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# Flavour anomalies and status of indirect probes of the Standard Model

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With the discovery of the Higgs boson and consequent completion of the Standard Model, there is no fundamental principle which demands the existence of new particles below the Planck scale. Indirect precision measurements of the properties of existing particles are therefore more essential than ever to probe beyond the reach of direct discovery and guide the development of collider-based experiments. In this context, quark flavour physics is a uniquely rich laboratory for indirect precision tests of the Standard Model. I give a brief overview of some recent highlights from the field and look ahead to what the next generation of experiments and facilities might bring.

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## 1. Introduction

Within the Standard Model (SM) of particle physics, flavour-changing quark transitions are governed by the Cabibbo-Kobayashi-Maskawa (CKM) unitary matrix and mediated by the weak force. This matrix can be described using three real and one imaginary parameters, and it is the non-zero value of this imaginary parameter which leads to Charge-Parity ($CP$) violation within the SM. Unitary relations between the elements of the CKM matrix define six triangles in the complex plane with equal areas. These areas are proportional to the amount of SM $CP$ violation. One of these triangles has sides and angles which are particularly convenient to measure using experimentally accessible quark transitions, and is commonly referred to as "the Unitarity Triangle".

If the SM is a complete and self-consistent description of reality, independent measurements of the angles and sides of the Unitarity Triangle should be compatible with one another and compatible with a triangle whose angles add up to 180°. Over the past 25 years flavour physics has confirmed that this SM picture of flavour-changing quark transitions holds to around the 10% level. [1–3] On the other hand we know that the amount of $CP$ violation in the SM is fundamentally insufficient to explain the observed matter-antimatter asymmetry of the universe. [4, 5] There must therefore exist new particles and forces which mediate flavour-changing quark transitions, and the self-consistency of the CKM picture of quark transitions must break down.

The question then is, at what energy scale do these new particles and forces reside? Given the discovery of the Higgs boson and its generally SM-like nature, there is no fundamental principle which requires new particles and forces at energy scales directly accessible in existing or near-term feasible collider experiments. Particles which are too massive to be directly produced in our colliders can nevertheless act as virtual participants in quark transitions, altering their frequency away from SM expectations. A more precise understanding of quark transitions is therefore an indispensible guide to the energy scale of physics beyond the SM.

Natural units are used throughout these proceedings, and charge conjugation is implied unless explicitly stated otherwise.

## 2. Mapping the apex of the CKM Unitarity Triangle

As shown in Figure 1, the past decades have seen tremendous progress in the experimental determination of the CKM unitarity triangle. The apex of this triangle (above the angle $\alpha$ in these plots) is of particular interest as it can be determined using several experimentally independent routes. The overall agreement of different experimental determinations of the apex directly probes the energy scale and quark coupling structure of putative physics beyond the SM. This is illustrated in Figure 2. New particles with $O(1)$ tree-level couplings to quarks are already ruled out to between $10^2$ and $10^5$ TeV, while particles with minimally-flavour violating [6] (MFV) tree-level couplings are excluded at between a few and $O(10)$ TeV depending on the operator in question. While measurements of charm and strange hadron processes give the most stringent constraints on generic tree-level couplings, measurements of beauty hadron processes tend to be more constraining for MFV processes – and even more so if the process is both MFV and loop-level.

Nevertheless, as discussed in Ref [7, 8], a global analysis of the experimental constraints on operators which mediate tree-level hadronic beauty decays shows that beyond SM effects of $O(10)$%

