Model-Independent Evidence for Exotic Hadron Contributions to $b^0J/\psi$ Decays

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Model-Independent Evidence for \( J/\psi p \) Contributions to \( \Lambda_b^0 \to J/\psi pK^- \) Decays

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The data sample of \( \Lambda_b^0 \to J/\psi pK^- \) decays acquired with the LHCb detector from 7 and 8 TeV \( pp \) collisions, corresponding to an integrated luminosity of 3 fb\(^{-1}\), is inspected for the presence of \( J/\psi p \) or \( J/\psi K^- \) contributions with minimal assumptions about \( K^- p \) contributions. It is demonstrated at more than nine standard deviations that \( \Lambda_b^0 \to J/\psi pK^- \) decays cannot be described with \( K^- p \) contributions alone, and that \( J/\psi p \) contributions play a dominant role in this incompatibility. These model-independent results support the previously obtained model-dependent evidence for \( P_c^+ \to J/\psi p \) charmonium-pentaquark states in the same data sample.

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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 from four quarks and an antiquark \[1,2\], hereafter referred to as pentaquarks. The distribution of \( J/\psi p \) mass \( (m_{J/\psi p}) \) in \( \Lambda_b^0 \to J/\psi pK^- \), \( J/\psi \to \mu^+\mu^- \) decays observed with the LHCb detector at the LHC shows a narrow peak suggestive of \( uu\bar{c}\bar{c} \) pentaquark formation, amongst the dominant formation of various excitations of the \( \Lambda \) [\(uds\)] baryon (\( \Lambda^+ \)) decaying to \( K^- p \) \[3\]. The inclusion of charge conjugate states is implied in this Letter.) Amplitude analyses were performed on all relevant masses and decay angles of the six-dimensional (6D) data, using the helicity formalism and Breit-Wigner amplitudes to describe all resonances. In addition to the previously well established \( \Lambda^+ \) resonances, two pentaquark resonances \( P_c(4380)^+ \) (9\(\sigma \) significance) and \( P_c(4450)^+ \) (12\(\sigma \)) were required in the model for a good description of the data. The mass, width, and fit fractions were determined to be 4380±8±29 MeV, 205±18±86 MeV, 8.4%±0.7%±4.3%, and 4450±2±3 MeV, 39±5±19 MeV, 4.1%±0.5%±1.1%, respectively. The Cabibbo suppressed \( \Lambda_b^0 \to J/\psi p\pi^- \) decays are consistent with the presence of these resonances \[4\].

The addition of further \( \Lambda^+ \) states beyond the well-established ones, and of nonresonant contributions, did not remove the need for two pentaquark states in the model to describe the data. Yet \( \Lambda^+ \) spectroscopy is a complex problem, as pointed out in a recent reanalysis of \( K\bar{N} \) scattering data \[5\], in which the well-established \( \Lambda(1800) \) state was not seen, and evidence for a few previously unidentified states was obtained. Theoretical models of \( \Lambda^+ \) baryons \[6–11\] predict a much larger number of higher mass excitations than is established experimentally \[12\]. The high density of predicted states, presumably with large widths, would make it difficult to identify them experimentally. Nonresonant contributions with nontrivial \( K^- p \) mass dependence may also be present. Therefore, it is worth inspecting the \( \Lambda_b^0 \to J/\psi pK^- \) data with an approach that is model independent with respect to \( K^- p \) contributions. Such a method was introduced by the BABAR Collaboration \[13\] and later improved upon by the LHCb Collaboration \[14\].

There it was used to examine \( \bar{B}^0 \to \psi(2S)\pi^+K^- \) decays, which are dominated by kaon excitations decaying to \( K^- \pi^+ \), in order to understand whether the data require the presence of the tetraquark candidate decay, \( Z(4430)^+ \to \psi(2S)\pi^+ \). In this Letter, this method is applied to the same \( \Lambda_b^0 \to J/\psi pK^- \) sample previously analyzed in the amplitude analysis \[3\]. The sensitivity of the model-independent approach to exotic resonances is investigated with simulation studies.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range \( 2<\eta<5 \), described in detail in Ref. \[15\]. The data selection is described in Ref. \[3\]. A mass window of \( \pm 2\sigma \) (\( \sigma=7.5 \) MeV) around the \( \Lambda_b^0 \) mass peak is selected, leaving \( n_{\text{sig}}^{\text{cand}}=27469 \) \( \Lambda_b^0 \) candidates for further analysis, with background fraction (\( \beta \)) equal to 5.4%. The background is subtracted using \( n_{\text{side}}^{\text{cand}}=10259 \) candidates from the \( \Lambda_b^0 \) sidebands, which extend from \( \pm 38 \) to \( \pm 140 \) MeV from the peak (see the Supplemental Material \[16\]).

