

Exploring Multiple Interpretations of $T_{cc}(3875)^+$ from the Experimental Distributions

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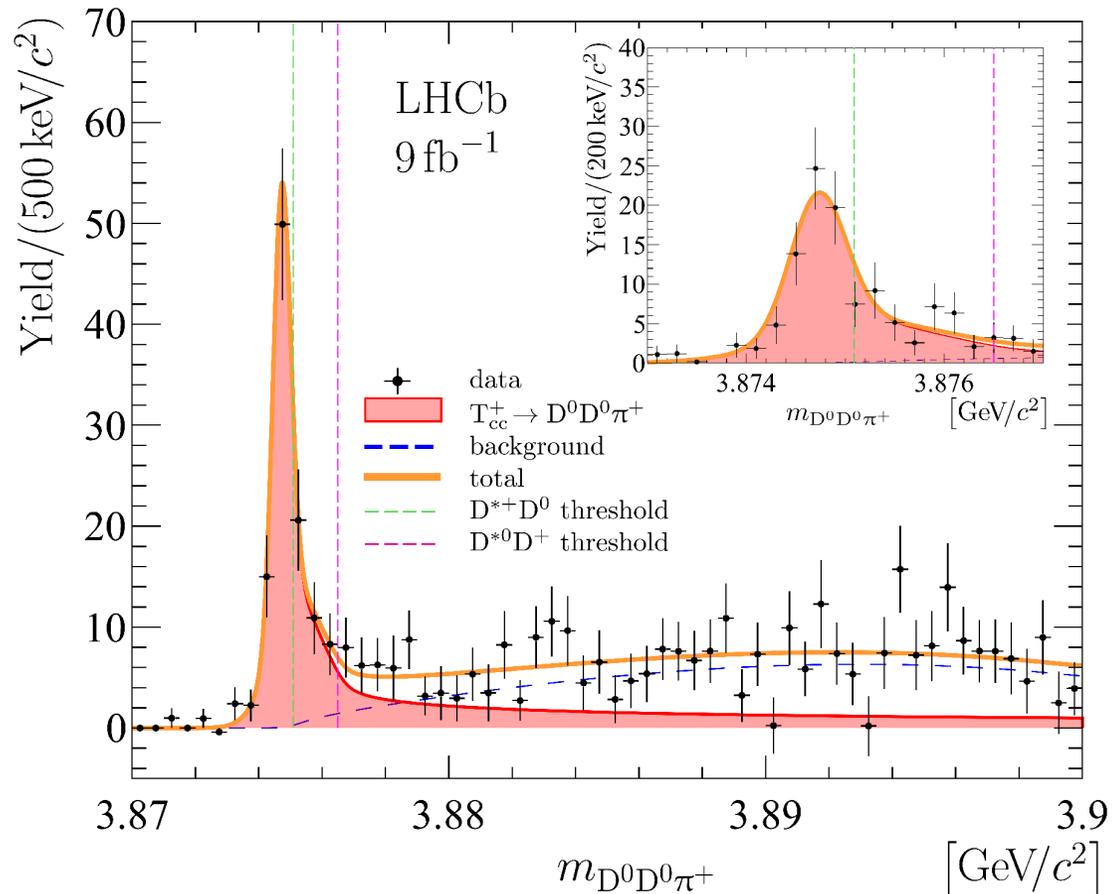
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Outline

- 1. Introduction**
- 2. Model construction**
- 3. Numerical results**
- 4. Summary and Outlook**

Observation of the $T_{cc}^+(cc\bar{u}\bar{d})$ by LHCb

► In 2021, $T_{cc}^+(cc\bar{u}\bar{d})$ is reported by LHCb!



LHCb, Nature Phys. 18 (2022) 751-754, Nature Commun. 13 (20) 3351

- Quantum number : $I(J^P) = 0(1^+)$
- Mass differences from $D^{*+}D^0$ threshold :

$$\begin{aligned} \delta m_{T_{cc}} &= m_{T_{cc}} - m_{D^{*+}D^0} \\ &= \begin{cases} -273 \pm 61 \text{ [keV/c}^2\text{]} & \text{(BW)} \\ -360 \pm 40 \text{ [keV/c}^2\text{]} & \text{(Pole)} \end{cases} \end{aligned}$$

