January 16, 2019

Proceedings of the Working group 3 “Rare B, D and K decays” for CKM 2018 (Heidelberg)

Michel De Cian[a], Sébastien Descotes-Genon[b], Karim Massri[c]

[a] *Laboratoire de Physique des Hautes Énergies, EPFL, 1015 Lausanne, Switzerland*

[b] *Laboratoire de Physique Théorique (UMR 8627), CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France*

[c] *CERN, European Organization for Nuclear Research, 1211 Geneva, Switzerland*

We provide an overview of the results presented during the sessions of Working Group 3 “Rare B, D and K decays, radiative and electroweak penguin decays, including constraints on V_{td}/V_{ts} and ϵ'/ϵ”, presented at the 10th International Workshop on the CKM Unitarity Triangle (CKM 2018) at Heidelberg University (September 17-21, 2018).

Rare B, D and K decays provide interesting probes of the Standard Model (SM), with a potential sensitivity to New Physics (NP) higher than other, more common, decays. Their experimental measurement is challenging, and their theoretical interpretation requires a precise knowledge of QCD at low energies, in the non-perturbative (hadronic) regime. The various b, c, s decays provide different types of tests of the Standard Model, which can be performed in different experimental settings and which may exhibit correlated deviations in models of New Physics.

1 B decays

1.1 Exclusive $b \to s\ell\ell$ transitions

$b \to s\ell\ell$ transitions are an excellent probe for physics beyond the SM, as they are forbidden on tree level. Several deviations from SM predictions have been observed in the differential branching ratios, the angular distributions and the ratio of the branching ratios of decays with muon and electron final states.

1.1.1 Differential branching ratios

The differential branching ratios of the decays $B^0 \to K^{*0}\mu^+\mu^-$ [1], $B^+ \to K^{*+}\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^0\mu^+\mu^-$ [2], $B^0_s \to \phi\mu^+\mu^-$ [3] and $\mathit{\Lambda}^0_b \to \mathit{\Lambda}\mu^+\mu^-$ [4] have been measured by the LHCb experiment. All measurements show smaller values than predicted in the region of low dilepton invariant mass, q^2, albeit large uncertainties in the theoretical predictions are present and limit the precision of these measurements.

1.1.2 Angular distributions

In the decays $B^0 \to K^{*0}\mu^+\mu^-$ [5–8], $B^+ \to K^+\mu^+\mu^-$ [9] and $\mathit{\Lambda}^0_b \to \mathit{\Lambda}\mu^+\mu^-$ [10] the angular distributions have been measured in the full q^2 region ($B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$) and in the q^2 interval $15\,\mathrm{GeV}^2/c^4$– $20\,\mathrm{GeV}^2/c^4$ ($\mathit{\Lambda}^0_b \to \mathit{\Lambda}\mu^+\mu^-$).

In the decay $\mathit{\Lambda}^0_b \to \mathit{\Lambda}\mu^+\mu^-$ for the first time all 34 angular observables were measured using a moments analysis. All results are in agreement with their SM predictions. The decay $B^+ \to K^+\mu^+\mu^-$ has only two angular observables, the forward-backward asymmetry A_{FB} and F_H, sensitive to (pseudo-)scalar and tensor contributions. Both observables were measured to be compatible with SM predictions.

In the decay $B^0 \to K^{*0}\mu^+\mu^-$, measurements of all angular parameters were performed, with the observable $P_5^{'}$ showing a deviation from the SM by 3.4 standard deviations in the LHCb measurement. A deviation of $P_5^{'}$ could be due to a value of the Wilson coefficient $\mathcal{C}_{9,}$ describing the strength of the vector coupling, different from its SM prediction. Or the discrepancy could be due to an underestimation of charm-loop effects. A possible strategy to distinguish both contributions is to fit the differential branching fraction of $B^0 \to K^{*0}\mu^+\mu^-$, modelling the contributing tree and penguin amplitudes using Breit-Wigner line shapes, to determine the relative contribution of long-distance (*i.e.* charm loop) and short-distance contributions. This measurement was already performed for the decay $B^+ \to K^+\mu^+\mu^-$ [11]. An alternative approach is to fit the continuous distribution of $P_5^{'}$ as described in Refs. [12] and [13].

1.1.3 Lepton Flavour Universality violation

The ratios $R_K = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+e^+e^-)}$ and $R_{K^*} = \frac{\mathcal{B}(B^0\to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0\to K^{*0}e^+e^-)}$ have been measured at the LHCb [14,15], BaBar [16] and Belle [17] experiments. While the precision of the results from BaBar and Belle are limited by the statistical precision, the LHCb results show a deviation from the SM. R_K is measured to be $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$, in the q^2 interval $1\,\mathrm{GeV}^2/c^4$– $6\ \mathrm{GeV}^2/c^4$, corresponding to a deviation of 2.6σ from the SM. R_{K^*} is measured to be $R_{K^*} = 0.66^{+0.11}_{-0.07} \pm 0.03$ in the q^2 interval $0.045\,\mathrm{GeV}^2/c^4$– $1.1\,\mathrm{GeV}^2/c^4$ and $R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05$ in the q^2 interval $1.1\,\mathrm{GeV}^2/c^4$– $6.0\,\mathrm{GeV}^2/c^4$. This corresponds to a deviation of 2.2 and 2.4 standard deviations from the SM. The predictions for both measurements have a negligible theoretical uncertainty, as hadronic effects cancel when forming the ratio.

