PROCEEDINGS OF SCIENCE

Tetra- and pentaquark spectroscopy

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Recent results on exotic spectroscopy from the LHCb experiment are introduced in these proceedings. They contain the evidence for a new pentaquark candidate decaying to $J/\psi p$ and $J/\psi \bar{p}$ in the $B_s^0 \to J/\psi p \bar{p}$ decays and the observation of four new resonances decaying to $J/\psi K^+$ and $J/\psi \phi$ in the $B^+ \to J/\psi \phi K^+$ decays, two of which are tetraquarks with strangeness.

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1. Introduction

Tetraquark and pentaquark states, also called exotic states, are hadrons with a more complex internal structure than the standard mesons and baryons and are composed by four and five quarks, respectively. Although they have been originally proposed by Gell-Mann [1] and Zweig [2] in the quark model, their first evidence was confirmed only in 2003 with the first tetraquark candidate, the $X(3872)$, observed by the Belle experiment in the $J/\psi\pi^+\pi^-$ mass spectrum [3]. The field of exotic spectroscopy has gained an increasing interest especially after the observation of pentaquark states, made by LHCb in 2015 in the $\Lambda_b^0 \to J/\psi pK^-$ decays [4]. More than thirty exotic states have been seen over the last few years. Recent results on exotic states from the LHCb experiment are reported in these proceedings.

2. Evidence for a new state decaying to $J/\psi p$ and $J/\psi \overline{p}$ system

The first observation of pentaquark states, $P_c(4380)^+$ and $P_c(4450)^+$, was reported by the LHCb experiment in 2015 in the analysis of $\Lambda_b^0 \to J/\psi pK^-$ decays [4]. In 2019, with an updated analysis performed with the full 9 fb^{-1} LHCb dataset, another state at mass 4312 MeV was observed and the peak at mass 4450 MeV was resolved into two separate peaks [5]. The $B_s^0 \to J/\psi p\overline{p}$ decay, first observed by the LHCb experiment in 2019 [6], may be sensitive to the resonant P_c structures [4, 5] decaying to $J/\psi p$ and $J/\psi\overline{p}$ final states and to the glueball $f_J(2220)$ predicted in Ref. [7]. The analysis of this mode is based on around 800 signal events collected by LHCb and corresponding to 9 fb^{-1} of integrated luminosity [8]. The selection has been optimised with multivariate techniques exploiting the information of the particle identification variables of the protons to distinguish between signal and background candidates. The fit to the $J/\psi p\overline{p}$ invariant mass is shown in Fig. 1. In order to investigate the resonant structure of this decay, a four-dimensional amplitude analysis of the flavour untagged B_s^0 sample is employed, using the helicity formalism [9] and assuming *CP* symmetry. The fit parameters are extracted from an unbinned maximum likelihood fit to the sum of the signal and the background components. The best model describing the data contains a non-resonant contribution in the $p\overline{p}$ decay chain plus two P_c resonances, P_c^+ and P_c^-, decaying to $J/\psi p$ and $J/\psi\overline{p}$, with mass and width fixed to the same values. These states are referred to as a single P_c state. The results of the fit are shown in Fig. 2, projected onto the phase-space variables, $(m_{p\overline{p}}, \cos\theta_\mu, \cos\theta_p, \varphi)$, and the $m(J/\psi p)$ and $m(J/\psi\overline{p})$ invariant masses. Different J^P hypothesis for the P_c state, *i.e.* $1/2^\pm, 3/2^\pm$, have been investigated but none of them can be excluded at the 90% of confidence level (CL). The mass and width of this P_c state are not compatible with the previously observed pentaquark states and are measured to be $M(P_c) = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})$ MeV and $\Gamma(P_c) = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})$ MeV, respectively. Its significance is estimated with a frequentist approach to lie in the range of 3.1 and 3.7σ depending on the J^P hypothesis considered, providing evidence for a new pentaquark-like state. With this analysis, no evidence is seen for either the $P_c(4312)$ state [5] or the glueball $f_J(2220)$ [7].

3. Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$

The $B^+ \to J/\psi\phi K^+$ mode has been previously studied by LHCb using the Run 1 dataset corresponding to 3 fb^{-1} [10]. Here, the results of the updated analysis performed with the full

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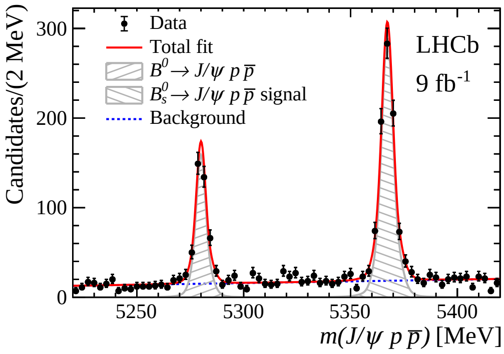

Figure 1: Fit to the $m(J/\psi p\bar{p})$ invariant mass, where the B_s^0 signal is modelled by two Crystal Ball functions and the combinatorial background by a first-order polynomial.

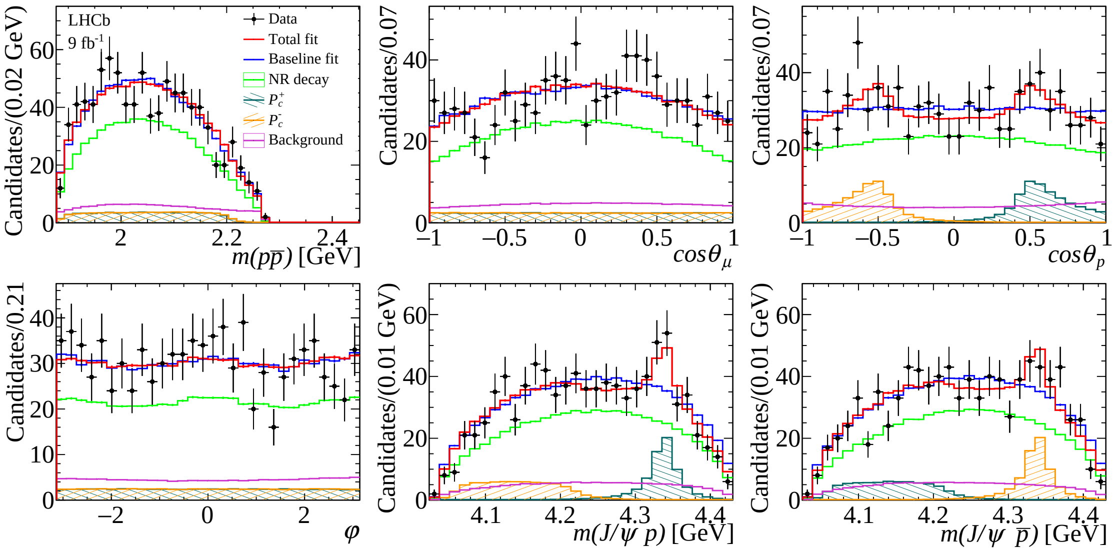

Figure 2: Projections of the angular $(\cos\theta_\mu, \cos\theta_p, \varphi)$ distributions, where θ_μ, θ_p are the helicity angles of the μ^- and the p in the J/ψ and X rest frame, respectively, and φ is the azimuthal angle between the decay planes, together with the invariant-mass distributions $(m(p\overline{p}), m(J/\psi p), m(J/\psi\overline{p}))$. Results of the fit from the baseline model (without the P_c state) are shown in blue and from the default model (with the P_c state) in red.

LHCb dataset (9 fb^{-1}) is presented [11]. Thanks to an improved selection with a more sophisticated usage of machine learning algorithms, it was possible to improve the signal yield by a factor of 6 with respect to Run 1 (about 24,000 candidates) and obtain a better background rejection (4% of background in a ± 15 MeV window around the B^+ peak). In the Dalitz plot shown in Fig. 3, four clear bands are present in the $J/\psi\phi$ invariant mass, corresponding to the X states previously observed by LHCb with the Run 1 analysis, *i.e.* $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$. In addition, a peak around 4 GeV in the $J/\psi K^+$ final state seems to suggest the existence of the Z_{cs}^+ tetraquark. A full amplitude analysis in six dimensions is carried out. Since the amplitude model used in Run 1 does not describe entirely the invariant mass projections, as shown in the bottom row of Fig. 4, it is extended by adding two resonances decaying to the $J/\psi\phi$ final state, the $X(4630)$ and the $X(4685)$,

