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Predicting another doubly charmed molecular resonance

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第四届重味物理与量子色动力学研讨会

Outline

- Background: Quantum chromodynamics (QCD) singlet, deuteron and N-N interactions
- Tcc structure and heavy flavor hadronic molecules
- Isospin breaking effects and possible doubly charmed molecular resonance
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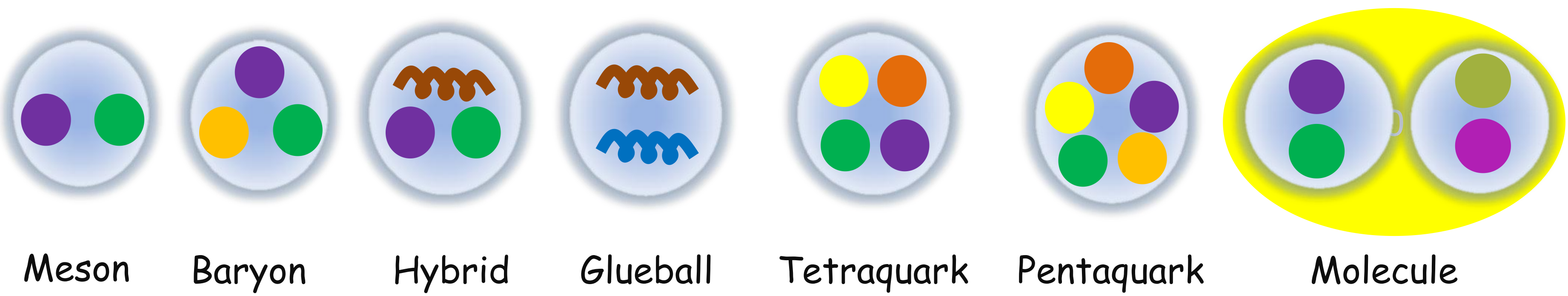
Background: QCD color singlet

Hadron
- Conventional QM states
  - Meson : $q\bar{q}$, $Q\bar{q}$, $Q\bar{Q}$
  - Baryon : qqq, Qqq, QQq, ...
- Exotic states
  - Molecular state
  - Hybrid meson
  - Glueball
  - Tetraquark
  - Pentaquark
  - ...

