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Exotic Spectroscopy at LHCb

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The LHCb collaboration achieved important results in the exotic spectroscopy sector using pp collision data collected with the LHCb detector at centre-of-mass energies of $\sqrt{s} = 7$ and $\sqrt{s} = 8\,\text{TeV}$ during Run1, corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$. These results include the discovery of two pentaquark candidates by an amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays, by a model-independent approach and by an amplitude analysis of $\Lambda_b^0 \to J/\psi p \pi^-$ decays. Following the interest arised from these discoveries, further LHCb studies related to the pentaquark spectroscopy have been carried out, including the first observation of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$ decays, a search for weakly decaying b-flavoured pentaquarks, and a search for exotic states in $\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-$ decays.

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1. Introduction

Hadrons beyond conventional mesons and baryons have been foreseen since the development of the Constituent Quark Model in 1964 [1, 2] and their existence is not forbidden by QCD as long as they form color-singlet configurations. However, for almost 40 years, none of these non-conventional states, namely exotic hadrons, were discovered. Since 2003, several hadrons decaying strongly in heavy quarkonium states but having mass, electrical charge and/or decay properties inconsistent with pure charmonium or bottomonium states, have been observed (see Refs. [3, 4] for recent reviews). The majority of heavy quarkonium states predicted by QCD-motivated potential models and by NRQCD have been discovered, confirming the validity of these models. Since the new quarkonium-like states do not fit with these spectra, they could be identified with exotic hadrons.

A coherent picture concerning the nature and the binding mechanism of these exotic hadrons is missing and more inputs from both the experimental and theoretical sides are required to understand these states. Discoveries of new exotic hadrons and searches for candidates foreseen by different phenomenological models will help to improve the understanding of these non-conventional states and hence the knowledge of the non-perturbative regime of QCD, also having an indirect impact on searches for New Physics.

The excellent performance of the LHC and of the LHCb detector allowed to obtain important results in the exotic spectroscopy sector. Especially the discovery of two pentaquark candidates by the LHCb collaboration triggered a lot of interest on the theoretical side and hence new searches for exotic candidates, aiming to test the various phenomenological models proposed to explain these non-conventional states. The analyses presented here use the full data sample collected by the LHCb detector during Run1.

2. Observation of two pentaquark candidates

The LHCb collaboration made the first observation of two pentaquark candidates through a 6D amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays [5]. Two Breit-Wigner amplitudes decaying to the $J/\psi p$ final state, labelled $P_c(4380)^+$ and $P_c(4450)^+$, were necessary to obtain a good fit quality. The significance of each of these resonances is more than 9 standard deviations. Their mass, width and fit fractions have been determined to be $4380 \pm 8 \pm 29\,\mathrm{MeV}$, $205 \pm 18 \pm 86\,\mathrm{MeV}$, $(8.4 \pm 0.7 \pm 4.3)\%$, and $4450 \pm 2 \pm 3\,\mathrm{MeV}$, $39 \pm 5 \pm 19\,\mathrm{MeV}$, $(4.1 \pm 0.5 \pm 1.1)\%$, respectively. In order to obtain a good fit quality in the angular projections, the two states must have opposite parities. The favourite assignments for their quantum numbers are $J^P = 3/2^-$ for the $P_c(4380)^+$ and $J^P = 5/2^+$ for the $P_c(4450)^+$, but the $J^P = (3/2^+, 5/2^-)$ and $J^P = (5/2^+, 3/2^-)$ assignments could not be excluded.

As shown in Fig. 1, $\Lambda_b^0 \to J/\psi p K^-$ decays also proceed through several intermediate contributions in the $m(pK^-)$ system. Given the large density of predicted $\Lambda^* \to pK^-$ states, the possible presence of non-resonant pK^- contributions and of Σ excitations, a 2D model-independent approach has been used to test the hypothesis that the pentaquark structures in the $J/\psi p$ projection are actually due to reflections of structures in the pK^- system [6].