The aim of this analysis is to assess the level of consistency of the data with the hypothesis that all \( \Lambda_b^0 \to J/\psi pK^- \) decays proceed via \( \Lambda_b^0 \to J/\psi \Lambda^+ \), \( \Lambda^+ \to pK^- \), with minimal assumptions about the spin and line shape of possible \( \Lambda^+ \) contributions. This will be referred to as the null hypothesis \( H_0 \). Here, \( \Lambda^+ \) denotes not only excitations of the \( \Lambda \) baryon, but also nonresonant \( K^- p \) contributions or excitations of the \( \Sigma \) baryon. The latter contributions are expected to be small \[17\]. The analysis method is two dimensional and uses the information contained in the
Dalitz variables, \((m_{Kp}^2, m_{J/Ψp}^2, m_{J/Ψp}^2)\), or equivalently, in \((m_{Kp}, \cos θ_{Λ}^c)\), where \(θ_{Λ}^c\) is the helicity angle of the \(K^-p\) system, defined as the angle between the \(\vec{p}_K\) and \(-\vec{p}_{J/Ψ}\) directions in the \(K^-p\) rest frame.

The \((m_{Kp}, \cos θ_{Λ}^c)\) plane is particularly suited for implementing constraints stemming from the \(H_0\) hypothesis by expanding the \(\cos θ_{Λ}^c\) angular distribution in Legendre polynomials \(P_l\),

\[
dN/d \cos θ_{Λ}^c = \sum_{l=0}^{l_{max}} \langle P_l^H \rangle P_l(\cos θ_{Λ}^c),
\]

where \(N\) is the efficiency-corrected and background-subtracted signal yield, and \(\langle P_l^H \rangle\) is an unnormalized Legendre moment of rank \(l\),

\[
\langle P_l^H \rangle = \int_{-1}^{+1} d \cos θ_{Λ}^c P_l(\cos θ_{Λ}^c) dN/d \cos θ_{Λ}^c.
\]

Under the \(H_0\) hypothesis, \(K^-p\) components cannot contribute to moments of rank higher than \(2J_{max}\), where \(J_{max}\) is the highest spin of any \(K^-p\) contribution at the given \(m_{Kp}\) value. This requirement sets the appropriate \(l_{max}\) value, which can be deduced from the lightest experimentally known \(Λ^+\) resonances for each \(J\), or from the quark model, as in Fig. 1. An \(l_{max}(m_{Kp})\) function is formed, guided by the values of resonance masses \((M_0)\) lowered by two units of their widths \((Γ_0)\): \(l_{max} = 3\) for \(m_{Kp}\) up to 1.64 GeV, 5 up to 1.70 GeV, 7 up to 2.05 GeV, and 9 for higher masses as visualized in Fig. 1.

Reflections from other channels, \(Λ^0 \rightarrow P^t K^-\), \(P^t \rightarrow J/Ψ p\) or \(Λ^0 \rightarrow Z_{c\bar{c}} p\), \(Z_{c\bar{c}} \rightarrow J/Ψ K^-\), would introduce both low and high rank moments (see the Supplemental Material [16] for an illustration). The narrower the resonance, the narrower the reflection, and the higher the rank \(l\) of Legendre polynomials required to describe such a structure.

