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The T_{cc}^{+} exotic state and its doubly bottom $B_{(s)}^{(*)}B_{(s)}^{(*)}$ counterparts

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Abstract. We have studied the exotic doubly charmed D^*D system providing a natural explanation for the peak recently observed by LHCb, in terms of $D^{*+}D^0$ and $D^{*0}D^+$ with isospin $I = 0$. The width has been evaluated accurately based on the decay widths of the D^* states. The $D^0D^0\pi^+$ decay mode of the bound state formed is studied in detail, showing a narrow peak below the $D^{*+}D^0$ threshold and some strength above it, as observed in the experiment. The remarkable agreement of this approach and the latter experimental analysis supports strongly the molecular nature of this state, the first example of a meson with two open charmed quarks. This study can be naturally extended to the bottom sector giving interesting features for the $B_{(s)}^{(*)}B_{(s)}^{(*)}$ counterparts found there. In addition, our previous study on the D^*D^* molecular state has been revisited taking into account the insights extracted from the T_{cc} state and the new results are included in the present manuscript.

1 Introduction

The interesting discovery of the two-open-charm meson state, the T_{cc} state, by the LHCb collaboration [1, 2] has brought new excitement into the field of hadron spectroscopy, with yet another state that does not have the standard $q\bar{q}$ nature of ordinary mesons. The characterizing features of the T_{cc} state are a mass very close to the $D^{*+}D^0$ and $D^{*0}D^+$ threshold as well as

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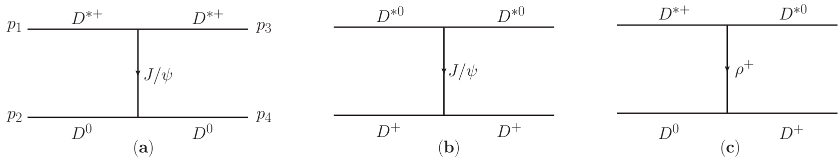

Figure 1. Diagrams considered for the interaction vector-pseudoscalar (VP).

a very small width. Being more precise, its mass is slightly below the $D^{*+}D^0$ threshold. Actually, the primary results of Ref. [1] were reanalysed by the LHCb Collaboration [2], using a unitary Breit-Wigner amplitude considering the experimental resolution. The results obtained differ from those reported in Ref. [1]. The new values obtained from the pole position of the state are

$$\delta m_{\text{exp}} = -360 \pm 40^{+4}_{-0}\ \text{keV}, \tag{1}$$

$$\Gamma = 48 \pm 2^{+0}_{-14}\ \text{keV}, \tag{2}$$

where δm_{exp} is the mass difference between the T_{cc} state and the $D^{*+}D^0$ threshold, while Γ represents the correspondig width. The closeness of this mass to the D^*D threshold makes one think about the possibility that this state could be a molecular state of D^*D. In fact, this structure was anticipated in Refs. [3–5]. The possible D^*D bound state would be analogous to the D^*D^* molecular state studied earlier in Ref. [6]. In that later work, predictions were made for another exotic state of $D^*\bar{K}^*$ nature that can be associated to the $X_0(2866)$ state reported in Ref. [7] (see update in Ref. [8]).

2 Formalism and results

Following [6, 8] we use the extension of the local hidden gauge approach to study the D^*D interaction, mediated by exchanges of ρ^+ and J/ψ vector mesons (diagrammatically represented in Fig. 1), and whose interaction kernel is given by

$$\begin{aligned} V_{ij} &= C_{ij}\, g^2\, (p_1 + p_3)\cdot(p_2 + p_4)\, \vec{\epsilon}\cdot\vec{\epsilon}\,' \\ &\to C_{ij}\, g^2\, \frac{1}{2}[3s - (M^2 + m^2 + M'^2 + m'^2) \\ &\quad -\frac{1}{s}(M^2 - m^2)(M'^2 - m'^2)]\, \vec{\epsilon}\cdot\vec{\epsilon}\,', \end{aligned} \tag{3}$$

where M, m are the initial vector, pseudoscalar masses and M', m' the corresponding final ones and, as can be seen in in Fig. 1, p_i are the corresponding incoming and outgoing momenta of the vector- and pseudoscalar-mesons in the CM framework with a total energy $\sqrt{s}$. The second expression in Eq. (3) is obtained by projection onto s-wave contribution. Also, since we are close to the D^*D threshold we neglect the ϵ^0 components of the vectors and work with the vector polarizations $\vec{\epsilon}, \vec{\epsilon}\,'$. The matrix C is a 2×2 matrix, where each element C_{ij} (with i and j covering the two channels considered in the basis) contains the information of the atractive or repulsive character as well as the strength of each transition, and it is given by

$$C = \begin{pmatrix} \frac{1}{M^2_{J/\psi}} & \frac{1}{m^2_\rho} \\ \frac{1}{m^2_\rho} & \frac{1}{M^2_{J/\psi}} \end{pmatrix}. \tag{4}$$

This interaction is attractive for the D^*D system in $I = 0$ and repulsive for $I = 1$. With this potential we solve the Bethe Salpeter equation

$$T = [1 - VG]^{-1}\, V, \tag{5}$$

in order to treat the interaction nonperturbatively.

