110. Pentaquarks

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Experimental searches for pentaquark hadrons comprised of light flavors have a long and vivid history. No undisputed candidates have been found in 50 years. The first wave of observations of pentaquark candidates containing a strange antiquark occurred in the early seventies, see e.g. a review in the 1976 edition of Particle Data Group listings for $Z_0(1780)$, $Z_0(1865)$ and $Z_1(1900)$ [1]. The last mention of these candidates can be found in the 1992 edition [2] with the perhaps prophetic comment "the results permit no definite conclusion - the same story for 20 years. [...] The skepticism about baryons not made of three quarks, and lack of any experimental activity in this area, make it likely that another 20 years will pass before the issue is decided." A decade later, a second wave of observations occurred, possibly motivated by specific theoretical predictions for their existence [3–5]. The evidence for pentaquarks was based on observations of peaks in the invariant mass distributions of their decay products. More data, or more sensitive experiments did not confirm these claims [6]. In the last mention of the best known candidate from that period, $\Theta(1540)^+$, the 2006 Particle Data Group listing [7] included a statement: "The conclusion that pentaquarks in general, and that Θ^+, in particular, do not exist, appears compelling." which well reflected the prevailing mood in the particle physics community until a study of $\Lambda_b^0 \to J\psi p K^-$ ($J\psi \to \mu^+\mu^-$) decays by LHCb [8](charge conjugate modes are implied). In addition to many excitations of the Λ baryon (hereafter denoted as Λ^* resonances) decaying to K^-p, these data contain a narrow peak in the $J\psi p$ mass distribution, which is evident as a horizontal band in the Dalitz plot (Fig. 110.1).

An amplitude analysis was performed to clarify the nature of this band that followed in the footsteps of a similar analysis of $\bar{B}^0 \to \psi(2S)\pi^+K^-$ ($\psi(2S) \to \mu^+\mu^-$) performed by the LHCb a year earlier in which the $Z(4430)^+$ tetraquark candidate [9] was confirmed and the resonant character of its amplitude was demonstrated by an Argand diagram [10]. The final states are very similar, with π^+ being replaced by p. The signal statistics, $26\,000 \pm 166$, and the background level, 5.4%, are also very comparable. The quasi-two-body amplitude model was constructed based on an isobar approximation (*i.e.* summing up Breit-Wigner amplitudes) and helicity formalism to parameterize dynamics of contributing decay processes. The amplitude fit spanned a kinematically complete, six-dimensional space of independent kinematic variables. All six dimensions of Λ_b decay kinematics were used in the amplitude fit, including invariant masses of K^-p (m_{Kp}) and $J\psi p$, ($m_{J\psi p}$) helicity angles (θ) of Λ_b, $J\psi$, Λ^* or pentaquark candidate $P_c^+ \to J\psi p$, and angles between decay planes of the particles. Fourteen reasonably well established Λ^* resonances were considered with masses and widths fixed to the values listed in 2014 PDG edition [11], and varied within their uncertainties when evaluating systematic errors. Their helicity couplings (1-6 complex numbers per resonance) were determined from the fit to the data. It was found that the Λ^* contributions alone failed to describe the data and it was necessary to add two exotic $P_c^+ \to J\psi p$ contributions to the matrix element (10 free parameters per resonance), before the narrow structure seen in $m_{J\psi p}$ could be reasonably well reproduced, as illustrated in Fig. 110.2.