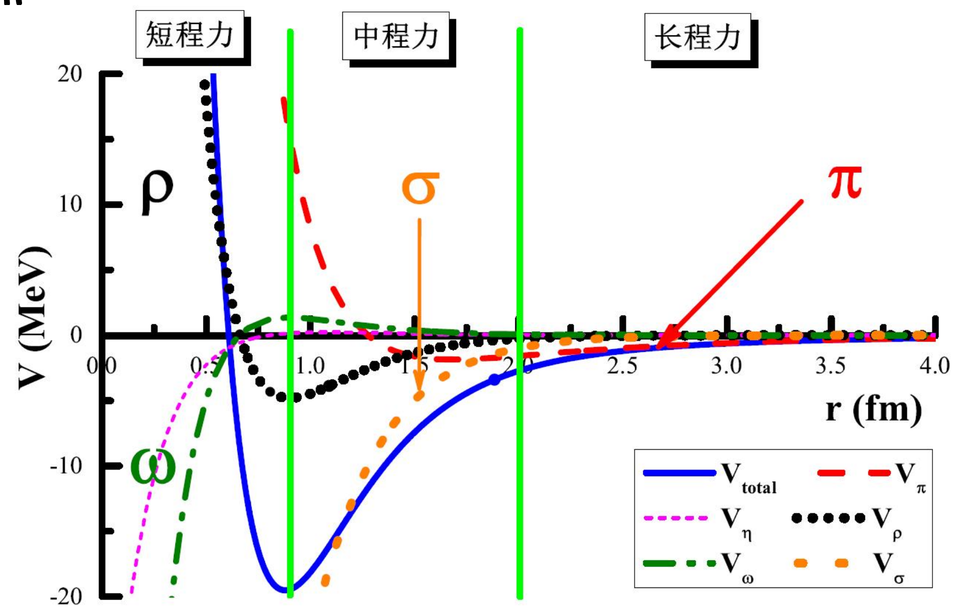


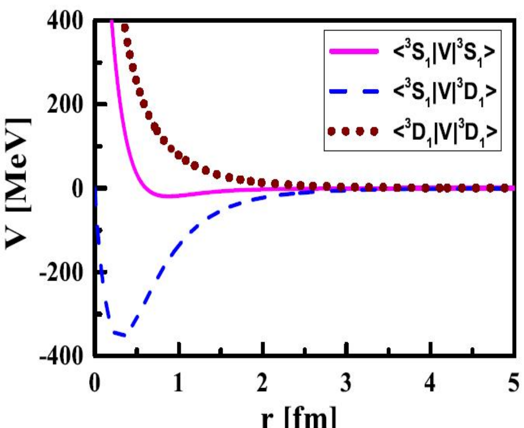
Deuteron

loosely bound molecular state, composed by a proton and a neutron

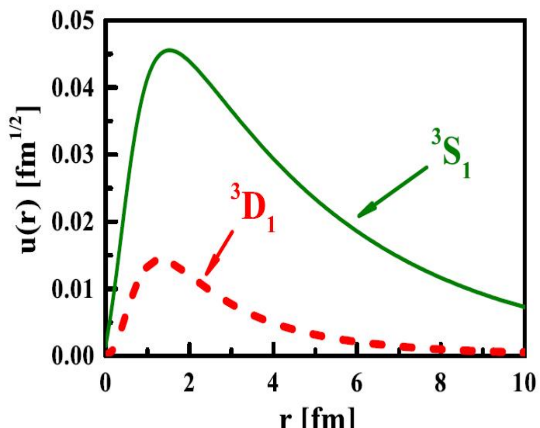
$I(J^P) = 0(1^+)$, $E = -2.225$ MeV, $R = 4.318$ fm

- **Long range：** $r \geq 2\text{fm}$； **one-π-exchange interacion dominant, attractive；**
- **Intermediate range：** $0.8fm \leq r \leq 2fm$； **one-σ-exchange interaction (two pion exchange process)， attractive；**
- **Short range：** $r \leq 0.8fm$； **ρ, ω-exchange interaction，repulsive.**





Effective potentials



Wave functions

- □ **S-D** wave mixing：tensor force；short range：$V_{SD} \gg V_{SS}$，important.
- □ $u_s(r) > u_D(r)$； S wave dominant，loosely bound

Heavy flavor hadronic molecules exist or not?

- Frequently deviated from the convention quark model as the masses, decay widths, various reactions, production and decay behaviors.
- Close to two hadrons thresholds, i.e., X(3872), Y(3940), Y(4140), Pc(4312), Pc(4440), Pc(4457)… molecules?

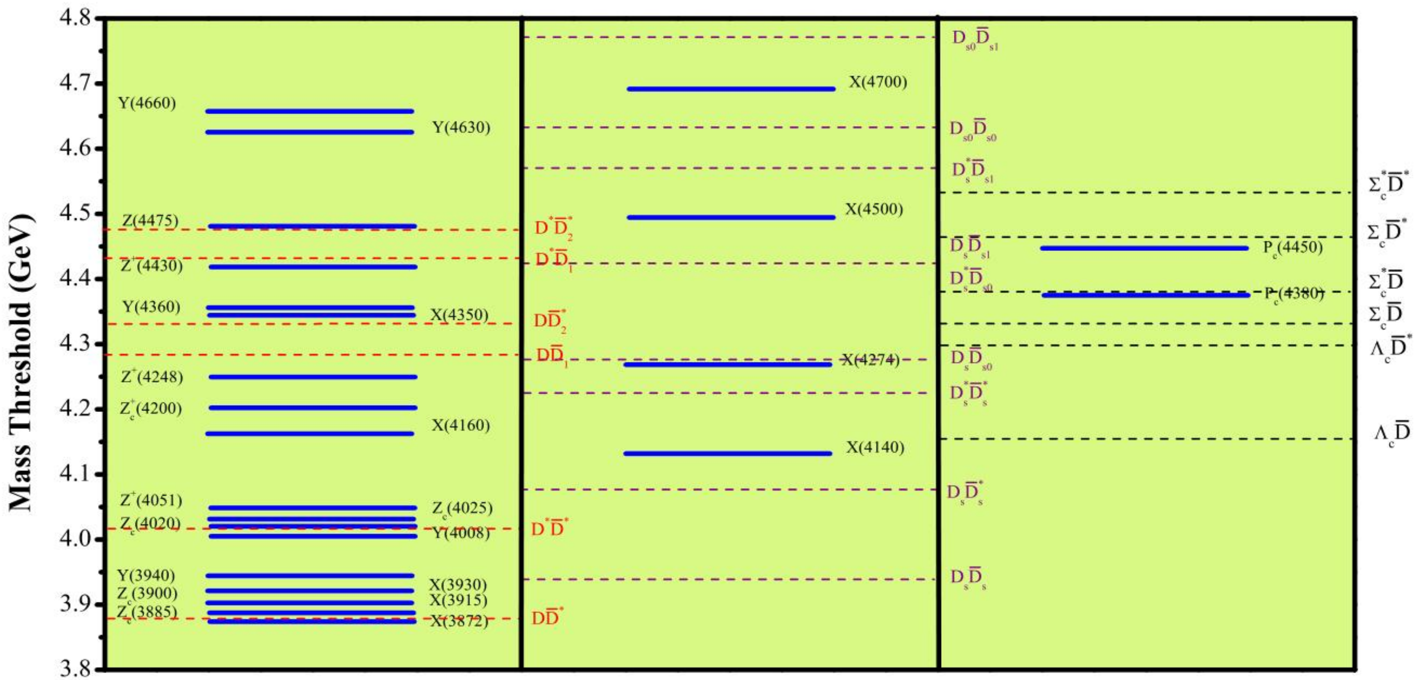


FIG. 1: (color online) A mass comparison between the heavy hadron-hadron systems and new exotics after 2003.

