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b and c hadron production and spectroscopy at LHCb

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Selected recent LHCb results on b and c hadron production and spectroscopy are presented. With $1\,\mathrm{fb}^{-1}$ pp collisions data collected at a center-of-mass energy of $\sqrt{s} = 7\,\mathrm{TeV}$ in 2011, the quantum numbers of the $X(3872)$ meson are determined to be 1^{++}. With $0.65\,\mathrm{fb}^{-1}$ data collected in 2011, upper limits at the 95% confidence level of the cross-section ratio of the Ξ_{cc}^{+} baryon to the Λ_c^{+} baryon are given for five different lifetime hypotheses. The weak decay of the B_c^{+} meson through c quark, $B_c^{+} \to B_s^0 \pi^{+}$, is observed for the first time. The lifetime of the Λ_b^0 baryon is measured at an unprecedented level.

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1. The LHCb experiment

LHCb detector[1], optimised for heavy flavour physics, is a single arm forward detector at the LHC. The detector consists of tracking system, RICH detectors, calorimeters and muon chambers. It covers the pseudo-rapidity range $2 < \eta < 5$, where b and c hadrons are produced copiously.

LHCb has recorded pp collision data at a center-of-mass energy of 7 TeV in 2010 and 2011, and at 8 TeV in 2012. The integrated luminosity is 36 pb^{-1}, 1.0 fb^{-1} and 2.0 fb^{-1} for 2010, 2011 and 2012, respectively.

2. The quantum numbers of the $X(3872)$ meson

The exotic particle $X(3872)$ meson was discovered by Belle experiment about 10 years ago[2], however, its nature remains mysterious. There are many models based on different hypotheses of the underlying structure of the $X(3872)$ meson in the market. The quantum numbers are crucial to distinguish these models. If $J^{\text{PC}} = 1^{++}$, then the $X(3872)$ meson could be a loosely-bound "molecule" of D^{*0} and $\overline{D^0}$ mesons, or a "tetra-quark" binding a di-quark and a di-antiquark, or a charmonium-molecule mixture, or the $^2P_1$charmonium state. And if $J^{\text{PC}} = 2^{-+}$, the $X(3872)$ meson could be the $^1D_2$ charmonium state. There are already several experimental constraints on the quantum numbers. The charge parity of the $X(3872)$ meson is known to be $+1$ since the radiative decay $X(3872) \to \gamma J/\psi$ has been observed[3]. The CDF experiment excluded all possibilities but 1^{++} and 2^{-+} by binned 3D angular analysis[4]. The result of the BaBar experiment favoured 2^{-+} but didn't exclude 1^{++}(C.L = 7%)[5]. Further measurements are needed to distinguish those two hypotheses.

LHCb performs a 5D angular analysis of the decay $B^+ \to [X(3872) \to (J/\psi \to \mu^+\mu^-)\pi^+\pi^-]K^+$ with 1 fb^{-1} data collected in 2011[6]. The angular correlations in the B^+ decay carry information about the $X(3872)$ quantum numbers. To discriminate these two hypotheses, a likelihood ratio test statistic is constructed

$$t = -2\ln\left[\frac{L(2^{-+})}{L(1^{++})}\right] \tag{2.1}$$

where $L(J^{\text{PC}})$ is the background subtracted likelihood. Using simulated experiments, the distribution of t for the two hypotheses can be obtained, as shown in Fig. 1.

The optimised selection yields 313 ± 26 $B^+ \to X(3872)K^+$ candidates. The t value observed in data is 99, which is quite consistent with the 1^{++} hypothesis, while significantly deviates from the 2^{-+} hypothesis. Assuming $t(2^{-+})$ follows the Gaussian distribution, the 2^{-+} hypothesis is rejected with a significance of 8.4σ.

3. Search for the doubly charmed baryon Ξ_{cc}^+

The quark model predicts the existence of the Ξ_{cc}^+ baryon. There are various theoretical predictions of the Ξ_{cc}^+ properties[7, 8, 9] with the majority yielding masses in the range 3500 – 3700 MeV/c^2 and lifetimes in the range 100 – 250 fs. The SELEX collaboration reported Ξ_{cc}^+ signals in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$[10] and $\Xi_{cc}^+ \to pD^+K^-$[11] decays. The state they observed had a mass of

