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Evidence for Exotic Hadron Contributions to $\Lambda_b^0 \to J/\psi p \pi^-$ Decays

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A full amplitude analysis of $\Lambda_b^0 \to J/\psi p\pi^-$ decays is performed with a data sample acquired with the LHCb detector from 7 and 8 TeV pp collisions, corresponding to an integrated luminosity of 3 fb^{-1}. A significantly better description of the data is achieved when, in addition to the previously observed nucleon excitations $N \to p\pi^-$, either the $P_c(4380)^+$ and $P_c(4450)^+ \to J/\psi p$ states, previously observed in $\Lambda_b^0 \to J/\psi pK^-$ decays, or the $Z_c(4200)^- \to J/\psi\pi^-$ state, previously reported in $B^0 \to J/\psi K^+\pi^-$ decays, or all three, are included in the amplitude models. The data support a model containing all three exotic states, with a significance of more than three standard deviations. Within uncertainties, the data are consistent with the $P_c(4380)^+$ and $P_c(4450)^+$ production rates expected from their previous observation taking account of Cabibbo suppression.

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From the birth of the quark model, it has been anticipated that baryons could be constructed not only from three quarks, but also four quarks and an antiquark [1,2], hereafter referred to as pentaquarks [3,4]. The distribution of the $J/\psi p$ mass ($m_{J/\psi p}$) in $\Lambda_b^0 \to J/\psi pK^-$, $J/\psi \to \mu^+\mu^-$ decays (charge conjugation is implied throughout the text) observed with the LHCb detector at the LHC shows a narrow peak suggestive of $uudc\bar{c}$ pentaquark formation, amidst the dominant formation of various excitations of the Λ $[uds]$ baryon (Λ^*) decaying to K^-p [5,6]. It was demonstrated that these data cannot be described with K^-p contributions alone without a specific model of them [7]. Amplitude model fits were also performed on all relevant masses and decay angles of the six-dimensional data [5], using the helicity formalism and Breit-Wigner amplitudes to describe all resonances. In addition to the previously well-established Λ^* resonances, two pentaquark resonances, named the $P_c(4380)^+$ (9σ significance) and $P_c(4450)^+$ (12σ), are required in the model for a good description of the data [5]. The mass, width, and fractional yields (fit fractions) were determined to be $4380 \pm 8 \pm 29$ MeV, $205 \pm 18 \pm 86$ MeV, $(8.4 \pm 0.7 \pm 4.3)\%$, and $4450 \pm 2 \pm 3$ MeV, $39 \pm 5 \pm 19$ MeV, $(4.1 \pm 0.5 \pm 1.1)\%$, respectively. Observations of the same two P_c^+ states in another decay would strengthen their interpretation as genuine exotic baryonic states, rather than kinematical effects related to the so-called triangle singularity [8], as pointed out in Ref. [9].

In this Letter, $\Lambda_b^0 \to J/\psi p\pi^-$ decays are analyzed, which are related to $\Lambda_b^0 \to J/\psi pK^-$ decays via Cabibbo suppression. LHCb has measured the relative branching fraction $\mathcal{B}(\Lambda_b^0 \to J/\psi p\pi^-)/\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-) = 0.0824 \pm 0.0024 \pm 0.0042$ [10] with the same data sample as used here, corresponding to 3 fb^{-1} of integrated luminosity acquired by the LHCb experiment in pp collisions at 7 and 8 TeV center-of-mass energy. The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [11,12]. The data selection is similar to that described in Ref. [5], with the K^- replaced by a π^- candidate. In the preselection a larger significance for the Λ_b^0 flight distance and a tighter alignment between the Λ_b^0 momentum and the vector from the primary to the secondary vertex are required. To remove specific $\bar{B}^0$ and $\bar{B}_s^0$ backgrounds, candidates are vetoed within a 3σ invariant mass window around the corresponding nominal B mass [13] when interpreted as $\bar{B}^0 \to J/\psi\pi^+K^-$ or as $\bar{B}_s^0 \to J/\psi K^+K^-$. In addition, residual long-lived $\Lambda \to p\pi^-$ background is excluded if the $p\pi^-$ invariant mass ($m_{p\pi}$) lies within ± 5 MeV of the known Λ mass [13]. The resulting invariant mass spectrum of Λ_b^0 candidates is shown in Fig. 1. The signal yield is 1885 ± 50, determined by an unbinned extended maximum likelihood fit to the mass spectrum. The signal is described by a double-sided crystal ball function [14]. The combinatorial background is modeled by an exponential function. The background of $\Lambda_b^0 \to J/\psi pK^-$ events is described by a histogram obtained from simulation, with yield free to vary. This fit is used to assign weights to the candidates using the *s*Plot technique [15], which allows the signal component to be projected out by weighting each event depending on the $J/\psi p\pi^-$ mass. Amplitude fits are performed by minimizing a six-dimensional unbinned negative log likelihood, $-2\ln\mathcal{L}$, with the background subtracted using these

