BSM ideas for ϵ'_K and other flavor anomalies

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Exotic Hadrons and Flavor Physics
Simons Center for Geometry and Physics
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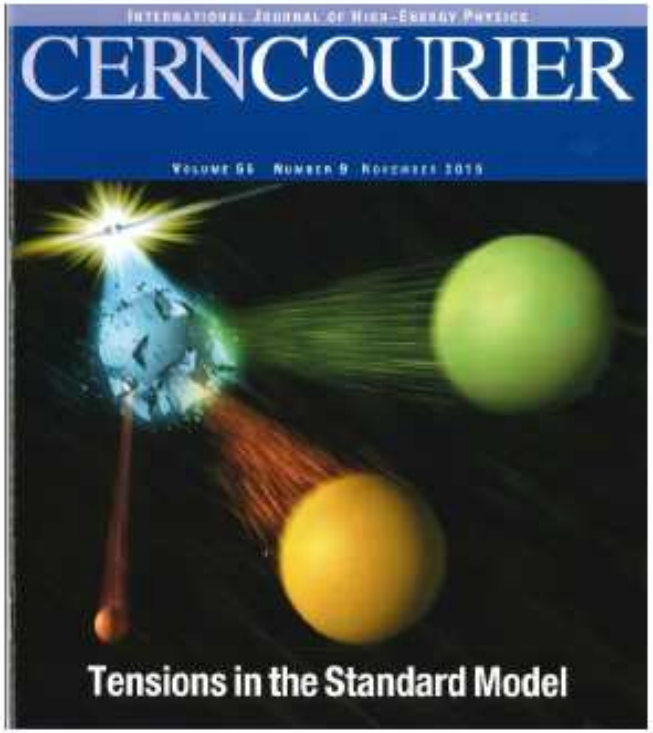
2 Accelerators Find Particles That May Break Known Laws of Physics

The LHC and the Belle experiment have found particle decay patterns that violate the Standard Model of particle physics, confirming earlier observations at the BaBar facility

By Clara Moskowitz | September 9, 2015 | Véalo en español



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Democracy suffers a blow—in particle physics

Three independent B-meson experiments suggest that the charged leptons may not be so equal after all.

Steven K. Blau 17 September 2015

Hints for New Physics in flavour observables

Contents

Introduction: flavour anomalies

(1) $b \to s\mu^+\mu^-$:
SM disfavored by 5.0σ (6D fit) to 5.8σ (1D fit) w.r.t. NP scenarios with $C_9^{\mu\mu} \sim 0.75\, C_9^{\mu\mu\mathrm{SM}}$, NP in $C_{10}^{\mu\mu}$ possible. J. Matias, HQL2018

(2) $B(b \to c\tau\nu)/B(b \to c\ell\nu)$, where $\ell = e, \mu$:
SM disfavored by 4σ. HFLAV 2017

(3) ϵ'_K (direct CP violation in $K \to \pi\pi$) off from SM prediction by 2.8σ based on RBC/UKQCD matrix elements

(4) Anomalous magnetic moment of the muon, $a_\mu \equiv (g-2)_\mu$:
deviates from the SM prediction by 3.7σ.
Keshavarzia,Nomura,Teubner, 1802.02995

This talk: focus on (3)

CP violation in $s \to d\bar{q}q$

The decays $K \to \pi^+\pi^-$ and $K \to \pi^0\pi^0$ involve the quark decays $s \to d\bar{u}u$ and $s \to d\bar{d}d$.

Charge-parity (CP) violation in $K \to \pi\pi$ decays is characterised by two quantities, ϵ_K and ϵ'_K.

CP violation (in K, D, and B physics) is a promising track in the hunt for new physics, complementary to rare decays.

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

Neutral K mesons:

K_{long} and K_{short} (linear combinations of K and $\overline{K}$).

Dominant decay channels:

$$K_{\text{long}} \to \pi\pi\pi \qquad \text{CP} = -1$$
$$K_{\text{short}} \to \pi\pi \qquad \text{CP} = +1$$

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

Neutral K mesons:

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$$K_{\rm short} \to \pi\pi \qquad \mathrm{CP} = +1$$

1964: Christenson, Cronin, Fitch and Turlay observe

$$K_{\rm long} \to \pi\pi$$

and therefore discover CP violation.