1.1.4 τ leptons in the final state

So far, only $b \to s\ell\ell$ transitions have been measured where ℓ is a muon or an electron. Given the low branching ratio of $\mathcal{O}(10^{-7})$ and the experimental challenge to reconstruct τ leptons, $b \to s\tau^+\tau^-$ processes are experimentally only weakly constrained. A deviation of the $R(X)$ ratios, with $X = J/\psi\,, D^{0*}, D^{+*}$ from the SM predictions, which is suggested by measurements of LHCb [18–20], BaBar [21, 22] and Belle [23–26], would lead to an enhancement of the branching ratio of $b \to s\tau^+\tau^-$ transitions, most significantly to the purely leptonic decay $B^0_s \to \tau^+\tau^-$. Given the possible reach with LHCb and Belle II, a discovery of a $b \to s\tau^+\tau^-$ processes would imply physics beyond the SM.

1.1.5 The purely leptonic decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

The decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are strongly suppressed in the SM due to being flavour-changing neutral currents and helicity suppression. They are sensitive to the Wilson coefficient $\mathcal{C}_{10}$ and the non-SM Wilson coefficients $\mathcal{C}_S$ and $\mathcal{C}_P$. The branching ratio of $B^0_s \to \mu^+\mu^-$ has been measured by the LHCb [27], ATLAS [28] and CMS [29] experiments, with the latest result from the ATLAS collaboration, being $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$. In the SM, only the heavy eigenstate decays into the dimuon final state, a measurement of the lifetime could therefore reveal a deviation from the SM. The lifetime has been measured by the LHCb experiment to be $\tau = (2.04 \pm 0.44 \pm 0.05)\,\mathrm{ps}$ and is compatible with the expectation. The precision is limited by the small number of observed events. The decay $B^0 \to \mu^+\mu^-$ is currently unobserved and upper limits are computed, with the most stringent one by the ATLAS collaboration, yielding $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ at 95% CL [28]. A plot with the ATLAS results is shown in Fig. 1.

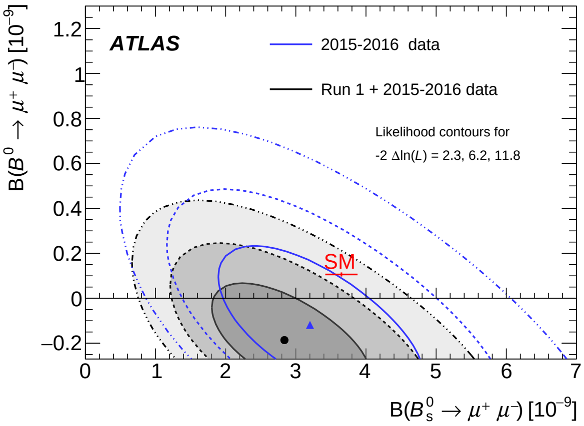

Figure 1: Likelihood contours for the combination of the Run 1 and 2015-2016 Run 2 results (shaded areas). The contours are obtained from the combined likelihoods of the two analyses, for values of $-2\Delta\log(L)$ equal to 2.3, 6.2 and 11.8. The empty contours represent the result from 2015-2016 Run 2 data alone. The SM prediction with uncertainties is indicated. Figure taken from Ref. [28].

1.2 Inclusive $B \to X_{d,s}\ell\ell$ decays

$B \to X_s\ell\ell$ (and $B \to X_s\gamma$) decays provide strong constraints on the short-distance Wilson coefficients $\mathcal{C}_7$ (and $\mathcal{C}_9$, $\mathcal{C}_{10}$), with interesting experimental prospects at Belle II. The computation relies on quark-hadron duality: the same computation can be performed using a hadronic or a quark language, the latter avoiding the complications due to hadronisation, provided that the observable is inclusive enough, *i.e.*, summed over a large set of kinematic configurations. Experimentally, one has however to perform cuts on E_γ or M_{X_s} that are difficult to tackle, introducing (hadronic) shape functions to be modelled theoretically/fitted experimentally. The charm resonances are signalled by charm loops inducing an m_c dependence, which is a significant source of uncertainty for $B \to X_s\ell\ell$, as well as higher orders in perturbation theory [30,31]. A general analytic computation for all values of m_c is difficult, but it is currently under investigation, recently in the case of $B \to X_s\gamma$. Recent improvements in NNLO computations have led to SM predictions for $B \to X_s\gamma$ with $E_\gamma > 1.6$ GeV of 6.9% (to be compared to 4.5% for the experimental average) [32, 33]. Another improvement in the accuracy of the prediction for $B \to X_{d/s}\ell\ell$ decays has been the recent inclusion of final states with a large number of particles, which can have a sizable contribution to inclusive $b \to s\ell\ell$ transitions [34].

1.3 Global fits

The measured branching ratios of the decays $B \to K^{*}\mu^{+}\mu^{-}$, $B \to K\mu^{+}\mu^{-}$, $B_s^0 \to \phi\mu^{+}\mu^{-}$, the inclusive decay rate $B \to X_s\mu^{+}\mu^{-}$ and the angular observables of $B^0 \to K^{*0}\mu^{+}\mu^{-}$ and $B_s^0 \to \phi\mu^{+}\mu^{-}$ are combined in a global fit [35,36]. The best fit point in the plane of the Wilson coefficients $\mathcal{C}_9$ and $\mathcal{C}_{10}$ shows a deviation from the SM by 5 standard deviations. When also allowing for different operators for electron or muon final states, the overall picture is unchanged, where a deviation from the SM is only seen in the muon final states, see Fig. 2.

