Double strangeness molecular-type pentaquarks from coupled channel dynamics

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Abstract. The existence of the nucleonic pentaquark resonances $P_c(4312)$, $P_c(4380)$, $P_c(4440)$ and $P_c(4457)$, established by the LHCb collaboration, has been one of the major discoveries in hadron physics in the latest years. This has been followed by the discovery of pentaquarks with one unit of strangeness, $P_{cs}(4338)$ and $P_{cs}(4457)$. Most of these states can be understood as hadronic molecules, namely bound states of a sufficiently attractive meson-baryon interaction. A widely used model, based on unitarized meson-baryon amplitudes obtained from vector meson exchange interactions derived from the hidden gauge formalism, which predicted these states prior to their discovery, is also predicting the existence of pentaquarks with double strangeness content, at around 4500 MeV and 4600 MeV [1]. Our model also suggest that one of these double strangeness pentaquarks can be seen in the weak decay of the Ξ_b baryon into $J/\Psi\phi\Xi$. A detailed study of this reaction is still under investigation, but in these proceedings we shall show some preliminary results, which confirm the possibility of observing traces of S=-2 pentaquark in invariant mass spectra of $J/\Psi\,\Xi$ pairs produced in the decays $\Xi_b \to J/\Psi\phi\Xi$.

1 Introduction

Since the turn of the millennium, an increasing amount of data obtained by several collaborations (Belle, BaBar, LHCb, BESII) has produced many exotic hadrons which appear to be inconsistent with the predictions of the conventional quark model. The discovery at LHCb [2, 3] of four excited nucleon resonances ($P_c(4312)$, $P_c(4380)$, $P_c(4440)$ and $P_c(4457)$), seen on the invariant mass distribution of $J/\Psi\,p$ pairs from the decay $\Lambda_b \to J/\Psi\;p\;K^-$, has been considered as the first clear evidence of the existence of pentaquark baryons, as a $c\bar{c}$ pair is necessary to explain their high mass. In a later experiment [4], the $J/\Psi\,\Lambda$ spectrum, obtained from the decay $\Xi_b^- \to J/\Psi\;\Lambda\;K^-$, also provided evidence for a pentaquark, this time with one unit of strangeness content, the $P_{cs}(4459)$, which was also compatible with a two-peaked interpretation. More recently, an analysis of the $B^- \to J/\Psi\;\Lambda\;\bar{p}$ decay points at the existence of another narrow hidden-charm pentaquark with strangeness, the $P_{cs}(4338)$ [5].

Among the various theoretical interpretations on the nature of these pentaquarks, the possibility that they could be structured as meson-baryon molecules was already predicted in [6, 7], prior to their discovery, and has gained interest ever since due to their proximity to various charmed meson-baryon thresholds (see [8, 9] and references therein). Many of

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these studies assume a t-channel vector meson exchange interaction between mesons and baryons, which is unitarized in coupled-channels. Furthermore, in the recent paper [1] the authors have shown that such type of model also predict double strangeness pentaquarks of molecular nature. The first one, $\Xi(4493)$, is a $J^P = 1/2^-$ resonance generated from the interaction of pseudoscalar mesons with baryons, which couples most strongly to the $\bar{D}\Omega_c$ and $\bar{D}_s\Xi_c'$ channels. The other one, $\Xi(4633)$, is a spin-degenerate resonance which can have $J^P = 1/2^-$ or $J^P = 3/2^-$ and is obtained from the interaction of vector mesons with baryons, and couples dominantly to the $\bar{D}^*\Omega_c$ and $\bar{D}_s^*\Xi_c'$ channels. The very interesting result is also that these molecular-type pentaquarks are dynamically generated in a very specific and unique way, via a strong non-diagonal attraction between the two heaviest meson-baryon channels.

It was also suggested in [1] that this latter state, $\Xi(4633)$, could potentially be seen in invariant mass spectra of $J/\Psi\,\Xi$ pairs produced in the decays $\Xi_b \to J/\Psi\phi\Xi$. And our recent study, [10], which will be briefly presented in these Proceedings, confirms this assumption.

2 The $\Xi_b \to J/\Psi\phi\Xi$ decay

Studying the $\Xi_b \to \Xi X \to \Xi\; J/\psi\; \phi$ decay we, apart from the search for the double strangeness pentaquark, have also a chance to study the interplay between the $X(4140)$ and $X(4160)$ resonances.[1] Similar to what was done in Refs. [11, 12], we use two independent primary decay mechanisms, one for $X(4160)$ and another for $X(4140)$. Since for the $X(4140)$ resonance we do not have a physical model to generate it, we introduce it as a Breit-Wigner whose parameters are fitted to experimental data. The $X(4160)$ can be obtained as a result of chiral unitarized coupled-channels calculation (Ref. [13]), i.e. as a meson-meson molecule resonance strongly coupled to $D_s^*\bar{D}_s^*$ channel.

