PROCEEDINGS OF SCIENCE

Spectroscopy of new heavy baryons

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This talk focuses on the spectroscopy of new heavy baryons, providing an overview of key developments in the field and the insights gained from past analyses. Rather than presenting a comprehensive review of the numerous studies conducted, the discussion aims to highlight the progress made, the evolution of analysis techniques, and future prospects. The presentation begins with a general introduction to heavy baryons, followed by a timeline of spectroscopy studies, using selected examples to illustrate major milestones. Various types of analyses employed in heavy baryon studies are discussed, with an emphasis on methodological improvements over time.

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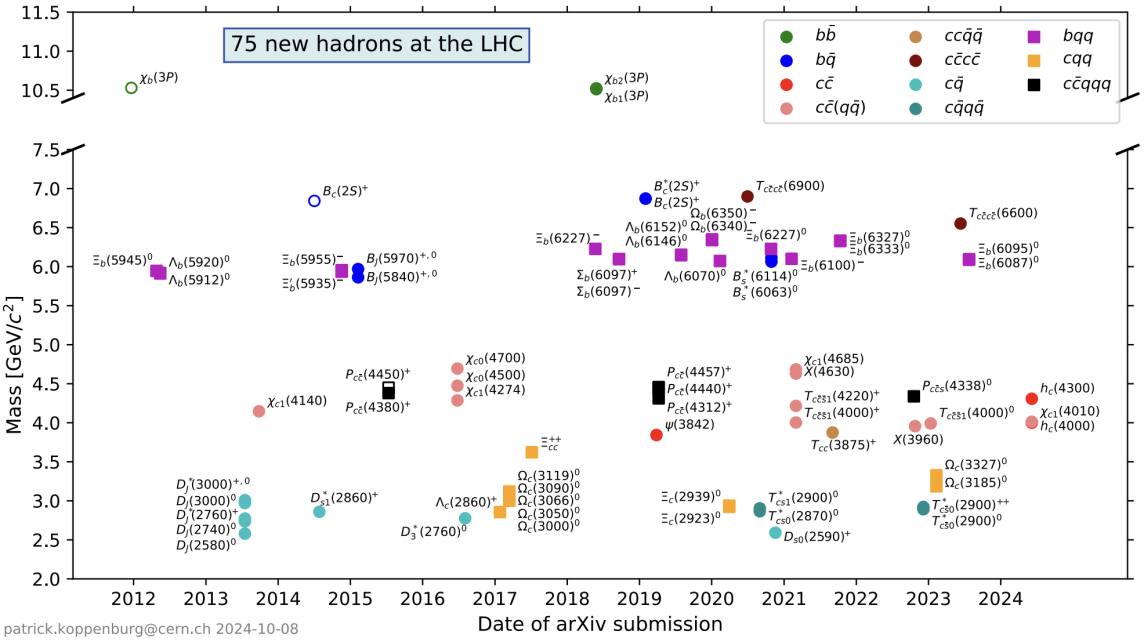

Figure 1: List of the new hadrons observed at the LHC at the time of writing [1].

1. Introduction

Quantum Chromodynamics (QCD) describes the behavior of strongly interacting particles. However, understanding its non-perturbative properties at low-energy scales remains an open challenge and an active area of research. In this context, the spectroscopy of heavy hadrons serves as a powerful tool for probing QCD in the non-perturbative regime. In recent years, heavy-quark spectroscopy has seen continuous advancements, both experimentally and theoretically. To date, more than 75 hadrons have been discovered at the LHC, as illustrated in Fig. 1, with contributions from all major experiments. This number continues to grow steadily, and with the upcoming high-luminosity upgrades, further discoveries are anticipated. Hadrons are organized into multiplets, yet several predicted states remain experimentally elusive. This discussion focuses primarily on the so-called "conventional states", composed of either three quarks (qqq) or a quark-antiquark pair ($q\bar{q}$). However, more complex structures, such as the so-called "exotic states" (e.g., tetraquarks and pentaquarks), are also theoretically possible and have been the subject of increasing interest.

2. Ingredients for a successful analysis: an example

Most spectroscopy analyses rely on several key features that are essential for successful measurements:

- High yields and clean samples, ensuring statistically significant results.
- Good momentum resolution, crucial for precise mass shape measurements.
- Well-motivated search strategies, guided by theoretical predictions and past observations to identify new resonances efficiently.

