Scalar, axial-vector and tensor resonances from $\rho(\omega)D^*$ and $D^*\bar{D}^*$, $D^*_s\bar{D}^*_s$

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Abstract

We apply a unitary approach together with a set of hidden-gauge Lagrangians to study the vector-vector interaction. First we explain the results using this model in SU(3). After, we study the case of the $\rho(\omega)D^*$ interaction within the model. In some cases we get strong enough attraction to bind the system. Concretely, we get one resonance for each spin $J = 0, 1, 2$. For $J = 1$ and 2 these resonances can be easily identified with the $D^*(2460)$ and $D^*(2640)$. Finally, we study the vector-vector interaction for the channels with quantum numbers charm $C = 0$ and strangeness $S = 0$ in the region around 4000 MeV. We get five poles, three of which could be identified with the Y(3940), Z(3930) and X(4160). These poles appear with quantum numbers $I = 0$ and $J^{PC} = 0^{++}, 2^{++}$ and 2^{++}, respectively, and can be considered as hadronic molecules made of $D^*\bar{D}^*$, $D^*_s\bar{D}^*_s$.

Introduction

In this talk, we report several works that combine coupled channel unitarity and hidden-gauge Lagrangians for the interaction of vector meson among themselves. These Lagrangians were introduced by Bando-Kugo-Yamawaki [1] and combined with unitary techniques related with the Bethe-Salpeter equation, provide a useful tool to generate resonances or bound states if the interaction is strong enough. These techniques were firstly applied to study the $\rho\rho$ interaction and the interaction was strong enough to bind the $\rho\rho$ system [2]. Thus, two bound states appeared as poles in the second Riemann sheet that could be identified with the $f_2(1270)$ and the $f_0(1370)$. The decay of these resonances to two or four pions was provided by a box or crossed box diagram from two ρ mesons going to the pions. These box diagrams provided a width comparable with the data quoted at the PDG [3], leading to a satisfactory model that provides mass, width and quantum numbers, as well as couplings, and thus, composition of these generated resonances that can be seen as hadronic molecules. Later works that we quote in the next Section have extended the model to study the vector-vector interaction in SU(3) and the $\rho(\omega)D^*$ system.

Recently, the B-factories at SLAC, KEK and CESR, which were originally constructed to test matter-antimatter asymmetries or CP violation, have discovered new hidden-charm states around the energy region of 4000 MeV. These new states do not seem to have a simple $c\bar{c}$ structure. They are naively called as XYZ particles. Some of them, which we consider in this manuscript, are the X(3940), the Y(3940), the X(4160) and the Z(3930).

The X(3940) and the X(4160) were observed by the Belle Collaboration in the $e^+e^- \to J/\psi X$ reaction as a $D\bar{D}^*$ and $D^*\bar{D}^*$ mass peak respectively [4]. On the other hand, the Y(3940) has been firstly observed by the Belle Collaboration and Babar has confirmed it in $B \to KY \to K\omega J/\psi$ decays [5]. Nevertheless, the values for the mass and width reported by Babar are smaller than the Belle's values. The production modes ensure that the X(4160) as well as the X(3940) and Y(3940) have C-parity positive.

Finally, the Z(3930) has been seen by Belle as a peak in the spectrum of $D\bar{D}$ mesons produced in $\gamma\gamma$ collisions. The Belle measurements favors the 2^{++} hypothesis, making the assignment of the Z(3930) to the $2^3P_2(\chi'_{c2})$ charmonium state possible [6, 7].

Previous theoretical work about the origin of these particles has been done. In [8], by solving the Schrödinger equation with a potential derived from effective Lagrangians, they found molecular solutions for the Y(3940) and the Y(4140) with $J^P = 0^+, 2^+$. In [9], the authors calculate the decay rates of the observed modes $Y(3940) \to J/\psi\omega$ and $Y(4140) \to J/\psi\phi$ for the particular case of $J^{PC} = 0^{++}$, taking the coupling constant from the compositeness condition [9], and the result supports the interpretation of the Y(3940) and the Y(4140) as $D^*\bar{D}^*$ and $D^*_s\bar{D}^*_s$ molecules respectively. Whereas, in [10] they apply QCD sum rules to evaluate the mass and they conclude that it is possible to describe the $Y(4140)$ as a $D^*_s\bar{D}^*_s$ molecular state.

