The NA62 Project at CERN: $K^+ \to \pi^+ \nu\bar{\nu}$ at the SPS

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There are currently three main directions in elementary particle physics. On the one hand experiments at the highest possible energies are searching for the origin of electroweak breaking and direct evidence of New Physics (NP); a second line of attack aims to study the properties of neutrinos, both of accelerator and cosmic origin, and of other astro-particle messengers. The third strategy is to explore the precision frontier looking for deviations from the Standard Model (SM) predictions in rare or forbidden processes. In this latter case, the sensitivity to NP originates from the virtual contributions that can involve all discovered and not yet discovered particles in higher order quantum loops and therefore can address, indirectly, energy scales even beyond those accessible at colliders. Some of the most interesting rare decays are those Flavour Changing Neutral Currents (FCNC) that can be predicted with small hadronic uncertainties in the SM. There are only very few observables where there is both sensitivity to NP and a well calculable expectation within the SM. A very good example is the $K^+ \to \pi^+ \nu\bar{\nu}$ decay which will be studied by the NA62 experiment at the CERN SPS.

1 Physics Motivation

The decisive progress that has taken place over the past decade has confirmed the Cabibbo-Kobayashi-Maskawa (CKM) picture [1,2] of quark-mixing and CP-Violation. As it can be seen, in Figure 1, where the constraints to the unitarity triangle are presented [3], all manifestations of CP-Violation (K and B decays and mixing) are consistent with *just* one complex phase in the CKM matrix. We should stress that the values of $\bar{\rho}$ and $\bar{\eta}$ are not so much relevant per se but that their over-constrained determination is important to signal possible inconsistencies of the Standard Model (SM) due to the presence of New Physics (NP). After all, if NP has to exist to make the SM consistent at high energy why its effects are not seen in precision flavor measurements? This

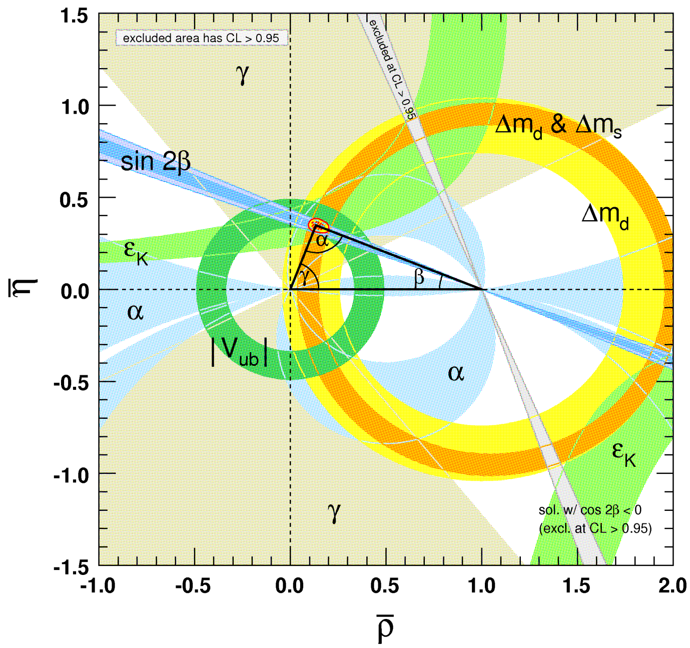

Figure 1: Constraints on the $\bar{\rho}$ $\bar{\eta}$ plane.

is the essence of the so called flavor problem [4]. To address this question requires a paradigm shift: once the charged current couplings are precisely determined from quantities unlikely to be affected by NP (e.g. tree decays), we should measure loop induced, well calculable, Flavor Changing Neutral Currents (FCNC) processes to detect a possible pattern of deviations. The importance to continue a strong experimental program in flavor physics in the LHC era was the object of an extended CERN workshop, whose proceedings provide detailed references and justification [5].

In this context, a theoretically pristine opportunity is represented by the $K \to \pi\nu\bar{\nu}$ decays[6,7]. The main reason for the exceptional theoretical cleanliness of the SM prediction for $K_L^0 \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$ stems from the fact that these transitions are described by Z^0-penguins and box diagrams mediated by $\mathcal{O}(G_F^2)$ interactions where a power-like GIM [8] mechanism suppresses the non-perturbative effects. This is generally not the case for gluon- and photon-penguins which are characterized by amplitudes proportional respectively to $\mathcal{O}(G_F\alpha_s)$ and $\mathcal{O}(G_F\alpha_{em})$ and therefore present only a logarithmical GIM suppression. A related feature is that these decays are mediated by one single effective operator:

$$Q_{sd}^{\nu\bar{\nu}} = (\bar{s}_L\gamma^\mu d_L)(\bar{\nu}_L\gamma_\mu\nu_L). \quad (1)$$

