The $\Lambda_b \to J/\psi K^0 \Lambda$ reaction and a hidden-charm pentaquark state with strangeness

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Abstract

We study the $\Lambda_b \to J/\psi K^0 \Lambda$ reaction considering both the $K^0\Lambda$ interaction with its coupled channels and the $J/\psi\Lambda$ interaction. The latter is described by taking into account the fact that there are predictions for a hidden-charm state with strangeness that couples to $J/\psi\Lambda$. By using the coupling of the resonance to $J/\psi\Lambda$ from these predictions we show that a neat peak can be observed in the $J/\psi\Lambda$ invariant mass distribution, rather stable under changes of unknown magnitudes. We stress that the peak obtained is not tied to the particular nature of this resonance and should be the same as far as the coupling to $J/\psi\Lambda$ is in S-wave and has a strength of about 0.5 of the one predicted or bigger.

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I. INTRODUCTION

Interests on pentaquark states have been reignited with the latest LHCb observation of the $P_c(4380)$ and $P_c(4450)$ in the $\Lambda_b \to J/\psi p K^-$ decay [1]. Since both states are observed in the $J/\psi p$ invariant mass distributions, their minimum quark components should be $c\bar{c}uud$. Due to the large charm quark mass, these states seem to be no less exotic than the $\theta^+(1540)$, whose first claim was made by the LEPS collaboration [2] (see also update in Ref. [3]) but later on found to be rather controversial experimentally [4]. A reanalysis of Ref. [3] was done in Refs. [5, 6], showing that the peak observed was a consequence of an artificial method used in Ref. [3] to determine invariant masses with an incomplete kinematics. The apparently exotic nature of the hidden-charm pentaquark states has aroused a lot of theoretical interests to interpret their nature. For instance, they have been proposed to be meson-baryon molecules [7–15], diquark-diquark-antiquark pentaquarks [16–20], compact diquark-triquark pentaquarks [21, 22], $\bar{D}$-soliton states [23], genuine multiquark states [24, 25], and kinematical effects related to the so-called triangle singularity [26–28]. [1]

Clearly, not all of the theoretical interpretations are consistent with each other. The molecular interpretations cannot easily accommodate simultaneously the two states with opposite parity, which is not the case for QCD sum rules. The fact that the Fock components in the wave function of a hadronic state are themselves not observable complicated further the discussion. As such, it has been stressed that to differentiate the various structures it is important to study the production and decay patterns of these pentaquark states, e.g., the weak decays of bottom baryons [31, 32], photo-productions [33–35], the $\pi^- p \to J/\psi n$ reaction [36], elastic and inelastic $J/\psi N$ cross sections [12], and the strong decays of these states [37]. Searches for the counterparts of these two states, such as its strangeness counterpart [38, 39], will offer new insight into their true nature as well.

In such a context, it is important to note that as proposed in a recent work [40], a reanalysis of the $\Lambda_b \to J/\psi \pi^- p$ decay is very important. In the $\pi^- p$ invariant mass distribution of this decay process, an enhancement followed by a dip can be seen [41]. A careful study of this decay showed that the structure is consistent with the existence of the $P_c(4450)$, which couples to $J/\psi p$ and coupled channels in S-wave [40] . It should be mentioned that the possibility that the peak seen in Ref. [41] could correspond to the $P_c(4450)$ was already noted

[1] See, Refs. [29, 30], for a nice summary of theoretical and experimental activities.

in Ref. [42], but the possibility that it would correspond to a resonance was not mentioned in the original experimental paper [41] probably because of the relatively low statistics.

In Ref. [40], the experimental structure close to 4450 MeV was reasonably described. The peak and dip structure was explained as the interference between S-wave $\pi^- p$ (and coupled channels) and $J/\psi p$ interactions. If this is confirmed by the ongoing LHCb analysis, it will give further support to the nature of the $P_c(4450)$ proposed in Refs. [43, 44]. It should be mentioned that the $\Lambda_b \to J/\psi \pi^- p$ decay was also discussed in Refs. [32, 42, 45].

Even before their observations, the existence of hidden-charm pentaquark states has been speculated in Refs. [43, 44, 46–53]. One should note that most theoretical approaches predicted the existence of the P_c counterparts. For instance, in the unitary approach of Ref. [43] that in addition to an isospin 1/2 and strangeness zero state, two more states are predicted in the isospin zero and strangeness −1 sector. [2] The impact of the existence of such (a) state(s) is recently discussed in Refs. [38, 39], showing that it is possible to observe it by a careful study of the $\Xi_b^- \to J/\psi K^- \Lambda$ decay and the $\Lambda_b \to J/\psi \eta \Lambda$ decay, regardless of its true nature, as long as it exists and couples in S-wave to $J/\psi \Lambda$ with a reasonable strength. In this present work, we extend such an idea to explore the $\Lambda_b \to J/\psi K^0 \Lambda$ decay. This decay channel is particularly interesting in view of the structure, which could well be the $P_c(4450)$, observed in the $\Lambda_b \to J/\psi \pi^- p$ invariant mass distribution [40, 41], because $\pi^- p$ and $K^0 \Lambda$ are coupled channels themselves.