The 2D model-independent approach is performed in bins of $m(pK^-)$ with the angular distribution in each bin described by a sum of Legendre polynomials. A resonance of spin J in the

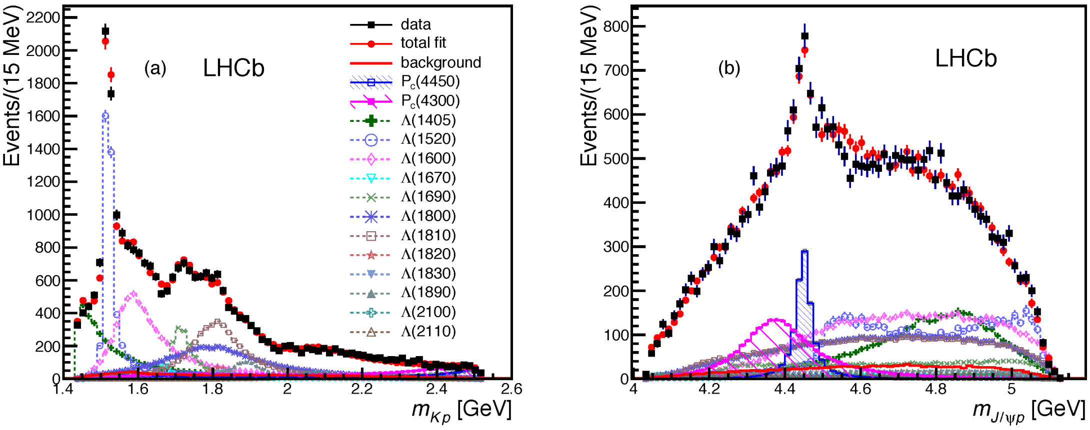


Figure 1: $m(pK^-)$ (a) and $m(J/\psi p)$ (b) fit projections when the $P_c(4380)^+$ and $P_c(4450)^+$ are included in the amplitude fit model.

pK^- system may only contribute to moments up to $2J$. In the absence of exotic contributions, the angular distributions are well described by a truncated sum at the value $l = l_{max}$ determined using theoretical predictions and observed resonances. To test for exotic contributions, a likelihood ratio is constructed between a null hypothesis in which only contributions up to l_{max} were included and an alternative hypothesis with higher moments also included. As shown in Fig. 2, the hypothesis test carried out performing pseudo-experiments demonstrates at more than 9σ that $\Lambda_b^0 \to J/\psi pK^-$ decays cannot be described by pK^- contributions alone.

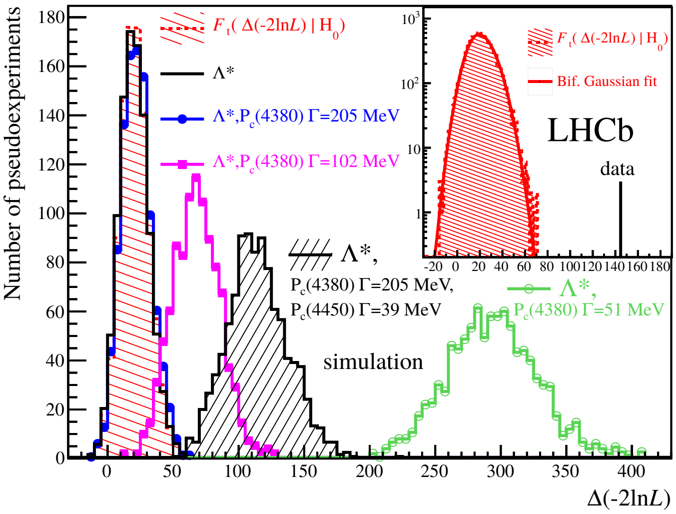


Figure 2: Difference in the profile likelihood ratio determined from various pseudo-experiments under various amplitude models in the model-independent approach. In the box there is the distribution of the profile likelihood ratio for pseudo-experiments generated under the null hypothesis H_0 (red hatched) and the value obtained in data (black vertical line).

The amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays also allowed checking the resonant character of the two pentaquark candidates by studying the Argand diagram of the corresponding exotic amplitudes. While the $P_c(4450)^+$ behaviour is consistent with the one expected from a resonance, the study is not conclusive for the $P_c(4380)^+$ amplitude given the available statistics in Run1 data.

Some phenomenological models advanced the interpretation of the $P_c(4450)^+$ peak as arising from kinematical effects related to the so-called triangle singularity [7, 8]. These pictures are motivated by the proximity of the $P_c(4450)^+$ mass to the $\chi_{c1}p$ threshold, that could explain a peaking structure in the $J/\psi p$ spectrum as due to the $\chi_{c1}p$ rescattering to the $J/\psi p$ final state. Moreover, the resulting Argand diagram would be compatible with the one observed by LHCb for the $P_c(4450)^+$. There are two possible rescattering mechanisms: a prompt three-body production $\Lambda_b^0 \to \chi_{c1} p K^-$ followed by the rescattering process $\chi_{c1} p \to J/\psi p$; a prompt two-body production $\Lambda_b^0 \to \chi_{c1}\Lambda^*(1890)$, where the proton decaying from the $\Lambda^*(1890)$ rescatters with the χ_{c1} to the $J/\psi p$ final state.

The last mechanism has been challenged by the amplitude analysis of $\Lambda_b^0 \to J/\psi p \pi^-$ decays, where exotic contributions are required to obtain an acceptable fit. $\Lambda_b^0 \to J/\psi p \pi^-$ decays are Cabibbo suppressed with respect to $\Lambda_b^0 \to J/\psi p K^-$ decays and hence the statistics is limited. However, the significance for the amplitude model with the two pentaquark candidates is 3.3σ. Another exotic amplitude modelling the tetraquark candidate $Z_c(4200)^- \to J/\psi \pi^-$, has been added to the model leading to a significance of the two pentaquark plus the $Z_c(4200)^-$ of 3.1σ. The evidence for the pentaquark states in $\Lambda_b^0 \to J/\psi p \pi^-$ decays provides a challenge for the triangular singularity mechanism involving the $\Lambda^*(1890)$, since the latter would need to be replaced by a particular N^* resonance to give a peak at the same energy and with the same relative strength of the $P_c(4450)^+$ in the two decay modes. This reinforces the interpretation of the $P_c(4450)^+$ as a genuine resonance.

3. Observations of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$ decays

The first triangular singularity mechanism described above can be tested by studying $\Lambda_b^0 \to \chi_{c1} p K^-$ decays. If the $P_c(4450)^+$ state was a rescattering effect, then it would not appear as an enhancement near the $\chi_{c1}p$ threshold in the $\Lambda_b^0 \to \chi_{c1} p K^-$ mode.

The LHCb collaboration provided the first observation of these decays and the measurement of the corresponding branching ratios [9]. The $\chi_{c(1,2)}$ are reconstructed into the $J/\psi\gamma$ decay mode. A kinematic fit is applied to the Λ_b^0 candidate, with the J/ψ and χ_{c1} masses constrained to their known values. This has the effect of producing separated peaks for the two decay modes as shown in Fig. 3.

The branching ratios with respect to the $\Lambda_b^0 \to J/\psi p K^-$ decay mode are determined to be

$$\frac{\mathscr{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathscr{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009, \tag{3.1}$$

$$\frac{\mathscr{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathscr{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009, \tag{3.2}$$

where the first uncertainty is statistical, the second systematic and the third due to the uncertainty on the branching ratios of the $\chi_{c(1,2)} \to J/\psi\gamma$ decays.

