Cambridge University Press
978-1-107-17158-9 — Multiquark Hadrons
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Excerpt
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Introduction

For long, we lived with the simplest paradigm[1]:

$$\text{Mesons} = q\bar{q}; \quad \text{Baryons} = qqq, \tag{1.1}$$

which rested on the absence of $I = 2$, $\pi\pi$ resonances, and of $S > 0$ baryons. Here I and S stand for isospin and strangeness, respectively. The case had to be revisited, however, because the lowest lying octet of scalar mesons, $\sigma(500)$, $\kappa(800)$, $f_0(980)$, and $a_0(980)$, does not fit in this picture, as seen in terms of their inverted mass hierarchies compared to the nonets of the pseudoscalar, vector, and axial-vector mesons.

It has been argued that the spectroscopy of the scalar nonet is better understood if one interprets them as consisting of tetraquarks. For example, $f_0(980)$ is assigned the quark structure

$$f_0(980) = \frac{[su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]}{\sqrt{2}}. \tag{1.2}$$

Here $[sq]$ ($[\bar{s}\bar{q}]$), $q = u, d$, are diquarks (antidiquarks) having definite spin and color quantum numbers. The tetraquark interpretation of the lowest-lying scalar nonet was pointed out long time ago (Jaffe, 1977; Alford and Jaffe, 2000). In addition, it was later stressed (Fariborz et al., 2008; 't Hooft et al., 2008) that tetraquark assignment may help explain a couple of other puzzles in this sector through the intervention of nonperturbative instanton effects, such as the decay $f_0(980) \to \pi\pi$. Their interpretation as $K\bar{K}$ hadron molecule states has also been put forward in a number of earlier papers (Weinstein and Isgur, 1990; Janssen et al., 1995; Locher et al., 1998). There is a good phenomenological case that the lowest-lying scalar nonet are non-$q\bar{q}$ mesons (Amsler and Tornqvist, 2004; Patrignani

[1] Baryons can now be constructed from quarks using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc., Murray Gell-Mann, 1964 (Gell-Mann, 1964; Zweig, 1964).

et al., 2016; Pelaez, 2016). We review the tetraquark interpretation in a chapter in this book, illustrating the role of instantons, and discuss the $q\bar{q}$ scalar mesons, which are higher in mass.

Experimental evidence for multiquark hadrons in the so-called heavy-light meson sector is not overwhelming. Two narrow states $D_{s0}^*(2317)^\pm$ and $D_{s1}^*(2463)^\pm$ have so far been seen in data at the B factories. A narrow state was found by BaBar (Aubert et al., 2003) at around 2.32 GeV in $D_s^\pm\pi^0$, in the data both on and off the $\Upsilon(4S)$ resonance, having a width compatible with the detector resolution. This is identified as $D_{s0}^*(2317)^\pm$. Following this, CLEO II (Besson et al., 2003) found a narrow resonance decaying into $D_s^{*\pm}\pi^0$, having a mass around 2.46 GeV. This is identified with $D_{s1}^*(2463)^\pm$. Their quark flavor content is either $c\bar{s}$ (if they are excited quark-antiquark states) or $c\bar{s}q\bar{q}$ (if they are multiquark states), and they have the orbital angular momentum $L = 1$, and spin-parity $J^P = 0^+$ (scalar) and 1^+ (axial-vector), respectively. However, their masses are much below the predicted ones for the $c\bar{s}$ P states and they are uncharacteristically narrow. Due to these features, $D_{s0}^*(2317)^\pm$ and $D_{s1}^*(2463)^\pm$ have been interpreted as $[cq][\bar{q}\bar{s}]$, $q = u, d$; tetraquarks (Cheng and Hou, 2003; Terasaki, 2003; Maiani et al., 2005). They have also been interpreted as $DK(DK^*)$ molecules (Barnes et al., 2003; Kolomeitsev and Lutz, 2004; Faessler et al., 2007; Lutz and Soyeur, 2008; Liu et al., 2013), using methods which range from phenomenological approaches to lattice QCD in which scattering of light pseudoscalar mesons (π, K) on charmed mesons (D, D_s) is studied. In particular, a decay width $\Gamma(D_{s0}^*(2317)^\pm \to D_s^\pm\pi^0) = (133\pm22)$ keV is predicted in the molecular interpretation (Liu et al., 2013). The corresponding width in the compact tetraquark interpretation is estimated to be typically $O(10)$ keV (Colangelo and De Fazio, 2003; Godfrey, 2003). These estimates are far below the current upper limit of 3.8 MeV (Patrignani et al., 2016).