Correlation of the hidden-charm molecular tetraquarks and the charmoniumlike structures existing in the $B \to XYZ + K$ process

Fu-Lai Wang,[1,2,*] Xin-Dian Yang,[1,2,†] Rui Chen,[4,5,‡] and Xiang Liu[1,2,3,§]

The molecular assignments to the three P_c states and the similar production mechanism between the $\Lambda_b \to P_c + K$ and $B \to XYZ + K$ convince us the B decaying to a charmonium state plus light mesons could be the appropriate production process to search for the charmoniumlike molecular tetraquarks. In this work, we systematically study the interactions between a charmed (charmed-strange) meson and an anticharmed (anticharm-strange) meson, which include the $D^{(*)}\bar{D}^{(*)}$, $\bar{D}^{(*)}\bar{D}_1$, $D^{(*)}\bar{D}_2^*$, $D_s^{(*)}\bar{D}_s^{(*)}$, $D_s^{(*)}\bar{D}_{s0}^*$, $D_s^{(*)}\bar{D}'_{s1}$, $D_s^{(*)}\bar{D}_{s1}$, $D_s^{(*)}\bar{D}_{s2}^*$ systems. After adopting the one-boson-exchange effective potentials, our numerical results indicate that, on one hand, there can exist a serial of isoscalar charmoniumlike $\mathcal{D}\bar{\mathcal{D}}$ and $\mathcal{D}_s\bar{\mathcal{D}}_s$ molecular states, on the other hand, we can fully exclude the charged charmoniumlike states as the isovector charmoniumlike molecules. Meanwhile, we discuss the two-body hidden-charm decay channels for the obtained $\mathcal{D}\bar{\mathcal{D}}$ and $\mathcal{D}_s\bar{\mathcal{D}}_s$ molecules, especially the $D^*\bar{D}^*$ molecular tetraquarks. By analyzing the experimental data collected from the $B \to XYZ + K$ and the mass spectrum and two-body hidden-charm decay channels for the obtained $\mathcal{D}\bar{\mathcal{D}}$ and $\mathcal{D}_s\bar{\mathcal{D}}_s$ molecules, we find several possible hints of the existence of the charmoniumlike molecular tetraquarks, i.e., a peculiar characteristic mass spectrum of the isoscalar $D^*\bar{D}^*$ molecular systems can be applied to identify the charmoniumlike molecule. We look forward to the future experiments like the LHCb, Belle II, and BESIII Collaborations can test our results with more precise experimental data.

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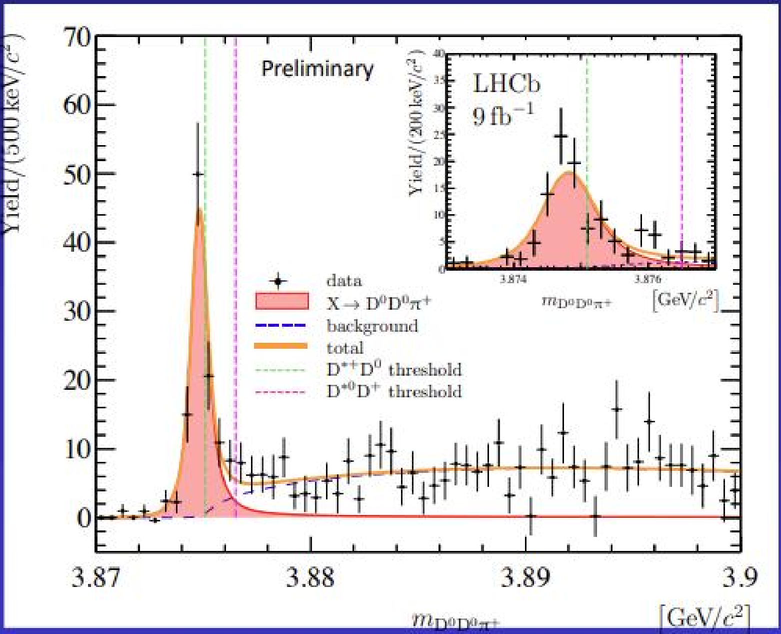
Observation of T_{cc}^{+} state

NEW

LHCb-PAPER-2021-031

- **First observation of a same-sign doubly charmed tetraquark T_{cc}^{+}**
  - Very narrow state in $D^0 D^0 \pi^+$ mass spectrum
  - Consistent with $cc\bar{u}\bar{d}$ tetraquark
  - Mass very close to $D^{*+}D^0$ mass thresholds
  - Manifestly exotic



