PROCEEDINGS OF SCIENCE

Direct CP violation in $K \to \pi\pi$ decays and supersymmetry

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The quantities ε'_K and ε_K measure the amount of direct and indirect CP violation in $K \to \pi\pi$ decays, respectively. Using the recent lattice results from the RBC and UKQCD Collaborations and a new compact implementation of the $\Delta S = 1$ renormalization group evolution we predict

$$\mathrm{Re}\,\frac{\varepsilon'_K}{\varepsilon_K} = (1.06 \pm 5.07) \times 10^{-4}$$

in the Standard Model. This value is $2.8\,\sigma$ below the experimental value of

$$\mathrm{Re}\,\frac{\varepsilon'_K}{\varepsilon_K} = (16.6 \pm 2.3) \times 10^{-4}.$$

In generic models of new physics the well-understood ε_K precludes large contributions to ε'_K, if the new contributions enter at loop level. However, one can resolve the tension in $\varepsilon'_K/\varepsilon_K$ within the Minimal Supersymmetric Standard Model. To this end two features of supersymmetry are crucial: First, one can have large isospin-breaking contributions (involving the strong instead of the weak interaction) which enhance ε'_K. Second the Majorana nature of gluinos permits a suppression of the MSSM contribution to ε_K, because two box diagrams interfere destructively.

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1. Formalism and Standard-Model prediction

Flavour-changing neutral current (FCNC) transitions of Kaons are extremely sensitive to new physics and probe mass scales far above the reach of current high-p_T experiments. $K \to \pi\pi$ decays give access to two CP-violating quantities, which are related to FCNC amplitudes changing strangeness S by one or two units, respectively. To define these quantities ε'_K and ε_K one first combines the decay amplitudes $A(K^0 \to \pi^+\pi^-)$ and $A(K^0 \to \pi^0\pi^0)$ into $A_0 \equiv A(K^0 \to (\pi\pi)_{I=0})$ and $A_2 \equiv A(K^0 \to (\pi\pi)_{I=2})$ where I denotes the strong isospin. Indirect CP violation (stemming from the $\Delta S = 2$ box diagrams) is quantified by

$$\varepsilon_K \equiv \frac{A(K_L \to (\pi\pi)_{I=0})}{A(K_S \to (\pi\pi)_{I=0})} = (2.228 \pm 0.011) \cdot 10^{-3} \cdot e^{i(0.97\pm0.02)\pi/4} \tag{1.1}$$

and was discovered in 1964 [1]. The measure of direct CP violation, which originates from the $\Delta S = 1$ Kaon decay amplitude, is[1]

$$\varepsilon'_K \simeq \frac{\varepsilon_K}{\sqrt{2}} \left[\frac{A(K_L \to (\pi\pi)_{I=2})}{A(K_L \to (\pi\pi)_{I=0})} - \frac{A(K_S \to (\pi\pi)_{I=2})}{A(K_S \to (\pi\pi)_{I=0})} \right] = (16.6 \pm 2.3) \cdot 10^{-4} \cdot \varepsilon_K. \tag{1.2}$$

This experimental result was established in 1999 and constituted the first measurement of direct CP violation in any decay [2]. Adopting the standard phase convention for the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, the real parts of the isospin amplitudes are experimentally determined as

$$\mathrm{Re}A_0 = (3.3201 \pm 0.0018) \times 10^{-7}\ \mathrm{GeV}, \qquad \mathrm{Re}A_2 = (1.4787 \pm 0.0031) \times 10^{-8}\ \mathrm{GeV}. \tag{1.3}$$

The master equation for $\varepsilon'_K/\varepsilon_K$ (see e.g. Ref. [3]) reads:

$$\frac{\varepsilon'_K}{\varepsilon_K} = \frac{\omega_+}{\sqrt{2}|\varepsilon_K^{\mathrm{exp}}|\mathrm{Re}A_0^{\mathrm{exp}}} \left\{ \frac{\mathrm{Im}A_2}{\omega_+} - \left(1 - \hat{\Omega}_{\mathrm{eff}}\right) \mathrm{Im}A_0 \right\}. \tag{1.4}$$

Here $\omega_+ \simeq \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0} = (4.53 \pm 0.02) \cdot 10^{-2}$ is determined from the charged counterparts of $\mathrm{Re}A_{0,2}$ and $\hat{\Omega}_{\mathrm{eff}} = (14.8 \pm 8.0) \cdot 10^{-2}$ quantifies isospin breaking. The quantities $|\varepsilon_K^{\mathrm{exp}}|$ and $\mathrm{Re}A_0^{\mathrm{exp}}$ are also taken from experiment, as indicated.

