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The NA62 experiment

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Summary. — We discuss the NA62 experiment which aims at the search for phenomena beyond the Standard Model (SM) by measuring the ratio $R_K = \Gamma(K^\pm \to e^\pm\nu(\gamma))/\Gamma(K^\pm \to \mu^\pm\nu(\gamma))$ and the ultra rare decay $K^+ \to \pi^+\nu\bar{\nu}$. First, we summarize the status of the R_K analysis, based on $\sim 40\%$ of the 2007-2008 NA62 data set, then, we describe the NA62 proposal to measure the branching ratio of the very rare decay $K^+ \to \pi^+\nu\bar{\nu}$ and we give an update on the status of the detectors needed to perform the measurement.

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1. – Introduction

The information coming from the rare kaon decays is a key element to understand the flavor structure of possible physics beyond the SM. In this perspective, the decay modes which are interesting to measure are the leptonic decay $K \to l\nu$ (K_{l2}) and the flavor-changing neutral-current process $K \to \pi\nu\bar{\nu}$. Due to the uncertainties on non-perturbative quantities like f_K (the decay constant of K-mesons), we cannot fully exploit the leptonic decay K_{l2} in constraining new physics, in spite of the fact that it is possible to obtain non-SM contributions which exceed the high experimental precision which has been achieved on this mode. On the other hand, when considering the ratio R_K of the electronic and muonic decay modes, the hadronic uncertainties cancel to a very large extent. As a result, the SM prediction of R_K is known with excellent acccuracy [1]:

$$R_K^{\mathrm{SM}} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_{\mathrm{QED}}) = (2.477 \pm 0.001) \times 10^{-5},$$

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where $\delta R_{\mathrm{QED}} = (3.78 \pm 0.04)\%$ is a correction due to the inner bremsstrahlung (IB) part of the radiative $K_{e2\gamma}$ process. By definition, the IB part is included in R_K, while the structure-dependent (SD) part is not. The factor $(m_e/m_\mu)^2$ accounts for the helicity suppression of the $K^\pm \to e^\pm \nu$ mode.

The current PDG average, $R_K^{\mathrm{PDG}} = (2.35 \pm 0.11) \cdot 10^{-5}$, is based on the results of three experiments from the 1970's. The recent preliminary results from NA48/2 [2] and KLOE [3] experiments lead to 1% precision.

Enhancement of R_K by a few percent is quite possible in minimal supersymmetric extensions of the SM, and it is expected to be dominated by the lepton flavor-violating contributions with the emission of the tau neutrino [4]:

$$R_K^{\mathrm{LFV}} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \cong \frac{\Gamma_{\mathrm{SM}}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{\mathrm{SM}}(K \to \mu\nu_\mu)}, \quad i = e, \mu, \tau.$$

In the large $\tan\beta$ regime ($\tan\beta = 40$) and with a relatively heavy $H^\pm$ ($M_H = 500\,\mathrm{GeV}/c^2$), $R_K^{\mathrm{LFV}} \simeq R_K^{\mathrm{SM}}(1 + 0.013)$.

The unique feature of the rare decays $K \to \pi\nu\overline{\nu}$ is that their SM branching ratios can be computed to an exceptionally high degree of precision. These transitions are described, indeed, by Z^0-penguin and box diagrams mediated by $\mathcal{O}(G_F^2)$ interactions where a power-like GIM mechanism suppresses the non-perturbative effects. A related feature is that these decays are mediated by one single effective operator, whose hadronic matrix elements can be extracted from the well-measured $K \to \pi e\nu$ decay rates. The recent SM prediction reads [5]

$$\mathrm{BR}(K^+ \to \pi^+\nu\overline{\nu}) = (0.85 \pm 0.07) \times 10^{-10}, \qquad \mathrm{BR}(K_L \to \pi^0\nu\overline{\nu}) = (2.76 \pm 0.40) \times 10^{-11}.$$

The precision of the theoretical predictions contrasts with the large uncertainties affecting the current experimental results [6, 7]:

$$\mathrm{BR}(K^+ \to \pi^+\nu\overline{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}, \qquad \mathrm{BR}(K_L^0 \to \pi^0\nu\overline{\nu}) \leq 6.7 \cdot 10^{-8}\ 90\%\,\mathrm{CL}.$$

The clean theoretical character of $K \to \pi\nu\overline{\nu}$ decays remains valid in all realistic extensions of the SM. As a result, precise measurements of $\mathrm{BR}(K \to \pi\nu\overline{\nu})$ provide unique and clean information about the flavor structure of any extension of the SM.

