IL NUOVO CIMENTO **46 C** (2023) 12
DOI 10.1393/ncc/i2023-23012-3

COLLOQUIA: La Thuile 2022

Classical and exotic spectroscopy at LHCb

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received 19 September 2022

Summary. — The latest results on classical and exotic spectroscopy obtained by the LHCb Collaboration studying proton-proton collisions are presented. These include studies related to both conventional states, namely mesons and baryons, and exotic ones, notably tetra and pentaquark structures. The $\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis with Λ_c^+ polarisation measurement, the observation of new excited Ω_c^0 and Ξ_b^0 baryons, and the study of charmonium contributions in $B^+ \to J/\psi\eta K^+$ are introduced. Regarding exotic states, the study of $\chi_{c1}(3872)$ production, the T_{cc}^+ tetraquark observation and the evidence of a new pentaquark state are presented. These new results extend the striking series of hadrons discovered and analysed by the LHCb Collaboration.

1. – Introduction

The LHCb detector, mainly designed to study flavour physics in proton-proton collisions, is the only LHC experiment fully instrumented in the forward pseudorapidity region $2 < \eta < 5$, providing complementary coverage with respect to the other LHC experiments. LHCb features excellent tracking performances, momentum resolution and particle identification capabilities.

Heavy hadron spectroscopy has become one of the main subjects studied by the LHCb Collaboration. Indeed, the LHCb detector turned out to be a discovery machine for new hadrons, far beyond initial expectations. Newly discovered hadrons comprise both conventional states, namely mesons and baryons, and exotic ones, notably tetra and pentaquark structures. LHCb is giving a major contribution to the understanding of the heavy hadron "taxonomy".

The systematic study of hadron properties and production gives a wealth of information: on the quark production mechanisms, for instance how heavy quarks arise from proton-proton collisions; on the formation of the hadron bound state from free quarks and gluons, known as hadronisation process; on the hadron internal structure, namely how its components are arranged in the bound state. These measurements are important for the study of quantum chromodynamics (QCD), especially in the low-energy regime, where, due to the large value of the strong force coupling constant, perturbation theory methods can not be applied. These studies allow to discriminate among theoretical predictions obtained in different effective low energy QCD approaches.

A detailed study of hadron properties and decays is possible at LHCb. Hadrons can be characterised by measuring their masses and decay widths. From the study of hadron decay angular distributions the spin-parity assignments can be determined, as well as, for spinful states, their polarisation. In the following a selection of the more recent LHCb results on classical and exotic spectroscopy is presented.

2. – Conventional hadrons

2˙1. *$\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis & Λ_c^+ polarisation measurement.* – The full phase space amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$ decays is performed on a subset of 400'000 candidates [1], corresponding to an integrated luminosity of about 0.50 fb^{-1}. These are selected from 13 TeV pp collisions datasets recorded by the LHCb detector, considering Λ_c^+ baryons produced from beauty hadron semileptonic decays, featuring very small residual background contribution.

The amplitude model and the Λ_c^+ polarisation vector are determined simultaneously from a maximum-likelihood fit to phase space distribution, as demonstrated in [2]. The amplitude model is written in the helicity formalism with a general method to deal with the matching of final particle spin states in different decay chains [3].

The amplitude model obtained provides a complete description of the $\Lambda_c^+ \to pK^-\pi^+$ decay, allowing to characterise the multiple overlapping K^*, Λ and Δ^{++} resonant contributions. The main contributions come from $\Delta^{++}(1232)$, $K^*(892)$ and $K^*(1430)$ states, as measured from their fit fractions. A significant enhancement in the $m^2_{pK^-}$ spectrum, in a region where no clear Λ resonances have been reported in the Particle Data Group review [4], is well described by a spin $1/2^-$ state, identified as a $\Lambda(2000)$ resonance. Its mass and width parameters are determined to be $m = 1970 \pm 4 \pm 13$ MeV and $\Gamma = 148 \pm 7 \pm 18$ MeV, respectively.

This analysis provides the first Λ_c^+ polarisation measurement in semileptonic production. In general, the baryon polarisation is an important probe for the baryon spin structure and its formation process via quark hadronisation. The Λ_c^+ polarisation in semileptonic production constitutes in perspective an additional observable for possible New Physics effects in $b \to c l \nu$ processes.