The hadronic matrix element can be extracted from the precisely measured $K^+ \to \pi^0 e^+\nu$ decay. The uncertainty due to the charm contribution present in the charged kaon case was reduced by the NNLO calculation [9]. Long distance contributions due to EW corrections [10] and due to light quarks were also recently computed [11]. Improvements to the determination of the hadronic matric element using semi-leptonic kaon decays were also performed [12]. After summation over the three lepton families, the SM branching ratios can be written as:

$$Br(K^+ \to \pi^+\nu\bar{\nu}(\gamma)) = \kappa_+(1+\Delta_{EM}) \times \frac{|V_{ts}^*V_{td}X_t(m_t^2) + \lambda^4\Re V_{cs}^*V_{cd}(P_c(m_c^2)+\delta P_{c,u})|^2}{\lambda^5} \quad (2)$$

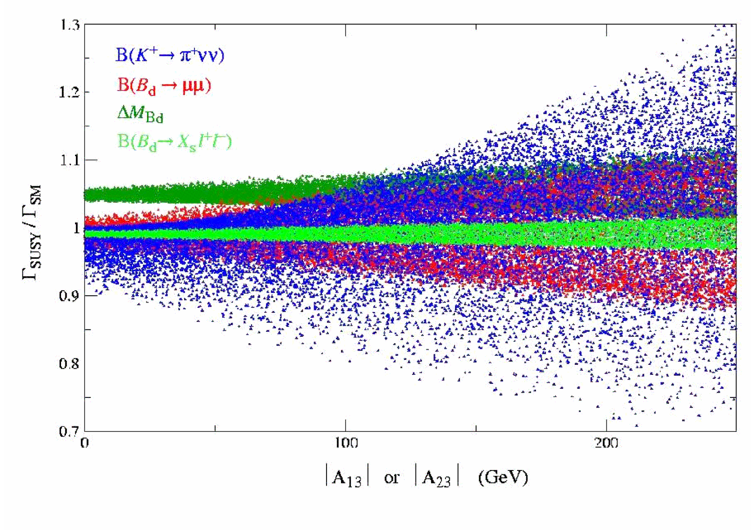

Figure 2: Sensitivity of precision observables to SUSY breaking trilinear couplings.

$$Br(K_L^0 \to \pi^0\nu\bar{\nu}) = \kappa_L \left(\frac{\Im V_{ts}^* V_{td}}{\lambda^5} X_t(m_t^2)\right)^2, \tag{3}$$

where $\kappa+$ and κ_L are numerical factors encoding the hadronic matrix elements whose uncertainties are negligible. A recent numerical appraisal of the above equations [10,13] gives: $Br(K^+ \to \pi^+\nu\bar{\nu}(\gamma)) = (0.85 \pm 0.07) \times 10^{-10}$ and $Br(K_L^0 \to \pi^0\nu\bar{\nu}) = (2.76 \pm 0.40) \times 10^{-11}$, where the uncertainty is mainly of parametric nature and not related to the non-perturbative effects. The precision of the theoretical predictions contrasts with the large uncertainties affecting the current experimental results [14,15]:

$$Br(Exp)(K^+ \to \pi^+\nu\bar{\nu}(\gamma)) = (1.73^{+1.15}_{-1.05}) \times 10^{-10} \tag{4}$$

$$Br(Exp)(K_L^0 \to \pi^0\nu\bar{\nu}) \leq 6.7 \times 10^{-8} \qquad 90\% \qquad CL. \tag{5}$$

The importance to measure precisely these reactions resides in the fact that their predictability power is preserved in many extensions of the SM. The SM is generally understood to be an effective field theory valid up to some energy scale. For instance, to avoid quadratic divergences introduced by the Higgs mechanism some NP must exist in the TeV range. Supersymmetry (SUSY) is a framework to make the Standard Model consistent up to the GUT scale. Generic SUSY has many parameters including extra CP-Violating phases and FCNC couplings. Fine tuning of the parameters is necessary to satisfy the experimental bounds (e.g. $K^0 - \bar{K}^0$ mixing, $\mu \to e\gamma$, neutron EDM, etc.). As shown in [16], scans of allowed parameters in the framework of the Minimal Supersymmetric Standard Model (MSSM) still leave possible a very wide range for the value of the $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L^0 \to \pi^0\nu\bar{\nu}$ branching ratios. In more constrained models, such as Minimal Flavor Violation (MFV), the FCNC effects are reduced by imposing that the flavor structures are aligned to those of the SM and new FCNC effects are confined to symmetry breaking terms. In this case very few observables maintain a significant sensitivity to NP. As shown in Figure 2, $K^+ \to \pi^+\nu\bar{\nu}$ is among the most sensitive observables for typical SUSY energy scales and parameters [17] in MFV models.