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

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

where I denotes the strong isospin.

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

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where I denotes the strong isospin.

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

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

discovered in 1964

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

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discovered in 1964

Direct CP violation (from decay amplitude):

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

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:

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

Here:

$$\omega_+ \simeq \frac{{\rm Re}A_2}{{\rm Re}A_0} = (4.53 \pm 0.02) \cdot 10^{-2} \simeq 1/22$$

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

Important theoretical ingredients: ${\rm Im}A_0$ and ${\rm Im}A_2$, 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.

To predict ϵ'_K one must calculate $\mathrm{Im}\, A_0$ and $\mathrm{Im}\, A_2$.

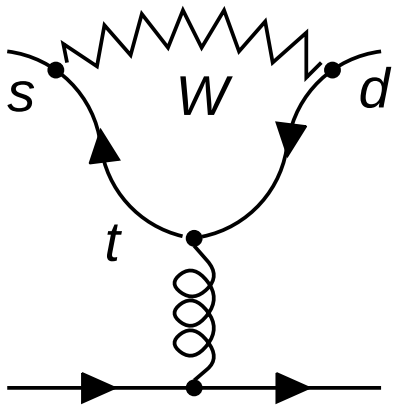
The calculation of $\mathrm{Im}\, A_0$ is very challenging and first reliable results employing lattice quantum chromo-dynamics are available only since 2015.

RBC and UKQCD Collaborations, 2015

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

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

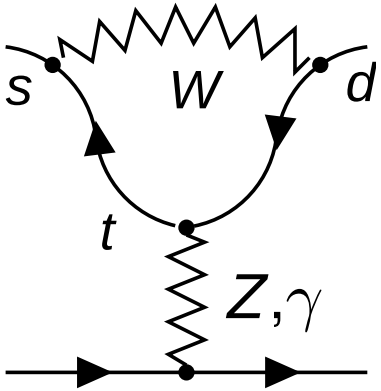
Matrix element: $\langle (\pi\pi)_{I=0} | Q_6 | K^0 \rangle$

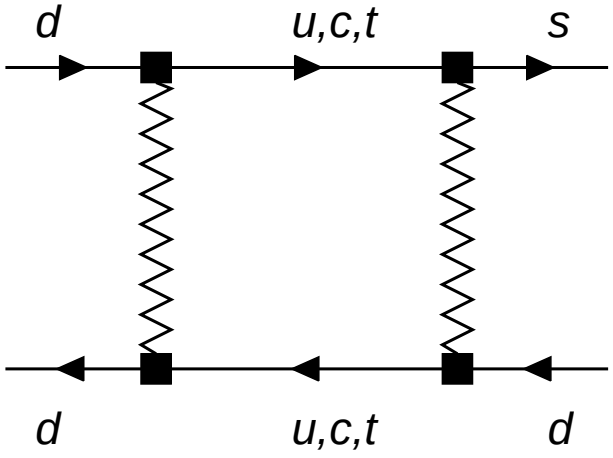


$\mathrm{Im}A_2$ is dominated by Z and photon penguin and box diagrams:

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





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

$$\frac{\epsilon'_K}{\epsilon_K} = (1.1 \pm 4.7_{\text{lattice}} \pm 2.0_{\text{other}}) \times 10^{-4} \qquad \text{(SM)}$$

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:

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

New physics

It is well-known for decades that ϵ'_K is very sensitive to new physics, with possibly large effects in standard extensions of the SM.

Special feature of ϵ'_K: Enhanced sensitivity to new physics breaking strong isospin, i.e. coupling differently to up and down quarks (which feeds the $\Delta I = 3/2$ amplitude A_2).

Physics Letters B

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Gluino penguins and ε'/ε

J.-M. Gérard [1], W. Grimus [2], Amitava Raychaudhuri [3]

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https://doi.org/10.1016/0370-2693(84)90068-6

Abstract

We calculate the penguin diagrams involving gluinos and discuss their implications on ϵ'/ϵ. The dominant contribution originates in the Kobayashi-Maskawa phase. Fixing this phase from the ϵ parameter, we find a smaller value of ϵ'/ϵ; than in the non-supersymmetric case alone.

Sensitivity to new physics

Generic models of heavy new physics typically have a larger impact on ϵ_K than on ϵ'_K.

$\Rightarrow$ Need clever ideas to suppress ϵ_K.

