The isospin and compositeness of the Tcc(3875) state

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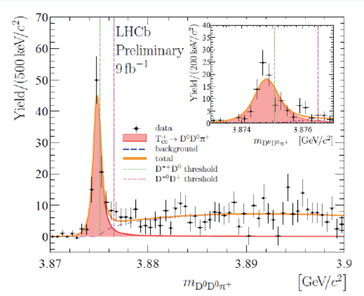
Dai, Abreu, Feijoo & Oset, Eur Phys J C 83 (2023) 983

Motivation

The discovery of the $T_{cc}(3875)$ by LHCb experiment: Nature Physics 18 (2022) 751; Nature Communication 13 (2022) 3351 was a turning point in hadron physics, showing the **first evidence** of a meson state clearly exotic with two open charm quarks.



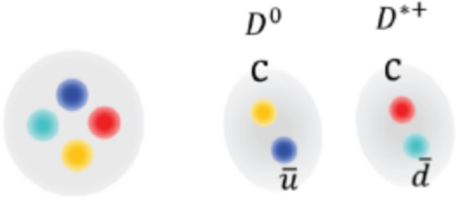
Its mass: $M_{T_{cc}} = M_{D^{*+}D^0} + \delta m_{\rm exp}$

Its width: $\Gamma = 48 \pm 2^{+0}_{-14}$ keV

with $M_{D^{*+}D^0} = 3875.09$ MeV

$\delta m_{\rm exp} = -360 \pm 40^{+4}_{-0}$ keV

$T_{cc}^+(3875)$ $(cc\bar{u}\bar{d})$



Compact (genuine) states? or **molecular states?** or **mixture of both?**

we can see the **debate** for various models for its origin and **nature** of $T_{cc}(3875)$.

debate of various models for $T_{cc}(3875)$

Molecular state

PLB826(2022)136897; CTP73(2021)125201;
PRD104(2021)114015; PRD104(2021)116010;
AHEP2022(2022)9103031; EPJC82(2022)581;
PLB829(2022)137052; PRD105(2022)014024;
PLB833(2022)137290; EPJC82(2022)313;
PRD105(2022)054015; EPJC82(2022)144;
JHEP06(2022)057; EPJA58 (2022)131;
Phys Rep 1019 (2023)1;
NPB985(2022)115994;PLB833(2022)137391;
EPJC82(2022)724;PRD105(2022)034028;
PLB841(2023)137918
. . . . . .

Compact state

PRD37(1988)744; ZPC57(1993)273; ZPC61(1994)271;
PLB393(1997)119; PLB123(1983)449; ZPC30(1986)457;
PRD105(2022)014021; EPJA58(2022)110;
. . . . . .

a mixture

PRD105(2022)014007;
Few Body Syst 35 (2004)175;
. . . . . .

debate $\Longrightarrow$ the nature of molecular or compact or mixture?

The couplings and isospin nature

- Isospin symmetry and the wave function at the origin gG (for s-wave)

  The values of G are similar for the two channels, so the couplings are what determine the isospin nature of the states. They obtained values of g_i for each channel which are of opposite sign and equal in size within 2-3%, as it corresponds to an $I = 0$ state [Gamermann, Nieves, Oset, Arriola, PRD 81 (2010) 014029] .

- The probability is given by $-g^2 \partial G/\partial s$

  They consider two channels: $D^0 D^{*+}$ (1) and $D^+ D^{*0}$ (2) [Feijoo,Liang, Oset, PRD 104 (2021) 114015]

  $\Longrightarrow P_1 = 69\%$ and $P_2 = 31\%$ thus $P_1 + P_2 = 1$

  The $\partial G/\partial s$ goes to infinity as we approach the threshold of the channel (even having good isospin), the probability of the channel whose threshold is closer to the mass of the state will be larger than the one of the other channel.

Feijoo, Liang, Oset, PRD104 (2021) 114015;
Du, Baru, Dong, Filin, Guo, Hanhart, Nefediev, Nieves, Wang, PRD105 (2022) 014024;
Cheng, Lin, Zhu, PRD106 (2022) 016012;
Albaladejo, PLB829 (2022) 137052;
$\Longrightarrow$ **assuming energy independent interaction potentials**

There is a similarity in all these results, and the probability of the first channel is bigger than the second channel.

Our purpose

We shall include **a general potential** for the interaction of the $D^0 D^{*+}$ and $D^+ D^{*0}$ channels, including the necessary terms with **energy dependence** to account for possible **nonmolecular components**.

