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Impact of $K_L \to \pi^0 \nu \bar{\nu}$ decay on high scale SUSY

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We analyze the contribution of the high-scale SUSY to the rare kaon decays $K_L \to \pi^0 \nu \bar{\nu}$ and $K^+ \to \pi^+ \nu \bar{\nu}$. Taking account of the recent LHC results for the Higgs discovery and the SUSY searches, we consider the high-scale SUSY at the $10-50$TeV scale in the framework of the non-minimal squark (slepton) flavor mixing. The chargino up-squark Z penguin dominates the SUSY contribution for these decays. At the 10 TeV scale of the SUSY, the chargino contribution can enhance the branching ratio of $K_L \to \pi^0 \nu \bar{\nu}$ in several times compared with the SM predictions whereas the predicted branching ratio of $K^+ \to \pi^+ \nu \bar{\nu}$ increases up to about three times of the SM one. Even if the SUSY scale is 50 TeV, the chargino process still enhances the branching ratio of $K_L \to \pi^0 \nu \bar{\nu}$ from the SM prediction by the factor two. We also discuss the correlation with the CP violating parameters ε_K and $\varepsilon'_K/\varepsilon_K$.

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1. Introduction

The K meson physics have provided important informations in the indirect search for New Physics (NP). Among them, the rare decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ are known as the theoretically clean processes [1] and strongly suppressed ones in the SM [2]. Therefore, these both processes have been considered to be one of the powerful probes of NP. Especially, since the $K_L \to \pi^0\nu\bar{\nu}$ process is the CP violating one, it is expected to open the NP window of the CP violating flavor structure with the CP violating parameters ε_K and $\varepsilon'_K/\varepsilon_K$.

The upper bound of the branching ratio of $K_L \to \pi^0\nu\bar{\nu}$ is given by the KEK E391a experiment [3], and the branching ratio of $K^+ \to \pi^+\nu\bar{\nu}$ measured by the BNL E787 and E949 experiments [4] is consistent with the SM prediction [2]; $BR(K_L \to \pi^0\nu\bar{\nu})_{\rm exp} < 2.6 \times 10^{-8}$ (90%C.L.) and $BR(K^+ \to \pi^+\nu\bar{\nu})_{\rm exp} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$. At present, the J-PARC KOTO experiment is an in-flight measurement of $K_L \to \pi^0\nu\bar{\nu}$ approaching to the SM predicted precision [5], while the CERN NA62 experiment studies the $K^+ \to \pi^+\nu\bar{\nu}$ process [6].

On the other hand, although the supersymmetry (SUSY) is one of the most attractive candidates for the NP, the SUSY signals have not been observed yet. The squark and the gluino masses are supposed to be at higher scale than 1 TeV [7]. Moreover, the SUSY models have been seriously constrained by the Higgs discovery, in which the Higgs mass is 126 GeV. These facts suggest a class of SUSY models with heavy sfermions.

Therefore, we investigate the high-scale SUSY contribution to $K_L \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$ in the framework of the mass eigenstate of the SUSY particles. We consider the relevant SUSY particle spectrum constrained by the observed Higgs mass [8] with the non-minimal squark (slepton) flavor mixing. This talk is based on the work Ref.[9].

2. Setup of the squark flavor mixing

We present the setup of our calculation in the framework of the high-scale SUSY. Current LHC results on SUSY that the lower bounds of the gluino mass and squark masses exceed 1 TeV may suggest the high-scale SUSY. Taking account of these recent results, we consider the high-scale SUSY at 10, 50 TeV, in which the $K \to \pi\nu\bar{\nu}$ decays are discussed.

For the SUSY scale of 10 to 50 TeV, we have already obtained the SUSY mass spectra which realize the Higgs mass at the electroweak scale with Renormalization Group Equation (RGE) running in previous work [8]. We use this numerical result for the SUSY particle mass spectrum, where the 1st and 2nd generation squarks are almost degenerate in mass due to the assumption of the universal soft masses. On the other hand, the 3rd generation squark masses obtain the large contribution from the RGE running due to the large Yukawa coupling of the top-quark. Therefore, we can neglect the mixing between 1st and 2nd squarks. Once the SUSY mass spectrum is fixed, we can calculate the left-right mixing angle θ^q, and they are very small in our framework.

