EXOTICS AT THE LHCb EXPERIMENT*

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Exotic hadrons are particles with quantum numbers that do not fit into three-quarks or quark–antiquark patterns. In this paper, very recent discoveries are presented: first pentaquark with a strange content, tetraquark isospin pair in decays to $D_s\pi$, and another tetraquark in D_sD_s final state.

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1. Introduction

The simplest quark combinations to form mesons and baryons are $q\bar{q}$ and qqq. This pattern defines quantum numbers J^{PC} of pseudoscalar and vector mesons and baryon octet and decuplet. Nevertheless, both Gell-Mann and Zweig noted in their original papers that more complex (called nowadays *exotic* structures), such as $qq\bar{q}\bar{q}$ and $qqqq\bar{q}$ could exist as well [1, 2].

A surprising discovery by the Belle experiment in 2003 of the first state with properties that do not fit into the potential model of *charmonium* became the onset of searches of *exotics*. The state $X(3872)$ was very narrow, right at the sum of the masses of a charmed-meson pair, decaying into $J/\psi\rho$ and $J/\psi\omega$ with almost equal decay rate [3]. At the LHC, more than 70 new hadrons have been observed to date, among them 23 are exotic, predominantly reported by the LHCb experiment [4].

Since we have now dozens of exotic states, the intriguing question is what is their nature. It is possible that the new particles are bags of four and five quarks, bound together through the exchange of gluons. They also might be more like atomic nuclei. In this "molecular" picture, a pentaquark is a three-quark baryon attached to a two-quark meson in the same way that protons and neutrons bind by exchanging short-lived π mesons. The other possibility is a formation of a diquark — a colored quark–quark state which

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could neutralize its color, binning with an antidiquark that manifests as a tetraquark. It might also happen that exotic states are the effect of the final-state rescattering. Molecular tetraquarks are expected to be only loosely bound, with masses near the sum of the masses of their constituent mesons. They should have rather a narrow width, and so is the main observation in the majority of current discoveries.

Such *exotic* hadrons play a crucial role in studies of Quantum Chromodynamics (QCD). Light *exotics* states provide a unique window to understand the nature of the strong force in the non-perturbative regime, at low $\Lambda_{\rm QCD}$, where evaluating of binning energy sets the scale of the hadron size and strong force range. Charmonium-like hadrons with non-standard quantum numbers are the subject of tests of non-relativistic potential models, while relative orbital angular momentum of the tetraquarks provides corrections to the mass formula.

2. LHCb experiment

The LHCb detector is a single-arm forward spectrometer installed at the Large Hadron Collider (LHC) designed for the study of hadrons containing b or c quarks [5, 6]. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the proton–proton interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photons, electrons, and hadrons are identified by a calorimeter system consisting of scintillating-pad and pre-shower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The LHCb experiment took data during Run 1 (2010–2013) and Run 2 (2015–2018), and collected more than 9 fb^{-1} of integrated luminosity. The next period, Run 3, has just started, proceeded by the first major upgrade of the spectrometer. The main aim of this modernization was to allow operation at the instantaneous luminosity up to $2 \times 10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which required upgrades in the readout system and almost the whole tracking system [7].

3. Spectroscopy of exotic states at the LHCb

The first unambiguous experimental evidence of the existence and confirmation of B-factories exotic hadrons was reported by the LHCb experiment in 2014 [8]. The measurement showed that the $Z(4430)^-$ state is composed of four quarks ($ccdu$). The analysis of Run 1 data in the following year revealed a significant pentaquark structure in the J/ψ mass distribution in $\Lambda_b \to J/\psi K^-$ decays [9]. The discovery of $P_c(4312)^+$ state was further reinforced in Run 2 analysis, not only confirming the previous result but also showing a two-peaked structure on the same mass spectrum, close to the $\Sigma_c^+ \bar{D}^{+0}$ mass threshold [10][1].

