Heavy quarkonia and multiquarks at B-factories

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This review will cover the most recent results from the B factories in the field of heavy quarkonia and multiquark systems. At Belle-II, the first data taking period beyond the $\Upsilon(4S)$ peak energy has been been devoted to the study of the region around $\sqrt{s} = 10.75$ GeV, where enhanced transition rates to lower bottomonia suggested the existance of a new exotic bound state. In turn, LHCb keeps discovering new tetraquarks and pentaquarks at steady pace. Most of them are composed by at least one $c\bar{c}$ pair, but recently also systems with two $c\bar{c}$ pairs and tetraquarks with open double charm have been found.

1 Introduction

The discovery of the J/ψ, in November 1974, followed by the one of the Υ states, only three years later, have played a key role in the affirmation of the Quark Model, which describes all the known particles subject to strong interactions. According to the naïve Quark Model, all hadrons can be described as bound states of three quarks (baryons), or a quark and an antiquark (mesons). Such model does not exclude the possibilty to add more $q\bar{q}$ pairs to the known baryons to describe their properties, e.g. the sea of light quarks in the nucleons. Nevertheless, essentially all known hadrons discovered until the new millenium could be accomodated within spectra using this basic model.

Between 2001 and 2003, the discovery of the X(3872) and Y(4260) particles at the B-factories opened new perspectives giving access to new landscapes in the field of hadron spectroscopy [1,2]. The idea of a $qq\bar{q}\bar{q}$ bound state, which had already been introduced to settle open issues in the scalar meson sector, found a fertile field of application to describe the plethora of observations which in a few years overloaded the charmonium spectra. Strictly speaking, the compact tetraquark model base ansatz is that a new spectroscopy arises from binding together diquark-antiquark pairs. In contrast, another class of models arises from the observation that most of the newly observed resonances were found in the proximity of known thresholds, an empirical evidence which allowed to build an effective field theory which describes the newly discovered states as hadronic molecules made of mesons, exactly as the nuclei are described as bound states of nucleons.

It must be said that more than twenty years have passed, but many of the questions on the nature of multiquark states are still unanswered, and in this paper I will use the term tetraquark for all new mesons without referring to a specific model. This review will be addressing only the most recent progress in this fertile sector of basic science, from two of the most productive facilities which yielded results in the recent years: the experiments LHCB at CERN and Belle-II (and its predecessor Belle) at KEK.

1.1 The Experiments Belle-II at KEK, and LHCB at CERN

The Belle-II detector is a nearly 4π magnetic spectrometer operating at the superKEKB e^+e^- asymmetric collider at center-of-mass energies in the proximity of the $\Upsilon(4S)$ resonance peak ($\sqrt{s}$=10.58 GeV). The apparatus is an upgrade of the Belle detector, which has been operated until 2010 at the KEKB collider. Belle-II subdetectors have been designed to withstand an increase of instantaneous luminosity by more than one order of magnitude. Belle-II started taking data in 2019 and has integrated 429 fb^{-1}, mostly on the peak of $\Upsilon(4S)$. Nevertheless, the results which will be discussed in this paper are from 3.5, 1.6, 9.8, 4.7 fb^{-1} of data taken at center-of-mass energies of 10.653, 10.701, 10.745 and 10.805 GeV respectively.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2< \eta <5$, operating at CERN LHC proton-proton collider. Most of the analyses discussed in this review use an integrated luminosity of 1.15, 2.08 and 6 fb^{-1} collected between 2011 and 2018 at center-of-mass energies of 7, 8, 13 TeV respectively.