In this manuscript we want to summarize briefly the formalism of the vector-vector interaction. Then, we want to show the simple case of the $\rho(\omega)$ D^* interaction. Finally, we study the case of a system of two vector meson with charm $C = 0$ and strangeness $S = 0$ around 4000 MeV (hidden charm sector).

Formalism: The VV interaction

Within the theorical framework, there are two main ingredients: first, we take the Lagrangians for the interaction of vector mesons among themselves, that come from the hidden gauge formalism of Bando-Kugo-Yamawaki [1]. Second, we introduce the potential V obtained from these Lagrangians (projected in s-wave, spin and isospin) in the

Bethe Salpeter equation:

$$T = (\hat{1} - VG)^{-1} V \ , \tag{1}$$

where G is the loop function. Therefore, we are summing all the diagrams containing zero, one, two... loops implicit in the Bethe Salpeter equation. Finally, we look for poles of the unitary T matrix in the second Riemann sheet. All this procedure is well explained in [2, 11]. In these works, two main vertices are taken into account for the computation of the potential V: the four-vector-contact term and the three-vector vertex, which are provided respectively from the Lagrangians:

$$\mathcal{L}_{III}^{(c)} = \frac{g^2}{2} \langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu \rangle \ , \tag{2}$$

$$\mathcal{L}_{III}^{(3V)} = ig \langle (\partial_\mu V_\nu - \partial_\nu V_\mu) V^\mu V^\nu \rangle \ . \tag{3}$$

By means Eq. (3), the vector exchange diagrams in Fig. 1 are calculated. The diagram in Fig. 1d) leads to a repulsive p-wave interaction for equal masses of the vectors [2] and only to a minor component of s-wave in the case of different masses [11]. Thus, the four-vector-contact term in Fig. 1a) and the t(u)-channel vector exchange diagrams in Fig. 1c) are responsible of the generation of resonances or bound states if the interaction is strong enough.

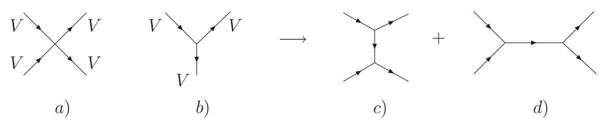

Figure 1: Terms of the $\mathcal{L}_{III}$ Lagrangian: a) four vector contact term, Eq. (2); b) three-vector interaction, Eq. (3); c) t and u channels from vector exchange; d) s channel for vector exchange.

In order to consider the pseudoscalar-pseudoscalar decay mode, and thus compare properly with the available experimental data for the width, a box diagram is also included, which we show in Fig. 2 for the particular case of the $\rho\rho$ system. Crossed box diagrams and box diagrams involving anomalous couplings were also calculated in [2], but they were much smaller, specially in the case of the anomalous coupling, than the contributions coming from the box diagrams in Fig. 2 and they were not considered in later works [11, 12, 13]. As we are interested in the region close to the two vector meson threshold, the three momenta of the external particles can be neglected compared with the mass of the vector meson, and thus, we can make $|\vec{q}|/M \sim 0$ for external particles, which considerably simplify the calculation. In Table 1, the eleven states found with this procedure in the work of [11], where the formalism is applied in SU(3), are shown. As one can see in this table, five of them can be identified with data in the PDG: the $f_0(1370)$, $f_0(1710)$, $f_2(1270)$, $f_2'(1525)$ and $K_2^*(1430)$. In this work, the integral of two-meson-vector loop function is calculated by means of the dimensional regularization method. This requires the introduction of one parameter, which is the subtraction constant, that is tuned to reproduce the mass of the tensor states, whereas the other states are predicted. In order to calculate the box diagrams, one has to introduce two parameters, the cut-off, Λ, for the integral, and one parameter, Λ_b, involved in the form factor used. These parameters were considered to be around 1 GeV and 1.4 GeV respectively in [2] to get reasonable values of the $f_0(1370)$ and $f_2(1270)$ widths. In the later work of [11], these values of Λ and Λ_b also provide a good description of the widths for the other states, as shown in Table 1.

