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Rare decays at LHCb

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Rare decays of beauty and charm hadrons and lepton flavour/number violating decays of tau leptons test the flavour structure of the underlying theory at the level of quantum corrections. They provide information on the couplings and masses of heavy virtual particles appearing as intermediate states. A review of recent results obtained by LHCb on these topics will be presented.

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1. Introduction

Among the six Standard Model (SM) quarks, up type and down type quarks transform into each other with relative ease. On the other hand, *direct* transitions among the three up type and three down type quarks (e.g. $b \to s$) are completely absent. These processes, called flavour changing neutral currents (FCNC), take at least 2 up-down transitions to occur, which makes them decidedly less probable.

The explanation to this is a result of hard work over many decades and is now embedded deep in the framework of the SM through the GIM-mechanism, which does not allow tree level FCNC transitions [1].

The best place to study FCNC is in rare meson decays. All together, there are four[1] possible FCNC transitions contributing to the rare meson decays: $b \to s$, $b \to d$, $s \to d$, and $c \to u$. They are all being studied at the LHCb detector.

The LHCb detector is a forward single-arm spectrometer at LHC, aimed at studies of CP-symmetry violation and rare decays in the LHC collider environment. It is discussed in more detail elsewhere [2].

In the current review we will present a selection of the latest and most interesting results on rare B meson decay channels. Rare B decays can be divided into three groups according to the final state:

[1]Top quark decays before it is able to form a bound state.

- **Semi-leptonic decays**: decays to a different meson and a lepton pair in the final state (e.g. $B_d^0 \to K^* \mu^+ \mu^-$),
- **Radiative decays**: decays to a different meson and a radiated photon in the final state (e.g. $B^\pm \to K^\pm \pi^\mp \pi^\pm \gamma$),
- **Leptonic decays**: decays with only a lepton pair in the final state (e.g. $B_{s,d}^0 \to \mu^+ \mu^-$).

1.1 New physics in FCNC

The elusive FCNC processes mediating the rare decays can be conveniently described using the effective Hamiltonian approach. The idea is to separate the short and long distance interactions and to write the Hamiltonian in operator basis. Every operator governs a different contribution to the decay [3]. For the $b \to s$ transition, it reads

$$\mathscr{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i^{'} O_i^{'}) + h.c. \tag{1.1}$$

Here, $O_i^{(')}$ are the operators describing the long distance effects and the short distance couplings are described by the Wilson coefficients $C_i^{(')}$. The primed operators differ from the unprimed operators[2] in their chirality $P_{R,L} = (1 \pm \gamma_5)/2$.

The New Physics (NP) models can either modify the Wilson coefficients or introduce new operators with their own Wilson coefficients. If that happens to be the case, we could see deviations in multiple observables; NP could alter the total branching ratio, or other observables such as the angular distribution of the decay products.

All this makes rare decays an excellent place for SM tests at extreme sensitivities. Table 1 shows how the three different kinds of rare B meson decays together allow us to examine many different Wilson coefficients.

2. Semi-leptonic decays: $B_d^0 \to K^* \mu^+ \mu^-$

The semi-leptonic decay $B_d^0 \to K^* \mu^+ \mu^-$ has the capacity to unveil the NP contributions not only for the SM electromagnetic and dileptonic operators $O_{7,9,10}^{(')}$, but also for the scalar and pseudoscalar operators $O_{S,P}^{'}$. Among these, the only non-negligible Wilson coefficients in the SM are $C_{7eff,9,10}^{SM}$ [23, 24].

Wilson coeff.	$B^\pm \to K_{res}^\pm \gamma$	$B_d^0 \to K^* \mu^+ \mu^-$	$B_{s,d}^0 \to \mu^+ \mu^-$
$C_7^{(')}$	✓	✓	-
$C_9^{(')}$	-	✓	-
$C_{10}^{(')}$	-	✓	✓
$C_S^{(')}$	-	✓	✓
$C_P^{(')}$	-	✓	✓

Table 1: Wilson coefficients that can contribute to different rare B decays.