The SUSY provides the new flavor mixing through the quark-squark-gaugino couplings and the lepton-slepton-gaugino ones. The 6×6 squark mass matrix $M^2_{\tilde{q}}$ in the super-CKM basis turns to the mass eigenstate basis by diagonalizing with rotation matrix $\Gamma^{(q)}$ as

$$m^2_{\tilde{q}} = \Gamma^{(q)} M^2_{\tilde{q}} \Gamma^{(q)\dagger} , \tag{2.1}$$

where $\Gamma^{(q)}$ is the 6×6 unitary matrix, and we decompose it into the 3×6 matrices as $\Gamma^{(q)} = (\Gamma_L^{(q)},\ \Gamma_R^{(q))})^T$ in the following expressions:

$$\Gamma_L^{(q)} = \begin{pmatrix} c_{13}^{qL} & 0 & s_{13}^{qL}e^{-i\phi_{13}^{qL}}c_{\theta^q} & 0 & 0 & -s_{13}^{qL}e^{-i\phi_{13}^{qL}}s_{\theta^q}e^{i\phi^q} \\ -s_{23}^{qL}s_{13}^{qL}e^{i(\phi_{13}^{qL}-\phi_{23}^{qL})} & c_{23}^{qL} & s_{23}^{qL}c_{13}^{qL}e^{-i\phi_{23}^{qL}}c_{\theta^q} & 0 & 0 & -s_{23}^{qL}c_{13}^{qL}e^{-i\phi_{23}^{qL}}s_{\theta^q}e^{i\phi^q} \\ -s_{13}^{qL}c_{23}^{qL}e^{i\phi_{13}^{qL}} & -s_{23}^{qL}e^{i\phi_{23}^{qL}} & c_{13}^{qL}c_{23}^{qL}c_{\theta^q} & 0 & 0 & -c_{13}^{qL}c_{23}^{qL}s_{\theta^q}e^{i\phi^q} \end{pmatrix},$$

$$\Gamma_R^{(q)} = \begin{pmatrix} 0 & 0 & s_{13}^{qR}s_{\theta^q}e^{-i\phi_{13}^{qR}}e^{-i\phi^q} & c_{13}^{qR} & 0 & s_{13}^{qR}e^{-i\phi_{13}^{qR}}c_{\theta^q} \\ 0 & 0 & s_{23}^{qR}c_{13}^{qR}s_{\theta^q}e^{-i\phi_{23}^{qR}}e^{-i\phi^q} & -s_{13}^{qR}s_{23}^{qR}e^{i(\phi_{13}^{qR}-\phi_{23}^{qR})} & c_{23}^{qR} & s_{23}^{qR}c_{13}^{qR}e^{-i\phi_{23}^{qR}}c_{\theta^q} \\ 0 & 0 & c_{13}^{qR}c_{23}^{qR}s_{\theta^q}e^{-i\phi^q} & -s_{13}^{qR}c_{23}^{qR}e^{i\phi_{13}^{qR}} & -s_{23}^{qR}e^{i\phi_{23}^{qR}} & c_{13}^{qR}c_{23}^{qR}c_{\theta^q} \end{pmatrix}, \qquad (2.2)$$

where we use abbreviations $c_{ij}^{qL,qR} = \cos\theta_{ij}^{qL,qR}$, $s_{ij}^{qL,qR} = \sin\theta_{ij}^{qL,qR}$, $c_{\theta^q} = \cos\theta^q$ and $s_{\theta^q} = \sin\theta^q$. We take $s_{12}^{qL,qR} = 0$ due to the degenerate squark masses of the 1st and the 2nd family. The θ^q is the left-right mixing angle between $\tilde{q}_L$ and $\tilde{q}_R$, and they are calculable once we have fixed the squark mass spectra. Then, there are free mixing parameters $\theta_{ij}^{qL,qR}$ and $\phi_{ij}^{qL,qR}$. For simplicity, we assume $s_{ij}^{qL} = s_{ij}^{qR}$. On the other hand, we scatter ϕ_{ij}^{qL} and ϕ_{ij}^{qR} in the $0 \sim 2\pi$ range independently. It should be noted that the mixing angles $s_{ij}^{qL(R)}$ have not been constrained by the experimental data of B, D and K mesons in the framework of the high-scale SUSY [8].

