Flavour anomalies: theoretical interpretation

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ALPS2018, Obergurgl, 16 Apr 2018

Introduction

Flavour physics is sensitive to virtual effects of heavy new physics.

Flavour-changing neutral current (FCNC) interactions probe scales up to 100 TeV and above, because in the Standard Model several suppression factors pile up:

- electroweak loop,
- small CKM elements, e.g. $|V_{ts}| = 0.04$, $|V_{td}| = 0.01$,
- Glashow-Iliopoulos-Maiani (GIM) suppression $\propto (m_c^2 - m_u^2)/M_W^2$, $(m_s^2 - m_d^2)/M_W^2$ in K and D decays.
- helicity suppression $\propto m_b/M_W$ in radiative and leptonic B decays.

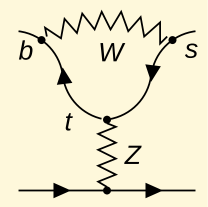
Cabibbo-Kobayashi-Maskawa (CKM) matrix:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Flavour anomaly 1: $b \to s\mu^+\mu^-$

Decays governed by $b \to s\mu^+\mu^-$:

- $B \to K\mu^+\mu^-$
- $B \to K^*\mu^+\mu^-$
- $B_s \to \Phi\mu^+\mu^-$



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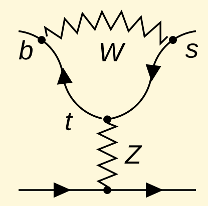

The decay $B \to K^*\mu^+\mu^-$ permits the measurement of angular observables, defined in terms of angles within and between the $K^* \to K\pi$ and $\mu^+\mu^-$ decay planes. One of those, called P_5', deviates from the SM prediction by more than 3σ in the LHCb and Belle experiments.

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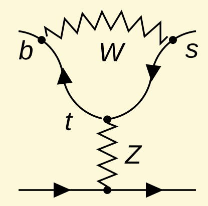

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The LHCb data for the branching-fraction ratios
$\frac{B(B \to K\mu^+\mu^-)}{B(B \to Ke^+e^-)}$ and $\frac{B(B \to K^*\mu^+\mu^-)}{B(B \to K^*e^+e^-)}$ are too small by $2.3-2.6\sigma$ in some bins of the lepton invariant mass q^2.

$B(B_s \to \Phi\mu^+\mu^-)$ is smaller than the SM prediction by 2.2σ.

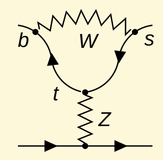
Effective hamiltonian

$$H = -\frac{4G_F V_{tb} V_{ts}^*}{\sqrt{2}} \sum_{\ell,\ell=e,\mu,\tau} \left[C_9^{\ell\ell} O_9^{\ell\ell} + C_{10}^{\ell\ell} O_{10}^{\ell\ell} \right] + \ldots$$

We are interested in the operators

$$O_9^{\ell\ell} = \frac{\alpha}{4\pi} [\bar{s}_L \gamma^\mu b_L] \, [\bar{\ell} \gamma_\mu \ell] \qquad O_{10}^{\ell\ell} = \frac{\alpha}{4\pi} [\bar{s}_L \gamma^\mu b_L] \, [\bar{\ell} \gamma_\mu \gamma^5 \ell]$$

The Wilson coefficients $C_9^{\ell\ell}$ and $C_{10}^{\ell\ell}$ can be reliably calculated from the Z-penguin diagram and other diagrams.

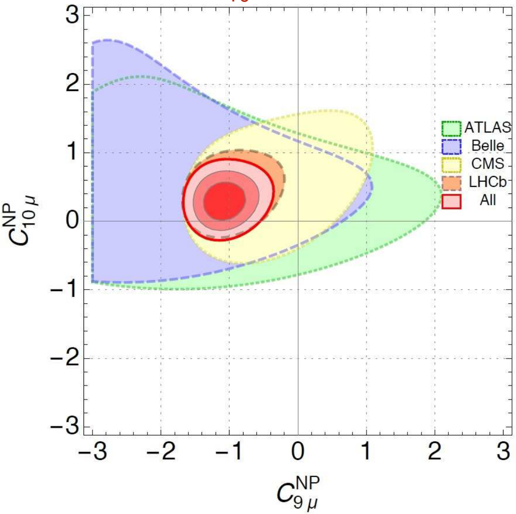


In the Standard Model

$$C_{9,10} \equiv C_{9,10}^{ee} = C_{9,10}^{\mu\mu} = C_{9,10}^{\tau\tau}.$$

Flavour universality of the weak interaction!