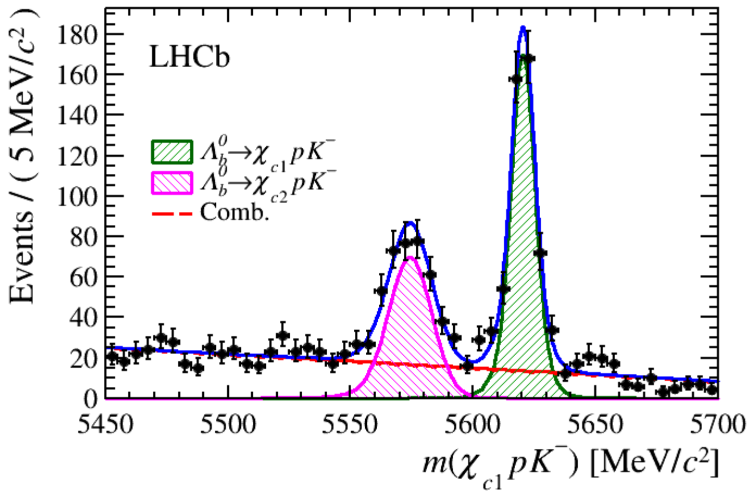


Figure 3: Fit to the $\Lambda_b^0 \to \chi_{c1} p K^-$ invariant mass distribution.

Given the limited statistics, the addition of Run2 data will be crucial to perform a first amplitude analysis of these decays, in order to test the interpretation of the $P_c(4450)^+$ peak as a rescattering effect.

4. Search for weakly decaying *b*-flavoured pentaquarks

The observation of charmonium-like pentaquark candidates raises many questions related to their internal structure, the existence of other pentaquark states and their binding mechanism, i.e. if they are molecular or tightly bound states. Different models, based on the Skyrme model [10], predict that the heavier the constituent quarks, the more tightly bound the pentaquark state should be [11, 12].

A search for long-lived pentaquarks with a lifetime of the order of other *b*-hadrons has been carried out by the LHCb collaboration [13]. These long-lived pentaquarks would be open-bottom pentaquarks where the *b* quark decays via the weak interaction. As shown in Table 1, four different final states are investigated. The final states involve a J/ψ because of the ease of triggering on $J/\psi \to \mu^+\mu^-$ events, meaning relatively large efficiencies and reduced backgrounds in the LHCb experiment. Depending on the mass of these pentaquarks (P_B^+), they could decay either strongly or weakly. For this reason, the search is restricted to a threshold lower than the mass for the corresponding strong decays, indicated by the subscript labelling the P_B^+ in Table 1.

Scanning the pentaquark invariant mass distributions in the four final states listed in Table 1, no signal is observed. Upper limits are set on the ratio

$$R = \frac{\sigma(pp \to P_b X)\mathscr{B}(P_b \to J/\psi X)}{\sigma(pp \to \Lambda_b^0 X)\mathscr{B}(\Lambda_b^0 \to J/\psi p K^-)}, \tag{4.1}$$

where the $\Lambda_b^0 \to J/\psi p K^-$ decay mode is used for normalization. As shown in Fig. 4, 90% CL limits are below 10^{-2} for all the considered final states.

Table 1: Quark content, weak decay mode and search window for the pentaquarks searched in Ref. [13].

Quark content	Decay mode	Search window [MeV]
$\bar{b}duud$	$P^+_{B^0p} \to J/\psi K^+\pi^- p$	4668-6220
$b\bar{u}udd$	$P^-_{\Lambda_b^0\pi^-} \to J/\psi K^-\pi^- p$	4668-5760
$b\bar{d}uud$	$P^+_{\Lambda_b^0\pi^+} \to J/\psi K^-\pi^+ p$	4668-5760
$\bar{b}suud$	$P^+_{B_s^0p} \to J/\psi\phi p$	5055-6305