As one can see, the model in SU(3) provides a good description of the properties of many physical states. In the next sections, we generalize the model to SU(4), where interesting new states will appear.

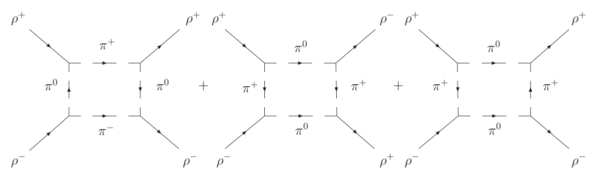

Figure 2: Box diagrams for the case of the $\rho\rho$ interaction.

Generalization to SU(4): The $\rho(\omega)$ D^* system

A previous step to generalize to SU(4) is to study the simple case of the channels with $C = 1$ and $S = 0$. That is a set of three channels: ρD^*, ωD^* and $D_s \bar{K}^*$. In fact, we want to focus the attention in the energy region around $2500 - 2600$ MeV, where there are several interesting resonances that can be found in the PDG. In view of the previous works of [2, 11], we hope to find a binding energy of $\sim 200 - 300$ MeV and the threshold of the $D_s \bar{K}^*$ channel is far away, concretely, it is 200 MeV above the ρD^* and ωD^* thresholds. Thus, we simplify even more the study to these two channels: ρD^* and ωD^*.

In order to follow the procedure of the works of [2, 11], the V matrix is straigthforward extended to SU(4), as it was done in the work of [14]:

$$V_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu \ , \tag{4}$$

where the ideal mixing has been taken for ω, ϕ and J/ψ. The details of the full procedure that we try to summarize in this section are well explained in [12]. Besides the four-vector contact diagrams, we have two kinds of vector-exchange diagrams, one is the exchange of one light vector meson, ρ or ω, and the other one is the exchange of a heavy vector meson, D^*. Of course, the last terms are proportional to $\kappa = \frac{m_\rho^2}{m_{D^*}^2} \sim 0.15$, and this gives rise to a corrections of the order of 10% of the ρ-exchange terms. Also,

$I^G(J^{PC})$	Theory	PDG data		
	(Mass, Width)	Name	Mass	Width
$0^+(0^{++})$	$(1520, 257-396)$	$f_0(1370)$	$1200 \sim 1500$	$200 \sim 500$
$0^+(0^{++})$	$(1720, 133-151)$	$f_0(1710)$	1724 ± 7	137 ± 8
$0^-(1^{+-})$	$(1802, 49)$	h_1		
$0^+(2^{++})$	$(1275, 97-111)$	$f_2(1270)$	1275.1 ± 1.2	$185.0^{+2.9}_{-2.4}$
$0^+(2^{++})$	$(1525, 45-51)$	$f'_2(1525)$	1525 ± 5	73^{+6}_{-5}
$1^-(0^{++})$	$(1777, 148-172)$	a_0		
$1^+(1^{+-})$	$(1703, 188)$	b_1		
$1^-(2^{++})$	$(1567, 47-51)$	$a_2(1700)$??		
$1/2(0^+)$	$(1639, 139-162)$	K^*_0		
$1/2(1^+)$	$(1743, 126)$	$K_1(1650)$?		
$1/2(2^+)$	$(1431, 56-63)$	$K^*_2(1430)$	1429 ± 1.4	104 ± 4

Table 1: Properties of the 11 dynamically generated states: pole positions, masses and widths in the real axes for two different Λ_b (parameter related to the form factor used in the calculation of the box diagram [11]) compared with the experiment. All the quantities are in units of MeV.

the $\rho\rho\omega$ and the $\omega\omega\omega$ vertices violate G-parity, whereas the $\rho\omega\omega$ vertex violates isospin, therefore, we do not have the exchange of one light vector meson in the $V(\rho D^* \to \omega D^*)$ and $V(\omega D^* \to \omega D^*)$ potentials. For this reason, these two terms, where only the four-vector contact term plus the D^*-exchange term contributes , are smaller compared with the $V(\rho D^* \to \rho D^*)$, term that mainly provides the interaction. As can be seen in Table 2, this term is of the order of -300 MeV in $I = 1/2$, whereas in $I = 3/2$, it is interesting to see that we get a repulsive interaction without any possible generated exotic states.