It is likely that $D_{s0}^*(2317)^\pm$ and $D_{s1}^*(2463)^\pm$ can be accommodated as excited $c\bar{s}$ P-wave states. A calculation in the heavy quark limit (Bardeen et al., 2003), which treats the 0^+ and 0^- $c\bar{s}$ mesons as chiral partners, reproduces the experimental mass difference $D_{s0}^*(2317)^\pm - D_s^\pm = 348$ MeV, though the power $O(\Lambda_{\mathrm{QCD}}/m_c)$ corrections are not expected to be small. In a quenched lattice QCD calculation (Bali, 2003), significantly larger $0^+ - 0^-$ meson mass splittings are predicted than what has been measured experimentally. This would suggest a non-$c\bar{s}$ interpretation. However, the non-$c\bar{s}$ approaches, mentioned above, predict lot more states, none of which has been seen so far. The heavy-light excited charm meson sector is remarkably quiet experimentally, and has not come up with any new candidates since the discovery of $D_{s0}^*(2317)^\pm$ and $D_{s1}^*(2463)^\pm$, and hence we shall not discuss this sector any more.

The situation with the heavy-light multiquark states in the beauty quark sector is not too dissimilar from the charm sector just discussed, i.e., there are no confirmed multiquark hadron states having the quark content $[bq][\bar{q}'\bar{s}]$, $q, q' = u, d$ (or its conjugate).[2] A couple of years ago, there was a lot of excitement in the multihadron community as the D0 experiment at Fermilab reported the observation of a new narrow structure in the $B_s^0\pi^+$ invariant mass (Abazov et al., 2016). Based on 10.4 fb^{-1} of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV, this candidate resonance, dubbed $X^\pm(5568)$, had a mass $M = 5568$ MeV and decay width $\Gamma = 22$ MeV. A state such as $X^\pm(5568)$ would be distinct in that a charged light quark pair cannot be created from the vacuum, leading to the unambiguous composition in terms of four valence quarks with different flavors – $\bar{b}\bar{d}su$. This promptly attracted considerable attention (see Ali et al. (2016a and references quoted therein), but skepticism was also raised (Burns and Swanson, 2016). Exciting a discovery as it would have been, $X^\pm(5568)$ has not been confirmed by the LHC experiments. Based on 3 fb^{-1} of pp collision data at $\sqrt{s} = 7$ and 8 TeV, yielding a data sample of B_s^0 mesons 20 times higher than that of the D0 collaboration, and adding then a charged pion, the $B_s^0\pi^+$ invariant mass measured by LHCb has shown no structure from the $B_s^0\pi^+$ threshold up to $M_{B_s^0\pi^+} \leq 5700$ MeV. Consequently, an upper limit on the ratio $\rho(X(5568)/B_s^0) < 0.024$ for $p_T(B_s^0) > 10$ GeV at 95 % C.L. has been set by LHCb (Aaij et al., 2016b), where the ratio $\rho(X(5568)/B_s^0)$ is defined as

$$\rho(X(5568)/B_s^0) \equiv \frac{\sigma(pp \to X^\pm(5568) + \text{anything}) \times \mathcal{B}(X^\pm(5568) \to B_s^0\pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})}. \tag{1.3}$$

A similar negative search for the $X^\pm(5568)$ is reported by the CMS collaboration, with an upper limit $\rho(X(5568)/B_s^0) < 0.011$ for $p_T(B_s^0) > 10$ GeV at 95 % C.L. (Sirunyan et al., 2017). This is to be compared with $\rho(X(5568)/B_s^0) = (8.6 \pm 2.4)\%$ measured by D0 (Abazov et al., 2016).

