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NA62 and KLEVER: Test of the standard model in ultra rare decays of kaon mesons

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Summary. — Among the kaon decays, $K \to \pi\nu\bar{\nu}$ are the cleanest environment 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 in the next three years. It has been commissioned with technical runs in 2014 and 2015 and some preliminary measurements of the detector performances are here reported. A feasibility study for a new experiment, planned to start in 2026 with the same NA62 infrastructure and aimed to measure BR($K_L \to \pi^0\nu\bar{\nu}$), has started and some preliminary considerations are here presented as well.

1. – $K \to \pi\nu\bar{\nu}$ at SPS at CERN

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) and, as such, are suppressed in the SM. Therefore their study is useful not only to determine CKM matrix elements, but also in the investigation of new physics effects. Among the FCNC mediated meson decays, they are the cleanest environment to search for new physics. Indeed the GIM mechanism implies a large suppression of the light quarks (u and c) exchange and 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. The theoretical SM values are BR($K^+ \to \pi^+\nu\bar{\nu}$) $= (8.4 \pm 1.0) \times 10^{-11}$ and BR($K_L \to \pi^0\nu\bar{\nu}$) $= (3.4 \pm 0.6) \times 10^{-11}$ [1]. The only measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$) has been obtained by E787 and E949 experiments and is BR($K^+ \to \pi^+\nu\bar{\nu}$) $= 1.73^{+1.15}_{-1.05} \times 10^{-10}$ [2], while for the neutral channel only an upper limit has been set by the E391 experiment [3] : BR($K_L \to \pi^0\nu\bar{\nu}$) $< 2.6 \times 10^{-8}$(90%) CL. New and more precise measurements are needed to test the SM. The charged channel BR

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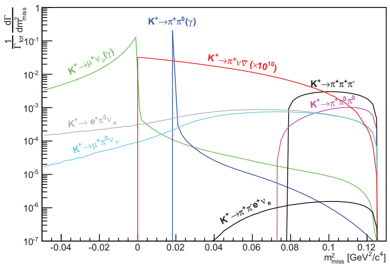

Fig. 1. – Theoretical distributions of the signal and main background processes.

will be measured by the NA62 Experiment, currently running at CERN Super Proton Synchrotron (SPS), which will be described in sect. **2**. It is important to measure also the neutral channel, which has even lower theoretical uncertainties due to less relevant light quark contribution, because different new physics models affect the rates for each channel differently. In sect. **3** a plan for the measurement of BR($K_L \to \pi^0 \nu \bar{\nu}$) at SPS is presented.

2. – Measurement of BR($K^+ \to \pi^+ \nu \bar{\nu}$) with NA62

The main purpose of the NA62 experiment [4] at CERN is to measure BR($K^+ \to \pi^+ \nu \bar{\nu}$) at least at the 10% precision level. The high momentum kaon beam ($\sim 75\,\mathrm{GeV}/c$) is obtained by making a 400 GeV proton beam, delivered by the SPS, impinging on a thick beryllium target. The experiment is expected to collect about 100 SM signal events and therefore, assuming a 10% signal acceptance, the kaon flux should correspond to at least 10^{13} K^+ decays in the fiducial volume. The background is constituted by the main K^+ decays. In particular, the dominant ones are $K^+ \to \mu^+ \nu_\mu$, $K^+ \to \pi^+ \pi^0$, $K^+ \to \pi^+ \pi^+ \pi^-$, $K^+ \to \pi^+ \pi^0 \pi^0$. The analysis strategy consists in detecting and matching the kaon and pion tracks and for the candidate event selection relies mainly on *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 main background processes is shown in fig. 1. Two signal regions are defined by the two important background contributions $K^+ \to \mu^+ \nu_\mu (\gamma)$ and $K^+ \to \pi^+ \pi^0 (\gamma)$. In order to achieve the desired precision, a background rejection factor of the order of 10^{-12} is required and needs to be measured with a precision of 10%. Such performance can be obtained only if excellent event kinematic reconstruction, particle identification and time resolution are achieved. Moreover hermetic photon and muon vetoes are needed. The required features led to the design and construction of the NA62 detector, whose schematic layout is shown in fig. 2. The beam is composed mostly by pions and protons, with only 6% of the beam's particles being K^+. In order to reduce the beam background a kaon identification detector is needed: the KTAG is a Cherenkov counter filled with N_2, it has 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. The inelastic interactions in the GTK are detected by a guard ring of scintillators, the CHANTI. The momentum and direction measurements of the charged decay products are measured by the STRAW spectrometer, which is required to have a relative momentum resolution of $\sigma_p/p = 0.32\% \oplus 0.008\% p\,(\mathrm{GeV}/c)$. The charged decay