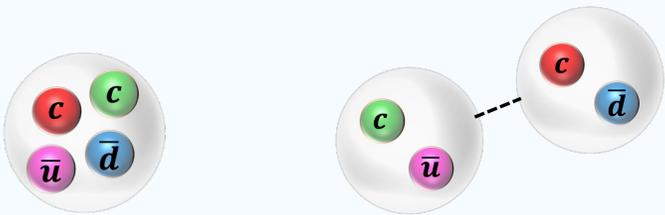
- Decay widths :

$$\Gamma = \begin{cases} -410 \pm 165 \text{ [keV/c}^2\text{]} & \text{(BW)} \\ -48 \pm 2 \text{ [keV/c}^2\text{]} & \text{(Pole)} \end{cases}$$

Motivation and Question

T_{cc}^+ internal structure ?

Pure DD^* molecular analysis
 \neq Exclusion of compact T_{cc}^+



Compact

Molecule

Compact and molecule mixing

Near-threshold effects?

- Coupled channel effect
- Isospin sym. breaking effect

$$DD^*, I = 0 \quad DD^*, I = 1$$

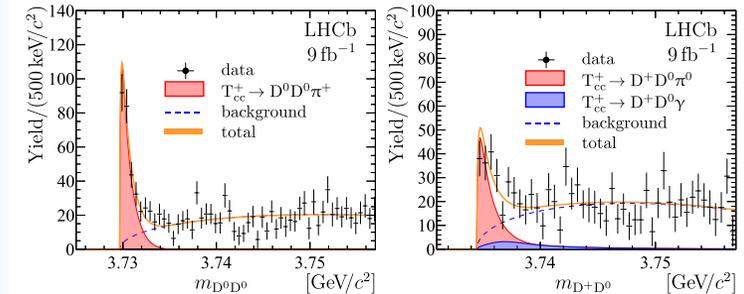
(wide range attractive) (repulsive at low p)

(e.g., S. Chen, et al., PLB **833**, 137391(2022))



$D^{*+}D^0 - D^{*0}D^+$ channel coupling

Other data ?



LHCb, Nature Phys. 18 (2022) 751-754,
 Nature Commun. 13 (20) 3351

D^0D^0 (Left), D^0D^+ (Right) distribution

Crosscheck of model

Model construction

1. Introduction

2. Model construction

3. Numerical results

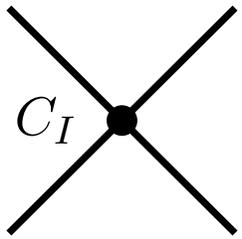
4. Summary and Outlook

Outline of analysis

1. $D^{*+}D^0 - D^{*0}D^+$ Coupled channel model

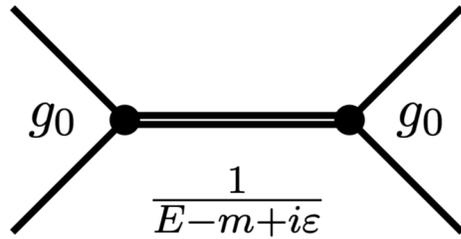
mixing of DD^* molecule and compact $cc\bar{u}\bar{d}$

Molecule term



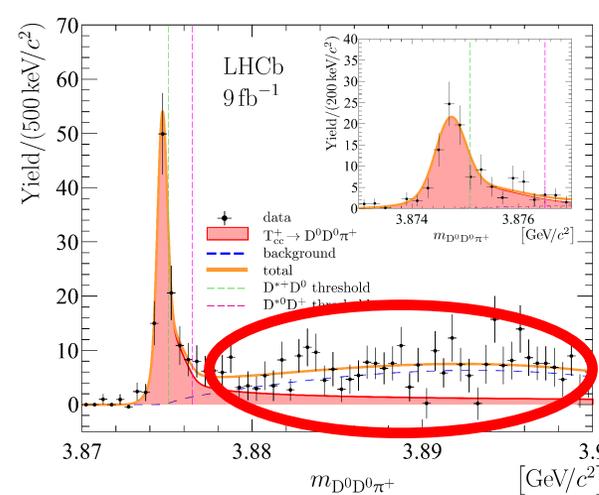
+

Compact T_{cc}^+ term



2. Determine the model parameters by fitting to $D^0D^0\pi^+$ line shape

(Fitted only 200 keV bin width data)



Significant background!

