Flavour Anomalies: Phenomenology and BSM Interpretations

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Contents

Introduction

Flavour physics

studies transitions between fermions of different generations.

flavour $=$ fermion species

$$\begin{pmatrix} u_L, u_L, u_L \\ d_L, d_L, d_L \end{pmatrix} \quad \begin{pmatrix} c_L, c_L, c_L \\ s_L, s_L, s_L \end{pmatrix} \quad \begin{pmatrix} t_L, t_L, t_L \\ b_L, b_L, b_L \end{pmatrix}$$

$$\begin{matrix} u_R, u_R, u_R & c_R, c_R, c_R & t_R, t_R, t_R \\ d_R, d_R, d_R & s_R, s_R, s_R & b_R, b_R, b_R \end{matrix}$$

$$\begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu,L} \\ \mu_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau,L} \\ \tau_L \end{pmatrix}$$

$$e_R \quad \mu_R \quad \tau_R$$

Standard Model (SM): Flavour changes are governed by the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix V.

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

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- The Yukawa interaction of the Higgs field is the only source of transitions between quarks of different generations (flavour violation) in the SM.
- Diagonalising the Yukawa matrices moves the flavour violation into the couplings of the W boson. The strength is encoded in V, i.e. the piece of the Lagrangian describing the W-$\overline{u}$-b couplings reads

$$L_{W\overline{u}b} = \frac{g_2}{\sqrt{2}} \left[\overline{u}_L V_{ub} \gamma^\mu b_L W_\mu^+ + \overline{b}_L V_{ub}^* \gamma^\mu u_L W_\mu^- \right]$$

Some flavoured mesons

charged:

$$K^+ \sim \bar{s}u, \quad D^+ \sim c\bar{d}, \quad D_s^+ \sim c\bar{s}, \quad B^+ \sim \bar{b}u, \quad B_c^+ \sim \bar{b}c,$$
$$K^- \sim s\bar{u}, \quad D^- \sim \bar{c}d, \quad D_s^- \sim \bar{c}s, \quad B^- \sim b\bar{u}, \quad B_c^- \sim b\bar{c},$$

neutral:

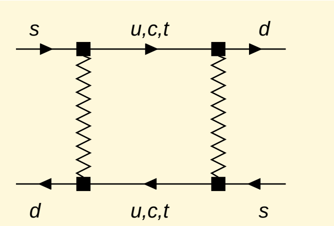
$$K \sim \bar{s}d, \qquad D \sim c\bar{u}, \qquad B_d \sim \bar{b}d, \qquad B_s \sim \bar{b}s,$$
$$\bar{K} \sim s\bar{d}, \qquad \bar{D} \sim \bar{c}u, \qquad \bar{B}_d \sim b\bar{d}, \qquad \bar{B}_s \sim b\bar{s},$$

The neutral K, D, B_d and B_s mesons mix with their antiparticles, $\bar{K}$, $\bar{D}$, $\bar{B}_d$ and $\bar{B}_s$ thanks to the weak interaction (quantum-mechanical two-state systems).

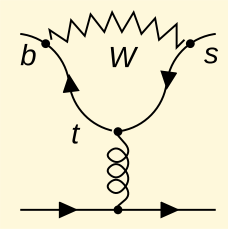
Flavour-changing neutral current (FCNC) processes

A process describing transitions between quarks of the same electric charge (e.g. $s \to d$, $b \to s$, or $c \to u$) is called FCNC process.
In the SM FCNC processes are a quantum effect, involving a loop Feynman diagram.

Examples:



$\mathrm{K}-\overline{\mathrm{K}}$ mixing



penguin diagram

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:

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

Generic models of new physics typically have new sources of unsuppressed FCNC transitions.

