

Call: CERN-RO

Project acronym: NA62

CERN Research Programme / Experiment: NA62

Annual Summary Document¹

Year: 2024

Months: 9

Project Title: Study of rare kaon decays at the CERN SPS / NA62

Project Work Plan (according to the contract)

Stage: III. HASC Maintenance & Operation (MO), reconstruction and MC software development; Exotic and Precision decays studies - part III

Activities:

- I. 1. - HASC MO, reconstruction and MC software development;
 - ALP study (Production of muon background, finalization of analysis);
 - BR($K^+ \rightarrow \pi^+ \pi^0; \pi^0 \rightarrow e^+ e^-$) (Background sources identification, relevant theory survey; MC implementation, Selection criteria – testing and optimizations).

Allocated budget: 1,076,000.00 lei

Realized budget: 1,076,000.00 lei

¹ Please fill in all the required items and do not alter the template

Study of rare kaon decays at the CERN SPS (NA62)

- 2024 Annual Summary -

1a. Group list (physicists, staff, postdocs, students):

Name	Position
Alexandru-Mario BRAGADIREANU	Research scientist (CS III) – IFIN-HH
Stefan-Alexandru GHINESCU	Research scientist (CS)– IFIN-HH,
Ovidiu-Emanuel HUTANU	Engineer - IFIN-HH
Petre-Constantin BOBOC	Research Assistant– IFIN-HH, PhD <i>Student</i>
Neagu IONEL	Engineer –IFIN-HH
Alina MOTORGA	Accountant- IFIN-HH

1b. Specific scientific focus of group (state physics of subfield of focus and group's role)

Physics: Standard Model

Subfield: Flavor Changing Neutral Current decays with neutrinos in the final state with focus on the measurement of the very rare kaon decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at the CERN SPS (NA62 Experiment).

Group role: Originally, to identify the π^+ coming from the $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ decay (source of background in the $m_{miss}^2 := (p_K - p_{track})^2$ distribution) with a hadron sampling calorimeter (HASC). The HASC was shown to be efficient also as photon veto in the rejection of background coming from $K^+ \rightarrow \pi^+ \pi^0$ decay, the upgrade of HASC being proposed in 2018. Evaluation of NA62 sensitivity to various dark matter decays to visible particles. Coordination of the Software and MC Validation working groups. Precision measurement of the $\pi^0 \rightarrow e^+ e^-$ branching ratio.

1c. Highlights of accomplishments in the last year

We maintained the HASC continuous operation during the 2024 NA62 Physics Run.

In the autumn of 2021, NA62 collected a dataset in beam dump mode. In 10 days of data-taking, around 1.4×10^{17} protons on TAX were collected. This dataset made possible investigating physics case of a dark photon (A'), dark scalars (S) and axion-like particles – or ALPs (a), decaying to various final states. The analysis of the decays of such particles to hadronic final states is well developed. The statistical combination of the searches for dark photons decaying into leptons or into hadrons is also close to finalization.

At the end of 2021, one of our group members started working in the Precision Measurements Working Group, on the measurement of the branching ratio of the process $K^+ \rightarrow \pi^+ \pi^0$; $\pi^0 \rightarrow e^+ e^-$. In the Chiral Perturbation Theory, the $\pi^0 \rightarrow e^+ e^-$ can be used to improve predictions of other pseudo-scalar meson decays to pairs of leptons. The selection has been finalized and the publication internal note is in progress and will be published at the end of 2024.

2. Scientific goals (2 pages)

The main goal of NA62 experiment [1] is to measure the branching ratio of the ultra- rare kaon decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at the CERN SPS. The standard Model (SM) prediction for the branching ratio is calculated with high precision [2],

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{SM} = (0.84 \pm 0.10) \times 10^{-10}$$

while significant deviations from the SM value are predicted by new physics models [3,4,5]

In addition to the main objective, thanks to its high beam intensity and detectors performance, NA62 has a wide physics programme: precise measurements of lepton universality in $K^+ \rightarrow l^+ \nu$ decays, searches for Lepton Number (LNV) and Lepton Flavor Number Violating (LFNV) processes and searches for exotic particles such as Dark Photons, Heavy Neutral Leptons, axion-like particles (ALPs), etc. In the framework of Physics Beyond Collider initiative, prospects for data taking in beam dump mode has been addressed too.