This paper is organized as follows. In Sec. II, we briefly describe the mechanism of the weak $\Lambda_b \to J/\psi K^0 \Lambda$ decay. Numerical results and discussions, focusing on the effects of variation of the mass, width, and coupling strength to $J/\psi \Lambda$ of the hidden-charm pentaquark state as well as the contributions of other N^* states in addition to the $N^*(1535)$, are presented in Sec. III, followed by a short summary in Sec. IV.

II. FORMALISM

The $\Lambda_b \to J/\psi K^0 \Lambda$ decay follows at quark level a process similar to the one described in the $\Lambda_b \to J/\psi K^- p$ decay [8, 55], the $\Xi_b \to J/\psi K \Lambda$ decay [38], the $\Lambda_b \to J/\psi \eta \Lambda$ decay [39], the $\Lambda_b \to J/\psi K \Xi$ decay [56], and the $\Lambda_b \to J/\psi \pi^- p$ decay [40]. In particular, the $\Lambda_b \to J/\psi K \Lambda$ decay appears as a coupled channel of the $\Lambda_b \to J/\psi \pi^- p$. Diagrammatically this

[2] It is interesting to mention the recent study on the existence of a $s\bar{s}uud$ state [54].

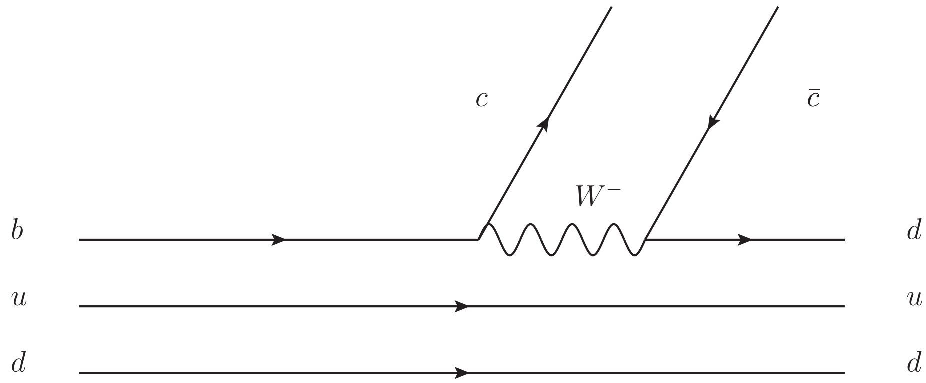

FIG. 1. Diagrammatic representation of the $\Lambda_b \to J/\psi + dud$ process.

decay is depicted in Fig. 1, where the $c\bar{c}$ pair combines to give the J/ψ and the dud quarks will recombine to provide the $K^0\Lambda$ state at the end.

It is interesting to note that the mechanism of Fig. 1 has the original u, d quarks acting as spectators. This is relevant, because, since the Λ_b has $I = 0$, then the ud original quarks have $I = 0$, and so will they have in the final state if they are spectators. This means that the final state will have the isospin of the "upper" d-quark, and hence $I = 1/2$. This picture is strongly supported by the experiment that does not show the smallest trace of a $\Delta(1232)$ in the $\pi^- p$ mass distribution [41]. In the related $\Lambda_b \to J/\psi K^- p$ decay, the ud original quarks of the Λ_b also act as spectators and in this case the extra s-quark leads to final $I = 0$, Λ^* baryon states, which were the only ones showing up in the $K^- p$ mass distribution in the experimental analysis of Ref. [1].

In addition, we assume that the ud quark pair of the original Λ_b goes into the final baryon upon hadronization of the three quarks produced in the first stage. Other possibilities involve transfer of one of these quarks to the final mesons and a large momentum transfer that strongly suppresses such mechanisms [55, 57].

In order to get a meson-baryon pair from the final three quarks of uud we must proceed with hadronization creating a $\bar{q}q$ pair with the quantum numbers of the vacuum. This process must involve the "upper" d-quark in Fig. 1 because the $K^0\Lambda$ system will be in S-wave in the final state and will have negative parity. Since the quarks of the $I = 0$ ud pair of the Λ_b are in the ground level, they will have positive parity and, hence, the "upper" d-quark must be the one that carries negative parity being in an excited $L = 1$ state. Since in the kaon system this quark will again be in the ground state, the hadronization must

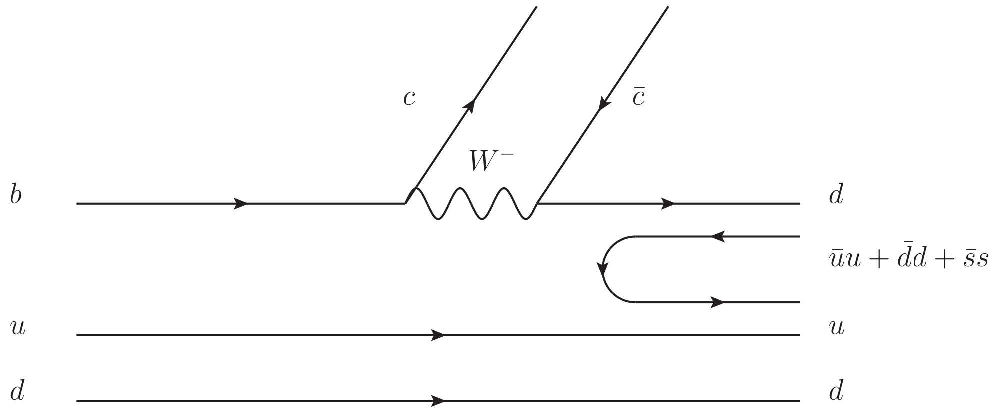

FIG. 2. Mechanism of Fig.1 with the hadronization by creation of the $\bar{u}u + \bar{d}d + \bar{s}s$ pair.

involve this quark. As a result, the hadronization proceeds as shown in Fig. 2

The exercise of finding which meson-baryon components come out from this hadronization was already done in Ref. [40], and the combination found is

$$|H\rangle = \pi^- p - \frac{1}{\sqrt{2}}\pi^0 n + \frac{1}{\sqrt{3}}\eta n + \sqrt{\frac{2}{3}} K^0\Lambda. \tag{1}$$

It is worth noting that the πN component has indeed $I = 1/2$, as well as the ηn and $K^0\Lambda$ components.

