Heavy flavour spectroscopy and properties at CMS

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Abstract. Recent CMS Experiment results on conventional spectroscopy and production of heavy flavour states in pp collisions at 13 TeV are reported, including the first observation of the $\Xi_b^- \to \psi(2S)\Xi^-$ decay. We discuss the measured properties of the ground and excited hadron states.

1 Introduction

The Compact Muon Solenoid (CMS) Experiment [1] is one of the two general-purpose detector at the CERN LHC and intended for a large variety of possible physics results. In particular, its excellent muon system, great p_T resolution and robust vertexing (including cascades of displaced vertices) allow the CMS Collaboration perform state-of-the-art studies within the heavy flavour sector. One of the key advantages for this area is the possibility to use the muons from charmonia decays (J/ψ and ψ(2S) mesons).

In this talk we report two recent results from the CMS Experiment: the first observation of the new $\Lambda_b^0 \to J/\psi\Xi^-K^+$ decay [2] and the first observation of the new $\Xi_b^- \to \psi(2S)\Xi^-$ decay and studies of the Ξ_b^{*0} baryon [3]. Both analyses use the data sample, collected in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2016–2018, corresponding to an integrated luminosity of 140 fb^{-1}.

2 Observation of the $\Lambda_b^0 \to J/\psi\Xi^-K^+$ decay

Multibody decays of b-hadrons to charmonia are proved to be a good laboratory for the searches of so-called "exotic" (multiquark) intermediate resonances. Studies of such states significantly improves our understanding of the Quantum Chromodynamics (QCD) mechanisms standing behind the hadron formation. Over the last years, LHCb Collaboration has reported about several new pentaquark-like particles with a hidden charm in the J/ψ plus a light baryon final state (such as $P_{c\bar{c}}^+$ states in the $\Lambda_b^0 \to J/\psi pK^-$ decay [4] or $P_{c\bar{c}s}(4338)^0$ in the $B^- \to J/\psi\Lambda K^-\Lambda\bar{p}$ decay [5]). The present results for the hidden charm pentaquarks are currently limited with the J/ψp and J/$\psi\Lambda$ (strange particle) final states, while there is a possibility to find a doubly strange pentaquark in the J/$\psi\Xi^-$ system. To investigate such an intermediate state, the CMS Collaboration has performed a search for a new decay channel of the Λ_b^0 baryon, namely $\Lambda_b^0 \to J/\psi\Xi^-K^+$ [2].

The reconstruction process for this decay starts with the selection of two opposite-sign muons, which are significantly displaced from a pp collisions primary vertex (PV) with

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the additional requirement of dimuon invariant mass to be close to the world-average J/ψ mass [6]. Then a Λ hyperon candidate is selected using its decay $\Lambda \to p\pi^-$, formed as the detached vertex with two originating V-like tracks with a zero summed charge (V0). An additional charged particle track with a pion mass assignment is then added, and it is fitted with a Λ pseudo-track into a common vertex, forming Ξ^- hyperon decay to $\Lambda\pi^-$. Finally, the Λ_b^0 candidates are obtained using the muons, Ξ^- particle and an additional kaon track in a kinematic vertex fit, which constrains the dimuon invariant mass to the world-average J/ψ mass [6]. Besides the signal channel $\Lambda_b^0 \to \mathrm{J}/\psi\Xi^-\mathrm{K}^+$, we also reconstruct the normalization channel $\Lambda_b^0 \to \psi(2\mathrm{S})\Lambda$, where the $\psi(2\mathrm{S})$ decays to $\mathrm{J}/\psi\pi^+\pi^-$. Its reconstruction procedure is very similar, however instead of forming a Ξ^- particle we obtain Λ_b^0 with a fit of muons, Λ and two pions into a common vertex. Selection criteria for the signal channel are optimised using the Punzi figure of merit [7].