Evidence of a charmonium pentaquark with strangeness was further reported in the analysis of $\Xi_b^- \to J/\psi \Lambda K^-$ with LHCb data corresponding to an integrated luminosity of 9 fb^{-1}. The narrow pentaquark $P_{cs}(4459)^0$ (new name: $P_{\psi s}^{\Lambda}(4459)^+$) was added to the $J/\psi \Lambda$ mass spectrum and with a significance of 3.1σ in the amplitude model. Its quark content was established as $c\bar{c}uds$ [11].

In the past years, the LHCb experiment reported also evidence of tetraquarks, just to mention narrow $Z_{cs}(4000)^+$ ($T_{\psi s1}^{\theta}$) state where light quark u is present in addition to heavy quarkonium $c\bar{c}$ and s quark, the four-charm tetraquark $T_{\psi\psi}(6900)^+$ discovered as an exotic narrow structure in the di-J/ψ mass spectrum [12, 13]. Another surprisingly narrow, with the width of the order of just 1 MeV, state decaying into $D^* D^0$ final state, predicted by various models, was confirmed by the LHCb as well. The resonance parameters of the proposed tetraquark $T_{cc}(3875)^+$, including the pole position, scattering length, effective range, and composition $c\bar{c}u\bar{u}$, were established, but there is no consensus about its exact nature, as it variously exhibits features of simple charmonium or a loosely bound molecule [14].

4. First pentaquark with strange content

The $B^- \to J/\psi \Lambda \bar{p}$ decay offers a unique opportunity to simultaneously search for two isospin tetraquarks in the $J/\psi \bar{p}$ and $J/\psi \Lambda$ systems [15]. The small Q-value of the decay provides excellent mass resolution, see Fig. 1 (left), which shows the most precise single measurement of the B^+ mass to date.

Signal B^- candidates are formed from a combination of J/ψ, Λ, and $\bar{p}$ originating from a common decay vertex. The Dalitz distribution shows some enhancement in the $J/\psi \bar{p}$ and $J/\psi \Lambda$ regions. The components of the projection of the invariant mass distribution of the $J/\psi \Lambda$ system are analysed in detail in Fig. 1 (right).

An amplitude analysis of the B^- candidates in the signal region is performed using a phenomenological model based on the interference of two-

[1] Due to a large number of new exotic states, the LHCb postulated the new naming scheme [4]. The main idea of the proposal exhibits an indication of the particle's quantum numbers: isospin, parity, and G-parity, along with letters T or P once the exotic nature as tetra- or pentaquark is confirmed. According to this rule, the above state has become $P_{\psi}^{N}(4312)^+$.

body resonances in the three decay chains. The decay amplitudes are defined as a function of the six-dimensional phase space and by five angular variables in the helicity basis.

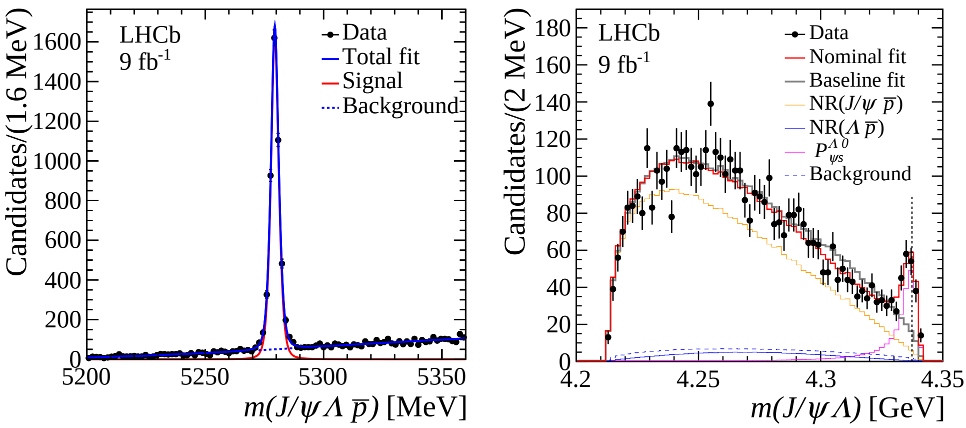

Fig. 1. (Color online) Invariant mass distribution of the $J/\psi\Lambda\bar{p}$ candidates. The data are overlaid with the results of the fit (left). Distributions of $J/\psi\Lambda$ invariant mass, the null-hypothesis model fit results are also shown in grey (right).