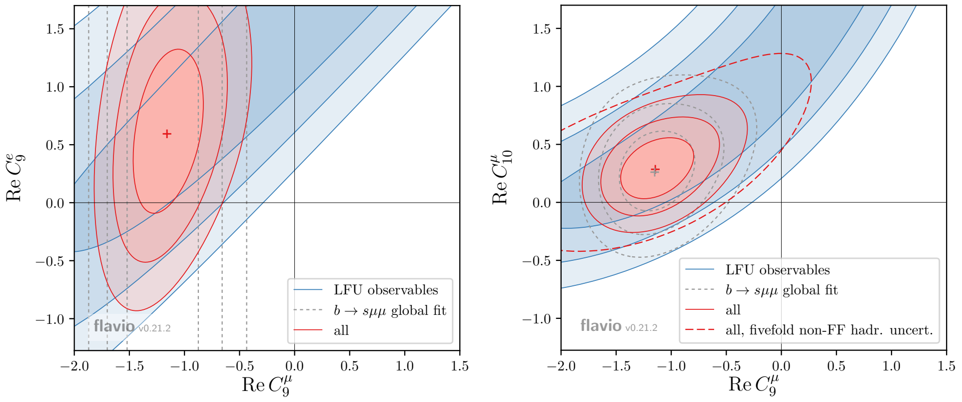

Figure 2: Compatibility of the best fit of the real part of the (left) flavour-specific Wilson coefficients $\mathcal{C}_9^{\mu,e}$ and (right) of $\mathcal{C}_9$ and $\mathcal{C}_{10}$ with the SM prediction. Figures taken from Ref. [36].

1.4 Radiative decays

1.4.1 Photon polarization in $b \to s\gamma$ decays

The photon polarization in $b \to s\gamma$ transitions is a sensitive probe for new physics. While it has been established that the photon is polarized in the decay $B^{+} \to K^{+}\pi^{-}\pi^{+}\gamma$ [37], a precise determination of the polarization requires an amplitude analysis to understand the resonant structure of the $K^{+}\pi^{-}\pi^{+}$ system, and an angular analysis. Such a measurement can be expected in the near future from Belle II and LHCb. An alternative approach to measure the polarization is to determine the time-dependent decay rate of $B \to X_s\gamma$ decays and the CP parameters C_{CP} and S_{CP}. These measurements have been performed by Belle and BaBar in the decays $B^0 \to K_S^0\pi^0\gamma$, $B^0 \to K_S^0\eta\gamma$ and $B^0 \to K_S^0\eta\gamma$ [38], where all results are compatible with the SM predictions. A novel approach is to measure the decay $B^0 \to K^0_S\pi^+\pi^-\gamma$ [39], as the Dalitz structure of $K^0_S\pi^+\pi^-$ allows to determine the real and imaginary part of the Wilson coefficients $\mathcal{C}_7$ and $\mathcal{C}_7'$, which is not possible when integrating over the Dalitz space. While extracting the full information about the photon polarization from the time-dependent decay rate requires the knowledge of the flavour of the B meson, the parameter A^Δ, related to the polarization, can be extracted without this knowledge. This measurement was performed by LHCb in the decay $B^0_s \to \phi\gamma$, yielding a value of $A^\Delta = -0.98^{+0.46+0.23}_{-0.52-0.20}$ [40]. This result is compatible with the SM at 2σ.

1.4.2 Isospin and ΔA_{CP} asymmetries in $B \to X_s\gamma$ decays

Belle has measured the isospin asymmetry and ΔA_{CP} in $B \to K^*\gamma$ decays [41], where the K^* was reconstructed in the $K^+\pi^-$, $K^+\pi^0$, $K^0_S\pi^+$ and $K^0_S\pi^0$ final states, with event yields between about 350 to 2300 signal candidates. The *CP* asymmetry was measured for the first time and yields $\Delta A_{CP} = (2.4 \pm 2.8 \pm 0.5)\%$. The isospin asymmetry was measured to be $\Delta_{0+} = (6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%$. While the *CP* asymmetry is compatible with the SM prediction, the isospin asymmetry deviates by 3.1σ from the SM prediction.

A similar measurement was performed for the inclusive X_s final state [42], with the results being $\Delta A_{CP} = (1.26 \pm 2.4 \pm 0.67)\%$ and $\Delta_{0-} = (1.70 \pm 1.39 \pm 0.87 \pm 1.15)\%$. Both results are compatible with the SM predictions and the results from BaBar.

1.5 Lepton Flavour Violation and other rare decays

1.5.1 Lepton Flavour Violation searches

The lepton-flavour violating decays $B^0 \to K^{*0}\mu^\pm e^\mp$ and $\Upsilon(3S) \to \mu^\mp e^\pm$ have been searched for, setting the most stringent upper limit on the branching ratio of $1.2 - 1.8 \times 10^{-7}$ at 90% CL for $B^0 \to K^{*0}\mu^\pm e^\mp$ [43], depending on the charge combination of the leptons, and 3.6×10^{-7} at 90% CL for $\Upsilon(3S) \to \mu^\pm e^\mp$.

Limits by the LHCb collaboration include $\mathcal{B}(B^0_s \to \mu^\pm e^\mp) < 6.3 \times 10^{-9}$ [44], $\mathcal{B}(B^0 \to \mu^\pm e^\mp) < 1.3 \times 10^{-9}$ [44] and $\mathcal{B}(H \to \mu^\pm\tau^\mp) < 26\%$ [45] for an SM Higgs, all at 95% CL.