The current experimental evidence for the multiquark states is based on hadrons with hidden charm ($c\bar{c}$) or hidden beauty ($b\bar{b}$) and a light quark-antiquark pair ($q\bar{q}$) in the valence approximation. The remarkable accuracy with which the spectra of $Q\bar{Q}$ states ($Q = c, b$) are predicted and measured has made it possible to discover *by difference* new states, where the valence quarks, indirectly or directly, do not agree with the standard paradigm (1.1). In 2003, Belle discovered the $X(3872)$ (Choi et al., 2003), a narrow width resonance, which decays into $J/\psi + (2\pi, 3\pi)$ and does not fit into the *charmonium* sequence of states. Since then, BaBar (Aubert et al., 2005b), CDF (Acosta et al., 2004), D0 (Abazov et al., 2004), CMS (Chatrchyan et al., 2013), and LHCb (Aaij et al., 2013a) have confirmed the $X(3872)$ and reported many other states, called $X(J^{PC} = 1^{++})$ and $Y(J^{PC} = 1^{--})$ mesons, which do not fit in the charmonium picture either.

[2] We use the term beauty for the fifth quark, the weak isospin partner of the top quark, but denote the bound $b\bar{b}$ state as bottomonium, following the standard usage.

A new chapter was opened by Belle in 2007, with the observation of a *charged charmonium* (Choi et al., 2008), called $Z^+(4430)$, in the decays of the B^0 meson[3]:

$$B^0 \to K^- + J/\psi + \pi^+. \tag{1.4}$$

The hadron $Z^+(4430)$ appeared as a peak in the distribution of the $J/\psi\ \pi^+$ invariant mass and it obviously had to have a valence quark composition made by two different pairs: $c\bar{c}$ and $u\bar{d}$. However, Babar later suggested (Aubert et al., 2009) that, rather than a genuine resonance, the $Z^+(4430)$ peak could simply be a reflection of the many $K^\star$ resonances present in the $K\pi$ channel. Finally, in 2014, with much larger statistics, LHCb gave convincing evidence (Aaij et al., 2014c) for the $Z^+(4430)$ to be a genuine Breit-Wigner resonance.

In the meanwhile, other similar states, $Z^+(3900)$ and $Z^+(4020)$, have been discovered by BES III (Ablikim et al., 2013a,b) and confirmed by BELLE (Liu et al., 2013) and by CLEO (Xiao et al., 2013). Last but not least, in 2015, two baryon resonances decaying in $J/\psi + p$ were discovered by LHCb (Aaij et al., 2015b), with valence quark composition $cuud\bar{c}$, promptly called *pentaquarks*. The existence of hadrons with a valence quark composition not fitting the paradigm (1.1) is by now established. It is an easy prediction that the unorthodox part of the hadron spectrum is bound to expand substantially in the next run of experiments at e^+e^- and proton colliders. We show in Fig. 1.1 the mass spectrum of the "anticipated" charmonia and the "unanticipated" charmonia-like states. The latter are called charged and neutral XYZ mesons, and the four exotic states, discovered by LHCb (Aaij et al., 2017b) in the $J/\psi\phi$ channel from the amplitude analysis of the $B^+ \to J/\psi\phi K^+$ decay, are also shown.

