What rare K decays can tell about the MSSM

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Abstract. Supersymmetric contributions to the theoretically clean $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, $K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0\mu^+\mu^-$ decays are briefly reviewed. Particular emphasis is laid on the information one could get on the MSSM flavor sector from a combined study of the four modes.

PACS. 12.60.Jv Supersymmetric models – 13.20.Eb Decays of K mesons

1 Introduction

The FCNC-induced decays, $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, $K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0\mu^+\mu^-$, are very suppressed in the Standard Model (SM), where they can be predicted very accurately. Therefore, these modes are ideal for probing possible New Physics effects[1]. In the present talk, the signatures of supersymmetry, in its simplest realization as the MSSM, are reviewed.

2 Rare K decays in the Standard Model

In the SM, the electroweak processes driving the rare K decays are the W box, Z and γ penguins[2], see Fig.1a. In this section, the excellent theoretical control reached on these contributions is summarized briefly.

The $K \to \pi\nu\bar{\nu}$ decays in the SM: The t-quark contribution to the Wilson coefficient of the dimension-six FCNC operator $(\bar{s}d)_{V-A}(\bar{\nu}\nu)_{V-A}$ is known at NLO[2], while the c-quark one has recently been obtained at NNLO[3]. The matrix-elements for this operator can be extracted from $K_{\ell 3}$ decays, including NLO isospin corrections[4]. For $K^+ \to \pi^+\nu\bar{\nu}$, residual c-quark effects from dimension-8 operators, along with long distance u-quark contributions, have also been computed [5]. For $K_L \to \pi^0\nu\bar{\nu}$, the indirect CP-violating contribution (ICPV), $K_L \xrightarrow{\varepsilon} K_1 \to \pi^0\nu\bar{\nu}$, is of about 1%[6], and the CP-conserving one is less than 0.01%[7]. Altogether, the SM predictions are

$$\mathcal{B}\left(K_L \to \pi^0\nu\bar{\nu}\right)_{\rm SM} = (2.49 \pm 0.39)\cdot 10^{-11},$$
$$\mathcal{B}\left(K^+ \to \pi^+\nu\bar{\nu}\right)_{\rm SM} = (7.83 \pm 0.82)\cdot 10^{-11}.$$

The error on $K_L \to \pi^0\nu\bar{\nu}$ is mainly parametric, i.e. dominated by $\operatorname{Im}\lambda_t$, $\lambda_t \equiv V_{ts}^* V_{td}$. For $K^+ \to \pi^+\nu\bar{\nu}$, which receives a significant c-quark contribution, the total error could be reduced with a better knowledge of m_c and through a lattice study of higher-dimensional operators[8].

The $K_L \to \pi^0\ell^+\ell^-$ decays in the SM: The situation is more involved because there are a priori three competing processes.

First, the t and c-quark contributions, known at NLO[2], generate both the dimension-six vector and axial-vector operators:

$$\mathcal{H}_{eff} = y_{7V}\left(\bar{s}d\right)_V\left(\bar{\ell}\ell\right)_V + y_{7A}\left(\bar{s}d\right)_V\left(\bar{\ell}\ell\right)_A\ .$$

The former produces the $\ell^+\ell^-$ pair in a 1^{--} state, the latter in both 1^{++} and 0^{-+} states.

Secondly, the ICPV contribution is related to $K_S \to \pi^0\ell^+\ell^-$, which is dominated by the Chiral Perturbation Theory (ChPT) counterterm a_S[9]. NA48 measurements give $|a_S| = 1.2 \pm 0.2$[10]. Producing $\ell^+\ell^-$ in a 1^{--} state, it interferes with the $(\bar{s}d)_V(\bar{\ell}\ell)_V$ contribution, arguably constructively[11,12]. This sign could also be fixed experimentally from A_{FB}^{μ}, the integrated forward-backward, or muon-energy asymmetry[13].

The final piece is the CP-conserving two-photon contribution, which produces the lepton pair in either a helicity-suppressed 0^{++} or phase-space suppressed 2^{++} state. The LO corresponds to the finite two-loop process $K_L \to \pi^0 P^+P^- \to \pi^0\gamma\gamma \to \pi^0\ell^+\ell^-$, $P = \pi, K$, exactly predicted by ChPT, and produces only 0^{++} states. Higher order corrections are estimated using experimental data on $K_L \to \pi^0\gamma\gamma$ for both the 0^{++} and 2^{++} contributions[11,14].