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Examples:

extra Higgses	⇒	Higgs-mediated FCNC's at tree-level , helicity suppression possibly absent,
squarks/gluinos	⇒	FCNC quark-squark-gluino coupling, no CKM/GIM suppression,
gauged $U(1)'$	⇒	FCNC couplings of an extra Z',
$SU(2)_R$ gauge bosons	⇒	helicity suppression absent

Most spectacular: Charged lepton FCNC decays such as $\mu \to e\gamma$: If you observe them, it's new physics!

Methodology

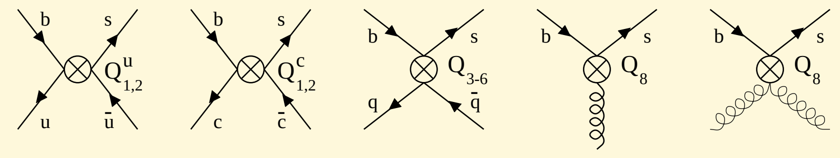
To predict the decay rate of some meson decay triggered by $b \to s\bar{q}q$ calculate an effective hamiltonian:

$$H = \frac{4G_F V_{ub}V_{us}^*}{\sqrt{2}} \sum_{j=1,2} C_j Q_j^u + \frac{4G_F V_{cb}V_{cs}^*}{\sqrt{2}} \sum_{j=1,2} C_j Q_j^c - \frac{4G_F V_{tb}V_{ts}^*}{\sqrt{2}} \sum_{j\geq 3} C_j Q_j$$

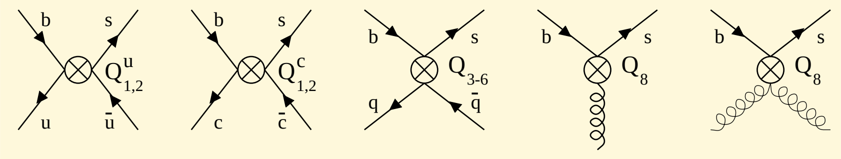
Here: G_F: Fermi constant

C_j: Wilson coefficients = effective couplings

Q_j: effective operators

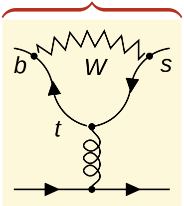


Matching calculations determine the coefficients C_j:



from:

W exchange



All dependence on the masses of heavy particles such as the top quark, *W* boson, squarks, *Z′* bosons, leptoquarks, …resides in the Wilson coefficients C_j.

For radiative decays $b \to s\gamma$ and semileptonic decays $b \to s\ell^+\ell^-$ need more operators.

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Next step: Calculate decay amplitude for $B \to f$ decay with e.g. $f = K\pi$, $K^*\gamma$, $K^*\mu^+\mu^-$,. . . :

$$\mathcal{A}(B \to f) =$$

$$\underbrace{\langle f|H|B\rangle = \frac{4G_F V_{ub} V_{us}^*}{\sqrt{2}} \sum_{j=1,2} C_j \, \underbrace{\langle f|Q_j^u|B\rangle}}_{\substack{\text{hadronic matrix element}\\ \text{contains strong interaction effects}}} + \ldots$$

New physics

Heavy new physics changes the Wilson coefficients and leads to correlated effects in many different B^+, B_d, B_s decays.

Bottom-up approach:

Step 1: Fit the Wilson coefficients to all data and identify those which deviate from their SM predictions.

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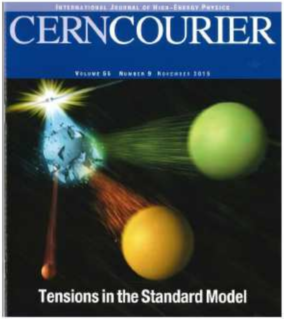
Step 3: Construct reasonable UV-complete theories.