In order to reach its main goal, NA62 needs to collect about 100 in-flight $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events, and to keep the total systematic uncertainty small. Assuming a 10% signal acceptance and a $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio of 10^{-10} , at least 10^{13} K^+ decays are required.

Since the $\nu \bar{\nu}$ pair is undetectable, the technique adopted by NA62 is to match an upstream K^+ track with a downstream π^+ track and to use the squared missing mass distribution $m_{miss}^2 := (P_K - P_\pi)^2$ to discriminate the signal from background (Figure 1). The main background events are expected to come from the other K^+ decay channels and accidental matching of an upstream track with a K^+ .

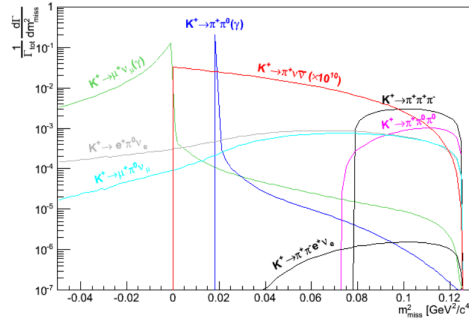


Figure 1: Squared missing mass distribution

2.1 NA62 Hadron Sampling Calorimeter (HASC)

The NA62 experimental setup proposed in the Technical Design Document [6] was improved, by the IFIN-HH team, with a new hadron calorimeter to veto the $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ events in which the π^- undergoes hadronic interaction in the first STRAW chambers and the more energetic π^+ (~ 40 GeV/c) which is traveling through the beam hole, not being detected by the IRC, then emerging at $Z > 253$ m.

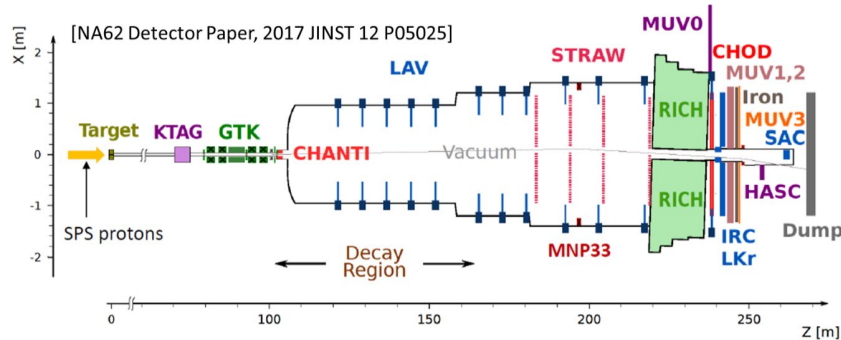


Figure 2: NA62 Experimental setup

Using the data coming from the upstream detectors (Figure 2) to select the $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays, namely the CEDAR and GTK for K^+ identification and the STRAW together with RICH,

CHOD and MUV to identify one of the π^+ , while HASC has to detect the second π^+ traveling through the beam pipe and deflected by the bending magnet.

HASC has been demonstrated to be effective (2016-2018 $\pi^+ \nu \bar{\nu}$ dataset) as photon veto, complementary to LAV, LKr, IRC and SAC calorimeters, an additional 30 % reduction of $\pi^+ \pi^0 (\gamma\gamma)$ background being obtained with HASC. This fact, stimulated the idea of using a second calorimeter HASC-like in a position symmetrical with respect to the beam axis, to double the π^0 rejection.

Each HASC station is made up of 9 identical modules recovered from a prototype developed by NA61 Collaboration. Each module is a sandwich of 120 lead/scintillator alternating tiles, with a total volume of $10 \times 10 \times 120 \text{ cm}^3$ (W x H x L). The sampling ratio is 4:1, the scintillator tiles having a dimension of $100 \times 100 \times 4 \text{ mm}$ while the lead thickness is 16 mm.



