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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 $D^{*}_{sJ}(2860)^{+}$ 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 $\vec{S} = \vec{s}_Q + \vec{s}_q$ 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^*_0, D'_1) with $J^P = (0^+, 1^+)$, and another with $j_q = 3/2$: (D_1, D^*_2) 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 $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$ 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 $D^*_{s2}(2573)^+$, while the contributions from $D^*_{s1}(2710)^+$ and $D^*_{sJ}(2860)^+$ are also clearly visible. The parameters of the $D^*_{s1}(2710)^+$ and $D^*_{sJ}(2860)^+$ states obtained from the fit are

$$
\begin{aligned}
M(D^*_{s1}(2710)^+) &= (2709.4 \pm 1.9_{\rm stat} \pm 4.5_{\rm syst})\,\mathrm{MeV}/c^2, \\
\Gamma(D^*_{s1}(2710)^+) &= (121.7 \pm 7.3_{\rm stat} \pm 12.1_{\rm syst})\,\mathrm{MeV}, \\
M(D^*_{sJ}(2860)^+) &= (2866.7 \pm 1.0_{\rm stat} \pm 6.3_{\rm syst})\,\mathrm{MeV}/c^2, \\
\Gamma(D^*_{sJ}(2860)^+) &= (64.5 \pm 3.2_{\rm stat} \pm 6.6_{\rm syst})\,\mathrm{MeV}.
\end{aligned}
$$

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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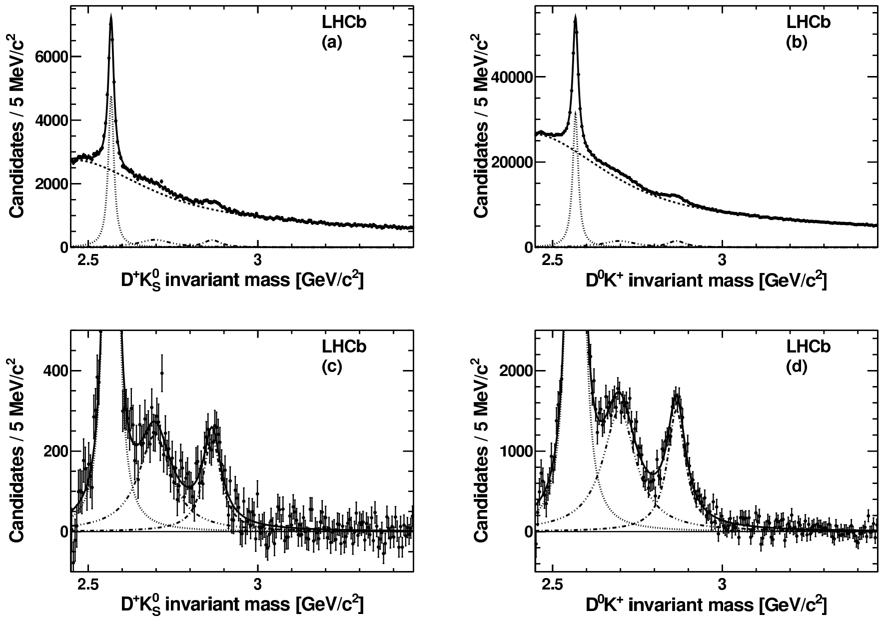

Figure 1: Invariant mass distributions for (a) $D^+K^0_S$ and (b) D^0K^+ combinations and background-subtracted distributions for (c) $D^+K^0_S$ and (d) D^0K^+.

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 $B^*\to B\gamma$ 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 $B_2^*\to B\pi$ and the $B_2^*\to B^*\pi$ yields is fixed to its theoretical expectation of 0.93 ± 0.18, as is the ratio of the B_1 and B_2^* widths (0.9 ± 0.2). The mass resolution (~ 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

