2025 NA62 Status Report to the CERN SPSC

NA62 Collaboration

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Abstract

The status of the NA62 experiment is reported. The 2024 data taking, the hardware and software activities, and the plans for 2025 are discussed. The status of the $K^+ \to \pi^+\nu\bar{\nu}$ analysis is presented, together with the highlights from the studies of rare and forbidden decays, as well as of the beam-dump data.

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1 Introduction

The NA62 experiment took data in 2016–2018, underwent several detector upgrades during long shutdown 2 (LS2), restarted the operations in 2021, took data in 2021, 2022, 2023 and 2024, and is approved to run until long shutdown 3 (LS3). 2016-18 data allowed NA62 to deliver the first $> 3\sigma$ evidence for the $K^+ \to \pi^+ \nu \bar{\nu}$ decay [1].

Since the previous report in April 2024 [2] NA62 took data in 2024 for about 200 days. During the run the beam intensity was kept fixed at 20×10^{11} protons per pulse (ppp) on average. No major issues with the beam delivery happened during data taking and the spill quality was good. A significant problem occurred with the positioning of one of the two P42 beam dump/collimators (TAX) in August: as a consequence, the affected P42 TAX was set to the nominal open position and not moved during the run. In total, NA62 has collected in 2024 more than 600K bursts (or spills), which amounts to the largest sample taken in one year. The TDC-based FELIX readout board replaced the TEL62 in the CHANTI detector, requiring a couple of weeks for full commissioning. In general, all the sub-detectors worked smoothly. The only minor problem was a not-working quarter chip in the station 0 of the Gigatracker (GTK0). The experiment took 10 days of data in dump configuration in August, and one week in July at low intensity to collect data for high precision measurements in the context of CKM physics.

The 2024 data have been processed online and their quality fully assessed. The reprocessing with the final calibration constants is completed. The fraction of bad bursts is less than 9%.

The analysis of the rare decay $K^+ \to \pi^+ \nu \bar{\nu}$ (PNN analysis) on the data collected in 2021–2022 has been completed and the final result delivered in September. The combination of the 2021–2022 data with the result from the 2016–2018 analysis has provided the first observation with $> 5\sigma$ confidence level of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay [3], leading to a measured branching ratio of $(13.0^{+3.3}_{-3.0}) \times 10^{-11}$. This result is a major achievement for NA62 and flavour physics in general, featured in press releases by CERN and all the major national scientific institutes, and triggered a vast interest of non-scientific media.

The analysis of the data taken so far has led to new physics results in the context of rare kaon and pion decays, and dark sector searches. Several analyses are in progress with results expected in 2025.

Continuous work is ongoing to keep the offline and online software up to date with the latest CERN-IT requirements. The Monte Carlo production is continuing and sophisticated biasing methods are being developed to generate significant samples of rare processes.

The 2024 YETS has been dedicated to detector maintenance. NA62 has restarted data taking on 17th April 2025 and plans to run for about 209 days. The baseline option is to take data at the same intensity as in 2024. Ten days in beam dump mode and one week at low intensity are also planned, as in 2024.

The document is organised as follows: Section 2 summarises the 2024 run; Section 3 details the main hardware activities that took place during the winter shutdown and the restart of the 2025 run; Section 4 describes the data quality monitoring system, the 2024 data processing and quality, the status of the software, computing and simulation; the $K^+ \to \pi^+ \nu \bar{\nu}$ result and prospects are reported in Section 5; Sections 6, 7 and 8 summarise the status of kaon decays and beam-dump dataset analyses; Section 9 lists the NA62 journal publications from May 2024 till April 2025.

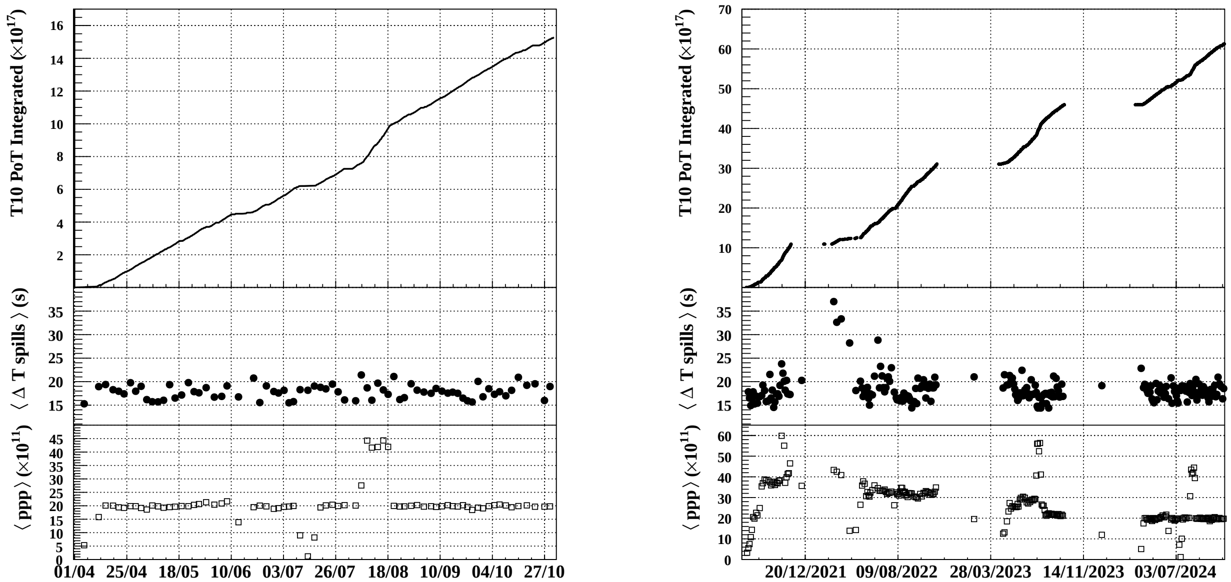

Figure 1: Characteristics of the beam delivered by the SPS to the T10 target in 2024 (left), and from 2021 to 2024 (right) as a function of the time. Top panel: integrated protons on target. Middle panel: time interval between two consecutive spills averaged over about 10^4 (left) or 2×10^4 (right) spills. Bottom panel: intensity (protons per pulse) from the T10 intensity monitor averaged over about 10^4 (left) or 2×10^4 (right) spills. Data reconstructed from TIMBER.

2 2024 Run

NA62 took data in 2024 for 200 days starting from the 10th of April. The kaon run lasted about 180 days with the standard trigger configuration for $K^+ \to \pi^+ \nu \bar{\nu}$. One week in mid-July was dedicated to data taking at very low intensity with a minimum bias trigger. From the 5th to the 15th of August NA62 operated in dump mode. The 2024 data taking ended on 31st October.

The main modification to the hardware concerned the CHANTI, that had its TEL62 readout replaced with the TDC-based FELIX boards.

The beam setup was successfully completed before the official start of the data taking. Initially, special data were taken to align the spectrometer, and to perform the pressure scan and the alignment of the CEDAR. The CHANTI FELIX was operating since the first day but required some weeks of commissioning during which the detector worked with reduced efficiency.

