Rare decays of B, D and K mesons

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Rare decays of beauty, charm and strange hadrons are particularly sensitive to contributions from beyond the Standard Model. Results on branching fractions, decay rates, asymmetries and lepton flavour non-universality of decays with leptons in the final state are presented. These results are obtained from numerous experimental facilities.

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1. Introduction

Flavour physics in general and rare decays in particular are sensitive probes to scrutinize the Standard Model (SM). As the SM amplitudes of rare decays are suppressed, any small new physics effects (NP) can compete in magnitude. Historically such precision measurements have led to remarkable discoveries, for example the measurements of the

- (lack of) $K^0 \to \mu^+\mu^-$ decays [1], which led to the introduction of **charm**;

- discovery of CP violation [2], which led to the prediction of the 3rd family like **bottom** [3];

- measurement of B^0 mixing [4], which led to the prediction of the **top** mass, $m_t > 50$ GeV.

In these proceedings the latest measurements on rare B, D and K decays are presented, which all fall in the class of flavour changing neutral current (FCNC) electroweak penguin (EWP) processes, as illustrated in Fig. 1. FCNC are not allowed at tree level in the SM and are thus loop-suppressed whereas new heavy particles can contribute significantly in these loop processes. Depending on the coupling strength, mass scales between a few TeV (for Standard Model-like couplings known as minimal flavour violation (MFV)) and few tens of TeV (for couplings of order unity) can be probed, with the current experimental accuracies.
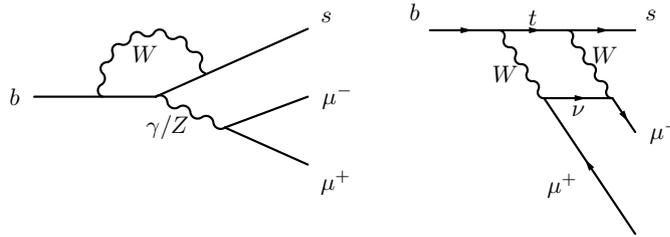

Figure 1: Flavour Changing Neutral Current processes in the Standard Model occur at loop level. The $s \to d\ell\ell$ and $c \to u\ell\ell$ processes are similar to the $b \to s\mu^+\mu^-$ diagrams shown here.

These FCNC processes can be realized with a large variety of hadrons, leading to the study of numerous decays. The decays that are discussed in these proceedings are tabulated in Tab. 1.

	Fully Leptonic	Rare semileptonic	
		Mesonic	Baryonic
Strange	$K_S^0 \to \mu^+\mu^-$	$K^+ \to \pi^+ \nu\bar{\nu}$	$\Sigma^+ \to p\mu^+\mu^-$
		$K^0 \to \pi^0 \nu\bar{\nu}$	$\psi(2S) \to \Lambda_c^+ p e^+ e^-$
Charm		$D \to hh'\mu^+\mu^-$	$\Lambda_c^+ \to p\mu^+\mu^-$
		$\psi \to D^0 e^+ e^-$	
Bottom	$B_{(s)}^0 \to \mu^+\mu^-$	$B \to K^{(*)}\mu^+\mu^-$	$\Lambda_b^0 \to \Lambda\mu^+\mu^-$
	$B_{(s)}^0 \to \tau^+\tau^-$	$B \to K^{(*)}e^+e^-$	
	$B_{(s)}^0 \to \mu^+ e^-$	$B_s^0 \to (K^*/\phi)\mu^+\mu^-$	

Table 1: Results on these decays are presented in this paper.

2. Strange

2.1 Leptonic: $K_S^0 \to \mu^+\mu^-$

Research on decays of hadrons containing strange quarks dates back to the very discovery of long-living particles in 1947 [5]. The $K^0 \to \ell^+\ell^-$ decay amplitude receives S-wave (A) and P-wave (B) components, $\mathscr{A}(K^0 \to \ell^+\ell^-) = \bar{u}_l(iB + A\gamma_5)v_l$ [6], resulting in different expectations for K_L^0 and K_S^0 decays. Long-distance contributions to $K_S^0 \to \mu^+\mu^-$ decays are small compared to the K_L^0 case, which makes the study of K_S^0 decays sensitive to new physics. Recently, the LHCb experiment entered this area with a new upper limit on the branching fraction,

$$\mathscr{B}(K_S^0 \to \mu^+\mu^-) < 0.8 \times 10^{-9} \text{ at 90\% CL } [7]. \tag{2.1}$$

This improves on an earlier LHCb measurement and constitutes the worlds best limit.

