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Search for $K^+ \to \pi^+ \nu \bar{\nu}$ at NA62

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Abstract

Among the meson decays, $K \to \pi \nu \bar{\nu}$ are the cleanest environment, from the theoretical point of view, where to search for new physics effects. The NA62 Experiment at CERN SPS aims to measure the BR($K^+ \to \pi^+ \nu \bar{\nu}$) with a 10% precision by the end of 2018. It has been commissioned with technical runs in 2014 and 2015, and some preliminary results of the detector performances and quality of data are here reported.

Keywords: Rare Kaon Decays, Flavor Physics, CERN SPS

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1. Motivation for a measurement of BR($K \to \pi \nu \bar{\nu}$)

The decays $K_L \to \pi^0 \nu \bar{\nu}$ and $K^+ \to \pi^+ \nu \bar{\nu}$ proceed through box and penguin diagrams and are mediated by Flavor Changing Neutral Currents (FCNC). As such they are are suppressed by the SM and therefore their study is useful not only to determine CMK matrix elements, but also in the investigation of new physics effects. Among the FCNC mediated decays, they are the cleanest environment, in the theoretical context, to search for new physics. Indeed the GIM mechanism implies a large suppression of the light quarks, u and c, and

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the quark level amplitude is dominated by the top quark term. This effect is summarized by stating that the decay is dominated by *short distance* contribution and implies that SM theoretical uncertainties are very low. By using the experimental value for the CKM input, the theoretical SM values are

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11} \tag{1}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11} \tag{2}$$

while, if the CKM parameters are taken to be exact, the two SM BRs above become

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (9.1 \pm 0.7) \times 10^{-11} \tag{3}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11} \tag{4}$$

[1][2]. Beyond standard model scenarios with new sources of flavor violations foresee large deviation from such SM values [4][3], making these decays a appealing probe of new physics. The only measurement of $BR(K^+ \to \pi^+ \nu\bar{\nu})$ has been obtained by E787 and E949 experiments and is

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10} \tag{5}$$

[5], while for the neutral channel only an upper limit has been set by the E391 experiment [6] :

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-8} (90\%) C.L. \tag{6}$$

. It is clear that new and more precise measurements are needed to test the SM.

2. The NA62 Experiment at CERN SPS

The main purpose of the NA62 experiment [7] at CERN is to measure $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$ at least at the 10% precision level. In order to get to this target, the number of selected events should be at least 100, the background yield should be at most 20% and it should be measured with a 10% precision. Assuming a 10% signal acceptance, the kaon flux should correspond to at least 10^{13} K^+ decays in the fiducial volume. Since the experiment is expected to run for about two years the design rate is 750 MHz. The Kaon beam is obtained from the Super Proton Sinchrotron (SPS) at CERN. A 400 GeV proton beam, delivered by the SPS with 10^{12} protons per second impinges a thick (40 cm) beryllium target and produces a beam composed for the most of π^+ (70%) and protons (23%), while the K^+ are only 6%. The collimators and achromat system selects 75 GeV positively charged particles with a momentum spread of $\sigma(p)/p \sim 1\%$ within a polar angle of 100 μrad.

3. Measurement strategy

The measurement strategy consists in detecting and matching the kaon and pion tracks and employs mainly the *squared missing mass* variable, defined as $m^2_{miss} = (p_{K^+} - p_{\pi^+})^2$, where p_{K^+} and p_{π^+} are 4-momenta. The theoretical prediction of the m^2_{miss} distribution, for the main background processes and for the signal times 10^{10}, is shown in Fig.1. Two signal regions are defined by the two important background contributions: $K^+ \to \mu^+ \nu_\mu(\gamma)$ and $K^+ \to \pi^+ \pi^0(\gamma)$. Tab.1 reports the branching ratio of the main Kaon decays. The goal to keep the background as ow as the 20% can be reached if the main decay channel events are reduced to the numbers reported in Tab.2. That can be obtained only if excellent event kinematic reconstruction, particle identification, time resolution and hermetic photon and muon vetoes are achieved. By taking into account such requirements, the NA62 detector has been built.

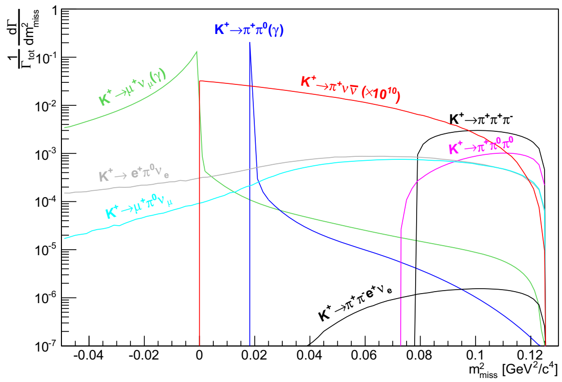

Figure 1: Theoretical predictions for the m^2_{miss} distribution, for the main background and the signal times 10^{10}.

