PROCEEDINGS OF SCIENCE

Amplitude analyses and results on three-body charmless hadronic *B* decays from LHCb

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Charmless b-hadron decays in the Standard Model are characterised by tree amplitudes that are in general comparable in size to loop amplitudes, and potentially by New Physics amplitudes. *CP*-violation measurements using Dalitz-plot analyses in multi-body decays enable the various contributions to be disentangled. We present the most recent measurements in this sector, notably results on $B_c^+ \to K^+K^-\pi^+$, $B_{d,s} \to \phi\pi^+\pi^-$, and suppressed $B^0 \to 3h$ decays, where h is a kaon or a pion.

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1. Introduction

The study of charmless b-hadron decays allows to put constraints on New Physics (NP) by studying loop-dominated or annihilation-dominated transitions. Indeed, the suppression of tree-level $b \to u$ amplitudes allows for these transitions to compete with or even dominate tree diagrams.

The study of hadronic three-body charmless transitions allows to access to a wealth of physics observables. Indeed, these decays can originate from several quasi-two-body (Q2B) decays that interfere, giving information on the relative phases between these contributions. Additionally, *CP*-violation effects can arise from the interference between different Q2B contributions. Several techniques can be used in the analysis of three-body decays, such as the Dalitz plot in the case of a fully pseudo-scalar final state, or angular analyses in other cases.

The LHCb detector ([1]) is located at the LHC accelerator at the Centre Européen pour la Recherche Nucléaire (CERN) in Geneva. It is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks.

Among other features of the LHCb detector, analyses of charmless hadronic three-body decays benefit from the excellent tracking resolution of, typically, $\delta_p/p \approx 0.5-1\%$ ([2]), and on a 95% $K^{\pm}/\pi^{\pm}$ separation over the 3–100 GeV/c kinematical range. The results presented in this document are from analyses of the full 3 fb^{-1} Run I dataset, collected at centre-of-mass energies of 7 and 8 TeV.

2. Search for $B_c^+ \to K^+K^-\pi^+$

In the Standard Model, decays of B_c^+ mesons with no b or c in the final and intermediary states can proceed only via $\overline{b}c \to W^+ \to u\overline{q}(q = d, s)$. Calculations predict branching fractions in the range $10^{-8} - 10^{-6}$ ([3, 4]). Any significant improvement could indicate the presence of $\overline{b}c$ annihilations involving particles beyond the SM, such as a mediating charged Higgs boson ([5, 6]).

Searches for B_c^+ meson decays to the $K^+K^-\pi^+$ final state have been performed in the fiducial region $p_T(B) < 20\,\mathrm{GeV}/c$ and $2.0 < y(B) < 4.5$ ([7]). Evidence for the decay $B_c^+ \to \chi_{c0}\pi^+$ is found with a significance of $4.0\,\sigma$. This result can be compared to the measurement involving another charmonium mode, $\frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathscr{B}(B_c^+ \to J/\psi\,\pi^+) = (7.0 \pm 0.3) \times 10^{-6}$ ([8, 9]). Figure 1 shows the distribution of data events on the Dalitz plot. The χ_{c0} region can be seen between the two red lines, while the annihilation region is located below the blue line.

An indication of $\overline{b}c$ weak annihilation with a significance of $2.4\,\sigma$ is reported in the region $\mathrm{m}(K^+K^-) < 1.834\,\mathrm{GeV}/c^2$. We obtain the annihilation-only branching fraction $R_{\mathrm{an},KK\pi} = \left(8.0^{+4.4}_{-3.8}(\mathrm{stat.}) \pm 0.6(\mathrm{syst.})\right) \times 10^{-8}$. Additionally, a 90%(95%) confidence level (CL) upper limit $R_{\mathrm{an},KK\pi} < 15(17) \times 10^{-8}$ is estimated by comparing profile likelihood ratios for the "signal+background" against "background-only" hypotheses.