A null-hypothesis model (nominal model), comprising two nonresonant contributions, does not describe the data well. Therefore, a new narrow structure is added to the nominal fit. The observation of a new pentaquark in decay to $J/\psi\Lambda$ is confirmed with high accuracy that exceeds 15σ. The mass and width are measured to be: $M(P_\psi^\Lambda) = 4338.2 \pm 0.7$ MeV and $\Gamma(P_\psi^\Lambda) = 7.0 \pm 1.2$ MeV. This represents the first observation of a strange pentaquark candidate with minimal quark content $c\bar{c}uds$. The $J^P = 1/2^-$ quantum numbers are preferred, and positive parity can be excluded at a 90% confidence level. The new pentaquark state is found at the threshold for $\Xi_c^+ D^-$ baryon–meson production.

5. Tetraquark isospin pair in $B^+ \to DD_s\pi$

The decays $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ are ideal channels to search for possible exotic states decaying to $D_s\pi$. The only resonances expected to contribute to the two decays are excited D^* resonances decaying to $\bar{D}^0\pi^-$ and $D_s^-\pi^+$ states.

The Dalitz plot for both decays shows a similar pattern so a combined amplitude analysis of the $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ decays with the amplitudes related through isospin symmetry is performed [16, 17]. Exited D^* states and S-wave components are added simultaneously to the two decays' fit, see Fig. 2.

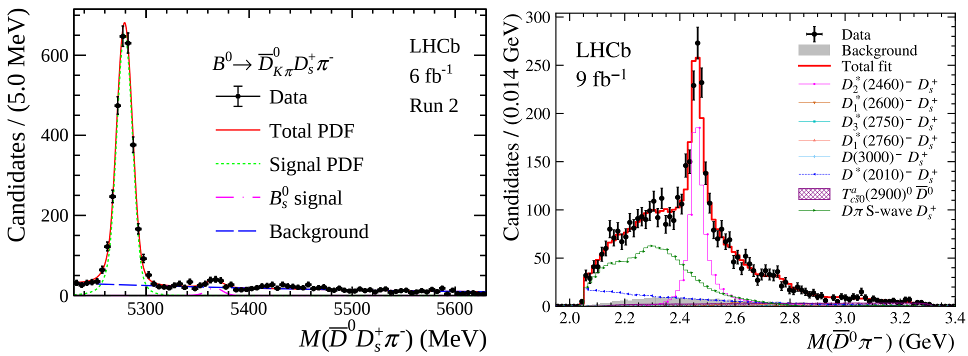

Fig. 2. Invariant mass of the $B^0 \to \bar{D}^0 D_s^+ \pi^-$ signal candidates (left). Projection of the fit result on $M(D^+\pi)$ after including the $T^a_{cs0}(2900)$ state (right).

A complex amplitude for the decay through each intermediate state using helicity formalism is done in one fit where all parameters are shared except the masses, widths, and complex parameters of different excited D^* states. The example projections of the fit results are shown in Figs. 2–3.

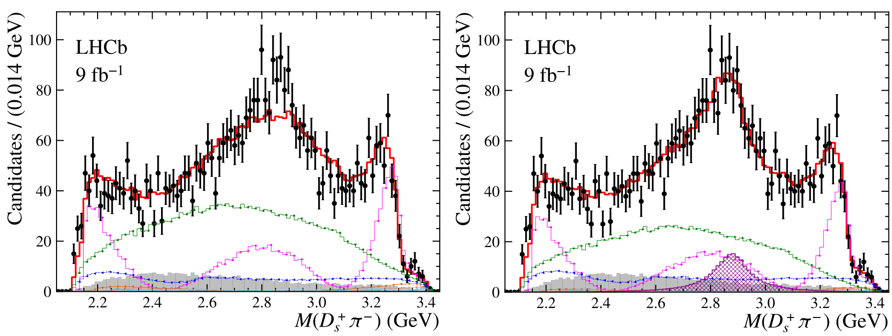

Fig. 3. Projection of the fit result on $M(D_s^+\pi)$ of $B^0 \to \bar{D}^0 D_s^+ \pi^-$ without (left) and with (right) $T^a_{c\bar{s}0}(2900)$ state. Lines are described in Fig. 2.