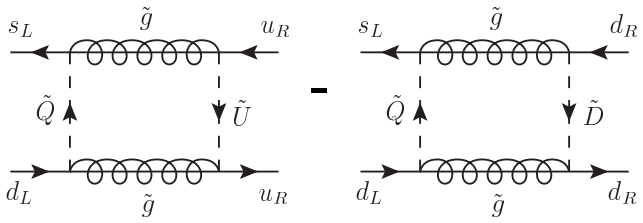
Minimal Supersymmetric Standard Model

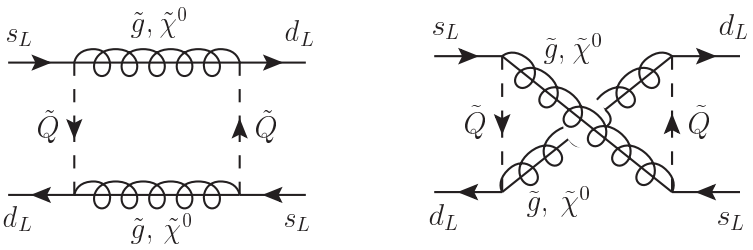
Supersymmetry has a mechanism

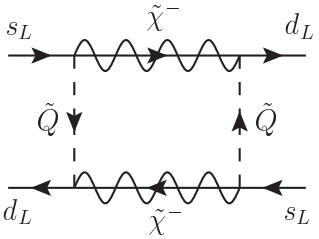
- to enhance $\mathrm{Re}A_2$, because it permits strong-isospin violation through splittings between right-handed up-squark and down-squark masses (Trojan penguins),

