Precision studies in flavour physics: a gateway to new laws of nature

Ulrich Nierste

Institute for Theoretical Particle Physics
Karlsruhe Institute of Technology

Karlsruhe Institute of Technology

Federal Ministry
of Education
and Research

LTP/PSI Colloquium, 18 Dec 2017

Contents

Introduction

Fundamental questions of physics:

1. What are the smallest building blocks of matter?
2. Which forces act between them?
3. How did the universe begin?

$\left.\begin{array}{l}1.\\2.\end{array}\right\}$ $\left\{\begin{array}{l}\text{Elementary Particle Physics}\\ = \\ \text{High Energy Physics}\end{array}\right.$

3. Cosmology, astrophysics

Standard Model of Elementary Particles

Fermions (= matter particles): quarks and leptons

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

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

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

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

"*L*" and "*R*" refer to "left" and "right" chirality. All these fermions have spin 1/2.

Three gauge interactions describe the strong and weak nuclear interaction and the electromagnetic interaction.

Standard Model of Elementary Particles

Fermions (= matter particles): quarks and leptons

$$\begin{array}{ccc}
\begin{pmatrix} u_L, u_L, u_L \\ d_L, d_L, d_L \end{pmatrix} & \begin{pmatrix} c_L, c_L, c_L \\ s_L, s_L, s_L \end{pmatrix} & \begin{pmatrix} t_L, t_L, t_L \\ b_L, b_L, b_L \end{pmatrix} \\
u_R, u_R, u_R & c_R, c_R, c_R & t_R, t_R, t_R \\
d_R, d_R, d_R & s_R, s_R, s_R & b_R, b_R, b_R \\
\begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix} & \begin{pmatrix} \nu_{\mu,L} \\ \mu_L \end{pmatrix} & \begin{pmatrix} \nu_{\tau,L} \\ \tau_L \end{pmatrix} \\
e_R & \mu_R & \tau_R
\end{array}$$

The left-handed doublets feel the weak force, while the right-handed singlets do not. The stable matter surrounding us is made from the up and down quarks and the electron of the first fermion generation.

The second and third generation comprise heavier copies of these particles which are short-lived and decay into lighter ones.

The neutrinos $\nu_{e,L}$, $\nu_{\mu,L}$, and $\nu_{\tau,L}$ are massless in the SM; neutrino masses are an added feature.

Standard Model forces

The three gauge interactions of the Standard Model are modeled after the electromagnetic interaction of an electron, with the minimal coupling of the electromagnetic vector field A^μ:

$$\frac{\partial}{\partial x_\mu} \underset{\substack{\big\uparrow \\ \text{electron field}}}{e(x)} \longrightarrow \frac{\partial}{\partial x_\mu} e(x) + iqA^\mu(x)e(x)$$

$A^\mu(x)$ (with $x = (t, \vec{x})$ labeling time and space coordinates) describes the photon, which is the gauge boson mediating the electromagnetic force. q is the electric charge.

Standard Model forces

The three gauge interactions of the Standard Model are modeled after the electromagnetic interaction of an electron, with the minimal coupling of the electromagnetic vector field A^μ:

$$\underset{\substack{\uparrow \\ \text{electron field}}}{\frac{\partial}{\partial x_\mu} e(x)} \longrightarrow \frac{\partial}{\partial x_\mu} e(x) + iqA^\mu(x)e(x)$$

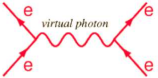
$A^\mu(x)$ (with $x = (t, \vec{x})$ labeling time and space coordinates) describes the photon, which is the gauge boson mediating the electromagnetic force. q is the electric charge.

The strong force involves 8 gauge bosons, the gluons $G^{\mu\, a}$, $a = 1, \ldots 8$.

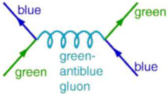
Standard Model forces

The form of these interactions follows from the powerful gauge symmetry principle, which is very predictive:

- All gauge bosons are massless.
- All gauge bosons have spin 1.
- The couplings of gauge bosons to different particles are related.



Electromagnetic

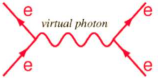


Strong Interaction

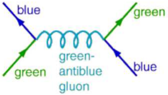
Standard Model forces

The form of these interactions follows from the powerful gauge symmetry principle, which is very predictive:

- All gauge bosons are massless.
- All gauge bosons have spin 1.
- The couplings of gauge bosons to different particles are related.