1.5.2 Other rare decays

Limits were set on $\mathcal{B}(B^- \to \lambda\overline{p}\nu\overline{\nu}) < 3.0 \times 10^{-5}$ at 90% CL by the BaBar experiment, $\mathcal{B}(B^+ \to D^+_s\phi) < 4.9 \times 10^{-7}$ at 95% CL [46], which is a pure annihilation decay, and $\mathcal{B}(\Lambda^+_c \to p\mu^+\mu^-) < 7.7 \times 10^{-8}$ at 90% CL [47] for a non-resonant dimuon, both by the LHCb experiment. The last decay is dominated by decays over an ω or ϕ resonance. A first observation of the decay $\Lambda_c^+ \to p\omega(\to \mu^+\mu^-)$ was achieved, when requiring the dimuon to originate from an ω meson, yielding a branching ratio of $\mathcal{B}(\Lambda_c^+ \to p\omega(\to \mu^+\mu^-)) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \times 10^{-4}$ [47].

The decay $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$ is a $b \to d\ell\ell$ transition, strongly suppressed in the SM and therefore potentially sensitive to effects beyond the SM. An excess over background was seen for the first time by the LHCb experiment. The integrated branching fraction was measured to be $\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = (2.9 \pm 1.0 \pm 0.2 \pm 0.3) \times 10^{-8}$ [48], which corresponds to a significance of 3.4σ.

The branching fraction of the $s \to d\ell\ell$ transition $\Sigma^+ \to p\mu^+\mu^-$ is dominated by long-distance effects, additionally the result from the HyperCP experiment saw an excess at the lower edge of the kinematically allowed q^2 region [49]. The branching ratio was measured to be $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3}) \times 10^{-8}$ [50] by the LHCb experiment, which corresponds to a significance of 4.1σ. No significant structure in q^2 was observed.

2 D decays

2.1 Potential for NP discovery

Radiative charm decays provide interesting tests of New Physics, both in the up sector (directly) and as a cross check of the B sector (through CKM if NP couples to weak doublets of quarks). They can be analysed in the model-independent framework of the effective Hamiltonian with three main operators contributing, $\mathcal{O}_{7,9,10}$, similarly to the B physics case [30, 51], and allowing for predictions for $D^0 \to V\gamma$ (with $V = \rho^0, \omega, \phi, \overline{K}^{*0}$) [52] and $D \to \pi\ell\ell$ (branching ratio, forward-backward asymmetry, lepton-flavour universality) [53, 54]. The latter are affected by very large long-distance contributions which are difficult to estimate. They can also be used to test trendy NP models to explain B anomalies, such as leptoquarks [54–56], with important constraints coming from $D^0 \to \mu\mu$, $D_{(s)} \to \mu\nu$, $D_s \to \tau\nu$.

2.2 Description of $D \to PP\ell\ell$

The decay $D^0 \to P_1P_2\ell^+\ell^-$ (with P_1, P_2 being pions and/or kaons) can provide interesting information on the $c \to u\ell\ell$ neutral current, but it requires analysing long-distance contributions [57]. The latter can be described using a resonance saturation model, writing the decay as $D^0 \to V\ell^+\ell^-$ with a subsequent decay $V \to P_1P_2$. The vector $D^0 \to V\ell^+\ell^-$ can be described assuming the dominance of the lowest vector/axial resonances and factorisation on the resulting weak matrix element. Predictions can be made for various modes, separating bremsstrahlung and direct emissions, with a good overall agreement with BaBar and Belle results for these modes [58–60], and with other theoretical descriptions for the long-distance contributions to these modes [61]. Additional topologies involving axial (rather than vector) intermediate resonances could turn out to be important (a third of the vector contribution). The analysis could allow one to understand better the cleanliness of angular asymmetries for these modes.

2.3 Recent experimental results

The BESIII experiment has presented various results on rare charm meson decays. Concerning charged currents, they reported the observation of $\mathcal{B}(D^0 \to a_0^- e^+\nu_e) = (1.33^{+0.33}_{-0.29} \pm 0.09) \times 10^{-4}$ [62] and searches for $D^+ \to D^0 e^+\nu_e$ [63] and $D \to \gamma e^+\nu$ [64] both constrained below 3.0×10^{-5} at 90% CL. For neutral currents, a comprehensive list of modes $D \to he^+e^-$ and $D \to hh'e^+e^-$ (with h and h' light strange and/or non strange mesons) has been studied, with upper limits between 10^{-5} and 10^{-6} improving significantly compared to previous experimental bounds [65]. Further searches are ongoing (lepton number violation through $D \to K\pi e^+e^+$, $D \to \pi^0\nu\bar{\nu}$).

The LHCb experiment has studied forward-backward, triple-product and *CP* asymmetries in $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$. These modes contain both short-distance (neutral current) and long-distance (resonance) contributions. All asymmetries could be interesting probes of NP, but they show a good compatibility with zero in agreement with the Standard Model [66].

LHCb has also presented new results for the branching fractions of $D^+ \to K^-K^+K^+$, $D^+ \to \pi^-\pi^+K^+$ and $D_s^+ \to \pi^-K^+K^+$, requiring a careful study of the background and an anlysis of the efficencies varying across the Dalitz plane. They improved significantly ratios of branching ratios between these decays, providing the world's best measurements [67].

