Studies of excited states of beauty hadrons at CMS

Kirill Ivanov on behalf of the CMS Collaboration
Moscow Institute of Physics and Technology, Russia
E-mail: kirill.ivanov@cern.ch

Abstract. Studies of excited states of beauty mesons and baryons, performed at the CMS Experiment, are presented. The first observation of $B_c^+(2S)$ and $B_c^{*+}(2S)$ states in the $B_c^+\pi^+\pi^-$ invariant mass spectrum is reported as well as the study of excited $\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$, $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ baryons decaying to $\Lambda_b^0\pi^+\pi^-$. The analyses use Run-2 data, collected in $pp$ collisions at $\sqrt{s} = 13$ TeV.

1. Introduction
Studies of excited states of heavy hadrons and measurements of their properties add valuable information to our understanding of interquark strong interaction and hadron formation. The CMS Experiment [1] at the CERN LHC is actively contributing new results in the heavy flavor spectroscopy.

In the present work, two recent results from the CMS Collaboration are reported: the observation of the new $B_c^+(2S)$ and $B_c^{*+}(2S)$ states in the $B_c^+\pi^+\pi^-$ invariant mass spectrum [2] and the study of excited $\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$, $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ baryons decaying to $\Lambda_b^0\pi^+\pi^-$. The latter spectrum also shows evidence for a broad enhancement in the 6040-6100 MeV region, whose true origin can not be clarified with the present data sample. Both analyses have been performed using proton-proton collisions data collected by the CMS experiment at the LHC at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 143 fb$^{-1}$ for [2] and 140 fb$^{-1}$ for [3]. The inclusion of charge-conjugated states is implied throughout the work.

2. Observation of $B_c^+(2S)$ and $B_c^{*+}(2S)$ in $B_c^+\pi^+\pi^-$ invariant mass spectrum
The mesons of the $B_c$ family are the lightest hadrons consisting of two heavy quarks: charm $c$ and beauty $b$. The spectrum of the heavier $B_c$ excited states is expected to decay predominantly via a cascade of photon emission since the beauty-charmed mesons do not annihilate into gluons. However, the $B_c(2S)$ states are also predicted to decay strongly: $B_c^+(2S)$ directly to $B_c^+\pi^+\pi^-$ and $B_c^{*+}(2S)$ to $B_c^{*+}\pi^+\pi^-$, where the soft photon from the following $B_c^{*+} \rightarrow B_c^+\gamma$ is not reconstructed. The detector resolution is smaller than $\Delta M \equiv [M(B_c^{*+}) - M(B_c^+)] - [M(B_c^+(2S)) - M(B_c^+(2S))]$, the $B_c^{*+}(2S)$ peak is expected to be observed at a lower value than the $B_c^+(2S)$ peak in the $B_c^+\pi^+\pi^-$ invariant mass distribution. The scheme of such transitions for the lightest $B_c$ state is provided in figure 1.

The LHC high energy and immense data statistics provide great opportunities for new searches of excited states via such strong decays. A structure consistent with $B_c^+(2S)$ with a mass $6842\pm4$(stat.$)\pm5$(syst.$)$ MeV was observed by the ATLAS Collaboration in 2014 using
Figure 1. Transitions between the lightest $B_c^+$ states, with solid and dashed lines indicating the emission of photons and pion pairs, respectively [2].

Run-1 data collected at 7 and 8 TeV [4], while the later 8 TeV analysis by the LHCb Collaboration showed no evidence for such a state [5]. In 2019 the CMS Experiment presented the observation of two well-resolved $B_c^+(2S)$ and $B_c^{+(2S)}$ signals in the $B_c^+(2S)^+\pi^+\pi^-$ final state together with the measurement of the $B_c^+(2S)$ mass, using full Run-2 2015-2018 data sample [2].

The CMS analysis used combinations of the dimuons with a track with pion mass assignment in order to reconstruct the ground $B_c^+$ state via $B_c^+\rightarrow J/\psi\pi^+$ decay. The $B_c^+$ candidates are obtained by performing a kinematic vertex fit of $\mu^+\mu^-\pi^+$, that constrains the dimuon invariant mass to the world-average $J/\psi$ mass [6]. From all reconstructed $pp$ collision vertices, the primary vertex (PV) is chosen as the one with the smallest pointing angle, which is the angle between the $B_c^+$ candidate momentum and the vector joining the PV with the reconstructed $B_c^+$ candidate decay vertex. Only the $B_c^+$ candidate with the highest $p_T$ is kept in every event.

