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Hidden charm pentaquarks in $\Lambda_b \to J/\psi K^- p$ decay

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In this talk I present a series of theoretical works regarding the $\Lambda_b \to J/\psi K^- p$ reaction from where a recent experiment by the LHCb collaboration at CERN claimed the existence of two hidden charm pentaquarks, $P_c(4380)^+$ and $P_c(4450)^+$. We discuss the possible explanations of the pentaquark states found within the picture of a dynamical meson-baryon molecule previously predicted made up mostly from $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ components. We consider the total $K^- p$ and $J/\psi p$ data including all the relevant resonances contributing to the spectra, and discuss the possible nature of both $P_c(4380)^+$ and $P_c(4450)^+$. We also discuss several important topics, like the role of the $\Lambda(1405)$ resonance, the effect of the contact term in the reaction, the viability of reproducing the data without the $P_c(4380)^+$ and the possible quantum numbers assignment to these pentaquarks.

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1. Introduction

From the advent of the quark model, other multiquark configuration in addition to $q\bar{q}$ and qqq were already expected. Among them the pentaquark is one of the most exotic possibilities. After the fiasco of the $\Theta^+(1540)$ pentaquark in the last decade, new excitement came after the claim of the discovery of two pentaquark states in the LHCb experiment [1, 2], which found a neat peak in the $J/\psi\, p$ invariant mass distribution from the $\Lambda_b \to J/\psi K^- p$ decay. Although two states are reported from the $J/\psi\, p$ invariant mass distribution, the first one, (called $P_c(4380)^+$), at lower energies, is quite broad and one does not see any peak in that distribution. However, the hidden charm state around 4450 MeV, called pentaquark $P_c(4450)^+$, shows up as a clear peak in this distribution.

On the theoretical side, in the work of ref. [3], it was found one state of $J^P = 3/2^-$ and $I = 1/2$ mostly made of $\bar{D}^*\Sigma_c$ at 4417 MeV, with a width of about 8 MeV, which has a coupling to $J/\psi N$, $g = 0.53$, and another one, mostly made of $\bar{D}^*\Sigma_c^*$ at 4481 MeV and with a width of about 35 MeV, which has a coupling to $J/\psi N$, $g = 1.05$. The $3/2^-$ signature is one of the possible spin-parity assignments of the observed narrow state and its mass falls between these two predictions. Although a preference for a $3/2^-$, $5/2^+$ assignment for the broad and narrow peaks, respectively, is indicated in the experimental work of [1], the fact is that the $5/2^+$, $3/2^-$ identification is also statistically acceptable, since the likelihood of both assignments is very similar. Even other assignments are not discarded in the experimental paper.

In the first part of this manuscript we summarize the work of ref. [5] where we combined the information obtained from the experiment on the $K^- p$ invariant mass distribution close to threshold and the strength of the peak in the $J/\psi\, p$ spectrum and compare them to the theoretical results that one obtains combining the results of [3] and [4]. As we shall see, we find a $K^- p$ invariant mass distribution above the $K^- p$ threshold, mainly due to the $\Lambda(1405)$, which agrees qualitatively with experiment, and the strength of this distribution together with the coupling that we find for the theoretical hidden charm state, produces a peak in the $J/\psi\, p$ spectrum, which agrees with the one reported in the experiment. These facts together provide support to the idea that the state found could be a hidden charm molecular state of $\bar{D}^*\Sigma_c - \bar{D}^*\Sigma_c^*$ nature In the second part we improve upon the previous analysis by considering the total $K^- p$ and $J/\psi p$ data including all the relevant resonances contributing to the spectra, and discuss the possibility of fitting the data without the $P_c(4380)^+$ and the role played by some contact terms.

2. The $K^- p$ and $J/\psi\, p$ distributions

In ref. [4, 5] it was shown that the relevant mechanisms for the $\Lambda(1405)$ production in the $\Lambda_b \to J/\psi K^- p$ decay are those depicted in Figs. 1(a) and 1(b). Fig. 1(a) shows the basic process to produce a $K^- p$ pair from the weak decay of the Λ_b. The final meson-baryon state undergoes final state interaction in coupled channels, Fig. 1(b), from where the $\Lambda(1405)$ is dynamically produced. Therefore the contribution to the $\Lambda_b \to J/\psi K^- p$ amplitude from the $\Lambda(1405)$ resonance, Figs. 1(a) and 1(b), is given by (see ref. [4, 5] for more details):