Let us start with the $\Xi_b \to \Xi\; J/\psi\; \phi$ decay via $X(4160)$ production. Since the $X(4160)$ strongly couples to the $D_s^*\;\bar{D}_s^*$ channel, we can start considering the $\Xi_b \to \Xi D_s^*\;\bar{D}_s^*$ weak decay mechanism (Fig. 1 (1)). Then, as shown in Fig. 1 (2), the $D_s^*\;\bar{D}_s^*$ lines form a loop, allowing multiple coupled channel interactions and generating dynamically the $X(4160)$, which then decays into J/ψ and ϕ. The amplitude of this process can be written as:

$$\mathcal{M}^P_{X_{4160}} = A(\vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_\phi) \cdot \vec{P}_\Xi G_{D_s^*\bar{D}_s^*} \frac{T_{D_s^*\bar{D}_s^*,J/\psi\phi}}{g_{D_s^*\bar{D}_s^*} g_{J/\psi\phi}}. \tag{1}$$

The A on the right side of the equation represents the strength of the $\Xi_b \to \Xi D_s^*\;\bar{D}_s^*$ weak decay, represented in Fig. 1 (1), which we are not going to study in details. This value can be taken as a constant due to the limited range of energies involved in the $\Xi_b \to \Xi\; J/\psi\; \phi$ decay as it is argued in Ref. [14]. The $(\vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_\phi) \cdot \vec{P}_\Xi$ factor denotes the P-wave operator which is the minimum partial wave we need in the weak vertex to conserve the angular momentum, since the spins of Ξ_b and Ξ are $J = 1/2$ while for the $X(4160)$ is $J = 2$. Here $\vec{\epsilon}_i$ represents the polarisation of the vector mesons in the $J/\psi\; \phi$ rest frame and $\vec{P}_\Xi$ the tree-momentum of the Ξ in the same frame. The factor $G_{D_s^*\bar{D}_s^*}$ indicates the contribution of the $D_s^*\bar{D}_s^*$ loop shown in Fig. 1 (2) and the $T_{D_s^*\bar{D}_s^*,J/\psi\phi}$ term is the coupled-channel unitarized amplitude for the $D_s^*\bar{D}_s^* \to J/\psi\; \phi$ process. Note that we divide it by the corresponding couplings constants. This is done for a proper comparison with the contribution of the $X(4140)$ term.

[1] In 2008, the Belle collaboration reported the existence of the $X(4160)$ [15] in the $e^-e^+ \to J/\psi D^*\bar{D}^*$ reaction and, during the following years, some groups reported the existence of a narrow $X(4140)$ with a width around 19 MeV [16–19]. Despite of these results, a more recent measurement of the $B^+ \to J/\psi\phi K^+$ decay from the LHCb collaboration [20] obtained a width of 83 MeV for the $X(4140)$, which is pretty large compared with the previous studies. It might be that the reason of this large width for $X(4140)$ is related to the fact that the two neighbouring states (the narrow $X(4140)$ state plus a wider $X(4160)$ resonance) were fitted together [11].