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



Democracy suffers a blow—in particle physics

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

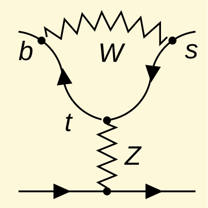
Steven K. Blau 17 September 2015

Hints for
New Physics
in flavour
observables

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

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

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



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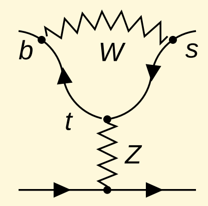

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The decay $B \to K^*\mu^+\mu^-$ permits the measurement of angular observables, defined in terms of angles within and between the $K^* \to K\pi$ and $\mu^+\mu^-$ decay planes. One of those, called P_5', deviates from the SM prediction by more than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

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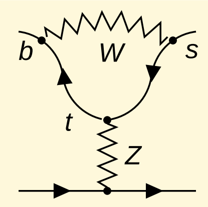

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The LHCb data for the branching-fraction ratios $\dfrac{B(B \to K\mu^+\mu^-)}{B(B \to Ke^+e^-)}$ and $\dfrac{B(B \to K^*\mu^+\mu^-)}{B(B \to K^*e^+e^-)}$ are too small by $2.3-2.6\sigma$ in some bins of the lepton invariant mass q^2.

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

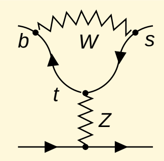
Effective hamiltonian

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

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.

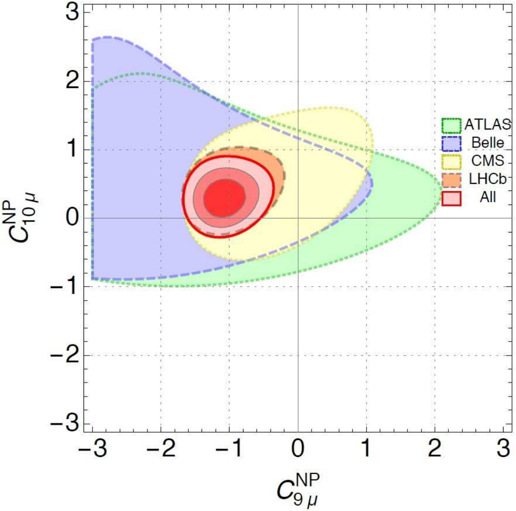


In the Standard Model

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

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 $C_{10}^{\mu\mu}$.



Plot from: Capdevila, Crivellin, Descotes-Genon, Matias, Virto 2017.

Several other analyses in 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.

The first evidence for this $b \to s\mu\mu$ anomaly was found in 2013 by Descotes-Genon, Matias, and Virto as well as Altmannshofer and Straub. Since then the initial significance of 3.9σ has steadily increased with more data.

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.

$\Rightarrow$ a theory mistake can fake new physics in $C_9^{\ell\ell}$!

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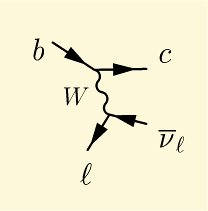
But: R_K and R_K^* are theoretically clean and exhibit deviations from the SM by $3-4\sigma$!

$\Rightarrow$ 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 $b \to c\tau\nu$:

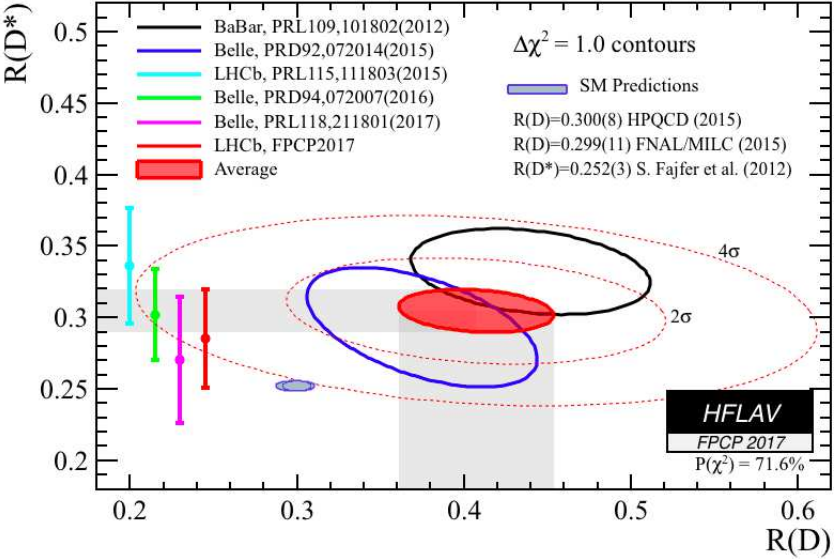
- $B \to D\tau\nu$
- $B \to D^*\tau\nu$
- $B_c \to J/\psi\tau\nu$



