Recent results in excited charm and beauty hadron spectroscopy

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Recent results in the spectroscopy of open charm and beauty hadrons are presented: these include measurement of the parameters of the $D^{*+}_{s1}(2710)$ and $D^{*+}_{s2}(2860)$ mesons at LHCb, the observation of excited $B^{(*)}_{s}$ mesons and measurement of their masses at LHCb, and observations of new beauty baryons at the Tevatron and LHC experiments.

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1. Introduction

The measurement of the parameters of the heavy-flavored hadrons is essential to test both heavy quark effective theory (HQET) and QCD sum rules. Whilst most progress in the quarkonium sector (conventional and exotic) is coming primarily from the B factories, the most recent results on open charm and beauty hadrons are coming from the hadron machines, the Tevatron and LHC. This report discusses the measurement of the parameters of the $D_{s1}^*(2710)^+$ and $D_{sj}^*(2860)^+$ mesons, the observation of the excited $B_{(s)}^{**}$ mesons and the measurement of their masses at LHCb, and new observations of beauty baryons by the Tevatron and LHC experiments.

2. Charm mesons

Charm mesons are a system of the heavy ($Q = c$) and a light ($q = u, d, s$) quarks, which are characterised by their total spin $S = \bar{s}_Q + \bar{s}_q$ and orbital momentum $\vec{L}$. The lowest-lying states have $L = 0$ and are denoted as $D$ (with the quantum numbers $J^P = 0^-$) and $D^*$ ($J^P = 1^-$). The states with the first orbital excitation ($L = 1$) form two doublets: one with $j_q = |\vec{L} + \vec{s}_q| = 1/2$ that consists of two states ($D_{q0}^u, D_{q1}^u$) with $J^P = (0^+, 1^+)$, and another with $j_q = 3/2$: ($D_{11}^s, D_{21}^s$) with $J^P = (1^+, 2^+)$. While the spectroscopy of the charmless states $D^0$ and $D^+$ follows the predictions of the HQET, the charmed-strange meson system is a more interesting case: the states $D_{s0}^q(2317)^+$ and $D_{s1}^q(2460)^+$ observed by BaBar [1] and Belle [2] almost a decade ago have masses considerably lower than the HQET predictions. The second wave of observations in $D_s$ sector came in 2006–2007 with the observations of $D_{s1}(2710)^+$ and $D_{sj}^*(2860)^+$ states [3, 4].

The existence of these states has recently been confirmed by the LHCb collaboration [6]. For this study LHCb use a sample of $pp$ collisions corresponding to 1 fb$^{-1}$ taken in 2011 at the center-of-mass (CM) energy $\sqrt{s} = 7$ TeV. The combinations $D^+K^0_S$ and $D^0K^+$ are studied, where $D$ and $K$ mesons are required to originate from the primary vertex of the $pp$ interaction. The invariant mass distributions for both combinations are shown in Fig. 1. A combined fit to both spectra is performed, where the signals are modeled by Breit-Wigner shapes with Blatt-Weisskopf form factors, and the background from random $DK$ combinations is represented by polynomial shapes. The most prominent peak in the distributions is $D_{s2}^q(2573)^+$, while the contributions from $D_{s1}^q(2710)^+$ and $D_{sj}^*(2860)^+$ are also clearly visible. The parameters of the $D_{s1}^q(2710)^+$ and $D_{sj}^*(2860)^+$ states obtained from the fit are

$$M(D_{s1}^q(2710)^+) = (2709.4 \pm 1.9_{\text{stat}} \pm 4.5_{\text{syst}}) \text{MeV}/c^2,$$

$$\Gamma(D_{s1}^q(2710)^+) = (121.7 \pm 7.3_{\text{stat}} \pm 12.1_{\text{syst}}) \text{MeV},$$

$$M(D_{sj}^*(2860)^+) = (2866.7 \pm 1.0_{\text{stat}} \pm 6.3_{\text{syst}}) \text{MeV}/c^2,$$

$$\Gamma(D_{sj}^*(2860)^+) = (64.5 \pm 3.2_{\text{stat}} \pm 6.6_{\text{syst}}) \text{MeV}.$$  

The largest contributions to the systematic errors are due to the signal and background models and the uncertainty in the invariant mass resolution. The results are consistent with the measurements performed by BaBar [5] and Belle [4]. There is no evidence for the state with mass above 3000 MeV/$c^2$ reported by BaBar in the $D^*K$ spectrum [5].
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Figure 1: Invariant mass distributions for (a) $D^+K_0^*$ and (b) $D^0K^+$ combinations and background-subtracted distributions for (c) $D^+K_0^*$ and (d) $D^0K^+$.