We get three states with $I = 1/2$ and $J = 0, 1$ and 2 respectively. We have fixed the value of μ as 1500 MeV and we have fine-tuned the subtraction constant α around its natural value of -2 [15], in order to get the position of the $D^*_2(2460)$ state at the PDG. Thus, we have chosen the value of $\alpha = -1.74$. Because of the strong interaction we get three bound states with practically no width except by the small width provided by the convolution of the ρ propagator to take into account its decay in two pions. But, the later inclusion of the πD box diagram allows us to get some more width comparable with the data in the PDG as can be seen in Table 3. In order to calculate the πD-box diagram, two different form factors for the vector-two-pseudoscalar vertex are considered. One is used in the works of [2, 11], which is inspired by the empirical form factors used in the study of vector meson decays [16]. The other one, is an exponential parametrization for an off-shell pion evaluated using QCD sum rules [17] using at the same time the experimental value of the $D^*D\pi$ coupling, $g^{exp}_{D^*D\pi}$. In both cases we get reasonable values of the width, with the preference, of course, for the use of $g^{exp}_{D^*D\pi}$. In Table 3, the values obtained for the last case are shown, where the parameter of the exponential form factor is taken as $\Lambda = 1$ GeV. The interesting thing in the calculation of the box diagram, is that this box diagram only has $J = 0$ and 2, therefore, the state found with $J = 1$ cannot decay to πD by means of this mechanism, which is the reason why we get a small width of 4 MeV, compared with the other states for $J = 0$ and 2. Thus, we find a reasonable explanation for why the $D^*(2640)$ has a small width, $\Gamma < 15$ MeV, when we associate to this state the quantum numbers $J^P = 1^+$.

The XYZ particles

In view of the results obtained in the cases of the vector-vector interaction in SU(3) and the $\rho(\omega)$ D^* system we make an attempt to study now the sector with $C = 0$ and $S = 0$. In the case of $I = 0$ we have 10 channels: $D^*\bar{D}^*(4017)$, $D^*_s\bar{D}^*_s(4225)$, $K^*\bar{K}^*(1783)$, $\rho\rho(1551)$, $\omega\omega(1565)$, $\phi\phi(2039)$, $J/\psi J/\psi(6194)$, $\omega J/\psi(3880)$, $\phi J/\psi(4116)$ and $\omega\phi(1802)$, and 6 channels for $I = 1$: $D^*\bar{D}^*(4017)$, $K^*\bar{K}^*(1783)$, $\rho\rho(1551)$, $\rho\omega(1558)$, $\rho J\psi(3872)$ and $\rho\phi(1795)$. The procedure is identical to the one explained in the previous sections, see [13] for practical details, except by the complication added due to the many channels involved. The function loop is computed by means of dimensional regularization and we fix the value of $\mu = 1000$ MeV as in the work of [11]. We establish two different subtraction constants, one for the channels involving two light vector meson, which is called

