The $T_{c3}(2900)$ as a threshold effect from the interaction of the $D^*K^*$, $D_s^*\rho$ channels

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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 $T_{c3}(2900)$, 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 $T_{c3}(2900)$ 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...
\( \bar{B}^0 \rightarrow D^0 D_s^- \rho^+ \). We produce this state with the external emission Cabibbo favored decay shown in Fig. 1 (left). In Fig. 1 (right) we depict the direct decay \( \bar{B}^0 \rightarrow D_s^- D^0 \pi^+ \) considered as background.

We evaluate the scattering matrix using the Bethe-Salpeter equation in the \( D^* K^* \) and \( D_s^* \rho \) channels,

\[
T = [1 - VG]^{-1} V ,
\]

with \( G \) the diagonal loop function for the intermediate mesons and \( V \) the transition potential. However, the state is observed in \( D_s \pi \), hence, the mechanism by means of which the reaction proceeds is given in Fig. 2. The amplitude for the process of Fig. 2 is given by,

\[
t = aG_{\rho D_s} (M_{\text{inv}}) \rho_{D_s K^*} (M_{\text{inv}}) \tilde{V} (\pi D_s, M_{\text{inv}}) ,
\]

where \( a \) is a normalization constant that we do not evaluate, unnecessary to show the shape of the \( \pi D_s \) mass distribution in the \( \bar{B}^0 \) decay, and \( M_{\text{inv}} \) is the invariant mass distribution of the \( D_s \pi \) final state. The vertex function \( \tilde{V} \) corresponding to the triangle loop of Fig. 3 can be easily evaluated.

We assume the resonance to be in \( J = 0 \), and that the vectors have small momenta with respect to their masses. Then, the structure of the triangle diagram of Fig. 3 is given by

\[
\tilde{V} = -i \int \frac{d^4 q}{(2\pi)^4} \epsilon_{K^*}^l \epsilon_{D^*}^j \epsilon_{D}^i \epsilon_{\rho}^f \frac{(2k + q)^l(2k + q)^j}{(P - q - k)^2 - m_{K^*}^2 + i\epsilon (P - q)^2 - m_{D^*}^2 + i\epsilon q^2 - m_{D}^2) + i\epsilon} \theta(q_{\text{max}} - q) \frac{1}{q^2 - m_{\rho}^2} .
\]

The loop function \( \tilde{V} \) 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,
Then, the structure of the triangle diagram of Fig. 3 is given by

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

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 \( \bar{B}^0 \to D^0 D_\tau^+ \) 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

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

Therefore, the mass distribution of \( \pi D_\tau^- \) in the \( \bar{B}^0 \) decay is given by,

\[
\frac{d\Gamma}{dM_{inv}} = \frac{1}{(2\pi)^3} \frac{1}{4M_B^2} p_{\rho D^0} |t'|^2,
\]

where \( p_{\rho D^0} = \frac{\lambda^{1/2}(M_B^2,m_{\rho D^0}^2,m_{\pi}^2)}{2M_B^2} \) and \( \tilde{p} = \frac{\lambda^{1/2}(M_B^2,m_{\rho D^0}^2,m_{\pi}^2)}{2M_B^2} \).

### 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 \( \bar{B}^0 \to D_\tau^- D^0 \pi^+ \), 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
Figure 4. $|T|^2$ for $C = 1; S = 1; I = 1; J = 0$ with $\alpha = -1.474$.

Figure 5. Left: invariant mass distribution for $D_s\pi$ from the decay $B \rightarrow \bar{D}D_s\pi$ compared to the experimental data from Ref. [2, 3]. Right: the same but with the error band obtained by changing the parameter for the background ($b$) 5% up and down.

model strongly supports the $T_{cs}(2900)$ as a cusp structure originated by the non-diagonal interaction $D^*K^* \rightarrow D_s^0\rho^*$, 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.

References