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Flavour-changing neutral currents making and breaking the standard model

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The standard model of particle physics is our best description yet of fundamental particles and their interactions, but it is known to be incomplete. As yet undiscovered particles and interactions might exist. One of the most powerful ways to search for new particles is by studying processes known as flavour-changing neutral current decays, whereby a quark changes its flavour without altering its electric charge. One example of such a transition is the decay of a beauty quark into a strange quark. Here we review some intriguing anomalies in these decays, which have revealed potential cracks in the standard model—hinting at the existence of new phenomena.

The standard model of particle physics has been a spectacularly successful theory for explaining the properties and interactions of fundamental particles, with many measurements confirming its predictions to extraordinary precision. However, cosmological observations of the apparent dark-matter content of the Universe, and of the dominance of matter over antimatter, suggest that the standard model is an incomplete theory. In addition, the standard model does not provide an explanation for the observed patterns of masses of elementary particles. Therefore, one of the current goals of experimental particle physics is to discover new particles and interactions—commonly referred to as 'new physics'—that could provide an explanation for these observations.

Searches for such new particles are performed in two ways. The first requires the production of a new particle directly from the collisions of highly energetic beams of protons or electrons. The new particle subsequently decays to a set of known standard model particles, whose properties are measured in particle physics detectors. The ATLAS[1] and CMS[2] collaborations at the Large Hadron Collider[3] (LHC) at CERN are examples of experiments that search directly for new particles produced through the collisions of proton beams at unprecedented energies and intensities.

The second method involves performing precise measurements of the properties of known decays of hadrons (composites of quarks) that are accurately described by the standard model. In this case, processes that occur via the weak force—such as the decay of a kaon (a hadron containing a strange quark) or of a b hadron (which contains a beauty quark)—are particularly interesting. As a consequence of quantum-field theory, such decays can occur through transient particles that have a physical mass larger than the amount of mass-energy available from the decaying particle. These transient particles are referred to as 'virtual'. Heavy new particles can cause large deviations from the standard model predictions of the decay rate and of the dynamics of the decay products. Precise measurements of such quantities are sensitive to particles beyond the standard model that have masses far exceeding the available collision energy of the LHC. The LHCb experiment[4] operating at the LHC is an example of an experiment that is searching for new physics through precision measurements of the properties of known decays.

Decays involving the weak force

The weak force is mediated by the heavy W^+, W^- and Z^0 bosons. Transitions mediated by the W^+ or W^- boson are known as charged-current processes, whereas those mediated by the Z^0 boson are known as neutral-current processes. There are six types (flavours) of quarks: down (d), up (u), strange (s), charm (c), beauty (b) and top (t). These quarks can change their flavour by interacting with the W^+ or W^- bosons, but cannot by interacting with the Z^0 boson.

Flavour-changing neutral currents (FCNCs)

By the end of the 1960s, the charged-current process that occurs when a charged kaon decays into a muon and a neutrino ($K^+ \to \mu^+\nu_\mu$) had been well established, but the neutral-current counterpart of this process, $K_L^0 \to \mu^+\mu^-$, had not been observed, posing a major puzzle in particle physics. At the time, only three different flavours of quark were known to exist, and while the existence of a fourth had been postulated[5], there was no experimental evidence for it. In 1970, Glashow, Iliopoulos and Maiani[6] provided an explanation (the GIM mechanism) behind the suppression of the neutral-current process relative to the charge-current process, by proposing the existence of a fourth type of quark with specific couplings to the known quarks. The contribution from this fourth quark would cancel out the contribution from other quarks involved in the $K_L^0 \to \mu^+\mu^-$ decay. In today's language, the strange quark and the down quark that make up the K_L^0 particle interact via a quantum-loop transition involving predominantly a W boson and either an up quark or a charm quark, as shown in Fig. 1a. Given the limitation that the quarks have the same mass, the diagram involving the up quark exactly cancels that of the charm quark, explaining the suppression of the $K_L^0 \to \mu^+\mu^-$ decay relative to the $K^+ \to \mu^+\nu_\mu$ decay.

The combination of experimental measurements and the proposed GIM mechanism provided an indirect observation of the charm quark, four years before it was observed directly[7,8], with the discovery of the J/ψ hadron (a bound state of a charm quark and an anticharm quark). Such interplay between experimental measurements and theoretical predictions of quark flavours has shaped the standard model over the past 50 years.

