New results on conventional heavy baryons from CMS

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Summary. — The present report summarizes recent CMS results in conventional and exotic hadron spectroscopy, obtained using the data collected at the Large Hadron Collider during the Run-2 data taking (2015-2018) with proton-proton collisions at $\sqrt{s} = 13$ TeV. The results include the first observation of the $\Lambda_b^0 \to J/\psi \Xi^- K^+$ decay mode and the observation of Λ_b^{**} and Ξ_b^{**} excited states.

The heavy flavour production cross section at the Large Hadron Collider (LHC) is several orders of magnitude greater than at e^+e^- colliders. The CMS experiment [1] at LHC exploits its 4π coverage and high resolution to perform challenging measurements in the Heavy Flavor sector, despite the complex initial state and high background in environments such as proton-proton (pp) collisions. Some of the recent CMS measurements concerning conventional spectroscopy in the charm and beauty sectors are presented here.

1. – Observation of excited Λ_b states

A study of the $\Lambda_b^0\pi^+\pi^-$ invariant mass distribution in the 5.9-6.4 GeV range is performed using up to 140fb^{-1} of pp collisions data at $\sqrt{s} = 13$ TeV collected by CMS during the 2016-2018 period [8]. The Λ_b^0 candidates are reconstructed in three different channels separately: (1) $\Lambda_b^0 \to J/\psi(\to \mu^+\mu^-)\Lambda^0$, (2) $\Lambda_b^0 \to \psi(2S)(\to \mu^+\mu^-)\Lambda^0$, and (3) $\Lambda_b^0 \to \psi(2S)(\to \mu^+\mu^-\pi^+\pi^-)\Lambda^0$, with $\Lambda^0 \to p\pi^-$.

The $\Lambda_b^0\pi^+\pi^-$ candidates are then reconstructed by adding two opposite-sign tracks to the Λ_b^0 candidate, while same-sign track pairs are used to define the control region. Further selection is applied, separately optimized for the two regions $m_{\Lambda_b^0\pi^+\pi^-} \lessgtr 5.95$ GeV. Two signals corresponding to the excitations $\Lambda_b(5912)$ and $\Lambda_b(5920)$, already observed by LHCb [9] and CDF [10], are observed by CMS near the kinematic threshold with significance of 5.7σ and well over 6σ, respectively (Fig. 1, left). In the high-mass region (Fig. 1, right) a narrow peak at 6150 MeV with a resolution of 3.8 MeV is observed, consistent with the superposition of the two Λ_b excited states $\Lambda_b(6146)$ and $\Lambda_b(6152)$, already observed at LHCb [11]. There is evidence of a broad enhancement in the region below 6.1 GeV, not present in the control region. A veto on possible contributions from intermediate states ($\Sigma_b^{(*)\pm} \to \Lambda_b^0\pi^\pm$) improves the agreement between the signal

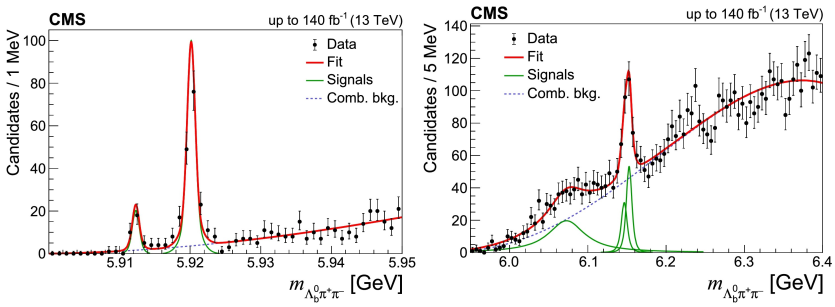

Fig. 1. – Invariant mass distribution of the selected $\Lambda_b^0\pi^+\pi^-$ candidates near the kinematic threshold (left) and in the high-mass region (right) [8]. Four signals are considered corresponding to the known Λ_b excitations: $\Lambda_b(5912)$, $\Lambda_b(5920)$, $\Lambda_b(6146)$, $\Lambda_b(6152)$. An additional contribution is introduced to describe the broad enhancement observed in the region below 6.1 GeV.

and control regions, but this hypothesis cannot be tested with the available sample size. A similar structure has been later observed at LHCb and it has been interpreted as a further excited state, $\Lambda_b^0(6072)$ [12].