Altogether, the predicted rates are

$$\mathcal{B}\left(K_L \to \pi^0 e^+e^-\right)_{\rm SM} = 3.54^{+0.98}_{-0.85}\left(1.56^{+0.62}_{-0.49}\right)\cdot 10^{-11},$$
$$\mathcal{B}\left(K_L \to \pi^0\mu^+\mu^-\right)_{\rm SM} = 1.41^{+0.28}_{-0.26}\left(0.95^{+0.22}_{-0.21}\right)\cdot 10^{-11},$$

for constructive (destructive) interference. The errors are detailed in [11,13,14], and are currently dominated by the one on the $K_S \to \pi^0\ell^+\ell^-$ rate measurements.

3 Rare K decays and supersymmetry

Even though the minimal supersymmetrization of the SM requires one super-partner for each SM particle

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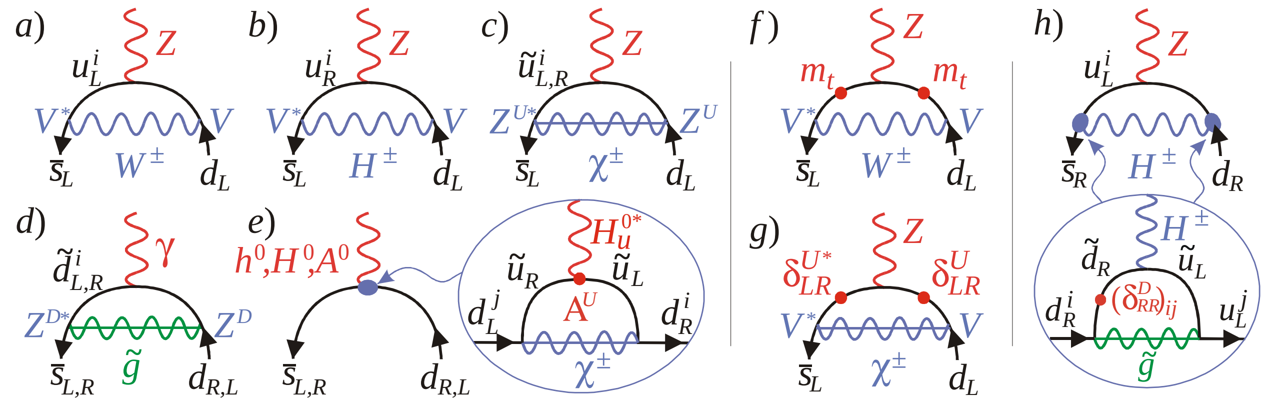

Fig. 1. $a-e$) Dominant MSSM contributions to rare K decays. $f-g$) Dominant sources of $SU(2)_L$-breaking in the Z-penguin. h) Schematic representation of the $H^{\pm}$ contribution to the Z-penguin at large $\tan\beta$.

(and two Higgs doublets), it is very constrained and involves only a few free parameters. However, SUSY must be broken, and the precise mechanism still eludes us. Therefore, in practice, an effective description is adopted, introducing all possible explicit soft-breaking terms allowed by the gauge symmetries. In the squark sector, there are LL and RR mass-terms and trilinear couplings giving rise to LR mass-terms after the Higgses acquire their VEV's, $\langle H^0_{u,d}\rangle = v_{u,d}$:

$$\mathcal{L}^{LL,RR}_{soft} = -\tilde{Q}^{\dagger}\mathbf{m}^2_Q\tilde{Q} - \tilde{U}\mathbf{m}^2_U\tilde{U}^{\dagger} - \tilde{D}\mathbf{m}^2_D\tilde{D}^{\dagger}\ ,$$
$$\mathcal{L}^{LR}_{soft} = -\tilde{U}\mathbf{A}^U\tilde{Q}H_u + \tilde{D}\mathbf{A}^D\tilde{Q}H_d\ ,$$

with $\tilde{Q} = (\tilde{u}_L, \tilde{d}_L)^T$, $\tilde{U} = \tilde{u}^{\dagger}_R$, $\tilde{D} = \tilde{d}^{\dagger}_R$. Obviously, $\mathbf{m}^2_{Q,U,D}$ and $\mathbf{A}^{U,D}$, which are $\mathbf{3}\times\mathbf{3}$ matrices in flavor-space, generate a very rich flavor-breaking sector as squark mass eigenstates can differ substantially from their gauge eigenstates.

