The NA62 experiment at CERN

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Abstract. $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is one of the theoretically cleanest meson decay where to look for indirect effects of new physics complementary to LHC searches. The NA62 experiment at CERN SPS is designed to measure the branching ratio of this decay with 10% precision. NA62 took data in 2014 and 2015 and will accumulate kaon decays till the end of 2018. The quality of data acquired in view of the final measurement will be presented. The experiment is also collecting data to search for exotic processes, like Lepton Flavour and Number violation and Axions.

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1. Introduction

NA62 is a fixed-target experiment studying the decay products of a high-intensity kaon beam. The NA62 apparatus is located in the CERN North Area at the SPS extraction site. Its main goal is measuring the Branching Ratio of the ultra-rare Flavor Changing Neutral Current (FCNC) kaon decay

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

with a 10% accuracy [1].

![Figure 1. Flavor Changing Neutral Current (FCNC) loop processes, highly suppressed by GIM mechanism, but theoretically very clean [2].](image)

This decay, together with its neutral partner $K_L \rightarrow \pi^0 \nu \bar{\nu}$, is driven by FCNC (see figure 1), and its branching ratio (BR) is highly suppressed by the GIM mechanism. The BR is predicted in Standard Model with high precision, making these processes extremely sensitive to new physics.

The actual Standard Model prediction [2] for the branching ratio is

$$BR_{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}.$$  

Should the experimental value be different from the prediction, new physics contributions have to be present.

On the other hand, this process is almost unexplored experimentally: the only existing measurement has been obtained combining datasets collected by Brookhaven National Laboratory (BNL) E787 and E949 experiments [3, 4]. The measured branching ratio, based on 7 candidates, is:

$$BR_{exp}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (17.3^{+11.5}_{-10.5} \times 10^{-11}).$$

2. The NA62 experimental apparatus

A schematic view of the NA62 apparatus [5] is shown in figure 2. NA62 exploits the 400 GeV/c proton beam delivered by the CERN SPS to create a secondary beam. The protons impinging on a beryllium target produce a hadron beam with a momentum 75 GeV/c and a rate of 750 MHz. The beam is composed of 71% pions, 23% protons, and 6% kaons.

2.1. Beam-particle identification and momentum measurement

Kaons are identified by a differential Cherenkov counter detector (CEDAR) equipped with a photon detector, called KTAG. The KTAG detector combines a time resolution of $\sim 100\text{ps}$ and a kaon identification efficiency higher than 95%.

The kaon direction, momentum and time are measured by the GigaTrakker (GTK) detector. It is composed of three stations interspersed by two pairs of dipole magnets. Each station is made of 200 $\mu$m thick silicon pixel matrix ($300 \times 300 \mu m^2$) coupled with 100 $\mu$m thick readout chip for a total of 0.5 $X_0$ per station with time resolution better than 200 ps and momentum resolution 0.2%. The GTK is operated in a high particle rate environment of 750 MHz.
2.2. Final-state particle momentum measurement

The decay products momentum is measured by the Straw spectrometer (STRAW). This detector is composed of 4 stations made of 1792 straw tubes positioned in 4 views (U, V, X, Y). They are operated in vacuum and located on each side of a dipole magnet which produces a vertical field of 0.36 T. The dipole magnet, reused from the earlier NA48 experiment, is placed after the second chamber and provides a 270 MeV/$c$ kick in the horizontal plane to charged-particle trajectory, allowing momentum measurement. The STRAW have momentum resolution better than 1%.

2.3. Final-state particle identification

A first pion/muon separation is obtained with the RICH detector, which is a Cherenkov counter.

This detector is 17 m long, filled with Neon at atmospheric pressure and equipped with 2000 photomultipliers. An evacuated beam pipe run through the detector to avoid beam interactions with the gas. The RICH is designed to operate in the momentum range of $15 \div 35$ GeV/$c$ and it leads to an additional muon suppression factor of $10^2$. The NA62 RICH is able to identify muons with a 99% efficiency. A time resolution of less than 100 ps ensures the time matching between primary and secondary tracks. Thanks to its high time resolution, the RICH is the reference time for the level-0 trigger system.

The Charged particle HODoscope (CHOD) consisting of 128 scintillator slabs arranged in 2 planes (horizontal and vertical) measures the track crossing time with $\sim$200 ps resolution. It also participates to the level-0 trigger as an independent system used for trigger efficiency purposes.

2.4. Photon-veto system

The photon-veto system allows to reject decays with $\pi^0$ in the final state with an inefficiency better than $10^{-8}$. The system covers the solid angle up to 50 mrad and it includes 4 different detectors (see figure 3):

- Large Angle Veto (LAV) covering the angle region 8.5 ÷ 50 mrad;
- Liquid Kripton electromagnetic calorimeter (LKr), vetoing the region 1 ÷ 8.5 mrad;
- Small Angle Calorimeter (SAC) and Inner Radius Calorimeter (IRC) covering the angle region < 1 mrad.