The exotic spectroscopy consisting of the X, Y, and Z hadrons is not confined to the charmonium sector alone, similar hadrons have been discovered in the bottomonium sector as well. The evidence for the first of these, dubbed as $Y_b(10890)$, is circumstantial, and it was triggered by the "anomalies" seen in 2008 by Belle (Chen et al., 2008) in the dipionic transitions $\Upsilon(nS)\pi^+\pi^-$ ($nS = 1S, 2S, 3S$), and $\Upsilon(1S)K^+K^-$, near the peak of the $\Upsilon(5S)$ resonance at $\sqrt{s} \sim 10.874$ GeV. Interpreting these events as coming from the process

$$e^+e^- \to \Upsilon(5S) \to \pi^+\pi^- + (\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)); K^+K^- + \Upsilon(1S), \tag{1.5}$$

yielded partial decay widths in the range $(0.52 - 0.85)$ MeV for the $\Upsilon(nS)\pi^+\pi^-$ channels, and 0.067 MeV for the $\Upsilon(1S)K^+K^-$ channel. These decay widths are to be compared with the Zweig-forbidden dipionic transitions from the decays of the lower-mass $\Upsilon(mS)$ states ($mS = 2S, 3S, 4S$) in the final state $\Upsilon(1S)\pi^+\pi^-$, which have partial decay widths ranging from 0.9 to 6 keV. Thus, the partial decay

[3] Throughout this book, charge conjugate states and processes are implied.

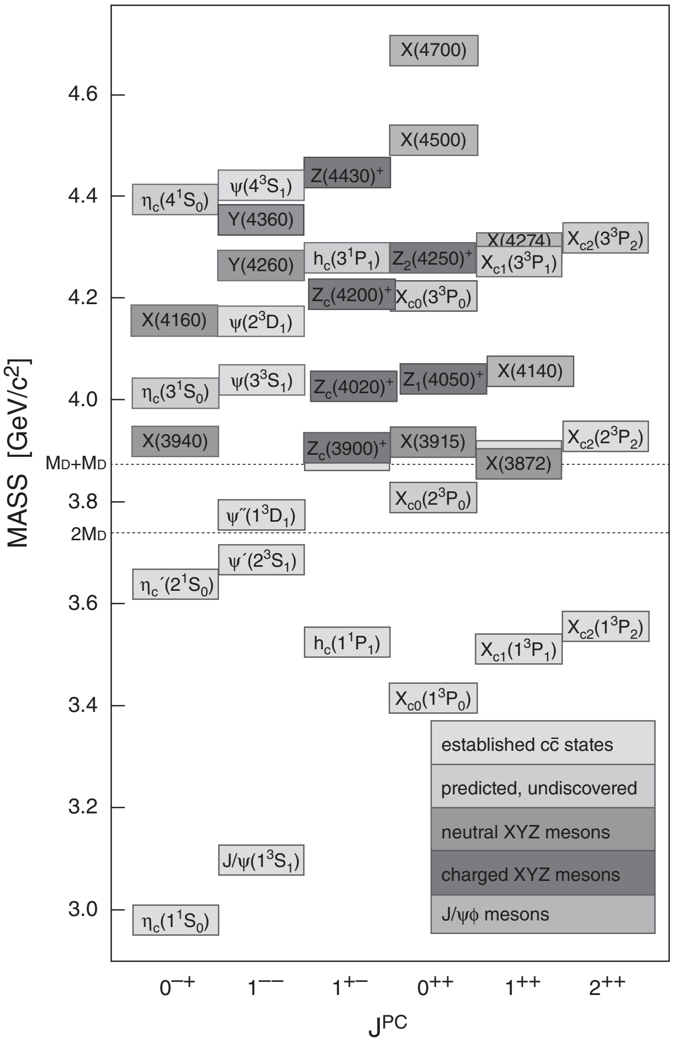

Figure 1.1 Anticipated charmonia and exotic charmonia-like states, called the charged and neutral XYZ mesons, as of 2015. Figure from Olsen (2015) updated by Sheldon Stone (2017) by including the four exotic $J/\psi\phi$ states discovered subsequently by LHCb (Aaij et al., 2017b).

widths in (1.5) are typically more than two orders of magnitude larger. Moreover, the dipion invariant mass spectra from (1.5) are very different than in the Zweig-forbidden $\Upsilon(4S) \to \pi^+\pi^- + \Upsilon(nS)$ decays.