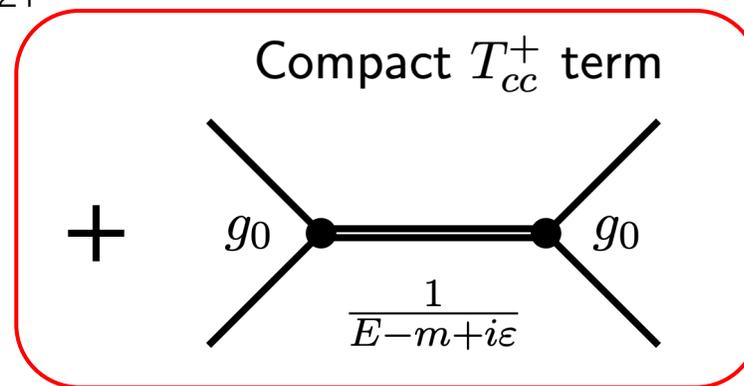
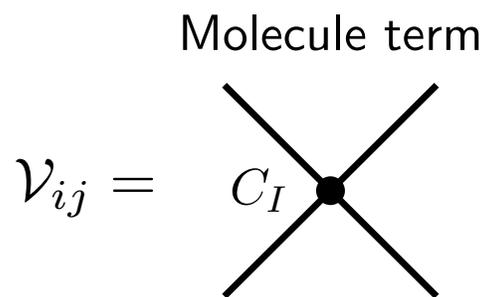
3. Analyze T_{cc}^+ properties from obtained DD^* coupled channel model.

$D^{*+}D^0 - D^{*0}D^+$ coupled channel model

- ▶ 2 channel scattering (Isospin basis $DD_{I=0,1}^*$, Particle basis $D^{*+}D^0 - D^{*0}D^+$)
- ▶ Interaction Lagrangian (Isospin basis $DD_{I=0,1}^*$) Compact T_{cc} couples to $I = 0$

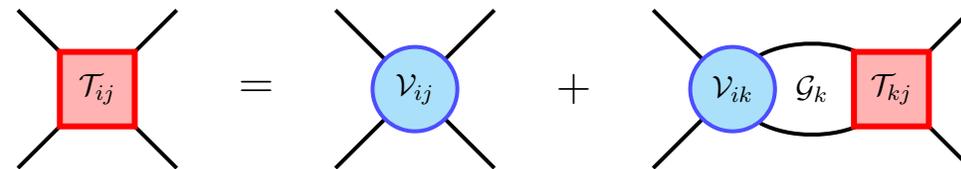
$$\mathcal{L}_{\text{int}} = - \sum_{I=0,1} C_I [D^* D]_I^\dagger [D^* D]_I - g_0 \left([D^* D]_{I=0}^\dagger T_{cc}^{\text{Bare}} + T_{cc}^{\text{Bare}\dagger} [D^* D]_{I=0} \right)$$

M.Albaladejo, PLB.824(2022)1370521



- ▶ Isospin basis $DD_{I=0,1}^* \rightarrow$ Particle basis $D^{*+}D^0 - D^{*0}D^+$

- ▶ $D^{*+}D^0 - D^{*0}D^+$ amplitude is obtained from L-S eq.



- ▶ Parameters are determined by fitting the experimental data: C_0, C_1, g_0, m

3 body decay (M. Albaladejo, PLB.824 (2022) 1370521)

► 3 body decay process

$$\mathcal{M}_\lambda(s, t, u; Q^2) = \alpha \left[\begin{array}{c} \text{Diagram 1: } D^0 \text{ and } \pi^+ \text{ from } D^{*+} \text{ vertex, } D^0 \text{ from } DD^* \text{ vertex} \\ \text{Diagram 2: } D^0 \text{ and } \pi^+ \text{ from } D^{*+} \text{ vertex, } D^0 \text{ from } DD^* \text{ vertex} \end{array} \right] + \beta \left[\begin{array}{c} \text{Diagram 3: } D^0 \text{ and } \pi^+ \text{ from } D^{*0} \text{ vertex, } D^0 \text{ from } DD^* \text{ vertex} \\ \text{Diagram 4: } D^0 \text{ and } \pi^+ \text{ from } D^{*+} \text{ vertex, } D^0 \text{ from } DD^* \text{ vertex} \end{array} \right]$$

\otimes : coupling of the source to DD^* states \bullet : $D^* \rightarrow D\pi$ amplitude
 \blacksquare : $DD^* \rightarrow DD^*$ scattering amplitude