As for the $D^0D^0\pi^+$ production we use the decay mechanism shown in Fig. 2, for a more detailed explanation see Ref [9], and we obtain the results of Fig. 3. These results are in good agreement with the analysis of LHCb whose results were obtained by means of the unitary amplitude and the values of which are shown in Eqs. (1) and (2).

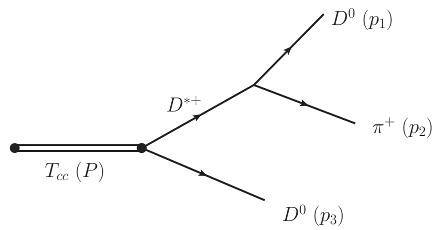

Figure 2. Mechanism for $D^0\pi^+D^0$ decay of the T_{cc} state. The diagram with $D^{*0}D^+$ decay does not lead to final $D^0D^0\pi^+$.

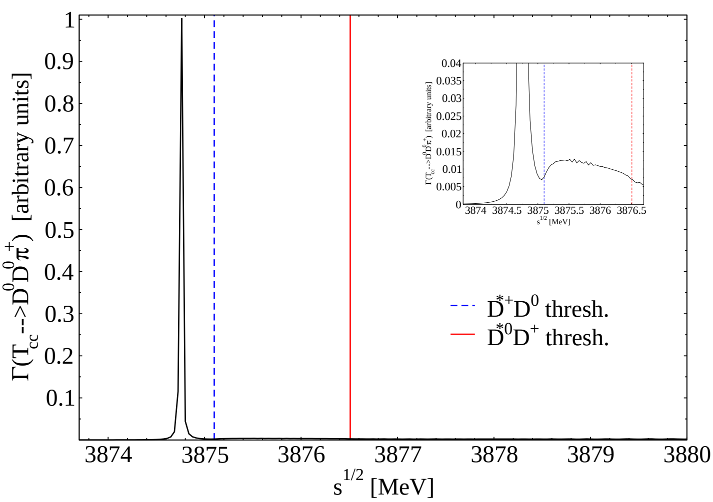

Figure 3. $\Gamma(\sqrt{s})$ for the decay of the T_{cc} into $D^0D^0\pi^+$.The inset in the figure is a zoom to illustrate the mass distribution between $D^{*+}D^0$ and $D^{*0}D^+$ thresholds.

The results obtained in this work have been extended to the study of the D^*D^* system in [10] where we find also bound states for $I = 0$ and $J = 1$, more bound that the T_{cc} and with a larger width, as shown in Table 1. The results are also extended to the study of the $B^{(*)}_{(s)}B^{(*)}_{(s)}$ states in [11], where we also find bound states as shown in Table 2.

Table 1. The predictions assuming 420 or 450 MeV cutoff values, as used for the T_{cc} state. The threshold masses for D^*D and $D_s^*D^*$ are 4017.1 MeV and 4122.46 MeV, respectively. The binding energy B is referred to the closest threshold and M and Γ stand for the mass and width of the predicted states, respectively.

	$q_{\rm max}$ = 450 MeV	$q_{\rm max}$ = 420 MeV
$M_{D^*D^*}$	4014.08 MeV	4015.54 MeV
$B_{D^*D^*}$	3.23 MeV	1.56 MeV
$\Gamma_{D^*D^*}$	2.3 MeV	1.5 MeV
$M_{D_s^*D^*}$	4122.46 MeV (cusp)	4122.46 MeV (cusp)
$\Gamma_{D_s^*D^*}$	70 − 100 KeV	70 − 100 KeV

Table 2. States of $J^P = 1^+$ obtained from the different sectors considered. The binding energy B is referred to the closest threshold and M and Γ stand for the mass and width of the predicted states, respectively..

States	M (MeV)	B (MeV)	Γ
B^*B $(I = 0)$	10583	21	14 eV
$B_s^*B - B^*B_s$ $(I = \frac{1}{2})$	10681	11	45 eV
B^*B^* $(I = 0)$	10630	19	8 MeV
$B_s^*B^*$ $(I = \frac{1}{2})$	10728	12	0.5 MeV

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