  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. Crivellin, Davidkov 2010

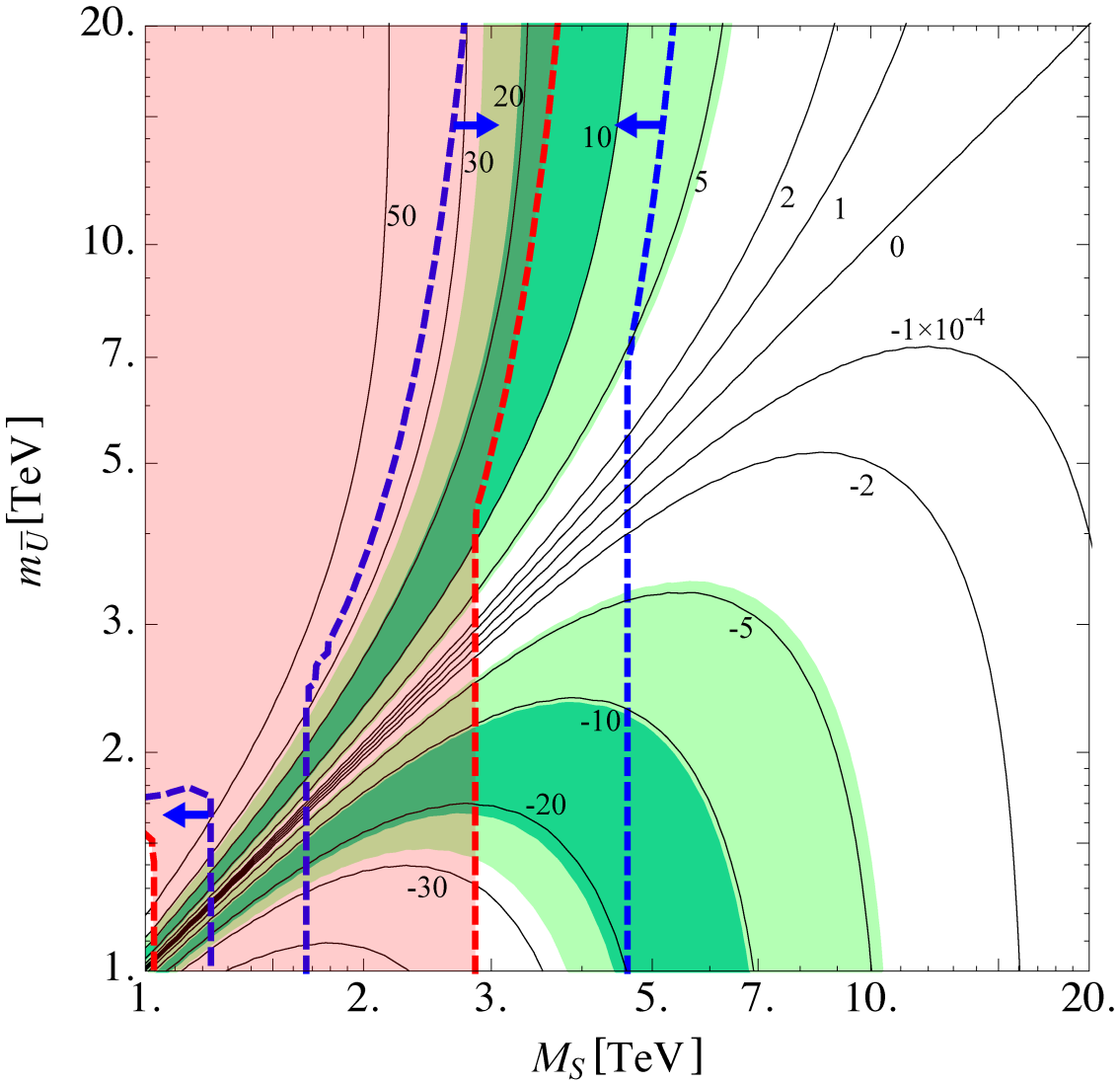






The supersymmetric contribution to $\mathrm{K}-\overline{\mathrm{K}}$ mixing vanishes for $M_{\tilde{g}} \sim 1.5 M_{\tilde{q}}$ and stays small for $M_{\tilde{g}} > 1.5 M_{\tilde{q}}$.

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

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

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

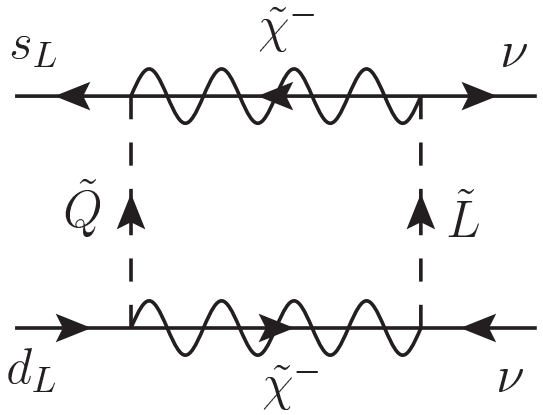
The (near) future of Kaon physics:

$$B(K^+ \to \pi^+\nu\bar{\nu}) \stackrel{\text{SM}}{=} (8.3 \pm 0.3) \cdot 10^{-11} \qquad \text{for NA62 (CERN)}$$

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

These branching ratios are theoretically extremely clean.