3 K decays

3.1 ε'/ε in and beyond the SM

The direct *CP* violation in $K \to \pi\pi$ decays, described by the ratio ε'/ε, plays a very important role in the tests of the SM and more recently in the tests of its possible extensions. A master formula for the ratio ε'/ε is obtained with a model-independent approach in the context of the $\Delta S = 1$ effective theory with operators invariant under QCD and QED and in the context of the Standard Model Effective Field Theory (SMEFT) with the operators invariant under the full SM gauge group. Such a formula, which allows to calculate automatically $(\varepsilon'/\varepsilon)_{\rm BSM}$ once the Wilson coefficients of all contributing operators are known at the electroweak scale $\mu_{\rm EW}$, reads as [68]

$$\left(\frac{\varepsilon'}{\varepsilon}\right)_{\rm BSM} = \sum_i P_i(\mu_{\rm EW})\ {\rm Im}\left[C_i(\mu_{\rm EW}) - C'_i(\mu_{\rm EW})\right],$$

where

$$P_i(\mu_{\rm EW}) = \sum_j \sum_{I=0,2} p_{ij}^{(I)}(\mu_{\rm EW}, \mu_c)\ \left[\frac{\langle \mathcal{O}_j(\mu_c)\rangle_I}{\rm GeV^3}\right].$$

The present master formula for ε'/ε can be applied to any theory beyond the Standard Model (BSM) in which the Wilson coefficients of all contributing operators have been calculated at the electroweak scale.

3.2 Experimental results on $K \to \pi\nu\bar{\nu}$ decays

The $K \to \pi\nu\bar{\nu}$ decays are flavour changing neutral current processes, highly suppressed due to quadratic GIM mechanism and to CKM suppression. The dominant contribution comes from the short-distance physics of the top quark loop, with negligible long-distance corrections. This makes them very clean theoretically and sensitive to physics beyond the SM, probing the highest mass scales among the rare meson decays. The NA62 experiment at CERN SPS is designed to measure the branching ratio of the $K^+ \to \pi^+\nu\bar{\nu}$ decay using a novel kaon decay-in-flight technique, while the KOTO experiment at JPARC aims to study the $K_L \to \pi^0\nu\bar{\nu}$ decay. Both experiments produced new results in 2018. The NA62 experiment observed one candidate event, which translates into an upper limit on the branching ratio [69] $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10}$ at 95% CL, compatible with the Standard Model prediction. The KOTO experiment improved the existing upper limits on the branching ratio of the neutral kaon decay by an order of magnitude [70]: $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 3.0 \times 10^{-9}$ at 90% CL.

3.3 Lattice results on $K \to \pi\nu\bar{\nu}$ and $K \to \pi\ell^+\ell^-$ decays

The rare $K \to \pi\nu\bar{\nu}$ and $K \to \pi\ell^+\ell^-$ decays proceed via a flavour changing neutral current and therefore may only be induced beyond tree level in the SM. This natural suppression makes these decays sensitive to the effects of potential new physics. The CP-conserving $K \to \pi \ell^+ \ell^-$ decay channels however are dominated by a single-photon exchange; this involves a sizeable long-distance hadronic contribution which represents the current major source of theoretical uncertainty. In preparation towards the computation of the long-distance contributions to these rare decay amplitudes using lattice QCD, an exploratory study using unphysical K and π masses have been performed. In particular, the $K \to \pi^+ \ell^+ \ell^-$ form factor $V(z)$ $(z = q^2/M_K^2)$ was evaluated for the first time, obtaining [71] $V(z) = 1.37(36), 0.68(39), 0.96(64)$ for the three values of $z = -0.5594(12), -1.0530(34), -1.4653(82)$ respectively.

3.4 Connecting $K \to \pi\nu\bar{\nu}$ and rare B decays

Lepton Flavor Universality (LFU) in the SM is ensured by the identical couplings of the electroweak gauge bosons to all three lepton flavours. This prediction has been probed at the permille level by stringent LFU tests performed in semileptonic K and π decays, in purely leptonic τ decays, and in electroweak precision observables. Recent hints of LFU violations in semileptonic B decays, for both charged-current and neutral-current mediated processes, might point to BSM contributions coupled mainly to the third generation of quarks and leptons, with some small (but non-negligible) mixing with the light generations. In order to satisfy this assumption, an Effective Field Theory (EFT) based on the $U(2)^n$ flavour symmetry is considered [72, 73]. Such a study shows that $\mathcal{O}(1)$ deviations from the SM are expected in the $K \to \pi\nu\bar{\nu}$ decays, which are the only K decays involving third-generation leptons in the final state. Moreover, the correlations between $\mathcal{B}(K \to \pi\nu\bar{\nu})$ and both $\mathcal{B}(B \to \pi\nu\bar{\nu})$ and $R(D^*)$ can be exploited to distinguish between different NP scenarios.

4 Acknowledgements

We thank all the participants for the quality of the presentations and the discussions during the sessions of the Working group. We also thank the organisers of the CKM18 workshop for the perfect organisation, as well as the warm and lively atmosphere of the conference.

References

[1] LHCb, R. Aaij *et al.*, *Measurements of the S-wave fraction in* $B^0 \to K^+\pi^-\mu^+\mu^-$ *decays and the* $B^0 \to K^*(892)^0\mu^+\mu^-$ *differential branch-*

ing fraction, JHEP **11** (2016) 047, `arXiv:1606.04731`, [Erratum: JHEP04,142(2017)].

[2] LHCb, R. Aaij *et al.*, *Differential branching fractions and isospin asymmetries of $B \to K^{(*)}\mu^+\mu^-$ decays*, JHEP **06** (2014) 133, `arXiv:1403.8044`.