3. Beauty mesons

Excited states of the $B$ mesons have been studied only by the Tevatron experiments until recently. The nomenclature of the excited $B$ states is similar to the one for the charmed states. There is a doublet of states $(B, B^*)$ with $L = 0$ and two doublets with $L = 1$. The doublet of states with $j_q = 1/2$ is expected to be wide (with typical widths $100 - 200$ MeV) and thus difficult to distinguish from the combinatoric background in the current environment. On the other hand, the states $(B_1, B_2^*)$ of the doublet with $j_q = 3/2$ are relatively narrow ($\Gamma = 10 - 20$ MeV). The neutral states $B_1^0$ and $B_2^{*0}$ have been observed by the D0 [7] and CDF [8] experiments. LHCb has performed the analysis of the $B^+\pi^-$ and $B^0\pi^-$ final states using a data sample corresponding to 336 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV to study the excited $B$ states [9]. The $B$ mesons are reconstructed in $J/\psi K^{(*)}, D\pi, D\pi\pi\pi$ decay modes. They are then combined with charged pion tracks, and the invariant mass difference spectra $m(B\pi) - m(B) - m(\pi)$ are studied (see Fig. 2).

Since $B_2^*$ can decay to both $B\pi$ and $B^*\pi$, and the soft photon from $B^* \rightarrow B\gamma$ decay is not reconstructed, it gives rise to two peaks in the spectrum with the mass difference of $m(B^*) - m(B) = 45.78$ MeV/$c^2$. The $B_1$ state decays to $B^*\pi$ only, and thus gives a single peak with the mass shifted by 45.78 MeV/$c^2$ due to lost soft photon. As a result, the peaks from both excited $B$ states overlap, and additional external constraints are needed to ensure a stable fit. In the current analysis, the ratio of the $B_2^* \rightarrow B\pi$ and the $B_2^* \rightarrow B^*\pi$ yields is fixed to its theoretical expectation of $0.93 \pm 0.18$, as is the ratio of the $B_1$ and $B_2^*$ widths ($0.9 \pm 0.2$). The mass resolution ($\sim 3$ MeV/$c^2$ in the simulation) is negligible compared to the widths of the excited $B$ states, thus Breit-Wigner shapes are used to
The mass difference \( m \) consistent with the measurements performed by CDF and D0, while the charged two signal contributions. The signals are parameterised with Gaussian shapes. The fit yields the again, one expects one peak in the spectrum from \( B \) narrow, with the widths much smaller than the invariant mass resolution (\( \sim 1 \) MeV/c\(^2\) for LHCb). The mass difference \( m(BK) - m(B) - m(K) \) spectrum from the LHCb analysis is shown in Fig. 3. Again, one expects one peak in the spectrum from \( B_{s1} \rightarrow B^+K \) decay, and two peaks from \( B_{s2}^* \) decaying to \( BK \) and \( B^*K \). The \( B_{s2}^* \rightarrow B^*K \) is not statistically significant, and thus the fit uses only two signal contributions. The signals are parameterised with Gaussian shapes. The fit yields the following values for the masses of two excited \( B_s \) states:

\[
M(B_{s1}^0) = (5828.99 \pm 0.08_{\text{stat}} \pm 0.13_{\text{syst}} \pm 0.45_{\text{B mass}}) \text{ MeV}/c^2,
M(B_{s2}^0) = (5839.67 \pm 0.13_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.29_{\text{B mass}}) \text{ MeV}/c^2.
\]

4. Beauty baryons

The system of heavy baryons has much more degrees of freedom compared to mesons. Baryons with a single heavy quark can be described as a system of a heavy quark and a light diquark. Even
in the absence of the orbital excitation, there is a large number of states with different quark content and spin configurations that can be classified by their isospin $I$, spin-parity $J^P$, and the spin-parity of the light diquark $j^P$ (see Table 1).

Many of these states with the charm quark, as well as the orbitally (and/or radially) excited states have been observed by the B factories. The system of beauty baryons, though, is much less well studied. Until recently, only some of the ground states have been observed experimentally. In the last few years, though, Tevatron and LHC experiments have reported many new observations of beauty baryonic states.