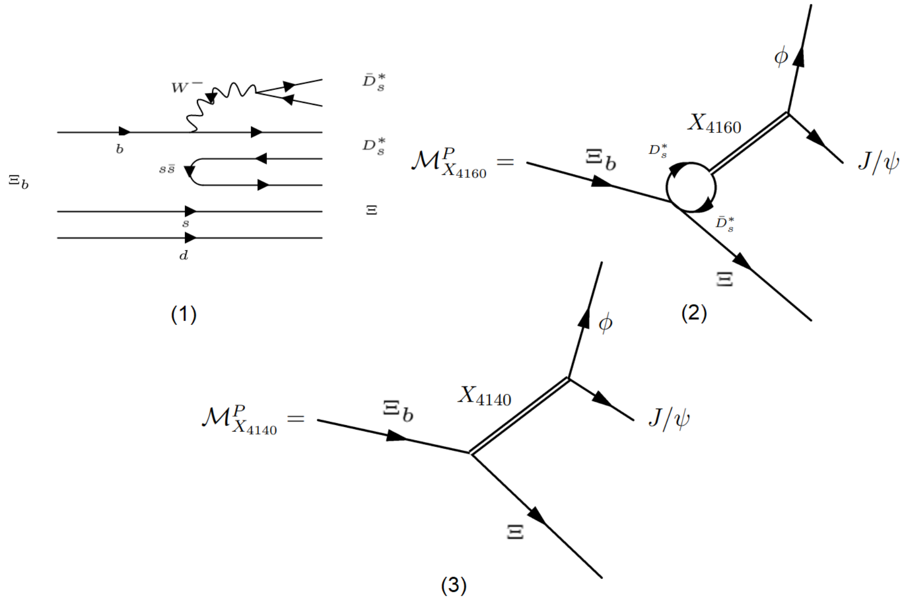

Figure 1. (1) Microscopic quark level $\Xi_b \to \Xi\, D_s^*\, \bar{D}_s^*$ transition, through internal emission.
(2) Mechanism for the $\Xi_b \to J/\psi\ \phi\ \Xi$ decay involving the $X(4160)$ resonance.
(3) Mechanism for the $\Xi_b \to J/\psi\ \phi\ \Xi$ decay involving the $X(4140)$ resonance.

Now we will discus the $X(4140)$ production process which is shown in Fig. 1 (3) and the associated amplitude is

$$\mathcal{M}^P_{X_{4140}} = \frac{\tilde{B}}{2M_{X(4140)}[M_{J/\psi\phi} - M_{X(4140)} + i\frac{\Gamma_{X(4140)}}{2}]}, \tag{2}$$

where the $X(4140)$ is parameterised with a Breit-Wigner, where $M_{J/\psi\phi}$ is the invariant mass of the $J/\psi\phi$ system and $M_{X(4140)}$ and $\Gamma_{X(4140)}$ are the mass and width of $X(4140)$ resonance, respectively. A new constant, connected to the strength of the $\Xi_b \to \Xi\, X(4140)$ weak decay is $B = \tilde{B}/M_{X(4140)}$ and in this process the dominant interaction is in S-wave, since the quantum number of the $X(4140)$ is $J = 1$.

Once we discussed the generation of the $\Xi\ J/\psi\ \phi$ final state in Ξ_b decay we want to focus on studying the final state interaction in the $\Xi\ J/\psi$ and $\Xi\ \phi$ channels. For the case of the final state interaction of $\Xi\ J/\psi$ pair, the Ξ and J/ψ legs from Fig. 1 (2) and (3) have to be closed, forming a loop, which can dynamically generate the $S = -2$ pentaquark. The $\Xi\ \phi$ final state interaction can produce excited Ξ states and has to be studied in a similar way.

The amplitude associated to the process with the final state interaction of the $J/\psi\Xi$ pair driven by the Ξ_b decay via the $X(4160)$ resonance is:

$$\mathcal{M}^{J/\psi\Xi}_{X_{4160}} = A(\vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_{\phi}) \cdot \left(\frac{\vec{P}_{\Xi} - \vec{P}_{\phi}}{2}\right) T_{J/\psi\Xi,J/\psi\Xi} I^{J/\psi\Xi}_{X_{4160}}, \tag{3}$$

where the superscript denotes the final state interaction channel. All the details of this calculations, in particular the expression for the integral $I^{J/\psi\Xi}_{X_{4160}}$, are given in [10]. The term $T_{J/\psi\Xi,J/\psi\Xi}$ captures the final state interaction contribution from $J/\psi\ \Xi$, which in this work we will model using a Breit-Wigner form:

$$T_{J/\psi\Xi,J/\psi\Xi} = \frac{g^2_{J/\psi\ \Xi}}{M_{J/\psi\ \Xi} - M + i\frac{\Gamma}{2}}, \tag{4}$$

there $M_{J/\psi\ \Xi}$ is the invariant mass of the $J/\psi\ \Xi$ system; $g_{J/\psi\ \Xi}$ is the coupling of the $S = -2$ pentaquark to the $J/\psi\ \Xi$ channel; and M and Γ denote correspondingly its mass and width (all these parameters have been given in [1]). In a similar way we can take into account the final state interaction in $\Xi\ \phi$ channel [10], although this is a bit out of the scope of these proceedings.