A global fit to all relevant observables (including those which comply with the SM prediction) consistently point to new physics with $C_9^{\mu\mu,\,\mathrm{NP}} \approx -\frac{1}{4} C_9^{\mathrm{SM}}$ and possibly also with NP contributions to $C_{10}^{\mu\mu}$.



Capdevila, Crivellin, Descotes-Genon, Matias, Virto 2017.

Methodology: In a global fit of the Wilson coefficients to all data one performs a likelihood ratio test, comparing the likelihood of the best-fit point to that of the SM scenario.

Result: For scenarios in which the new physics is assumed to be only in $C_{9,10}^{\mu\mu}$ (and possibly in the coefficients $C_{9,10}^{\mu\mu\,\prime}$ of the chirality-flipped operators), the statistical significance of the new-physics hypothesis is between 5.0σ and 5.7σ. The sign and magnitude of the deviation is consistent in all observables, and observables insensitive to $C_{9,10}^{\mu\mu}$ are measured SM-like.

Capdevila, Crivellin, Descotes-Genon, Matias, Virto 2017.

Explanation within the SM:

The predictions for $B_s \to \Phi\mu^+\mu^-$ and P_5' involve hadronic physics, one needs non-perturbative methods (i) to constrain the contributions from $(c, \bar{c})$ resonances which convert to (μ^+, μ^-) through a virtual photon and (ii) to calculate the $B_s \to \Phi$ and $B \to K^*$ form factors.

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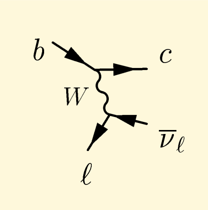
But: R_K and R_K^* are theoretically clean and exhibit deviations from the SM by $3-4\sigma$!

$\Rightarrow$ We need a conspiracy between a malign statistical fluctuation (or a mistake in electron ID) and a theoretical mistake, such that the $b \to se^+e^-$ data look SM-like!

Flavour anomaly 2: $b \to c\tau\nu$

Decays governed by $b \to c\tau\nu$:

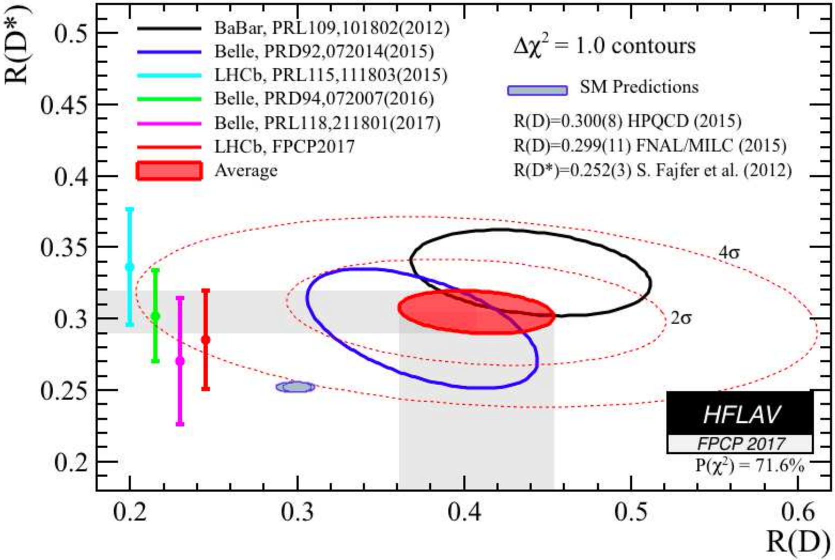
- $B \to D\tau\nu$
- $B \to D^*\tau\nu$
- $B_c \to J/\psi\tau\nu$



$$R(D) = \frac{B(B \to D\tau\nu)}{B(B \to D\mu\nu)}, \quad R(D^*) = \frac{B(B \to D^*\tau\nu)}{B(B \to D^*\mu\nu)}$$ and

$$R(J/\psi) = \frac{B(B_c \to J/\psi\tau\nu)}{B(B_c \to J/\psi\mu\nu)}$$ are all measured larger than predicted in the SM.

