PROCEEDINGS OF SCIENCE

Spectroscopy at LHCb

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LHCb is an experiment optimized to perform measurements in the flavour sector at the LHC. The precise tracking capabilitity of the experiment together with the large datasets collected allow to study the properties of heavy hadrons with unprecedented precision. In these proceedings three recent results are discussed: the measurement of the Ω_b^- mass, the observation of new B_c^+ decay modes and the determination of the $X(3872)$ quantum numbers.

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1. Introduction

LHCb [1] is a dedicated b physics experiment at the Large Hadron Collider (LHC). The production of b pairs at the LHC is peaked in the forward region. Hence, the experiment is designed as a single arm spectrometer covering the polar angle of 15 - 300 mrad. During the first run of the LHC an integrated luminosity of 1 fb^{-1} was collected at a centre-of-mass energy of 7 TeV during 2011 and a further 2 fb^{-1} at 8 TeV during 2012. This dataset contains a large sample of $b \to J/\psi X$ events that are being used to perform studies of the properties of b-hadrons and charmonium states with unprecedented precision. In these proceedings three new measurements which were presented at the 2013 winter conferences are discussed: the measurement of the Ω_b^- mass, observation of new B_c^+ decay modes and the determination of the $X(3872)$ quantum numbers.

2. Measurement of the Ω_b^- mass

In the last decade the large datasets collected by hadron machines has allowed the first detailed studies of the properties of b-baryons. An outstanding puzzle from studies at the Tevatron studies is the value of the Ω_b^- mass. Both the CDF and D0 experiments observed the Ξ_b^- and Ω_b^- baryons but whilst the values of the Ξ_b^- mass they measured are consistent, those for the Ω_b^- are widely different [2, 3, 4].

Recently, LHCb has resolved this discrepancy [5] using a sample of 1 fb^{-1} of pp collision data collected at 7 TeV. Candidate Ξ_b^- and Ω_b^- decays are reconstructed in the $J/\psi\Xi^-$ and $J/\psi\Omega^-$ decay modes respectively. Signals with a significance larger than 5σ are seen for both modes (Fig. 1). The masses of these baryons are measured to be:

$$\begin{aligned} M(\Xi_b^-) &= 5795.8 \pm 0.9\,(\text{stat}) \pm 0.4\,(\text{syst})\ \text{MeV}/c^2, \\ M(\Omega_b^-) &= 6046.0 \pm 2.2\,(\text{stat}) \pm 0.5\,(\text{syst})\ \text{MeV}/c^2. \end{aligned}$$

The dominant source of uncertainty is due to the knowledge of the momentum scale of the spectrometer which is judged to be 0.3% from studies of a variety of other fully reconstructed decays including $B^+ \to J/\psi K^+$, $J/\psi \to \mu^+\mu^-$ and $K_s \to \pi^+\pi^-$. The result for the Ξ_b^- mode is in agreement with but more precise than the measurements made by CDF and D0 [2, 3]. That for the Ω_b^- agrees with the CDF result [2] and strongly disfavours the D0 result [4].

The same data sample has been used to make a more precise measurement of the Λ_b^0 mass using the $J/\psi\Lambda^0$ decay mode. A value of

$$M(\Lambda_b^0) = 5619.53 \pm 0.13\,(\text{stat}) \pm 0.45\,(\text{syst})\ \text{MeV}/c^2,$$

is found.

3. B_c^+ physics

The B_c^+ meson was first observed by the CDF collaboration decaying semileptonically [6]. Subsequently, the exclusive $B_c^+ \to J\psi\pi^+$ decay was observed both at the Tevatron and the LHC [7, 8]. More recently, the first observation of the $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ mode was made by LHCb [9]. For the 2013 winter conferences LHCb has presented observations of three new B_c^+ decay modes together with an improved measurement of the mass of this particle.

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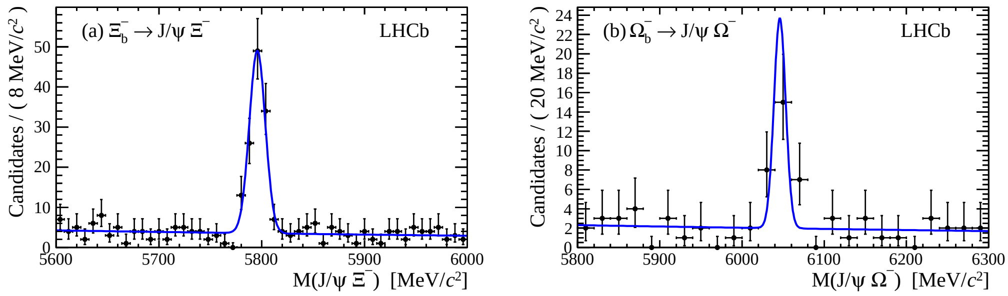

Figure 1: Invariant mass distributions for (a) $\Xi_b^- \to J/\psi\Xi^-$ candidates and (b) $\Omega_b^- \to J/\psi\Omega^-$ candidates taken from Ref. [5].