► $D^0 D^0 \pi^+$ invariant mass distribution

$$\mathcal{N}_{\text{ev}}(Q^2) = \mathcal{N}_0 \left(\frac{Q_{\text{th}}^2}{Q^2} \right)^{3/2} \int_{s_{\text{th}}}^{s_{\text{max}}(Q^2)} ds \int_{t_-(s, Q^2)}^{t_+(s, Q^2)} dt \sum_\lambda |\mathcal{M}_\lambda(s, t, u; Q^2)|^2$$

► Considering experimental resolution (LHCb, Nature Phys. 18 (2022) 751-754, Nature Commun. 13 (2022) 3351)

$$\bar{\mathcal{N}}_{\text{ev}}(Q^2) = \int dE R_{\text{LHCb}}(E, \sqrt{Q^2}) \mathcal{N}_{\text{ev}}(E^2)$$

► Additional parameters

\mathcal{N}_0 : normalization, α : $D^{*+} D^0$, β : $D^{*0} D^+$ production ratios

Numerical results

1. Introduction

2. Model construction

3. Numerical results

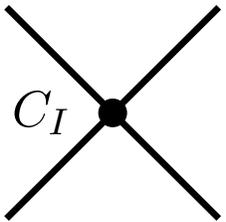
4. Summary and Outlook

Outline of fitted results

► Fitted results (3 different scenario with a comparable χ^2 value.)

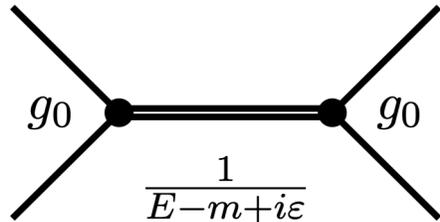
- Mixing of Molecular and Compact state (M+C)

Molecule term



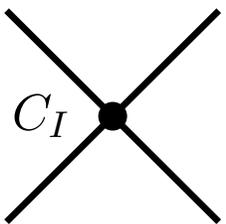
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Compact T_{cc}^+ term



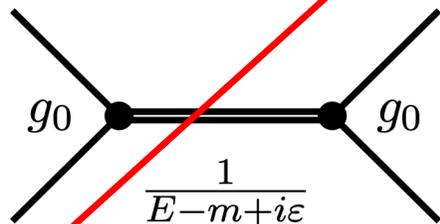
- Pure molecular results (Mol. 1, Mol. 2)