2 The legacy of B factories

One of the most successful decisions taken by the Belle Collaboration was to devote a steadily increasing fraction of luminosity on the $\Upsilon(5S)$ peak. Originally meant to provide record samples of B_s mesons, it turned out to be a very prolific source of transitions to narrow bottomonia, which led to the discovery of three missing $b\bar{b}$ states, i.e. $h_b(1P), h_b(2P), \eta_b(2S)$, and the surprising observation of the $Z_b(10610)$ and $Z_b(10650)$ states, the first and so far only charged bottomonium-like states. Belle integrated 121 fb^{-1} of data at $\sqrt{s} = 10.86 GeV$, and additional data were taken scanning the region between 10.65 and 11.1 GeV with 22 points, integrating about 1 fb^{-1} of data on each point. The main result of the analysis of the scan data was the observation of a new bump in the $e^+e^- \to \Upsilon(1,2,3S)\pi^+\pi^-$ cross section around 10.75 GeV, in an energy region where the B inclusive production has a local minimum, and the closest vector $b\bar{b}$ candidate, $\Upsilon(3^3D_1)$ pole, lies 50 to 100 MeV below. Similarly, the Y(4260) was discovered by Babar in a region of minimal D meson yield, which resulted to be very prolific for studies on charmonium-like states, as confirmed by Belle, and fully exploited by the BES-III experiment at Beijing. The data taken at BES-III allowed to resolve details which could not be done by the B-factories, which coarsely scanned the 4 GeV region with the technique of radiative return. The Y(4260) vector resonance, which is now understood as the superposition of the narrow $\psi(4220)$ and the broad $\psi(4320)$, can suggest that a similar level of complexity may be found in the proximity of the structure found at 10.75 GeV, which in the rest of the paper will be referred to as the $\Upsilon(10750)$.

3 Belle-II scan at 10.75 GeV

The first searches for signals at 10.75 GeV were inspired by three decay modes of the $\psi(4220)$: the hadronic decays to $J/\psi\pi^+\pi^-$ and to $\omega\chi_c$, and the radiative decay to X(3872).

The reaction $e^+e^- \to \Upsilon(1S)\omega\gamma$ is quite promising because it can yield result on two of the above mentioned decay modes: the $\omega\chi_b$ transition and the search for the bottomonium analogue of X(3872), which is expected to decay to $\Upsilon\omega$. Expectations were soon satisfied: Belle-II has observed a strong signal $\omega\chi_b$, at 10.75 GeV, even 50% larger than the $\Upsilon(2S)\pi^+\pi^-$ transition which led to its discovery.

The Born cross section measured at Belle-II and the one measured at Belle on the Υ(5S) peak are shown in Fig.1 and can be used to extract the coupling of the new bound state to the e^+e- and $\omega\chi_{bJ}$ channels, in the two cases of constructive (Solution I) or destructive (Solution II) interference with the continuum. Instead of a decay mode of $\Upsilon(5S)$, the $\omega\chi_b$(1P) events at 10.86 GeV can be considered a tail of the resonance at 10.75 GeV.

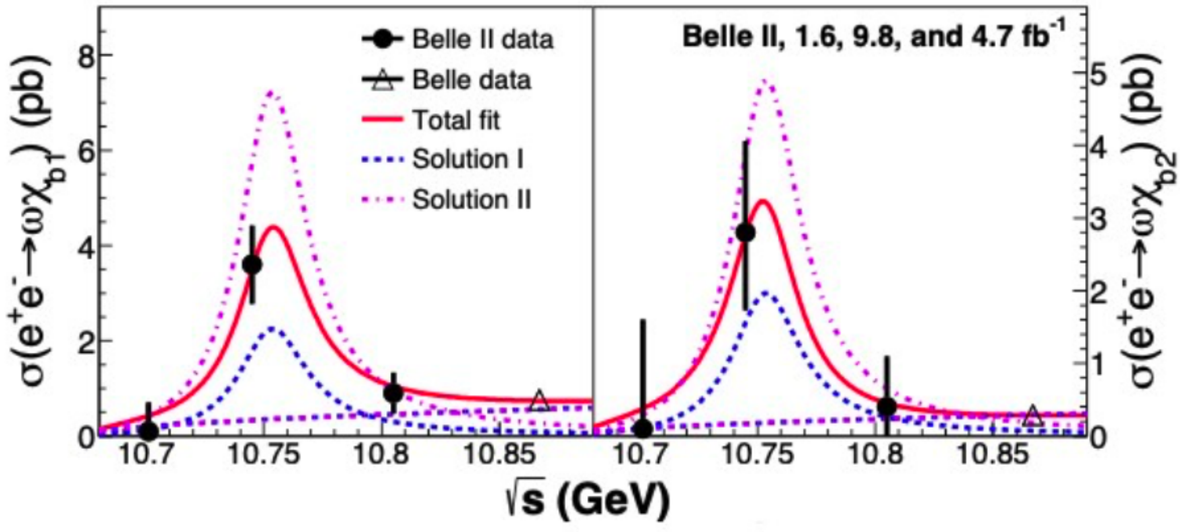

Figure 1 – Born Cross section of $e^+e^- \to \omega\chi_b(1P)$, in Belle (triangle) and in Belle-II (circles). Solution I(II) refers to constructive (destructive) interference with the continuum.

