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The NA62 Experiment at CERN: Prospects for the $K^+ \to \pi^+ \nu \bar{\nu}$ Measurement

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The NA62 Experiment aims to measure the branching ratio of the ultra-rare $K^+ \to \pi^+ \nu \bar{\nu}$ decay with 10% precision, collecting ~ 100 events with the SM branching fraction in 3 years of data taking. The NA62 experimental strategy and the detector layout are described.

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The NA62 Experiment at CERN Super-Proton-Synchrotron (SPS) [1] aims to measure the branching ratio of the ultra-rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$ with 10% precision, collecting ~ 100 Standard Model (SM) events in 3 years of data taking, starting in 2015.

The $K^+ \to \pi^+ \nu\bar{\nu}$ decay is a Flavour Changing Neutral Current (FCNC) process, therefore in the SM is forbidden at the tree level. Furthermore, it is highly CKM-suppressed: $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu}) \propto \lambda^{10}$. These properties make this decay very sensitive to new physics.

The SM expectation is $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (7.81^{+0.80}_{-0.71} \pm 0.29) \times 10^{-11}$ [2] and the current experimental measurement is $\mathscr{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$ [3], which is based on 5+2 candidates observed by the E787 and E949 experiments at the Brookhaven National Laboratory (BNL).

1. The experimental strategy

A $K^+ \to \pi^+ \nu\bar{\nu}$ event is characterised by a positively-charged track identified as a kaon, a positively-charged track identified as a pion and the absence of any other detected particles. All the other events leading to the same experimental response, such as a $K^+ \to \pi^+ \pi^0$ decay where the π^0 is undetected, can contribute to the background.

In the NA62 experiment, the main source of background to $K^+ \to \pi^+ \nu\bar{\nu}$ events is due to the other decay channels of the K^+. In particular, the most frequent K^+ decay channels, reported in Tab. 1 [1,4], have a branching ratio up to 10^{10} times greater than the one expected for the signal. Therefore, to achieve a signal-background ratio $S/B \simeq 10$, they must be kept under control at the challenging level of 10^{11}. Besides, due to the two neutrinos in the final state, it is not possible to fully reconstruct a $K^+ \to \pi^+ \nu\bar{\nu}$ decay. Thus, hermetic photon vetoes, excellent particle identification systems and a precise measurement of the event kinematics are crucial aspects for the success of the experiment.

Decay channel	Branching ratio (%)	Suppression strategy
$K^+ \to \mu^+ \nu$	63.55 ± 0.11	μ veto + two-body kinematics
$K^+ \to \pi^+ \pi^0$	20.66 ± 0.08	Photon veto + two-body kinematics
$K^+ \to \pi^+ \pi^+ \pi^-$	5.59 ± 0.04	Charged particle veto + kinematics
$K^+ \to \pi^0 e^+ \nu$	5.07 ± 0.04	E/p + photon veto
$K^+ \to \pi^0 \mu^+ \nu$	3.353 ± 0.034	μ veto + photon veto
$K^+ \to \pi^+ \pi^0 \pi^0$	1.761 ± 0.022	Photon veto + kinematics

Table 1: Most frequent K^+ decay channels and relative suppression strategy in the NA62 experiment.

Unlike the experiments E787 and E949 [3] which used kaons at rest, the NA62 experiment will be using high-momentum (~ 75 GeV/c) K^+ decaying in flight [1]. An advantage of this choice is the higher energy of the decay products, which decreases the π^0 detection inefficiency of the $K^+ \to \pi^+ \pi^0$, the $K^+ \to \pi^+ \pi^0 \pi^0$ and $K^+ \to \pi^0 \ell^+ \nu$ decays ($\ell = e, \mu$). A disadvantage of a high-momentum beam is that pions and protons cannot be efficiently separated from kaons. As a consequence, the tracking detectors upstream the decay region are exposed to a particle flux ~ 17 times greater than the kaon one.