The resulting $J/\psi\pi^+$ invariant mass distribution is presented in figure 2 (a). The data are superimposed to the unbinned maximum-likelihood fit, composed of one $B_c^+$ signal, modeled with a double Gaussian function with a common mean, and three background components. The first one is described by a first-order polynomial and corresponds to combinatorial background, the second one presents partially reconstructed $B_c^+\rightarrow J/\psi\pi^+X$ decays below 6.2 GeV and is modelled with a generalized ARGUS function convolved with a Gaussian resolution, and the latter one, whose shape is obtained in MC simulation, describes the contribution from the $B_c^+\rightarrow J/\psi K^+$ decay. The normalization of the last component is fixed relative to the $B_c^+\rightarrow J/\psi\pi^+$ using the known branching fraction ratio [6] and reconstruction efficiency from simulation studies. The fit returns the $B_c^+$ signal yields, masses and resolution of, respectively equal to, 7629 $\pm$ 225, 6271.1 $\pm$ 0.5 MeV and 33.5 $\pm$ 2.5 MeV, where the uncertainties are statistical only.

For the search for excited $B_c^+(2S)$ states the $B_c^+$ candidates from the signal region (6.2–6.355 GeV, indcuted in figure 2 (a) with vertical dashed lines) are combined with two opposite-sign tracks. Since the lifetime of excited $B_c^+(2S)$ states is expected to be negligible, resulting in prompt decays, the tracks must originate from the PV. A kinematic fit of $B_c^+\pi^+\pi^-$ candidates to the common vertex is performed. As for the inclusive $B_c^+$ signal, in case of multiple candidates in a single event only the candidate with the highest $p_T(B_c^+\pi^+\pi^-)$ is kept.

The invariant mass distribution of the selected $B_c^+\pi^+\pi^-$ candidate is presented in figure 2 (b). The variable $M(B_c^+\pi^+\pi^-) - M(B_c^+) + m_{B_c}$ is used to cancel the effect of $B_c^+$ non-zero detector
resonance. Two clear well-resolved peaks are observed, consistent with the expectations of excited \(B_c^+ (2S)\) and \(B_c^{+(2S)}\) mesons. The position of the signals is also consistent with the mass of the peak, observed by the ATLAS Experiment [4]. An unbinned extended maximum-likelihood fit is performed, with signal peaks described as a Gaussian function for both of them, and the combinatorial background is modelled with a third-order polynomial. The two small contributions to the peaks, considered to be from \(B_c^+ \rightarrow J/\psi K^+\) decay, are described with the signal shape which normalization fixed to the ratio of inclusive \(B_c^+\) channels yields. The fit result is \(67 \pm 10\) events for the lower-mass peak and \(51 \pm 10\) — for the higher-mass one, with a mass difference \(\Delta M = 29.1 \pm 1.5\) MeV, where the uncertainties are statistical only. The Gaussian resolutions are approximately 6 MeV, consistent with the results from MC simulation studies.

The alternative fit with the signals described with a Breit-Wigner function convolved with the Gaussian resolution, fixed to the one obtained in MC, gives a result consistent with zero for the natural width value.

The local statistical significance of the two-peaks hypothesis with respect to the single-peak one, calculated using likelihood-ratio technique, is more than 6\(\sigma\). Given the prediction about the \(B_c^+\) excited states mass splitting, since \(\Delta M\) is significantly larger than detector resolution, the higher-mass peak is expected to correspond to the \(B_c^+ (2S)\) meson, with a mass equal to 6871.0 \(\pm 1.2\) (stat.) MeV, and the lower peak corresponds to the \(B_c^{+(2S)}\) excitation.

Several sources of systematic uncertainties in the measured mass and mass difference are considered. Most of them, such as the sensitivity to the selection (rapidity, \(p_T\)), possible differences between data and simulation resolution, potential misalignments of the tracker detectors, using of alternative background models and variation of \(B_c^+\) mass window (related with partial reconstructed \(B_c^+\) decays) lead to a negligible change in measurements. The main source of systematic uncertainties originates from signal model variation, where for an alternative fit the Gaussian function was replaced by a Breit--Wigner function for both signal peaks. The observed deviations from the baseline values, equal to 0.8 MeV for \(M(B_c^+ (2S))\) and 0.7 MeV for \(\Delta M\), are taken as the corresponding systematic uncertainty.

**Figure 2.** The invariant mass distributions of \(B_c^+\) (a) and \(B_c^{+(2S)}\) (b) candidates, superimposed with the fit results [2]. The vertical dashed lines of the plot (a) indicate the \(B_c^+\) mass window retained for the reconstruction of the \(B_c^+ (2S)\) and \(B_c^{+(2S)}\) candidates, which signals are presented in the plot (b).

