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New results in Λ_b^0 baryon physics at CMS

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The study of excited Λ_b^0 states and their mass measurement by the CMS experiment is reported, as well as the observation of the $\Lambda_b^0 \to J/\psi\Lambda\phi$ decay and the measurement of its branching fraction, relative to the $\Lambda_b^0 \to \psi(2S)\Lambda$ decay. Both analyses use proton-proton collision data collected at $\sqrt{s} = 13$ TeV.

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1. Introduction

Studies of b baryons are of great importance for testing mechanisms responsible for the dynamics of quarks and baryon formation. Spectroscopy and branching fraction measurements of baryons containing heavy-flavour quarks can test heavy-quark effective theory [1] predictions. Due to the large production of $b\bar{b}$ pairs at the CERN LHC, CMS, LHCb and ATLAS are excellent experiments for detailed studies of Λ_b^0 and have already performed numerous investigations in this sector. In addition, Λ_b^0 decays are a rich source of different exotic states like new pentaquarks $P_c(4312)^+$, $P_c(4380)^+$ and $P_c(4450)^+$, which were observed in the $J/\psi p$ invariant mass spectrum in $\Lambda_b^0 \to J/\psi p K^-$ decays by the LHCb Collaboration [2, 3].

The present work reports recent results in Λ_b^0 baryon physics at CMS: the study of excited Λ_b^0 decaying into the $\Lambda_b^0\pi^+\pi^-$ final state [4] and the observation of the $\Lambda_b^0 \to J/\psi\Lambda\phi$ decay [5]. Both analyses were performed using proton-proton collision data collected at $\sqrt{s} = 13$ TeV by the CMS experiment at the LHC, corresponding to an integrated luminosity of $140\,\mathrm{fb}^{-1}$ for [4] and $60\,\mathrm{fb}^{-1}$ for [5].

2. Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$

Λ_b^0 is the lightest baryon which contains a b quark, thus its excited states are studied intensively. In addition, there are a lot of different theoretical predictions for excited states in the mass region between 5.9 and 6.4 GeV. However, the predictions usually do not suggest any narrow mass search-window, neither specify expected natural widths, nor production cross sections of the states. These aspects make experimental searches very challenging and important for probing theoretical models.

In 2012 the LHCb Collaboration observed two excited Λ_b^0 states, $\Lambda_b^0(5912)$ and $\Lambda_b^0(5920)$, decaying to the $\Lambda_b^0\pi^+\pi^-$ final state [6]. After that, the CDF Collaboration tried to confirm this observation, but reported only an evidence of the $\Lambda_b^0(5920)$ state [7]. In 2019, the LHCb Collaboration observed two more states in a higher-mass region with masses and natural widths [8]: $M(\Lambda_b^0(6146)) = 6146.17 \pm 0.43$ MeV, $\Gamma(\Lambda_b^0(6146)) = 2.9 \pm 1.3$ MeV and $M(\Lambda_b^0(6152)) = 6152.51 \pm 0.38$ MeV, $\Gamma(\Lambda_b^0(6152)) = 2.1 \pm 0.9$ MeV. Recently, the CMS Collaboration published a paper dedicated to the excited Λ_b^0 states, confirming two states near threshold, as well as the peak in the higher-mass region [4]. In addition, CMS reported an evidence for a new broad structure in the mass region 6040 – 6100 MeV.

Since CMS does not have charged hadron identification, nor dedicated triggers for 3-tracks displaced vertices, Λ_b^0 baryons are reconstructed in channels with charmonium in the final state: $\Lambda_b^0 \to J/\psi\Lambda$ and $\Lambda_b^0 \to \psi(2S)\Lambda$, where J/ψ decays into $\mu^+\mu^-$, $\psi(2S)$ is reconstructed in both $\mu^+\mu^-$ and $J/\psi\pi^+\pi^-$ modes and Λ candidates are formed from displaced two-prong vertices, assuming the $\Lambda \to p\pi^-$ decay. In this analysis, a total of 46000 Λ_b^0 candidates were reconstructed.

To reconstruct the Λ_b^0, two opposite-charged muons are fitted into a common vertex with the Λ candidate, where the dimuon mass is constrained to the world-average [9] J/ψ or $\psi(2S)$ mass. When the $\psi(2S)$ is reconstructed through the $J/\psi\pi^+\pi^-$ mode, two additional tracks with pion mass hypotheses are added to the kinematic fit. Then, the Λ_b^0 candidate is combined with two opposite-sign (OS) tracks originating from the primary vertex (PV). To improve the resolution of the $\Lambda_b^0\pi^+\pi^-$

invariant mass, all the tracks forming the PV and the Λ_b^0 candidate are refitted together in a common vertex. The mass variable used in this analysis is defined as $m_{\Lambda_b^0\pi^+\pi^-} = \mathrm{M}(\Lambda_b^0\pi^+\pi^-) - \mathrm{M}(\Lambda_b^0) + \mathrm{M}^{\mathrm{PDG}}_{\Lambda_b^0}$.

