PROCEEDINGS OF SCIENCE

Radiative b-hadron decays at LHCb

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Radiative b-hadron decays are an instance of rare decays that occur through flavor changing neutral currents (FCNC). They are suppressed in the standard model (SM) of particle physics. However, they are sensitive to new contributions from physics beyond the Standard Model (BSM) that can affect the observables that can be measured at LHCb. The following proceedings cover the three latest results by LHCb in this field, namely the search for $B_s^0 \to \mu^+\mu^-\gamma$, and two amplitude analysis: $B_s^0 \to K^+K^-\gamma$ and $\Lambda_b^0 \to pK^-\gamma$.

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1. Introduction

Radiative b-hadron decays cannot occur at tree level in the Standard Model (SM). Instead they take place predominantly via loop interactions. As a consequence, these type of decays are considered Rare decays. Rare decays are both challenging and interesting: on one hand they are difficult to observe due to limited statistics but on the other hand they are powerful probes for physics beyond the Standard Model (BSM) since different models can have sizeable effects on different observables. Radiative decays have historically attracted the attention of several physics experiments. This effort is currently led by B factories and by the LHCb experiment at CERN, providing either complementary or competitive results. Remarkably, LHCb has opened the window to the observation of radiative decays of b-baryons thanks to the unprecedented high energy of colliding proton bunches that LHC provides. A relevant downside of this approach in comparison to experiments at electron-positron B factories is the presence of a large background of particles coming from the underlying event.

In this talk three new results by LHCb in the radiative decays field are presented: Search for $B_s^0 \to \mu^+\mu^-\gamma$ [1], amplitude analysis of $B_s^0 \to K^+K^-\gamma$ [2] , amplitude analysis of $\Lambda_b^0 \to pK^-\gamma$ [3]

1.1 Search for $B_s^0 \to \mu^+\mu^-\gamma$

A search for the decay $B_s^0 \to \mu^+\mu^-\gamma$ using LHCb 2016-2018 dataset corresponding to 5.4 fb^{-1} is presented in reference [1]. Such decays have a branching fraction prediction based on the SM as low as $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{high\ q^2} = (8.9\pm1.0)\times10^{-10}$ [4], where q^2 is the squared mass of the dimuon system. Statistics are therefore the main challenge to observe it, unless BSM models enhance this process. Compared to $B_s^0 \to \mu^+\mu^-$, the helicity suppression is lifted, partially compensating for the difficulty of reconstructing the photon in the final state. LHCb has already looked for $B_s^0 \to \mu^+\mu^-\gamma$ decays as a partially reconstructed background contribution to $B_s^0 \to \mu^+\mu^-$ [5]. The main advantage of fully reconstructing the final state is gaining access to the full dimuon system squared mass range. Different regions of q^2 receive contributions from different physical processes. To fully extract its physics potential, the aim of the analysis is to measure the branching fractions in three different q^2 regions as well as the combined region and a region vetoing the $\phi\gamma$ resonance.

The processing of data mainly includes a preselection based on cuts in geometrical and kinematic variables and is followed by two multilayer perceptron classifiers that further reduce backgrounds. The channel $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ is used as normalization channel to partially cancel uncertainties and the channel $B_s^0 \to \phi(\to K^+K^-)\gamma$ is used to control data-simulation discrepancies.

No statistically significant signal is found so results are given as upper limits on the branching fractions at 95% confidence level. Results are shown in Fig 1 together with the result of the previous search by LHCb and compared to theoretical predictions using different methods [4, 6–11].

1.2 $B_s^0 \to K^+K^-\gamma$ Amplitude analysis

Reference [2] presents an amplitude analysis for the dikaon structure in the $B_s^0 \to K^+K^-\gamma$ decay using the full run I and run II dataset of LHCb, corresponding to an integrated luminosity of 9 fb^{-1}. So far only the $B_s^0 \to \phi\gamma$ transition had been observed in the B_s^0 radiative decays sector, so this analysis constitutes the first observation of its radiative decay to orbitally excited K^+K^- states.