The next step is to consider the final state interaction of these channels to give $K^0\Lambda$ at the end. This means that, to have $K^0\Lambda$ in the final state, we can have it by direct production in the $|H\rangle$ production, by rescattering of $K^0\Lambda \to K^0\Lambda$, or by primary production of πN or ηN that go to $K^0\Lambda$ after rescattering. This is depicted in Fig. 3 and analytically this is taken into account by means of

$$T = V_p[h_{K^0\Lambda} + \sum_i h_i G_i(M_{K^0\Lambda}) t_{i\to K^0\Lambda}(M_{K^0\Lambda})], \tag{2}$$

where $i \equiv \pi^- p, \pi^0 n, \eta n, K^0\Lambda$, and

$$h_{\pi^- p} = 1, h_{\pi^0 n} = -\frac{1}{\sqrt{2}}, h_{\eta n} = \frac{1}{\sqrt{3}}, h_{K^0\Lambda} = \sqrt{\frac{2}{3}}. \tag{3}$$

The G_i function in Eq. (2) is the loop function of a meson-baryon and $t_{i\to K^0\Lambda}$ are the scattering matrices of the coupled channels. We take the matrix $t_{i\to K^0\Lambda}$ from the chiral unitary approach of Ref. [58], and the loop function G_i from Ref. [40]. Some relevant discussions will be given in the end of this section. The factor V_p in Eq. (2), which we take

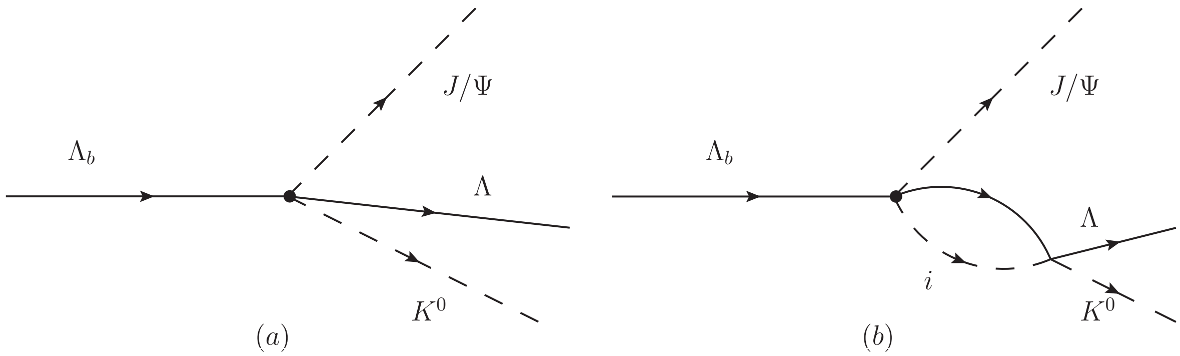

FIG. 3. Final state interaction of the meson baryon components: (a) tree level contribution, (b) rescattering.

as constant, accounts for the weak and hadronization form factors, which are rather smooth in the limited region of invariant masses that we study [59, 60].

By means of the formalism so far described we could get the $K^0\Lambda$ invariant mass distribution in this reaction. Yet, our purpose is to see if in this reaction one could see a signal of a hidden-charm strange molecular state of $J^P = 3/2^-$ predicted in Refs. [43, 44], mostly made of $D^*\Xi_c'$. The detailed structure of this state is of no much relevance here, because the only information needed is that this state couples to $J/\psi\Lambda$, which becomes a decay channel. The only relevant information is the coupling of the resonance to the $J/\psi\Lambda$ system, $g_{J/\psi\Lambda}$, by means of which we can construct the $J/\psi\Lambda \to J/\psi\Lambda$ amplitude as

$$t_{J/\psi\Lambda\to J/\psi\Lambda} = \frac{g^2_{J/\psi\Lambda}}{M_{J/\psi\Lambda} - M + i\Gamma/2}. \tag{4}$$

In Refs. [43, 44] the mass obtained was $4547 - 6.4i$, but in Ref. [38] we made a guess of the mass which would be the one of the $P_c(4450)$ seen in the $\Lambda_b \to J/\psi K^- p$ decay plus an average extra mass of $\Delta M \simeq 200$ MeV due to the mass difference between the s-quark and the u, d ones. Thus, tentatively, we begin with a mass M in Eq. (4) $M \simeq 4650$ MeV, but we will change this mass to see what happens for other values. Similarly, the width obtained in Refs. [43, 44] was $\Gamma \simeq 13$ MeV, we use $\Gamma = 10$ MeV but we will also see what happens for different values of the width.