The models describe the data well in the different invariant mass projections, except for the $M(D_s^+\pi)$ distributions, where peaking structures near 2.9 GeV in the data cannot be attributed to any exited D^* component. Therefore, an additional $D_s^+\pi$ state is added to each decay. Its mass and width are free parameters, and different J^P assignments are tested. The improvement in the fit is evident in Fig. 3 (right), whereas $J^P = 0^+$ provides the best description of the data. Two new resonances, named $T^a_{c\bar{s}0}(2900)$ and $T^a_{c\bar{s}0}(2900)^{++}$, are therefore introduced, along with the interference with the existing D^* states. The significances, including systematic effects, are 6.6σ and 4.8σ respectively. The masses and widths of the new tetraquarks are presented in Table 1.

Table 1. Mass and width on two new *csud* tetraquarks [17].

Particle	Mass [GeV]	Width [GeV]
$T^a_{c\bar{s}0}(2900)^0$	$2.892 \pm 0.014 \pm 0.015$	$0.119 \pm 0.026 \pm 0.013$
$T^a_{c\bar{s}0}(2900)^{++}$	$2.921 \pm 0.017 \pm 0.020$	$0.137 \pm 0.032 \pm 0.017$

The Argand diagram of the $T^a_{c\bar{s}0}(2900)$ state is consistent with the Breit–Wigner lineshape and further supports its resonant character. This observation accounts for the first observation of a doubly-charged tetraquark together with its neutral isospin partner.

6. Tetraquark candidate in $B^+ \to D_s^+ D_s^- K^+$

Decays from the family of $B \to D_{(s)} D_{(s)} K$ are prospective processes to investigate open- and hidden-charm spectroscopy including exotic states. The first observation of the $B^+ \to D_s^+ D_s^- K^+$ decay (Fig. 4 (left)) provides a good opportunity to study resonances in the $D_s^+ D_s^-$ final states [18, 19].

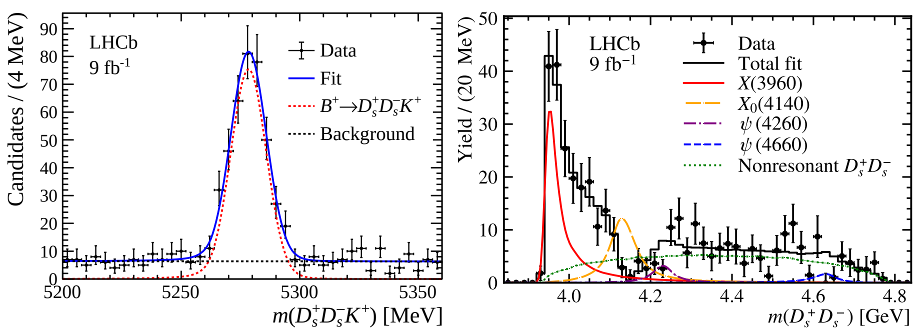

Fig. 4. Invariant mass of the $D_s^+ D_s^- K^+$ signal candidates (left) [18]. Mass distribution of $D_s^+ D_s^-$ (right). Projection of the fit with the baseline model is also shown [19].

The amplitude analysis of the $D_s^+ D_s^-$ system revealed the near-threshold peaking structure, denoted as $X(3960)$. The fit comprised two known 1^{--} states $\psi(4260)$ and $\psi(4660)$, and two new 0^{++} X states. The scalar $X(3960)$ is crucial to describe the enhancement in the $D_s^+ D_s^-$ spectrum, the other state $X_0(4140)$ is added to model the dip in the region of mass 4140 MeV, as shown in Fig. 4 (right). The helicity formalism is used to construct the amplitude model which describes the $D_s^+ D_s^-$ mass well, see Fig. 5. In the assumed model, the $X_0(4140)$ state produces the dip around 4140 MeV via destructive interference with non-resonant 0^{++} and $X(3960)$ components.