The first new mode studied is the decay $B_c \to \psi(2S)\pi^+$ [10]. Using 1 fb^{-1} of data collected in pp collision data at 7 TeV LHCb has observed this mode with a significance of 5.2 σ. The fitted yield of this mode is 20 ± 5 events giving:

$$\frac{B(B_c^+ \to \psi(2S)\pi^+)}{B(B_c^+ \to J/\psi(2S)\pi^+)} = 0.250 \pm 0.068\,(\text{stat}) \pm 0.014, (\text{syst}) \pm 0.006\,(\text{BR})$$

where the last uncertainty is due to the knowledge of the branching ratios of the dimuon decays of the J/ψ and $\psi(2S)$ mesons.

The second study is of decays to the $J/\psi D_s^+$ final state [11]. This is the first measurement to be made with the full 3 fb^{-1} of data collected during the first LHCb run. Figure 2 shows the invariant mass distribution for selected candidates. A narrow peak at the known B_c^+ mass is seen together with a broad structure below it. The former is due to the $B_c^+ \to J/\psi D_s^+$ mode whilst the latter is compatible with partially reconstructed $B_c^+ \to J/\psi D_s^{*+}$ decays. This component is modelled by two templates determined using the simulation that account for the helicity amplitudes present in the decay $\mathscr{A}_{\pm\pm}$ and $\mathscr{A}_{00}$. The significance of both signals is in excess of 9σ. The branching ratio of the $B_c^+ \to J/\psi D_s^+$ mode relative to the $B_c^+ \to J\psi\pi^+$ mode is measured to be

$$\frac{B(B_c^+ \to J/\psi D_s^+)}{B(B_c^+ \to J/\psi\pi^+)} = 2.96 \pm 0.67\,(\text{stat}) \pm 0.25\,(\text{syst}).$$

The ratio of branching fractions for $B_c^+ \to J/\psi D_s^{*+}$ to $B_c^+ \to J/\psi D_s^+$ is measured to be

$$\frac{B(B_c^+ \to J/\psi D_s^{*+})}{B(B_c^+ \to J/\psi D_s^+)} = 2.36 \pm 0.56\,(\text{stat}) \pm 0.10\,(\text{syst}).$$

The results are consistent with the expectations from naive factorization and the theory predictions given in [12].

The low energy release in the $B_c^+ \to J/\psi D_s^+$ mode allows a measurement of the B_c^+ mass to be made with negligible systematic uncertainty related to the momentum scale calibration. The mass of the B_c^+ is found to be

$$m(B_c^+) = 6276.28 \pm 1.44\,(\text{stat}) \pm 0.36\,(\text{syst})\ \text{MeV}/c^2,$$

using a value of $m(D_s^+) = 1968.31 \pm 0.2\,\text{MeV}/c^2$ obtained by averaging the results given in [13] and [14]. This is the most precise measurement of the B_c^+ mass to date and in agreement with the

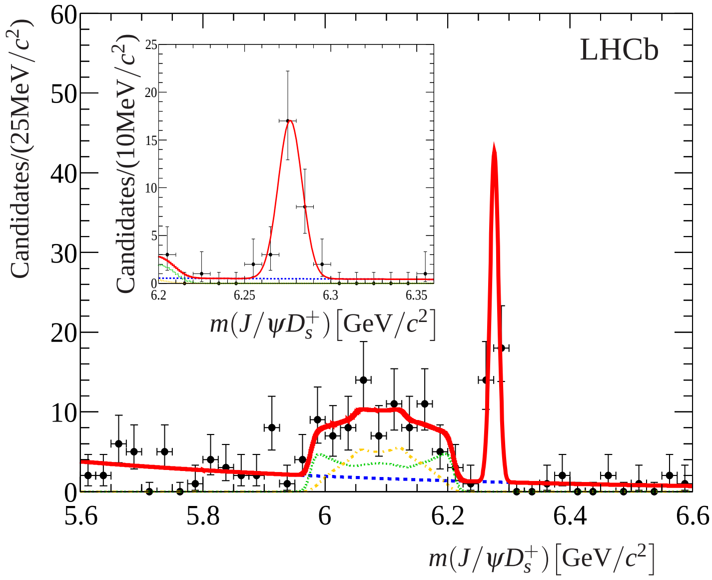

Figure 2: Mass distributions for selected $J/\psi D_s^+$ pairs taken from Ref. [11]. The curve represents the result of a fit to the model described in the text. The contribution from the $B_c^+ \to J/\psi D_s^{*+}$ decay mode is shown with thin green dotted and thin yellow dash-dotted lines for $\mathscr{A}_{\pm\pm}$ and $\mathscr{A}_{00}$ amplitudes, respectively. The insert shows a zoom of the B_c^+ mass region.