The measured invariant mass distributions are provided in Fig. 1. The $\mathrm{J}/\psi\Xi^-\mathrm{K}^-$ distribution presents a narrow peak at the Λ_b^0 mass on top of a smooth background. The results of an unbinned extended maximum likelihood fit are also shown, where the signal is modelled with a Student's t-distribution and background is described with an exponential function.

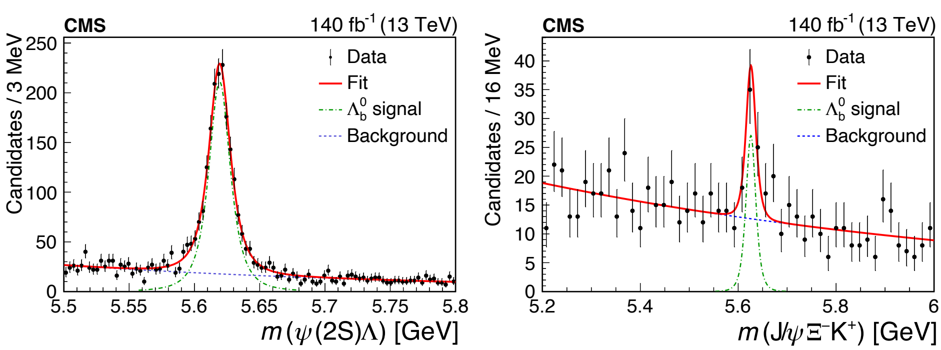

Figure 1. Obtained $\psi(2\mathrm{S})\Lambda$ (left) and $\mathrm{J}/\psi\Xi^-\mathrm{K}^-$ (right) invariant mass distributions with superimposed fit results [2].

We have evaluated the local statistical significance of the $\Lambda_b^0 \to \mathrm{J}/\psi\Xi^-\mathrm{K}^+$ signal using the likelihood ratio technique, comparing a signal-plus-background hypothesis versus a background-only hypothesis. The obtained value varies in the range from 5.3 to 5.9 standard deviations, which allows us to claim the first observation of the new decay. We have also measured its branching fraction with respect to the $\Lambda_b^0 \to \psi(2\mathrm{S})\Lambda$ channel:

$$\begin{aligned}\mathcal{R} \equiv \frac{\mathcal{B}\left(\Lambda_b^0 \to \mathrm{J}/\psi\Xi^-\mathrm{K}^+\right)}{\mathcal{B}\left(\Lambda_b^0 \to \psi(2\,\mathrm{S})\Lambda\right)} &= \frac{N\left(\Lambda_b^0 \to \mathrm{J}/\psi\Xi^-\mathrm{K}^+\right)}{N\left(\Lambda_b^0 \to \psi(2\,\mathrm{S})\Lambda\right)}\,\frac{\epsilon_{\psi(2\mathrm{S})\Lambda}}{\epsilon_{\mathrm{J}/\psi\Xi^-\mathrm{K}^+}}\,\frac{\mathcal{B}\left(\psi(2\,\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-\right)}{\mathcal{B}\left(\Xi^- \to \Lambda\pi^-\right)} \\ &= [3.38 \pm 1.02(\mathrm{stat}) \pm 0.61(\mathrm{syst}) \pm 0.03(\mathcal{B})]\%,\end{aligned} \tag{1}$$

where the last uncertainty is related to the uncertainties in the $\psi(2\mathrm{S})$ and Ξ^- branching fractions. In this formula N and ϵ represent the measured number of signal events in data and the total efficiency from Monte Carlo (MC) simulation, respectively. The choice of the normalization channel is quite natural since it has similar topology and kinematic properties, allowing us to significanty reduce systematic uncertainties, related with muons and tracks reconstruction, in the measured ratio $\mathcal{R}$.

