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Status of the CERN NA62 Experiment

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Abstract. The $K^+ \to \pi^+\nu\bar{\nu}$ decay is one of the theoretically cleanest meson decays to look for indirect effects of new physics in a complementary way to direct searches at the LHC. The NA62 experiment at CERN SPS is designed to measure the branching ratio of this decay with 10% precision. NA62 is taking data since 2014, eventually reaching the final designed beam intensity. Using a sample of data taken in 2015, the experimental performances in view of the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio measurement is reported.

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1. Introduction

The $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ are flavour changing neutral current decays proceeding through box and electroweak penguin diagrams. A quadratic GIM mechanism and a strong Cabibbo suppression make these processes extremely rare. Using the value of tree-level elements of the Cabibbo-Kobayashi-Maskawa (CKM) triangle as external inputs, the Standard Model (SM) predicts [1, 2]:

$$\begin{aligned} BR(K^+ \to \pi^+\nu\bar{\nu}) &= (8.4 \pm 1.0) \times 10^{-11} \\ BR(K_L \to \pi^0\nu\bar{\nu}) &= (3.4 \pm 0.6) \times 10^{-11}. \end{aligned}$$

The knowledge of the external inputs dominate the uncertainties on the predictions. The theoretical accuracy, instead, is at percent level because: the short distance physics dominates thanks to the top quark exchange in the loop; the hadronic matrix elements cancel almost completely in the normalization of the $K \to \pi\nu\bar{\nu}$ branching ratios (BR) to the precisely measured BR of the $K^+ \to \pi^0 e^+\nu$. The dependence on the CKM parameters partially cancels in the correlation between $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$. Therefore simultaneous measurements of the two BRs' would allow a theoretical clean exploitation of the CKM triangle using kaons only.

The $K \to \pi\nu\bar{\nu}$ decays are extremely sensitive to physics beyond the SM, probing the highest mass scales among the rare meson decays. The largest deviations from SM are expected in models with new sources of flavour violation, owing to weaker constraints from B physics [3, 4]. The experimental value of ε_K, the parameter measuring the indirect CP violation in neutral kaon decays, limits the range of variation expected for $K \to \pi\nu\bar{\nu}$ BRs' within models with currents of defined chirality, producing typical correlation patterns between charged and neutral modes [5]. Results from LHC direct searches strongly limit the range of variation mainly in supersymmetric models [6, 7]. Anyway thanks to the SM suppression and to the existing weak experimental constraints from K physics, significant variations of the $K \to \pi\nu\bar{\nu}$ BRs' from the SM predictions induced by new physics at mass scales up to 100 TeV are still possible providing a measurement with 10% precision at least.

Only the charged mode has been observed so far and the present experimental status is [8, 9, 10]:

$$\begin{aligned} BR(K^+ \to \pi^+\nu\bar{\nu})_{exp} &= \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11} \\ BR(K_L \to \pi^0\nu\bar{\nu})_{exp} &< 2.6 \times 10^{-8} \;\; 90\% \; CL. \end{aligned}$$

2. The NA62 apparatus for $K^+ \to \pi^+\nu\bar{\nu}$

A measurement of the BR of the $K^+ \to \pi^+\nu\bar{\nu}$ decay with 10% precision at least is the main goal of the NA62 experiment at CERN [11, 12]. The experiment plans to collect about 10^{13} kaon decays in few years using 400 GeV/c protons from SPS. As a consequence 10% signal acceptance and order of 10% signal to background ratio are required to attain the design precision [14]. The proton energy and the above requests both on kaon statistics and signal acceptance force the use of a kaon decay in flight technique. The 12 orders of magnitude of background rejection requires the use of almost independent experimental techniques to suppress unwanted final states.