best previous measurement which used the $B_c^+ \to J\psi\pi^+$ mode [15]:

$$m(B_c^+) = 6273.7 \pm 1.3\,(\text{stat}) \pm 1.6\,(\text{syst})\ \text{MeV}/c^2.$$

4. Determination of the X(3872) quantum numbers

The last years have seen a resurgence of interest in the spectroscopy of exotic hadron states that do not fit in the conventional charmonium spectrum. This interest was generated by the observation of the charmonium-like $X(3872)$ state by the Belle collaboration in 2003 [16]. Though the existence of the $X(3872)$ has been confirmed by many experiments [17, 18, 19, 20] its nature is still uncertain. The state does not fit well into the quark model picture, and exotic interpretations have been suggested: for example that it is a tetraquark [22] or a loosely bound deuteron-like $D^{*0}\overline{D}^0$ 'molecule' [23]. Prior to the analysis described below the quantum numbers of the $X(3872)$ had been restricted by the CDF collaboration to be either 1^{++} or 2^{-+} [24].

To distinguish between the two possibilites LHCb has performed a five-dimensional angular analysis of $X(3872)$ mesons produced in the $B^+ \to J/\psi K^+$ decay chain that decay to the $J/\psi\pi^+\pi^-$ final state [25]. Using this decay chain has the advantage that the polarization of the $X(3872)$ is determined by the decay kinematics. The study is performed using data corresponding to an integrated luminosity of 1 fb^{-1} of collected at 7 TeV. To distinguish between the two possible hypotheses for the quantum numbers a likelihood ratio test is performed. The value of this test statistic found in data, t_{data}, is compared with the distribution found in simulated experiments (Fig. 3). The data favours the 1^{++} hypothesis and the 2^{-+} hypothesis is rejected with a significance of 8.4σ. This result rules outs the assignment of the $X(3872)$ as the $\eta_{c2}(1^1D_2)$ charmonium state, the only plausible assignment in the conventional charmonium picture. Hence, the $X(3872)$ is likely exotic in nature. To distinguish between the various interpretations more measurements are needed. The dataset collected by LHCb will be critical to further elucidate the nature of this state.

For the molecular interpretation of the $X(3872)$ state to be valid it should be a bound state. That is to say the mass of the $X(3872)$ should be less than the sum of the D^{0*} and D^0 masses. Using the values given in [13] the binding energy is estimated to be $E_{\rm B} = 0.21 \pm 0.32\,{\rm MeV}/c^2$ where the uncertainty is limited by the knowledge of the D^0 mass. To reduce this uncertainty, LHCb has made a new measurement of this quantity [14] using the $D^0 \to K^-K^+K^-\pi^+$ mode:

$$M(D^0) = 1864.75 \pm 0.15\,({\rm stat}) \pm 0.11\,({\rm syst})\,{\rm MeV}/c^2.$$

This result is consistent with previous measurements and has similar precision [13].

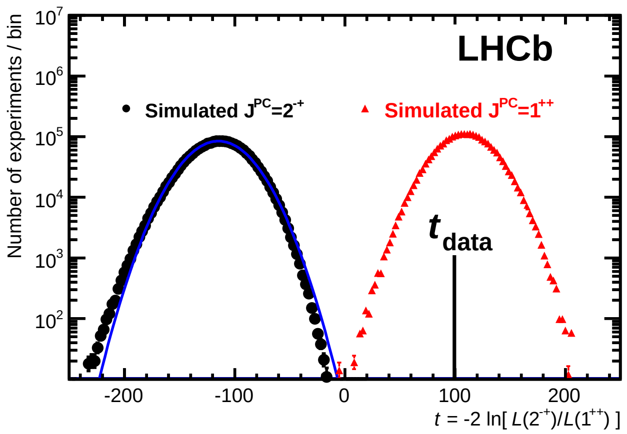

Figure 3: Distribution of the likelihood test statistic, t, for the simulated experiments with $J^{PC} = 2^{-+}$ (black circles) and with $J^{PC} = 1^{++}$ (red triangles) from Ref. [25]. A Gaussian fit to the 2^{-+} distribution is overlaid (blue solid line). The value of the test statistic for the data, t_{data}, is shown by the solid vertical line.

5. Summary and Outlook

The LHCb experiment has profited from its large collected dataset to make many measurements related to the spectroscopy of b-hadrons and quarkonia. In these proceedings three recent results related to b-baryons, B_c^+ physics and exotic quarkonia have been presented. Further results that exploit the large dataset collected in the first LHCb run in all these areas are expected.

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