FCNCs in decays of beauty quarks

Another example of a FCNC process involves the transition of a beauty quark into a strange quark. This process can occur through the same quantum-loop transition of the GIM mechanism, but is dominated by the contribution from the top quark, as shown in Fig. 1b.

Owing to the large collision energy of the proton beams at the LHC, hundreds of billions of b hadrons have been produced. As a result, the LHCb collaboration's measurements of FCNC decays of b hadrons are

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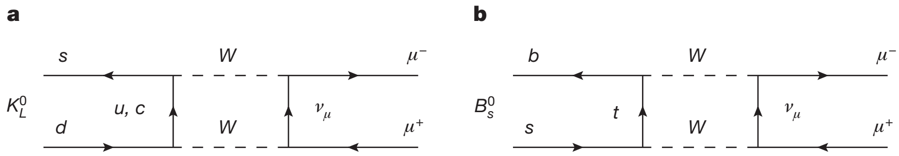

Figure 1 | Examples of FCNC decays. Feynman diagrams depicting two FCNC decays. **a**, The decay $K_L^0 \to \mu^+\mu^-$. The strange quark (s) and the down quark (d) that make up the K_L^0 particle interact via a quantum-loop transition involving two virtual W bosons, either a virtual up quark (u) or a virtual charm quark (c), and a muonic neutrino (ν_μ). The outcome is two neutrinos, μ^+ and μ^-. **b**, The decay $B_s^0 \to \mu^+\mu^-$. The B_s^0 particle is made up of a beauty (b) and a strange (s) quark. This decay can occur through the same quantum-loop transition as in **a**, but involves a virtual top quark (t) instead.

often the most precise available, with important contributions also being made by the CMS and ATLAS experiments. By contrast, a previous generation of experiments—BaBar[9] and Belle[10]—collided beams of electrons and positrons, producing fewer b hadrons (by a factor of approximately 1,000) than the LHC. However, the clean environment of an electron–positron collider did allow certain measurements to be made that are difficult in the rather complicated proton–proton collision process at the LHC.

A particularly rare b-hadron FCNC decay involves the decay of a B_s^0 hadron (which comprises a beauty antiquark and a strange quark) into a pair of muons, denoted $B_s^0 \to \mu^+\mu^-$. Using a combination of data from the CMS and LHCb experiments[11], this decay was for the first time observed to a significance of more than five standard deviations placing stringent constraints on new physics models, such as supersymmetry. Another more common FCNC process involves the decay of a beauty quark into a strange quark and two leptons (leptons are electrons, muons, tauons and neutrinos). These decays are known as semileptonic, as their decay products comprise part leptons and part hadrons. Measurements of the properties of these decays are sensitive to new particles with masses up to around 100 TeV (ref. 12). Recent measurements of semileptonic FCNC decays have revealed discrepancies with standard model predictions, which could indicate the existence of a new particle that is similar to the Z^0 boson of the standard model but up to 30 times heavier. Alternatively, these discrepancies could also be explained through unexpectedly large effects of the strong force, acting between the quarks involved in the process.

Here we review the latest measurements of FCNC decays of b hadrons and how these measurements are revealing potential cracks in the standard model.

Discovery of the decay $B_{(s)}^0 \to \mu^+\mu^-$

The purely leptonic decays of neutral B hadrons (B_s^0 and B^0, which comprise a beauty antiquark bound to a strange quark or a down quark, respectively) into two muons are particularly rare $b \to s\ell\ell$ transitions, denoted $B_{(s)}^0 \to \mu^+\mu^-$. These decays are suppressed not only by the GIM mechanism, but also by angular momentum conservation and by the chiral nature of the weak force (helicity suppression). This suppression is not necessarily present for new-physics particles. For example[13–16], extensions of the standard model such as supersymmetry[15,16] predict the existence of additional Higgs bosons[13,14] that can substantially enhance the rate of these decays.

The standard model prediction[17–20] of the relative probability of a B_s^0 or B^0 meson decaying into two muons (the branching fraction) is calculated to be: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$. These branching-fraction predictions are particularly precise thanks to the purely leptonic final state, which reduces the dependence on computations of the strong force. The decay $B^0 \to \mu^+\mu^-$ is a factor of 30 times rarer than its B_s^0 counterpart, as down quarks couple more weakly than do strange quarks to the top quark[21,22].