Figure 1 shows the NA62 apparatus for $K^+ \to \pi^+\nu\bar{\nu}$ used to take data since 2014. Protons impinge on a Be target producing secondary charged particles, 6% of which are kaons. A 100 m long beam line selects, collimates, focuses and transports charged particles of 75 ± 0.8 GeV/c momentum. A Cerenkov counter (KTAG) filled with N_2 gas along the beam line identifies and timestamps kaons. Three silicon pixel stations (Gigatracker) of $6 \times 3\ cm^2$ surface trace and timestamp all the beam particles. The Gigatracker faces the full 750 MHz beam rate, the KTAG the rate from kaons only. A guard ring detector (CHANTI) tags possible hadronic interactions of beam particles at the entrance of a 120 m long evacuated tank. The tank has a transverse

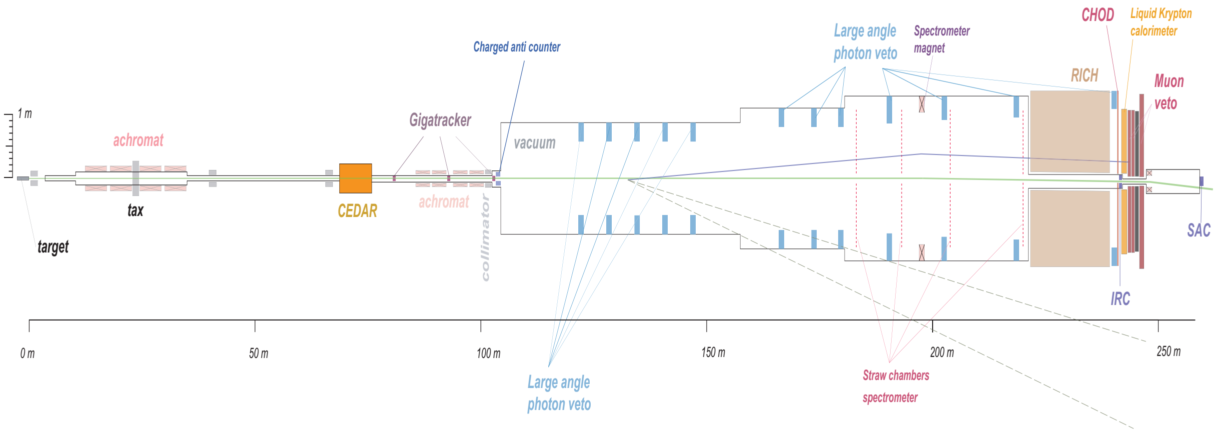

Figure 1. Scheme of the NA62 layout for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$.

section with circular shape of radius varying from 1 to 1.4 m. About 10% of kaons decay in the first 80 m. The tank hosts 11 of 12 large angle annular electromagnetic calorimeters (LAV) made of lead glass blocks, surrounding the decay and downstream volumes to catch γs' emitted from kaon decays with angles up to 50 mrad with respect to the beam axis. A magnetic spectrometer made of straw tube arrays grouped in four chambers and located in vacuum along the last 40 m of the evacuated tank, traces charged particles. Holes of about 6.5 cm radius around the beam axis in the chambers let the undecayed beam particles passing through. An aluminum window closes off the tank just downstream of the last chamber of the spectrometer. The beam particles continue traveling in vacuum along the axis trough a 9cm radius beam pipe attached to the aluminum window and traversing the detectors downstream. A 17 m long RICH counter filled with Ne gas separates π^+, μ^+ and e^+ up to 40 GeV/c. The time of charged particles is measured both with RICH and with scintillator arrays (CHOD) placed downstream to the RICH. The liquid Krypton electromagnetic calorimeter (LKr) inherited from the NA48 CERN experiment [13] detects forward γs' and complements the RICH in particle identification. A shashlik small-angle annular calorimeter (IRC) in front of LKr detects γs' directed on the inner edges of the LKr hole around the beam axis. An hadronic calorimeter made of two modules of iron-scintillator sandwiches (MUV1 and MUV2) provides further π^+-μ^+ separation. A fast scintillator array (MUV3) identifies and triggers muons with sub-nanosecond time resolution. A shashlik calorimeter (SAC) placed on the beam axis downstream of a dipole magnet bending off-axis the rest of beam particles, detects γs' down to zero angle. The downstream detectors are illuminated by particles produced in kaon decays and upstream beam activity, corresponding to less than 1% of the beam rate. A multi-level trigger architecture is used. Timing information from CHOD, RICH, MUV3 and calorimetric variables from electromagnetic and hadronic calorimeters are build up on FPGAs' memories mounted on the readout TEL62 boards [15] to issue level zero trigger conditions. Software-based variables from KTAG, CHOD, LAV and magnetic spectrometer provide higher level trigger requirements.