A general potential for $i = 1$ for $D^0 D^{*+}$ and $i = 2$ for $D^+ D^{*0}$ channels

$$V = \begin{pmatrix} V_{11} & V_{12} \\ V_{12} & V_{22} \end{pmatrix} ,$$

We carry fits to data

$\Longrightarrow$ evaluate the probabilities P_1, P_2 of the two channels

$\Longrightarrow$ then $Z = 1 - (P_1 + P_2)$ (the probability of other possible nonmolecular components)

We shall see that the results strongly support the molecular picture, with a negligible probability of a nonmolecular component.

Formalism

A general potential for $i = 1$ for $D^0 D^{*+}$ and $i = 2$ for $D^+ D^{*0}$ channels

$$V = \begin{pmatrix} V_{11} & V_{12} \\ V_{12} & V_{22} \end{pmatrix},$$

from where the **scattering matrix** is

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

where G_i **are the loop functions** regularized in the cutoff method, with

$$G = \int_{|\boldsymbol{q}|<q_{\max}} \frac{d^3 q}{(2\pi)^3} \frac{\omega_1 + \omega_2}{2\,\omega_1 \omega_2} \frac{1}{s - (\omega_1 + \omega_2)^2 + i\epsilon}$$

where $\omega_i = \sqrt{\boldsymbol{q}^2 + m_i^2}$, m_1 is the mass of the D and m_2 that of D^*. The value of $q_{\max}$ reflects the range of the interaction in momentum space and will be obtained from the fits to the data.

Scattering lengths and effective ranges

From the effective range expansion and scattering matrix, we can obtain

$i = 1$: at threshold of $D^0 D^{*+}$

$$
\begin{aligned}
-\frac{1}{a_1} &= -8\pi\sqrt{s}\,T_{11}^{-1} = -8\pi\sqrt{s}\left[\frac{1 - V_{11}G_2}{V_{11} + (V_{12}^2 - V_{11}^2)\,G_2} - Re\,G_1\right]\Big|_{s=s_1} \\
r_{0,1} &= -\frac{\sqrt{s_1}}{\mu_1}\frac{\partial}{\partial s}\left\{16\pi\sqrt{s}\left[\frac{1 - V_{11}G_2}{V_{11} + (V_{12}^2 - V_{11}^2)\,G_2} - Re\,G_1\right]\right\}\Big|_{s=s_1}
\end{aligned}
$$

$i = 2$: at threshold of $D^+ D^{*0}$

$$
\begin{aligned}
-\frac{1}{a_2} &= -8\pi\sqrt{s}\,T_{22}^{-1} = -8\pi\sqrt{s}\left[\frac{1 - V_{11}G_1}{V_{11} + (V_{12}^2 - V_{11}^2)\,G_1} - Re\,G_2\right]\Big|_{s=s_2} \\
r_{0,2} &= -\frac{\sqrt{s_2}}{\mu_2}\frac{\partial}{\partial s}\left\{16\pi\sqrt{s}\left[\frac{1 - V_{11}G_1}{V_{11} + (V_{12}^2 - V_{11}^2)\,G_1} - Re\,G_2\right]\right\}\Big|_{s=s_2}
\end{aligned}
$$

The couplings and the probabilities of the channels

From the residues of the T matrix at binding of T_{cc},

$$
\begin{aligned}
g_1^2 &= \lim_{s\to s_0}(s-s_0)\,T_{11} = \frac{V_{11}+(V_{12}^2-V_{11}^2)\,G_2}{\frac{\partial}{\partial s}\,\mathrm{DET}}\Big|_{s=s_0}\,,\\
g_2^2 &= \lim_{s\to s_0}(s-s_0)\,T_{22} = \frac{V_{11}+(V_{12}^2-V_{11}^2)\,G_1}{\frac{\partial}{\partial s}\,\mathrm{DET}}\Big|_{s=s_0}\,,\\
g_1 g_2 &= \lim_{s\to s_0}(s-s_0)\,T_{12} = \frac{V_{12}}{\frac{\partial}{\partial s}\,\mathrm{DET}}\Big|_{s=s_0}
\end{aligned}
$$

we have the probabilities for the $D^0 D^{*+}$ and $D^+ D^{*0}$ channels, respectively, as

$$
P_1 = -g_1^2\,\frac{\partial G_1}{\partial s}\Big|_{s=s_0}\,,\qquad P_2 = -g_2^2\,\frac{\partial G_2}{\partial s}\Big|_{s=s_0}
$$

and the **nonmolecular component**

$$
Z = 1-(P_1+P_2)
$$

Conditions and parameters

isospin basis

$$|D^*D, I=0\rangle = -\frac{1}{\sqrt{2}}(D^{*+}D^0 - D^{*0}D^+)$$

$$|D^*D, I=1\rangle = -\frac{1}{\sqrt{2}}(D^{*+}D^0 + D^{*0}D^+)$$

a) due to isospin symmetry
   $V_{11} = V_{22}$
b) from the experimental analysis
   $V_{12} > 0\,; \quad V_{12} > |V_{11}|$
c) demanding a pole at s_0
   reduce a parameter

