developed.
- Wire position measurement technique with an optical microscope is developed.
- A device for the straw tubes production is described in a journal paper.

During the NA62 experimental runs in 2016-2018, a JINR group member (S. Shkarovskiy) was an official expert responsible for the Spectrometer performance and for the Spectrometer part of the Detector Control System (DCS).

JINR group members are performing in total about 250 shifts during that period.

Schedule of the proposed activities and potential risks

The proposed prolongation of the NA62 project in JINR to the period of 2019-2021 includes 2 years of the CERN accelerators Long Shutdown 2 (LS2) in – 2019 and 2020. During this shutdown period, NA62 collaboration plans to obtain the intermediate physical result for the golden mode $K^+ \to \pi^+ \nu\bar{\nu}$ based on the statistics collected in the 2016-2018 data taking runs. It should correspond to about 20 events expected with the branching ratio calculated from the Standard Model. The analysis of the data collected before LS2 should provide a significant result as input to the update of the European Strategy for Particle Physics and a solid extrapolation to the ultimate NA62 sensitivity achiveable after LS2.

Third year of the proposed Project prolongation (2021) is expected to be the next period of NA62 data taking that will increase the collected statistics with the improved special shielding in the beamline (that will suppress upstream background and increase the signal acceptance due to the relaxing of decay position cut).

So for the end of the proposed Project extension one can expect the most precise result of the golden mode branching ratio and the additional collected data sample needed for the further improvement of the precision. The complete nominal NA62 statistics (~ 100 SM events) may be collected only during the next stages.

The means required to analyse the data and to interpret the results include mainly the educated manpower for the data analysis and for the NA62 Spectrometer maintaining as well as the travel expenses to participate in the NA62 run in 2021 and to attend some international conferences. No considerable extra equipment is expected to be provided by the participating teams.

The potential risks for the project extension period are much smaller than the risks foreseen from the very beginning of the project. Many problems related to the novel detector elements creation were considered in the Technical Design Document [2]. They have been solved finally, but it required a considerable delays of data taking, that is the main explanation why the NA62 goal is not achieved yet. JINR group never was responsible for the delays. 2014, 2015 and the most of 2016 were the setup building stage with a completely operational Spectrometer.

Moreover, two more problems have appeared without any scenarios (and this is the second reason why the NA62 aim is not achieved yet):

- Unexpectedly high variations of the beam intensity (beam is also provided for LHC, and we are just a second priority user). It leads to much higher maximum intensity on detectors, and then – to the problems with back-end electronics, so we must limit the used intensity per burst with respect to the nominal value (40% in 2016 → 60% in 2017).

- The new sofisticated source of background has been discovered (related to upstream interactions and decays) that enforce us to decrease the fiducial volume, so currently the actual acceptance is smaller than in the Project design.

Fortunately, the performed analysis of 2016 data show that no other risks of this kind may appear, and only some improvements are expected. As a result, the goal of ~ 100 events may be achieved only with the run prolongation in 2021, at least for 2 years. The improvements in electronics firmware and upstream particles shielding are in progress.

The realistic risks we could consider now include the following scenarios:

- There will be no NA62 run prolongation after LS2 (low probability).
  Spare strategy for this case:
  - analysis of the collected data that will give about 20 SM events of $\pi\nu\bar{\nu}$
  - other additional analyses of kaon rare decays with the available statistics.
- There will be not enough manpower for the fast finishing of all the additional analyses. Spare strategy:
  - we will try to attract even more brilliant young people
  - we will finish all analyses later in parallel with another stages of the project (currently we still work on the NA48/2 data collected in 2003/2004).

<u>JINR group contributions and responsibilities for 2019-2021</u>

The list of JINR group contributions and responsibilities include:

- Fine calibration and alignment of straw detector on the basis of collected data.
- Improvement of the straw detector Monte Carlo simulation used for the main NA62 analysis.
- Participation in the analysis of rare background sources for $K^+ \rightarrow \pi^+\nu\bar{\nu}$.
- Data processing and analysis of the collected experimental data to measure the four-lepton decay modes of charged kaon.
- Search for the light sgoldstio signatures.
- Diagnostics and necessary repair of the Spectrometer straw chambers and their low and high voltage power supply during the shutdown in 2019-2020.
- Participation in the next NA62 data taking run in 2021.
- Support the NA62 Spectrometer during the data taking run in 2021.