Molecule term

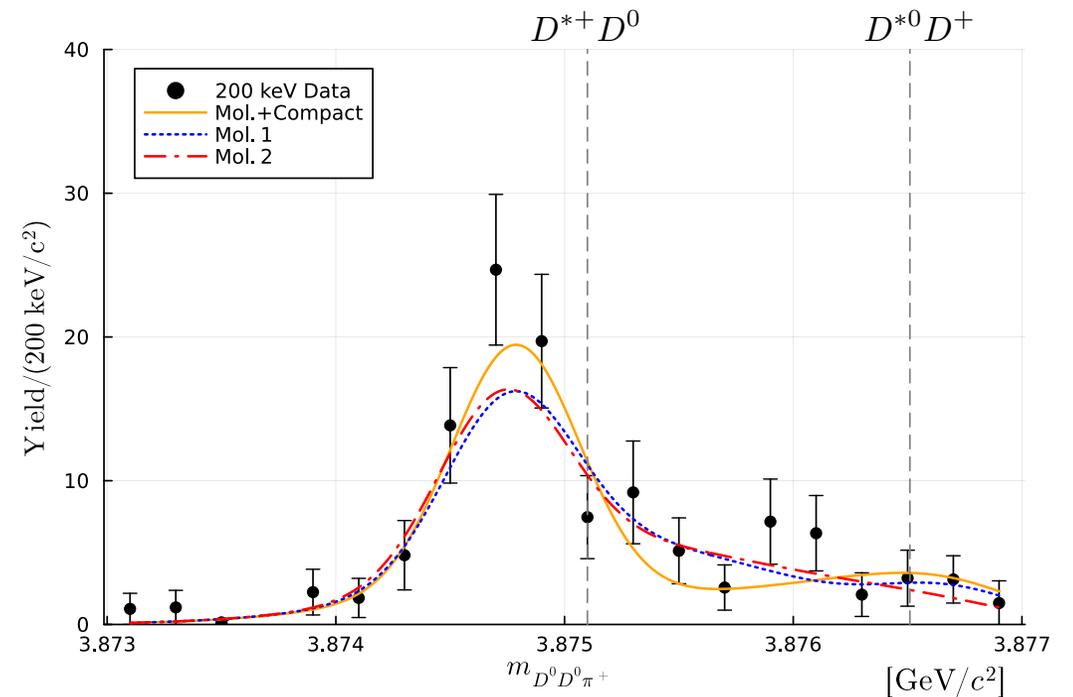


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Compact T_{cc}^+ term



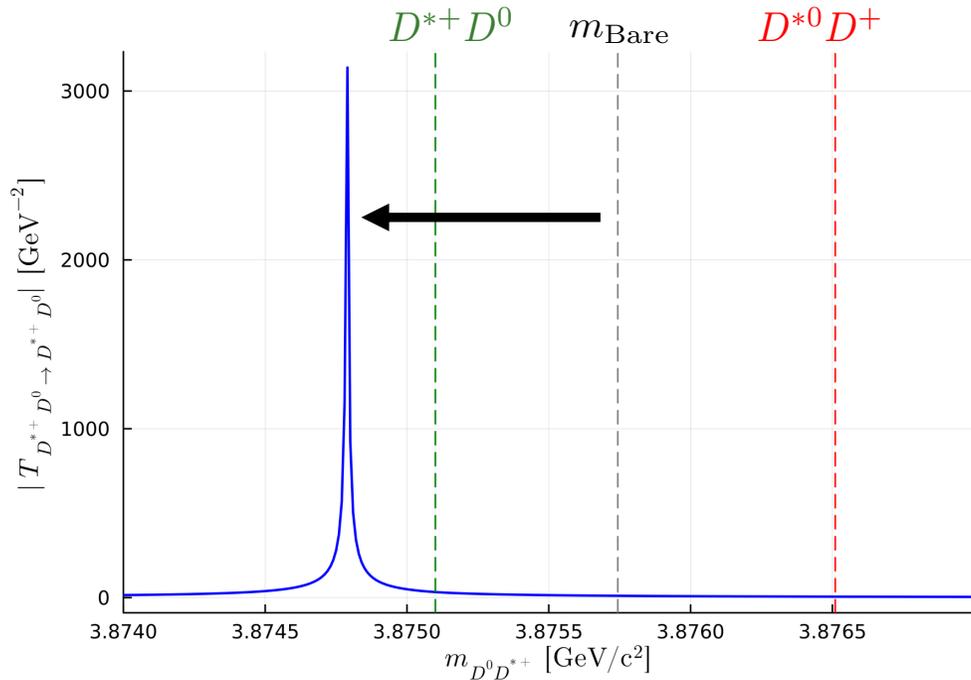
(The case that compact state locates far from the thresholds)



$D^0 D^0 \pi^+$ line shape

Model	$\chi^2/\text{d.o.f.}$
<u>Mol.+Compact (M+C)</u>	$15.0/(19 - 6) = 1.15$
Mol. 1	$16.0/(19 - 6) = 1.23$
Mol. 2	$15.9/(19 - 6) = 1.22$

Mixing of DD^* mol. + Compact T_{cc}^+



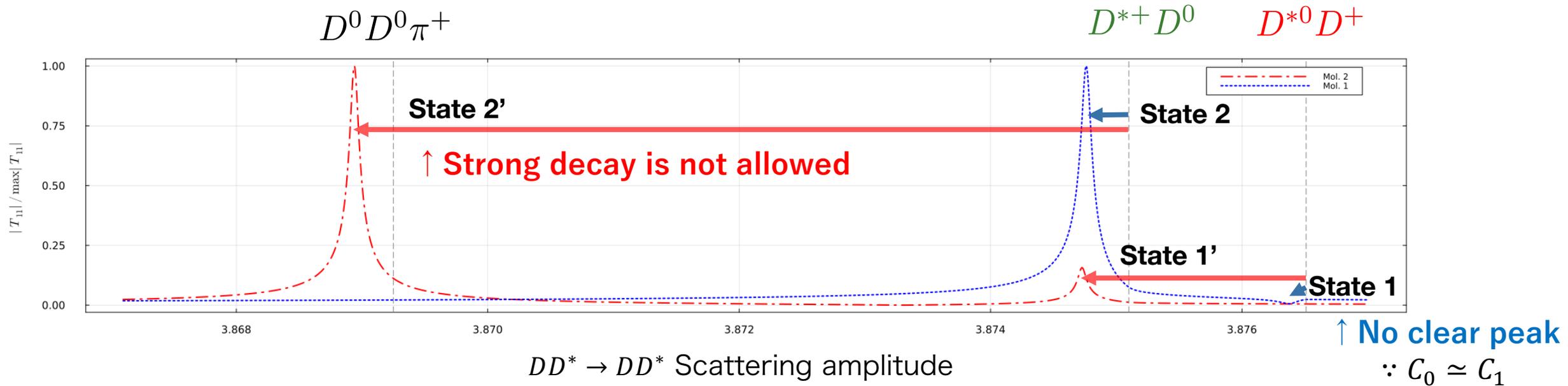
$DD^* \rightarrow DD^*$ scattering amplitude