Table 1: BR of the main background kaon decays.

Decay	BR
$K^+ \to \mu^+ \nu_\mu(\gamma)$	63%
$K^+ \to \pi^+ \pi^0(\gamma)$	21%
$K^+ \to \pi^+ \pi^+ \pi^-$	6%
$K^+ \to \pi^+ \pi^0 \pi^0$	2%
$K^+ \to \pi^0 e^+ \nu_e$	5%
$K^+ \to \pi^0 \mu^+ \nu_\mu$	3%

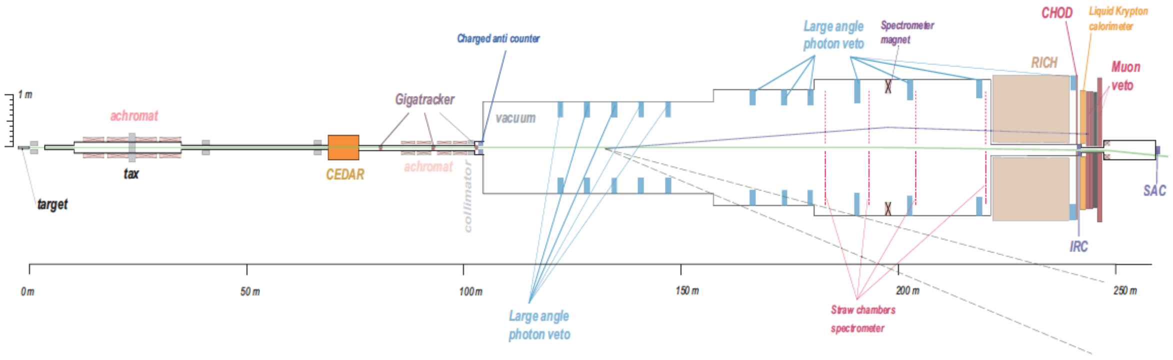

Figure 2: Drawing of the NA62 apparatus at SPS.

Table 2: Design expected number of events per years for the main kaon decays.

Decay mode	event/year
SM $K^+ \to \pi^+ \nu \bar{\nu}$	45
Total Bkg	10
$K^+ \to \pi^+ \pi^0$	5
$K^+ \to \pi^+ \pi^0 \gamma^{IB}$	1.5
$K^+ \to \mu^+ \nu_\mu$	1
$K^+ \to \pi^+ \pi^+ \pi^-$	< 1
$K^+ \to \pi^+ \pi^- e^+ \nu$	< 1
$K^+ \to \mu^+ \nu_\mu \gamma^{IB}$	0.5
$K^+ \to \pi^0 e^+ (\mu^+) \nu$	negligible

4. The NA62 apparatus

A sketch of the NA62 apparatus is shown in Fig.2. In order to reduce the beam background a kaon identification detector is needed: the KTAG is a Cherenkov counter filled by N_2 with an efficiency greater than 95%, and a time resolution better than 100 ps. The Kaon momentum and direction measurements are performed by a Kaon spectrometer, the Gigatracker (GTK). That is composed of three stations, each one made of 200 μm (0.5 X_0) thick silicon sensors with a momentum resolution of 0.2% and operates at a 750 MHz rate. The inelastic interactions in the GTK, are detected by a veto detector designed on purpose: the CHANTI. The momentum and direction measurements of the charged decay products are measured by the STRAW spectrometer, with a relative momentum resolution of $\sigma_p/p = 0.32\% \oplus 0.008\% p$ (GeV/c). One of the main background is the decay $K^+ \to \pi^+\pi^0$ and requires an hermetic photon veto system composed by the following subdetectors.