For the final state interaction in the presence of the $X(4140)$ resonance we can repeat similar calculations and obtain [10]:

$$\mathcal{M}^{J/\psi\Xi}_{X_{4140}} = \tilde{B} T_{J/\psi\Xi, J/\psi\Xi} I^{J/\psi\Xi}_{X_{4140}} . \tag{5}$$

And finally we sum the corresponding amplitudes up obtaining the full amplitude:

$$\overline{|\mathcal{M}|^2} = |A|^2 \overline{|\mathcal{M}_{4160}|^2} + |\tilde{B}|^2 \overline{|\mathcal{M}_{4140}|^2} = |A|^2 \Big(\overline{|\mathcal{M}_{4160}|^2} + \beta \overline{\mathcal{M}_{4140}|^2} \Big), \tag{6}$$

where the bar represents the sum over polarisations and $\beta = |\tilde{B}|^2/|A|^2$. Note that, since the weak decay goes in P-wave for the $X(4160)$ contribution and in S-wave for the $X(4140)$ contribution, the cross term in $\overline{|\mathcal{M}_{4160} + \mathcal{M}_{4140}|^2}$ cancels as these two partial waves are orthogonal and do not interfere. It is also important to comment that, although the overall factor $|A|^2$ is not known, it is not relevant for the shape of the obtained distributions. The form of the distributions, and not its absolute value, will be our main observable. We are exploring if the position of the peak and its width can be measured in several model situations. So our final results will be given in arbitrary units, therefore we will set it as $|A|^2 = 1$ from here to the end of this work.

The β acts like a relative weight between the $X(4140)$ and $X(4160)$ contributions. In this work we will not calculate its value and we do not have any experimental result to compare it, so we take the value of β from Ref. [11] to solve this issue. In this reference the authors study the interplay between $X(4160)$ and $X(4140)$ in the $B^+ \to J/\psi\ \phi\ K^+$ decay. The mechanism involving the $X(4160)$ in this reaction is rather similar at the quark level to our diagram shown in Fig. 1 (1), but without the spectator s quark in the initial and final state. Hence the topology of the diagrams is similar also in the case of $X(4140)$. Therefore the β value in our reaction may be similar as that in Ref. [11], but we do not expect it to be the exactly the same, since the partial waves involved in the their weak decay vertex are P-wave and D-wave for the $X(4140)$ and $X(4160)$ resonances respectively.

3 Results and discussion

In this section we shall discuss the obtained results for the $J/\psi\ \Xi$ mass distribution, where we expect to see the signature of the $S = -2$ pentaquark. According to [1] this state has a mass $M_R = 4633$ MeV and a width $\Gamma_R = 80$ MeV, and couples rather strongly to the $J/\psi\ \Xi$ channel, with a coupling constant value of $g_{J/\phi\Xi} = -1.62 + 0.38i$. We will take these values for the pole position and coupling as the nominal ones and we will vary them within a reasonable range to explore the sensitivity of our results with respect to the pentaquark parameters.

In Fig. 2 we can see the $J/\psi\ \Xi$ spectrum, where the dashed blue line is obtained using only the tree-level diagram, while the red line includes also the FSI effects. In this latter curve we should see the signal of the $S = -2$ pentaquark, generated in the $J/\psi\ \Xi$ interaction. First of all, as seen in Fig. 2, the background shows itself a peak structure around 4730 MeV. The effect of the pentaquark is the appearance of a bump around the nominal pentaquark mass of 4633 MeV that could be detected. Note that the pentaquark interferes with the background positively and, even being a wide resonance, it has an important effect on the spectrum due to its strong coupling to the $J/\psi\ \Xi$ channel.

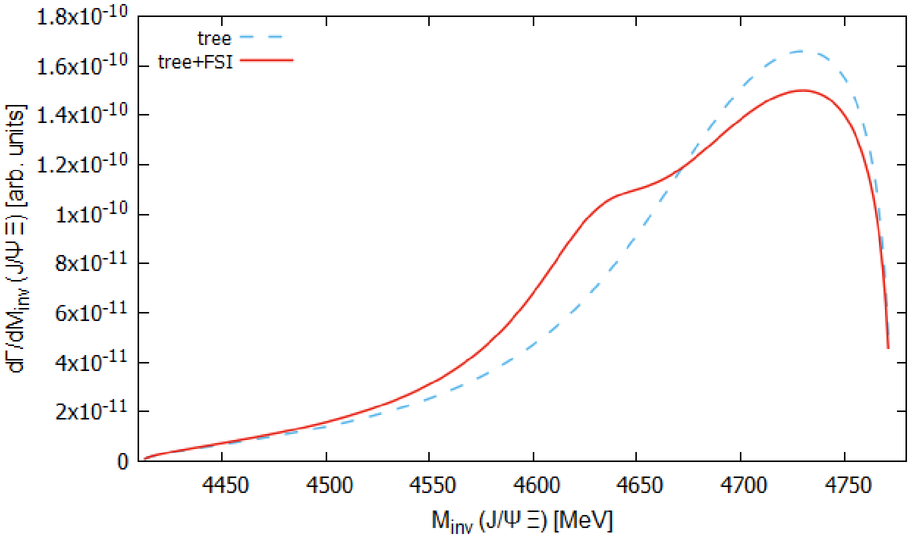

Figure 2. The $J/\psi\ \Xi$ spectrum, where the dashed blue line corresponds to the tree level diagram and the red one is obtained also taking into account the final state interactions that generates the $S = -2$ pentaquark.