A fit to the invariant mass of the dimuon candidates $m_{\mu\mu}$ can be performed to measure the yields of the B_s^0 and B^0 signals. These yields can then be used to determine the branching fractions of the $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays. Figure 2 shows the invariant mass distribution of $m_{\mu\mu}$, along with the fit result, identified in the CMS and LHCb data. The measured branching fractions[23] are: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8^{+0.7}_{-0.6}\right) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9^{+1.6}_{-1.4}\right) \times 10^{-10}$. The statistical significances of the hypothesis that the excess of data over the background is attributed to signal are 6.2 and 3.0 standard deviations for the B_s^0 and B^0 mode, respectively. This represented the first observation of the $B_s^0 \to \mu^+\mu^-$ decay, after more than three decades of searching. Recently, the ATLAS collaboration also published its results on the search for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays[24], but no significant excess was observed in the signal region. However, given the uncertainties related to these two sets of measurements[23,24], they are still compatible within each other. Moreover, so far the measured branching fractions are in agreement with the standard model predictions. More data will make it possible to reduce the uncertainty in the measurements and potentially reveal effects of new physics.

Semileptonic $b \to s\ell\ell$ transitions

Another FCNC decay occurs when the b hadron is not annihilated (as in the leptonic decay described above), but instead its beauty quark decays into a new strange quark and two leptons. Such decays are not helicity-suppressed, and so occur about 1,000 times more frequently than does the $B_{(s)}^0 \to \mu^+\mu^-$ decay. This means that thousands of signal decays can be collected, allowing for a more detailed study of their behaviour.

Branching fractions and lepton flavour universality

The simplest property to measure for these decays is the branching fraction, as before. For semileptonic decays, the branching fraction is measured as a function of the squared four-momentum transferred to the two leptons, q^2. This is important because the influence of new physics—as well as theoretical uncertainties arising from strong-force interactions—depends on q^2.

The branching fraction has been measured as a function of q^2 for several types of b-hadron decays. For almost all of these channels, the branching-fraction measurements sit below the theoretical predictions[25–27]. While presenting an interesting pattern, these data are not significant by themselves, because of the relatively large theoretical uncertainties associated with the branching-fraction predictions.

In addition, one can consider the ratio of branching fractions between decays involving electrons and muons. Owing to its interaction with the Higgs boson, the muon is 200 times heavier than the electron; but apart from that it interacts in exactly the same way as the electron in the standard model. This concept is known as 'lepton universality'. New particles that are not predicted by the standard model do not have to follow this behaviour, and so looking at the branching-fraction ratios is a very sensitive way to search for physics beyond the standard model. In rare b-hadron decays, the most well known example of these ratios is known as $\mathcal{R}_K$: $\mathcal{R}_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$. This ratio is known to be unity in the standard model, with very high precision[28,29]. Any measurement that deviates significantly from unity would be an unambiguous sign of physics beyond the standard model. The most precise measurement of the ratio $\mathcal{R}_K$ was performed by the LHCb collaboration[30] and was found to be $\mathcal{R}_K = 0.745^{+0.090}_{-0.074} \pm 0.036$, where the first uncertainty is statistical and the second systematic. The measurement is 2.6 standard deviations below the standard model expectation of unity, implying an excess of the decay involving electrons with respect to the muonic decay,

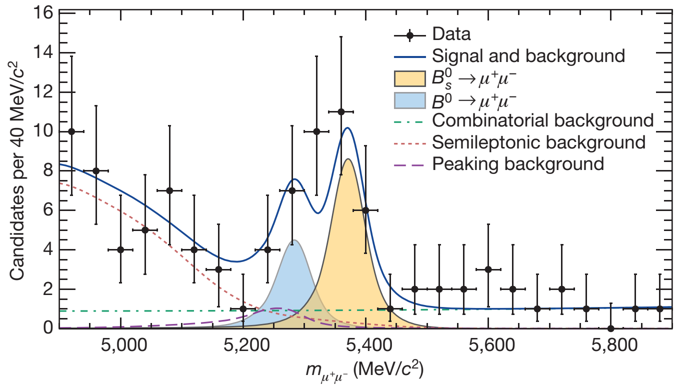

Figure 2 | Observation of the decay $B_s^0 \to \mu^+\mu^-$. The graph shows the distribution of the dimuon invariant mass, $m_{\mu^+\mu^-}$, as found in the combined CMS and LHCb measurement[23]. Superimposed on the data points (black dots) are the following: blue line, the fit obtained from the combined signal-plus-background results; yellow area, the component of the signal that results from the B_s^0 decay; blue area, the component of the signal that results from the B^0 decay; dashed green line, the combinatorial background made of a random combination of two muons produced by independent sources; dashed red line, the sum of semileptonic background decays; violet dashed line, the background obtained when the hadrons from the decay $B \to hh'$ are misidentified as muons. The excess of data seen in the peak of this graph shows the discovery of the decay $B_s^0 \to \mu^+\mu^-$. Image reproduced from ref. 23, Nature Publishing Group.

