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Recent studies of pentaquarks at LHCb

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Studying the properties and behavior of pentaquarks deepens our understanding of quantum chromodynamics (QCD) and the strong interactions. The LHCb experiment, with a large heavy-flavor dataset and detector performance optimized for beauty and charm hadron studies, is uniquely positioned to explore the properties of heavy-flavor pentaquark states. This talk highlights the latest advancements in the study of pentaquark states within the LHCb experiment, including study of pentaquark states in both prompt and non-prompt production. These results hold important reference value for understanding the formation of pentaquark states.

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[*] Speaker

1. Introduction

Pentaquarks, exotic particles composed of five quarks, pose a challenge to our understanding of the strong interaction and the fundamental structure of matter. In 2015, the first observation of two pentaquark candidates in the $\Lambda_b^0 \to pJ/\psi K^-$ decay[1] by the LHCb collaboration sparked further exploration in this field [1]. Subsequent discoveries, including $P_\psi^N(4337)^+$, $P_\psi^N(4440)^+$, $P_\psi^N(4457)^+$, $P_\psi^N(4312)^+$, $P_{\psi s}^\Lambda(4338)^0$, and $P_{\psi s}^\Lambda(4459)^0$, have further expanded our knowledge in this area [2–5]. These hidden-charm pentaquarks display diverse characteristics. Measurements of their mass, width, decay modes, and quantum numbers provide valuable information about their origins and inner structures.

The proximity of pentaquark masses to charm meson and charm baryon thresholds suggests a potential loosely bound state. Alternative models like the compact pentaquark and kinematical effect hypotheses offer different explanations. The ongoing debate over spin-parity assignments and branching ratios underscores the complexity of pentaquark understanding. Research at the LHCb aims to address these challenges and enhance our comprehension of pentaquarks. This talk includes a review of the recent results from LHCb regarding the decay of b-hadrons into pentaquarks and the exploration of prompt production of pentaquarks in proton-proton (pp) collisions.

2. Pentaquark-related studies in b-hadron open-charm decay

Exploring the resonant structure of the $\Lambda_b^0 \to \Lambda_c^+\overline{D}^{(*)0}K^-$ and $\Lambda_b^0 \to \Sigma_c^{(*)++}D^{(*)-}K^-$ decay modes holds significant interest. This is due to the fact that the $\Lambda_c^+\overline{D}^{(*)0}$ and $\Sigma_c^{(*)++}D^{(*)-}$ systems serve as the open-charm counterparts to the $p(uud)J/\psi(c\bar{c})$ final state, within which the $P_\psi^{N+}(c\bar{c}uud)$ pentaquark resonances have been experimentally observed. In numerous theoretical models, it is expected that these pentaquarks will decay into $\Lambda_c^+\overline{D}^{(*)0}$ and $\Sigma_c^{(*)++}D^{(*)-}$ states. However, the estimated branching fractions (BF) for these decays in relation to the pJ/ψ decay mode show a wide range of differences, covering several orders of magnitude. In the initial stage of the pentaquark search in these decays, a search for the corresponding Λ_b^0 decays is performed. The branching fraction measurement of these Λ_b^0 decays, combined with the theoretical predictions of $P_\psi^{N+} \to pJ/\psi$, $P_\psi^{N+} \to \Lambda_c^+\overline{D}^{(*)0}$, and $P_\psi^{N+} \to \Sigma_c^{(*)++}D^{(*)-}$ branching fraction ratios, helps to estimate the feasibility of using these decays to validate the molecular hypothesis.

The decays $\Lambda_b^0 \to \Lambda_c^+\overline{D}^{(*)0}K^-$ and $\Lambda_b^0 \to \Lambda_c^+D_s^{(*)-}$ have been observed for the first time in the pp collision data at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $5.4\,\text{fb}^{-1}$ collected with the LHCb detector [6]. The selection of charmed hadrons is based on multivariate analysis (MVA), and partial reconstruction is also considered, where signals from π^0 or photons may be missed. The signal shapes for partially-reconstructed components are determined using kernel density estimation (KDE) from simulation, and efficiency effects are taken into consideration. The distinction between single-charm and charmless background is determined through a three-dimensional fit on the Λ_b^0 mass, Λ_c^+ mass, and $\overline{D}^0$ mass.

