Studies of meson-like exotic states at LHCb

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The LHCb experiment exploits decays of beauty hadrons as well as prompt production in proton-proton collisions to investigate exotic mesons, especially in the charmonium mass region. Using large data samples collected during the Run I and Run II LHCb investigates exotic states to better understanding QCD. Recent results on exotic meson spectroscopy are presented.

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The exotic mesons such as tetraquarks and hadronic molecules, which consist of four quarks are predicted by QCD. In order to study possible exotic mesons and cusp structures the LHCb experiment has performed a series of measurements by looking for intermediate resonances in the exclusive B and B_s^0 mesons decays, as well as for hadroproduction of exotic hadrons. Searches for purely hadronic decay modes of the $X(3872)$, observations of exotic candidates decaying to $J/\psi\phi$, studies of the $Z(4430)^-$ and search for the $X(5568)^-$, as discussed in this proceeding have been performed using a data sample collected at $\sqrt{s} = 7$ and 8 TeV with an integrated luminosity of $\int \mathcal{L} dt = 3\,fb^{-1}$. The search for fully beautiful tetraquark $X_{bb\bar{b}\bar{b}}$ has been performed using a data sample collected at $\sqrt{s} = 7, 8$ and 13 TeV with an integrated luminosity of $\int \mathcal{L} dt = 6.3\,fb^{-1}$.

The $X(3872)$ state is the exotic hadron [1, 2], which has been observed in different production processes, contrary to most of other exotic hadron candidates. The LHCb collaboration performed a series of measurements clarifying the nature of the $X(3872)$: determined its quantum numbers to be 1^{++} [3, 4], observed the $X(3872) \to \psi(2S)\gamma$ decay [5], which indicates charmonium component in the X(3872), and measured its prompt production in pp collisions [6]. Recently, LHCb performed searches of $X(3872)$ decays to hadrons. The $X(3872) \to p\bar{p}$ decay has been searched with no signal observed [7]. The $X(3872) \to \phi\phi$ decay has been searched using a sample of inclusive b-hadron decays [8], yielding an upper limit at the 95% (90%) confidence level of:

$$\frac{\mathscr{B}(b \to X(3872)X) \times \mathscr{B}(X(3872) \to \phi\phi)}{\mathscr{B}(b \to \chi_{c1}X) \times \mathscr{B}(\chi_{c1} \to \phi\phi)} < 0.39\,(0.34). \qquad (1)$$

Studies of exotics candidates decaying to $J/\psi\phi$ at LHCb have been performed using a data sample of $B^+ \to J/\psi\phi K^+$ decays[1] [9, 10]. A full six-dimensional amplitude analysis has been performed. The fit assuming contributions only from all possible K^{*+} states decaying to ϕK^+ fails to describe the data yielding a p-value below 10^{-7}. Contributions from the four states decaying to $J/\psi\phi$ are needed with significance of more than 5σ to describe the data. The fit, which includes contributions from these states gave a p-value of 0.22; the result of the fit is shown on Fig. 1. The summary of the measured masses[2], natural widths and established quantum numbers of observed exotics candidates are listed in Tab. 1. Further investigations with a larger data sample are needed to test cusp hypotheses of observed structures [11].
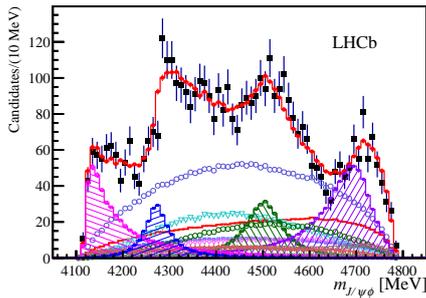
Figure 1: The projection of the fit (red line) to $M(J/\psi\phi)$ distribution in $B^+ \to J/\psi\phi K^+$ decays. Contributions from X(4140) (magenta), X(4274) (blue), X(4500) (green) and X(4700) (violet) are shown with filled hatches.

	M, MeV	Γ, MeV	J^{PC}
$X(4140)$	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^{++}
$X(4274)$	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	1^{++}
$X(4500)$	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^{++}
$X(4700)$	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^{++}

Table 1: Mass (M), natural width (Γ), quantum numbers J^{PC} of observed exotics candidates decaying to $J/\psi\phi$.

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[1] The inclusion of charge-conjugate states is implied throughout

[2] Natural units are used throughout the paper

A four-dimensional amplitude analysis has been performed to study the $Z(4430)^-$ **state** using a data sample of $B^0 \to \psi(2S)\pi^- K^+$ decays [12]. The fit assuming contributions only from possible K^{0*} states decaying to $K^+\pi^-$ failed to describe the data. Therefore, a contribution from $Z(4430)^- \to \psi(2S)\pi^-$ is needed, yielding a significance of the $Z(4430)^-$ of at 13.9σ. The measured mass $M_{Z(4430)^-} = 4475 \pm 7^{+15}_{-25}$ MeV and width $\Gamma_{Z(4430)^-} = 172 \pm 12^{+37}_{-34}$ MeV are compatible with and more precise than the measurement by Belle [13]. The quantum numbers are established to be $J^P = 1^+$ with a significance more than 9σ over the alternative hypothesis. More data are needed to distinguish between resonance and cusp hypotheses in future. In addition, the model independent confirmation of $Z(4430)^-$ by moments analysis is performed [14].