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A retrospective look at the evolution of experimental knowledge highlights how the discovery of new states has progressed over time as larger datasets have become available. The first step in these analyses is to achieve high yields, enabling access to rare states. Additionally, the signal-to-background (S/B) ratio plays a critical role, particularly in complex searches where background suppression is challenging. A prime example is the Λ_b^0 baryon, which serves as a fundamental building block for many b-baryon analyses. It also provides a clean control sample for a variety of calibration and branching fraction measurements. Figure 2 illustrates the advantages and limitations of different trigger strategies used in these searches. Beyond the threshold, new resonances can

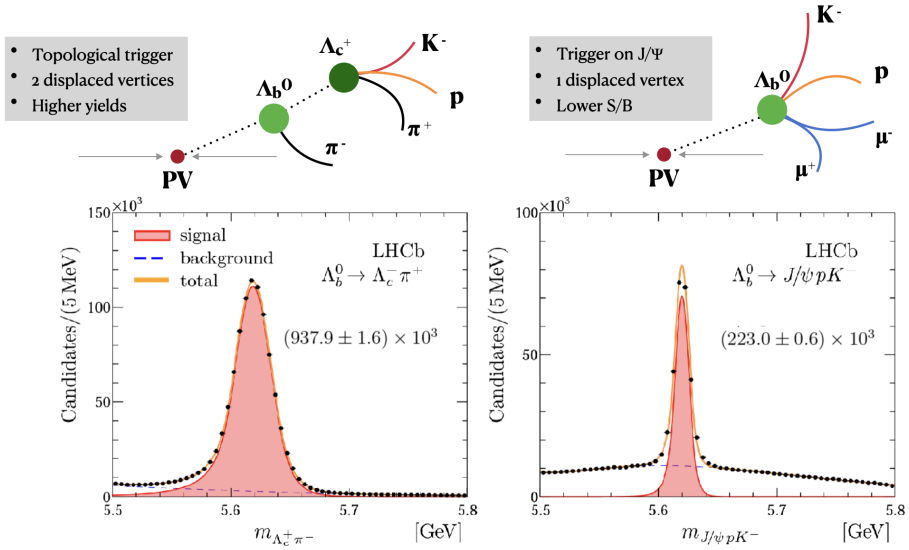

Figure 2: Λ_b^0 baryon candidates can be selected in different final states and using different trigger strategies. Yields and mass distributions are shown for final states containing hadrons and/or muons. Both strategies offer advantages and drawbacks. Images are taken from [2].

be identified through strong decays, where a rich spectrum of excited states is expected. A brief overview of the observed Λ_b excitation spectrum is presented in Figure 3, along with the time of discovery.

3. Experimental missing states

Several heavy-baryon states remain experimentally elusive, most notably Σ_b^0, Σ_b^{*0}, and $\Xi_b^{\prime 0}$. The primary challenge in detecting these states arises from their strong decays, which predominantly produce final states containing π^0 mesons. The reconstruction of neutral particles in the high-background environment of the LHC presents significant experimental difficulties. Despite these challenges, the masses and decay widths of these states can be estimated using isospin symmetry and lattice QCD calculations, which also provide predictions for their decay patterns. The expected properties of the Σ_b states are illustrated in Figure 4, along with newly observed excitations [3]. Furthermore, experimental resolution and efficiency estimates can, in principle, be extracted from recent publications with minimal reliance on simulations, offering a data-driven approach to improving search strategies for these missing states.

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4. Most recent observation of new baryons

Recent searches for new baryonic states have led to the observation of previously unreported resonances in both charged and neutral final states $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ [4]. The Ξ_b baryons form an isospin doublet, consisting of the quark compositions (bsu, bsd). Their ground states correspond to configurations with zero orbital angular momentum ($L = 0$) between the b quark and the lighter sq diquark. Three such non-excited isospin doublets are expected, characterised by different values of spin-parity (J^P) and diquark total angular momentum (J_{sq}). To enhance the statistical significance of these studies, the yields of both Ξ_b^0 and Ξ_b^- have been significantly increased by considering multiple final states, including some that had never been observed experimentally. While final states with a larger number of charged tracks pose greater experimental challenges due to increased background levels, signal yields are expected to increase by up to 50% or more. Samples of Ξ_b^0 and Ξ_b^- baryons are selected using Boosted Decision Tree (BDT) algorithms, trained on simulated signal and data sidebands for background suppression. Additional vetoes are applied where necessary to suppress contamination from Λ_b decays. Mass differences are extracted by performing fits using resolution curves derived from simulations, which are further validated through extensive

