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

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Combine decay amplitudes $A(K^0 \to \pi^+\pi^-)$ and $A(K^0 \to \pi^0\pi^0)$ into

$$A_0 \equiv A(K^0 \to (\pi\pi)_{I=0}) \qquad \text{and} \qquad A_2 \equiv A(K^0 \to (\pi\pi)_{I=2}),$$

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Indirect CP violation (from $\mathrm{K}-\overline{\mathrm{K}}$ mixing):

$$\epsilon_K \equiv \frac{A(K_L \to (\pi\pi)_{I=0})}{A(K_S \to (\pi\pi)_{I=0})} = (2.228 \pm 0.011) \cdot 10^{-3} \cdot e^{i(0.97 \pm 0.02)\pi/4}$$

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Direct CP violation (from decay amplitude):

$$\epsilon'_K \simeq \frac{\epsilon_K}{\sqrt{2}} \left[\frac{\langle(\pi\pi)_{I=2}|K_L\rangle}{\langle(\pi\pi)_{I=0}|K_L\rangle} - \frac{\langle(\pi\pi)_{I=2}|K_S\rangle}{\langle(\pi\pi)_{I=0}|K_S\rangle} \right] = (16.6 \pm 2.3) \cdot 10^{-4} \cdot \epsilon_K$$

discovered in 1999

Experimentally well-known:

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

$\uparrow$

assumes PDG convention for CKM elements

Master equation for ϵ'_K:

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

Here:

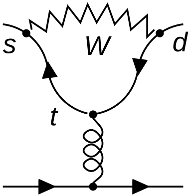
$$\omega_+ \simeq \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0} = (4.53 \pm 0.02) \cdot 10^{-2}$$

ϵ_K quantifies indirect CP violation in $\mathrm{K}-\overline{\mathrm{K}}$ mixing,
$\hat{\Omega}_{\rm eff} = (14.8 \pm 8.0) \cdot 10^{-2}$ quantifies isospin breaking.

Important theoretical ingredients: $\mathrm{Im}A_0$ and $\mathrm{Im}A_2$, calculated from the effective $|\Delta S| = 1$ hamiltonian describing $s \to d q \overline{q}$ decays.

The enhanced sensitivity to $\Delta I = 3/2$ transitions (such as electroweak penguins and boxes) is a special feature of ϵ'_K.

$\mathrm{Im}A_0$ is dominated by gluon penguins:



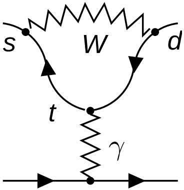
Operator: $Q_6 = \overline{s}_L^j \gamma_\mu d_L^k \sum_q \overline{q}_R^k \gamma^\mu q_R^j$

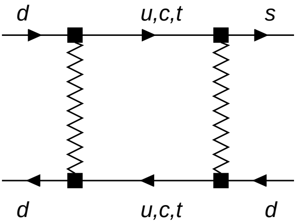
Matrix element: $\langle (\pi\pi)_{I=0} | Q_6 | K^0 \rangle$

$\mathrm{Im}A_2$ is dominated by photon penguin and box diagrams:

Operator: $Q_8 = \frac{3}{2} \overline{s}_L^j \gamma_\mu d_L^k \sum_q e_q \overline{q}_R^k \gamma^\mu q_R^j$

Matrix element: $\langle (\pi\pi)_{I=2} | Q_8 | K^0 \rangle$





$$\frac{\epsilon'_K}{\epsilon_K} = (16.6 \pm 2.3) \times 10^{-4} \qquad \text{(experiments: NA62, KTeV)}$$

$$\frac{\epsilon'_K}{\epsilon_K} = (1.0 \pm 4.7 \pm 1.5 \pm 0.6) \times 10^{-4} \qquad \text{(SM-NLO)}$$

Kitahara,UN,Tremper,1607.06727

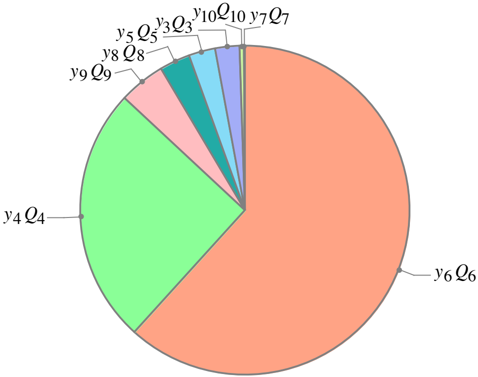
The prediction uses the lattice-QCD results from RBC-UKQCD, Phys. Rev. Lett. **115** 212001 (2015).