I	S	Contact	ρ-exchange	D^*-exchange	$\sim$ Total$[I(J^P)]$
$1/2$	0	$+5g^2$	$-2\frac{g^2}{M_\rho^2}\,(k_1+k_3)\cdot(k_2+k_4)$	$-\frac{1}{2}\frac{\kappa\, g^2}{M_\rho^2}\,(k_1+k_4)\cdot(k_2+k_3)$	$-16g^2[1/2(0^+)]$
$1/2$	1	$+\frac{9}{2}g^2$	$-2\frac{g^2}{M_\rho^2}\,(k_1+k_3)\cdot(k_2+k_4)$	$+\frac{1}{2}\frac{\kappa\, g^2}{M_\rho^2}\,(k_1+k_4)\cdot(k_2+k_3)$	$-14.5g^2[1/2(1^+)]$
$1/2$	2	$-\frac{5}{2}g^2$	$-2\frac{g^2}{M_\rho^2}\,(k_1+k_3)\cdot(k_2+k_4)$	$-\frac{1}{2}\frac{\kappa\, g^2}{M_\rho^2}\,(k_1+k_4)\cdot(k_2+k_3)$	$-23.5g^2[1/2(2^+)]$
$3/2$	0	$-4g^2$	$+\frac{g^2}{M_\rho^2}\,(k_1+k_3)\cdot(k_2+k_4)$	$+\frac{\kappa\, g^2}{M_\rho^2}\,(k_1+k_4)\cdot(k_2+k_3)$	$+8g^2[3/2(0^+)]$
$3/2$	1	0	$+\frac{g^2}{M_\rho^2}\,(k_1+k_3)\cdot(k_2+k_4)$	$-\frac{\kappa\, g^2}{M_\rho^2}\,(k_1+k_4)\cdot(k_2+k_3)$	$+8g^2[3/2(1^+)]$
$3/2$	2	$+2g^2$	$+\frac{g^2}{M_\rho^2}\,(k_1+k_3)\cdot(k_2+k_4)$	$+\frac{\kappa\, g^2}{M_\rho^2}\,(k_1+k_4)\cdot(k_2+k_3)$	$+14g^2[3/2(2^+)]$

Table 2: $V(\rho D^* \to \rho D^*)$ for the different spin-isospin channels including the exchange of one heavy vector meson. The approximate Total is obtained at the threshold of ρD^*.

$I^G[J^P]$	Theory	PDGdata		
	(Mass, Width)	Name	Mass	Width
$1/2^+(0^+)$	(2608, 61)	"$D_0^*(2600)$"		
$1/2^+(1^+)$	(2620, 4)	$D^*(2640)$	2637	< 15
$1/2^+2^+)$	(2465, 40)	$D^*(2460)$	2460	$37-43$

Table 3: Masses and widths (in units of MeV) obtained in the case of the use of an exponential form factor with $\Lambda = 1$ GeV compared with the experiment.

as α_L, and the other one, for the channels involving two heavy vector meson: α_H. When one channel involves both kind of mesons, one heavy and one light vector meson, we also put α_L. The value of α_L is set to get the position of the pole $f_2(1270)$ as $\alpha_L = -1.65$, like it was done in the work of [11]. Thus, we get the correct position of the poles found in this work. The α_H constant is set to -2.07 in order to get the position of the pole found in $S = 0$ around 3940 MeV. By the fact of having several channels, ones involving heavy mesons and the other light mesons, the g parameter in the Lagrangian must be different for the different cases. Thus, we put $g = M_\rho/(2f_\pi) = 4.17$ for light mesons, and $g_D = M_{D^*}/(2f_D) = 6.9$, $g_{D_s} = M_{D_s^*}/(2f_{D_s}) = 5.47$, $g_{\eta_c} = M_{J/\psi}/(2f_{\eta_c}) = 5.2$, when one D^*, D_s^* or J/ψ meson is involved. The $D\bar{D}$ decay mode is also considered by means of a box diagram as it was done in [12], but the effect is small compared with the (light) vector-(light or heavy) vector decay modes. The results for the pole position obtained together with a possible assignment with some of the XYZ particles observed in the energy region of 4000 MeV is given in Table 4. In order to do a proper comparison with the experiment, we give in Table 5 the XYZ discovered up to now in which we are interested, which is taken from [6].