In order to study the effect of this hidden-charm strange state in the process we take into account the $J/\psi\Lambda$ interaction as depicted in Fig. 4. Therefore, the final amplitude $\mathcal{M}$ for

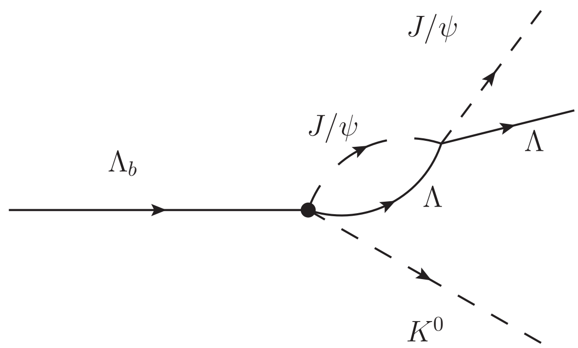

FIG. 4. Final state interaction of the $J/\psi\Lambda$ state.

the process is given by

$$\begin{aligned}\mathcal{M}(M_{J/\psi\Lambda}, M_{K^0\Lambda}) &= V_p\Big[h_{K^0\Lambda} + \sum_i h_i G_i(M_{K^0\Lambda}) t_{i\to K^0\Lambda}(M_{K^0\Lambda}) \\ &\quad + h_{K^0\Lambda} G_{J/\psi\Lambda}(M_{J/\psi\Lambda}) t_{J/\psi\Lambda\to J/\psi\Lambda}(M_{J/\psi\Lambda})\Big] \\ &= T_{\text{tree}} + T_{K^0\Lambda} + T_{J/\psi\Lambda}\end{aligned} \tag{5}$$

where we have explicitly spelled out the arguments $(M_{K^0\Lambda}, M_{J/\psi\Lambda})$ of the different G and t_{ij} functions. The $t_{J/\psi\Lambda\to J/\psi\Lambda}$ amplitude is given by Eq. (4) and the value of $g_{J/\psi\Lambda} \simeq 0.5$ from Refs. [43, 44]. We will also investigate what happens under changes of this value. The $G_{J/\psi\Lambda}$ function is given in Refs. [43, 44] using dimensional regularization and the parameters used are $\mu = 1000$ MeV and $a_\mu = -2.3$.

Since the amplitude $\mathcal{M}$ of Eq. (5) depends on the two invariant masses we will use the two dimensional mass distribution of [61]

$$\frac{d^2\Gamma}{dM^2_{J/\psi\Lambda} dM^2_{K^0\Lambda}} = \frac{1}{(2\pi)^3} \frac{4M_{\Lambda_b} M_\Lambda}{32 M^3_{\Lambda_b}} \bar{\sum}\sum |\mathcal{M}(M_{J/\psi\Lambda}, M_{K^0\Lambda})|^2, \tag{6}$$

where the factor $4M_{\Lambda_b^0} M_\Lambda$ is due to our normalization of the spinors, i.e., $\bar{u}u = 1$. By integrating Eq. (6) over one or the other invariant mass we obtain the mass distribution of $J/\psi\Lambda$ or $K^0\Lambda$.

One technical point is that following Ref. [40] we take the G_i loop functions in Eq. (5) their values using a cut off of $|\vec{q}_{\text{max}}| = 1200$ MeV, instead of those used in Ref. [58], where dimensional regularization was used that required some odd subtraction constants to account for missing channels that were later identified as ρN and $\pi\Delta$ [62]. Since the channels in the loop of Fig. 3 only contain the πN, ηN, and $K\Lambda$ channels, the use of the G_i function of

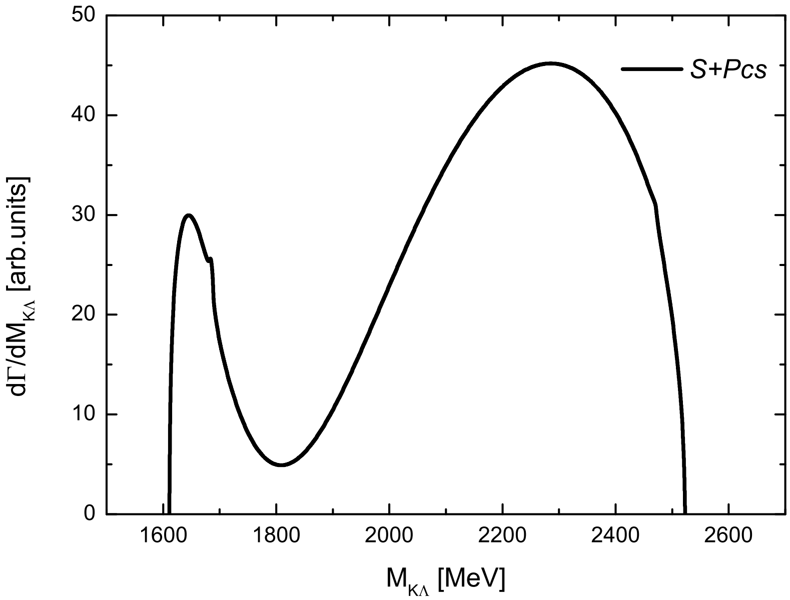

FIG. 5. $K^0\Lambda$ mass distribution with the amplitude of Eq. (5), where S denotes the contribution of the contact and S-wave $K\Lambda$ interaction, Eq. (2), and P_{cs} that of the hidden-charm state with strangeness, Eq. (4).