2. – Observation of a new excited Ξ_b state

CMS has also reported the observation of a new state in the $\Xi_b^-\pi^+\pi^-$ system using up to 140 fb^{-1} of pp collisions data at $\sqrt{s} = 13$ TeV collected during the 2016-2018 period at LHC [13]. The event selection requires a combination of dimuon triggers targeting $J/\psi \to \mu^+\mu^-$, then Ξ_b^- candidates are reconstructed in three decay channels separately: (1) $\Xi_b^- \to J/\psi\Xi^-$, (2) $\Xi_b^- \to J/\psi\Lambda^0K^-$ and (3) $\Xi_b^- \to J/\psi\Sigma^0K^-$, with $\Xi^- \to \Lambda^0\pi^-$, $\Lambda^0 \to p\pi^-$ and $\Sigma^0 \to \Lambda^0\gamma_{soft}$, where the soft photon γ_{soft} is not reconstructed. The candidates are selected with criteria optimized for each decay channel and the signal yields are extracted with an UML fit.

Excited Ξ_b^- candidates are reconstructed by adding two opposite-sign tracks from the same pp collision vertex as Ξ_b^- to it, while same-sign tracks are used to define the control region. Since the contribution of the intermediate resonance $\Xi_b^{*0} \to \Xi_b^-\pi^+$ is expected to be dominant [14, 15], the requirement $m(\Xi_b^{*0})$ - $m(\Xi_b^-)$ - $m_\pi^{PDG} < 20.73$ MeV is added (peak expected at 15.73 MeV). The fully reconstructed channels (1) and (2) are combined as they have similar resolution.

A simultaneous UML fit is performed on the two data samples (Fig. 2) , resulting in the observation of a peak at $m(\Xi_b^{**-}) = 6100.3 \pm 0.2$ (stat.) $\pm\, 0.1$ (syst.) $\pm\, 0.6$ (Ξ_b^-) MeV, where the last term originates from the uncertainties on the Ξ_b^- mass, with local statistic significance greater than 6σ. An upper limit on the resonance width is set at 95% confidence level: $\Gamma(\Xi_b^{**-}) < 1.9$ MeV. Since the new $\Xi_b(6100)^-$ is consistent with the lightest orbitally excited baryon, the analogy with the Ξ_c system [14, 15] suggests its spin and light diquark angular momentum are $J^P = 3/2^-$ and $j_{ds} = 1$.

3. – Observation of the $\Lambda_b^0 \to J/\Psi\Xi^-K^+$ decay

In [2] CMS reports the search for the $\Lambda_b^0 \to J/\psi\Xi^-K^+$ decay performed using up to 140 fb^{-1} of pp collisions data at $\sqrt{s} = 13$ TeV collected during the 2016-2018 period.