The $Z(4430)^-$ state may similarly be found in the $B_s^0 \to \psi(2S)\pi^- K^+$ decays. The LHCb experiment has made an observation of $B_s^0 \to \psi(2S)\pi^- K^+$, and the relative branching fraction with respect to corresponding B^0 decay has been measured to be:

$$\frac{\mathscr{B}(\bar{B}_s^0 \to \psi(2S)K^+\pi^-)}{\mathscr{B}(B^0 \to \psi(2S)K^+\pi^-)} = 5.38 \pm 0.36(stat) \pm 0.22(syst) \pm 0.31(f_s/f_d)\%, \qquad (2)$$

where the first uncertainty is statistical, second is systematical and the last uncertainty is related to the b-quark fragmentation ratio f_s/f_d. Similar measurement has been done in the $K^*(892)$ region for the $B_s^0 \to \psi(2S)K^*(892)$ decay mode. No signal for the $Z(4430)^-$ has been observed in the $\psi(2S)\pi^-$ invariant mass distribution. The search of the $Z(4430)^-$ in the B_s^0 decays will benefit from larger data sample collected at 13 TeV.

The $X(5568)^-$ has been claimed by D0 collaboration decaying to $B_s^0\pi^-$ [15]. The LHCb experiment has collected much larger data sample of B_s^0 mesons. No sign of $X(5568)^- \to B_s^0\pi^-$ has been observed for three different transverse momentum requirements at LHCb [16].

The fully beautiful tetraquark $X_{bb\bar{b}\bar{b}}$ below the $\eta_b\eta_b$ threshold has been searched in the decay $\Upsilon\mu^+\mu^-$ using the $\Upsilon(1S) \to \mu^+\mu^-$ decay for normalisation [17]. No signal for the $X_{bb\bar{b}\bar{b}} \to \Upsilon(1S)\mu^+\mu^-$ was observed. The fit to the $\Upsilon(1S)\mu^+\mu^-$ invariant mass is shown on Fig. 2. The upper limit has been extracted as function of assumed invariant mass of $X_{bb\bar{b}\bar{b}}$ as shown on Fig. 3.

In summary, the Run I data sample allows a series of measurements and searches for exotic hadrons with increasing sensitivity. A systematic study of the $X(3872)$ state are leading to understanding of its nature. Amplitude analysis of exclusive B-meson decays demonstrated that significant contributions from exotic candidates in the $J/\psi\phi$ and $\psi(2S)\pi^-$ spectra are needed. The properties of these states have been measured with better precision and the natural width of the
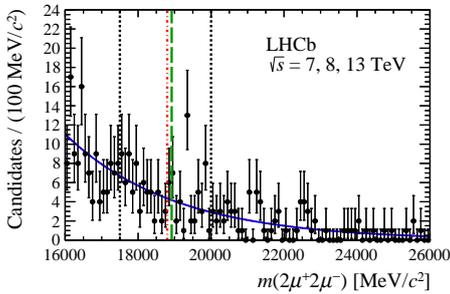
Figure 2: The fit to $M(\Upsilon(1S)\mu^+\mu^-)$ distribution. The blue line shows the curve of the fit, data points are shown in black. The red dashed line shows the $\eta_b\eta_b$ threshold, the green dashed line shown the $\Upsilon(1S)\Upsilon(1S)$ threshold.
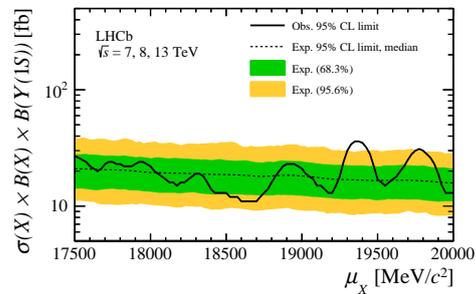
Figure 3: The 95% upper limit (black line) for $X_{bb\bar{b}\bar{b}}$ production cross-section. The $\sigma(X)$ denotes the $X_{bb\bar{b}\bar{b}}$ production cross-section, the $B(X)$ denotes the branching fraction of the $X_{bb\bar{b}\bar{b}} \to \Upsilon(1S)\mu^+\mu^-$ decay, the $B(Y)$ denotes the branching fraction of the $\Upsilon(1S) \to \mu^+\mu^-$ decay.

$X(4174)$ was measured to be much larger than the previous world average value. No sign of the $X(5568)^-$ claimed by D0 has been observed by LHCb. The search of fully beautiful tetraquark has been performed using Run I and Run II data samples with no signal observed. The Run II data sample will allow to perform more measurements of B_s^0 decays and to improve precision of measurements presented here. Its higher statistics will be also used to search for other mechanisms of exotic hadron candidates production and improve understanding of their nature.

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