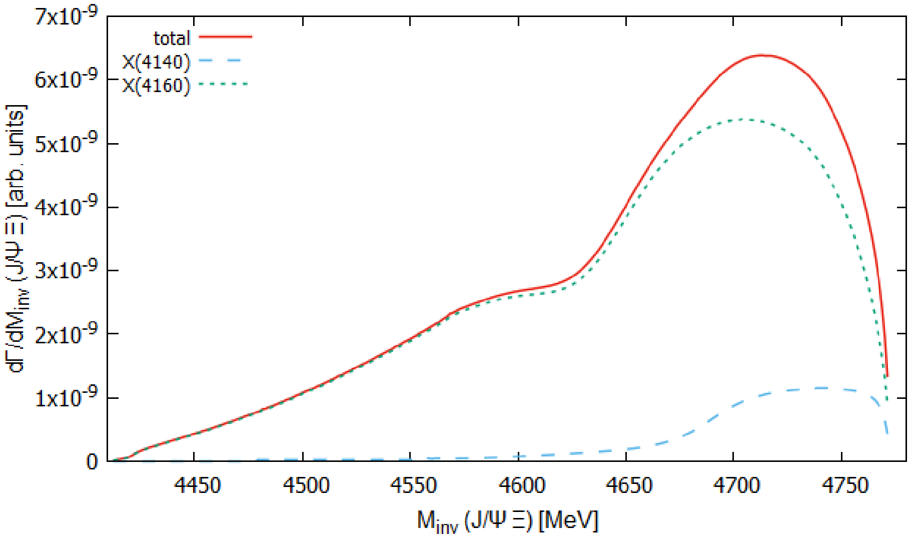

Figure 3. The red line represents the $J/\psi\ \Xi$ spectrum computed with a narrow $X(4140)$ plus a $X(4160)$, while the blue and the green ones show the individual contribution from the $X(4140)$ and the $X(4160)$, respectively.

Let's now consider the calculation with a narrow $X(4140)$ and a wide $X(4160)$ resonances. The results (with FSI) can be seen in Fig. 3, where the blue and the green curves show the individual contribution of the $X(4140)$ and the $X(4160)$ resonances respectively, while the red curve is the sum of both contributions. Note that the $X(4160)$ contribution is dominant with respect to that of the $X(4140)$. It is also important to see that, in contrast to the previous case, the signal of the pentaquark interferes negatively with the background. Thus, such an experimental measurement potentially allows us also to discriminate whether the truly nature of $X(4140)$ state is only one wide resonance or it is the combination of a narrow $X(4140)$ state plus a $X(4160)$ one.

Since we know there can exist some theoretical uncertainties, we tried to modify the pentaquark pole position by ±50 MeV and to allow for a 20% of variation of the coupling $g_{J/\phi\Xi}$ - our results clearly show that the presence of the double strangeness pentaquark is experimentally detectable in all cases.

Thus, our work should stimulate experiments looking for these type of pentaquarks, the discovery of which would enrich the family of their already observed $S = 0$ and $S = -1$ pentaquark partners. From a hadronic molecular perspective, it is interesting to note that the usually adopted alternative of molecular binding through a long-range interaction mediated by the exchange of pions between the constituent hadrons is not possible in the heavy part of strangeness $S = -2$ sector. Thus, if $\Xi(4633)$ (or $\Xi(4493)$) will be observed, their interpretation as molecules would require a change of paradigm, since they could only be bound through heavier-meson exchange models as shown in [1].

Aknowledgements. V.K.M. and A.R. acknowledge support from the Ministerio de Ciencia e Innovación of Spain through the Unit of Excellence María de Maeztu 2020-2023 award to the Institute of Cosmos Sciences (CEX2019-000918-M) and under the project PID2020-118758GB-I00. Support from the EU STRONG-2020 project under the program H2020-INFRAIA-2018-1, grant agreement no. 824093, is also acknowledged.

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