Table 1: Results for Γ_{ee} B($\Upsilon(10750) \to \omega\chi_{bJ}$).

	Solution I	Solution II
Γ_{ee} B($\Upsilon(10750) \to \omega\chi_{b1}$)	$0.63 \pm 0.39 \pm 0.20$	$2.01 \pm 0.38 \pm 0.76$
Γ_{ee} B($\Upsilon(10750) \to \omega\chi_{b2}$)	$0.53 \pm 0.46 \pm 0.15$	$1.32 \pm 0.44 \pm 0.55$

In contrast, the search for the X_b in the $\omega\chi_{bJ}$ channel did not yield any observable signal in the energy region between 10.45 and 10.65 GeV/c^2.

Besides a new measurement of the $\Upsilon(1,2,3S)\pi^+\pi^-$ branching ratios, more studies are under way using the Belle-II scan data to investigate the nature of the $\Upsilon(10750)$, searching for other decay channels such as $\omega\eta_b$, ηh$_b$(1P), h$_b$(1,2P)$\pi^+\pi^-$.

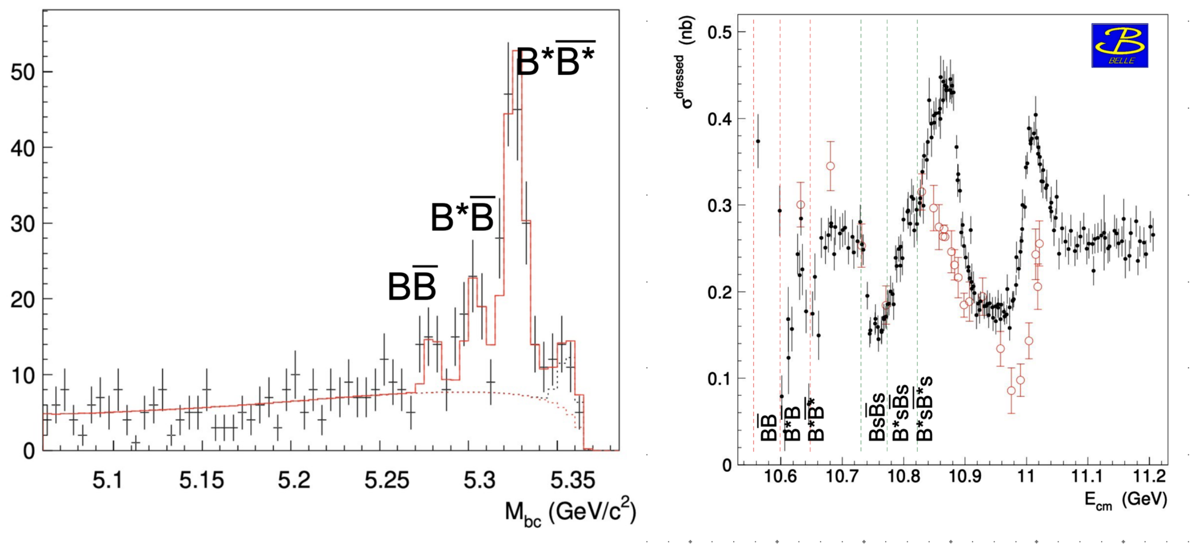

Figure 2 – Left: M$_{bc}$ distribution in one of the scan points, showing the peaks corresponding to the three exclusive processes. Right: the sum of exclusive $B\bar{B} + B\bar{B}^* + B^*\bar{B}*$ cross sections measured by Belle (red dots), compared to $\sigma_{b\bar{b}}$ measured by Babar (black dots).

If the exotic nature of the $\Upsilon(10750)$ is almost given for granted, another analysis of Belle scan data is showing that also the well known $\Upsilon(5S)$ peak may be more complex. By fully reconstructing the decay products of one B meson, and studying the recoil mass, Belle has measured [3] for the first time the cross section of the two-body exclusive decays to $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$. Such analysis has recently been updated by Belle-II adding the four points of the scan mentioned above.