For the project prolongation period the participation of the group will include:
- Technical hardware support of the Spectrometer (3 persons).
- Spectrometer on-call expert during the data taking, Detector Control System development and maintenance (1).
- Software for the data quality control development and maintenance (2).
- Participation in the MC development in the Spectrometer part (1).

- Physical analysis: specific background sources for $\pi\nu\bar{\nu}$, additional physical goals for our group (10 persons with a different intensity).

Participants publications, PhD theses and presentations at conferences

The NA62 data analysis is currently in its initial stage, that is why no PhD theses have been defended so far on the basis of NA62 data. We plan three PhD to be prepared by the young physicists joined to NA62 JINR team recently.

11 journal papers [3,10,11,13,15,16,17,19,20,21,23] have been published with the Dubna group participation in 2016-2018. In 9 of them [10,13,15,16,17,19,20,21,23] the Dubna group members are the principal co-authors. In two preprints published in 2016-2018 there where principal co-authors from Dubna group [12,18].

Obtained results in 2016-2018 were presented at the international conferences, including 12 presentations given by the representatives of JINR group [14,22,24-33].

The series of scientific works of Dubna group “Development and construction of gas-filled detectors based on a new type of straw tubes for operation in vacuum in the track spectrometer of the NA62 experimental set-up” was awarded a first JINR prize (2017) in the nomination of scientifically-methodical works. Two patents for inventions are obtained by the JINR group members in 2016 [34,35].

## Estimation of human resources

The following Table lists the NA62 JINR group members with their roles and participation.

| Name | FTE | Work (apart from common duties like shifts) |
|---|---|---|
| D. Baygarashev | 1.0 | Data quality control, calibration, physical analysis |
| A. Baeva | 0.5 | Physical analysis |
| S. Gevorkian | 1.0 | Theory of rare decays, MC models development |
| L. Glonti | 0.5 | Spectrometer calibration and performance checks. |
| E. Goudzovski | 0.1 | MC development, analysis |
| D. Emelyanov | 1.0 | Software tools development, analysis |
| T. Enik | 0.3 | Hardware development and support |
| V. Kekelidze | 0.1 | Project leader |
| A.Korotkova | 0.7 | Physical analysis |
| D.Madigozhin | 1.0 | MC development, data quality control, analysis |
| M. Misheva | 0.3 | Physical analysis |
| N. Molokanova | 0.9 | Physical analysis |
| S. Movchan | 0.2 | Hardware development and support |
| I. Polenkevich | 0.0 | Currently in a long vacation (child) |
| Yu. Potrebenikov | 0.5 | Project leader |
| S. Shkarovskiy | 1.0 | DCS development, hardware support, analysis |
| **TOTAL FTE** | **9.1** | |

In the realization of previous stages of the NA62 project at JINR 12 experts of different fields have been involved. We propose to have 2 more PhD students for the participation in the third part of the Project.

Form № 26

## **Requested resources for Proposal realization**

| | Units. | Requirement resources in 2019-2021 | The offer of the Laboratory on distribution of resources | | |
|---|---|---|---|---|---|
| | | | 1-year | 2-year | 3-year |
| The basic units and the equipment: | | | | | |
| Necessary resources:<br>a) Laboratory Fabric<br>b) DB of the Laboratory | <br>norm-hour<br>norm-hour | | | | |
| c) The accelerator<br>d) The reactor<br>e) Computers | hour.<br>hour.<br>hour. | | | | |
| Working costs | thousand US $ | | | | |
| Source of financing:<br>budget<br>including foreign currency means | Thousand US $ | 380 | 103 | 103 | 174 |
| Contributions of collaborants<br>Grants (INTAS+ISTC)<br>Sponsors<br>Contracts<br>Other sources | thousand US $<br>thousand US $<br>thousand US $<br>thousand US $<br>thousand US $ | 10 | 0 | 5 | 5 |

Project leaders: Kekelidze V.D.