- ▶ $DD_{I=0,1}^*$ 4-point interaction $C_{I=0,1}$ is weak
Peak disappears in the $g_0 \rightarrow 0$ limit.
→ This peak dominated by the compact component.

$$\mathcal{V}_{ij} = \frac{1}{2} \begin{pmatrix} C_0 + C_1 & -C_0 + C_1 \\ -C_0 + C_1 & C_0 + C_1 \end{pmatrix} + \frac{1}{2} \frac{1}{E - m_{\text{bare}}} \begin{pmatrix} g_0^2 & -g_0^2 \\ -g_0^2 & g_0^2 \end{pmatrix}$$

Model	β/α	C_0 [GeV $^{-2}$]	C_1 [GeV $^{-2}$]	g_0 [GeV $^{-1/2}$]	m_{bare} [GeV]	$\chi^2/\text{d.o.f.}$
<u>Mol.+Compact (M+C)</u>	0.29	-1.38	-0.31	± 0.14	3.8757	15.0/(19 - 6) = 1.15

Only DD^* mol. w/o compact



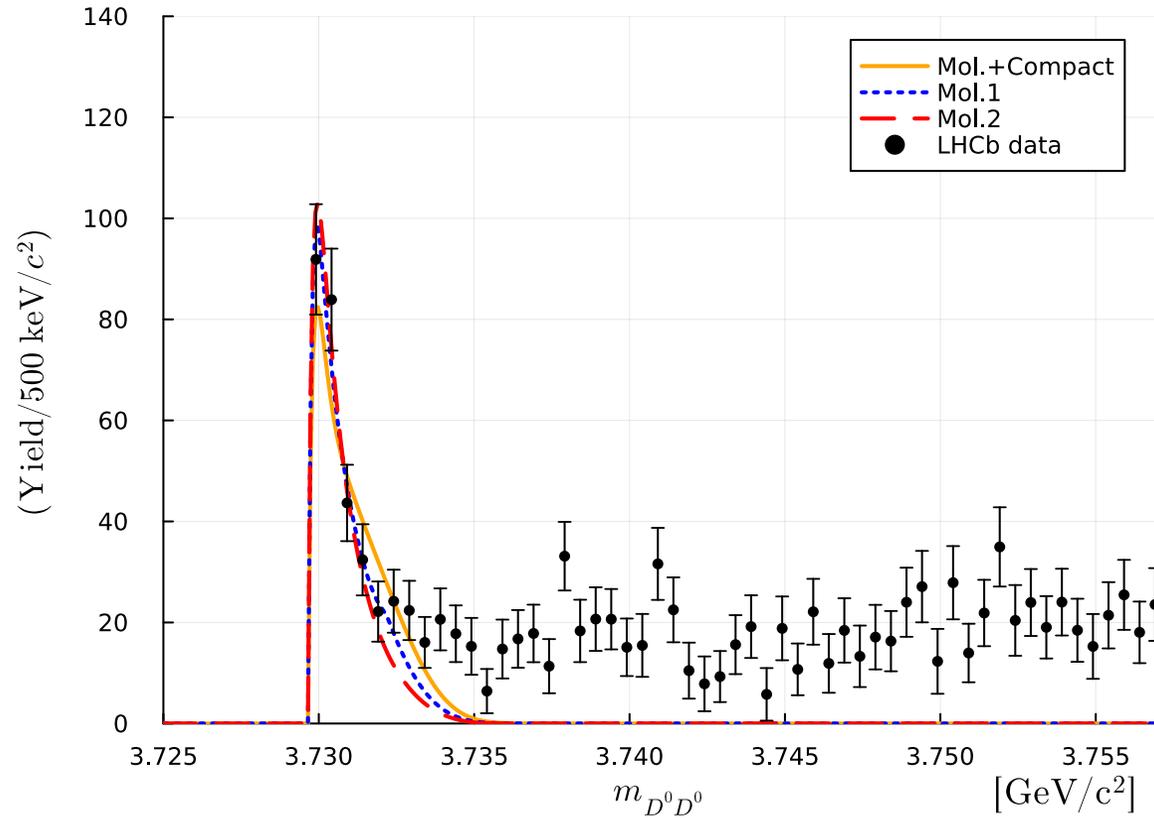
- $DD_{I=0,1}^*$ 4-point coupling constants $C_0 \simeq C_1$ are close and earn enough attraction
 - Isospin symmetric interaction seems to be dominant (M. Sakai, et al., PRD.**109**(2024)054016)
 - 2 channels are decoupled $\because C_0 - C_1 \simeq 0$, then 2 bound states are obtained.