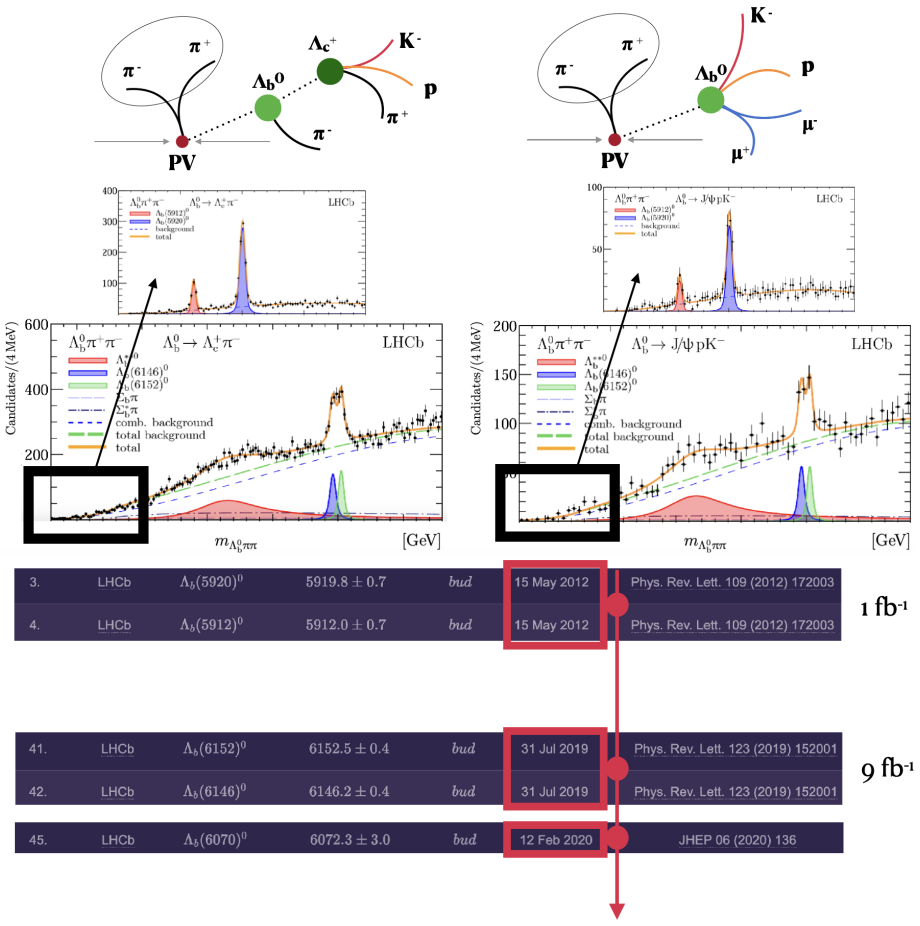

Figure 3: Evolution of experimental observations in time of the Λ_b^{**} states. The more data become available, the more states become experimentally accessible. Images taken from [2].

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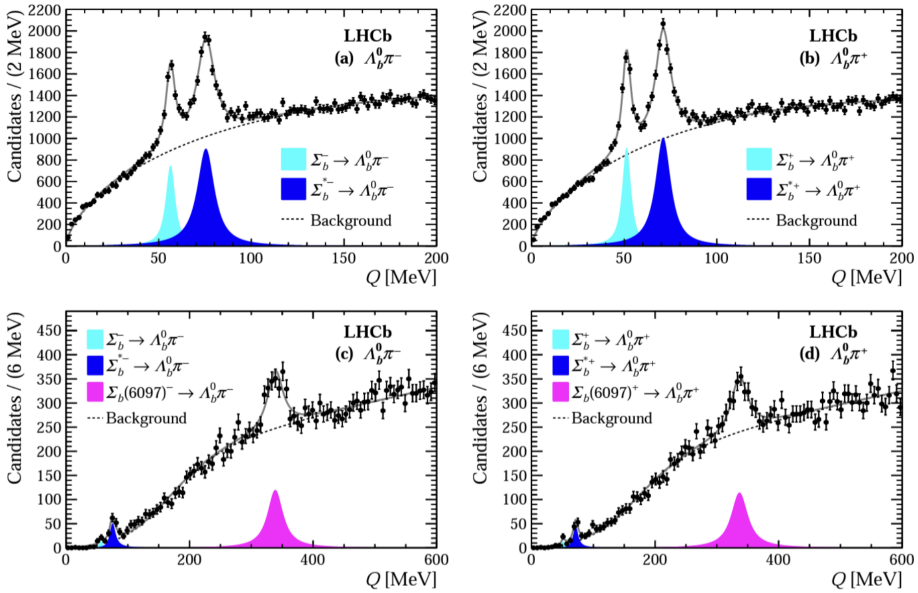

Figure 4: Observation of $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ states at LHCb [3]. The states, initially reported by CMS have been studied promptly by other experiments.