The important theoretical ingredients encoding potential new-physics effects are $\mathrm{Im}A_0$ and $\mathrm{Im}A_2$, which are calculated from the effective hamiltonian $H^{|\Delta S|=1}$ describing $s \to d q\bar{q}$ decays. This hamiltonian is known for a while at the level of next-to-leading-order (NLO) in QCD [4] and a precise prediction of $\varepsilon'_K/\varepsilon_K$ is challenged by the difficulty to calculate the hadronic matrix elements of the operators in $H^{|\Delta S|=1}$. Within the Standard Model (SM) $\mathrm{Im}A_0$ is dominated by gluon penguins, with roughly 2/3 stemming from the matrix element $\langle (\pi\pi)_{I=0}|Q_6|K^0\rangle$ with the operator

$$Q_6 = \bar{s}_L^j \gamma_\mu d_L^k \sum_q \bar{q}_R^k \gamma^\mu q_R^j. \tag{1.5}$$

About 3/4 of the contribution to $\mathrm{Im}A_2$ stems from $\langle (\pi\pi)_{I=2}|Q_8|K^0\rangle$ with

$$Q_8 = \frac{3}{2} \bar{s}_L^j \gamma_\mu d_L^k \sum_q e_q \bar{q}_R^k \gamma^\mu q_R^j. \tag{1.6}$$

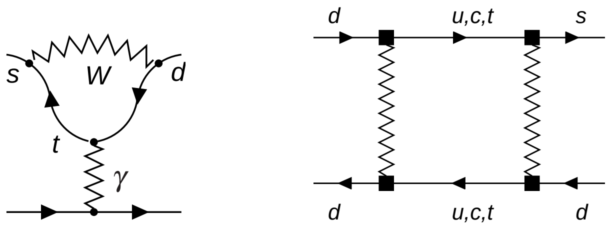

Figure 1: Sample diagrams of electroweak penguins and boxes, which contribute to the Wilson coefficient of Q_8.

The Wilson coefficient of Q_8 stems from electroweak penguins and box diagrams (Fig. 1). Lattice-gauge theory has $\langle(\pi\pi)_{I=2}|Q_8|K^0\rangle$ (and thereby $\mathrm{Im}A_2$) under good control for some time [5], while lattice calculations of $\langle(\pi\pi)_{I=0}|Q_6|K^0\rangle$ and the other matrix elements entering $\mathrm{Im}A_0$ are new [6]. The results are consistent with earlier analytic calculations in the large-N_c "dual QCD" approach [7]. Using these matrix elements from lattice QCD we find [8]

$$\frac{\varepsilon'_K}{\varepsilon_K} = (1.06 \pm 4.66_{\text{Lattice}} \pm 1.91_{\text{NNLO}} \pm 0.59_{\text{IV}} \pm 0.23_{m_t}) \times 10^{-4}. \qquad (1.7)$$

The various sources of errors are indicated in the subscripts, with "NNLO" referring to unknown higher-orders of the perturbative expansion and "IV" meaning isospin violation. Adding the errors in quadrature gives the result in the abstract. We use the methodology of [9], which exploits the CP-conserving data of Eq. (1.3) to constrain the matrix elements. To arrive at Eq. (1.7) we have implemented a novel compact solution of the renormalization group equations; the result is in full agreement with the calculation in Ref. [3]. Eq. (1.7) disagrees with the experimental number in Eq. (1.2) by 2.8 standard deviations. The original lattice paper, Ref. [6], quotes a smaller discrepancy. The discussion at this conference has indicated that the combination of Eq. (1.3) with Fierz identities between different matrix elements has lead to the sharper prediction in Refs. [3, 8].