Electromagnetic



Strong Interaction

The weak force is special: The gauge bosons $W^{\mu +}$, $W^{\mu -}$, and Z^{μ} are massive, because the underlying gauge symmetry is broken by the Brout-Englert-Higgs mechanism.

charges
electromagnetic

quarks
strong

quarks leptons
weak interaction

Electroweak interaction

Gauge symmetry group: $SU(2) \times U(1)_Y$
with quantum numbers weak isospin and hypercharge.

Compare the electroweak gauge theory to electrodynamics:

$U(1)$ gauge transformations multiply the fermion fields with hypercharge y with a x-dependent phasefactor $\exp[i\phi(x)y]$.

Left-handed fermion fields transform as *doublets* under $SU(2)$, meaning that their gauge transformation is a multiplication with $\exp[i\phi_j(x)\sigma_j/2]$ with the Pauli matrices σ_j.

The electroweak theory involves the gauge fields $W^{+\mu}$, $W^{-\mu}$, and W_3^μ for $SU(2)$ and B^μ for $U(1)_Y$.

The vacuum expectation value of the Higgs field h is non-zero:

$$\langle 0|h|0\rangle = \sqrt{2}v$$

with $v = 174$ GeV. Thus the vacuum state (which is the ground state of Nature) does not possess the $SU(2) \times U(1)_Y$ symmetry, which is thereby spontaneously broken to the electromagnetic $U(1)_{\mathrm{em}}$.
(Modeled after BCS theory of superconductivity.)

$W^{\pm\mu}$ and

$$Z^{\mu} = W_3^{\mu} \cos\theta_W - B^{\mu} \sin\theta_W$$

become massive, while the photon field

$$A^{\mu} = W_3^{\mu} \sin\theta_W + B^{\mu} \cos\theta_W$$

stays massless. All masses of elementary particles are proportional to the Higgs vacuum expectation value v.

$W^{\pm\mu}$ and

$$Z^\mu = W_3^\mu \cos\theta_W - B^\mu \sin\theta_W$$

become massive, while the photon field

$$A^\mu = W_3^\mu \sin\theta_W + B^\mu \cos\theta_W$$

stays massless. All masses of elementary particles are proportional to the Higgs vacuum expectation value v.

The Higgs boson h has spin 0. It has been discovered in 2012 by the LHC experiments ATLAS and CMS. It gives rise to two new types of interaction:

- the Yukawa interaction of the Higgs field with quarks and leptons
  → relevant for this talk,
- the Higgs self-interaction
  → hard to study experimentally.

Doublets: $Q_L^j = \begin{pmatrix} u_L^j \\ d_L^j \end{pmatrix}$ und $L^j = \begin{pmatrix} \nu_L^j \\ \ell_L^j \end{pmatrix}$

$j = 1, 2, 3$ labels the generation.

Examples: $Q_L^3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$, $L^1 = \begin{pmatrix} \nu^{eL} \\ e_L \end{pmatrix}$

Singlets: u_R^j, d_R^j and e_R^j.

Doublets: $Q_L^j = \begin{pmatrix} u_L^j \\ d_L^j \end{pmatrix}$ und $L^j = \begin{pmatrix} \nu_L^j \\ \ell_L^j \end{pmatrix}$

$j = 1, 2, 3$ labels the generation.

Examples: $Q_L^3 = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$, $L^1 = \begin{pmatrix} \nu^{eL} \\ e_L \end{pmatrix}$

Singlets: u_R^j, d_R^j and e_R^j.

Important: Only left-handed fields couple to the W boson. The weak interaction violates the parity symmetry in a maximal way!

Yukawa interaction

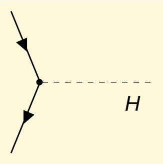
Higgs doublet H with vacuum expectation value $\langle 0|H|0\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$.

Charge-conjugate doublet: $\widetilde{H} \equiv \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} H^*$ with

vacuum expectation value $\langle 0|\widetilde{H}|0\rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$

Quark Yukawa lagrangian:

$$-L_Y = Y^d_{jk}\,\overline{Q}^j_L\,H\,d^k_R \;+\; Y^u_{jk}\,\overline{Q}^j_L\,\widetilde{H}\,u^k_R \;+\; \text{h.c.}$$



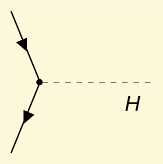
Yukawa interaction

Higgs doublet H with vacuum expectation value $\langle 0|H|0\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$.

