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Observation of $J/\psi\, p$ Resonances Consistent With Pentaquark States

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Observation of $J/\psi\, p$ resonances with the LHCb detector in the $\Lambda_b^0 \to J/\psi\, pK^-$ decays consistent with pentaquark states is reported together with earlier LHCb results on the tetraquark candidates.

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The quark model was born out of symmetries discovered among the light meson and baryons. The three light quarks u, d, s were proposed as fundamental representation of this approximate SU(3)-flavor symmetry. All known mesons could be constructed by taking $q\bar{q}$ combinations, $3 \otimes \bar{3}$, while all baryons fit qqq combinations, $3 \otimes 3 \otimes 3$. Long before the dynamics of quark interactions was fully understood, Gell-Mann [1] and Zweig [2] suggested the possibility of particles built from more than the minimal quark content. In particular, tetraquark mesons built from $qq\bar{q}\bar{q}$ combinations and pentaquark baryons $qqqq\bar{q}$ were suggested. While initially there were many skeptics doubting existence of quarks, there were essentially none left after the "November 1974 revolution", when the J/ψ particle was discovered [3, 4] followed by observations of other excited $c\bar{c}$ mesons [5]. With the c quark mass being sufficiently heavy for the charmonium states to be treated as two-body bound state in a simple non-relativistic quantum mechanical approach, the mass spectrum and the quantum numbers of the observed long-lived states were reproduced with astonishing precision [6–8]. Quarks were no longer mathematical abstractions but physical constituents inside hadrons. It was not very useful to talk about an SU(4)-flavor symmetry including the c-quark, due to its heavy mass. However, the flavor dependence of hadronic structures was factored out into varying quark masses, while the flavor independence of strong interactions found its natural explanation in the exact SU(3)-color gauge symmetry of Quantum Chromo-Dynamics. This symmetry, does support the idea of tetra- and penta-quark states. In QCD, diquark combinations [9, 10], (qq) or $(\bar{q}\bar{q})$, are expected to have attractive forces forming complex $\bar{3}$ and 3 representations, respectively. Since they are not color neutral, they must couple to other colored structures to create color neutral hadrons observable in experiments. In fact, combining a quark (3) with a diquark (complex $\bar{3}$) is an alternative way to build a baryon, $(q(qq))$, instead of a direct three quark coupling, (qqq), which is also possible in QCD. Diquark (complex $\bar{3}$) combined with diantiquark (complex 3) leads to a color neutral tetraquark, $((qq)(\bar{q}\bar{q}))$, while diquark ($\bar{3}$) - diquark ($\bar{3}$) - antiquark ($\bar{3}$) to a pentaquark, $((qq)(qq)\bar{q})$. Unfortunately at present, lattice QCD calculations for such multi-quark structures are not advanced enough to know if bound states with sufficiently long lifetime are created to be detectable. The latter is likely to depend on the quark masses involved [11–14].

Experimental searches for both tetra- and penta-quark hadrons made out of light flavors have a long history. No undisputed candidates have been found in 50 years. Observations of pentaquarks candidates have an especially vivid history. The first wave of observations of pentaquark candidates with a strange antiquark inside happened 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 $Z_1(1900)$ [15]. The last mention of these candidates can be found in the 1992 edition [16] with perhaps a 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 came about, possibly motivated by the theoretical predictions of their existence [17–19]. The evidences for pentaquarks were 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 [20]. In the last mention of the best known candidate from that period, $\Theta(1540)^+$, the 2006 Particle Data Group listing [21] included a statement: "The conclusion that pentaquarks in general, and that Θ^+, in particular, do not exist, appears compelling." which well reflected prevailing mood of majority of particle physicists since then.

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In the same period, intriguing observations started trickling in from the investigation of states containing $c\bar{c}$ pairs and masses above the threshold for decay of charmonium states to $D\bar{D}$ meson pairs. As OZI allowed decays, they lead to large resonance widths of the order of $\sim 10^2$ MeV. Yet, an extremely narrow $X(3872)$ state with $\Gamma < 1.2$ MeV [5], was discovered by the Belle collaboration in 2003 at a mass indistinguishable from the $D^0\bar{D}^{*0}$ threshold [22], $M_{X(3872)} - M_{D^0} - M_{D^{*0}} = -0.11 \pm 0.19$ MeV [5], and exhibiting unusually large isospin violation via its decays to $\rho^0 J/\psi$ and $\omega J/\psi$. While the $\eta(1^1D_2)$ $J^{PC} = 2^{-+}$ $c\bar{c}$ state predicted near this mass, and the $\chi_c(2^3P_1)$ $J^{PC} = 1^{++}$ predicted at somewhat higher mass, would be narrow since they are forbidden to decay to $D\bar{D}$, the exact mass coincidence with the threshold and the isospin violation fueled speculations that it could be a 1^{++} $D\bar{D}^*$ molecule [23], $(c\bar{q})(\bar{c}q)$ $(q = u,d)$, or even a tightly bound 1^{++} tetraquark $((cu)(\bar{c}\bar{u}))$ [24], attracted to this particular mass value by the $D^0\bar{D}^{*0}$ cusp [25].

