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CMS results on beauty baryon spectroscopy

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Recent beauty baryon physics results from the CMS collaboration, obtained using the proton-proton collision data collected at $\sqrt{s} = 13\,$TeV, are discussed. Observation of the $\Lambda_b^0 \to \mathrm{J}/\psi\Lambda\phi$ decay and measurement of its branching fraction, relative to the $\Lambda_b^0 \to \psi(2S)\Lambda$ decay, is reported. The excited baryon states $\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$, $\Lambda_b(6146)^0$, and $\Lambda_b(6152)^0$ are confirmed and their masses are measured. Observation of a new excited beauty strange baryon, labeled as $\Xi_b(6100)^{*-}$, is presented.

Keywords: Hadron spectroscopy; baryon spectroscopy; excited states; flavor physics; flavor spectroscopy.

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1. Introduction

The CMS experiment [1] at the LHC is providing new important results in the Heavy Flavor physics sector. In this report, recent results of the studies of beauty baryon spectroscopy are discussed. Charge-conjugate states are implied throughout the text. The reconstruction of signal candidates is based on charmonium resonances (J/ψ or $\psi(2S)$) reconstructed in the dimuon decay modes and Λ hypherons reconstructed via displaced two-track vertices corresponding to the $\Lambda \to p\pi^-$ decays.

2. Observation of the $\Lambda_b^0 \to \mathrm{J}/\psi\Lambda\phi$ decay

The mass spectrum of J/ψ and baryon presents an important and (relatively) experimentally-clean landscape to search for pentaquark signals [2, 3]. The search for the $\Lambda_b^0 \to \mathrm{J}/\psi\Lambda\phi$ decay is performed using the 13 TeV pp collision data collected with the CMS experiment in 2018. The signal candidates are reconstructed using the $\phi \to K^+K^-$ process, and the decay $\Lambda_b^0 \to \psi(2S)$, followed by $\psi(2S) \to \mathrm{J}/\psi\pi^+\pi^-$, is used as the normalization channel. Signal and normalization channels have the same number of tracks in the final state, thus reducing systematic uncertainties. Standard requirements are applied on muon and track reconstruction qualities, χ^2 probabilities of the vertex fits, and the secondary vertex displacement vector from the pp collision vertex.

The observed $\mathrm{J}/\psi\ \Lambda\phi$ invariant mass distribution is shown in Fig. 1a), where the signal is modelled with a double-Gaussian function and the smooth background with a third-order polynomial function [4].

The number of signal $\Lambda_b^0 \to \mathrm{J}/\psi\Lambda\mathrm{K}^+\mathrm{K}^-$ events is 380 ± 32 and the background-subtracted $M(\mathrm{K}^+\mathrm{K}^-)$ distribution is shown in Fig. 1b). It is fit with a sum of first order polynomial background function and Breit-Wigner convolved with the resolution for ϕ signal, resulting in 286 ± 29 signal ϕ candidates. The statistical significance of the observed signal is about 10σ in the asymptotic approximation. The yield in the normalization channel $\Lambda_b^0 \to \psi(2S)\Lambda$ is 884 ± 37.

The branching fraction ratio, accounting for the difference in the reconstruction efficiencies, is measured to be [4]