Charge-conjugate doublet: $\widetilde{H} \equiv \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} H^*$ with

vacuum expectation value $\langle 0|\widetilde{H}|0\rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$

Quark Yukawa lagrangian:



$$-L_Y = Y^d_{jk}\, \overline{Q}^j_L\, H\, d^k_R \;+\; Y^u_{jk}\, \overline{Q}^j_L\, \widetilde{H}\, u^k_R \;+\; \text{h.c.}$$

The Yukawa matrices Y^f are arbitrary complex 3×3 matrices.
Plug in $\langle 0|H|0\rangle$ and $\langle 0|\widetilde{H}|0\rangle$:

$$-L_Y = Y^d_{jk} v\, \overline{d}^j_L d^k_R \;+\; Y^u_{jk} v\, \overline{u}^j_L u^k_R \;+ \ldots$$

The mass matrices $M^d = Y^d v$ and $M^u = Y^u v$ are not diagonal!

The mass matrix of the three up-type quarks u, c, and t is M^u. The mass matrix of the three down-type quarks d, s, and b is M^d.

The quark mass matrices are not diagonal.

$\Rightarrow$ $u^j_{L,R}, d^j_{L,R}$ do not describe physical quarks!
We must find a basis in which M^d M^u are diagonal!

These matrices can be diagonalised by four unitary rotations of the left-handed and right-handed up-type and down-type quark fields.

Only one of these four rotations is physical. With the original quark fields (weak eigenstates) $d_L^{1,2,3\prime} = d_L', s_L', b_L'$ get the quark mass eigenstates

$$d_L^{j\prime} = \sum_{k=1}^{3} V_{jk} d_L^k,$$

while $u_{L,R}^{j\prime} = u_{L,R}^j$ and $d_R^{j\prime} = d_R^j$.

Only one of these four rotations is physical. With the original quark fields (weak eigenstates) $d_L^{1,2,3\prime} = d_L', s_L', b_L'$ get the quark mass eigenstates

$$d_L^{j\prime} = \sum_{k=1}^{3} V_{jk} d_L^k ,$$

while $u_{L,R}^{j\prime} = u_{L,R}^j$ and $d_R^{j\prime} = d_R^j$.
In the new "physical" basis $M^u = Y^u v$ and $M^d = Y^d v$ are diagonal.
V appears in the coupling of the W-bosons:

$$L_W = \frac{g_2}{\sqrt{2}} \left[\overline{u}_L V \gamma^\mu d_L W_\mu^+ + \overline{d}_L V^\dagger \gamma^\mu u_L W_\mu^- \right]$$

Here $d_L = (d_L, s_L, b_L)$ and $u_L = (u_L, c_L, t_L)$ are now the mass eigestates, i.e. the fields corresponding to the physical quarks.

Flavour physics

studies transitions between fermions of different generations.

flavour = fermion species

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

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

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

$$e_R \qquad \mu_R \qquad \tau_R$$

V is the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

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

V is the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

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

To summarise:

- The Yukawa interaction is the only source of transitions between quarks of different generations (flavour violation) in the SM.

V is the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

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

To summarise:

- The Yukawa interaction is the only source of transitions between quarks of different generations (flavour violation) in the SM.
- Flavour violation only appears in the coupling 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

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

Constants of nature

…in natural units (Planck units):

- speed of light $c = 1$:
  $[\text{length}] = [\text{time}], \quad [\text{energy}] = [\text{mass}] = \text{ GeV}$
- Planck's constant $\hbar = 1$:
  $[\text{length}] = [\text{time}] = [\text{energy}^{-1}] = \text{ GeV}^{-1}$
- dielectric and magnetic constant $4\pi\epsilon_0 = \frac{\mu_0}{4\pi} = 1$:
  $$[\text{el. charge}] = 1, \quad V = -\frac{Q}{r}$$
- Boltzmann constant $k = 1$:
  $[\text{temperature}] = \text{ GeV}$

All units are powers of GeV. E.g. a particle of mass M interacting with other particles mediates a force of range $1/M$.

We can organise particle physics in terms of hierarchical energy scales, thanks to the Appelquist-Carazzone decoupling theorem:

> If a gauge theory valid at energy scale M_1 is embedded into a larger theory with new particles of mass $M_2 \gg M_1$, the effects on observables probed at the scale M_1 are suppressed by powers of M_1/M_2.

All units are powers of GeV. E.g. a particle of mass M interacting with other particles mediates a force of range $1/M$.

We can organise particle physics in terms of hierarchical energy scales, thanks to the Appelquist-Carazzone decoupling theorem:

> If a gauge theory valid at energy scale M_1 is embedded into a larger theory with new particles of mass $M_2 \gg M_1$, the effects on observables probed at the scale M_1 are suppressed by powers of M_1/M_2.