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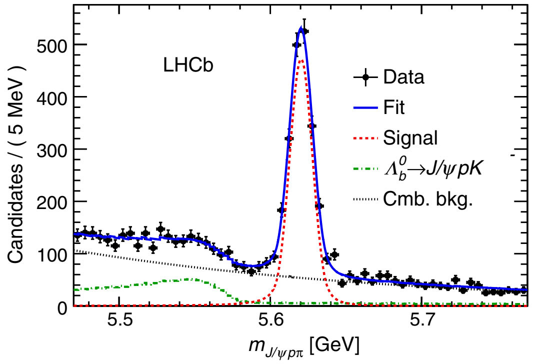

FIG. 1. Invariant mass spectrum for the selected $\Lambda_b^0 \to J/\psi p\pi^-$ candidates.

TABLE I. The N^* resonances used in the different fits. Parameters are taken from the PDG [13]. The number of LS couplings is listed in the columns to the right for the two versions (RM and EM) of the N^* model discussed in the text. To fix overall phase and magnitude conventions, the $N(1535)$ complex coupling of lowest LS is set to (1, 0).

State	J^P	Mass (MeV)	Width (MeV)	RM	EM
$NR\ p\pi$	$1/2^-$	...	...	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	...	3
$N(1700)$	$3/2^-$	1700	150	...	3
$N(1710)$	$1/2^+$	1710	100	...	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	...	3
$N(1900)$	$3/2^+$	1900	200	...	3
$N(2190)$	$7/2^-$	2190	500	...	3
$N(2300)$	$1/2^+$	2300	340	...	3
$N(2570)$	$5/2^-$	2570	250	...	3
Free parameters				40	106

weights and the efficiency folded into the signal probability density function, as discussed in detail in Ref. [5].

Amplitude models for the $\Lambda_b^0 \to J/\psi p\pi^-$ decays are constructed to examine the possibility of exotic hadron contributions from the $P_c(4380)^+$ and $P_c(4450)^+ \to J/\psi p$ states and from the $Z_c(4200)^- \to J/\psi\pi^-$ state, previously reported by the Belle Collaboration in $B^0 \to J/\psi K^+\pi^-$ decays [16] (spin parity $J^P = 1^+$, mass and width of $4196^{+31}_{-29}{}^{+17}_{-13}$ MeV and $370 \pm 70^{+70}_{-132}$ MeV, respectively). By analogy with kaon decays [17], $p\pi^-$ contributions from conventional nucleon excitations (denoted as N^*) produced with $\Delta I = 1/2$ in Λ_b^0 decays are expected to dominate over Δ excitations with $\Delta I = 3/2$, where I is isospin. The decay matrix elements for the two interfering decay chains, $\Lambda_b^0 \to J/\psi N^*$, $N^* \to p\pi^-$ and $\Lambda_b^0 \to P_c^+\pi^-$, $P_c^+ \to J/\psi p$ with $J/\psi \to \mu^+\mu^-$ in both cases, are identical to those used in the $\Lambda_b^0 \to J/\psi pK^-$ analysis [5], with K^- and Λ^* replaced by π^- and N^*. The additional decay chain, $\Lambda_b^0 \to Z_c^- p$, $Z_c^- \to J/\psi\pi^-$, is also included. Helicity couplings, describing the dynamics of the decays, are expressed in terms of LS couplings [5], where L is the decay orbital angular momentum, and S is the sum of spins of the decay products. This is a convenient way to incorporate parity conservation in strong decays and to allow for reduction of the number of free parameters by excluding high L values for phase-space suppressed decays.