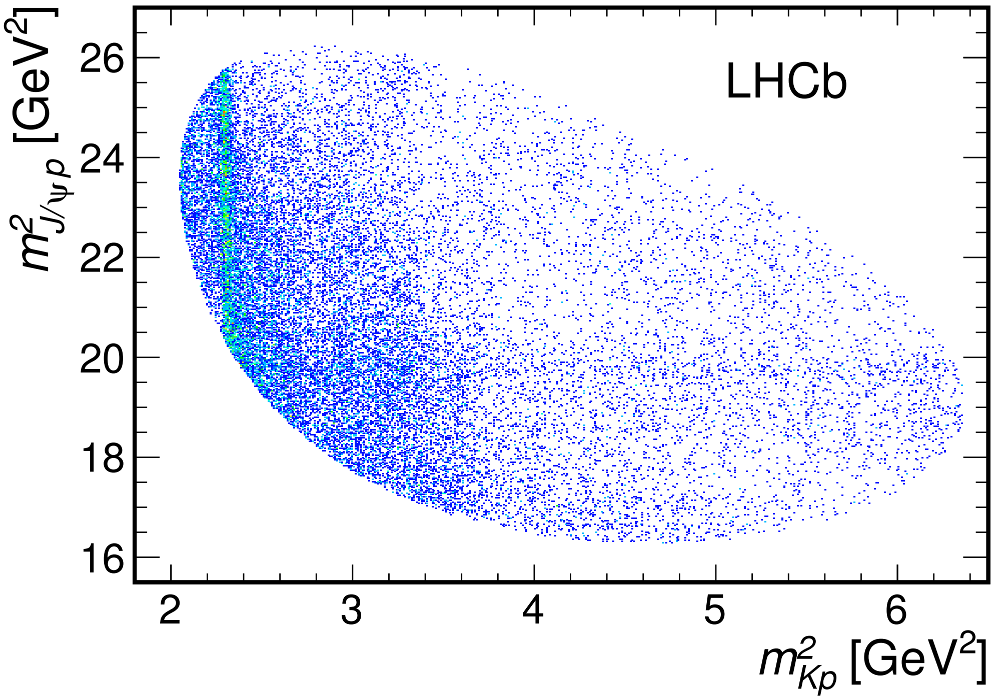

Figure 110.1: Dalitz plot distributions for $\Lambda_b^0 \to J\psi p K^-$ decays as observed by LHCb.

The lower mass state, $P_c(4380)^+$, has a fitted mass of $4380 \pm 8 \pm 29$ MeV, width of $205 \pm 18 \pm 86$ MeV, fit fraction of $8.4 \pm 0.7 \pm 4.2$ % and significance of 9σ. The higher mass state, $P_c(4450)^+$, has a fitted mass of $4449.8 \pm 1.7 \pm 2.5$ MeV, narrower width of $39 \pm 5 \pm 19$ MeV, a fit fraction of $4.1 \pm 0.5 \pm 1.1$ % and significance of 12σ. The need for a second P_c^+ state becomes visually apparent in the $m_{J\psi p}$ distribution for events with high values of m_{Kp}, where Λ^* contributions are the smallest (in the inset of Fig. 110.2). Even though contributions from the two P_c^+ states are most visible in this region, they interfere destructively in this part of the Dalitz plane. The constructive P_c^+ interference makes their combined contribution the largest at the other end of their band on the Dalitz plane, corresponding to the opposite end of the $\cos\theta_{P_c^+}$ distribution (see Fig. 8b in Ref. 8). This pattern requires them to be of opposite parity. A similar interference pattern is observed in the $\cos\theta_{\Lambda^*}$ distribution (Fig. 7 in Ref. 8), which is a consequence of parity-doublets in the Λ^* spectrum. Unfortunately, spins of the two P_c^+ states were not uniquely determined. Within the statistical and systematic ambiguities, $(3/2, 5/2)$ and $(5/2, 3/2)$ combinations with either $(-,+)$ or $(+,-)$ parities, were not well resolved. The other combinations were disfavored. The Argand diagrams for the two P_c^+ states are shown in Fig. 110.3. They were obtained by replacing the Breit-Wigner amplitude for one of the P_c^+ states at a time by a combination of independent complex amplitudes