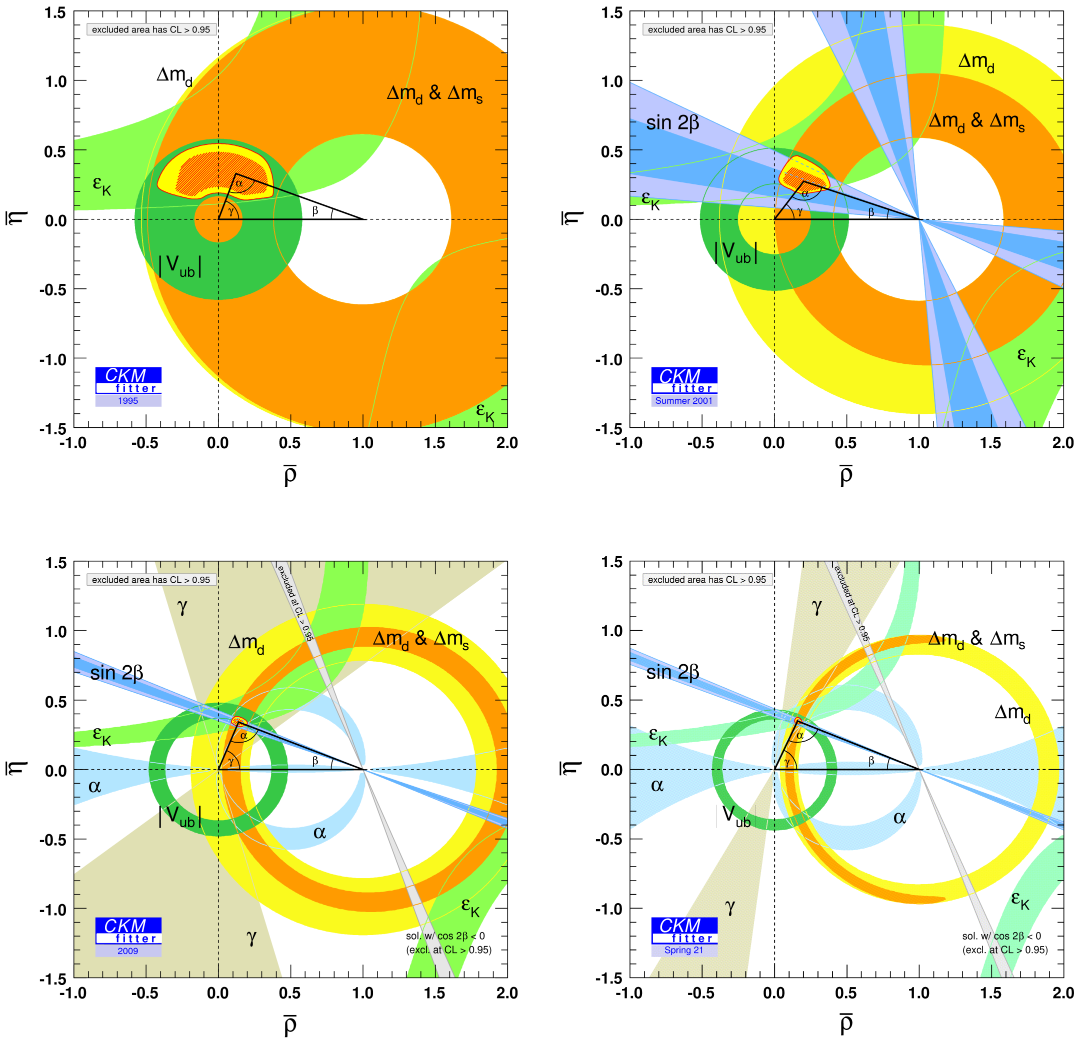


**Figure 1:** Evolution of constraints on the CKM unitarity triangle over time. Clockwise from top left: prior to the top quark discovering in 1995; after the first b-factory measurements of the angle $\beta$ in 2001; prior to the LHC startup in 2009; in January 2022. Reproduced from Ref [3].

remain allowed. It is therefore not the case, as one often hears, that "loop decays are sensitive to new physics" while "tree-level decays are SM standard candles". A more precise experimental understanding of both tree-level and loop-level SM processes and their global coherence is essential in attempting to indirectly infer the scale and nature of physics beyond the SM.

The direct tree-level determination of the CKM angle $\gamma$ has seen the biggest experimental gains over the last ten years, driven by the exploitation of the 2011-2018 LHCb dataset. The precision of the direct determination of $\gamma$ has evolved from $(68^{+10}_{-11})^{\circ}$ in the summer of 2011 [3] to $(65.4^{+3.8}_{-4.2})^{\circ}$ in 2021 [10]. Because the CKM angle $\gamma$ must be measured together with a number of nuissance parameters and no single process dominates the experimental sensitivity, its value is commonly extracted from a global statistical analysis of all the relevant experimental measurements.

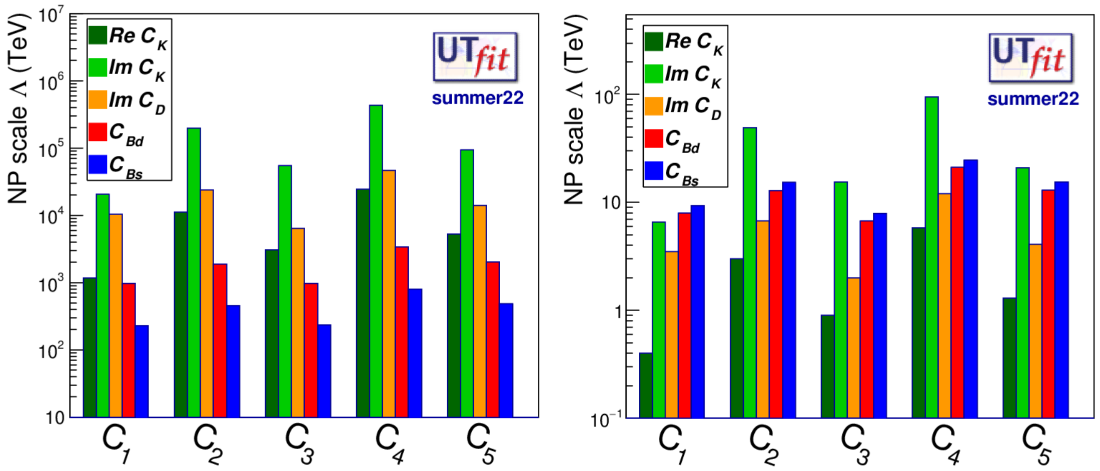


**Figure 2:** Bounds on the energy scale of physics beyond the SM ("NP scale") arising from different *CP* violating processes. The Wilson coefficients which contribute to the processes in question are labelled on the horisontal axis. The left plot shows bounds for tree-level generic couplings, while the right plot shows bounds for tree-level MFV couplings. Prepared by the UTFit collaboration and used with permission. For the latest UTFit analysis please see Ref [2].

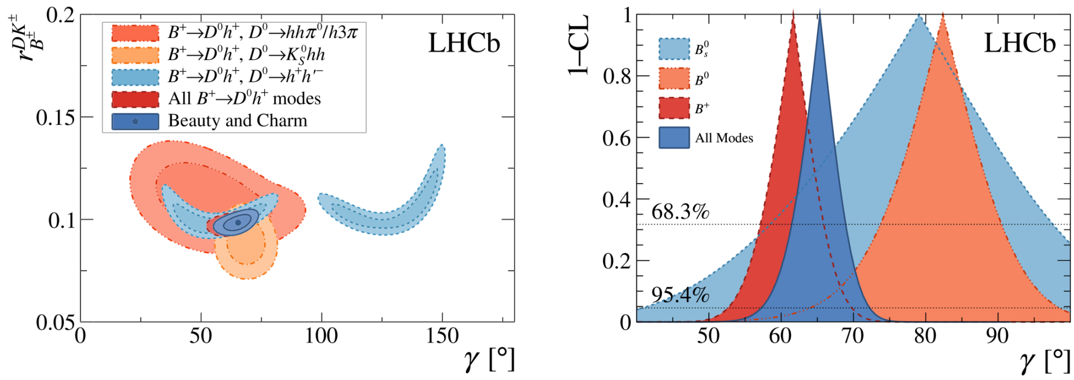


**Figure 3:** (Left) One dimensional $1-\mathrm{CL}$ profiles for $\gamma$ from the combination using inputs from the decay modes labelled in the legend. (Right) Profile likelihood contours for the beauty decay parameters versus $\gamma$, showing the breakdown of sensitivity amongst different sub-combinations of modes. The contours indicate the 68.3% and 95.4% confidence region. Reproduced from Ref [10].

