The ϵ'_K anomaly: consequences for supersymmetry and $K \to \pi\nu\bar{\nu}$

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New physics at the junction of flavor and collider phenomenology
Portorož, 21 Apr 2017

Kaon revival

Flavour-changing neutral current (FCNC) transitions of Kaons probe virtual effects of very high mass scales.

Example: ϵ_K quantifying CP violation in $\mathrm{K}-\overline{\mathrm{K}}$ mixing is dominated by loops with top quarks.

$\Rightarrow$ experiment at 0.5 GeV probes physics at 173 GeV

Kaon revival: Why now?

(i) theoretical control of ϵ_K increases steadily (hadronic matrix elements and NNLO QCD under good control, $\epsilon_K \propto |V_{cb}|^4$ issue improving),

(ii) ϵ'_K now tractable with lattice QCD,

(iii) upcoming measurements of theoretically clean branching ratios $B(K^+ \to \pi^+ \nu \bar{\nu})$ (by NA62) and $B(K_L \to \pi^0 \nu \bar{\nu})$ (by KØTØ),

(iv) no new particles found at LHC:
   $\Rightarrow$ weaker rationale for Minimal Flavour Violation (MFV)

If the flavour structure of new physics is unrelated to the SM Yukawa sector, one expects the largest effects in Kaon (and $\mu \to e$) FCNC processes.

CP violation in $K \to \pi\pi$

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

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

where I denotes the strong isospin.

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

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

discovered in 1964

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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:

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

$\uparrow$

assumes PDG convention for CKM elements

Master equation for ϵ'_K:

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

Here:

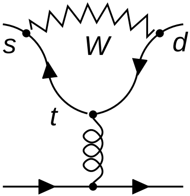
$$\omega_+ \simeq \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0} = (4.53 \pm 0.02) \cdot 10^{-2}$$

$\hat{\Omega}_{\mathrm{eff}} = (14.8 \pm 8.0) \cdot 10^{-2}$ quantifies isospin breaking.

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



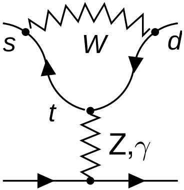
Operator: $Q_6 = \bar{s}^j_L \gamma_\mu d^k_L \sum_q \bar{q}^k_R \gamma^\mu q^j_R$

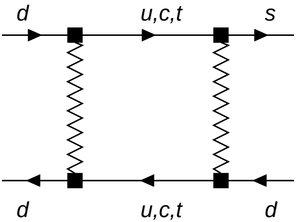
Matrix element: $\langle (\pi\pi)_{I=0} | Q_6 | K^0 \rangle$

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

Operator: $Q_8 = \frac{3}{2} \bar{s}^j_L \gamma_\mu d^k_L \sum_q e_q \bar{q}^k_R \gamma^\mu q^j_R$

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





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

$$\frac{\epsilon'_K}{\epsilon_K} = \left(1.1 \pm 4.7_{\text{lattice}} \pm 1.9_{\text{NNLO}} \pm 0.6_{\text{isosp. br.}} \pm 0.2_{m_t}\right) \times 10^{-4} \qquad \text{(SM)}$$

Kitahara,UN,Tremper, JHEP 1612 (2016) 078

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

Discrepancy with a significance of 2.8σ!

Our prediction uses the methodology of Buras et al. (JHEP 1511 (2015) 202) (taking $\mathrm{Re}A_{0,2}$ from data), NLO formulae from Buras et al., and a new formula for the RG evolution.

Buras, Jäger, Gorbahn (JHEP 1511 (2015) 202) find a 2.9σ deviation:

$$\frac{\epsilon'_K}{\epsilon_K} = (1.9 \pm 4.5) \times 10^{-4} \qquad \text{(SM)}$$

Sensitivity to new physics

Standard Model:

Cabibbo-Kobayashi-Maskawa (CKM) factor:

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

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

Generic loop-induced new physics:

some flavour-violating parameter δ with $|\delta| \gg |\tau|$ to compensate for suppression from heavy new-physics mass:

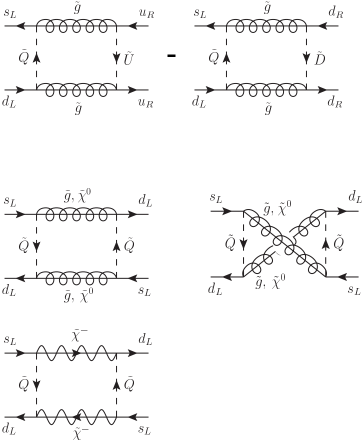
$$\epsilon_K'^{\,\mathrm{NP}} \propto \mathrm{Im}\,\delta \qquad \text{and} \qquad \epsilon_K^{\mathrm{NP}} \propto \mathrm{Im}\,\delta^2.$$

$\Rightarrow$ If $\epsilon_K'^{\,\mathrm{NP}} \sim \epsilon_K'^{\,\mathrm{SM}}$, expect $\epsilon_K^{\mathrm{NP}} \gg \epsilon_K^{\mathrm{SM}}$.

$\Rightarrow$ Need clever ideas to suppress ϵ_K^{NP}.

The MSSM has a mechanism

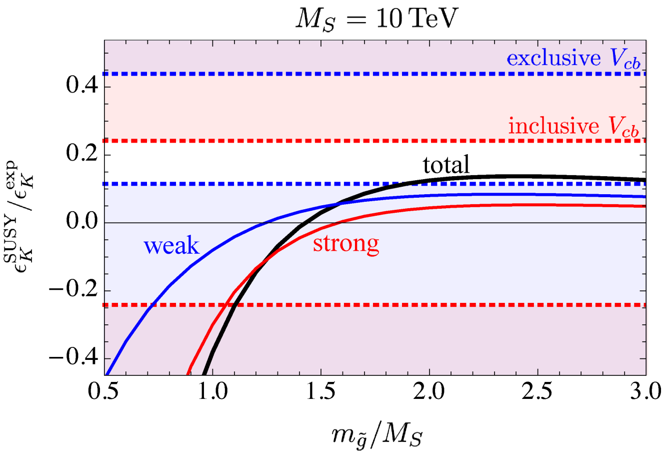
- to enhance $\mathrm{Re} A_2$, because it permits strong-isospin violation through splittings between right-handed up-squark and down-squark masses (Trojan penguins),
  Grossman, Kagan, Neubert 1999.
- to suppress the $K-\overline{K}$ mixing amplitude thanks to the Majorana nature of the gluinos, with negative interference of two box diagrams. Crivellin, Davidkov 2010



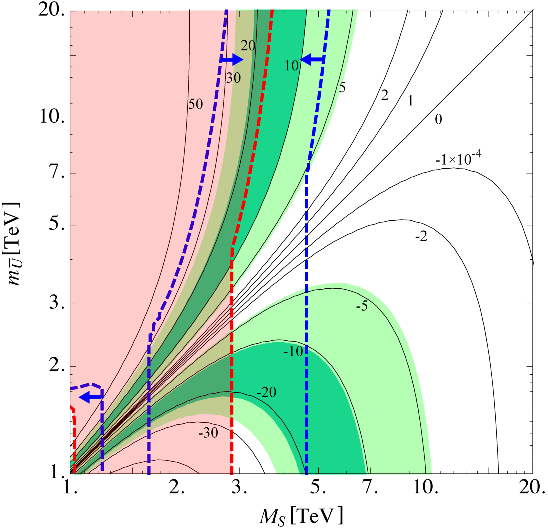
The second feature makes the MSSM contribution to $K-\overline{K}$ mixing vanish for $M_{\tilde{g}} \sim 1.5 M_{\tilde{q}}$, it stays small for $M_{\tilde{g}} > 1.5 M_{\tilde{q}}$.

Teppei Kitahara, UN, Paul Tremper, Phys. Rev. Lett. 117 (2016) 091802

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



Explain ϵ'_K



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

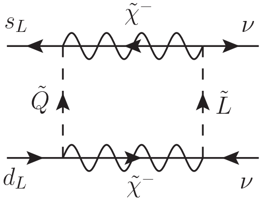
The (near) future of Kaon physics:

$$B(K^+ \to \pi^+\nu\bar{\nu}) \stackrel{\text{SM}}{=} (8.3 \pm 0.5) \cdot 10^{-11} \qquad \text{for NA62 (CERN)}$$

$$B(K_L \to \pi^0\nu\bar{\nu}) \stackrel{\text{SM}}{=} (2.9 \pm 0.2) \cdot 10^{-11} \qquad \text{for KØTØ (J-PARC)}$$

These branching ratios are theoretically extremely clean.