E.g. quantum electrodynamics (QED) is embedded in the Standard Model (SM) of Elementary Particle Physics. The SM correction to the QED prediction for the $e^- e^- \to e^- e^-$ scattering cross section with centre-of-mass energy E is of order E^2/M_Z^2, where M_Z is the mass of the Z boson.

Decoupling theorem

Blessing:

One could formulate e.g. atomic physics ($E_1 \sim 10\,\mathrm{eV}$) without understanding nuclear physics ($E_2 \sim 100\,\mathrm{MeV}$) and the SM ($E_2 \sim \sqrt{1/G_F} \sim 200\,\mathrm{GeV}$) without understanding quantum gravity ($E_2 = M_{\rm Planck} \sim \sqrt{1/G_N} \sim 10^{19}\,\mathrm{GeV}$).

Curse:

To find laws of physics beyond the SM ("new physics") we must build colliders with $E_2 > E_{\rm SM} \sim \sqrt{1/G_F}$ or with high statistics to reach the precision $E_{\rm SM}^2/E_2^2$.

G_F: Fermi constant

G_N: Newton constant

Prime strategy for precision physics: Identify observables for which the SM contribution is parametrically suppressed, while permitting unsuppressed new-physics contributions.

⇒ flavour-changing neutral current (FCNC) processes

Physics beyond the Standard Model

The Standard Model correctly describes almost all laboratory experiments correctly, in the full energy range from atomic physics to the LHC.

Why aren't we happy with it?

Physics beyond the Standard Model

Why aren’t we happy with it?

The Standard Model fails to explain

- the dark matter in the universe, which we infer from cosmology and astrophysics,
- the preponderance of matter over antimatter (baryon asymmetry),
- neutrino masses (easy to fix, but must discriminate between two possibilities).

Physics beyond the Standard Model

Why aren't we happy with it?

The Standard Model fails to explain

- the dark matter in the universe, which we infer from cosmology and astrophysics,
- the preponderance of matter over antimatter (baryon asymmetry),
- neutrino masses (easy to fix, but must discriminate between two possibilities).

The Standard Model raises questions, whose answers call for a more fundamental theory: Are the three gauge forces related? What has gravity do do with them? Why are most fermion masses so small (e.g. $m_e/m_t \approx 3 \cdot 10^{-6}$)? Why are there three fermion generations? Which mechanism governs flavour violation?...

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).

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:

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

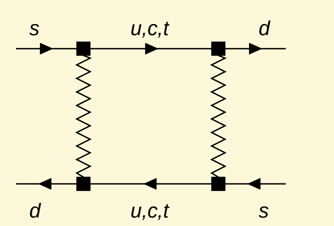
The neutral K, D, B_d and B_s mesons mix with their antiparticles, $\bar{K}$, $\bar{D}$, $\bar{B}_d$ and $\bar{B}_s$ thanks to the weak interaction (quantum-mechanical two-state systems).

$\Rightarrow$ gold mine for fundamental parameters

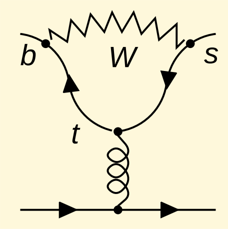
Flavour-changing neutral current (FCNC) processes

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.

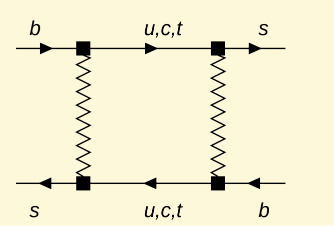
Examples:



$K-\overline{K}$ mixing



penguin diagram



Virtual particles, with masses much higher than the energy of the process, affect the strength of FCNC transition. E.g. $\mathrm{B_s} - \overline{\mathrm{B}}_\mathrm{s}$ mixing is dominated from the diagram with internal top quark ($m_t \sim 170\,\mathrm{GeV} \gg m_{B_s} \sim 5\,\mathrm{GeV}$).

$\Rightarrow$ FCNC processes are highly sensitive to physics beyond the SM.

New physics

In the flavour-changing neutral current (FCNC) processes of the Standard Model several suppression factors pile up:

- FCNCs proceed through electroweak loops, no FCNC tree graphs,

New physics

In the flavour-changing neutral current (FCNC) processes of the Standard Model several suppression factors pile up:

- FCNCs proceed through electroweak loops, no FCNC tree graphs,
- small CKM elements, e.g. $|V_{ts}| = 0.04$, $|V_{td}| = 0.01$,

New physics

In the flavour-changing neutral current (FCNC) processes of the Standard Model several suppression factors pile up:

- FCNCs proceed through electroweak loops, no FCNC tree graphs,
- small CKM elements, e.g. $|V_{ts}| = 0.04$, $|V_{td}| = 0.01$,
- Glashow-Iliopoulos-Maiani (GIM) suppression in loops with charm or down-type quarks, $\propto (m_c^2 - m_u^2)/M_W^2$, $(m_s^2 - m_d^2)/M_W^2$.

