STATUS AND PERSPECTIVES WITH EXOTIC STATES AT LHCb*

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The analysis of the full LHC Run 1 data set of proton–proton collision events collected with the LHCb detector, corresponding to an integrated luminosity of 3.0 fb^{-1}, is yielding several improved results on exotic hadron candidates, such as $X(3872)$ and $Z(4430)^+$, as well as the first observation of two new states compatible with the pentaquark hypothesis. Run 2 data allow LHCb to further sharpen the experimental picture, opening up the possibility to observe new states. The measurements of the properties of these exotic states and the Run 2 prospects will be presented, including the determination of their quantum numbers, with model-dependent and independent methods.

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1. Introduction

Quantum Chromodynamics (QCD) is a well-established theory of strong interactions which, despite its major success, does not allow to derive the hadron spectrum analytically from its Lagrangian. Besides lattice QCD, which tries to solve the problem numerically, many phenomenological models were proposed to describe hadron spectrum. The first and the simplest model, the quark model, categorized hadrons successfully into two families: mesons and baryons, composed of a quark–antiquark pair or three quarks, correspondingly. However, QCD allows much richer hadron spectrum. Already in 1964 Gell-Mann [1] and Zweig [2] proposing their quark model expected not only existence of mesons $q\bar{q}$ and baryons qqq but also the possible existence of tetraquarks $q\bar{q}q\bar{q}$ and pentaquarks $qqqq\bar{q}$. Those hypothetical states are considered exotic from the point of view of the naive quark model,

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however, they are truly legitimate QCD states. The term *exotic* in the context of hadron physics is also applicable to the J^{PC} quantum number of hadrons. In the quark model, the parity and charge parity of a neutral meson can be expressed as $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$. The sequence of quantum numbers J^{PC}: 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} is not allowed in a simple $q\bar{q}$ system and they are known as explicitly exotic, and if observed for a new state would indicate their exotic interpretation.

In the mass region of charmonium, the first experimental evidence of states not fitting well into conventional charmonium description came in 2003 with observation by the Belle experiment of a resonance in $J/\Psi\pi^+\pi^-$ final state named $X(3872)$ [3]. In the later years, the family of particles not fitting into charmonium description extended to more then ten states, labelled as X, Y, Z states. The observed charmonium-like states have been studied in several production mechanisms: B meson decays, initial state radiation (ISR) in the e^+e^- annihilation, the double-charmonium production processes, and two-photon fusion processes. Initially, the naming convention was such that X referred to neutral states containing $c\bar{c}$ with quantum numbers different from 1^{--}, Y referred to neutral 1^{--} states seen in e^+e^- annihilation and Z referred to charged states, but after some Ys have been observed in different processes, this rule is not strictly followed any more. Recently, the family of exotic mesons resonances has been extended by exotic baryon resonances in $J/\Psi p$ discovered by the LHCb, which is discussed later in this paper.

The LHCb detector [4, 5] is a single-arm forward spectrometer covering the pseudorapidity range of $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector elements that are particularly relevant to the results presented here are: a silicon-strip vertex detector surrounding the pp interaction region that allows c- and b-hadrons to be identified from their characteristically long flight distance; a tracking system that provides a measurement of momentum, p, of charged particles; and two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons.

Despite the high background level inherent to hadronic collisions, the detector allows to study exotic hadrons produced in heavy flavour decays and the main results obtained by the LHCb Collaboration in this field are summarized in this paper.

2. Determination of $X(3872)$ properties

The $X(3872)$ state was discovered in $B^{+,0} \to X(3872)K^{+,0}$, $X(3872) \to \pi^+\pi^- J/\psi$, $J/\psi \to \ell^+\ell^-$ decays by the Belle experiment [3] and subsequently confirmed by other experiments [6–8]. The state is narrow, $\Gamma < 1.2\,\mathrm{MeV}$, and its mass, $3871.69 \pm 0.17\,\mathrm{MeV}$ [9], is close to the $D\bar{D}^*$ threshold 3871.81 ± 0.09 MeV. Observation of decays $X(3872) \to \rho J/\Psi$ and $X(3872) \to \omega J/\Psi$ with comparable branching fractions indicates violation of isospin symmetry. Observation of the $X(3872) \to \gamma J/\Psi$ decay imposes positive its C-parity [10]. The possibility of quantum number J^{PC} assignment has been narrowed down by the CDF measurements [11] to two possibilities 1^{++} and 2^{-+} via an analysis of the angular correlations.