Figure 3: HASC module longitudinal section (left) and optical readout couplings (right)

Each HASC module is organized in 10 longitudinal read-out sections, each scintillator tile of every single section (Figure 3) being optically coupled with 1 mm^2 round Wave-Length Shifting (WLS) optical fibers. In the rear side of each module there are 10 optical connectors, originally designed to be coupled with $3 \times 3 \text{ mm}^2$ green sensitive Micro-pixel Avalanche Photodiodes (MAPD), currently S12572-015C Hamamatsu SiPM sensors being used.

The FE electronics and SiPM's installed on the new HASC station, are cooled down to about $21 \text{ }^\circ\text{C}$ using a system designed by our group, which consists of 3 Peltier thermoelectric coolers / module and a water-air heat exchanger used to blow cold air in the modules endcap cases. The temperature is maintained constant by a temperature controller – MCU based – which regulates the Peltier supply voltage via a PID routine. Due to last moment mechanical incompatibilities, we were not able in June 2021 to upgrade the old HASC station with new mechanics and Peltier cooling, but we were able to accommodate the cooling with air, which lowered the nominal temperature of SiPM's from $36 \text{ }^\circ\text{C}$ to about $24 \text{ }^\circ\text{C}$.

2.2 Study of dark matter

Thanks to its high beam intensity and detectors performance NA62 can achieve sensitivity to new-physics scenarios. Since 2018, IFIN-HH team is actively involved in the study of dark matter in various portals [7]. Our original goal, the study of the Higgs-coupled dark scalar, had to be postponed due to the urgency of finalizing the $ALP \rightarrow \gamma\gamma$ sensitivity evaluation. Significant efforts have been made during 2020-2021 to simulate the muon-induced background for this physics case. However, the analysis has been halted when NA62 collected another beam dump sample (1.4×10^{17} POT). The Exotics Working Group started investigating the physics case of a dark photon (A') decaying into a pair of leptons. The dark photon is a vector field, symmetric under $U(1)$ transformations, that feebly interacts with the Standard Model fields. Both the mass $M_{A'}$ and the coupling ϵ are free parameters of the model. More details on the model can be found in [8,9]. NA62 is sensitive to decays of such particles only for ϵ of the order of $10^{-7} - 10^{-5}$ [10]. Our team was highly involved in several aspects of this analysis. The primary goal was to fully implement the analysis of the $A' \rightarrow e^+e^-$ analysis to derive new exclusion regions in the model parameter space. Additionally, our team led the effort to combine the results of this analysis with the previous one, on the $A' \rightarrow \mu^+\mu^-$ analysis [10]. The results obtained for dark scalars can also be interpreted in terms of other exotic particles.

We are currently involved in the searches for several exotic particles decaying into hadronic final states.

2.3 Precision measurement of the $\pi^0 \rightarrow e^+e^-$ decay rate

In the framework of Chiral Perturbation Theory, the $\pi^0 \rightarrow e^+e^-$ decay rate measurement provides a tight experimental constraint on calculations. The process has negligible short-distance contributions and is the best-measured pseudo-scalar decay to a pair of leptons. Immediate benefits of the decay rate precision measurement are improved predictions of rates for other pseudo-scalars decays to lepton pairs, such as $\eta \rightarrow \mu^+\mu^-$ and the long-distance contribution of the $K_L^0 \rightarrow \mu^+\mu^-$ decay. In the latter case, the short-distance contribution is a potential source of information on $|V_{td}|$.

Efforts to measure the $\pi^0 \rightarrow e^+e^-$ decay rate within NA62 have been made in the past, but conclusions were never reached. The analysis was restarted by one of our Ph.D. students in June 2022, with the goal of measuring the branching ratio of the $K^+ \rightarrow \pi^+\pi^0; \pi^0 \rightarrow e^+e^-$