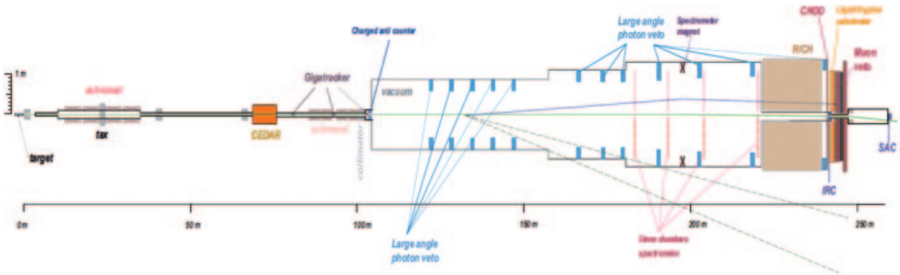

Fig. 2. – Schematic view of the NA62 detector layout.

products are timed with a 200 ps resolution by a fast array of scintillators, the *Charged HODoscope* (CHOD). The identification of the charged secondary particles is performed by the Ring Imaging CHerenkov (RICH) detector, which 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, and should have time resolution less than 100 ps. One of the most important backgrounds is the decay $K \to \pi^0\pi^0$ which 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 constitute a hadronic calorimeter which triggers on hadron deposits and a fast scintillator array (MUV3) identifies and triggers muons. NA62 has taken data in 2014 and 2015, these preliminary runs were aimed to test the beam line and to check the reliability of the hardware and readout of the detectors. In 2015 the beam intensity has been varied in a wide range. Data samples collected at low intensity have been used to check the quality of the data and the performance of the subdetectors. 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 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. Figure 3 (left) plots the quantity m^2_{miss} *versus* the spectrometer track momentum for events selected in such a way. By using the GTK information the m^2_{miss} resolution is measured to be 1.2×10^{-3} GeV$^2/c^4$ (very close to the design value), a factor 3 lower than the one obtained with the nominal kaon beam kinematics. Figure 3 (right) shows the radius of the RICH ring spatially and timely matched to a STRAW track, *vs.* 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

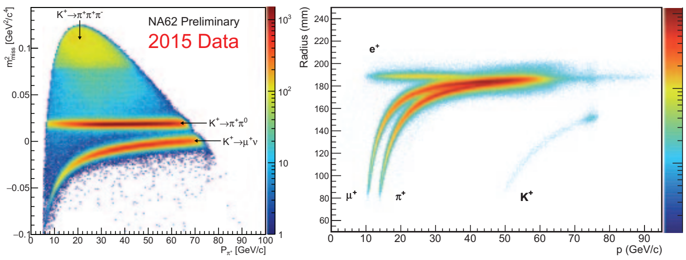

Fig. 3. – Right: m^2_{miss} *versus* momentum of the single track in kaon decay selection. Left: RICH ring radius *versus* momentum measured by the STRAW.

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 $\sim 80\%$ corresponds to a muon suppression factor of 10^2, close to the design target and improved in 2016 run. The rejection of the $K^+ \to \pi^+\pi^0$ events is implemented by requiring at least a photon in one of the electromagnetic calorimeters, LAV, LKr, IRC and SAC. The inefficiency of π^0 detection should be 10^{-8} by design, while the measurement with 2015 data results in a 90% CL upper limit of 10^{-6}, 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%.