- **Parameters of T_{cc}^{+}**
  - Fit structure with P-wave relativistic Breit-Wigner

$$\begin{aligned} \delta m_{\rm BW} &= -273 \pm 61 \pm 5\,^{+11}_{-14}\,\mathrm{keV}/c^2\,, \\ \Gamma_{\rm BW} &= 410 \pm 165 \pm 43\,^{+18}_{-38}\,\mathrm{keV}\,, \end{aligned}$$

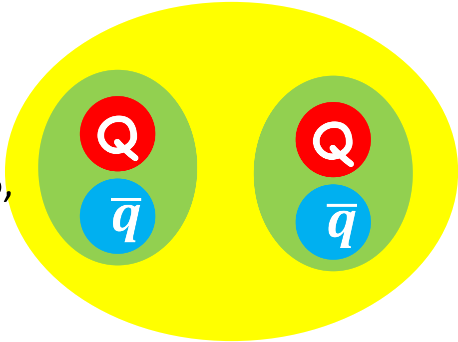
  - Uncertainties stat, syst and due $J^P = 1^+$ assumption
  - Significance for signal > 10 σ
  - Significance for $\delta m_{BW} < 0$ 4.3 σ

Recent LHCb results on exotic meson candidates
Ivan Polyakov

Borrowing from Franz Muheim - LHCb highlights

Theoretical explanations

Doubly charmed molecular states



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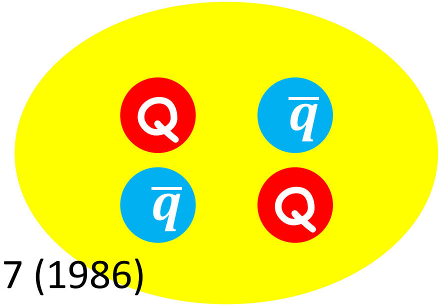
Doubly charmed compact tetraquark states



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Earlier predictions for doubly charmed molecular states

Chin. Phys. Lett. 38, 092001 (2021)

Perfect DD^* molecular prediction matching the T_{cc} observation at LHCb

Ning Li[1,*] Zhi-Feng Sun[2,3,4,†] Xiang Liu[2,3,4,‡] and Shi-Lin Zhu[5,§]

In 2012, we investigated the possible molecular states composed of two charmed mesons [Phys.Rev. D 88, 114008 (2013), arXiv:1211.5007 [hep-ph](2012)] . The D^*D system with the quantum numbers of $I(J^P) = 0(1^+)$ was found to be a good candidate of the loosely bound molecular state. This state is very close to the D^*D threshold with a binding energy around 0.47 MeV. This prediction was confirmed by the new LHCb observation of T_{cc}^+ [see Franz Muheim's talk at the European Physical Society conference on high energy physics 2021].

			$D^{(*)}D^{(*)}$							
I	J^P		OPE				OBE			
	0^+		×				×			
0	1^+	Λ(GeV)	1.05	1.10	1.15	1.20	0.95	1.00	1.05	1.10
		B.E. (MeV)	1.24	4.63	11.02	20.98	0.47	5.44	18.72	42.82
		M (MeV)	3874.61	3871.22	3864.83	3854.87	3875.38	3870.41	3857.13	3833.03
		r_{rms}(fm)	3.11	1.68	1.12	0.84	4.46	1.58	0.91	0.64
		P_1(%)	96.39	92.71	88.22	83.34	97.97	92.94	85.64	77.88
		P_2(%)	0.73	0.72	0.57	0.42	0.58	0.55	0.32	0.15
		P_3(%)	2.79	6.45	11.07	16.11	1.41	6.42	13.97	21.91
		P_4(%)	0.08	0.13	0.14	0.13	0.04	0.09	0.08	0.05

Channels: 0 1^+ $[DD^*]_-(^3S_1)$ $[DD^*]_-(^3D_1)$ $D^*D^*(^3S_1)$ $D^*D^*(^3D_1)$

