Heavy flavour spectroscopy at LHCb

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Abstract
We summarize the main measurements performed with the LHCb detector on spectroscopy in the heavy-quark sector. Most of the results use full or part of the sample recorded during 2011 data taking, 1 fb\textsuperscript{-1}, in pp collisions at √s = 7 TeV.

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1. Introduction
The spectrum of heavy hadrons is predicted from several theoretical frameworks. The experimental confirmation of the different predicted states, and their properties, acts as a powerful test on the nature of the strong interactions. Current experimental facilities are working hard and collaborating in order to shed light in this sector, which up to now is far from being fully understood.

2. The LHCb detector
The LHCb detector is a single-arm forward spectrometer covering a unique rapidity range (2 < η < 5), where b\bar{b} cross section is larger. This corresponds to a ~4% of the solid angle coverage and ~40% in acceptance of heavy quark production cross-section. The LHCb detector \cite{1} is specialized in beauty and charm physics studies, exhibiting outstanding tracking, vertexing and particle identification capabilities. In 2011, the detector recorded about 1.0 fb\textsuperscript{-1} of integrated luminosity in pp collisions at √s = 7 TeV, more than the 90% of the luminosity delivered by the Large Hadron Collider (LHC) to LHCb.

3. Heavy meson spectroscopy

3.1. The D_{s1}^*(2700)\textsuperscript{+} and D_{sJ}^*(2860)\textsuperscript{+} states
There are several open questions trying to explain the observed c\bar{s} spectrum. The mass of the observed D_{s0}^*(2317)\textsuperscript{+} and D_{s1}(2460)\textsuperscript{+} states \cite{2}, was measured to be smaller than the theoretical predictions \cite{3}. A second set of high mass states were observed by the B factories \cite{4}, the D_{s1}(2700)\textsuperscript{+}, D_{sJ}^*(2860)\textsuperscript{+} and D_{sJ}(3040)\textsuperscript{+}. The first state was observed in D^0K-like and 3-body B decay modes, the second in D^{*0}K-like and the last one in D^*K modes. Many interpretations on the nature and spin-assignment of the D_{sJ}^*(2860)\textsuperscript{+} state can be found \cite{5}, but there is a lack of experimental inputs to fully understand these states. These higher mass states are still awaiting to be confirmed by other experiments.

Using a 1 fb\textsuperscript{-1} of data collected in 2011, the LHCb experiment reconstruct inclusively produced D^*K_S^0 and D^0K^\textsuperscript{+} combinations, in order to confirm the existence of the D_{sJ}^*(2700)\textsuperscript{+} and D_{sJ}^*(2860)\textsuperscript{+} states and to measure their masses and widths \cite{6}. Meson candidates are reconstructed as D^+ \rightarrow K^-\pi^+\pi^+, D^0 \rightarrow K^+\pi^- and K_S^0 \rightarrow \pi^+\pi^- . Signal purity of the meson samples was found to be larger than 95% in the signal region. Large combinatorial suppression is achieved by selecting events with cosθ > 0, where θ is the angle formed by the momentum of the K meson in the DK rest frame and the momentum of the DK-system in the laboratory frame. This variable must be symmetric for the signal events. The optimization of the selection criteria uses the working point the significance of the large D_{sJ}^*(2573)\textsuperscript{+} peak, present in the analysis of both, D^*K_S^0 and D^0K^\textsuperscript{+}, pairs.

Data is modelled with a simultaneous binned maximum likelihood fit to the D^*K_S^0 and D^0K^\textsuperscript{+} samples. Signal events are described using relativistic Breit-Wigner distributions including the form factors, and background events are described using a linear combinations of Chebyshev polynomials from order 1 to 6.
where the least contributing parameters are fixed to a preliminary fit to avoid correlations and improve fit stability. The invariant mass distributions and the fit projections are shown in Fig. 1.