Since an exotic state, $Y(4260)$, having $J^{PC} = 1^{--}$, was seen in the charmonium sector in the decay channel $J/\psi\pi^+\pi^-$, it was argued that the anomalous events in (1.5) could possibly be coming from the production and decays of the bottomonium-counterpart (Hou, 2006). The production cross sections for the states $(\Upsilon(1S), \Upsilon(2S), \Upsilon(3S))\pi^+\pi^-$ was subsequently measured as a function of $\sqrt{s}$ between 10.83 GeV and 11.02 GeV, and it was found that the data did not agree with the line shape of the $\Upsilon(5S)$. The mass and decay width of the resonance, $Y_b(10890)$, was measured as $[10888.4^{+2.7}_{-2.6}$ (stat) $\pm$ 1.2 (syst)] MeV and $[30.7^{+8.3}_{-7.0}$ (stat) $\pm$ 3.1 (syst)] MeV, respectively (Adachi et al., 2008). The phenomenology of $Y_b(10890)$ was subsequently worked out in a number of papers (Ali et al., 2010a, 2011; Ali and Wang, 2011; Chen et al., 2011b).

The status of Y_b at this stage is not clear, as it lies very close in mass to the canonical and well-established bottomonium state $\Upsilon(5S)$, and both of them have the same quantum numbers $J^{PC} = 1^{--}$. A search for $Y_b(10890)$ through the so-called R_b energy-scan at the KEK B-factory, with

$$R_b \equiv \frac{\sigma(e^+e^- \to b\bar{b})}{\sigma(e^+e^- \to \mu^+\mu^-)} \tag{1.6}$$

did not confirm its existence and Belle has put an upper bound on the electronic width $\Gamma(Y_b \to e^+e^-) \leq 9$ eV at 90% confidence level (Santel et al., 2016). On the other hand, very clear peaks are seen in the $R_{\Upsilon(nS)\pi^+\pi^-}$ energy-scan at the KEK B-factory, where

$$R_{\Upsilon(nS)\pi^+\pi^-} \equiv \frac{\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)}{\sigma(e^+e^- \to \mu^+\mu^-)}, \tag{1.7}$$

in the $\Upsilon(5S)$ and $\Upsilon(6S)$ regions (Santel et al., 2016). These peaks, with rather large branching ratios in the decays of $\Upsilon(5S)$ and $\Upsilon(6S)$, remain enigmatic. Apart from the processes shown in Eq. (1.5), other dipionic transitions from $\Upsilon(5S)$ are also found to have very high decay rates, such as $\pi + \pi + h_b(1P, 2P)$, with $h_b(1P, 2P)$ the bottomonium spin-singlet P-wave states. The dipion recoil mass spectrum from the $\Upsilon(5S)$ is shown in Fig. 1.2. Understanding this spectrum without the intervention of multiquark states is not possible. Apart from the dichotomy $Y_b(10890)/\Upsilon(5S)$, the four-quark states $Z_b^\pm(10610)$ and $Z_b^\pm(10650)$, discovered later by Belle, play a fundamental role, as discussed below and in detail in this book.

Unfortunately, the dipionic transitions from the regions near the $\Upsilon(5S)$ and $\Upsilon(6S)$, which have led to the discovery of a number of anticipated bottomonium states $h_b(nP)$, and exotic states, $Z_b^\pm(10610)$ and $Z_b^\pm(10650)$, have not been checked by independent experiments, as no e^+e^- annihilation experiment in this energy range is available at present, and the next e^+e^- experiment under construction, Belle II, will start taking data only in 2019. In our opinion, high-luminosity data from Belle II is direly needed to settle several open issues, of which the existence of $Y_b(10890)$ is one.