Ref. [62] was not justified and we use instead the more natural cut off regularization. We must note, however, that this choice does not affect the behavior of the $J/\psi\Lambda$ distribution around the peak that we will find , which is the main point of the paper.

III. RESULTS AND DISCUSSIONS

We present here the results. In Fig. 5 we show the $K^0\Lambda$ mass distribution taking into account the amplitude of Eq. (5). Note that this amplitude only contains S-wave for both the $K^0\Lambda$ scattering and the $J/\psi\Lambda$ one. With the chiral unitary approach that we use, the $N^*(1535)(1/2^-)$ resonance can be dynamically generated, which is below the $K^0\Lambda$ threshold, but still will show up with an enhancement of the $K^0\Lambda$ mass distribution close to threshold. Yet, there will be contributions from other N^* resonances which are not generated by the approach of Ref. [58]. We can take into account the effect of some relevant resonances, only to show that they do not affect the peak of the $J/\psi\Lambda$ mass distribution.

By looking at the Dalitz plot of the process, shown in Fig. 6, we see that resonances

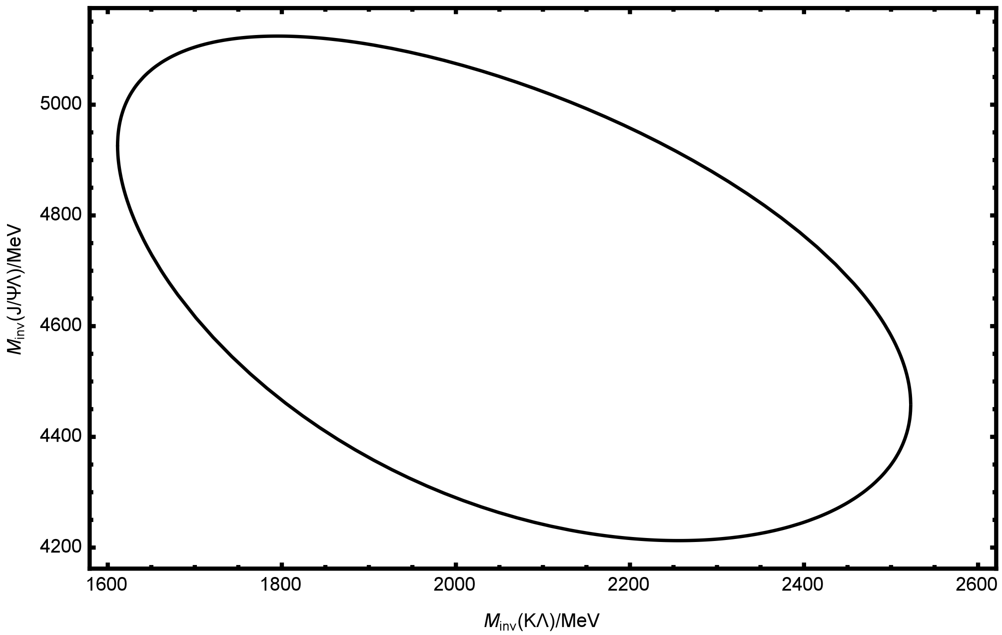

FIG. 6. Dalitz plot for $\Lambda_b \to J/\psi K^0 \Lambda$.

decaying into $K^0\Lambda$ with a mass less than 1750 MeV only contribute to $J/\psi\Lambda$ invariant masses beyond the peak in the $J/\psi\Lambda$ mass around 4650 MeV. Hence we only consider N^* resonances from the PDG [61] above 1750 MeV with some coupling to $K^0\Lambda$. None of them has a sizable coupling, and the few branching ratios are of the order of 10% or less with large uncertainties. In view of this we take an extreme position of considering a couple of resonances, associating them a role in the $K^0\Lambda$ mass distribution rather sizable, simply to see that, even then, there are no visible effects in the behavior of the peak of the $J/\psi\Lambda$ mass distribution.

Thus, we consider the contributions of two resonances. The first one is the $N^*(1895)$ $(1/2^-)$, and the other one the $N^*(1900)$ $(3/2^+)$. The first one, a two star resonance, according to Ref. [63], has a branching fraction to $K\Lambda$ of $18 \pm 5\%$. The $N^*(1900)$ is a three star resonance and has a branching fraction to $K\Lambda$ of $0 \sim 10\%$ according to Ref. [61] and $16 \pm 5\%$ according to Ref. [63]. The $N^*(1895)(1/2^-)$ has the same quantum numbers as the $N^*(1535)$ and its contribution will add coherently. Hence we add to the amplitude $\mathcal{M}$ of Eq. (5) the term

$$T_{N^*(1895)} = \frac{\alpha M_{N^*(1895)}}{M_{K\Lambda} - M_{N^*(1895)} + i\Gamma_{N^*(1895)}/2} \tag{7}$$

and we tune the parameter α to get a sizable effect in the $K^0\Lambda$ mass distribution. This is

