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Rare and very rare decays of hadrons at LHCb(*)

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Summary. — This contribution presents the most recent results related to rare and very rare decays involving hadrons at the LHCb experiment. These results encompass the decays $\Lambda_b^0 \to D_s^- p$ and $\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+$, using data obtained from proton-proton collisions at a center-of-mass energy of 13 TeV during the LHC Run 2 data-taking, corresponding to a total integrated luminosity of ~ 6 fb^{-1}. Additionally, this contribution includes the differential branching fraction measurement of the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ decay and updates on the searches for the $D^0 \to \mu^+\mu^-$ and $K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$ decays.

1. – Introduction

Despite its remarkable accomplishments, the Standard Model (SM) continues to be an incomplete framework, leaving various unanswered questions in its wake. Many of its problems can be studied by exploring the flavour sector, delving into the properties and interactions of different particle flavours and the mixing between them. The Large Hadron Collider beauty (LHCb) experiment at CERN has proven itself to be an ideal setting for investigating flavour physics.

The LHCb detector [1] [2] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. Within LHCb, the rare decays search program continues to push the boundaries of particle physics by shedding light on the most elusive and intriguing processes involving hadrons.

In the next sections, recent LHCb results on the $\Lambda_b^0 \to D_s^- p$ and $\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+$ decays are presented, following the differential branching fraction measurement of the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ decay and updates on the searches for the $D^0 \to \mu^+\mu^-$ and $K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$ decays. It is worth noting that the $\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+$ decay is CKM-favoured and does not belong to the category of rare decays. However, it is presented as an important recent result of the LHCb experiment.

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2. – First observation and branching fraction measurement of the $\Lambda_b^0 \to D_s^- p$ decay

The first observation and branching fraction measurement of the $\Lambda_b^0 \to D_s^- p$ decay is reported by the LHCb experiment [3]. The following results are obtained using proton-proton (pp) collision data collected at centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 6 fb^{-1}, during the Run 2 of the Large Hadron Collider (LHC) between 2015 and 2018. The $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ decay is chosen as normalisation channel, due to its topological similarity to the signal decay and relatively high branching fraction. Candidates for both signal and normalisation channels are reconstructed through the decays $D_s^- \to K^- K^+ \pi^-$ and $\Lambda_c^+ \to p K^- \pi^+$, respectively. The branching fraction of the $\Lambda_b^0 \to D_s^- p$ decay is evaluated as

$$(1) \qquad \mathcal{B}(\Lambda_b^0 \to D_s^- p) = \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-) \frac{N_{\Lambda_b^0 \to D_s^- p}}{N_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}} \frac{\epsilon_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}}{\epsilon_{\Lambda_b^0 \to D_s^- p}} \frac{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}{\mathcal{B}(D_s^- \to K^- K^+ \pi^-)}.$$

While efficiencies ϵ_X are evaluated using simulated candidates and calibration data samples, yields N_X are determined using unbinned maximum-likelihood fits to the $D_s^- p$ and $\Lambda_c^+ \pi^-$ invariant-mass distributions. The fit to the invariant-mass distribution of $\Lambda_b^0 \to D_s^- p$ candidates is shown in fig. 1.

The measured $\Lambda_b^0 \to D_s^- p$ branching fraction is found to be

$$(2) \qquad \mathcal{B}(\Lambda_b^0 \to D_s^- p) = (12.6 \pm 0.5 \pm 0.3 \pm 1.2) \times 10^{-6},$$

where the first uncertainty is statistical, the second systematic and the third due to the uncertainty of the $\Lambda_b^0 \to \Lambda_c^+ \pi^-$, $D_s^- \to K^- K^+ \pi^-$ and $\Lambda_c^+ \to p K^- \pi^+$ branching fractions. This measurement will serve as input for future studies of factorisation in hadronic Λ_b^0 decays.

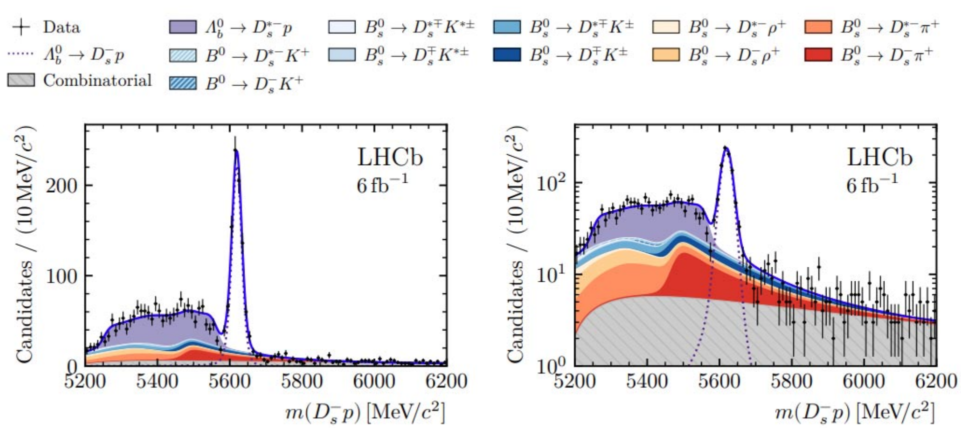

Fig. 1. – Invariant-mass distribution of $\Lambda_b^0 \to D_s^- p$ candidates, in (left) linear and (right) logarithmic scale, where the fit projections of the signal and background contributions are overlaid. The individual components in the fit are illustrated in the legend. Figures taken from ref. [3].