The fit projections on the Λ_b^0 mass for the $\Lambda_c^+D_s^{(*)-}$ mode and $\Lambda_c^+\overline{D}^{(*)0}K^-$ mode are shown in Fig. 1(a) and Fig. 1(b), respectively. The ratios of branching fractions with respect to the

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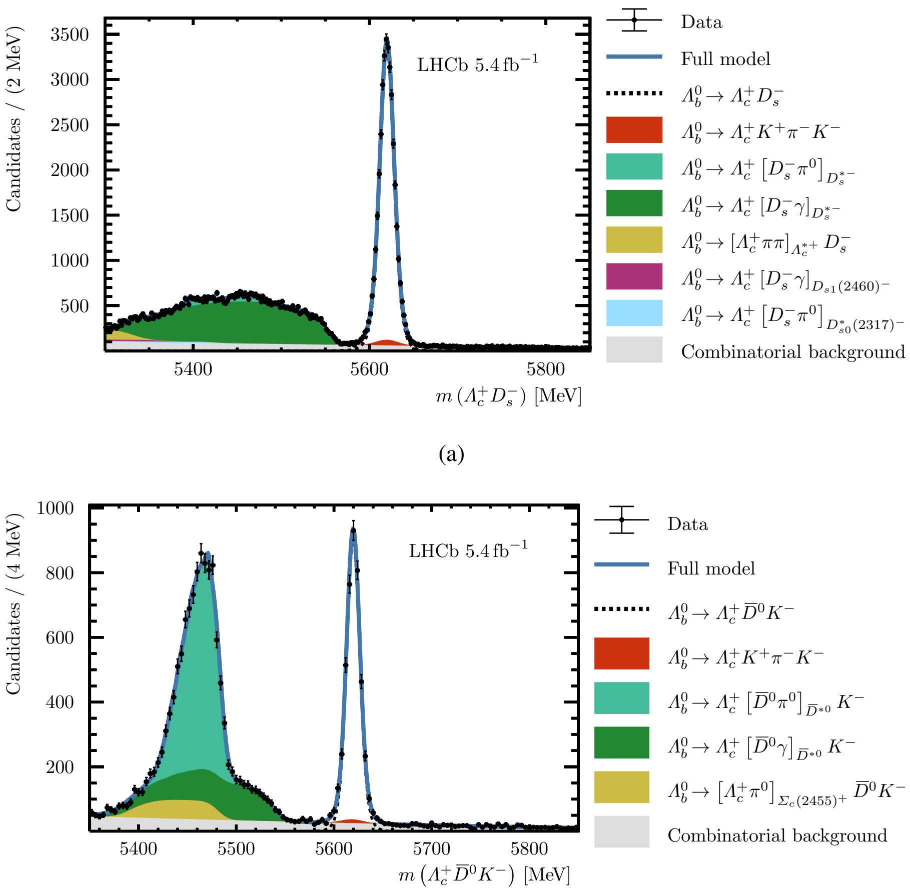
[1] The charge-conjugated process is included throughout.



(a)

(b)

Figure 1: Invariant-mass distributions of (a) $\Lambda_c^+ D_s^{(*)-}$ and (b) $\Lambda_c^+ \overline{D}^{(*)0} K^-$ candidates with the results of the baseline fit overlaid.

$\Lambda_b^0 \to \Lambda_c^+ D_s^-$ mode are measured as follows:

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.1908^{+0.0036}_{-0.0034}{}^{+0.0016}_{-0.0018} \pm 0.0038,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.589^{+0.018}_{-0.017}{}^{+0.017}_{-0.018} \pm 0.012,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 1.668 \pm 0.022^{+0.061}_{-0.055},$$

where the first uncertainties are statistical, the second uncertainties are systematic, and the third (if present) are due to the uncertainties on the branching fractions of the intermediate charm meson decay modes.