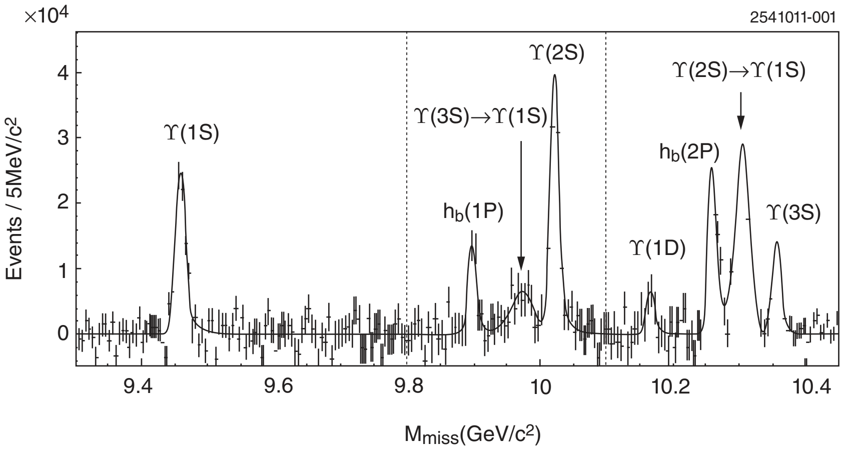

Figure 1.2 The mass spectrum of the hadrons (called $M_{\rm miss}$), recoiling against the $\pi^+\pi^-$ pair in the e^+e^- annihilation data taken near the peak of the $\Upsilon(5S)$. The data, with the combinatoric background and K_S^0 contribution subtracted (points with error bars) and signal component of the fit functions (overlaid) (Adachi et al., 2012). Reprinted with permission from [I. Adachi et al. (Belle Collaboration), *Phys. Rev. Lett.*, **108**, 032001, 2012; http:dx.doi.org/10.1103/PhysRevLett.108 .032001]. Copyright (2012) by the American Physical Society.

The spectrum shown in Fig. 1.2 strongly suggests that experiments at the LHC could measure the production of $\Upsilon(5S)$ and $\Upsilon(6S)$ through the Drell-Yan mechanism or in strong interaction production processes. For this, one has to concentrate on the decays $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$, and likewise for $\Upsilon(6S) \to \Upsilon(nS)\pi^+\pi^-$, though with reduced rates. Searching for the resonances in a Drell-Yan process and hadronic collisions in four charged-particle final states, such as $\mu^+\mu^-\pi^+\pi^-$, has the potential of discovering J/ψ-like and Υ-like multiquark states. The traditional method of measuring the bottomonium states through the dileptonic (e^+e^- or $\mu^+\mu^-$) final states will not work, however, as the corresponding branching ratios are tiny. Apart from this, Y_b-like hadrons, with $J^{PC} = 1^{--}$, can also be searched for in e^+e^- annihilation, in the so-called radiative return process

$$e^+e^- \to \gamma + Y(J^{PC} = 1^{--}) \tag{1.8}$$

but, again, their production cross sections are expected to be rather small due to the small anticipated electronic decay widths $\Gamma(Y) \to e^+e^-$. No $X_b(J^{PC} = 1^{++})$ exotic hadron has been discovered so far in the bottomonium sector, though they are being searched for by the ATLAS and CMS collaborations at the LHC, but the current experimental sensitivity falls way short of the discovery threshold.

The charged bottomonium-like hadrons, $Z_b^{\pm}(10610)$ and $Z_b^{\pm}(10650)$, have been discovered in the decays

$$\begin{aligned} Y_b(10890)/\Upsilon(5S) &\to Z_b^{\pm}(10610) + \pi^{\mp}, \\ Y_b(10890)/\Upsilon(5S) &\to Z_b^{\pm}(10650) + \pi^{\mp}, \end{aligned} \tag{1.9}$$

with the subsequent decays into $h_b(1P, 2P)\pi^{\pm}$, and $\Upsilon(1S, 2S, 3S)\pi^{\pm}$, going at almost the same rate. Since $h_b(1P, 2P)$ are spin-singlet states, and $\Upsilon(1S, 2S, 3S)$ are spin-triplets, similar rates of the dipionic transitions in these final states from $Y_b(10890)/\Upsilon(5S)$ pose a challenge. This is yet another anomalous feature of the $\Upsilon(5S)$ decays. Here also, multiquark states come to the rescue. Tetraquark interpretation of the $Z_b^{\pm}(10610)$ and $Z_b^{\pm}(10650)$, which have in their Fock space both spin-0 and spin-1 components, offer a natural explanation, though they can also be accommodated in the hadron molecule interpretation. More data are needed for the classification of the exotic hadrons in the bottomonium sector. Apart from the dipionic transitions, other decay channels, such as

