PROCEEDINGS OF SCIENCE

Exotic spectroscopy at LHCb

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The LHCb experiment is designed to study the properties and decays of heavy flavored hadrons produced in pp collisions at the LHC. The latest results from LHCb regarding exotic hadron spectroscopy are presented. In particular the discovery of a narrow doubly charmed tetraquark decaying promptly to $D^0 D^0 \pi^+$, the evidence of a new strange pentaquark candidate in the $J/\psi\Lambda$ mass spectrum, the observation of a doubly charged tetraquark and its neutral partner in the $D_s\pi$ system, the observation of $X(3960)$ decaying to $D_s^+ D_s^-$, the evidence of a new tetraquark in $J/\psi K_s$, the search prompt pentaquarks in charm final states and the study of the $\chi(3872)$ nature using radiative decays.

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1. Introduction

Since the formulation of the quark model, hadronic states beyond the conventional $q\bar{q}$ combinations and three quarks combinations have been proposed. Various exotic hadrons are predicted, including pentaquarks ($qqqq\bar{q}$) and tetraquarks ($qq\bar{q}\bar{q}$) [1, 2]. In the early 2000s, a new hadron with exotic properties was observed, the $\chi(3872)$ [3], followed shortly after by the discovery of many other charmonium-like and bottomonium-like states. This document describes some of the recent results from LHCb in exotic hadron spectroscopy.

2. Observation of a doubly charmed tetraquark

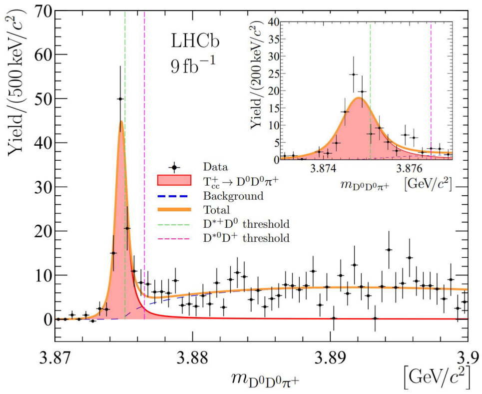

Figure 1: Distribution of $D^0D^0\pi^+$ mass, the contribution of the non-D^0 background has been statistically subtracted. The result of the fit described in the text is overlaid. The $D^{*+}D^0$ and $D^{*+}D^+$ thresholds are indicated with the vertical dashed lines.

A hadron with two heavy quarks Q and two light antiquarks q, such as $bb\bar{u}\bar{d}$, $bc\bar{u}\bar{d}$ and $cc\bar{u}\bar{d}$, is a candidate to form a long-lived exotic state, stable with respect to the strong interaction [4–7].

Using the data of Run 1 (2011-2012) and Run 2 (2015-2018), corresponding to $9fb^{-1}$, the $D^0D^0\pi^+$ invariant mass was reconstructed, requiring that the three particles are produced from the same vertex [8]. The resulting invariant mass distribution for the selected candidates is shown in Fig. 1. The narrow peak near the $D^{*+}D^0$ threshold is fitted using an extended maximum likelihood fit. The statistical significance of the observed $T_{cc}^+ \to D^0D^0\pi^+$ signal is estimated using Wilks' theorem to be 22 standard deviations, fixing the spin parity assignement to $J^P = 1^+$ and $I = 0$ as expected from a $cc\bar{u}\bar{d}$ ground state. A study on the properties of the T_{cc}^+ [9] found the pole parameters to be

$$\delta m_{BW} = -361 \pm 40 keV/c^2, \qquad \Gamma_{BW} = 47.8 \pm 1.9 keV$$

The observation of this $cc\bar{u}\bar{d}$ tetraquark candidate close to the $D^{*+}D^0$ threshold provides strong support for the theory approaches and models that predict the existence of a $bb\bar{u}\bar{d}$ tetraquark stable with respect to the strong and electromagnetic interactions.