Several sources of systematic uncertainties are accounted for, however the total systematic uncertainty is dominated by the background description. Here, we change the background parameterization and the fit bounds, and we also study for background fluctuations. For the $D_J^{*+}(2700)^+$ state we measure the mass $2709.2\pm1.9$ (stat)$\pm4.5$ (syst) MeV/$c^2$ and width $115.8\pm7.3$ (stat)$\pm12.1$ (syst), MeV/$c^2$, while for the $D_J^{*0}(2860)^+$ state we measure a mass of $2866.1\pm1.0$ (stat)$\pm6.3$ (syst) MeV/$c^2$ and width $69.9\pm3.2$ (stat)$\pm6.6$ (syst) MeV/$c^2$. In addition we observe $6724\pm596$ and $45315\pm2186$ $D_J^{*+}(2700)^+$ events, and $4825\pm347$ and $31603\pm1257$ $D_J^{*0}(2860)^+$ events in $D^0K^0$ and $D^0K^+$ respectively, where the errors are statistical only. These measurements represent the first observation of these two states in a hadron collider and are in agreement with previous results from the B-factories.

### 3.2. Orbitally excited $B^{*+}$ mesons

The properties of the excited B mesons containing a light quark are predicted by Heavy Quark Effective Theory (HQET) in the limit of infinite b-quark mass [3, 7]. Under the heavy quark approximation the B mesons are characterized by three quantum numbers: the orbital angular momentum $L (S, P, D$ for $L = 0, 1, 2$ respectively), the angular momentum of the light quark $j_q = |L \pm 1/2|$, and the total angular momentum $J = |j_q \pm 1/2|$. For $L = 1$ there are four different possible $(J; j_q)$ combinations, all parity-even. These are known as the orbitally excited states or $B^{*+}$ states. Among these states we have the $B_1(5721)^0$ and $B_2(5747)^0$, observed in $B^{*+}\pi^-$ and $B^*\pi^-$ decays [8]. At LHCb, we reconstruct these decay modes, but also the $B^0\pi^-$ and $B^0\pi^+$ where we must observe the isospin partners of the mentioned states.

In this analysis, we use an integrated luminosity of 336.5 pb$^{-1}$, collected by the LHCb detector between May and July of 2011 [9]. The soft photons from the $B^0\pi^-$ decay are not reconstructed, therefore objects decaying to both $B^0\pi^+$ and $B^0\pi^-$ are expected to show two peaks in the $B^0\pi^-$ invariant mass distribution, separated by a quantity corresponding to the $M(B^{*0}) - M(B^0)$ mass difference. The $B^0$ meson is reconstructed into the following final states: $J/\psi(\mu^+\mu^-)K^*(892)^0(K^+\pi^-)$, $D^-\pi^+$ and $D^\pi^+\pi^-\pi^+$, with $D^- \to K^-\pi^+\pi^-$. We combine the $B^0$ candidate with tracks, which are required to originate from the same proton-proton interaction. The companion track is required to be identified as a pion, to have good quality track fit, $p_T > 1$ GeV/c and $p > 10$ GeV/c. For convenience, we study the invariant mass relative to the threshold, which has the form $Q(B^0\pi^-) = M(B^0\pi^-) - M(B^0) - M(\pi^-)$, where $M(B^0)$ and $M(\pi^-)$ are the nominal masses of the mesons quoted by Ref. [10].

The combinatorial background shape is extracted from data, using a sample of reconstructed $B^{*+}\pi^-$ combinations, since the wrong-sign decay $B^0\pi^-$ has structures created by contributions from $B^0 \to \bar{B}^0$ mixing. A significant excess, not attributed to any resonant state, is observed in the $Q(B^0\pi^-)$ with respect to the $Q(B^*\pi^+)$ distribution, interpreted as an associated production due to b-jet hadronization, Fig. 2. This component is described using a kernel-like distribution. Signal resonances in the $Q$-distribution are modeled using relativistic Breit-Wigner lineshapes. The detector resolution is about 3 MeV/$c^2$ and can safely be neglected. The fit results are shown in Fig. 2. Here we observe the feeddown from the $B^+_1/B^*_2 \to B^{*0}\pi^+$ and the $B^*_2 \to B^0\pi^+$ states. To improve fit convergence, the relative width between the $B^+_1$ and the $B^*_2$ is fixed to 0.9 and the relative yield between the $B^*_2 \to B^{*0}\pi^+$ and $B^*_2 \to B^0\pi^+$ fixed to 0.93, from theoretical predictions [3, 7].

