The $T_{c\bar{s}}(2900)$ as a threshold effect from the interaction of the $D^*K^*$, $D_s^*\rho$ channels

Raquel Molina$^1,\ast$ and Eulogio Oset$^1,\ast\ast$

$^1$Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain

Abstract. We investigate the $D^*K^*$ and $D_s^*\rho$ interaction in coupled channels within the hidden gauge formalism. A structure is developed around their thresholds, short of producing a bound state, which leads to a peak in the $D_s^+\pi^-$ mass distribution in the $B^0 \rightarrow \bar{D}^0 D_s^+\pi^-$ decay compatible with the experimental data. We conclude that the interaction between the $D^*K^*$ and $D_s^*\rho$ is essential to produce the cusp structure that we associate to the recently seen $T_{c\bar{s}}(2900)$, and that its experimental width is mainly due to the decay width of the $\rho$ meson. The peak obtained together with a smooth background reproduces fairly well the experimental mass distribution observed in the $B_0 \rightarrow \bar{D}^0 D_s^+\pi^-$ decay.

1 Introduction

The $D^*K^*$ system was investigated in [1] and three states were found corresponding to $I = 0, J^P = 0^+, 1^+$ and $2^+$. The $2^+$ state was identified with the $D_{s2}^*(2573)$ state, and served to set the scale for the regularization of the loops, allowing predictions in the other sectors. There, the $I = 1$ interaction of the $D^*K^*$ and $D_s^*\rho$ channels was also studied and, a cusp was found for $J = 0$ and $J = 1$ around the $D_s^*\rho$ threshold.

Recently, the LHCb Collaboration has observed an state in the $D_s^+\pi^-$, $D_s^+\pi^+$ mass distributions in the $B^0 \rightarrow \bar{D}^0 D_s^+\pi^-$ and $B^- \rightarrow D^- D_s^+\pi^+$ decays, respectively, at 2900 MeV [2, 3]. Indeed, the state branded as $T_{c\bar{s}}(2900)$ with $J^P = 0^+$, as seen in $D_s^+\pi^-$ and $D_s^+\pi^+$, exhibits an $I = 1$ character and it has also been associated with $J^P = 0^+$. On the other hand, 2900 MeV is just the threshold of the $D^*K^*$ channel. Thus, one is finding a $I = 1 J^P = 0^+$ state in the threshold of $D^*K^*$ (the $D_s^*\rho$ is only 14 MeV below neglecting the $\rho$ width), which could correspond to the cusp found in [1].

In the present work we look again at the interaction of $D^*K^*$ and $D_s^*\rho$ channels, taking into account the $K^*$ and $\rho$ widths and also the decay of the states found into the $D_s\pi$ channel where it has been observed, comparing our results with the recent experimental findings.

2 Formalism

In Ref. [2] a peak is found in the $D_s\pi$ invariant mass in the $B^0 \rightarrow \bar{D}^0 D_s^+\pi^-$ and $B^+ \rightarrow D^- D_s^+\pi^+$ decays. In order to have a $b$ quark rather than a $\bar{b}$ quark, we look at the reaction
of the respect to their masses. Then, the structure of the triangle diagram of Fig. 3 is given by channels, the $D_s^{−}$ decay into $D_s^{−} D^0 \rho^+$.

However, the state is observed in $D_s^{−} \rho^+$, hence, the mechanism by means of which the reaction $D_s^{−} \rho^+$ is produced and decays into $\pi^+ D_s^{−}$.