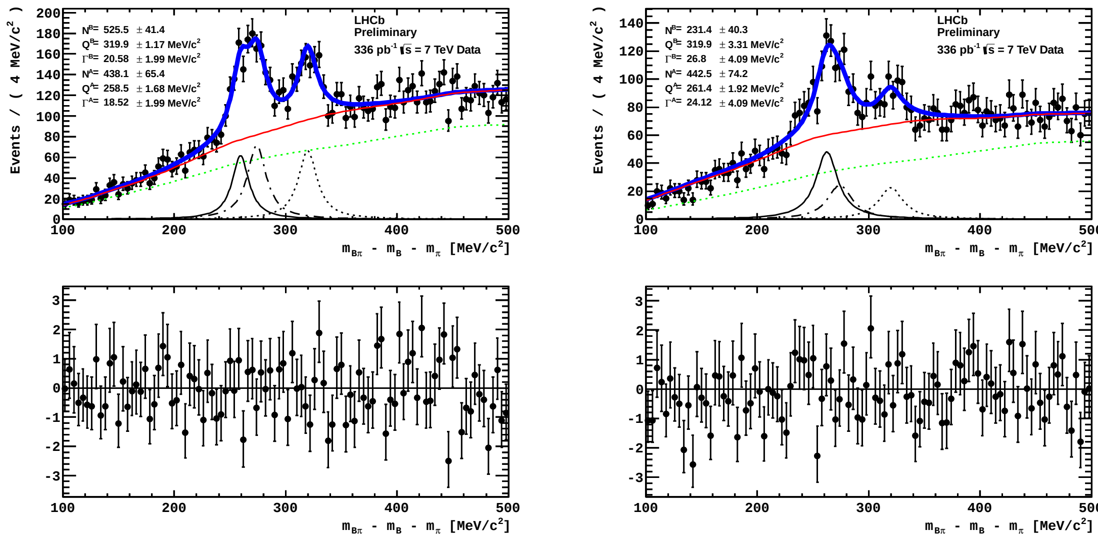

Figure 2: Distributions of invariant mass difference $m(B\pi)-m(B)-m(\pi)$ for (a) $B^0\pi$ and (b) $B^+\pi^-$ combinations.

model the signals. The results of the fit are

$$M(B_1^0) = (5724.1 \pm 1.7_{\rm stat} \pm 2.0_{\rm syst} \pm 0.5_{\rm B\ mass})\ {\rm MeV}/c^2,$$
$$M(B_1^+) = (5726.3 \pm 1.9_{\rm stat} \pm 3.0_{\rm syst} \pm 0.5_{\rm B\ mass})\ {\rm MeV}/c^2,$$
$$M(B_2^{*0}) = (5738.6 \pm 1.2_{\rm stat} \pm 1.2_{\rm syst} \pm 0.3_{\rm B\ mass})\ {\rm MeV}/c^2,$$
$$M(B_2^{*+}) = (5739.0 \pm 3.3_{\rm stat} \pm 1.6_{\rm syst} \pm 0.3_{\rm B\ mass})\ {\rm MeV}/c^2,$$

where the last uncertainty is due to the B meson mass. The parameters of the B_1^0 and B_2^{*0} states are consistent with the measurements performed by CDF and D0, while the charged B_1^+ and B_2^{*+} states are observed for the first time.

The study of the B^+K^- spectrum allows one to understand the excitations in the beauty-strange system, B_{s1} and B_{s2}^*. Due to proximity of these states to the kinematic threshold, these states are narrow, with the widths much smaller than the invariant mass resolution (~ 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 $B_{s1}\to B^*K$ decay, and two peaks from B_{s2}^* decaying to BK and B^*K. The $B_{s2}^*\to B^*K$ 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:

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

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

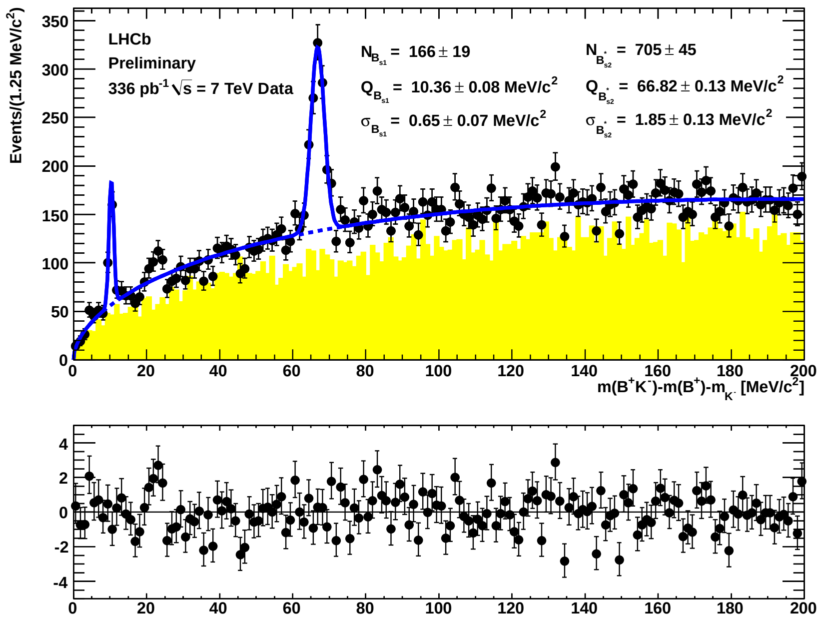

Figure 3: Distributions of the invariant mass difference $m(BK) - m(B) - m(K)$ for B^+K^- combination.