The left plot in Fig.2 shows the three peaks in recoil mass which allow to distinguish the 2-body processes. The red circles in the right plot show the sum of these three cross sections, compared to the fully inclusive B meson cross section, which includes B$_s$ meson production and three body processes, measured by Babar [5]. The $\sigma(B\bar{B}+B\bar{B}^*+B^*\bar{B}*)$ saturates the inclusive $b\bar{b}$ cross section until the $B_s^*\bar{B}_s^*$ threshold, where it peaks. A full coupled channel analysis including also the decays to narrow bottomonia has been performed [6] and will need further improvements to understand in detail the hadronization of b-quarks in the resonance region.

4 Recent LHCB discoveries on tetraquark states

In this review, I am going to report only about the most recent observations of tetraquarks done by LHCb, that, with the world's largest sample of reconstructed B decays, has published a plethora of papers on new charmonium-like states.

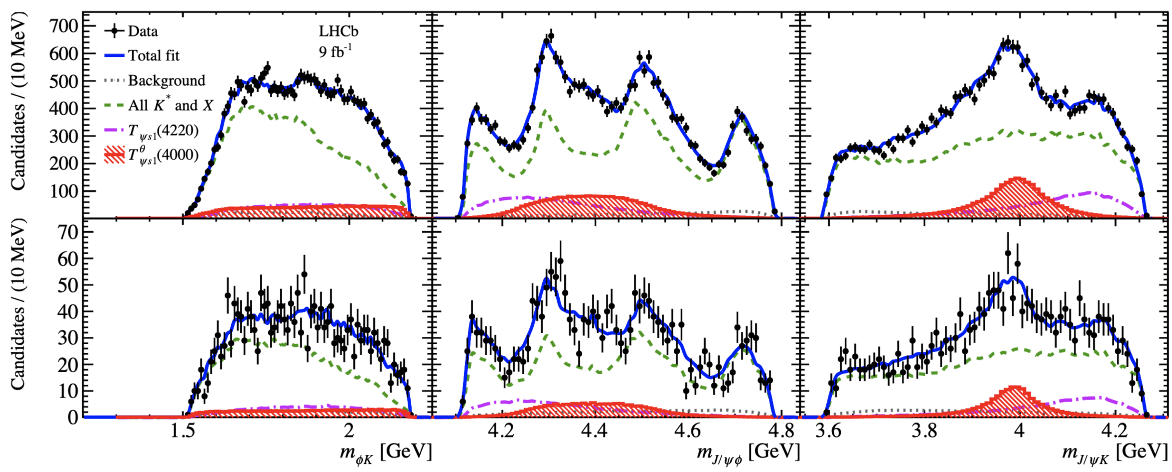

Figure 3 – Projections of the Dalitz plot of $B^{\pm} \to J/\psi K^{\pm}\phi$, above, and of $B^0 \to J/\psi K^0_S\phi$, below.

4.1 Charmed strange tetraquarks

Surely, the B decay with the largest density of tetraquarks candidates is $B \to J/\psi\phi K$, because the Dalitz plot contains bands in both the $J/\psi K$ and the $J/\psi\phi$ projections. From the decays of the charged B mesons, LHCb had discovered the tetraquarks $T^{\theta}_{\Psi s1}(4000)^+$ and $T^{\theta}_{\Psi s1}(4220)^+$, with quark content $c\bar{c}u\bar{s}$. This year, LHCb has found evidence [7] of the isospin partner $T^{\theta}_{\Psi s1}(4000)^0$ from the full amplitude analysis of the Dalitz Plot of the $B^0 \to J/\psi\phi K^0_S$ decay, and its charge conjugate. The significance of this evidence is 4σ, which increases to 5.4 standard deviations if we assume isospin symmetry with the charged partner. More statistics is needed to independently assess the observation of the neutral $T^{\theta}_{\Psi s1}(4220)^0$ state, which is anyway visible in the projection, in the central plot of the lower row of Figure 3.

4.2 Double $c\bar{c}$ tetraquarks

The decays of B hadrons are not the only source of many recently discovered multiquark states. The correlated electromagnetic production of double charmonia, discovered by Belle twenty years ago, has been a gold mine for the search of charmonia and charmonium-like states; a similar process can take place also in gluon-gluon scattering at hadron colliders.

