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Spectroscopy and hadronic structure measurements

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The study of properties of conventional and exotic states is crucial for investigating the internal structure of hadrons. Recent results on conventional and exotic spectroscopy obtained from the LHC experiments will be presented in this work. As for the conventional spectroscopy, it concerns the observation of excited Ξ_b states and the search for baryons in the bc sector. Regarding exotic states, several analyses of the exotic state, $X(3872)$, will be discussed, combining the results of the LHCb, ATLAS and CMS collaborations. Finally, recent results on tetraquarks and pentaquarks obtained by the LHCb collaboration will be presented, with a focus on the doubly charm tetraquark, T_{cc}^{+}, and the pentaquark $P_{\psi}^{N}(4337)$.

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1. Introduction

Over the past ten years, more than 60 new hadrons have been discovered at the LHC. These observations are challenging our current understanding of Quantum Chromodynamics (QCD) and the validity of the Heavy Quark Effective Theory (HQEF) [1]. Since QCD does not operate in the perturbative regime at the distance scales characteristic of observable hadrons, several non-perturbative models have been proposed to describe the properties of heavy hadrons and exotic states. On one hand, HQEF predicts the masses of heavy hadrons containing charm and beauty quarks by performing an expansion in terms of Λ_{QCD}/m_Q, where Λ_{QCD} is the QCD mass scale of the order of 200 MeV and m_Q is the mass of the heavy quark, i.e. the c or b quark. To validate this approximation, precise measurements of the excited hadronic properties are required. On the other hand, many phenomenological models inspired by QCD have been developed to describe the properties of exotic states, which are states with a minimal quark content other than $q\bar{q}$ and qqq, like tetraquarks and pentaquarks. Depending on the model, multi-quark states can be color bound states or molecules made up of hadrons. Therefore, it is crucial to study these states in both production and decay to help discriminate between different theoretical models [2]. In this work, a review of recent results of conventional and exotic spectroscopy from the LHC experiments will be presented.

2. Conventional spectroscopy

In recent years new observations of excited charged and neutral Ξ_b states have been made by CMS [3] and LHCb [4]. In 2021, CMS observed a narrow resonance $\Xi_b(6100)^-$ decaying to $\Xi_b{}^-\pi^+\pi^-$, consistent with the orbitally excited 1D state. Due to its narrow width, an upper limit on its width is set to 1.9 MeV at 95% of confidence level (CL). Afterwards, LHCb observed two new neutral states, the $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$, in the $\Lambda_b^0K^-\pi^+$ final state, as shown in Fig. 1, with widths consistent with mass resolution, and belonging to the 1D doublet of $J^P = 3/2^+$ and $5/2^+$.

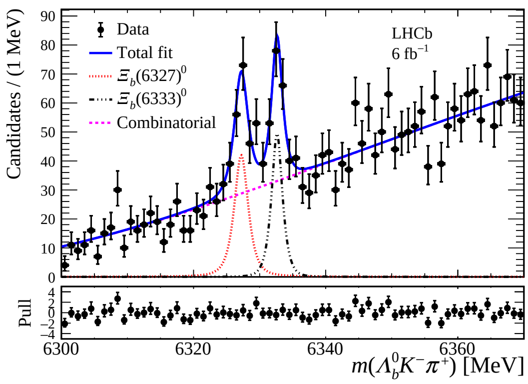

Figure 1: Invariant mass distributions of $\Lambda_b^0K^-\pi^+$ candidates, Ref. [4].