[2] SM predicts the Wilson coefficients corresponding to the primed operators, $C_i^{'}$, are negligibly small.

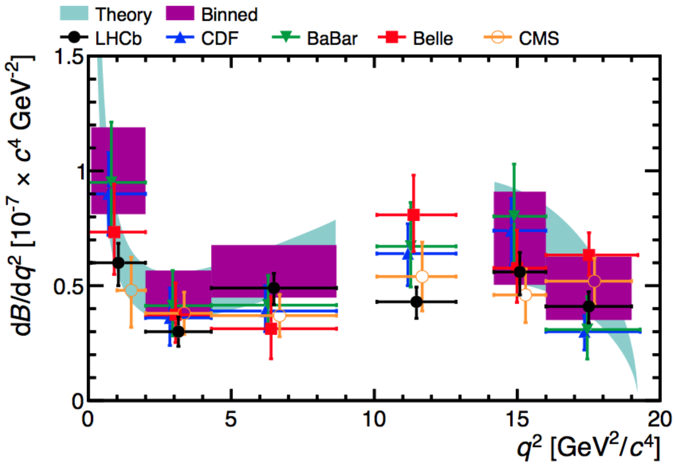

Figure 1: The differential branching ratio $\mathrm{d}\mathscr{B}/\mathrm{d}q^2$ for $B_d^0 \to K^*\mu^+\mu^-$ in bins of the invariant dimuon mass squared q^2. The latest measurements and their uncertainties are shown with coloured markers. The SM prediction [19] and its average over the experimental bins are shown by the blue band and purple rectangles, respectively.

2.1 Branching ratio measurements

The total branching ratio for the decay $B_d^0 \to K^*\mu^+\mu^-$ has been measured previously by several experiments [4, 5, 7, 6] to be

$$BR(B_d^0 \to K^*\mu^+\mu^-)_{exp} = (1.06 \pm 0.10) \times 10^{-6}, \tag{2.1}$$

which is in good agreement with SM prediction [8 – 11].

Although the total branching ratio agrees with the SM prediction, NP could still modify the differential branching ratio, $\mathrm{d}\mathscr{B}/\mathrm{d}q^2$. The differential branching ratio, $\mathrm{d}\mathscr{B}/\mathrm{d}q^2$, has also been measured by the main experiments in the field [12 – 14].

Recently, LHCb [15] and CMS [17] published their results based on the 2011 data sets of $1.0fb^{-1}$ and $5.2fb^{-1}$, respectively. Different $\mathrm{d}\mathscr{B}/\mathrm{d}q^2$ measurements are all in good agreement with SM prediction [19, 23] (Fig. 1).

2.2 Angular distributions

Given the agreement between the aforementioned branching ratio measurement and the SM prediction, some NP models could still have an effect on angular distributions of the $B_d^0 \to K^*\mu^+\mu^-$ final state particles. This is where the experimental front line currently resides.

The differential decay rate depends on four variables: the dilepton invariant mass squared (q^2), and three decay angles named θ_l, θ_K, and ϕ (defined in Fig. 2).

The difficulty lies in how to parameterize all four experimental observables in a way to be sensitive to NP effects, but at the same time, insensitive to hadronic effects that arise from large form factor uncertainties. For the best parameterization, different compromises have been proposed (independently by several authors [25 – 28]) between the theoretical cleanliness and the simplicity in their experimental accessibility.