$$Y_b(10890)/\Upsilon(5S) \to \Upsilon(1S) + (K^+K^-, \eta\,\pi^0) \tag{1.10}$$

are expected to be quite revealing, and the dipion-, dikaon-, and the $(\eta\,\pi^0)$- invariant mass distributions as well. We anticipate that the exotic spectroscopy in the bottomonium sector will take a central place in Belle II measurements, and, in all likelihood, also in the high-luminosity LHC run at $\sqrt{s} = 13$ TeV, which is well under way.

What about the exotic baryons? Pentaquarks, consisting of four quarks and an antiquark, are the much sought after exotic mesons whose discovery had to wait for the commissioning of the LHC. Since most of the tetraquarks are observed in the decays of the B and B_s mesons, it was a natural expectation that the decays of the Λ_b-baryons may reveal similar exotic baryonic structures. LHC is, among other things, a Λ_b factory, as they are profusely produced in high-energy pp collisions. In particular, in the acceptance of the LHCb experiment, about 20% of all b-flavored hadrons are Λ_b^0s (Aaij et al., 2012a). The baryonic analog of the well-studied B-meson decay $B^0 \to J/\psi K^+K^-$ is the Λ_b decay $\Lambda_b^0 \to J/\psi K^- p$, yielding four charged particles $(J/\psi \to \mu^+\mu^-)K^-p$, which could be used effectively to pin down the Λ_b^0 decay vertex, thus offering an excellent method to precisely measure the Λ_b^0 lifetime. With this motivation, a dedicated study of the process

$$pp \to b\bar{b} \to \Lambda_b X; \quad \Lambda_b \to K^- J/\psi p, \tag{1.11}$$

was undertaken by the LHCb collaboration, using some 26,000 signal candidates with about 1400 background events (Aaij et al., 2014d). A closer examination of the decay products, in particular the Dalitz-distribution $m^2_{J/\psi p}$ versus m^2_{Kp}, showed an anomalous feature (Aaij et al., 2015b). There were vertical bands (in m^2_{Kp}) in the data, corresponding to the anticipated $\Lambda^* \to K^- p$ resonant structures, and an unexpected horizontal band (in $m^2_{J/\psi p}$) near 19.5 GeV^2. The Dalitz plot projections showed significant structures in the $K^- p$ spectrum, coming essentially from the Feynman diagram (a) in Fig. 2.13, but there was also a peak in the $J/\psi p$ mass spectrum. A statistically good fit of the $m_{J/\psi p}$ distribution was shown to be consistent with the presence of two resonant states, henceforth called $P_c(4450)^+$ and $P_c(4380)^+$, with the following characteristics

$$M = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}; \quad \Gamma = 39 \pm 5 \pm 19 \text{ MeV}, \tag{1.12}$$

and

$$M = 4380 \pm 8 \pm 29 \text{ MeV}; \quad \Gamma = 205 \pm 18 \pm 86 \text{ MeV}. \tag{1.13}$$

Both of these states carry a unit of baryonic number and have the valence quarks $P_c^+ = \bar{c}cuud$. The preferred J^{P} assignments of the pentaquarks are $5/2^+$ for the $P_c(4450)^+$ and $3/2^-$ for the $P_c(4380)^+$ (Aaij et al., 2015b). So far, these are the only five-quark states observed in an experiment. This concludes our overview of the current experimental situation.