We have a **energy dependent potential**

$$V_{11} = V'_{11} + \frac{\alpha}{m_V^2}(s - s_0)$$

$$V_{12} = V'_{12} + \frac{\beta}{m_V^2}(s - s_0)$$

where α, β are dimensionless free parameters, $m_V = 800$ MeV, s_0 is the mass squared of the T_{cc}.

We have five free parameters $q_{\max}$, V'_{11}, V'_{12} and α, β (dimensionless) in our fits.

Two different strategies to fit the experimental LHCb data [Nature Commun. 13 (2022) 3351]

Two different strategies

by fitting the scattering lengths and effective ranges

$\Downarrow$ fit (a)

The experimental LHCb data
[Nature Commun. 13 (2022) 3351;
arXiv: 2203.04622 neglecting the D^* width

$$a_1 = 6.134 \pm 0.51 \text{ fm}\,,$$

$$r_{0,1} = -3.516 \pm 0.50 \text{ fm}$$

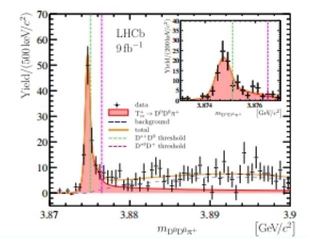
$$a_2 = (1.707 \pm 0.30) - i\,(1.07 \pm 0.30) \text{ fm}\,,$$

$$r_{0,2} = (0.259 \pm 0.30) - i\,(3.769 \pm 0.30) \text{ fm}$$

by fitting the $D^0D^0\pi^+$ mass distribution

$\Downarrow$ fit (b)

Nature Commun. 13 (2022) 3351



corrected by the experimental resolution and parametrized in terms of a unitary amplitude (consider D^* width explicitly)

In the evaluation

a) correlation between $V'_{11} - V'_{12}$ and $q_{\max}$
There is a tradeoff

b) correlation of α and β
what matters is the $\alpha - \beta$ combination

we use the resampling (bootstrap) method, which is particularly suited for the case that there are strong correlations between the parameters.

fit (a) use six data: $a_1, r_{0,1}$ which are real, and $a_2, r_{0,2}$ which are complex
fit (b): direct fit to the $D^0 D^0 \pi^+$ mass distribution

$\Downarrow$ resampling (bootstrap) method

We evaluate the average value of these magnitudes and the dispersion of each of the observables, as

$$\overline{P}_1 = \frac{1}{N} \sum_i P_{1,i}\,, \qquad (\Delta P_1)^2 = \frac{1}{N} \sum_i (P_{1,i} - \overline{P}_1)^2$$

fit (a) The obtained scattering lengths and effective ranges

a_1 [fm]	$r_{0,1}$ [fm]	a_2 [fm]	$r_{0,2}$ [fm]
6.04 ± 0.11	-3.55 ± 0.37	$(1.72 \pm 0.12) - i\,(1.07 \pm 0.03)$	$(0.29 \pm 0.08) - i\,(3.76 \pm 0.14)$

The experimental LHCb data
[Nature Commun. 13 (2022) 3351; arXiv: 2203.04622 neglecting the D^* width

$$a_1 = 6.134 \pm 0.51 \text{ fm}\,, \quad r_{0,1} = -3.516 \pm 0.50 \text{ fm}$$

$$a_2 = (1.707 \pm 0.30) - i\,(1.07 \pm 0.30) \text{ fm}\,, \quad r_{0,2} = (0.259 \pm 0.30) - i\,(3.769 \pm 0.30) \text{ fm}$$

It is seen that the **agreement** with the experiment is **remarkable.**

fit (a) The obtained coupling constants and probabilities

g_1 [MeV]	g_2 [MeV]	P_1	P_2	Z
3727 ± 54	-3752 ± 164	0.67 ± 0.02	0.26 ± 0.02	0.07 ± 0.03

The obtained P_1, P_2 of the order of 69%, 28% with uncertainties of the order of 2%, and $Z = 0.07 \pm 0.03$ $\Rightarrow$ T_{cc} **as a clear molecular state made of the $D^0 D^{*+}$ and $D^+ D^{*0}$ components.**

The obtained couplings g_1 and g_2 are very close and with opposite sign
$\Rightarrow$ indicating that we have basically a state of isospin **I=0**.