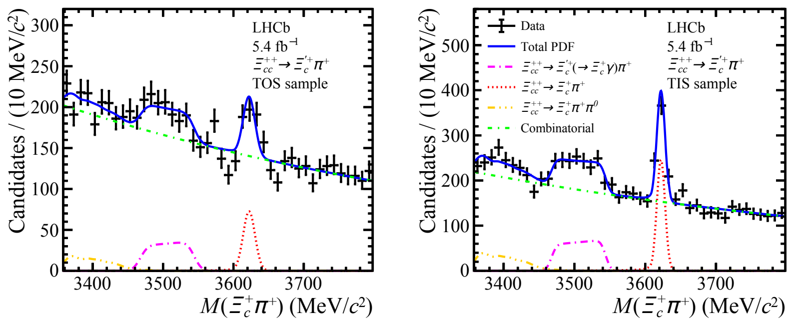

Fig. 2. – Reconstructed invariant-mass distribution of the Ξ_{cc}^{++} candidates from the (left) TOS and (right) TIS samples, with the results of the fit overlaid. The $\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$ component is shown as a purple dashed line, the $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$ component as a red dotted line, the $\Xi_{cc}^{++} \to \Xi_c^+\pi^+\pi^0$ component as a yellow dashed line and the combinatorial component as a green dashed line. Figures taken from ref. [4].

3. – Observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$

The decay $\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$ has been observed and its branching fraction relative to that of the normalisation channel $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$ has been measured by the LHCb experiment [4] using pp collisions collected at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.4 fb^{-1}.

The $\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$ is partially reconstructed, with the photon from the $\Xi_c^{\prime +} \to \Xi_c^+\gamma$ decay not reconstructed, while the Ξ_c^+ is reconstructed from the $\Xi_c^+ \to pK^-\pi^+$ final state for both signal and normalisation modes.

The branching fraction of the signal decay relative to that of the normalisation channel is defined as

$$\frac{\mathcal{B}\left(\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+\right)}{\mathcal{B}\left(\Xi_{cc}^{++} \to \Xi_c^+\pi^+\right)} = \frac{N_{\Xi_c^{\prime +}}}{N_{\Xi_c^+}} \times \frac{\epsilon_{\Xi_c^+}}{\epsilon_{\Xi_c^{\prime +}}}, \tag{3}$$

The signal yield N_X is determined by performing an unbinned maximum-likelihood fit to the $\Xi_c^+\pi^+$ invariant mass distribution in data while the efficiency ϵ_X is evaluated from simulated samples. The $\Xi_c^+\pi^+$ distribution is divided into Trigger On Signal (TOS) and Trigger Independent from Signal (TIS) samples, as defined in ref. [5]. The fitted TOS and TIS invariant-mass distributions for the Ξ_{cc}^{++} reconstructed and selected candidates are shown in fig. 2.

The combination of the measured relative branching fraction in the TOS and TIS samples leads to

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\pi^+)} = 1.41 \pm 0.17 \pm 0.10. \tag{4}$$

where the first uncertainty is statistical and the second systematic.

The result is not consistent with present theoretical predictions [6] and will provide inputs for future calculations.

4. – Measurement of the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ differential branching fraction

The first measurement of the differential branching fraction for the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ decay, using pp collisions data corresponding to an integrated luminosity of 9 fb^{-1} recorded at center-of-mass energies of 7, 8 and 13 TeV during both Run 1 and Run 2, is presented by the LHCb experiment [7].

The $\Lambda_b^0 \to \Lambda(1520)(\to pK^-)\mu^+\mu^-$ differential branching fraction is evaluated in intervals of the squared dimuon mass q^2, relative to the normalization channel $\Lambda_b^0 \to pK^-J/\psi$, according to the formula

$$\left\{\frac{d\mathcal{B}\left[\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-\right]}{dq^2}\right\}_{q^2_{\rm min}}^{q^2_{\rm max}} = \frac{1}{(q^2_{\rm max}-q^2_{\rm min})}\frac{\mathcal{B}\left(\Lambda_b^0 \to pK^-J/\psi\right)\mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)}{\mathcal{B}\left[\Lambda(1520) \to pK^-\right]} \times \frac{N_{\Lambda(1520)\mu^+\mu^-}}{N_{pK^-J/\psi}}\frac{\varepsilon_{pK^-J/\psi}}{\varepsilon_{\Lambda(1520)\mu^+\mu^-}}. \tag{5}$$

While the efficiencies ϵ_X are evaluated from simulated samples, the yields for both signal and normalisation modes are estimated by fitting to the corresponding invariant mass distributions in data. The differential branching fraction of the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ decay in intervals of q^2 is shown in fig. 3.