3. Search for $B_{d,s} \to \phi\pi^+\pi^-$

The decays $B_{d,s} \to \phi\pi^+\pi^-$ have not been observed before. They are examples of Flavour Changing Neutral Current (FCNC) decays, which provide a sensitive probe for the effect of physics beyond

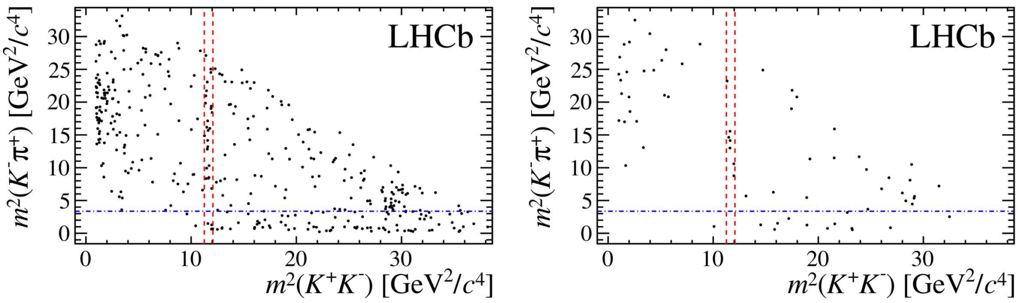

Figure 1: Distribution of events in the signal region $6.2 < \mathrm{m}(K^+K^-\pi^+) < 6.35\,\mathrm{GeV}/c^2$ on the $m^2(K^-\pi^+)$ vs. $m^2(K^+K^-)$ plane for (left) $\mathscr{O}_{\mathrm{BDT}} > 0.12$ and (right) $\mathscr{O}_{\mathrm{BDT}} > 0.18$, where $\mathscr{O}_{\mathrm{BDT}}$ is the output variable of a Boosted Decision Tree (BDT). The vertical red dashed lines represent a band of width $\pm 60\,\mathrm{MeV}/c^2$ around the χ_{c0} mass. The horizontal blue dot-dashed line indicates the upper bound of the annihilation region at $m(K^-\pi^+) = 1.834\,\mathrm{GeV}/c^2$, representing 17% of the available phase-space area.

the Standard Model because their amplitudes are described by loop (or penguin) diagrams where new particles may enter ([10]).

We report the first observation of the inclusive decay $B_s^0 \to \phi\pi^+\pi^-$ ([11]). The branching fraction in the invariant-mass range $400 < \mathrm{m}(\pi^+\pi^-) < 1600\,\mathrm{MeV}/c^2$ is measured to be

$$\mathscr{B}\left(B_s^0 \to \phi\pi^+\pi^-\right) = (3.48 \pm 0.23 \pm 0.17 \pm 0.35) \times 10^{-6}, \tag{3.1}$$

where the uncertainties are statistical, systematic, and related to the $B_s^0 \to \phi\phi$ control channel, respectively.

Evidence is also seen for the inclusive decay $B^0 \to \phi\pi^+\pi^-$ with a significance of $4.5\,\sigma$. The branching fraction in the invariant-mass range $400 < \mathrm{m}(\pi^+\pi^-) < 1600\,\mathrm{MeV}/c^2$ is measured to be

$$\mathscr{B}\left(B^0 \to \phi\pi^+\pi^-\right) = (1.82 \pm 0.25 \pm 0.41 \pm 0.14) \times 10^{-7}. \tag{3.2}$$

An amplitude analysis is used to separate out exclusive contributions to the B_s^0 decays. Figure 2 shows the fit to background-subtracted distributions of angular variables in data events.

The decay $B_s^0 \to \phi f_0(980)$ is observed with a significance of $8\,\sigma$, and the branching fraction is

$$\mathscr{B}\left(B_s^0 \to \phi f_0(980), f_0(980) \to \pi^+\pi^-\right) = \left(1.12 \pm 0.16^{+0.09}_{-0.08} \pm 0.11\right) \times 10^{-6}. \tag{3.3}$$

The decay $B_s^0 \to \phi f_2(1270)$ is observed with a significance of $5\,\sigma$, and the branching fraction is

$$\mathscr{B}\left(B_s^0 \to \phi f_2(1270), f_2(1270) \to \pi^+\pi^-\right) = \left(0.61 \pm 0.13^{+0.12}_{-0.05} \pm 0.06\right) \times 10^{-6}. \tag{3.4}$$

There is also a contribution from higher mass S-wave $\pi^+\pi^-$ states in the region 1350–1600 MeV/c^2, which could be described by a superposition of the $f_0(1370)$ and the $f_0(1500)$ resonances. There is $4\,\sigma$ evidence for the decay $B_s^0 \to \phi\rho^0$ with a branching fraction of

$$\mathscr{B}\left(B_s^0 \to \phi\rho^0, \rho^0 \to \pi^+\pi^-\right) = (2.7 \pm 0.7 \pm 0.2 \pm 0.2) \times 10^{-7}. \tag{3.5}$$

This is lower than the Standard Model prediction of $\left(4.4^{+2.2}_{-0.7}\right) \times 10^{-7}$ ([12]), but still consistent with it, and provides a constraint on possible contributions from NP in this decay.