To suppress the combinatorial background, different requirements on topological variables were applied. The selection criteria were optimized separately for the near threshold and the higher-mass regions.

The $\Lambda_b^0\pi^+\pi^-$ invariant mass distribution near threshold is shown in Fig. 1. Two excited Λ_b^0 states are present, when each has a local significance higher than 5 standard deviations. The distribution is described by two double Gaussian functions for signals, whose shapes were determined from Monte-Carlo (MC) simulations, and a threshold function for the combinatorial background contribution. From an unbinned maximum-likelihood fit the masses of the excited Λ_b^0 states were extracted: $\mathrm{M}(\Lambda_b^0(5912)) = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17$ MeV and $\mathrm{M}(\Lambda_b^0(5920)) = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17$ MeV, where the first uncertainty is statistical, the second is systematic, and the last uncertainty is related to the uncertainty of the world-average Λ_b^0 mass.

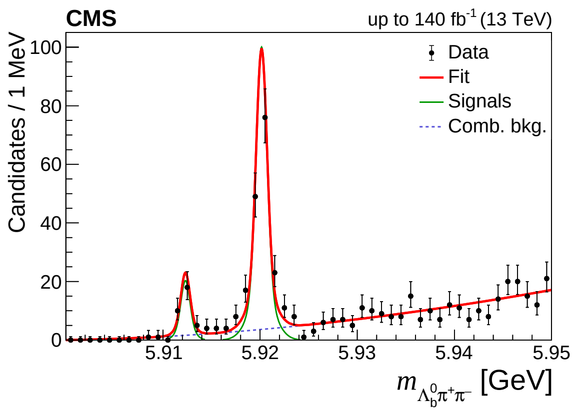

Figure 1: Invariant mass distribution of the selected $\Lambda_b^0\pi^+\pi^-$ candidates near the mass threshold [4].

In Fig. 2 the $\Lambda_b^0\pi^+\pi^-$ invariant mass distribution is represented for the higher-mass region. There is a clear structure near 6150 MeV with a local significance above 5 standard deviations, but the CMS resolution prevents to resolve it clearly in two peaks. Using the natural widths measured by the LHCb Collaboration and the known MC resolution, this structure was fitted as two excited states, where each was described by the convolution of a Breit–Wigner function with a double Gaussian. Another broad structure is evident, which is present only in the OS distribution. It was fitted with the same shape as the other peaks, with the natural width set free to float. The background contribution was described by a product of threshold and first-order polynomial functions. The measured masses are $\mathrm{M}(\Lambda_b^0(6146)) = 6146.5 \pm 1.9 \pm 0.8 \pm 0.2$ MeV, $\mathrm{M}(\Lambda_b^0(6152)) = 6152.7 \pm 1.1 \pm 0.4 \pm 0.2$ MeV and $6073 \pm 5(\mathrm{stat})$ MeV for the broad enhancement, where the third uncertainty is the uncertainty in the world-average Λ_b^0 mass value. The natural width of the broad enhancement is $55 \pm 11(\mathrm{stat})$ MeV.

The nature of the broad excess is still unclear, but some correlations between the structure and intermediate Σ_b and Σ_b^* baryon states were reported. At the same time the LHCb Collaboration observed a similar structure, consistent with the one reported by the CMS Collaboration [10].

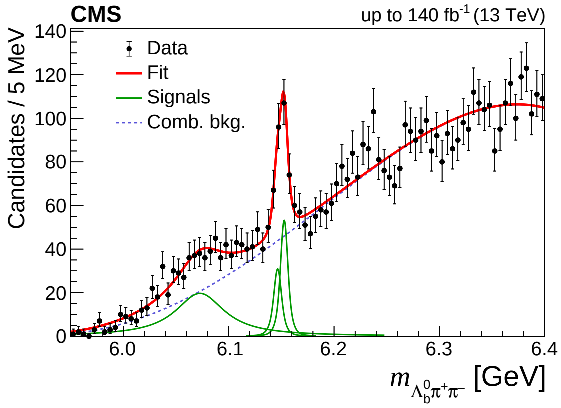

Figure 2: Invariant mass distribution of the selected $\Lambda_b^0\pi^+\pi^-$ candidates in the higher-mass region [4].

3. Observation of the $\Lambda_b^0 \to J/\psi\Lambda\phi$ decay

The $\Lambda_b^0 \to J/\psi\Lambda\phi$ decay is a baryonic analogue of $B^+ \to J/\psi\phi K^+$, where several experiments found a rich resonance structure in the $J/\psi\phi$ mass spectrum [11–14]. The observation of the $\Lambda_b^0 \to J/\psi\Lambda\phi$ decay provides the opportunity to probe the production process of these exotic states. In addition this decay gives the opportunity to investigate the $J/\psi\Lambda$ mass spectrum with a sufficient high statistics to check for the presence of pentaquark states.