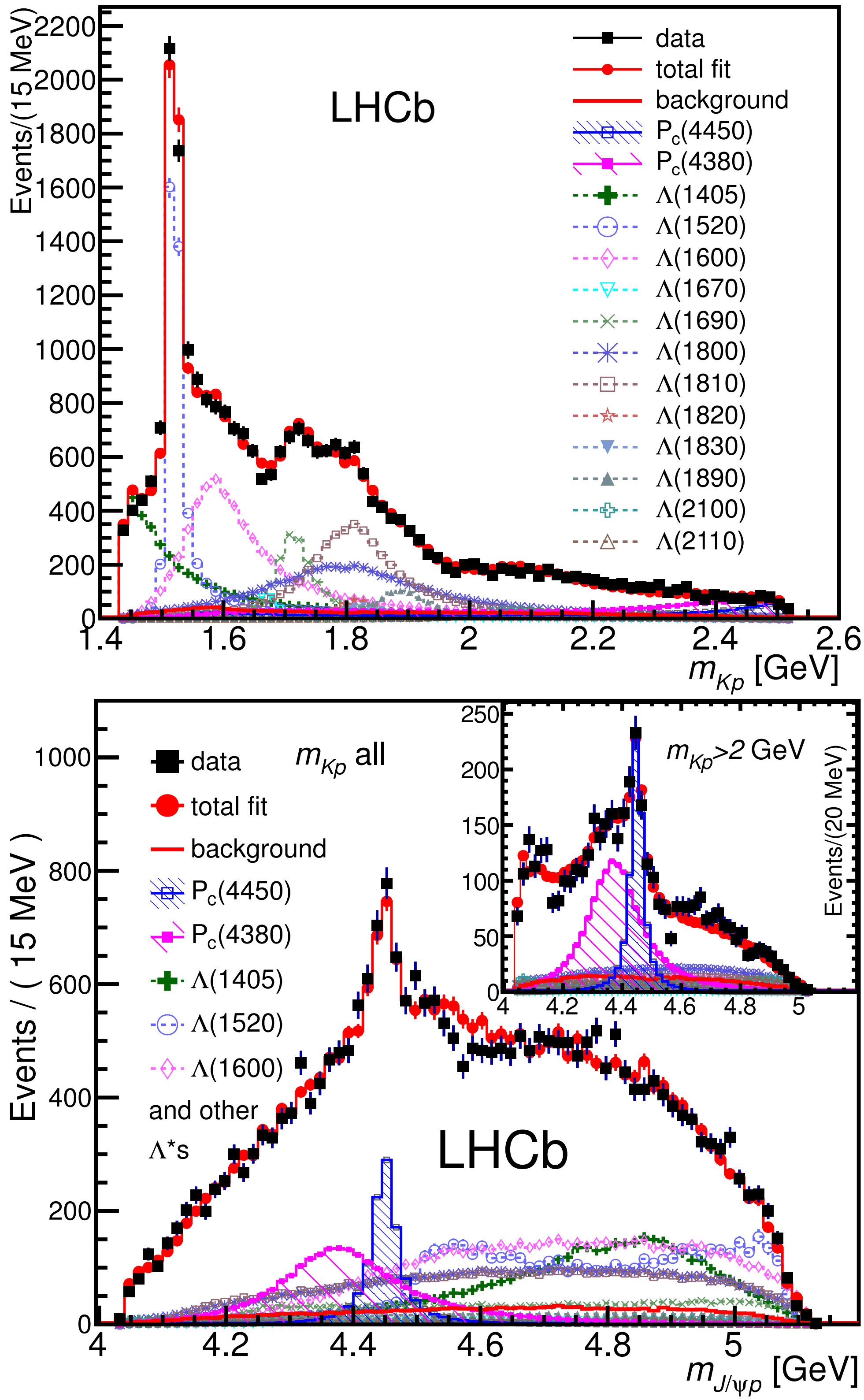

Figure 110.2: Projections of the amplitude fits with $P_c(4380)^+$ and $P_c(4450)^+$ states to the $\Lambda_b^0 \to J\psi pK^-$ data onto the invariant mass distributions of m_{Kp} (top) and $m_{J\psi p}$ (bottom).

at six equidistant points in the $\pm\Gamma_0$ range (interpolated in mass for continuity) which were fit to the data simultaneously with the other parameters of the full matrix element model. While the narrower $P_c(4450)^+$ state shows the expected resonant behavior, the diagram for $P_c(4380)^+$ deviates somewhat from the expectation. The statistical errors are large, especially for the broader $P_c(4380)^+$ state. Higher statistics data might make these diagrams more conclusive. The addition of further Λ states beyond the well-established ones, of Σ excitations (expected to be suppressed) and of non-resonant contributions with a constant amplitude, did not remove the need for two pentaquark states in the model to describe the data. Yet Λ^* spectroscopy is a complex problem, from both experimental and theoretical points of view. This is illustrated by the recent reanalysis of $\bar{K}N$ scattering data [12] in which the $\Lambda(1800)$ state, which was previously considered to be "well established", is not seen, and where evidence for a few previously unidentified states is included. In fact, all theoretical models of Λ^* baryons [13–18] predict a much larger number of higher mass excitations than is established experimentally. Because of the high density of predicted states, presumably with large widths, these may be difficult to identify experimentally. Non-resonant contributions with a non-trivial K^-p mass dependence may also be present. Therefore, LHCb also inspected their data with an approach that is nearly model-independent with respect to K^-p contributions [19].