In our MSSM scenario:
Contributions from wino-like chargino box:



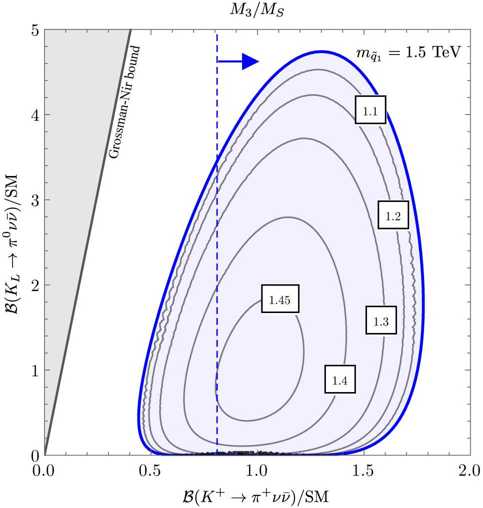
Giancarlo D'Ambrosio, Andreas Crivellin, Teppei Kitahara, UN, 1703.05786

$K \to \pi\nu\bar{\nu}$

Our MSSM scenario makes falsifiable predictions for $B(K^+ \to \pi^+\nu\bar{\nu})$ and $B(K_L \to \pi^0\nu\bar{\nu})$:

$m_{\tilde{q}_1} = 1.5\,\text{TeV}$: mass of the lightest ($\tilde{s}_L$–$\tilde{d}_L$–mixed) squark,
slepton mass $m_{\tilde{L}} \geq 300\,\text{GeV}$,
M_3: gluino mass, GUT relations for $M_{1,2}$,
M_S: mass of all other sparticles.

The number in the squares show the value for M_3/M_S needed to cancel the MSSM contribution to ϵ_K.



In order to exhaust the bounds on $B(K^+ \to \pi^+\nu\bar{\nu})$ and $B(K_L \to \pi^0\nu\bar{\nu})$, one must fine-tune M_3 or the CP phase $\arg\Delta_{sd}^{LL}$: For $\arg\Delta_{sd}^{LL} = \pm\pi/2$ the MSSM contribution to ϵ_K vanishes, while ϵ'_K is maximised.

If you allow for at most 10% fine-tuning in ϵ_K, you find (for GUT relations between $M_{1,2,3}$):

$$\frac{B(K^+ \to \pi^+\nu\bar{\nu})}{B(K^+ \to \pi^+\nu\bar{\nu})_{\rm SM}} \leq 1.1 \qquad \text{and} \qquad \frac{B(K_L \to \pi^0\nu\bar{\nu})}{B(K_L \to \pi^0\nu\bar{\nu})_{\rm SM}} \leq 1.2.$$

$\longrightarrow$ need upgrade KØTØ–step2, aiming at $\mathcal{O}(100)$ events.

Furthermore: if the new-physics contribution to ϵ'_K is positive (as indicated by present data), find

$$\mathrm{sgn}\left[B(K_L \to \pi^0\nu\overline{\nu}) - B^{\mathrm{SM}}(K_L \to \pi^0\nu\overline{\nu})\right] = \mathrm{sgn}\left(m_{\overline{U}} - m_{\overline{D}}\right)$$

Here $\overline{U}$ and $\overline{D}$ denote the right-handed up and down squarks, respectively.

Could collider experiments ever achieve this?

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.
- $B(K \to \pi\nu\overline{\nu})$ data will test our scenario. $B(K_L \to \pi^0\nu\overline{\nu})$ can determine, whether the right-handed up squark is heavier or lighter than the right-handed down squark.

Backup

Standard Model:

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

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 $|\epsilon_K^{\rm NP}| \leq |\epsilon_K^{\rm SM}|$, so that

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

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).