Discrepancy with a significance of 2.9σ!

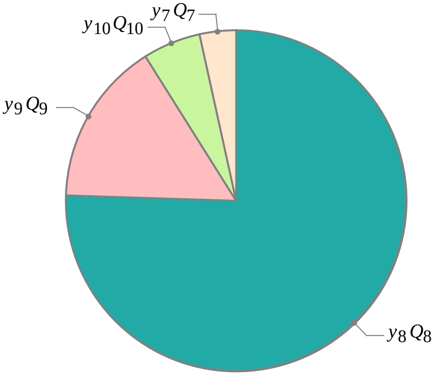
Our prediction uses the methodology of Buras et al. (JHEP 1511 (2015) 202), taking $\mathrm{Re}A_{0,2}$ from data, and a new formula for the RG evolution, building on Adams,Lee, Phys.Rev. D75 (2007) 074502.

Relative contributions of different operators

$\mathrm{Im} A_0$



$\mathrm{Im} A_2$



Standard Model:

Cabibbo-Kobayashi-Maskawa (CKM) factor:

$$\tau = -\frac{V_{td}V_{ts}^*}{V_{ud}V_{us}^*} \sim (1.5 - 0.6i) \cdot 10^{-3}$$

$$\epsilon_K'^{\,\mathrm{SM}} \propto \mathrm{Im}\,\frac{\tau}{M_W^2} \qquad \text{and} \qquad \epsilon_K^{\mathrm{SM}} \propto \mathrm{Im}\,\frac{\tau^2}{M_W^2}.$$

Generic new physics:

Some flavour-violating parameter: δ

$$\epsilon_K'^{\,\mathrm{NP}} \propto \mathrm{Im}\,\frac{\delta}{M^2} \qquad \text{and} \qquad \epsilon_K^{\mathrm{NP}} \propto \mathrm{Im}\,\frac{\delta^2}{M^2}.$$

with new heavy particle mass $M \gg M_W$.

But data require $|\epsilon_K^{\mathrm{NP}}| \leq |\epsilon_K^{\mathrm{SM}}|$, so that

$$\left|\frac{\epsilon_K'^{\,\mathrm{NP}}}{\epsilon_K'^{\,\mathrm{SM}}}\right| \leq \frac{\left|\epsilon_K'^{\,\mathrm{NP}}/\epsilon_K'^{\,\mathrm{SM}}\right|}{\left|\epsilon_K^{\mathrm{NP}}/\epsilon_K^{\mathrm{SM}}\right|} = \mathcal{O}\left(\frac{\mathrm{Re}\,\tau}{\mathrm{Re}\,\delta}\right).$$

If new physics enters through loops, we need $|\delta| \gg |\tau|$ to compensate for $M \gg M_W$, but then ϵ_K prohibits large effects in ϵ_K'.

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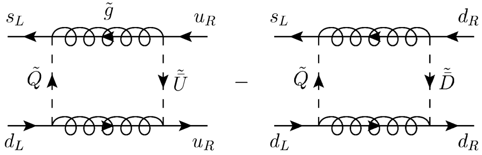
Solutions in the literature:

- tree-level new physics (e.g. Z') with $|\delta| \sim |\tau|$
- fine-tuning of the CP phase to get $\mathrm{Re}\,\delta \sim 0$
- exploit special features of supersymmetry (this talk).