Using the observed $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-$ decay mode as a reference, LHCb also reports the first observation of four $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ decay modes using the pp collision data at the same energy point corresponding to an integrated luminosity of 6 fb^{-1} [7]. The yields of the signal decays were determined using unbinned two-dimensional maximum likelihood fits to the invariant mass distributions of the final-state particles. The fit projections for $\Lambda_b^0 \to \Sigma_c^{(*)++} D^- K^-$ candidates and $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{*-} K^-$ candidates are shown in Figs. 2(a)(b) and Figs. 2(c)(d), respectively. The significances, considering systematic uncertainties, well exceed five standard deviations.

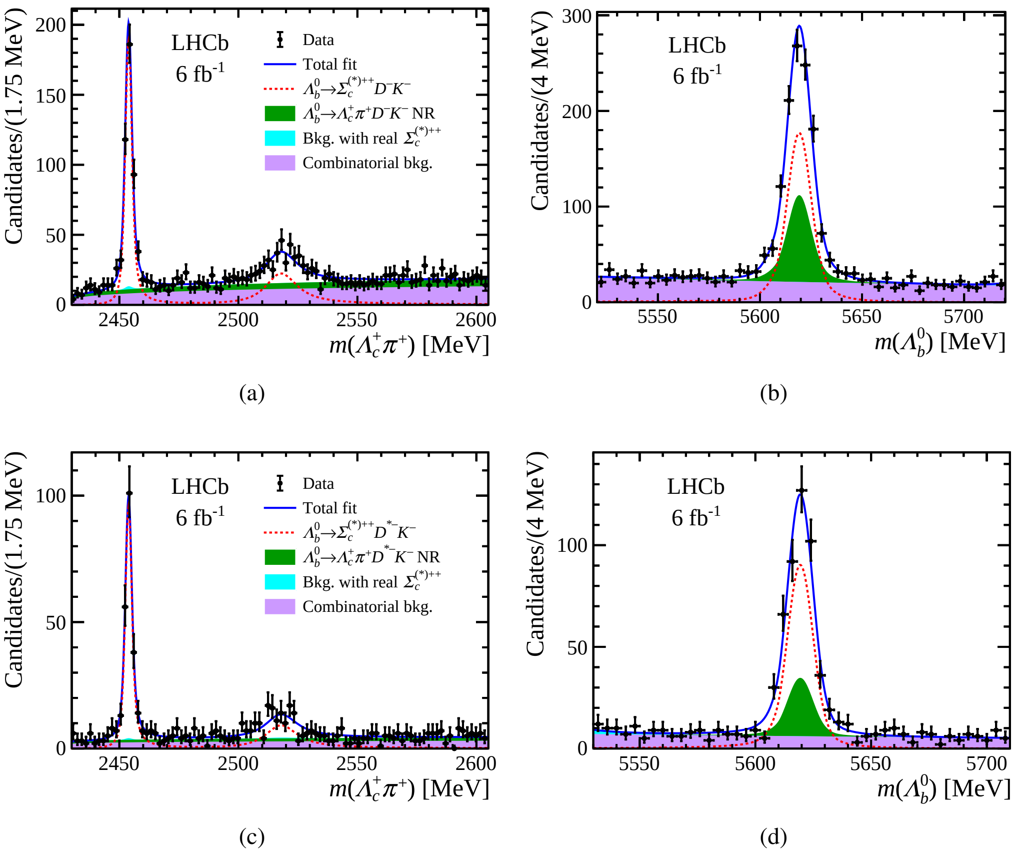


Figure 2: Two-dimensional invariant mass fits of the$\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ decay, projected onto (left) $m(\Lambda_c^+\pi^+)$ and (right) $m(\Lambda_b^0)$.

To enhance the precision of the branching fraction determinations, an event-by-event efficiency parameterized in terms of Λ_b^0 Dalitz variables is taken into account. Subsequently, the following branching fraction ratios are measured:

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)} = 0.282 \pm 0.016 \pm 0.016 \pm 0.005,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{*++} D^- K^-)}{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)} = 0.460 \pm 0.052 \pm 0.028,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)} = 2.261 \pm 0.202 \pm 0.129 \pm 0.046,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{*++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)} = 0.896 \pm 0.137 \pm 0.066 \pm 0.018.$$

These measured branching fractions provide insights into factorization assumptions in effective theories and establish the normalization for future pentaquark searches in $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ and $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ decays with more datasets to become available following the LHCb upgrade.