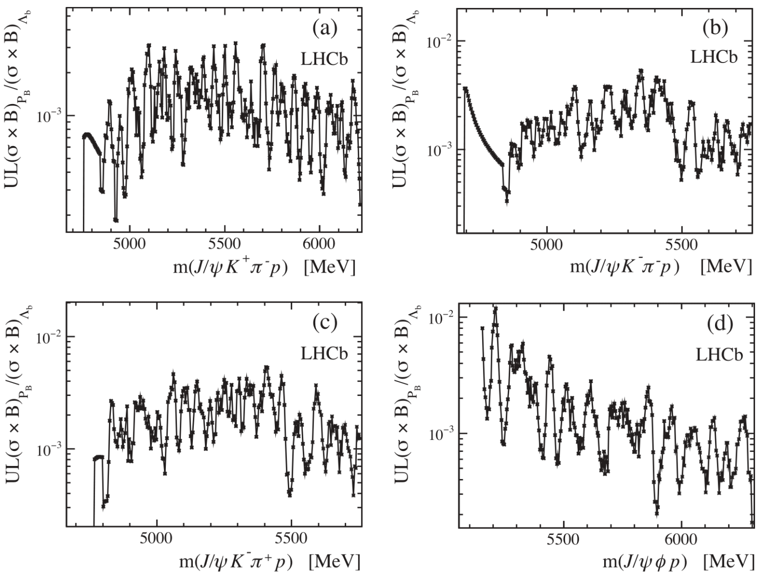


Figure 4: Upper limits on R at 90% CL for the four explored final states.

5. Search for dibaryon states in $\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-$ decays

QCD-color-motivated models can be used to interpret the tetraquarks and pentaquarks candidates observed so far. In particular, colour antisymmetric diquarks can replace antiquarks in conventional hadrons to give conventional and exotic hadrons. If diquarks are good building blocks to assemble hadrons, after the discovery of the pentaquark candidates by LHCb, the missing structures to be discovered are dibaryons. As pointed out in Ref. [14], the lightest charmed dibaryon D_c^+ could manifest via $\Lambda_b^0 \to \bar{p}D_c^+$ decays, hence having a mass $m(D_c^+) < 4682\,\text{MeV}$. The D_c^+ could proceed either via string breaking to the $pP_c^0(\to \Lambda_c^+\pi^-)$ final state, where P_c^0 is a lighter, yet undiscovered, neutral pentaquark state, or via quark rearrangement to the $p\Sigma_c^0(\to \Lambda_c^+\pi^-)$ final state.

The LHCb collaboration carried out a search for dibaryon states in $\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-$ decays [15]. The decay $\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-$ is observed for the first time, and its branching ratio with respect to $\Lambda_b^0 \to \Lambda_c^+\pi^-$ is measured to be

$$\frac{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-)}{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032, \tag{5.1}$$

where the first uncertainty is statistical and the second systematic.

The resonances in the $\Lambda_c^+\pi^-$ system are studied. Two resonant structures corresponding to the $\Sigma_c(2445)^0$ and $\Sigma_c^*(2520)^0$ states are observed through an unbinned maximum likelihood fit, shown in Fig. 5, and the ratios of branching fractions with respect to the $\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-$ are determined to be

$$\frac{\mathscr{B}(\Lambda_b^0 \to \Sigma_c(2445)^0 p\bar{p})}{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-)} = 0.089 \pm 0.015 \pm 0.006, \tag{5.2}$$

$$\frac{\mathscr{B}(\Lambda_b^0 \to \Sigma_c^*(2520)^0 p\bar{p})}{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-)} = 0.119 \pm 0.020 \pm 0.014, \tag{5.3}$$

where the first uncertainty is statistical and the second systematic. No other peaks that could possibly be identified with a P_c^0 are seen.

