

THEORETICAL PERSPECTIVE ON THE NA62 PHYSICS PROGRAM

CHRISTOPHER SMITH

Institut für Theoretische Teilchenphysik, Karlsruhe Institute of Technology, D-76128 Karlsruhe, Germany

Soon the NA62 experiments will start looking for the very rare K decays. In this talk, their theoretical interests in the search for New Physics are briefly reviewed. Then, other possible targets for NA62 are discussed, ranging from the semileptonic modes to the radiative and lepton-flavor violating modes.

1 New physics searches

The rare K decays are ideally suited to search for New Physics (NP). Besides the loop suppression of the underlying FCNC processes, they are significantly suppressed by the CKM matrix elements. Indeed, compared to the $b \rightarrow s, d$ transitions, they scale dominantly as

$$s \rightarrow d \sim |V_{td}V_{ts}^\dagger| \sim \lambda^5 \ll b \rightarrow d \sim |V_{td}V_{tb}^\dagger| \sim \lambda^3, \quad b \rightarrow s \sim |V_{ts}V_{tb}^\dagger| \sim \lambda^2, \quad (1)$$

with $\lambda \approx 0.22$. To give an example, imagine that New Physics is encoded into the following effective operators

$$\mathcal{H}_{eff} = \frac{c_{sd}}{\Lambda^2}(\bar{s}\Gamma d)(\bar{\nu}\Gamma\nu) + \frac{c_{bd}}{\Lambda^2}(\bar{b}\Gamma d)(\bar{\nu}\Gamma\nu) + \frac{c_{bs}}{\Lambda^2}(\bar{b}\Gamma s)(\bar{\nu}\Gamma\nu), \quad (2)$$

Thus, when this NP is generic, $c_{ij} = \mathcal{O}(1)$, the constraints from rare K decays are potentially the toughest. A measurement of $K \rightarrow \pi\nu\bar{\nu}$ close to its SM prediction would require $\Lambda \gtrsim 75$ TeV. Even accounting for possible model-dependent loop and gauge couplings, this measurement would be the most difficult to reconcile with the existence of generic NP at a relatively low scale. This is one instance of the so-called NP flavor puzzle.

Alternatively, the NP model could preserve the CKM scalings (1). Such models are referred to as satisfying Minimal Flavor Violation¹ (see also²). When this is the case, it could show up at a scale $\Lambda \lesssim 1$ TeV without violating the experimental bounds. In addition, when MFV is enforced within the MSSM, the effects on the rare K decays are expected to be small, beyond the experimental sensitivity. This has been analyzed at moderate³ and large $\tan\beta$ ^{4,5} (with $\tan\beta \equiv v_u/v_d$ and $v_{u,d}$ the two MSSM Higgs vacuum expectation values), without R-parity⁶, or with MFV imposed at the GUT scale⁷. Turning this around, the rare K decays are one of the best places to look for deviations with respect to MFV. If the flavor-breaking transitions induced by NP are not precisely aligned with those of the SM (tuned by the CKM), large effects could show up.

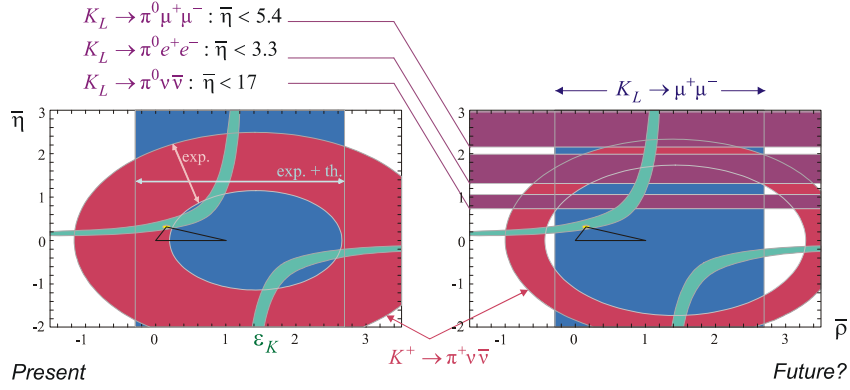


Figure 1: Rare K decays in the $\bar{\rho} - \bar{\eta}$ place: the situation now (left) and in a hypothetical future (right).

1.1 Where do we stand and where do we go?

To test the CKM picture of the SM, it is customary to represent the constraints coming from flavor physics in the $\bar{\rho} - \bar{\eta}$ plane. As shown in Fig.1, rare K decays are currently not competitive compared to B physics observables. Furthermore, though mostly experimentally driven, this situation should persist for the foreseeable future.