The Belle experiment soon also discovered the first charged state with the mass well above the $D\bar{D}^{(*)}$ thresholds, but decaying to the $c\bar{c}$ state instead [26]. The minimal quark content of this so-called $Z(4430)^+$ is $c\bar{c}u\bar{d}$. One of experimental complications here is to extract the information on this exotic $Z(4430)^+$ state, produced in $B^0 \to Z(4430)^+K^-$ and decaying via $Z(4430)^+ \to \psi'\pi^+$, in the presence of more prevalent $B^0 \to \psi'K^*$, $K^* \to K^-\pi^+$ decays, where K^*s are various kaon excitations. This state was initially claimed by Belle at $4433 \pm 4 \pm 2$ MeV with a narrow width, $45\,^{+18}_{-13}\,^{+30}_{-13}$ MeV, determined via naive fits to the $\psi'\pi^+$ distribution with ad hoc assumptions about the K^* backgrounds and neglecting possible interferences between the $Z(4430)$ and K^* contributions. The BaBar collaboration, which had a comparable data set, did not see evidence for this state and demonstrated consistency of their $\psi'\pi^+$ mass spectrum with reflections of possible K^* contributions, however they did not numerically contradict the Belle results [27]. The Belle collaboration later reanalyzed their data, with an amplitude-fit approach [28,29], which can correctly account for the $Z(4430) - K^*$ interferences, and renewed their claim for a significant $Z(4430)^+$ state, albeit with a higher mass, $4485\,^{+22}_{-22}\,^{+28}_{-11}$ MeV, and substantially larger width, $200\,^{+41}_{-46}\,^{+26}_{-35}$ MeV. Also note the significant reevaluation of the systematic uncertainties.

The LHCb experiment has been able to advance the experimental understanding of the tetraquark candidates introduced above, $X(3872)$ and $Z(4430)^+$, as well as to contribute the first observation of pentaquark candidates with $c\bar{c}$ pairs inside, thanks to its unique experimental capabilities [30]. As an experiment at a high energy hadron collider, it enjoys b quark production rates which are 1000 times larger than in the previous generation of the e^+e^- B factories where the Belle and BaBar detectors operated. Even after correcting for the smaller reconstruction efficiencies and shorter accumulated beam time, LHCb was able to accumulate in Run I of the LHC, data samples of B decays to J/ψ and light hadrons which are a factor 10 larger than previously available at the B factories. The signal purity is even slightly better than in Belle and BaBar, thanks to the long visible lifetime of the lightest hadrons with a b quark. This not only minimizes combinatorial backgrounds from the particles produced in the primary pp collisions, but also in the decays of the companion $\bar{b}$ hadron. A very important benefit of collecting data at a hadronic collider is a simultaneous production of B, B_s, B_c and Λ_b^0, in contrast with B factories where B_s samples require dedicated runs, and B_c and Λ_b^0 are not accessible. LHCb also has unique advantages over the general purpose detectors at LHC (ATLAS and CMS) or Tevatron (CDF and D0). As the first experiment dedicated to heavy flavors at the hadronic collider, it is equipped with a pair of RICH detectors for hadron identification, providing strong background suppression in the final states containing charged kaons or protons. The forward geometry of LHCb results in a compact volume, thus a smaller number of electronic channels translating to a smaller event size, which makes it affordable to trigger on heavy flavors with low transverse momentum ($p_{\rm T}$) thresholds on muons form the J/ψ or ψ' decays and with a large trigger bandwidth to tape (up to 5 kHz during Run I). Even though not employed in the analyses discussed here, the LHCb is also equipped with purely hadronic triggers on the final states produced in decay vertices detached from primary pp interaction points.