The NA62 experiment has the potential of performing the measurement of the rare $\pi^0 \rightarrow e^+e^-$ decay, the neutral pion originating from the $K^+ \rightarrow \pi^+\pi^0$ decay [11]. The current PDG average branching ratio is $B_{PDG}(\pi^0 \rightarrow e^+e^-) = (6.46 \pm 0.33) \cdot 10^{-8}$, the average being influenced mainly by the KTEV result $B_{KTEV}(\pi^0 \rightarrow e^+e^-) = (6.44 \pm 0.25 \pm 0.22) \cdot 10^{-8}$, result obtained from 794 events originating from $K_L \rightarrow 3\pi^0$ decay [12]. During background studies and selection updates done in 2023 about 600 signal events are expected in Run 1 data sample, assuming 5% acceptance from $(8.62 \pm 0.27) \cdot 10^{11}$ Kaon decays. Even with a lower number of expected signal events than in the KTEV sample, our analysis has several advantages. We obtain better Data/MC agreement due to proper treatment of radiative corrections and by accounting for the photon conversions (from Dalitz decay). Our analysis is also less affected by systematic uncertainties. The internal note will be published at the end of 2024 with a scientific paper planned to be submitted in 2025.

3. Scientific achievements in the last three years corresponding to the actual program funding

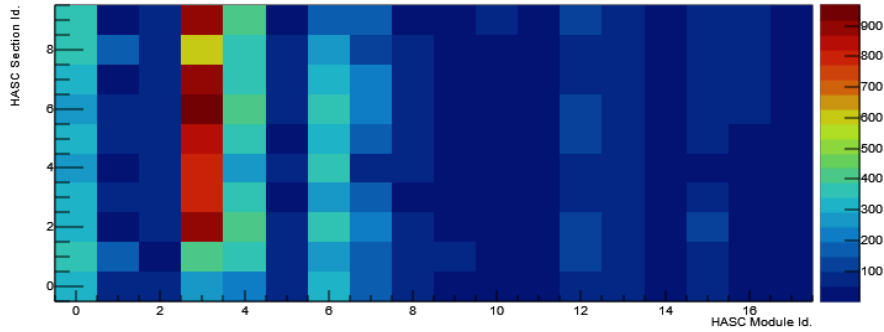


Figure 4: Screenshot of the 2D hit map used in the Online Monitor of NA62

The installation and commissioning of new HASC was finalized at the end of June 2021. We then updated the Online Monitor tool, which is used during data-taking by shifters to ensure a smooth operation. Figure 4 shows the 2D hit-map with modules 0-8 belonging to the old HASC and 9-17 to the new HASC that is always on display during the run.

After the installation of the new HASC stations, we also changed the procedure used for the assessment of the quality of the acquired data. The new procedure uses muon tracks, whose momenta and positions are determined by the STRAW (Fig. 2), together with requiring a MUV3 signal associated both geometrically and in time. Figure 5 shows the time difference between the muon (MUV3 time) and the closest HASC signal in time. We emphasize that, there is a large improvement in the time resolution of the old HASC, the current time resolution being less than half with respect to 2018 data, while the time resolution of new HASC is even better due do better cooling. In Figure 6 we show the effective efficiency of both stations for a particular run of the 2021 sample.

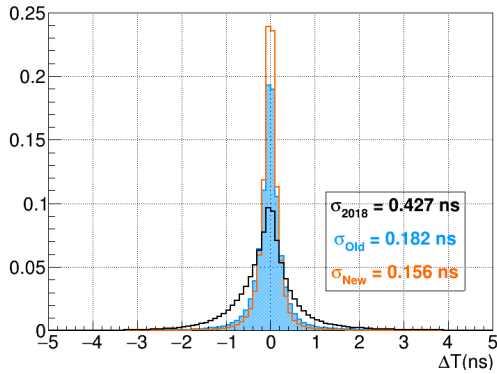


Figure 5: Muon – HASC time difference, blue for the old station and orange for the new one

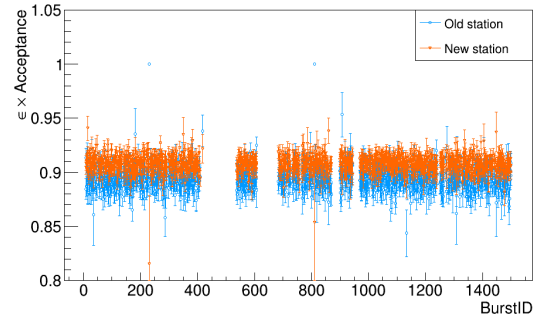


Figure 6: Effective efficiency by station through a run, blue of old and orange for new

In 2022, a campaign was started to make it possible to run the NA62 reconstruction software in multi-threaded mode. This feature is critical in view of the increased beam intensity, for online monitoring purposes. The IFIN-HH team participated in this task by rewriting most of the reconstruction software for HASC and parts of the software for other detectors.