2.1 Beam

The SPS and the extraction line worked smoothly for the whole data taking and provided a beam of optimal quality. At the beginning of August the first P42 TAX showed increasing frictions when moving because leaning against the H8 TAX, often preventing a correct repositioning. A decision was taken to keep the first P42 TAX fixed at the 14 mm hole position until the end of data taking and to move only the second P42 TAX to grant access to ECN3 during normal beam time, if needed. In addition, the TAX positioning problem caused a horizontal mis-aligment between the two TAX, such that the 14 mm hole of the first TAX prevented the use of smaller holes in the second TAX that are essntial to provide a low intensity beam. In total, the SPS delivered in 2024 1.52×10^{18} protons on the T10 target (PoT) (Fig. 1-left, top panel), of which

Table 1: Summary of the Start-of-Burst signals (SoB), the bursts, and the protons on target collected from 2021 to 2024.

Year	SoB [10^3]	Bursts with beam on T10 [10^3]	Bursts collected [10^3]	PoT(Kaon) [10^{18}]	PoT(Dump) [10^{18}]
2024	942	734	636	1.29	0.23
2023	655	514	443	1.17	0.27
2022	817	553	402	1.78	–
2021	374	251	145	0.60	0.14

Table 2: Summary of the 2024 data taking performance compared to previous years. Columns 2 to 5 are the T4 and T10 availability, the NA62 availability, and DAQ efficiency. The last column is the product of the entries of columns 2 to 5. The 2021 and 2023 performance includes the period in dump mode that was not considered in the performance reported in [2] and [4].

Year	T4	T10	NA62	DAQ	Total
2024	0.794	0.981	0.920	0.941	0.675
2023	0.812	0.967	0.922	0.935	0.677
2022	0.715	0.950	0.878	0.828	0.494
2021	0.738	0.915	0.850	0.796	0.454

1.29×10^{18} in kaon mode and 0.23×10^{18} in dump mode. The average time difference between two consecutive bursts was about 18 s. The actual time difference varied during the run from 14.4 s to 20–25 s, depending on the activities in parallel to the SFTPRO cycle (Fig. 1-left, middle panel). The intensity on T10 was kept stable during the whole kaon run at 20×10^{11} ppp on average (Fig. 1-left, bottom panel). This amount of protons per pulse corresponded in 2024 to an average instantaneous beam intensity of 410 MHz of hadronic particles hitting the GTK detector, a value measured on data from the out-of-time activity of the GTK detector itself. This was the rate that maximized the $K^+ \to \pi^+ \nu \bar{\nu}$ yield, according to the intensity study performed in 2023 [2] and it was 25% lower than the 2022 intensity. Intensity fluctuations of 10% or more were observed on a daily basis. The beam intensity was decreased to 10^{11} ppp during the low intensity run and increased to 45×10^{11} ppp during the dump. This last value was about 20% lower than that of the 2023 dump run because of radiation alarms in the TAX area experienced in the attempt to reach the 2023 intensities.

Figure 1-right summarizes the integrated PoTs, the duty cycle and the intensity delivered by the SPS to the T10 target from 2021 to 2024. The spikes in intensity correspond to the data taking periods in dump mode. The intensity scan and the tuning of the optimal intensity are clearly visible in 2023 and 2024. The differences in the beam intensity between 2021, 2022 and the first period of 2023 are mainly due to degradation of the beam monitors.

2.2 Data-taking performance

Table 1 lists the number of bursts delivered on the T10 target and those collected by NA62, and the integrated protons on target in kaon and dump mode, from 2021 to 2024. The number of

Start-of-Burst (SoB) signals delivered by the SPS reported in the table is an estimator of the number of expected spills that could have been collected if both the beam line and NA62 were 100% efficient. Table 2 summarizes the data taking performance from 2021 to 2024 obtained from an analysis of the SPS spills. The T4 availability is the fraction of SoBs recorded with beam on T4. The T10 availability is the fraction of the spills recorded with beam on T4 that also had beam on T10 and accounts for the amounts of issues with the beam line and the NA62 detectors that required access to the ECN3 cavern. The NA62 availability is the fraction of the spills with beam on T4 and T10 actually written on disk. Missing spills are due to hardware problems being fixed without stopping the beam on T10. The DAQ efficiency is the fraction of spills recorded by NA62 with a number of triggers consistent with what expected from the intensity. This fraction accounts for possible issues of the online data flow. The 2024 performance are in line with those of 2023, confirming the significant improvement since 2022.

3 Status of the hardware

3.1 KTAG

During the 2024 data collection period, a failure in one octant of the KTAG system required the replacement of the associated front-end electronics, specifically the NINO board and its corresponding ELMB card. A systematic test of all available KTAG front-end spare boards was conducted during the 2024 YETS and confirmed a baseline level of functioning spares for reliable KTAG operation in 2025 and 2026.

As part of the annual maintenance procedures, the KTAG chiller system underwent standard servicing in preparation for the 2025 data-taking. This included draining, flushing, cleaning, and refilling the system and replacement of four water pipes degraded because of aging.

Significant updates were implemented in the CEDAR-H Safety Protocol, with the aim of improving the reliability of the system and aligning with the revised safety practices. A new version of the protocol document was released at the beginning of 2025, introducing the following key modifications [5]:

1. Removal of the "Diaphragm Motor No N_2 Flux" DSS interlock. This interlock associated with nitrogen flushing of the diaphragm motor was deprecated and removed from the DSS. This decision followed the permanent decommissioning of the diaphragm motor, which was rendered inoperable due to mechanical damage incurred in May 2023. As a result, the motor was fully disconnected from the system. Full-range diaphragm scans, once part of the commissioning procedures, are no longer required for regular NA62 operations, making the interlock obsolete.

2. Upgrade of hydrogen leak detection mechanism. A detailed and updated description of the Flammable Gas Detection System (FGDS)[1] was included in the revised CEDAR-H Safety Protocol. The FGDS, maintained by EN/AA, provides a robust and reliable solution for hydrogen leak detection, significantly improving over previous pressure-based detection methods. The system triggers a DSS interlock if the hydrogen concentration exceeds 20% of the Lower Explosion Limit (LEL), thereby ensuring immediate shutdown of both the high-voltage and low-voltage systems for the KTAG and GTK detectors. Consequently, the existing "H_2 Leak" DSS interlock, based on pressure sensor readings rather than direct

[1] The Flammable Gas Detection System was installed in TCC8 in July 2023.

explosive atmosphere detection, was removed. The pressure-based signal originating from the GCS now issues a non-blocking warning displayed in the DCS Alarm Table. The FGDS has assumed the role of primary safety measure for explosive gas detection, offering a direct, precise, and fail-safe mechanism.

These updates collectively strengthen the operational robustness and safety monitoring of the KTAG system, while simplifying the interlock logic and improving overall maintainability without compromising risk mitigation.