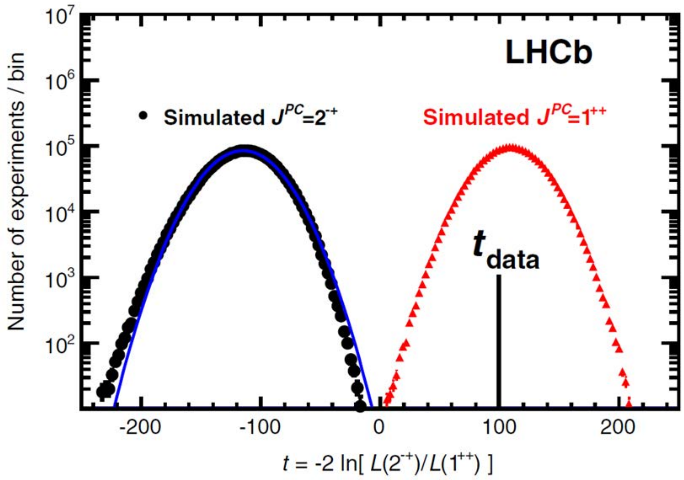

Figure 1: The distribution of the likelihood ratio t from simulated experiments for 1^{++} (red triangles) and 2^{-+} (black dots). The black vertical line indicates the t value observed in data.

3519 MeV/c^2 and a lifetime consistent with zero. The subsequent searches at FOCUS, BaBar and Belle didn't find any evidence for this state.

LHCb search for the Ξ_{cc}^+ baryon through $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ with 0.65 fb^{-1} data collected in 2011[12]. A multivariate method is employed to optimise the signal selection. No significant signal is observed after all the selections, as is shown in Fig 2. We hence measure the upper limit of the production cross-section ratio relative to Λ_c^+

$$R \equiv \frac{\sigma(\Xi_{cc}^+)\mathscr{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} = \frac{N_{\rm sig}}{N_{\rm con}}\frac{\varepsilon_{\rm con}}{\varepsilon_{\rm sig}} = \alpha N_{\rm sig} \quad (3.1)$$

where α is the single-event-sensitivity and is obtained from simulation. Since the efficiency depends on the lifetime of Ξ_{cc}^+, which we consider not known, α is calculated under five different lifetime hypotheses, and the corresponding upper limits at the 95% confidence level of R are given.

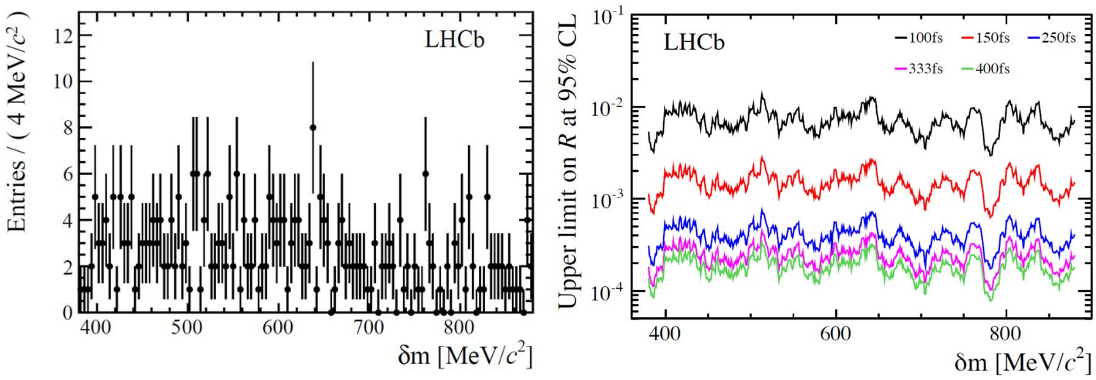

Figure 2: (Left) The Ξ_{cc}^+ mass spectrum after all the selections. (Right) Upper limits at the 95% confidence level of R for five different lifetime hypotheses.

4. First observation of $B_c^+ \to B_s^0 \pi^+$

B_c^+ mesons are unique since they are the only double heavy-flavoured mesons in the quark model. They hvae very rich structure and are ideal places to test various models. The B_c^+ meson is discovered in $B_c^+ \to J/\psi \mu^+ \nu$ by CDF [13], and its first full reconstruction channel is $B_c^+ \to J/\psi \pi^+$[14]. Many new decay modes of B_c^+ are observed at LHCb, but most of them decay through b quark. Using the full $3\,\text{fb}^{-1}$ data at LHCb, $B_c^+ \to B_s^0 \pi^+$, which is a B_c^+ decay through c quark, is observed for the first time[15]. The B_s^0 is reconstructed using $D_s^- \pi^+$ and $J/\psi \phi$ final states. Multivariate methods are optimised for these two final states, respectively. The $B_c^+ \to B_s^0 \pi^+$ decay with $B_s^0 \to D_s^- \pi^+$ are observed with a significance of 7.5σ, and with $B_s^0 \to J/\psi \phi$ are observed with a significance of 5.5σ. The invariant mass distribution of the selected B_c^+ candidates are shown in Fig. 3.