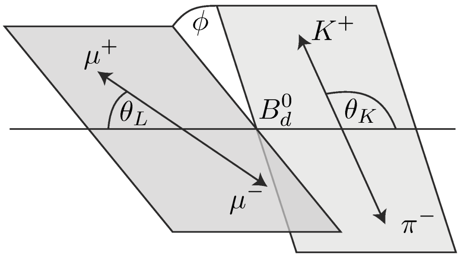

Figure 2: Three helicity angle definitions for $B_d^0 \to K^* \mu^+ \mu^-$ system. θ_l is the angle between the muons in the dimuon rest frame and the B^0 flight direction. θ_K is similarly defined as θ_l, but for the K^{*0} daughters. ϕ is the angle between the dimuon and K^{*0} decay plane.

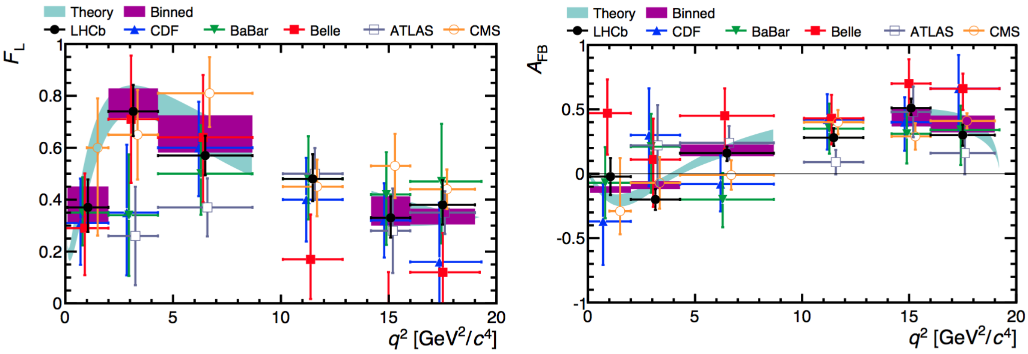

Figure 3: The fraction, F_L, of longitudinal polarised K^{*0} mesons (left) and the forward-backward asymmetry of leptons with respect to the B^0 flight direction, A_{FB} (right) in the decay $B_d^0 \to K^* \mu^+ \mu^-$. Both are measured as a function of the invariant dimuon mass squared, q^2, and by different experiments. The SM prediction [19] and its average over the experimental bins are shown by the blue band and the purple rectangles, respectively.

The choice of parameterization in the $B_d^0 \to K^* \mu^+ \mu^-$ LHCb result, has gone through a rapid evolution. As the first approach, all three LHC experiments (LHCb [15], CMS [17], and ATLAS[3] [18]) measured the two observables[4]:

- the fraction of longitudinal polarised K^{*0} mesons, F_L,
- and the forward-backward asymmetry of leptons with respect to the B^0 flight direction, A_{FB}.

No significant deviation from the SM predictions [19] is seen in either case (see Fig. 3). In addition, LHCb reports also the zero-crossing point, q_0^2, for A_{FB}. This quantity has never been measured before, and the LHCb result (4.9 ± 0.9) GeV^2/c^4 is in good agreement with SM prediction of $3.9 - 4.3$ GeV^2/c^4 [20 – 22]

F_L and A_{FB} are in good agreement with the SM, but they are also rather sensitive to hadronic uncertainties. Larger hadronic uncertainties could easily hide subtle NP effects. In order to improve sensitivity to NP effects, LHCb was able to extract the theoretically cleaner versions of A_{FB}, so called transverse asymmetries A_T^{Re} and A_T^2. Again, both are in agreement with the SM prediction [25, 27].

[3] ATLAS analysis is done on the full 2011 data set of $4.9 fb^{-1}$.

[4] F_L and A_{FB} have also been measured earlier by the B factories [12, 13] and CDF [14].