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

Uncertainties from form factor calculations efficiently cancel in the SM predictions for these ratios.


R(D*)
R(D)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
0.6
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, FPCP2017
Average
Δχ² = 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(χ²) = 71.6%

Heavy Flavour Averaging Group (HFLAV):

$$
\begin{aligned}
R(D)^{\rm exp} &= 0.403 \pm 0.040 \pm 0.024 \\
&\qquad > \quad R(D)^{\rm SM} = 0.300 \pm 0.008 \qquad \text{by } 2.2\sigma \\
R(D^*)^{\rm exp} &= 0.304 \pm 0.013 \pm 0.007 \\
&\qquad > \quad R(D^*)^{\rm SM} = 0.257 \pm 0.005 \qquad \text{by } 3.3\sigma
\end{aligned}
$$

Combined significance: 4σ

New: QED corrections could reduce the $R(D)$ tension to 1.8σ.

de Boer, Kitahara, Nisandžić, 1803.05881

The LHCb measurement

$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18 \qquad \text{PRL 120 (2018) 121801}$$

is $\sim 2\sigma$ above SM estimates.

$B \to D\tau\nu$ was identified early as a competitive analyser of charged-Higgs effects.

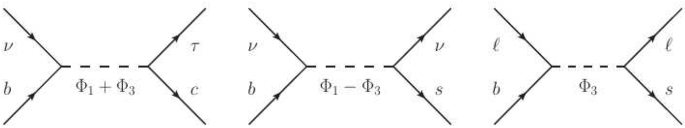
UN, Trine, Westhoff, PRD78 (2008) 015006
Kamenik, Mescia, PRD78 (2008) 014003

In 2012 a simultaneous explanation of $R(D)$, $R(D^*)$, and $B(B^+ \to \tau\nu)$ data was possible in a generic two-Higgs doublet model.

Today this explanation is disfavoured by the distribution of the lepton invariant mass^2 (q^2), the B_c lifetime (Alonso, Grinstein, Camalich, Phys.Rev.Lett. 118 (2017) 081802) and limits from Higgs searches.

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

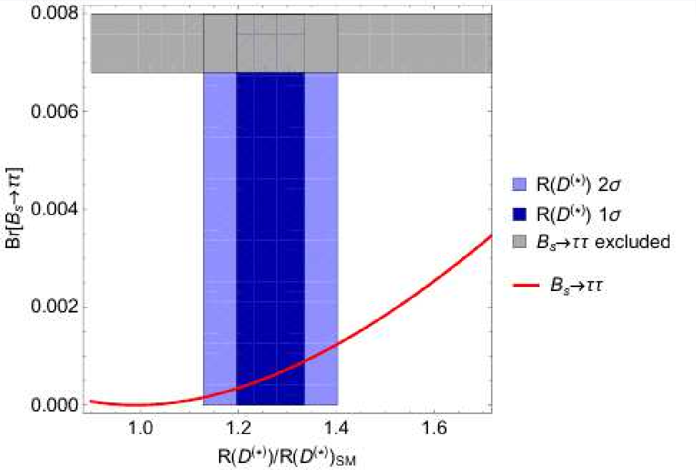
Most popular: leptoquarks
Example for an explanation with scalar leptoquarks:



↑

need two leptoquarks to suppress
excessive contributions to $b \to s\bar{\nu}\nu$

Crivellin, Müller, Ota 2017



Model predicts sizable enhancement of $B \to \tau\tau$ and permits the forbidden decays $B \to K\tau^{\pm}\mu^{\mp}$ and $\tau \to \mu\gamma$.