The Large Angle Veto is composed of 12 stations placed along the NA62 length. Each station is in turn composed of 4 or 5 layers of lead-glass blocks coupled to photomultipliers. The LKr, located just downstream of the RICH detector, is reused from the NA48 experiment. The IRC and SAC are lead-plastic scintillator calorimeters. The IRC is used to cover the small angle around the LKr central hole, while the SAC is located at the very end of the experiment, after a magnet bending away all the charged particle remaining in the beam.

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Figure 2. Schematic section of the NA62 experimental setup (indicative scale).
2.5. Hadronic calorimeters and muon veto
The iron/scintillator hadronic calorimeters provide further pion/muon separation. Together with RICH, they guarantee a separation inefficiency of $10^{-7}$. Finally the fast muon veto detector (MUV) composed of an iron wall followed by 5 cm thick scintillators, coupled to PMTs, identifies muons. Muon Veto provides also signals for the trigger system.

3. NA62 trigger and data acquisition
In order to reduce the raw data rate, NA62 makes use of a 3-level trigger system consisting of:

- L0 hardware: from 10 MHz to 1 MHz
- L1 software: from 10 MHz to 100 kHz
- L2 software: from 100 kHz to 10 kHz

The hardware L0 trigger processor receives reduced information (trigger primitives) from a subset of detectors to issue the L0 trigger. The L0 logic is implemented on an FPGA, handling a maximum of $\sim 10$ MHz of trigger primitives from CHOD, RICH, LAV12, Calorimeters, and MUV.

When the detector acquisition systems receive the L0 trigger, they transfer data from the readout electronics to a dedicated farm of computers. On the farm a 2-stage software based high-level Trigger (L1 and L2) runs with the purpose of reducing data rate down to a manageable level. This is done by rejecting as much as possible all the main decay modes of the $K^+$, being $K^+ \rightarrow \mu^+\nu$ ($\sim 60\%$) and $K^+ \rightarrow \pi^+\pi^0$ ($\sim 20\%$), while keeping a large efficiency for the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ signal.

Assuming 10% signal acceptance, at least the observation of $10^{13}$ $K^+$ decays is required to reach the designed precision level. In this framework the fully functional experimental apparatus is expected to detect $\sim 45$ events per year.

4. Data-quality studies
The $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay is characterised by one track in the GTK making a vertex with one charged track identified as $\pi^+$ in the detector downstream. A key variable used to distinguish the signal from the background is the squared missing mass defined as:

$$m_{\text{miss}}^2 \overset{\text{def}}{=} (p_{K^+} - p_{\pi^+})^2$$
where $p_{K^+}$ and $p_{\pi^+}$ are the four momenta of incoming kaon and outgoing pion respectively (the pion mass is assumed for the outgoing particle). It is possible to identify two regions in the $m_{miss}^2$ distribution where the signal to background ratio is most favourable (see figure 4).

![Figure 4](image_url)

**Figure 4.** Theoretical $m_{miss}^2$ distribution for signal and backgrounds from the main $K^+$ decay modes. In the figure the two regions where the signal/ratio is larger are highlighted.

In this section, some results coming from a study on data quality based on data collected in 2015 and relevant for the measurement of the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay are presented.
4.1. Kinematic results
A single outgoing track must form a vertex with the incoming kaon, required to be in the 65-metre long region between the last GTK station and the first STRAW chamber. A quality check on the vertex is based on the distance of closest approach (CDA) between the GTK hit location and the tracks reconstructed in the STRAW spectrometer. CDA must be less than 1.5 cm.

Further selection requirements for the signal are:

- The track projection needs to spatially intersect an energy deposits in the calorimeters and the corresponding hit in the CHOD.
- The associated CHOD hit must be in time with the KTAG candidate.

![Figure 5. $m_{\text{miss}}^2$ versus the momentum of the downstream track in single-track events confirmed by GTK and KTAG signals.](image)

The squared missing mass of tracks that satisfy all those constraints are reported in figure 5 as a function of the track momentum measured with the STRAW spectrometer. In this plot, one can clearly distinguish the three main kaon decay channels: $K \rightarrow \pi^+\pi^+\pi^-$ on the top, $K \rightarrow \pi^+\pi^0$ as an horizontal band centred around the value of neutral pion mass, and $K \rightarrow \mu^+\nu$ at the bottom when the pion mass hypothesis results in a negative missing mass values. The plots shown in this paper, are based on datasets recorded in 2015 at around 3% of nominal intensity.