Selection criteria and backgrounds can also produce high-\(l\) structures in the \(\cos θ_{Λ}^c\) distribution. Therefore, the data are efficiency corrected and the background is subtracted. Even though testing the \(H_0\) hypothesis involves only two dimensions, the selection efficiency has some dependence on the other phase-space dimensions, namely the \(Λ^0\) and \(J/Ψ\) helicity angles, as well as angles between the \(Λ^0\) decay plane and the \(J/Ψ\) and \(Λ^+\) decay planes. Averaging the efficiency over these additional dimensions \((Ω_a)\) would introduce biases dependent on the exact dynamics of the \(Λ^+\) decays. Therefore, a six-dimensional efficiency correction is used. The efficiency parametrization, \(e(m_{Kp}, \cos θ_{Λ}^c, Ω_a)\), is the same as that used in the amplitude analysis and is described in Sec. V of the supplement of Ref. [3].

In order to make the analysis as model independent as possible, no interpretations are imposed on the \(m_{Kp}\) distribution. Instead, the observed efficiency-corrected and background-subtracted histogram of \(m_{Kp}\) is used. To obtain a continuous probability density function, \(F(m_{Kp}|H_0)\), a quadratic interpolation of the histogram is performed, as shown in Fig. 2. The essential part of this analysis method is to incorporate the \(1 ≤ l_{max}(m_{Kp})\) constraint on the \(Λ^+\) helicity angle distribution: \(F(m_{Kp}, \cos θ_{Λ}^c|H_0) = F(m_{Kp}|H_0) F(\cos θ_{Λ}^c|H_0, m_{Kp})\), where \(F(\cos θ_{Λ}^c|H_0, m_{Kp})\) is obtained via linear interpolation between neighboring \(m_{Kp}\) bins of

\[
F(\cos θ_{Λ}^c|H_0, m_{Kp}) = \sum_{i=0}^{l_{max}(m_{Kp})} \langle P_i^N \rangle P_i(\cos θ_{Λ}^c),
\]

where \(k\) is the bin index. Here, the Legendre moments \(\langle P_i^N \rangle\) are normalized by the yield in the corresponding \(m_{Kp}\) bin, since the overall normalization of \(F(\cos θ_{Λ}^c|H_0, m_{Kp})\) to the data is already contained in the \(F(m_{Kp}|H_0)\) definition. The data are used to determine

\[
\langle P_i^N \rangle = \sum_{i=1}^{n_{max}} w_i e_i P_i(\cos θ_{Λ}^c).
\]

Here, the index \(i\) runs over selected \(J/Ψ pK^-\) candidates in the signal and sideband regions for the \(k\)th bin of \(m_{Kp}\).
the efficiency correction, and $H$ distribution, as any deviations from $m_{J/\psi}$ includes replacing $\cos \theta_{\Lambda^c}$ with $m_{J/\psi}$ and integrating over $m_{K_p}$. This integration is carried out numerically, by generating large numbers of simulated events uniformly distributed in $m_{K_p}$ and $\theta_{\Lambda^c}$, calculating the corresponding value of $m_{J/\psi}$, and then filling a histogram with $\mathcal{F}(m_{K_p}, \cos \theta_{\Lambda^c}|H_0)$ as a weight. In Fig. 4, $\mathcal{F}(m_{J/\psi}|H_0)$ is compared to the directly obtained efficiency-corrected and background-subtracted $m_{J/\psi}$ distribution in the data.

To probe the compatibility of $\mathcal{F}(m_{J/\psi}|H_0)$ with the data, a sensitive test can be constructed by making a specific alternative hypothesis ($H_1$). Following the method discussed in Ref. [14], $H_1$ is defined as $l \leq l_{\text{large}}$, where $l_{\text{large}}$ is not dependent on $m_{K_p}$ and large enough to reproduce structures induced by $J/\psi p$ or $J/\psi K$ contributions. The significance of the $I_{\max}(m_{K_p}) \leq l \leq l_{\text{large}}$ Legendre moments is probed using the likelihood ratio test,

$$\Delta(-2 \ln L) = \sum_{i=1}^{n_{\text{eff}} + n_{\text{side}}} w_i \ln \frac{\mathcal{F}(m_{J/\psi}|H_0)/I_{H_0}}{\mathcal{F}(m_{J/\psi}|H_1)/I_{H_1}},$$