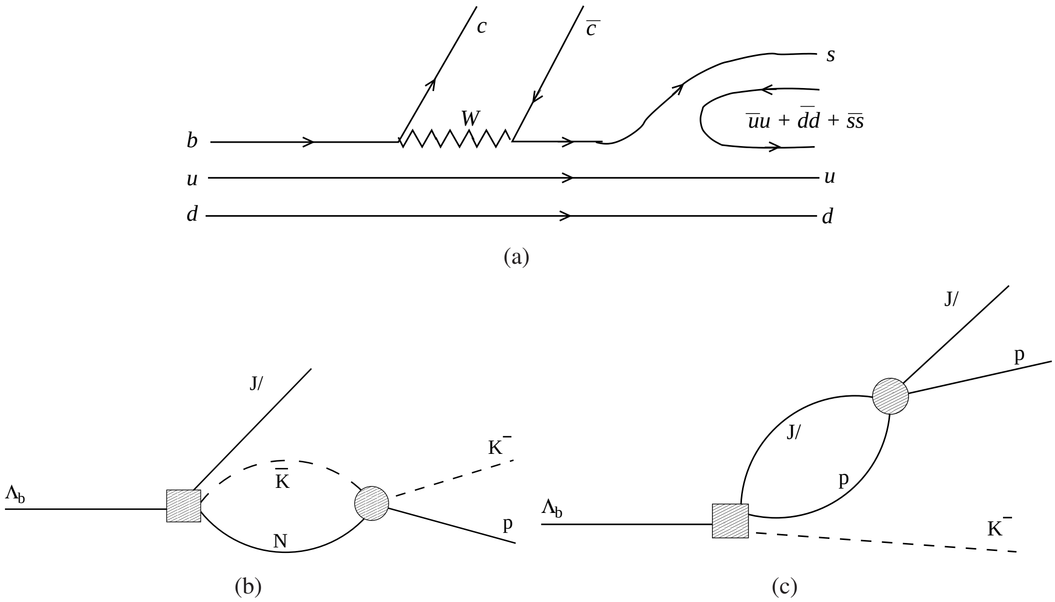


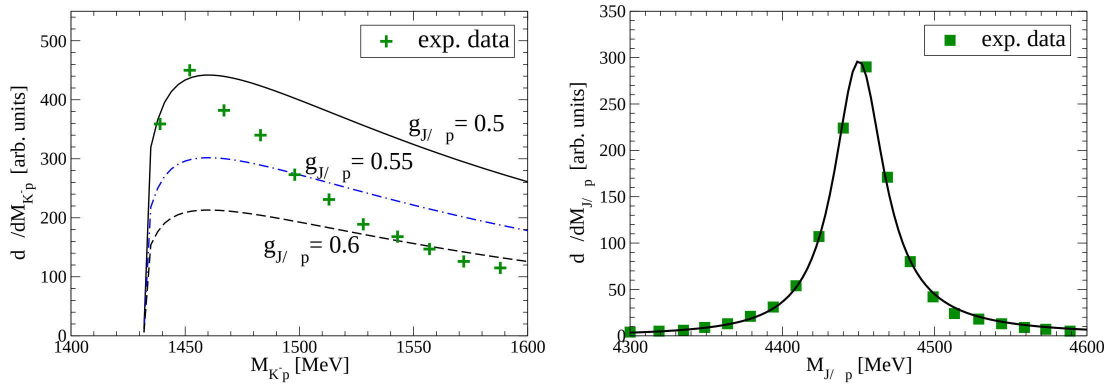
Figure 1: Mechanisms for the $\Lambda_b \to J/\psi K^- p$ reaction implementing the final state interaction

$$T^{(K^- p)}(M_{K^- p}) = V_p \left(h_{K^- p} + \sum_i h_i G_i(M_{K^- p})\, t_{i K^- p}(M_{K^- p}) \right), \tag{2.1}$$

where $M_{K^- p}$ is the $K^- p$ invariant mass, h_i are numerical $SU(3)$ factors relating the production of the different meson-baryon channels i in the hadronization (which explicit value and derivation can be found in ref. [4, 5]), and V_p accounts for CKM matrix elements and kinematic prefactors. Since we do not need the absolute normalization of the invariant mass distributions in the present work, the value of V_p can be taken to be appropriate, as will be explained below when discussing the results. In Eq. (2.1), G_i represents the meson-baryon loop function and t_{ij} stands for the s-wave meson-baryon unitarized scattering amplitudes from ref. [7]. Note that the $\Lambda(1405)$ is not included as an explicit degree of freedom but it appears dynamically in the highly non-linear dynamics involved in the unitarization procedure leading to the t_{ij} amplitudes. Actually two poles are obtained for the $\Lambda(1405)$ resonance at $1352 - 48i$ MeV and $1419 - 29i$ MeV [7].