In summary, given the firm bases on which the theory stands both within and beyond the SM, the study of these decays represents an exquisite experimental challenge. In the remainder of this paper we describe how the NA62 experiment intends to address this challenge by making a precise measurement of the decays $K^+ \to \pi^+\nu\bar{\nu}$ at the CERN SPS with kaon decays in flight.

2 Principle of NA62

The CERN proton complex is unique. Plans for the next round of Fixed Target experiments at CERN are based on the consideration that the Super-Proton-Synchrotron (SPS) is needed as LHC proton injector only on a part-time basis. For the rest of the time it can provide 400 GeV/c protons for fast or slow extraction experiments. The $K^+ \to \pi^+\nu\bar{\nu}$ decay has been discovered using the stopped kaon technique [14]. A proposal to study the reaction in flight was approved at FNAL but not carried out [18]. At CERN we have taken the approach [19,20] to exploit a high momentum kaon beam to improve the rejection of the background induced by $K^+ \to \pi^+\pi^0$ decays. The in-flight decays at high momentum require the instrumentation of a large decay volume but avoids the scattering and backgrounds introduced by the stopping target. The NA62 experimental technique exploits:

1. Precise timing to associate the outgoing π^+ to the correct incoming parent particle (K^+).
2. Kinematic rejection of backgrounds induced by two- and three-body kaon decays.
3. Hermetic vetoes of μ and γ.
4. Particle Identification (K^+/π^+ and π^+/μ^+).

The proposed NA62 detector layout is presented in Figure 3. A 75 GeV/c unseparated hadron beam with an instantaneous rate of about 800 MHz and a kaon fraction of $\approx 6\%$ enters a long decay tank. Particle identification of the beam particles is provided by a differential Cherenkov counter (CEDAR) while event-by-event tracking, timing and refined momentum measurement is provided by a silicon micro-pixel Gigatracker(GTK) detector [21,22] placed in a four-dipole magnetic achromat. The large decay tank is surrounded by twelve stations of photon anti-counters (ANTI). The decay particles are tracked by four stations of straw tubes (STRAW) operated in the vacuum tank itself to reduce the effect of multiple scattering. A 17 m long RICH detector provides π/μ separation up to 35 GeV/c. The NA48 Liquid krypton Calorimeter (LKR) [23]is employed as photon veto in the forward region and a muon veto detector (MUV) provides fast muon rejection. The sensitivity of the experiment is not limited by the proton flux available but by the rate that can be handled by the GTK detector. For comparison, NA62 requires a similar amount of protons on target as NA48, the predecessor kaon experiment at CERN. In the next subsections we briefly describe the proposed technique.

2.1 Precise Timing

The choice to employ an unseparated beam requires a beam tracker with outstanding rate capabilities. The beam size (60 mm $\times$ 27 mm) and divergence (0.1 mrad) are too large to provide a good enough constraint on the direction of the incoming kaon and therefore each beam particle has to be tracked on an event-by-event basis by the GTK. To allow the association with the decay particle without too many ambiguities introduced by accidental tracks, the GTK must provide a time resolution of about 200 ps per station. The timing of the decay pion is provided by the RICH detector. Tests performed with a full length RICH prototype have measured [24] 65ps time resolution, a performance which satisfies completely the experimental requirements. To appreciate the importance of the timing on the performance of NA62 it is sufficient to mention that if the association between the kaon and the pion is wrong, the kinematic rejection is jeopardized because the constraint given by the two-body kinematics is weakened and $K^+ \to \pi^+\pi^0$ events can be mistaken for signal if both photons from the π^0 decay are not detected.