Searches in the bc sector have already started but no observation has been made so far. In particular, LHCb searched for neutral candidates in the $\Lambda_c^+\pi^-$ and $\Xi_c{}^+\pi^-$ final states [5] and for charged candidates in the $J/\psi\,\Xi_c{}^+$ final state [6]. Upper limits are set at 95% CL on R, which is

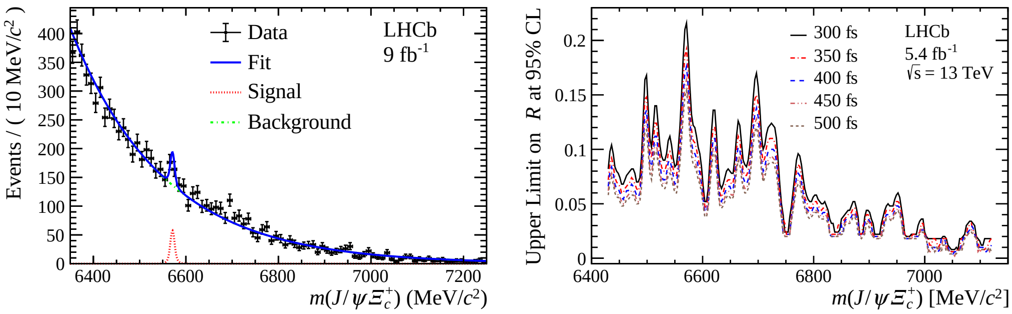

Figure 2: $m(J/\psi \Xi_c{}^+)$ invariant mass distribution of selected Ξ_{bc}^+ candidates for the full data set (left) and upper limit on the production ratio R at 95% of CL (right), Ref. [6].

defined as the production cross-section multiplied by the branching ratio of the mode of interest and normalised to the $\Lambda_b^0(\Xi_b) \to \Lambda_c^+(\Xi_c)\pi^-$ and $B_c^+ \to J/\psi D_s^+$ for the charged and neutral Ξ_{bc} candidates, respectively. As an example, Fig. 2 shows the fit to the $J/\psi \Xi_c{}^+$ invariant mass for the Ξ_{bc}^+ candidates and the upper limits on R as a function of the invariant mass.

3. Exotic spectroscopy

3.1 Nature of the $X(3872)$ state, also known as $\chi_{c1}(3872)$

The first exotic state in the charmonium sector ever discovered was the neutral $X(3872)$, also known as $\chi_{c1}(3872)$, from the Belle experiment in 2003 [7], decaying to $J/\psi\rho^0$ and $J/\psi\omega$. Its exotic nature is still under debate. Its mass, around 3872 MeV$/c^2$, cannot be associated with any expected $c\overline{c}$ levels and is close to the $m(D^0 + \overline{D}^{*0})$ mass threshold. Its quantum numbers, $J^{PC} = 1^{++}$ [8], are not compatible with the ones of charmonium states close to its mass. Its width is extremely narrow, as measured by LHCb [9] and does not match predictions for conventional charmonia. After twenty years from its discovery, many studies of $X(3872)$ production and decay mechanisms are still ongoing, in order to establish the nature of this state. In this section, an overview of the most important results will be reported, starting from decay processes of the $X(3872)$ state and, then, moving to production mechanisms.

Studying the ρ and ω contamination in the $\chi_{c1} \to \pi^+\pi^- J/\psi$ decays can give an hint on the theoretical interpretation of this state. Indeed, since the $\chi_{c1}(3872)$ particle is an isosinglet state, the $\chi_{c1} \to \rho^0 J/\psi$ decay is isospin violating, while $\chi_{c1} \to \omega J/\psi$ is isospin conserving. Since isospin violating decays of charmonium states are highly suppressed, quantifying the isospin violation in $\chi_{c1} \to \rho^0 J/\psi$ decays is important to understand the nature of the $\chi_{c1}(3872)$ state. The presence of the $\rho(770)$ contamination in the $\chi_{c1} \to \pi^+\pi^- J/\psi$ decays was found to explain the $m(\pi^+\pi^-)$ distribution peaking near the upper kinematic limit, close to the ρ^0, by CMS [10] and ATLAS experiments [11]. Fig. 3 (left) shows the normalised differential $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$ decay width in bins of $m(\pi^+\pi^-)$, with the data analysed by ATLAS, compared to the MC predictions. Recently, LHCb has analysed the $B^+ \to K^+\chi_{c1}(3872)(\to \pi^+\pi^- J/\psi)$ decays, with an integrated luminosity of 9 fb^{-1} [12]. In contrast to older results, they found a large disagreement between the $m(\pi^+\pi^- J/\psi)$ at high dipion masses and the $\chi_{c1} \to \rho^0 J/\psi$ simulations. This effect is related to the previous EvtGen [13] simulations which do not correctly take into account the impact of