NA62 has commissioned the beam line, detectors, trigger and data acquisition systems in 2014 and 2015. The Gigatracker operated in 2015 with a partial hardware configuration and has been fully commissioned n 2016. Low intensity data using a minimum bias trigger configuration have been collected in 2015 both for detector performance studies and physics analysis. NA62 has taken data in 2016 for physics at intensities up to 50% of the nominal one.

In the following sections, results from the low intensity 2015 sample to exploit the data quality in view of the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ measurement is described. Physics analysis on both 2015 and 2016 data are on-going.

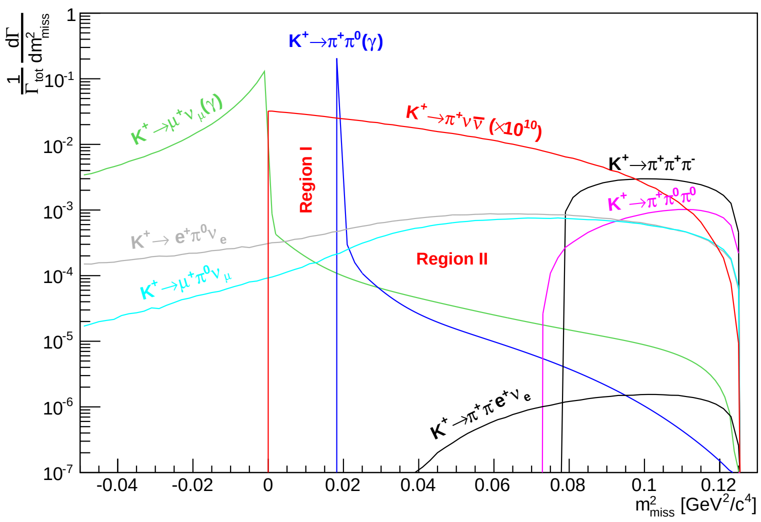

Figure 2. Theoretical m^2_{miss} distribution for signal and backgrounds from the main K^+ decay modes: the backgrounds are normalized according to their branching ratio; the signal is multiplied by a factor 10^{10}.

3. Principles of the Measurement

The signature of the signal is one track in Gigatracker compatible with a kaon hypothesis and one in the detector downstream. Kaon decays and beam−related activity are sources of background. Let P_K and P_{π^+} the 4-momenta of the kaon and the charged particles produced from kaon decay under the π^+ mass hypothesis, respectively. The squared missing mass distribution of the signal, $m^2_{miss} = (P_K - P_{\pi^+})^2$, has a three−body decay shape, while more than 90% of the charged kaon decays are mostly peaking, as shown in Figure 2. Signal is looked for in two signal regions around the $K^+ \to \pi^+\pi^0$ peak. Semileptonc decays, radiative processes, main kaon decay modes via reconstruction tails and beam induced tracks span across these regions. Therefore kinematic reconstruction, photon rejection, particle identification and sub-nanoseconds timing coincidences between subdetectors must be employed to get the final background rejection. A tight requirement on P_{π^+} between 15 and 35 GeV/c boosts the background suppression further, as will be shown in the next section. Monte Carlo studies performed in past years [14] have shown that NA62 can reach the goal, exploiting multiple and almost uncorrelated techniques to suppress the main background sources.

4. 2015 data quality analysis and prospects for the $K^+ \to \pi^+\nu\bar{\nu}$ measurement

The 2015 data offer the possibility to verify the detector performances in terms of timing, kinematic resolution, particle identification and γ rejection. To this purpose a single track selection has been set up as a preliminary step towards the $K^+ \to \pi^+\nu\bar{\nu}$ measurement.