On the other hand, in refs. [3, 8], it was shown that the $J/\psi N$ final state interaction in coupled channels, considering also the $\bar{D}^* \Lambda_c$, $\bar{D}^* \Sigma_c$, $\bar{D}\Sigma_c^*$ and $\bar{D}^* \Sigma_c^*$, produces poles in the $J^P = 3/2^-$, $I = 1/2$, sector at $4334 + 19i$ MeV, $4417 + 4i$ MeV and $4481 + 17i$ MeV, which couple sizeably to $J/\psi p$ (see table II in ref. [3]). The mechanism for the final $J/\psi N$ state interaction is depicted in Fig. 1(c). The filled circle in that figure represents the final $J/\psi p \to J/\psi p$ unitarized scattering amplitude. In refs. [3, 8] the coupling of the dynamically generated resonance to $J/\psi p$, $g_{J/\psi p}$ where obtained giving a range from about 0.5 to 1, which are genuine predictions of the theory.

In Fig. 2 we show the results for the $K^- p$ and $J/\psi p$ invariant mass distributions compared to the experimental data of ref. [1]. The absolute normalization is arbitrary but the same for both panels. In the data shown for the $K^- p$ mass distribution only the $\Lambda(1405)$ contribution is included, i.e., it shows the result of the $\Lambda(1405)$ component of the experimental analysis carried out in [1].



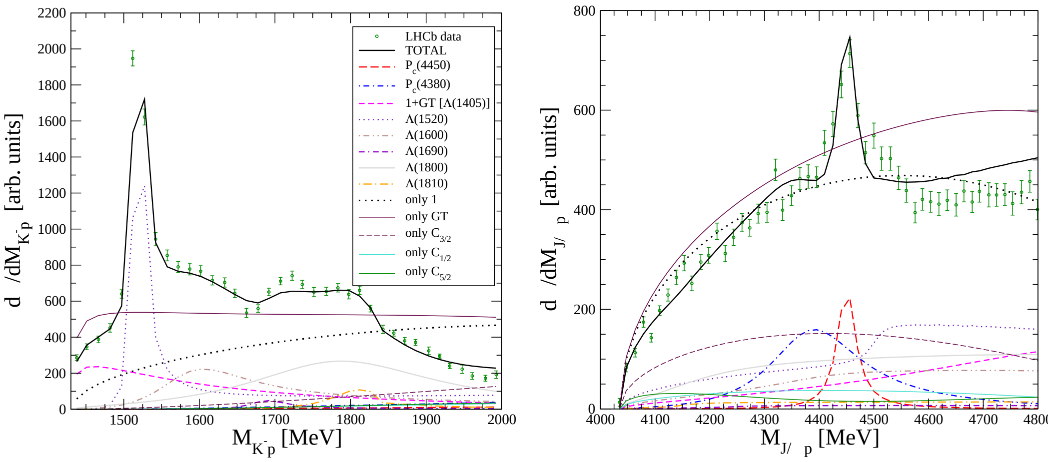
(a) (b)

Figure 2: Results for the $K^- p$ and $J/\psi p$ invariant mass distributions compared to the data of ref. [1].

Similarly, the experimental $J/\psi p$ mass distribution shown in Fig. 2(b) only considers the contribution from the $P_c(4450)^+$. The different curves are evaluated considering different values for the coupling of the $P_c(4450)^+$ to $J/\psi p$, ($g_{J/\psi p} = 0.5$, 0.55 and 0.6). For each value of $g_{J/\psi p}$, V_P has been normalized such that the peak of the $J/\psi p$ distribution agrees with experiment, and this is why there is only one curve for the $J/\psi p$ mass distribution. The results are very sensitive to the value of the $J/\psi p$ coupling since the $J/\psi p$ partial decay width is proportional to $g^4_{J/\psi p}$. The figure shows that a value for the coupling of about 0.5 can account fairly for the relative strength between the $J/\psi p$ and $K^- p$ mass distributions. This value of the coupling is of the order obtained in the extended local hidden gauge unitary approach of refs. [3, 8] which is a non-trivial consequence of the theoretical model since the value of this coupling is a reflection of the highly non-linear dynamics involved in the unitarization of the scattering amplitudes. This provides support to the interpretation of the $P_c(4450)^+$ state as dynamically generated from the coupled channels considered and to the $3/2^-$ signature of the state.

3. Inclusion of more resonances

The experimental analysis [1] included many different Λ resonances in addition to the pentaquarks, considering possible different quantum number assignments for them and all angular dependences relative to the decay products of the J/ψ. In the previous section no further Λ resonances, (in addition to the $\Lambda(1405)$), were considered. In the present section, which is a summary of the work in ref. [6], we aim at reproducing the total $K^- p$ and $J/\psi p$ invariant mass and thus we must add the relevant Λ contributions to the process. In our analysis it is enough to consider only those Λ resonances which gave a sizable contribution to the final cross section in [1] which, in addition to the $\Lambda(1405)$ discussed above, turn out to be $\Lambda(1520)$ $(3/2^-)$, $\Lambda(1600)$ $(1/2^+)$, $\Lambda(1690)$ $(3/2^-)$, $\Lambda(1800)$ $(1/2^-)$ and $\Lambda(1810)$ $(1/2^+)$. The Λ resonances (except the $\Lambda(1405)$ which, as explained above, is dynamically generated) are parametrized by a Breit-Wigner shape with Flatté parametrization of the width, considering also spin and momentum structure of the resonance (see the Appendix of ref. [6]). Furthermore, contact terms with the different spin and angular momentum of the J/ψ and kaon are also considered as explained in the Appendix of ref. [6]). These



