PROCEEDINGS OF SCIENCE

Rare decays of Λ_b^0, B_c^+ and other b-hadrons at LHCb

Anna Lupato[a,*]

On behalf of LHCb Collaboration

[a] *The University of Manchester, Manchester, UK*

E-mail: anna.lupato@cern.ch

Rare b-hadron decays are sensitive probes of New Physics through the study of branching fractions, angular observables and CP asymmetries among others. Moreover, the LHCb experiment has the opportunity to study rare decays of heavy b-quark hadrons such as Λ_b baryons, which cannot be explored at the B factories. Recent results from the LHCb experiment are presented and their interpretation is discussed.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

*Speaker

PoS(ICHEP2020)394

1. Introduction

The transitions mediated by flavour-changing neutral currents (FCNC) are forbidden at tree level in the Standard Model (SM) and can only proceed through amplitudes involving electroweak loop (penguin and box) Feynman diagrams. Therefore, they are rare in the SM, are sensitive to new particles entering the loop-level transition, which can modify decay properties, and are an ideal place to search for effects beyond the SM. The potential contributions of new particles to these processes can be manifested as modifications in the rate of particular decay modes or in changes in the angular distribution of the final-state particles. Several deviations have already been seen in the mesonic $b \to s l^+ l^-$ differential branching ratios, in the angular observables [1] [2] [3] [4] and in the CP observables [5]. Moreover, clean tests provided by lepton flavour universality measurements show a discrepancy of 2.5σ with respect the SM [10] [11]. These results are all dominated by statistical uncertainties and it will be fundamental to perform the measurements with larger dataset in Run 3 of LHC. Furthermore, the baryonic decays provide complementary observables since they are sensitive to different spin-structure beyond SM effects and are produced abundantly at the LHC. Further tests are therefore critical to improve the statistical significance of the measurements and to understand the origin of any discrepancies.
This paper presents the last baryonic results from the LHCb Collaboration: the test of Lepton Universality with $\Lambda_b^0 \to pKl^+l^-$ decays [6], the first observation of the radiative decay $\Lambda_b^0 \to \Lambda\gamma$ [7] and the measurement of angular moments of the decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ at low hadronic recoil [8].

2. Test of Lepton Universality with $\Lambda_b^0 \to pKl^+l^-$ decays

In the SM, the electroweak couplings of the charged leptons are independent of their flavour (Lepton Flavour Universality (LFU)) and then the properties of decays to leptons of different flavours are expected to be the same up to corrections related to the lepton mass. This property has been already tested in B-meson decays at LHCb, by measuring the ratio of the branching fractions for $B \to H\mu^+\mu^-$ and $B \to He^+e^-$ (where H represents K or K^* meson), integrated over a range of the squared dilepton invariant mass, q^2 [10] [11]. All these measurements resulted to be around 2.5 standard deviations below the SM expectation. The first measurement in the baryonic sector has been performed at LHCb on the $\Lambda_b^0 \to pKl^+l^-$ decays. It is performed as a double ratio of:

$$R_{pK} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^-\mu^-\mu^+)}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to \mu^-\mu^+))} \Big/ \frac{\mathcal{B}(\Lambda_b^0 \to pK^-e^-e^+)}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to e^-e^+))}$$

The candidates for the normalization channel $\Lambda_b^0 \to pK^-J/\psi(\to l^-l^+)$ are selected using similar criteria to that of the non-resonant counterpart.
These ratios allow for very precise tests of LFU, as hadronic uncertainties cancel in their theoretical predictions. In the SM, they are expected to be close to unity with O(1%) precision [9] [11]. The measurement has been performed using proton-proton collision data corresponding to an integrated luminosity of 4.7 fb^{-1} recorded with the LHCb experiment