$$\mathcal{V}_{ij} = \frac{1}{2} \begin{pmatrix} C_0 + C_1 & -C_0 + C_1 \\ -C_0 + C_1 & C_0 + C_1 \end{pmatrix}$$

Model	β/α	C_0 [GeV ⁻²]	C_1 [GeV ⁻²]
<u>Mol.+Compact (M+C)</u>	0.29	-1.38	-0.31
<u>Mol. 1</u>	0.058	-22.9	-20.2
<u>Mol. 2</u>	0.93	-29.5	-23.6

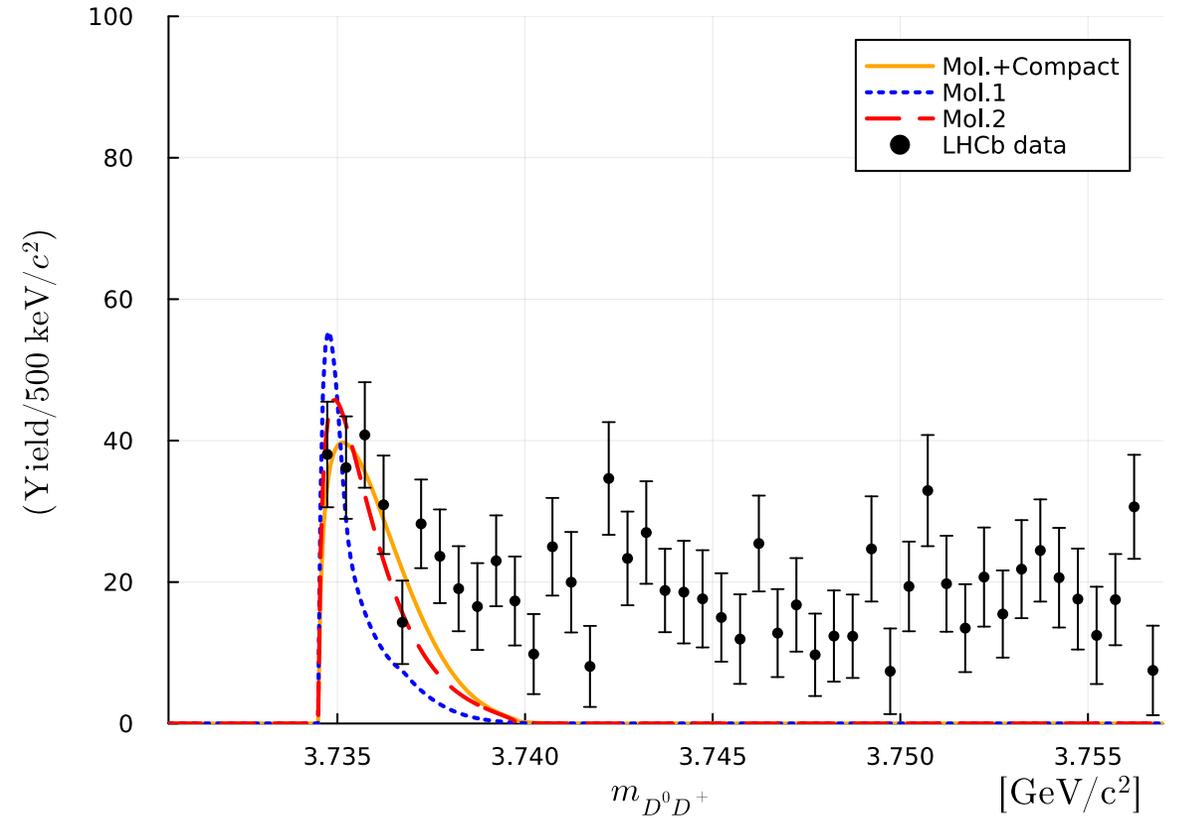
Crosscheck with $D^0 D^0$ and $D^0 D^+$ distributions