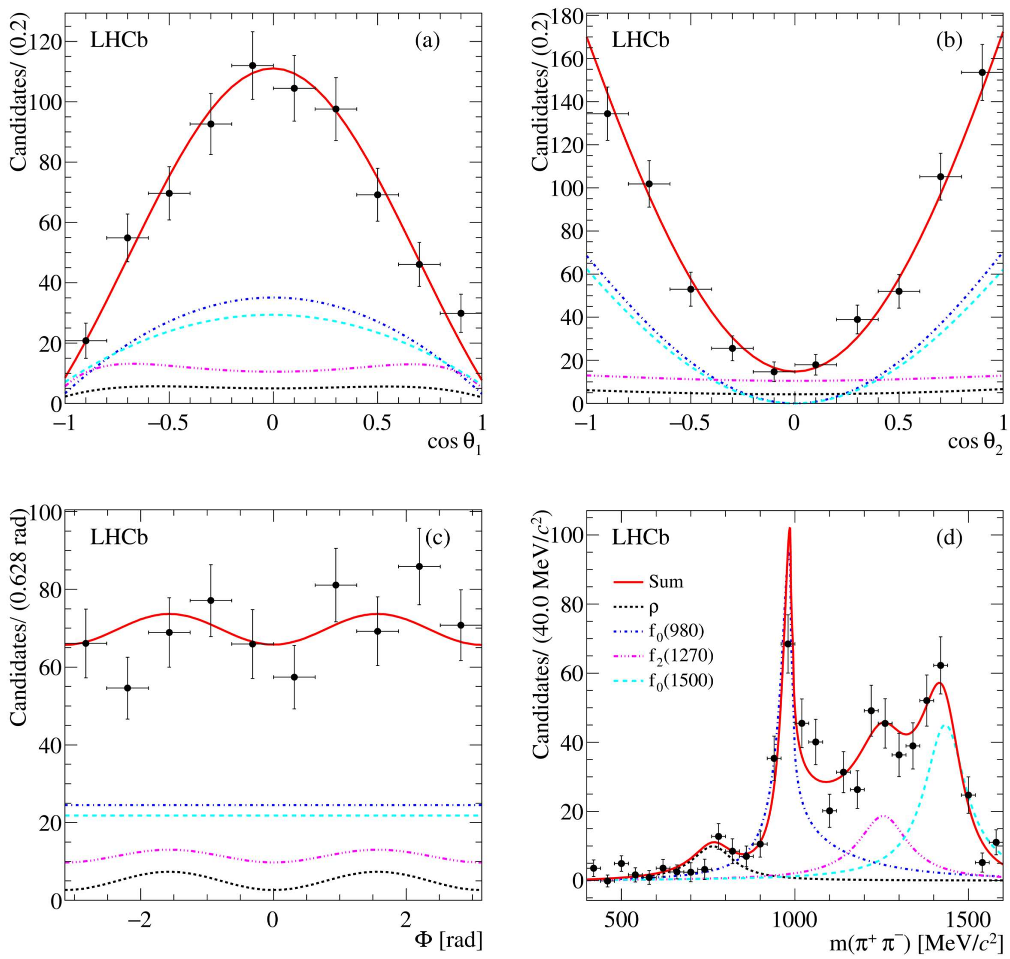

Figure 2: Projections of (a)$\cos(\theta_1)$, (b) $\cos(\theta_2)$, (c) Φ, and (d) $m(\pi^+\pi^-)$ for the best fit to background-subtracted $B_s^0 \to \phi\pi^+\pi^-$ events. The ρ^0 contribution is shown by the dotted black line, the $f_0(980)$ by the dot-dashed blue line, the $f_2(1270)$ by the double-dot-dashed magenta line and the $f_0(1500)$ by the dashed cyan line.