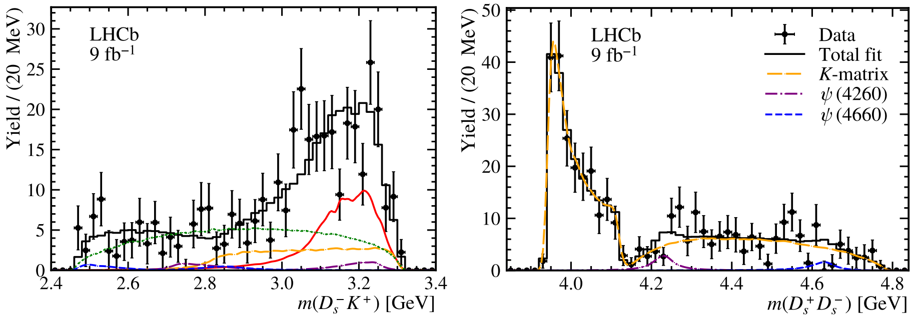

Fig. 5. Invariant mass distribution of $D_s^- K^+$ (left). Fits are described in Fig. 4. $D_s^+ D_s^-$ mass with K-matrix parameterisations (right).

The masses, widths, and spin of new states are shown in Table 2. The 0^{++} spin assignment is preferred over 1^{--} and 2^{++} hypothesis by 9.3σ and 12.3σ respectively.

Table 2. Summary of the new states observed in the $D_s^+ D_s^-$ mass spectrum [19].

Particle	Mass [GeV]	Width [GeV]	J^{PC}
$X(3960)$	$3.956 \pm 0.005 \pm 0.001$	$0.043 \pm 0.013 \pm 0.008$	0^{++}
$X_0(4140)$	$4.133 \pm 0.006 \pm 0.006$	$0.067 \pm 0.017 \pm 0.007$	0^{++}

Testing the possibility that the dip in the $D_s^+ D_s^-$ invariant mass around 4140 MeV depends on the presence of $J/\psi\phi$ threshold, a simple K-matrix model that contains the single resonance $X(3960)$ and two coupled channels, $D_s^+ D_s^-$ and $J/\psi\phi$. The fit demonstrates that $D_s^+ D_s^-$ mass distribution can also be modeled by $J/\psi\phi \to D_s^+ D_s^-$ re-scattering without losing the fit quality, see Fig. 5 (right).

7. Summary

The LHCb experiment plays currently the leading role among all the LHC experiments in the spectroscopy of standard and non-standard hadrons. Using the proton–proton collision data collected at centre-of-mass energies 7, 8, and 13 TeV between 2011 and 2018, corresponding to an integrated luminosity of 9 fb^{-1}, more than 20 new exotic states were observed. Among the very recent discoveries, a new resonant structure in the $J/\psi\Lambda$ system is found. The pentaquark $P_\psi^N(4312)^+$ is the first observation of a pentaquark candidate with strange quark content. Since it is found at the threshold for $\Xi_c^+ D^-$, its nature is both molecular or it might be a compact system of five quarks.

The observation of isospin doublet $T^a_{c\bar{s}0}(2900)$ and $T^a_{c\bar{s}0}(2900)^{++}$ is the first report on exotic mesons with four different quark flavors. In addition, searches of the $T^a_{c\bar{s}0}(2900)^+ \to D_s^+\pi^0$ are ongoing.

A near-threshold peaking structure, referred to as $X(3960)$, is observed in the $D_s^+D_s^-$ mass spectrum with high accuracy. The comparison of its with the width of the decay of $B^+ \to D^+D^-K^+$ indicates its exotic nature.

With the significantly larger data samples that will be collected by the upgraded LHCb detector in the coming years, the nature of exotic hadrons, and the existence of the possible new states, will be further explored.

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