$$T_{cc}^+ \rightarrow D^0 D^0 \pi^+$$



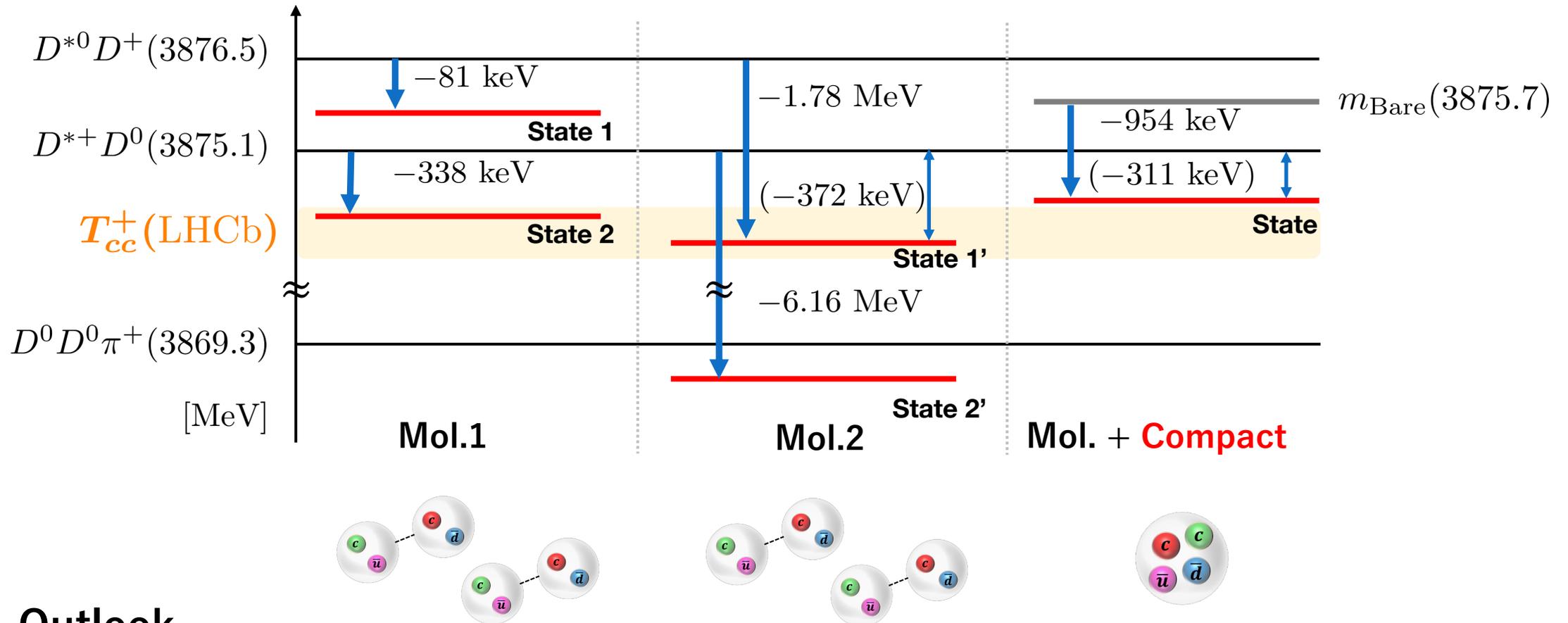
➤ $D^0 D^0$ (Left) : no clear difference

$$T_{cc}^+ \rightarrow D^0 D^+ \pi^0$$



➤ $D^0 D^+$ (Right) : Peak of Mol. 1 is narrow?

Summary and Outlook



► Outlook

- Extend the model (four-point interaction \rightarrow meson exchange interaction)
- Comparison with $X(3872)$ ($\chi_{c1}(3872)$).