at center-of-mass energies of 7, 8 and 13 TeV. It has been done in a wide q^2 region between 0.1 GeV^2/c^4 and 6.0 GeV^2/c^4 . The lower boundary is chosen to be far enough from the dimuon kinematic threshold so that the effect of radiative corrections is negligible on the R_{pK} ratio.The upper boundary is set to reduce contamination from the radiative tail of the J/ψ resonance. The first challenge of this measurement derives from the different way muons and electrons interact with the detector. In particular, the former are characterized by a high reconstruction efficiency and clear experimental signature, while the latter emit a large amount of bremsstrahlung that results in a degraded B momentum and mass resolution. Therefore, a bremsstrahlung recovery algorithm is used to improve the electron momentum reconstruction: clusters not associated with charged tracks are searched for electromagnetic calorimeter in a region defined by the extrapolation of the electron track upstream of the magnet and added to the measured electron momentum. This procedure is limited due to the energy threshold on the bremsstrahlung reconstructed photon, the acceptance of the calorimeters and the presence of energy deposits wrongly identified as the bremsstrahlung clusters. Moreover, due to the higher occupancy of the electromagnetic calorimeter compared to that of the muon stations, the constraint on the trigger bandwidth requires to impose higher thresholds on the transverse energy of electrons than those on the transverse momentum of muons, causing a partial loss of electron samples. To partially mitigate this effect, decays to final states with electrons have been selected through the electron hardware trigger, using clusters associated to the hadrons in the final state and selecting events that are not associated with the signal Λ_b^0 decay products. The main sources of background arises from the misidentification of one of the final-state hadrons ($B_S^0 \to KKl^-l^+$, $\bar{B}^0 \to \bar{K}^* J/\psi$), from the contribution of partially reconstructed background and due to the random combinations of tracks, which remains after the selection. A maximum-likelihood fit to the invariant-masses of $\Lambda_b^0 \to pK^-\mu^-\mu^+$ and $\Lambda_b^0 \to pK^-e^-e^+$ has been performed to resonant and non-resonant channels separately, across various data-taking periods for both trigger categories. The main systematical uncertainties are due to partially reconstructed background shapes in the electron channel. The ratio R_{pK} has been obtained directly from the fit to data candidates and results:

$$R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

compatible with unity within one standard deviation and in agreement with the deviations observed in lepton-universality tests with B mesons.

3. First observation of the radiative decay $\Lambda_b^0 \to \Lambda\gamma$

The decay $\Lambda_b^0 \to \Lambda\gamma$ proceeds via the $b \to s\gamma$ flavour-changing neutral-current transition. This process is forbidden at tree level in the SM and is therefore sensitive to new particles entering the loop-level transition. Radiative b-baryon decays have never been observed and offer a unique benchmark to measure the photon polarization due to the non-zero spin of the initial and final-state particles [12]. In particular, the $\Lambda_b^0 \to \Lambda\gamma$ decay has been proposed as a suitable mode for the study of the photon polarization, since the helicity of the Λ hyperon can be measured, giving access to the helicity structure of the $\Lambda_b^0 \to \Lambda\gamma$

transition [13] [14]. The $\Lambda_b^0 \to \Lambda\gamma$ decay is experimentally challenging to reconstruct. At high-energy hadron colliders the Λ_b^{00} decay vertex cannot be determined directly due to the long lifetime of the weakly decaying Λ baryon and the unknown photon direction, when reconstructed as a cluster in the electromagnetic calorimeter. Therefore, it is not possible to use the displacement with respect to the primary vertex to separate background coming directly from the pp collisions. Using a data sample of pp collisions corresponding to an integrated luminosity of 1.7 fb^{-1} collected by the LHCb experiment at a center-of-mass energy of 13 TeV, the radiative decay $\Lambda_b^0 \to \Lambda\gamma$ is observed for the first time. The decay $B^0 \to K^{*0}\gamma$ has been used as the normalization channel. Potential contamination from neutral pions reconstructed as a single cluster in the calorimeter is suppressed by exploiting neutral particle identification tools. The dominant background is formed by real baryons and random photon and another important background is $\Lambda_b^0 \to \Lambda\eta$. The invariant-mass distribution of the selected candidates is used to disentangle signal from background through a maximum likelihood fit. The yield of signal and normalization events is obtained from a simultaneous extended unbinned maximum likelihood fit to data. The ratio is given by:

$$\frac{N(\Lambda_b^0 \to \Lambda\gamma)}{N(B^0 \to K^{*0}\gamma)} = \frac{f_{\Lambda_b^0}}{f_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} \times \frac{\mathcal{B}(\Lambda_b^0 \to p\pi^-)}{\mathcal{B}(B^0 \to K^+\pi^-)} \times \frac{\epsilon(\Lambda_b^0 \to \Lambda\gamma)}{\epsilon(B^0 \to K^{*0}\gamma)}$$

where $\frac{f_{\Lambda_b^0}}{f_{B^0}}$ is the ratio of hadronization fractions measured at LHCb [15] , $\mathcal{B}$ are the branching fractions and ϵ is the combined reconstruction and selection efficiency for the given decay obtained from simulation and calibration samples. A simultaneous extended maximum likelihood fit to data candidates has been performed and the signal branching fraction is measured to be

$$\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^6$$

where the quoted uncertainties are statistical, systematic and systematic from external inputs, respectively [7] .

4. Angular moments of the decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ at low hadronic recoil

In extensions of the SM the angular distribution of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ decay can be modified significantly providing a large number of particularly sensitive observables [16]. The decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ has several important phenomenological differences to the B-meson decays: the Λ_b^0 baryon is a spin-half particle and could be produced polarised; the transition involves a diquark system as a spectator, rather than a single quark; and the Λ baryon decays weakly resulting in observables related to the hadronic part of the decay that are not present in the meson decays. The decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ therefore provides an important additional test of the SM predictions, which can be used to improve our understanding of the nature of the anomalies seen in the B-meson decays. The LHCb collaboration firstly studied the rate of the decay as a function of the dimuon invariant mass squared, q^2 [1] and after presented the first measurement of the full basis of angular observables for the decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ in the range $15 < q^2 < 20$ GeV $^2/c^4$ [8], where an evidence for a signal was found. The measurement uses pp collision data, corresponding to an integrated luminosity of approximately 5 fb^{-1} , collected by LHCb detector between 2011 and 2016 at centre-of-mass energies of 7, 8 and 13 TeV. The angular distribution of the decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ can be described using a normal unit-vector, $\vec{n}$, defined by the vector product of the beam direction and the Λ_b^0 momentum vector and five angles: the angle, θ, between $\vec{n}$ and the Λ baryon direction in the rest frame of the Λ_b^0 baryon; polar and azimuthal angles θ_l and ϕ_l describing the decay of the dimuon system; and polar and azimuthal angles θ_b and ϕ_b describing the decay of the Λ baryon. The full angular distributions can be described as a sum of 34 terms:

$$\frac{d^5\Gamma}{\vec{\Omega}} = \frac{3}{32\pi^2}\sum_i^{34} K_i f_i(vec\Omega)$$

where $\vec{\Omega} = (cos\theta,\ \cos\theta_l,\ \phi_l,\ \cos\theta_b,\ \phi_b)$, f_i are the angular functions and K_i are coefficients which depend on the underlying short-distance physics and on the form factors. The K_i parameters are determined using the method of moments. The background is subtracted using weights obtained by fitting the $p\pi\mu^+\mu^-$ invariant mass distributions. The trigger, reconstruction and selection distort the measured angular distributions and therefore a correction to the angular efficiency has been applied using simulated events. The model has been cross-checked by using $B \to J/\psi K_s$ and $\Lambda_b^0 \to \Lambda J/\psi$ decays in data. All parameters resulted compatible with the SM predictions: K_{11-34} resulted compatible with no initial Λ_b^{00} polarization and the largest discrepancy has been seen in K_6 which resulted to be 2.6σ from SM predictions. The K_i observables have been combined to determine the following angular asymmetries:

$$A_{FB}^l = \frac{3}{2}K_3 = -0.39 \pm 0.04 \pm 0.01$$

$$A_{FB}^h = K_4 + \frac{1}{2}K_5 = -0.30 \pm 0.05 \pm 0.02$$

$$A_{FB}^{lh} = \frac{3}{4}K_6 = +0.25 \pm 0.04 \pm 0.01$$

where the first uncertainties are statistical and the second are the systematic uncertainties. The forward-backward asymmetries A_{FB}^l (leptonic) and A_{FB}^h (hadronic) are in good agreement with the SM predictions. The asymmetry A_{FB}^{lh} , which is proportional to K_6 is 2.6 standard deviations from its SM prediction.