We evaluate the scattering matrix using the Bethe-Salpeter equation in the diagonal loop function for the intermediate mesons and $G$ is naturally regularized with a cutoff $q_{\text{max}}$, the same one used to regularize the $D^{∗}K^+$ and $D_s^{∗}\rho$ loops when studying their interactions. The equivalent $q_{\text{max}}$ used in [1] was 1100 MeV. We find,
Figure 3. Triangle diagram accounting for the $R \to \pi \bar{D}$, decay of the $R$ resonance of $I = 1$ generated with the $\rho \bar{D}$, $\bar{D}^* \bar{K}^*$ coupled channels.

\[
\bar{V} = -\int \frac{d^3 q}{(2\pi)^3} \frac{(2\vec{k} + \vec{q})^2}{8\omega_{K^*}(q)\omega_{D^*}(q)\omega_K(\vec{q} + \vec{k})} \frac{1}{P^0 - \omega_{D^*}(q) - \omega_{K^*}(q) + i\epsilon} \times \left\{ \frac{1}{P^0 - k^0 - \omega_{D^*}(q) - \omega_K(\vec{q} + \vec{k}) + i\epsilon} + \frac{1}{k^0 - \omega_{K^*}(q) - \omega_K(\vec{q} + \vec{k}) + i\epsilon} \right\},
\]

which shows the different cuts of the loop diagram when pairs of the internal particles of the loop are placed on-shell.

Then, we consider that the transition amplitude for $\bar{B}^0 \to D^0 D_s^- \pi^+$ is given by a constant background (considering the dominance of s-wave in the coupling of the bottom meson to the pseudoscalars), see Fig. 1 (right), together with the scattering amplitude of the diagram in Fig. 2, which accounts for the interaction of the $VV$ coupled channels. It reads as

\[
t' = aG_{\rho D^*}(M_{\text{inv}})\rho_{\rho \bar{D}^* D^*}(M_{\text{inv}})\bar{V}(\pi D_s, M_{\text{inv}}) + b.
\]

Therefore, the mass distribution of $\pi D_s^-$ in the $\bar{B}^0$ decay is given by,

\[
\frac{d\Gamma}{dM_{\text{inv}}} = \frac{1}{(2\pi)^3} \frac{1}{4M_B^2} p_{D^*} \bar{p} |t'|^2
\]

where $p_{D^*} = \frac{\lambda^{1/2}(M_B^2, m_{D^*}^2, M_{\text{inv}}^2)}{2M_B}$ and $\bar{p} = \frac{\lambda^{1/2}(M_B^2, m_{\rho^*}^2, m_{\pi}^2)}{2M_B}$.

2.1 Results

We take into account the decay widths of the vector mesons $K^*$ and $\rho$ by means the convolution of the $G$ function in Eq. (1) [4]. The result for the $T$ matrix in $I = 1; J = 0$ is shown in Fig. 4. The cusp obtained for $J = 0$ has become wider. The position of the cusp is similar, it shows up slightly above the $D^* K^*$ threshold and around 2920 MeV, with a width coming basically from the decay of the $\rho$ into $\pi \pi$. We have also obtained visible peaks in the scattering amplitudes for $J = 1$ and 2 [4].

Finally, we show the result of the invariant mass distribution of the decay $\bar{B}^0 \to D_s^- D^0 \pi^+$, Eq. (6), in comparison with the LHCb experimental data [2, 3] in Fig. 5 (left). In Eq. (6), we adjusted the constants $a$ and $b$ to reproduce well the experimental data around the $T_{cs}(2900)$ resonance, and we obtain $a = 2.1 \times 10^3$ and $b = -1.45 \times 10^3$. As can be seen, our model describes well the experimental data. A peak is obtained around the threshold of the $D^* K^*$ channel. Since these results were obtained fixing the subtraction constant to obtain the $T_{cs}(2900)$, this also supports the molecular picture of this state as $D^* K^*$ of [5]. Thus, our
model strongly supports the $T_c(2900)$ as a cusp structure originated by the non-diagonal interaction $D^*_sK^+ \rightarrow D^*_s\rho$, with a width mainly due to the decay of the $\rho$ meson into $\pi\pi$.

Finally, it is interesting to give a band of errors by changing the background, we do this to show the sensitivity of the results to this background. We have done this, keeping the value of $a$, needed to get the strength of the peak of the distribution, by varying the parameter $b$ of the background by 5% (up and down). This is shown in Fig. 5 (right). The band obtained overlaps with the errors of the data.

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