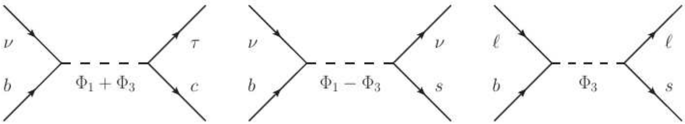
The SM prediction is very robust.



R(D*)
R(D)
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, FPCP2017
Average
$\Delta\chi^2 = 1.0$ contours
SM Predictions
R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)
4σ
2σ
HFLAV
FPCP 2017
$P(\chi^2) = 71.6\%$

Which new physics could simultaneously explain the $b \to s\mu^+\mu^-$ and $b \to c\tau\nu$ anomalies?

Most popular: leptoquarks



Crivellin, Müller, Ota 2017

$\rightarrow$ see next talk by Andreas Crivellin

Alternative explanation: Z' boson from some extended gauge symmetry.
E.g. SU(3)×SU(3)×U(1) model.

Buras et al., JHEP 1302 (2013) 023, JHEP 1402 (2014) 112

Descotes-Genon, Moscati, Ricciardi, arXiv:1711.03101

A Z' boson can have flavour-changing couplings, like $\bar{s}$–b–Z' and mediate $b \to s\ell^+\ell^-$ at tree-level.
Problem: $B_s - \overline{B}_s$ mixing constrains this coupling and enforces a dangerously tight upper bound on the Z' mass.

di Luzio, Lenz, Kirk, arXiv:1712.06572

Flavour anomaly 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 another promising track in the hunt for new physics.

CP violation

Parity transformation P: $\vec{x} \rightarrow -\vec{x}$

Charge conjugation C: Exchange particles and antiparticles, e.g. $e^- \leftrightarrow e^+$

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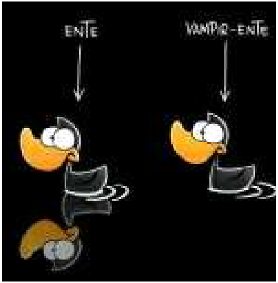

CP violation

Neutral K mesons:

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

Dominant decay channels:

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

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

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1964: Christenson, Cronin, Fitch and Turlay observe

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

and therefore discover CP violation.

$$\epsilon_K \equiv \frac{\langle (\pi\pi)_{I=0} | H | K_{\text{long}} \rangle}{\langle (\pi\pi)_{I=0} | H | K_{\text{short}} \rangle} = (2.229 \pm 0.010) \cdot 10^{-3} e^{i 0.97\pi/4}.$$


M. C. E S C H E R.

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.

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

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

discovered in 1964

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Direct CP violation (from decay amplitude):

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

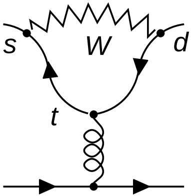
discovered in 1999

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:



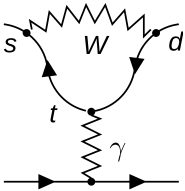
Operator: $Q_6 = \bar{s}^j_L \gamma_\mu d^k_L \sum_q \bar{q}^k_R \gamma^\mu q^j_R$

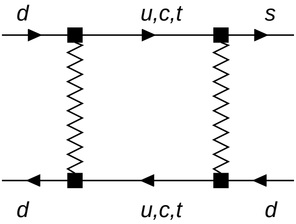
Matrix element: $\langle (\pi\pi)_{I=0} | Q_6 | K^0 \rangle$

$\mathrm{Im}A_2$ is dominated by 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: $\langle (\pi\pi)_{I=2} | Q_8 | K^0 \rangle$





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

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

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!