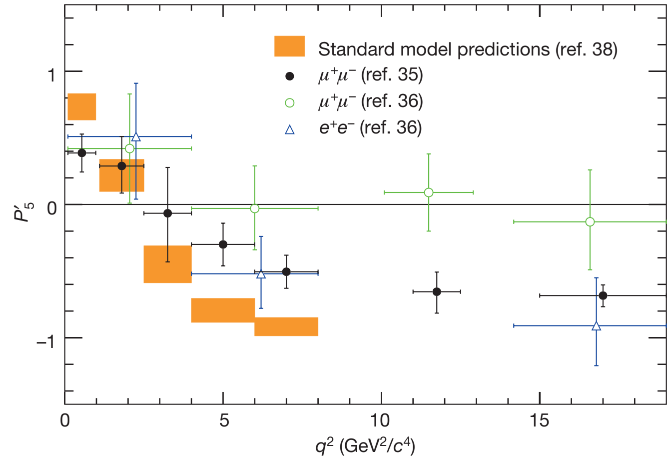

Figure 3 | Measurements of the P_5' observable in $B \to K^*\ell^+\ell^-$ decays. P_5' is a measure of the chiral asymmetry of the interference between the transversely and longitudinally polarized amplitudes of the decay $B \to K^*\ell^+\ell^-$. Measurements of P_5' are shown here as a function of the squared four-momentum transferred to the leptons, q^2. The q^2 regions around 9 GeV^2/c^4 and 12 GeV^2/c^4 have been removed owing to the presence of narrow resonances resulting from charm–anticharm particles ($c\bar{c}$), J/ψ and $\psi(2S)$, respectively. In the q^2 region just below the J/ψ resonance (at 9 GeV^2/c^4), the observable P_5' is measured to be less negative than the standard model prediction. The filled black circles (muon (μ^+ and μ^-) final states) and orange squares (standard model predictions) are reproduced from ref. 35, the latter based on data from ref. 38. The green circles and blue triangles are from ref. 36 and show different measurements performed for muon (μ^+ and μ^-) and electron (e^+ and e^-) final states, respectively.

which is not predicted by the standard model. A powerful cross-check of the analysis involves comparing the branching-fraction ratio of the normalization channel $B^+ \to J/\psi K^+$, where the J/ψ decays into electrons or muons. This ratio is consistent with unity and gives confidence that the experimentally detected differences in muons and electrons are well understood[30]. The result is consistent with the measurements performed by the BaBar[31] and Belle[32] collaborations, which are compatible with the standard model.

In addition to studying b-hadron decays into a specific final state, one can also consider the inclusive $b \to s\ell\ell$ process, where the final state can comprise any number of hadrons. The theoretical uncertainty in predicting this inclusive branching fraction is smaller than the uncertainty in predicting a specific final state. The BaBar and Belle collaborations have measured this process[33,34], and the results are consistent with the standard model prediction, albeit with larger experimental uncertainties than for measurements of specific decays. These collaborations report the branching fractions involving electrons and muons separately. However, so far no significant discrepancy with lepton universality has been seen.

Angular analysis of the decay $B \to K^*\ell^+\ell^-$

As well as influencing the rate of FCNC decays, particles in models beyond the standard model can modify the distribution of the decay products in space. In the standard model, the spatial distribution (or 'angular distribution') of the final-state particles from the FCNC decay of the b hadron is precisely known. The angular distribution reflects the nature of the virtual particle mediating the decay. For instance, if the b hadron is stationary, a spin-0 (scalar) interaction will result in an isotropic distribution of the products of the b-hadron decay. In contrast, a spin-1 interaction—which is either antisymmetric (vector) or symmetric (axial-vector) under a parity (mirror reflection) transformation—will result in the decay products concentrating in certain regions of space, owing to the conservation of angular momentum in the decay. As a consequence, the measurement of the angular distribution of the leptons in $b \to s\ell\ell$ transitions is sensitive not only to the presence of particles beyond the standard model, but also to their spin.