However, this way of presenting the impact of K physics for the search for NP is not doing justice to its true potential. The main reason why rare K decays are not competitive is their significant CKM suppression compared to typical B physics observables. But being so suppressed leaves more chances for NP to be competitive. Sizeable deviations with respect to the SM could easily show up. This is illustrated by the second plot in Fig.1, where an imaginary future situation is drawn. Despite the rather large error bands standing for both theoretical and hypothetical experimental errors, the deviations could be sufficient to clearly signal non-standard physics. Importantly, this NP needs not affect all the rare K decays equally. The global pattern of deviation would be an important piece of information to reconstruct the NP at play.

1.2 How to disentangle New Physics effects

The first target of NA62 is the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay, induced by the Z penguin and its associated W box. Technically, this FCNC has a peculiar sensitivity to the high-scale because it would be represented by a dimension-six operator if $SU(2)_L$ was exact. Instead, after the spontaneous breakdown of $SU(2)_L$, the operator $\bar{s}\gamma_\mu d H^\dagger D^\mu H$ becomes $v^2 \bar{s}\gamma_\mu d H Z^\mu$, which is effectively of dimension four and enhanced by two powers of the electroweak vacuum expectation value $v \approx 250$ GeV. Most NP models affect the Z penguin (or lead to an indistinguishable $V \otimes (V - A)$ operator). This has been extensively studied, so let us just cite, besides the analyses within MFV quoted previously, the MSSM at moderate $\tan\beta$ (chargino loops)^{3,8}, MSSM at large $\tan\beta$ (charged Higgs loops)⁵, R-parity violation (non MFV)⁹, enhanced electroweak penguins¹⁰, Little Higgs¹¹, extra dimensions¹², fourth generation¹³,...

Since $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ just gives one number, we need more information to disentangle all these models. A first clue would be provided by the CP-violating $K_L \rightarrow \pi^0 \nu \bar{\nu}$ mode. Model-independently¹⁴, the current measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ allows for up to a factor 30 enhancement of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ with respect to its SM value. The discriminating power of the pair of $K \rightarrow \pi \nu \bar{\nu}$ decays is shown in Fig. 2, where the grid in the allowed region is a function of the theoretical error on their SM predictions.

In general, the NP decouple smoothly as its mass scale increases or its flavor-breaking couplings decrease, so there is naturally a cluster of models around the SM values in Fig. 2. Thus,

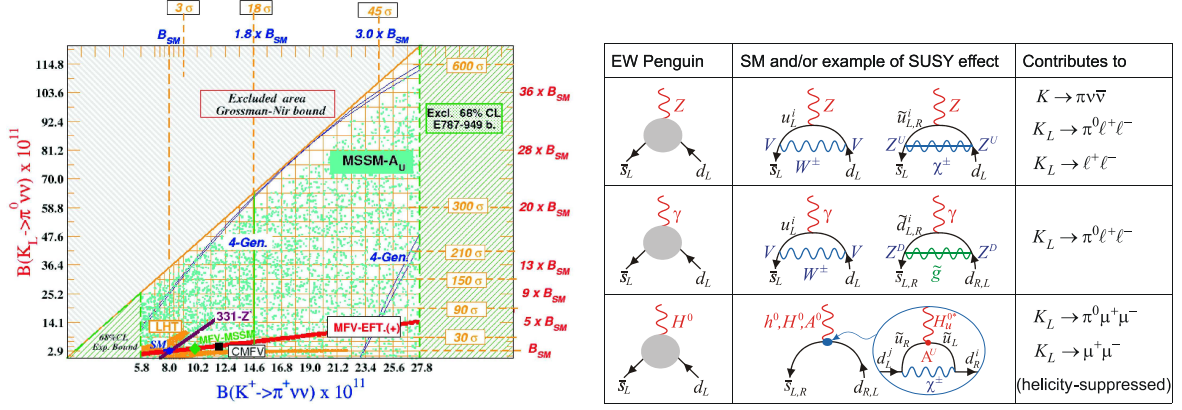


Figure 2: The discriminating power of (left) the pair of decays $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ – $K_L \rightarrow \pi^0 \nu \bar{\nu}$, and of (right) the full set of rare K decays, with examples of effects in the MSSM.

in case the deviations are not large, information beyond $K \rightarrow \pi \nu \bar{\nu}$ will be needed to identify the NP at play. To this end, one should turn to the $K_L \rightarrow \pi^0 \ell^+ \ell^-$ ($\ell = e, \mu$) decays. Though less clean than $K \rightarrow \pi \nu \bar{\nu}$ theoretically (see next section), their sensitivity to NP is significantly different¹⁵ because $\ell^+ \ell^-$ not only couple to the Z , but also to the γ and, for $\ell = \mu$, to the Higgs(es). In Fig. 2 are examples of mechanism within the MSSM affecting these various electroweak structures. Going back to Fig. 1, the fictitious pattern depicted could be interpreted as indicating NP in the Z penguin, since $K \rightarrow \pi \nu \bar{\nu}$ disagree with the SM, in the γ penguin since $K_L \rightarrow \pi^0 e^+ e^-$ disagree with $K \rightarrow \pi \nu \bar{\nu}$, and in the Higgs penguins because $K_L \rightarrow \pi^0 \mu^+ \mu^-$ is significantly larger than $K_L \rightarrow \pi^0 e^+ e^-$.