The substantial differences among the various theoretical predictions prevent making a firm statement regarding the level of agreement between the experimental measurement and the theoretical predictions.

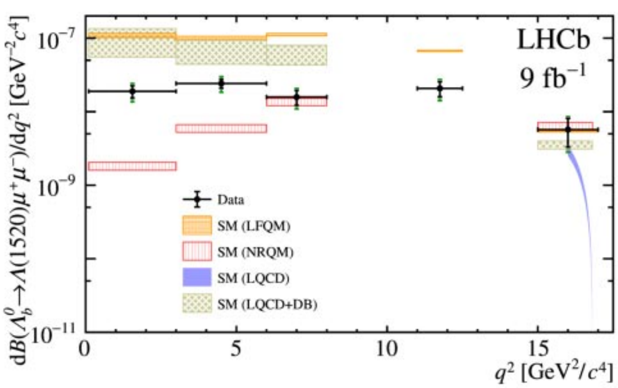

Fig. 3. – Differential branching fraction of the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ decay in intervals of q^2. The error bars in black, gray and green represent the measured results with statistical, systematic and $\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi)$ uncertainties taken into account. Also shown are the SM predictions using the form factors calculated with the nonrelativistic quark model (NRQM) [8], light-front quark model (LFQM) [9], joint lattice QCD and dispersive bound (LQCD+DB) [10] and lattice QCD (LQCD) [11]. Note that the LQCD prediction is only available for q^2 above 16 GeV$^2/c^4$, and the trend instead of the bin average is shown. This motivates further refinement of theoretical calculations. Figure taken from ref. [7].

5. – Search for rare decays of D^0 mesons into two muons

A search for the $D^0 \to \mu^+\mu^-$ decay is reported by the LHCb experiment [12], based on data collected in pp collisions corresponding to 9 fb^{-1} of integrated luminosity, recorded between Run 1 and Run 2 at center-of-mass energies of 7, 8 and 13 TeV.

For this analysis, the $D^{*+} \to D^0\pi^+$ decay is exploited to improve the background rejection. This decay also allows the $D^0 \to \mu^+\mu^-$ yield to be obtained from a two-dimensional fit to the dimuon invariant mass and to the difference between the D^{*+} and D^0 candidate masses. The yield is then converted to the decay branching fraction by normalising to the $D^0 \to K^-\pi^+$ and $D^0 \to \pi^+\pi^-$ decays, selected concurrently to the signal. No excess with respect to the background expectation has been found and an upper limit has been set at 90% C.L,

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1 \times 10^{-9}. \tag{6}$$

This measurement establishes the most stringent limit on the relevant Flavor-Changing Neutral Current (FCNC) couplings within the charm sector. It also allows to set additional constraints on physics models beyond the SM which predict the branching fractions of the $D^0 \to \mu^+\mu^-$ decay and to describe results from B physics measurements.

6. – Search for $K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$ decays at LHCb

Searches for the $K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$ decays are presented by the LHCb experiment [13]. In this analysis, pp collision data collected between 2016 and 2018 at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.1 fb^{-1}, are exploited.

The $K^0_S \to \mu^+\mu^-\mu^+\mu^-$ decays are reconstructed from two pairs of muons with opposite charges, with a four-muon mass resolution approximately equal to 4 MeV/c^2, forming a sufficiently detached secondary vertex with an invariant mass lower than 600 MeV/c^2. Due to the difficulty at LHCb to differentiate the K^0_L and K^0_S decays, the $K^0_L \to \mu^+\mu^-\mu^+\mu^-$ decays are neglected when setting an upper limit on $\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-)$, and vice versa.

The measured upper limits at 90% C.L. are the first reported for the $K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$ decay modes and are found to be

$$\begin{aligned} &\mathcal{B}\left(K^0_{\mathrm{S}} \to \mu^+\mu^-\mu^+\mu^-\right) < 5.1 \times 10^{-12}, \\ &\mathcal{B}\left(K^0_{\mathrm{L}} \to \mu^+\mu^-\mu^+\mu^-\right) < 2.3 \times 10^{-9}. \end{aligned} \tag{7}$$

The obtained upper limits are the first reported for the $K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$ decay modes. The values indicate very good prospects for the LHCb upgrade [14], which could achieve sensitivities comparable to the SM prediction for $\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-)$, which is $\sim (1-4) \times 10^{-14}$, with an integrated luminosity of 300 fb^{-1}.

7. – Conclusions

In summary, recent results on rare decays involving hadrons at LHCb are reported. The first observation and branching fraction measurement of the $\Lambda^0_b \to D^-_s p$ decay and the observation of the $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$ decay are illustrated. Additionally, the measurement of the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ differential branching fraction and upper limits for the $D^0 \to \mu^+\mu^-$ and $K_{S(L)}^0 \to \mu^+\mu^-\mu^+\mu^-$ decays are presented.

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