3. Observation of a $J/\psi\Lambda$ resonance consistent with a strange pentaquark candidate in $B^- \to J/\psi\Lambda\bar{p}$ decays

Evidence for a $P^{\Lambda^0}_{\psi_s} = c\bar{c}uds$ pentaquark candidate was found in the $J/\psi\Lambda$ system in the $\Xi_b^- \to J/\psi\Lambda K^-$ decay [10]. The $B^- \to J/\psi\Lambda\bar{p}$ decay offers the opportunity to simultaneously search for pentaquarks candidates in the $J/\psi\bar{p}$ and $J/\psi\Lambda$ systems.

The LHCb experiment studied the decay $B^- \to J/\psi\Lambda\bar{p}$ [11]. 4400 events were collected selecting J/ψ, Λ and $\bar{p}$ candidates originating from the same vertex. A six-dimensional amplitude fit with the $m_{\Lambda\bar{p}}$ invariant mass and five angular variables has been applied to describe the data. There are no well-established resonances that decay into the $J/\psi\Lambda$ and $J/\psi\bar{p}$ final states. A fit with this baseline model do not correctly describe the data, as shown in Fig. 2 (grey line). The addition of a resonance in the $J/\psi\Lambda$ invariant mass, parametrized with a relativistic Breit–Wigner, allow for a better description of the data, as shown in Fig. 2 (red line). $J = 1/2$ is established and positive parity can be excluded at 90% confidence level. The mass and width of the new pentaquark candidate are measured to be

$$m_{P^{\Lambda^0}_{\psi s}} = 4338.21 \pm 0.7 \pm 0.4 MeV/c^2, \qquad \Gamma_{P^{\Lambda^0}_{\psi s}} = 7.0 \pm 1.2 \pm 1.3 MeV$$

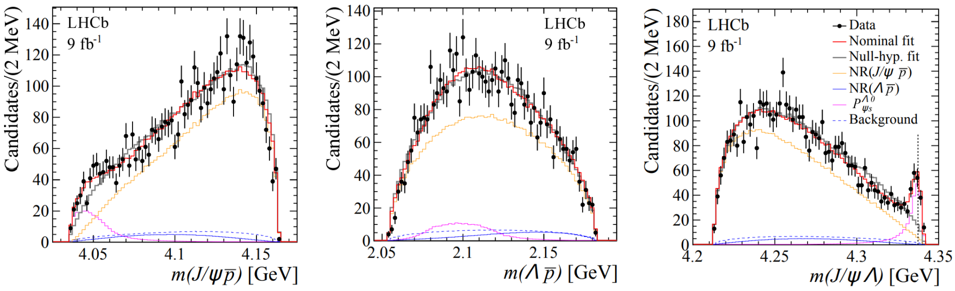

Figure 2: Distributions of invariant mass. Fit results to data using the nominal model are superimposed. The null-hypothesis model fit results are also shown in grey. The $\Xi_c^+ D^-$ baryon-meson threshold at $4.337 GeV/c^2$ is indicated with a vertical dashed line in the $m_{J/\psi\Lambda}$ invariant mass distribution.

4. Observation of a doubly charged tetraquark and its neutral partner

Two new resonant structures, $X_0(2900)$ and $X_1(2900)$, were observed by the LHCb collaboration in the D^-K^+ mass spectrum of the $B^+ \to D^+D^-K^+$ decay [13, 14]. Predictions of a doubly charged tetraquark $c\bar{s}u\bar{d}$ and its isospin partner $c\bar{s}\bar{u}d$ were made based on those observations [15–20]. 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 $D_s\pi$ since the only states expeced to contribute are the well-known $\bar{D}^*$. LHCb collected ~ 4000 and ~ 3750 events for the neutral and charged channel, respectively [21, 22]. The conventional contributions in the two decays include the known D^* and excited D^* resonances [23]. In order to have a better description of the data two $D_s^+\pi$ states are introduced, $T^a_{c\bar{s}0}(2900)^0$ and $T^a_{c\bar{s}0}(2900)^{++}$, as shown in Fig. 3. The mass and width are found to be

