XYZ states at LHCb

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Abstract. The latest years have observed a resurrection of interest in searches for exotic states motivated by precision spectroscopy studies of beauty and charm hadrons providing the observation of several exotic states. The latest results on spectroscopy of exotic hadrons are reviewed, using the proton-proton collision data collected by the LHCb experiment. The document focuses among others on the confirmation of the resonant nature of the Z(4430) mesonic state and observation of $J/\Psi\phi$ structures consistent with exotic states. LHCb has also made significant contributions to the determination of the quantum numbers of the X(3872) state and excluded the existence of the X(5568) tetraquark candidate.

1 Introduction

Bound states of quarks would be new states of matter beyond the simple quark-model picture, where only two types of quark combinations are required to account for the existing hadrons, i.e. $q\bar{q}$ combinations form mesons, while baryons are made up of three quarks. Up to now many new exotic states have been observed at b-factories, Tevatron and LHC experiments with masses lying on the limits of the quarkonia spectrum. They may coincide with other SU(3) color-neutral combinations of quarks and gluons such as gg glueballs, $q\bar{q}g$ hybrids, $q\bar{q}q\bar{q}$ tetraquarks, $\bar{q}qqqq$ pentaquarks etc., predicted in the quark model proposed by Gell-Mann and Zweig in 1960s [1]. The world's largest data sample of beauty and charm hadrons collected by LHCb during LHC Runs I and II provides great opportunities for studying the production and properties of heavy hadrons. Since such exotic states are experimentally hard to find in the light quark sector, the first discovery of the narrow exotic tetraquark state X(3872) by the Belle collaboration [2] was made only in 2003, leading to a revolution in the exotic hadron spectroscopy. Up to now several other exotic states have been observed, all involving heavy quark systems. The LHCb experiment has already collected an impressive set of results on exotic heavy flavour states, with the first unambiguous spin-parity assignments of the X(3872) [3], confirmation of resonant nature of the $Z(4430)^-$ [4] or observation of puzzling $J/\Psi\phi$ structures consistent with exotic states [6, 7]. The present document describes some recent results from LHCb in exotic hadron spectroscopy. For all the studies the LHCb data corresponding to 3 fb^{-1} of integrated luminosity in 7 and 8 TeV pp collisions has been used.

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2 $X(3872)$ **composition**

The $X(3872)$ state was first discovered by Belle experiment in 2003 [2], being the first charmonium-like exotic state ever observed, and led to a revolution in exotic hadron spectroscopy. It was observed as an unexpected structure in the $J/\psi\pi^+\pi^-$ invariant mass while investigating $B^+ \to J/\psi K^+\pi^+\pi^-$ decays. Since its dicovery, it has been seen by seven different experiments in both B decays and the prompt production. The quantum numbers of the $X(3872)$ state were held down by the CDF collaboration to be 1^{++} or 2^{-+} [8], but its nature is still discussed, drawing a lot of theoretical interests. As the $X(3872)$ state has a mass close to the $D^{*+}D^-$ threshold it may be an example of a hadron molecule with an extremely small binding energy [9]. On the other hand, decaying into $J/\psi\pi^+\pi^-$, it may be interpreted as a charmonium excitation. Moreover, the comparable branching fractions of the decay modes $X(3872) \to J/\psi\rho$ and $X(3872) \to J/\psi\omega$ lead to the strong violation of isospin symmetry, and may be a premise that $X(3872)$ is a molecule, as $D^{*+}D^-$ state is a superposition of isospin 0 and 1. First LHCb analysis was based on the 7 TeV dataset and aimed at the measurement of the mass and production cross-section in $B^+ \to X(3872)K^+$ with $X(3872)$ decaying into $J/\psi\pi^+\pi^-$ and $J/\psi \to \mu^+\mu^-$. This allowed to pin down spin-parity to be 1^{++} [3]. More recently, LHCb has performed a full five-dimensional angular analysis without any assumptions on orbital angular momentum [10], which was possible using improved statistics from the full 3 fb^{-1} LHC Run I dataset (see Fig. 1). The quantum numbers of the $X(3872)$ were determined to be $J^{PC} = 1^{++}$, and the only alternative assignment allowed by previous measurements, i.e. $J^{PC} = 2^{-+}$ [8], is excluded with a significance of more than 8σ. In this analysis the amplitude model included previously ignored D-wave components. However, D-wave components were found to be negligible, and it turned out that the $X(3872)$ decay is mainly through the S-wave. Important information on $X(3872)$ state can be extracted from its radiative decay mode. As electromagnetic transitions among charmonium states are well-defined, radiative transitions may be a sensitive probe of exotic structure. Various theoretical interpretations predict different values of the ratio $R_{\psi\gamma} = B(X(3872) \to \psi(2S)\gamma)/B(X(3872) \to J/\psi\gamma)$. LHCb has recently found a 4.4σ evidence of the $X(3872) \to \psi(2S)\gamma$ in $B^+ \to X(3872)K^+$, and measured its branching fraction relative to $X(3872) \to J/\psi\gamma$, i.e. $R_{\psi\gamma} = 2.46 \pm 0.64(stat) \pm 0.29(syst)$ [11]. This result indicates a presence of charmonium component in the $X(3872)$, however it cannot definitively exclude a pure $D^{*+}D^-$ molecule interpretation.
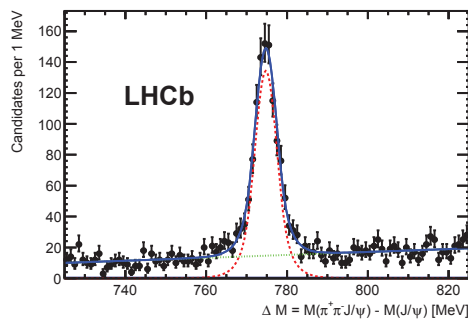