Potrebenikov Yu.K.

The total expenses for the creation of new elements of detectors for the NA62 experiment are estimated at the level of 40 million Swiss francs (CHF) where the JINR contribution according the MoU is 1.5 million Swiss francs.

Expenditures of the research group for the last 3 years

The total JINR expenses during 2016-2018 years to the third stage of the project (the theme of 1096) realization are **$504.7k**. About $10 thousand have been paid by CERN and collaboration NA62 for the support of the straw detector; about $10k is allocated by CERN for travel support of the JINR experts to CERN. The NA62 Collaboration allocates 30K CHF in 2016 for JINR engineers needed to support of common works into the Collaboration during the preparation of the experiment.

Justification of the requested expenditures

The volume of the necessary funding for the years 2019-2021 from the JINR budget is **$380k**. Most of the funds required for the participation of JINR employees in experimental run 2021 of the NA62 set-up and maintenance the work for a development of straw detectors and on-line software systems for control this work, for the payment of JINR contributions into the collaboration common fund in accordance with the obligations under the MoU, to provide computer and technical support of simulation, processing and analysis of accumulated experimental data. Funding from other sources will be at least $10k.

Form № 29

## Cost calculation from JINR budget.

| № | Expenses item | Unit | 2019 | 2020 | 2021 | 2019 – 2021 |
|---|---|---|---|---|---|---|
| | Direct costs for the project | | | | | |
| 0. | Operational costs | K USD | 35 | 35 | 35 | 105 |
| 1. | Accelerators | | | | | |
| 2. | Design office | | | | | |
| 3. | Workshops | | | | | |
| 4. | Materials and consumables | K USD | 5 | 5 | 10 | 20 |
| 5. | Equipment | K USD | 10 | 10 | 15 | 35 |
| 6. | Payments for R&D works performed according contracts | K USD | | | | |
| 7. | Travel expenses, including: | K USD | 53 | 53 | 114 | 220 |
| | a) to countries a) outside the ruble zone | K USD | *50* | *50* | *110* | *210* |
| | b) to the ruble zone countries | K USD | *3* | *3* | *4* | *10* |
| | c) according to protocols | | | | | |
| | **Total direct expenses** | **K USD** | **103** | **103** | **174** | **380** |

Project leaders: Kekelidze V.D.

Potrebenikov Yu.K.

## **Strengths, Weaknesses, Opportunities, Threats**

The strengths of the project extension include the following:

- fundamental importance of the scientific program;
- fully operating NA62 detector setup built with the JINR essential participation;
- a large amount of experimental data collected in 2016-2018;
- a strong support for the data taking prolongation after 2020 from CERN side;
- experience in analysis of senior participants of the JINR team;
- young participants who will in future bring the best CERN practice into JINR projects;

Main weakness is caused by the inevitable temporary difficulties of transition from the mainly hardware activity to the data analysis stage that is overlaid with the lasting NA62 Spectrometer-related duties. This weakness will be overcomed by means of the new participants training for the data analysis exploiting the existing experience of the other group members obtained earlier in the NA48/2 experiment.

The non-trivial opportunities of the project are the improved measurements of some rare decay modes based on the large statistics of kaon decays. Also there is a chance to find new physics in the case if new results will be incompatible with SM. Additionally, the participation in software development and detector calibration for NA62 will increase the qualification of young participants that may be needed in other JINR experiments.

No ongoing competition is known currently in the measurement of the charged kaon golden mode. So there are no external threats to the project extension importance.