As shown in Figure 3 while the combination of $B^+$ decays continues to drive the precision with which $\gamma$ is known, $B^0$ and $B^0_s$ decays have a non-negligible impact on the central value of the global fit. Moreover, at the current level of experimental sensitivity, it has become helpful to include measurements of $D^0$ mixing parameters in the global fit to $\gamma$. The overall quality of the LHCb global fit to $\gamma$ is excellent, with an 84% goodness of fit based on 151 input observables and 52 free fit parameters. While the data samples collected by Belle II are not yet big enough to affect the determination of $\gamma$, the analysis of Ref [11] clearly demonstrates the improved performance of the Belle II detector, particularly in terms of its mass resolution, with respect to Belle.

The ratio of CKM matrix elements $|V_{ub}/V_{cb}|$ leads to a complementary tree-level constraint

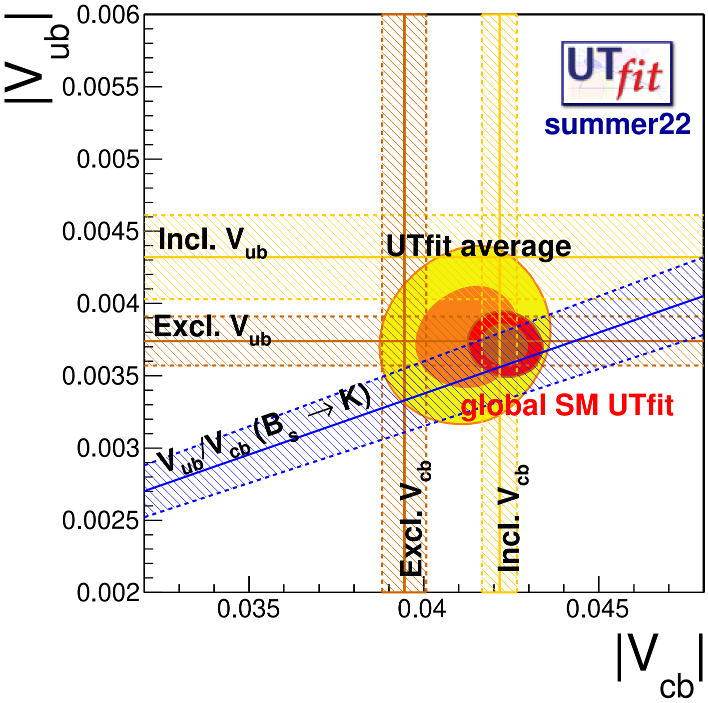


**Figure 4:** Status of the global determination of $V_{ub}$ and $V_{cb}$. Reproduced from Ref [2].

on the unitarity triangle. The combination of this ratio and $\gamma$ pinpoints the apex of the triangle, and can then be tested for consistency with e.g. the combination of $\sin(2\beta)$, $\Delta m_d$, and $\Delta m_s$. The CKM parameters $V_{ub}$ and $V_{cb}$ are determined from the measurement of the $b \to u l \nu_l$ and $b \to c l \nu_l$ semileptonic decay processes. In both cases there is an experimental choice between isolating specific exclusive processes such as $B^0 \to \pi^- l^+ \nu_l$ and performing an inclusive measurement by tagging the presence of a $b \to (u,c)$ transition using global event properties. (Hadron collider experiments can only perform exclusive measurements.) The tradeoff is that while exclusive processes have much smaller backgrounds, they require additional theory inputs to interpret the experimental observables in terms of CKM parameters.

There is a longstanding tension between the inclusive and exclusive determinations for both $V_{ub}$ and $V_{cb}$. The latest UTFit analysis [2] summarised in Figure 4 shows that this tension is currently at $> 3\sigma$ for $V_{cb}$ and $2-3\sigma$ depending on the precise inputs used for $V_{ub}$. Contrary to $\gamma$ this is an area where Belle II can already make competitive measurements. Its recent exclusive analyses lead to $V_{ub} = (3.55\pm0.12\pm0.13\pm0.17)\cdot10^{-3}$ [12] (where the three uncertainties are respectively statistical, systematic, and theoretical) and $V_{cb} = (38.53 \pm 1.15) \cdot 10^{-3}$ [13], in agreement with other exclusive measurements. The tension between inclusive and exclusive determinations is generally taken as a sign of imperfectly understood experimental (in the inclusive) or theoretical (in the exclusive) effects, rather than physics beyond the SM. In this context a "third way" towards $V_{ub}$ is offered by the purely leptonic decays $B^+ \to (\tau,\mu)^+ \nu_(\tau,\mu)$ which have much smaller theoretical uncertainties than the semileptonic $B^0 \to \pi^- l^+ \nu_l$ processes but as they proceed through an annihiliation diagram are also much less statistically sensitive. Belle II expects [14] to measure $V_{ub}$ from each these processes with a relative uncertainty of around 2.5% with its full dataset, which is significantly better than the current global precision and underlines their importance in the legacy understanding of the CKM unitarity triangle. The corresponding $V_{cb}$ processes would only be accessible at a high-luminosity $E^+e^-$ collider operating at the $Z$ pole such as FCC-ee, as discussed in Section 5.

## 3. $CP$ violation in charm hadrons: from discovery to characterization

While decays of beauty hadrons can exibit large, even near-maximal [15], $CP$ violation, this is not the case for decays of charm hadrons. Both $D^0$ meson mixing and charm hadrons decays predominantly proceed through diagrams involving the first two quark generations, whose CKM couplings are $CP$-conserving at leading order in the Wolfenstein parametrisation [16] of the CKM matrix. The largest $CP$-violating effects, of order one permille, are expected in singly-Cabibbo suppressed decays, while $CP$-violation in the interference of mixing and decay is further suppressed to order $10^{-5}$. [17] The study of charm $CP$ violation therefore requires unusually large datasets and an exquisite control of detector-inducted charge asymmetries.

Fortunately, the LHC is the biggest charm factory ever constructed, with a few percent [18] of all $pp$ collisions producing a $c\bar{c}$ pair. And unlike in beauty decays, where decays with the largest $CP$ violating effects often have effective branching ratios of $10^{-5}$ or smaller, experimentally accessible singly-Cabibbo suppressed charm decays have branching ratios of order $10^{-3}$. In addition, although not designed for the study of charm $CP$ violation, the LHCb detector – particularly its trigger system – has proven sufficiently flexible [19] to enable a highly efficient collection of charm hadron decays to final states involving charged particles. This enabled LHCb to observe $CP$ violation in charm for the first time in 2019 [20] by measuring the difference in $CP$ asymmetries between $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays. The measured value of $A_{CP} = (-15.4 \pm 2.9) \cdot 10^{-4}$ is of roughly the expected size within the Standard Model.