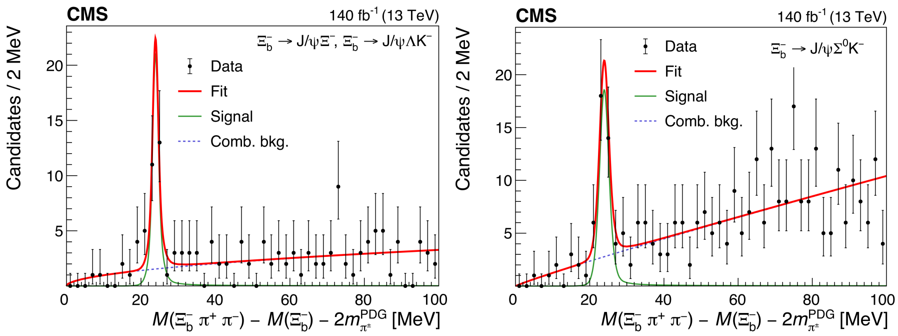

Fig. 2. – Invariant mass distribution of the selected $\Xi_b^-\pi^+\pi^-$ candidates for the combination of the fully reconstructed decay channels $\Xi_b^- \rightarrow J/\psi\Xi^-$ and $\Xi_b^- \rightarrow J/\psi\Lambda^0 K^-$ (left) and the partially reconstructed decay $\Xi_b^- \rightarrow J/\psi\Sigma^0 K^-$ (right) [13]. The mass difference variable plotted on the abscissa does not depend on the Ξ_b^- reconstruction channel. The first two decays can be combined since they have similar resolution, while the latter has a 30% larger mass resolution. A narrow peak consistent with a signal from the excited $\Xi_b(6100)^-$ is observed with local statistical significance larger than 6 σ.

The $J/\psi \rightarrow \mu^+\mu^-$, $\Xi^- \rightarrow \Lambda\pi^-$, and $\Lambda \rightarrow p\pi^-$ channels are used to reconstruct the intermediate decay products. The normalization channel is chosen to be $\Lambda_b^0 \rightarrow \psi(2S)\Lambda$, with subsequent $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ and $J/\psi \rightarrow \mu^+\mu^-$ decays, because of its similar decay topology and kinematics to the signal decay, leading to the reduction of many systematic uncertainties.

Only events firing a trigger requiring two opposite-sign muons, compatible with a displaced J/ψ meson, and a track compatible with the dimuon vertex. The final selection is optimized using the Punzi figure of merit [3]. The variables used in the optimization include: p_t of all decay products, the flight length significance of the Λ_b^0,Λ and Ξ baryons and the corresponding pointing angles; the vertex fit probabilities; the mass windows for Λ and Ξ. With the final selection, the background is reduced by a factor of 15 after the optimization, while the signal efficiency is at 70%.

In the mass distribution of the $\Psi(2S)\Lambda$, the signal is modelled with a Student's t-distribution [4] with all parameters (mean, σ, n) floating (Fig. 3, left). The measured

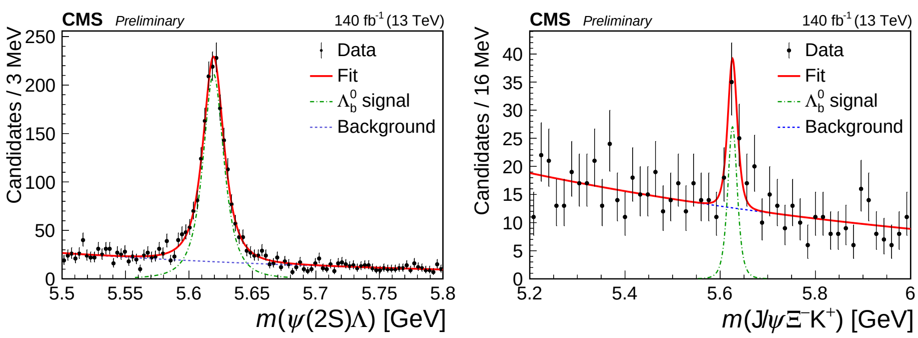

Fig. 3. – The measured $\Psi(2S)\Lambda$ invariant mass distribution with the fit results overlaid (left). [2]. The measured $J\Psi\Xi^- K^+$ invariant mass distribution with the fit results overlaid (right).

invariant mass distribution of the selected $J/\Psi\Xi^- K^+$ shows A narrow peak at the Λ_b^0 mass is seen on top of a smooth background (Fig. 3, right). The Λ_b^0 signal is also modelled with a Student's t-distribution with the n parameter fixed to the value found by fitting the simulated distribution, due to the limited signal yield of $N(\Lambda_b^0 \to J\Psi\Xi^- K^+) = 46 \pm 11$. The background is fitted with an exponential function with free parameters. The Λ_b^0 mass returned by the fit ($5625.9 \pm 3.2 MeV$) agrees with the PDG world-average [14]. The width of the signal peak (σ) is found to be $10.4 \pm 3.3 MeV$, consistent with the value found in simulation $6.6 \pm 0.2 MeV$.