2. – The NA62 experiment

The NA62 experiment is a fixed target experiment at the Super Proton Syncrotron (SPS) of CERN which inherits from the experience, the infrastructure and some of the detectors of the NA48s experiments. Two phases can be distinguished for the NA62 experiment. In the first one, the aim is the R_K measurement with an accuracy better than 0.4% on data collected during 2007 and 2008. The second is the $K^+ \to \pi^+\nu\overline{\nu}$ measurement with a 10% accuracy.

3. – The R_K measurement

NA62 collected almost $160 \cdot 10^3$ K_{e2} candidates during four months of data taking in 2007 and additional two weeks in 2008. To improve the $K_{e2}/K_{\mu 2}$ separation, a kaon beam with a $75\,\mathrm{GeV}/c$ central momentum and a narrow momentum band ($\Delta(p)/p = 2\%$)

was used. The K_{e2} decay signature consists of a single reconstructed track, thus the background in the K_{e2} sample induced by the beam halo becomes an important issue. Since the beam halo background was much higher for K_{e2}^- ($\sim 20\%$) than for K_{e2}^+ ($\sim 1\%$), most of the data sample ($\sim 90\%$) was taken with K^+ beam only and about 10% with K^- beam only. K_{e2} and $K_{\mu 2}$ were collected simultaneously so that the results do not depend on the kaon flux measurement and many systematic effects cancel at first order. Detailed Monte Carlo (MC) simulations have been developed, however, they are used only to evaluate the geometric acceptance corrections and the "energetic" bremsstrahlung events for muons as discussed below. R_K is computed in bins of the reconstructed momentum of the charged track.

The following subdetectors, located downstream a vacuum decay volume, are relevant for the R_K measurement:

- A magnetic spectrometer composed of four drift chambers (DCHs) and a spectrometer magnet used to measure the momenta of the charged particles. Each chamber has four views. The resolution of the track momentum is $\sigma(p)/p = (0.47 \oplus 0.02\, p)\%$ (p in GeV/c).
- A plastic scintillator hodoscope (HOD) with good time resolution ($\sigma(t) \sim 200\,\text{ps}$) used to produce fast trigger signals.
- A liquid-krypton electromagnetic calorimeter (LKr) used for gamma detection and particle identification. It is an almost homogeneous ionization chamber with high granularity. The energy resolution is $\sigma(E)/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV).

3˙1. *Event selection.* – Due to the topological similarity of K_{e2} and $K_{\mu 2}$ decays, a large part of the selection conditions is common for both channels, which leads to cancellations of systematic uncertainties in R_K. We require:

- only one charged particle track reconstructed by the spectrometer within the geometrical acceptance with a momentum between 15 and 65 GeV/c and a good reconstructed vertex;
- no cluster in the LKr associated to a track with an energy $> 2\,\text{GeV}$.

To separate K_{e2} from $K_{\mu 2}$ decays, we use

- Particle identification based on the ratio of the track energy deposit in the LKr to its momentum measured by the spectrometer (E/p). Particles with E/p between 0.95 and 1.1 are identified as electron, particles with E/p less than 0.2 are identified as muon.
- Kinematical identification of K_{e2} and $K_{\mu 2}$ based on the reconstruction of the squared missing mass, $m^2_{\text{miss}} = (p_K - p_l)^2$, assuming the track to be an electron or a muon. A sufficient kinematical separation of K_{e2} and $K_{\mu 2}$ decays in the region of high lepton momentum ($p > 30\,\text{GeV}/c$) is not achievable.