The first significant contribution of LHCb to exotic hadron spectroscopy, was to establish the $X(3872)$ spin and parity [31]. The helicity formalism was used to parameterize angular distributions in $B^+ \to X(3872)K^+$, $X(3872) \to \rho^0 J/\psi$, $\rho^0 \to \pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$. Three polar helicity angles, θ_X, θ_ρ, $\theta_{J/\psi}$, and two azimuthal angles between the decay planes, $\Delta\phi_{X,\rho}$, $\Delta\phi_{X,J/\psi}$, enter the formula for the matrix element, which contained up to 5 independent complex helicity couplings per J^P hypothesis, to be determined from the data as unknown nuisance parameters. The helicity couplings are more conveniently expressed as LS couplings, since the latter are all independent. Here, L is the orbital angular momentum in the X decay, and S is the total spin of ρ^0 plus J/ψ. The initial analysis was performed by assuming that the lowest value of L would dominate the decays. The key aspect of the analysis was to analyze full five-dimensional (5D) angular correlations. With a data sample which had statistical fluctuations only 30% smaller than in the previous attempt to use the angular distributions in this decay chain by Belle [32], the 1^{++} and 2^{-+} assignments were separated completely, while no separation between them was achieved in the analysis by Belle, which utilized only 1D distributions. The likelihood ratio test with unbinned 5D likelihoods was used by LHCb by comparing the value of that ratio for the two J^{PC} hypotheses as obtained on the data with the simulations of pseudoexperiments under the disfavored J^{PC}. Adding dimensions to an unbinned likelihood does not complicate the analysis much but it adds statistical power. When using all degrees of the decay kinematics the efficiency effects can be folded in without approximations by performing the normalization of the probability density function (PDF) by summing up values of the matrix element squared over Monte Carlo events generated uniformly in the decay phase-space and passed through the simulation of the detector response and of the selection criteria. The background in the $X(3872)$ sample is due to $B^+ \to J/\psi K^{*+}$, $K^{*+} \to K^+\pi^+\pi^-$ decays. Since the $X(3872)$ has an undetectably small natural width, the exact composition of this background is not important and can be subtracted using sidebands of the $X(3872)$ mass peak in the $m_{\pi^+\pi^- J/\psi}$ distribution. We subtracted it in the log-likelihoods using the *sPlot* technique [33] by assigning to each candidate an event weight, based on its $m_{\pi^+\pi^- J/\psi}$ value (so called "sFit" approach). The data favored the 1^{++} assignment by an overwhelming margin. This year, an update to this analysis was published. Using the full Run I data sample, 1011 ± 38 signal events were analyzed with the same technique but this time without restrictions on L values, thus fitting a larger number of helicity couplings to the data [34]. The 1^{++} assignment was confirmed and an upper limit on the D wave fraction of $< 4\%$ at 95% CL in the $X(3872) \to \rho^0 J/\psi$ decays was set. The LHCb has also measured the ratio of the branching fractions, $\mathscr{B}(X(3872) \to \psi'\gamma)/\mathscr{B}(X(3872) \to J/\psi\gamma) = 2.48 \pm 0.64 \pm 0.29$ [35], making it likely that $X(3872)$ has a significant $\chi_c(2^3P_1)$ component attracted to the threshold mass, likely mixed with a molecular state which gives raise to the strong isospin violation in its decays due to the separation of the $D^0\bar{D}^{*0}$ and $D^+\bar{D}^{*-}$ thresholds. An admixture of a tightly bound tetraquark is also possible.

The multi-dimensional likelihood approach and the helicity formalism was also used by LHCb

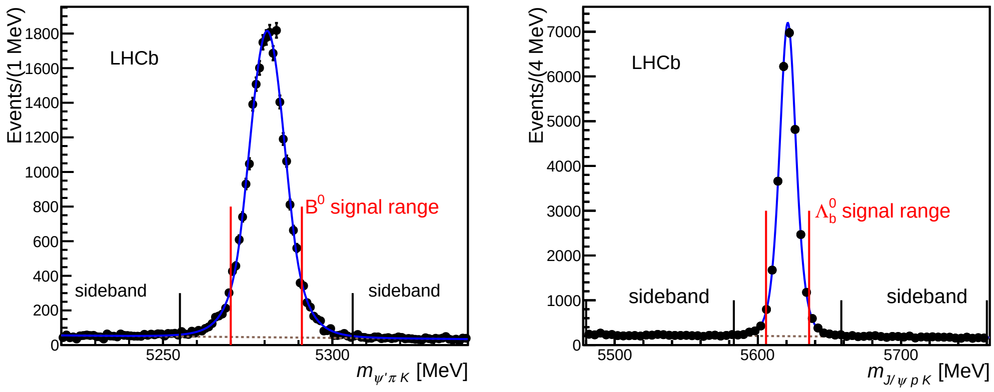

Figure 1: Distributions of invariant mass of selected $B^0 \to \psi' \pi^+ K^-$ (left) and $\Lambda_b^0 \to J/\psi\, pK^-$ (right) candidates. The data are shown by black points. The total fits (solid blue lines) of the signal peaks on top of the smooth backgrounds (dashed grey lines) are superimposed. The longer red vertical lines indicate the signal range used in the amplitude analyses. The shorter black vertical lines indicate the sidebands used to parameterize the background shapes in the amplitude fits. The bin size and mass ranges are different (the B^0 peak in narrower).