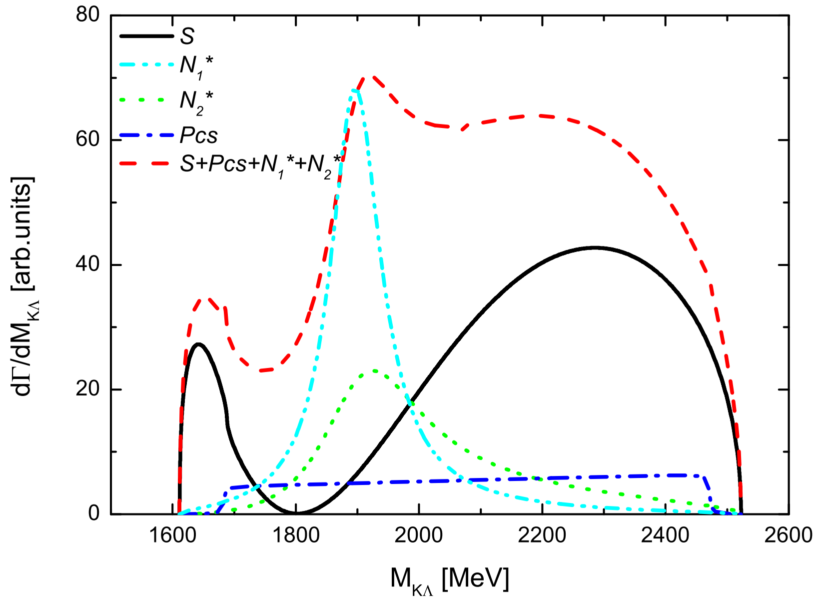

FIG. 7. Effect of including the $N^*(1895)$ and $N^*(1900)$ resonances in $K^0\Lambda$ mass distribution, where S denotes the contribution of the contact and S-wave $K\Lambda$ interaction, Eq. (2), P_{cs} that of the hidden-charm state with strangeness, Eq. (4), N_1^* that of the $N^*(1895)$, and N_2^* that of the $N^*(1900)$.

shown in Fig. 7.

The effect of the $N^*(1900)$ is taken into account in a different way, because this one, having different quantum numbers, will add incoherently to $d\Gamma/dM_{K\Lambda}$. In this case we take into account the contribution of this resonance by substituting $|\mathcal{M}|^2$ of Eq. (5) by

$$|\mathcal{M}|^2 \to |\mathcal{M}|^2 + \beta \tilde{P_K}^2 \left| \frac{1}{M_{K\Lambda} - M_{N^*(1900)} + i\Gamma_{N^*(1900)}/2} \right|^2, \tag{8}$$

where $\tilde{P_K}$ is the K^0 momentum in the $K^0\Lambda$ rest frame to take into account that a $3/2^+$ state requires $K^0\Lambda$ in P-wave. The effect of introducing this resonance can be seen in the $K^0\Lambda$ mass distribution of Fig. 7. As we have mentioned, the couplings α, β of these two resonances are taken such as to have a relatively large effect of these two resonances in the $K^0\Lambda$ mass distribution.

Next we go to the $J/\psi\Lambda$ mass distribution. In Fig. 8, we show this distribution corresponding to the amplitude $\mathcal{M}$ of Eq. (5). One observes a clear peak around 4650 MeV corresponding to the pole in the $t_{J/\psi\Lambda\to J/\psi\Lambda}$ amplitude, associated to the hidden-charm

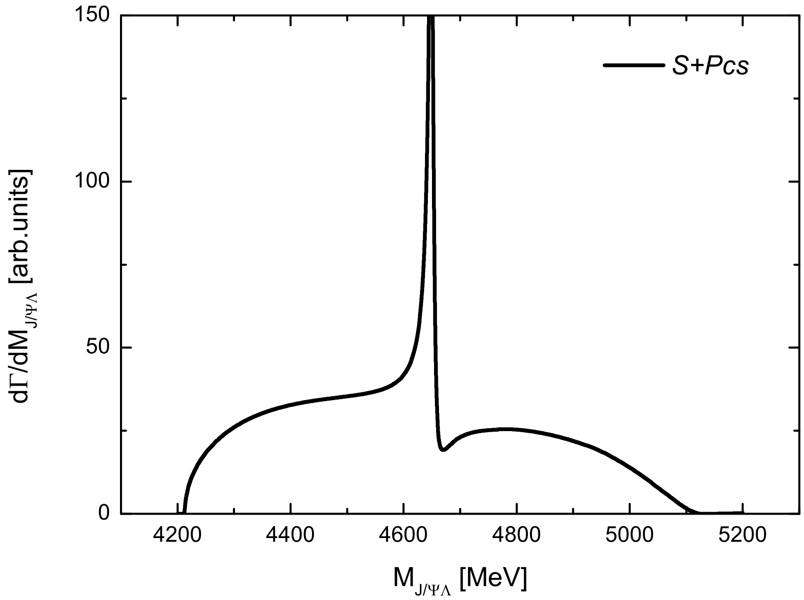

FIG. 8. $J/\psi\Lambda$ mass distribution with the amplitude of Eq. (5), where S denotes the contribution of the contact and S-wave $K\Lambda$ interaction, Eq. (2), and P_{cs} that of the hidden-charm state with strangeness, Eq. (4).

strange resonance of Refs. [43, 44].

In Fig. 9, we show the effect of changing the width of the hidden-charm state with strangeness. One can observe that as the width increases from about 10 MeV, predicted in Refs. [43, 44], the peak becomes less pronounced. If the width is larger than 30 MeV, it seems that the existence of the resonance can only be inferred from the interference effect, namely, a slight enhancement followed by a dip.