New physics

In the flavour-changing neutral current (FCNC) processes of the Standard Model several suppression factors pile up:

- FCNCs proceed through electroweak loops, no FCNC tree graphs,
- small CKM elements, e.g. $|V_{ts}| = 0.04$, $|V_{td}| = 0.01$,
- Glashow-Iliopoulos-Maiani (GIM) suppression in loops with charm or down-type quarks, $\propto (m_c^2 - m_u^2)/M_W^2$, $(m_s^2 - m_d^2)/M_W^2$.
- helicity suppression in radiative and leptonic decays, because FCNCs involve only left-handed fields, so helicity flips bring a factor of m_b/M_W or m_s/M_W.

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

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

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,
vector-like quarks	⇒	FCNC couplings of an extra Z',
$\mathrm{SU(2)_R}$ gauge bosons	⇒	helicity suppression absent

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

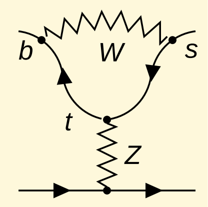
Examples:

extra Higgses	⇒	Higgs-mediated FCNC's at tree-level , helicity suppression possibly absent,
squarks/gluinos	⇒	FCNC quark-squark-gluino coupling, no CKM/GIM suppression,
vector-like quarks	⇒	FCNC couplings of an extra Z',
$\mathrm{SU(2)_R}$ gauge bosons	⇒	helicity suppression absent

FCNC processes are sensitive to scales above $\Lambda \sim 100\,\mathrm{TeV}$.

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

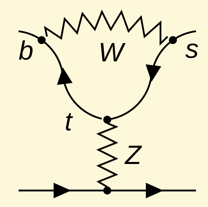
Flavour anomaly 1: $b \to s\mu^+\mu^-$



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

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

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



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

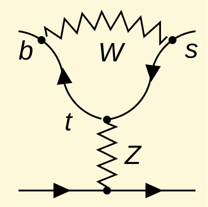
- $B \to K\mu^+\mu^-$
- $B \to K^*\mu^+\mu^-$
- $B_s \to \Phi\mu^+\mu^-$

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.

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

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

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



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.

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 $2.3 - 2.6\sigma$.

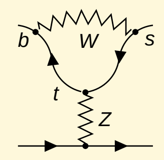
$B(B_s \to \Phi\mu^+\mu^-)$ is smaller than the SM prediction by 2.2σ.

Effective hamiltonian

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

We are interested in the operators

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



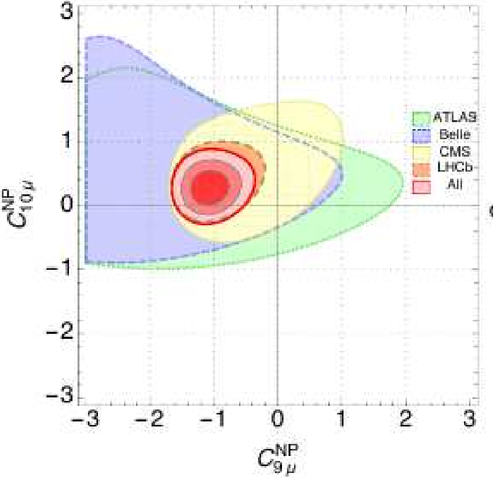
The Wilson coefficients $C_9^{\ell\ell}$ and $C_{10}^{\ell\ell}$ can be reliably calculated from the Z-penguin diagram and other diagrams.

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

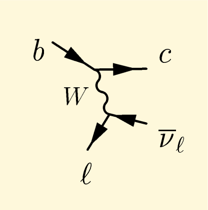


Capdevila, Crivellin, Descotes-Genon, Matias, Virto 2017.