The Λ_c^+ polarisation is measured in Λ_c^+ helicity systems, with the muon momentum defining the transverse components. A large Λ_c^+ polarization modulus is found, $65-70\%$ depending on the Λ_c^+ helicity system employed. The polarisation is mostly parallel to the Λ_c^+ momentum in the system defined from an approximate rest frame of the decaying beauty hadron, while it is mostly transverse in the system defined from the laboratory frame. The polarisation component normal to the Λ_c^+-muon plane, which is odd under time-reversal operation, is compatible with zero. Polarisation components are measured with uncertainties of order 0.01.

The amplitude model obtained constitutes a Λ_c^+ polarimeter, applicable to Λ_c^+ polarisation measurements in other systems, especially important for datasets with limited number of events. A large sensitivity to the polarization of the amplitude model is measured, which, considering the significant branching fraction of the $\Lambda_c^+ \to pK^-\pi^+$ decay, shows this decay is the best probe for Λ_c^+ polarization.

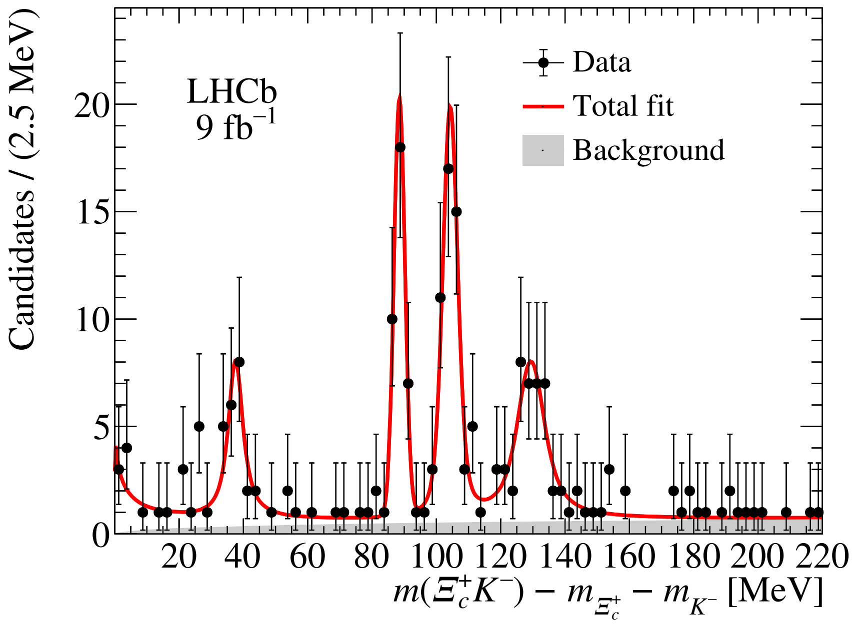

Fig. 1. – Distribution of the reconstructed mass difference between the $\Xi_c^+K^-$ invariant mass and the Ξ_c^+ and K^- masses, with the fit results overlaid.

2·2. *Observation of excited* Ω_c^0 *baryons in* $\Omega_b^- \to \Xi_c^+K^-\pi^-$ *decays*. – The first observation of the $\Omega_b^- \to \Xi_c^+K^-\pi^-$ decay has been reported by the LHCb Collaboration [5]. The full dataset of proton-proton collisions recorded by the LHCb detector has been analysed, comprising collisions at centre-of-mass energies of 7, 8 and 13 TeV for a total integrated luminosity of 9 fb^{-1}. Four excited Ω_c^0 baryons have been observed in the $\Xi_c^+K^-$ invariant mass spectrum, shown in fig. 1, with statistical significance exceeding six standard deviations for each.

They have been identified as $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$ and $\Omega_c(3090)^0$ states, which have been previously observed both in prompt proton-proton collisions by LHCb [6] and in electron-positron production by the Belle Collaboration [7]. Their masses and widths have been measured, with an upper limit set on the narrow $\Omega_c(3050)^0$ state, $\Gamma_{\Omega_c(3050)^0} < 1.6$ MeV at 95% CL.

