Studies of quarkonia and doubly-heavy hadrons at LHCb

Zhiyu Xiang[*][†]

University of Chinese Academy of Sciences,
No.19(A) Yuquan Road, Beijing, China

E-mail: xiangzhiyu16@mails.ucas.ac.cn

The measurements of quarkonia and doubly-heavy hadrons in *pp* collisions provide crucial inputs to study both perturbative and non-perturbative quantum chromodynamics. LHCb has a broad physics program of studies of quarkonia and doubly-heavy hadrons. In this proceeding, six recent measurements from the LHCb collaboration are reported: the $\psi(2S)$ production cross-sections measurement, the updated measurement of $\eta_c(1S)$ production cross-section, the observation of a new charmonium state X(3842), the observation of an excited B_c^+ state, the precision measurement of B_c^+ mass, and end this report with the first search of Ξ_{bc}^0.

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[*]Speaker

[†]On behalf of the LHCb collaboration

1. Introduction

Heavy-flavour hadrons, containing open or hidden charm and beauty flavour, are among the most important tools for the study of Quantum Chromodynamics (QCD) in high-energy hadronic collisions. The heavy-quark mass acts as a long distance cut-off so that the partonic hardscattering process can be calculated in the framework of perturbative QCD (pQCD) down to low transverse momenta (p_T). Therefore, the studies of quarkonia and doubly-heavy hadrons provides a crucial testing ground for both perturbative and non-perturbative aspects of QCD calculations. The LHCb detector [1, 2], with its high momentum resolution, great particle identification capability and flexible trigger strategy, is perfectly suited to study heavy flavour hadrons features.

2. Measurement of $\psi(2S)$ production cross-sections

In high-energy pp collisions, charmonium states can be produced directly from hard collisions, through the feed-down from excited states, or via weak decays of b-hadrons. The first two contributions are referred to as prompt production, while the third component can be separated by exploiting the lifetime of b-hadrons. For prompt J/ψ production the feed-down contribution is large. This complicates the comparison between theoretical calculations and experimental results. On the contrary, the feed-down contribution to $\psi(2S)$ mesons is negligible [3], thus theoretical calculations can be directly compared with measurements.

The cross-sections of $\psi(2S)$ meson production in pp collisions at centre-of-mass energy of $\sqrt{s} = 13$ TeV are measured with a data sample collected by the LHCb corresponding to an integrated luminosity of 275 pb^{-1} [4]. The production cross-sections for prompt $\psi(2S)$ and those from b-hadron decays ($\psi(2S)$-form-b) are determined in the rapidity range $2.0 < y < 4.5$ and in the transverse momentum range $2 < p_T < 20$ GeV/c. The production cross-sections integrated over this kinematic region are

$$\sigma(\text{prompt } \psi(2S), \ 13 \text{ TeV}) = 1.430 \pm 0.005 \ (\text{stat}) \pm 0.099 \ (\text{syst}) \ \mu\text{b},$$
$$\sigma(\psi(2S)\text{-from-}b, 13 \text{ TeV}) = 0.426 \pm 0.002 \ (\text{stat}) \pm 0.030 \ (\text{syst}) \ \mu\text{b}.$$

A new measurement of $\psi(2S)$ production cross-sections at $\sqrt{s} = 7$ TeV is also performed using data corresponding to an integrated luminosity of 614 pb^{-1}. The integrated production cross-sections in the kinematic range $3.5 < p_T < 14$ GeV/c and $2.0 < y < 4.5$ are

$$\sigma(\text{prompt } \psi(2S), \ 7 \text{ TeV}) = 0.471 \pm 0.001 \ (\text{stat}) \pm 0.025 \ (\text{syst}) \ \mu\text{b},$$
$$\sigma(\psi(2S)\text{-from-}b, 7 \text{ TeV}) = 0.126 \pm 0.001 \ (\text{stat}) \pm 0.008 \ (\text{syst}) \ \mu\text{b}.$$

All results show reasonable agreement with theoretical calculations.

3. Measurement of the $\eta_c(1S)$ production cross-section

LHCb measured the prompt $\eta_c(1S)$ production cross-section in pp collisions at $\sqrt{s} = 7, 8$ TeV to be below the predictions based on J/ψ prompt production data, and only marginal consistency was found between measurements and theoretical predictions at next-to-leading-order for both prompt production and production in b-hadron decays for the $\eta_c(1S)$ and J/ψ [5]. A study of the $\eta_c(1S)$

prompt production at $\sqrt{s} = 13$ TeV [6] provides a further test for theories predicting the J/ψ and $\eta_c(1S)$ hadroproduction cross-sections and the J/ψ polarisation.