What to expect from SUSY in rare K decays: In the SM, the Z-penguin is the dominant contribution, and is tuned by λ_t (Fig.1a). The four MSSM corrections depicted in Figs.1$b-e$ (together with box diagrams), represent the dominant corrections, and are thus the only MSSM effects for which rare K decays can be sensitive probes. Let us briefly describe each of them. First, there is the charged Higgs contribution to the Z-penguin (Fig.1b), which is, at moderate $\tan\beta = v_u/v_d$, aligned with the SM one ($\sim\lambda_t$). Then, there is the supersymmetrized version of Figs.1$a-b$, with charginos – up-squarks in place of $W^{\pm}/H^{\pm}$ – up-quarks in the loop (Fig.1c), and which is sensitive to the mixings among the six up-squarks (Z^U), a priori not aligned with the CKM mixings. Another purely supersymmetric contribution, relevant only for charged lepton modes, is the gluino electromagnetic penguin (Fig.1d), sensitive to down-squark mixings (Z^D). The last class of effects consists of neutral Higgs FCNC (Fig.1e), and arises at large $\tan\beta\approx 50$. Indeed, the 2HDM-II structure of the Higgs couplings to quarks, required by SUSY, is not preserved beyond leading order due to $\mathcal{L}_{soft}$, and the "wrong Higgs", H_u, gets coupled to down-type quarks, $\mathcal{L}_{eff}\supset \bar{d}^i_R Y^{ik}_d(H^0_d + \epsilon Y^{\dagger}_u Y_u H^{0\dagger}_u)^{kj} d^j_L$[15]. Clearly, once the Higgses acquire their VEV's, there is a mismatch between quark mass eigenstates and Higgs couplings; both are no longer diagonalized simultaneously and Higgs FCNC are generated[16].

Bottom-up approach and Minimal Flavor Violation: There are too many parameters in $\mathcal{L}_{soft}$ to have any hope to fix them all from rare K decays. At the same time, however, the observed suppression of FCNC transitions and CP-violating phenomena seem to indicate that only small departures with respect to the SM are possible. Therefore, one starts from a lowest-order basis in which the flavor-breakings due to $\mathbf{m}^2_{Q,U,D}$ and $\mathbf{A}^{U,D}$ are minimal. This can take the form of $mSUGRA$, alignment of squarks with quarks or the Minimal Flavor Violation hypothesis (MFV). In a second stage, one probes the possible signatures of departures from this minimal setting. The goal being, ultimately, to constrain SUSY-breaking models, which imply specific soft-breaking structures. At that stage, information from rare K decays, colliders and B-physics must of course be combined.

Here we adopt MFV as the lowest order basis, i.e. we impose that the SM Yukawas $\mathbf{Y}_{u,d}$ are the only sources of flavor-breaking[17]. In practice, this means that $\mathcal{L}_{soft}$ terms can be expanded as ($a_i, b_i\sim O(1)$, and A_0, m_0 set the supersymmetry-breaking scale)

$$\begin{aligned}\mathbf{m}^2_Q &= m^2_0(a_1\mathbf{1} + b_1\mathbf{Y}^{\dagger}_u\mathbf{Y}_u + b_2\mathbf{Y}^{\dagger}_d\mathbf{Y}_d \\ &\quad + b_3(\mathbf{Y}^{\dagger}_d\mathbf{Y}_d\mathbf{Y}^{\dagger}_u\mathbf{Y}_u + \mathbf{Y}^{\dagger}_u\mathbf{Y}_u\mathbf{Y}^{\dagger}_d\mathbf{Y}_d)),\\ \mathbf{m}^2_U &= m^2_0(a_2\mathbf{1} + b_4\mathbf{Y}_u\mathbf{Y}^{\dagger}_u),\\ \mathbf{A}^U &= A_0\mathbf{Y}_u(a_4\mathbf{1} + b_6\mathbf{Y}^{\dagger}_d\mathbf{Y}_d)\ ,\end{aligned}$$