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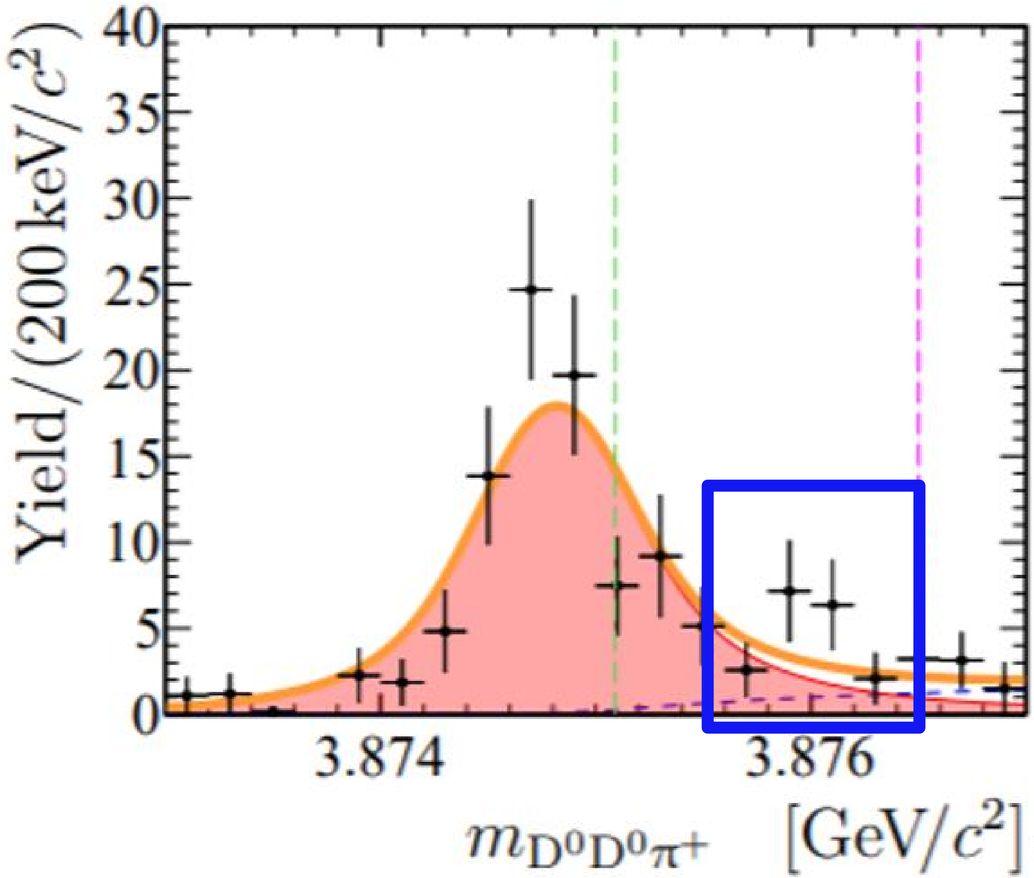
$T_{cc}^{+} = (D^{*+}D^{0} + D^{*0}D^{+})/\sqrt{2}$

$D^{*+}D^{0}$ $D^{*0}D^{+}$



- The very tiny binding energy can amplify the **isospin breaking effect**.
- The interactions between the $D^{*+}D^{0}$ and $D^{*0}D^{+}$ are almost the same.
- If the Tcc is the $D^{*+}D^{0}$ molecule, there should exist the other $D^{*0}D^{+}$ molecule.
- A minor structure existing between the $D^{*+}D^{0}$ and $D^{*0}D^{+}$ threshold, a real structure? How to understand? Why is not significant?

One-boson-exchange (OBE) model

Yukawa, Proc. Phys. Math. Soc. Japan 17, 48 (1935)

- 1935, Yukawa: pion-exchange and nucleon-nucleon interaction
- Nijimegen potential and Bonn potential: scalar meson **σ exchange~two π** exchange; vector meson-ρ/ω exchange~**multi-π** exchange

1
- **OBE model**
- **Scattering amplitude**

$$\langle f|S|i\rangle = \delta_{fi} + i\langle f|T|i\rangle = \delta_{fi} + i(2\pi)^4\delta^4(p_f - p_i)\mathcal{M}_{fi}$$

$$\langle f|S|i\rangle = \delta_{fi} - i(2\pi)\delta(E_f - E_i)V_{fi}(p)$$

2
- **Breit approximation**
- **Effective potential in momentum space**

$$V_{fi}(p) = -\frac{\mathcal{M}_{fi}}{\sqrt{\prod_f 2p_f^0 \prod_i 2p_i^0}} \approx -\frac{\mathcal{M}_{fi}}{\sqrt{\prod_f 2m_f^0 \prod_i 2m_i^0}}$$

3
- **Fourier transformation**
- **Effective potential in coordinate space**

$$V(r) = \int \frac{d^3q}{(2\pi)^3} e^{i\mathbf{q}\cdot\mathbf{r}} \mathcal{V}_{fi}(\mathbf{q})\mathcal{F}^2(q^2, m_E^2)$$

One free parameter

Form factor $\mathcal{F}(q^2, m^2) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}$ Λ, m and q are the cutoff, mass and four-momentum of the exchanged meson, respectively.

$\Lambda \sim 1.0$ GeV

N. A. Tornqvist, Z. Phys. C 61, 525 (1994)
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Effective Lagrangians: Heavy quark symmetry and chiral symmetry

$$V = \begin{pmatrix} \mathcal{V}^{D^0D^{*+}\to D^0D^{*+}} & \mathcal{V}^{D^+D^{*0}\to D^0D^{*+}} \\ \mathcal{V}^{D^0D^{*+}\to D^+D^{*0}} & \mathcal{V}^{D^+D^{*0}\to D^+D^{*0}} \end{pmatrix}$$

$$\mathcal{V}^{D^0D^{*+}\to D^0D^{*+}} = -g_s^2\mathcal{Y}_\sigma + \frac{g^2}{3f_\pi^2}\mathcal{Z}'_{\pi 0} - \frac{1}{4}\beta^2 g_V^2(\mathcal{Y}_\rho - \mathcal{Y}_\omega) + \frac{2}{3}\lambda^2 g_V^2 \mathcal{X}_{\rho 0}$$

$$\mathcal{V}^{D^+D^{*0}\to D^+D^{*0}} = -g_s^2\mathcal{Y}_\sigma + \frac{g^2}{3f_\pi^2}\mathcal{Z}_{\pi 1} - \frac{1}{4}\beta^2 g_V^2(\mathcal{Y}_\rho - \mathcal{Y}_\omega) + \frac{2}{3}\lambda^2 g_V^2 \mathcal{X}_{\rho 1}$$