We have also investigated our current sensitivity regarding the potential pentaquark signals in the 2-body intermediate invariant mass distributions $J/\psi\Xi^-$, $J/\psi K^-$ and $\Xi^- K^-$, provided in Fig. 2. The data is extracted using $_s\mathcal{P}$lot technique to subtract background and compared with the predictions of phase space MC simulation. With the current very low statistics of 46 ± 11 signal events, the distributions are in agreement, however it is clear that more data is needed to fully explore the internal dynamics of the $\Lambda_b^0 \to J/\psi\Xi^- K^+$ decay.

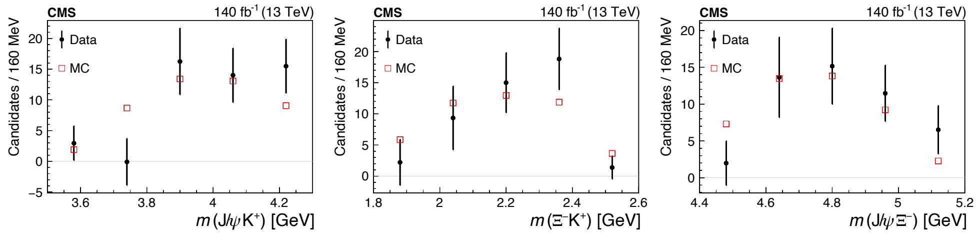

Figure 2. 2-body intermediate invariant mass distributions of the $\Lambda_b^0 \to J/\psi\Xi^- K^+$ decay [2].

3 Observation of the $\Xi_b^- \to \psi(2S)\Xi^-$ decay and studies of the Ξ_b^{*0} baryon

The Ξ_b baryon family are of isodoublet states composed of qsb quarks, where q represents an up or a down quark for the Ξ_b^0 and Ξ_b^- states, respectively. Three such isodoublets are neither orbitally nor radially excited (the Ξ_b ground states with $J^P = 1/2^+$ and $j_{qs} = 0$, Ξ_b' with $J^P = 1/2^+$ and $j_{qs} = 1$, and Ξ_b^* with $J^P = 3/2^+$ and $j_{qs} = 1$). Three of the states with $j_{qs} = 1$ have been previously observed at the LHC by CMS [8] and LHCb [9, 10] via their $\Xi_b^-\pi^+$ and $\Xi_b^0\pi^-$ decays. Several more heavy Ξ_b resonances, supposed to be $1P$ and $1D$ excited states, have been also recently observed by the CMS and LHCb experiments [6].

The spectrum of different Ξ_b states and their strong decays can be classified relatively easy (especially for the lightest excitations). On the other hand, the description of the different weak decay modes of the ground-state baryons in the framework of heavy-quark effective theory (HQET) [11] presents a significant theoretical challenge, thus predictions of the branching fractions to various final states are less straightforward. Measurements of the decays and properties of both ground and excited Ξ_b states provide essential input to our understanding of the complicated QCD mechanisms responsible for the quark dynamics inside hadrons, and in this paper we present studies of Ξ_b^- baryon decays and measurement of Ξ_b^{*0} baryon properties [3].

The Ξ_b^- baryon ground state is reconstructed via two main decay modes: $\Xi_b^- \to \psi\Xi^-$, followed by $\psi \to \mu^+\mu^-$, where ψ stands for both J/ψ and $\psi(2S)$ mesons, or $\Xi_b^- \to J/\psi\Lambda K^-$. The reconstruction procedure is similar to those previously described for the $\Lambda_b^0 \to J/\psi\Xi^- K^+$ decay, with Ξ_b^- candidates are obtained from a kinematic vertex fit of muons and Ξ^- or muons, Λ and K^- for $\psi\Xi^-$ or $J/\psi\Lambda K^-$ channel, respectively. For the $\Xi_b^- \to \psi(2S)\Xi^-$ mode we also reconstruct a chain with two additional pion tracks, corresponding to $\psi(2S) \to J/\psi\pi^+\pi^-$ decay. The pictorial schemes of the decay topologies are provided in Fig. 3.