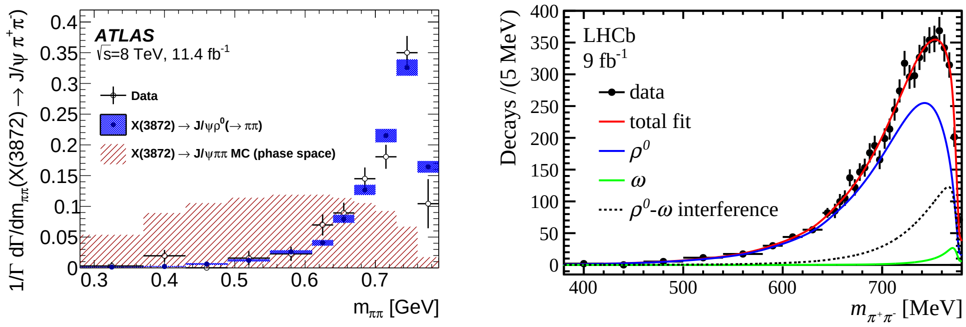

Figure 3: Di-pion invariant mass spectrum from ATLAS [11] (left) and LHCb [12] (right).

the phase-space factors (proportional to $p_{J/\psi}p_{\pi}$) on resonance masses in a decay sequence. Once this correction is implemented, the results show the presence of a sizeable $\rho^0 - \omega$ interference, which was previously considered as part of the ρ^0 contribution, as can be seen in Fig. 3 (right). Although the ω contribution remains small on its own ($\sim 2\%$), it is enhanced by the interference with the ρ, increasing it to 19%. The ratio of isospin violating and isospin conserving couplings, $g_{\chi_{c1}\to\rho_0 J/\psi}/g_{\chi_{c1}\to\omega J/\psi}$, is then measured to be 0.29 ± 0.04, which is much larger than expected for a charmonium state ($g_{\psi(2S)\to\pi^0 J/\psi}/g_{\psi(2S)\to\eta J/\psi} = 0.045 \pm 0.001$).

Similar conclusions have been obtained studying other decay processes of the χ_{c1} state, such as the $B^0_s \to \chi_{c1}(3872)(\to \pi^+\pi^- J/\psi)\Phi(\to K^+K^-)$ decays, observed by CMS in 2020 [14]. In this analysis, the signal yield is extracted from a simultaneous 2D fit of the $m(\pi\pi J/\psi)$ and $m(K^+K^-)$ invariant mass distributions. The branching ratio (BR) is measured to be of the order of 4×10^{-6}. Comparisons of BRs of different B meson decays show that the measured value for B^0_s is compatible with the one for B^0 but about two times smaller than the one for B^+, on the contrary to what happens to the decays through the $\psi(2S)$ state, which give compatible BRs for all B meson decays. This indicates that the $X(3872)$ formation in B meson decays is different from the one of the conventional $\psi(2S)$ charmonium state. Therefore, both results support the exotic interpretation for this state.

The production mechanism of the $\chi_{c1}(3872)$ may provide evidence for the nature of this exotic state. Indeed, it is expected that collisions with comoving particles can occur and break the $\chi_{c1}(3872)$ up into its constituents depending on the spatial configuration of the state and the binding energy. Therefore, high multiplicity collisions can be exploited to separate a large-sized molecular state ($\sim$ 10 fm) from a compact tetraquark ($\lesssim$ 1 fm). First of all, CMS [10] and ATLAS [11] measured the prompt $X(3872)$ production cross-section multiplied by the BR of $X(3872) \to J/\psi\pi^+\pi^-$, as a function of p_T and at central rapidity in pp collisions. The CMS collaboration found that the prediction for the cross-section based on a $D^0\overline{D}^{*0}$ molecular model [15] underestimated the measured cross-section by over 3σ. While the ATLAS collaboration obtained that the cross-section can be described by a model composed of a mixture of the $\chi_{c1}(2P)$ charmonium state and a $D^0\overline{D}^{*0}$ molecule [16], where the $\chi_{c1}(3872)$ is produced predominantly through its $\chi_{c1}(2P)$ component. LHCb has also contributed to the X production in pp collisions [17], releasing a measurement of the differential prompt production of the ratio of $\chi_{c1}(3872)$ and $\psi(2S)$ in the $\pi^+\pi^- J/\psi$ decay channel as a function of the number of tracks (N_{tracks}) in the vertex detector. As shown in Fig. 4, the prompt production is suppressed as multiplicity increases. This result is compatible with predictions based