cross-checks on data. Two new baryons, with quark content bsu, are observed in the $\Xi_b^0\pi^+\pi^-$ final state. This measurement employs final states with up to nine charged tracks, most of which are pions, highlighting the excellent performance of the LHCb tracking, reconstruction, and particle identification (PID) systems. Additionally, the decay mode $\Xi_b^0 \to \Xi_c^+\pi^-\pi^+\pi^-$ is observed for the first time. The properties of the previously known Ξ_b^{0*}, $\Xi_b^{\prime-}$, and Ξ_b^{*-} baryons are also measured with high precision. All decay patterns closely resemble those seen in the Ξ_c^0 and Ξ_c^+ baryon systems. A natural interpretation of these new states is that they correspond to P-wave excitations, where the orbital angular momentum between the b quark and the qs diquark is $l = 1$. The expected dominant decay mode of the lighter state is $\Xi_b^{\prime}\pi$, while the heavier state preferentially decays via $\Xi_b^*\pi$. The lighter Ξ_b^{**-} could not be directly observed, as it is expected to decay predominantly via the intermediate $\Xi_b^{\prime 0}$ resonance, which lies below the threshold for decay into $\Xi_b^-\pi^+$. However, hints of the decay $\Xi_b^{**-} \to \Xi_b^{\prime 0}(\Xi_b^0\pi^0)\pi^-$ are observed in the $\Xi_b^0\pi^-$ mass spectrum as a partially reconstructed feed-down component. All mass plots involved are shown in Fig. 5.

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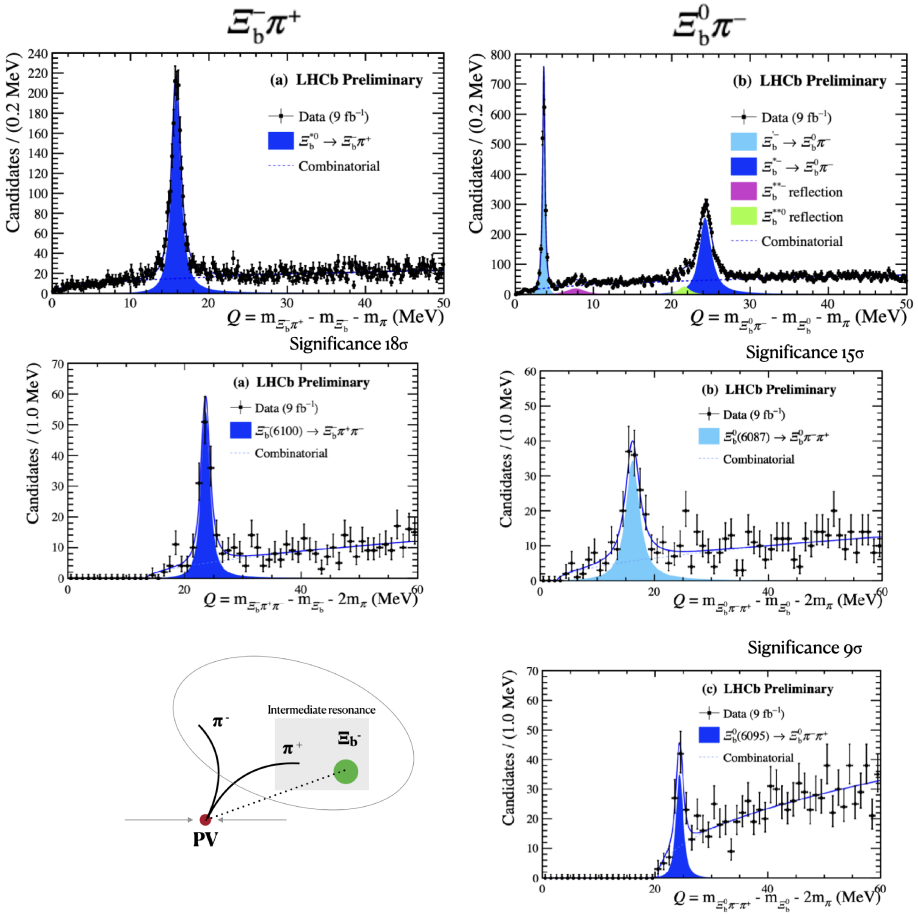

Figure 5: Key measurements and new observations from [4]. New states in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ final states are clearly visible.

References

[1] The LHCb collaboration., Koppenburg, P. List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates. LHCb-FIGURE-2021-001, 2021, and 2024 updates.

[2] The LHCb collaboration., Roel, A. Observation of a new baryon state in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum. JHEP06(2020)136.

[3] The LHCb collaboration., Roel, A. Observation of two resonances in the $\Lambda_b^0\pi^\pm$ systems and precise measurement of $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ properties. PRL 122, 012001 (2019).

[4] The LHCb collaboration., Roel, A. Observation of new baryons in the $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ systems. PRL 131, 171901.

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