Large and clean samples of weakly decaying ground-state baryons are essential in order to

<table>
<thead>
<tr>
<th>Name</th>
<th>Quark content</th>
<th>$I$</th>
<th>$j^P$</th>
<th>$J^P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_Q$</td>
<td>$Qud$</td>
<td>0</td>
<td>0$^+$</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>$\Sigma_Q$</td>
<td>$Qqq$</td>
<td>1</td>
<td>1$^+$</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>$\Sigma_Q$</td>
<td>$Qqq$</td>
<td>1</td>
<td>1$^+$</td>
<td>3/2$^+$</td>
</tr>
<tr>
<td>$\Xi_Q$</td>
<td>$Qsq$</td>
<td>1/2</td>
<td>0$^+$</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>$\Xi'_Q$</td>
<td>$Qsq$</td>
<td>1/2</td>
<td>1$^+$</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>$\Xi''_Q$</td>
<td>$Qsq$</td>
<td>1/2</td>
<td>1$^+$</td>
<td>3/2$^+$</td>
</tr>
<tr>
<td>$\Omega_Q$</td>
<td>$Qss$</td>
<td>0</td>
<td>1$^+$</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>$\Omega'_Q$</td>
<td>$Qss$</td>
<td>0</td>
<td>1$^+$</td>
<td>3/2$^+$</td>
</tr>
</tbody>
</table>

Figure 3: Distributions of the invariant mass difference $m(BK) - m(B) - m(K)$ for $B^+K^-$ combination.

Table 1: Classification of heavy baryons with one heavy quark $Q$. 

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study the strong transitions of excited beauty baryons. The $\Lambda_b^0$ baryons are produced copiously in the hadronic environment. CDF reconstructs the signal of $19300 \Lambda_b^0 \rightarrow \Lambda_c^+\pi$ decays with the signal-to-background ratio around 1.9 [10] in their 6 fb$^{-1}$ data sample of $p\bar{p}$ collisions at 1.96 TeV. A recent analysis of LHCb [11] based on 1 fb$^{-1}$ statistics of $pp$ collisions with $\sqrt{s} = 7$ TeV uses the sample of $70540 \pm 330 \Lambda_b^0$ reconstructed in the same final state with the signal-to-background ratio of 11.

The ground state of the strange content $\Xi_b^-$ as well as the doubly-strange $\Omega_b^-$ have been studied previously by D0 [12, 13] and CDF [14]. While the measured mass of the $\Xi_b^-$ agrees well between the measurements of the two collaborations, the value of the $\Omega_b^-$ mass is inconsistent, with the results of two measurements differing by more than 100 MeV/c$^2$. LHCb has performed a study of these states with 576 pb$^{-1}$ data sample at $\sqrt{s} = 7$ TeV [15]. The $\Xi_b^-$ baryons are reconstructed in the decay chain $\Xi_b^- \rightarrow J/\psi\Xi^-, \Xi^- \rightarrow \Lambda^0\pi^-, \Lambda^0 \rightarrow p\pi^-; \text{the signal of } 72.2 \pm 9.4 \text{ events is observed.}$ Similarly, $13.9^{+4.5}_{-3.8} \text{ events are observed in the decay } \Omega_b^- \rightarrow J/\psi\Omega^-, \Omega^- \rightarrow \Lambda^0K^-, \Lambda^0 \rightarrow p\pi^-; \text{ the significance of } \Omega_b^- \text{ signal is above } 5 \text{ standard deviations.}$ The masses of these states are measured to be

$$M(\Xi_b^-) = 5796.5 \pm 1.2_{\text{stat}} \pm 1.2_{\text{syst}} \text{MeV}/c^2,$$

$$M(\Omega_b^-) = 6050.3 \pm 4.5_{\text{stat}} \pm 2.2_{\text{syst}} \text{MeV}/c^2.$$

The $\Omega_b^-$ mass is in a good agreement with the CDF measurement [14], but is in contradiction with the D0 result [13].