Using the asymptotic formula described in [5], since the conditions to apply Wilks' theorem [6] are satisfied, the significance is found to be 5.8 standard deviations. Testing several alternative models of signal and background, the significance varies in the range from 5.27 to 5.85 standard deviations, well above the 5σ threhsold.

On the other hand, the sensitivity of this analysis to potential pentaquark signals in the intermediate invariant mass distributions of the $\Lambda_b^0 \to J\Psi\Xi^- K^+$ decay is limited by the low signal yield. Nevertheless, the two-body invariant mass distributions obtained with the *splot* technique [7] have been examined and found to be consistent with the phase space simulation without any narrow peaks.

Finally, the branching fraction of the newly observed $\Lambda_b^0 \to J\Psi\Xi^- K^+$ decay, with respect to the $\Lambda_b^0 \to \psi(2S)\Lambda$ decay, is measured to be

$$\frac{\mathcal{B}\left(\Lambda_\mathrm{b}^0 \to \mathrm{J}/\psi\Xi^-\mathrm{K}^+\right)}{\mathcal{B}\left(\Lambda_\mathrm{b}^0 \to \psi(2\mathrm{S})\Lambda\right) \times \mathcal{B}\left(\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-\right)} = [7.3 \pm 2.3 \pm 2.6]\%,$$

where the first uncertainty is statistical and the second one is systematic, using

$$\mathcal{R} \equiv \frac{\mathcal{B}\left(\Lambda_\mathrm{b}^0 \to \mathrm{J}/\psi\Xi^-\mathrm{K}^+\right)}{\mathcal{B}\left(\Lambda_\mathrm{b}^0 \to \psi(2S)\Lambda\right)} = \frac{N\left(\Lambda_\mathrm{b}^0 \to \mathrm{J}/\psi\Xi^-\mathrm{K}^+\right)}{N\left(\Lambda_\mathrm{b}^0 \to \psi(2\mathrm{S})\Lambda\right)} \frac{\epsilon_{\psi(2S)\Lambda}}{\epsilon_{\mathrm{J}/\psi\Xi^-\mathrm{K}^+}} \times \frac{\mathcal{B}\left(\psi(2S) \to \mathrm{J}/\psi\pi^+\pi^-\right)}{\mathcal{B}\left(\Xi^- \to \Lambda\pi^-\right)}$$

where N and ϵ stand for the number of signal events measured in data and the total efficiency, respectively. The systematic uncertainties considered take into account the choice of the signal model (3.9%); the choice of the background model (6.7%); the uncertainty on the efficiency ratio due to the limited size of the simulated samples (5.6%); the non-$\Psi(2S)$ background contribution in the $J/\Psi\pi^+\pi^-$ mass region (2.5%); the differences in the tracking efficiencies for the two channels (2.3%); the choice of the selection criteria (33.5%).

Using the known value of $B(\psi(2S) \to J/\Psi\pi^+\pi^-) = 34.68 \pm 0.30\%$ [14], the ratio R is measured as:

$$\mathcal{R} \equiv \frac{\mathcal{B}\left(\Lambda_\mathrm{b}^0 \to \mathrm{J}/\psi\Xi^-\mathrm{K}^+\right)}{\mathcal{B}\left(\Lambda_\mathrm{b}^0 \to \psi(2\mathrm{S})\Lambda\right)} = [2.5 \pm 0.8 \text{ (stat) } \pm 0.9 \text{ (syst)}]\%.$$

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