Following this observation, attention is turning to the systematic characterisation of $CP$ violation in charm. The goal is to measure it in as many different modes as possible, as has been done for beauty decays. Figure 5 neatly illustrates the progress achieved in measuring $CP$ asymmetry in $D^0 \to K^+K^-$ decays over the past decades. The statistical power of the hadron colliders is clear from the uncertainties of the CDF and LHCb measurements compared to the B-factories. However the upgraded LHCb detector will take this a step further by operating a fully software trigger, improving efficiencies by up to a factor five [19] for charm decays. When combined with the five times greater instantaneous luminosity, this upgrade promises another leap forward in sensitivity. Figure 6 shows how the latest LHCb measurement of $CP$ asymmetry in $D^0 \to K^+K^-$ can be transformed into a two-dimenstional constraint on $CP$ asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ using the previously quoted measurement of their difference. From this LHCb concludes to have first evidence of $CP$ violation in $D^0 \to \pi^+\pi^-$ decays of $a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \cdot 10^{-4}$.

There are several important caveats to this progress which must be noted. First of all, charm decays are phenomenologically more complicated than beauty decays because the charm quark mass is much closer to the nonperturbative QCD scale. While an observation of $CP$ violating effects on the order of a few percent would have challenged any reasonable Standard Model explanation, this has not occured. Secondly decays involving neutral particles in the final state are much harder



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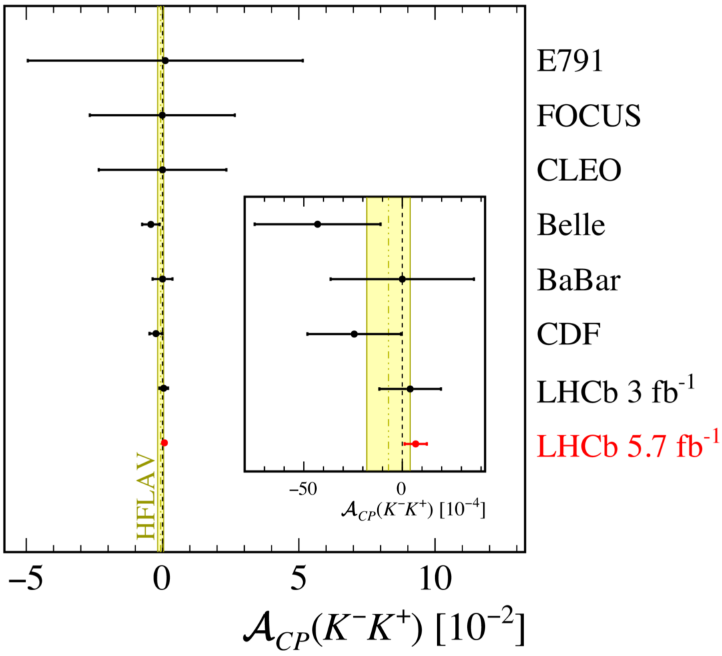


**Figure 5:** Measurements of $CP$ violation from various experiments in $D^0 \to K^+K^-$ decays, with the latest LHCb result highlighted in red. The vertical band corresponds to the average of all measurements previous to the presented, computed by HFLAV [1], where it is assumed that $CP$ is conserved in mixing and in the interference between decay and mixing. This assumption is necessary when results from different experiments are compared. Reproduced from Ref [21].

from an experimental point of view for hadron colliders, while Belle 2 will not have the statistical sensitivity to probe them at the required level. The picture of $CP$ violation in charm will therefore necessarily remain more limited than that in beauty hadrons. Nevertheless charm remains a unique laboratory for studying the CKM mechanism in up-type quarks, and the upgraded LHCb detector does have the raw statistical reach to not only measure $CP$ asymmetries in individual decays but also to probe $CP$ violation in the interference of mixing and decay to the expected Standard Model level. For these reasons, and precisely because no other existing or planned experiment can match this reach, it is imperative that the full potential of LHCb for charm is realised in the next decades.

## 4. Searching for anomalous lepton couplings

Within the Standard Model lepton flavour is a conserved quantity, while the electroweak gauge bosons have universal couplings to the three lepton generations. There is no reason why physics beyond the Standard Model must respect these symmetries, so that searches for lepton flavour violating (LFV) or lepton universality violating (LUV) processes are natural null tests of the SM. In addition, leptonic and semi-leptonic flavour-changing neutral currents (FCNC) are highly suppressed in the Standard Model, so that even relatively small contributions from new particles or couplings can lead to visible deviations from SM predictions. Searches for anomalous lepton

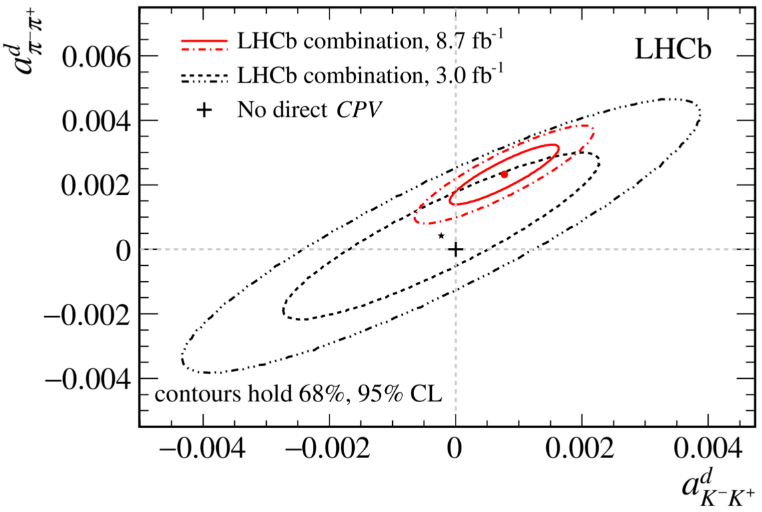


**Figure 6:** Central values and two-dimensional confidence regions in the $(a^d_{\pi^+\pi^-}, a^d_{K^+K^-})$ plane. Reproduced from Ref [21].

couplings consequently lead to highly complementary constraints on the nature and energy scale of beyond SM physics.