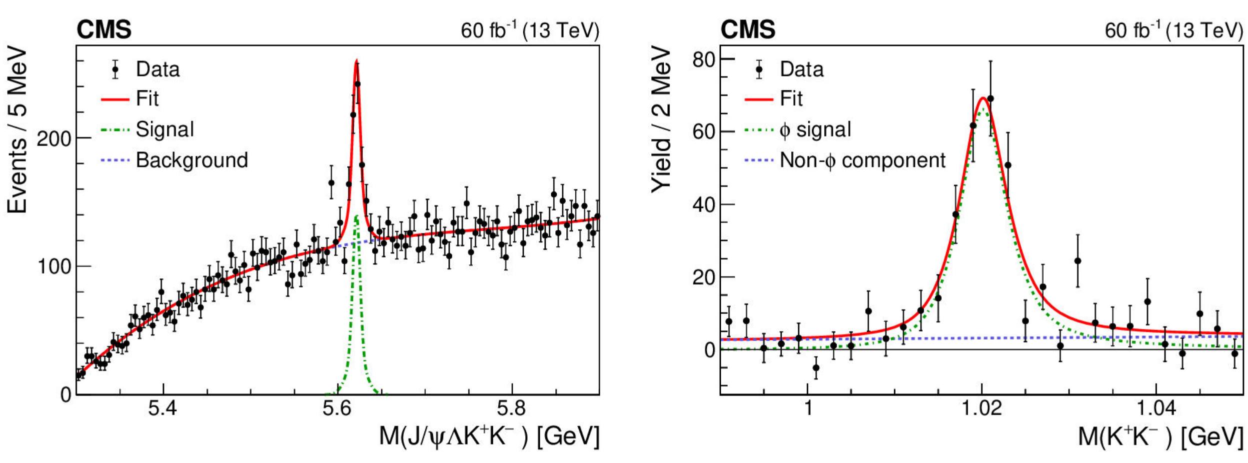

FIGURE 1. a) The $\mathrm{J}/\psi\ \Lambda\phi$ invariant mass distribution in data. b) Background-subtracted K^+K^- invariant mass distribution [4].

$$\frac{\mathcal{B}(\Lambda_b^0 \to \mathrm{J}/\psi\Lambda\phi)}{\mathcal{B}(\Lambda_b^0 \to \psi(2\mathrm{S})\Lambda)} = 8.26 \pm 0.90(\mathrm{stat}) \pm 0.68(\mathrm{syst}) \pm 0.11(\mathrm{PDG})\%,$$

where the last uncertainty is related to the known branching fractions of the decays $\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-$ and $\phi \to \mathrm{K}^+\mathrm{K}^-$.

3. Study of excited Λ_b^0 states

The excited states of Λ_b^0 baryon are studied in their decays into $\Lambda_b^0\pi^+\pi^-$, where the ground state Λ_b^0 is reconstructed in 3 decay channels: $\Lambda_b^0 \to \mathbf{J}/\psi\Lambda(\mathrm{J}/\psi \to \mu^+\mu^-)$, $\Lambda_b^0 \to \psi(2\mathrm{S})\Lambda(\psi(2\mathrm{S}) \to \mu^+\mu^-)$ and $\Lambda_b^0 \to \psi(2\mathrm{S})\Lambda(\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-)$. Since the lifetime of the excited Λ_b^0 states is negligible, the two additional charged pions are selected from the tracks forming the Λ_b^0 production vertex. The selection criteria were optimized using Punzi figure of merit [5].

A dedicated primary vertex (PV) refitting procedure was developed in order to improve the mass resolution. Instead of using raw 4-momenta of pions or the 4-momenta from the $\Lambda_b^0\pi^+\pi^-$ vertex fit, a new approach is used: all the tracks forming the PV, including the two tracks from the $\Lambda_b^0\pi^+\pi^-$ candidate, and the "virtual track" of Λ_b^0 , are fit into a common vertex, to define the refitted 4-momenta of Λ_b^0 and the two pions, which are then combined into the refitted $\Lambda_b^0\pi^+\pi^-$ candidate. According to the studies in simulation, this innovative procedure significantly (by up to 50%) improves the $m_{\Lambda_b^0\pi^+\pi^-}$ resolution.

The low-mass (between the kinematic threshold and 5.95 GeV) and high-mass (up to 6.4 GeV) regions of $m_{\Lambda_b^0\pi^+\pi^-}$ are analyzed separately, as described below.