The largest systematic uncertainty in the mean $Q$ values for the observed states, arises from variations in the selection requirements (0.95%), and from the uncertainty on the $B^0$ mass. The mean values are corrected for possible biases, calculated from simulated toy samples generated from the experimental PDF. The final results are $M(B^{*+}_1) = (5726.3 \pm 1.9 \pm 3.0 \pm 0.5)$ MeV/$c^2$ and $M(B^{*+}_2) = (5739.0 \pm 3.3 \pm 1.6 \pm 0.3)$ MeV/$c^2$, where
4. Heavy baryon spectroscopy

4.1. Mass of the $\Xi_b^-$ and $\Omega_b^-$ ground states

Very little is known about b baryons. There are seven ground-state ($J^P = 1/2^-$) baryons involving a b quark and two light ($u, d$ or $s$) quarks. These are the $\Lambda_b^0$ isospin singlet, the $\Sigma_b$ triplet, the $\Xi_b$ strangeness 1 doublet, and the $bss$ state $\Omega_b$. According to the [10], only five of these baryons have been observed and have measured masses, without confirmation on their quantum numbers.

Using a 620 pb$^{-1}$ integrated luminosity sample, we measure the masses of the strange $b$-baryons $\Omega_b^-$ and $\Xi_b^-$ [12], which are reconstructed via the decay chains $J/\psi\Omega^-(\Lambda_b^0K^-)$ and $J/\psi\Xi^-(\Lambda_b^0\pi^-)$, respectively, with $J/\psi \rightarrow \mu^+\mu^-$ and $\Lambda_b^0 \rightarrow p\pi^-$. The mass measurement of the $\Omega_b^-$ is of particular interest, since the values reported for this state by the CDF and DØ collaborations are inconsistent at the 6σ level [11]. Both decays share a similar topology and the presence of long-lived particles and multiple vertices in the decay chain is exploited in the selection process. High background levels are observed near the interaction point, mainly from inclusive $J/\psi$ production, thus we reconstruct only candidates with lifetime above 0.3 ps. The mass resolution of the strange $b$-hadrons is improved by applying a constraint to the mass of the daughters in the vertex fit. The final selection places restrictions on the particle identification and quality of the final state tracks. In addition, a momentum calibration is applied based on a large sample of $J/\psi \rightarrow \mu^+\mu^-$ candidates, that corrects for the description of the magnetic field and tracking system.

The invariant mass distributions for the selected $\Omega_b^-$ and $\Xi_b^-$ candidates is shown in Fig. 3. The signal candidates are described by Gaussian distributions, where the width for the $\Xi_b^-$ is extracted from simulated data and for the $\Omega_b^-$ it is estimated by scaling the $\Xi_b^-$ resolution by the ratio of the $\Omega_b^-$ and $\Xi_b^-$ masses.

The systematic uncertainties in the measurement of the masses are dominated by the momentum scale calibration. A detailed description of the evaluation of this effect can be found in Ref. [13]. The final result for the masses are $M(\Xi_b^-) = 5796.5 \pm 1.2 \pm 1.2$ MeV/$c^2$ and $M(\Omega_b^-) = 6050.3 \pm 4.5 \pm 2.2$ MeV/$c^2$, where the first uncertainty is statistical and the second one due to systematic effects. These results correspond to the best measurements of these masses to date. The measured $\Omega_b$ mass is compatible with the CDF measurement $M(\Omega_b^-) = 6054.4 \pm 6.9$ MeV/$c^2$, but enlarge the discrepancy of the global average with the measurement performed by the DØ collaboration, $M(\Omega_b^-) = 6165 \pm 16$ MeV/$c^2$ [11].