4. Branching fractions of $B^+ \to K^+K^+\pi^-$ and $B^+ \to \pi^+\pi^+K^-$

Transitions of the type $b \to ss\overline{d}$ and $b \to dd\overline{s}$ are rare in the SM ([13, 14]). The calculation of the $b \to ss\overline{d}$ amplitude results in branching fractions of at most $\mathscr{O}(10^{-11})$.

Including all statistical and systematic uncertainties, the ratios of branching fractions are calculated to be

$$\frac{\mathscr{B}(B^+ \to K^+K^+\pi^-)}{\mathscr{B}(B^+ \to K^+K^-\pi^+)} = (-7.5 \pm 4.9 \pm 1.0) \times 10^{-3}, \tag{4.1}$$

$$\frac{\mathscr{B}(B^+ \to \pi^+\pi^+K^-)}{\mathscr{B}(B^+ \to \pi^+\pi^-K^+)} = (1.1 \pm 4.0 \pm 0.1) \times 10^{-4}, \tag{4.2}$$

where the uncertainties are statistical and systematic, respectively ([15]). To obtain upper limits on the branching fractions, the frequentist approach of Feldman and Cousins ([16]) is used to determine 90% and 95% confidence region bands that relate the true values of the branching fractions to the measured numbers of signal events. These bands are constructed using the results of simulation studies that account for relevant biases in the fit procedure and include statistical and systematic uncertainties. The confidence region bands are shown in Fig. 3. The 90% (95%) confidence level

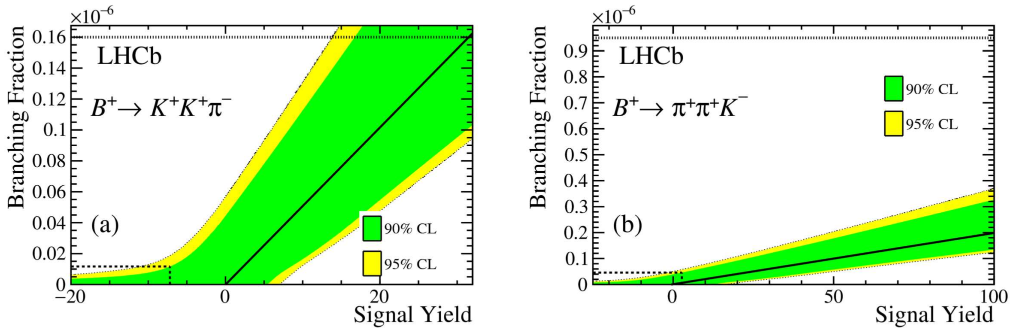

Figure 3: Feldman-Cousins 90% (green) and 95% (yellow) CL bands for (a) $B^+ \to K^+K^+\pi^-$ and (b) $B^+ \to \pi^+\pi^+K^-$ decays, including statistical and systematic uncertainties.

(CL) upper limits are found to be

$$\mathscr{B}\left(B^+ \to K^+K^+\pi^-\right) < 1.1 \times 10^{-8} (1.8 \times 10^{-8}) \text{ at } 90\% \; (95\%) \text{ CL}, \tag{4.3}$$

$$\mathscr{B}\left(B^+ \to \pi^+\pi^+K^-\right) < 4.6 \times 10^{-8} (5.7 \times 10^{-8}) \text{ at } 90\% \; (95\%) \text{ CL}. \tag{4.4}$$

In summary, no evidence is found for the highly-suppressed decays $B^+ \to K^+K^+\pi^-$ and $B^+ \to \pi^+\pi^+K^-$, and upper limits are placed on their branching fractions. The results are approximately fourteen and twenty times more stringent than previous measurements ([17, 18, 19]) and constrain various extensions of the SM ([20, 21]).

5. Conclusion

The analysis of three-body hadronic charmless decays in LHCb already allows to set constraints on NP and to observe new channels of interest, such as $B_{d,s} \to \phi\pi^+\pi^-$, using the Run I data of LHCb. During the next few years, the increased datasets will allow to access to more observables, such as $\beta_{(s),\mathrm{eff}}$ and γ, using amplitude analyses.

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