The $\Omega_c(3120)^0$ state, observed in different production modes [6,7], has not been seen in the present analysis, which sets an upper limit for its production. An enhancement at the $m(\Xi_c^+K^-)$ threshold is seen, similar to that reported by the LHCb analysis [6], with a significance of 4.3 standard deviations. Its presence in this decay mode can not be due to partially reconstructed radiative decays, but more data are needed to understand its origin.

The spin J of the four excited Ω_c^0 baryons has been analysed via their helicity angle distributions. The $J = 1/2$ assignment is rejected for $\Omega_c(3050)^0$ and $\Omega_c(3065)^0$ states with statistical significances of 2.2 and 3.6 standard deviations, respectively. The spin assignment $\frac{1}{2}, \frac{1}{2}, \frac{3}{2}, \frac{3}{2}$ for the four states (in mass order) proposed in different works [8], is rejected with a global significance of 3.5σ. The $\frac{1}{2}, \frac{3}{2}, \frac{3}{2}, \frac{5}{2}$ assignment, which would suggest a different structure for the $\Omega_c(3120)^0$ state, is consistent with data.

2·3. *Observation of new excited Ξ_b^0 states in $\Lambda_b^0 K^- \pi^+$.* – Two narrow excited Ξ_b^0 states have been observed in the $\Lambda_b^0 K^- \pi^+$ mass spectrum by the LHCb Collaboration [9], using the full data sample of proton-proton collisions recorded by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $6\,\text{fb}^{-1}$. The masses of the two new states, $\Xi_b^0(6327)$ and $\Xi_b^0(6333)$, are measured to be

$$\begin{aligned}
m_{\Xi_b^0(6327)} &= 6327.28^{+0.23}_{-0.21}(stat) \pm 0.08(syst) \pm 0.24(m_{\Lambda_b^0})\,\text{MeV},\\
m_{\Xi_b^0(6333)} &= 6332.69^{+0.17}_{-0.18}(stat) \pm 0.03(syst) \pm 0.22(m_{\Lambda_b^0})\,\text{MeV},\\
\Delta m &= 5.41^{+0.26}_{-0.27}(stat) \pm 0.06(syst)\,\text{MeV}.
\end{aligned}$$

Natural widths are consistent with zero, with upper limits set to

$$\begin{aligned}
\Gamma_{\Xi_b^0(6327)} &< 2.20(2.56)\,\text{MeV at } 90(95)\%\ \text{CL},\\
\Gamma_{\Xi_b^0(6333)} &< 1.55(1.85)\,\text{MeV at } 90(95)\%\ \text{CL}.
\end{aligned}$$

These states are not seen in the $m(\Lambda_b^0 K^+ \pi^-)$ invariant mass spectrum, with opposite charges for kaon and pion tracks.

The statistical significance of the double state hypothesis with respect the background-only one is larger than nine standard deviations. The significance computed with respect to the single state hypothesis is larger than five standard deviations. The observed states are consistent with a doublet of 1D Ξ_b^0 resonances with spin-parity $J^P = 3/2^+$ and $5/2^+$.

2·4. *Study of charmonium contributions in $B^+ \to J/\psi \eta K^+$.* – A study of $B^+ \to J/\psi \eta K^+$ decays, with subsequent $J/\psi \to \mu^+\mu^-$ and $\eta \to \gamma\gamma$ transitions has been performed by the LHCb Collaboration [10], on the full LHCb dataset corresponding to an integrated luminosity of $9\,\text{fb}^{-1}$. The presence of charmonia, charmonium-like and possible exotic states is investigated studying the $J/\psi \eta$ mass spectrum. Evidence for $\psi_2(3823)$ and $\psi(4040)$ state contributions is found, with statistical significance of 3.4 and 4.7 standard deviations, respectively. In particular, the evidence for the $\psi_2(3823) \to J/\psi \eta$ decay is obtained for the first time. The production rate associated to these states is measured by the branching fraction ratio with respect to the $B^+ \to \psi(2S)(\to J/\psi \eta)K^+$ decay,

$$\begin{aligned}
F_{\psi_2(3823)} &= (5.95^{+3.38}_{-2.55}),\\
F_{\psi(4040)} &= (40.6 \pm 11.2).
\end{aligned}$$

Other charmonium, charmonium-like and possible hypothetical states have not been seen. Upper limits for several states have been computed. As an example, the upper limit for the C-odd partner of the $\chi_{c1}(3872)$, named X'_C, is set to $F_{X'_C} < 1.9\%$ at 90% confidence level.