The effect of changing the mass of the hidden-charm strange resonance can be seen in Fig. 10. It is clear that, by changing the mass of the resonance, the peak position varies, but the relevant point here is that the peak always appears even if this mass is varied in a wide range of values.

Another test that we perform is to see what happens when we change the coupling $g_{J/\psi\Lambda}$, as shown in Fig. 11. We can see that the peak is rather stable and one can clearly see a structure even for values of $g_{J/\psi\Lambda}$ as low as 0.3. One should note that the effect seen here is not tied to the nature of the resonance. The only fact we have used is that this resonance

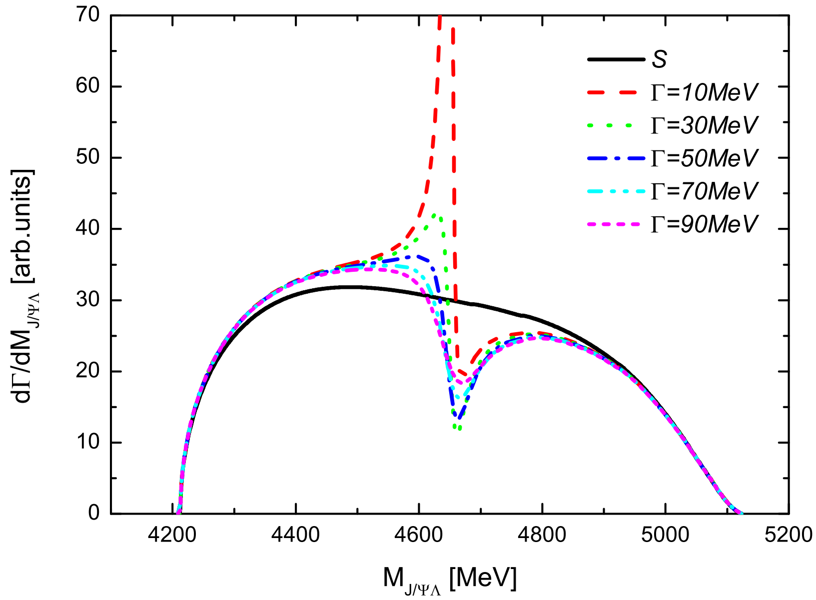

FIG. 9. Effect of changing the width of the hidden-charm strange resonance in the $J/\psi\Lambda$ mass distribution, where S denotes the contribution of the contact and S-wave $K\Lambda$ interaction, Eq. (2), and Γ the width of the hidden-charm state with strangeness.

couples to $J/\psi\Lambda$ in S-wave and that the coupling has the strength that we have taken.

Next we want to see the effect of the extra resonances $N^*(1895)$ and $N^*(1900)$ in the $J/\psi\Lambda$ mass distribution. This is shown in Fig. 12. It is clear that the consideration of the $N^*(1895)$ and $N^*(1900)$ resonances leads to a larger $J/\psi\Lambda$ mass distribution to match the increase found in the $K^0\Lambda$ mass distribution, but what is important for us is that the structure of the peak is not spoiled by the consideration of these or other possible resonances. The conclusion is then that, should there be a resonance with strangeness and a reasonable coupling to $J/\psi\Lambda$ in S-wave in the region of masses studied here, its observation in the $J/\psi\Lambda$ mass spectrum of the $\Lambda_b \to J/\psi K^0\Lambda$ decay would be inevitable.

IV. CONCLUSION

We have performed a theoretical study of the $\Lambda_b \to J/\psi K^0\Lambda$ reaction with the aim of making predictions for the possible observation of a baryon state of hidden-charm with strangeness that was predicted in Refs. [43, 44]. We take into account the most important

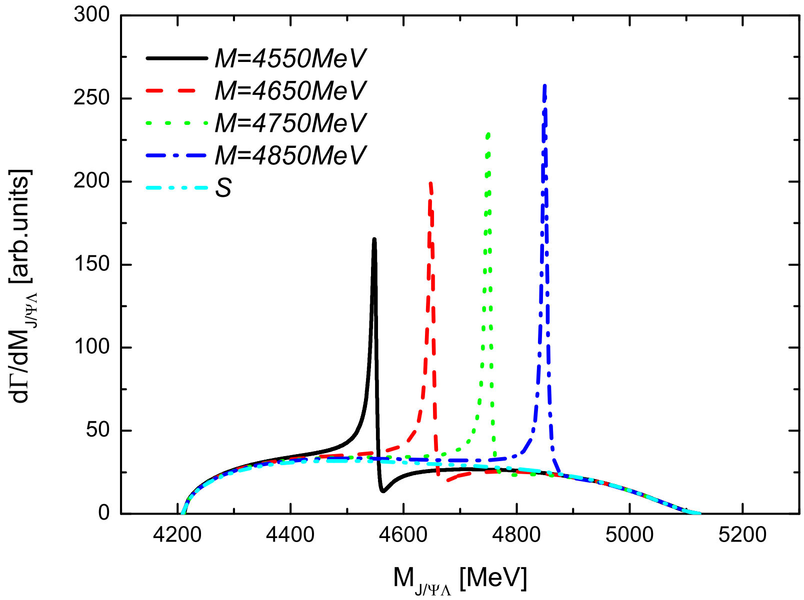

FIG. 10. Effect of changing the mass of the hidden-charm strange resonance in the $J/\psi\Lambda$ mass distribution, where S denotes the contribution of the contact and S-wave $K\Lambda$ interaction, Eq. (2), and M the mass of the hidden-charm state with strangeness.