[3] LHCb, R. Aaij *et al.*, *Angular analysis and differential branching fraction of the decay $B_s^0 \to \phi\mu^+\mu^-$*, JHEP **09** (2015) 179, `arXiv:1506.08777`.

[4] LHCb, R. Aaij *et al.*, *Differential branching fraction and angular analysis of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ decays*, JHEP **06** (2015) 115, `arXiv:1503.07138`, [Erratum: JHEP09,145(2018)].

[5] LHCb, R. Aaij *et al.*, *Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using 3 fb^{-1} of integrated luminosity*, JHEP **02** (2016) 104, `arXiv:1512.04442`.

[6] CMS, A. M. Sirunyan *et al.*, *Measurement of angular parameters from the decay $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV*, Phys. Lett. **B781** (2018) 517, `arXiv:1710.02846`.

[7] CMS, V. Khachatryan *et al.*, *Angular analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$ from pp collisions at $\sqrt{s} = 8$ TeV*, Phys. Lett. **B753** (2016) 424, `arXiv:1507.08126`.

[8] ATLAS, M. Aaboud *et al.*, *Angular analysis of $B_d^0 \to K^*\mu^+\mu^-$ decays in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, JHEP **10** (2018) 047, `arXiv:1805.04000`.

[9] CMS, C. Collaboration, *Measurement of angular observables in the decay B+ to K+ mu+ mu- from proton-proton collisions at sqrt[s]=8TeV*, .

[10] LHCb, R. Aaij *et al.*, *Angular moments of the decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ at low hadronic recoil*, JHEP **09** (2018) 146, `arXiv:1808.00264`.

[11] LHCb, R. Aaij *et al.*, *Measurement of the phase difference between short- and long-distance amplitudes in the $B^+ \to K^+\mu^+\mu^-$ decay*, Eur. Phys. J. **C77** (2017) 161, `arXiv:1612.06764`.

[12] T. Blake *et al.*, *An empirical model to determine the hadronic resonance contributions to $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$ transitions*, Eur. Phys. J. **C78** (2018) 453, `arXiv:1709.03921`.

[13] C. Bobeth, M. Chrzaszcz, D. van Dyk, and J. Virto, *Long-distance effects in $B \to K^*\ell\ell$ from analyticity*, Eur. Phys. J. **C78** (2018) 451, `arXiv:1707.07305`.

[14] LHCb, R. Aaij *et al.*, *Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays*, Phys. Rev. Lett. **113** (2014) 151601, `arXiv:1406.6482`.

[15] LHCb, R. Aaij *et al.*, *Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$ decays*, JHEP **08** (2017) 055, `arXiv:1705.05802`.

[16] BaBar, J. P. Lees *et al.*, *Measurement of Branching Fractions and Rate Asymmetries in the Rare Decays $B \to K^{(*)}l^+l^-$*, Phys. Rev. **D86** (2012) 032012, `arXiv:1204.3933`.

[17] Belle, J.-T. Wei *et al.*, *Measurement of the Differential Branching Fraction and Forward-Backword Asymmetry for $B \to K^{(*)}\ell^+\ell^-$*, Phys. Rev. Lett. **103** (2009) 171801, `arXiv:0904.0770`.

[18] LHCb, R. Aaij *et al.*, *Measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$*, Phys. Rev. Lett. **120** (2018) 121801, `arXiv:1711.05623`.

[19] LHCb, R. Aaij *et al.*, *Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$*, Phys. Rev. Lett. **115** (2015) 111803, `arXiv:1506.08614`, [Erratum: Phys. Rev. Lett.115,no.15,159901(2015)].

[20] LHCb, R. Aaij *et al.*, *Measurement of the ratio of the $B^0 \to D^{*-}\tau^+\nu_\tau$ and $B^0 \to D^{*-}\mu^+\nu_\mu$ branching fractions using three-prong τ-lepton decays*, Phys. Rev. Lett. **120** (2018) 171802, `arXiv:1708.08856`.

[21] BaBar, J. P. Lees *et al.*, *Evidence for an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays*, Phys. Rev. Lett. **109** (2012) 101802, `arXiv:1205.5442`.

[22] BaBar, J. P. Lees *et al.*, *Measurement of an Excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ Decays and Implications for Charged Higgs Bosons*, Phys. Rev. **D88** (2013) 072012, `arXiv:1303.0571`.

[23] Belle, M. Huschle *et al.*, *Measurement of the branching ratio of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle*, Phys. Rev. **D92** (2015) 072014, `arXiv:1507.03233`.

[24] Belle, Y. Sato *et al.*, *Measurement of the branching ratio of $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ relative to $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays with a semileptonic tagging method*, Phys. Rev. **D94** (2016) 072007, `arXiv:1607.07923`.

[25] Belle, S. Hirose *et al.*, *Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$*, Phys. Rev. Lett. **118** (2017) 211801, `arXiv:1612.00529`.

[26] Belle, S. Hirose *et al.*, *Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ with one-prong hadronic τ decays at Belle*, Phys. Rev. **D97** (2018) 012004, `arXiv:1709.00129`.

[27] LHCb, R. Aaij *et al.*, *Measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction and effective lifetime and search for $B^0 \to \mu^+\mu^-$ decays*, Phys. Rev. Lett. **118** (2017) 191801, `arXiv:1703.05747`.

[28] ATLAS, M. Aaboud *et al.*, *Study of the rare decays of B_s^0 and B^0 mesons into muon pairs using data collected during 2015 and 2016 with the ATLAS detector*, Submitted to: JHEP (2018) `arXiv:1812.03017`.