In parallel with the experimental discoveries, a large theoretical activity has gone into the interpretation of the new particles. To be sure, nobody has challenged the validity of Quantum Chromodynamics (QCD) or has invoked the presence of new types of fundamental constituents. Rather, the existence of different pictures in the interpretation of the data reflects the remarkable ignorance about the exact solutions of nonperturbative QCD. Different interpretations call into play different approximations, or different regimes of the basic QCD force, to arrive at seemingly contradictory pictures. Thus, the pieces of this new dynamical puzzle will have to be put together painstakingly, and it is conceivable that there are more than a single template which QCD seems to be making use of in the dynamics of these exotic hadrons.

The most conventional explanation of the exotic states is in terms of kinematic effects due to the opening of new channels (also trademarked as *cusps*). While it is a logical possibility, it is less likely to hold sway to accommodate all or most of these hadrons. This is due to the unconventional dynamics required in this scenario to produce narrow structures as cusps, like the $X(3872)$, and the fact that the phase of the charged state $Z^{\pm}(4430)$ and of at least one pentaquark resonance, $P_c(4450)^+$, measured by the LHCb, become 90° at the peak, which is a telltale signature of a Breit-Wigner resonance. Thus, with more data, this scenario can be checked by doing an Argand analysis of the decay amplitudes in question.

It is more likely that hadron spectroscopy finds itself at the threshold of a new era, and in anticipation thereof, three dynamical models of the X, Y, Z, and P_c hadrons have been put forward in the current literature as viable explanations.

We briefly review them later in this chapter, and will discuss them in more detail in the subsequent chapters of this book.

The first picture goes under the name *compact tetraquarks*, which are bound states of color nonsinglet diquark-antidiquarks, tightly bound by gluons, very much along the same lines as colored quark-antiquark pairs are bound into color-neutral mesons. This view then opens a secondary layer of compact hadrons in QCD, which, in principle, are even more numerous than the quark-antiquark mesons. The tetraquark picture relies as a guiding framework on the nonrelativistic Constituent Quark Model, which gives quite accurate picture of the conventional $q\bar{q}$ and qqq mesons and baryons, including charmed and beauty hadrons. The starting point is the attraction within a color antisymmetric quark pair, which arises in perturbative QCD due to one gluon exchange and in nonperturbative QCD due to instanton interaction. This makes diquarks and antidiquarks the basic units to build X, Y, Z, and P_c hadrons, with mass splittings due to spin-spin interactions and orbital momentum excitation.

The rekindled interest in tetraquarks is mostly data driven, as they provide a template for the newly found quarkonium-like states, both neutral and charged. Prior to this, for a long time, tetraquarks were banished from the observable hadron spectrum by field-theory arguments. In particular, their reputation as *bona fide* hadrons was tarnished by a theorem due to Sidney Coleman, which stated that tetraquark correlation functions for $N \to \infty$ (N is the number of colors) reduce to disconnected meson-meson propagators (Coleman, 1980). Hence, according to this argument, they do not exist as poles in the scattering amplitudes. Lately this large-N argument has been put to question by Steven Weinberg (2013b) and by others. They noted that the existential issue for tetraquarks is not so much the dominance of the disconnected diagrams in the $N \to \infty$ limit. Indeed, if the connected tetraquark correlation functions do develop poles for finite N, it does not matter much that the residue is not of leading order for $N \to \infty$. After all, it was observed, meson-meson interactions do vanish as well in this limit, and we do not believe that mesons are free particles. The catch could rather be that the decay widths increase in the large-N limit, making these states undetectable. By explicit examination one sees, however, that, once tetraquark correlation functions are properly normalized, the decay rates do indeed vanish as $N \to \infty$, reassuring that there is no prima facie field-theoretic argument against their existence and visibility. This is the line of argument which we will pursue here in this book at some length.

There is no evidence of a diquark structure in light baryons, such as neutron and proton. In particular, data on deep inelastic scattering on a proton, such as at HERA, can be analyzed in terms of quarks and gluons without the need of invoking diquarks. However, heavy-light baryons with a single heavy quark (Qqq) do admit an interpretation as heavy quark-light diquark systems (Lichtenberg, 1975;