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



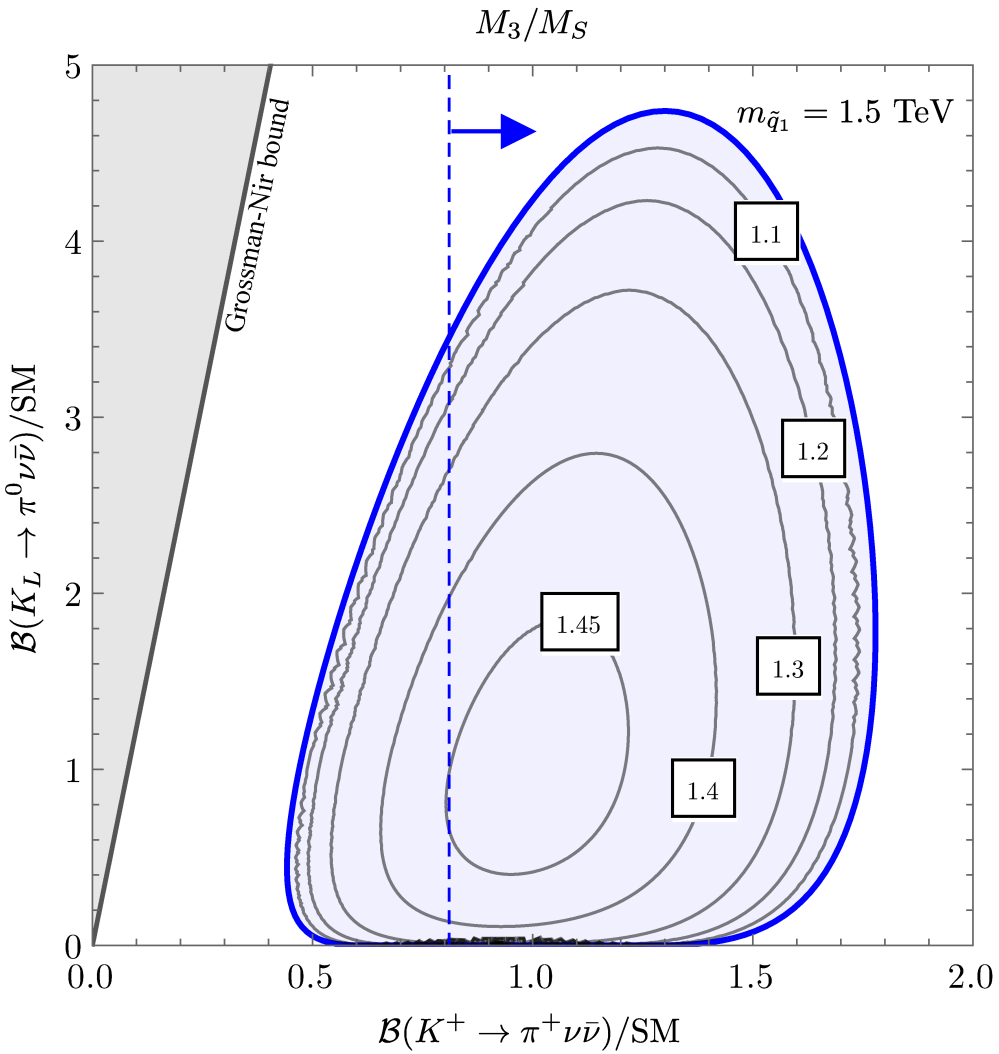
Giancarlo D'Ambrosio, Andreas Crivellin, Teppei Kitahara, UN, 1703.05786

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

Allowed region for the two branching ratios:

$m_{\tilde{q}_1} = 1.5\,\text{TeV}$ is the mass of the lightest ($\tilde{s}_L$–$\tilde{d}_L$–mixed) squark,
M_3 is the gluino mass, GUT relations for $M_{1,2}$,
M_S is the 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.



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

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

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

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

Could collider experiments ever achieve this?

Alternative explanations: Z' or modified $\bar{s}-d-Z$ coupling

Exhaustive study: A.J. Buras, JHEP 1604 (2016) 071

General pattern:

Modified $\bar{s}_L-d_L-Z$ or $\bar{s}_R-d_R-Z$ penguin:

- $B(K_L \to \pi^0\bar{\nu}\nu) \leq B(K_L \to \pi^0\bar{\nu}\nu)^{\rm SM}$
- Enhancement of $B(K^+ \to \pi^+\bar{\nu}\nu)$ by factors of 2 (for $\bar{s}_L-d_L-Z$) or 5.7 (for $\bar{s}_R-d_R-Z$) possible.
- Simultaneous enhancements of $B(K_L \to \pi^0\bar{\nu}\nu)$ and $B(K^+ \to \pi^+\bar{\nu}\nu)$ possible only if both $\bar{s}_L-d_L-Z$ and $\bar{s}_R-d_R-Z$ present.

U(1)$'$ models with tree-level $\bar{s}-d-Z'$ coupling:

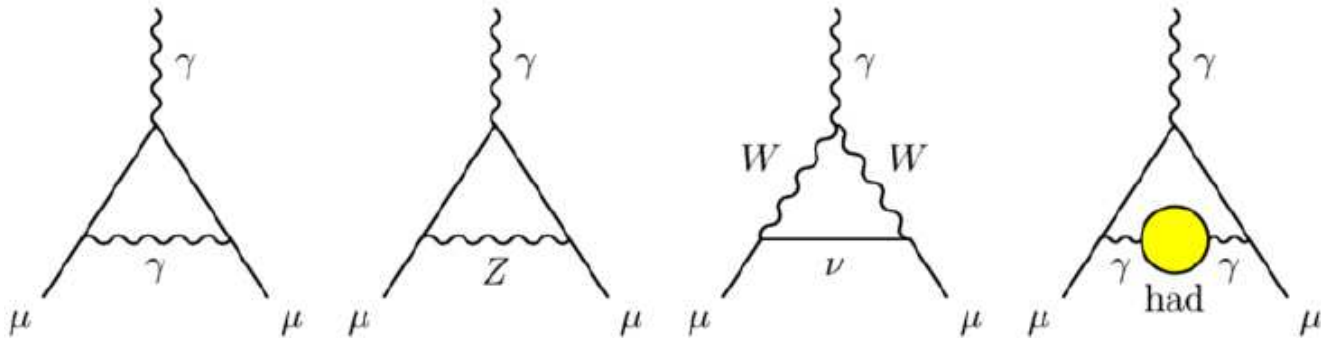
- Effects of $B(K_L \to \pi^0\bar{\nu}\nu)$ and $B(K^+ \to \pi^+\bar{\nu}\nu)$ correlated, as long as ϵ_K is SM-like.
- Z' can affect ϵ'_K through Wilson coefficient C_6 or C_8 affecting the $K_{\rm long}-K_{\rm short}$ mass difference ΔM_K with opposite signs.

See also: Buras et al. Eur.Phys.J. C 74; JHEP 1511, 166 (2015)

Endo et al., Phys.Lett. B771 (2017) 37

Muon magnetic dipole moment

SM diagrams:



a_μ involves the magnetic operator

$$y_\mu L_\mu \Phi \sigma_{\alpha\beta} \mu_R F^{\alpha\beta} \supset y_\mu v \, \mu_L \sigma_{\alpha\beta} \mu_R F^{\alpha\beta} = m_\mu \, \mu_L \sigma_{\alpha\beta} \mu_R F^{\alpha\beta}$$

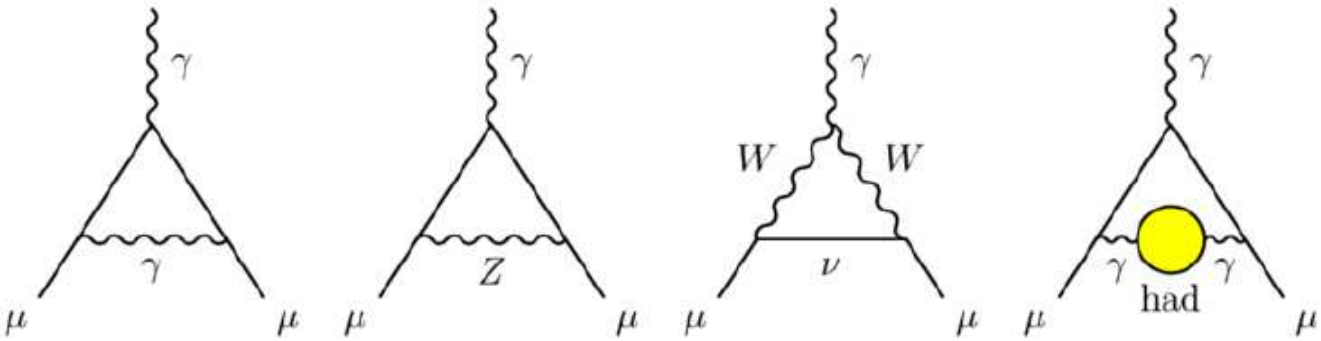
Higgs doublet

muon Yukawa coupling

could be replaced by other mass in flavoured NP models

Muon magnetic dipole moment

SM diagrams:



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Higgs doublet

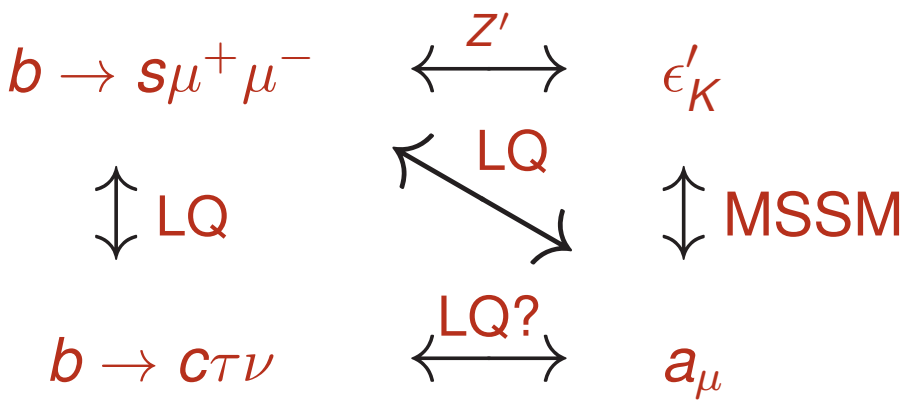
muon Yukawa coupling

could be replaced by other mass in flavoured NP models

In leptoquark models $a_\mu \propto m_t$ possible.