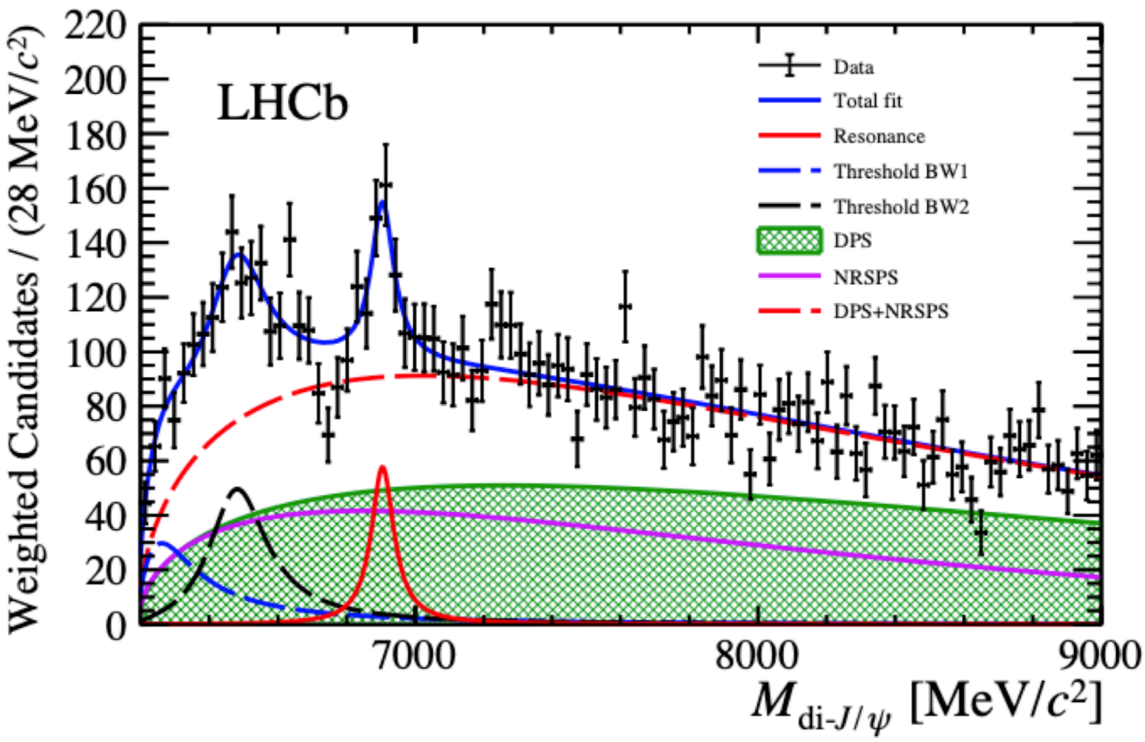

Figure 4 – Observation of X(6900) and other structures at LHCB

The large sample of hadronic collisions at the highest energies and the thoroughly tested dimuon triggers yielded very large samples of J/ψ and Υ mesons reconstructed with high efficiency. Using 9 fb^{-1} of pp collision data collected at $\sqrt{s}$=7.8 and 13 TeV, LHCB observed resonant structures in the invariant mass distribution of J/ψ pairs [9], coming from the primary vertex, to reduce contamination from products of B decays. Correlated production of two J/ψ proves that more than two $c\bar{c}$ pairs can be produced by single parton scattering (SPS), that can be either non resonant (NRSPS) or resonant, in the proximity of the thresholds, where tetraquark bound states may be expected.

Table 2: Mass and Width of the X(6900) state observed by LHCB.

	without interference	with interference
Mass	6905 $\pm$ 11 $\pm$ 7 MeV/c^2	6886 $\pm$ 11 $\pm$ 11 MeV/c^2
Width	80 $\pm$ 19 $\pm$ 33 MeV	168 $\pm$ 33 $\pm$ 69 MeV

The di-J/ψ mass distribution below 9 GeV/c^2 is shown in Fig.4: above the smooth continuum, modeled as a sum of NRSPS and double parton scattering (DPS) contributiions, tuned at high energy, a clear peak at 6.9 GeV/c^2 together with a bump closer to the threshold and a dip between them. Another peak with lower significance is visible at 7.2 GeV/c^2. The peak at 6.9 GeV, dubbed X(6900), which is in the proximity of the $\chi_{c0}\chi_{c1}$ threshold, has been fitted either as a single Breit-Wigner resonance, or as the result of interference between the resonance and the NRSPS+DPS continuum. The results are summarized in Table 2.