Searches for lepton-flavour (and/or lepton-number) violating decays of hadrons have been carried out across a wide range of initial and final states by many experiments, as summarized by HFLAV [1], and to date no significant signal has been observed. These searches sometimes also involve changes in the baryon number, since a popular class of beyond SM models maintain $B-L$ as a conserved quantity. Numerous LFV decays of the $\tau$ lepton have been searched for, with the same outcome [1]. While hadron and $\tau$-lepton decays can be studied at generic collider experiments, dedicated facilities are required to search for LFV decays of the muon. Such experiments have also failed to find any signal of LFV [1].

The universality of lepton couplings to the electroweak gauge bosons is an accidental symmetry of the Standard Model, but one which gives rise to some of the theoretically cleanest tests of the SM in quark transitions. This is particularly true when considering the decays of beauty hadrons for which short-range operators are known to dominate, in which case the theoretical uncertainties associated with specific lepton universality predictions can be controlled at the percent level. Since the surprising 2012 BaBar measurement of an excess of $B \to D(*)\tau\bar{\nu_\tau}$ decays [22], there has been a range of persistent hints for lepton universality (LU) breaking in a range of $b \to s\ell\ell$ and $b \to c\ell\bar{\nu}_\ell$ transitions. There is no completely straightforward theoretical intepretation of these lepton universality "anomalies", and accomodating both large tree-level effects in $\tau-\mu$ universality and large loop-level effects in electron-muon universality requires any putative beyond SM operators to have highly hierarchical couplings to the different lepton and quark generations.

The current status of the most sensitive LUV tests in $b \to c\ell\bar{\nu}_\ell$ transitions, commonly referred to as R(D) and R(D$^*$), is summarized in Figure 7. These measurements test the universality between the $\tau$ and light leptons, although for experimental reasons LHCb has only measured $\tau-\mu$ universality while the b-factories combine $\tau-\mu$ and $\tau-e$ measurements to improve sensitivity.

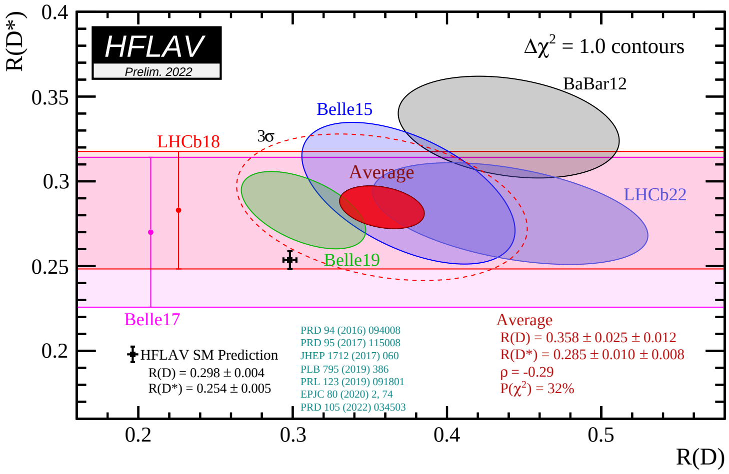


**Figure 7:** Current experimental constraints in the R(D) − R(D*) plane compared with the Standard Model prediction. Reproduced from HFLAV [1].

The best measurements of electron-muon lepton universality in these processes are compatible with the SM expectation of 1 at the 2% level [23]. The combined agreement with the SM, as evaluated by HFLAV, is $3.2\sigma$. The global fit has a P-value of 32%, which speaks to the generally excellent agreement between the different experimental measurements. It is also notable that no published measurement has placed either R(D) or R(D*) below the predicted SM value. LHCb has measured the baryonic analogue [24] of R(D) in $\Lambda_b \to \Lambda_c \tau$ transitions using charged hadronic decays of the $\tau$, and the $B_c^+$ analogue [25] in $B_c^+ \to J/\psi\tau$ transitions using the muonic decay of the $\tau$. These measurements are also compatible with the Standard Model.

At present the experimental measurements are statistically limited, and the majority of LHCb's dataset has yet to be analysed. We can therefore expect the two LHCb measurements in this average to be improved on in the coming years, each gaining roughly a factor two in sensitivity even before data from the upgraded LHCb detector is considered. In addition the $B_s^0$ analogues of these LUV tests, R($D_s$) and R($D_s^*$), as well as the charged charm analogue R($D^+$), are currently being pursued at LHCb and will also add complementary information. All of these LUV tests will be performed with both the muonic and hadronic decays of the $\tau$. Since the detector performance and backgrounds are substantially different in these two cases, their compatibility reinforces the experimental robustness of the results similarly to the use of hadronic or leptonic opposite-side tags to reconstruct these decays at BaBar, Belle, and Belle 2. If the anomaly persists at roughly the current size, Belle 2 and the upgraded LHCb detector should both be able to make single-experiment observations of LUV, which would be crucial to give confidence in the experimental robustness of the results. In this context the development of cross-experiment tools for coherently simulating the impact of beyond SM physics on the kinematics and geometry of these decays, such as HAMMER [26], is also of great importance.

The $b \to s\ell\ell$ family of processes (including the phenomenologically similar $bs \to \ell\ell$) have been studied in three primary ways to date. First, the search for the rare leptonic decays $B_{s,d}^0 \to \mu^+\mu^-$, and the subsequent measurement of their branching fractions and effective lifetimes. Second,