Still on the reconstruction side, we have investigated possibilities to improve the clustering algorithm of HASC aiming at reducing the random veto. Up to now hit clustering was performed using temporal information only. One of the drawbacks of this method is that hits in both stations are clustered together if they are close enough in time. A promising algorithm that uses both spatial and temporal information is a variation of the “Density-based spatial clustering of applications with noise” (DBSCAN) algorithm [13]. Preliminary studies using muons show that the random veto decreases with this method by about 20%.

NA62 has been given green light for data-taking until the end of 2025. Afterwards, the ECN3 building will host another experiment. The NA62 Collaboration formulated a proposal for the High Intensity Kaon Experiment (HIKE). The Letter of Intent (LoI) has been finalized and submitted to the SPS Committee in November 2022 [14]. Our group contributed to the LoI with a proposal for an upgraded version of the HASC, with emphasis on signal rates, temporal resolution, and geometrical coverage.

The total signal rate observed in HASC (both stations) during the NA62 data taking in 2022 at nominal intensity is about 1.21 MHz (with 1 MHz generated by the Old HASC). The most active channel counts at most 0.05 MHz. Therefore, signal rates do not pose a problem in the operation of HASC in HIKE, assuming linearity with beam intensity.

The main issue in the operation of the current HASC at the HIKE proposed intensity is the random veto. It is determined chiefly by the time resolution of the detector, presently at 370 ps (430 ps) FWHM for the New HASC (Old HASC). For HIKE, the resolution should be improved to about 100 ps. We proposed solutions for using either SiPMs or Photomultiplier Tubes (PMTs):

- HAMAMATSU S13362-3050DG SiPM [15] with time resolution of 110 ps (FWHM) [16], 4 times lower dark counts and 5 times higher gain.
- HAMAMATSU H14220A PMT [17], which could be used to readout individual scintillator plates (instead of groups of 6, as done presently).

Finally, we studied the geometrical coverage of HASC for the $K^+ \rightarrow \pi^+\pi^+\pi^-$ and $K^+ \rightarrow \pi^+\pi^0$ backgrounds for $K^+ \rightarrow \pi^+\nu\bar{\nu}$. We showed that the current setup of HASC provides near-optimal coverage.

At the end of 2021, NA62 collected a beam dump sample, approximately 10 times larger (1.4×10^{17} POT) than the one collected in 2017-2018. The focus of the Exotics Working Group shifted from the $ALP \rightarrow \gamma\gamma$ search to another interesting physics case, that of a dark photon (A') decaying to a pair of leptons. The IFIN-HH group contributed significantly to this analysis by: developing tools to assess the data quality; studying the efficiency of various cuts used in the selection algorithm; simulating the background induced by halo muons. To maximize the scientific output, the analysis has been split in 2 parts. Up until august 2022, we focused on the $A' \rightarrow \mu^+\mu^-$ channel. The

resulting 90% CL exclusion region extends beyond the reach of past experiments in the mass range 211 MeV – 550 MeV for coupling values around 2×10^{-6} [10].