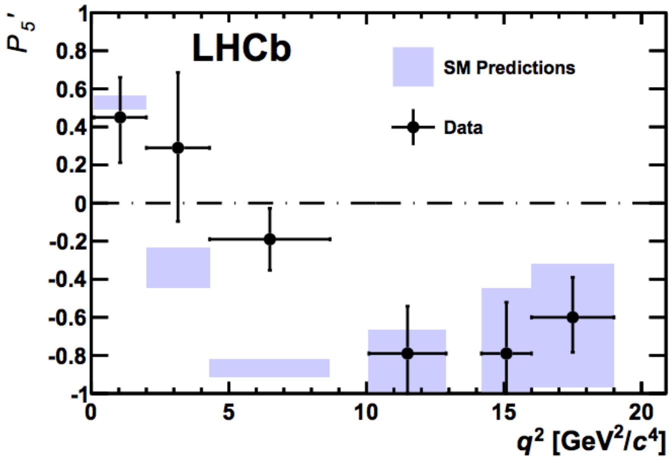

Figure 4: Measured values of $P_5^{'}$ (black points) compared with SM predictions [23] (blue bands). LHCb observes discrepancy in the second and third bin (see the text).

The latest result from LHCb [16] on $B_d^0 \to K^* \mu^+ \mu^-$ completes the proposed theoretically clean basis of $P_{1,2,3}$ and $P_{4,5,6}^{'}$ primary observables [23, 26]. In general, the measurements again agree with SM expectations [23], but not all.

LHCb sees a sizeable discrepancy of 3.7σ in the interval $4.30 < q^2 < 8.68$ GeV^2/c^4 for the observable $P_5^{'}$. The measurement of $P_5^{'}$ along with SM prediction are shown in Fig. 4, note the discrepancy in the second and third bin. Integrating over the region $1.0 < q^2 < 6.0$GeV^2/c^4, discrepancy in $P_5^{'}$ reduces to 2.5σ.

The observed discrepancy could point to a situation where the Wilson coefficient C_9 ($C_9 = C_9^{SM} + C_9^{NP}$) is smaller than expected in the SM due to $C_9^{NP} < 0$. As has been hypothesised in [24], this would be the case in some $Z^{'}$ gauge boson models. Measurements with more data and further theoretical studies will be crucial here to draw more definitive conclusions.

3. Radiative decays: $B^\pm \to K^\pm \pi^\mp \pi^\pm \gamma$

The SM prediction for the inclusive branching ratio [43] agrees well with the observed experimental value by the B factories [35, 34, 36], $BR(b \to s\gamma) = (3.55 \pm 0.24) \times 10^{-4}$. In the case of $B^\pm \to K_{res}^\pm \gamma$, NP models could alter only the polarisation of the emitted photon without affecting the branching ratio. Hence, the next important test in $B^\pm \to K_{res}^\pm \gamma$ is to measure the polarisation of the out-going photon.

According to the SM, the photon in $b \to s\gamma$ is predominantly left-handed. Right-handed contribution still exists, but is strongly suppressed[5], down to the order of a few percent [40–42]. Several models beyond the SM, such as the left-right symmetric model (LRSM) [29–32] and the minimal supersymmetric model (MSSM) [33], predict the photon acquires a significant right-handed component.

[5]The right-hand *helicity* state of a quark also contains a small (weakly interacting) left-handed *chiral* part, which leads to a right-handed photon in the final state. The suppression is given by the ratio of the quark masses, m_s/m_b.

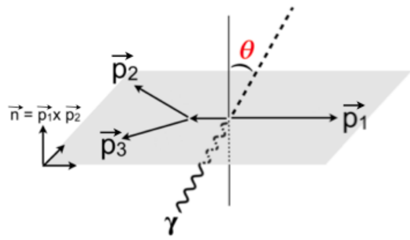

Figure 5: Sketch of a $B^- \to K^-_{res}\gamma \to P_1P_2P_3\gamma$ decay in the rest frame of the intermediate resonance (K_{res}). The angle θ is between the direction opposite to the photon momentum, and the normal to the decay plane of the $P_1P_2P_3$ hadronic system, defined by $\vec{p}_1 \times \vec{p}_2$. For the $B^- \to K^-\pi^+\pi^+\gamma$ decay we have $P_1 = \pi^-$, $P_2 = \pi^+$ and $P_3 = K^-$

3.1 Measuring photon polarisation

The measurement of photon polarisation in $B^\pm \to K^\pm_{res}\gamma$, where K_{res} is a kaon resonance, starts by looking for the four final state particles: K,π,π, and γ.