Figure 4 presents the invariant mass distributions for the $J/\psi\Xi^-$, $J/\psi\Lambda K^-$ and $\psi(2S)\Xi^-$ candidates, where the latter divided into the two modes of $\psi(2S)$ reconstruction: $\mu^+\mu^-$ or $J/\psi\pi^+\pi^-$. An unbinned extended maximum likelihood fit is performed on each of these distributions, where the signal is described with the double Gaussian function with a common

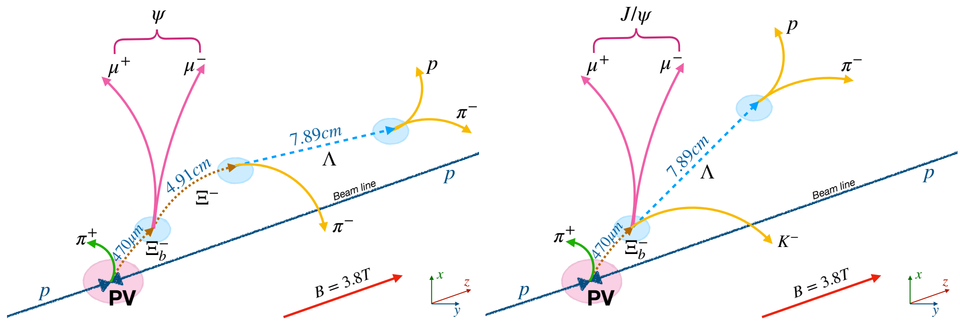

Figure 3. The $\Xi_b^{*0} \to \Xi_b^- \pi^+$ decay topology in which the Ξ_b^- baryon decays to $\psi\Xi^-$ with $\psi \to \mu^+\mu^-$ (upper) or $J/\psi\Lambda K^-$ (lower), where ψ refers to the J/ψ and $\psi(2S)$ mesons [3].

mean and the background is described with a first-order polynomial or an exponential function. The $J/\psi\Lambda K^-$ distribution also presents a contribution from the partially reconstructed $\Xi_b^- \to J/\psi\Sigma^0 K^-$ decay, where photon from $\Sigma^0 \to \Lambda\gamma$ decay is not detected. This contribution is taken into account by including an asymmetric Gaussian in the fit, with its shape parameters are fixed from MC simulation.