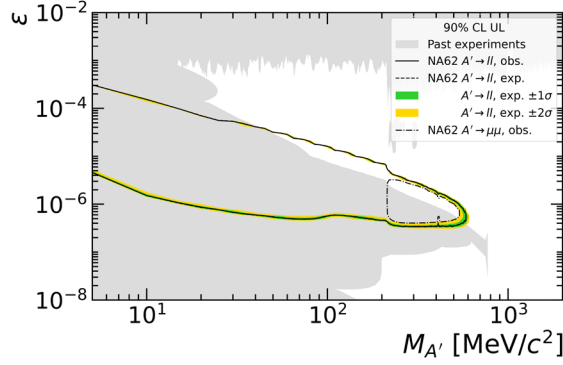


Figure 7: Exclusion contour obtained by the combined $A' \rightarrow e^+e^-$ and $A' \rightarrow \mu^+\mu^-$ searches. Grey areas indicate regions excluded by past experiments. The continuous line represents the observed exclusion contour obtained at 90% CL. The dashed line is the median expected exclusion contour. The $\pm 1\sigma$ and $\pm 2\sigma$ bands are shown in green and yellow, respectively. The dot-dashed contour is the one obtained by NA62 in the $A' \rightarrow \mu^+\mu^-$ search.

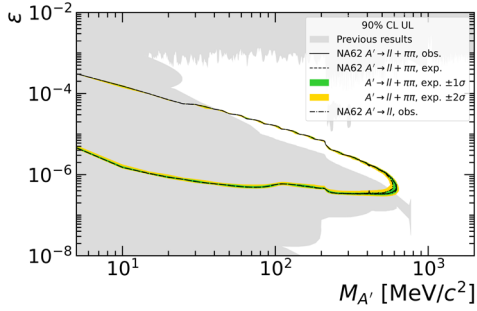


Figure 8: Exclusion contour obtained by the combination of $A' \rightarrow l^+l^-$ and $A' \rightarrow \pi^+\pi^-$ searches. The same color conventions as in are Figure 7 used.

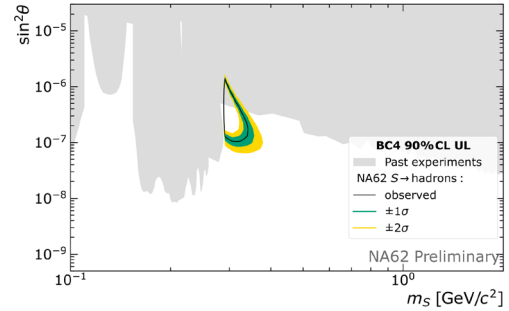


Figure 9: Exclusion contour obtained by the $S \rightarrow$ hadrons search. The same color conventions as in Figure 7 is used.

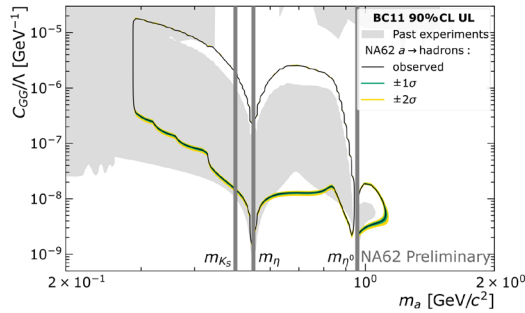


Figure 10: Exclusion contour obtained by the $a \rightarrow$ hadrons search. The same color convention as in Figure 7 is used.

The analysis of the $A' \rightarrow e^+e^-$ channel has been finalized in March 2023, this time our team having the leading role in across all aspects of the analysis. The results of this analysis extend the exclusion region significantly at low dark photon masses with some contributions also in the large mass range. The internal note has been published and the scientific paper is accepted for publication. In addition to the above, our team had the role of providing a suitable method for the statistical combination of the $A' \rightarrow e^+e^-$ search result with the previous NA62 search result $A' \rightarrow \mu^+\mu^-$ [10]. The exclusions region obtained by the combined $A' \rightarrow e^+e^-$ and $A' \rightarrow \mu^+\mu^-$ searches is shown in in Figure 7.

At the end of 2023 the analysis of other decay channels and other exotic particles started with the same dataset. The focus is on the production dark photons, dark scalars or ALPs which subsequently

decay into hadrons. A summary of the 36 combinations of production and decay channels is presented in Table 1. Our team led the efforts on the production of MC samples for the various background sources. We were also involved in the statistical combination of the $A' \rightarrow ll$ with the $A' \rightarrow$ hadrons results. The preliminary exclusion contour is presented in Figure 8, considering only the $\pi^+\pi^-$ hadronic final state.

