PROCEEDINGS OF SCIENCE

Charmless B-decays at LHCb

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These proceedings summarise three recent papers from the LHCb Collaboration in the area of charmless b-decays. The branching fraction for the decay $B_s^0 \to \phi\phi$ is measured and a search for the highly suppressed decay $B^0 \to \phi\phi$ is performed. The decay $B_s^0 \to \eta'\eta'$ is observed for the first time and the CP asymmetries in the decays $B^+ \to \eta' K^+$ and $B^+ \to \phi K^+$ are measured. Finally, the decay $B^0 \to \rho^0\rho^0$ is observed for the first time and its longitudinal polarisation is measured.

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1. Introduction

The class of hadronic B-decays that do not contain any charmonium or open-charm particles in their decay tree are often referred to as charmless decays. Precision measurements of these decays are a promising area to search for physics beyond the Standard Model (BSM). The effects of BSM physics are expected to enter through higher order or loop diagrams where precision measurements could indicate deviations from Standard Model (SM) predictions. Charmless B-decays are of particular interest since the amplitude of the first order tree-level diagrams normally contain the CKM element $|V_{ub}|$, due to the smallness of this element [1] loop or higher order diagrams can compete in strength. Hence BSM processes entering through loop diagrams can make a measurable contribution to observables. Some charmless decays proceed through flavour changing neutral currents which are forbidden at the tree level in the SM, hence these decays are suppressed and BSM diagrams can also here make sizeable contributions.

The LHCb experiment [2, 3] is very well suited for measuring charmless b-hadron decays. The branching ratios of the decays of interest are small ($\sim 10^{-5} - 10^{-6}$) for the reasons outlined above. LHCb profits from the very large $b\bar{b}$ production cross section at the LHC, $75 \pm 5.4 \pm 13\,\mu$b at 7 TeV [4], collecting large statistics samples of these decays. However, the experimental environment is very challenging at a hadron collider due to the even larger total inelastic cross section, hence the challenge is to reconstruct, trigger on and select these fully hadronic decays. The LHCb Experiment is designed and optimised for this task with excellent tracking performance, a selective and efficient trigger, and particle identification separating protons, pions and kaons in the full acceptance.

The full spectrum of beauty hadrons is produced at the LHC, therefore LHCb can make measurements of charmless decays of B^0, B^0_s, B^+ and B^+_c mesons and several different B-baryons.

Three measurements from the LHCb Experiment are presented in these proceedings, all based on the data set of 3 fb^{-1} collected 2011 and 2012 at centre of mass energy of 7 and 8 TeV respectively. These are described in Sections 2–4 and the paper concludes in Section 5.

2. $\mathrm{B}^0_{(\mathrm{s})} \to \phi\phi$ branching ratio

The decay $\mathrm{B}^0_{(\mathrm{s})} \to \phi\phi$ proceeds through penguin processes and is important for CP violation studies, for instance measuring the CP violating phase in the $\mathrm{b} \to \mathrm{s\bar{s}s}$ transition [5, 6]. It also serves as a normalisation mode for or is present as a background in other decay modes, hence knowing its branching fraction is important. The previous best measurement was performed by the CDF Experiment [5] and the present measurement by LHCb is a significant improvement on that result.

The analysis [7] measures the branching ratio of $\mathrm{B}^0_\mathrm{s} \to \phi\phi$ relative to the the decay $\mathrm{B}^0 \to \phi\mathrm{K}^{*0}$ and takes into account the relative efficiencies of the two decays and the relative probability of $\mathrm{b\bar{b}}$ pairs hadronising into B^0_s and B^0 mesons (referred to as f_s/f_d). The ratio of efficiencies is determined from simulation, apart from the particle identification efficiencies that are determined by a data-driven method based on charm decays where the identity of the final state particles are determined from kinematic constraints alone. The value of $f_s/f_d = 0.259 \pm 0.015$ is taken from the LHCb measurement in Ref. [8].