$$m_{T^a_{c\bar{s}0}(2900)^0} = 2879 \pm 17 \pm 18 MeV/c^2, \qquad \Gamma_{T^a_{c\bar{s}0}(2900)^0} = 153 \pm 28 \pm 20 MeV,$$

$$m_{T^a_{c\bar{s}0}(2900)^{++}} = 2935 \pm 21 \pm 13 MeV/c^2, \quad \Gamma_{T^a_{c\bar{s}0}(2900)^{++}} = 143 \pm 38 \pm 25 MeV$$

The significances are evaluated to be 8.0σ and 6.5σ fot the neutral and charged resonance, respectively, including systematic uncertainties. The mass and width differences between the two resonances are compatible with the assumption of the two states being isospin partners. $J^P = 0^+$ is favoured with 7.5σ.

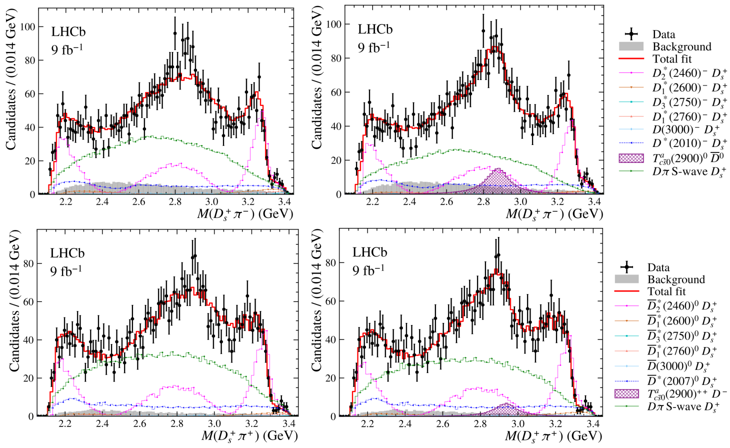

Figure 3: Distributions of $m_{D_s^+\pi^-}$ (top) and $m_{D_s^+\pi^+}$(bottom) candidates, on the left fitted with the nominal model and on the right with the addition of the new state. The data are overlaid with the results of the fits.

5. Observation of a resonant structure near the $D_s^+D_s^-$ threshold in the $B^+ \to D_s^+D_s^-K^+$ decay

Numerous theoetical developments [24–28] point to a potential resonant structure in the vicinity of the $D_s^+D_s^-$ threshold in the invariant-mass spectrum. An amplitude analysis of about 360 reconstructed $B^+ \to D_s^+D_s^-K^+$ events has been performed [29]. In order to correctly describe the structure in the $D_s^+D_s^-$ two known 1^{--} charmonium states, $\psi(4260)$ and $\psi(4660)$ [23], and two new 0^{++} X states, denoted as $X(3960)$ and $X(4140)$, are needed, the fit results are shown in Fig. 4. The mass and width of the two resonances are found to be:

$$m_{X(3960)} = 3956 \pm 5 \pm 10 MeV/c^2, \quad \Gamma_{X(3960)} = 43 \pm 13 \pm 8 MeV,$$
$$m_{X(4140)} = 4133 \pm 6 \pm 6 MeV/c^2, \quad \Gamma_{X(4140)} = 67 \pm 17 \pm 7 MeV$$

The $X(3960)$ is found with a significance of 12.6σ. The $X(4140)$ is found with a significance of 3.8σ. It is also tested the possibility that the dip near $4.1 GeV/c^2$ can be modelled by the $J/\psi\phi \to D_s^+D_s^-$ rescattering, using the K-Matrix formalism. The results are compatible with the ones obtained by the addition of the $X(4140)$, so no conclusion can be drawn on the existence of this resonance. Further studies are needed to identify the nature of the $X(3960)$.