and similarly for $\mathbf{m}^2_D$ and $\mathbf{A}^D$, such that all FCNC's and CP-violation are still essentially tuned by the CKM matrix. For example, the dominant contributions to the Z-penguin are those breaking the $SU(2)_L$ gauge-symmetry[18,19]. In the SM, this breaking is achieved through a double top-quark mass insertion (Fig.1f). Similarly, in the MSSM, it is the double $\tilde{t}_L-\tilde{t}_R$ mixing via the $\mathbf{A}^U$ trilinear terms which plays the dominant role (Fig.1g in the sCKM basis)[20]. Within MFV, this gives a factor $m^2_t\ \lambda_t\ |a_4 - \cot\beta\mu^*|^2$ [21], still enhanced by m^2_t and tuned by λ_t.

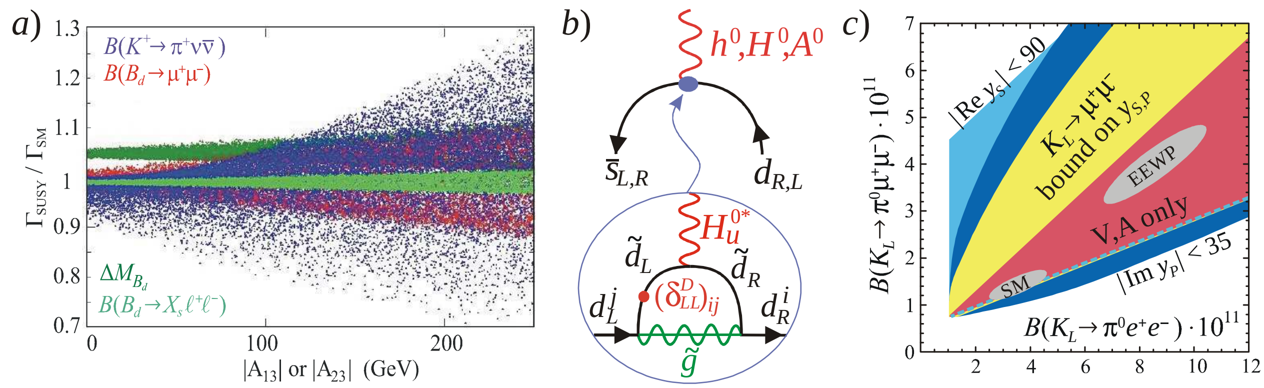

Fig. 2. *a*) Sensitivity of $K^+ \to \pi^+\nu\bar{\nu}$ to $\mathbf{A}^U$ terms, compared to B-physics observables. *b*) Schematic representation of the neutral Higgs FCNC beyond MFV, at large $\tan\beta$. *c*) Impacts of dim-6 FCNC operators in the $\mathcal{B}(K_L \to \pi^0\mu^+\mu^-)$ vs. $\mathcal{B}(K_L \to \pi^0 e^+e^-)$ plane.

4 Supersymmetric effects in $K \to \pi\nu\bar{\nu}$

SUSY effects in the (axial-)vector operators, $(\bar{s}d)_{V\pm A}(\bar{\nu}\nu)_{V-A}$, cannot be distinguished since only $(\bar{s}d)_V(\bar{\nu}\nu)_{V-A}$ contributes to the $K \to \pi\nu\bar{\nu}$ matrix-element. All MSSM effects are thus encoded into a single complex number, $X^\nu \equiv y_L^\nu + y_R^\nu$ [19]:

$$\mathcal{H}_{eff} = y_L^\nu\,(\bar{s}d)_{V-A}\,(\bar{\nu}\nu)_{V-A} + y_R^\nu\,(\bar{s}d)_{V+A}\,(\bar{\nu}\nu)_{V-A}$$
$$\to (y_L^\nu + y_R^\nu)\,(\bar{s}d)_V\,(\bar{\nu}\nu)_{V-A}\ .$$