Sensitivity to new physics

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

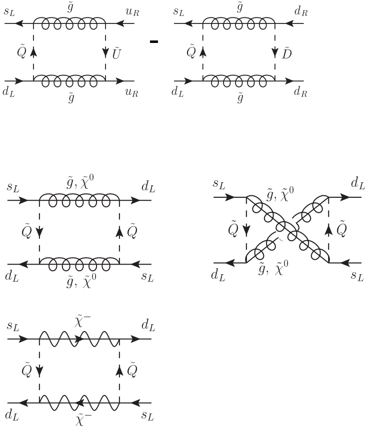
$\Rightarrow$ Need clever ideas to suppress ϵ_K.

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),

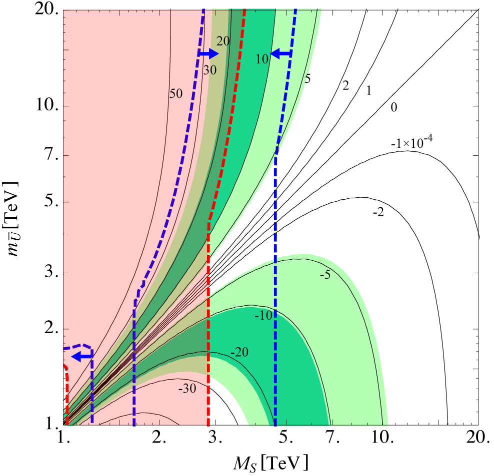
  Grossman, Kagan, Neubert 1999.

- 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

Alternative explanation: $\bar{s}$–d–Z coupling from new physics, stemming typically from Z–Z' mixing.

Buras et al. Eur.Phys.J. C 74; JHEP 1511, 166 (2015), 1604,071 (2016)

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

A common explanation of anomaly 1 and 3?

What next?

Which other manifestations could the physics underlying the flavour anomalies have?

- Spectacular changes of $B \to K^{(*)}\tau\tau$.
- Lepton-flavour violation: $b \to s\tau^\pm\mu^\mp$, $b \to s\tau^\pm e^\mp$, $b \to s\mu^\pm e^\mp$, $\mu \to e\gamma$.
- Upcoming measurements of rare decays
  - $B(K^+ \to \pi^+\nu\bar{\nu}) \overset{\text{SM}}{=} (8.3 \pm 0.3) \cdot 10^{-11}$ NA62 (CERN)
  - $B(K_{\text{long}} \to \pi^0\nu\bar{\nu}) \overset{\text{SM}}{=} (2.9 \pm 0.2) \cdot 10^{-11}$ KØTØ (J-PARC)
- ATLAS/CMS discovery of a leptoquark or Z' or ...???

Summary

- Flavour physics probes new physics associated with scales up to 100 TeV and above.
- Current data on $b \to s\mu^+\mu^-$ decays point to a new interaction of the form $[\bar{s}_L\gamma^\mu b_L]\,[\bar{\mu}\gamma_\mu\mu]$ or $[\bar{s}_L\gamma^\mu b_L]\,[\bar{\mu}_L\gamma_\mu\mu_L]$.
- Data on $b \to c\tau\nu$ disagree with their SM predictions. Both anomalies hint to the violation of lepton-flavour universality, a cornerstone of the weak interaction.
- Promising for future discoveries: $B \to K^{(*)}\tau\tau$, $B \to K^{(*)}\tau\mu$, $B_s \to \mu e$, $B \to K\mu e$, $\mu \to e\gamma\ldots$

Summary

- CP violation in $K \to \pi\pi$ decays disagrees with the SM prediction by 2.8σ. This deviation can be accomodated with supersymmetry without violating lower bounds on the masses of the supersymmetric particles from LHC searches.
- Alternative explanation: $\bar{s}$–d–Z coupling.
- 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.

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

Wake-up call for New Physics?