[29] CMS, LHCb, V. Khachatryan *et al.*, *Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data*, Nature **522** (2015) 68, `arXiv:1411.4413`.

[30] S. de Boer, *Two loop virtual corrections to $b \to (d, s)\ell^+\ell^-$ and $c \to u\ell^+\ell^-$ for arbitrary momentum transfer*, Eur. Phys. J. **C77** (2017) 801, `arXiv:1707.00988`.

[31] M. Benzke, T. Hurth, and S. Turczyk, *Subleading power factorization in $\bar{B} \to X_s \ell^+\ell^-$*, JHEP **10** (2017) 031, `arXiv:1705.10366`.

[32] M. Misiak *et al.*, *Updated NNLO QCD predictions for the weak radiative B-meson decays*, Phys. Rev. Lett. **114** (2015) 221801, `arXiv:1503.01789`.

[33] M. Czakon *et al.*, *The $(Q_7, Q_{1,2})$ contribution to $\overline{B} \to X_s\gamma$ at $\mathcal{O}(\alpha_s^2)$*, JHEP **04** (2015) 168, `arXiv:1503.01791`.

[34] T. Huber, Q. Qin, and K. K. Vos, *Five-particle contributions to the inclusive rare $\bar{B} \to X_{s(d)}\,\ell^+\ell^-$ decays*, Eur. Phys. J. **C78** (2018) 748, `arXiv:1806.11521`.

[35] W. Altmannshofer, C. Niehoff, P. Stangl, and D. M. Straub, *Status of the $B \to K^*\mu^+\mu^-$ anomaly after Moriond 2017*, Eur. Phys. J. **C77** (2017) 377, `arXiv:1703.09189`.

[36] W. Altmannshofer, P. Stangl, and D. M. Straub, *Interpreting Hints for Lepton Flavor Universality Violation*, Phys. Rev. **D96** (2017) 055008, `arXiv:1704.05435`.

[37] LHCb, R. Aaij *et al.*, *Observation of Photon Polarization in the bs Transition*, Phys. Rev. Lett. **112** (2014) 161801, `arXiv:1402.6852`.

[38] Heavy Flavor Averaging Group, Y. Amhis *et al.*, *Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2016*, Eur. Phys. J. **C77** (2017) 895, `arXiv:1612.07233`, updated results and plots available at `https://hflav.web.cern.ch`.

[39] S. Akar *et al.*, *The time-dependent CP asymmetry in $B^0 \to K_{\rm res}\gamma \to \pi^+\pi^-K^0_S\gamma$ decays*, `arXiv:1802.09433`.

[40] LHCb, R. Aaij *et al.*, *First experimental study of photon polarization in radiative B^0_s decays*, Phys. Rev. Lett. **118** (2017) 021801, `arXiv:1609.02032`, [Addendum: Phys. Rev. Lett.118,no.10,109901(2017)].

[41] Belle, T. Horiguchi *et al.*, *Evidence for Isospin Violation and Measurement of CP Asymmetries in $B \to K^*(892)\gamma$*, Phys. Rev. Lett. **119** (2017) 191802, `arXiv:1707.00394`.

[42] S. Watanuki *et al.*, *Measurements of isospin asymmetry and difference of direct CP asymmetries in inclusive $B \to X_s\gamma$ decays*, in *39th International Conference on High Energy Physics (ICHEP 2018) Seoul, Gangnam-Gu, Korea, Republic of, July 4-11, 2018*, 2018. `arXiv:1807.04236`.

[43] Belle, S. Sandilya *et al.*, *Search for the lepton-flavor-violating decay $B^0 \to K^{*0}\mu^\pm e^\mp$*, Phys. Rev. **D98** (2018) 071101, `arXiv:1807.03267`.

[44] LHCb, R. Aaij *et al.*, *Search for the lepton-flavour violating decays $B^0_{(s)} \to e^\pm\mu^\mp$*, JHEP **03** (2018) 078, `arXiv:1710.04111`.

[45] LHCb, R. Aaij *et al.*, *Search for lepton-flavour-violating decays of Higgs-like bosons*, Eur. Phys. J. **C78** (2018) 1008, `arXiv:1808.07135`.

[46] LHCb, R. Aaij *et al.*, *First observation of $B^+ \to D^+_s K^+K^-$ decays and a search for $B^+ \to D^+_s\phi$ decays*, JHEP **01** (2018) 131, `arXiv:1711.05637`.

[47] LHCb, R. Aaij *et al.*, *Search for the rare decay $\Lambda^+_c \to p\mu^+\mu^-$*, Phys. Rev. **D97** (2018) 091101, `arXiv:1712.07938`.

[48] LHCb, R. Aaij *et al.*, *Evidence for the decay $B^0_S \to \overline{K}^{*0}\mu^+\mu^-$*, JHEP **07** (2018) 020, `arXiv:1804.07167`.

[49] HyperCP, H. Park *et al.*, *Evidence for the decay Sigma+ —¿ p mu+ mu-*, Phys. Rev. Lett. **94** (2005) 021801, `arXiv:hep-ex/0501014`.

[50] LHCb, R. Aaij *et al.*, *Evidence for the rare decay* $\Sigma^+ \to p\mu^+\mu^-$, Phys. Rev. Lett. **120** (2018) 221803, `arXiv:1712.08606`.

[51] S. de Boer, B. Mller, and D. Seidel, *Higher-order Wilson coefficients for* $c \to u$ *transitions in the standard model*, JHEP **08** (2016) 091, `arXiv:1606.05521`.