3.2 GTK

After a thorough investigation of the GTK0 issue (detailed in [2]), several problems related to the power distribution and to an interlock board were discovered and fixed. As a matter of precaution, the oldest operational module was installed as GTK0. The data taking in 2024 restarted smoothly until June 3rd, when the read-out of GTK0 stopped decoding data signals coming from chip 7 due to a sudden change in the DAQ link output frequency. This problem was soon mitigated by applying one of the available test configurations on the chip clock distributor, resulting in the correct signal frequency. On June 14th, the encoding of the signal transferred through one of the four data links of this chip suddenly changed, adding invalid characters at the end of each IDLE word, and thus preventing the normal communication between the chip and the read-out board. The quarter chip responsible for this data loss was excluded and the module remained installed and operating in this configuration until the end of the run. The module will be investigated further once transport to Meyrin is allowed by RP. However, the peculiarity of failure experienced in 2024 suggests a possible aging issue unrelated to the 2023 problem.

The restart of the operation in 2025 was successful despite some initial issues. A small leak from the cooling plate of the module installed as GTK2 was observed after the installation. The module was promptly replaced and is currently in the laboratory for tests. A week later, an AC/DC power converter (A3486), which is a part of CAEN EASY-chain responsible for delivering low voltage to the detector, failed. The converter was sent to CAEN for repair, and the operation was restored with a spare power converter lent by the CERN electronics pool. Finally, a recurring problem with insufficient amount of coolant in the GTK cooling plant led to the detector shut down after a few days of data taking. The issue was temporarily solved by refilling the coolant but an intervention to fix the leak is planned.

3.3 CHANTI and Veto Counter

During the 2024 run, the CHANTI TEL62-based readout was fully replaced, transitioning to the new TDC-Felix system. A problem with the timing distribution of the TDCs was identified at the beginning of the 2024 run, leading to inefficiencies in roughly 7% of the 2024 total collected spills. This anomaly was successfully cured by an update of the firmware of the TDC boards after the first month of data taking. Part of the inefficiency was recovered at sofware level as described in 4.2.

The Veto Counter worked properly in 2024 without experiencing significant issues in both the TEL62 and FELIX readouts.

3.4 Straw, RICH, CHODs, MUV3

The Straw spectrometer operated smoothly in 2024. In an attempt to further improve data taking efficiency by reducing detector down-time, two front-end boards requiring majority ($\mathcal{O}(10)$ per year) of power-cycles were replaced during the 2024 YETS. One of the Wiener MPOD crates housing low-voltage and high-voltage power supplies broke as a consequence of an unexpected power cut in ECN3 during YETS, when the detector was being prepared for the 2025 data taking. The faulty crate was sent for repair and a spare is now installed in the detector.

The RICH, hodoscope detectors and the MUV3 worked properly all along the 2024 run.

3.5 LKr, LAV, IRC, SAC, MUV12, HASC

All the calorimeters performed smoothly in 2024. No issues were experienced beyond the usual maintenance and operation tasks during data taking needed to keep the hardware well functioning. The LKr experienced a lower amount of readout hardware problems than in previous years but a slightly higher rate of faults of the fan units of the readout crates due to aging. This prompted a replacement of all the fan units that took place during the YETS.

3.6 Trigger, PC farm

Both the L0TP+ and L1 worked smoothly during the whole 2024 run. A new L0 trigger line was added in 2024 to study the rare decay $K^+ \to \pi^0\pi^0 l^+\nu$. This trigger exploited primitive information from the electromagnetic calorimeter requiring at least four reconstructed electromagnetic clusters that had to satisfy suitable isolation criteria. The effect of this trigger line on the overall DAQ rate was negligible. The same trigger is used also in 2025.

At the beginning of the 2024 data taking the old PCs of the PC-farm were replaced with new and more powerful servers and the PC-farm software was upgraded. In particular the Ethernet packets capture driver was migrated from pfring to dpdk tool. During the 2024 data taking, the PC-farm software experienced an increased rate of crashes with respect to 2023 causing a data collection inefficiency of few percents. A thorough investigation of the software performed during the YETS led to the discovery and fix of some problems in the PC-farm software that explained part of the crashes. As a result, the rate of crashes has significantly dropped during the first month of data taking in 2025.

3.7 Restart of data taking in 2025

During the YETS the faulty P42 TAX was moved to align the largest hole with the beam. This allowed the 2 mm and 4 mm holes of the second TAX to be used again for low intensity and standard muon runs. The beam tuning in 2025 started at the beginning of April and was completed one week before the restart of data taking. Several special runs have been performed for detector commissioning once the beam was ready. The problem of the GTK power system previously reported caused only a short delay in detector commissioning that was completed in time for the restart of the physics data taking. The beam monitor of the T10 target was found to be severely degraded, with the response varying up to 40% across the surface. This problem presently affects the reading of the intensity at T10 of the SPS Page1. For this reason the setting of the optimal intensity this year was defined according to the instantaneous intensity measured on the reconstructed data, and required some days to allow the full processing of the data collected.

NA62 plans to run in 2025 mostly for kaon physics at the optimal beam intensity. A continuous control of the spill quality is required, like in previous years. About 10 days in dump mode at $\times 1.5$ nominal intensity and about a week at few % of the kaon run intensity are also planned, like in 2024.

4 Software and computing

4.1 Data quality monitoring system

The quality of NA62 data relies on the online data quality monitoring system. This system is organised in three levels, described in the following. Since the 2024 data taking, the full monitoring system runs on AlmaLinux 9.

1. Fast Processing is meant to provide histograms in the Control Room and on the web for almost real-time monitoring. As soon as a spill is collected, a subset of data taken by a minimum bias trigger is processed using the standard offline reconstruction software. A dedicated PC dispatches the histograms. The time from taking data to displaying the histograms depends on the instantaneous intensity, and was about two minutes in 2024.

2. Fast Post-Processing takes place at the end of a run, and provides a monitoring tool for detector experts on a daily basis, with larger statistics than the first level. This step makes use of the output files from the fast processing, therefore the delay time, typically few hours, depends only on the length of the run.

3. Prompt Processing relies on the offline processing of all the data from the raw files temporary stored on EOS. This level performs the full detector calibrations, filters the data and runs several analysis routines. The delay time is typically a few days, and is sensitive to possible configuration changes that may occur during data taking, halting the prompt processing of the whole run if not propagated to the software quickly enough.

During the 2024 run, more than 92% of the spills were fully processed by the prompt processing, in line with the 2023 data taking, and confirming a significant improvement with respect to 2022 and before.

4.2 2024 data processing and quality

The 2024 data taking ended in November, and the offline central reprocessing was completed by January 2025. The reprocessing software runs dedicated data-quality routines for each subsystem to tag the “bad” spills to exclude from physics analyses. The full 2024 data sample is split into six standard kaon mode subsamples (A, B, C, D, E, F in chronological order) according to the main features of the data taking, the low intensity kaon mode subsample (few % of the standard kaon beam intensity), and the beam-dump mode subsample. Once the bad spill are discarded, the data quality is almost uniform within each subsample.

The 2024 data sample consists of 567×10^3 SPS spills in standard kaon mode. According to the offline central reprocessing, less than 9% of them are flagged as bad and excluded from the PNN analysis, in line with the fraction of bad spills observed in 2023. The majority of problems come from the first part of the data-taking (subsample A), due to the previously reported initial issues in the FELIX CHANTI read-out system. A new CHANTI reconstruction algorithm was developed to properly handle the inefficient spills, leading to recover approximately 65% of the affected spills during the period impacted by the TDCs' problem. Other sources of bad spills are: anomalies in one or more subsystems used in the PNN analysis; the spills were collected with trigger conditions inappropriate for the PNN analysis; or non-recoverable processing failures. The PNN analysis exhibits the largest fraction of bad bursts as it makes use of all the subdetectors. Some of the spills declared bad for PNN are usable in other physics analyses that do not rely on the information coming from all subsystems.