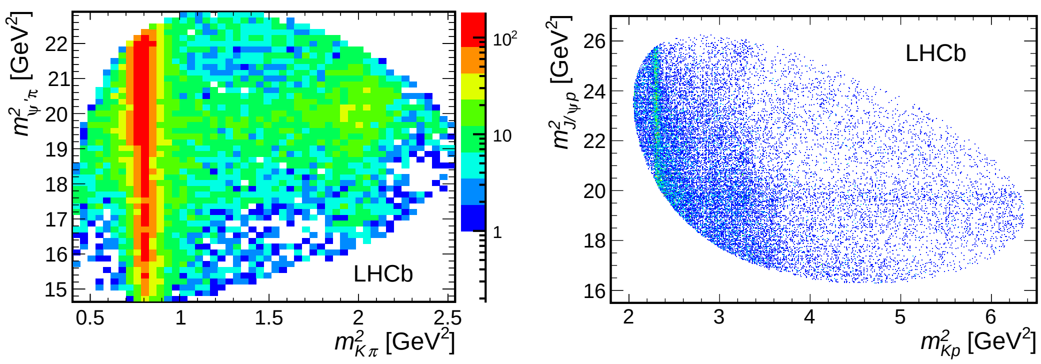

Figure 2: Dalitz plot distributions for $B^0 \to \psi' \pi^+ K^-$ (left) and $\Lambda_b^0 \to J/\psi\, pK^-$ (right) candidates.

to analyze $B^0 \to \psi' \pi^+ K^-$, $\psi' \to \mu^+\mu^-$ for a presence of the exotic $Z(4430)^+ \to \psi' \pi^+$ state [36]. The number of reconstructed B^0 decays in this decay mode, $25\,176 \pm 174$, was 12.5 times larger than in the Belle and BaBar measurements with a factor of two smaller background fraction: 4.1% in the sample used in the amplitude analysis. The background PDF was constructed from the parameterized distributions observed in the sidebands of the B^0 peak in the $m_{\psi'\pi K}$ distribution (Fig. 1), in so called "cFit" approach. The Dalitz plot of $m_{\psi'\pi}{}^2$ vs. $m_{K\pi}{}^2$ (Fig. 2) shows a horizontal band around the expected $Z(4430)^+$ mass (~ 20 GeV ^{2}), which is best visible in between the vertical bands corresponding to the $K^*(892)$ and $K_2^*(1430)$ resonances. The significance of the $Z(4430)^+$ contribution can be probed via a likelihood ratio test between the hypothesis that $B^0 \to \psi' K^*$, $K^* \to \pi^+ K^-$ contributions alone could describe the data well and the hypothesis that $Z(4430)^+$ must be included in the matrix element model. Two polar helicity angles, θ_{K^*}, θ_ψ, and one azimuthal angle between the decay planes of ψ' and K^* describe the angular distributions in the decays containing K^* resonances. There are 1-3 independent complex helicity couplings per each resonances as nuisance parameters. The presence of many, though well established, K^* resonances is a new factor in the matrix element formula which now also depends on the invariant mass of $K^-\pi^+$ system, $m_{K\pi}$, thus the likelihood is four-dimensional. The $K^-\pi^+$ allows only natural J^P combinations. The default K^* model included $J^P = 0^+$ non-resonant term, $K_0^*(800)$, $K_0^*(1430)$, 1^- $K^*(892)$, $K_1^*(1410)$, $K_1^*(1680)$ and 2^+ $K_2^*(1430)$. In the extended model we also allowed the 3^- $K_3^*(1780)$ state which has the mass above the phase space limit. The default (extended) K^* model contained 32 (38) free parameters to fit. The relative change of magnitude and phase of each resonance with the mass is assumed to follow relativistic Breit-Wigner formula (so called Isobar approach). The numerical values of the helicity couplings reflect the relative intensities and phases between various resonances (with only one resonance overall normalization and overall phase are arbitrary). The $B^0 \to Z(4430)^+K^-$, $Z(4430)^+ \to \psi'\pi^+$, $\psi' \to \mu^+\mu^-$ contribution to the matrix element depends on its own angles, θ_Z, ${\theta_\psi}^Z$, $\Delta\phi_{Z,\psi}$, and mass $m_{\psi'\pi}$. They can be all derived from the variables used in the K^* decay chain, and thus do not represent independent phase space dimensions. For example, for a given $m_{K\pi}$ value, $m_{\psi'\pi}$ and $\cos\theta_{K*}$ can be used interchangeably. The mass and the width of $Z(4430)^+$ were considered to be unknown and determined from the data. Various J^P assignments were tried. The fits with the K^* contributions alone failed to describe the data, especially in the $m_{\psi'\pi}$ projection (Fig. 3), even when the extended model was used. This has been also demonstrated without a model of the K^* resonances, using analysis of moments of the $\cos\theta_{K^*}$ distribution [37].