3. – Exotic hadrons

3·1. *$\chi_{c1}(3872)$ production in pp collisions at $\sqrt{s} = 8, 13\,\text{TeV}$.* – The production cross-section of the $\chi_{c1}(3872)$ state in proton-proton collisions has been measured by LHCb [11], relative to that of the $\psi(2S)$ meson. It has been measured at 8 and 13 TeV centre-of-mass collision energies, using datasamples corresponding to integrated luminosities of 2 and 5.4 fb^{-1}, respectively. This measurement complements the multiplicity-dependent production studied by the LHCb Collaboration [12] and should help clarifying the structure of the exotic $\chi_{c1}(3872)$ state.

The $\chi_{c1}(3872)$ production is measured for both states directly produced in proton-proton collisions (prompt) and those produced from beauty hadron decays (nonprompt). Both $\chi_{c1}(3872)$ and $\psi(2S)$ resonances are reconstructed in the $J/\psi\,\pi^+\pi^-$ final state. The double differential cross-section is measured as a function of $\chi_{c1}(3872)$ transverse momentum p_{T} and rapidity y, in the kinematic range $4 < p_{\mathrm{T}} < 20\,\text{GeV}/c$ and $2.0 < y < 4.5$.

The prompt ratio increases with p_{T}, showing the $\chi_{c1}(3872)$ production is enhanced with respect to the $\psi(2S)$ one at high p_{T}. For nonprompt production no dependence on p_{T} is seen. The production ratio is compared between different centre-of-mass production energies, showing no significant difference. The absolute production cross section is also determined at 13 TeV centre-of-mass energy, found to agree in the $p_{\mathrm{T}} > 10\,\text{GeV}/c$ region with NLO NRQCD predictions [13], which model the $\chi_{c1}(3872)$ as a mixture of molecular states.

3˙2. *Observation of the exotic tetraquark T_{cc}^+ in $D^0D^0\pi^+$*. – The LHCb Collaboration has studied the $D^0D^0\pi^+$ mass spectrum using the full LHCb dataset of proton-proton collisions, corresponding to an integrated luminosity of 9 fb^{-1}.

A very narrow state has been observed [14], at a mass of $\approx$ 3875 MeV/c^2, with a statistical significance of 21.7 standard deviations. The state parameters have been determined fitting the mass spectrum using a 2-body relativistic Breit-Wigner function for the observed peak. The mass of the state has been measured relatively to the $D^{*+}D^0$ mass threshold,

$$m_{T_{cc}^+} - m_{D^{*+}} - m_{D^0} = -273 \pm 61 \pm 5^{+11}_{-14}\,\text{keV},$$

with a statistical significance for the hypothesis of a mass below threshold of 4.3σ. The measured width is

$$\Gamma_{T_{cc}^+} = 410 \pm 65 \pm 43^{+18}_{-38}\,\text{keV}.$$

The $D^0D^0\pi^+$ mass spectrum with fit results overlaid is shown in fig. 2.

This state can be interpreted as the first double charm tetraquark observed to date, named T_{cc}^+, featuring a minimal quark content $cc\bar{u}\bar{d}$. The measured mass and width are consistent with the expected values for a T_{cc}^+ isoscalar tetraquark ground state with quantum numbers $J^P = 1^+$.