3˙2. *Background.* – In very rare cases a muon can deposit over $\sim 95\%$ of its energy in the LKr calorimeter by "energetic" bremsstrahlung events, faking an electron. The probability of such an event in the NA62 experimental conditions is $\sim 3 \times 10^{-6}$. However, due to the helicity suppression of the electron channel, the background in the

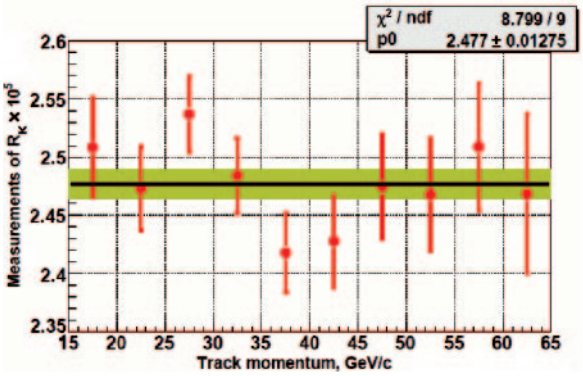

Fig. 1. – Ten independent measurements of R_K in bins of track momentum. An overall offset is applied to hide the result. Uncertainties due to $K_{e2\gamma}$ background correlated between momentum bins are excluded.

K_{e2} sample originating from the $K_{\mu2}$ decays amounts to several percent and is one of the central issues of the analysis. We perform a direct measurement of this probability to validate in the highly energetic muon range the theoretical computation of the bremsstrahlung cross-section which is used to evaluate the $K_{\mu2}$ background. To collect pure muon sample and avoid the electron contamination from muon decays, a lead wall was installed between the hodoscope planes during certain periods of data taking. The measured momentum dependence of the probability is in excellent agreement with the results obtained from simulation. The simulation also demonstrates that the presence of the lead wall significantly modifies the probability. The preliminary result for the background contamination is $(8.07 \pm 0.21)\%$. The uncertainty is due to the limited size of the data sample used to validate the MC simulation with the lead wall setup. Analysis with additional muon samples collected in 2008 is expected to improve the precision of the estimation.

By definition, another background source for the K_{e2} decay is the SD radiative $K_{e2\gamma}$ decay. In this case the background contamination is evaluated by using MC simulation and the uncertainty is due to the limited experimental and theoretical knowledge of the process. Fortunately, the relevant $K_{e2\gamma}$ kinematic region is accessible for a model-independent branching ratio measurement. Such a measurement, based on the NA62 2007 data sample, has started and is expected to improve the corresponding systematic uncertainty on R_K.

The background contamination in the K_{e2} sample induced by beam halo muons decaying to electrons kinematically and geometrically compatible to a K_{e2} decay is directly measured with the 2007 K^- only sample to be $(1.23 \pm 0.07)\%$. An additional K^- only sample collected in 2008, which is half the size of the 2007 one, will allow a further improvement of the uncertainty. Beam halo contamination in the $K_{\mu2}$ sample is measured to be 0.14% with the same technique as for the K_{e2} decay. Other minor background contributions to the $K^\pm \to e^\pm\nu$ decay ($\sim 0.1\%$) are due to $K^+ \to \pi^0 e^+ \nu$ and $K^+ \to \pi^+\pi^0$ decays.

3˙3. *Analysis summary and prospects.* – The independent measurements of R_K in track momentum bins performed on $\sim 40\%$ of the whole data sample are presented in fig. 1 with an overall offset artificially applied to set the result of the fit to the SM expectation. The

TABLE I. – *Summary of the main uncertainties on the R_K measurement.*

Source	$\delta R_K/R_K$
Statistical	0.43%
$K_{\mu 2}$	0.25%
K_{e2}	0.32%
Beam halo	0.10%
Total	$\sim$ 0.60%

stability of R_K over momentum bins points to a good control over the main systematic effects. The statistical and the systematic uncertainties are listed in table I. The whole data sample of $160 \cdot 10^3$ K_{e2} candidates will allow pushing the statistical uncertainty below the 0.3% level and the ultimate precision of the measurement is expected to reach 0.4%, as declared in the proposal [8].

4. – The $K^+ \to \pi^+\nu\overline{\nu}$ measurement

The NA62 Collaboration has proposed [9] to measure the branching ratio of the very rare decay $K^+ \to \pi^+\nu\overline{\nu}$. The aim is to observe $\sim$ 100 signal events in two years of data taking with a background-to-signal ratio smaller than 10%. To have a larger signal acceptance (10%), we propose to study the reaction in flight.