Crivellin, Müller, Ota 2017

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: $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ 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 in $K \to \pi\pi$

Neutral K mesons:

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

Dominant decay channels:

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

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

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

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1964: Christenson, Cronin, Fitch and Turlay observe

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

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.

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where I denotes the strong isospin.

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

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

discovered in 1964

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Direct CP violation (from decay amplitude):

$$\epsilon'_K \simeq \frac{\epsilon_K}{\sqrt{2}}\left[\frac{\langle(\pi\pi)_{I=2}|K_{\text{long}}\rangle}{\langle(\pi\pi)_{I=0}|K_{\text{long}}\rangle} - \frac{\langle(\pi\pi)_{I=2}|K_{\text{short}}\rangle}{\langle(\pi\pi)_{I=0}|K_{\text{short}}\rangle}\right] = (16.6\pm2.3)\cdot10^{-4}\cdot\epsilon_K$$

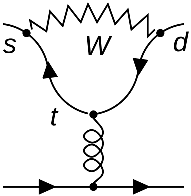
discovered in 1999

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:



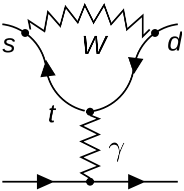
Operator: $Q_6 = \bar{s}^j_L \gamma_\mu d^k_L \sum_q \bar{q}^k_R \gamma^\mu q^j_R$

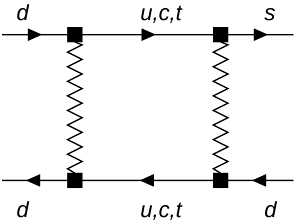
Matrix element: $\langle (\pi\pi)_{I=0} | Q_6 | K^0 \rangle$

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





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

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

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!

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.

Sensitivity to new physics

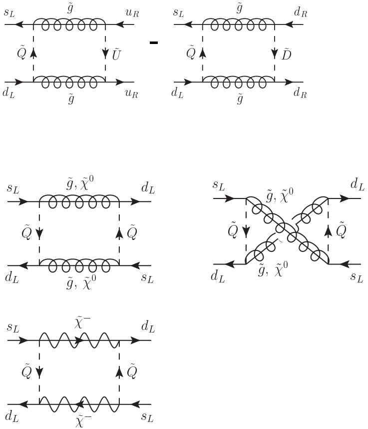
Generic models of heavy new physics typically have a larger impact on ϵ_K than on ϵ'_K.

$\Rightarrow$ Need clever ideas to suppress ϵ_K.

Supersymmetry

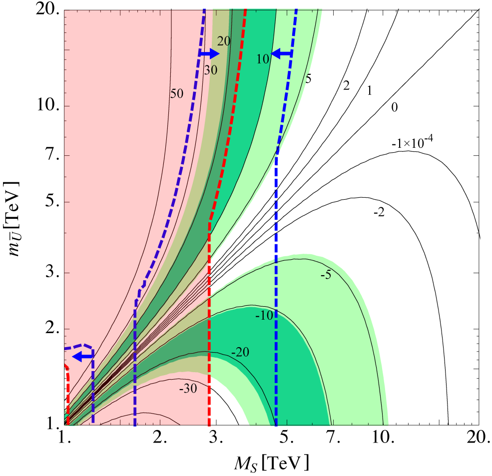
Supersymmetry has a mechanism

- 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, $M_{\tilde{g}} = 1.5M_S$

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?

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

The (near) future of Kaon physics:

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

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

These branching ratios are theoretically extremely clean.

Distinguish MSSM and Z' scenarios through different footprints on the $K \to \pi\nu\bar{\nu}$ decays!