The Small Angle Calorimeter (SAC) and Inner Ring Calorimeter (IRC) provide an effective photon veto in the angular range < 1 mrad. Both detectors have lead and scintillator plates arranged using Shashlyk configuration. The Liquid Krypton electromagnetic calorimeter (LKr), used in the NA48/2 experiment, covers the range between 1 and 8.5 mrad. It is a quasi-homogenous ionization chamber $26X_0$ deep, that allows to measure the full electromagnetic shower and hence to have an extra particle identification. Twelve stations of Large Angle Veto (LAV) cover the angular range between 8 and 50 mrad. Stations are made of lead-glass blocks and have an inefficiency $\sim 10^4$ for photons with $E > 0.5$ GeV. Another important background is $K^+ \to \mu\nu_\mu$, therefore a muon veto system is necessary. Two modules of iron-scintillator sandwiches (MUV1 and MUV2) constitute a hadronic calorimeter which triggers on hadron deposits and a fast scintillator array (MUV3) identifies and triggers muons. The identification of the charged secondary particles, pions and muons, is performed by the hadronic calorimeters (MUV1 and MUV2) and the Ring Imaging CHerenkov (RICH) detector. The RICH detector provides a pion identification efficiency of 90% and a muon misidentification at most of 1% in the momentum range [15,35] GeV/c. It is used also as Level 0 trigger with a time resolution lower than 100 ps. FPGAs memories, mounted on the readout TEL62 boards [8], collect data from CHOD, RICH and MUV3 detectors which provide the Level-0 trigger information which is aimed to reduce the rate from 10 MHz to 1 MHz. The higher level trigger requirements employ variables computed at software level, using information from KTAG, LAV and STRAW and bring the rate as down as 20 kHz. During few months in 2014 and the full 2015 the NA62 experiment collected data in the socalled *technical runs*, during which the detector performances and the quality of data were checked. That is described in the next section. At the end of 2015 the status of the apparatus was the following. The beamline has been commissioned till the nominal intensity, the GTK was partially commissioned while the KTAG, STRAW, MUVs, RICH, photon veto system were fully operational. The Level-0 trigger was commissioned and the software level trigger was partially commissioned.

5. Quality of data in the pilot runs

Data samples collected at low intensity have been used to check the quality of the data and the performances of the subdetectors. In the following, some results obtained with about 1% of the nominal intensity are reported. The sample was selected to be similar to the one which will be used for the measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$). The aim is to select events with only one downstream track: (*single-track events*). The KTAG and GTK select events in which such single track arises from a K^+ decay, their time resolution have been measured to be less than 100 ps for the KTAG and 200 ps for the GTK, reaching the expectations. The downstream tracks are detected by the STRAW spectrometer and matched to energy deposits in the LKr and in the CHOD, which defines the time. Furthermore it is associated to the upstream GTK track in time and space, form a vertex with it in the decay region and in time with the KTAG signal. If in one event, there is a track selected in this way and not forming a vertex with any other selected track, that event is defined as single-track event. The m^2_{miss} resolution is greatly reduced by using the kaon kinematic measured by the GTK. Figure 3 compares the resolution obtained when the nominal values for the kaon beam are used with the one obtained using the information from the GTK as a function of the pion momentum; it clearly shows the improvement and how it approaches the design values. Fig.4 shows the m^2_{miss} versus the downstream track momentum for these selected single-track events. Instead, by requiring that the downstream track is not in time with any KTAG candidate, the scatter plot in Fig. 5 is obtained. It gives useful information about the composition of the beam background: the downstream tracks arise from π^+s from the beam, or from elastic and inelastic scattering of beam particles with the material of the beam line elements. Fig.6 shows the radius of the RICH ring spatially and timely matched to a STRAW track, versus the momentum measured by the STRAW. The contribution of different particles is clearly visible. In order to study the π/μ separation in the RICH, two samples with $15 < p < 35$ GeV/c and dominated by respectively by $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu_\mu$ were selected by exploiting kinematics and MUV3 calorimetric informations. From a preliminary analysis a pion efficiency of ~ 80% corresponds to a muon suppression factor of 10^2, close to the design target and improved in 2016 run. An additional contribution to the π/μ separation will be provided by the calorimeters, whose identification performances are currently being analysed.

The most important background is the decay $K^+ \to \pi^+\pi^0$. The rejection of such kind of events is implemented by requesting at least a photon in one of the electromagnetic calorimeters, LAV, LKr, IRC and SAC. The target of a 10^8 suppression factor, is fulfilled by asking that the photon detection has an inefficiency lower than

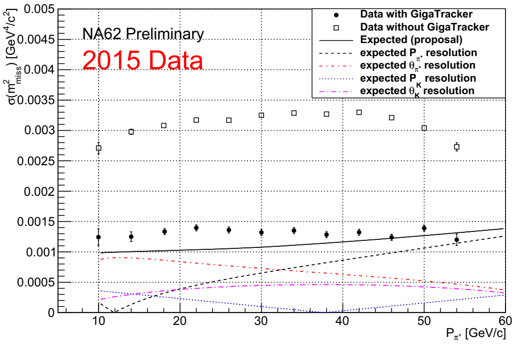

Figure 3: Resolution of the m^2_{miss} as a function of the downstream track momentum.