In addition, 21×10^3 SPS spills were collected in kaon mode at low beam intensity (Section 7), and further 50×10^3 spills were collected in beam-dump mode (Section 8). Central offline reprocessing of these two datasets was completed by December 2024.

4.3 Computing, framework and software updates

All NA62 virtual machines (VMs) hosted on the CERN cloud infrastructure were upgraded to AlmaLinux 9 during 2024. These VMs are used for a wide range of tasks, including managing the processing of data and MC samples, updating databases with run-related information, and regularly performing code quality checks and software framework tests on GitLab. The upgrade was necessary due to the end of support for the CentOS 7 operating system previously in use.

Several event biasing schemes were introduced at the simulation level as part of the ongoing effort to disentangle all the different background mechanisms across multiple physics cases, including the $K^+ \to \pi^+ \nu\bar{\nu}$ decay. The decay generator library has been routinely expanded to support the ongoing rare kaon decay analyses, the beam-dump programme and exploratory studies.

The STRAW track reconstruction was improved in 2025, leading to an increased efficiency for multi-track events, in particular those with five tracks in final state. New GTK reconstructions using Kalman filter and neural network algorithms are being developed and currently under test. The timing of KTAG and RICH was also improved thanks to a new likelihood-based reconstruction that accounts for non-Gaussian tails in the PMT response.

The `na62jobs` component, which standardizes and automates user job submission on the CERN batch system, has been continuously updated throughout 2024 in response to user feedback.

4.4 Computing resources

A total of 3.16 PByte of raw data were written to CTA in 2024. Presently, the total amount of NA62 data on CTA accumulated since 2012 is about 29 PBytes, of which 52% is raw data and 48% is backup of processing output.

NA62 keeps a copy of the raw data in the CTA system at the Rutherford Appleton Laboratory in the UK. Data taken in 2016–2018 were copied in 2021, and data taken in 2021–2023 were copied in early 2024. During the 2024 data taking, raw data were copied to RAL while they were still in the EOS buffer, avoiding the need to stage them back from CTA.

After processing and filtering, NA62 data are kept on EOS for individual user analyses, and backed up on CTA. The projection made in 2020 based on 2018 data estimated a yearly increase of about 1 PByte. The NA62 normal yearly allocation of 1.3 PByte was granted in March 2024, with an additional allocation of 1 PByte approved at the end of 2024, and the normal 2025 allocation of 1.3 PByte in March 2025. Presently, the total quota is 13.1 PByte, of which 200 TByte are reserved for online usage, that is raw data to CTA and prompt processing.

NA62 has currently a fair share allocation of 10000 nodes on the CERN condor system for processing raw data, performing individual data analyses, and producing part of the MC samples.

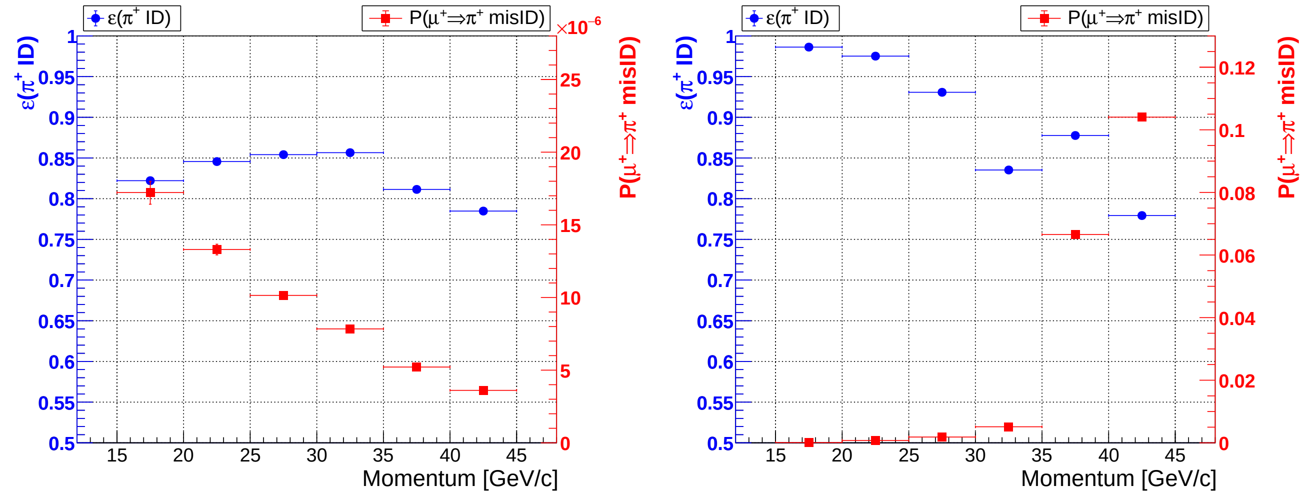

Figure 2: Particle identification performance (defined as in figure 2 of [3]) as a function of momentum, using information from LKr, MUV1,2 and MUV3 (left), and from RICH (right), in 2024 data. The π^+ identification efficiency is shown as blue circles (left vertical axis) and the probability of mis-identifiaction of a μ^+ as a π^+ is shown as red squares (right vertical axis).

NA62 would like to express its gratitude to the IT Department for their continuous support and expertise in assisting the needs of the experiment, and in particular to Xavier Espinal and Bernd Panzer-Steindel, for the excellent support and services provided.

5 $K^+ \to \pi^+\nu\bar{\nu}$ analysis

5.1 Observation of the $K^+ \to \pi^+\nu\bar{\nu}$ decay

On the 24$^{\text{th}}$ of September 2024, in a CERN EP seminar, the NA62 collaboration announced a new result using 2021 and 2022 data and combining this with previously published results from 2016–2018 data [1]. The 2021–2022 dataset doubles the expected number of signal events and an additional 31 candidate events were selected, giving a total of 51 candidate events to date with a total background expectation of 18^{+3}_{-2}. The branching ratio was measured to be $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$ and the background-only hypothesis was rejected with significance above $5\,\sigma$. This therefore constitutes the first observation of the $K^+ \to \pi^+\nu\bar{\nu}$ decay which is also the rarest meson decay ever observed with $5\,\sigma$ significance. This result has been published in JHEP [3]. A paper with the interpretation of this result in terms of limits on $\mathcal{B}(K^+ \to \pi^+ X)$, where X is a hidden sector mediator decaying into invisible dark matter candidates or a pair of Standard Model particles, is in preparation.

5.2 Analysis of the 2023–2024 dataset

As discussed in the 2024 SPSC report [2], the 2021–2022 dataset was taken at around the maximum intensity of the NA62 experiment, and it was found that the optimal working point was predicted to be at around 75% of this maximum. Therefore, from mid-August 2023 the intensity was reduced to the optimal working point. The data-taking efficiency in 2024 (Section 2) was the best achieved to date, providing an excellent new dataset for analysis.