3. Pentaquark-related studies in pp prompt production

LHCb also performed investigations for hidden-charm pentaquark states decaying to $\Sigma_c^{(*)}\overline{D}^{(*)}$, $\Lambda_c^+ D^{(*)}$, and $\Lambda_c^+ \pi D^{(*)}$ final states in the pp prompt production [8]. The data utilized in this study were also collected by the LHCb detector, corresponding to an integrated luminosity of $5.7\,\text{fb}^{-1}$ at a center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$. The analysis begins by selecting events using the dedicated trigger for open-charmed hadrons, which includes the reconstruction of Λ_c^+ baryons in the $\Lambda_c^+ \to pK^-\pi^+$ decay mode for both the signal and normalization channels, as well as charm mesons in their respective decays. To enhance signal purity, stringent particle identification and vertex quality requirements are applied, and signal regions are selected based on fits to the baryon and meson spectra, requiring the mass to be within a 3σ window around the mean mass value. A kinematic fit is then performed to constrain the mass of intermediate charm hadrons to their known values and ensure they originate from the same primary vertex. The Q-value spectrum is fitted using a simultaneous extended unbinned maximum-likelihood fit to the background and signal regions, with the background shape shared between them. A scan of the Q-value distribution is performed from the kinematic threshold up to $600\,\text{MeV}/c^2$ in steps of $4\,\text{MeV}/c^2$. Local p-values are determined and corrected for the look-elsewhere effect (LEE), and the corrected p-values are used to set upper limits on the pentaquark yields relative to that of the Λ_c^+ baryon in the $\Lambda_c^+ \to pK^-\pi^+$ decay mode at 90% and 95% confidence levels. The most significant deviation is seen as 3σ in the $\Lambda_c^+\pi^+D^-$ combination, of which the fit result is shown in Fig. 3. The known pentaquark candidates have been scrutinized, and their signal yields have been determined to be statistically consistent with zero.

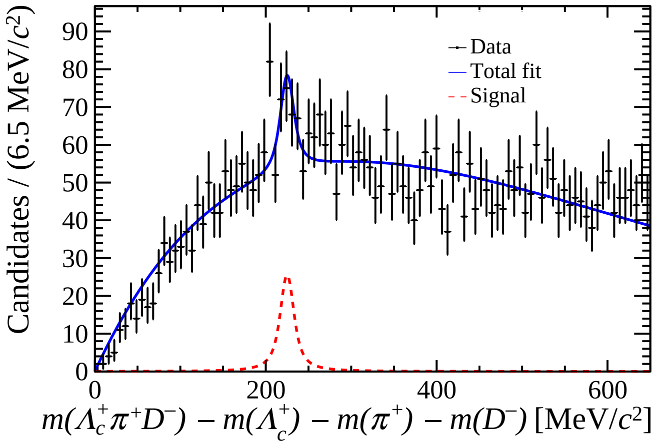


Figure 3: Distribution of the Q-value and its fit projection in the $\Lambda_c^+\pi^+D^-$ system, where the most significant peaking structure is seen.

4. Summary

Over the past two years, LHCb collaboration has conducted research focusing on pentaquark studies by investigating specific decay modes in b-hadrons as well as examining them in direct pp productions. These studies have contributed useful insights into the structural characteristics and decay mechanisms of pentaquarks.

Involving about $\int \mathcal{L}\,\mathrm{d}t = 15\,\mathrm{fb}^{-1}$ of data and enhanced trigger efficiency [9], the ongoing LHCb Run 3 data-taking holds the potential for significant advancements in the pentaquark research. The collaboration is poised to potentially identify additional exotic states and decay modes, thereby enriching our comprehension of pentaquarks and their inherent properties. The increased statistical precision will also enable precise measurements of cross-sections for established pentaquark candidates, thereby corroborating theoretical frameworks and providing illumination on the underlying production mechanisms. Future objectives include searching for new decay modes to enhance our understanding of pentaquark dynamics and determining their quantum numbers for systematic classification within the framework of quantum chromodynamics (QCD) or beyond.

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