For the lepton sector, the mixing matrices $\Gamma_{L(R)}^{(\ell)}$ have the same structure as the quark one in the charged-lepton flavors, however, there is only the left-handed $\Gamma_L^{(\nu)}$ in neutrinos.

In our calculations, the chargino contributions dominate the $K \to \pi\nu\bar{\nu}$ processes [10]. Since the charged Higgs is heavy, $\mathcal{O}$(10TeV), the charged Higgs contribution is suppressed.

3. Numerical analysis

Let us discuss the high-scale SUSY contribution to the $K \to \pi\nu\bar{\nu}$ processes. We take the CKM parameters V_{cb}, $\bar{\rho}$ and $\bar{\eta}$ at the 90 % C.L. of the experimental data:

$$|V_{cb}| = (41.1 \pm 1.3)\times 10^{-3}, \qquad \bar{\rho} = 0.117 \pm 0.021, \qquad \bar{\eta} = 0.353 \pm 0.013. \qquad (3.1)$$

In the beginning, we show the numerical result at the SUSY scale of 10 TeV. Fig.1 (*left*) shows the prediction on the $BR(K_L \to \pi^0\nu\bar{\nu})$ vs. $BR(K^+ \to \pi^+\nu\bar{\nu})$ plane, where phase parameters are constrained by the observed $|\varepsilon_K|$ with the experimental error-bar of 90%C.L. Here, we fix the mixing parameters in Eq.(2.2) by taking the common value $s_{i3}^{uL} = s_{i3}^{uR} = s^u = 0.1$ $(i = 1,2)$ and $s_{i3}^{dL} = s_{i3}^{dR} = s^d = 0.1$ $(i = 1,2)$ for the up-quark and the down-quark sectors, respectively. The chargino up-squark Z penguin dominates the SUSY contribution to these branching ratios. The SUSY contributions can enhance the branching ratio of $K_L \to \pi^0\nu\bar{\nu}$ in several times compared with the SM predictions [2].On the other hand, the predicted $BR(K^+ \to \pi^+\nu\bar{\nu})$ increases up to about three times.Although there is a strong constraint from ε_K, these processes can be enhanced even if the SUSY scale is 10 TeV. It is also noticed that the predicted lower bound is reduced to much smaller than 10^{-11} due to the cancellation between the SM and SUSY contributions.

Fig.1 (*right*) shows the case of the SUSY scale of 50 TeV, where the mixing angle is fixed at $s^u = s^d = 0.3$. Although the predicted region is reduced considerably comparing to the case of the

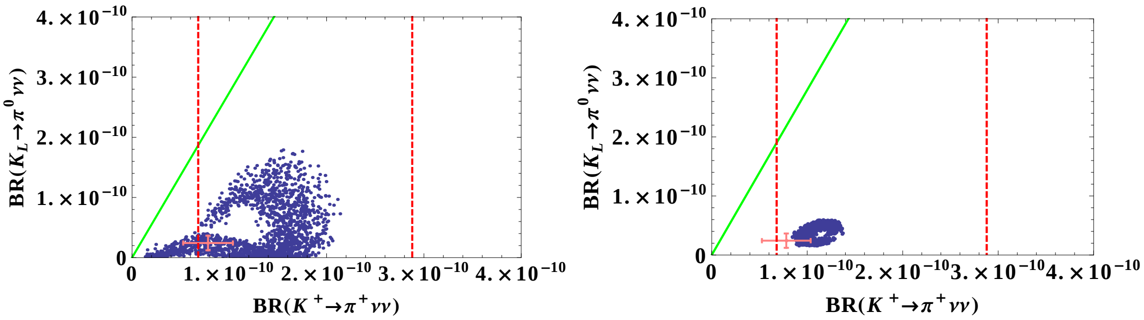

Figure 1: The predicted $BR(K_L \to \pi^0 \nu\bar{\nu})$ versus $BR(K^+ \to \pi^+ \nu\bar{\nu})$ at the SUSY scale of 10 TeV with the mixing angle of $s^u = s^d = 0.1$ (*left*) and at the SUSY scale of 50 TeV with the mixing angle of $s^u = s^d = 0.3$ (*right*). The pink cross denotes the SM predictions. The red dashed lines are the 1σ experimental bounds for $BR(K^+ \to \pi^+ \nu\bar{\nu})$. The green slanting line shows the Grossman-Nir bound [14].