2.2 Rare semileptonic: $K \to \pi\nu\bar{\nu}$ and $\Sigma^+ \to p\mu^+\mu^-$ decays

The NA62 experiment at the SPS observed a single $K^+ \to \pi^+\nu\bar{\nu}$ candidate, whereas 0.27 signal events and 0.15 background events were expected. The KOTO experiment at J-PARC did not observe any neutral kaon decays, leading to new limits on the branching fraction,

$$\begin{aligned} \mathscr{B}(K^+ \to \pi^+\nu\bar{\nu}) &< 14 \times 10^{-10} \text{ at 95\% CL } [8], \\ \mathscr{B}(K_L^0 \to \pi^0\nu\bar{\nu}) &< 30 \times 10^{-10} \text{ at 90\% CL } [9], \end{aligned} \tag{2.2}$$

while the SM expectations for the branching fractions are 0.84×10^{-10} and 0.3×10^{-10} for the K^+ and K_L^0 decay, respectively [10]. By 2019 the NA62 collaboration might have analyzed their total available dataset, with approximately 20 expected K^+ decays, according to Standard Model predictions, whereas the KOTO collaboration expects to improve the upper limit on the K_L^0 branching fraction to 12×10^{-10}.

The LHCb collaboration further contributed to the study of rare decays of hadrons containing strange quarks by studying the baryonic decay $\Sigma^+ \to p\mu^+\mu^-$. A resonant structure in the dimuon invariant mass around 214 MeV, close to the dimuon threshold, was reported by the HyperCP experiment with the observation of three events [11]. No evidence for such an exotic scalar particle X is found by LHCb,

$$\begin{aligned} \mathscr{B}(\Sigma^+ \to p\mu^+\mu^-) &= (2.2^{+1.8}_{-1.3}) \times 10^{-8} \\ \mathscr{B}(\Sigma^+ \to pX(\to \mu^+\mu^-)) &< 1.4 \times 10^{-8} \text{ at 90\% CL } [12]. \end{aligned} \tag{2.3}$$

3. Charm

3.1 Rare semileptonic: D^0, ψ and Λ_c decays

Rare charm decays are of interest as down-type quarks constitute to the loop diagrams, in contrast to *B* or *K* decays, and new particles might in principle couple differently to the up-quark sector. The rarest charm decay ever observed is reported,

$$\mathscr{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.6 \pm 1.2) \times 10^{-7},$$
$$\mathscr{B}D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.33) \times 10^{-7} \text{ [13]}. \tag{3.1}$$

The addition of the data set recorded in 2015 and 2016 by LHCb allowed for an angular analysis, showing that the CP- and forward-backward asymmetries are consistent with zero [14].

No significant signal is observed of the baryonic decay,

$$\mathscr{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7 \times 10^{-8} \text{ at 90\% CL [15],} \tag{3.2}$$

where the regions of the dimuon mass around the ρ^0/ω and ϕ resonances are used as normalisation.

The BESIII collaboration also studied FCNC decays of *D*-mesons, but with an electron pair in the final state, and upper limits are set in the following ranges,

$$\mathscr{B}(D^+ \to h^\pm e^+ e^\mp) < [3-12] \times 10^{-5} \text{ at 90\% CL },$$
$$\mathscr{B}(D^+ \to h^+ h^0 e^+ e^-) < [1.1-2.6] \times 10^{-5} \text{ at 90\% CL },$$
$$\mathscr{B}(D^0 \to h^+ h^- e^+ e^-) < [0.7-4.1] \times 10^{-5} \text{ at 90\% CL },$$
$$\mathscr{B}(D^0 \to h^0 e^+ e^-) < [0.3-1.2] \times 10^{-5} \text{ at 90\% CL [16],} \tag{3.3}$$

where $h = \pi, K$. Similarly, rare charm decays can be studied with charmonium decays, i.e. with a charm quark also as spectator quark, and the following limits on branching fractions of ψ decays to $e^+ e^-$ pairs are set,

$$\mathscr{B}(J/\psi \to D^0 e^+ e^-) < 8.5 \times 10^{-8} \text{ at 90\% CL },$$
$$\mathscr{B}(\psi(2S) \to D^0 e^+ e^-) < 14 \times 10^{-8} \text{ at 90\% CL [17],}$$
$$\mathscr{B}(\psi(2S) \to \Lambda_c^- p e^+ e^-) < 170 \times 10^{-8} \text{ at 90\% CL [18].} \tag{3.4}$$