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The kinematics of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay is sketched in Fig. 1: since the two neutrinos are undetectable, only the K^+ 3-momentum $\vec{p}_K$ and the π^+ 3-momentum $\vec{p}_\pi$ can be measured. Therefore, the kinematics can be fully described by the squared missing mass variable $m^{2\,(\pi)}_{miss}$,

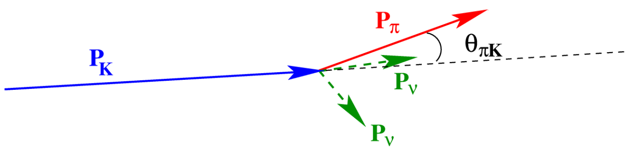

Figure 1: Kinematics of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay.

defined as the square of the difference between the kaon candidate 4-momentum P_K and the pion candidate 4-momentum P_π, assuming the detected particles are actually a K^+ and a π^+:

$$m^{2\,(\pi)}_{miss} \stackrel{def}{=} (P_K - P_\pi)^2 \tag{1.1}$$

$$= m_K^2 + m_\pi^2 - 2E_K E_\pi + 2|\vec{p}_K||\vec{p}_\pi| \cos\theta_{\pi K}, \tag{1.2}$$

where $E_K = \sqrt{|\vec{p}_K|^2 + m_K^2}$, $E_\pi = \sqrt{|\vec{p}_\pi|^2 + m_\pi^2}$ and $\theta_{\pi K}$ is the angle between $\vec{p}_K$ and $\vec{p}_\pi$. Fig. 2 shows the $m^{2\,(\pi)}_{miss}$ distribution for signal and backgrounds from the main K^+ decay channels: the backgrounds are normalized according to their branching ratio; the signal is multiplied by a factor 10^{10} [5].

The variable $m^{2\,(\pi)}_{miss}$ can be used to reject 92% of the backgrounds from the most frequent K^+ decay channels by defining two signal regions in which a significant increase in the signal-background ratio S/B is expected:

Region I: between 0 and the $K^+ \to \pi^+\pi^0$ peak;

Region II: between the $K^+ \to \pi^+\pi^0$ peak and the $K^+ \to \pi^+\pi^+\pi^-$ threshold $\approx 4m_\pi^2$.

2. The NA62 detector

The NA62 experiment will be using K^+ decaying in flight from an unseparated $(75 \pm 1.0)\,\mathrm{GeV}/c$ hadron beam. The 65 m-long decay region is contained in a vacuum (at $< 10^{-6}$ mbar) cylindrical tank, to keep the background due to the beam scattering below the level of 1 event/year.

2.1 Tracking systems

A precise measurement of the kaon and the pion momenta is essential for the selection of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay and to reduce the background cutting on the $m^{2\,(\pi)}_{miss}$ variable. In the NA62 experiment, the detectors involved in momentum measurement are two:

1. The GigaTracker spectrometer, formed of 3 silicon pixel detectors mounted around the four dipole magnets of an achromat, to measure the kaon momentum and direction with a resolution $\sigma(p)/p \sim 0.2\%$ and $\sigma_\theta = 16\,\mu$rad.