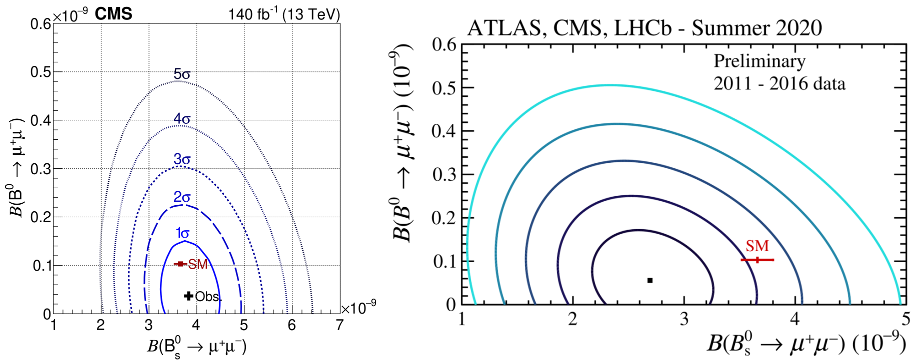


**Figure 8:** Two dimensional likelihood contours for the $B^0_{s,d} \to \mu^+\mu^-$ branching fractions. The Standard Model prediction is marked SM in red. The left plot is the latest CMS standalone result, while the right plot is a previous combination of ATLAS, CMS, and LHCb results. The left plot is reproduced from Ref [30], the right plot is reproduced from Ref [31].

measurements of the angular properties and differential decay rates of $b \to s\mu^+\mu^-$ decays. And third, the study of electron-muon universality through the comparison of the decay rates of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$ processes. In contrast to the tree-level $b \to c\ell\bar{\nu}_\ell$, the rarity of the loop-level $b \to s\ell\ell$ transitions have until now precluded the possibility of precise tests involving $\tau$ leptons, which are far harder to reconstruct efficiently and cleanly. The $\tau$ decays will remain inaccessible to LHCb or Belle 2 if their branching fraction agrees with the Standard Model prediction, but should be accessible at a future electron-positron collider operating at the $Z$ pole. [27]

The rare leptonic decays $B^0_{s,d} \to \mu^+\mu^-$ are only currently accessible at the LHC. While $B^0_s \to \mu^+\mu^-$ has been observed since 2014 thanks to a combined analysis of CMS and LHCb data, the even rarer $B^0_d \to \mu^+\mu^-$ decay is yet to be observed. A particular interest with these decays is that their branching fractions can be predicted with small theoretical uncertainties in the SM, and indeed most of those uncertainties come from a limited knowledge of CKM parameters [28, 29]. The most precise single measurement of the $B^0_s \to \mu^+\mu^-$ process comes from a new CMS [30] measurement which is in excellent agreement with Standard Model predictions. This is also the case for the CMS measurement of the $B^0_s \to \mu^+\mu^-$ effective lifetime, which provides complementary phenomenological information. The two-dimensional likelihood contours in the $B^0_{s,d} \to \mu^+\mu^-$ branching fractions for this latest CMS result are compared with a previous combination of ATLAS, CMS, and LHCb results in Figure 8. A new combination, which is not ready at the time of writing, will clearly lie significantly closer to the SM value than the previous one.

The analogous process in the charm sector, $D^0 \to \mu^+\mu^-$, is dominated by long-distance contributions and has never been observed, though LHCb recently published [32] an updated (and world-best) limit on its branching fraction. Searches for the much more heavily helicity-suppressed $B^0_{s,d} \to e^+e^-$ decays and the enhanced but experimentally much more complex $B^0_{s,d} \to \tau^+\tau^-$ decays have so far been compatible with the background-only hypothesis [33, 34].

The semi-leptonic family of $b \to s\mu^+\mu^-$ decays give rise to a plethora of observables linked to the angular structure of the decays and their differential decay rate. The muonic mode is the most experimentally accessible and hence by far the most studied to date, but the same phenomenological arguments apply to the electron and $\tau$ modes as well. The phenomenological interest in these decays is illustrated in Figure 9, which shows which Wilson coefficients encoding the relevant short-distance physics (and hence sensitive to putative particles beyond the SM) contribute depending on the dimuon invariant mass squared. The photon pole region relates studies of $b \to s\mu^+\mu^-$ processes to those of $b \to s\gamma$, which are generally considered together in phenomenological fits that try and establish compatibility between the experimental data and SM hypothesis.

A wide range of neutral and charged beauty hadron $b \to s\mu^+\mu^-$ decays have been studied across a range of experiments, and the reader is invited to consult HFLAV [1] for an up-to-date summary. Interestingly, a coherent pattern of deviations from Standard Model predictions [35–40] has emerged from the combined analysis of these measurements in terms of the Wilson coefficients. While no single measurement or indeed observable has a significance more than $5\sigma$ from the SM, their combined interpretation exceeds $5\sigma$ under a wide range of theoretical assumptions. Doubts nevertheless remain about the precise role of charmonium resonances in these processes, an effect commonly referred to as "charm loops" in the literature, which some groups argue [40, 41] can fully explain the observed deviations without the need for any physics beyond the Standard Model. There are ongoing attempts to experimentally clarify the size of these charm loop contributions. State of the art approaches extract their size directly from data. Such measurements have already been performed for $B^\pm \to K^\pm\mu^+\mu^-$, where minimal inference was found [42] between the short and long distance (charm-loop) contributions. Measurements of the non-local contributions to $B^0 \to K^{*0}\mu^+\mu^-$ are currently being preformed at LHCb using models based on Ref. [43] or Ref. [44, 45]. The results of these analyses will by definition depend on the theory model used. However if their results are coherent and the ensemble of experimental analyses and underlying theory models shows no indications for large charm-loop contributions, it will strengthen the argument that these deviations are driven by beyond SM contributions. Nevertheless it remains unclear at what point the community will reach a consensus on the precise quantitative impact of charm loops on $b \to s\mu^+\mu^-$ decays. Consequently even if individual $b \to s\mu^+\mu^-$ processes or observables cross the $5\sigma$ threshold, it is unlikely there will be an uncontested declaration that physics beyond the Standard Model has been discovered.

No such caveats apply to LUV tests in $bs \to \ell\ell$ processes. The relative decay rates of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$ processes are predicted to within 1% in the Standard Model [47], and most of even this uncertainty is attributed to the modelling of electron energy losses in the experimental apparatus rather than theoretical uncertainties of the type which arose in $b \to s\mu^+\mu^-$ decays. For this reason there has been a great deal of interest in the community as over the past eight years evidence seemed to accumulate of electron-muon LUV effects in $bs \to \ell\ell$ decays. Most of this evidence was driven by LHCb measurements as the sensitivity of the b-factory datasets was too small to meaningfully contribute to the global analysis.

