RECENT LHCb RESULTS ON MULTIQUARK STATES*

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The excellent performance of the LHCb experiment has opened the road to precise hadron spectroscopy studies. A rich variety of new resonances has already been discovered for the last years. The very recent LHCb results on pentaquarks and tetraquarks are presented here.

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1. Introduction

Particles with an alternative quark content, known as exotic states, along with conventional mesons and baryons, made of a quark–antiquark pair ($q_1\bar{q}_2$) and three quarks ($q_1q_2q_3$), respectively, have been actively discussed since the birth of the constituent quark model [1].

The LHCb experiment at the LHC at CERN was designed specifically for the study of particles containing b or c quarks and to provide precise measurements in the field of hadron spectroscopy. LHCb has already published precise particle mass determination and discovered new hadron decays and new hadrons, including exotic states. Some of them have already been reported at past editions of this conference series.

The LHCb detector [2, 3] is a single-arm forward spectrometer covering the pseudorapidity range of $2 < \eta < 5$. The online event selection is performed by a trigger [4], comprising a hardware stage which selects events with high-p_{T} tracks, followed by a software stage that applies a full event reconstruction. Simulation is required to model the effects of the detector acceptance and the imposed selection requirements; the simulated samples are generated as described in [5].

In this paper, very recent LHCb results on states composed of four different quark types, that present unambiguous evidence of tetraquarks, and pentaquark states, which have a minimal quark content of three quarks plus

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a quark–antiquark pair, are reported. The study is based on proton–proton (pp) collision data at the centre-of-mass energies of 7, 8 (Run 1), and 13 TeV (Run 2), recorded between 2011 and 2018 by the LHCb detector, and corresponding to integrated luminosity of 9 fb^{-1}, *i.e.* the full Run1+Run2 data sample.

2. Recent results on tetraquark states at the LHCb

2.1. Doubly charmed tetraquark T_{cc}^{+}

The observation of the double charmed baryon Ξ_{cc}^{++}, containing two c quarks and a u quark, discovered by the LHCb experiment [6, 7], stimulated the search for a $cc\bar{u}\bar{d}$ tetraquark state, given the relationship between the properties of the two states. In particular, the measured mass of the Ξ_{cc}^{++} baryon with quark content ccu implies that the mass of the $cc\bar{u}\bar{d}$ tetraquark is close to the sum of the masses of D^0 and D^{*+} mesons, with quark content of $c\bar{u}$ and $c\bar{d}$, respectively, as suggested in [8].

The observation and the study of a narrow state in the $D^0D^0\pi^+$ mass spectrum near the $D^{*+}D^0$ mass threshold, compatible with a T_{cc}^{+} tetraquark state, has been recently reported by the LHCb [9, 10]. Charge conjugate decays are implied in this analysis.

Events with two good quality D^0 candidates, reconstructed in the $D^0 \to K^-\pi^+$ decay channel, are selected and combined with a positively charged pion; all these particles are required to originate from the same primary vertex with a kinematic fit on the $D^0D^0\pi^+$ system. Figure 1 shows the resulting $D^0D^0\pi^+$ mass distribution for selected $D^0D^0\pi^+$ combinations: a narrow peak is clearly visible near the $D^{*+}D^0$ mass threshold.

The maximum-likelihood fit to the $D^0D^0\pi^+$ mass distribution is performed using a model consisting of the signal and background components. The signal is described by the convolution of the detector resolution, assumed Gaussian, with a resonant shape, modelled by a relativistic P-wave Breit–Wigner (BW) function. The detector resolution is modelled by the sum of two Gaussian functions with a common mean; the root mean square of the resolution function is around 400 keV$/c^{-2}$. A study of the $D^0\pi^+$ mass distribution for $D^0D^0\pi^+$ combinations in the region above the $D^{*+}D^0$ but below 3.9 GeV$/c^{-2}$ shows that approximately 90% of all random $D^0D^0\pi^+$ combinations contain a genuine D^{*+} meson. On the basis of this observation, the background component is parametrized by the product of a two-body phase space above $D^{*+}D^0$ mass and a positive second-order polynomial, see [9] for other details of the analysis. The statistical significance of the peak is overwhelming. The location of the peak relative to the $D^{*+}D^0$ mass threshold is determined to be $\delta m_{\mathrm{BW}} = -273 \pm 61 \pm 5^{+11}_{-14}$ keV$/c^{-2}$ and the width of the peak is $\Gamma_{\mathrm{BW}} = 410 \pm 165 \pm 43^{+18}_{-38}$ keV; the first uncertainty