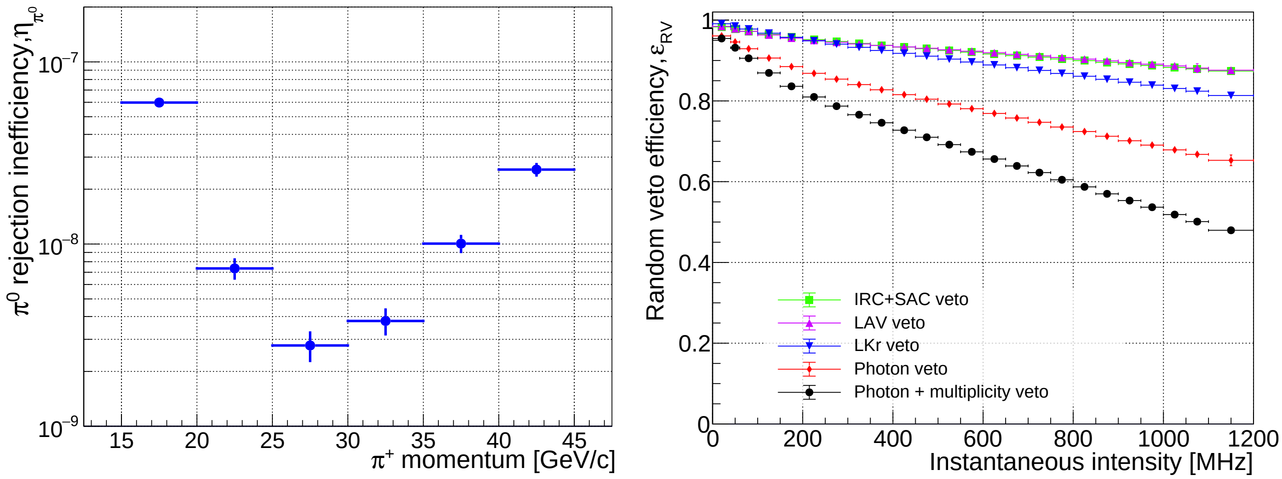

Figure 3: Left: π^0 rejection inefficiency (defined as in figure 3-left of [3]) as a function of the π^+ momentum in 2024 data. Right: random veto efficiency (defined as in figure 4-right of [3]) as a function of the instantaneous beam intensity in 2024 data.

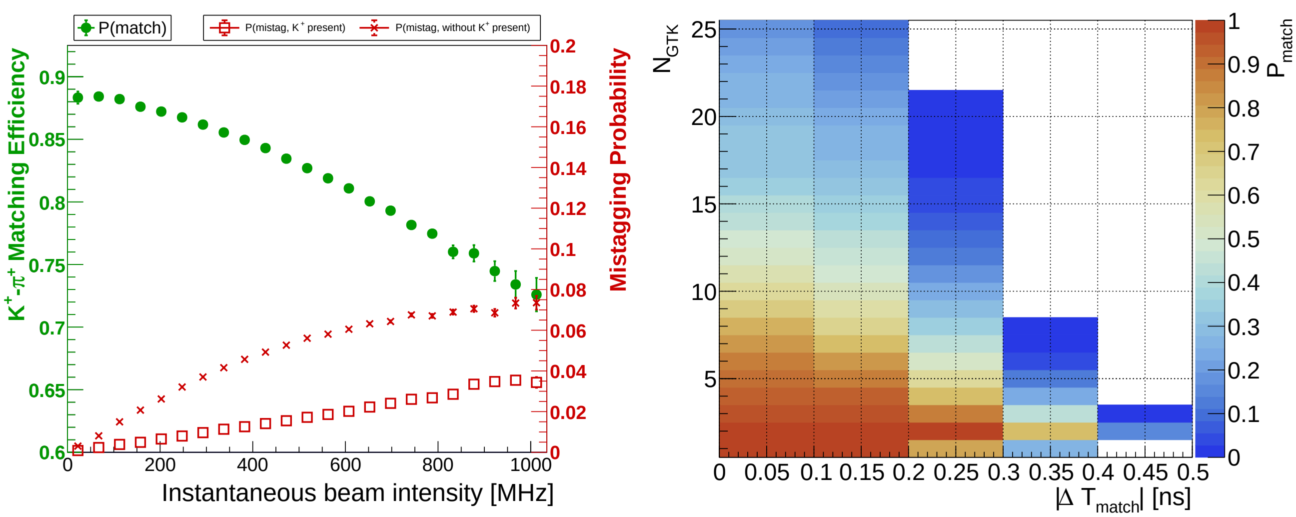

Figure 4: Left: K^+–π^+ matching performance, showing the efficiency of the matching (green, left vertical axis) and the probability of 'mistagging' an incorrect GTK candidate as the parent K^+ of a selected π^+ (red, right vertical axis), measured in a $K^+ \to \pi^+\pi^+\pi^-$ control sample in 2024 data. Right: matching probability (defined as in figure 9-right of [3]) measured in the $K^+ \to \pi^+\pi^0$ normalization sample in 2024 data.

Table 3: Main figures of merit of the ongoing $K^+ \to \pi^+\nu\bar{\nu}$ analysis of 2023 and 2024 datasets; the 2022 dataset is also reported for comparison. Numbers from 2023 and 2024 are preliminary. The beam intensity is measured by counting the out-of-time GTK tracks; $N_{\pi\pi}$ is the number of selected $K^+ \to \pi^+\pi^0$ normalization events; N_K is the effective number of collected kaon decays; $\varepsilon_{\rm RV}$ is the random veto efficiency; $N_{\pi\nu\nu}$ is the number of expected SM $K^+ \to \pi^+\nu\bar{\nu}$ events, assuming $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = 8.4 \times 10^{-11}$; $B_{\rm total}$ is the number of expected background events, summing all the relevant background sources. Details on the definition and the meaning of these figures of merit are provided in [3].

Dataset	2022	2023	2024
Number of spills $[10^3]$	326	363	519
$<$ Beam intensity $>$ [GHz]	0.57	0.48	0.41
$< N_{\pi\pi}/\text{spill} >$ $[10^2]$	4.9	4.7	4.4
N_K $[10^{12}]$	2.3	2.5	3.3
$\varepsilon_{\rm RV}$	0.63	0.68	0.73
$N_{\pi\nu\nu}$	8	9	13
$N_{\pi\nu\nu}/\text{spill}$ $[10^{-5}]$	2.5	2.5	2.6
$B_{\rm total}/N_{\pi\nu\nu}$	1.1	1.1	1.0

The work-in-progress results of the ongoing $K^+ \to \pi^+\nu\bar{\nu}$ analysis of the 2023 and 2024 datasets are summarized in table 3. Figures 2, 3 and 4 report the preliminary performance of the offline analysis of 2024 data, in line with what observed in the 2021–2022 dataset [3]. These preliminary results show how the data-taking conditions in 2024 lead to a slightly higher signal yield per spill. This occurs thanks to a lower signal loss due to random activity in veto detectors that compensates the lower number of normalization events selected per spill. In addition, a slightly decrease of the expected relative background is observed and an increase of the overall expected signal yield, given the smoother and therefore more efficient collection of SPS spills. In summary, the addition of the 2023–2024 dataset is expected at least to double the signal yield of the already published 2016–2022 dataset [3], with the same level of relative background.