4. Beauty

4.1 Leptonic: $B^0_{(s)} \to \mu^+\mu^-$, $B^0_{(s)} \to \tau^+\tau^-$ and $B^0_{(s)} \to e^+\mu^-$

The quest for the $B^0_s \to \mu^+\mu^-$ lasted for many decades, culminating in its observation in 2012 [19]. It arguably forms the most important result of the LHC after the Higgs discovery, as the SM prediction is very precise, and any deviation can be a hint of the existence of e.g. new scalar particles in the MSSM framework [20]. The latest results include data from the LHCb collaboration recorded in 2015 and 2016,

$$\mathscr{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9},$$
$$\mathscr{B}(B^0 \to \mu^+\mu^-) < 0.34 \times 10^{-9} \text{ at 95\% CL }, \text{ [21]} \tag{4.1}$$

where the largest contribution to the systematic uncertainty originates from the knowledge on the production rate of B^0_s mesons [22]. New scalar couplings could potentially leave the branching fraction unchanged, while affecting the CP structure. A novel CP-even component would be visible as a reduction in the measured lifetime [20], while the SM predicts a lifetime corresponding to the lifetime of the heavy (CP-odd) B_s mass eigenstate, $\tau_{B^0_s \to \mu^+\mu^-} = \tau_H = 1.658$ ps. A first measurement of the effective lifetime is reported,

$$\tau(B^0_s \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps [21]}. \tag{4.2}$$

Decays to τ lepton pairs are particularly interesting, as the helicity suppression is largely lifted in the SM, and because new particles might couple differently to the third generation. Experimentally however, the measurement is challenging due to the missing neutrinos, and due to the penalty of the subsequent τ branching fraction,

$$\mathscr{B}(B^0_s \to \tau^+\tau^-) < 5.2 \times 10^{-3} \text{ at 90\% CL }, \tag{4.3}$$
$$\mathscr{B}(B^0 \to \tau^+\tau^-) < 1.6 \times 10^{-3} \text{ at 95\% CL } \text{ [23]}. \tag{4.4}$$

while the SM prediction is $(7.7 \pm 0.5) \times 10^{-7}$ and $(2.2 \pm 0.2) \times 10^{-7}$ for B^0_s and B^0, respectively [24]. Models with vector leptoquarks that couple to the third generation predict branching fractions as large as 10^{-4} [25].

Recently renewed interest has arisen in the search for lepton flavour violating (LFV) decays, as it has been argued that lepton flavour non-universality (LFNU) implies LFV [26]. The following limits have been set,

$$\mathscr{B}(B^0_s \to e^+\mu^-) < 6.0 \times 10^{-9} \text{ at 90\% CL }, \tag{4.5}$$
$$\mathscr{B}(B^0 \to e^+\mu^-) < 1.0 \times 10^{-9} \text{ at 90\% CL } \text{ [27]}. \tag{4.6}$$

4.2 Rare semileptonic: $B \to K\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$ and $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ decays

The $b \to s\mu^+\mu^-$ process can be studied with a variety of hadronic decay modes. The decay rates of the decays $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^{*0}\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$ and $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ are measured consistently below expectations.

A particularly rich experimental system is provided by $B^0 \to K^{*0}\mu^+\mu^-$ decays. In addition to the decay rate (as a function of the dimuon invariant mass squared q^2), numerous angular observables, like the forward-backward asymmetry and other angular asymmetries, can be compared to SM expectations. Many theoretical uncertainties cancel in the determination of angular asymmetries, resulting in accurate probes of new physics effects. Moreover, angular observables can be used to determine the type of the coupling of any new physics contribution, being sensitive to the Lorentz structure.