At moderate $\tan\beta$, chargino penguins are the dominant MSSM contributions because of their quadratic sensitivity to up-squark mass-insertions (Figs.1*c*, 1*g*). Within MFV, this means, given the m_t enhancement present in the δ^U_{LR} sector, that $K \to \pi\nu\bar{\nu}$ are particularly sensitive. Still, a significant enhancement would require a very light stop and chargino[21], mostly because of the constraint from $\Delta\rho$[22]. Any enhancement $\gtrsim 5\%$ would thus falsify MFV if sparticles are found above $\sim 200GeV$, and if $\tan\beta \gtrsim 5$ (to get rid of the $H^\pm$ contribution). Turning on generic $\mathbf{A}^U$ terms, the largest deviations arise in $K \to \pi\nu\bar{\nu}$, see Fig.2*a*[21]. Further, the decoupling is slower than for observables sensitive to chargino boxes like ε_K. All in all, given that $K^+ \to \pi^+\nu\bar{\nu}$ has already been seen, how large the effect could be for $K_L \to \pi^0\nu\bar{\nu}$? By an extensive, adaptive scanning over the MSSM parameter space, Ref.[23] has shown that the GN model-independent bound[24] can be saturated, which represents a factor ~ 30 enhancement of $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ over the SM.

At large $\tan\beta$, the chargino contributions may no longer represent the dominant effect. While the Higgs FCNC obviously does not contribute (Fig.1*e*), higher order effects in the $H^\pm$ contribution to the Z-penguin (Fig.1*h*), sensitive to δ^D_{RR}, can become sizeable beyond MFV[25]. Further, this contribution is slowly decoupling as M_H increases compared to tree-level neutral Higgs exchanges, as for example in $B_{s,d} \to \mu^+\mu^-$.

SUSY effects in other dimension-six operators, $(\bar{s}d)(\bar{\nu}(\mathbf{1},\gamma_5)\nu)$ and $(\bar{s}\sigma_{\mu\nu}d)(\bar{\nu}\sigma^{\mu\nu}(\mathbf{1},\gamma_5)\nu)$, require active right-handed neutrinos and will not be discussed here[26]. Another possible class of operators, since the neutrino flavors are not detected, are $(\bar{s}\Gamma^A d)(\bar{\nu}^i\Gamma^B\nu^j)$ with $i \neq j$ and $\Gamma^{A,B}$ some Dirac structures. In the MSSM, such lepton-flavor violating operators arise only from suppressed box diagrams, and cannot lead to significant effects[27]. However, they could be sizeable in the presence of R-parity violating terms[27,28].

5 Supersymmetric effects in $K_L \to \pi^0\ell^+\ell^-$

Though the SM predictions for these modes are less accurate than for $K \to \pi\nu\bar{\nu}$, they are sensitive to more types of New Physics operators[13]. Indeed, the final-state leptons are now charged and massive. Therefore, besides electromagnetic effects, common to both the muon and electron modes, the relatively large muon mass opens the possibility to probe a whole class of helicity-suppressed effects.

SUSY effects in the QCD operators, i.e. in the chromomagnetic $\bar{s}\sigma_{\mu\nu}dG^{\mu\nu}$ or four-quark operators, have no direct impact on $K_L \to \pi^0\ell^+\ell^-$. Indeed, as said in Sect. 2, the two-photon CPC piece is fixed entirely in terms of the measured $K \to \pi\pi\pi$, $\pi\gamma\gamma$ modes[11,14], while the ICPV contribution is fixed from the measured ε_K and $K_S \to \pi^0\ell^+\ell^-$ rate[9]. At the low scale $\mu \lesssim m_c$, new physics can thus explicitly enter through semi-leptonic FCNC operators only.

SUSY effects in the SM operators, which are the vector and axial-vector operators, can in principle be disentangled thanks to the different sensitivities of the two modes to the axial-vector current (as discussed in Sec. 2, it also produces $\ell^+\ell^-$ in a helicity-suppressed 0^{-+} state). Various MSSM contributions can enter in y_{7A} and y_{7V}. First, chargino contributions to the Z-penguin (Fig.1*c*) enter as $y_{7A}, y_{7V} \sim (\delta^U_{RL})^*_{32}(\delta^U_{RL})_{31}$, and are thus directly correlated to the corresponding contribution to $K \to \pi\nu\bar{\nu}$[21,29]. Within MFV, the maximal effect for $K_L \to \pi^0\ell^+\ell^-$ is about one third of the one for $K_L \to \pi^0\nu\bar{\nu}$, hence may be inaccessible due to theoretical uncertainties. Secondly, gluino contributions to the electromagnetic operator $\bar{s}\sigma_{\mu\nu}dF^{\mu\nu}$ (Fig.1*d*) can be absorbed into $y_{7V} \sim (\delta^D_{RL})_{12}$. Even if directly correlated with ε'/ε, sizeable effects in $K_L \to$