The angular distribution of the decay $B \to K^*\ell^+\ell^-$ (where K^* denotes an excited state of a kaon that subsequently decays to a ground-state kaon and a pion) is particularly sensitive to the effects of new physics, as one can measure the polarization of both the K^* and the dimuon pair. In total there are at least 16 independent measurable quantities (observables) that describe the decays of both $B \to K^*\ell^+\ell^-$ and its CP conjugate, $\overline{B} \to \overline{K}^*\ell^+\ell^-$ decay (in CP symmetry, a particle is swapped for its antiparticle, and its spatial coordinates are mirror-reflected). One example of these quantities is the fraction of decays in which the K^* is longitudinally polarized in relation to the total decay rate; another is the difference between the number of decays in which the muons are forward-moving or backward-moving relative to the B momentum in the dimuon rest frame, again as a fraction of the total decay rate. The measurements of all quantities are performed in different regions of q^2, because the influence of new particles, and the theoretical uncertainties of the standard model prediction, depends on q^2.

The LHCb collaboration has performed measurements of all 16 observables[35] for the muonic mode, $B \to K^*\mu^+\mu^-$. Most of these measurements, when taken individually, are compatible with the predictions of the standard model. There are, however, some discrepancies. The quantity P_5' is a measure of the chiral asymmetry of the interference between the transversely and longitudinally polarized amplitudes of the decay $B \to K^*\ell^+\ell^-$. The measurements of P_5' in the q^2 region just below the J/ψ resonance show less negative values than those predicted by the standard model (Fig. 3). For example, the two LHCb measurements closest to the J/ψ region are 2.8 and 3.0 standard deviations away from the standard model predictions. The Belle collaboration has also measured this quantity for the electronic and muonic modes[36], both of which are compatible with the LHCb measurements and with lepton universality. The dominant uncertainties of the measurements are statistical in nature and are therefore expected to decrease with a larger dataset. For a more exhaustive collection of recent experimental data from FCNC beauty decays, see ref. 37; for standard model predictions, see ref. 38.

To maximize the sensitivity of these measurements to the effect of new physics, a more rigorous approach is required. This involves combining all measurements of $B \to K^*\ell^+\ell^-$ and other $b \to s\ell\ell$ decays, including measurements of $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ transitions. By exploiting the known correlations between all these measurements from theory and

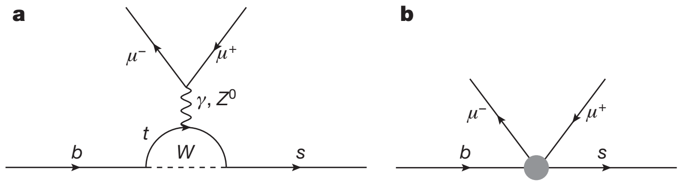

Figure 4 | Illustration of an effective field theory for $b \to s\ell^+\ell^-$ decays. **a**, Feynman 'penguin' diagram for the transition of a b quark (left) into an s quark (right) according to the standard model; this transition is realised by the exchange of a virtual W boson and a virtual top quark (t), which radiate a virtual photon (γ) or a virtual Z^0 boson, in turn producing a couple of muons of opposite charge. **b**, Feynman diagram for the same transition using an effective theory description, in which the $b \to s\ell^+\ell^-$ process can be described by a diagram that does not depend on the top quark, or on the W and Z^0 bosons.

looking for a pattern in the observed discrepancies, a clearer picture of potential new-physics effects can be formed.

Interpretation

The energy scale of b-hadron decays is set by the mass of the initial b quark, which is approximately 5 GeV. However, the particles involved in the quantum-loop transition of the GIM mechanism, such as the W boson and the top quark, have physical masses of around 100 GeV. Decays of hadrons through FCNC transitions can therefore be described by an effective theory[39], which does not explicitly depend on the degrees of freedom of, for instance, the top quark and the W and Z^0 bosons that become relevant at higher energy scales (Fig. 4). Instead, the effects of such contributions are described in terms of quantum-mechanical operators: Wilson operators[40], which encode the Lorentz structure of a particular interaction; and Wilson coefficients, which give the strength of the interaction.