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

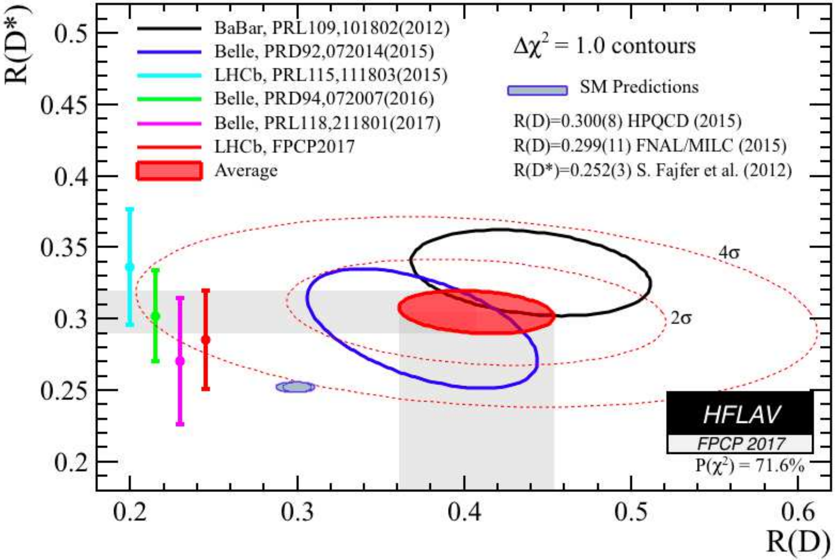
Decays governed by $b \to c\tau\nu$:

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



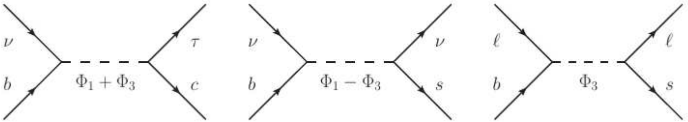
$$R(D) = \frac{B(B \to D\tau\nu)}{B(B \to D\mu\nu)}, \quad R(D^*) = \frac{B(B \to D^*\tau\nu)}{B(B \to D^*\mu\nu)}$$ and

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

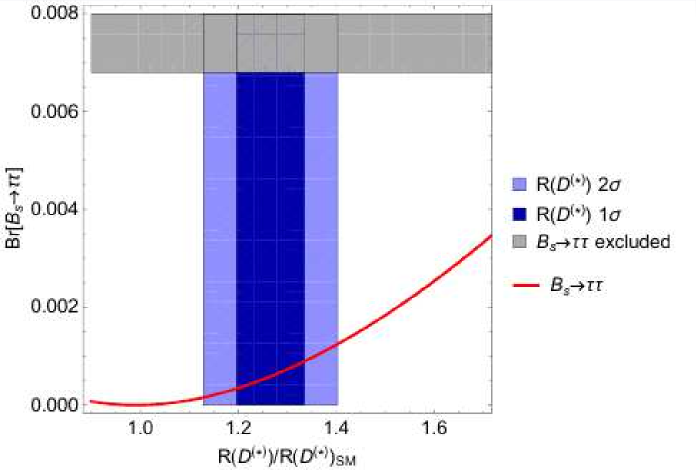

R(D*)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, FPCP2017
Average
Δχ² = 1.0 contours
SM Predictions
R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)
4σ
2σ
HFLAV
FPCP 2017
P(χ²) = 71.6%
0.2
0.3
0.4
0.5
0.6
R(D)

Which new physics could explain all this?

Most popular: leptoquarks



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

Leptoquark models explaining the $b \to s\mu\mu$ anomaly can lift $B(\mu \to e\gamma)$ to a discovery level.
$\mu \to e\gamma$ is studied by the MEG experiment at PSI.

Crivellin, Müller, Signer, Ulrich 2017

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.

Discrete symmetries

Parity transformation P:	$\vec{x} \to -\vec{x}$
Charge conjugation C:	Exchange particles and antiparticles, e.g. $e^- \leftrightarrow e^+$
Time reversal T:	$t \to -t$

C and P

1954/1955: CPT is a symmetry of every Lorentz-invariant quantum field theory.

C and P

1954/1955:	CPT is a symmetry of every Lorentz-invariant quantum field theory.
1956/1957:	P is not a symmetry of the microscopic laws of nature!

C and P

1954/1955: CPT is a symmetry of every Lorentz-invariant quantum field theory.

1956/1957: P is not a symmetry of the microscopic laws of nature!

1964: CP is not a symmetry of the microscopic laws of nature!

C and P

1954/1955:	CPT is a symmetry of every Lorentz-invariant quantum field theory.
1956/1957:	P is not a symmetry of the microscopic laws of nature!
1964:	CP is not a symmetry of the microscopic laws of nature!
⇒	Also the T symmetry must be violated, there is a microscopic arrow of time!

K and M

1973: Explanation of CP violation by postulating a third fermion generation.

K and M

1973: Explanation of CP violation by postulating a third fermion generation.