The X(6900) bump (but not the dip) was recently confirmed by CMS experiment [10], with a mass of 6927 ± 9 ± 5 MeV/c^2, and a width of 122 ± 22 ± 19 MeV, together with two more peaks, at 6522 ± 10 ± 12 MeV/c^2 and at 7287 ± 19 ± 5 MeV/c^2.

Double charmonium resonances have recently been searched also in Belle datasets, using the radiative return to select $J/\psi\eta_c$ pairs at energies close to the threshold, but no significant peaks have been observed. Further studies on this process are planned with more statistics at Belle-II.

4.3 Double charm baryons and tetraquarks

The discovery of baryons containing a pair of charm quarks, announced by LHCb in 2017 [11], has promptly triggered a plethora of theoretical predictions, on the existence of the T_{cc}, a tetraquark made of two charm quarks and one light anti-diquark: most of the predictions were clustering in the proximity of the $D\bar{D}^*$ threshold.

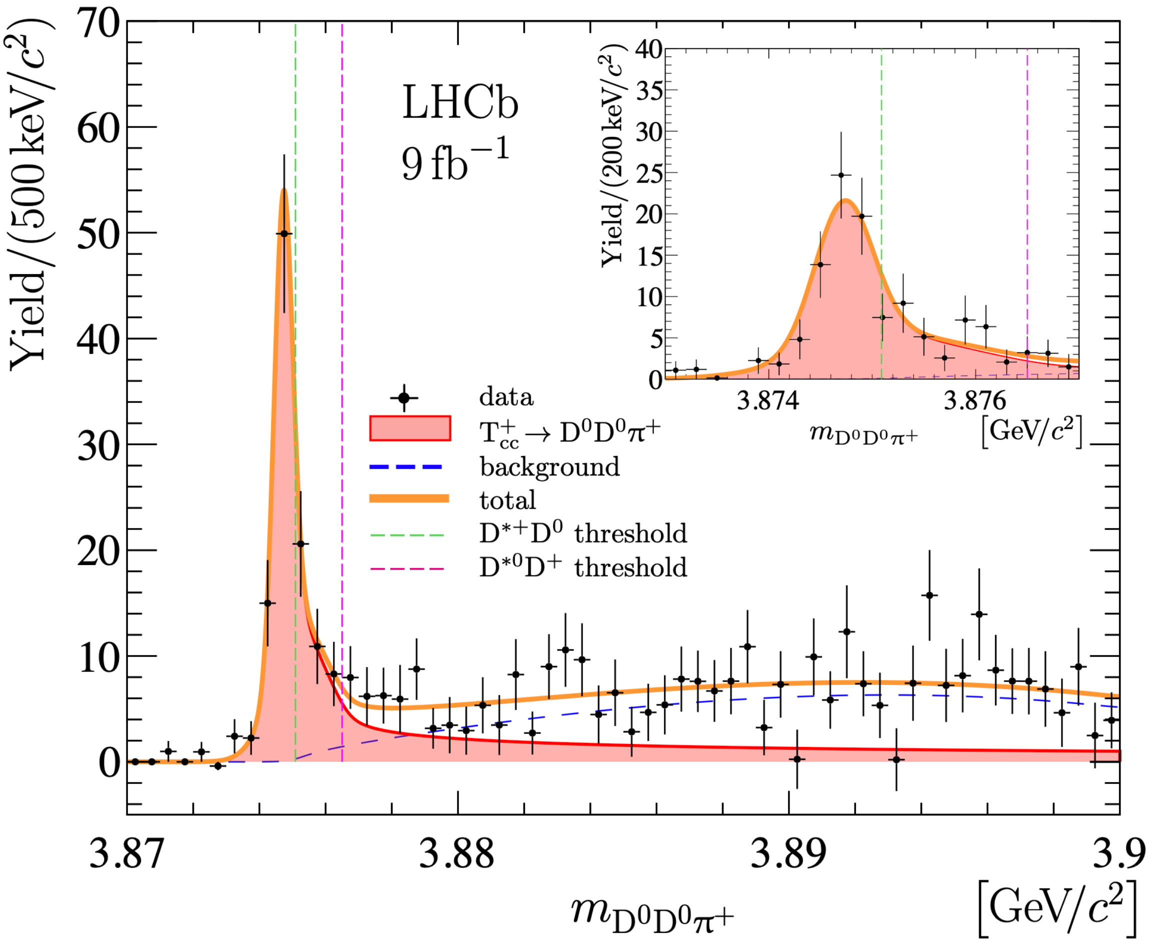

Figure 5 – The T_{cc} peak in $M(D^0D^0\pi^+)$; the vertical lines show the D^0D^{*+} and D^+D^{*0} thresholds.

In 2021, LHCb has published the observation [12] of a very narrow state (Γ = 47.8 ± 1.9 keV, half the width of the J/ψ), with a peak fitted at ΔM= 359±40 keV below the D^0D^{*+} mass threshold (3875.10 MeV/c^2), decaying to $D^0D^0\pi^+$. Figure 5 shows the mass distribution, zoomed in the inset: the vertical lines correspond to the D^0D^{*+} (green) and the D^+D^{0*} (pink) thresholds. The best spin-parity assignment for this state is $J^P = 1^+$, as for the X(3872), which has a mass of 3871.65 MeV/c^2. LHCb has also searched for doubly charged partners decaying to D^+D^{*+}, but no candidates were found, indicating that probably the T_{cc} has I=0. The possibility that this state is actually a $D^0\bar{D}^0\pi^+$ bound state followed by the $\bar{D}^0 \to D^0$ oscillation after the decay is excluded by the absence of peaks in the $D^0\bar{D}^0\pi^+$ mass spectrum at the same mass. A very interesting consequence of this observation is the prediction of a very deeply bound T_{bb} state (200 MeV binding energy?) which is therefore very actively searched for at the LHC.

5 Recent LHCB discoveries on pentaquark states

A pentaquark can be modeled either as a bound state of a baryon and a meson or as a strongly bound aggregate of two diquarks and an antiquark.