3. Study of excited \(\Lambda_b^0\) states decaying to \(\Lambda_b^0 \pi^+ \pi^-\)

Most of the studies of excited beauty baryons are related to the lightest of their ground states, \(\Lambda_b^0\) baryon, consisting of udb quarks. The first doublet of \(\Lambda_b^0\) excitations, \(\Lambda_b^0(5912)^0\) and \(\Lambda_b^0(5920)^0\),
was observed by the LHCb Collaboration in 2012 via its decay to \( \Lambda_b^0 \pi^+ \pi^- \) [7], with their mass measured to be 5911.97 ± 0.67 MeV and 5919.77 ± 0.67 MeV. While there was no confirmation of the \( \Lambda_b(5912)^0 \) state existence, the evidence for the heavier \( \Lambda_b(5920)^0 \) state was reported by the CDF Collaboration in 2013 [8]. In 2019, two narrow higher-mass states were observed in the \( \Lambda_b^0 \pi^+ \pi^- \) invariant mass spectrum by the LHCb Experiment [9], with their masses and natural widths reported to be \( M(\Lambda_b(6146)^0) = 6146.17 \pm 0.43 \text{ MeV} \), \( \Gamma(\Lambda_b(6146)^0) = 2.9 \pm 1.3 \text{ MeV} \), and \( M(\Lambda_b(6152)^0) = 6152.51 \pm 0.38 \text{ MeV} \), \( \Gamma(\Lambda_b(6152)^0) = 2.1 \pm 0.9 \text{ MeV} \). A recent paper by the CMS Collaboration [3] confirms the existence of all four excited \( \Lambda_b^0 \) states as well as provides the evidence of a new broad structure in the 6040-6100 MeV region of \( \Lambda_b^0 \pi^+ \pi^- \) invariant mass spectrum.

The CMS analysis used \( \Lambda_b^0 \rightarrow J/\psi \Lambda \) and \( \Lambda_b^0 \rightarrow \psi(2S) \Lambda \) decay channels, where \( J/\psi \) is reconstructed in \( \mu^+ \mu^- \) channel and \( \psi(2S) \) is reconstructed in both \( \mu^+ \mu^- \) and \( J/\psi \pi^+ \pi^- \rightarrow \mu^+ \mu^- \pi^+ \pi^- \) channels. The \( \Lambda \) candidates are formed from displaced two-prong vertices, assuming the \( \Lambda \rightarrow p \pi^- \) decay.

The \( \Lambda_b^0 \) and \( \Lambda_b^0 \pi^+ \pi^- \) reconstruction procedure is similar to the one reported in a previous \( B_s^+ \pi^+ \pi^- \) analysis [2]. The reconstructed \( \Lambda \) and \( J/\psi \) (\( \psi(2S) \)) candidates are refitted to a common vertex with dimuon mass constrained to the world-average value, and the PV is chosen as the one with the smallest pointing angle. Then the \( \Lambda_b^0 \) candidates are combined with two opposite-sign tracks, originated from the PV. Combinations with two same-sign (SS) pions are used as a control channel. The selected \( \Lambda_b^0 \) candidate and all tracks forming the PV are refit to a common vertex in order to improve the \( \Lambda_b^0 \pi^+ \pi^- \) invariant mass resolution by up to 50%. The mass variable \( m_{\Lambda_b^0 \pi^+ \pi^-} = M(\Lambda_b^0 \pi^+ \pi^-) - M(\Lambda_b^0) + m_{\Lambda_b^0} \) is used to improve the resolution.

![Figure 3](image-url)

**Figure 3.** The invariant mass distributions of \( \Lambda_b^0 \pi^+ \pi^- \) candidates [3] near the threshold area. The peaks correspond to \( \Lambda_b(5912)^0 \) and \( \Lambda_b(5920)^0 \) signals.

In order to suppress the combinatorial background, the selection criteria for the \( \Lambda_b^0 \pi^+ \pi^- \) study were optimised using the Punzi figure of merit \( S/(\sqrt{S} + \sqrt{B}) \) [10], where the signal \( S \) is estimated from MC simulated samples and the background \( B \) — from the same-sign distribution in the signal area. The optimisation was performed separately for the near threshold and higher-mass regions. Only the highest \( p_T(\Lambda_b^0 \pi^+ \pi^-) \) candidate is kept in an event for the higher-mass region.