6 Rare decay measurements

The broad NA62 rare decay programme is enabled by dedicated lepton-pair trigger lines, as well as prescaled multi-track and minimum-bias trigger lines [6]. The L0 trigger lines for collection of lepton pairs are based on RICH and CHOD multiplicity requirements, total energy deposited in the LKr, and MUV3 signal multiplicity conditions. The corresponding L1 trigger conditions involve beam kaon identification in the KTAG and reconstruction of a negatively charged track in the STRAW spectrometer. The dataset collected so far is equivalent to about 10^{13} kaon decays into di-electrons and electron-muon pairs, and 1.5×10^{13} kaon decays into di-muons. The datasets collected with generic multi-track and minimum-bias trigger conditions exceed 10^{11} kaon decays.

Since the previous SPSC review in April 2024, we published the first search for the lepton number violating decay $K^+ \to \pi^0\pi^-\mu^+e^+$ and lepton flavour violating decays $K^+ \to \pi^0\pi^+\mu^-e^+$, $K^+ \to \pi^0\pi^+\mu^+e^-$ using the 2016-18 dataset [7]. Upper limits of 2.9×10^{-10}, 3.1×10^{-10} and 5.0×10^{-10}, respectively, are obtained at 90% CL for the branching ratios of these decays. This

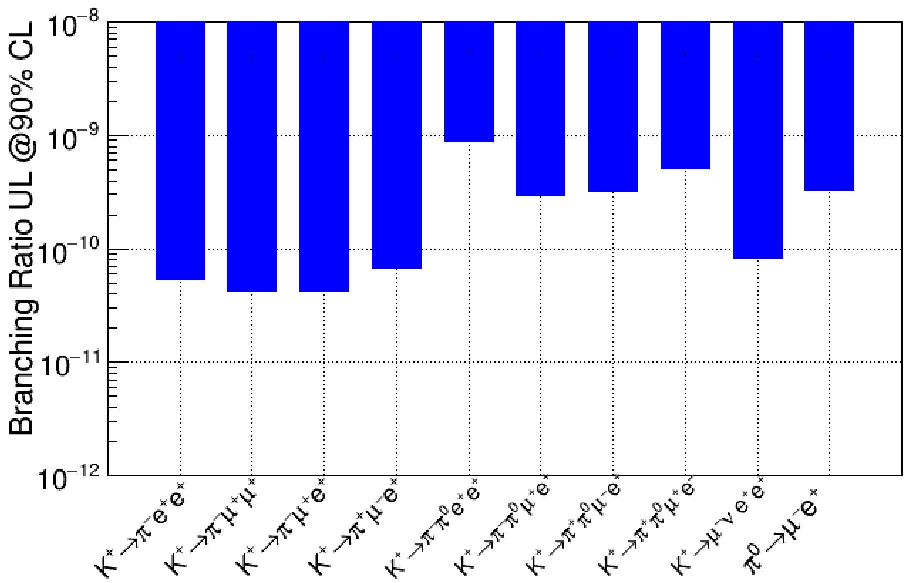

Figure 5: Summary of the results of the NA62 searches for LFV and LNV processes performed using the 2016-18 statistics; the $K^+ \to \pi^- \mu^+ \mu^+$ analysis is based on 25% of the 2016-18 datasets.

work completes the programme of searches for lepton flavour and number violating K^+ and π^0 decays with the 2016-18 dataset, addressing ten possible decay modes in total, the results of which are summarized in Fig. 5 [8–11]. Consolidation of the analyses for the full dataset is in progress. With the full dataset, we expect an order of magnitude improvement in sensitivity for most decay modes, thanks to the removal of the di-lepton trigger prescaling factors for the data taken from 2021 onwards. For the $K^+ \to \pi^- \ell^+ \ell^+$ decays characterized by the largest geometrical acceptances, we expect to reach the $\mathcal{O}(10^{-12})$ sensitivity to the decay branching ratios.

We also published the first detection of a tagged neutrino candidate based on the dataset collected in 2022 [12] in which about 0.2 signal and $0.03^{+0.04}_{-0.02}$ background events are expected. The candidate consists of a $K^+ \to \mu^+ \nu_\mu$ decay where both charged particles are reconstructed by the upstream (GTK) and downstream (STRAW) trackers, and the neutrino is detected via its charged-current interaction in the liquid krypton calorimeter. This result demonstrates the feasibility of the neutrino tagging technique, potentially opening new prospects for accelerator-based neutrino physics. The NA62 dataset collected in 2023–2024 will be used to significantly improve the statistical power of this result.

In March 2025, we presented a new upper limit on heavy neutral lepton (HNL) production in $\pi^+ \to e^+ N$ decays of the beam pions based on the 2017–2024 dataset. Upper limits on the HNL mixing parameter $|U_{e4}|^2$ are established at the level of 10^{-8} in the range 95–126 MeV/c^2 (Fig. 6), improving on the limits from the PIENU experiment [13] with stopped pions. An article is in preparation.

7 Low intensity minimum bias data-taking

In July 2024, ten days of data were collected by the NA62 experiment operating at low intensity and with minimum bias trigger settings. This dataset contains a high-statistics and pure sample

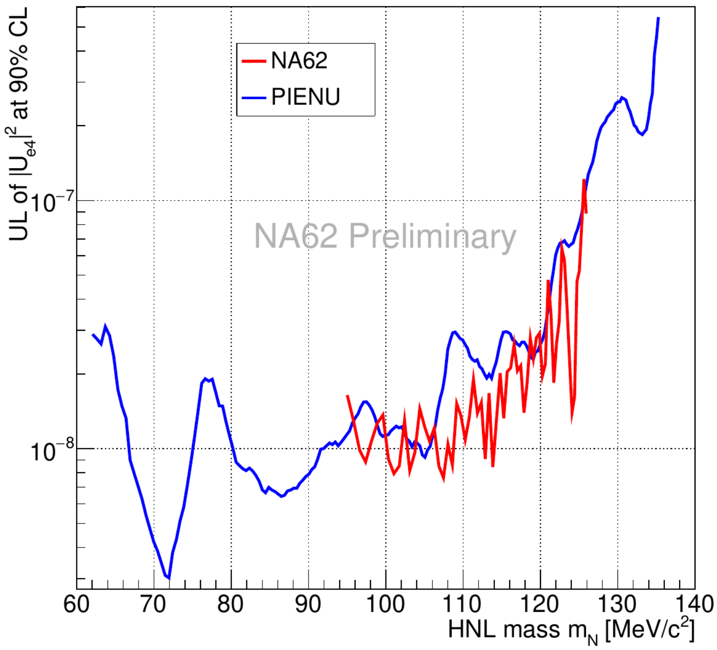

Figure 6: NA62 upper limits at 90% CL of the heavy neutral lepton mixing parameter $|U_{e4}|^2$ obtained from a search for the $\pi^+ \to e^+N$ decay of beam pions, compared with the results from the PIENU experiment.

of common kaon decays, which are usually excluded by the restrictive triggers required when operating NA62 at high rates. For this data-taking, a minimum bias trigger was deployed, which only requires the presence of at least one charged track, based on a CHOD signal at L0 and a reconstructed STRAW track at L1. This allows simultaneous and unbiased collection of all common K^+ decays. Precision studies using this dataset open up new research opportunities for the collaboration.