σ, ρ, ω-exchange effective potentials: exactly the same
π-exchange effective potential: very similar

$$\mathcal{V}^{D^+D^{*0}\to D^0D^{*+}} = -\frac{g^2}{6f_\pi^2}\left(\mathcal{Z}_{\pi 2} - \frac{1}{3}\mathcal{Z}_{\eta 2}\right) + \frac{1}{2}\beta^2 g_V^2\mathcal{Y}_\rho - \frac{1}{3}\lambda^2 g_V^2(\mathcal{X}_{\rho 2} - \mathcal{X}_{\omega 2})$$

Approximate relation $\quad V_\pi^{D^+D^{*0}\to D^0D^{*+}} \sim -2V_\pi^{D^0D^{*+}\to D^0D^{*+}}$

[1] R. Machleidt, K. Holinde, and C. Elster, Phys. Rep. 149, 1 (1987).
[2] F. L. Wang, R. Chen, Z. W. Liu, and X. Liu, Phys. Rev. C 101, 025201 (2020).
[3] C. Isola, M. Ladisa, G. Nardulli, and P. Santorelli, Phys. Rev. D 68, 114001 (2003).

Numerical results 1: bound state properties

Bound state solutions for the coupled $D^{*+}D^0/D^{*0}D^+$ systems with $J^P = 1^+$

- Binding energy **E=-259.90 keV**, overlaps with the mass of Tcc
- Typical loosely bound molecular state: root-mean-square radius is **6.28 fm**
- S-wave $D^{*+}D^0$ and $D^{*0}D^+$ components are dominant.
- Probabilities: $P(D^{*+}D^0)$: $P(D^{*0}D^+) =$ 72.52%: 25.85%
- **The isospin breaking effect is very important.**

$\Lambda = 1.16\,\mathrm{GeV}$

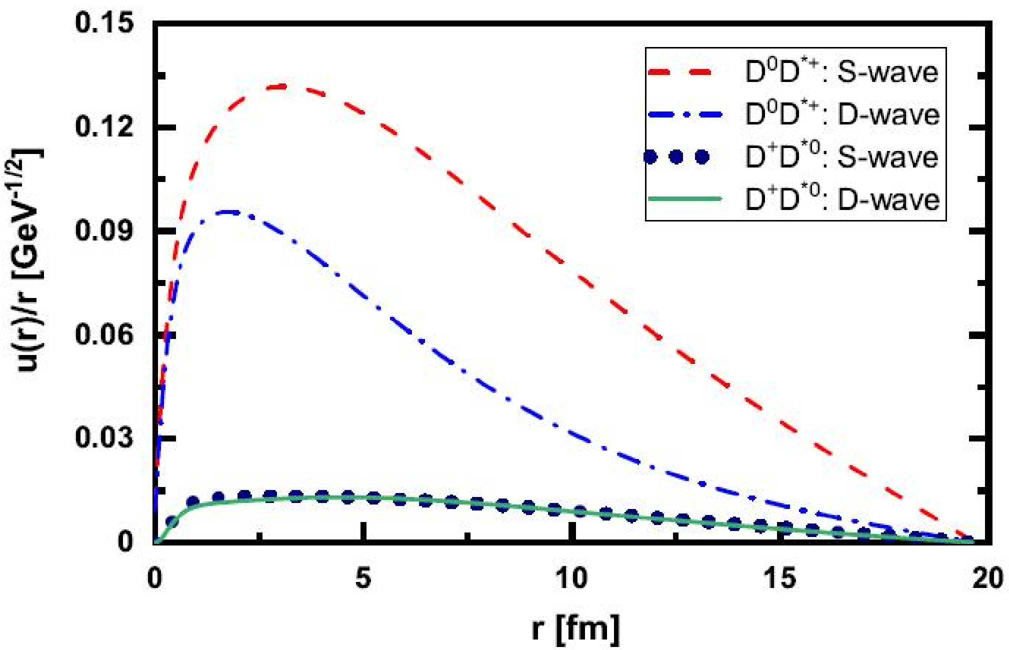

FIG. 1: The radial wave functions for the doubly charmed D^0D^{*+}/D^+D^{*0} molecular state with $J^P = 1^+$.

