\( \varepsilon'/\varepsilon \) and Rare \( K \) Decays in the Standard Model and Supersymmetry

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After briefly reviewing the status of \( \varepsilon'/\varepsilon \) in the Standard Model, I discuss SUSY contributions to \( \varepsilon'/\varepsilon \), \( K^+ \to \pi^+\nu\bar{\nu} \), \( K_L \to \pi^0\nu\bar{\nu} \) and \( K_L \to \pi^0 e^+e^- \). While in the simplest case of the MSSM with Minimal Flavour Violation the main effect is a suppression of these transitions with respect to the Standard Model, large enhancements are possible in more general SUSY models, with interesting correlations among the different processes.

1. Introduction

After the new measurements of \( \varepsilon'/\varepsilon \) provided by the KTeV and NA48 collaborations, \( \text{Re} \varepsilon'/\varepsilon = (28.0 \pm 4.1) \) \[1\], \( \text{Re} \varepsilon'/\varepsilon = (14.0 \pm 4.3) \) \[2\], some very interesting theoretical questions have arisen: i) Does the Standard Model (SM) prediction for \( \varepsilon'/\varepsilon \) agree with the above experimental results? ii) What kinds of new physics can improve the agreement with the experiment? iii) In particular, in the framework of SUSY models, in what region of SUSY parameter space can large contributions to \( \varepsilon'/\varepsilon \) arise? iv) What is the impact of \( (\varepsilon'/\varepsilon)_{\text{exp}} \) on predictions for rare \( K \) decays, both in the SM and beyond?

In this talk, I will briefly discuss the above questions. Unfortunately, most of them depend very strongly on poorly understood hadronic dynamics. Therefore, for most of the above questions no conclusive answers can be provided at present.

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2. A quick look at \( \varepsilon'/\varepsilon \) in the SM

The basic formula for \( \varepsilon'/\varepsilon \) is given by
\[
\frac{\varepsilon'}{\varepsilon} = \text{Im} \lambda_t \cdot F_{\varepsilon'},
\]
where
\[
F_{\varepsilon'} = \left[ P^{(1/2)} - P^{(3/2)} \right],
\]
and we have neglected the small phase difference between \( \varepsilon \) and \( \varepsilon' \). Here
\[
\langle Q_i \rangle_I \equiv \langle (\pi\pi)_I | Q_i | K \rangle ,
\]
\[
r = \frac{G_F \omega}{2|\varepsilon|\text{Re} A_0} \quad \text{and} \quad \omega = \frac{\text{Re} A_2}{\text{Re} A_0} \sim \frac{1}{22} \] \[6\]
(see however ref. \[3\] for possible isospin breaking effects in \( \omega \)). The complete listing of the four-fermion operators \( Q_i \) is given for example in \[4\]. The Wilson coefficient functions \( y_i(\mu) \) were calculated including the complete next-to-leading order (NLO) corrections in \[5\]. The details of these calculations can be found there and in the review \[6\].

It is customary (and convenient) to write \( \langle Q_i \rangle_I \equiv \langle (Q_i)_I \rangle_{\text{VIA}} B_i^{(I)} \), where the \( B_i^{(I)} \) parameterize the deviation of the full matrix elements from the Vacuum Insertion Approximation (VIA). However, by doing so one introduces
a strong dependence on the mass of the strange quark $m_s$, which could be avoided if one were able to compute directly the full matrix element $\hat{t}$.

The sum in (4) and (5) runs over all contributing operators. $P^{(3/2)}$ is fully dominated by electroweak penguin contributions. $P^{(1/2)}$ on the other hand is governed by QCD penguin contributions. Isospin breaking in the quark masses ($m_u \neq m_d$) induces a further $\Delta I = 3/2$ contribution. The latter effect is described by $\Omega_{\eta,\eta'}$.