Figure 1. The fit of the $X(3872)$ signal to the distribution of ΔM for $B^+ \to J/\Psi K^+\pi^+\pi^-$ candidates. The solid blue line represents the total fit, dashed red line the signal component, and dotted green line indicates the background component. Figure adopted from [10].

3 $X \to J/\Psi\phi$ **states**

Since the peaks around 4140 and 4274 MeV in the $J/\Psi\phi$ mass system have been found by
the CDF collaboration [12], and then confirmed by D0 [13] and CMS [14], there has been an
increasing experimental and theoretical interest in $J/\Psi\phi$ mass structures in $B^+ \to J/\Psi\phi K^+$
decays. As the mass and width of X(4140) state measured in these experiments have been
found to be unexpectedly narrow, it has been suggested that the X(4140) peak may be a
molecular state, tetraquark, hybrid or rescattering effect. In LHCb all dimensions of the decay
kinematics have been analysed in order to maximize sensitivity to the decay dynamics and to
avoid biases due to averaging over some dimensions in presence of the non-uniform detector
efficiency. 4289± 151 of $B^+ \to J/\Psi\phi K^+$ decays have been reconstructed, with relatively low
background across the entire $J/\Psi\phi$ mass range [6, 7]. A six-dimensional amplitude analysis
have been applied, including resonant contributions from K^* decaying to ϕK^+. Parameters of
four resonant states measured with a high significance are summarized in Table 1. Results of
the fit to the $J/\Psi\phi$ mass spectrum are shown in Fig. 2, where the resonances are described
by the Breit-Wigner distribution, and the angular distributions are calculated using helicity
formalism. LHCb results indicate that e.g. the X(4140) width is substantially larger than
previously determined, suggesting that there cannot be conclusive insight what such states
may be.

Table 1. Parameters of four resonant states decaying to $J/\Psi\phi$.

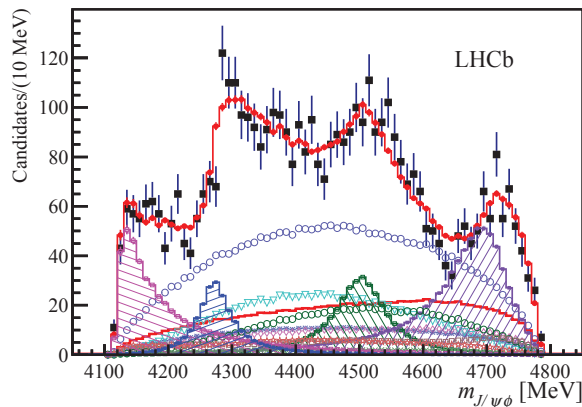| State	σ	mass [MeV]	Γ [MeV]	J^{PC}
X(4140)	8.4	$4146.5 \pm 4.5^{+4.6}_{2.8}$	$83 \pm 21^{+21}_{14}$	1^{++}
X(4274)	6.0	$4273.3 \pm 8.3^{+17.2}_{3.6}$	$56 \pm 11^{+8}_{11}$	1^{++}
X(4500)	6.1	$4506 \pm 11^{+12}_{15}$	$92 \pm 21^{+21}_{20}$	0^{++}
X(4700)	5.6	$4704 \pm 10^{+14}_{24}$	$120 \pm 31^{+42}_{33}$	0^{++}

Figure 2. Distributions of the ϕK^+ (top left), $J/\Psi K^+$ (top right) and $J/\Psi\phi$ (bottom right) invariant
masses for the $B^+ \to J/\Psi\phi K^+$ coandidates from data (black points), compared to the results of the
default amplitude fit containing eight $K^{*+} \to \phi K^+$ and $X \to J/\Psi\phi$ contributions. The total fit is given
by the red points with error bars, and individual fit components are also shown. Figure adopted from [7].