Makoto Kobayashi and Toshihide Maskawa:
CP Violation in the Renormalizable Theory of Weak Interaction,
Prog.Theor.Phys.49:652-657,1973,

K and M

1973: Explanation of CP violation by postulating a third fermion generation.

Makoto Kobayashi and Toshihide Maskawa:
CP Violation in the Renormalizable Theory of Weak Interaction,
Prog.Theor.Phys.49:652-657,1973,
$\sim$9300 citations (ranks 3rd in elementary particle physics).

Nobel Prize 2008.

K and M

1973: Explanation of CP violation by postulating a third fermion generation.

Makoto Kobayashi and Toshihide Maskawa:
CP Violation in the Renormalizable Theory of Weak Interaction,
Prog.Theor.Phys.49:652-657,1973,
$\sim$9300 citations (ranks 3rd in elementary particle physics).

Nobel Prize 2008.

Maximal P violation

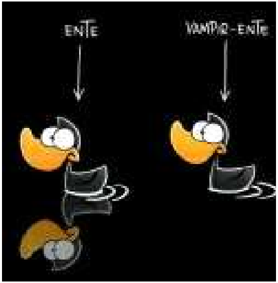
In the SM only left-handed fields feel the charged weak interaction, no couplings of the W-boson to u_R^j, d_R^j, and e_R^j.

Early monograph on parity violation:

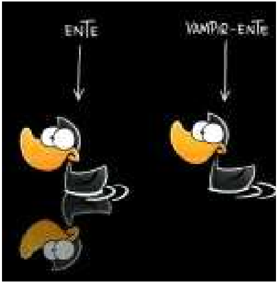
Early monograph on parity violation:

Lewis Carroll:
Alice through the looking glass

Maximal parity violation



Maximal parity violation



Charge conjugation C maps left-handed (particle) fields on right-handed (antiparticle) fields and vice versa:

$\psi_L \xleftrightarrow{C} \psi_L^C$, where $\psi_L^C \equiv (\psi^C)_R$ is right-handed.

$\Rightarrow$ The weak interaction also violates C!

Charge conjugation C maps left-handed (particle) fields on right-handed (antiparticle) fields and vice versa:

$$\psi_L \xleftrightarrow{C} \psi_L^C, \qquad \text{where} \quad \psi_L^C \equiv (\psi^C)_R \text{ is right-handed.}$$

$\Rightarrow$ The weak interaction also violates C!

But: Nothing prevents CP and T from being good symmetries…

Charge conjugation C maps left-handed (particle) fields on right-handed (antiparticle) fields and vice versa:

$$\psi_L \xleftrightarrow{C} \psi_L^C, \qquad \text{where} \quad \psi_L^C \equiv (\psi^C)_R \text{ is right-handed.}$$

$\Rightarrow$ The weak interaction also violates C!

But: Nothing prevents CP and T from being good symmetries…

…except experiment!

CP violation

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

Neutral K mesons:

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

Dominant decay channels:

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

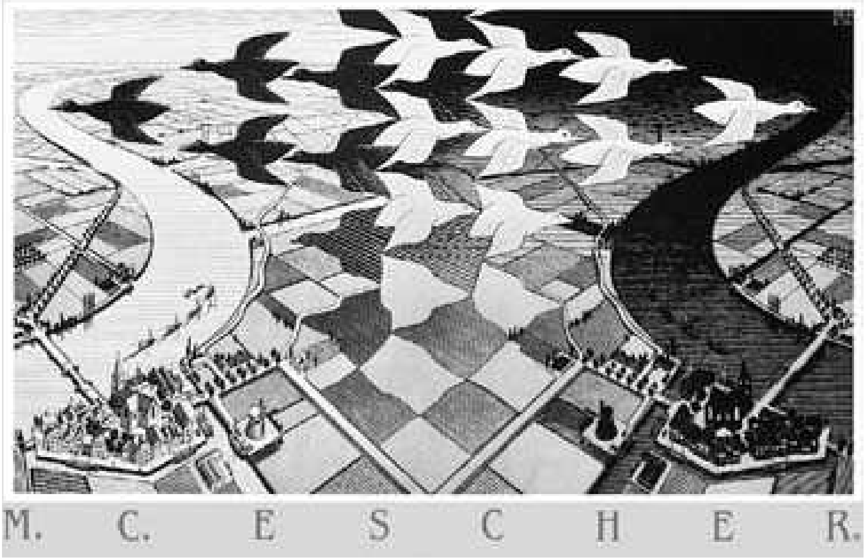
$$K_{\mathrm{short}} \to \pi\pi \qquad \mathrm{CP} = +1$$

1964: Christenson, Cronin, Fitch and Turlay observe

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

and therefore discover CP violation.