The dominant contributions in the SM come from the QCD-penguin operator $Q_6$ and from the electroweak-penguin operator $Q_8$, as discussed in refs. [4], where further details as well as the full expressions for $\varepsilon'/\varepsilon$ can be found. $\varepsilon'/\varepsilon$ can then be written as

$$\varepsilon'/\varepsilon = \text{Im} \lambda_t F'_\varepsilon (m_t, \alpha_s, m_s, B_6^{(1/2)}, B_6^{(3/2)}, \Omega_{\eta,\eta'}, \Omega_{\eta',\eta}),$$

where only the main dependencies have been shown. $\text{Im} \lambda_t \equiv \text{Im} V_{td} V^*_{ts}$ has to be determined using the information on the Unitarity Triangle (UT) coming from $V_{ub}, V_{cb}, \varepsilon_K$ and $\Delta M_{B_s^0}$. Since the $\Delta I = 1/2$ contribution of $Q_6$ and the $\Delta I = 3/2$ contribution of $Q_8$ have opposite signs and cancel each other to a large extent, the final result for $\varepsilon'/\varepsilon$ depends very strongly on $B_6^{(1/2)}$ and $B_8^{(3/2)}$. Unfortunately, while $B_8^{(3/2)}$ can be reliably computed with lattice QCD (see ref. [10] for an up-to-date review), at present there is no computation of $B_6^{(1/2)}$ from first principles. Although some suggestions on how to compute $B_6^{(1/2)}$ on the lattice, including Final State Interactions (FSI), have been recently made [11], we have to face the fact that no reliable prediction for $B_6^{(1/2)}$ is currently available. This precludes to a large extent the possibility of a precise computation of $\varepsilon'/\varepsilon$ in the SM. If the value of $B_6^{(1/2)}$ is close to unity, then the SM prediction is smaller than the experimental value of $\varepsilon'/\varepsilon$. For instance, using $B_K = (0.80 \pm 0.15)$, $m_s(m_c) = (130 \pm 25)$ MeV, $B_6^{(1/2)} = (1.0 \pm 0.3)$, $B_8^{(3/2)} = (0.8 \pm 0.2)$ and $\Omega_{\eta,\eta'} = (0.16 \pm 0.03)$ as recently obtained in ref. [12] (see however [13] for an estimate of the uncertainties in isospin breaking effects), one gets the following prediction for $\varepsilon'/\varepsilon$ [14,15]:

$$\varepsilon'/\varepsilon_{\text{NDR}} = (9.2^{+6.8}_{-4.0}(19.3)) \times 10^{-4},$$

(7)

Since $B_6^{(1/2)}$ is certainly the less known ingredient in (4), it is instructive to compute $\varepsilon'/\varepsilon$ leaving $B_6^{(1/2)}$ as a free parameter. One gets, with the same choice of parameters as above,

$$(\varepsilon'/\varepsilon)_{\text{NDR}} = (16.2^{+8.9}_{-5.3} B_6^{(1/2)} - 7.8^{+2.0}_{-2.2}) \times 10^{-4}. \quad (8)$$

Other recent theoretical estimates of $\varepsilon'/\varepsilon$ are reported in table 1. They differ in the evaluation of the relevant hadronic matrix elements. The Rome group is using lattice results wherever they are available [14-16]. Their results are in good agreement with the estimates in eq. (6). The Dortmund group is computing higher order terms in the chiral and $1/N$ expansions, which unfortunately contain quadratic divergences. This makes it very difficult to reliably match their estimates of the hadronic matrix elements with the short distance computation [18]. The difficulty in the matching with the short distance part is also a limitation for Chiral Quark Model computations such as the one performed by the Trieste group [17]. The same problems arise in the Extended Nambu-Jona-Lasinio Model used by the Dubna group [21]. The Taipei group has applied generalized factorization to the computation of $K \to \pi\pi$ amplitudes [22]. Being just a general parameterization of nonleptonic decay amplitudes, gener-

| Reference       | $\varepsilon'/\varepsilon$ [10^{-4}] |
|-----------------|-------------------------------------|
| Munich         | $9.2^{+4.0}_{-4.0}(MC)$             |
| Munich         | $1.4 \to 32.7$ (S)                  |
| Rome           | $8.1^{+10.3}_{-9.5}$ (MC)            |
| Rome           | $-13.0 \to 37.0$ (S)                |
| Trieste        | $22 \pm 8$ (MC)                     |
| Trieste        | $9 \to 48$ (S)                      |
| Dortmund       | $6.8 \to 63.9$ (S)                  |
| Montpellier    | $24.2 \pm 8.0$                      |
| Granada-Lund   | $34 \pm 18$                        |
| Dubna-DESY     | $-3.2 \to 3.3$ (S)                  |
| Taipei         | $7 \to 16$                         |
| Barcelona-Valencia | $17 \pm 6$                  |
alized factorization provides no dynamical information. In order to obtain predictions for $\varepsilon'/\varepsilon$, some simplifying assumptions have to be made in order to reduce the number of unknown parameters. Unfortunately, these assumptions cannot be justified from first principles, nor can they be verified experimentally. QCD sum rules have been used in the Montpellier estimate of $\varepsilon'/\varepsilon$ \cite{13}. The Granada-Lund group has used the X-boson method to match the short-distance computation to an estimate of the matrix elements performed at the NLO in the $1/N$ expansion in the chiral limit \cite{20}.

