Heavy Flavour Spectroscopy at LHCb

Ao Xu (on behalf of LHCb collaboration)

*Department of Engineering Physics, Tsinghua University
 30 Shuangqing Rd, 100084 Beijing, China
 Center for High Energy Physics, Tsinghua University
 30 Shuangqing Rd, 100084 Beijing, China
 xua17@mails.tsinghua.edu.cn*

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Recent results on heavy flavour spectroscopy with data collected by the LHCb detector are highlighted, including studies of exotic hadrons, the observation of five Ω_c^0 resonances, and the observation of the Ξ_{cc}^{++} baryon.

Keywords: Heavy flavour physics; Spectroscopy; Large Hadron Collider.

1. Introduction

Study of hadron spectroscopy can provide invaluable information for quantum chromodynamics, which describes strong interactions between quarks and gluons. This article reports recent results on heavy flavour spectroscopy from the LHCb experiment. The LHCb detector is a single-arm forward spectrometer designed for studies of particles containing b or c quarks, described in detail in Refs. 1, 2.

In LHC Run 1, the detector collected pp collision data corresponding to an integrated luminosity of about 1 (2) fb^{-1} at $\sqrt{s} = 7$ (8) TeV in 2011 (2012). During LHC Run 2, a data sample corresponding to an integrated luminosity of about 0.3 (1.7) fb^{-1} at $\sqrt{s} = 13$ TeV are collected in 2015 (2016).

2. Heavy exotic hadron spectroscopy

2.1. Observation of the decays $\Lambda_b^0 \rightarrow \chi_{cJ} p K^-$

LHCb observed two pentaquark candidates $P_c(4380)^+$ and $P_c(4450)^+$ in the amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays in 2015³, which were confirmed by a model-independent analysis⁴. (Inclusion of charge-conjugate processes is implied

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Fig. 1. Fits to the (a) $\Lambda_b^0 \rightarrow \chi_{c1} p K^-$ and (b) $\Lambda_b^0 \rightarrow J/\psi p K^-$ invariant mass distributions.

throughout.) The $P_c(4450)^+$ mass is close to the $\chi_{c1} p$ threshold, which leaves the possibility of describing the state as kinematic rescattering effects. This could be tested by the analysis of the decay $\Lambda_b^0 \rightarrow \chi_{c1} p K^-$.

As an initial stage in the investigation of this hypothesis, the observation of $\Lambda_b^0 \rightarrow \chi_{cJ} p K^-$ decays is achieved using the Run 1 data sample, where $J = 1, 2$, and the branching fractions relative to that of $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays are measured⁵. In the decay chains $\Lambda_b^0 \rightarrow \chi_{cJ} p K^-$ and $\Lambda_b^0 \rightarrow J/\psi p K^-$, the intermediate resonances χ_{cJ} and J/ψ are reconstructed with the decays $\chi_{cJ} \rightarrow J/\psi \gamma$ and $J/\psi \rightarrow \mu^+ \mu^-$. A kinematic fit is applied to the Λ_b^0 candidates with χ_{c1} and J/ψ masses constraint to their known values. As a result, Separate peaks are produced in the $m(\chi_{c1} p K^-)$ distribution. The signal yields of the modes are determined by the fits to the $m(\chi_{c1} p K^-)$ and $m(J/\psi p K^-)$ distributions shown in Fig. 1. The measured yields of Λ_b^0 are 453 ± 25 , 285 ± 23 , and 29815 ± 178 for the χ_{c1} , χ_{c2} , and J/ψ channels, respectively. The ratios of branching fractions are found to be

$$\begin{aligned} \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)} &= 0.242 \pm 0.014 \pm 0.013 \pm 0.009, \\ \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)} &= 0.248 \pm 0.020 \pm 0.014 \pm 0.009, \text{ and} \\ \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c1} p K^-)} &= 1.02 \pm 0.10 \pm 0.02 \pm 0.05, \end{aligned}$$

where the uncertainties are due to statistical, systematic, and the uncertainty on the branching fractions of the $\chi_{cJ} \rightarrow J/\psi \gamma$ decays, respectively. Unlike in $B \rightarrow \chi_{cJ} K$ decays^{6,7}, no suppression of the χ_{c2} mode relative to χ_{c1} mode is observed. The amplitude analysis of the $\Lambda_b^0 \rightarrow \chi_{c1} p K^-$ decay is under way.