Numerical results 2: resonance

Phase shifts for the coupled $D^{*+}D^{0}/D^{*0}D^{+}$ systems with $J^P = 1^+$

A typical Breit-Wigner resonance: δ =(n+1/2)π

$\Lambda = 1.16\,\mathrm{GeV}$

$$\sigma_{\mathrm{Max}}(E_0) \qquad \Gamma = 2/\left(\frac{d\delta(E)}{dE}\right)_{E_0}$$

Existing a doubly charmed resonance T'_{cc}

$m = 3876$ MeV $\Gamma = 412$ keV

- T'_{cc} : not a shape-type resonance but a Feshbach-type resonance.
- Disappear: turn off the contribution from the $D^{*0}D^{+}$ channel.
- The isospin breaking effect plays a very important role in forming the T'_{cc}

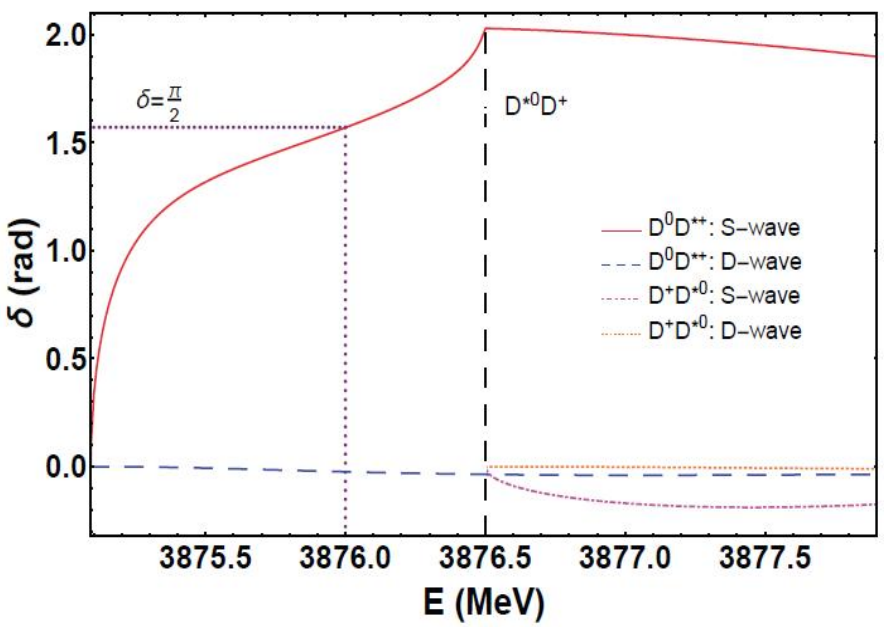

FIG. 2: Phase shifts for the coupled D^0D^{*+}/D^+D^{*0} system with $J^P = 1^+$. Here, we adopt the same cutoff value $\Lambda = 1.16$ GeV, the dotted line shows the mass position of the obtained doubly charmed resonance.

Conclusion

Fitting the $D^0D^0\pi^+$ mass spectrum

Doubly charmed molecular state
$m_1 = 3.8747$ GeV, $\Gamma_1 = 410$ keV
The observed Tcc state
Dominant channel: S-wave $D^{*+}D^0$
$P(D^{*+}D^0):P(D^{*0}D^+) = 2.8:1$

Doubly charmed resonance
$m_2 = 3.8760$ GeV, $\Gamma_2 = 412$ keV
Dominant channel: S-wave $D^{*0}D^+$
The minor structure
Why is not significant?