[52] S. de Boer and G. Hiller, *Rare radiative charm decays within the standard model and beyond*, JHEP **08** (2017) 091, `arXiv:1701.06392`.

[53] S. de Boer and G. Hiller, *Flavor and new physics opportunities with rare charm decays into leptons*, Phys. Rev. **D93** (2016) 074001, `arXiv:1510.00311`.

[54] S. Fajfer and N. Konik, *Prospects of discovering new physics in rare charm decays*, Eur. Phys. J. **C75** (2015) 567, `arXiv:1510.00965`.

[55] I. Dorner *et al.*, *Physics of leptoquarks in precision experiments and at particle colliders*, Phys. Rept. **641** (2016) 1, `arXiv:1603.04993`.

[56] D. Beirevi, N. Konik, O. Sumensari, and R. Zukanovich Funchal, *Palatable Leptoquark Scenarios for Lepton Flavor Violation in Exclusive* $b \to s\ell_1\ell_2$ *modes*, JHEP **11** (2016) 035, `arXiv:1608.07583`.

[57] L. Cappiello, O. Cata, and G. D'Ambrosio, *Standard Model prediction and new physics tests for* $D^0 \to h^+h^-\ell^+\ell^-(h = \pi, K : \ell = e, \mu)$, JHEP **04** (2013) 135, `arXiv:1209.4235`.

[58] LHCb, R. Aaij *et al.*, *First observation of the decay* $D^0 \to K^-\pi^+\mu^+\mu^-$ *in the* ρ^0-ω *region of the dimuon mass spectrum*, Phys. Lett. **B757** (2016) 558, `arXiv:1510.08367`.

[59] LHCb, R. Aaij *et al.*, *Observation of* D^0 *meson decays to* $\pi^+\pi^-\mu^+\mu^-$ *and* $K^+K^-\mu^+\mu^-$ *final states*, Phys. Rev. Lett. **119** (2017) 181805, `arXiv:1707.08377`.

[60] BaBar, J. P. Lees *et al.*, *Observation of the decay* $D^0 \to K^-\pi^+e^+e^-$, Submitted to: Phys. Rev. Lett. (2018) `arXiv:1808.09680`.

[61] S. De Boer and G. Hiller, *Null tests from angular distributions in* $D \to P_1P_2l^+l^-$, $l = e, \mu$ *decays on and off peak*, Phys. Rev. **D98** (2018) 035041, `arXiv:1805.08516`.

[62] BESIII, M. Ablikim *et al.*, *Observation of the Semileptonic Decay* $D^0 \to a_0(980)^- e^+ \nu_e$ *and Evidence for* $D^+ \to a_0(980)^0 e^+ \nu_e$, Phys. Rev. Lett. **121** (2018) 081802, `arXiv:1803.02166`.

[63] BESIII, M. Ablikim *et al.*, *Search for the rare decay* $D^+ \to D^0 e^+ \nu_e$, Phys. Rev. **D96** (2017) 092002, `arXiv:1708.06856`.

[64] BESIII, M. Ablikim *et al.*, *Search for the radiative leptonic decay* $D^+ \to \gamma e^+ \nu_e$, Phys. Rev. **D95** (2017) 071102, `arXiv:1702.05837`.

[65] BESIII, M. Ablikim *et al.*, *Search for the rare decays* $D \to h(h')e^+e^-$, Phys. Rev. **D97** (2018) 072015, `arXiv:1802.09752`.

[66] LHCb, R. Aaij *et al.*, *Measurement of Angular and CP Asymmetries in* $D^0 \to \pi^+\pi^-\mu^+\mu^-$ *and* $D^0 \to K^+K^-\mu^+\mu^-$ *decays*, Phys. Rev. Lett. **121** (2018) 091801, `arXiv:1806.10793`.

[67] LHCb, R. Aaij *et al.*, *Measurement of the branching fractions of the decays* $D^+ \to K^-K^+K^+$, $D^+ \to \pi^-\pi^+K^+$ *and* $D_s^+ \to \pi^-K^+K^+$, Submitted to: JHEP (2018) `arXiv:1810.03138`.

[68] J. Aebischer *et al.*, *Master formula for* ε'/ε *beyond the Standard Model*, `arXiv:1807.02520`.

[69] NA62, E. Cortina Gil *et al.*, *First search for* $K^+ \to \pi^+\nu\bar{\nu}$ *using the decay-in-flight technique*, `arXiv:1811.08508`.

[70] KOTO, J. K. Ahn *et al.*, *Search for the* $K_L \to \pi^0\nu\bar{\nu}$ *and* $K_L \to \pi^0 X^0$ *decays at the J-PARC KOTO experiment*, `arXiv:1810.09655`.

[71] N. H. Christ *et al.*, *First exploratory calculation of the long-distance contributions to the rare kaon decays* $K \to \pi\ell^+\ell^-$, Phys. Rev. **D94** (2016) 114516, `arXiv:1608.07585`.

[72] M. Bordone, D. Buttazzo, G. Isidori, and J. Monnard, *Probing Lepton Flavour Universality with* $K \to \pi\nu\bar{\nu}$ *decays*, Eur. Phys. J. **C77** (2017) 618, `arXiv:1705.10729`.

[73] M. Bordone, C. Cornella, J. Fuentes-Martin, and G. Isidori, *A three-site gauge model for flavor hierarchies and flavor anomalies*, Phys. Lett. **B779** (2018) 317, `arXiv:1712.01368`.