Combining these two channels, the fraction of B_s^0 that comes from B_c^+ decay is measured to be

$$\frac{\sigma(B_c^+)\mathscr{B}(B_c^+ \to B_s^0 \pi^+)}{\sigma(B_s^0)} = \left(2.38 \pm 0.35(\text{stat.}) \pm 0.11(\text{syst.})^{+0.17}_{-0.12}(\tau_{B_c^+})\right) \tag{4.1}$$

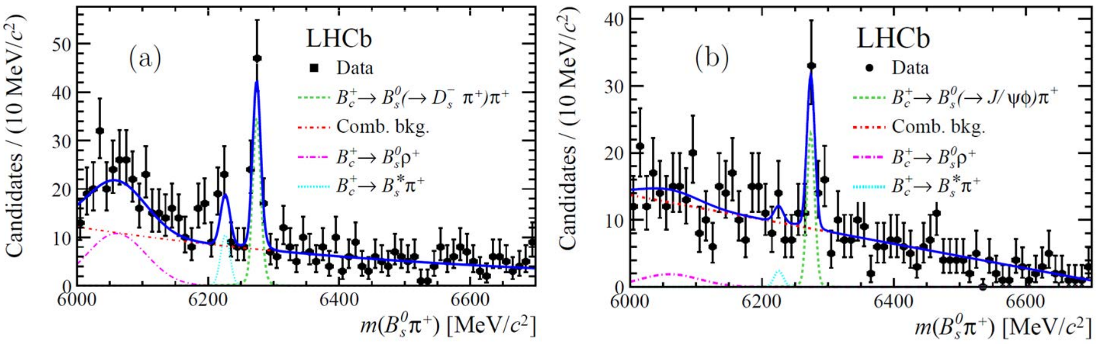

Figure 3: The invariant mass distribution of B_c^+ candidates with B_s^0 reconstructed by (Left) $D_s^- \pi^+$ and (Right) $J/\psi \phi$.

5. Measurement of Λ_b^0 lifetime

The heavy quark expansion (HQE) provides a perturbative expansion in the inverse heavy quark mass for inclusive rates. It has proved to be very successful in the B sector[16]. In this model the lifetime of Λ_b^0 and B^0 are expected to be approximately the same within several percent. The lifetime ratio between Λ_b^0 and B^0 is predicted to be $0.98 + \mathscr{O}(1/m_b^3)$[17]. However, the ratio measured by LEP is 0.798 ± 0.052, which significantly deviated from 1. Recent measurements from CDF, ATLAS and CMS indicate lifetimes of Λ_b^0 and B^0 are indeed close but the uncertainties are large. A precise measurement with a smaller uncertainty is necessary to resolve this ambiguity.

The LHCb experiment performs the Λ_b^0 lifetime measurement with $1\,\text{fb}^{-1}$ of 2011 data[18]. The strategy is to make a relative measurement to B^0. Therefore the Λ_b^0 and B^0 are reconstructed through two topological identical decays: Λ_b^0 is reconstructed by $\Lambda_b^0 \to J/\psi\, p K^-$, and B^0 by $\overline{B^0} \to$

$J/\psi\,\pi^+K^-$. Assuming most part of the acceptance and the detector resolution effects cancel in the ratio, the ratio can be expressed as

$$R(t) = R(0)(1+\alpha t)\exp(-\Delta t) \tag{5.1}$$

where $(1+\alpha t)$ is the residual effect of the acceptance function, $\Delta = 1/\tau_{\Lambda_b^0} - 1/\tau_{B^0}$. The parameter α is determined from simulation: $\alpha = 0.0033 \pm 0.0024\,\mathrm{ps}^{-1}$.

Fit the yield ratio in bins of decay time, the parameter is found to be $\Delta = 16.4 \pm 8.2 \pm 4.4\,\mathrm{ns}^{-1}$. Using the world-average value of τ_{B^0}, the lifetime ratio is computed

$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 0.976 \pm 0.012 \pm 0.006 \tag{5.2}$$

which is quite consistent with the HQE prediction. The update with full statistics of $3\,\mathrm{fb}^{-1}$ data is expected soon.

6. Conclusion

The LHCb detector has an excellent performance in 2010-2012 and produced many important physics results. The quantum numbers of $X(3872)$ is determined to be 1^{++}. The doubly charmed baryon Ξ_{cc}^+ is searched and upper limits are given. The first b-meson-to-b-meson decay $B_c^+ \to B_s^0\pi^+$ is observed. The lifetime of Λ_b^0 is precisely measured and the tension between theory and experiment is resolved.

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