Leskow, D'Ambrosio, Crivellin, Müller, PRD95 (2017) 055018

Pattern of common explanations



Anomaly	predictions	postdictions
$b \to s\mu^+\mu^-$		
lepton-flavour universal	Z'	
LFU violating		Z', leptoquark
$b \to c\tau\nu$	charged Higgs	leptoquark
ϵ'_K	MSSM, Z'	MSSM, Z'
a_μ	MSSM	leptoquark

Summary

- CP violation in $K \to \pi\pi$ decays disagrees with the SM prediction by 2.8σ. This deviation can be accomodated in the MSSM without violating lower bounds on the masses of the supersymmetric particles from LHC searches.
- Alternative explanation: U(1)$'$ models with Z'-$\bar{s}$–d couplings.
- Both the MSSM and leptoquark models can further explain a_μ, but leptoquarks cannot fully explain ϵ'_K.
- Promising for future discoveries: $K^+ \to \pi^+ \overline{\nu}\nu$ and $K_{\rm long} \to \pi^0 \overline{\nu}\nu$ to discriminate between different explanations of ϵ'_K.
- Z' models may simultaneously explain $b \to s\mu^+\mu^-$ and ϵ'_K. Do we see first hints of horizontal gauge dynamics?
- Leptoquark models can link $b \to s\mu^+\mu^-$ to $b \to c\tau\nu$.

Penguins in $b \to s\mu^+\mu^-$ or $s \to d\bar{q}q$:

Wake-up call for New Physics?

Backup

Sensitivity to new physics

Standard Model:

Cabibbo-Kobayashi-Maskawa (CKM) factor:

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

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

Generic loop-induced new physics:

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

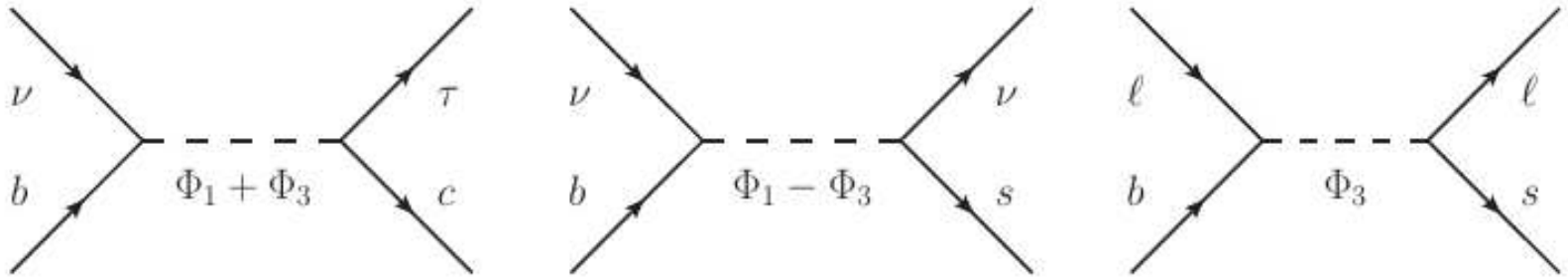
$$\epsilon_K'^{\mathrm{NP}} \propto \mathrm{Im}\,\delta \qquad \text{and} \quad \epsilon_K^{\mathrm{NP}} \propto \mathrm{Im}\,\delta^2.$$

$\Rightarrow$ 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}.

Leptoquarks

A simultaneous explanation of $b \to s\mu^+\mu^-$ and $b \to c\tau\nu$ with scalar leptoquarks needs two leptoquarks to suppress excessive contributions to $b \to s\bar{\nu}\nu$:



Crivellin, Müller, Ota 2017

Alternative explanation: vector leptoquark with quantum numbers $(3, 0, 2/3)$.

Buttazzo,Greljo,Isidori,Marzocca 2017; Calibbi,Crivellin,Li 2017