2. A supersymmetric solution

The large factor $1/\omega_+$ multiplying $\mathrm{Im}A_2$ in Eq. (1.4) renders $\varepsilon'_K/\varepsilon_K$ especially sensitive to new physics in the $\Delta I = 3/2$ decay $K \to (\pi\pi)_{I=2}$. This feature makes $\varepsilon'_K/\varepsilon_K$ special among all FCNC processes. However, it is difficult to place a large effect into ε'_K without overshooting ε_K: The SM contributions to both quantities are governed by the CKM combination

$$\tau = -\frac{V_{td}V_{ts}^*}{V_{ud}V_{us}^*} \sim (1.5 - i0.6) \cdot 10^{-3}. \qquad (2.1)$$

Our quantities scale as

$$\varepsilon_K'^{\text{SM}} \propto \mathrm{Im}\,\frac{\tau}{M_W^2} \qquad \text{and} \qquad \varepsilon_K^{\text{SM}} \propto \mathrm{Im}\,\frac{\tau^2}{M_W^2}. \qquad (2.2)$$

[1] Accidentally, $\varepsilon'_K/\varepsilon_K$ is essentially real.

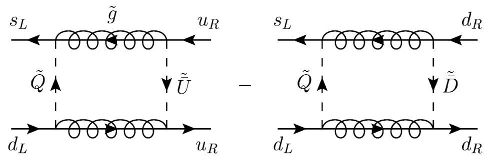

Figure 2: "Trojan penguin" diagrams [12]. The difference of the two boxes contributes to the $\Delta I = 3/2$ amplitude and increases with the mass difference among right-handed up-type ($\tilde{U}$) and down-type ($\tilde{D}$) squark. $\tilde{Q}$ denotes a left-handed squark, which is a strange-down mixture.

In new-physics scenarios τ is replaced by some new $\Delta S = 1$ parameter δ and M_W is replaced by some particle mass $M \gg M_W$. The new-physics contributions scale as

$$\varepsilon_K'^{\rm NP} \propto {\rm Im}\,\frac{\delta}{M^2}, \qquad \text{and} \qquad \varepsilon_K^{\rm NP} \propto {\rm Im}\,\frac{\delta^2}{M^2}. \tag{2.3}$$

If new-physics enters through a loop, the only chance to have a detectable effect in ε_K' is a scenario with $|\delta| \gg |\tau|$. Using Eqs. (2.2) and (2.3) the experimental constraint $|\varepsilon_K^{\rm NP}| \leq |\varepsilon_K^{\rm SM}|$ entails

$$\left|\frac{\varepsilon_K'^{\rm NP}}{\varepsilon_K'^{\rm SM}}\right| \leq \frac{\left|\varepsilon_K'^{\rm NP}/\varepsilon_K'^{\rm SM}\right|}{\left|\varepsilon_K^{\rm NP}/\varepsilon_K^{\rm SM}\right|} = \mathscr{O}\left(\frac{{\rm Re}\,\tau}{{\rm Re}\,\delta}\right). \tag{2.4}$$

Thus large effects in ε_K' from loop-induced new physics are seemingly forbidden. Many studies of ε_K' indeed involve new-physics scenarios with tree-level contributions to ε_K' [10], in which the requirement $|\delta| \gg |\tau|$ can be relaxed.

Here we present an explanation of the measurement in Eq. (1.2) by a supersymmetric loop effect [11]. We circumvent the argument in Eq. (2.4) by exploiting two special features of the Minimal Supersymmetric Standard Model (MSSM): Firstly, the MSSM permits large $\Delta I = 3/2$ transitions mediated by the strong interaction ("Trojan penguins") [12]. These enhanced amplitudes occur if the mass splitting between the right-handed up and down squarks is sizable (see Fig. 2). Secondly, the Majorana nature of the gluino permits the suppression of ε_K, which receives contributions from two squark-gluino box diagrams ("regular" and "crossed"). These diagrams cancel each other efficiently, once the gluino mass $m_{\tilde{g}}$ and the squark mass $m_{\tilde{Q}}$ in the loop satisfy $m_{\tilde{g}} \geq 1.5 m_{\tilde{Q}}$ [13]. In our scenario, the mass scale M_S of the supersymmetric particles is large, of order 3–7 TeV. Squark flavour mixing appears only among the left-handed doublets. We choose the CP-violating phase of the (2,1) element Δ_{sd}^{LL} of the left-handed squark mass matrix equal to $\arg(\Delta_{sd}^{LL}) = \pi/4$. The results are shown in Fig. 3