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The ϕ and K^{*0} candidates are formed by combinations of opposite charged tracks identified to be either kaons or pions, whose invariant masses have to be within $15\,\text{MeV}/c^2$ ($50\,\text{MeV}/c^2$) of the ϕ (K^{*0}) mass. These are combined to form signal and normalisation candidates with vetoes against $\phi\phi$ and ϕK^{*0} cross feed and against D^+ and D_s^+ decays. The selection consists of a pre-selection stage and a Boosted Decision Tree (BDT) [9] trained on simulated $B^0 \to \phi K^{*0}$ events and background from the data sidebands. The BDT cut is optimised to maximise the $B^0 \to \phi K^{*0}$ yield. The fits to the mass spectra are shown in Figure 1, and the yields are determined to be 2349 ± 49 $B_s^0 \to \phi\phi$ decay candidates and 6680 ± 86 $B^0 \to \phi K^{*0}$ decay candidates.

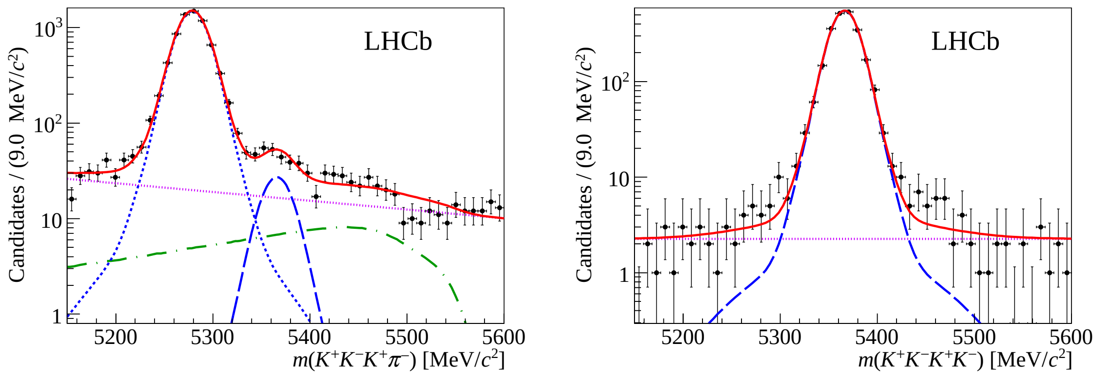

Figure 1: Fits to the invariant mass spectra of the (left) signal and (right) normalisation channel. The $K^+K^-K^+K^-$ spectrum is described by models of the $B_s^0 \to \phi\phi$ (blue dashed)) and combinatorial background (purple dotted). The $K^+K^-K^+\pi^-$ spectrum is described by models of the $B_{(s)}^0 \to \phi K^{*0}$ (blue dotted/dashed), peaking backgrounds (green dash-dotted) and combinatorial background (purple dotted).

The yields are corrected for non-resonant contributions determined from angular analyses [5, 10]. The ratio of branching ratios of the signal and normalisation mode is determined to be $1.84 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst}) \pm 0.11\,(f_s/f_d)$. Using the known branching fraction of $B^0 \to \phi K^{*0}$ the following absolute branching fraction is obtained

$$\mathscr{B}(B_s^0 \to \phi\phi) = (1.84 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst}) \pm 0.11\,(f_s/f_d) \pm 0.12\,(\text{norm})) \times 10^{-5}.$$

The decay decay $B^0 \to \phi\phi$ is highly suppressed and the SM predictions are in the range $0.1 - 3 \times 10^{-8}$ but could be enhanced in some extensions to the SM. The previous best limit for this mode is $\mathscr{B}(B^0 \to \phi\phi) < 2.0 \times 10^{-7}$ at 90% CL set by the BaBar Collaboration [11]. The analysis described above is extended to a search for this decay, where the main change is that the cut on the BDT output variable is optimised using a frequentist figure of merit (FoM) [12] to maximise the probability of finding the first evidence for this decay. The observed signal yield is compatible with zero (5 ± 6 candidates) and an upper limit of $\mathscr{B}(B^0 \to \phi\phi) < 2.8 \times 10^{-8}$ at 90% CL is set.

3. First observation of $B_s^0 \to \eta'\eta'$

The final state of the decay $B_s^0 \to \eta'\eta'$ is CP even and hence it gives access to CP violating observables in a similar but complementary way as the decay $B_s^0 \to \phi\phi$, without the need for an angular analysis. This analysis led to the first observation of this decay [13]. The branching ratio is predicted to be similar to that of its SU(3) partner $B^+ \to \eta' K^+$, hence in the order of 10^{-5}.