The operators that contribute depend on the specific decay that is being analysed. For example, the Wilson operator $\mathcal{O}_9$ describes the $b \to s\ell\ell$ decay mediated by vector interaction, whereas $\mathcal{O}_{10}$ corresponds to an axial-vector interaction. The strength of each interaction is expressed in terms of corresponding Wilson coefficients, $\mathcal{C}_9$ and $\mathcal{C}_{10}$. Deviations of $\mathcal{C}_9$ or $\mathcal{C}_{10}$ from their standard model expectations would not only indicate the presence of one or more new particles mediating the decay, but also provide information about the spin of those particles.

Global analyses

The challenge in predicting the behaviour of semileptonic $b \to s\ell\ell$ decays is related to the part of the decay that is mediated by the strong force, which is responsible for the dynamics of the initial-state and final-state hadrons. The effects of the strong force in these decays cannot be determined within the framework of perturbation theory and are therefore difficult to calculate, unlike the effects of the electroweak force. These strong-force effects introduce relatively large uncertainties in measurements such as the branching fractions of $b \to s\ell\ell$ decays. To minimize the impact of these uncertainties, ratios of observables are constructed that partially cancel the uncertainties related to the strong force. The angular observable P_5' is such a construction, formed from the ratio of decay amplitudes, and has asmaller uncertainty than do the individual amplitudes themselves[41]. The degree of cancellation is an important point, and is what the residual theoretical uncertainty depends most heavily upon.

Another key feature of these global analyses is the use of the complementarity between different measurements. For example, the branching fraction of $B_s^0 \to \mu^+\mu^-$ is mediated in the standard model by an axial-vector interaction, and so is sensitive to the Wilson coefficient $\mathcal{C}_{10}$ squared. The semileptonic $b \to s\ell\ell$ transitions have both vector and axial-vector contributions, and their branching fractions are sensitive to the sum of $\mathcal{C}_{10}$ squared and $\mathcal{C}_9$ squared. Angular observables are sensitive to various combinations, depending on the particular observable that is being studied. By combining all information, the values of all the different Wilson coefficients can be deduced. The result for $\mathcal{C}_9$ and $\mathcal{C}_{10}$ is shown in

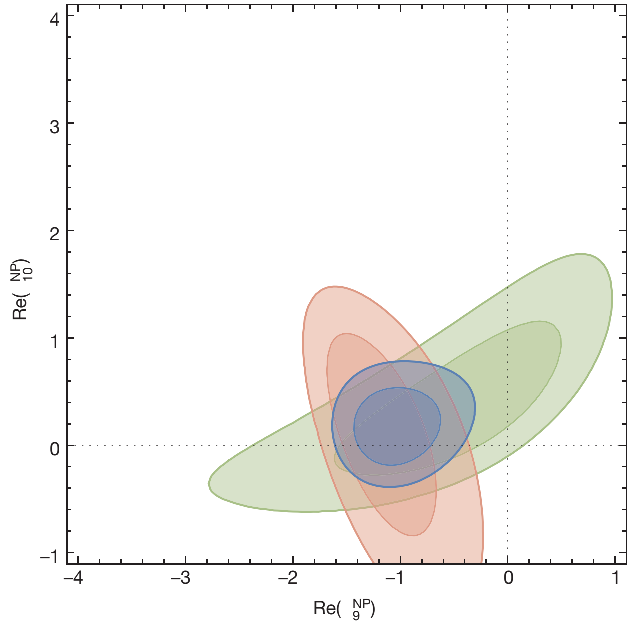

Figure 5 | Global fit of rare beauty decays. Global fit for new-physics contributions to the real part of the vector and axial-vector Wilson coefficients, $\mathcal{C}_9^{\mathrm{NP}}$ and $\mathcal{C}_{10}^{\mathrm{NP}}$. The contours indicate 68% (inner contours) and 95% (outer contours) confidence regions. The red contours show the constraints from angular analysis; the green contours show the constraints from branching-fraction measurements; and the blue contours show the combination of all information. The experimental measurements demonstrate a sizable negative contribution of new physics to $\mathcal{C}_9$. Image reproduced from ref. 54, Springer.

Fig. 5, and indicates that a significantly negative contribution to the standard model value for $\mathcal{C}_9$ is preferred. Globally, the likelihood that there is an additional contribution to $\mathcal{C}_9$ is supported to around three to four standard deviations, depending on the analysis and on which observables are included[12,38,42–54]. This significance includes both experimental and theoretical uncertainties.