Table 1. Sensitivity of rare K decays to MSSM effects, with and without MFV, and with moderate and large $\tan\beta$. The dominant contributions come from single, $(\delta^i_j)_{12}$, and/or double (e.g. $(\delta^i_j)^*_{32}(\delta^i_j)_{31}$) mass insertions (see text).

MSSM scenario	$K \to \pi\nu\bar{\nu}$	$K_L \to \pi^0\ell^+\ell^-$
MFV, $\tan\beta \approx 2$	Best sensitivity, but maximal enhancement < 20-25%	Less sensitive, but precisely correlated with $K \to \pi\nu\bar{\nu}$
MFV, $\tan\beta \approx 50$	Negligible effects ?	
General, $\tan\beta \approx 2$	Best probes of δ^U_{LR} (quadratic dependence in δ^U_{LR})	δ^U_{LR} : correlated with $K \to \pi\nu\bar{\nu}$ δ^D_{LR} : correlated with ε'/ε (but cleaner)
General, $\tan\beta \approx 50$	Good probes of δ^D_{RR} (slow decoupling as $M_H \to \infty$)	Good probes of $\delta^D_{RR,LL}$, correlated with $K_L \to \mu^+\mu^-$ (but cleaner)

$\pi^0\ell^+\ell^-$ are still possible[30]. Finally, $H^\pm$ contributions arise at large $\tan\beta$ (Fig.1*h*), with $y_{7A}, y_{7V} \sim (\delta^D_{RR})_{12}$, and are directly correlated with those for $K \to \pi\nu\bar{\nu}$[25].

SUSY effects in the (pseudo-)scalar operators, which can be helicity-suppressed or not:

$$\mathcal{H}_{eff} = y_S\,(\bar{s}d)\left(\bar{\ell}\ell\right) + y_P\,(\bar{s}d)\left(\bar{\ell}\gamma_5\ell\right) + y'_S\,(\bar{s}\gamma_5 d)\left(\bar{\ell}\ell\right) + y'_P\,(\bar{s}\gamma_5 d)\left(\bar{\ell}\gamma_5\ell\right)\ .$$

The first (last) two operators contribute to $K_L \to \pi^0\ell^+\ell^-$ ($K_L \to \ell^+\ell^-$). In the MSSM at large $\tan\beta$, they arise from Higgs FCNC[31], and are thus helicity-suppressed (Fig.2*b*). Sizeable effects for the muon mode are possible beyond MFV, where they are sensitive to $(\delta^D_{RR,LL})_{12}$ and $(\delta^D_{RR})_{23}(\delta^D_{LL})_{31}$ mass-insertions. Also, even if this contribution is correlated to the one for $K_L \to \mu^+\mu^-$, given the large theoretical uncertainties for this mode, a factor ~ 4 enhancement is still allowed (Fig.2*c*)[13]. On the other hand, helicity-allowed contributions to these operators do not arise in the MSSM. They could appear in the presence of R-parity violating couplings, but, baring fine-tuning, their effects must be small to avoid overproducing $K_L \to e^+e^-$[13].

SUSY effects in the (pseudo-)tensor operators, $(\bar{s}\sigma_{\mu\nu}d)(\bar{\ell}\sigma^{\mu\nu}(\mathbf{1},\gamma_5)\ell)$, the last possible dimension six semi-leptonic FCNC operators, are helicity-suppressed in the MSSM[32] and, being also phase-space suppressed, do not lead to any significant effect [13]. Further, they cannot arise from R-parity violating couplings.

6 Conclusion

The $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, $K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0\mu^+\mu^-$ decay modes are the only theoretically clean windows into the $\Delta S = 1$ sector. If SUSY is discovered, the pattern of deviations they could exhibit with respect to the SM (see Table 1) will be essential to constrain the MSSM parameter-space, and hopefully unveil the nature of the SUSY-breaking mechanism.

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