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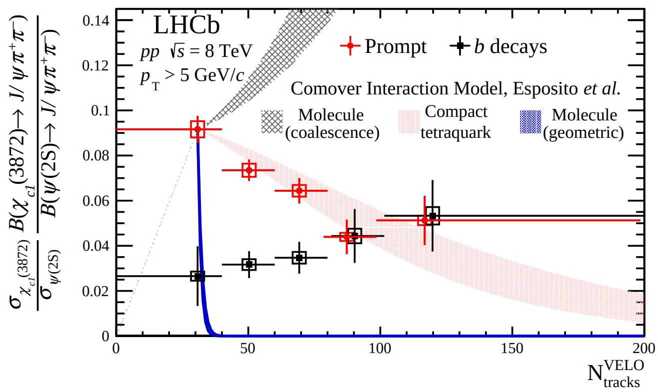

Figure 4: The ratio of the $\chi_{c1}(3872)$ and $\psi(2S)$ cross sections measured in the $J/\psi\pi^+\pi^-$ channel as a function of the track multiplicity [17].

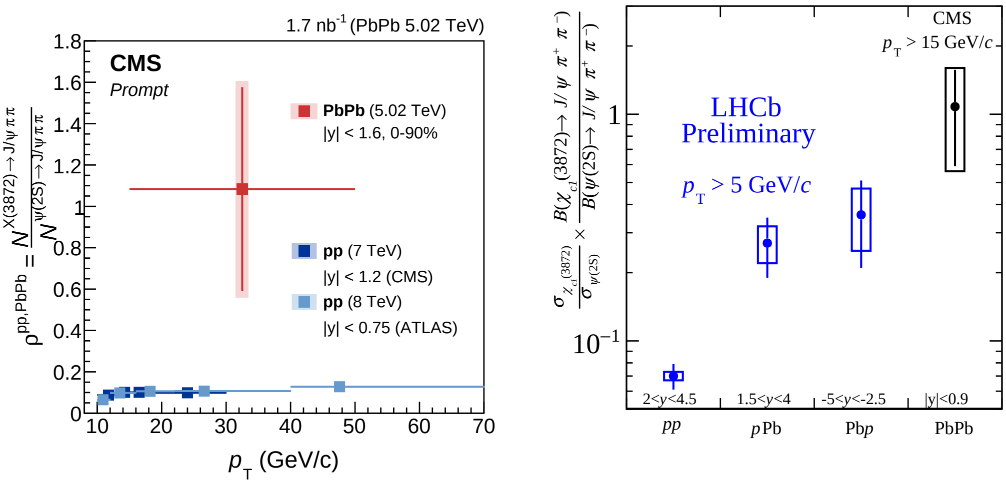

Figure 5: Production cross-section ratios of χ_{c1} over $\psi(2S)$ measured by CMS as a function of p_T [20] (left) and as a function of multiplicity, summarised by LHCb [21] (right).

on the comover interaction model [18, 19], which supports it being a compact tetraquark. Indeed, a compact tetraquark has a slightly larger radius and breakup cross-section than the charmonium $\psi(2S)$ state, and, therefore, the ratio $\sigma_{\chi_{c1}}/\sigma_{\psi(2S)}$ decreases with multiplicity, as observed in data.