3. – Plans for a measurement of BR($K_L \to \pi^0\nu\bar{\nu}$) at SPS

We are investigating the feasibility of performing a measurement of BR($K_L \to \pi^0\nu\bar{\nu}$) using a high-energy secondary neutral beam at the CERN SPS in a successor experiment to NA62. The planned experiment would reuse the NA48 liquid-krypton calorimeter and some of the NA62 infrastructure; the measurement technique is complementary to the upgrade of KOTO experiment at J-PARC [5] and would provide comparable sensitivity. The timescale for research and development, construction, and commissioning of the new experiment would require many years; we assume that the experiment would be ready at the start of LHC Run 4 (early 2026). As in NA62, the proposed experiment makes use of a 400 GeV primary proton beam interacting on a 400 mm beryllium rod target. It impinges the target with an angle of 2.4 mrad, which optimizes the K_L to neutron and photon flux ratios according to parameterization in [6] and FLUKA simulation. The beam line has been designed to have a system of three collimators and an absorber to reduce the huge rate of photons. The secondary beam polar angle acceptance is 0.3 mrad and contains about $2.8 \times 10^{-5} K_L$'s per proton incident on the target (*pot*). The K_L momentum distribution peaks around 35 GeV/c and has a mean at about 97 GeV/c There will be $6.3 \times 10^{-7} K_L$ decays in the fiducial volume per pot. Assuming the Standard-Model value of BR($K_L \to \pi^0\nu\bar{\nu}$) and an acceptance fraction of 10%, for the experiment to observe 100 signal events, about $3 \times 10^{13} K_L$'s must decay in the fiducial volume. Thus, an integrated proton flux of 5×10^{19} pot is required, which we assume is delivered at a rate of 10^{19} pot/yr over the course of five years. This intensity is 6 times larger than the current NA62 one, therefore a extensive upgrades to the beam line cavern will be needed. Beside the NA48 LKr calorimeter, the experiment will be composed by a system of photon veto detectors, a sketch is shown in fig. 4. Unlike the charged channel, the K_L momentum is broadly distributed, and a much larger fraction of background photons are emitted at large polar

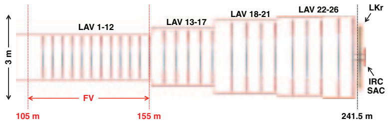

Fig. 4. – Schematic layout of neutral beamline.

angle. The photon veto system is required to cover a polar angle up to 100 mrad and to be highly efficient down to 100 MeV. These requirements are not satisfied by the NA62 LAV, and we plan to construct 26 new large angle veto with a different geometry. One possible design for the LAVs for the proposed experiment would be similar to the Vacuum Veto System detectors planned for the CKM experiment at Fermilab [7]. One of the most difficult challenge of the experiment will be the design of detectors for photons at small polar angle, where the beam neutron and photon fluxes are very high. The veto is needed down to 0.4 mrad and must intercept also photons from K_L passing through the beam pipe. According to a preliminary FLUKA and GEANT4 simulation of the beam line, the beam contains 3 GHz of neutrons and 700 MHz of photons to which the detector should be insensitive. The design studies for such veto detector are ongoing. Furthermore an Intermediate Ring Calorimeter (IRC) should not intercept the beam but should cover the LKr bore to detect photons from downstream decays. A fast simulation study has been performed in order to estimate the most important background from K_L decays, which is $K_L \to \pi^0\pi^0$. Events are selected if there are exactly two hits in the LKr and no hits on any of the veto detectors. By imposing the π^0 mass, the invariant mass of the two photons is used to get the z position of the π^0 vertex (z_{vtx}). The z_{vtx} is required to be in the fiducial volume, in the range (105,155) m, a distance between the clusters should be greater than 35 cm and the transverse momentum of the two photons system $p_T(\gamma\gamma) > 0.12$ GeV. Out of 9.6×10^8 generated signal events, 1.9×10^6 are selected, while out of 1.2×10^{12} generated $K_L \to \pi^0\pi^0$, 85 are selected. That corresponds to 19 signal events and 17 $K_L \to \pi^0\pi^0$ background events in one year of data taking. The $K_L \to \pi^0\pi^0$ sample, is composed of events in which the two clusters come from two γ's from the same π^0 (51%), events in which the two clusters are from two γ's from different π^0's (14%), and events in which at least one of the two clusters is a fused cluster from two or more γ's (35%). By taking into account that the K_L beam is reduced of about 35% by the absorber in the beam line, in five years of data taking the expected SM signal events are 60 and a signal over background ratio of 1. Although some aspects of the experiment need further study and a better optimization, from these preliminary studies we can conclude that a measurement of $K^+ \to \pi^+\nu\bar{\nu}$ at CERN SPS is feasible with no major change in the NA62 infrastructure.

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