As it is shown in Table 4, we find one pole with a mass ~ 3940 MeV for each spin $J = 0, 1$ and 2 and $I = 0$. The modules of the coupling contants to the different channels are obtained from the residues of the amplitudes and they are given in Tables 6 and 7. From Table 6, we see that these three poles around 3940 MeV are about $50-70\%$ $D^*\bar{D}^*$ and $20-30\%$ $D_s^*\bar{D}_s^*$, whereas all the other channels account only for $10-30\%$ or less. In Table 5 (experimental data) there are also three states around this mass. The state that we found for $I = 1$ is discarded to be associated with one of these states, because in our model this state decays to $D\bar{D}$ and not to $\omega J/\psi$, thus cannot be associated with the X(3940), since the $D\bar{D}$ decay has not been observed [4], whereas it cannot be associated to the Y(3940) either, because the experimental state decays to $\omega J/\psi$. On the other hand, we find a width so large that it is likely to be assigned to the Z(3930). In that way, the state found for $I = 1$ is a prediction of the model. In Table 4 we call it as $Y_p(3912)$, where 'p' stands for prediction. For this state, we find that the $D^*\bar{D}^*$ channel contributes 60%, whereas the sum of the modules of the couplings for the rest of the channels gives $\sim$ 40%.

Although, at first one could think that the three states that we found around 3940 MeV for $I = 0$ could correspond to those in Table 5, this assignment can lead to error. The reason is that all the three experimental states have C-parity positive, while our state for $J = 1$ has C-parity negative. From the experimental point of view, this is clear by the production mechanism: e^+e^- has C-parity negative (it comes from a photon) and as the J/ψ has also C-parity negative, the X(3940) must have C-parity positive. Thus, the state that we found for $J = 1$ is also a prediction.

In Table 5, we find that there are two different experimental measures for the mass and width of the Y(3940). One is done by Babar and the other one by Belle with bigger values for both magnitudes. The point in favor to the assignment of the state that we found with $J^{PC} = 0^{++}$ to the Y(3940) is the calculation of the $\Gamma((3943, 0^+[0^{++}]) \to \omega J/\psi)$ that can be done straightforwardly by means of the formula:

$$\Gamma((3943, 0^+[0^{++}]) \to \omega J/\psi) = \frac{p\,|g_{Y\omega J/\psi}|^2}{8\pi\, M_Y^2} \quad (5)$$

where p is the momentum of ω in the resonance rest frame. Taking the modules of the coupling $|g_{Y\omega J/\psi}| = 1445$ MeV from Table 6, we obtain $\Gamma((3943, 0^+[0^{++}]) \to \omega J/\psi) = 1.52$ MeV, compatible with the expected experimental value for this decay, $\Gamma(Y(3940) \to \omega J/\psi) > 1$ MeV [6]. Then, we have found a natural explanation on why this rate is much larger than it would be if it corresponded to a hadronic transition between charmonium states.

On the other hand, the two states that we find in $I = 0$ for $J = 2$, with masses $M = 3922$ and 4157 MeV, are assigned to the Z(3930) and X(4160) respectively, by the proximity of the mass, width and quantum numbers. The structure of the state found with $M = 4157$ MeV is radically different to the other states. We see from Table 6, that the $D_s^*\bar{D}_s^*$ coupling accounts for the 49%, whereas the $D^*\bar{D}^*$ coupling gives only the 3%, being the sum of the contributions of all the other channels of $\sim 48\%$.

Conclusions

We have studied the vector-vector interaction combining coupled channel unitarity and the hidden gauge Lagrangians for the interaction of vector mesons. The strong interaction found is enough to generate bound states and resonances. In the case of SU(3), five of the eleven poles found can be associated with states in the PDG. Within this picture, the $f_2(1270)$ and the $K_2^*(1430)$ are $\rho\rho$ and ρK^* bound states respectively. Also, we have studied the $\rho(\omega)D^*$ interaction, and we find a strong interaction that provides one bound state for each spin $J = 0, 1$ and 2. We can assign the states with $J = 1$ and 2 to the $D^*(2640)$ and $D_2^*(2460)$ respectively, whereas the state obtained for $J = 0$ is a prediction of the model: '$D_0^*(2600)$'. In this scheme, the $D_2^*(2460)$ and the $D_0^*(2600)$ decay to πD by means of a box diagram. However, this decay is not possible for $J = 1$, providing a natural explanation of the comparatively small width found in the PDG for this state, $\Gamma < 15$ MeV.