Heavy-ion collisions can give additional information on the production of the χ_{c1} state. It is expected that in relativistic heavy ion (HI) collisions, the formation of the quark gluon plasma (QGP) could enhance or suppress the production of the $X(3872)$ particle through the quark coalescence mechanism. For this model, molecules are easier to be produced and destroyed than tetraquark, and, therefore, an enhancement of the $\chi_{c1}(3872)$ production yield is expected in the case of a molecular state. CMS [20] and LHCb [21] have studied χ_{c1} production in PbPb and pPb collisions, respectively. The CMS collaboration achieved the first evidence of the χ_{c1} state at 4.2σ in HI collision, by studying inclusive $J/\psi\pi^+\pi^-$ decays [20]. They also performed a measurement of the ratio of prompt χ_{c1} and $\psi(2S)$ production cross-sections as a function of p_T, as reported in Fig. 5 (left). The results indicate that the prompt X-to-$\psi(2S)$ ratio may be much larger in PbPb collisions

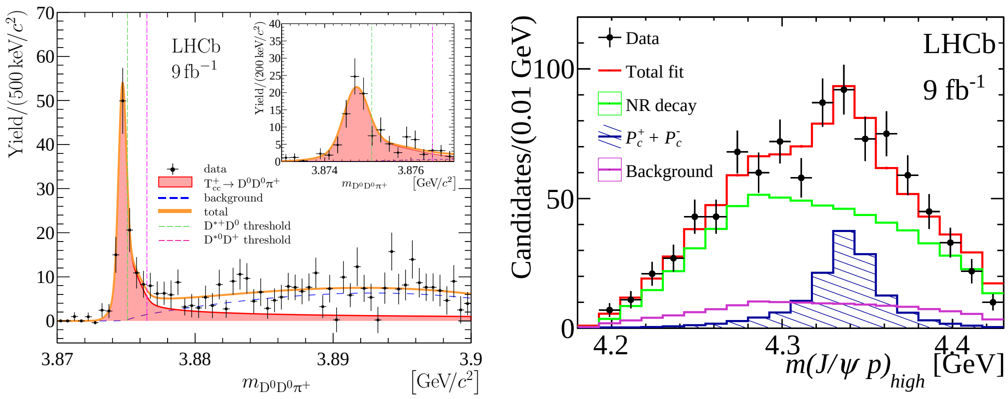

Figure 6: Invariant mass distribution of $D^0D^0\pi^+$ (left) [23] and of the maximum of $m(J/\psi p)$ and $m(J/\psi\overline{p})$ (right) [25].

than in pp collisions. However, the large uncertainties preclude from drawing conclusions. In order to understand the behaviour at the interplay between low (pp) and high (PbPb) multiplicity, LHCb studied the production cross-sections using pPb collisions [21]. Results for the ratio of prompt χ_{c1}-to-$\psi(2S)$ production are summarised in Fig. 5 (right). An increasing trend is observed going from pp to PbPb collisions, confirming the enhancement of the χ_{c1} production observed by CMS in PbPb collisions. Therefore, at high density quark coalescence can become the dominant mechanism affecting the χ_{c1} production and this seems to favour the molecular hypothesis for this state. In conclusion, the results of the χ_{c1} production are controversial, in pp collisions a decreasing trend favours the tetraquark hypothesis, while at higher multiplicity an inversion of the behaviour is observed, which seems to favour the molecular interpretation. These results indicate that more studies need to be carried out to better understand the production dynamics at high collision rate. Finally, no conclusion can be drawn at the moment on the theoretical interpretation for the χ_{c1} exotic state. It could be either a molecule or a tight tetraquark or even a mixture of the two.

3.2 Other results of tetra- and pentaquark states

In recent years, around 15 new hadrons with exotic properties have been observed by LHCb. In this summary, we report the observation of the T_{cc}^{+} doubly charm tetraquark and the evidence for the $P_{\psi}^{N}(4337)$ pentaquark state in B_s^0 meson decays. The new naming scheme for exotic hadrons is used in these proceedings [22].