A representation of the Dalitz plane distribution was constructed using the observed m_{Kp} distribution and Legendre polynomial moments of the cosine of the Λ^* helicity angle determined from the data as a function of m_{Kp}. The maximal rank of the moments generated by the K^-p contributions alone cannot be higher than twice the largest total angular momentum. Since high-spin Λ^* states cannot significantly contribute at low m_{Kp} values, high rank moments were excluded from the representation (see Fig. 1 and 3 in Ref. 19). When projected onto $m_{J\psi p}$ axis of the Dalitz plane, this representation cannot describe the data as shown in Fig. 110.4. The disagreement was quantified to be at least 9σ, thus the hypothesis that only K^-p contributions can generate the observed $m_{J\psi p}$ mass structure could be rejected with very high confidence without any assumptions about number of K^-p contributions, their resonant or non-resonant character, their mass shapes or their interference patterns. This proved a need for contributions from exotic hadrons or from rescattering effects of conventional ones. However, this approach is not suitable for their characterization.

Many theoretical groups interpreted the P_c^+ states in terms of diquarks and triquarks as building blocks of a compact pentaquark [20–26]. The pair of states of opposite parity with the 3/2 spin assignment to $P_c(4380)^+$ and 5/2 to $P_c(4450)^+$ can be achieved by increasing the angular momentum between the constituents by one unit, which can also make the heavier state narrower. However, their mass splitting is too small to be only due to this mechanism [20] and requires fine-tuning of such models. It is also not clear if centrifugal barrier factor provides enough width suppression via spatial separation of c and $\bar{c}$ quarks to explain the width ratio between the two P_c^+ states and the narrowness of $P_c(4450)^+$ in absolute units as the phase space for $J/\psi p$ decay is very large (more than 400 MeV).

More effective width suppression mechanism is offered by a loosely bound charmed baryon-anticharmed meson molecular model, in which c and $\bar{c}$ can be separated to much