The remaining weakly-decaying beauty baryon, $\Xi_b^0$, has been discovered by CDF only recently [16]. CDF use the decay chain $\Xi_b^0 \rightarrow \Xi_c^+\pi^-, \Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+, \Xi^- \rightarrow \Lambda^0\pi^- \text{ to search for } \Xi_b^0 \text{ in their } 4.2 \text{ fb}^{-1} \text{ data sample.}$ A clean signal of $25.3^{+5.6}_{-5.4} \text{ has been observed, with a significance of } 6.8 \text{ standard deviations.}$ The $\Xi_b^0$ mass measured in this analysis is

$$M(\Xi_b^0) = 5787.8 \pm 5.0_{\text{stat}} \pm 1.3_{\text{syst}} \text{MeV}/c^2.$$

The LHCb collaboration has also observed a hint of $\Xi_b^0$ production in the study of $D^0pK^-$ final state with a sample of 330 pb$^{-1}$ [17], corresponding to $27 \pm 10 \text{ events with the significance of } 2.6 \text{ standard deviations.}$ The mass of $\Xi_b^0$ is measured to be

$$M(\Xi_b^0) = 5802.0 \pm 5.5_{\text{stat}} \pm 1.7_{\text{syst}} \text{MeV}/c^2.$$

$\Sigma_b$ baryons that decay strongly to $\Lambda_b^0\pi$ have been observed by CDF [18]; recently the analysis has been updated with 6 fb$^{-1}$ data sample [10]. $\Lambda_b^0$ candidates are combined with the charged pion tracks, and the invariant mass difference $Q = m(\Lambda_b^0\pi) - m(\Lambda_b^0) - m(\pi)$ spectra are studied. The spectra are shown in Fig. 4. Ground states $\Sigma_b^0$ and spin excitations $\Sigma_b^{\pm}$ are observed in the spectra. Masses and natural widths of these states are obtained from the fit with the signal contributions modeled with Breit-Wigner shapes; the fit results are given in Table 2. The neutral states of the $\Sigma_b^{(*)}$ triplets still remain unobserved.

Observation of the excited $\Xi_b^0$ baryon has been reported very recently by the CMS collaboration [19] in the analysis of 5.3 fb$^{-1}$ of data with $\sqrt{s} = 7$ TeV. CMS studies the decay chain $\Xi_b^0 \rightarrow \Xi^-\pi^+, \Xi^- \rightarrow J/\psi\Xi^-, \Xi^- \rightarrow \Lambda^0\pi^-$. A signal of $108 \pm 14 \text{ } \Xi_b^-$ decays is observed, and 21
nations from the CDF analysis [18].

The kinematic fit with Λ final state and is combined with a pair of pion track coming from the primary interaction vertex.

The quark model predicts two to Λ Ξ where the last uncertainty is due to the precision of deviations, and the result of the mass measurement is

\[ Q = m(Λ_{b}^{0}π^{0}) - m(Λ_{b}^{0}) - m(π^{0}) \]

for (a) Λ_{b}^{0}π^{−} and (b) Λ_{b}^{0}π^{+} combinations from the CDF analysis [18].

Figure 4: Spectra of the mass difference \( Q = m(Λ_{b}^{0}π^{0}) - m(Λ_{b}^{0}) - m(π^{0}) \) for (a) Λ_{b}^{0}π^{−} and (b) Λ_{b}^{0}π^{+} combinations from the CDF analysis [18].

Table 2: Properties of the Σ_{b}^{(s)±} states obtained in the analysis by CDF [18].

<table>
<thead>
<tr>
<th>State</th>
<th>( Q ), MeV/c^2</th>
<th>Mass ( M ), MeV/c^2</th>
<th>Width ( Γ ), MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Σ_{b}^-</td>
<td>56.2^{+0.6+0.1}_{−0.5−0.4}</td>
<td>5815.5^{+0.6}_{−0.5} ± 1.7</td>
<td>4.9^{+5.1}_{−2.1} ± 1.1</td>
</tr>
<tr>
<td>Σ_{b}^-</td>
<td>75.8 ± 0.6^{+0.1}_{−0.6}</td>
<td>5835.1 ± 0.6^{+1.7}_{−1.8}</td>
<td>7.5^{+2.2}_{−1.8} ± 0.9</td>
</tr>
<tr>
<td>Σ_{b}^+</td>
<td>52.1^{−0.9−0.1}_{+0.8+0.4}</td>
<td>5811.3^{−0.8}_{+0.9} ± 1.7</td>
<td>9.7^{+3.8}_{−2.8} ± 1.2</td>
</tr>
<tr>
<td>Σ_{b}^{++}</td>
<td>72.8 ± 0.7_{−0.6}</td>
<td>5832.1 ± 0.7^{+1.7}_{−1.8}</td>
<td>11.5^{+2.7+1.0}_{−2.8−1.5}</td>
</tr>
</tbody>
</table>