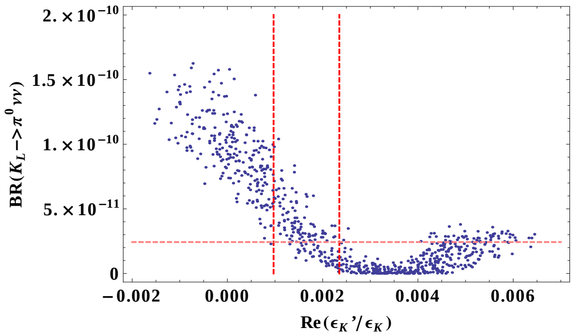

Figure 2: The predicted $BR(K_L \to \pi^0 \nu\bar{\nu})$ versus $\mathrm{Re}(\varepsilon'_K/\varepsilon_K)$ with $s^u, s^d = 0.1$ at the SUSY scale of 10 TeV. The red dashed lines denote the 3σ experimental bounds of $\mathrm{Re}(\varepsilon'_K/\varepsilon_K)$. The pink dashed line denotes the central value of the SM prediction for $BR(K_L \to \pi^0 \nu\bar{\nu})$.

10 TeV scale in Fig. 1 (*left*), the predicted branching ratio of $K_L \to \pi^0 \nu\bar{\nu}$ is enhanced in two times from the SM prediction, and the branching ratio of $K^+ \to \pi^+ \nu\bar{\nu}$ could be enhanced from the SM prediction in three times.

Let us discuss a correlation between the ratio $\varepsilon'_K/\varepsilon_K$ and the branching ratio of $K_L \to \pi^0 \nu\bar{\nu}$. The recent estimation for $\varepsilon'_K/\varepsilon_K$ in SM is upgraded by Ref.[11] taking account of the progress in lattice calculation. Here we calculate $\varepsilon'_K/\varepsilon_K$ by using the formula for $\varepsilon'_K/\varepsilon_K$ including the estimation for the hadronic matrix element in Ref.[12]. Fig. 2 shows the prediction on the $BR(K_L \to \pi^0 \nu\bar{\nu})$ vs. $\varepsilon'_K/\varepsilon_K$. It is found that the enhancement $BR(K_L \to \pi^0 \nu\bar{\nu})$ implies the suppression of $\varepsilon'_K/\varepsilon_K$ as same as the results in other work [13]. This correlation is understood by the fact that the electroweak penguin contributes to $\varepsilon'_K/\varepsilon_K$ with negative sign. If the enhancement in the branching ratio for $K_L \to \pi^0 \nu\bar{\nu}$ will be measured by KOTO in the near future, it will give strong constraint to the NP structure in $\varepsilon'_K/\varepsilon_K$.

4. Summary

We have studied the contribution of the high-scale SUSY to the $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ processes. These rare decays play an important role in the decision of the CP phase in the CKM matrix, furthermore, they are also sensitive to the flavor structure of the NP.

Taking account of the recent LHC results for the Higgs discovery and the SUSY searches, we consider the high-scale SUSY at the $10-50$ TeV scale. Then, we have discussed the effect of SUSY on $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ in the mass eigenstate basis of the SUSY particles assuming the non-minimal squark (slepton) flavor mixing.

We have calculated the SUSY contribution to the branching ratios of $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$, where phase parameters are constrained by the observed ε_K. The Z penguin mediated chargino dominates the SUSY contribution for these decays. At the 10 TeV scale of the SUSY, its contribution can enhance the branching ratio of $K_L \to \pi^0 \nu\bar{\nu}$ in several times compared with the SM predictions whereas the predicted branching ratio $BR(K^+ \to \pi^+ \nu\bar{\nu})$ increases up to about three times of the SM prediction in the case of the up-squark mixing $s^u = 0.1$. Even if the SUSY scale is 50 TeV, the chargino process still enhances the branching ratio of $K_L \to \pi^0 \nu\bar{\nu}$ from the SM prediction in the factor two. We also discuss the correlation between $\varepsilon'_K/\varepsilon_K$ and the branching ratio of $K_L \to \pi^0 \nu\bar{\nu}$, which is sensitive to the NP.

We expect the measurement of these processes will be improved by the J-PARC KOTO experiment and CERN NA62 experiment in the near future.

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