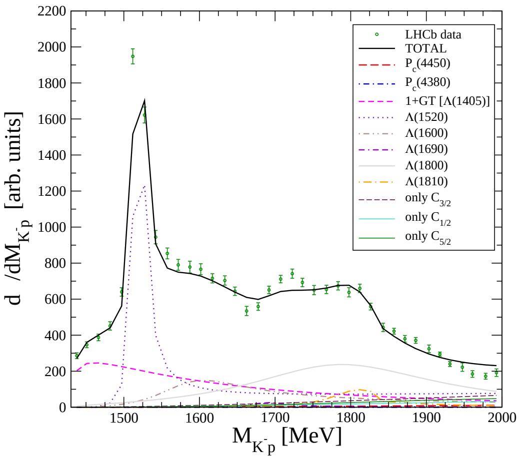
(a) (b)

Figure 3: (Color online). Panels (a) and (b): experimental data used to fit the model and results from the fit with the full model for the $K^- p$ and $J/\psi\, p$ invariant mass distributions respectively and for the $(3/2^-, 3/2^-)$ case.

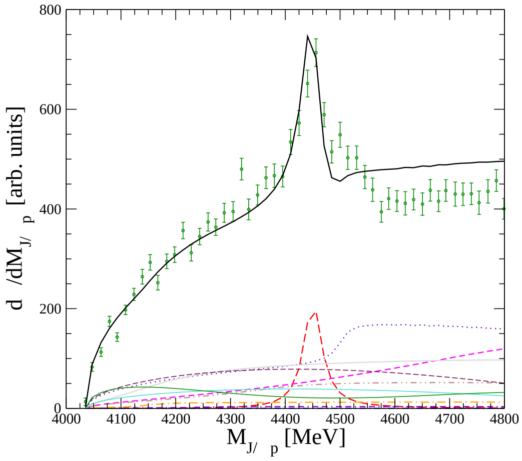
contact terms were found to be negligible in the experimental fit [1] but we will explain in the results section that some of them could indeed play an important role. For the pentaquarks also different momentum structure which depends on the different possible quantum number assignment are considered. We have carried out different fits to the experimental data [1] considering the following possibilities for the spin-parity of the pentaquarks (J_A^P, J_B^P) where J_A^P and J_B^P stand for the spin-parity of the $P_c(4380)$ and $P_c(4450)$ respectively. Neither of them provides a remarkably better fit than the rest.

First we show in the (a) and (b) panels of Fig. 3 the result of the fit to the experimental data [1] and the individual contributions of the different resonances. In ref. [5] it was pointed out that the experimental support for the existence of the $P_c(4380)$ state was not as clear as for the $P_c(4450)$ one. To shed some light into this issue we next carry out a fit removing the $P_c(4380)$ term. The result is shown in Fig. 4a and b. This fit without $P_c(4380)$ is just slightly worse compared to that in Figs. 3a and b, (about a 20% bigger χ^2/dof), but it is specially very similar or even better in the lowest region of the $J/\psi p$ mass distribution. We have traced the reason for the good agreement in the low $J/\psi p$ mass region when removing the $P_c(4380)$ to the $J^P = 5/2^+$ contact term. (The shape of this contact term by itself corresponds to the label "only $C_{5/2}$" in the figures.) We see that with a slight increase of this contact term when the $P_c(4380)$ contact term is removed (compare curves "only $C_{5/2}$" between figures Figs. 3b and Fig. 4b), a similar effect as the one of the $P_c(4380)$ can be largely accommodated. It is worth noting than in the experimental analysis [1] only contact terms up to $J = 3/2$ are included.

Furthermore, in ref [6] we provide a wide discussion of the important role played by the tree level contact elementary $\Lambda_b \to J/\psi K^- p$ production and the $K^- p$ rescattering. The interference of these two terms gives rise to the $\Lambda(1405)$ resonance in our case, and we showed that this procedure, implementing unitarity in coupled channels, produced results in remarkable agreement with those of the analysis of [1], where a $\Lambda(1405)$ resonance Breit-Wigner term (accounting for Flatté effect)



(a)



(b)

Figure 4: (Color online). Same as Fig. 3 but removing the $P_c(4380)$ from the fit.

was introduced. The agreement is not trivial or general, but occurs in the present case.

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