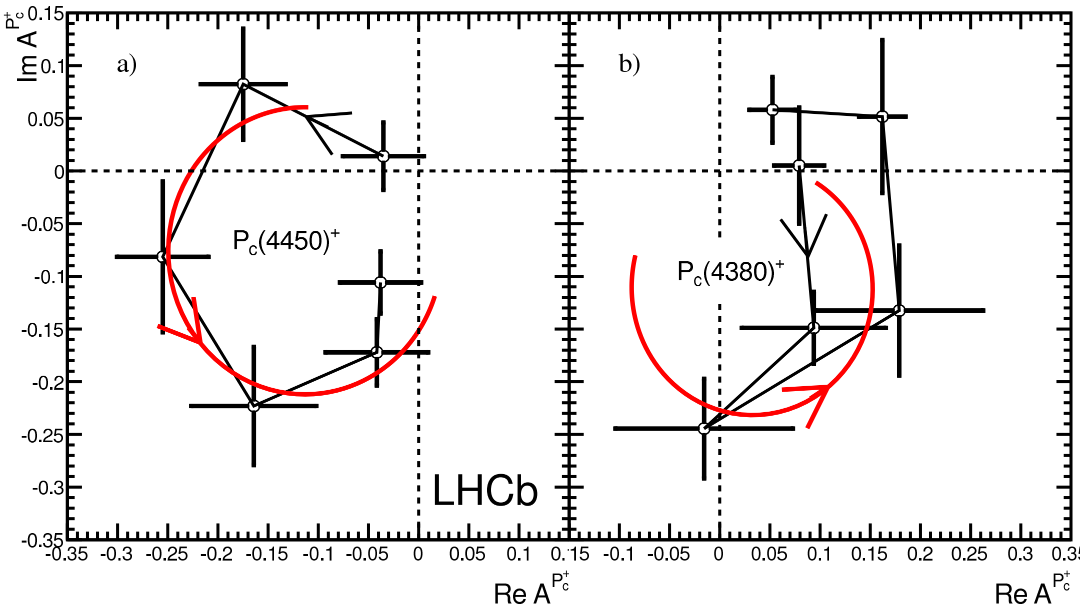

Figure 110.3: Fitted values of the real and imaginary parts of the amplitudes of the $P_c(4450)^+$ (left) and $P_c(4380)^+$ (right) states for $\Lambda_b^0 \to J\psi pK^-$ shown in the Argand diagrams as connected points with the error bars (masses increase counterclockwise). The solid red curves are the predictions from the Breit-Wigner formula, with resonance masses and widths set to the nominal fit results, scaled to the displayed points.

larger distances resulting in a smaller probability of them getting close to each other in order to make a J/ψ. Since molecular binding energy cannot be large, masses of such molecules must be near the sum of the baryon and meson masses. The narrowness of $P_c(4450)^+$ and its proximity to appropriate baryon-meson mass threshold make the molecular model attractive in spite of its inability to account for other features of the LHCb results (see below).

In order to view the narrow pentaquark in a wider perspective, it is useful to consider it together with several analogous exotic states with hidden charm and bottom in the meson sector. This provides additional significant motivation for the molecular model. At least five exotic mesons are close to thresholds of two heavy-light mesons: $X(3872)$ [27–30], $Z_b(10610)$ and $Z_b(10650)$ in the bottomonium sector [31–35] and $Z_c(3900)$ [36–40] and $Z_c(4020/4025)$ [41–43] in the charmonium sector (see Table II if Ref. 44). They share several important features: a) their masses are near thresholds and their spin and parity correspond to S-wave combination of the two mesons; b) they are very narrow, despite very large phase space for decay into quarkonium + pion(s); c) the branching fractions for "fall apart" mode into two mesons are much larger than branching fractions for decay