The three hadrons in the final state can be used to form a plane. It is then possible to extract information about photon polarisation from the angular distribution of the photon direction with respect to the decay plane (see Fig. 5).

The shape of this distribution, as well as up-down asymmetry between the number of events found on the each side of the plane, has been determined. As the photon polarisation, λ_γ, is proportional to the up-down symmetry, measuring an up-down asymmetry different from zero corresponds to demonstrating that the photon is polarised.

The $K\pi\pi$ mass spectrum contains many different resonances. At present, some of the single resonances have been experimentally observed, such as $K_1(1270)^+$ [37] and $K_2^*(1430)^+$ [34, 35]. For some underlying resonances, there exist upper limits, such as for $K_1(1400)^+$ [37]. But in general, the different resonances in the spectrum cannot be easily distinguished due to the overlap.

Each of these resonances can contribute differently to the inclusive up-down asymmetry. Moreover, the interference between overlapping resonances can enhance or dilute the asymmetry. The present lack of knowledge of the structure of the $K\pi\pi$ mass spectrum makes it unfortunately impossible to translate the measurement into an actual value of the photon polarisation λ_γ. For this reason, LHCb has provided experimental values necessary for the determination of the photon polarisation parameter [39] as soon as the mass spectrum has been better understood.

3.2 Results from LHCb

The latest analysis from LHCb on the photon polarisation from $B^\pm \to K^\pm\pi^\mp\pi^\pm\gamma$ has been performed on the full $2fb^{-1}$ LHCb data sample collected from pp collisions at $\sqrt{s} = 8TeV$ in 2012. A total signal yield of more than 8000 events is obtained fitting the overall model to the $2fb^{-1}$ data sample.

The mass spectrum of $K\pi\pi$ is shown in Fig.6. No evident peak other than the dominant $K_1(1270)^+$ can be observed. As suggested in [42], the analysis is done in two $K\pi\pi$ invariant

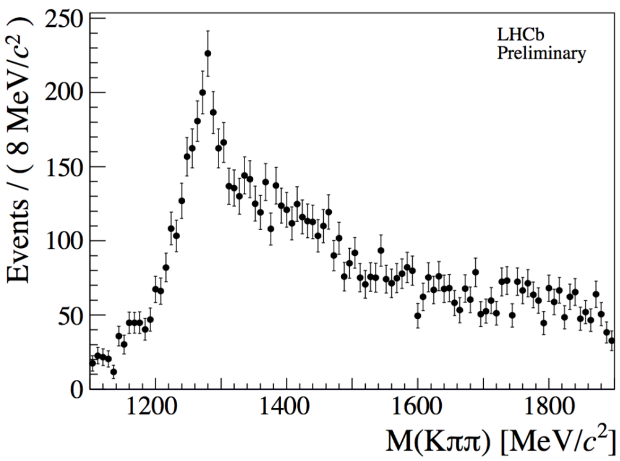

Figure 6: Background-subtracted $K\pi\pi$ invariant mass distribution, obtained using the sPlot technique [44]

mass regions[6]. The up-down asymmetry is extracted from a simultaneous fit to four samples, split according to the B candidate charge and photon direction (up or down).

Two independent measurements of the up-down asymmetry are obtained from the full asymmetry fit, one for each charge of the B meson. The results are in perfect agreement and when combined, the measured up-down asymmetry in the $B^{\pm} \to K^{\pm}\pi^{\mp}\pi^{\pm}\gamma$ becomes

$$\mathscr{A}_{ud} = 0.085 \pm 0.019(stat) \pm 0.003(syst). \tag{3.1}$$

The overall significance with respect to zero is found to be 4.6σ. This is equivalent to stating we have witnessed a strong evidence for parity violation. The LHCb result will, hopefully very soon, allow the estimation of the photon polarisation. This would be the first measurement of such quantity.