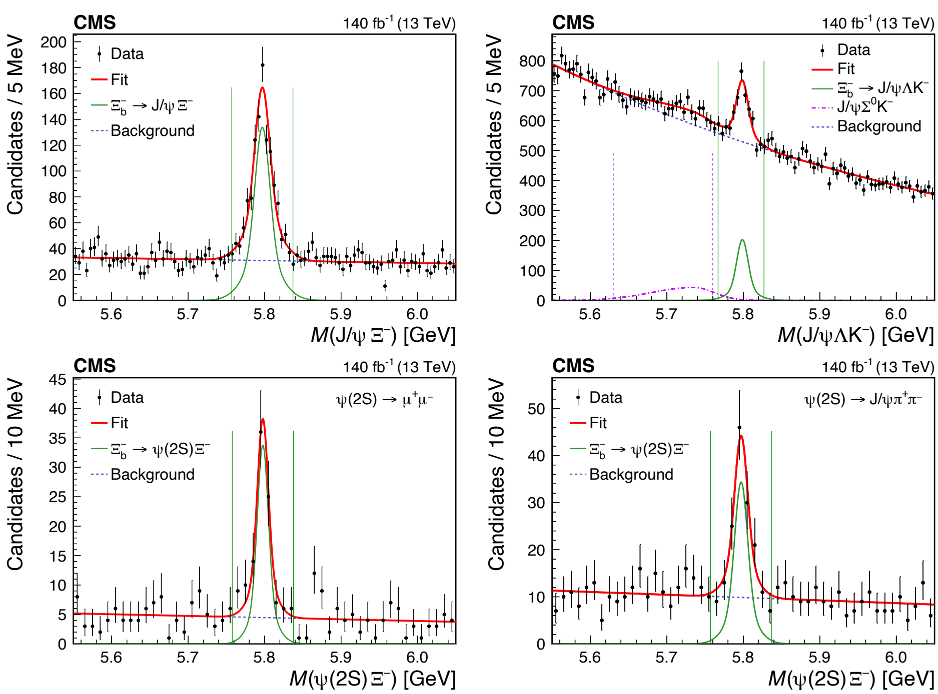

Figure 4. Invariant mass distributions of the selected $J/\psi\Xi^-$ (upper left), $J/\psi\Lambda K^-$ (upper right), and $\psi(2S)\Xi^-$ [lower row, with $\psi(2S) \to \mu^+\mu^-$ (left) and $\psi(2S) \to J/\psi\pi^+\pi^-$ (right)] candidates, with superimposed fit results [3].

Statistical significance of the $\Xi_b^- \to \psi(2S)\Xi^-$ signal is estimated with the likelihood ratio technique similar as we have done for the $\Lambda_b^0 \to J/\psi\Xi^- K^+$ decay. The obtained value is well above 5 standard deviation, claiming the first observation of the new decay. We have also measured its branching fraction w.r.t. the normalization channel $\Xi_b^- \to J/\psi\Xi^-$ (again, allowing us to reduce many possible sources of systematic uncertainties):

$$R = \frac{\mathcal{B}(\Xi_b^- \to \psi(2S)\Xi^-)}{\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)} = \frac{N(\Xi_b^- \to \psi(2S)\Xi^-)}{N(\Xi_b^- \to J/\psi\Xi^-)} \frac{\epsilon(\Xi_b^- \to J/\psi\Xi^-)}{\epsilon(\Xi_b^- \to \psi(2S)\Xi^-)} \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)} \quad (2)$$
$$= 0.84^{+0.21}_{-0.19}(\text{stat}) \pm 0.10(\text{syst}) \pm 0.02\,(\mathcal{B}),$$

where the last uncertainty is related with the to the uncertainties in the J/ψ and $\psi(2S)$ branching fractions. The N and ϵ refer to similar quantities as those in Eq. (1).

For the following studies of the $\Xi_b^-\pi^+$ system, the selected Ξ_b^- candidates within the mass windows, shown in the Fig. 4 with green (purple) lines for the fully (partially) reconstructed events, are combined with a charged pion track, originating from the PV. In order to improve the detector resolution, we apply a dedicated procedure of PV kinematic refit as done in previous CMS papers [12, 13].