The tetraquark, $T_{cc}^{+}(3875)$, is observed in prompt hadro-production, decaying to $D^0D^0\pi^+$ final state [23, 24], by analysing the data collected by LHCb and corresponding to 9 fb^{-1} of luminosity. It is the first exotic candidate with the same sign doubly charm and it has purely exotic quark content, being made up by $cc\overline{u}\overline{d}$ quarks. Its mass, ~ 3875 MeV, is close to the $D^*(2010)^+D^0$ threshold and it has a very narrow width of ~ 410 keV. Fit results are shown in Fig. 6 (left). The measured mass and width are consistent with the expected values for a T_{cc}^{+} isoscalar tetraquark ground state with quantum numbers $J^P = 1^+$.

The $P_{\psi}^{N}(4337)$ pentaquark candidate is seen in the analysis of $B_s^0 \to J/\psi p\overline{p}$ decays made by LHCb with the full dataset [25]. This result is the first evidence of a pentaquark candidate in B meson decays. It is seen decaying to $J/\psi p$ and $J/\psi\overline{p}$ with a statistical significance of 3.1-3.7σ

depending on the J^P hypothesis. In Fig. 6 (right), the maximum of $J/\psi p$ and $J/\psi\overline{p}$ distribution is shown, where the sum of the P_ψ^{N+} and P_ψ^{N-} is highlighted in blue. Neither the previous pentaquark states observed in the Λ_b decays [26, 27] are present in the $B_s^0 \to J/\psi p\overline{p}$ decays, nor the $P_\psi^N(4337)$ state is observed in Λ_b decays. Different theoretical interpretations have been put forward to explain this feature. The state could be either a compact pentaquark [28] due to the different internal spin structure of the di-quark pair or a triangle cusp [29] due to different interference patterns between the $\Lambda_c^+ D^*$ and $\Sigma_c\overline{D}$ threshold cusps. A measurement of the quantum numbers of this state would help distinguish among these interpretations.

4. Conclusions

An overview of many promising results of conventional and exotic spectroscopy have been presented in these proceedings on behalf of the LHC experiments. On one hand, precise measurements of excited hadron spectroscopy have been carried out. The b-hadron spectrum is populated with new excited Ξ_b states, the $\Xi_b(6100)^-$, the $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$, and searches in the bc sector have already been started. Although no observations are possible in the bc sector, UL on possible Ξ_{bc} states open a new sector of investigation. On the other hand, the exotic spectroscopy field is attracting a lot of interest. The first exotic state, the $\chi_{c1}(3872)$, is the most studied exotic ever. An overview of recent results of decay processes and production mechanisms of the $\chi_{c1}(3872)$ state has been presented. Results of ρ and ω contamination in the $\chi_{c1} \to \pi^+\pi^- J/\psi$ decays and comparisons of branching ratio of B meson decays support the exotic interpretation for this state. Studies of χ_{c1} production mechanisms in pp and heavy ion collisions have made a lot of progress recently, with new excited results released by the CMS and LHCb experiments. However, the results are still controversial in the low and high multiplicity regime and no conclusion on the theoretical interpretations can be drawn at the moment. Finally, new exotic states observed by LHCb in the last year have been presented, focusing on the observation of the doubly charm tetraquark T_{cc}^+ and the evidence for the $P_\psi^N(4337)$ pentaquark candidate.

Many exciting results are yet to come in the near future thanks to the data that will be collected during Run 3. Explorations in the doubly charm and in the bc sectors will be carried out and will enrich the spectra of conventional hadrons. Access to the bc sector will also be possible for tetra- and pentaquark states, as well as searches for exotics states containing $b\bar{b}$ pairs. Thanks to higher statistics, we would be able to confirm the already observed states and measure their quantum numbers, as well as to find new exotic partners that will possibly fit into flavour multiplets, in order to help discriminate among theoretical models. Although LHCb, CMS and ATLAS experiments have mostly contributed to the spectroscopy so far, ALICE has extended its physics program to cover this area starting from Run 5, in particular with the proposal of studying the $\chi_{c1}(3872)$ production down to low p_T and the T_{cc} structure [30].

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