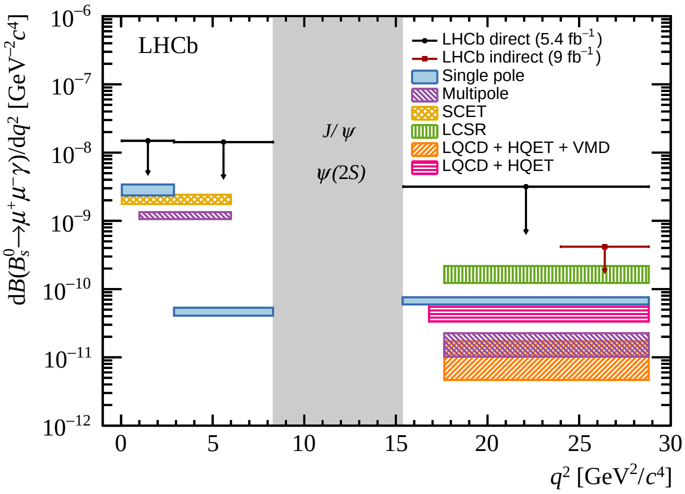

Figure 1: Differential branching fraction of the $B_s^0 \to \mu^+\mu^-\gamma$ decay in intervals of q^2. The black arrows represent the limits set in this paper at 95% CL

Some nice features that simplify the complexity of the fit particular to this mode are the absence of a S-wave component, the cancellation of the interference of odd and even spin resonance and the cancellation of detector asymmetries by folding the helicity angle observable by the operation $\cos\theta_{KK} \to |\cos\theta_{KK}|$.

To extract the combinatorial and partially reconstructed background components the sPlot technique [12] is employed. Furthermore, backgrounds in which one hadron is misidentified are accounted for using data driven techniques. Charm hadrons are largely present in the LHCb environment. To remove such a background the charm-veto cut $m_{K\gamma} < 2000$ MeV/c^2 is applied to the dataset. The nonuniform acceptance in the Dalitz plane is parameterized and accounted for. Finally, the isobar model is used to fit the amplitudes in the $(m_{KK}, |\cos\theta_{KK}|)$ plane. The isobar model for the signal amplitude is built by selecting the possible contributions among the well-established unflavored isoscalar mesons that have been observed in the dikaon final state and accepting only those that favor the negative log-likelihood of the fit.

The results of the fit in terms of fit fractions and phases are reported in Table 1. The overall tensor contribution to the amplitude is measured as

$$\mathcal{F}_{\{f_2\}} = 16.8 \pm 0.5\,(\text{stat}) \pm 0.7\,(\text{syst})\%,$$

Using the world average measurements for the branching fraction of $\phi(1020)$ and $f_2(1270)$, $f_2'(1525)$ into K^+K^-, the following ratios are extracted:

$$\frac{\mathcal{B}(B_s^0 \to f_2'(1525)\gamma)}{\mathcal{B}(B_s^0 \to \phi(1020)\gamma)} = 0.194^{+0.009}_{-0.008}\ (\text{stat.})^{+0.014}_{-0.005}\ (\text{syst.}) \pm 0.005\ (\mathcal{B})$$

$$\frac{\mathcal{B}(B_s^0 \to f_2(1270)\gamma)}{\mathcal{B}(B_s^0 \to \phi(1020)\gamma)} = 0.25^{+0.09}_{-0.07}\ (\text{stat.})^{+0.06}_{-0.10}\ (\text{syst.}) \pm 0.03\ (\mathcal{B}),$$

$$\frac{\mathcal{B}(B_s^0 \to \phi(1680)\gamma)}{\mathcal{B}(B_s^0 \to \phi(1020)\gamma)} \times \mathcal{B}(\phi(1680) \to K^+K^-) = 0.026^{+0.004}_{-0.003}\ (\text{stat.}) \pm 0.005\ (\text{syst.}).$$

Table 1: Absolute and relative fit fractions and the associated isobar phase for the best-fit solution. The first quoted uncertainties are statistical and correspond to the 68.3% intervals derived from pseudoexperiments, while the second are systematic.