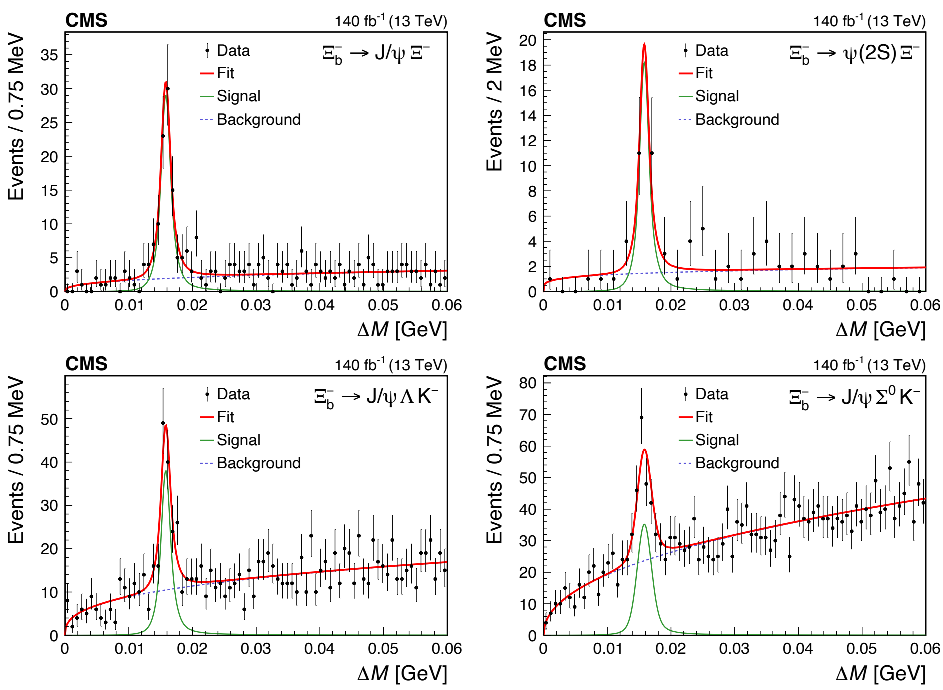

Figure 5. The mass difference ΔM distribution of the selected $\Xi_b^-\pi^+$ candidates for the decay channel labeled on each plot with results of the simultaneous fit overlaid [3].

Figure 5 presents the distributions of the invariant mass difference variable, defined as $\Delta M = M(\Xi_b^-\pi^+) - M(\Xi_b^-) - m^{\text{PDG}}(\pi^+)$, for the selected $\Xi_b^-\pi^+$ candidates separately for four channels of Ξ_b^- reconstruction. The ΔM variable allows us to subtract the Ξ_b^- mass resolution, resulting with significant improvement for possible signal sensitivity. We see a clear peak near the kinematic threshold in all 4 distributions, corresponding to the known Ξ_b^{*0} resonance. To describe this signal, we use a relativistic Breit–Wigner function, convoluted with a Gaussian detector resolution, which shape is fixed with the values obtained in the MC simulation, while the background is described with a threshold function.

In order to measure the parameters of the Ξ_b^{*0} baryon, we use a simultaneous fit of all four channels, where the mass and natural width of the peak are shared parameters of the fit, while the mass resolutions, yields, and background parameters are different. The measured mass difference and natural width of the Ξ_b^{*0} state are $\Delta M(\Xi_b^{*0}) = 15.810 \pm 0.077(\text{stat}) \pm 0.032(\text{syst})\,\text{MeV}$, $\Gamma(\Xi_b^{*0}) = 0.87^{+0.22}_{-0.20}(\text{stat}) \pm 0.16(\text{syst})\,\text{MeV}$.

We have also measured the ratio of the Ξ_b^{*0} to Ξ_b^- production:

$$R_{\Xi_b^{*0}} = \frac{\sigma(pp \to \Xi_b^{*0} X)\,\mathcal{B}(\Xi_b^{*0} \to \Xi_b^- \pi^+)}{\sigma(pp \to \Xi_b^- X)} = \frac{N(\Xi_b^{*0} \to \Xi_b^- \pi^+)}{N(\Xi_b^-)} \frac{\epsilon(\Xi_b^-)}{\epsilon(\Xi_b^{*0} \to \Xi_b^- \pi^+)} \\ = 0.23 \pm 0.04(\text{stat}) \pm 0.02(\text{syst}). \quad (3)$$

4 Conclusions

The CMS Experiment is actively contributing to the heavy flavour physics, providing the observations of the new beauty decays. We report the first observation of the $\Lambda_b^0 \to J/\psi \Xi^- K^+$ decay and the measurement of its branching fraction w.r.t. the known $\Lambda_b^0 \to \psi(2S)\Lambda$ decay [2]. The 2-body invariant mass distributions, where possible exotic intermediate resonances could be found, are also studied. The first observation of the new $\Xi_b^- \to \psi(2S)\Xi^-$ decay is reported as well together with its relative branching fraction to the $\Xi_b^- \to J/\psi \Xi^-$ decay [3]. We have also performed a study of the Ξ_b^{*0} baryon, providing the new measurements of its mass, natural width and the relative production w.r.t. the ground Ξ_b^- state.

While both analyses suffer from large statistical limitations and uncertainties, the new data from the ongoing Run-3 at the LHC is expected to significantly improve the situation and allow us to report new exciting results.

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