What can we learn from the results in table 1? First of all, one should stress that, although quite improbable, it is not impossible to obtain $\varepsilon'/\varepsilon \sim 2 \times 10^{-3}$ using the Munich and Rome analyses. However, clearly a larger value of $B_6^{(1/2)}$ would improve the agreement with the experimental data. It is tempting to suppose that there is a common origin for the large value of $\varepsilon'/\varepsilon$ and the $\Delta I = 1/2$ rule. However, to relate these two quantities one has to make some dynamical assumption \cite{24} or to use some model, such as the ones discussed above. It is quite interesting that most of the model-dependent computations presently available, in which a connection between $\varepsilon'/\varepsilon$ and the $\Delta I = 1/2$ rule is established, find central values for $\varepsilon'/\varepsilon$ in the ballpark of the experimental value. However, more theoretical progress is needed to put this connection on solid grounds. Another interesting possibility, recently proposed in ref. \cite{23}, is that the large FSI in the $\Delta I = 1/2$ channel enhances the $\Delta I = 1/2$ matrix elements and effectively gives $B_6^{(1/2)} \sim 1.5$. Unfortunately, a reliable quantitative evaluation of FSI effects in $\langle Q_6 \rangle_{(1/2)}$ is not available yet, since the method applied in ref. \cite{23} to resum the pion bubble diagrams suffers from systematic uncertainties and only applies to the lowest order in the $1/N$ expansion (see refs. \cite{23,24} for further details and different opinions on this subject).

3. $\varepsilon'/\varepsilon$ and Rare $K$ Decays in SUSY with Minimal Flavour Violation

From the above discussion, it is clear that there is certainly still room for a large New Physics contribution to $\varepsilon'/\varepsilon$. It is therefore worthwhile to explore possible SUSY effects in $\varepsilon'/\varepsilon$. Let us start by considering a very constrained class of SUSY models, the MSSM with Minimal Flavour Violation (MFV), where no new phase and no new source of Flavour Violation is introduced. In this kind of extensions of the SM, all flavour and CP violation is governed by the CKM matrix. Rare $K$ decays and $\varepsilon'/\varepsilon$ can then be affected by SUSY in two ways. First of all, new contributions to the $\Delta S = 2$ amplitude, which in this class of models turn out to be always positive, modify the UT fit, resulting in smaller values for $\text{Im}\lambda_1$ and $\text{Re}\lambda_1$, and therefore suppressing $\varepsilon'/\varepsilon$ and rare $K$ decays. Then, there are new contributions to the $\Delta S = 1$ amplitudes. In a few cases, these can enhance the SM amplitudes and overcompensate the suppression due to $\text{Im}\lambda_1$ and $\text{Re}\lambda_1$, resulting in larger values of $\varepsilon'/\varepsilon$ and larger BR’s for rare $K$ decays. In most cases, however, the net effect is a suppression with respect to the SM. I summarize here the results of a recent detailed analysis in this class of models \cite{14}, taking into account all the available constraints (direct searches of SUSY particles, $\text{BR}(b \rightarrow s\gamma)$, precision electroweak data, lower bounds on the neutral Higgs mass):

- In most of the allowed parameter space, the overall effect is a suppression of $\varepsilon'/\varepsilon$, mainly due to the positive contributions to $\varepsilon$, as already found in ref. \cite{27};

- The strongest suppression of $\varepsilon'/\varepsilon$, of about a factor of two, is obtained for low $\tan\beta$, low $m_{H^\pm}$, for a light, mainly right-handed stop and for large splitting between the stops;