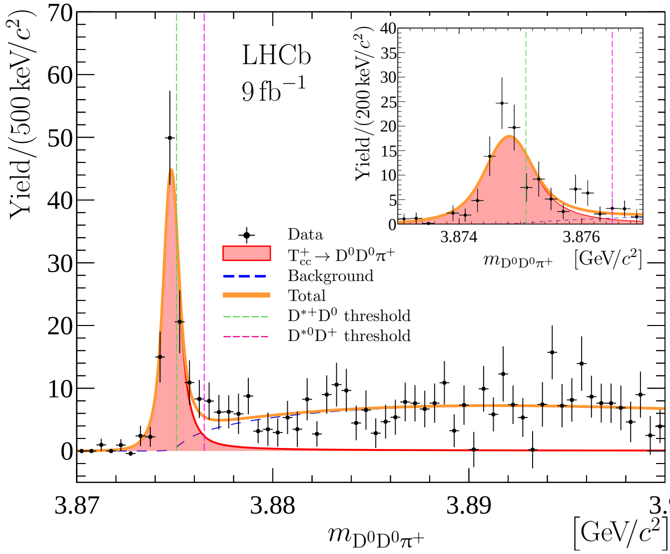

Fig. 1. Distribution of the $D^0D^0\pi^+$ mass with the result of the fit described in the text. The inset shows a zoomed signal region with a fine binning. Uncertainties on the data points are statistical only and represent one standard deviation. Figure adopted from [9].

is statistical, the second is systematic, and the third is related to the assignment of the J^P quantum numbers. This state is consistent with a T_{cc}^+ tetraquark ground state with quantum numbers $J^P = 1^+$. The measured $\delta m_{\rm BW}$ value corresponds to a mass of approximately 3875 MeV. This is the narrowest exotic state observed to date. The minimal quark content for this state is $cc\bar{u}\bar{d}$.

2.2. Observation of a doubly charged tetraquark

The $B^0 \to \bar{D}^0 D_s^+\pi^-$ and $B^+ \to D^- D_s^+\pi^+$ decays are ideal channels to search for possible exotic states decaying to $D_s\pi$. A joint amplitude analysis of the $B^0 \to \bar{D}^0 D_s^+\pi^-$ and $B^+ \to \bar{D}^- D_s^+\pi^+$ decays was performed [11, 12] where amplitudes in the two-decay modes are related through isospin symmetry. Charmed mesons are reconstructed in $\bar{D}^0 \to K^+\pi^-$, $\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$, $D^- \to K^+\pi^-\pi^+$, and $D_s^+ \to K^+K^-\pi^+$. Further details on the selections and on the criteria applied to suppress specific peaking backgrounds can be found in [12]. After the selections, 4420 $B^0 \to \bar{D}^0 D_s^+\pi^-$ candidates and 3750 $B^+ \to D^- D_s^+\pi^+$ candidates are retained. Extended maximum likelihood fits are performed to the $\bar{D}^0 D_s^+\pi^-$ and $D^- D_s^+\pi^+$ invariant-mass distributions separately in order to extract signal yields, all in the range of $[5230, 5630]$ MeV. The functions used to describe signal and background shapes are given in [12]. The purities of the $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ samples are 90.7% and 95.2%, respectively. A joint amplitude analysis is performed to determine the contributions of intermediate states in the decays. In the $M(D_s\pi)$ projection of each channel, two new $D_s\pi$ exotic resonances are included in the fit model in order to describe peaking structures near 2.9 GeV. Amplitude fits with separate $T^a_{c\bar{s}0}(2900)^0$ and $T^a_{c\bar{s}0}(2900)^{++}$ resonance parameters give for masses and widths:

$$
\begin{aligned}
M\left(T^a_{c\bar{s}0}(2900)^0\right) &= 2.892 \pm 0.014 \pm 0.015 \text{ GeV}\,,\\
\Gamma\left(T^a_{c\bar{s}0}(2900)^0\right) &= 0.119 \pm 0.026 \pm 0.012 \text{ GeV}\,,\\
M\left(T^a_{c\bar{s}0}(2900)^{++}\right) &= 2.921 \pm 0.017 \pm 0.019 \text{ GeV}\,,\\
\Gamma\left(T^a_{c\bar{s}0}(2900)^{++}\right) &= 0.137 \pm 0.032 \pm 0.014 \text{ GeV}\,,
\end{aligned}
$$

which are in good agreement. The first and second uncertainties are statistical and systematic, respectively. The significance of the two resonances is found to be 8.0σ for $T^a_{c\bar{s}0}(2900)^0$ and 6.5σ for $T^a_{c\bar{s}0}(2900)^{++}$. This is the first observation of a doubly charged tetraquark candidate $T^a_{c\bar{s}0}(2900)^{++}([c\bar{s}u\bar{d}])$, and of its neutral isospin partner, $T^a_{c\bar{s}0}(2900)^0([c\bar{s}\bar{u}d])$. They provide evidence for a new type of open-charm tetraquark states with c and $\bar{s}$ quarks.

3. Recent results on pentaquark states at LHCb

3.1. New pentaquarks in $J/\psi p$ and $J/\psi\bar{p}$ systems

A search for pentaquarks was performed in the $B_s^0 \to J/\psi p\bar{p}$ channel [13]. This decay was observed for the first time by the LHCb experiment in 2019 [14]. The measurement is performed untagged, such that decays of B_s^0 and $\bar{B}_s^0$ are not distinguished and analysed together. Events with two pairs of oppositely charged tracks were selected, where the first pair is required to be consistent with muons originating from a J/ψ meson and the particles of the second pair are identified as protons; all the four tracks are required to originate from the same common vertex, significantly displaced from its associated pp primary vertex. Full details on the analysis and the selection criteria can be found in [13]. Figure 2 shows the distribution of $m(J/\psi p\bar{p})$ effective mass, where the B^0 and B_s^0 signals are well visible.