6. Evidence of a $J/\psi K_s^0$ structure in $B^0 \to J/\psi\phi K_s^0$ decays

Two states, $T^\theta_{\psi s1}(4000)^+$ and $T_{\psi s1}(4220)^+$, were observed in $B^+ \to J/\psi\phi K^+$ decays by the LHCb experiment [30]. The search for $T^0_{\psi s}$, the isospin partner of the $T^+_{\psi s}$, will help identifying the full $SU(3)$ nonet that involves these states.

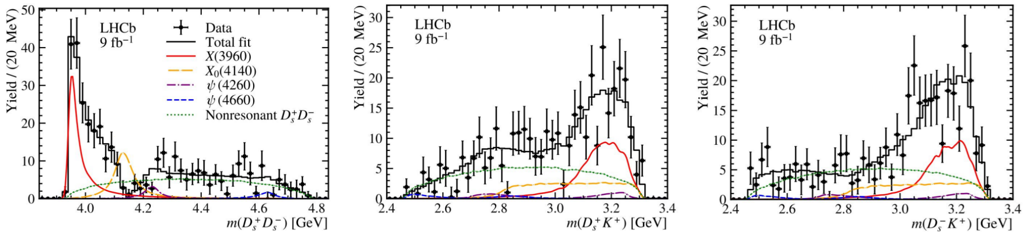

Figure 4: Background-subtracted invariant-mass distributions (left) m($D_s^+D_s^-$), (center) m($D_s^+K^+$) and (right) m($D_s^-K^+$) for the $B^+ \to D_s^+D_s^-K^+$ signal. The projections of the fit with the baseline amplitude model are also shown.

The LHCb experiment reconstructed ~ 1900 $B^0 \to J/\psi\phi K_s^0$ events [31]. An amplitude fit is performed simultaneously to the neutral and charged channel in order to improve the stability of the fitter, the amplitudes in the two decay modes are related through isospin symmetry. Nine K^* components, seven X ($J/\psi\phi$ known exotic states) components, two $T_{\psi s1}$ states, and a $J/\psi\phi$ nonresonant component are included, as shown in Fig. 5. Evidence of a $J/\psi K_s^0$ structure, denoted the $T^{\theta}_{\psi s1}(4000)^0$ state, with a significance of 4.0σ. The mass and width of this state are measured to be:

$$m_{T^{\theta}_{\psi s1}(4000)^0} = 3991^{+12+9}_{-10-17} MeV/c^2, \qquad \Gamma_{T^{\theta}_{\psi s1}(4000)^0} = 105^{+29+17}_{-25-23} MeV$$

If the isospin symmetry is imposed for the neutral and charged $T_{\psi s1}(4000)$ states, the significance of $T^{\theta}_{\psi s1}(4000)^0$ is 5.4σ.

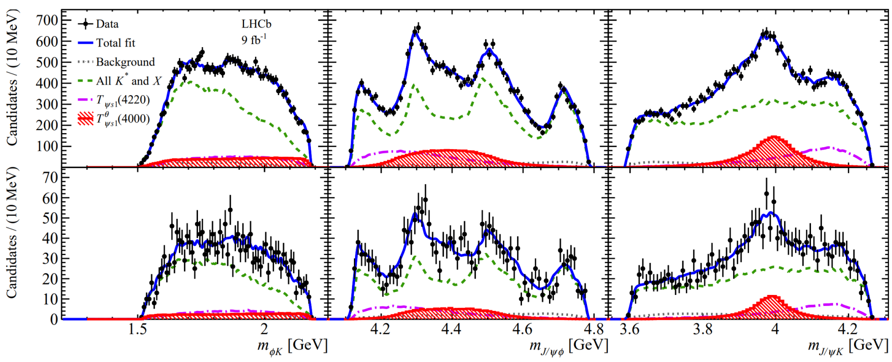

Figure 5: Distributions of (left) $m_{\phi K}$, (middle) $m_{J\psi K\phi}$, and (right) $m_{J\psi K}$, overlaid with the corresponding projections of the default fit model. The upper and lower rows correspond to the $B^+ \to J/\psi\phi K^+$ and $B^0 \to J/\psi\phi K_s^0$decays, respectively.