- A modest ($7\%$) enhancement of $\varepsilon'/\varepsilon$ can be obtained for relatively large $\tan\beta$ and $m_{H^\pm}$ and for a light chargino;

- The same pattern emerges for rare $K$ decays: $\text{BR}(K^+ \rightarrow \pi^+\nu\bar{\nu})$, $\text{BR}(K_L \rightarrow \pi^0\nu\bar{\nu})$ and $\text{BR}(K_L \rightarrow \pi^0e^+e^-)$ are mainly suppressed with respect to the SM prediction, up to approximately a factor of two, while only very modest enhancements are possible.
Table 2
The minimal and maximal values of the the ratios $T$ without constraints and with all constraints taken into account.

|        | No Constr. | All Constr. |
|--------|------------|-------------|
| $T$    | min max    | min max     |
| $T(\text{Im}\lambda_t)$ | 0.57 1.00 | 0.66 1.00 |
| $T(\text{Re}\lambda_t)$ | 0.78 1.00 | 0.81 1.00 |
| $T(\varepsilon'/\varepsilon)$ | 0.42 1.07 | 0.53 1.07 |
| $T(K^+ \to \pi^+\nu\bar{\nu})$ | 0.59 1.09 | 0.65 1.02 |
| $T(K_L \to \pi^0\nu\bar{\nu})$ | 0.28 1.12 | 0.41 1.03 |
| $T(K_L \to \pi^0e^+e^-)$ | 0.33 1.10 | 0.48 1.10 |

The minimal and maximal values of the ratios $T$, defined as the prediction in the MSSM with MFV normalized to the SM central value, are reported in table 2 (see ref. [14] for details).

4. $\varepsilon'/\varepsilon$ and Rare $K$ Decays in General SUSY Models

The situation drastically changes when one abandons the assumption of MFV and allows for the most general flavour and CP structure in the soft SUSY breaking terms. In this case, there are in general new independent contributions to $\Delta S = 2$, $\Delta B = 2$ and $\Delta S = 1$ transitions, with arbitrary phases. Furthermore, the so-called magnetic moment and chromomagnetic operators, negligible in the SM, can give large contributions to $\varepsilon'/\varepsilon$ and $K_L \to \pi^0e^+e^-$. The new flavour and CP violating parameters introduced in these models are subject to quite stringent constraints coming from the available FCNC data [28, 29]. However, it is interesting that, compatibly with these tight constraints, large contributions to $\varepsilon'/\varepsilon$ and rare $K$ decays are still possible [28, 31]. A combined analysis shows that interesting correlations can be established between these new contributions [31]. In the rest of this talk, I will briefly review three possible scenarios in which large SUSY contributions to $\varepsilon'/\varepsilon$ and rare $K$ decays are present.

$\pi^0e^+e^-$ the direct CP violating contribution to this decay.

4.1. Scenario I: Enhanced $Z^0$ Penguins

Colangelo and Isidori pointed out some time ago that a large $\bar{s}dZ$ vertex can be induced in the presence of large $t_R\bar{s}_L$ and $t_R\bar{d}_L$ mixings [30]. The $\bar{s}dZ$ vertex has a strong impact not only on the decays $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$ and $K_L \to \pi^0e^+e^-$, but also on $\varepsilon'/\varepsilon$ [32]. The experimental results on $\varepsilon'/\varepsilon$ then constrain the possible enhancement of rare decays. The effective $\bar{s}dZ$ vertex can be written as

$$\mathcal{H}_{\text{eff}}^{\bar{s}dZ} = \frac{G_F}{\sqrt{2}} \frac{e}{M_Z^2} \cos \Theta_W Z_{ds\bar{s}}\gamma_\mu Z_{\nu d_L} + \text{h.c.},$$

where

$$Z_{ds} = \lambda_t C_9(x_t) + \Lambda_t.$$  \hspace{1cm} (9)

Here the first term on the r.h.s is the Standard Model contribution (evaluated in the ‘t Hooft-Feynman gauge) and $\Lambda_t$ is an effective SUSY coupling, whose definition is given in ref. [31], where further details can be found. Since $Z_{ds}$ gives a negative contribution to $\varepsilon'/\varepsilon$, a large value of $\varepsilon'/\varepsilon$ favours negative values of $Z_{ds}$ (i.e. with the opposite sign compared to the SM). In table we report the upper bounds on rare decays for $\varepsilon'/\varepsilon = 2 \times 10^{-3}$ [33]. The upper bounds depend on the sign of $\Lambda_t$ and on the value of the SM coupling $\lambda_t$.