2.2. Observation of $J/\psi \phi$ structures

Both positive and negative results of searches for the $X(4140)$ structure in the decay $B^+ \rightarrow J/\psi \phi K^+$ have been reported by various experiments^{8,9,10,11,12}. An amplitude analysis of this decay could help to achieve a better understanding by considering the reflections of K^* states in the $J/\psi \phi$ invariant mass distribution. This

Fig. 2. Distributions of $m_{J/\psi \phi}$ for the fit results with (left) model containing only K^{*+} contributions and (right) model containing eight K^{*+} and five X contributions.

Table 1. Results for significances, masses, widths, and quantum numbers of the exotic states in the best-fit model.

Resonance	Significance	Mass (MeV)	Γ (MeV)	J^{PC} (Significance)
$X(4140)$	8.4σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^{++} (5.7σ)
$X(4274)$	6.0σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{+8.4}_{-11.1}$	1^{++} (5.8σ)
$X(4500)$	6.1σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^{++} (4.0σ)
$X(4700)$	5.6σ	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^{++} (4.5σ)

is performed by LHCb using the full Run 1 data ^{13,14}. The yield of $B^+ \rightarrow J/\psi \phi K^+$ events after selection is 4289 ± 151 , with a background fraction of $(23 \pm 6)\%$ in the B^+ mass region used in the amplitude analysis.

The left plot of Fig. 2 shows that the amplitude model with kaon excitations alone failed to describe the data in the $m_{J/\psi \phi}$ distribution. The best-fit resonance model contains seven K^{*+} states, four X states, and ϕK^+ and $J/\psi \phi$ nonresonant components, with 98 free parameters in the fit. The fit projection on the $m_{J/\psi \phi}$ plane is shown in the right plot of Fig. 2. Four exotic states contribute in the model, with parameters summarized in Table 1.

2.3. Search for structure in the $B_s^0 \pi^\pm$ mass spectrum

The D0 experiment claimed evidence of a narrow structure in the $B_s^0 \pi^\pm$ mass spectrum, referred to as $X(5568)$ ¹⁵. If confirmed, $X(5568)$ would provide important information of the bounding mechanism of the multi-quark structure, since its mass is dominated by one heavy quark instead of the heavy quark-antiquark pair of previously observed exotic states.

The search has been conducted using Run 1 data ¹⁶. The B_s^0 samples are reconstructed through decays to $D_s^- \pi^+$ with $D_s^- \rightarrow K^+ K^- \pi^-$, and decays to $J/\psi \phi$ with $J/\psi \rightarrow \mu^+ \mu^-$ and $\phi \rightarrow K^+ K^-$. After the event selection, a B_s^0 sample of about 10^5 mesons is acquired, which is 20 times larger than that used by the D0 experiment. A fit to the $B_s^0 \pi^\pm$ mass spectrum has been performed to obtain quantitative results. No significant signal is observed. The upper limits at 90(95)% C.L. of the ratio of cross-section, $\rho_X^{\text{LHCb}} \equiv \frac{\sigma(pp \rightarrow X + \text{anything}) \times \mathcal{B}(X \rightarrow B_s^0 \pi^\pm)}{\sigma(pp \rightarrow B_s^0 + \text{anything})}$, are evaluated to be

Fig. 3. The distribution of $m(\Xi_c^+ K^-)$ of the reconstructed candidates passing the likelihood ratio selection.

$\rho_X^{\text{LHCb}}[p_T(B_s^0) > 5 \text{ GeV}] < 0.011(0.012)$, $\rho_X^{\text{LHCb}}[p_T(B_s^0) > 10 \text{ GeV}] < 0.021(0.024)$, and $\rho_X^{\text{LHCb}}[p_T(B_s^0) > 15 \text{ GeV}] < 0.018(0.020)$.