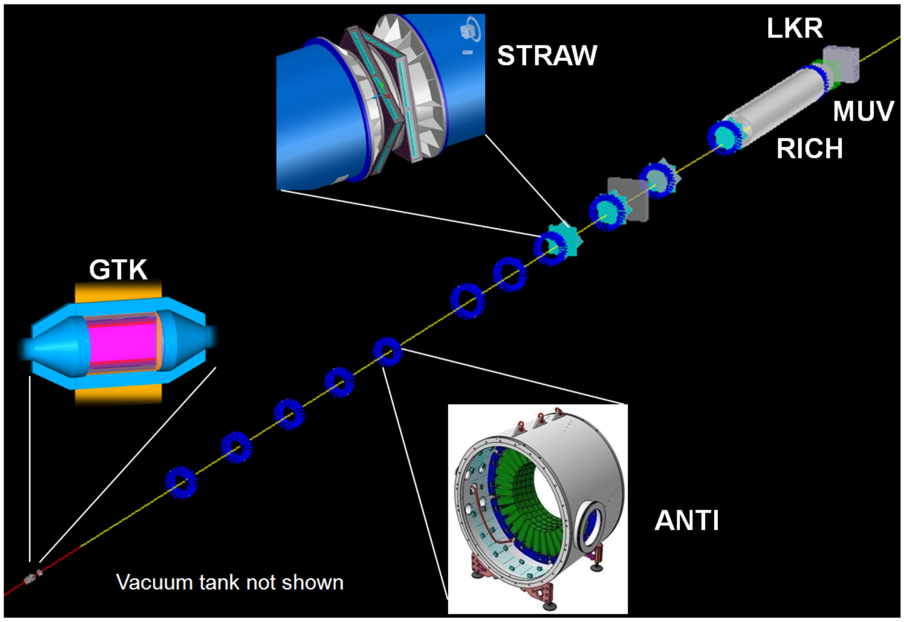

Figure 3: Elements of the NA62 experimental setup, the decay tank is not shown.

2.2 Kinematic Rejection

About 92 % of the kaon decays are kinematically constrained and can be rejected applying a cut on the missing mass variable computed under the hypothesis that the charged particle is a pion. To illustrate the power of the kinematical rejection, the missing mass distribution

$$m^2_{miss} = (\tilde{P}_K - \tilde{P}_\pi)^2 \simeq m^2_K \left(1 - \frac{|P_\pi|}{|P_K|}\right) + m^2_\pi \left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\theta^2_{\pi K} \tag{6}$$

for frequent kaon decays and for the expected signal is shown in Figure 4 in arbitrary scale. The expected (simulated) NA62 missing mass resolution is shown in Figure 5. 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.

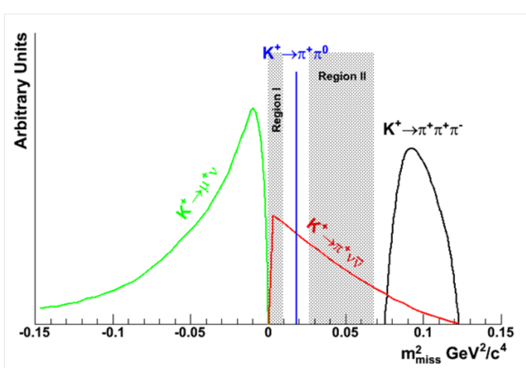

Figure 4: Missing mass recoiling against the charged particle assumed to be a pion for different kaon decays (arbitrary scale).

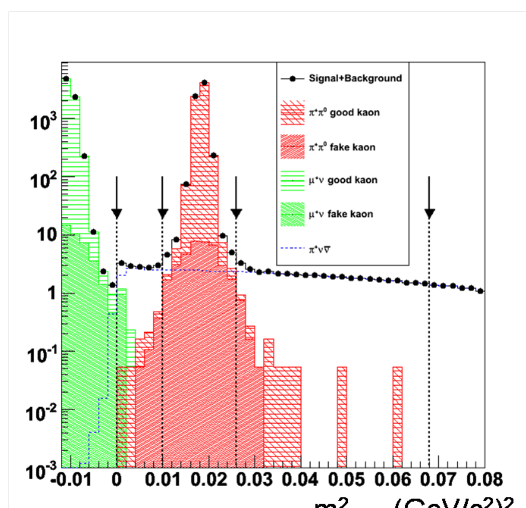

Figure 5: Simulated missing mass resolution for the NA62 spectrometer.