The MSSM has a mechanism

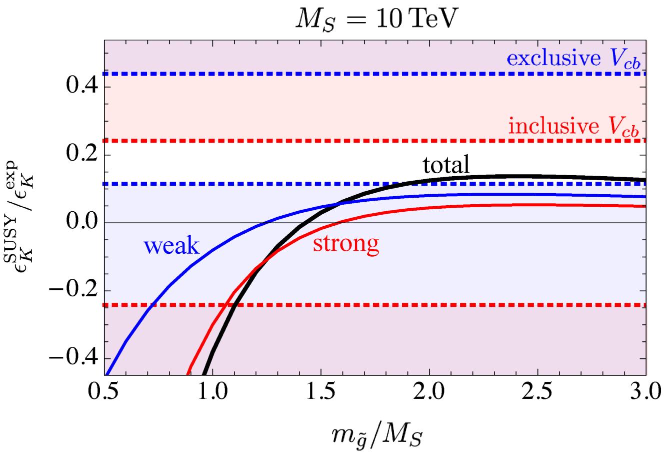
- to enhance $\mathrm{Re}A_2$, because it permits strong-isospin violation through splittings between right-handed up-squark and down-squark masses (Trojan penguins),
  Grossman, Kagan, Neubert 1999.
- to suppress the $\mathrm{K}-\overline{\mathrm{K}}$ mixing amplitude thanks to the Majorana nature of the gluinos, with negative interference of two box diagrams.

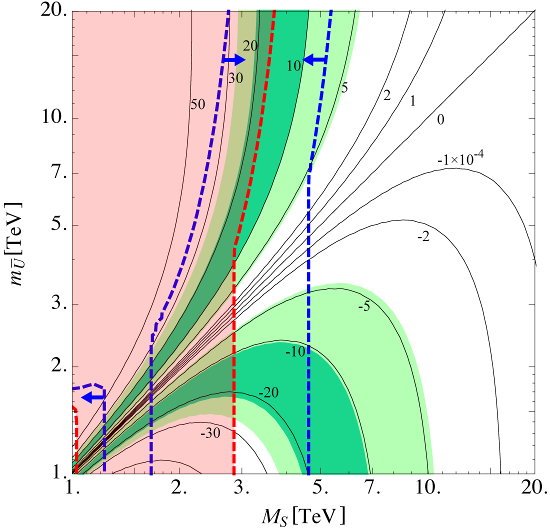
The second feature makes the MSSM contribution to $\mathrm{K}-\overline{\mathrm{K}}$ mixing vanish for $M_{\tilde{g}} \sim 1.5 M_{\tilde{q}}$, it stays small for $M_{\tilde{g}} > 1.5 M_{\tilde{q}}$.



Teppei Kitahara, UN, Paul Tremper, 1604.07400, to appear in Phys.Rev.Lett

Choose:
Sparticle masses $M_S \sim 10$ TeV, $M_{\tilde{g}} > 1.5 M_S$, flavour mixing in down-squark mass matrix only with $\arg \Delta_{sd}^{LL} = \pi/4$.





x-axis: generic sparticle mass, $M_{\tilde{g}} = 1.5 M_S$

y-axis: right-handed up-squark mass

red region: excluded by ϵ_K if $|V_{cb}|$ from inclusive decays is correct

blue dashes: delimit allowed region, if $|V_{cb}|$ from exclusive decays is correct

Summary

- The new lattice results for the matrix element $\langle(\pi\pi)_{I=0}|Q_6|K^0\rangle$ from RBC-UKQCD points to a tension between the experimental value of ϵ'_K and the Standard-Model prediction.
- If new physics enters through loops, a sizable effect in ϵ'_K requires a new source of flavour violation which is much larger then the CKM factor $\mathrm{Im}\,\frac{V_{td}V_{ts}^*}{V_{ud}V_{us}^*} \sim 6 \cdot 10^{-4}$. But then the effect on ϵ_K will typically be too big.
- In the MSSM one can simultaneously enhance ϵ'_K and suppress the new-physics contributions to ϵ_K. This requires flavour mixing among left-handed squarks, masses of right-handed up-type squarks different from those of the down-type squarks, and a gluino mass above 1.5 times the mass of the left-handed squarks.

Penguins: Wake-up call for new physics?