Numerous experiments have performed angular analyses, notably from the BaBar [29], LHCb [30] ATLAS [31] CMS [32, 33] and Belle [37] experiments, as shown in the left of Fig. 2. A particularly interesting angular observable is the S_5 asymmetry, which sums the forward/upward with backward/downward going kaons, and quantifies the asymmetry with the complementary event sample. The P_5' observable (defined in Ref. [34] and references therein) is less dependent on form factors and is obtained by dividing S_5 by $\sqrt{F_T F_L}$. The angular observables - most notably P_5', combined with the decay rate measurements, shows a tension with the SM expectations. Global fits to about 200 measurements of the $b \to s\mu^+\mu^-$ process from all aforementioned experiments show a significant improvement in the fit quality of about $\Delta\chi^2 \sim 25$ (e.g. in Ref.[38]). This is obtained when beyond-the-SM vector (V) or vector-axial $V - A$ couplings are allowed for, quantified through the effective coupling strengths C_9^{NP} and $C_9^{NP} - C_{10}^{NP}$, respectively. These so-called Wilson coefficients quantify the left-handed couplings to the quarks, whereas the right-handed couplings to the quarks are usually indicated by the C_i' coefficients. It is an appealing feature that it is possible to consistently explain all deviating measurements by a single, simple, adjustement of either the vector, or $V - A$ coupling. This eases the model building to provide possible explanations of the observations, like models containing Z' bosons or leptoquarks (see for example Ref. [25] and references therein).

Recently, also the FCNC $b \to d\mu^+\mu^-$ electroweak penguin process was probed in B_s^0 decays,

$$\mathcal{B}(B_s^0 \to K^{*0}\mu^+\mu^-) = (2.9 \pm 1.1) \times 10^{-8} \text{ [28]}, \tag{4.7}$$

which could provide a very interesting comparison to the angular observables in the $B^0 \to K^{*0}\mu^+\mu^-$ case, once a sufficiently large event sample will be available.

4.3 Lepton Flavour Non-Universality

The excitement of the collection of small deviations in the $b \to s\mu^+\mu^-$ decay rates and angular observables is augmented by theoretically clean tests of lepton flavour universality in rare decays, quantified through the ratio of $\mu^+\mu^-$ over e^+e^- decay rates,

$$R_K = 0.745^{+0.09}_{-0.074} \pm 0.036 \text{ [35]}, \tag{4.8}$$

$$R_{K*} = 0.66^{+0.11}_{-0.07} \pm 0.03 \text{ [36]} \qquad \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2, \tag{4.9}$$

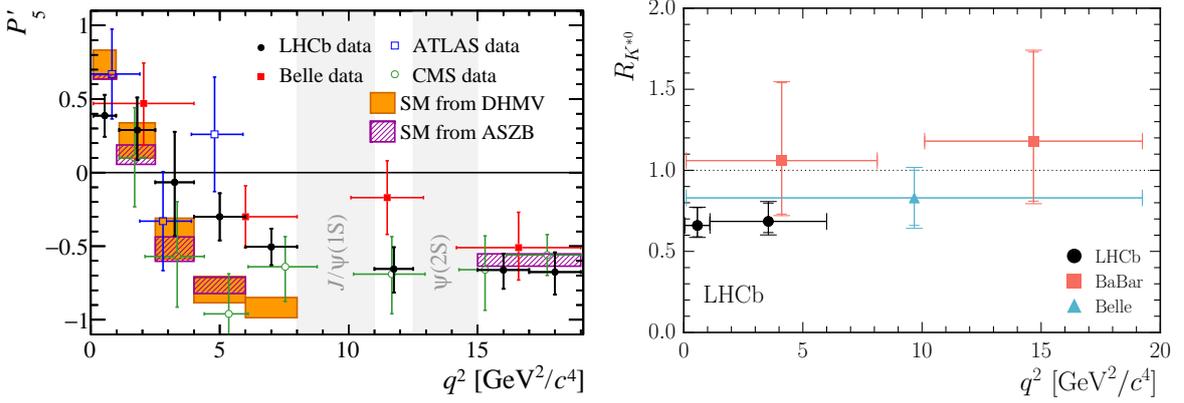$$R_{K*} = 0.69^{+0.11}_{-0.07} \pm 0.05 \text{ [36]} \qquad \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2. \tag{4.10}$$

Figure 2: Compilation of results on $b \to s\ell\ell$ flavour-changing neutral-current decays: P_5' (left) and R_K^* (right) as a function of the invariant mass squared q^2 of the lepton pair.