A significant variation from the standard model of more than three standard deviations corresponds to a P value of less than 0.3%. In particle physics, the statistical significance that is needed to claim a discovery is more stringent, being at the level of five standard deviations, or a P value of less than one in a million. This strict definition of observation is used because hundreds of analyses are performed in high-energy physics each year. Over a period of time, it is inevitable that a few discrepancies of three standard deviations will appear. What is encouraging here is that the global significance is driven by different smaller discrepancies, which are based on different experimental and theoretical systematic uncertainties. Nevertheless, it is important to remain cautious when interpreting the results.

Interpretation beyond the standard model

The deviations described above with respect to the standard model predictions could be explained by the existence of a new particle, not predicted by the standard model, whose contribution to the decay amplitude destructively interferes with the standard model diagram. If this particle were also to interact differently with electrons and with muons, it could also explain the deviation seen in $\mathcal{R}_K$. There is a multitude of new-physics models that could explain some or all of these anomalies. Here we give two well studied examples.

One example of an extension to the standard model that could explain these deviations involves a heavy version of the Z^0 boson, denoted Z' (refs 43, 51). Such an extension to the model must satisfy direct searches for such particles at the CMS and ATLAS experiments, which in practice means either that the Z' candidate must be at least 30 times heavier than the standard model Z^0 boson, or that it must have small couplings to the up and down quarks. If the Z' is very heavy, it would not have a sizable impact on the decay compared with the standard model contribution, unless it could change the flavour of quarks directly without going through a quantum-loop transition. This model has consequences for other flavour observables, such as B_s^0 oscillations, where the B_s^0 hadron could annihilate to produce a Z' boson, which would then decay to $\overline{B}_s^0$. The interesting outcome of these Z' models is that there is room to satisfy all existing experimental constraints and explain all $b \to s\ell\ell$ anomalies. If such a hypothesis were confirmed, it would it be a major breakthrough in particle physics and could be the first real step towards addressing any of the outstanding questions in fundamental physics[55].

Another proposed particle that could explain the deviations from the standard model is a leptoquark[56]—which, as the name suggests, carries quantum numbers of both quarks and leptons and can directly couple to the two. Here, typical solutions require a leptoquark that couples more strongly to the second and third generations of decay than to the first. This hierarchical flavour structure can naturally explain the lepton non-universality ratio $\mathcal{R}_K$, and could be related to other hints of lepton non-universality seen in other b-hadron decays[57,58]. Interestingly, there are some models (see, for example, ref. 59) that predict a leptoquark mass of around 1 TeV, which with some luck could be directly observed at the LHC.

Interpretation within the standard model

As well as undergoing the FCNC process, the b hadron can decay into a final state containing a strange hadron and a pair of muons, via the process $B \to K^* J/\psi$, with the J/ψ often decaying into two muons. As this decay ($B \to K^* J/\psi$ then $J/\psi \to \mu^+\mu^-$) shares the same final state as the signal decay $B \to K^*\mu^+\mu^-$, the two processes undergo quantum-mechanical interference, which can mimic the effects of physics beyond the standard model. As discussed above, the strong interaction at the energy scale corresponding to the B-hadron mass is difficult to compute theoretically. The strong interaction for the process $B \to K^* J/\psi$ with $J/\psi \to \mu^+\mu^-$ is particularly difficult to calculate, because this process receives much larger contributions from the strong force than does the FCNC $B \to K^*\mu^+\mu^-$ decay.

The decay of a b hadron into a final state containing a strange hadron and a pair of muons proceeds via the J/ψ and the $\psi(2S)$ hadrons (an excited state of J/ψ) 99% of the time. The branching fractions of these decays are known to a relative precision of 5%, which constrains the size of the interference with the FCNC decay. However, an additional complication arises owing to the Heisenberg uncertainty principle, which relates the lifetime of a hadron to its mass-energy. The short lifetime of the J/ψ hadron results in a small but non-negligible spread of possible values of mass that this hadron can have before it decays. Such a spread is known as the 'natural width' of the hadron. The problem therefore lies in considering the effect of the interference between the FCNC decay $B^0 \to K^{*0}\mu^+\mu^-$ and the $B^0 \to K^{*0} J/\psi$ decay, with the latter being very far away from the nominal mass of the J/ψ hadron.