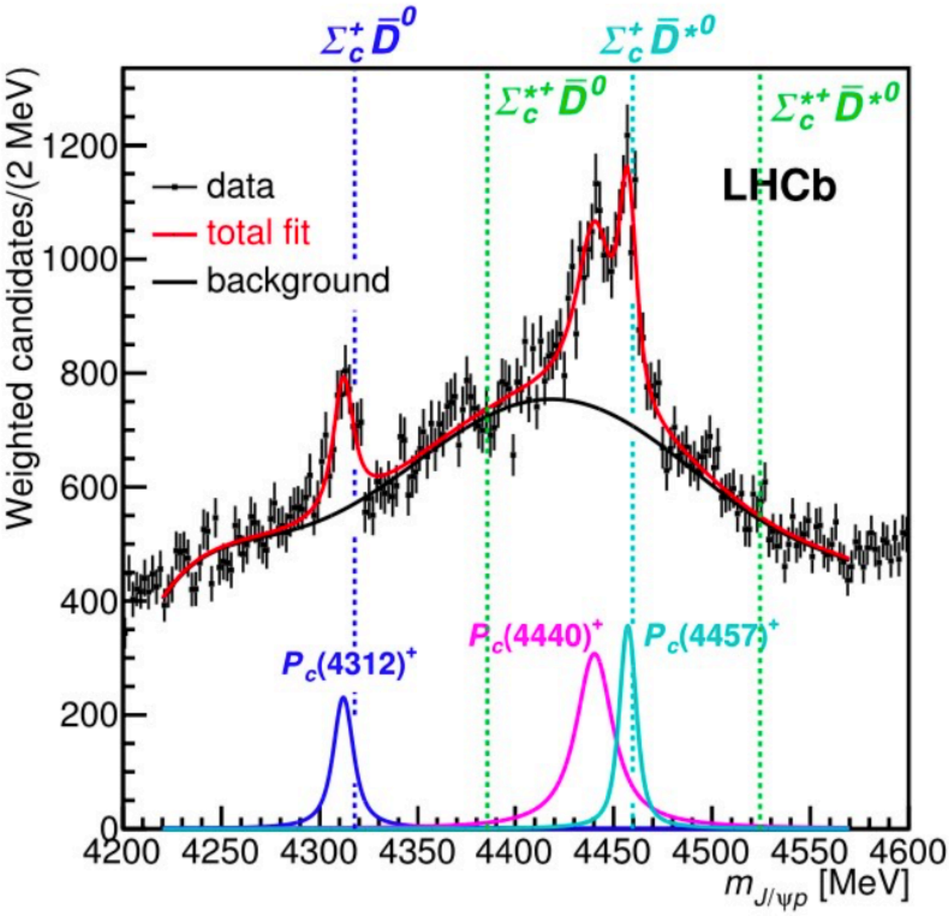

Figure 6 – The three P_c pentaquark structures in the M(p J/*psi*) projections of the Λ_b decay to p J/*psi* K^-, with vertical lines indicating the thresholds.

The first pentaquark states were discovered by LHCb [13] in the Dalitz plot analysis of the Λ_b decay to K^-p J/ψ. Three states were observed so far in the p J/ψ mass spectrum: one, the $P_c(4312)$ in the proximity of the $\Sigma_c\bar{D}^0$ threshold, and two, the $P_c(4440)$ and the $P_c(4457)$, just below the $\Sigma_c\bar{D}^{*0}$ threshold, as shown in Fig.6.

It is important to underline that no structures were seen in the proximity of the two $\Sigma_c^{*+}\bar{D}^0$ and $\Sigma_c^{*+}\bar{D}^{*0}$ thresholds. The first evidence uds$c\bar{c}$ candidate [14] has reported in 2020 in the Dalitz Plot analysis of the Ξ_b^- decays to $K^-\Lambda$ J/ψ at a mass of 4458.8 GeV/c^2. More recently, LHCb claimed finally the observation [15] of a lighter strange pentaquark, P_{cs}, with a mass of 4338 MeV/c^2, in B^- decays to $\bar{p}\Lambda J/\psi$, as shown in Fig.7.