A satisfactory description of the data was achieved only after $J^P = 1^+$ $Z(4430)^+$ contribution was added, as illustrated in Figs. 4, 5 (the inset shows the part of the data in between the $K^*(892)$ and $K_2^*(1430)$ resonances) and 6. From the value of the likelihood ratio obtained on the data between the fits without and with $Z(4430)^+$, the significance of this state was established at 14σ using statistical simulations. The likelihood ratio between different J^P hypotheses established the 1^+ assignment at 9.7σ, confirming the 3.4σ evidence from the similar analysis by Belle. The measured mass, $4475 \pm 7^{+15}_{-25}$ MeV, width, $172 \pm 13^{+37}_{-34}$ MeV, and fit fraction, $5.9 \pm 0.9^{+1.5}_{-3.3}$ %, are consistent, but more precise, than the Belle results. Thanks to large statistics the LHCb was able to probe the $m_{\psi'\pi}$ dependence of $Z(4430)^+$ amplitude without imposing a Breit-Wigner formula. The real and imaginary parts of this amplitude were divided into six $m^2_{\psi'\pi}$ bins of equal width between 18.0 and 21.5 GeV^2 range, and fitted simultaneously with the helicity couplings of the K^* model.[1] They are shown in the Argand diagram (Fig. 7). The phase motion with the mass is counterclockwise, with the fastest change around the maximum of the amplitude, a characteristic of a resonance. This was the first demonstration of such a behavior for an exotic hadron candidate containing heavy quarks. It rules out the rescattering model by Pakhlov-Uglov [38], offered as an explanation for the $Z(4430)^+$ mass peak, since it predicted a phase mass running in the opposite direction. However, the latter is not a general feature of all rescattering models. The $J^P = 1^+$ quantum numbers rule out $D^*\bar{D}_1$ or $D^*\bar{D}_1^*$ molecular states as an explanation for $Z(4430)^+$. Assuming, the unconfirmed $D(2600)$ state [5] is a 2^3S_1 excitation, a $D\bar{D}(2600)$ molecule is not ruled out [39, 40], which calls for an experimental confirmation of $D(2600)$ and determination of its J^P. The other plausible ex-

[1] The D wave in the $Z(4430)^+$ decay was set to zero, since it was insignificant (1.3σ) when allowed in the default model.

planation is a tightly bound tetraquark state [41], possibly a radial excitation of $Z(3900)^+$ observed by BES-III and Belle [42, 43]. The presence of nearby thresholds (the $D\bar{D}^*$ threshold is 17 ± 4 MeV below the $Z(3900)^+$ mass [5]) could be coincidental or could play a role in attracting them. Rescattering of $D\bar{D}^*$ for $Z(3900)^+$ [44,45] and of $D\bar{D}^{*'}$ for $Z(4430)^+$ above their thresholds is also a possibility.

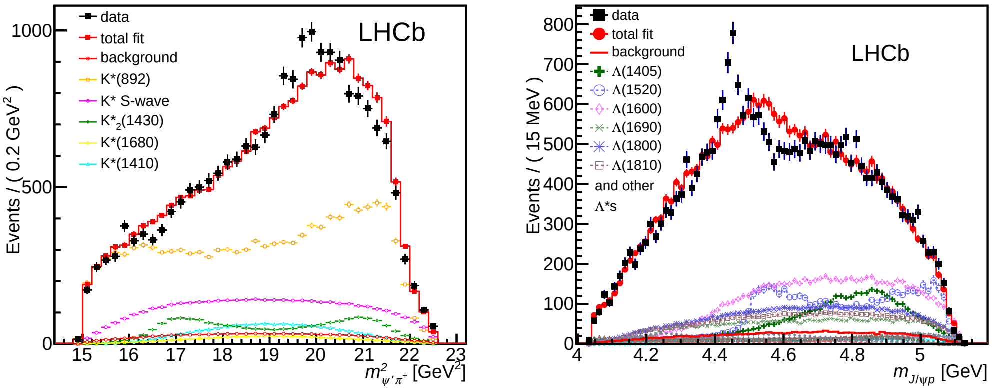

Figure 3: Projections of the amplitude fits without exotic hadron contributions onto the invariant mass distributions of $m^2_{\psi'\pi}$ for $B^0 \to \psi'\pi^+K^-$ (left) and of $m_{J/\psi\,p}$ for $\Lambda_b^0 \to J/\psi\,pK^-$ (right).

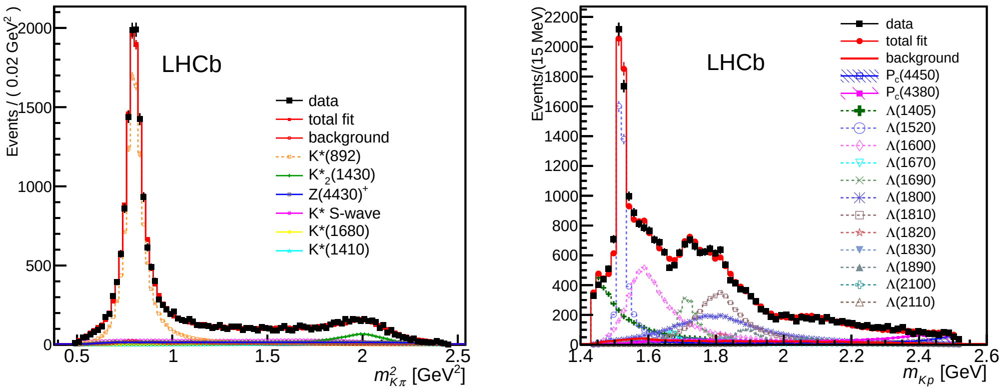

Figure 4: Projections of the amplitude fits with the exotic hadron contributions onto the invariant mass distributions of $m^2_{K\pi}$ for $B^0 \to \psi'\pi^+K^-$ (left) and of m_{Kp} for $\Lambda_b^0 \to J/\psi\,pK^-$ (right).