In 2022, one of our PhD students started working in the Precision Measurement Group, on the measurement of the branching ratio of the $\pi^0 \rightarrow e^+e^-$ decay. Experimentally, additional radiative photons may appear in the final state. A kinematic variable $x = m_{ee}^2/m_\pi^2$ is defined. The analysis is based on the reconstructed invariant mass of the electron and positron tracks (m_{ee}) forming a vertex in the fiducial volume ($105 \text{ m} < z_{vtx} < 180 \text{ m}$). Contributions were focused on the selection algorithm, resulting in increased signal acceptance and higher particle identification (PID) efficiency with respect to previous studies. For this analysis only 2017 and 2018 datasets are considered, with the obtained signal yield of $597 \pm 29 K^+ \rightarrow \pi^+\pi^0; \pi^0 \rightarrow e^+e^-$ events. The $K^+ \rightarrow \pi^+e^+e^-$ decay was chosen as normalization due to identical final state of the signal achieving cancellation of certain several systematics. A total of 12160 normalization candidates were selected with a sample purity of $>99.9\%$. The m_{ee} distributions for signal and normalization selections is shown in Figure 11. The effective number of Kaon decays was found to be $N_K = (8.62 \pm 0.08_{stat} \pm 0.26_{ext}) \times 10^{11}$.

For $x > 0.95$ the partial Dalitz decay branching ratio represents about 3.3% of the $B(\pi^0 \rightarrow e^+e^-(\gamma))$. The preliminary branching ratio obtained is $B_{NA62}(\pi^0 \rightarrow e^+e^-(\gamma), x > 0.95) = (5.86 \pm 0.30_{stat} \pm 0.11_{syst} \pm 0.19_{ext}) \times 10^{-8}$.

Using the latest radiative corrections ([18], [19]), the “no-rad” result can be extrapolated: $B_{NA62}(\pi^0 \rightarrow e^+e^-, no - rad) = (6.22 \pm 0.39) \times 10^{-8}$.

The obtained precision is comparable to KTeV measurements and the two results are consistent, with the central value of NA62 preliminary result being lower and aligning with theoretical expectations.

An internal note writeup is in progress and will be published at the end of 2024. For the Run 2 datasets (only 2022 dataset alone has twice the statistics of the Run 1 dataset) a dedicated analysis is planned.

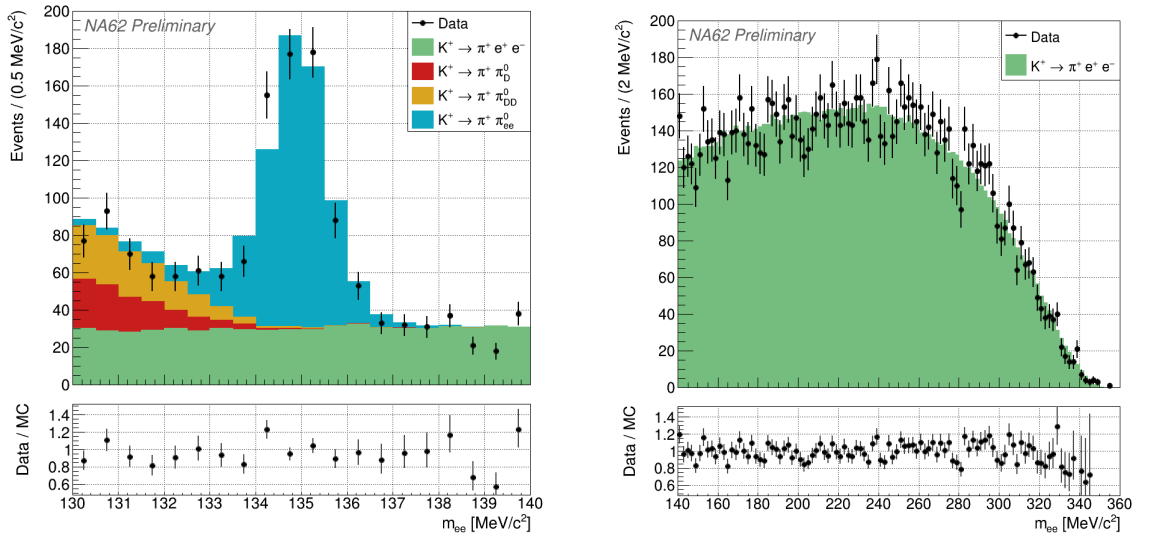


Figure 11: Left: m_{ee} distribution for signal selection. Right: m_{ee} distribution for candidates satisfying the normalization conditions.