State	Fit fraction [%]	Relative fit fraction [%]	Phase [deg.]
$\phi(1020)$	$70.3^{+0.9}_{-1.0}{}^{+1.0}_{-1.2}$	100	0 (fixed)
$f_2(1270)$	$0.8{\pm}0.3^{+0.2}_{-0.3}$	$1.2^{+0.4}_{-0.3}{}^{+0.3}_{-0.5}$	$-55^{+13}_{-17}{}^{+25}_{-17}$
$f_2'(1525)$	$12.1^{+0.6}_{-0.5}{}^{+0.9}_{-0.4}$	$17.3^{+0.8}_{-0.7}{}^{+1.3}_{-0.5}$	0 (fixed)
$\phi(1680)$	$3.8^{+0.6}_{-0.5}{\pm}0.7$	$5.4^{+0.9}_{-0.6}{}^{+1.0}_{-1.1}$	$137^{+5}_{-6}{\pm}8$
$\phi_3(1850)$	$0.3^{+0.2}_{-0.1}{}^{+0.2}_{-0.1}$	$0.4^{+0.3}_{-0.2}{}^{+0.3}_{-0.2}$	$-61^{+16}_{-13}{}^{+13}_{-12}$
$f_2(2010)$	$0.4{\pm}0.2^{+0.2}_{-0.1}$	$0.6^{+0.3}_{-0.2}{}^{+0.3}_{-0.2}$	$43^{+30}_{-24}{}^{+52}_{-59}$
$(KK)_{NR}$	$0.5^{+0.4}_{-0.2}{}^{+0.3}_{-0.2}$	$0.6^{+0.5}_{-0.3}{}^{+0.5}_{-0.3}$	$165^{+6}_{-16}{\pm}9$

1.3 $\Lambda_b^0 \to pK^-\gamma$ Amplitude analysis

LHCb has performed various analysis involving rare decays of b-baryons, such as lepton universality tests for $\Lambda_b^0 \to pK^-\ell^+\ell^-$ [13] decays, a search for *CP* violation in $\Lambda_b^0 \to pK^-\mu^+\mu^-$ decays [14] and a measurement of the branching fraction of the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ decay [15]. Direct interpretations of these results regarding models for physics beyond the Standard Model are difficult given the lack of detailed knowledge of the resonant structure of the pK^- spectrum in different regions of the dilepton invariant-mass spectrum. In reference [3] the amplitude analysis of the hadronic structure at the photon pole of the recoiling system $\Lambda_b^0 \to pK^-\gamma$ is presented. This constitutes the first observation of this decay. Furthermore, such results provide important feedback for low energy QCD theoretical description and open the door to measurements of photon polarization in this decay in case a source of polarized Λ_b^0 particles is available in the future.

Similarly to the analysis reported in section 1.2, combinatorial and partially reconstructed background contributions are statistically subtracted. The Dalitz plane is also defined by two components, m_{pK} and the helicity angle θ_p, and the nonuniform acceptance of signal candidates across the plane is modeled and accounted for. The fit model for this analysis uses the helicity formalism, more complex compared to section 1.2 given the different spin couplings that the Λ_b^0 particle can have with the final state. The helicity formalism is explained in detail in reference [16]. In addition to summing over the possible intermediate states one now has to sum over all the allowed initial, final state and intermediate particle helicities, and to sum over the possible spin couplings. The correspondent Clebsch-Gordan factors have to be added. Finally, the fit components are the couplings and the results are expressed in terms of the fit fractions.