The decay $\Lambda_b^0 \to J/\psi\,pK^-$ ($J/\psi \to \mu^+\mu^-$) was observed for the first time by LHCb and used for the precision measurement of the Λ_b^0 lifetime [46,47]. In addition to many excitations of the Λ baryon (hereafter denoted as Λ^* resonances) decaying to pK^-, the data contained a narrow peak in the $J/\psi\,p$ mass distribution, which is easy to spot as a horizontal band in the Dalitz plot (Fig. 2). An amplitude analysis was necessary to clarify its nature. Since this analysis, described in detail in Ref. [48], follows in footsteps of the $Z(4430)^+$ analysis, it is interesting to illustrate the similarities and the differences. The final state is very similar, with π^+ being replaced by p. The

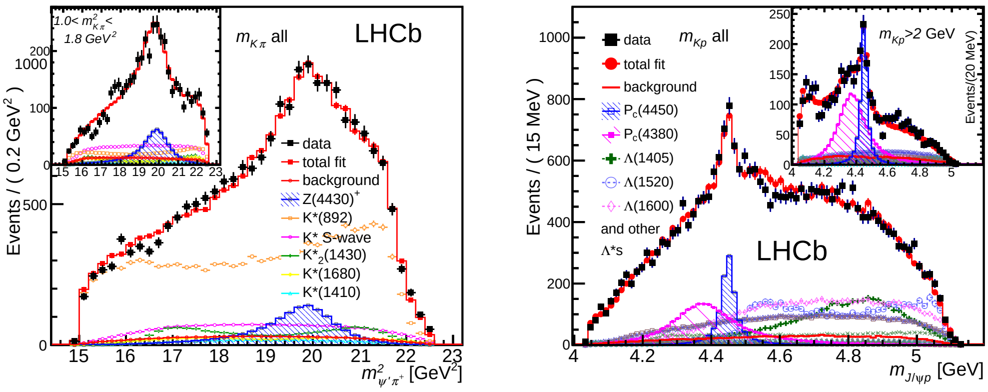

Figure 5: Projections of the amplitude fits with the exotic hadron contributions (see the text) onto the invariant mass distributions of $m^2_{\psi'\pi}$ for $B^0 \to \psi'\pi^+K^-$ (left) and of $m_{J/\psi\, p}$ for $\Lambda_b^0 \to J/\psi\, pK^-$ (right). The insets show the parts of the data samples in which the contributions from the non-exotic hadrons are the smallest.

signal statistics, $26,000 \pm 166$, and the background level, 5.4%, are very comparable as illustrated in Fig. 1. The cFit is used as the default approach, while sFit is used for cross-checks. The role of $K^* \to \pi^+K^-$ resonances is taken by $\Lambda^* \to pK^-$. There is a significant complication to the description of the full angular phase-space because the Λ_b^0 carries a spin of $1/2$, while the B^0 has no spin. This introduces an additional polar angle, $\theta_{\Lambda_b^0}$, and makes the Λ_b^0 decay plane serve as a reference for the Λ^* and J/ψ decay planes, $\Delta\phi_{\Lambda_b^0,\Lambda^*}$, $\Delta\phi_{\Lambda_b^0,\psi}$, instead of only their relative orientation being relevant. Thus, the likelihood function becomes six dimensional. The Λ_b^0 spin substantially increases the number of independent helicity couplings per resonance (4-6 complex numbers). Since unlike the π^+, the proton also carries a spin, both natural and unnatural J^P combinations are allowed for the Λ^*s. Furthermore, since J/ψ is significantly lighter than ψ', the phase space extends to higher excitations. Last but not least, baryons have a richer spectrum of the excitations than mesons. Together, these three factors lead to a much larger number of conventional resonances to consider than in the $Z(4430)^+$ analysis. Reasonably well established[2] Λ^* resonances are included in the default model: $J^P = 1/2^-$ $\Lambda(1405)$, $\Lambda(1670)$, $\Lambda(1800)$, $1/2^+$ $\Lambda(1600)$, $\Lambda(1810)$, $3/2^-$ $\Lambda(1520)$, $\Lambda(1690)$, $3/2^+$ $\Lambda(1890)$, $5/2^-$ $\Lambda(1830)$, $5/2^+$ $\Lambda(1820)$, $\Lambda(2110)$, and $7/2^-$ $\Lambda(2100)$. To reduce the number of LS couplings to fit, we neglect higher L values, using progressively less of them when moving closer to the kinematic upper bound on Λ^* mass, since the orbital angular momentum barrier should become more effective. Even after this reduction there are 64 free parameters to fit. We have also constructed an extended Λ^* model, in which all L couplings are allowed and two additional resonances are added: $9/2^+$ $\Lambda(2350)$ and $\Lambda(2585)$ assumed to be $5/2^-$. The extended Λ^* model has 146 free parameters to be determined from the data. The Λ^* contributions alone fail to describe the data even with the extended model. While the m_{Kp} distribution is reasonably well reproduced, the $m_{J/\psi\, p}$ distribution cannot be explained as illustrated in Fig. 3. It is necessary to add two exotic $P_c^+ \to J/\psi\, p$ contributions to the matrix element (20 additional free parameters),