In addition, LHCb also reports for the first time the CP-asymmetry for the decay $B^{\pm} \to K^{\pm}\pi^{\mp}\pi^{\pm}\gamma$. In agreement with the SM [43], it has been found to be compatible with zero [39]:

$$\mathscr{A}_{CP} = -0.007 \pm 0.015(stat) \pm 0.008(syst). \tag{3.2}$$

4. Leptonic decays: $B^0_{s,d} \to \mu^+\mu^-$

$B^0_{s,d} \to \mu^+\mu^-$ decays are fully leptonic decays involving a $b \to s$ or a $b \to d$ transition, but yielding only in a muon pair in the final state. This has many interesting consequences, e.g. the $B^0_{s,d} \to \mu^+\mu^-$ decays are also helicity suppressed in addition to GIM suppression. This classifies them as not just rare, but very rare decays. Due to the rareness, the main experimental efforts currently lie in measuring the first possible observable - the branching ratio.

Theoretically, $B^0_s \to \mu^+\mu^-$ decays are rather clean channels. Due to purely leptonic final state, the usually large hadronic uncertainties, only need to be considered for the initial state. Although

[6]The first region is dominated by the $K_1(1270)$ resonance. The second mainly includes the $K_1(1400)$, $K_2^*(1430)$ and $K^*(1410)$ resonances.

the theory uncertainties are rather low, the final estimates depend on a number of choices made along the way.

One of the latest theory predictions [46, 45] demonstrates how the recent impressive progress in lattice determination of the B_s decay constant, f_{Bs}, has changed the game. The relative uncertainty contribution from the decay constant that used to be by far the most dominant one, is currently at the same level with the uncertainty originating from CKM matrix elements, both at about 4%. The total relative error budget stays well below 10%.

The present best estimates from [46, 45] to be compared with the experimental[7] branching ratio are:

$$\begin{aligned} BR(B_s^0 \to \mu^+\mu^-) &= (3.56 \pm 0.18) \times 10^{-9}, \\ BR(B_d^0 \to \mu^+\mu^-) &= (1.07 \pm 0.10) \times 10^{-10}. \end{aligned} \tag{4.1}$$

In calculating Eq. 4.1, a scheme has been chosen in which the next-to-leading-order (NLO) corrections of the electroweak (EW) origin are likely to be negligible. The QCD corrections are accounted up to NLO. In [47, 48], the calculation of NLO EW corrections and one level higher NNLO QCD corrections, are both included to the branching ratio calculation. The reported results are in good agreement with the results in Eq. 4.1

$$\begin{aligned} BR(B_s^0 \to \mu^+\mu^-) &= (3.65 \pm 0.23) \times 10^{-9}, \\ BR(B_d^0 \to \mu^+\mu^-) &= (1.06 \pm 0.09) \times 10^{-10}. \end{aligned} \tag{4.2}$$

4.1 $B^0_{s,d} \to \mu^+\mu^-$ in LHCb

The latest LHCb $B_s^0 \to \mu^+\mu^-$ analysis [49] has been performed on a combined 2011 ($1fb^{-1}$ of pp collision data at $\sqrt{s} = 7TeV$) and 2012 ($2fb^{-1}$ of pp collision data at $\sqrt{s} = 8TeV$) data set. The overall analysis strategy has been kept similar to the previous LHCb $B_s^0 \to \mu^+\mu^-$ analysis on $2fb^{-1}$ of data [50]. The analysis itself has been updated by using (i) improved detector alignment and (ii) completely re-optimised multivariate classifier.