4.2. Scenario II: Enhanced Chromomagnetic Penguin

Another interesting possibility arises in models in which there is a sizable $\bar{s}_Rd_L$ mixing. In this kind of models, a large contribution is induced to the magnetic and chromomagnetic operators

$$Q^+ = \frac{Q_+}{16\pi^2} (\bar{s}_L\sigma^{\mu\nu} F_{\mu\nu} d_R \pm \bar{s}_R\sigma^{\mu\nu} F_{\mu\nu} d_L),$$

$$Q^\pm = \frac{Q^\pm}{16\pi^2} (\bar{s}_L\sigma^{\mu\nu} t^a G_{\mu\nu} d_R \pm \bar{s}_R\sigma^{\mu\nu} t^a G_{\mu\nu} d_L).$$

The chromomagnetic contribution to $\varepsilon'/\varepsilon$ is unfortunately affected by a large uncertainty in the evaluation of the hadronic matrix element. However, it is interesting to notice that in SUSY models with non-abelian flavour symmetries a chromomagnetic contribution to $\varepsilon'/\varepsilon$ in the ball-park of $2 \times 10^{-3}$ can naturally arise [34]. Large contributions of this kind can also arise in Left-Right
SUSY models. In some models, a large contribution to \( Q \overline{g} \) corresponds to a large contribution to \( Q \gamma \). In this case, \( BR(K_L \rightarrow \pi^0e^+e^-) \) can be sizably enhanced over the SM prediction, up to one order of magnitude (see ref. [31] for a detailed analysis).

### 4.3. Scenario III: Isospin Breaking in Squark Masses

Finally, let me briefly mention an interesting possibility proposed by Kagan and Neubert [35]. In SUSY models in which isospin breaking arises in quark masses, SUSY-QCD box diagrams give rise to the \( \Delta I = 3/2 \) transitions, which, as discussed in Sect. 2, enter in \( \varepsilon'/\varepsilon \) with the enhancement factor \( 1/\omega \sim 22 \). The \( d_L-\tilde{s}_L \) mixing is needed in order to generate \( \Delta S = 1 \) transitions with this kind of diagrams.

### 5. Conclusions

Comparing the recent measurements of \( \varepsilon'/\varepsilon \) in eq. (8) with the theoretical estimate of the Munich group in eq. (9), it is clear that, for the range of parameters used in the Munich analysis in ref. [14], the SM prediction is somewhat lower than the experimental average. Within the framework of the SM, many suggestions have recently been made that bring the theoretical predictions closer to the experimental value. As I discussed in Sect. 2, most of model-dependent estimates of \( \varepsilon'/\varepsilon \) suggest a connection between the \( \Delta I = 1/2 \) rule and the large value of \( \varepsilon'/\varepsilon \). However, more theoretical work is needed to put this intriguing possibility on solid grounds. On the other hand, a lot of room is still available for large SUSY contributions to \( \varepsilon'/\varepsilon \). The possibility of SUSY effects in \( \varepsilon'/\varepsilon \) is certainly very exciting, in a world in which all other FCNC observables perfectly agree with SM predictions. If one considers the “simplest” SUSY extension of the SM, the MSSM with MFV, the results are however not so encouraging: for both \( \varepsilon'/\varepsilon \) and rare \( K \) decays, in most of the allowed parameter space the net effect is a depletion of all these observables with respect to the SM prediction. More interesting possibilities arise in those SUSY extensions of the SM in which new sources of flavour and CP violation are introduced. Remarkably, in most of these models the potentially large contributions to \( \varepsilon'/\varepsilon \) are accompanied by even larger contributions to rare \( K \) decays, which can for example enhance \( BR(K_L \rightarrow \pi^0\nu\overline{\nu}) \) and \( BR(K_L \rightarrow \pi^0e^+e^-) \) one order of magnitude above the SM upper bound. We therefore eagerly await for future progress both on the theoretical side, with improved estimates of hadronic matrix elements, and on the experimental side, with improved measurements of \( \varepsilon'/\varepsilon \) and more stringent upper bounds and measurements of rare \( K \) decays.

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