To reconstruct Λ_b^0 candidates, two oppositely-charged muons are combined with the Λ candidate and two OS tracks with assigned kaon mass hypotheses. All these particles are fitted in a common vertex, with dimuon mass constrained to the world-average J/ψ mass. The $\Lambda_b^0 \to \psi(2S)\Lambda$ decay was chosen as a normalization channel due to the same topology, when the $\psi(2S)$ was reconstructed in the $J/\psi\pi^+\pi^-$ final state.

The $J/\psi\Lambda K^+K^-$ invariant mass distribution is provided in Fig. 3 (left). A very clear peak at the Λ_b^0 mass with a local significance more than 9 standard deviations is present. The distribution was described by a double Gaussian function for the signal component, whose shape was determined from MC, and a third-order Bernstein polynomial for combinatorial background. The fit results in a number of signal events $N(\Lambda_b^0 \to J/\psi\Lambda K^+K^-) = 380 \pm 32$. To obtain the correct $N(\Lambda_b^0 \to J/\psi\Lambda\phi)$ signal yield, the K^+K^- invariant mass distribution was extracted from the signal component using the sPlot technique [15]. This plot is shown in Fig. 3 (right). The distribution was described by the convolution of a Breit–Wigner function with a double Gaussian resolution for the ϕ component, where the resolution shape was fixed to MC and the ϕ natural width to the world-average value, and the non-ϕ contribution was fitted with a first-order Bernstein polynomial. The fit results in a signal yield of 286 ± 29 events.

The $\psi(2S)\Lambda$ invariant mass of the normalization channel was fitted with the same functions as $M(J/\psi\Lambda K^+K^-)$ (see Fig. 4). The signal yield obtained from the fit procedure is $N(\Lambda_b^0 \to \psi(2S)\Lambda) = 884 \pm 37$.

The measured branching fraction ratio of the two decays is: $\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda\phi)/\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda) = (8.26 \pm 0.90 \pm 0.68 \pm 0.11(\mathcal{B})) \times 10^{-2}$, where the first uncertainty is statistical, the second is systematic, and the last uncertainty reflects the uncertainties in the world-average branching fractions of ϕ and $\psi(2S)$ decays to the reconstructed final states.

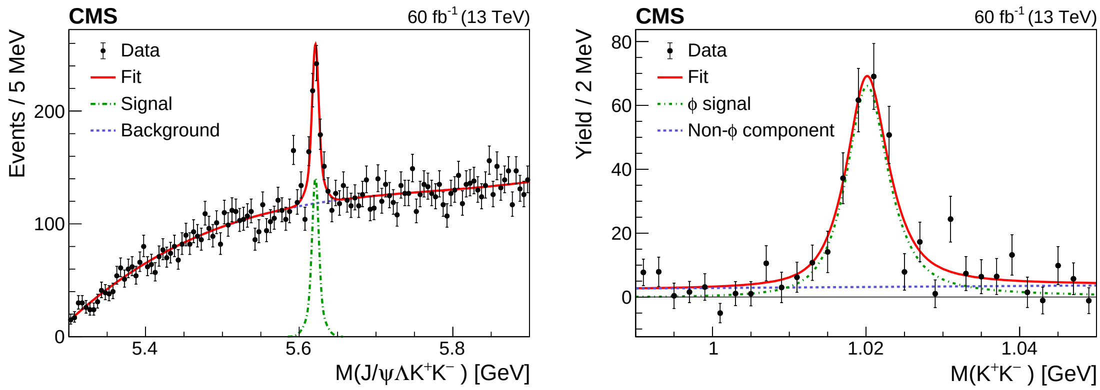

Figure 3: The invariant mass distributions of $J/\psi \Lambda K^+K^-$ (left) and background-subtracted K^+K^- (right) [5].

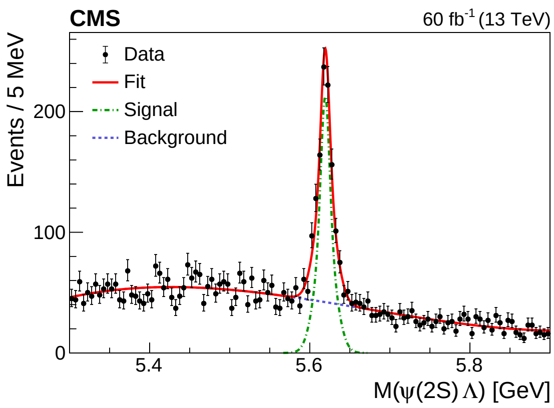

Figure 4: The invariant mass distribution of $\Lambda_b^0 \to \psi(2S)\Lambda$ candidates [5].

4. Conclusion

The CMS Collaboration contributes actively to b physics, in particular to Λ_b^0 baryon studies. Four excited Λ_b^0 states were confirmed and their mass measurement was performed. In addition, a new broad structure in the 6040 – 6100 MeV mass region was reported for the first time. Moreover, the $\Lambda_b^0 \to J/\psi\Lambda\phi$ decay was observed and the branching fraction ratio $\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda\phi)/\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)$ was measured.

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