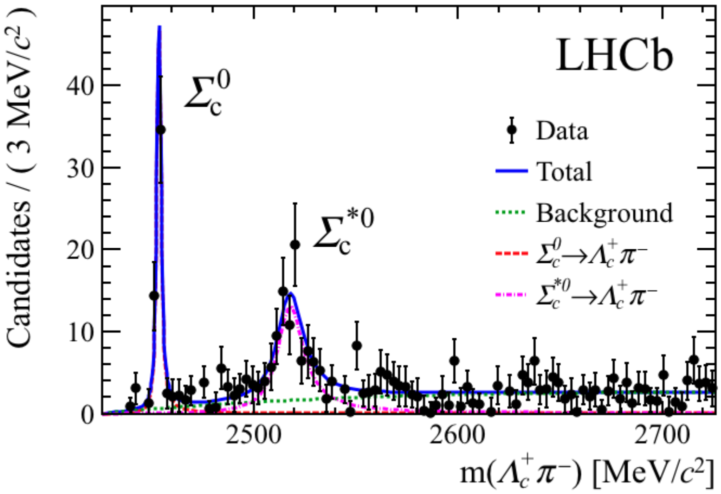


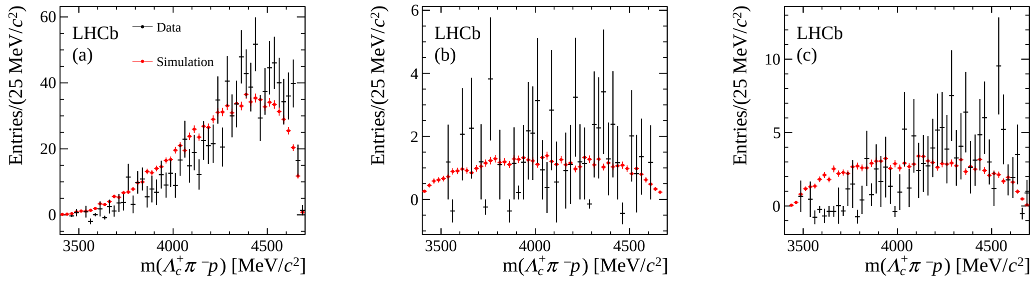
Figure 5: Unbinned maximum likelihood fit to the $m(\Lambda_c^+\pi^-)$ distribution. The yield of the $\Sigma_c(2445)^0$ component is 59 ± 10 and the yield of the $\Sigma_c^*(2520)^0$ component is 104 ± 17.

The existence of dibaryon resonances $D_c^+ \to p\Sigma_c^0$ is investigated in the $\Lambda_c^+\pi^- p$ system considering the full $\Lambda_c^+\pi^-$ spectrum (Fig. 6(a)), the $\Sigma_c(2445)^0$ region (Fig. 6(b)) and the $\Sigma_c^*(2520)^0$ region (Fig. 6(c)). No evidence for such dibaryon states is found.

6. Conclusions

The excellent performance of the LHC and of the LHCb detector allowed to extend the physics programme of the LHCb experiment, originally designed to perform CP violation and rare decays measurements. In particular, important results in the exotic spectroscopy sector have been achieved, giving inputs to the phenomenological models proposed to explain the nature and the binding mechanism of exotic hadrons.

However, a coherent picture of these non-conventional hadrons is still missing and it requires other theoretical and experimental work. In the short term, LHCb will provide a crucial role on the subject adding the analysis of Run2 data. In the long term, the upgraded LHCb will be able to cope



(a) (b) (c)

Figure 6: Background-subtracted invariant mass spectrum of the $\Lambda_c^+\pi^-p$ system in (a) the full $\Lambda_c^+\pi^-$ mass spectrum, (b) the $\Sigma_c(2445)^0$ region and (c) the $\Sigma_c^*(2520)^0$ region. Data points are in black while the red points are phase-space simulated events.

with a five-fold increase in the instantaneous luminosity. Moreover, thanks to a trigger system fully implemented in software, the efficiency on fully hadronic decay modes will significantly increase, opening exciting opportunities for the exotic spectroscopy sector.

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