[2]The resonances with the *** and **** classifications by the PDG [5].

before the narrow structure seen in $m_{J/\psi p}$ is reasonably well reproduced. This is achieved already with the reduced Λ^* model as illustrated in Figs. 4 and 5. The lower mass state, $P_c(4380)^+$, has a mass of $4380 \pm 8 \pm 29$ MeV, a width of $205 \pm 18 \pm 86$ MeV, a fit fraction of $8.4 \pm 0.7 \pm 4.2$ % and a significance of 9σ. The higher mass state, $P_c(4450)^+$, has a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV, a narrower width of $39 \pm 5 \pm 19$ MeV, a fit fraction of $4.1 \pm 0.5 \pm 1.1$ % and a significance of 12σ. A need for a second P_c^+ state becomes visually apparent when high m_{Kp} region is inspected, where the Λ^* backgrounds are the smallest (in the inset of Fig. 5). Even though the two P_c^+ states are best 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. This pattern requires them to be of opposite parity. The similar interference pattern is observed in the $\cos\theta_{\Lambda^*}$ distribution shown in Fig. 6, which is a consequence of parity-doublets in the Λ^* spectrum. Unfortunately, spins of the two P_c^+ states are not uniquely determined. Within the statistical and systematic ambiguities, $(3/2, 5/2)$ and $(5/2, 3/2)$ combinations with either $(-,+)$ or $(+,-)$ parities, could not be well resolved. The other combinations are disfavored. The Argand diagrams for the two P_c^+ states with their amplitudes binned in the $\pm\Gamma_0$ range are shown[3] in Fig. 7. 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, reflecting the larger contribution from the conventional hadrons under the signal peaks than in the $Z(4430)^+$ analysis.

The observed P_c^+ pair can be accommodated in the diquark model of tightly bound pentaquarks, via a difference in the orbital angular momentum of diquarks between the states, which explains their opposite parities [49–51]. In this model, the heavier state has a spin of 5/2, which also explains its smaller width due to the orbital angular momentum barrier factor in its decay. The narrower state can be also accommodated as a 3/2 baryon-meson molecule, either $\Sigma_c^+ \bar{D}^{*0}$ [52–55] or $p\chi_c(1P_1)$ [56]. The broader state could be a $3/2^-$ $\Sigma_c^{*+}\bar{D}^0$ molecule. The spin 5/2 cannot be reached in the molecular model, since the $L = 1$ molecular states are very unlikely to be bound. Rescattering models have been also proposed [57–59]. While they can produce peaks at the right masses, with the counterclockwise running of phase with the mass, they are expected to be very small except for the S-wave scattering. Since they use the same actors as the molecular models, they cannot explain the spin 5/2 either.

In summary, thanks to its unique capabilities, the LHCb experiments has made several important contributions to the spectroscopy of exotic hadrons. The quantum numbers of $X(3872)$ were established, and its radiative decays to ψ' and J/ψ investigated, narrowing down the scope of its plausible models. The $Z(4430)^+ \to \psi'\pi^+$ state has been confirmed in the amplitude analysis of the $B^0 \to \psi'\pi^+K^-$ decays, together with its quantum numbers. The first investigation of the Argand diagram for a heavy tetraquark candidate has been accomplished. It makes a resonant interpretation of the $Z(4430)^+$ more likely. In a similar amplitude analysis of the $\Lambda_b^0 \to J/\psi pK^-$ decays, two pentaquark candidates, $P_c(4380)^+$ and $P_c(4450)^+$, decaying to $J/\psi p$ have been observed with

[3]They are shown for the slightly preferred $(3/2^-, 5/2^+)$ assignment. They are very similar for the second most likely assignment, $(3/2^+, 5/2^-)$. The coupling corresponding to the lowest *LS* values was set to one, while the other *LS* couplings were allowed to float together with all parameters of the Λ^* model. One P_c^+ state is parameterized this way at a time, while the other is assumed to follow the Breit-Wigner formula.