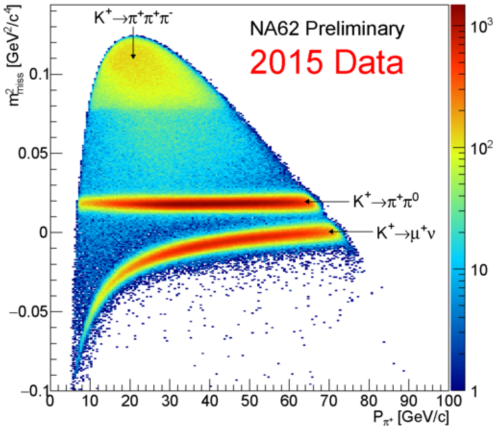

Figure 4: m^2_{miss} versus the momentum of the downstream track in single-track events.

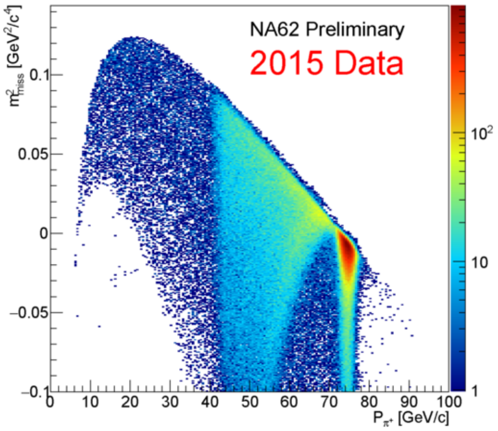

Figure 5: m^2_{miss} versus the momentum of the downstream track in single-track events with no KTAG signals in coincidence.

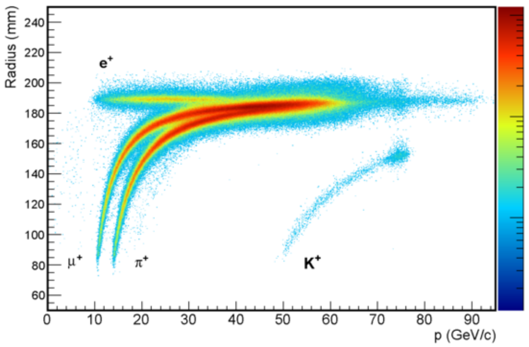

Figure 6: RICH ring radius versus momentum track as measured by the STRAW.

10^{-5} for energy greater than 10 GeV. Figure 7 shows the inefficiency for the detection of π^0 when the only LKr calorimeter is used, when LKr and LAV are used and when the full photon veto system is employed. The sample is obtained with the single-track selection and particle identification. The measurement of the efficiency with 2015 data results in less than 10^{-6} at 90% C.L. but it is statistically limited. New measurements are ongoing with 2016 data. The signal efficiency has been measured by considering a sample of muons from $K^+ \to \mu^+\nu_\mu$ and a sample of π^+ with momentum of 75 GeV/c arising from the beam elastic scattering upstream. It is about 90%.

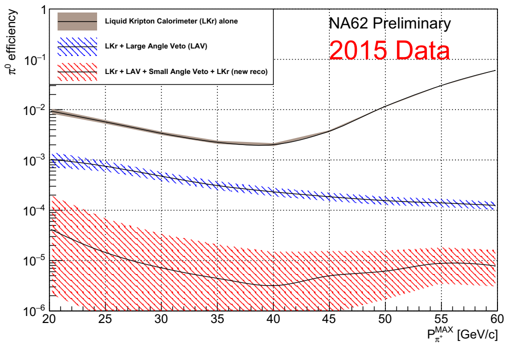

Figure 7: π^0 efficiency as a function of π^+ momentum for different composition of the γ veto system.

6. Conclusions and outlook

The 2016 run is ongoing and preliminary data analysis of the detector performances confirm the expectations anticipated in 2015. In particular, the calorimetric L0 trigger, designed for $K^+ \to \pi^+\nu\bar{\nu}$ is operational, the beam intensity is currently stable at 20%, the GTK is running with its complete configuration, the RICH underwent some hardware improvements and, from preliminary studies, reached its design performances. The experiment will run till the end of 2018 and is expected to collect about 100 SM signal events. It is well on track to reach the aimed precision for the main measurement, and besides that a wide physics program is foreseen, with measurements of interest both within SM and beyond SM contexts, improving the existent measurements and limits.

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