Figure 2 summarizes the results of the analysis. The largest resonant contributions to the $\Lambda_b^0 \to pK^-\gamma$ decay are found to arise from the $\Lambda(1800)$, $\Lambda(1600)$, $\Lambda(1890)$ and $\Lambda(1520)$ states, in decreasing order. The largest interference term involves the $\Lambda(1405)$ and $\Lambda(1800)$ baryons. Compared to the spectrum in the $\Lambda_b^0 \to J/\psi pK^-$ analysis [17], heavier resonances are more dominant. Resonances $\Lambda(1810)$ and $\Lambda(1820)$ feature potential ambiguity. Lastly, sub-threshold resonance $\Lambda(1405)$ is much smaller in the radiative mode. Uncertainties are dominated by external

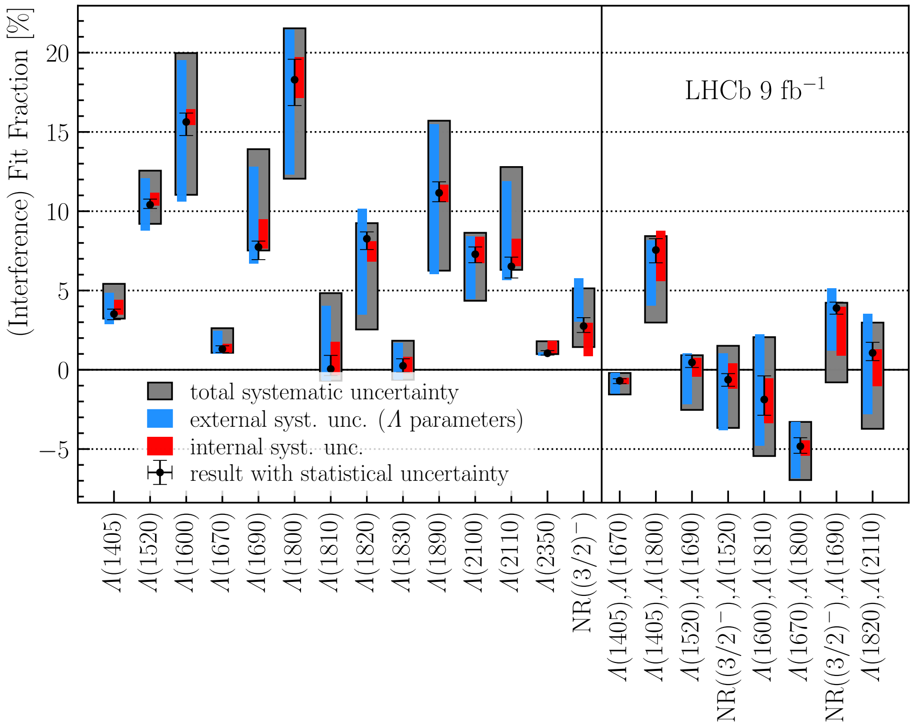

Figure 2: Final results for the fit fractions and interference fit fractions. The vertical line separates the fit from the interference fit fractions. The error bars represent the different sources of uncertainty.

inputs, namely the masses and lineshapes of the Λ resonances, so the accuracy of the analysis could benefit from more precise knowledge in that area.

2. Outline and conclusions

In conclusion, the three newest contributions from LHCb in the radiative b-hadron decays have been presented. This is the search for $B_s^0 \to \mu^+\mu^-\gamma$, and two amplitude analysis, one for $B_s^0 \to K^+K^-\gamma$ and one for $\Lambda_b^0 \to pK^-\gamma$. In the case of the search, larger sample sizes would be needed in order to reach an observation and help to clear the picture of the theoretical predictions. Nevertheless, setting up upper limits already helps in constraining various possible new physics scenarios. The run 3 of LHCb with increased instantaneous luminosity and a more flexible trigger system is expected to provide a nice enhancement on the statistical coverage on it's measurements. The results from both $B_s^0 \to K^+K^-\gamma$ and $\Lambda_b^0 \to pK^-\gamma$ amplitude analysis constitute first observations of the corresponding decays to various resonances, and provide powerful inputs to the interpretation of related measurements.

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