One leading motivation for this bespoke data was to address the current tension, at the level of approximately 3σ, between experimental measurements and the predicted unitarity of the 1$^{\text{st}}$ row of the CKM matrix. This requires precision measurements of ratios of the branching ratios of combinations of the most common K^+ decays. For example, a measurement of the ratio $\mathcal{B}(K^+ \to \pi^0\mu^+\nu)/\mathcal{B}(K^+ \to \mu^+\nu)$ with a precision of 0.5% or better can provide considerable impact in clarifying the current tension [14]. However, there are several other uses for this dataset, including: measurements of V_{us}/V_{ud}, studies of the form factors of $K^+ \to \pi^0\ell^+\nu$ decays, and studies of beam-particle interactions. In addition, this clean minimum-bias and almost zero pile-up dataset can be used to further cross-validate and improve NA62 simulations.

A dedicated data-taking period with low intensity, set at about 1% of the maximum NA62 intensity (i.e. $\sim 6\,$MHz of particles in the GTK), was chosen such that a uniform minimum-bias dataset could be collected to allow best control over systematic uncertainties. The ten days of data collected constitute approximately 3×10^9 kaon decays in the fiducial volume. This sample, together with an equivalent sample size that is going to be taken in 2025, will lead to per-mille statistical precision for the ratios of the common kaon decay branching ratios.

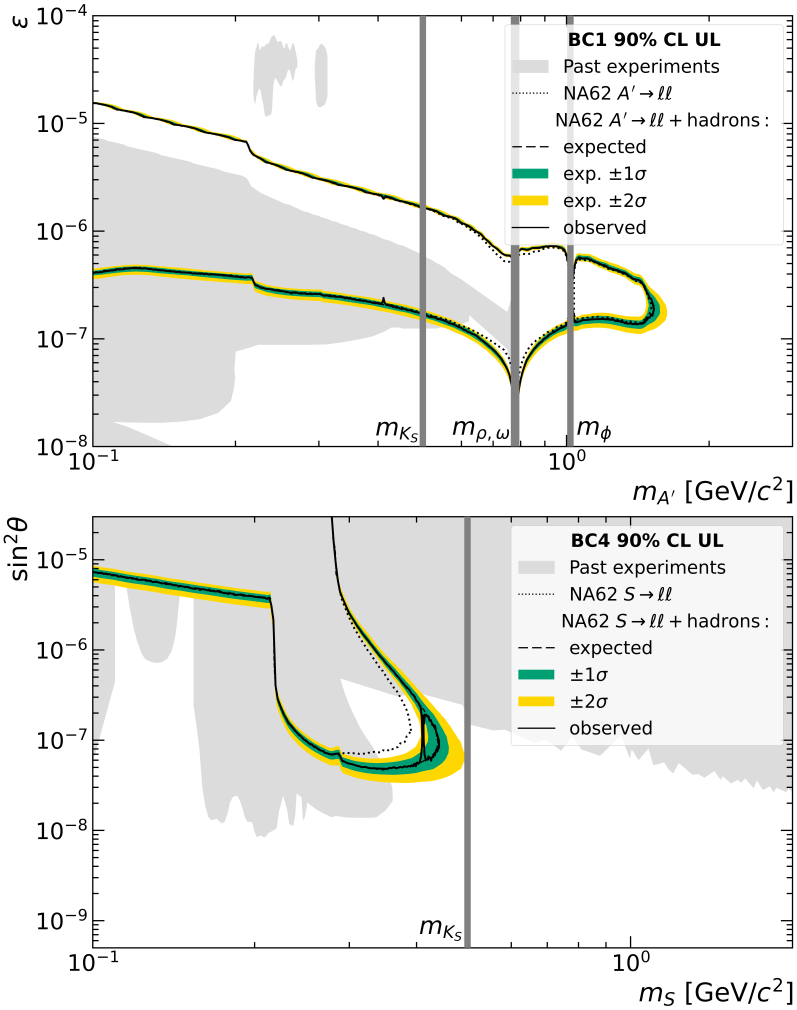

Figure 7: Observed 90% CL exclusion contours in the coupling constant versus mass plane in the dark photon BC1 (top) and dark scalar BC4 (bottom) benchmark scenario [15] combining hadronic and di-lepton channels. Expected $\pm 1\sigma$ and $\pm 2\sigma$ bands correspond to the uncertainty in the number of protons on target.

8 Results from beam-dump operation

NA62 has achieved sensitivities to long-lived light mediators in a variety of new-physics scenarios. From 2021 until the end of 2024, NA62 has collected more than 6×10^{17} POTs in the beam-dump mode. The last column of Table 1 presents the statistics collected each year. The 2.3×10^{17} POT in 2024 were collected under a slightly different configuration of the P42 achromat magnets compared to 2021 and 2023. In 2021 and 2023, the three upstream B1 achromat magnets were running at their maximum current, and a scan of the secondary particle rate reaching the NA62 detector was performed by varying the current feeding the the last achronmat magnet B2. The current corresponding to the minimum background rate was chosen as the default for beam-dump data-taking. In 2024, the same scan on the B2 magnet was conducted while maintaining the current of the B1 magnets at the same value used during kaon data-taking. Although the rate of secondary particles reaching the detector did not change significantly, the kinematic spectrum was altered, potentially leading to an increase in background. For this reason, the scheduled beam-dump data-taking in 2025 is planned to be conducted under the same configuration as in

2021.

In total, three analyses have been published using the beam-dump data sample from 2021, corresponding to 1.4×10^{17} POT. They include di-muon, di-electron and hadronic final states [16–18]. Since the last NA62 SPSC review in April 2024, the collaboration has completed the analysis and publication of the 'hadronic analysis'. The NA62 2021 beam-dump data sample has been investigated for decays of new physics particles into $\pi^+\pi^-$, $\pi^+\pi^-\gamma$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^0\pi^0$, $\pi^+\pi^-\eta$, K^+K^- and $K^+K^-\pi^0$ final states, with no signal observed. Combining this result with the previous searches for the di-lepton final states, e^+e^- and $\mu^+\mu^-$, using the same dataset, new regions of dark scalar, dark photon and axion-like particle parameter spaces are excluded, improving on previous experimental searches. Fig. 7 reports two representative exclusion contours obtained from the analysis of the 2021 dump data.

The results prove the absence of background limitation for statistics of 10^{18} POT and beyond, allowing to increase the sensitivity for new-physics searches by employing more data. The di-lepton and hadronic analyses of the combined 2021-2024 datasets are ongoing. Improvements in the selection, more complete description of the backgrounds and larger statistics allow a significant increase in the sensitivity beyond the published 2021 results.