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

Name	Quark content	I	j^p	J^P
Λ_Q	Qud	0	0^+	$1/2^+$
Σ_Q	Qqq	1	1^+	$1/2^+$
Σ^*_Q	Qqq	1	1^+	$3/2^+$
Ξ_Q	Qsq	1/2	0^+	$1/2^+$
Ξ'_Q	Qsq	1/2	1^+	$1/2^+$
Ξ^*_Q	Qsq	1/2	1^+	$3/2^+$
Ω_Q	Qss	0	1^+	$1/2^+$
Ω^*_Q	Qss	0	1^+	$3/2^+$

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 study the strong transitions of excited beauty baryons. The Λ_b^0 baryons are produced copiously in the hadronic environment. CDF reconstructs the signal of 19300 $\Lambda_b^0 \to \Lambda_c^+\pi$ 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 ± 330 Λ_b^0 reconstructed in the same final state with the signal-to-background ratio of 11.

The ground state of the strange content Ξ_b^- as well as the doubly-strange Ω_b^- have been studied previously by D0 [12, 13] and CDF [14]. While the measured mass of the Ξ_b^- agrees well between the measurements of the two collaborations, the value of the Ω_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 Ξ_b^- baryons are reconstructed in the decay chain $\Xi_b^- \to J/\psi\Xi^-$, $\Xi^- \to \Lambda^0\pi^-$, $\Lambda^0 \to p\pi^-$; the signal of 72.2 ± 9.4 events is observed. Similarly, $13.9^{+4.5}_{-3.8}$ events are observed in the decay $\Omega_b^- \to J/\psi\Omega^-$, $\Omega^- \to \Lambda^0 K^-$, $\Lambda^0 \to p\pi^-$; the significance of Ω_b^- signal is above 5 standard deviations. The mases of these states are measured to be

$$M(\Xi_b^-) = 5796.5 \pm 1.2_{\rm stat} \pm 1.2_{\rm syst}\,{\rm MeV}/c^2,$$
$$M(\Omega_b^-) = 6050.3 \pm 4.5_{\rm stat} \pm 2.2_{\rm syst}\,{\rm MeV}/c^2.$$

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

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

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

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

Σ_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]. Λ_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 $\Sigma_b^\pm$ 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 Ξ_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 $\Xi_b^{*0} \to \Xi_b^-\pi^+$, $\Xi_b^- \to J/\psi\Xi^-$, $\Xi^- \to \Lambda^0\pi^-$. A signal of 108 ± 14 Ξ_b^- decays is observed, and 21

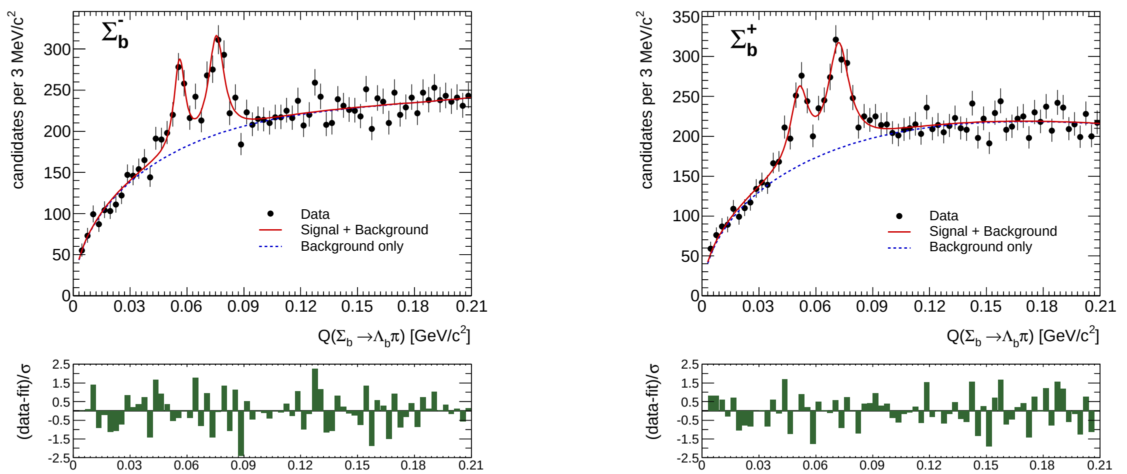

Figure 4: Spectra of the mass difference $Q = m(\Lambda_b^0\pi) - m(\Lambda_b^0) - m(\pi)$ for (a) $\Lambda_b^0\pi^-$ and (b) $\Lambda_b^0\pi^+$ combinations from the CDF analysis [18]

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Table 2: Properties of the $\Sigma_b^{(*)\pm}$ states obtained in the analysis by CDF [18].