A further study of the properties of the T_{cc}^+ resonance state has been performed [15]. A different function has been employed to model the resonance peak in the $D^0D^0\pi^+$ mass spectrum, a unitarized 3-body Breit-Wigner. This model features an enhanced tail above $D^{*+}D^0$ threshold with respect the 2-body function, and an increased statistical significance for a peak under threshold, of 9σ. The resonance pole mass difference with respect to the $D^{*+}D^0$ threshold δm_{pole}, the pole width Γ_{pole}, the scattering length a and

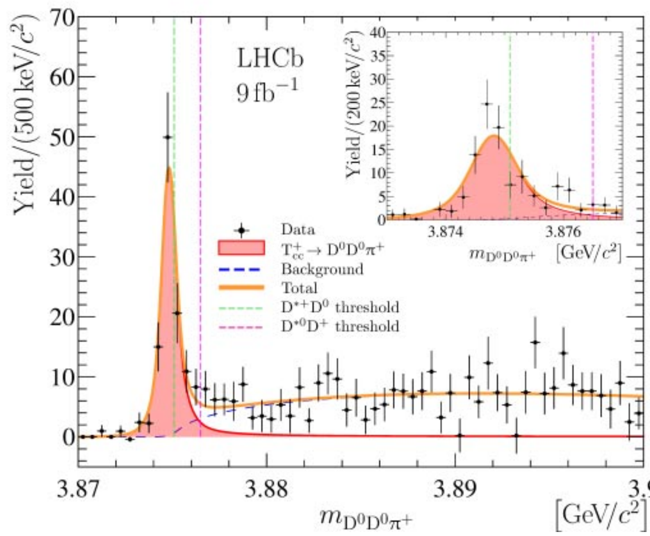

Fig. 2. – The $D^0D^0\pi^+$ invariant mass distribution where the contribution of the non-D^0 background has been subtracted, with the fit results overlaid.

the coupling constant of the T_{cc}^+ state to the D^*D system $|g|$ have been measured,

$$\begin{aligned}\delta m_{pole} &= -360 \pm 40^{+4}_{-0}\,\text{keV},\\ \Gamma_{pole} &= 48 \pm 2^{+0}_{-14}\,\text{keV},\\ a &= [(-7.16 \pm 0.51) + i(1.85 \pm 0.28)]\ \text{fm}\\ |g| &> 5.1(4.3)\,\text{GeV}\text{at } 90(95)\%\ \text{CL}.\end{aligned}$$

Possible isospin partners of the T_{cc}^+ resonance, T_{cc}^0, T_{cc}^{++}, have been searched for in different DD invariant mass spectra, but no hint of their presence has been observed. The observed T_{cc}^+ is therefore consistent with the hypothesis of a singlet state. Moreover, a strong and unexpected dependence of the T_{cc}^+ production with the underlying proton-proton event multiplicity has been observed, resembling the pattern observed for the $\chi_{c1}(3872)$ state [12].

3˙3. *Evidence of a new pentaquark structure in $B_s^0 \to p\bar{p}J/\psi$ decays.* – The amplitude analysis of flavour-untagged $B_s^0 \to p\bar{p}J/\psi$ decays has been performed by the LHCb Collaboration [16], exploiting the full dataset of proton-proton collisions recorded by the LHCb experiment, corresponding to an integrated luminosity of 9 fb^{-1}. Evidence for a new structure in $J/\psi\, p$ and $J/\psi\,\bar{p}$ mass spectra has been obtained, with mass and width measured to be

$$\begin{aligned}m &= 4337^{+7}_{-4} \pm 2\,\text{MeV},\\ \Gamma &= 29^{+26}_{-12} \pm 14\,\text{MeV}.\end{aligned}$$

This structure can be interpreted as new pentaquark candidate $P_c^+(4337)$ with minimal quark content $c\bar{c}uud$, decaying to $P_c^+ \to J/\psi\, p$ or $P_c^- \to J/\psi\,\bar{p}$ according to its charge.

Its statistical significance is between 3.1 and 3.7 standard deviations, depending on the spin-parity assigned to the state, which is not distinguishable with the available data. This state is different from the pentaquark states observed by the LHCb Collaboration in $\Lambda_b^0 \to J/\psi\, pK^-$ decays [17].

4. – Conclusions

A selection of the latest results of the LHCb Collaboration on classical and exotic spectroscopy have been presented. These include studies related to both conventional and exotic states, with new resonances observed as well as advanced studies of already known contributions. The latest findings extend the striking series of hadrons discovered by the LHCb Collaboration, which constitute a wealth of information available for theoretical studies. Interestingly the trend of newly discovered states is still increasing, suggesting possible surprises just round the corner.

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