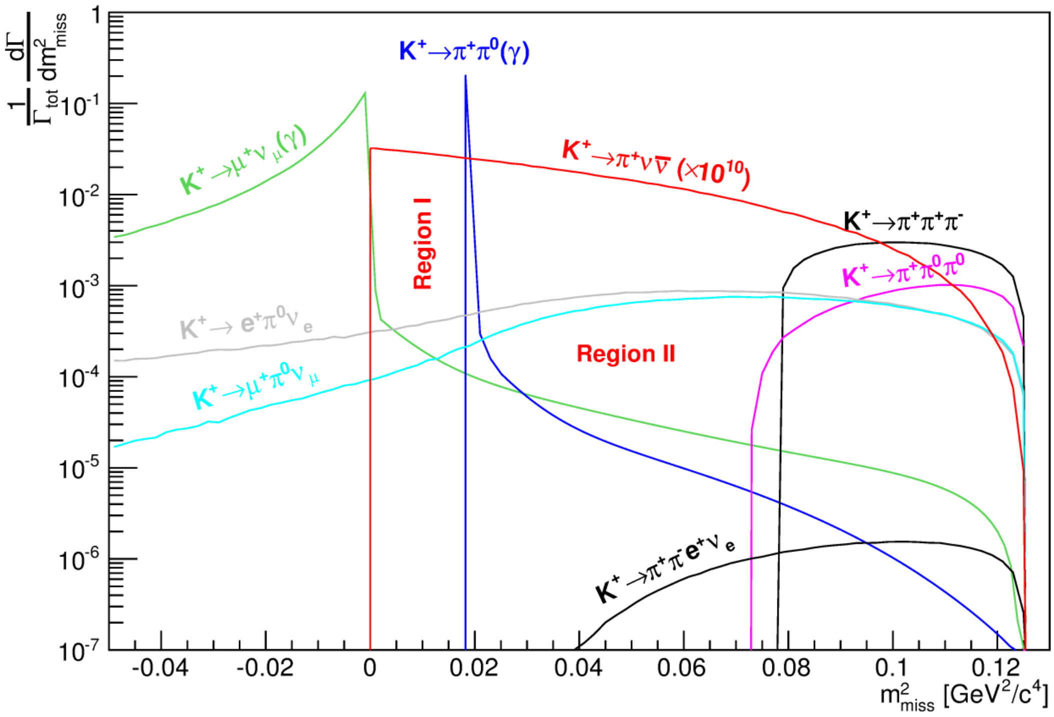

Figure 2: $m_{miss}^{2\,(\pi)}$ distribution for signal and backgrounds from the main K^+ decay channels: the backgrounds are normalized according to their branching ratio; the signal is multiplied by a factor 10^{10}.

2. The Straw Tracker, made of 4 straw chambers and a dipole magnet with momentum kick $p_t = 270\,\text{MeV}/c$, to measure momentum, position and direction of the charged particles originating from the decay region. The expected momentum resolution is $\sigma(p)/p = (0.32 \oplus 0.008 \cdot p)\%$.

2.2 Particle identification detectors

Kaon identification is required to reduce at negligible level the background due to the beam interaction with residual gas in the vacuum tank; pion identification is essential to reject $K^+ \to \mu^+ \nu$ decays at the required level. The detectors dedicated to particle identification are three:

1. The CEDAR/KTAG, a Cerenkov Differential counter to identify 45 MHz kaons in the unseparated beam with at least 95% efficiency and time resolution below 100 ps;

2. The Muon veto system (MUV), formed of two classic iron-scintillator sandwich calorimeters and one array of 12×12 scintillator tiles, to veto the $K^+ \to \mu^+ \nu$ decays at the 10^5 level;

3. The RICH, a ring-imaging Cherenkov counter with time resolution below 100 ps, to provide an additional 10^2 rejection for the π-μ separation and to have a precise timing of the pion candidate.

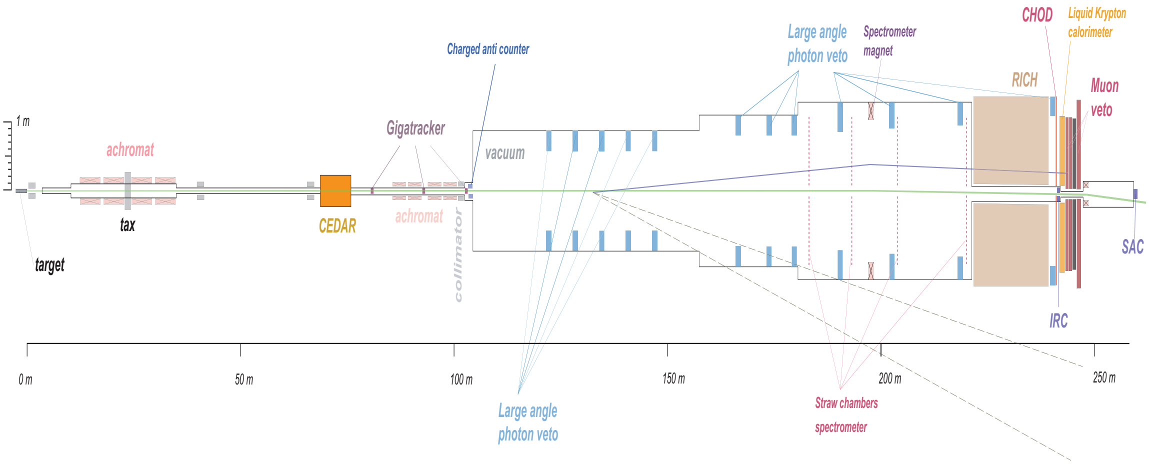

Figure 3: The NA62 detector layout [6].