3. Summary

Novel lattice results reveal a tension between the measured value of ε_K' in Eq. (1.2) and the SM prediction in Eq. (1.7). Within the MSSM one can simultaneously enhance ε_K' and suppress unwanted effects in ε_K. Our MSSM scenario works with large superpartner masses in the 3–7 TeV range and thereby comply with bounds from collider searches. Crucial elements are $m_{\tilde{g}} \geq 1.5 M_{\tilde{Q}}$, a sizable mass splitting between right-handed up and down squarks, and flavour mixing among left-handed squarks.

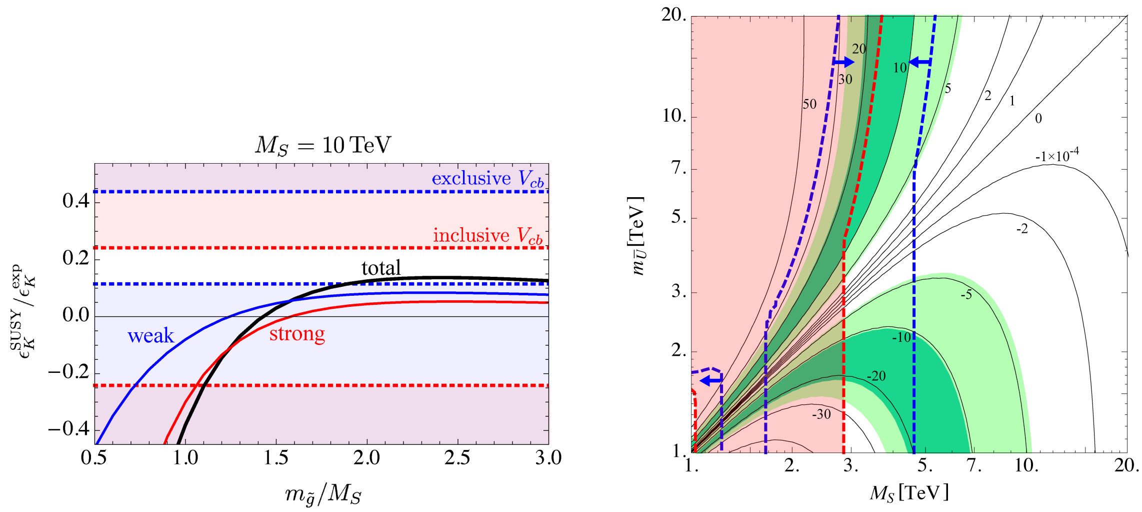

Figure 3: Left: $\varepsilon_K^{\rm SUSY}/\varepsilon_K^{\rm SM}$ as a function of $m_{\tilde g}/M_S$ for a common mass $M_S = 10\,$TeV of all superpartners except the gluino. Right: Parameter region explaining $\varepsilon'_K/\varepsilon_K$ while complying with the measured ε_K for the point $m_{\tilde g} = 1.5 M_S$ and $M_S = m_{\tilde Q} = m_{\tilde D}$. The lines labeled with negative values of the MSSM contribution $\varepsilon_K'^{SUSY}/\varepsilon_K$ correspond to correct (positive) solutions if the CP phase is appropriately adjusted. The SM prediction for ε_K strongly depends on $|V_{cb}|$. The blue (red) lines in both plots delimit the region which complies with ε_K if $|V_{cb}|$ is determined from exclusive (inclusive) $b \to c\ell\nu$ decays. If the exclusive determination is correct, some new physics in ε_K is welcome. In the inclusive case the forbidden region is marked with the red shading. For more details see Ref. [11], from which the plots are taken.

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PoS(ICHEP2016)564