Tracks reconstructed in the straw spectrometer matching in space energy depositions in calorimeters and signals in CHOD are selected. Matched CHOD signals define the time of the tracks with 200 ps resolution. A track not forming a common vertex within the decay region with any other in-time track defines a single track event. The last Gigatracker station and the first plane of the straw spectrometer bound the decay region. A vertex is defined as the average position of two tracks projected back in the decay region at the distance of closest (CDA) approach less than 1.5 cm. In order to select a single track event originated from kaon decays, a Gigatracker track is required to match the downstream track both in time and space,

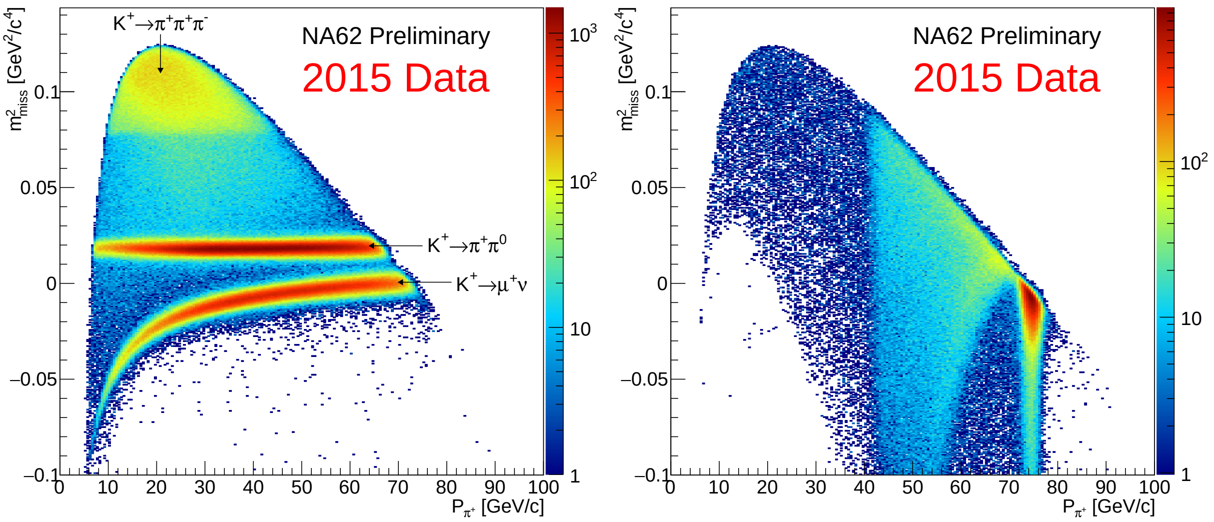

Figure 3. m^2_{miss} distribution under π^+ mass hypothesis as a function of the momentum of the track measured in the straw spectrometer after selection for single track from kaon decays (left). Same distribution as left-side picture, but asking for single track without a positive kaon tag in time in KTAG (right).

forming with it a vertex in the decay region, and to be in-time also with a kaon-like signal in KTAG. Figure 3 (left) shows the m^2_{miss} versus the spectrometer track momentum for 2015 data recorded at low intensity. The time resolutions of the KTAG and of a Gigatracker track has been measured in the range of 100 and 200 ps, respectively, matching the design values. The KTAG is also used in anti-coincidence with a Gigatracker track to select single track events not related to kaons (Figure 3 right). This technique shows that decay from beam π^+, elastic scattering of beam particles in the material along the beam line (KTAG and Gigatracker stations) and inelastic scatterings in the last Gigatracker station are the main sources of tracks downstream originated from beam−related activity. The sample of single track events from kaon decays selected above is used to study kinematic resolution, particle identification and γ rejection.