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## Attachments

**Referee's report on the Proposal of prolongation of the project**
**"MEASUREMENT OF THE RARE DECAY $K^+ \rightarrow \pi^+ \nu\nu$**
**AT THE CERN SPS (NA62)"**

The probability of the super-rare decay $K^+ \rightarrow \pi^+ \nu\nu$ (of the order of $10^{-10}$) is directly connected to the CKM matrix parameters, related to CP-violation. Theoretically clean, it gives a chance to find a statistically significant deviation from Standard Model and to open experimentally the "new physics" domain.

To accomplish the NA62 experiment on the CERN SPS, aimed to measure the branching ratio of $K^+ \rightarrow \pi^+ \nu\nu$ decay with a nearly 10% precision, the extraordinary experimental requirements are met. One of them is the need to measure the charged particle angles and momenta with a high precision in the conditions of minimum multiple Coloumb scattering. So the key element of NA62 detector is the Straw magnetic spectrometer that is produced of the very light drift tubes, containing a small amount of matter. JINR group together with the dedicated CERN team were responsible for this detector element design and production, as well as and for all the related R&D.

After the spectrometer installation in 2014 and extensive testing during the commissioning run in 2015, the physical data taking have been performed in 2016 - 2018. Now the experiment is entering the stage of the physical data analysis. And JINR group starts to take part in the extraction of the physical results from collected data, including the additional studies of the rare four-lepton decays of charged kaons.

During the period of 2016 - 2018 a series of works have been done by JINR group, and many important results have been achieved. On the basis of NA48/2 data, a new upper limit on the rate of the lepton number violating decay $K \rightarrow \pi\mu\mu$ has been obtained. On the basis of NA62 data collected in 2007, a neutral pion electromagnetic transition form factor slope has been measured. New limits have been set on the squared matrix element $|U_{\mu 4}|^2$ describing the mixing between the muon and hypothetical heavy neutrino states. These results were reported in details on the NA62 Collaboration meetings by JINR participants and have been presented at the international conferences.

Few special software tools for the NA62 spectrometer control and calibration have been developed. The results of the completed work on the spectrometer design and building have been published in a series of journal papers. A review of the kaon decay studies performed by NA48, NA48/1 and NA48/2 collaborations as well as a series of theoretical works has been prepared and published.

Accomplished work stages are adequate to the financial expences that have been assigned for the project. In my opinion, the presented report related to the 2016 - 2018 should be approved.

The on-going and planned works are adequate to the financing to be allocated for the project in 2019 - 2021, and I am sure that a strong recommendation to prolong the NA62 project in JINR in 2019 - 2021 have to be done.

At the same time I recommend to authors to extend the participation in data analysis and obtaining results, by involving to these works and experienced and young physicists for whom it would become excellent school.

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Report on the project

**“Measurement of the Rare Decay $K^+ \to \pi^+ \nu\nu$ at the CERN SPS”**

In general, the project is implemented in VBLHEP JINR starting from the year 2010. In its current form, it consists of the formulation and specification of participation of scientists and engineers of VBLHEP JINR in NA62 experiment at SPS in the framework of wide international collaboration in CERN for years 2019-2021 after realization of three stages during the period 2010-2018.

At the very beginning of the project it was planned to measure the Cabibbo-Kobayashi-Mascawa matrix elements with 10% precision in order to test the validity of Standard Model or, if present, to observe the deviations from it. This objective led to the formulation of the central goal of NA62 experiment, which is to register approximately 80-100 events of very rare decay $K^+ \to \pi^+ \nu\nu$ assuming 10% signal acceptance or better and $10^{-10}$ branching ratio.

In the sections “Physical motivation” and “Additional physical goals” the authors of the project emphasize that large scale statistics of kaon decays together with high accuracy measurements make it possible to search for other rare kaon decays with aims to check the existence of supersymmetry particle sgolstino, to search the new light candidates to the dark matter, to study possible heavy neutral lepton production and to check the validity of the Chiral perturbation theory.