events peak in the Ξ_{b}^{−}π^{+} spectrum (see Fig. 5). The significance of the observation is 5.7 standard deviations, and the result of the mass measurement is

\[ M(Ξ_{b}^{0}) = 5945.0 ± 0.7_{\text{stat}} ± 0.3_{\text{syst}} ± 2.7_{\text{PDG}} \text{ MeV/c}^2, \]

where the last uncertainty is due to the precision of Ξ_{b}^{0} mass. This state is interpreted as the Ξ_{b}^{0} baryon with the quantum numbers \( J^P = 3/2^{−} \). Ξ_{b}^{−} is expected to be below kinematic threshold for Ξ_{b}π decay, while the decays of orbital excitations Ξ_{b}^{*} with \( L = 1 \) to Ξ_{b}π are forbidden by parity conservation.

No experimental evidence of the orbitally-excited beauty baryons was available until recently. The quark model predicts two \( L = 1 \) excitations of Λ_{b}^{0} with \( J^P = 1/2^{−} \) and \( 3/2^{−} \). Both should decay to Λ_{b}^{0}π^{−}π^{−} or Λ_{b}^{0}γ, depending on their mass. Most theoretical predictions give masses above the Λ_{b}^{0}π^{−}π^{−} threshold at 5900 MeV/c^2, but below Λ_{b}π threshold.

The first observation of orbitally-excited beauty baryons has been made by LHCb [11] in the final state Λ_{b}^{0}π^{−}π^{−} using 1 fb\(^{−1}\) of data at \( \sqrt{s} = 7 \) TeV. The Λ_{b}^{0} is reconstructed in Λ_{c}^{−}π^{−} final state and is combined with a pair of pion track coming from the primary interaction vertex. The kinematic fit with Λ_{b}^{0} and Λ_{c}^{−} mass constraints is performed to improve the invariant mass.
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Figure 5: Invariant mass difference $m(\Xi_c^+\pi^-) - m(\Xi_c^-) - m(\pi^+)$ distribution from CMS analysis.

Figure 6: Invariant mass distribution of $\Lambda_b^0\pi^+\pi^-$ combinations from LHCb analysis.

resolution. The spectrum of the $\Lambda_b^0\pi^+\pi^-$ invariant masses is shown in Fig. 6. Two narrow peaks are evident at the masses around 5912 MeV/$c^2$ and 5920 MeV/$c^2$, with the signal yields of $16.4 \pm 4.7$ and $49.5 \pm 7.9$ events, respectively. The proximity of the kinematic threshold gives excellent invariant mass resolution, 0.2–0.3 MeV/$c^2$. The fit of the spectrum yields the following masses for the two states:

$$M_{\Lambda_b^0(5912)} = 5911.95 \pm 0.12_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.66_{\text{mass}} \text{MeV}/c^2,$$

$$M_{\Lambda_b^0(5920)} = 5919.76 \pm 0.07_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.66_{\text{mass}} \text{MeV}/c^2,$$

The significances of the observation (including the systematic effects and trial factor in the mass range 5900–5950 MeV/$c^2$) are 4.9 and 10.1 standard deviations, respectively. The upper limits on the natural widths of the two states are also obtained:

$$\Gamma_{\Lambda_b^0(5912)} < 0.82 \text{ MeV},$$

$$\Gamma_{\Lambda_b^0(5920)} < 0.71 \text{ MeV}$$

at the 95% confidence level.

5. Summary

Numerous new results in charm and beauty hadron spectroscopy have appeared in the recent two years. After the start of LHC, the LHCb experiment has not only confirmed some of the observations made previously by the Tevatron and B factories (such as the observation of $D_{s1}(2710)^+$, $D_{sJ}^*(2860)^+$ and $B^{s*0}_{(s)}$ mesons, $\Xi_c^-$ and $\Omega_c^-$ baryons), but has also observed a number of new states: $B^{**+}$ mesons and orbitally excited $\Lambda_b^0$ baryons. Several new observations have been performed in the relatively unexplored system of beauty baryons by other experiments. These are the discoveries of the $\Xi_b^0$ by CDF and of the $\Xi_b^{*0}$ by CMS. The masses of the new beauty hadrons are consistent with the theoretical predictions. For most of these particles the quantum numbers have not been measured experimentally yet.
References

[17] LHCb collaboration, LHCb-CONF-2011-036