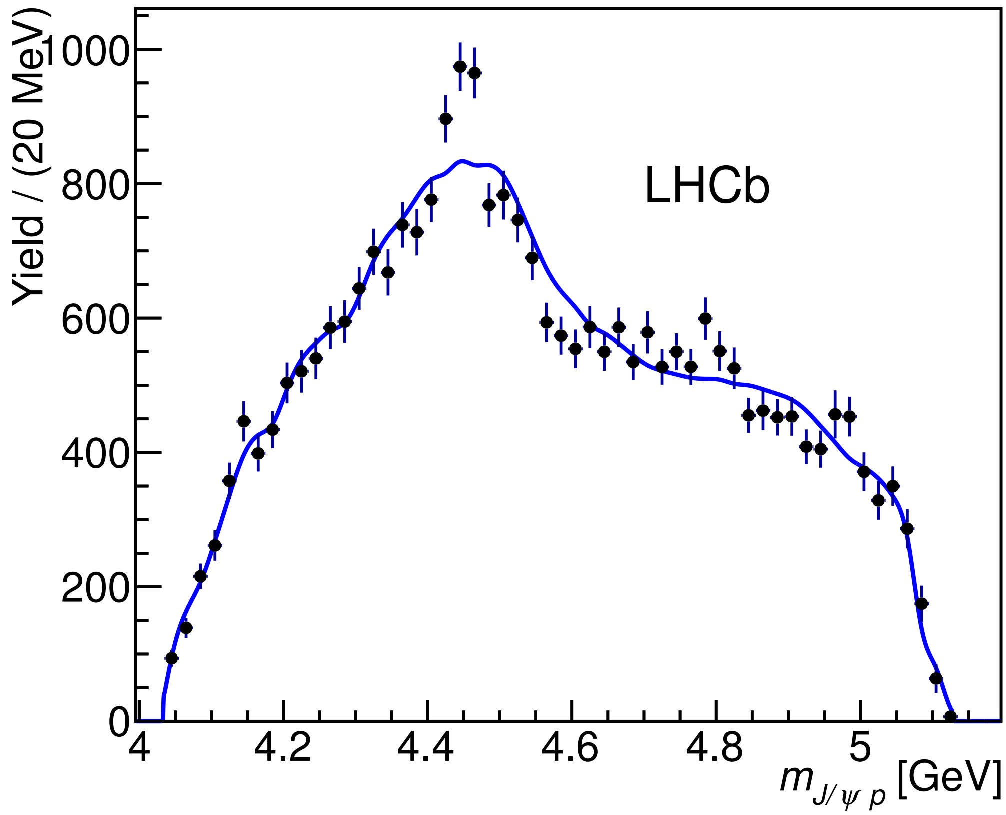

Figure 110.4: The efficiency-corrected and back-ground-subtracted distribution of $m_{J\psi p}$ for the data (black points with error bars), with the reflection of $K^{-}p$ mass distribution and of the moments of the $K^{-}p$ helicity angle, which can be accommodated by any plausible $K^{-}p$ contribution (solid blue line) superimposed. The data and the reflection are inconsistent at $> 9\sigma$ level.

into quarkonium and pion(s); d) there are no states at two pseudoscalar thresholds ($\bar{D}D$ and $\bar{B}B$), where there can be no binding through pseudoscalar exchange.

The above provide a strong hint that these states are deuteron-like loosely bound states of two heavy mesons [45–53]. It is then natural to conjecture that similar bound states might exist of two heavy baryons [54,55], or a meson and a baryon or a baryon and an antibaryon, leading to a rather accurate prediction of the $P_c(4450)^{+}$ mass as $3/2^{-}$ $\Sigma_c \bar{D}^{*}$ molecule: 4462.4 MeV [56,44]. It is essential that the two hadrons be heavy, in order to minimize the repulsive kinetic energy [54–57].

One may also consider a wider framework of doubly heavy baryon-meson hadronic molecules, which might include mixtures of various two-hadron states [58,59]. In this context it is important to keep in mind that the molecule's width cannot be smaller than the sum of its constituents' widths [60–62].

Following the LHCb discovery, several groups carried out a detailed analysis of the P_c^+ states as hadronic molecules [63–71]. The molecular picture has also been extended to a hadronic molecule built from a colored "baryon" and "meson" [72].

When trying to interpret both $P_c(4380)^+$ and $P_c(4380)^+$ as hadronic molecules, it is essential to remember that these two states have opposite parities. Thus one cannot construct both of them as S-wave bound states of a meson and a baryon with natural parities. Therefore, the interpretation of the P_c^+ states as hadronic molecules has been by no means unanimous. Moreover, the molecular model is not consistent with one of the P_c^+ states having a spin of 5/2, since S-wave combinations of baryon-meson combination that can produce such spin have thresholds which are too high in mass to be plausible. Therefore, the confirmation or disproval of the presence of this high-spin structure is a critical test of the molecular model. The large $P_c(4380)^+$ width is also difficult to accommodate in the molecular bound state model, but could have its origin in baryon-meson rescattering effects discussed below.

Shortly after the experimental discovery it has been conjectured that the observed resonances could be kinematic effects due to vicinity of thresholds and so-called triangle singularity [73–76]. While these effects might explain the large $P_c(4380)^+$ width, since such models involve S-wave rescattering of virtual baryon-meson pairs, they also cannot be reconciled with one of the P_c^+ peaks having effective spin of 5/2.

In addition to the molecular and diquark approach, the P_c^+ pentaquarks have also been analysed within the soliton picture of baryons, as a bound state of a soliton and an anticharmed meson [77]. Quite recently an interesting attempt has been made to explain the narrow width of tetraquarks and pentaquarks by extending to these states the string junction picture of baryons in QCD [78].

More extensive reviews of the theoretical issues can be found in Refs. 79,80.

So far the P_c^+ states have been observed by only one experiment in only one channel. It is essential to explore other possible experimental channels. Proposals have been made for searching for heavy pentaquarks in photoproduction [81–83], (c.f. also related work on computation of $J/\psi(\eta_c)N$ and $\Upsilon(\eta_b)N$ cross sections [84]) , in heavy ion collisions at LHC [85], in pA collisions [86], and in pion-induced processes [87,88].

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