The η' is reconstructed in the mode $\eta' \to \pi^+\pi^-\gamma$ and the candidates are selected with rectangular cuts that maximise the same FoM as mentioned previously [12], but in this case optimised for first observation. The signal yield is determined from fits to the $\pi^+\pi^-\gamma$ and $\eta'\,\eta'$ mass spectra, shown in Figure 2, and found to be 36.4 ± 7.8 (stat) ± 1.6 (syst) candidates. The signal significance is determined to be 6.4 σ using Wilks' theorem, including both statistical and systematic uncertainties.

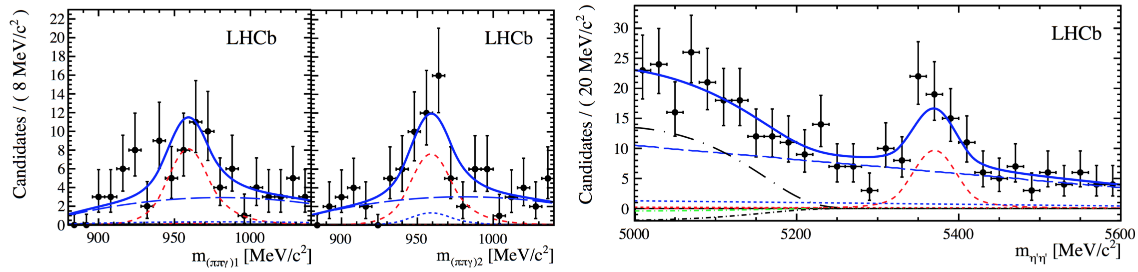

Figure 2: Fits to the two $\pi^+\pi^-\gamma$ invariant mass spectra (left) and to the $\eta'\,\eta'$ mass spectrum (right). The fit includes the signal peaks (red short-dashed), partially reconstructed background (black dash-dotted), combinatorial background with (blue dotted) and without (blue long-dashed) a reconstructed η'.

The branching ratio is determined relative to the decay $B^+ \to \eta' K^+$ and the value for the hadronisation fraction f_s/f_d is used [8], assuming that the probabilities for hadronising into a B^0 or B^+ meson are the same. The relative efficiencies for the particle identification, photon reconstruction and trigger are determined with data-driven methods, and the remaining relative efficiencies are determined from simulation. The relative branching fraction of $\frac{\mathscr{B}(B_s^0 \to \eta'\eta')}{\mathscr{B}(B^+ \to \eta' K^+)} = 0.47 \pm 0.09\,(\text{stat}) \pm 0.04\,(\text{syst})$ is determined, and using the known branching fraction for the decay $B^+ \to \eta' K^+$ results in an absolute branching fraction of

$$\mathscr{B}(B_s^0 \to \eta'\eta') = (3.31 \pm 0.64\,(\text{stat}) \pm 0.28\,(\text{syst}) \pm 0.12\,(\text{norm})) \times 10^{-5}.$$

The CP asymmetries for the normalisation channel and for $B^+ \to \phi K^+$ are also measured. The raw asymmetries are measured from fits to the mass spectra and the CP asymmetries are determined using the fact that the production and detection asymmetries are identical for the two channels and are also the same for the decay $B^+ \to J/\psi\, K^+$. The CP asymmetry for the decay $B^+ \to J/\psi\, K^+$ is small and well known, hence the CP asymmetries can be calculated from the difference $\mathscr{A}^{CP}(B^+ \to \eta' K^+,\ B^+ \to \phi K^+) - \mathscr{A}^{CP}(B^+ \to J/\psi\, K^+) = \mathscr{A}_{raw}(B^+ \to \eta' K^+,\ B^+ \to \phi K^+) - \mathscr{A}_{raw}(B^+ \to J/\psi\, K^+)$. Using the known CP asymmetry for $B^+ \to J/\psi\, K^+$ [14] the physical CP asymmetries are determined to be

$$\mathscr{A}^{CP}(B^+ \to \eta' K^+) = (-0.2 \pm 1.2\,(\text{stat}) \pm 0.1\,(\text{syst}) \pm 0.6\,(\text{norm}))\ \times 10^{-2}$$
$$\mathscr{A}^{CP}(B^+ \to \phi K^+) = (+1.7 \pm 1.1\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.6\,(\text{norm}))\ \times 10^{-2}.$$