Using a data sample corresponding to an integrated luminosity of 2 fb^{-1}, the production of the $\eta_c(1S)$ at $\sqrt{s} = 13$ TeV is studied in the range of $2.0 < y < 4.5$ and $6.5 < p_T < 14.0$ GeV/c. The cross-section for prompt production of $\eta_c(1S)$ mesons relative to that of the J/ψ meson is measured using the $p\overline{p}$ decay mode and is found to be $\sigma_{\eta_c(1S)}/\sigma_{J/\psi} = 1.69 \pm 0.15 \pm 0.10 \pm 0.18$. The quoted uncertainties are, in order, statistical, systematic and due to uncertainties on the branching fractions of the $J/\psi \rightarrow p\overline{p}$ and $\eta_c(1S) \rightarrow p\overline{p}$ decays. The prompt $\eta_c(1S)$ production cross-section is determined to be $\sigma_{\eta_c(1S)} = 1.26 \pm 0.11 \pm 0.08 \pm 0.14$ μb, where the last uncertainty includes that on the J/ψ cross-section. The ratio of the branching fractions of b-hadron decays to the $\eta_c(1S)$ and J/ψ states is measured to be $\mathcal{B}_{b \rightarrow \eta_c X}/\mathcal{B}_{b \rightarrow J/\psi X} = 0.48 \pm 0.03 \pm 0.03 \pm 0.05$ where the last uncertainty is due to those on the branching fractions of the $\eta_c(1S)$ and J/ψ decays. The difference between the $\eta_c(1S)$ and J/ψ masses is also determined to be $113.0 \pm 0.7 \pm 0.1$ MeV/c^2, which is the most precise single measurement to date.

4. Observation of a new charmonium state X(3842)

Plenty of charmonium states have been observed experimentally and their spectrum is well described by the potential models [7]. But still many of the conventional states remain unobserved. Moreover, starting from the discovery of $\chi_{c1}(3872)$ more than twenty exotic states which do not fit into the conventional charmonium spectrum are observed. To distinguish between them, it is necessary to account for all of the predicted hidden-charm states, to make the precise measurements of their parameters and to continue a search for new exotic states.

Using the full statistics collected by LHCb, corresponding to an integrated luminosity of 9 fb^{-1}, the $D^0\overline{D}^0$ and D^+D^- mass spectra are investigated [8]. The D^0 and D^+ candidates are reconstructed using $D^0 \rightarrow K^-\pi^+$ and $D^+ \rightarrow K^-\pi^+\pi^+$ decay modes. The $D\overline{D}$ combination mass spectra are shown in Figure 1 (left). Four peaking structures are clearly seen in the spectra. Two of the peaks correspond to the known $\psi(3770)$ and $\chi_{c2}(3930)$ charmonium states. A narrow peak close to the threshold represents partially reconstructed $\chi_{c1}(3872) \rightarrow D^{*0}\overline{D}^0$ with subsequent $D^{*0} \rightarrow D^0\gamma$ or $D^{*0} \rightarrow D^0\pi^0$ decay with γ or π^0 missing. The narrow peak with mass about 3840 MeV/c^2 is identified with a new charmonium state, referred to as X(3842).

Simultaneous fits to the $D^0\overline{D}^0$ and D^+D^- combinations mass distributions are performed in three overlapping mass regions in order to better parametrise the background. Fit result is shown in Figure 1 (right) for one of the mass regions containing X(3842) state only. Measured parameters of the new X(3842) state are

$$m_{X(3842)} = 3842.71 \pm 0.16 \text{ (stat)} \pm 0.12 \text{ (syst)} \text{ MeV}/c^2,$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \text{ (stat)} \pm 0.35 \text{ (syst)} \text{ MeV}.$$