4 Confirmation of resonant nature of $Z(4430)^-$

The best candidate for tetraquark, the $Z(4430)^-$ state, was first observed by the Belle collaboration [15] in 2008 looking at the charged resonance structure in the $\psi(2S)\pi^-$ invariant mass distribution of the decay $B^0 \to \psi(2S)K^+\pi^-$. A relatively narrow peak has been found, $\Gamma \approx 45$ MeV, in the $\psi(2S)$ mass spectrum with a mass of 4433 ± 5 MeV. Such a structure was not found by the BaBar collaboration, and the observed enhancement could not be explained as a reflection of the known K^* states. However, the results did not rule out the existence of $Z(4430)^-$ either [16]. Such a resonance is particularly interesting as it is most likely exotic, with minimal quark content $c\bar{c}u\bar{d}$. This is because it cannot be comprised of only two quarks. After reperforming the Belle analysis in 2013, based on a full amplitude analysis and using more data containing about 2000 signal events, the significance obtained was 5.2σ for the $Z(4430)^-$ state, with the mass $M_Z = 4485\pm22^{+28}_{-11}$ MeV and width $\Gamma_Z = 200^{+41}_{-46}{}^{+26}_{-35}$ MeV, favouring the $J^P = 1^+$ spin-parity assignment by more than 3.4σ. Using about an order of magnitude larger signal statistics as compared to Belle or BaBar experiments, i.e. 3 fb^{-1} of integrated luminosity available from LHC running in 2011 and 2012, LHCb collected about 25,000 B^0 signal events and observed the $Z(4430)^-$ with a significance larger than 13.9 σ [4]. Both a model independent analysis [5] (BaBar like) used to check whether the $m_{\psi(2S)\pi^-}$ spectrum could be understood in terms of any combination of known K^* resonances, and also a full amplitude analysis [4] (Belle like) in order to extract quantitative information about the $Z(4430)^-$ mass, width and spin, have been performed by the LHCb collaboration. A good agreement between the data and the projection of the fit including $Z(4430)^-$ state may be observed in Fig. 3(left), where the measured mass of $4475\pm7^{+15}_{-25}$ MeV and width of $172\pm13^{+37}_{-34}$ MeV are consistent with the values obtained by the Belle experiment. Fig. 3(right) shows the Argand diagram of the $Z(4430)^-$ amplitude, demonstrating for the first time the resonance behaviour of exotic state. The spin-parity is measured to be 1^+, by excluding 0^-, 1^-, 2^- and 2^+ hypotheses by at least 9.7σ. For a charged charmonium state, $Z(4430)^-$ has a minimum quark content of $c\bar{c}u\bar{d}$, which does not coincide with the traditional quark model.
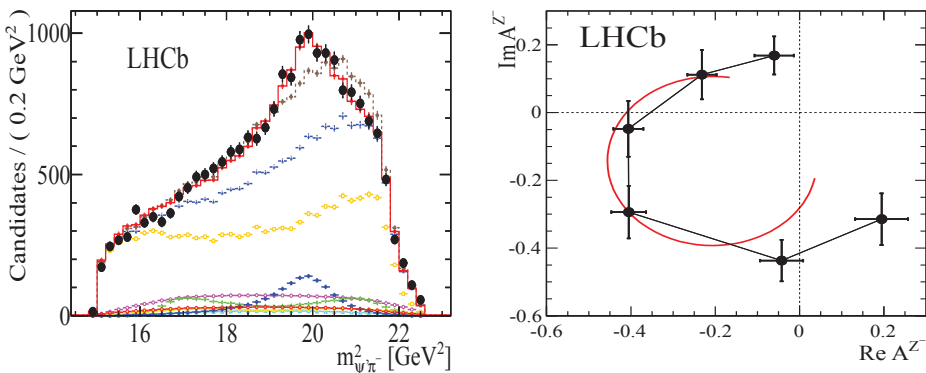

Figure 3. (Left) Distribution of $m^2_{\psi(2S)\pi^-}$, where black dots represent data, the red solid and brown dashed lines indicate the total fit with and without the $Z(4430)^-$ component. (Right) Fitted values of $Z(4430)^-$ amplitude in six $m^2_{\psi(2S)\pi^-}$ bins shown in an Argand diagram. Figure adopted from [4].