4. Group members (table)

- List each member, their role in project(s) and the % time on each project (analysis, R&D, detector operation, detector construction, etc.)

Name	Role	FTE
Alexandru-Mario BRAGADIREANU	HASC upgrade, maintenance, and operation; detector control system; reconstruction software.	0.66
Stefan-Alexandru GHINESCU	Data analysis, MC simulation and reconstruction software	0.67
Ovidiu-Emanuel HUTANU	HASC upgrade, maintenance, and operation;	0.89
Petre-Constantin BOBOC	Data analysis	0.67
Neagu IONEL	HASC upgrade and maintenance	0.50
Alina MOTORGA	Project accountant	0.29
	TOTAL	3.68

- List former students (in last 5 years) and current position/job and institution
 - Victor-Radu Voicu – Programmer, Bit Soft srl, Bucharest
 - Andreea Căluț - Student, Faculty of Physics, Bucharest University

5. Papers and talks in last year

5.1 Papers:

- E. Cotrina Gil et al, NA62 Collaboration, *Search for leptonic decays of dark photons at NA62*, Phys. Rev. Lett. – accepted for publication.

5.2 Talks:

- [Recent results from precision measurements at the NA62 experiment](#), New Trends in High-Energy and Low-x Physics, 04 September 2024, Sfântu Gheorghe, Romania.
- [Update on Simulations of PNN Control Samples](#), NA62 Pinunu WG, 03 September 2024.
- [Searches of exotic decays with NA62 in beam-dump mode](#), XIII International Conference on New Frontiers in Physics 2024, 03 September 2024, Chania, Greece.
- [Summary of Activities](#), NA62 Software & MC Validation WG, 02 September 2024.
- [Summary of Activities](#), NA62 Software & MC Validation WG, 10 July 2024.
- [Update on Simulations of PNN Control Samples](#), NA62 Pinunu WG, 22 May 2024.
- [SW/MC status](#), NA62 Software & MC Validation WG, 22 May 2024.
- [Summary of Activities](#), NA62 Software & MC Validation WG, 24 April 2024.
- [Latest results from precision measurements at the NA62 experiment](#), 31st International Workshop on Deep Inelastic Scattering, 10 April 2024, Grenoble, France.
- [Pi0ee Analysis](#), Precision Measurements WG, 1 March 2024.
- [Summary of Activities](#), NA62 Software & MC Validation WG, 29 February 2024.
- [A Simulation of PNN Control Samples](#), NA62 Pinunu WG, 28 February 2024.

6. Further group activities (1 page)

- Collaborations, local synergies

The multifunction rack control unit (MRCU) hardware was developed and built in the framework of NUCLEU 16 42 01 03 Project. The MRCU firmware and the high-level software were developed in the framework of the present project, the MRCU unit being operated at CERN ECN3 since July 2016 being part of the HASC Control system.

7. Budget request for the next year

		lei
Type of expenditures		2024
1	PERSONNEL EXPENDITURES, from which:	761942
	1.1. wages and similar income, according to the law	745176
	1.2. contributions related to salaries and assimilated incomes	16766
2	LOGISTICS EXPENDITURES, from which:	144834
	2.1. capital expenditures	45334
	2.2. stocks expenditures	30000
	2.3. expenditure on services performed by third parties (including the contribution to CERN)	69500
3	TRAVEL EXPENDITURES	80000
4	INDIRECT EXPENDITURES – (OVERHEADS) *	435971
TOTAL EXPENDITURES (1+2+3+4)		1422747
Indirect Expenditures = General IFIN-HH Overheads (35% from 1+ 2.2 +3) + Particle Physics Department Overheads (15 % from 1 + 2.2 +3)		

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