The \( \Lambda_b^0 \pi^+ \pi^- \) invariant mass distribution near the threshold is presented in figure 3. Two narrow and well-resolved peaks correspond to \( \Lambda_b(5912)^0 \) and \( \Lambda_b(5920)^0 \) states. Both signals are described with double Gaussian functions with a common mean with effective resolutions equal
to 0.6 MeV and 0.8 MeV, obtained from MC. The remaining smooth background is described by a threshold function \((x - x_0)^\alpha\), where \(x_0\) is the \(\Lambda_b^0\pi^+\pi^-\) mass threshold value. The unbinned maximum-likelihood fit returns the signal yields and masses equal to, respectively, \(28_{-10}^{+12}\) and \(6146_{-5}^{+7}\) for the \(\Lambda_b^0\pi^+\pi^-\) signal. The natural widths are taken from the LHCb Collaboration measurement \([9]\). The broad enhancement is modelled with the a Breit-Wigner resolution, fixed from simulation (about 3.8 MeV). The measured masses are \(6146.5 \pm 1.9\) MeV, \(6152.7 \pm 1.1\) MeV and \(6073 \pm 5\) MeV for \(\Lambda_b^0\pi^+\pi^-\), \(\Lambda_b(6152)^0\) and the broad state, respectively, and their fitted signal yields are \(301_{-10}^{+12}\) and \(35\) events. The obtained natural width of the broad enhancement is \(55 \pm 5\) MeV.

The signals local significance, evaluated with the likelihood-ratio technique, is above 6\(\sigma\) and 113\(\pm35\) events. The 6.15 GeV peak is described with two signal functions, which are the convolution of a Breit–Wigner function with a double Gaussian resolution, fixed from simulation (about 3.8 MeV). The natural widths are taken from the LHCb Collaboration measurement \([9]\). The broad enhancement is modelled with the a Breit-Wigner function convolved with a double Gaussian resolution (obtained from simulation study). Finally, the background is described with a threshold function multiplied by a first-order polynomial. The measured masses are \(6146.5 \pm 1.9\) MeV, \(6152.7 \pm 1.1\) MeV and \(6073 \pm 5\) MeV for \(\Lambda_b^0\pi^+\pi^-\), \(\Lambda_b(6152)^0\) and the broad state, respectively, and their fitted signal yields are \(301 \pm 72\), \(70 \pm 35\) and \(113 \pm 35\) events. The obtained natural width of the broad enhancement is \(55 \pm 5\) MeV. The signals local significance, evaluated with the likelihood-ratio technique, is above 6\(\sigma\) for the 6.15 GeV structure and about four standard deviations for the broad excess.

Several possible sources of systematic uncertainties in the measured masses have been considered. The alternative fit functions include single Gaussian resolution for signals decteptrion and a threshold function, multiplied by first- (second-) order polynomials for low (high) mass regions, for the background description. Several fits with alternative \(m_{\Lambda_b^0\pi^+\pi^-}\) ranges are performed, including one without the broad enhancement presence. A possible difference between data and MC simulation was estimated from the \(\Lambda_b^0 \rightarrow J/\psi\Lambda\) signal study.
and was found to be about 3.5%. Several alternative fits were performed by varying the natural widths of \( \Lambda_b(6146)^0 \) and \( \Lambda_b(6152)^0 \) states. As for the \( B^+\pi^+\pi^- \) study [2], possible misalignments of the tracker detectors lead to a negligible change in measurements. The resulting systematic uncertainties are 0.009 MeV, 0.011 MeV, 0.77 MeV and 0.41 MeV for \( M(\Lambda_b(5912)^0) \), \( M(\Lambda_b(5920)^0) \), \( M(\Lambda_b(6146)^0) \) and \( M(\Lambda_b(6152)^0) \) states, respectively.

4. Conclusion
In summary, the CMS Experiment provides valuable contributions to the spectroscopy of excited hadrons. Two new well-resolved \( B_c^+(2S) \) and \( B_c^+(2S) \) mesons were observed for the first time in \( B^+\pi^+\pi^- \) invariant mass spectrum [2], consistent with the previous ATLAS Collaboration single-peak observation. The following LHCb Collaboration analysis confirmed the two states existence [11]. Also, four excited \( \Lambda_b^0 \) baryons, namely \( \Lambda_b(5912)^0 \), \( \Lambda_b(5920)^0 \), \( \Lambda_b(6146)^0 \) and \( \Lambda_b(6152)^0 \) were confirmed (most of them are the first confirmation), and their masses were measured. In addition, the first evidence of a broad enhancement in the region of 6040-6100 MeV is reported [3]. Later the LHCb Collaboration observed the broad state with a mass of about 6072 MeV [12], consistent with the CMS result.

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