mechanisms in the $K^0\Lambda$ interaction that can interfere with the production amplitude for this molecular state, and we find that with the couplings of the resonance to the $J/\psi\Lambda$ channel found in Refs. [43, 44], and even 0.5 of that, one obtains a clear peak in the $J/\psi\Lambda$ mass distribution. We played with uncertainties, changing the mass of the resonance and its coupling to $J/\psi\Lambda$, and we found the peak signal rather stable. The peak remained distinguishable even after we introduced the effect of other resonances which do not appear in our theoretical framework. The results of the work are not tied to the nature of this resonance and all that matters is that, whatever the nature of such a resonance, it couples to $J/\psi\Lambda$ in S-wave and has a coupling of the order of $g_{J/\psi\Lambda} \simeq 0.3$ or bigger (the value of Refs. [43, 44] is $g_{J/\psi\Lambda} \simeq 0.5$). In view of this, and the fact that the $\Lambda_b \to J/\psi\pi^-p$ decay has already been observed and is under reanalysis by the LHCb group at present [64], we can only encourage to look also for the $K^0\Lambda$ channel, which is a coupled channel to the π^-p, in order to eventually observe this promising "sister" of the $P_c(4450)$ resonance.

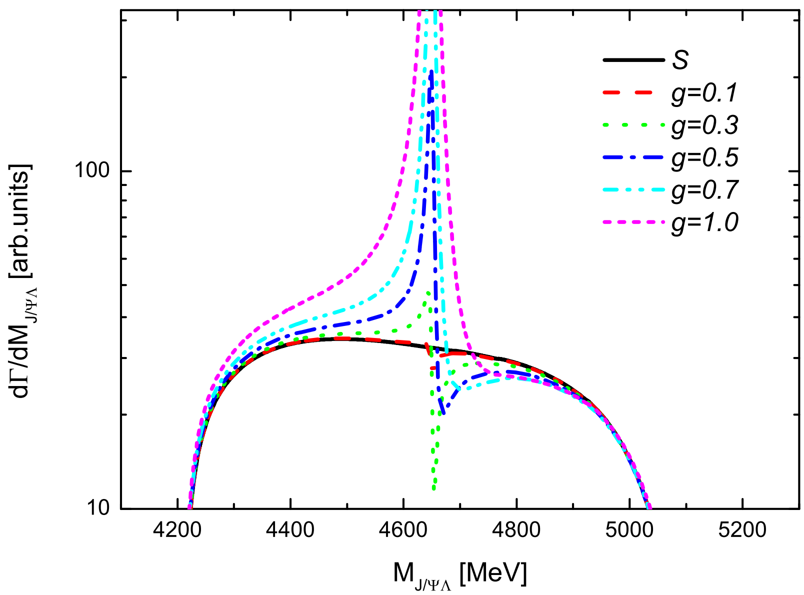

FIG. 11. Effect of changing the coupling $g_{J/\psi\Lambda}$ of the hidden-charm strange resonance in the $J/\psi\Lambda$ mass distribution, where S denotes the contribution of the contact and S-wave $K\Lambda$ interaction, Eq. (2), and g the coupling to $J/\psi\Lambda$ of the hidden-charm state with strangeness.

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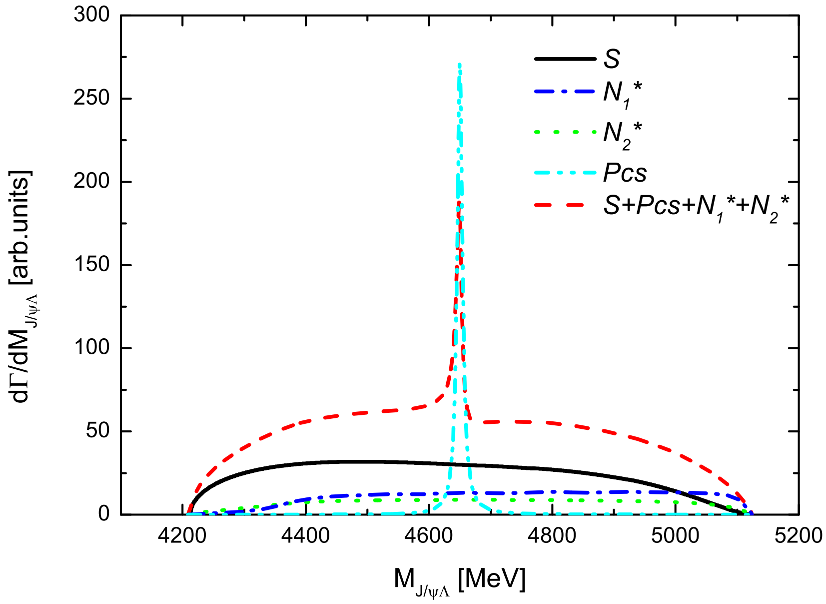

FIG. 12. Effect of including the $N^*(1895)$ and $N^*(1900)$ resonances in $J/\psi\Lambda$ mass distribution, where S denotes the contribution of the contact and S-wave $K\Lambda$ interaction, Eq. (2), P_{cs} that of the hidden-charm state with strangeness, Eq. (4), N_1^* that of the $N^*(1895)$, and N_2^* that of the $N^*(1900)$.

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