fit (b) Direct fit to the $D^0D^0\pi^+$ mass distribution [Nature Commun. 13 (2022) 3351]

we are using now the G functions accounting for the width of the D^*

$$G = \int_{|\boldsymbol{q}|<q_{\max}} \frac{d^3q}{(2\pi)^3} \, \frac{\omega_1+\omega_2}{2\,\omega_1\omega_2} \, \frac{1}{\sqrt{s}+\omega_1+\omega_2} \, \frac{1}{\sqrt{s}-\omega_1-\omega_2+i\,\frac{\sqrt{s'}}{2\,m_{D^*}}\Gamma_{D^*}(s')}$$

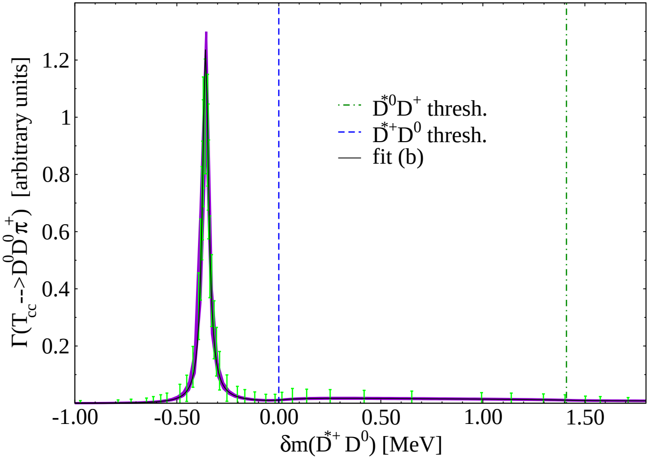
where $s' = (\sqrt{s}-\omega_D)^2 - \boldsymbol{q}^2$ and $\Gamma_{D^*}(s')$ from PRD104 (2021) 114015

We perform a best fit by taking 44 points to fit the $D^0D^0\pi^+$ mass distribution.

$\Downarrow$ resampling (bootstrap) for estimating the statistical uncertainties

we obtain the average values of the observables and their dispersion in the resampling method

We perform a best fit directly to the $D^0D^0\pi^+$ mass distribution [Nature Commun. 13 (2022) 3351]



fit (b) The obtained observables of scattering lengths and effective ranges

The obtained average values and their dispersion

$$
\begin{aligned}
a_1 &= (7.60 \pm 0.14) - i\,(1.73 \pm 0.09))\ \text{fm} \\
r_{0,1} &= -2.94 \pm 0.04\ \text{fm} \\
a_2 &= (1.99 \pm 0.07) - i\,(1.25 \pm 0.23))\ \text{fm} \\
r_{0,2} &= (0.11 \pm 0.17) - i\,(2.74 \pm 0.22)\ \text{fm}
\end{aligned}
$$

Compared with [Nature Commun. 13 (2022) 3351] when the D^* width is explicitly taken into account

$$a_1^{exp} = [(7.16 \pm 0.51) - i\,(1.85 \pm 0.28)]\ \text{fm}\,, \qquad a_2^{exp} = (1.76 - i\,1.82)\ \text{fm}$$

It is seen that the agreement is perfect within errors.

fit (b) The obtained binding energy, width, coupling constants and probabilities

The obtained average values and their dispersion

$$B = 360 \pm 2\ \mathbf{keV}\,, \quad \Gamma = 38 \pm 1\ \mathbf{keV}$$
$$g_1 = 3875 \pm 51\ \mathbf{MeV}\,, \quad g_2 = -4077 \pm 72\ \mathbf{MeV}$$
$$P_1 = 0.697 \pm 0.017\,, \quad P_2 = 0.301 \pm 0.009$$

The obtained couplings g_1 and g_2 are very close and with opposite sign and very similar to those with the fit (a) $\Rightarrow$ indicating that we have basically a state of isospin I=0.

The obtained $P_1 + P_2 = 0.998 \pm 0.024$ in fit (b), **which are also remarkably similar to those with fit (a)** $\Rightarrow$ indicating again the molecular nature of the T_{cc} state.

Summary

We have performed fits to the data of the LHCb collaboration by using two different strategies. In a model independent way,

1) starting from the scattering length and effective range of the $D^{*+}D^0$, $D^{*0}D^+$ channels;

2) or from the experimental $D^0D^0\pi^+$ mass distribution.

We conclude that the $T_{\rm cc}$ is a molecular state of the $D^{*+}D^0$, $D^{*0}D^+$ components.

using all the available experimental information (not only the **binding** but also the **scattering length and effective range**) was **essential** to reach the present conclusions.

– The end –