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


M. C. E S C H E R.

1964: Discovery of CP violation in $K \to \pi\pi$ decays. The size of the effect is governed by the mass of the top quark (of which no one had a clue at the time).

$$m_t \approx 350 \times m_K$$

CP violation in the SM

Observation by Kobayashi and Maskawa:

A 3×3 quark mixing matrix can accomodate a physical complex phase, which leads to CP violation, while a 2×2 matrix cannot. $\Rightarrow$ prediction of the third generation!

Within the Standard Model the Kobayashi-Maskawa phase δ_{KM} of the (CKM) matrix

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

governs CP violation in all quark decays!

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.

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.

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

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.

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

Direct CP violation (from decay amplitude):

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

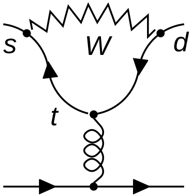
discovered in 1999

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:



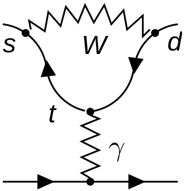
Operator: $Q_6 = \bar{s}^j_L \gamma_\mu d^k_L \sum_q \bar{q}^k_R \gamma^\mu q^j_R$

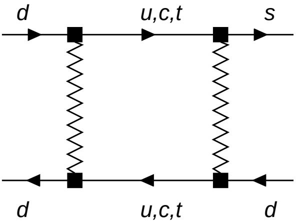
Matrix element: $\langle (\pi\pi)_{I=0} | Q_6 | K^0 \rangle$

$\mathrm{Im}A_2$ 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

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

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

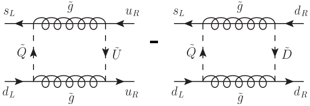
$\Rightarrow$ If $\epsilon_K'^{\,\mathrm{NP}} \sim \epsilon_K'^{\,\mathrm{SM}}$, expect $\epsilon_K^{\mathrm{NP}} \gg \epsilon_K^{\mathrm{SM}}$.

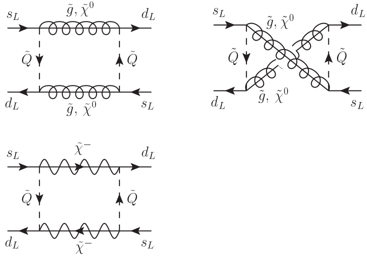
$\Rightarrow$ Need clever ideas to suppress ϵ_K^{NP}.

Supersymmetry

Supersymmetry has a mechanism

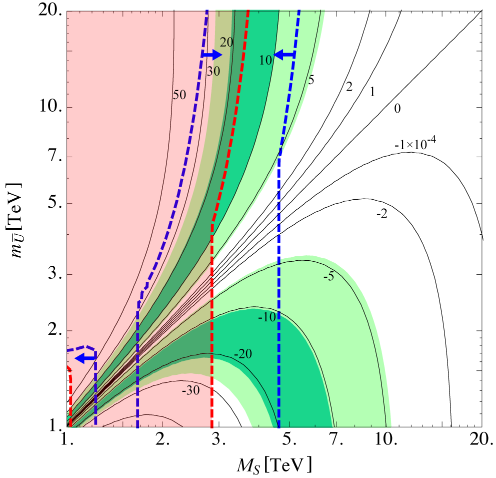
- to enhance $\mathrm{Re}A_2$, because it permits strong-isospin violation through splittings between right-handed up-squark and down-squark masses (Trojan penguins),
  Grossman, Kagan, Neubert 1999.
- to suppress the $\mathrm{K}-\overline{\mathrm{K}}$ mixing amplitude thanks to the Majorana nature of 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, $M_{\tilde{g}} = 1.5 M_S$

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

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

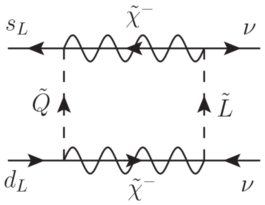
The (near) future of Kaon physics:

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

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

These branching ratios are theoretically extremely clean.

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



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

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

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

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

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

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

Summary

- Flavour physics probes new physics associated with scales above 100 TeV, well beyond the energy of current colliders.
- 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

- All measured non-zero CP-violating quantities involve FCNC amplitudes and are excellent probes of new physics, because the SM is predictive. (In the SM there is one CP phase only!)
- 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.
- Promising for future discoveries: $K^+ \to \pi^+\overline{\nu}\nu$ and $K_L \to \pi^0\overline{\nu}\nu$.

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

Wake-up call for New Physics?