5 No evidence of the $X(5568)$ tetraquark

The first evidence for $X(5568)^{\pm} \rightarrow B_s^0 \pi^{\pm}$ tetraquark candidate was reported by D0 collaboration with a significance of 3.9σ in 2016 [17]. More recently, this state has been reported again by the D0 [18] collaboration, but has not been confirmed by CDF [19], resulting in a confusing experimental situation. This potential four-flavored $b s u d$ exotic state was found first in D0 using the $p\bar{p}$ collisions at $\sqrt{s}$ = 1.97 TeV. The relative production rate between the $X(5568)$ and B_s^0, multiplied by the $X \rightarrow B_s^0$ branching fraction was found to be $\rho_X^{D0}(10 < p_T(B_s^0) < 15 \text{ GeV}) = 9.1 \pm 2.6(stat) \pm 1.6(syst)\%$ and $\rho_X^{D0}(15 < p_T(B_s^0) < 30 \text{ GeV}) = 8.2 \pm 2.7(stat) \pm 1.6(syst)\%$, with an average of $\rho_X^{D0} = 8.6 \pm 1.9(stat) \pm 1.4(syst)\%$, being not particularly relevant without the actual limit. One may expect similar rate to be found also in other experiments, if the value measured by D0 is universal. The LHCb analysis used full Run I dataset from LHC running in 2011 and 2012, collecting a huge and clean sample of B_s^0 mesons, where the selection requirements for the B_s^0 and the companion follow those in previous well-understood LHCb analyses. It was based on searching for $X(5568)$ decaying into $B_s^0 \pi^{\pm}$, with $B_s^0 \rightarrow D_s^- \pi^+$ and $B_s^0 \rightarrow J/\psi \phi$, where $D_s^- \rightarrow K^+ K^- \pi^-$, $J/\psi \rightarrow \mu^+ \mu^-$ and $\phi \rightarrow K^+ K^-$ [20]. The total signal sample was about 110,000, being about twenty times larger than in the D0 analysis, and with much less background. In order to clean B_s^0 sample a sequential cut-based selection has been applied, together with the mass constraints on J/ψ and D_s^- to improve mass resolution. The background coming from random combinations of pions with true or fake B_s^0 candidates was described by the polynomial. As no significant $X(5568)$ signal was found for either of the three $p_T(B_s^0)$ cuts: >5, 10, or 15 GeV (see e.g. Fig. 4), the upper limits at the 95% confidence level have been calculated to be $\rho_X^{LHCb}(p_T(B_s^0) > 5 \text{ GeV}) < 0.011$, $\rho_X^{LHCb}(p_T(B_s^0) > 10 \text{ GeV}) < 0.021$ and $\rho_X^{LHCb}(p_T(B_s^0) > 15 \text{ GeV}) < 0.018$.
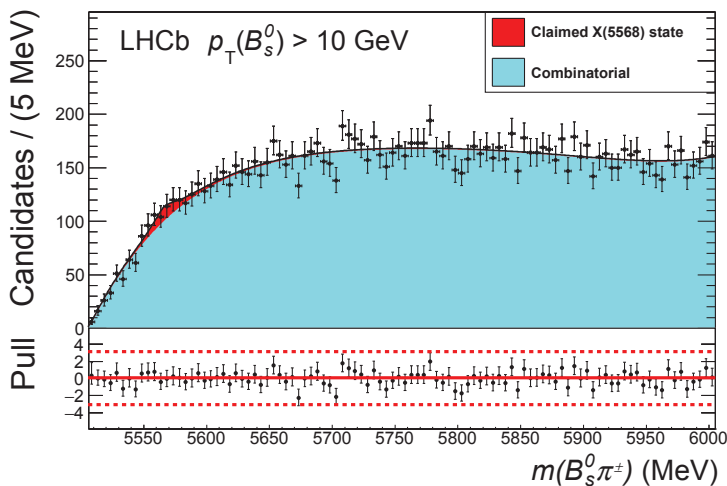

Figure 4. Fit to the $B_s^0 \pi^{\pm}$ spectrum showing no significant excess at the $X(5568)$ mass for $p_T(B_s^0) > 10$ GeV. Figure adopted from [20].

6 Conclusions

Numerous new exotic states, many of which awaiting confirmation and further investigation, were discovered since the first observation of the $X(3872)$ state. Detailed exotic spectroscopy measurements were performed in the LHCb experiment using data samples collected during the Run I phase of LHC running. LHCb has recently provided valuable contributions to the heavy flavour spectroscopy, such as a decisive confirmation of the existence and resonant nature of $Z(4430)^-$ state in both model independent and amplitude approaches, or an observation of candidates for tetraquark states in $X \rightarrow J/\Psi\phi$. Moreover, after determining the $X(3872)$ quantum numbers, the decay $X(3872) \rightarrow \psi(2S)\gamma$ has been established with a significance of 4.4σ. Many more precise spectroscopic measurements from LHCb are expected using the Run II data samples, allowing for analysing other final states and for extending present analyses.

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