The resolution of the m^2_{miss} measured from the width of the $K^+ \to \pi^+\pi^0$ peak is in the range of 1.2×10^{-3} GeV$^2/c^4$, close to the 10^{-3} GeV$^2/c^4$ design value. The resolution is a factor 3 larger if the nominal kaon momentum is taken, instead of the event by event Gigatracker measured value. The tracking system of NA62 is also designed to provide a rejection factor in the range of $10^4 \div 10^5$ for $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$ using m^2_{miss} to separate signal from backgrounds, respectively. The $K^+ \to \pi^+\pi^0$ kinematic suppression is measured using a sub-sample of single track events from kaon decays selected by requiring the additional presence of two γs' compatible with a π^0 in the LKr calorimeter. This constraint defines a sample of $K^+ \to \pi^+\pi^0$ with negligible background even in the signal m^2_{miss} regions, allowing the study of the far tails of the m^2_{miss}. The measured $K^+ \to \pi^+\pi^0$ suppression factor is of the order of 10^3. The partial hardware Gigatracker arrangement used in 2015 mainly limits the suppression because of m^2_{miss} tails due to beam track mis-reconstruction.

The particle identification of NA62 is designed to separate π^+ from μ^+ and e^+ in order to guarantee at least 7 order of magnitude suppression of $K^+ \to \mu^+\nu$ in addition to the kinematic rejection. RICH and calorimeters are employed together to this purpose. The sample of $K^+ \to \pi^+\pi^0$ used for kinematic studies and a sample of $K^+ \to \mu^+\nu$ selected among single track events from kaon decays by asking for the presence of signals in MUV3, are used to study the π^+-μ^+ separation in the RICH. About 10^2 muon suppression for 80% π^+ efficiency is measured in a momentum region between 15 and 35 GeV/c. Above 35 GeV/c the separation degrades quickly as expected from the Cerenkov threshold curves for π^+ and μ^+ in Neon. The RICH provides also an even better separation between π^+ and e^+. The same π^+ and μ^+ samples allow the calorimetric muon-pion separation to be investigated. Simple cut and count analysis provide a muon suppression factor within $10^4 \div 10^6$ for a π^+ efficiency in a $90\% \div 50\%$ range. Several analysis techniques are under study to optimise the separation.

NA62 is designed to suppress $K^+ \to \pi^+\pi^0$ by 8 orders of magnitude by detecting at least one γ from π^0 decay in one of the electromagnetic calorimeters (LAV, LKr, IRC, SAC) spanning an angular region up to 50 mrad. The π^0 suppression profits from the angle-energy correlation of the two π^0 γs' and the cut at 35 GeV/c maximum π^+ momentum at analysis level. This allows the above suppression to be reached even in presence of a single γ detection inefficiency of 10^{-5} for γ above 10 GeV and even higher for γ of lower energy. The suppression of π^0 from $K^+ \to \pi^+\pi^0$ is measured on data looking at the scaling of the m^2_{miss} π^0 peak after applying conditions for γ rejection to the single track events from kaon decays selected above. The measured π^0 veto inefficiency on the 2015 data is statistically limited at 10^{-6} (90% CL) as an upper limit. The corresponding signal efficiency is above 90%, the losses being mainly due to π^+ interactions in the RICH material producing extra clusters in LKr.

To conclude, the preliminary analysis of the low intensity 2015 data shows that NA62 is approaching the design sensitivity for measuring $K^+ \to \pi^+\nu\bar{\nu}$.

5. NA62 Physics Program beyond $K^+ \to \pi^+\nu\bar{\nu}$

The performances of the apparatus allow physics opportunities beyond the $K^+ \to \pi^+\nu\bar{\nu}$ to be addressed. NA62 can significantly improve the existing limits on lepton flavour and number violating decays like $K^+ \to \pi^+\mu^\pm e^\mp$ or $K^+ \to \pi^- l^+ l^+$. Experimentally π^0 physics can take advantage of the performances of the electromagnetic calorimeters and processes like $\pi^0 \to invisible$ or dark photon production can be investigated. Thanks to the quality of the kinematic reconstruction, searches for heavy neutrino produced in $K^+ \to l^+\nu$ decays can improve the present sensitivity. The longitudinal scale of the apparatus opens the possibility to search for long−living particles through their decays, like 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 program simultaneously with the $K^+ \to \pi^+\nu\bar{\nu}$ program. The full exploitation of this physics will constitute the core of the NA62 program beyond 2018.

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