2 Hadronic uncertainties and Chiral Perturbation Theory

The rare K decays proceed dominantly through Short-Distance (SD) processes, with only residual Long-Distance (LD) effects, see Fig.3. Still, to make the most from future measurements, control over these effects is compulsory. To this end, the strategy is to use Chiral Perturbation Theory (ChPT) to relate the hadronic uncertainties occurring for rare K decays to other observables, which thus constitute important secondary targets for NA62. We can distinguish two kinds of LD effects. The first are the matrix elements of the effective light-quark operators induced by the short-distance physics (i.e., penguins with top and charm quarks²), and the second are genuine LD processes (i.e., penguins with up quarks).

For the matrix elements, all the necessary information can be extracted from the charged-current semileptonic $K \rightarrow \pi \ell \nu$ decays (called $K_{\ell 3}$). In the isospin limit, their matrix elements $\langle \pi | \bar{s} \gamma_\mu u | K \rangle$ are equal to those of the neutral current, $\langle \pi | \bar{s} \gamma_\mu d | K \rangle$, up to some Clebsch-Gordan coefficients. Within ChPT, the isospin breaking effects can be brought under control, ensuring a few per-mil accuracy for the matrix elements¹⁶. This represents a tiny fraction of the overall error on the SM predictions for the $K \rightarrow \pi \nu \bar{\nu}$ rates¹⁷, and could even be further improved with better measurements of the $K_{\ell 3}$:

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}(\gamma))^{\text{SM}} = 8.5(7) \cdot 10^{-11} \quad (47_{CKM}, 20_{SD}, 30_{LD}, 3_{ME})\%, \quad (3)$$

$$B(K_L \rightarrow \pi^0 \nu \bar{\nu})^{\text{SM}} = 2.8(4) \cdot 10^{-11} \quad (69_{CKM}, 27_{SD}, 4_{ME})\%, \quad (4)$$

where in the breakdown of the errors, CKM indicates parametric errors, and ME those from the matrix elements. In this respect, we should mention that the $K_{\ell 3}$ decays are also essential to extract¹⁸ V_{us} , which enters in the parametric uncertainty.

The second kind of LD effects all occur for the charged lepton modes, and are due to the γ and $\gamma\gamma$ penguins, see Fig.3. These FCNC, contrary to the Z penguin, do not suppress light-quark

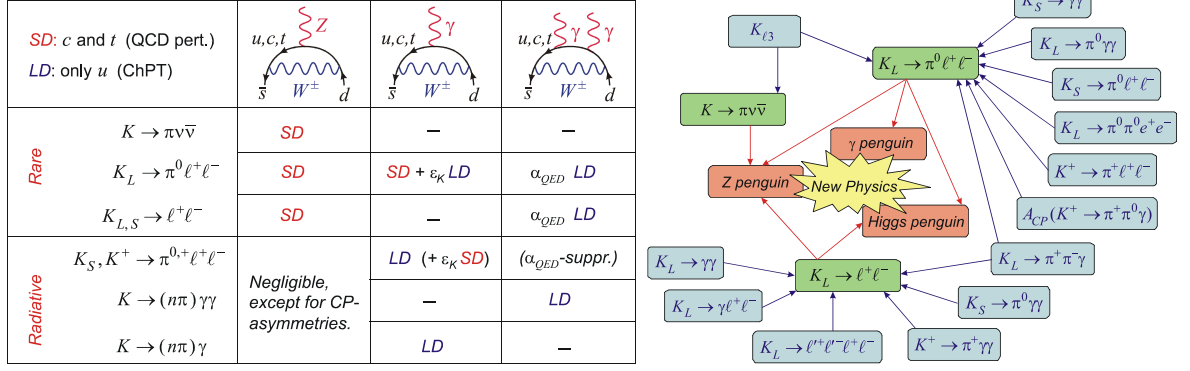


Figure 3: Anatomy of the rare K decays in the SM, and strategies to fix their LD uncertainties.

contributions. It is only thanks to the CP symmetry that the bulk of the LD contributions is projected out for $K_L \rightarrow \pi^0 \ell^+ \ell^-$. To estimate the remaining LD effects, one can use those modes in which the γ or $\gamma\gamma$ penguin is CP-conserving, and represent the dominant contributions. We will not detail here the strategies depicted in Fig.3, and instead refer to some recent theoretical works along these lines¹⁹. The main message is that all these radiative modes should be tackled by NA62. Not only are they interesting by themselves to study the interplay between the strong, weak, and electromagnetic interactions (including the QED anomaly), but they are also an important ingredient in the search for NP.