A maximum-likelihood fit is performed to the $J/\psi p\bar{p}$ invariant mass distribution (see [13] for details); the $B^0 \to J/\psi p\bar{p}$ component has the same shape as the B_s^0 signal. The combinatorial background is modelled by a first-order polynomial with parameters determined from the fit to data.

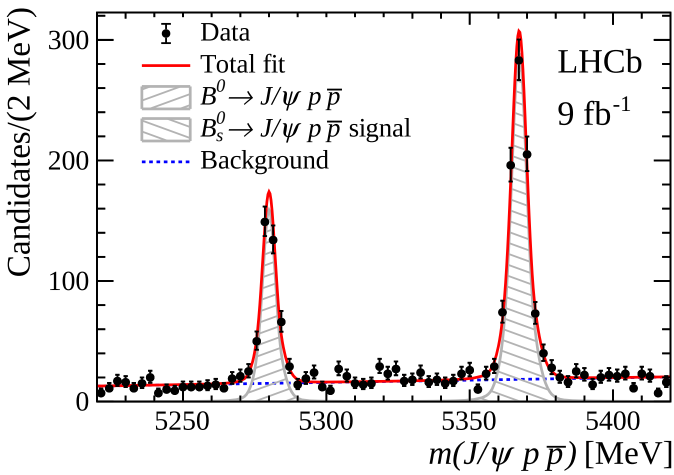

Fig. 2. Invariant-mass distribution $m(J/\psi p\bar{p})$ for reconstructed signal candidates: the result of the fit described in the text is overlaid. Figure adapted from [13].

The B_s^0 signal decays from the fit are 797 ± 31 events and the combinatorial background fraction in the B_s^0 signal window of 3σ around the mass peak ($[5357, 5378]$ MeV) is estimated to be $(14.9 \pm 0.6)\%$.

The $m(J/\psi p)$ and $m(J/\psi \bar{p})$ invariant mass distributions of the reconstructed B_s^0 candidates in the B_s^0 signal region show hints of structure in the region around (4.3–4.4) GeV. An investigation of the nature of these enhancements, with the help of an amplitude analysis of the B_s^0 candidates was performed. The results of the fits show evidence for a Breit–Wigner-shaped resonance in the $m(J/\psi p)$ and $m(J/\psi \bar{p})$ invariant masses compatible with a new pentaquark state with mass $M_{P_c} = 4337^{+7+2}_{-4-2}$ MeV and width $\varGamma_{P_c} = 29^{+26+14}_{-12-14}$ MeV, where the first uncertainty is statistical and the second systematic. The statistical significance is in the range of 3.1 to 3.7σ, depending on the assigned J^P hypothesis. No state is visible in the $m(p\bar{p})$ system.

3.2. Observation of a strange pentaquark candidate in $B^- \to J/\psi \varLambda \bar{p}$ decays

A narrow resonance in the $J/\psi \varLambda$ system, consistent with a pentaquark candidate with strangeness, has been recently observed with high significance [15], by performing an amplitude analysis of the $B^- \to J/\psi \varLambda \bar{p}$ decays, that offer the unique opportunity to simultaneously search for pentaquark candidates in $J/\psi \bar{p}$ and $J/\psi \varLambda$ systems.

Signal B^- candidates are formed from combinations of $J/\psi \to \mu^+\mu^-$, $\varLambda \to p\pi^-$, and $\bar{p}$ candidates, originating from a common decay vertex significantly displaced from the associated pp primary vertex. See [15] for the complete description of the details of the candidate selection. A maximum likelihood fit is performed to the $m(J/\psi\Lambda\bar{p})$ distribution, resulting in a signal yield of 4617 ± 73 and retaining for amplitude analysis about 4400 candidates, with a purity of 93.0% in the signal region of $\pm 2.5\sigma$ around the mass peak. As a result of the analysis of one-dimensional projections of invariant mass (see [15] for details), a new resonant structure in the $J/\psi\Lambda$ system is found with high statistical significance, representing the first observation of a pentaquark candidate with strange quark content, with mass $M = 4338.2 \pm 0.7 \pm 0.4$ MeV and width $\Gamma = 7.0 \pm 1.2 \pm 1.3$ MeV, where the first uncertainty is statistical and the second systematic; the state is named $P_{\psi s}^{\Lambda}(4338)^0$, with spin $J = 1/2$ assigned and parity $P = -1$ preferred.

4. Conclusions and outlook

LHCb has been continually producing interesting results on exotic states. Run 3 started this year with the LHCb upgraded detector and we expect to record about 50 fb^{-1} at the end of Run 4. The LHCb physics program for new Upgrade 2 has already been approved and we expect to record about 300 fb^{-1} at the end of Run 5. A precision determination of the characteristics of observed hadrons and observation of new states are expected next years.

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