Flavour anomaly 4: Muon magnetic dipole moment

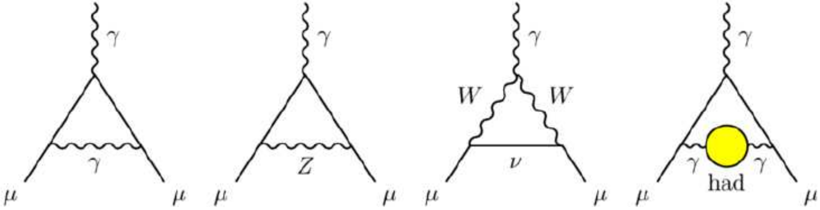
The anomalous magnetic moment of the muon, $a_\mu \equiv (g-2)\mu$, deviates from the SM prediction by

$$a_\mu^{\mathrm{SM}} - a_\mu^{\mathrm{exp}} = -(270 \pm 73) \cdot 10^{-11},$$

which corresponds to a discrepancy of 3.7σ.

Keshavarzia,Nomura,Teubner, 1802.02995

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

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

$\nearrow$ $\uparrow$ $\uparrow$

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

$$\begin{tikzcd}
b \to s\mu^+\mu^- \arrow[rr, leftrightarrow, "Z'"] \arrow[d, leftrightarrow, "\text{LQ}"] \arrow[drr, leftrightarrow, "\text{LQ}"] & & \epsilon'_K \arrow[d, leftrightarrow, "\text{MSSM}"] \\
b \to c\tau\nu \arrow[rr, leftrightarrow, "\text{LQ?}"] & & a_\mu
\end{tikzcd}$$

The scalar leptoquark (LQ) explanations only work for two out of the three processes/quantities $b \to s\mu^+\mu^-$, $b \to c\tau\nu$, and a_μ.

Other avenues:

Vector leptoquarks for $b \to s\mu\mu$ and $b \to c\tau\nu$:

Buttazzo,Greljo,Isidori,Marzocca, JHEP 1711 (2017) 044

Calibbi,Crivellin,Li, 1709.0069

Barbieri,Murphy,Senia, Eur.Phys.J. C77 (2017) 8

Blanke,Crivellin, 1801.07256

Extra (vector-like) fermions and scalars for $b \to s\mu\mu$ and a_μ:

Arnan,Crivellin,Hofer,Mescia, JHEP 1704 (2017) 043

Light, feebly coupled Z' for $b \to s\mu\mu$:

Sala,Straub, PLB774 (2017) 205

…and many more.

What next?

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

- Spectacular effects in $B \to K^{(*)}\tau^+\tau^-$ to be probed by the upcoming Belle II experiment.
- Lepton-flavour violation: $b \to s\tau^\pm\mu^\mp$, $b \to s\tau^\pm e^\mp$, $b \to s\mu^\pm e^\mp$, $\mu \to e\gamma$, $\tau \to \mu\gamma$.
- 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

- 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 $[\bar{s}_L\gamma^\mu b_L]\,[\bar{\mu}_L\gamma_\mu\mu_L]$.
  see talk by David Straub
- This evidence for new physics is robust and has steadily grown to more than 5σ over five years with new measurements. Alternative explanations require a conspiracy of experimental and/or theoretical mistakes.
- Promising for future discoveries: $B \to K^{(*)}\tau^+\tau^-$, $B \to K^{(*)}\tau\mu$, $B_s \to \mu e$, $B \to K\mu e$, $\mu \to e\gamma\ldots$
- 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. Are there experimental issues with $B \to D^*\tau\nu$ or τ reconstruction in general?
- Leptoquark models could link $b \to s\mu^+\mu^-$ to $b \to c\tau\nu$.

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.
- 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.
- Z' models may simultaneously explain $b \to s\mu\mu$ and ϵ'_K. Do we see first hints of horizontal gauge dynamics?

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

Wake-up call for New Physics?