4. First observation of $B^0 \to \rho^0\rho^0$

The CKM angle α can be measured by a combined analysis of the decays $B^0 \to \rho^+\rho^-$, $B^+ \to \rho^+\rho^0$ and $B^0 \to \rho^0\rho^0$ [15]. The Belle and BaBar experiments have published angular analyses the first mode [16, 17] and Belle II is expected to significantly improve the precision of these measurements. The decay $B^0 \to \rho^0\rho^0$ is well suited for LHCb since all particles in the final state are charged. This analysis [18] presents the first observation of this decay. Belle and BaBar found evidence for the decay and measured the longitudinal polarisation, albeit with some tension between their measured values.

Candidates are formed by combining $\pi^+\pi^-$ pairs consistent with being $B^0_{(s)}$ decays. After a pre-selections stage, the signal purity is further enhanced by applying a BDT selection and particle identification criteria. Furthermore, vetoes are applied against charmonium and D^0 decays and against three-body combinations in the low mass region. The fit to the mass spectrum is shown in Figure 3, giving a signal yield of 634 ± 29 B^0 and 101 ± 13 B^0_s candidates. The B^0_s peak in this spectrum is observed unambiguously.

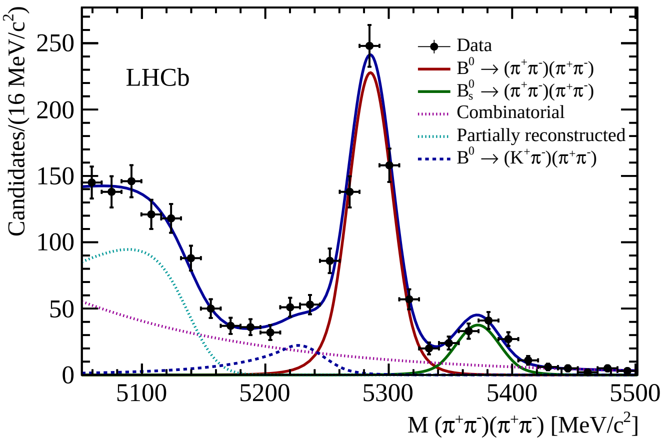

Figure 3: Fit to the $\pi^+\pi^-\pi^+\pi^-$ mass spectrum.

An amplitude analysis is performed on the $B^0 \to \pi^+\pi^-\pi^+\pi^-$ candidates in the spectrum, using the invariant mass of the $\pi^+\pi^-$ pairs and two angular variables. The amplitude model contains in addition to the $B^0 \to \rho^0\rho^0$ decay also vector-vector, vector-scalar and vector-tensor components. See Ref. [18] for details. The fraction of $B^0 \to \rho^0\rho^0$ candidates is determined to be $0.619 \pm 0.072\,(\text{stat}) \pm 0.049\,(\text{syst})$ resulting in approximately 390 signal candidates and a signal significance of 7.1 σ. The longitudinal polarisation is determined to be $f_L = 0.745^{+0.048}_{-0.058}\,(\text{stat}) \pm 0.034\,(\text{syst})$.

The branching ratio is measured relative to the decay $B^0 \to \phi K^{*0}$ and the relative efficiencies are integrated over the phase space taking the amplitude model into account. This gives the relative branching ratio of $\frac{\mathscr{B}(B^0\to\rho^0\rho^0)}{\mathscr{B}(B^0\to\phi K^{*0})} = 0.094 \pm 0.017\,(\text{stat}) \pm 0.009\,(\text{syst})$, and using the known branching ratio of $B^0 \to \phi K^{*0}$ the resulting branching ratio is

$$\mathscr{B}(B^0 \to \rho^0\rho^0) = (0.94 \pm 0.17\,(\text{stat}) \pm 0.09\,(\text{syst}) \pm 0.06\,(\text{norm})) \times 10^{-6}.$$

5. Conclusion

The LHCb experiment has excellent capabilities to study charmless b-hadron decays. These proceedings summarise three recent papers in this area and present seven world-best measurements. LHCb will continue to produce results on charmless b-hadron decays and in other areas in the years to come as more data will be collected.

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