State	Q, MeV/c^2	Mass M, MeV/c^2	Width Γ, MeV
Σ_b^-	$56.2^{+0.6+0.1}_{-0.5-0.4}$	$5815.5^{+0.6}_{-0.5} \pm 1.7$	$4.9^{+3.1}_{-2.1} \pm 1.1$
Σ_b^{*-}	$75.8 \pm 0.6^{+0.1}_{-0.6}$	$5835.1 \pm 0.6^{+1.7}_{-1.8}$	$7.5^{+2.2+0.9}_{-1.8-1.4}$
Σ_b^+	$52.1^{+0.9+0.1}_{-0.8-0.4}$	$5811.3^{+0.9}_{-0.8} \pm 1.7$	$9.7^{+3.8+1.2}_{-2.8-1.1}$
Σ_b^{*+}	$72.8 \pm 0.7^{+0.1}_{-0.6}$	$5832.1 \pm 0.7^{+1.7}_{-1.8}$	$11.5^{+2.7+1.0}_{-2.2-1.5}$

events peak in the $\Xi_b^-\pi^+$ spectrum (see Fig. 5). The significance of the observation is 5.7 standard deviations, and the result of the mass measurement is

$$M(\Xi_b^{*0}) = 5945.0 \pm 0.7_{\rm stat} \pm 0.3_{\rm syst} \pm 2.7_{\rm PDG}\ \text{MeV}/c^2,$$

where the last uncertainty is due to the precision of Ξ_b^- 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 $\Xi_b\pi$ decay, while the decays of orbital excitations Ξ_b^{**} with $L = 1$ to $\Xi_b\pi$ 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 $\Lambda_b^0\pi^+\pi^-$ or $\Lambda_b^0\gamma$, depending on their mass. Most theoretical predictions give masses above the $\Lambda_b^0\pi^+\pi^-$ threshold at 5900 MeV/c^2, but below $\Sigma_b\pi$ threshold.

The first observation of orbitally-excited beauty baryons has been made by LHCb [11] in the final state $\Lambda_b^0\pi^+\pi^-$ using 1 fb^{-1} of data at $\sqrt{s} = 7$ TeV. The Λ_b^0 is reconstructed in $\Lambda_c^+\pi^-$ 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

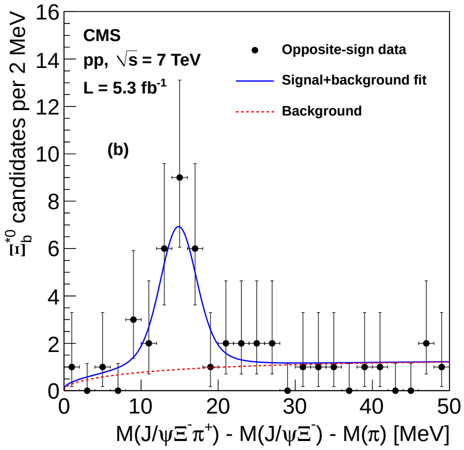

Figure 5: Invariant mass difference $m(\Xi_b^- \pi^+) - m(\Xi_b^-) - m(\pi^+)$ distribution from CMS analysis [19].

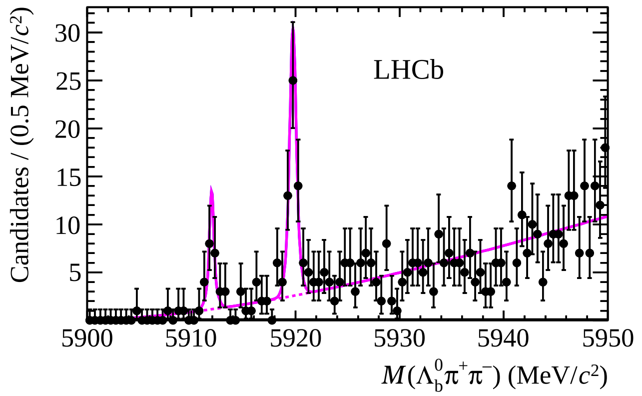

Figure 6: Invariant mass distribution of $\Lambda_b^0 \pi^+ \pi^-$ combinations from LHCb analysis [11].

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 ± 4.7 and 49.5 ± 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:

$$M_{\Lambda_b^{*0}(5912)} = 5911.95 \pm 0.12_{\rm stat} \pm 0.03_{\rm syst} \pm 0.66_{\Lambda_b^0\ {\rm mass}}\,{\rm MeV}/c^2,$$
$$M_{\Lambda_b^{*0}(5920)} = 5919.76 \pm 0.07_{\rm stat} \pm 0.02_{\rm syst} \pm 0.66_{\Lambda_b^0\ {\rm mass}}\,{\rm MeV}/c^2,$$

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:

$$\Gamma_{\Lambda_b^{*0}(5912)} < 0.82\,{\rm MeV},$$
$$\Gamma_{\Lambda_b^{*0}(5920)} < 0.71\,{\rm MeV}$$

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 $B_{(s)}^{**0}$ mesons, Ξ_b^- and Ω_b^- baryons), but has also observed a number of new states: B^{**+} mesons and orbitally excited Λ_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 Ξ_b^0 by CDF and of the Ξ_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.

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