7. Search for prompt production of pentaquarks in charm hadron final states

Many exotic hadrons mass are in the proximity of hadron-hadron thresholds. More detailed experimental and theoretical examination are required to understand if this is just coincidental or related to their structure. A search for the known pentaquark $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ [32], other pentaquarks with hidden charm in the prompt $\Sigma_c\bar{D}^{(*)}$, $\Sigma_c^*\bar{D}^{(*)}$, $\Lambda_c^+\bar{D}^{(*)}$ and $\Lambda_c^+\pi\bar{D}^{(*)}$ mass spectra and others containing two charm quarks in the $\Sigma_c D^{(*)}$, $\Sigma_c^* D^{(*)}$, $\Lambda_c^+ D^{(*)}$ and $\Lambda_c^+\pi D^{(*)}$ mass spectra has been performed [33]. No clear signals are observed, upper limits are set as function of Q-value. For all cases the yields are compatible with zero when fitting using a signal model based on known pentaquark states.

8. Probing the nature of the $\chi_{c1}(3872)$ state using radiative decays

Since the discovery of the $\chi_{c1}(3872)$ [3], the properties of this state have been intensively studied but its nature is still under debate. The investigation of the radiative decays of the $\chi_{c1}(3872)$ state into the $\psi(2S)\gamma$ and $J/\psi\gamma$ final states offers an approach to study its nature [34]. The calculated ratio of partial radiative decay widths into the $\psi(2S)\gamma$ and $J/\psi\gamma$ final states shows significant variation based on the assumed nature of the $\chi_{c1}(3872)$ state and is defined as follow:

$$R_{\psi\gamma} = \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}. \tag{1}$$

The LHCb collaboration used the $B^+ \to \chi_{c1}(3872)K^+$ to study the radiative decays of the $\chi_{c1}(3872)$ [35]. The significance of the $B^+ \to (\chi_{c1}(3872) \to \psi(2S)\gamma)K^+$ signal is found to be 4.8 and 6.0 standard deviations for the Run 1 and Run 2 data-taking periods, which is the first observation of the $\chi_{c1}(3872) \to \psi(2S)\gamma$ decay. The ratio of branching fractions for the two decays is measured separately for the Run 1 and Run 2 data-taking periods. This ratio is interpreted as the ratio of the partial decay widths for the $\chi_{c1}(3872) \to \psi\gamma$ decays from Eq. 1. The combined obtained value is found to be $R_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$. This results is in agreement with the results of the Belle [36] and BaBar experiment [37] but in notably tension with the upper limit set by the BESIII collaboration [38].

9. Conclusion

In conclusion, recent results on exotic spectroscopy from the LHCb experiment are presented. The T_{cc} tetraquark is observed decaying to $D^0D^0\pi^+$ with a very high significance. A new strange pentaquark has been observed in the $B^- \to J/\psi\Lambda\bar{p}$ decay. Two new tetraquark, compatible with the hypotesis of being isospin partners, are observed in the $B^0 \to \bar{D}^0D_s^+\pi^-$ and $B^+ \to D^-D_s^+\pi^+$ decay. The evidence of a structure near $4GeV$ in the the $J/\psi K_s^0$ system in the $B^0 \to J/\psi\phi K_s^0$ decay. No evidence are found for prompt production of pentaquark in charm final states. The analysis of the radiative decays of the $\chi_{c1}(3872)$ measured a value of the ratio of partial radiative decay widths that provides an arguments in favour of a compact component in the $\chi_{c1}(3872)$ structure.

The larger data size, combined with the new trigger strategy, of Run 3 will allow to search for new states that cannot be studied with the current dataset.

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