with normalizations $I_{H_{0,1}}$ determined via Monte Carlo integration. Note that the explicit event-by-event efficiency factor cancels in the likelihood ratio, but enters the likelihood normalizations. In order for the test to have optimal sensitivity, the value $l_{\text{large}}$ should be set such that the statistically significant features of the data are properly described. Beyond that the power of the test deteriorates. The limit $l_{\text{large}} \to \infty$ would result in a perfect description of the data, but a weak test since then the test statistic would pick up the fluctuations in the data. For the same reason, it is also important to choose $l_{\text{large}}$ independently of the actual data. Here, $l_{\text{large}} = 31$ is taken, one unit larger
than the value used in the model-independent analysis of $B^0 \to \psi(2S)\pi^+ K^-$ [14], as baryons have half-integer spins. The result for $\mathcal{F}(m_{J/\psi p}\mid H_1)$ is shown in Fig. 4, where it is seen that $l_{\text{large}} = 31$ is sufficient. To make $\mathcal{F}(m_{J/\psi p}\mid H_{0,1})$ continuous, quadratic splines are used to interpolate between nearby $m_{J/\psi p}$ bins.

The numerical representations of $H_0$ and of $H_1$ contain a large number of parameters, requiring extensive statistical simulations to determine the distribution of the test variable for the $H_0$ hypothesis: $\mathcal{F}_1[\Delta(-2\ln L)\mid H_0]$. A large number of pseudoexperiments are generated with $n_{\text{sig}}^{\text{cand}}$ and $n_{\text{side}}^{\text{cand}}$ equal to those obtained in the data. The signal events, contributing a fraction $(1-\beta)$ to the signal region sample, are generated according to the $\mathcal{F}(m_{Kp}, \cos \theta_{\Lambda^+}, \Omega_\lambda)\mid H_0$ function with parameters determined from the data. They are then shaped according to the $c(m_{Kp}, \cos \theta_{\Lambda^+}, \Omega_\lambda)$ function, with the $\Omega_\lambda$ angles generated uniformly in phase space. The latter is an approximation, whose possible impact is discussed later. Background events in sideband and signal regions are generated according to the 6D background parametrization previously developed in the amplitude analysis of the same data (Ref. [3] supplement). The pseudoexperiments are subject to the same analysis procedure as the data. The distribution of values of $\Delta(-2\ln L)$ over more than 10 000 pseudoexperiments determines the form of $\mathcal{F}_1[\Delta(-2\ln L)\mid H_0]$, which can then be used to convert the $\Delta(-2\ln L)$ value obtained from data into a corresponding $p$ value. A small $p$ value indicates non-$\Lambda^+$ contributions in the data. A large $p$ value means that the data are consistent with the $\Lambda^+$-only hypothesis, but does not rule out other contributions.

Before applying this method to the data, it is useful to study its sensitivity with the help of amplitude models. Pseudoexperiments are generated according to the 6D amplitude model containing only $\Lambda^+$ resonances (the reduced model in Table I of Ref. [3]), along with efficiency effects. The distribution of $\Delta(-2\ln L)$ values is close to that expected from $\mathcal{F}_1[\Delta(-2\ln L)\mid H_0]$ (black open and red falling hatched histograms in Fig. 5), thus verifying the 2D model-independent procedure on one example of the model. They also indicate that the nonuniformities in $c(\Omega_\lambda)$ are small enough not to significantly bias the $\mathcal{F}_1[\Delta(-2\ln L)\mid H_0]$ distribution when approximating the $\Omega_\lambda$ probability density via a uniform distribution. To test the sensitivity of the method to an exotic $P_c^+ \to J/\psi p$ resonance, the amplitude model described in Ref. [3] is used, but with the $P_c(4450)^+$ contribution removed. Generating many pseudoexperiments from this amplitude model produces a distribution of $\Delta(-2\ln L)$, which is almost indistinguishable from the $\mathcal{F}_1[\Delta(-2\ln L)\mid H_0]$ distribution (blue dotted and red falling hatched histograms in Fig. 5), thus predicting that for such a broad $P_c(4380)^+$ resonance ($\Gamma_p = 205$ MeV), the false $H_0$ hypothesis is expected to be accepted (type II error), because the $P_c(4380)^+$ contribution inevitably feeds into the numerical representation of $H_0$. Simulations are then repeated while reducing the $P_c(4380)^+$ width by subsequent factors of 2, showing a dramatic increase in the power of the test (histograms peaking at 60 and 300). Figure 5 also shows the $\Delta(-2\ln L)$ distribution obtained with the narrow $P_c(4450)^+$ state restored in the amplitude model and $P_c(4380)^+$ at its nominal 205 MeV width (black rising hatched histogram). The separation from $\mathcal{F}_1[\Delta(-2\ln L)\mid H_0]$ is smaller than that of the simulation with a $P_c(4380)^+$ of comparable width (51 MeV) due to the smaller $P_c(4450)^+$ fit fraction. Nevertheless, the separation from $\mathcal{F}_1[\Delta(-2\ln L)\mid H_0]$ is clear; thus, if this amplitude model is a good representation of the data, the $H_0$ hypothesis is expected to essentially always be rejected.