The core sections of the project are devoted to the description of main parts of the NA62 experimental setup. It is stressed that the setup has been constructed and tested during the autumn 2014 run with CERN SPS beams. The experts from JINR participated in the construction and installation of the track spectrometer detectors designed and built during the two NA62 project stages completed in JINR Dubna during time periods 2010-2012 and 2013-2015. The experimental setup has to ensure the fulfilment of two main tasks – desired suppression of the background and the usage of a high intensity unseparated $K^+$ beam. Main steps on how to do it are presented as well.

The main results achieved during the time period 2016-2018 are presented in three separate sections: namely, results concerning the installation of some parts of experimental setup in 2016-2017, the analysis of the 2003-2010 data from NA48/2 and NA62 experiments performed in 2016 – 2018, and some theoretical and methodical results including problems with backend electronics of some detectors. For example, the experimental data for the new rare decay $K^{\pm} \to \pi^{\pm}\pi^0 e^+ e^-$ were analyzed, which were obtained for the first time in NA48/2. About 5 × 10^11 K + decays have been taken to study the K + → π+νν decay. Preliminary results from the K+ → π + ν ν analysis based on about 5% of the 2016 statistics are summarized in the project.

Results obtained in 2016-2018 were presented in many international conferences by the JINR participants. The JINR group gave substantial contribution to the construction of NA62 experimental setup, brought significant methodological contribution to the experiment, which resulted in two patents.

I observe that at present time the activities of the JINR group are highly visible in intellectual, technical, methodological and scientific areas. Based on the facts presented in the project I arrived at the conclusion that the JINR team is at the present moment fully integrated into the preparation of the NA62 experiment and data collection and analysis. Many of the key hardware components were developed and installed by the JINR team.

I consider the required financial support, which should ensure the trouble free activity of JINR group and should cover the expenses for the realization of the experiment by the JINR side, to be justified and adequate.

I have following comments and questions concerning this project:

1. The weaknesses and potential risks of this project are not presented. Consequently, there are no prepared strategies on how to handle the risk scenarios.
2. Experiment is running from 2015 - for 3 years. Why the aim of the experiment (to gather 80-100 events) has not been achieved yet? When it is expected that this main goal of the experiment will be achieved?
3. It is not clear to me what fraction of accumulated data has been analyzed up to now (5% ? - what is the reason for such a low fraction?)?
4. Why is there a scheduled break in data collection for the next two years?
5. From the prolongation of the proposal it is not clear to me what the main physics goals will be addressed (improvement of $BR(K^+ \rightarrow \pi^+ \nu\nu)$?)? What is the target precision, what kind of conditions should be met (e.g. how many hours/month of running, at what luminosity, etc.)?
6. When the first results related to the supersymmetric sgolstino are expect, or when will collected data needed for the analysis of the given process be statistically sufficient?
7. I would appreciate a more detailed description of how the group will participate in this experiment (technical support in hardware, software, data analysis?). Are there participating JINR scientists who could be the principal authors responsible for writing the publication? It should be addressed why there is a plan to accept two new PhD students into the group?

I consulted these questions with one of the team leaders Yu.K. Potrebenikov, who has already answered them. I advise that his answers, which I consider to be very well thought out, be incorporated into the project.

**Despite these objections the benefits of this project are undeniable. It will contribute to the success of the NA62 experiment in a significant manner and consequently to the success of JINR on an international scale. I fully support its approval and financing.**

Michal Hnatič

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12.03.2018

**ABSTRACT OF THE MINUTES**
**OF THE MARCH 20, 2018**
**VBLHEP STC MEETING**

23 STC members were present at the meeting out of a total of 40 STC members.

VBLHEP STC heard the report and considered the proposal on continuation of the NA62 project within the framework of theme (02-1-1096-2010/2019) "Study of Rare Charged Kaon Decays and Search for Dark Sector in Experiment at the CERN SPS". STC decided to endorse the report and to recommend that PAC for Particle Physics support continuation of the project until the end of 2021 with first priority.

Referees: G.A.Shelkov, M.Gnatich.

/ VBLHEP STC Chairman — Yu.A.Panebratsev

VBLHEP STC Scientific Secretary — / S.P.Merts