The mass value and the small natural width of the new state suggest the interpretation as the $\psi_3(1^3D_3)$ charmonium state with quantum numbers $J^{PC} = 3^{--}$ [9]. In addition, prompt hadroproduction of the $\chi_{c2}(3930)$ and $\psi(3770)$ charmonium states are seen for the first time and their parameters are measured to be
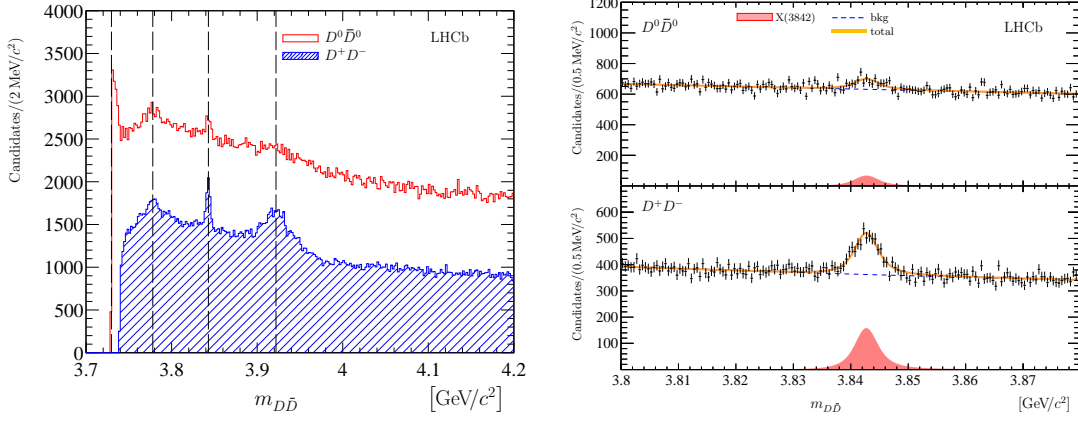
Figure 1: (left) The open red histogram represents $D^0\overline{D}^0$ combination mass spectra, the blue dashed histogram for D^+D^- combination mass spectra. (right) The (top) $D^0\overline{D}^0$ and (bottom) D^+D^- combination mass spectra in narrow region. Different components employed in the fit are indicated in the legend.

$$m_{\chi_{c2}(3930)} = 3921.9 \pm 0.6 \text{ (stat)} \pm 0.2 \text{ (syst) MeV}/c^2,$$
$$\Gamma_{\chi_{c2}(3930)} = 36.6 \pm 1.9 \text{ (stat)} \pm 0.9 \text{ (syst) MeV},$$
$$m_{\psi(3770)} = 3778.1 \pm 0.7 \text{ (stat)} \pm 0.6 \text{ (syst) MeV}/c^2.$$

The measured parameters of $\chi_{c2}(3930)$ state are in 2σ tension with respect to the current world average [3].

5. Observation of an excited B_c^+ state

The B_c meson family has a rich spectrum. There are two $B_c(2S)$ states, $B_c(2^1S_0)^+$ and $B_c^*(2^3S_1)^+$. The $B_c(2^1S_0)^+$ decays to $B_c^+\pi^+\pi^-$ and $B_c^*(2^3S_1)^+$ decays to $B_c^*(1^3S_1)^+(\to B_c^+\gamma)\pi^+\pi^-$. The γ from the $B_c^*(1^3S_1)^+$ decay is too soft to reconstruct in LHCb. According to studies in Ref. [10], when γ is missing, the reconstructed $B_c^*(2^3S_1)^+$ mass is shifted down by the mass difference between the $B_c^*(1^3S_1)^+$ and B_c^+ states, and the mass resolution is only slightly degraded.

Using pp collision data corresponding to an integrated luminosity of 8.5 fb^{-1} recorded by the LHCb at $\sqrt{s} = 7, 8$ and 13 TeV, the excited $B_c^*(2^3S_1)^+$ state in the $B_c^+\pi^+\pi^-$ invariant-mass spectrum is observed [11], as shown in Figure 2. The $\Delta M \equiv M(B_c^+\pi^+\pi^-) - M(B_c^+)$ peak with mass about 566 MeV/c^2 is consistent with expectations of the $B_c^*(2^3S_1)^+$. The observed peak has a reconstructed mass of 6841.2 ± 0.6 (stat) ± 0.1 (syst) ± 0.8 (B_c^+) MeV/c^2, where the last uncertainty is due to the limited knowledge of the B_c^+ mass. A second state is seen with a global (local) statistical significance of 2.2σ (3.2σ) and a mass of 6872.1 ± 1.3 (stat) ± 0.1 (syst) ± 0.8 (B_c^+) MeV/c^2, and is consistent with the $B_c(2^1S_0)^+$ state. These mass measurements are the most precise to date.