4.2. Neutral ground state b baryons

With a 330 fb$^{-1}$ sample, of data recorded in 2011 by the LHCb detector, we reconstruct the $\Lambda_b^0\pi^-$, $D^0\rho\pi^-$ and $D^0pK^-$ invariant mass spectra, with $D^0 \rightarrow K^-\pi^+$ and $\Lambda_b^+ \rightarrow K^-\pi^+\pi^0$, in order to look for neutral $b$ baryons [14]. The two vertex topology shown in all the decay chains and a tight particle identification in all tracks are exploited in the selection criteria.

Several components are carefully identified in each data sample, based in the study of Monte Carlo simulated samples and using wrong-sign data combinations. Figure 4(left) shows a large and clean peak corresponding to the $\Lambda_b^0 \rightarrow \Lambda_c^-\pi\pi$ decay. This state is also observed...
in the $D^0 p h^-(h = K, \pi)$ combinations, but with smaller yield. The large purity of these kind of events is crucial for the study of excited $b$ hadrons, as explained in Sec. 4.3. The measured parameters are in agreement with the PDG [10]. In addition, the $D^0 p K^-$ spectrum (Fig. 4 right), shows a hint of the presence of the neutral beauty strange baryon $\Xi_b^0$, with a significance of 2.6 standard deviations, including systematic effects.

4.3. Observation of excited $b$ baryons

Excited $\Lambda_b^0$ baryons with $J^P = 1/2^-, 3/2^-$, are predicted in different scenarios [15], expected to decay to $\Lambda_b^0$ via radiative or dipion emission. With the large data sample in 2011 by the LHCb detector, 1 fb$^{-1}$, and combining previously described $\Lambda_b^0$ baryons with two oppositely charged pions coming from the same vertex, we reconstruct the total invariant mass and look for the existence of the predicted $\Lambda_b^0$ excited baryons [16]. The full decay chain is fitted constraining the masses of the $\Lambda_b^0$ and $\Lambda_c^+$ hadrons to their nominal value. The particular topology of this decay, with multiple vertices, is used to reject combinatorial events.

Figure 5 shows the $\Lambda_b^0 \pi^+ \pi^-$ invariant mass distribution and the fit function. Two narrow peaks are observed, the first near the threshold and the second about 5.92 GeV/$c^2$ in the invariant mass. These two signals are modeled using a sum of Gaussian distributions, with the widths of the core components fixed to the obtained from Monte Carlo simulations. The upper limits in the width are obtained convolving the signal functions with Breit-Wigner distributions. The background model is extracted from the study of wrong-sign $\Lambda_b^0 \pi^+ \pi^-$ combinations.

The two new states are interpreted as the $1/2^-$ and $3/2^-$ orbital excitations of the ground state $\Lambda_b^0$, and were found to have masses of 5911.95 $\pm$ 0.12(stat) $\pm$ 0.03(syst) $\pm$ 0.66($\Lambda_b^0$ mass) MeV/$c^2$ and 5919.76 $\pm$ 0.07(stat) $\pm$ 0.02(syst) $\pm$ 0.66($\Lambda_b^0$ mass) MeV/$c^2$, respectively. Upper limits on the natural widths are set to be $\Gamma(\Lambda_b^0 (1/2^-)) < 0.82$ MeV and $\Gamma(\Lambda_b^0 (3/2^-)) < 0.71$ MeV, with a mass resolution of the order of 0.2 MeV. The observation of the $\Lambda_b^0 (1/2^-)$ at 4.9 and $\Lambda_b^0 (3/2^-)$ at 10.1 standard deviations, represents the first observation of excited $b$ baryon states.

5. Conclusions

We summarized a few selected results on heavy flavor spectroscopy at the LHCb detector. We expect many new results with the analysis of the 2011 and 2012 data samples. The LHCb experiment has shown outstanding capabilities and is in a good position to explore the spectra of heavy quark states, as well as to produce competitive results in the heavy flavors sector.

References