4˙1. *Kinematics and backgrounds.* – The signature of the $K^+ \to \pi^+\nu\overline{\nu}$ event is only one track in the final state and anything else. The main background sources are the $K^+ \to \mu^+\nu$ (63.5%) and the $K^+ \to \pi^+\pi^0$ (20.9%) decays.

Background events rejection relies on:

– precise timing to associate the outgoing π^+ to the correct incoming K^+,

– kinematic rejection of backgrounds induced by two- and three-body kaon decays,

– μ and γ veto,

– particle identification (K^+/π^+ and π^+/μ^+).

4˙2. *Detector layout.* – The detector layout is shown in fig. 2. A 75 GeV/c unseparated hadron beam with an instantaneous rate of $\sim$ 800 MHz and a kaon fraction of $\sim$ 6% enters the decay tank. Particle identification of the beam particles is provided by a differential Čerenkov counter (CEDAR). The timing, tracking and momentum measurement of the beam particles is provided by silicon micro-pixel detectors (GTK) placed in a four-dipole magnetic achromat. The decay tank is surrounded by twelve stations of photon anti-counters (ANTI) and the decay particles are tracked by four stations of straw tubes (STRAWs) operating in vacuum to reduce the multiple scattering effects. The π/μ separation up to 35 GeV/c is provided by a ring imaging Čerenkov detector (RICH). The NA48 liquid-krypton calorimeter (LKr) is used as a photon veto in the forward region and a muon veto detector (MUV) provides fast muon rejection. The sensitivity of the experiment is limited by the rate that can be handled by the GTK detectors.

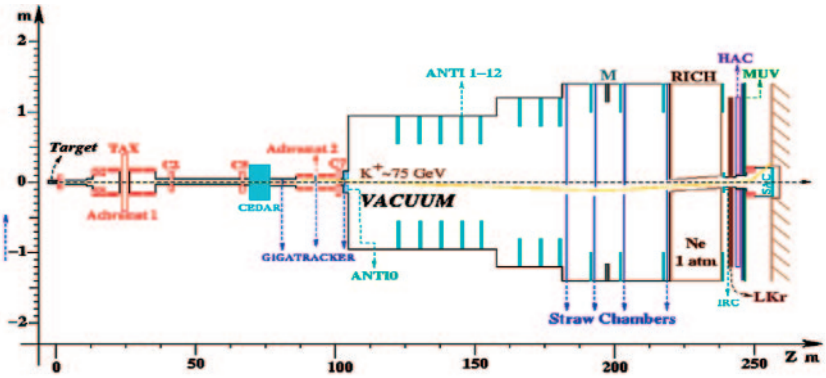

Fig. 2. – The NA62 detector layout.

4·3. *Experimental requirements.* – To allow the association with the decay particle without too many ambiguities introduced by accidental tracks, the GTK must provide a time resolution of $\sim 200\,\text{ps}$ per station, while the crossing time of the decay pion must be measured by the RICH with a resolution of $\sim 100\,\text{ps}$.

We define the missing squared mass $m^2_{\text{miss}} = (p_K - p_\pi)^2$ on the assumption that the charged decay product is a pion. About 92% of the total background is kinematically constrained and can be rejected by applying a cut on m^2_{miss}. By assuming a 10% signal acceptance, a background-to-signal ratio smaller than 10% requires a resolution on $m^2_{\text{miss}} \sim 10^{-3}\,\text{GeV}^2/c^4$, which implies stringent requirements on the GTK and STRAWs performances ($\sigma \sim 100\,\mu\text{m}$). The remaining 8% of background spams across the signal regions. In this case, rejection relies only on γ, μ veto and particle identification.