2.3 Photon Vetoes

The photon veto system is essential to reduce to the required level the background due to many K^+ decay channels, the most challenging of which is the $K^+ \to \pi^+\pi^0$ decay. The requirement on the π^+ momentum $p < 35\,\mathrm{GeV}/c$ guarantees that the two photons from the π^0 have a total energy of $\sim 40\,\mathrm{GeV}$. Considering a rejection power of 10^4 for the $m^{2\,(\pi)}_{miss}$ cut, the probability to miss both photons must be less than 10^{-8}. A suitable way to satisfy such requirement is to install hermetic photon vetoes for photons travelling with an angle ϑ up to 50 mrad. The detectors providing an angular coverage up to 50 mrad can be divided in three groups:

- The Large Angle Vetoes (LAV): 12 stations (ANTI 1-12) made of rings of lead-glass blocks recovered from the OPAL electromagnetic calorimeter barrel [7], and provide the coverage of the region $8.5\,\mathrm{mrad} < \vartheta < 50\,\mathrm{mrad}$;

- The LKr electromagnetic calorimeter, a quasi-homogeneous ionisation chamber with energy resolution $\sigma_E/E = 0.032/\sqrt{E} \oplus 0.09/E \oplus 0.0042$ [8], providing the coverage of the forward region ($1.5\,\mathrm{mrad} < \vartheta < 8.5\,\mathrm{mrad}$);

- The Small Angle Vetoes (SAV): the Intermediate Ring Calorimeter (IRC) and the Small Angle Calorimeter (SAC), two shashlyk calorimeters each made of 70 iron-scintillator planes of thickness 1.5 mm+1.5 mm, to cover the region around the beam pipe ($\vartheta \leq 1.5\,\mathrm{mrad}$).

With this configuration, only 0.2% of the $K^+ \to \pi^+\pi^0$ events with π^+ momentum between 15 and 35 GeV/c have a low-energy photon escaping at larger angles, while the other one is within the detector acceptance. More than 80% of such events have both photons from the π^0 in the LKr calorimeter, while most of the remaining events have one photon in the LKr calorimeter and one in the LAVs.

2.4 Trigger and Data Acquisition System

The particle rate to which the downstream detectors will be exposed is expected to be $\sim$ 10 MHz [9, 10]. Due to such high rate and to the channel count ($\sim 10^5$), a “triggerless” acquisition system in which all the data are unconditionally transferred to PCs in infeasible for the NA62 experiment. Therefore, a variety of hardware lowest-level (L0) triggers will be used to reduce the overall rate below ~ 1 MHz but preserving most of the decays of interest. The maximum allowed latency of the L0 trigger decision-taking algorithms is 1 ms, limited by the GigaTracker Spectrometer readout. Following a L0 trigger, most sub-detectors will transfer data to dedicated PCs, where two trigger levels (L1 and L2) will be applied via software, to reach a final rate of ~ 10 kHz. For each of the two L1 and L2 trigger levels the maximum allowed latency is $\sim \mathscr{O}(1\,\mathrm{s})$.

Different trigger systems and algorithms are being considered and tested. In particular, two different technologies are being investigated for the implementation of the L0 Trigger Processor:

FPGA-based: an electronic board hosting field-programmable gate arrays (FPGAs) devices, in which filter algorithms are implemented at the firmware level;

PC-based: a commodity PC which stores data into the memory, performs filter algorithms and interfaces with the sub-detectors acquisition boards via a PCI-Express board [10].

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