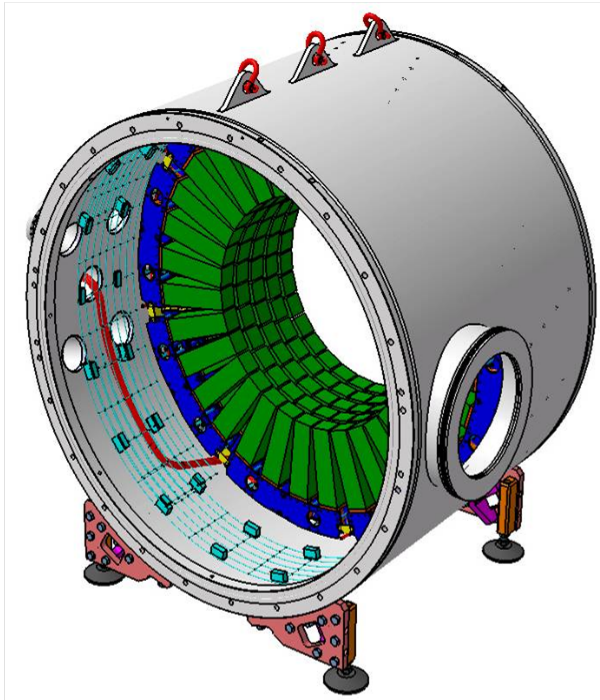

Figure 6: Artist's view of one ANTI station. The Lead Glass blocks are arranged in five staggered crowns. A photon from a kaon decay crosses at least $\approx$15 X_0.

2.3 Muon and Photon Vetoes

By limiting the highest momentum range of the π^+ to 35 GeV/c one insures that, for the potentially dangerous backgrounds originating from the $K^+ \to \pi^+\pi^0$ decay, at least 40 GeV of electro-magnetic energy is deposited in hermetic calorimeters so that the π^0 can hardly be missed. Hence, the signature of the experiment is the time coincidence between a high momentum incoming K^+ and an outgoing π^+ coupled to a lot of missing energy carried away by the undetected neutrino-antineutrino pair. According to our estimates, based on data accumulated in NA48 and test beams and to simulation, a π^0 suppression factor of the order of 10^8 can be achieved. The ANTI are made from Lead Glass blocks recovered from the OPAL Electromagnetic calorimeter [25] and arranged into twelve stations surrounding the decay vacuum. The drawing of one station in presented in Figure 6. Extensive measurements of the photon detection capability of the NA48 Liquid Krypton Calorimeter (LKR) were performed using a sample of $K^+ \to \pi^+\pi^0$ collected by NA48 and selected kinematically without using calorimeter information. The inefficiency to detect high energy photons (photon energies larger than 10 GeV) was found to be less than 10^{-5}. This figure, coupled to the geometrical acceptance of the ANTI counters and their measured photon detection efficiency satisfies the experiment specifications for the π^0 rejection.

The suppression of muons is crucial for two reasons. Although the $K^+ \to \mu^+\nu$ decay is reconstructed outside the missing mass signal region when a muon is mistakenly assumed to be a pion, the rate of these events is so high that a muon detector based on calorimetry (MUV) with good segmentation is required to avoid the feed-down of background events into the signal region. On the other hand, the rate of single muon tracks crossing the experiment is very high and a suppression of these events at the earliest stage of the trigger selection is essential to limit the lowest level trigger rate to about 1 MHz.

Decay Mode	Events/year
Signal (flux 4.8 $\times 10^{12}$)	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
$K^+ \to e^+(\mu^+)\pi^0\nu$, others	-
Total Expected Backgrounds	$\leq$7.5

Table 1: Signal and background events expected for NA62 year of data taking.

2.4 Particle Identification

The positive event by event identification of the K^+ in the unseparated hadron beam is important to avoid that pions scattered in the residual gas in the decay tank mimic the signal. This is achieved using a differential Cherenkov counter of the CEDAR [26] equipped with new optics and front-end and filled with pressurized hydrogen. To further suppress backgrounds that might originate from kaon decays with muons and from decays not kinematically constrained, a 17 m long RICH counter equipped with photomultipliers provides strong particle identification. The π^+/μ^+ separation provided by the RICH is expected to exceed two standard deviations up to 35 GeV/c.

3 Physics Sensitivity

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 given in Table 1. By extrapolating from the NA48 experience, it is expected that a 10% measurement of the $Br(K^+ \to \pi^+\nu\bar{\nu})$ at the SM level can be achieved with two years of data taking.

4 Status of the Experiment

The Physics case to study rare kaon decays at the SPS during the LHC era is very strong. The project was approved by the CERN Research Board on December 5, 2008 and the Memorandum of Understanding between the Collaborating Institutes is under preparation. Construction of the new experiment should take about two and a half years and the first data taking is expected to take place in 2012. With ≈ 50 times the kaon flux of NA48/2, the previous charged kaon experiment at CERN, the NA62 physics menu, in addition to the very rare decays, promises to be rich ranging from the precision-tests of lepton universality to the study of the strong interaction at low energy. There should be good material for both the Electro-Weak and the QCD Moriond sessions in 201X!

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