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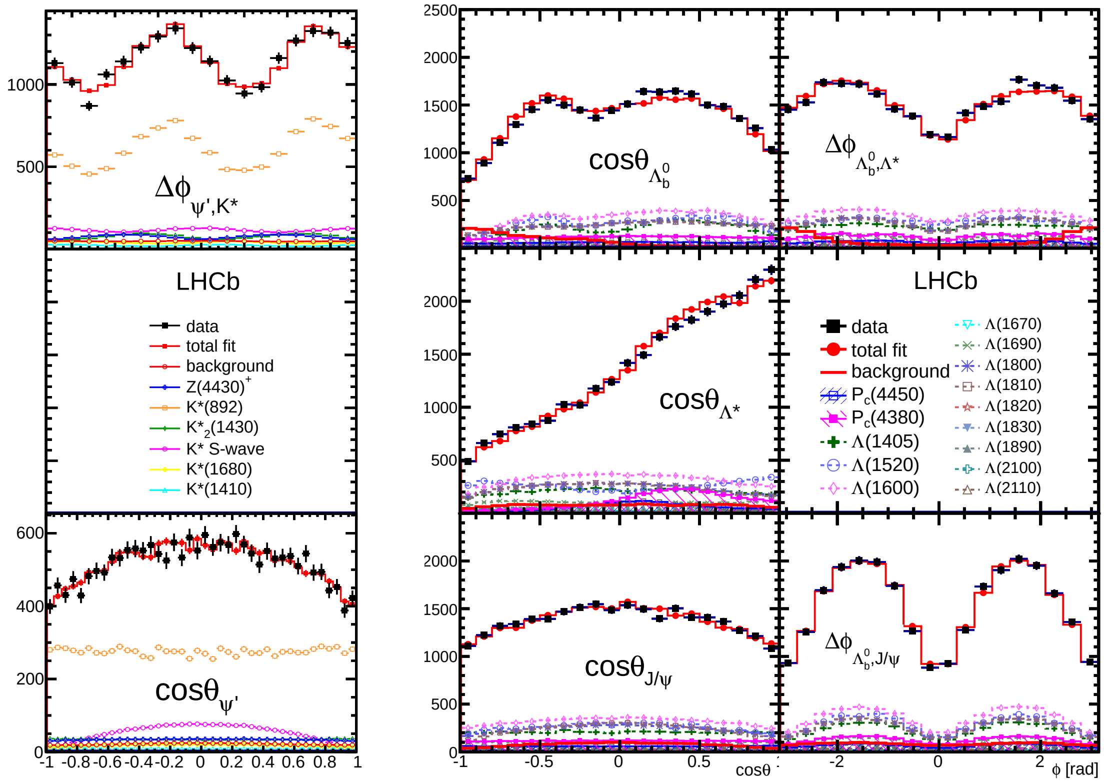

Figure 6: Projections of the amplitude fits with the exotic hadron contributions (see the text) onto the angular variables of the decay chains involving non-exotic hadrons only for $B^0 \to \psi'\pi^+K^-$ (left) and for $\Lambda_b^0 \to J/\psi\, pK^-$ (right).

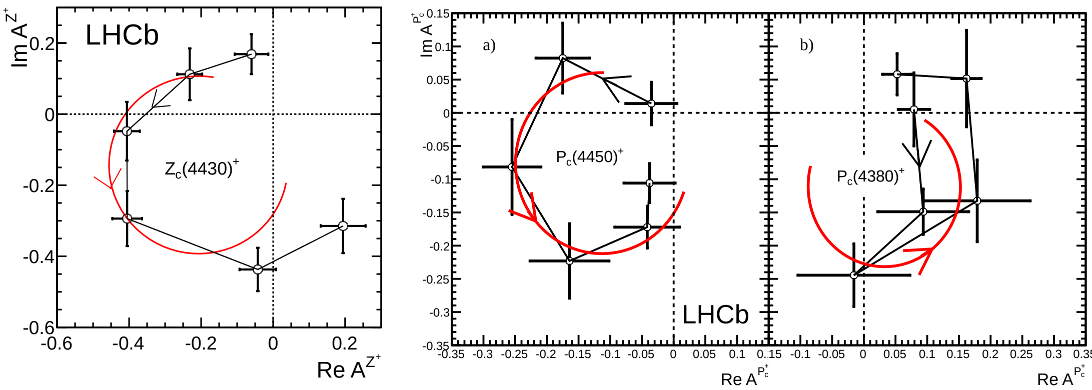

Figure 7: Fitted values of the real and imaginary parts of the amplitudes for the exotic states divided into six bins of equal width in the mass peak region of the $Z(4430)^+$ state for $B^0 \to \psi'\pi^+K^-$ (left) and of the $P_c(4450)^+$ and $P_c(4380)^+$ states for $\Lambda_b^0 \to J/\psi\, pK^-$ (two plots on the right), 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.

overwhelming significance. This resurrects pentaquarks from the ashes for the second time[4]; this time with a heavy $c\bar{c}$ pair inside. Given the role the charmonium system played in establishing the quark model, and later in producing a zoo of tetraquark candidates (for a recent review see Ref. [60]), this should not be a surprise. Hopefully, this observation will turn into a "July 2015 revolution" in hadron spectroscopy. However, much of experimental and theoretical work remains to be done to clarify the nature of the observed four- and five-quark structures.

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