6. Precision measurement of B_c^+ meson mass

Studies of the B_c meson can reveal information on heavy-quark dynamics and improve our understanding of the strong interaction. Due to the presence of two heavy-quarks the mass spectrum of the B_c states can be predicted with much better precision than many other hadronic systems.
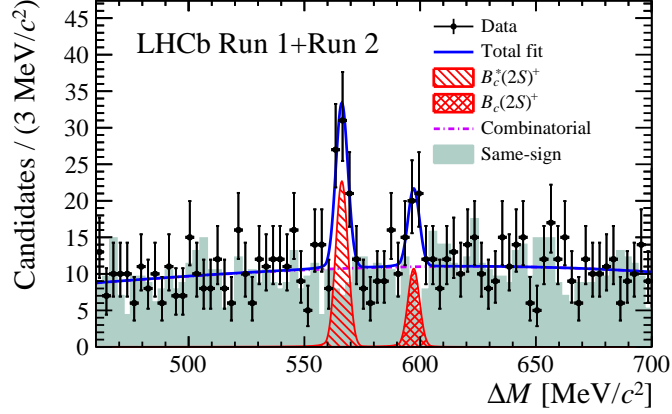
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Figure 2: Distribution of $\Delta M = M(B_c^+ \pi^+ \pi^-) - M(B_c^+)$ with the fit results overlaid. The same-sign distribution has been normalized to the data in the $B_c^*(2^3 S_1)^+$ sideband region.

The world average of the B_c^+ mass has an uncertainty of 0.8 MeV/c^2 [3], which is the dominant systematic uncertainty in the $B_c^{(*)}(2S)^+$ mass measurements [11].

A precision measurement of the B_c^+ mass is performed using pp collision data collected with LHCb at $\sqrt{s} = 7, 8$ and 13 TeV, corresponding to an integrated luminosity of 9 fb^{-1} [12]. Combining the results of the individual decay channels: $B_c^+ \to J/\psi \pi^+$, $B_c^+ \to J/\psi \pi^+ \pi^- \pi^+$, $B_c^+ \to J/\psi p \bar{p} \pi^+$, $B_c^+ \to J/\psi D_s^+$, $B_c^+ \to J/\psi D^0 K^+$ and $B_c^+ \to B_s^0 \pi^+$, the B_c^+ meson mass is measured to be $6274.47 \pm 0.27 \text{ (stat)} \pm 0.17 \text{ (syst)}$ MeV/c^2. This is the most precise measurement of the B_c^+ meson mass to date. In addition, the difference between B_c^+ and B_s^0 masses is measured to be $907.75 \pm 0.37 \text{ (stat)} \pm 0.27 \text{ (syst)}$ MeV/c^2.

7. First search for $\Xi_{bc}^0 \to D^0 p K^-$

The baryons with two heavy quarks are of interest for the theoretical consideration, since for their description would combined approach involving the features of the effective theory of heavy quarks (HQET), nonrelativistic QCD (NRQCD) and potential nonrelativistic QCD (pNRQCD) because in this system the interaction of light quark with the heavy quarks is essential as well as the interaction between the heavy quarks.

A first search for the doubly-heavy Ξ_{bc}^0 baryon using its decay to the $D^0 p K^-$ final state is performed using pp collision data at $\sqrt{s} = 13$ TeV collected by LHCb, corresponding to an integrated luminosity of 5.4 fb^{-1} [13]. No significant signal is found in the invariant mass range from 6.7 to 7.2 GeV/c^2. Upper limits are set at 95% credibility level on the ratio of the Ξ_{bc}^0 production cross-section times its branching fraction to $D^0 p K^-$ relative to that of the $\Lambda_b^0 \to D^0 p K^-$ decay, in the region of $5 < p_T < 25$ GeV/c and $2.0 < y < 4.5$. Upper limits range from 1.7×10^{-2} to 3.0×10^{-1} for the considered Ξ_{bc}^0 lifetime hypotheses, 100 to 500 fs.

8. Summary

Several recent LHCb results on quarkonia and doubly-heavy hadrons in pp collisions have been reported. More precise measurement of $\psi(2S)$ production at $\sqrt{s} = 7$ and 13 TeV show reasonable

agreement with theoretical prediction. First $\eta_c(1S)$ production measurement at $\sqrt{s} = 13$ TeV is in 2σ agrees with prediction by the colour-singlet model [14]. A new charmonium state X(3842) is observed. The prompt hadroproduction of $\psi(3770)$ and $\chi_{c2}(3930)$ states are first observed. Observation of excited $B_c^{(*)}(2S)^+$ and most precise mass measurement to date. Most precise measurement of B_c^+ mass. First search for $\Xi_{bc}^0 \rightarrow D^0 p K^-$ and upper limit set. More results of quarkonia and doubly-heavy hadrons at LHCb are expected in the near future.

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