5. Conclusion

The Rare decays are useful tools to search for New Physics beyond the SM. Hints of tension with the SM predictions are observed in $b \to sl^+l^-$ meson transitions in differential branching ratios, angular observables and in the tests of lepton flavour universality. The rare baryonic decays are sensitive to different spin-structure Beyond Standard Model effects with respect to the mesonic decays. All LHCb measurements peformed with baryonic decays at LHCb are in agreement with SM prediction. Several measurements are dominated by the statistical uncertainty and therefore more data is needed to confirm or exclude the presence of New Physics contributions in these decays.

References

[1] R. Aaij *et al.* [LHCb], JHEP **06** (2015), 115 [erratum: JHEP **09** (2018), 145] doi:10.1007/JHEP06(2015)115 [arXiv:1503.07138 [hep-ex]].

[2] R. Aaij *et al.* [LHCb], JHEP **09** (2015), 179 doi:10.1007/JHEP09(2015)179 [arXiv:1506.08777 [hep-ex]].

[3] R. Aaij *et al.* [LHCb], JHEP **06** (2014), 133 doi:10.1007/JHEP06(2014)133 [arXiv:1403.8044 [hep-ex]].

[4] R. Aaij *et al.* [LHCb], JHEP **02** (2016), 104 doi:10.1007/JHEP02(2016)104 [arXiv:1512.04442 [hep-ex]].

[5] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **125** (2020) no.1, 011802 doi:10.1103/PhysRevLett.125.011802 [arXiv:2003.04831 [hep-ex]].

[6] R. Aaij *et al.* [LHCb], JHEP **05** (2020), 040 doi:10.1007/JHEP05(2020)040 [arXiv:1912.08139 [hep-ex]].

[7] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **123** (2019) no.3, 031801 doi:10.1103/PhysRevLett.123.031801 [arXiv:1904.06697 [hep-ex]].

[8] R. Aaij *et al.* [LHCb], JHEP **09** (2018), 146 doi:10.1007/JHEP09(2018)146 [arXiv:1808.00264 [hep-ex]].

[9] J. Fuentes-Martín, G. Isidori, J. Pagès and K. Yamamoto, Phys. Lett. B **800** (2020), 135080 doi:10.1016/j.physletb.2019.135080 [arXiv:1909.02519 [hep-ph]].

[10] R. Aaij *et al.* [LHCb], Phys. Rev. Lett. **122** (2019) no.19, 191801 doi:10.1103/PhysRevLett.122.191801 [arXiv:1903.09252 [hep-ex]].

[11] R. Aaij *et al.* [LHCb], JHEP **08** (2017), 055 doi:10.1007/JHEP08(2017)055 [arXiv:1705.05802 [hep-ex]].

[12] M. Gremm, F. Kruger and L. M. Sehgal, Phys. Lett. B **355** (1995), 579-583 doi:10.1016/0370-2693(95)00722-W [arXiv:hep-ph/9505354 [hep-ph]].

[13] T. Mannel and S. Recksiegel, J. Phys. G **24** (1998), 979-990 doi:10.1088/0954-3899/24/5/006 [arXiv:hep-ph/9701399 [hep-ph]].

[14] G. Hiller and A. Kagan, Phys. Rev. D **65** (2002), 074038 doi:10.1103/PhysRevD.65.074038 [arXiv:hep-ph/0108074 [hep-ph]].

[15] R. Aaij *et al.* [LHCb], Phys. Rev. D **100** (2019) no.3, 031102 doi:10.1103/PhysRevD.100.031102 [arXiv:1902.06794 [hep-ex]].

[16] W. Detmold and S. Meinel, Phys. Rev. D **93** (2016) no.7, 074501 doi:10.1103/PhysRevD.93.074501 [arXiv:1602.01399 [hep-lat]].