Table I lists the N^* resonances considered in the amplitude model of $p\pi^-$ contributions. There are 15 well-established N^* resonances [13]. The high-mass and high-spin states (9/2 and 11/2) are not included, since they require $L \geq 3$ in the Λ_b^0 decay and therefore are unlikely to be produced near the upper kinematic limit of $m_{p\pi}$. Theoretical models of baryon resonances predict many more high-mass states [18], which have not yet been observed. Their absence could arise from decreased couplings of the higher N^* excitations to the simple production and decay channels [19] and possibly also from experimental difficulties in identifying broad resonances and insufficient statistics at high masses in scattering experiments. The possibility of high-mass, low-spin N^* states is explored by including two very significant, but unconfirmed, resonances claimed by the BESIII Collaboration in $\psi(2S) \to p\bar{p}\pi^0$ decays [20]: $1/2^+$ $N(2300)$ and $5/2^-$ $N(2570)$. A nonresonant $J^P = 1/2^-$ $p\pi^-$ S-wave component is also included. Two models, labeled "reduced" (RM) and "extended" (EM), are considered and differ in the number of resonances and of LS couplings included in the fit as listed in Table I. The reduced model, used for the central values of fit fractions, includes only the resonances and L couplings that give individually significant contributions. The systematic uncertainties and the significances for the exotic states are evaluated with the extended model by including all well-motivated resonances and the maximal number of LS couplings for which the fit is able to converge.

All N^* resonances are described by Breit-Wigner functions [5] to model their line shape and phase variation as a function of $m_{p\pi}$, except for the $N(1535)$, which is described by a Flatté function [21] to account for the threshold of the $n\eta$ channel. The mass and width are fixed to the values determined from previous experiments [13]. The couplings to the $n\eta$ and $p\pi^-$ channels for the $N(1535)$ state are determined by the branching fractions of the two channels [22]. The nonresonant S-wave component is described with a function that depends inversely on $m_{p\pi}^2$, as this is found to be preferred by the data. An alternative description of the $1/2^-$ $p\pi^-$ contributions, including the $N(1535)$ and nonresonant components, is provided by a K-matrix model obtained from multichannel partial wave

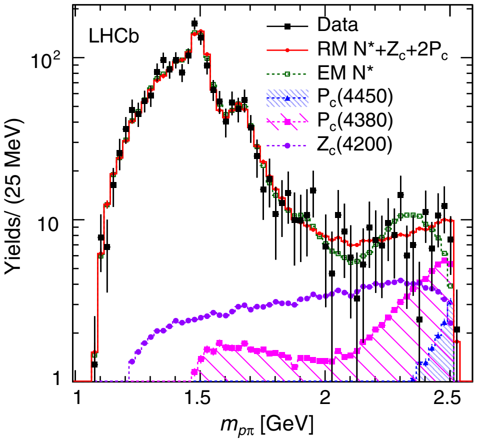

FIG. 2. Background-subtracted data and fit projections onto $m_{p\pi}$. Fits are shown with models containing N^* states only (EM) and with N^* states (RM) plus exotic contributions.

analysis by the Bonn-Gatchina group [22,23] and is used to estimate systematic uncertainties.

The limited number of signal events and the large number of free parameters in the amplitude fits prevent an open-ended analysis of $J/\psi p$ and $J/\psi\pi^-$ contributions. Therefore, the data are examined only for the presence of the previously observed $P_c(4380)^+$, $P_c(4450)^+$ states [5] and the claimed $Z_c(4200)^-$ resonance [16]. In the fits, the mass and width of each exotic state are fixed to the reported central values. The LS couplings describing $P_c^+ \to J/\psi p$ decays are also fixed to the values obtained from the Cabibbo-favored channel. This leaves four free parameters per P_c^+ state for the $\Lambda_b^0 \to P_c^+\pi^-$ couplings. The nominal fits are performed for the most likely $(3/2^-, 5/2^+)$ J^P assignment to the $P_c(4380)^+$, $P_c(4450)^+$ states [5]. All couplings for the 1^+ $Z_c(4200)^-$ contribution are allowed to vary (ten free parameters).