The search for the $B^0_{s,d} \to \mu^+\mu^-$ starts by looking at the dimuon spectrum around the mass of the neutral B mesons. Dominant background in our analysis arises from the random combinations of muons passing our selection. The classifier plays a crucial role in reducing this combinatorial background.

The triggered and selected events with two muons in the final state are thereafter analysed by their dimuon invariant mass and the output of the BDT classifier. Events are divided between 8 bins according to the BDT output, with rapidly decreasing combinatorial background likelihood towards the higher bins.

The BDT classifier is trained using the Monte Carlo (MC) simulated signal and background samples, whereas the signal output is designed to be uniform. More importantly, the final signal distribution in BDT is calibrated on the data using the $B^0_{s,d} \to h^+h^-$ sample.

We perform an unbinned invariant dimuon mass fit simultaneously in all the bins and extract the candidate yield. The fit is also designed to include the main uncertainties in the analysis. The signal shape parameters in dimuon mass have been taken from the Monte-Carlo studies. The signal

[7] The flavour untagged and time integrated branching ratio.

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mass resolution has been measured on the data by combining the results obtained with a power-law interpolation between the charmoniom and bottomonium resonances decaying into two muons, with those obtained with a fit of the mass distributions of $B^0 \to K^+\pi^-$, $B^0 \to \pi^+\pi^-$, and $B_s^0 \to K^+K^-$ samples. The two methods are in agreement and the combined results are $\sigma_{B_s^0} = 23.2 \pm 0.4$ MeV/c^2 and $\sigma_{B^0} = 22.8 \pm 0.4$ MeV/c^2.

Finally, the candidate yield is normalised using two normalisation channels with relatively well known absolute branching ratios, $B_u^+ \to J/\psi K^+$ and $B_d^0 \to K^+\pi^-$. For the $BR(B_s^0 \to \mu^+\mu^-)$ measurement, the systematic uncertainty has been lowered in the new analysis. The main contributions to the systematic uncertainty arises from the ratio of the hadronisation ratios f_s/f_d, and LHCb has recently updated the result with reduced uncertainties [51].

The most recent LHCb results are [49]:

$$\begin{aligned} BR(B_s^0 \to \mu^+\mu^-) &= (2.9^{+1.1}_{-1.0}) \times 10^{-9}, \\ BR(B_d^0 \to \mu^+\mu^-) &= (3.7^{+2.4}_{-2.1}) \times 10^{-10}, \end{aligned} \tag{4.3}$$

with significance of 4.0σ and 2.0σ, respectively. As the measurement on $B_d^0 \to \mu^+\mu^-$ is not statistically significant, LHCb also updated the upper limit $BR(B_d^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ at 95% CL.

4.2 $B_{s,d}^0 \to \mu^+\mu^-$ combination

The newest result from the CMS collaboration [52] on the $B_{s,d}^0 \to \mu^+\mu^-$ decays are highly compatible and in complete agreement to what LHCb Collaboration

$$\begin{aligned} BR(B_s^0 \to \mu^+\mu^-) &= (3.0^{+1.0}_{-0.9}) \times 10^{-9}, \\ BR(B_d^0 \to \mu^+\mu^-) &= (3.5^{+2.1}_{-1.8}) \times 10^{-10}, \end{aligned} \tag{4.4}$$

with slightly higher significance of 4.3σ for $B_s^0 \to \mu^+\mu^-$, and 2.0σ for $B_d^0 \to \mu^+\mu^-$. (with limit $BR(B_d^0 \to \mu^+\mu^-) < 1.1 \times 10^{-10}$ at 95%*CL*). The LHCb results have been combined with the CMS results to give the World's most precise measurements on the very rare decays[8] $B_{s,d}^0 \to \mu^+\mu^-$ [56]:

$$\begin{aligned} BR(B_s^0 \to \mu^+\mu^-) &= (2.9 \pm 0.7) \times 10^{-9}, \\ BR(B_d^0 \to \mu^+\mu^-) &= (3.6^{+1.6}_{-1.4}) \times 10^{-10}. \end{aligned} \tag{4.5}$$

The combined $BR(B_s^0 \to \mu^+\mu^-)$ has a statistical significance greater than 5σ. This is the first observation of the decay $B_s^0 \to \mu^+\mu^-$. The combined significance for the $B_d^0 \to \mu^+\mu^-$ is lower than 3σ. The combined result compare well with the SM expectations (see Fig. 7).