After passing the feasibility studies, several analyses of the full collected sample are ongoing. These include the search for semi-leptonic decays, allowing searches for new physics fermions, such as heavy neutral leptons, and search for purely neutral final states, potentially enhancing the sensitivity for pseudoscalar mediators. Feasibility studies for other, more exotic, new physics scenarios are ongoing, exploiting the full potential of the collected datasets.

9 NA62 publications

Since the last NA62 SPSC review in April 2024, the collaboration has completed the following publications:

- E. Cortina Gil et al. (NA62 collab.), Search for leptonic decays of the dark photon at NA62, Physical Review Letters, Volume 133 (2024) 111802 [17].
- A. Bethani et al. (NA62 collab.), Development of a new CEDAR for kaon identification at the NA62 experiment at CERN, Journal of Instrumentation, Volume 19 (2024) P05005 [19].
- M.U. Ashraf et al. (NA62 collab.), First search for $K^+ \to \pi^0\pi\mu e$ decays, Physics Letters B, Volume 859 (2024) 139122 [7].
- E. Cortina Gil et al. (NA62 collab.), First detection of a tagged neutrino in the NA62 experiment, Physics Letters B, Volume 863 (2024) 139345 [12].
- E. Cortina Gil et al. (NA62 collab.), Observation of the $K^+ \to \pi^+\nu\bar{\nu}$ decay and measurement of its branching ratio, Journal of High Energy Physics, Volume 2025, Issue 02, p.191 [3].
- E. Cortina Gil et al. (NA62 collab.), Search for hadronic decays of feebly-interacting particles at NA62, arXiv.2502.04241[hep-ex], accepted for publication by EPJC [18].

More papers are in preparation and already at internal review stage:

- E. Cortina Gil et al. (NA62 collab.), Hidden sector searches using $K^+ \to \pi^+X$ decays at NA62, in preparation.

- E. Cortina Gil et al. (NA62 collab.), Search for heavy neutral leptons in π^+ decays to positrons, in preparation.

The collaboration is actively contributing to major international conferences and topical workshops with recently published or preliminary physics results from NA62 data analyses. From May 2024 to April 2025, collaboration speakers presented 59 talks at international conferences of which 25 were invited talks, 32 were held in plenary sessions, 27 in parallel sessions and 2 at Instrumentation Conferences. More contributions are already foreseen for the future 2025 conferences. Most notably, the highlights presented in Section 5 are presented at Moriond EW 2025 and Moriond QCD 2025.

References

[1] E. Cortina Gil et al. "Measurement of the very rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay". In: *JHEP* 06 (2021), p. 093. DOI: 10.1007/JHEP06(2021)093. arXiv: 2103.15389 [hep-ex].

[2] NA62 Collaboration. "2024 NA62 Status Report to the CERN SPSC". In: *CERN-SPSC-2024-012, SPSC-SR-345* (2024). URL: https://cds.cern.ch/record/2896093.

[3] E. Cortina Gil et al. "Observation of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay and measurement of its branching ratio". In: *JHEP* 02 (2025), p. 191. DOI: 10.1007/JHEP02(2025)191. arXiv: 2412.12015 [hep-ex].

[4] NA62 Collaboration. "2023 NA62 Status Report to the CERN SPSC". In: *CERN-SPSC-2023-013, SPSC-SR-326* (2023). URL: https://cds.cern.ch/record/2856997.

[5] V. Falaeev et al. "Safety protocol for CEDAR with Hydrogen gas radiator". In: *EDMS* (2025). URL: https://edms.cern.ch/document/2920580/2.

[6] E. Cortina Gil et al. "Performance of the NA62 trigger system". In: *JHEP* 03 (2023), p. 122. DOI: 10.1007/JHEP03(2023)122. arXiv: 2208.00897 [hep-ex].

[7] M. U. Ashraf et al. "First search for $K^+ \to \pi^0 \pi \mu e$ decays". In: *Phys. Lett. B* 859 (2024), p. 139122. DOI: 10.1016/j.physletb.2024.139122. arXiv: 2409.12981 [hep-ex].

[8] E. Cortina Gil et al. "Searches for lepton number violating K^+ decays". In: *Phys. Lett. B* 797 (2019), p. 134794. DOI: 10.1016/j.physletb.2019.07.041. arXiv: 1905.07770 [hep-ex].

[9] E. Cortina Gil et al. "Search for Lepton Number and Flavor Violation in K^+ and π^0 Decays". In: *Phys. Rev. Lett.* 127.13 (2021), p. 131802. DOI: 10.1103/PhysRevLett.127.131802. arXiv: 2105.06759 [hep-ex].

[10] E. Cortina Gil et al. "Searches for lepton number violating $K^+ \to \pi^-(\pi^0)e^+e^+$ decays". In: *Phys. Lett. B* 830 (2022), p. 137172. DOI: 10.1016/j.physletb.2022.137172. arXiv: 2202.00331 [hep-ex].

[11] E. Cortina Gil et al. "A search for the $K^+ \to \mu^- \nu e^+ e^+$ decay". In: *Phys. Lett. B* 838 (2023), p. 137679. DOI: 10.1016/j.physletb.2023.137679. arXiv: 2211.04818 [hep-ex].

[12] E. Cortina Gil et al. "First detection of a tagged neutrino in the NA62 experiment". In: *Phys. Lett. B* 863 (2025), p. 139345. DOI: 10.1016/j.physletb.2025.139345. arXiv: 2412.04033 [hep-ex].

[13] A. Aguilar-Arevalo et al. “Improved search for heavy neutrinos in the decay $\pi \to e\nu$”. In: *Phys. Rev. D* 97.7 (2018), p. 072012. DOI: 10.1103/PhysRevD.97.072012. arXiv: 1712.03275 [hep-ex].

[14] V. Cirigliano et al. “Scrutinizing CKM unitarity with a new measurement of the Kμ3/Kμ2 branching fraction”. In: *Phys. Lett. B* 838 (2023), p. 137748. DOI: 10.1016/j.physletb.2023.137748. arXiv: 2208.11707 [hep-ph].

[15] J. Beacham et al. “Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report”. In: *J. Phys. G* 47.1 (2020), p. 010501. DOI: 10.1088/1361-6471/ab4cd2. arXiv: 1901.09966 [hep-ex].

[16] E. Cortina Gil et al. “Search for dark photon decays to $\mu^+\mu^-$ at NA62”. In: *JHEP* 09 (2023), p. 035. DOI: 10.1007/JHEP09(2023)035. arXiv: 2303.08666 [hep-ex].

[17] E. Cortina Gil et al. “Search for Leptonic Decays of Dark Photons at NA62”. In: *Phys. Rev. Lett.* 133.11 (2024), p. 111802. DOI: 10.1103/PhysRevLett.133.111802. arXiv: 2312.12055 [hep-ex].

[18] E. Cortina Gil et al. “Search for hadronic decays of feebly-interacting particles at NA62”. In: (Feb. 2025). arXiv: 2502.04241 [hep-ex].

[19] A. Bethani et al. “Development of a new CEDAR for kaon identification at the NA62 experiment at CERN”. In: *JINST* 19.05 (2024), P05005. DOI: 10.1088/1748-0221/19/05/P05005. arXiv: 2312.17188 [hep-ex].