The fits show a significant improvement when exotic contributions are included. When all three exotic contributions are added to the EM N^*-only model, the $\Delta(-2\ln\mathcal{L})$ value is 49.0, which corresponds to their combined statistical significance of 3.9σ. Including the systematic uncertainties discussed later lowers their significance to 3.1σ. The systematic uncertainties are included in subsequent significance figures. Because of the ambiguity between the $P_c(4380)^+$, $P_c(4450)^+$ and $Z_c(4200)^-$ contributions, no single one of them makes a significant difference to the model. Adding either state to a model already containing the other two, or the two P_c^+ states to a model already containing the $Z_c(4200)^-$ contribution, yields significances below 1.7σ [0.4σ for adding the $Z_c(4200)^-$ after the two P_c^+ states]. If the $Z_c(4200)^-$ contribution is assumed to be negligible, adding the two P_c^+ states to a model without exotics yields a significance of 3.3σ. On the other hand, under the assumption that no P_c^+ states are produced, adding the $Z_c(4200)^-$ to a model without exotics yields a significance of 3.2σ. The significances are determined using Wilks' theorem [24], the applicability of which has been verified by simulation.

A satisfactory description of the data is already reached with the RM N^* model if either the two P_c^+, or the Z_c^-, or all three states, are included in the fit. The projections of the full amplitude fit onto the invariant masses and the decay angles reasonably well reproduce the data, as shown in Figs. 2–5. The EM N^*-only model does not give good descriptions of the peaking structure in $m_{J/\psi p}$ observed for $m_{p\pi} > 1.8$ GeV [Fig. 3(b)]. In fact, all contributions to $\Delta(-2\ln\mathcal{L})$ favoring the exotic components belong to this $m_{p\pi}$ region. The models with the P_c^+ states describe the $m_{J/\psi p}$ peaking structure better than with the $Z_c(4200)^-$ alone (see Supplemental Material [25]).

The model with all three exotic resonances is used when determining the fit fractions. The sources of systematic uncertainty are listed in Table II. They include varying the masses and widths of N^* resonances, varying the masses and widths of the exotic states, considering N^* model

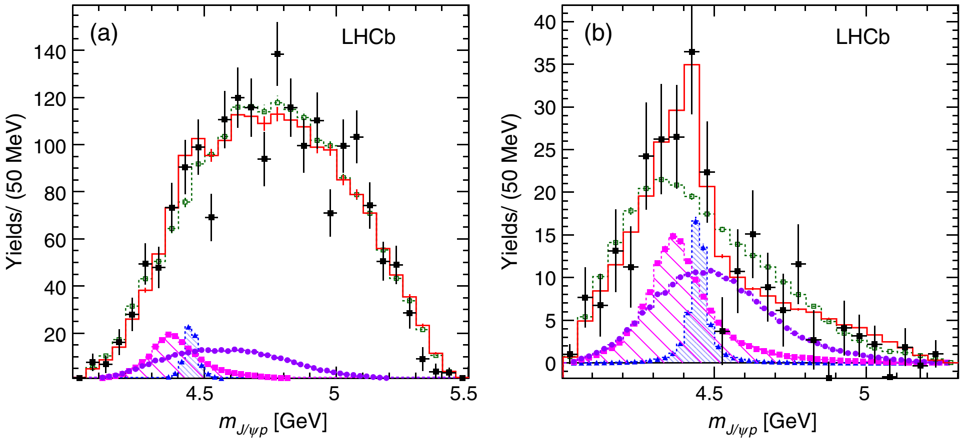

FIG. 3. Background-subtracted data and fit projections onto $m_{J/\psi p}$ for (a) all events and (b) the $m_{p\pi} > 1.8$ GeV region. See the legend and caption of Fig. 2 for a description of the components.