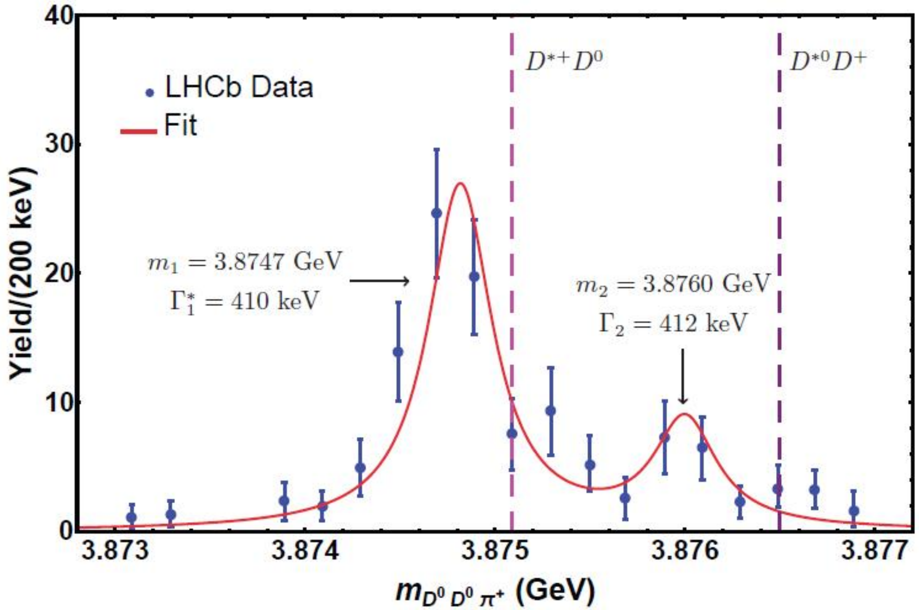

FIG. 3: The fit to the experimental data of the $D^0D^0\pi^+$ mass spectrum through the obtained masses and width for the doubly molecule and the doubly resonance. Here, $\Gamma_1^* = 410$ keV is the experimental width of the newly T_{cc}^+ [4]. The dash lines label the D^0D^{*+} and D^+D^{*0} mass thresholds.

The isospin breaking effect does play an important role in generating this doubly charmed molecular tetraquark

Decay behaviors

T_{cc}^{+}: $P(D^{*+}D^{0}):P(D^{*0}D^{+}) = 2.8:1$

Mixing angle

$$\begin{pmatrix} |T_{cc}^{+}\rangle \\ |T_{cc}'^{+}\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |D^0 D^{*+}\rangle \\ |D^+ D^{*0}\rangle \end{pmatrix} \qquad \theta = \pm 30.8^\circ$$

Amplitudes

$$\begin{aligned}
\mathcal{A}_{T_{cc}^{+}\to D^0 D^0 \pi^+} &= \cos\theta \mathcal{A}_{D^0 D^{*+}\to D^0 D^0 \pi^+} + \sin\theta \mathcal{A}_{D^+ D^{*0}\to D^0 D^0 \pi^+}, \\
\mathcal{A}_{T_{cc}^{+}\to D^+ D^0 \pi^0} &= \cos\theta \mathcal{A}_{D^0 D^{*+}\to D^+ D^0 \pi^0} + \sin\theta \mathcal{A}_{D^+ D^{*0}\to D^+ D^0 \pi^0}, \\
\mathcal{A}_{T_{cc}'^{+}\to D^0 D^0 \pi^+} &= -\sin\theta \mathcal{A}_{D^0 D^{*+}\to D^0 D^0 \pi^+} + \cos\theta \mathcal{A}_{D^+ D^{*0}\to D^0 D^0 \pi^+}, \\
\mathcal{A}_{T_{cc}'^{+}\to D^+ D^0 \pi^0} &= -\sin\theta \mathcal{A}_{D^0 D^{*+}\to D^+ D^0 \pi^0} + \cos\theta \mathcal{A}_{D^+ D^{*0}\to D^+ D^0 \pi^0}, \\
\mathcal{A}_{T_{cc}^{+}\to D^0 D^+ \gamma} &= \cos\theta \mathcal{A}_{D^0 D^{*+}\to D^0 D^+ \gamma} + \sin\theta \mathcal{A}_{D^+ D^{*0}\to D^0 D^+ \gamma}, \\
\mathcal{A}_{T_{cc}'^{+}\to D^0 D^+ \gamma} &= -\sin\theta \mathcal{A}_{D^0 D^{*+}\to D^0 D^+ \gamma} + \cos\theta \mathcal{A}_{D^+ D^{*0}\to D^0 D^+ \gamma}.
\end{aligned}$$

Decay ratios

$$\begin{aligned}
\mathcal{R}_1 &= \Gamma[T_{cc}^{+} \to D^0 D^0 \pi^+]/\Gamma[T_{cc}'^{+} \to D^0 D^0 \pi^+] = \cos^2\theta : \sin^2\theta = 2.80 \\
\mathcal{R}_2 &= \Gamma[T_{cc}^{+} \to D^0 D^+ \gamma] : \Gamma[T_{cc}'^{+} \to D^0 D^+ \gamma] = \sin^2\theta : \cos^2\theta = 0.35 \\
\mathcal{R}_3 &= \Gamma[T_{cc}^{+} \to D^+ D^0 \pi^0]/\Gamma[T_{cc}'^{+} \to D^+ D^0 \pi^0] \text{ less than } 0.7
\end{aligned}$$

T_{cc}^{+}: $D^0 D^0 \pi^+$ **decay mode shall be the prime channels**

$T_{cc}^{+\prime}$: $D^0 D^+ \gamma$ **and** $D^+ D^0 \pi^0$ **decay mode shall be the prime channels**

Summary

- ✓ Perform an isospin breaking effect analysis on the coupled $D^{*+}D^0/D^{*0}D^+$ systems with $J^P=1^+$
- ✓ The observed T_{cc}^+ state can be explained as a doubly charmed molecular state, mainly composed by the S-wave $D^{*+}D^0$ channel
- ✓ Predict a doubly charmed resonance $T_{cc}^{+\prime}$

$m_2 = 3.8760$ GeV, $\Gamma_2 = 412$ keV

$D^0D^+\gamma$ and $D^+D^0\pi^0$ decay modes shall be the prime channels