In order to determine firmly the J^{PC} quantum numbers of $X(3872)$, the angular correlations in the B^+ decay chain were analysed using an unbinned maximum-likelihood fit [12] with the probability density function (PDF) defined in the 5D angular space $\Omega = (\cos\theta_X, \cos\theta_{\pi\pi}, \Delta\phi_{X,\pi\pi}, \cos\theta_{J/\Psi}, \Delta\phi_{X,J/\Psi})$, where θ_X, θ_ρ and $\theta_{J/\psi}$ are the helicity angles in the $X(3872)$, ρ and J/ψ decays, respectively, and $\Delta\phi_{X,\rho}$, $\Delta\phi_{X,J/\psi}$ are the angles between the decay planes of the $X(3872)$ particle and of its decay products. The likelihood ratio test favours 1^{++} hypothesis with the alternative spin hypothesis excluded with a significance of more than 16 standard deviations.

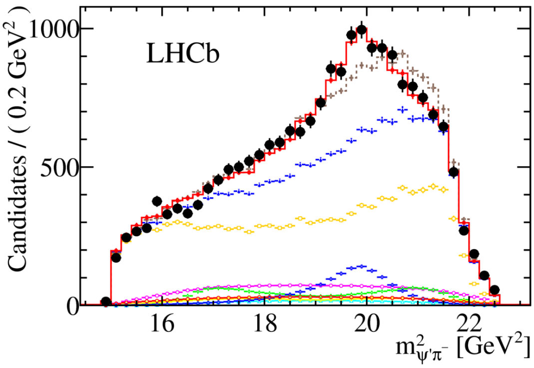
In addition, the LHCb performed another measurement which helped to reveal the nature of $X(3872)$ state, namely the ratio of branching fractions of radiative decays $R_{\Psi\gamma} = B(X(3872) \to \Psi(2S)\gamma)/B(X(3872) \to J/\Psi\gamma)$ [13]. The $R_{\Psi\gamma}$ is predicted to be in the range of $(3-4)\times 10^{-3}$ for a $D\bar{D}^*$ molecule, 1.2–15 for pure charmonium state and 0.5–5 for a molecule-charmonium mixture. The analysis of data based on 3 fb^{-1} of the integrated luminosity measured $R_{\Psi\gamma} = 2.46 \pm 0.64 \pm 0.29$, which does not support pure $D\bar{D}^*$ molecular interpretation.

3. Confirmation of the resonant nature of $Z(4430)^-$ state

The Belle Collaboration found an evidence [14] for a narrow $Z^-(4430)$ peak with width $\Gamma = 45^{+18}_{-13}{}^{+30}_{-13}$ MeV and $M = 4433 \pm 4 \pm 2$ MeV in the $(\Psi'\pi^+)$ mass distribution in the $B \to \Psi' K\pi$ decays. The minimal quark content of such a state is $c\bar{c}d\bar{u}$, which is the first unambiguous evidence for a meson beyond traditional $q\bar{q}$ model. However, the BaBar Collaboration was able to describe the observed $m_{\Psi'\pi^-}$ in terms of reflections of K^* states with a spin $J \leq 3$. Belle updated the results [15] with 4D amplitude analysis with $Z^-(4430)$ significance more than 5.2σ and $J^P = 1^+$ favoured by more than 3.4σ.

The LHCb analysed the data corresponding to 3 fb^{-1} of integrated luminosity with about 25 000 $B \to \Psi' K\pi$ candidates. Two analyses have been performed by the LHCb Collaboration: 4D amplitude analysis [16] (Fig. 1, left) and model-independent confirmation of $Z(4430)$ existence [17].

The significance of a resonance has been established at the level $> 13.9\sigma$ and the $J^P = 1^+$ hypothesis is favoured with others ruled out at significance $> 9\sigma$. A model-independent analysis, whose main goal was to check



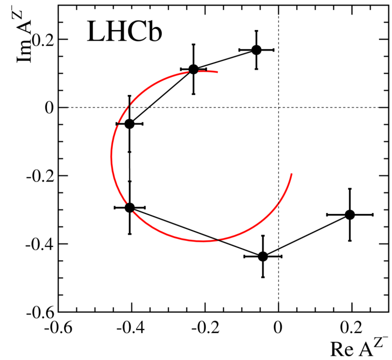


Fig. 1. Distributions of the fit variables (black data points) together with the projections of the 4D fit. The solid red (dashed brown) histogram represents the total amplitude with (without) the Z_1^-. The other points illustrate various subcomponents of the fit (left). Fitted values of the Z_1^- amplitude in six $m^2_{\psi'\pi^-}$ bins, shown in an Argand diagram (connected points with the error bars, $m^2_{\psi'\pi^-}$ increases counterclockwise) (right) [16].

if the structures in the $M_{\Psi(2S)\pi}$ spectrum can be explained as reflections of the resonance activity in the $K\pi$ system, ruled out the hypothesis that the structure of the $\Psi(2S)\pi$ spectrum can be described as reflection of the activity of the resonances in the $K\pi$ system with more than 8σ. The Argand plot demonstrated behaviour characteristic for a resonance, *i.e.* a circular trajectory in the complex plane with a fast change of phase crossing the maximum of amplitude (Fig. 1, right).