We need a muon rejection with an inefficiency below 10^{-7} and a 10^{-8} inefficiency in vetoing the π^0. A muon rejection factor of 10^{-5} can be achieved exploiting the different penetration probability through matter of muons and pions. A further $5 \cdot 10^{-3}$ suppression factor can be provided by the RICH. As far as the π^0 veto is concerned, by limiting the highest range of the π^+ to $35\,\text{GeV}/c$ one ensures that, for the potentially dangerous backgrounds originating from the $K^+ \rightarrow \pi^+\pi^0$ decay, at least $40\,\text{GeV}$ of electromagnetic energy is deposited in hermetic calorimeters so that the π^0 can hardly be missed. According to our estimates, based on data accumulated in NA48 and test beams and simulation the photon detection efficiency satisfies the experiment specifications for the π^0 rejection.

4·4. *Status of the experiment.* – The GKT will be made of three silicon pixel stations placed along the beam line. The sensor technology is based on p-in-n. Each station covers an area of $60 \times 27\,\text{mm}^2$ with the area split into $300 \times 300\,\mu\text{m}^2$ pixels $200\,\mu\text{m}$ thick. Important R&D studies are underway concerning sensors, bump-bonding, cooling and read-out chips [10].

STRAWs will operate in vacuum to minimize the multiple scattering of the outgoing pion. The STRAW tracker will contain four chambers. Each chamber will have four views (x, y, u, v). The straw wall will be $36\,\mu\text{m}$ metalised Mylar. The baseline for the detector gas is a mixture of CO_2 (80%), Isobutan C_4H_{10} (10%) and CF_4 (10%). A prototype of the STRAW tracker was operated in a vacuum tank in 2007 and 2008 at the CERN SPS. The achieved position resolution is in line with the expectations.

TABLE II. – *Signal and background events expected in one year of* NA62 *data taking.*

Decay mode	Events/year
Signal (flux 4.8×10^{12})	55
$K^+ \to \pi^+\pi^0$	2.4
$K^+ \to \mu^+\nu$	1.2
$K^+ \to e^+\pi^+\pi^-\nu$	≤ 1.6
Other 3-track decays	≤ 0.8
$K^+ \to \pi^+\pi^0\gamma$	1.1
$K^+ \to \mu^+\nu\gamma$	0.4
$K^+ \to 1^+(\mu^+)\pi^0\nu$, others	—
Total expected background	≤ 7.5

The RICH will be composed by a cylindrical vessel 18 m long with a diameter of ~ 4 m filled with neon at atmospheric pressure. Tests performed with a full length RICH prototype have measured a 50 μrad angle resolution and a 65 ps time resolution [11], which satisfies completely the experimental requirements. Additional tests are foreseen to validate the π/μ separation.

The photon veto system must be fully hermetic in an angular range from 0 to 50 mrad. It will be composed by the ANTIs, the NA48 LKr calorimeter and two forward calorimeters (IRC and SAC). The ANTIs will be made of lead glass blocks recovered from the OPAL electromagnetic calorimeter and arranged into 12 stations surrounding the decay vacuum. A 25 blocks prototype has been tested at BTF in Frascati with a 471 MeV electron beam. An energy resolution $\sigma(E)/E = 9.7\%$ and a cluster time resolution $\sigma(t) = 560$ ps have been measured. An additional test with μ and K has been performed at CERN in October 2008. Extensive measurements of the photon detection capability of the NA48 LKr were performed using a sample of $K^+ \to \pi^+\pi^0$ collected by NA48. The inefficiency to detect high-energy photons ($E > 10$ GeV) was found to be less than 10^{-5}.

4·5. *Perspectives.* – The sensitivity of the experiment was evaluated by Monte Carlo simulation. The number of expected signal and background events for one year of data taking is shown in table II. We expect to measure the branching ratio of $K^+ \to \pi^+\nu\overline{\nu}$ with a 10% accuracy in two years of data taking.

5. – Conclusions

The R_K analysis on a partial data sample ($\sim 40\%$) is well advanced and aims at a preliminary result with $\sim 0.7\%$ accuracy. The analysis demonstrates that the overall uncertainty of 0.4%, as declared in the proposal, is within reach.

The experiment to measure the branching ratio of $K^+ \to \pi^+\nu\overline{\nu}$ has been approved by the CERN SPSC and Research Board. The R&D program is close to the end and the construction has already started. The construction should take about two and a half years and the first data taking is expected to take place in 2012.

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