The discrepancy in P_5' between measurements and the standard model predictions is localized in a q^2 region approximately 1,000 natural widths away from the nominal J/ψ mass. The effect of this resonance in this region depends on the level of quantum-mechanical interference between the FCNC decay and the decay involving a J/ψ hadron. In global analyses of $b \to s\ell\ell$ transitions, this interference is estimated using the method described in refs 60 and 61, which relies on a non-perturbative quantum-chromodynamics calculation, starting at low q^2 values and extrapolated to higher q^2 values using knowledge of the spectrum of hadronic states, such as the J/ψ and $\psi(2S)$ hadrons. Given the difficulties in calculating these contributions, there is much discussion in the field regarding whether the level of the interference between the FCNC decay and the decay involving the J/ψ hadron could result in the discrepancies seen in P_5'. Disentangling this effect from the more exotic explanation enlisting new particles is of the highest priority for both experimental and theoretical particle physicists.

Summary and outlook

FCNC decays continue to play an important part in understanding the fundamental forces of nature. Not only have they been crucial in the development of the standard model, the present set of discrepancies also provides evidence for new particles that would extend the standard model and could lead to a more complete description of particle physics. At the moment, however, this evidence is intriguing but inconclusive, and the most important question now is whether these discrepancies could instead be explained by a combination of statistical fluctuations and contributions by charmoniums (such as the J/ψ hadron). The former possibility will be addressed with the increased dataset collected at the LHC during 2015 to 2018, which is expected to be four times larger than the dataset used in the measurements described here. The larger dataset would also allow a more precise test of the q^2 dependence of the P_5' discrepancy—a characteristic that would be present only if the deviation were due to hadronic interactions.

As well as obtaining more data, there is a specific analysis that could help to shed light on the observed discrepancies from standard model predictions. This would involve measuring the level of quantum-mechanical interference between the FCNC decay and the decay that proceeds via charmonium states. Such a measurement would be crucial to understanding the validity of theoretical predictions of this quantity, and therefore of standard model predictions of $b \to s\ell\ell$ processes. We note that the axial-vector Wilson coefficient, $\mathcal{C}_{10}$, is not affected by the interference of the FCNC decay with decays involving charmonium states. In global fits to the Wilson coefficients, there is a solution in which the contribution of new physics to $\mathcal{C}_9$ and to $\mathcal{C}_{10}$ is equal in magnitude. If this scenario were realized, then one would expect the branching fraction of $B_s^0 \to \mu^+\mu^-$ decay to remain lower than the standard model prediction, and that deviations would start appearing in other angular observables of $B^0 \to K^{*0}\mu^+\mu^-$ decays.

Another type of analysis—which avoids complicated discussion of hadronic uncertainties—requires measurements that test the hypothesis of lepton universality. Measurements of $b \to s\ell\ell$ processes that involve other hadrons in the final state (for example, measurements of $\mathcal{R}_{K^*}$) should soon provide a valuable piece to this puzzle, as well as improving the precision of $\mathcal{R}_K$ measurement with more data. Moreover, with more data, an angular analysis of final states that comprise electrons can be performed, as in ref. 36. If the angular distribution of $B^0 \to K^{*0}e^+e^-$ is significantly different from that of $B^0 \to K^{*0}\mu^+\mu^-$, it would be an unambiguous signal of new physics.

Looking further ahead, an upgrade of the Belle experiment, Belle II (ref. 62), is being commissioned at the moment. Over its lifetime—from 2018 to 2025—it will collect 50 times more data than its predecessor. The Belle II experiment will be particularly important for further testing lepton universality in $b \to s\ell\ell$ decays, but also for measuring the decay properties of the inclusive $b \to s\ell\ell$ process. The standard model predictions of inclusive decays have different theoretical uncertainties to those of the decays to specific final states described here. Therefore, inclusive $b \to s\ell\ell$ measurements could help to disentangle new-physics and standard model interpretations of the observed discrepancies.

The LHCb, CMS and ATLAS detectors will also undergo upgrades, increasing the number of signal decays collected by at least a factor of 30 compared with those described here. The motivation for such a dataset is clear. In the pessimistic scenario that the anomalies discussed fade with time owing to statistical variations, then the largest possible dataset will be needed to reveal smaller putative contributions from new physics. If instead the more optimistic scenario is realized—that these anomalies remain—then a huge dataset from these decays would allow a detailed study of the exact model behind these new-physics effects, and of whether such a model could address any of the outstanding questions in fundamental physics.

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