Figure 2 shows the reconstructed $\Lambda_b^0\pi^+\pi^-$ mass distribution near the mass threshold. Two prominent narrow peaks are observed in the distribution, corresponding to the $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ decays into $\Lambda_b^0\pi^+\pi^-$, reported previously by LHCb [6] and CDF (only $\Lambda_b(5920)^0$) [7]

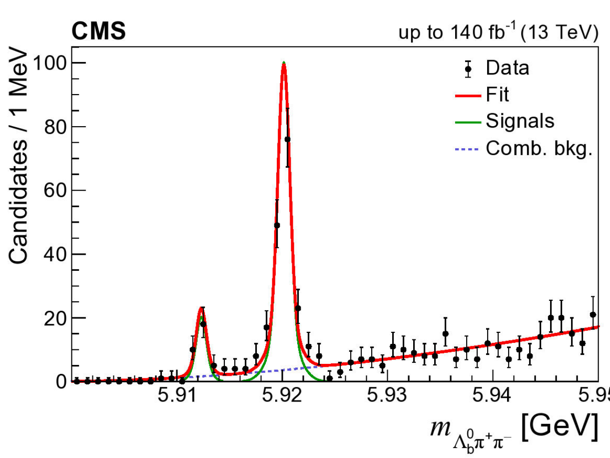

FIGURE 2. Observed $m_{\Lambda_b^0\pi^+\pi^-}$ distribution near threshold [8].

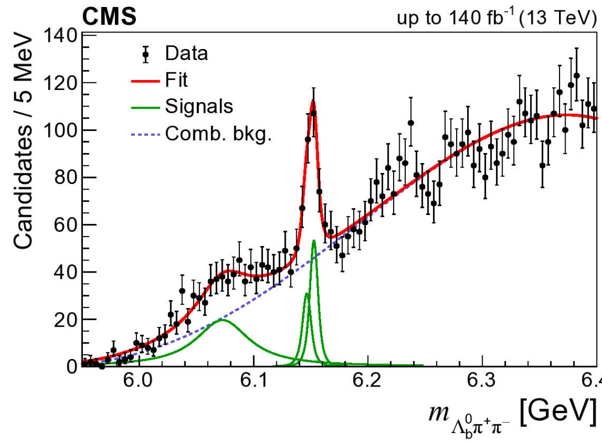

FIGURE 3. Observed $m_{\Lambda_b^0\pi^+\pi^-}$ distribution between 5.95 and 6.4 GeV [8].

collaborations. The distribution is modelled with a sum of two signal functions (double-Gaussian distributions with mean value floating and shape parameters fixed to simulation) and a threshold function for the background description. The fit is used to measure the masses of the $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states and to estimate the significance of the observed signals: 5.7 and over 6σ [8]. This corresponds to the first confirmation with $> 5\sigma$ significance of both the $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states.

The $\Lambda_b^0\pi^+\pi^-$ mass distribution up to 6.4 GeV is shown in Fig. 3. It presents a broad enhancement between 6.0 and 6.1 GeV and a narrow peak at about 6.15 GeV. The latter one is consistent with being a superposition of $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ signals reported previously by LHCb [9]. There is no such broad excess in the mass distribution of Λ_b^0 and two pions of the same sign [8]. The distribution is modelled with a sum of three signal functions, representing the two narrow peaks at 6.15 GeV and a wide enhancement, and a modified threshold function for the background description. The signal functions are the Breit–Wigner functions (with natural widths fixed to those measured by LHCb for $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ [9]) convoluted with the mass resolution. The fit results are shown in Fig. 3.

The measured masses of the $\Lambda_b(6146)^0$, $\Lambda_b(6152)^0$, and the wide enhancement are, respectively, 6146.5 ± 1.9 MeV, 6152.7 ± 1.1 MeV, and 6073 ± 5 MeV, where the uncertainties are statistical-only [8]. The Breit–Wigner width of the broad state is 55 ± 11 MeV. This broad state was later confirmed by the LHCb collaboration [10].

This is the first confirmation of existence of the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states and a first evidence for a new resonant structure decaying into $\Lambda_b^0\pi^+\pi^-$ with mass around 6070 MeV and width of the order of 50 MeV.