3. Heavy conventional hadron spectroscopy

3.1. Observation of five excited Ω_c^0 states

Compared to other charmed baryons, our knowledge of Ω_c^0 spectra is very limited. Only the ground states of $J^P = 1/2^+$ Ω_c^0 and $J^P = 3/2^+$ $\Omega_c(2770)^0$ are observed. A search for new Ω_c^0 resonances decaying to $\Xi_c^+ K^-$ is performed with Run 1 and 2015 data¹⁷. The Ξ_c^+ candidates are reconstructed with $pK^-\pi^+$ final states.

The distribution of $m(\Xi_c^+ K^-)$ is shown in Fig. 3, where five narrow structures are observed. Further checks show that no combinatorial background, other resonances and mis-identification candidates contribute to these narrow structures. The mass, width, and yield of each resonance are extracted through a binned χ^2 fit to the $m(\Xi_c^+ K^-)$ spectrum in the range from the threshold to 3450 MeV. Resonances are described by spin-zero relativistic Breit-Wigner functions convolved with the experimental resolution. Feed-down contributions due to partial reconstruction are included with shape parameters fixed to simulation results. The fit results are shown in Table 2. Future investigations can determine the quantum numbers by studying possible three-body decays and reconstructing these states in decays of heavy baryons.

3.2. Observation of the doubly charmed baryon Ξ_{cc}^{++}

Doubly charmed baryons are predicted by the quark model, including one isospin doublet ($\Xi_{cc}^{++}(ccu)$ and $\Xi_{cc}^+(ccd)$) and one isospin singlet ($\Omega_{cc}^+(ccs)$). Experimentally, there is a long-standing puzzle in the Ξ_{cc} system. An observation of Ξ_{cc}^+ baryons was reported by the SELEX experiment in two decay modes, with a few unexpected features^{18,19}. Searches at other experiments, however, reported negative results of the structure claimed by SELEX^{20,21,22,23}.

The search for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decays is conducted with 2016 data²⁴. The Λ_c^+ candidates are reconstructed through $pK^-\pi^+$ final states. A significant

Table 2. Results of the fit to $m(\Xi_c^+ K^-)$ for the mass, width, and yield for each resonance.

Resonance	Mass (MeV)	Γ (MeV)	Yield
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$

Fig. 4. Distributions of (left) the invariant mass of $\Lambda_c^+ K^- \pi^+ \pi^+$ for right-sign (RS) signal sample, $\Lambda_c^+ K^- \pi^+ \pi^-$ for wrong-sign (WS) control sample, and $[pK^- \pi^+] K^- \pi^+ \pi^+$ with $[pK^- \pi^+]$ combinations in the Λ_c^+ mass sidebands for side-band (SB) control sample and (right) the fit result in the mass window.

structure is observed at around 3620 MeV in the Ξ_{cc}^{++} mass spectrum, while no structure is found in the control samples, as is shown in the left plot of Fig. 4. The same structure is also observed in the data sample collected in 2012. To determine the yield and significance of the structure, as well as the peak mass, an unbinned extended maximum likelihood fit is performed in the mass window 3620 ± 150 MeV, as is shown in the right plot of Fig. 4. The signal significance is above 12σ with a yield of 313 ± 33 . The measured mass is $3621.40 \pm 0.72 \pm 0.27 \pm 0.14$ MeV, where the uncertainties are statistical, systematic, and due to the uncertainty of the Λ_c^+ mass, respectively.

Possible mis-identification contributions are found to be negligible. In addition, when requiring the decay time larger than 5 times the resolution, the significance of signal is still above 12σ , which confirms the inconsistency with a strong decay. The mass of the observed Ξ_{cc}^{++} is consistent with most theoretical predictions, while inconsistent (103 ± 2 MeV larger) with being an isospin partner with the structure reported by the SELEX experiment.

4. Conclusion and prospects

Rich results of heavy flavour spectroscopy have been produced by LHCb, and recent results are highlighted. More exciting results are expected with enlarged data sample.

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