3 Precision physics

The NA62 experiment aims at producing about 10^{13} kaons per year. At that level, one is clearly entering a high-precision era in kaon physics. Thus, besides the rare K decays, there are many observables worth including in the physics program. Of course, to really appreciate if an observable is worth the experimental effort, one should first reassess whether theory can match the unprecedented precision, or at least whether the theoretical control is sufficient to access to some interesting physics. Though this work is currently in progress, let us mention a few possible targets.

3.1 CP-violation

The dominant $K \rightarrow \pi\pi$ decays permit to extract the indirect CP-violating parameter ϵ_K , due to the $\Delta S = 2$ mixing, and the direct CP-violating parameter ϵ' , due to $\Delta S = 1$ penguins. Both are already well known experimentally, and the ball is in the theorists' camp. While lattice²⁰ has a good prospect at reaching a percent level precision for the matrix elements of the effective $\Delta S = 2$ light-quark operator, problems remain for ϵ' . The question is thus whether NA62 could help in this respect.

There are several other windows into direct CP-violation, the first of which being the rare K decays discussed previously. But besides these, one could also turn to direct CP-asymmetries,

$$A_{CP} = \frac{\Gamma(K^+ \rightarrow X) - \Gamma(K^- \rightarrow \bar{X})}{\Gamma(K^+ \rightarrow X) + \Gamma(K^- \rightarrow \bar{X})}, \quad X = \pi\pi\pi, \pi\pi\ell\nu, \pi\pi\gamma, \pi\gamma\gamma, \pi\ell\bar{\ell}, \dots, \quad (5)$$

as studied for example in Refs.^{15,19,21,22}. Of course, these asymmetries are in general very small, but they have specific sensitivities to scalar, electroweak, or QCD penguins. They would provide complementary information with respect to the rare K decays. The main issues for NA62 are first to run with both K^- and K^+ beams, and then to be able to reach asymmetries in the

$10^{-4} - 10^{-5}$ range. If K^- beams are not practical, phase-space asymmetries for a given K^+ decay mode could also help. Note that the neutral K decays are in general less clean because indirect CP-violation is dominant; i.e. a CP-asymmetry essentially gives back the already well-measured ε_K , relegating direct CP-violating effects to small corrections.

3.2 Other subjects under investigation

There are many other possible targets for NA62, which we can organize in two categories. From them, either we would learn more about QCD in the non-perturbative regime, or we would directly constrain NP. In the former case, improving our theoretical control on QCD effects leads indirectly to better NP constraints, by allowing us to fine-tune our theoretical tools like ChPT or Lattice QCD.

A first set of targets are the leptonic and semileptonic decays $K_{\ell 2}$ and $K_{\ell 3}$, which provide very delicate tests of the SM. We have discussed earlier how $K_{\ell 3}$ data permits to fix rare K decay matrix elements.. In addition, as presented at this conference, these modes also permit to test leptonic universality²³ and the CKM unitarity²⁴. Furthermore, their measurements allow for high precision studies of the charge-current form-factors, including isospin breaking effects, and could provide one of the best sources of information on the light-quark mass ratios²⁵.

Other modes of interests are the lepton-flavor violating decay channels $K \rightarrow (\pi)\mu e$. Those are forbidden in the Standard Model, so any event would unambiguously signal the presence of NP. As such, they should certainly be included in the NA62 physics program, even though in most (but not all²⁶) models, they are correlated with purely leptonic observables like $\mu \rightarrow e\gamma$, and thus already severely constrained²⁷.

Finally, we should mention the $K_{\ell 4}$ decays as well as the hadronic decays giving us access to the $\pi\pi$ scattering phases, which have been the focus of intense theoretical work²⁸. Also, pion and hyperon decays are accessible to NA62, which could complement or improve the experimental situation in some channels.

4 Conclusion

The upcoming NA62 experiment at CERN, as well as the KOTO experiment in Japan, is in a perfect situation to unravel the still elusive NP. First, its main targets, the rare $K \rightarrow \pi\nu\bar{\nu}$ decays, are under excellent control theoretically. The non-parametric errors on the SM predictions for their rates are well below 10%. Second, the impact of various NP scenarios have been extensively studied, and usually found significant. Taken in combination with the rare $K_L \rightarrow \pi^0\ell^+\ell^-$ decays, they will permit a detailed analysis of the $s \rightarrow d$ transition. This is an essential ingredient in the LHC era if one aims at reconstructing the flavor sector of the NP at play²⁹.

Acknowledgments

This work is supported by the European Commission RTN network, Contract No. MRTN-CT-2006-035482 *FLAVIANet*, and by project C6 of the DFG Research Unit SFT-TR9 *Computergestützte Theoretische Teilchenphysik*.

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