I discuss the estimate of the CP-violating parameter $\varepsilon'/\varepsilon$ based on hadronic matrix elements computed in the chiral quark model. This estimate suggested, before the current experimental results, that the favored value of $\varepsilon'/\varepsilon$ in the standard model is of the order of $10^{-3}$. I briefly review the physical effects on which this result is based and summarize current estimates.

If we imagine to be back in 1997—looking at the experimental results for the ratio $\varepsilon'/\varepsilon$ and its theoretical estimates—we will find ourselves in a rather confusing situation in which the theoretical estimates favor values of the order of $10^{-4}$ and the experiments disagree by more than $3\sigma$ of their errors, and, moreover, do not rule out the super-weak scenario in which $\varepsilon'/\varepsilon$ vanishes (for a review, see, [1]). That was the situation when we decided to assess our theoretical understanding and possibly provide a new estimate. The crucial point was, and still is, that, if there is no sizable cancellation between some of the relevant effective operators, the order of magnitude of $\varepsilon'/\varepsilon$ is bound to be of the order of $10^{-3}$. A simple argument for this is presented in [2]. The problem is that any cancellation, or the lack thereof, among the operators heavily depends on the size of the hadronic matrix elements and, in 1997, there was no estimate of them that was free of hard-to-control assumptions.

Was it possible to improve on this situation? We wanted to estimate the hadronic matrix elements in a systematic manner without having first to solve QCD (not even by lattice simulation). To do this we needed a model that would be simple enough to understand its dynamics and, at the same time, not too simple so as to still include what we thought was the relevant physics. We chose the chiral quark model [3] in which all coefficients of the relevant chiral lagrangian are parameterized in terms of just three parameters: the quark and gluon condensates, and the quark constituent mass. The model makes possible a complete estimate of all matrix elements, it includes non-factorizable effects, chiral corrections and final-state interaction, all of which we thought to be relevant. In order to determine the three free parameters of the model, the experimental CP-conserving, isospin $I = 0$ and 2 components of the $K \to \pi\pi$ amplitudes, respectively $A_0$ and $A_2$, are fitted to obtain the values reported in [4] for the parameters. The systematic uncertainty of this approach is included by varying the fit by 30% around the experimental values of the amplitudes. Notice that the parameter values turn out to be rather close to those found by independent estimates, even though a priori they could have
been any number. Moreover, the $\Delta I = 1/2$ rule is reproduced in a natural manner (see for a discussion). This rule is such a fundamental feature of kaon physics that no estimate of $\varepsilon'/\varepsilon$ can be said reliable unless it also reproduces this selection rule.

These results are stable under changes of the renormalization scale and $\gamma_5$-scheme (see for details).

Having fixed the model-dependent parameters, we can proceed and compute the ratio $\varepsilon'/\varepsilon$. As it can be seen from fig. 2, the gluon penguin operator $Q_6$ dominates all other operators so that the final value of CP-violating ratio turns out to be of the expected order of $10^{-3}$, and the standard model does not mimic the super-weak scenario. This is the main result of our analysis; its publication in 1997 correctly predicted the current experimental results. The present estimate is an update of the short-distance inputs which also contains an improved treatment of the uncertainties. To estimate the uncertainty of our result we can vary, according to a Gaussian distribution, all the short-distance inputs and by a flat distribution the model-dependent parameters to obtain the distribution of values shown in fig. 3. Such a distribution gives the value

$$\varepsilon'/\varepsilon = (2.2 \pm 0.8) \times 10^{-3},$$  \hfill (1)

in good agreement with the current experimental average

$$\varepsilon'/\varepsilon = (1.9 \pm 0.46) \times 10^{-3},$$  \hfill (2)

where the error has been inflated according to the Particle Data Group procedure to be used when averaging over experimental data with substantially different central values. In a more conservative approach all inputs are varied with uniform probability over their whole ranges to obtain

$$0.9 \times 10^{-3} < \varepsilon'/\varepsilon < 4.8 \times 10^{-3}. $$  \hfill (3)

Given the intrinsic difficulty of the computation, I do not expect in the near future smaller uncertainties.

It is easy to go back into the computation and understand the final result. Chiral loops and final-state interactions both tend to enhance the $A_0$ amplitudes by making the gluon penguin contribution larger. Larger gluon penguins dominate the contribution of the electro-weak sector in $\varepsilon'/\varepsilon$ and no effective cancellation between the two occurs. Nonfactorizable (soft) gluon corrections make $A_2$ smaller. They play an important role in the $\Delta I = 1/2$ rule and in the determination of the model-dependent parameters although not directly in $\varepsilon'/\varepsilon$ where only penguin operators enter. Most of these effects can be summarized by saying that the bag factor $B_6$ of the the gluon operator $Q_6$ is much larger (at a given scale) than its vacuum-saturation value of 1.
Many of the points suggested by the chiral quark model analysis have been taken up by other groups after the current experiments favored a value of $\varepsilon'/\varepsilon$ of the order of $10^{-3}$. In particular, chiral corrections, non-factorizable effects, final-state interactions and effective-model estimates have been discussed recently.

In Fig. 4 current estimates are summarized; the same figure shows that, nowadays, contrarily to what is still too often repeated in papers and seminars, most standard model estimates agree with the experiments and with the prediction of the chiral quark model.

Because of its simplicity, the chiral quark model is clearly not the final word and it can now be abandoned—as a ladder used to climb a wall after we are on the other side—as we work for better estimates, in particular, those from the lattice simulations.

Acknowledgments

It is a pleasure to thank my collaborators S. Bertolini and J. O. Eeg and my former students V. Antonelli and E. I. Lashin for the work done together.

References

1. S. Bertolini, J. Eeg and M. Fabbrichesi, Rev. Mod. Phys. 72, 65 (2000).
2. M. Fabbrichesi, Nucl. Phys. B (Proc. Suppl.) 86, 322 (2000).
3. K. Nishijima, N. Cim. 11, 698 (1959); F. Gursey, N. Cim. 16 (1960) 23 and Ann. Phys. 12, 91 (1961); J. A. Cronin, Phys. Rev. 161, 1483 (1967); S. Weinberg, Physica 96A, 327 (1979); A. Manohar and H. Georgi, Nucl. Phys B234, 189 (1984); D. Espriu et al., Nucl. Phys B345, 22 (1990).
4. S. Bertolini et al., hep-ph/0002234; M. Fabbrichesi, hep-ph/0002235.
5. S. Bertolini et al., Nucl. Phys. B514, 63 (1998).
6. KTeV Collaboration (A. Alavi-Harati et al.), Phys. Rev. Lett. 83, 22 (1999); NA48 Collaboration (A. Ceccucci), http://www.cern.ch/NA48/.
7. S. Bertolini et al., Nucl. Phys. B514, 93 (1998).
8. T. Hambye et al., Nucl. Phys. B564, 391 (2000); hep-ph/0001088.
9. A. A. Bel’kov et al., hep-ph/9907335.
10. H.-Y. Cheng, Mod. Phys. Lett. A14, 2453 (1999).
11. E. Pallante and A. Pich, Phys. Rev. Lett. 84, 2508 (2000); E. A. Paschos, hep-ph/9912230; A. J. Buras et al., Phys. Lett. B480, 80 (2000).
12. S. Bosch et al., Nucl. Phys. B565, 3 (2000); M. Ciuchini et al., Nucl. Phys. B573, 201 (2000).
13. J. Bijnens and J. Prades, hep-ph/0005189.