The value of the $\Delta(-2\ln L)$ test variable obtained from the data is significantly above the $\mathcal{F}_1[\Delta(-2\ln L)\mid H_0]$ distribution (see the inset of Fig. 5). To estimate a $p$ value the simulated $\mathcal{F}_1[\Delta(-2\ln L)\mid H_0]$ distribution is fitted with a bifurcated Gaussian function (asymmetric widths); the significance of the $H_0$ rejection is 10.1$\sigma$ standard deviations.

To test the sensitivity of the result to possible biases from the background subtraction, either the left or the right sideband is exclusively used, and the weakest obtained rejection of $H_0$ is 9.8$\sigma$. As a further check, the sideband subtraction is performed with the sPlot technique [18], in which the $w_i$ weights are obtained from the fit to the $m_{J/\psi pK}$ distribution for candidates in the entire fit range. This increases the significance of the $H_0$ rejection to 10.4$\sigma$. Loosening the cut on the boosted decision tree variable discussed in Ref. [3] increases the signal efficiency by 14%.
while doubling the background fraction $\beta$, and causes the significance of the $H_0$ rejection to increase to 11.1$\sigma$. Replacing the uniform generation of the $\Omega_\ell$ angles in the $H_0$ pseudoexperiments with that of the amplitude model without the $P_+ (4380)$ and $P_+ (4450)$ states, but generating $(m_{K\pi}, \cos \theta_N)$ in the model-independent way, results in a 9.9$\sigma$ $H_0$ rejection.

Figure 4 indicates that the rejection of the $H_0$ hypothesis has to do with a narrow peak in the data near 4450 MeV. Determination of any $P_+^+$ parameters is not possible without a model-dependent analysis, because $P_+^+$ states feed into the numerical representation of $H_0$ in an intractable manner.

The $H_0$ testing is repeated using $m_{J/\psi K}$ instead of $m_{J/\psi p}$. The $m_{J/\psi K}$ distribution, with $\mathcal{F}(m_{J/\psi K}|H_0)$ and $\mathcal{F}(m_{J/\psi K}|H_1)$ superimposed, is shown in Fig. 6. The $\Delta(-2 \ln L)$ test gives a 5.3$\sigma$ rejection of $H_0$, which is lower than the rejection obtained using $m_{J/\psi p}$, thus providing model-independent evidence that non-$\Lambda^c$ contributions are more likely of the $P_+^+ \rightarrow J/\psi p$ type. Further, in the model-dependent amplitude analysis [3], it was seen that the $P_+^+$ states reflect into the $m_{J/\psi K}$ distribution in the region in which $\mathcal{F}(m_{J/\psi K}|H_0)$ disagrees with the data.

In summary, it has been demonstrated at more than nine standard deviations that the $\Lambda^c_0 \rightarrow J/\psi p K^-\bar{p}$ decays cannot all be attributed to $K^-p$ resonant or nonresonant contributions. The analysis requires only minimal assumptions on the mass and spin of the $K^-p$ contributions; no assumptions on their number, their resonant, or nonresonant nature, or their line shapes have been made. Non-$K^-p$ contributions, which must be present in the data, can be either of the exotic hadron type, or due to rescattering effects among ordinary hadrons. This result supports the amplitude model-dependent observation of the $J/\psi p$ resonances presented previously [3].

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