Several sources of systematic uncertainties in the measured masses are considered. They include the choice of the signal model, the background model, and the difference in the mass resolution between the data and simulation. The uncertainty related to possible detector misalignment is considered

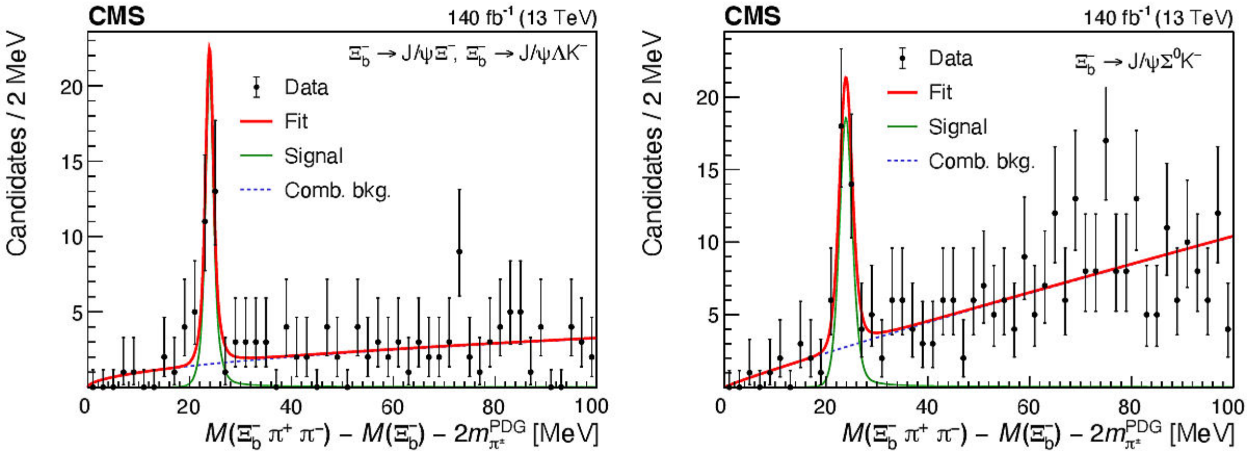

FIGURE 4. a) Observed $\Xi_b^-\pi^+\pi^-$ mass distribution for the fully-reconstructed channels, $J/\psi\Xi^-$ and $J/\psi\Lambda K^-$, and b) the partially-reconstructed $J/\psi\sum^0 K^-$ channel [11].

to be negligible. For the $\Lambda_b(6146)^0$ and $\Lambda_b(6146)^0$ states, additional uncertainties are evaluated by removing the wide excess region from the fit and by varying the natural widths of the states within their uncertainties reported by LHCb [9]. The total systematic uncertainty is estimated to be 9 KeV, 11 KeV, 0.77 MeV, and 0.41 MeV for $\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$, $\Lambda_b(6146)^0$, and $\Lambda_b(6152)^0$, respectively [8].

The resulting mass measurements are [8]

$$M(\Lambda_b(5912)^0) = 5912.32 \pm 0.12(\text{stat}) \pm 0.01(\text{syst}) \pm 0.17(\Lambda_b^0)\ \text{MeV},$$
$$M(\Lambda_b(5920)^0) = 5920.16 \pm 0.07(\text{stat}) \pm 0.01(\text{syst}) \pm 0.17(\Lambda_b^0)\ \text{MeV},$$
$$M(\Lambda_b(6146)^0) = 6146.5 \pm 1.9(\text{stat}) \pm 0.8(\text{syst}) \pm 0.2(\Lambda_b^0)\ \text{MeV},$$
$$M(\Lambda_b(6152)^0) = 6152.7 \pm 1.1(\text{stat}) \pm 0.4(\text{syst}) \pm 0.2(\Lambda_b^0)\ \text{MeV},$$

where the last uncertainties are related to the uncertainty in the known value of Λ_b^0 mass. In addition, a broad excess of events is found, consistent with a Breit–Wigner resonance with mass of $6073{\pm}5$ MeV and natural width of $55{\pm}11$ MeV, where the uncertainties are statistical only [8].