The two LHCb measurements which drove the bulk of the tension with the SM were electron-muon univerality tests in $B^\pm \to K^\pm\ell\ell$ ($R_K$) and $B^0 \to K^{*0}(892)\ell\ell$ ($R_{K^{*0}}$) decays. The standalone measurement of $R_K$ using the full LHCb dataset in the "central" $q^2$ range 1.1–6.0 GeV$^2$ reported [48] $3.1\sigma$ evidence of LUV. The earlier measurement of $R_{K^{*0}}$ in central $q^2$ as well as in the "low" $q^2$ range 0.045–1.1 GeV$^2$, while using only a quarter of the available LHCb data, deviated [49] from the SM prediction in a coherent way, with significances in each $q^2$ range of 2–$2.5\sigma$. The absolute size of the deviations coherently pointed to around a 15% breaking of electron-muon universality, with an overall significance which did not however rise to the level of discovery. The deviation at

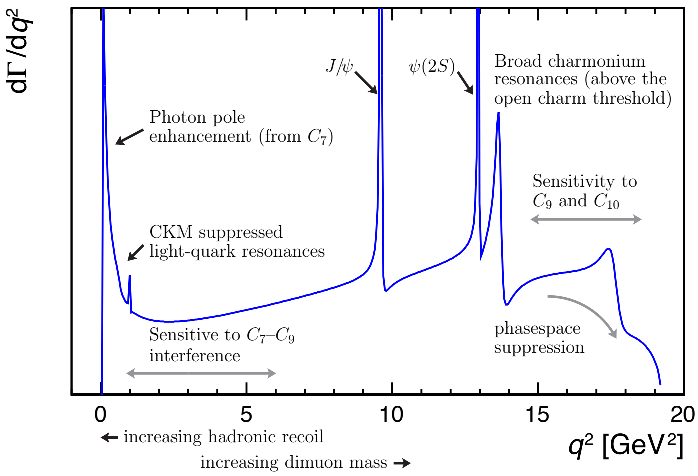


**Figure 9:** Cartoon illustrating the dimuon mass squared, $q^2$, dependence of the differential decay rate of $B \to K^*\ell^+\ell^-$ decays. The different contributions to the decay rate are also illustrated. For $B \to K\ell^+\ell^-$ decays there is no photon pole enhancement due to angular momentum conservation. Caption and illustration reproduced from Ref [46] with permission of the authors.

low $q^2$ was particularly perplexing since this region is dominated by the photon pole (see Figure 9) and beyond SM effects of this magnitude at the photon pole were ruled out by other, dedicated, measurements.

The recently published [50] combined LHCb analysis of $R_K$ and $R_{K^{*0}}$ using the full available LHCb data sample has clarified the situation. Both of the lepton universality (LU) ratios are measured at both low and central $q^2$, and all four LU measurements are fully compatible with the SM with the largest single deviation being around $1\sigma$. The primary reason for this change is a more accurate treatment of backgrounds in which a hadron is misidentified as an electron. The combined analysis applies more stringent identification criteria compared to previous LHCb publications, inherently reducing the impact of such backgrounds. It is nevertheless necessary to also model the residual misidentified backgrounds in the invariant mass fit which measures the electron mode signal yields, which was not done in previous publications. Data in a control region enriched in such misidentified backgrounds are extrapolated into the signal region using transfer maps computed from data calibration samples.

The remaining backgrounds which enter the final fit are shown in Figure 10. As can be seen they contain peaking shapes which could not be absorbed by other fit components in the previous analyses and therefore biased them away from the SM. It should however be underlined that the data-driven treatment of backgrounds allows all four LU measurements to remain statistically limited, which gives confidence that LHCb should eventually be able to test electron-muon LUV in $bs \to \ell\ell$ to the percent level, matching uncertainties on the SM predictions. Belle 2 will also be able to contribute to these tests [51] albeit with reduced sensitivity, though its real strength in this area lies in the unique and phenomenologically complementary ability to measure $bs \to \nu_\ell\nu_\ell$ processes [14, 52].

With both the $B_s^0 \to \mu^+\mu^-$ branching fraction and $bs \to \ell\ell$ electron-muon LU observables