The KTAG can also be used in anti-coincidence with a Gigatracker track in order to select single track events not related to kaons. This technique allows to study the background generated by the non-kaon beam. Figure 6 shows the main sources of non-kaon tracks:

- decay from beam $\pi^+$,
- elastic scattering of beam particles in the material along the beam line (KTAG and Gigatracker stations),
- inelastic scatterings in the last GTK station.

The resolution of the $K^+ \rightarrow \pi^+\pi^0$ squared missing mass peak is essential to reduce the tails that can span across the two signal regions. In figure 7 the squared missing mass resolution is
Figure 6. $m_{miss}^2$ vs $P_{\pi^+}$ momentum, under $\pi^+$ mass hypothesis. The downstream track was required to be in anti-coincidence with the kaon track in KTAG.

plotted as a function of momentum. The resolution measured is $1.2 \times 10^{-3} \text{GeV}^2/c^4$, close to the design value represented by the solid black line.

Figure 7 shows that the resolution increases by a factor of three if a coincidence with the GTK detector is not required.

Figure 7. $\sigma(m_{miss}^2)$ distribution obtained with individual kaon track measured with GTK (black points) and assuming kaon track aligned on the central beam axis (empty squares). The solid line shows the expected distribution evaluated as the sum of the various contributions coming from $P_\pi$, $\theta_\pi$, $P_K$, $\theta_K$ shown by the different dashed lines.
4.2. Particle identification

The particle identification systems of NA62 are designed to separate $\pi^+$ from $\mu^+$ and $e^+$ in order to guarantee at least 7 orders of magnitude suppression of $K^+ \rightarrow \mu^+\nu_\mu$, in addition to the kinematic rejection. The RICH is designed to contribute with a factor 100 to this rejection.

To study the performance, $K^+ \rightarrow \mu^+\nu_\mu$ and $K^+ \rightarrow \pi^+\pi^0$ decays were selected applying the kinematic constraints, Muon Veto, and calorimetric information. The positive tracks were selected to have a momentum between 15 and 35 GeV/c. Figure 8 shows that remaining muon contamination of 0.01 corresponds to a pion efficiency of 80%, close to the design target. This figures were improved in the 2016 run.

![Figure 8. $\pi^+$ efficiency as a function of $\mu^+$ remaining contamination measured by the RICH.](image)

4.3. Photon veto

The photon veto system has to provide a suppression factor of $10^8$ to reject $\pi^0$ from the decay: $K^+ \rightarrow \pi^+\pi^0$ ($\pi^0 \rightarrow \gamma\gamma$).

The rejection of such events is implemented by vetoing the events containing at least one photon in one of the electromagnetic calorimeters, LAV, LKr, IRC or SAC. The target suppression factor, is reached thanks to a photon detection inefficiency lower than $10^{-5}$ for energy greater than 10GeV. This is true for pions that have at least 35 GeV/c momentum. Figure 9 shows the inefficiency for the detection of $\pi^0$: when only the LKr calorimeter is used, when LKr and LAV are used, and when the full photon veto system is used. The measurement of the efficiency with 2015 data results is less than $10^{-6}$ at 90% C.L. but it is statistically limited. New measurements are ongoing on 2016 datasets.

5. NA62 physics besides $K^+ \rightarrow \pi^+\nu\bar{\nu}$

Thanks to the performance of the NA62 apparatus, physics beyond the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ ultra-rare decay can be addressed. NA62 can significantly improve the existing limits on lepton flavour and number violating decays like $K^+ \rightarrow \pi^+\mu^+e^-$ or $K^+ \rightarrow \pi^+l^+l^-$. Experimentally $\pi^0$ physics can take advantage of the performances of the electromagnetic calorimeters and processes like $\pi^0 \rightarrow invisible$ or dark photon production can be investigated. Thanks to the quality of the kinematic reconstruction, searches for heavy neutral lepton $(N)$ produced in $K^+ \rightarrow l^+N$ decays can be performed at NA62 and improve the present sensitivity.
The longitudinal scale of the apparatus opens the possibility to search for long-lived particles through their decays. Dark photon, heavy neutral leptons or axion-like particles produced at the target or in beam dump configurations. NA62 is already addressing part of the above physics programme simultaneously with the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ measurement.

6. Conclusions and Prospects

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is one of the theoretically cleanest meson decay to look for indirect effects of new physics complementary to LHC searches. The NA62 experiment will measure the branching ratio of this decay with 10% precision. NA62 took data in 2014 and 2015. In 2016 the first NA62 physics run took place, collecting about $10^{12}$ kaon decays, data are currently being analysed. The data-quality studies show that the physics sensitivity for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay is in line with the design, allowing NA62 to mark CERNs return to the exploration of the Standard Model using high-intensity kaon beams.

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