4. Observation of a new $\Xi_b(6100)^{*-}$ baryon

On the contrary to the $\Lambda_b^0\pi^+\pi^-$ system, the $\Xi_b^-\pi^+\pi^-$ system has never been explored previously. However, by analogies with $\Lambda_b^0\pi^+\pi^-$ and the charm sector (excited Ξ_c states), there are possibly excited Ξ_b^- baryon states that can decay into $\Xi_b\pi^+\pi^-$. In the study performed by the CMS experiment, the ground state Ξ_b^- is reconstructed in 3 decay channels: $\Xi_b^- \to J/\psi\Xi^-$, $\Xi_b^- \to J/\psi\Lambda K^-$, and $\Xi_b^- \to J/\psi\Sigma^0 K^-$, where the last channel is only partially reconstructed via $J/\psi\Lambda K^-$ system and the soft photon from $\Sigma^0 \to \Lambda\gamma$ decay is not reconstructed. The Ξ^- hyperon is reconstructed through the $\Xi^- \to \Lambda\pi^-$ decay, and, as previously, two prompt pions are added to Ξ_b^0 to form $\Xi_b^0\pi^+\pi^-$ candidates. As in $\Lambda_b^0\pi^+\pi^-$ analysis, the selection criteria were optimized using Punzi figure of merit and the PV refitting procedure is used to improve the invariant mass resolution. Since the $\Xi_b^{**-} \to \Xi_b^-\pi^+\pi^-$ decay is expected to proceed through the intermediate Ξ_b^{*0} resonance, a corresponding mass requirement is applied on the selected $\Xi_b^-\pi^+$ candidates.

Simulation studies show that the $\Xi_b^0\pi^+\pi^-$ mass resolution is slightly worse in the case of partially-reconstructed $\Xi_b^0 J/\psi\sum^0 K^-$ channel, however, the $\Xi_b^0\pi^+\pi^-$ mass peak position is the same thanks to the usage of the mass difference variable, therefore the $\Xi_b^0\pi^+\pi^-$ mass distributions are obtained separately for this partially-reconstructed decay mode and for the two fully-reconstructed channels ($J/\psi\Xi^-$ and $J/\psi\Lambda K^-$), as shown in Fig. 4.

The prominent narrow peak, observed in both distributions near the threshold, is assumed to correspond to a new baryonic state, called $\Xi_b(6100)^{*-}$. The distributions are modelled with a sum of the signal function (relativistic Breit–Wigner convolved with the mass resolution extracted from simulations) and a threshold function for the background description. The fit is performed simultaneously on the fully- and partially-reconstructed candidates. The fitted mass of the newly observed state is 6100.3 ± 0.2 MeV and the statistical significance of the excess exceeds 6σ [11]. The natural width of $\Xi_b(6100)^{*-}$ is consistent with zero, and the obtained upper limit on it is 1.9 MeV at 95% confidence level. The sources of the systematic uncertainties are similar to those for the $\Lambda_b^0\pi^+\pi^-$ analysis, and the total systematic uncertainty in the $\Xi_b(6100)^{*-}$ mass is 0.09 MeV.

The reported mass measurement is [11]

$$m(\Xi_b(6100)^{*-}) = 6100.3 \pm 0.2(\text{stat}) \pm 0.1(\text{syst}) \pm 0.6\,(\Xi_b^-)\ \text{MeV}\,.$$

5. Summary

The decay $\Lambda_{\rm b}^0 \to {\rm J}/\psi\Lambda\phi$ is observed and its branching fraction is measured with respect to $\mathcal{B}(\Lambda_b^0 \to \psi(2{\rm S})\Lambda)$ using the $\sqrt{s} = 13$ TeV pp collision data. The excited states of Λ_b^0 baryon are studied in their decays into $\Lambda_b^0\pi^+\pi^-$ including a confirmation of 4 previously reported states and an evidence for a new broad resonance. The new excited beauty-strange baryon with a mass of about 6100 MeV and small (< 1.9 MeV) natural width is observed with a statistical significance exceeding 6σ.

These results demonstrate the versatility of the CMS experiment, which was initially designed for high-p_T physics, but proves to be able to also provide the state-of-the-art results in the heavy flavor spectroscopy sector.

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