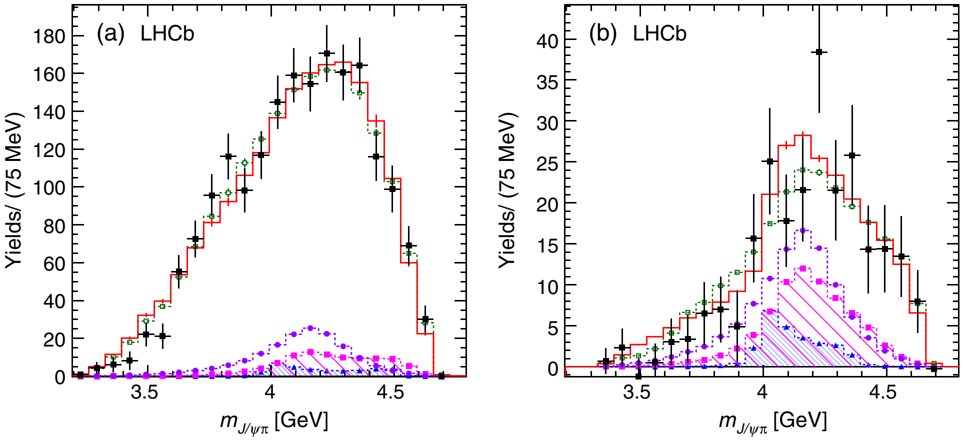

FIG. 4. Background-subtracted data and fit projections onto $m_{J/\psi\pi}$ for (a) all events and (b) the $m_{p\pi} > 1.8$ GeV region. See the legend and caption of Fig. 2 for a description of the components.

dependence and other possible spin parities J^P for the two P_c^+ states, varying the Blatt-Weisskopf radius [5] between 1.5 and 4.5 GeV^{-1}, changing the angular momenta L in Λ_b^0 decays that are used in the resonant mass description by one or two units, using the K-matrix model for the S-wave $p\pi$ resonances, varying the fixed couplings of the P_c^+ decay by their uncertainties, and splitting Λ_b^0 and J/ψ helicity angles into bins when determining the weights for the background subtraction to account for correlations between the invariant mass of $J/\psi p\pi^-$ and these angles. A putative $Z_c(4430)^-$ contribution [16,26,27] hardly improves the value of $-2\ln\mathcal{L}$ relative to the EM N^*-only model, and thus is considered among systematic uncertainties. Exclusion of the $Z_c(4200)^-$ state from the fit model is also considered to determine the systematic uncertainties for the two P_c^+ states.

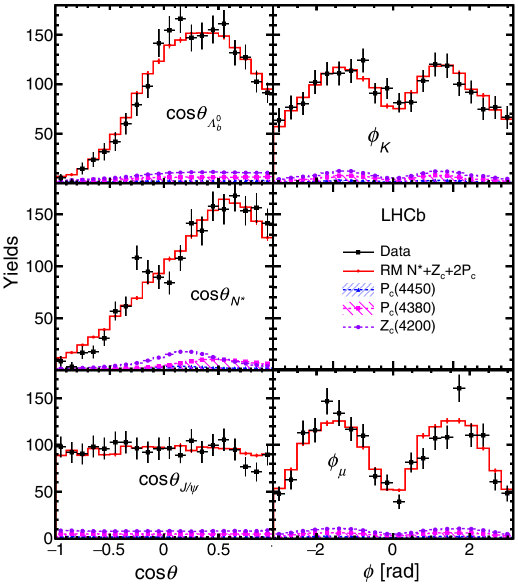

FIG. 5. Background-subtracted data and fit projections of decay angles describing the N^* decay chain, which are included in the amplitude fit. The helicity angle of particle P, θ_P, is the polar angle in the rest frame of P between a decay product of P and the boost direction from the particle decaying to P. The azimuthal angle between decay planes of Λ_b^0 and N^* (of J/ψ) is denoted as ϕ_π (ϕ_μ). See Ref. [5] for more details.

The EM model is used to assess the uncertainty due to the N^* modeling when computing significances. The RM model gives larger significances. All sources of systematic uncertainties, including the ambiguities in the quantum number assignments to the two P_c^+ states, are accounted for in the calculation of the significance of various contributions, by using the smallest $\Delta(-2\ln\mathcal{L})$ among the fits representing different systematic variations.

The fit fractions for the $P_c(4380)^+$, $P_c(4450)^+$ and $Z_c(4200)^-$ states are measured to be $(5.1 \pm 1.5^{+2.6}_{-1.6})\%$,

TABLE II. Summary of absolute systematic uncertainties of the fit fractions in units of percent.