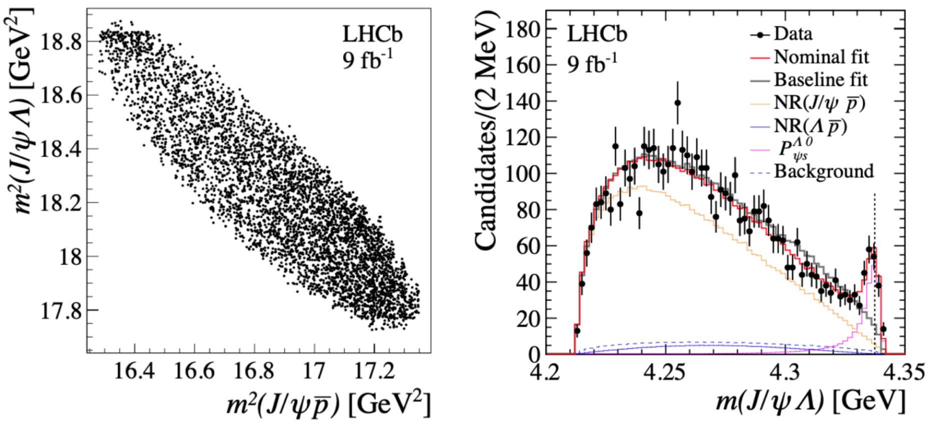

Figure 7 – Left: Dalitz plot of the B$^-$ decay to $\bar{p}\Lambda J/\psi$; Right: M(J/$\psi\Lambda$ projection showing the P$_{cs}$ pentaquark on the edge of phase space.

6 Conclusions and prospects

More than twenty years after the observation of X(3872), the field of hadron spectroscopy witnesses a steady flow of new discoveries that keep on broadening the landscape. Despite the struggle of phenomelogists to sort all this cornucopia of bound states, non perturbative QCD is blossoming in all its variety. For the time being, we can only ask for more statistics to gain further insights on the deep complexity of the heavy hadrons. Both Belle-II and LHCb are planning to take data throughout this decade, providing a continuous flow of new exciting discoveries.

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