The SM predicts ratios close to unity, with very small uncertainty, as most theoretical uncertainties originating from form factors or charm-loop effects, cancel in the ratio. The measurements on R_{K*} are shown in the right of Fig. 2. However, it is difficult to explain the deviation (albeit only 2.2 standard deviations) from unity of the ratio R_{K*} in the low-q^2 bin, even when invoking new physics. As the low-q^2 bin is dominated by the photon pole (quantified through the Wilson coefficient C_7), and as it is known that the photon couples equally to charged particles, new physics effects are not expected to have a large impact in this q^2 region.

Experimentally many possible systematics cancel, because $R_{K(*)}$ is determined as double ratio, normalized to the $B \to K^{(*)}J/\psi(\ell\ell)$ decay rates. The single ratio $R_{J/\psi} = \mathscr{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))/\mathscr{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))$ is less precise, but forms an extremely stringent test, and is studied as a function of numerous kinematic quantities. The average ratio is determined to be $R_{J/\psi} = 1.043 \pm 0.006(\text{stat}) \pm 0.045(\text{sys})$. The double ratio using the $K^*\psi(2S)$ final state (in place of $K^*\ell\ell$) is measured to be consistent with unity within 1σ of the statistical uncertainty of 2%.

An angular analysis of $B^0 \to K^*e^+e^-$ would give important complementary information, and could possibly reconcile the intriguing measurements of the angular distributions of $B^0 \to K^*\mu^+\mu^-$ decays and the low decay rates of $B \to K\mu^+\mu^-$ decays compared to $B \to Ke^+e^-$ decays.

The Belle collaboration has indeed compared the anomalous P_5' measurement with muons in the final state, with the measurement using electrons. The current precision does not allow to draw firm conclusions yet, but it is interesting to note that the P_5' measurement with electrons agrees better with the SM predictions [37].

Combined with the deviating measurements of the ratio of semileptonic $B \to D^{(*)}\tau\nu$ over $B \to D^{(*)}\ell\nu, \ell = \mu, e$ decays, it is tempting to speculate on new physics scenarios where new particles couple mainly to the τ leptons (even competing with tree level SM semileptonic decays), and to a lesser extent to muons (thus competing with SM loop processes), and negligibly to electrons (see e.g. Refs. [25, 26] and references therein).

5. Conclusions and outlook

A world-wide effort is ongoing in the area of flavour-changing neutral-currents, most notably regarding $b \to s\ell\ell$ electroweak penguin processes. Intriguing tensions with the Standard Model have been observed, while showing a consistent picture among the experimental data from numerous different experiments.

Both the historical measurements (e.g. on $K^0 \to \mu^+\mu^-$ or B^0-mixing), and the current excitement on rare beauty decays, clearly shows the power of precision flavour physics, being sensitive to phenomena at multi-TeV energy scales. In addition, the novel angular analysis of charm decays promises a new window on possible new physics effects in the up-quark sector.

The sensitivities of all measurements presented here are dominated by the statistical uncertainties, which justifies increased efforts in future flavour experiments, like the upcoming LHCb Upgrade I and Belle II experiments, the optimization of the triggers strategies in ATLAS and CMS, and the plans for a future LHCb Upgrade II [39]. Table 2 illustrates the potential of the future dedicated flavour physics facilities, in terms of event yields of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$ decays.

	2010	2014	2019	2024	2026	2030	2040
LHCb				Upgrade I			Upgrade II
		Run-1	Run-2	Run-3		Run-4	
		3 fb^{-1}	9 fb^{-1}	23 fb^{-1}		50 fb^{-1}	300 fb^{-1}
		111(2500)	0.5(10)k	1.4(30)k		3.3(70)k	20(400)k
Belle	Belle I				Belle II		
	0.7 ab^{-1}				50 ab^{-1}		
	127(185)				10(13)k		

Table 2: Comparison of estimated event yields for the decays $B^0 \to K^{*0}e^+e^-$ $(\mu^+\mu^-)$. The LHCb estimates are taken from Ref. [39], whereas the Belle yields are taken from Ref. [37], and scaled to 50 ab^{-1} using the relative luminosity.

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