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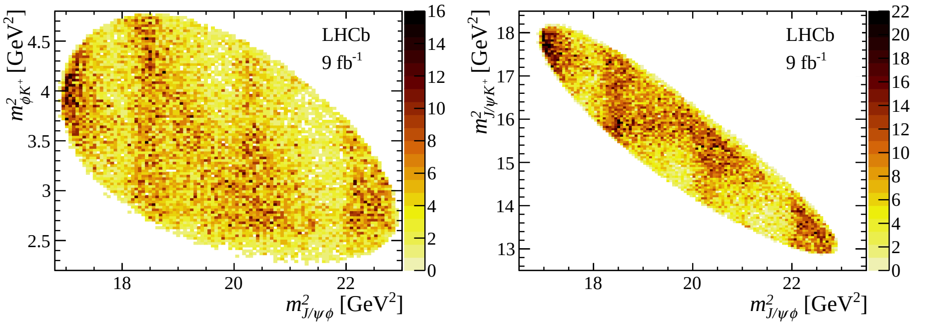

Figure 3: Dalitz plot of the $J/\psi\phi$ mass squared against the ϕK^+ (left) and the $J/\psi K^+$ (right) mass squared.

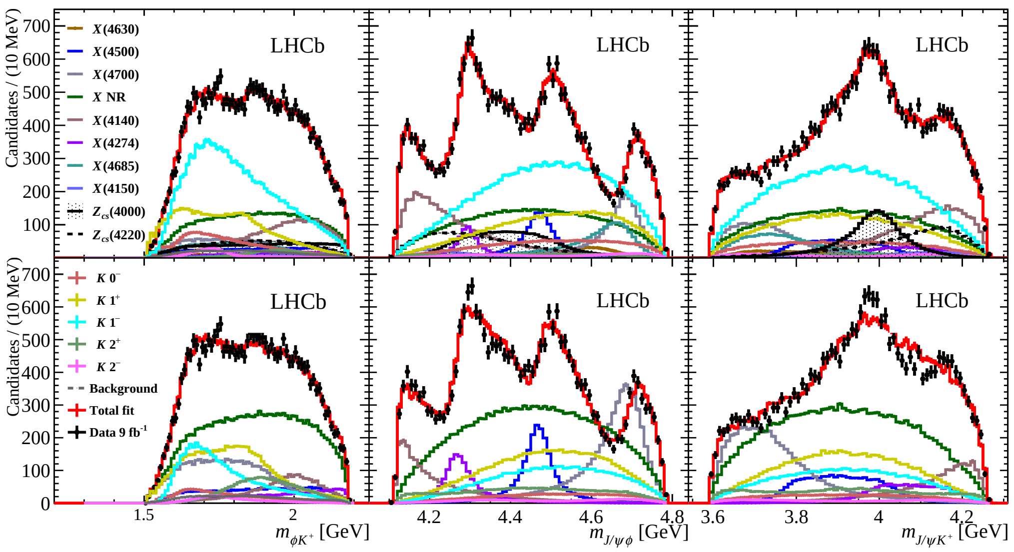

Figure 4: Projections over the $m(\phi K^+), m(J/\psi\phi)$ and $m(J/\psi K^+)$ invariant masses of the amplitude fit performed with the Run 1 model only (bottom) and the full model (top).

and two resonances decaying to $J/\psi K^+$, the $Z_{cs}(4000)^+$ and the $Z_{cs}(4220)^+$, which are candidates of tetraquarks with strangeness. All four states have been observed with a significance larger than 5σ. The quantum numbers have been determined for the $X(4685)$ and the $Z_{cs}(4000)^+$ states to be 1^+, while it is not possible to precisely assign them to the $X(4630)$ and the $Z_{cs}(4220)^+$ states.

4. Conclusion

Promising results on tetra- and pentaquark spectroscopy have been presented, focusing on the analysis of $B^0_s \to J/\psi p\overline{p}$ decays, which reports the evidence for a new pentaquark-like state at mass 4337 MeV, and the analysis of the $B^+ \to J/\psi\phi K^+$ decays, with the observation of two new Z^+_{cs} tetraquarks with strangeness and two new X states. However, more exciting results are yet to come in the near future by analysing the current LHCb dataset or the larger one that will be available after the LHCb upgrade.

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