Finally, we have studied the $C = 0$ and $S = 0$ sector around the energy region of 4000 MeV. We find one state with mass ~ 3940 MeV for each spin $J = 0, 1$ and 2. Only the states with $J = 0$ and 2 can be associated the XYZ particles with mass ~ 3940 MeV in the PDG. Concretely, we associate the $J^{PC} = 0^{++}$ state with the Y(3940), and the 2^{++} state with Z(3930). Nevertheless, the $J^{PC} = 1^{+-}$ cannot be associated with known states and it becomes a prediction. The only state that we find for $I = 1$, with $J^{PC} = 2^{++}$, cannot be associated either, because of the decay modes and the large width. This new prediction could be observed in the $\rho J/\psi$ channel. For those states with masses around 3940 MeV, we find that the $D^*\bar{D}^*$ channel accounts for the $50 - 70\%$.

Our model predicts another state with mass around 4160 MeV and quantum numbers $I^G[J^{PC}] = 0^+[2^{++}]$, which we identify as the X(4160) by the proximity of the mass, width and C-parity. This state has a different structure, being the $D*_s\,\bar{D}_s^*$ channel the one contributing most to the generation of the state.

The region around 3940 MeV is very interesting and there could be more resonances not yet seen in this region. The findings of this work should motivate the experimentalist to look into this region in the channels that involve light vector - light vector or light vector - heavy vector like $K^*\bar{K}^*$ and $\rho J/\psi$.

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$I^G[J^{PC}]$	Theory	Experiment			
	(Mass, Width)	Name	Mass	Width	J^{PC}
$0^+[0^{++}]$	(3943, 17)	$Y(3940)$	3943 ± 17	87 ± 34	J^{P+}
			$3914.3^{+4.1}_{-3.8}$	33^{+12}_{-8}	
$0^-[1^{+-}]$	(3945, 0)	"$Y_p(3945)$"			
$0^+[2^{++}]$	(3922, 55)	$Z(3930)$	3929 ± 5	29 ± 10	2^{++}
$0^+[2^{++}]$	(4157, 102)	$X(4160)$	4156 ± 29	139^{+113}_{-65}	J^{P+}
$1^-[2^{++}]$	(3912, 120)	"$Y_p(3912)$"			

Table 4: Comparison of the mass, width and quantum numbers with the experiment. All the quantities are in units of MeV.

State	M (MeV)	Γ (MeV)	J^{PC}	Decay modes	Production modes
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma$
$X(3940)$	3942 ± 9	37 ± 17	J^{P+}	$D\bar{D}^*$	$e^+e^- \to J/\psi X(3940)$
$Y(3940)$	3943 ± 17	87 ± 34	J^{P+}	$\omega J/\psi$	$B \to KY(3940)$
	$3914.3^{+4.1}_{-3.8}$	33^{+12}_{-8}			
$X(4160)$	4156 ± 29	139^{+113}_{-65}	J^{P+}	$D^*\bar{D}^*$	$e^+e^- \to J/\psi X(4160)$

Table 5: Properties of the candidate XYZ mesons.

$I^G[J^{PC}]$	$\sqrt{s}_{pole}$	$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$	$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$0^+[0^{++}]$	$3943 + i7.4$	18822	8645	15	52	1368	1011	422	1445	910	240
$0^-[1^{+-}]$	$3945 + i0$	18489	8763	40	0	0	0	0	0	0	0
$0^+[2^{++}]$	$3922 + i26$	21177	6990	44	84	2397	1999	1794	2433	3061	789
$0^+[2^{++}]$	$4169 + i66$	1319	19717	87	73	2441	3130	2841	2885	5778	1828

Table 6: Quantum numbers, pole positions and modules of the couplings $|g_i|$ in units of MeV for $I = 0$.

$I^G[J^{PC}]$	$\sqrt{s}_{pole}$	$D^*\bar{D}^*$	$K^*\bar{K}^*$	$\rho\rho$	$\rho\omega$	$\rho J/\psi$	$\rho\phi$
$1^-[2^{++}]$	$3919 + i74$	20869	152	0	3656	6338	2731

Table 7: Quantum numbers, pole position and modules of the couplings $|g_i|$ in units of MeV for $I = 1$.