Source	$P_c(4450)^+$	$P_c(4380)^+$	$Z_c(4200)^-$
N^* masses and widths	± 0.05	± 0.23	± 0.31
P_c^+, Z_c^- masses and widths	± 0.32	± 1.27	± 1.56
Additional N^*	${}^{+0.08}_{-0.23}$	${}^{+0.59}_{-0.55}$	${}^{+0.71}_{-2.92}$
Inclusion of $Z_c(4430)^-$	$+0.01$	$+0.97$	$+2.87$
Exclusion of $Z_c(4200)^-$	-0.15	$+1.61$	$\cdots$
Other J^P	${}^{+0.38}_{-0.00}$	${}^{+0.92}_{-0.28}$	${}^{+0.00}_{-2.16}$
Blatt-Weisskopf radius	± 0.11	± 0.17	± 0.21
$L_{\Lambda_b^0}^{N^*}$ in $\Lambda_b^0 \to J/\psi N^*$	± 0.07	± 0.46	± 0.04
$L_{\Lambda_b^0}^{P_c}$ in $\Lambda_b^0 \to P_c^+\pi^-$	-0.05	-0.17	$+0.09$
$L_{\Lambda_b^0}^{Z_c}$ in $\Lambda_b^0 \to Z_c^- p$	± 0.07	± 0.22	± 0.53
K-matrix model	-0.03	$+0.11$	-0.02
P_c^+ couplings	± 0.14	± 0.31	± 0.36
Background subtraction	-0.07	-0.13	-0.39
Total	${}^{+0.55}_{-0.48}$	${}^{+2.61}_{-1.58}$	${}^{+3.43}_{-4.04}$

$(1.6^{+0.8}_{-0.6}{}^{+0.6}_{-0.5})\%$, and $(7.7 \pm 2.8^{+3.4}_{-4.0})\%$ respectively, and to be less than 8.9%, 2.9%, and 13.3% at 90% confidence level, respectively. When the two P_c^+ states are not considered, the fraction for the $Z_c(4200)^-$ state is surprisingly large, $(17.2 \pm 3.5)\%$, where the uncertainty is statistical only, given that its fit fraction was measured to be only $(1.9^{+0.7}_{-0.5}{}^{+0.9}_{-0.5})\%$ in $B^0 \to J/\psi K^+\pi^-$ decays [16]. Conversely, the fit fractions of the two P_c^+ states remain stable regardless of the inclusion of the $Z_c(4200)^-$ state. We measure the relative branching fraction $R_{\pi/K} \equiv \mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)/\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)$ to be $0.050 \pm 0.016^{+0.026}_{-0.016} \pm 0.025$ for $P_c(4380)^+$ and $0.033^{+0.016}_{-0.014}{}^{+0.011}_{-0.010} \pm 0.009$ for $P_c(4450)^+$, respectively, where the first error is statistical, the second is systematic, and the third is due to the systematic uncertainty on the fit fractions of the P_c^+ states in $J/\psi pK^-$ decays. The results are consistent with a prediction of (0.07–0.08) [28], where the assumption is made that an additional diagram with internal W emission, which can only contribute to the Cabibbo-suppressed mode, is negligible. Our measurement rules out the proposal that the P_c^+ state in the $\Lambda_b^0 \to J/\psi pK^-$ decay is produced mainly by the charmless Λ_b^0 decay via the $b \to u\bar{u}s$ transition, since this predicts a very large value for $R_{\pi/K} = 0.58 \pm 0.05$ [29].

In conclusion, we have performed a full amplitude fit to $\Lambda_b^0 \to J/\psi p\pi^-$ decays allowing for previously observed conventional $(p\pi^-)$ and exotic ($J/\psi p$ and $J/\psi\pi^-$) resonances. A significantly better description of the data is achieved by either including the two P_c^+ states observed in $\Lambda_b^0 \to J/\psi pK^-$ decays [5], or the $Z_c(4200)^-$ state reported by the Belle Collaboration in $B^0 \to J/\psi\pi^-K^+$ decays [16]. If both types of exotic resonances are included, the total significance for them is 3.1σ. Individual exotic hadron components, or the two P_c^+ states taken together, are not significant as long as the other(s) is (are) present. Within the statistical and systematic errors, the data are consistent with the $P_c(4380)^+$ and $P_c(4450)^+$ production rates expected from their previous observation and Cabibbo suppression. Assuming that the $Z_c(4200)^-$ contribution is negligible, there is a 3.3σ significance for the two P_c^+ states taken together.

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