5. Summary

LHCb is studying all the rare FCNC playing role in the rare meson decays. There are many interesting published results, of which the main rare *B* decay results have been covered in here.

[8] In this combination, not all the correlations between the CMS and LHCb parameters have been taken into account. A more elaborate combination of the results is currently being conducted.

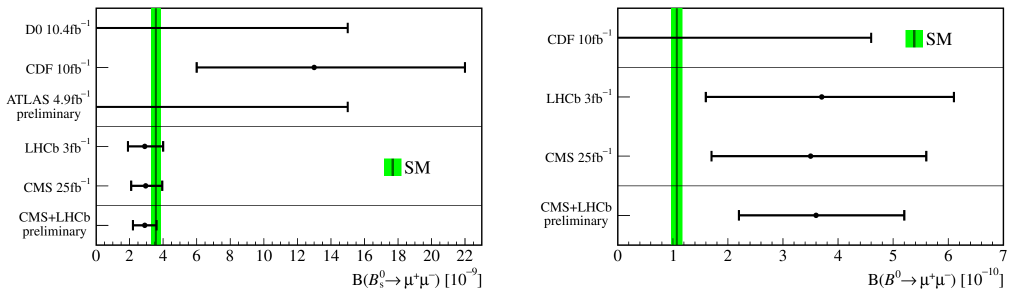

Figure 7: Comparison of previous results [53 – 55], the latest CMS and LHCb results [52, 49], the combined value, and the SM prediction (vertical line) for (left) the time-integrated branching fraction $BR(B_s^0 \to \mu^+\mu^-)$ and (right) $BR(B_d^0 \to \mu^+\mu^-)$. Upper limits at 95 % CL are shown as bars starting at zero, while other measurements are shown as data points with $\pm 1\sigma$ combined statistical and systematic uncertainties. The width of the vertical band represents the uncertainty in the SM prediction.

The very rare decay $B_{s,d}^0 \to \mu^+\mu^-$ has been observed after the long-lasting search of more than 25 years. The combined results from LHCb [49] and CMS [52] result in a branching ratios of

$$\begin{aligned} BR(B_s^0 \to \mu^+\mu^-) &= (2.9 \pm 0.7) \times 10^{-9}, \\ BR(B_d^0 \to \mu^+\mu^-) &= (3.6^{+1.6}_{-1.4}) \times 10^{-10}. \end{aligned} \tag{5.1}$$

The semi-leptonic decay $B_d^0 \to K^*\mu^+\mu^-$ offers many interesting observables for the NP searches in addition to the inclusive branching ratio. LHCb analysis on the semi-leptonic decay $B_d^0 \to K^*\mu^+\mu^-$ on 2011 shows good agreement to the SM in most of the observables. But also includes an interesting deviation from the SM prediction for one of the observable called P_5' [16].

In the radiative decay $B^\pm \to K_{res}^\pm \gamma$, NP effects could significantly affect the photon polarisation that in the SM is predominantly left-handed. LHCb has performed an analysis on the 2012 data ($2fb^{-1}$ collected at $sqrts = 8TeV$) and measured a variable directly related to the photon polarization, the up-down asymmetry. The measured up-down asymmetry is significantly different from zero, demonstrating the photon is indeed polarised. The exact translation into the polarisation measurement is awaiting the theory progress in understanding the $K\pi\pi$ mass spectrum, though.

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