4. Discovery of $P_c^+(4380)$ and $P_c^+(4450)$ states

The LHCb experiment collected 26007 ± 166 candidates for decay $\Lambda_b \to J/\Psi K^- p$ with 3 fb^{-1} of integrated luminosity, which was used for a precise measurement of the Λ_b lifetime. This decay is expected to be dominated by $\Lambda^* \to K^- p$ resonances; however, it could also have exotic contribution that results in resonant structure in the $J/\Psi p$ mass spectrum. It appears that an unexpected resonant structure has been observed in the Dalitz plot [18] in a $J/\Psi p$ channel. A resonance decaying strongly to $J/\Psi p$ must have a $c\bar{c}uud$ quark content, *i.e.* pentaquark and irrespective of the internal binding mechanism it was labelled as P_c^+. To exclude reflections generated by the Λ^* states, a full amplitude analysis is necessary. The 6D amplitude analysis (5 angles and m^2_{pK}) has been performed with 14 (16) Λ^* states included and it was established that Λ^* reflections do not explain the structure in $m_{J/\Psi p}$. It appears that the amplitude fit of $\Lambda_b \to J/\Psi K^- p$ cannot be satisfactory described without two Breit–Wigner shaped resonances in the $J/\Psi p$ mass spectrum $P_c(4380)^+$ and $P_c(4450)^+$ (Fig. 2). The significance of the observed resonances are 9σ and 12σ, correspondingly. The parities of the two states are opposite with the preferred spins being $3/2$ for one state and $5/2$ for the other. For the $P_c(4450)^+$, the Argand diagram is consistent with a rapid counter-clockwise change of phase characteristic for resonance.

Different interpretations have been proposed for observed resonances including tightly bound pentaquarks [20], a molecular model with meson exchange for binding [21] or rescattering effect [22].

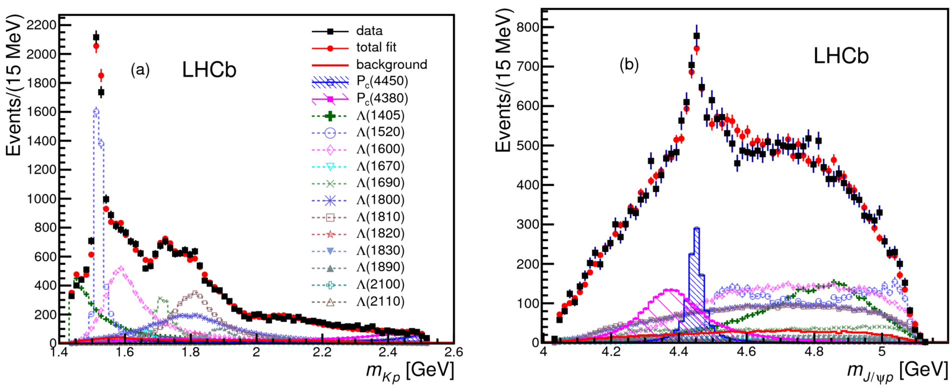


Fig. 2. Fit projections for (a) m_{Kp} and (b) $m_{J/\psi p}$ for the reduced Λ^* model with two P_c^+ states. The data are shown as full (black) squares, while the full (red) points show the results of the fit. The solid (red) histogram shows the background distribution. The open squares (blue) with the shaded histogram represent the $P_c(4450)^+$ state, and the shaded histogram topped with filled squares (purple) represents the $P_c(4380)^+$ state [18].

5. Summary and future perspective

With 3 fb^{-1} of integrated luminosity collected in Run 1, the LHCb provided a valuable contribution to the spectroscopy of exotic hadrons: the quantum numbers of $X(3872)$ $J^{PC} = 1^{++}$ have been established; the study of $X(3872)$ radiative decays disfavours their pure molecular interpretation; the resonant nature of $Z(4430)^-$ has been confirmed; two exotic states in the $J/\Psi p$ channel with charmonium pentaquark interpretation have been discovered.

In Run 2 that started in 2015 with an energy growth from 8 TeV to 13 TeV, the $\sigma(c\bar{c})$ and $\sigma(b\bar{b})$ increased by $\approx 60\%$, the improvements in trigger system increased an output bandwidth from 5 kHz to 12 kHz, which allows to record more data and, as a result, Run 2 promises about twice as much $b\bar{b}$ and $c\bar{c}$ pair per fb^{-1}, and $\mathcal{L} \sim 5$ fb^{-1} compared to 3 fb^{-1} in Run 1. Many potential measurements of exotic hadrons are limited by statistics and increase in collected data promises new discoveries.

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