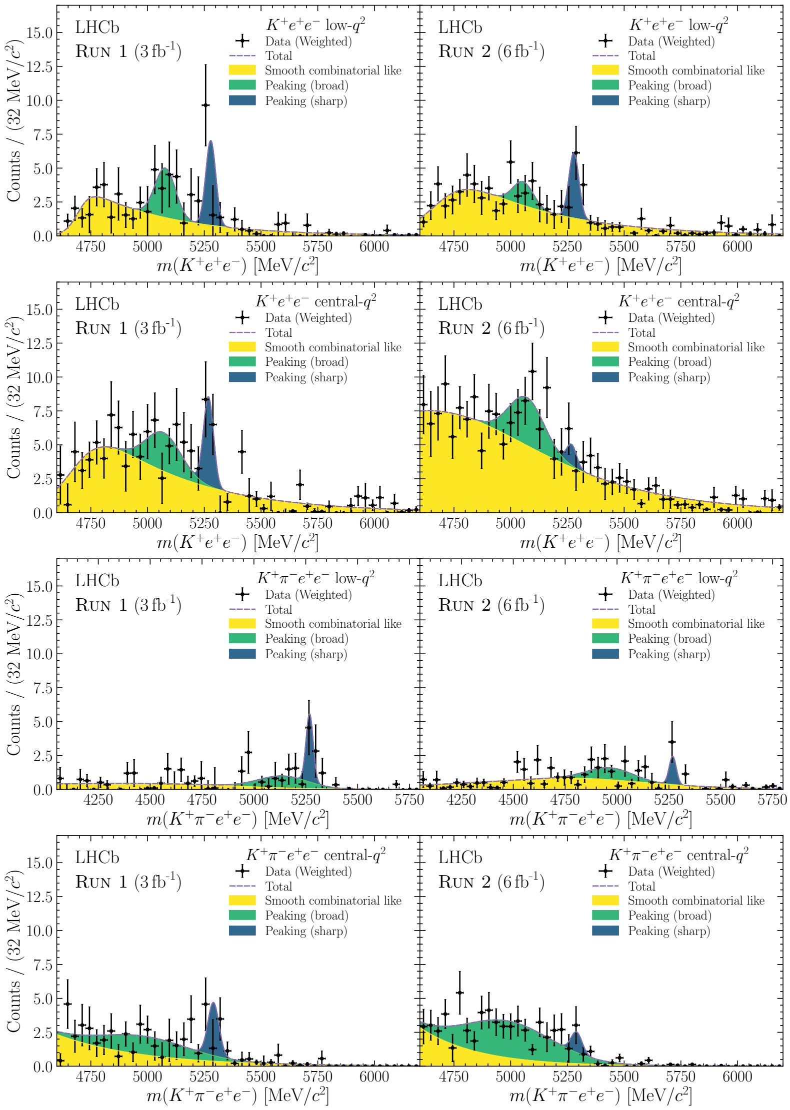


**Figure 10:** Template shapes for misidentified backgrounds obtained from data. The shapes for Run 1 are given on the left, the shapes for Run 2 are given on the right. From top to bottom, the shapes for $R_K$ in low $q^2$, $R_K$ in central $q^2$, $R_{K^{*0}}$ in low $q^2$, and $R_{K^{*0}}$ in central $q^2$ regions are given. Caption and illustration reproduced from Ref [50].

reverting back to the Standard Model, the phenomenological picture of lepton couplings in beauty hadron decays becomes remarkably stark. The Wilson coefficient $C_{10,\mu}$ (i.e. for muonic decays) is now in good agreement with the Standard Model whatever is assumed about hadronic uncertainties in $bs \to \ell\ell$ decays. On the other hand the coefficient $C_{9,\mu}$ requires very significant beyond SM contributions if the charm loops are considered to give a subleading effect. As discussed earlier, there is currently no consensus on the impact of charm loops. Some groups argue [41] that if a parametrisation is used to accomodate the full range of possible charm loop effects then $C_{9,\mu}$ becomes entirely compatible with the Standard Model, albeit within large uncertainties. Other groups argue [45] that we non-local effects cannot account for the full deviation from the Standard

Model no matter what is assumed about them. Whether or not the anomalous effects observed in the angular distributions and differential branching fractions of $b \to s\mu^+\mu^-$ decays are caused by physics beyond the SM is of course an important question. But it is also important to find experimental ways to pin down the effect of the charm loops, since the uncertainties associated with the parametric treatment of Ref [41] degrade not only the discovery potential but also the utility of $b \to s\mu^+\mu^-$ decays in setting limits on the energy scale of physics beyond the SM. The ongoing LHCb analyses which seek to measure charm loops in data will therefore be crucial to the accurate interpretation of this phenomenological picture.

## 5. Future experiments and facilities

Over the next decades a range of existing and planned experiments will improve our knowledge of the experimental observables discussed in these proceedings. The goal, broadly speaking, is to gain nearly an order of magnitude in sensitivity for transitions involving hadrons and factors for those involving leptons. In doing so experiments will probe ever greater energy scales and place ever more stringent constraints on the nature of physics beyond the SM. A full exploitation of the High Luminosity LHC dataset, only possible if the second upgrade of the LHCb detector [53] is approved and built, will push the exclusion limits on even loop-level MFV couplings to the TeV range across the board. This progress, together with the datasets collected by Belle 2 [14] and its putative future upgrade, will complement direct searches at currently accessible energy scales and arguably complete the physics exploitation of the LHC as a machine. It is also important to highlight the role of BES III in this endeavour, which can provide unique strong phase data on charm decays from samples taken at the $\Psi(3770)$ threshold. As discussed in Refs [54–56] this data is invaluable to allow LHCb and Belle 2 to achieve ultimate sensitivity on the CKM angle $\gamma$ in particular. Beyond this horizon, the FCC-ee collider retains significant potential for flavour physics if operated at the $Z$ threshold [27]. Even if FCC-ee may not improve on world-average sensitivites in many areas of flavour physics, it promises a unique combination of statistical reach and ability to control backgrounds for decays involving $\tau$-leptons which will fill in some of the gaps which remain in our knowledge once the LHC work is done.

Much ink has been spilled on the physics cases for all these planned experiments and I do not wish to needlessly reproduce those arguments here. However I would like to use these proceedings to highlight the long-term challenge of ensuring a coherent combined interpretation of results across the different experiments. Traditionally assured by HFLAV, the basic assumption of the last decades has been that combinations can be performed *a posteriori* using metadata provided by the collaborations in their papers or associated files. While these methods have worked well during the period where individual measurements broadly explored the $O(10\%)$ range of sensitivity, the transition to the few percent sensitivity range has coincided with a decade in which LHCb has been if not the only then certainly the dominant source of flavour physics results. Given the complexity of LHCb's internal combinations, it is not immediately obvious that we won't find some unknown unknowns waiting for us once high-sensitivity combining of LHCb and Belle 2 results begins in earnest. Indeed future precision combinations may need to get closer to the raw data in order to give the most useful information, particularly for what concerns correlations between systematic uncertaintes and correlated assumptions baked into the simulated samples used by analyses. Existing and nascent initiatives in this direction within the community should in my view be encouraged and strengthened, as should be genuinely cross-experiment (i.e. in both content and governance) software initiatives that enable this work to be performed in a coherent way.

## 6. Conclusion

The last decades of experimental results have shown that the CKM mechanism describes the bulk of flavour-changing quark transitions. While current experimental results still allow substantial room for physics beyond the SM, this physics is increasingly constrained to exist at currently inaccessible energy scales and/or to have highly suppressed flavour couplings. In the coming three decades, existing and planned collider experiments will improve on our knowledge of quark flavour physics by around one order of magnitude, testing the CKM mechanism and rare flavour-changing processes at the percent level or better. This improvement in our knowledge of quark physics will require tremendous advances in detector and collider technology, but it is feasibly within reach. It may well prove an exquisitely constructed epitaph to a century of progress in understanding elementary particles. After all this work is done there is no guarantee that we will have any better idea of the nature of physics beyond the Standard Model than we do today, and we will certainly have reached the limit of iterative improvements to the basic experimental methods of the past 50 years. It is nevertheless the case that the nature of quark transitions is one of the most fundamental properties of reality, and therefore demands to be understood to the best of our ability. The legacy of knowledge which we will accumulate in the process is its own reward and justification.



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