X3872的一些有效场论研究

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第四届LHCb前沿物理研讨会
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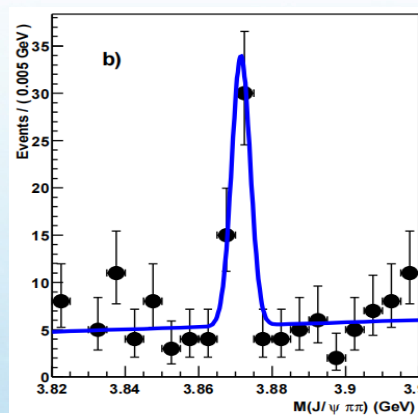
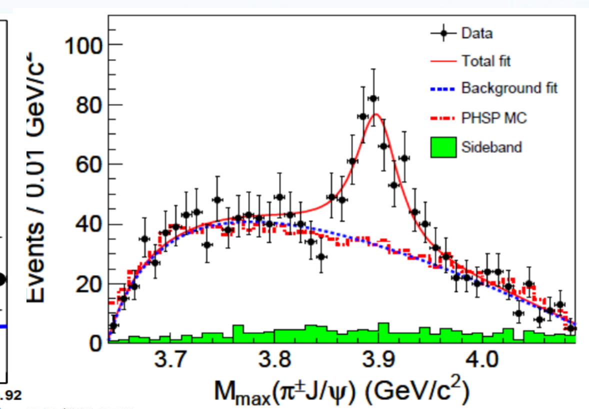
Outlines

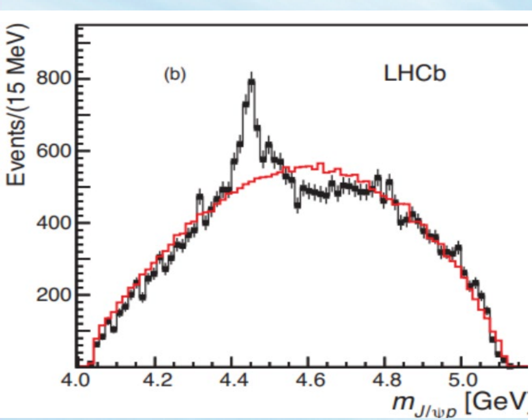
1. Introduction
2. Formalism
3. X3872 and T_{cc}
4. Summary

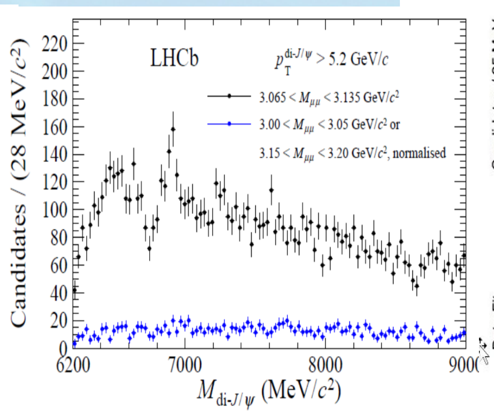
Introduction

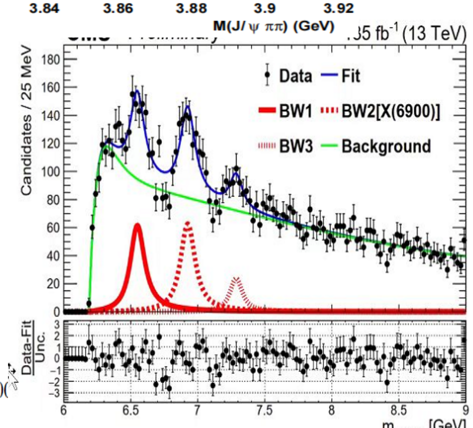
- X(3872) by Belle, in 2003
- Z_c(3900) by BESIII and Belle, in 2013
- P_c states by LHCb, in2015
- T_{cc}, X(6900)....
- Their nature?
  - Quantum number?
  - pole location?
  - The inner structure?

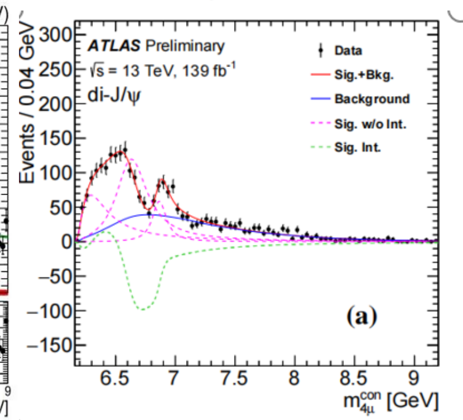












X3872

- Mass puzzle: below or above the threshold?

F.K. Guo, PRL 122 (2019) 20, 202002

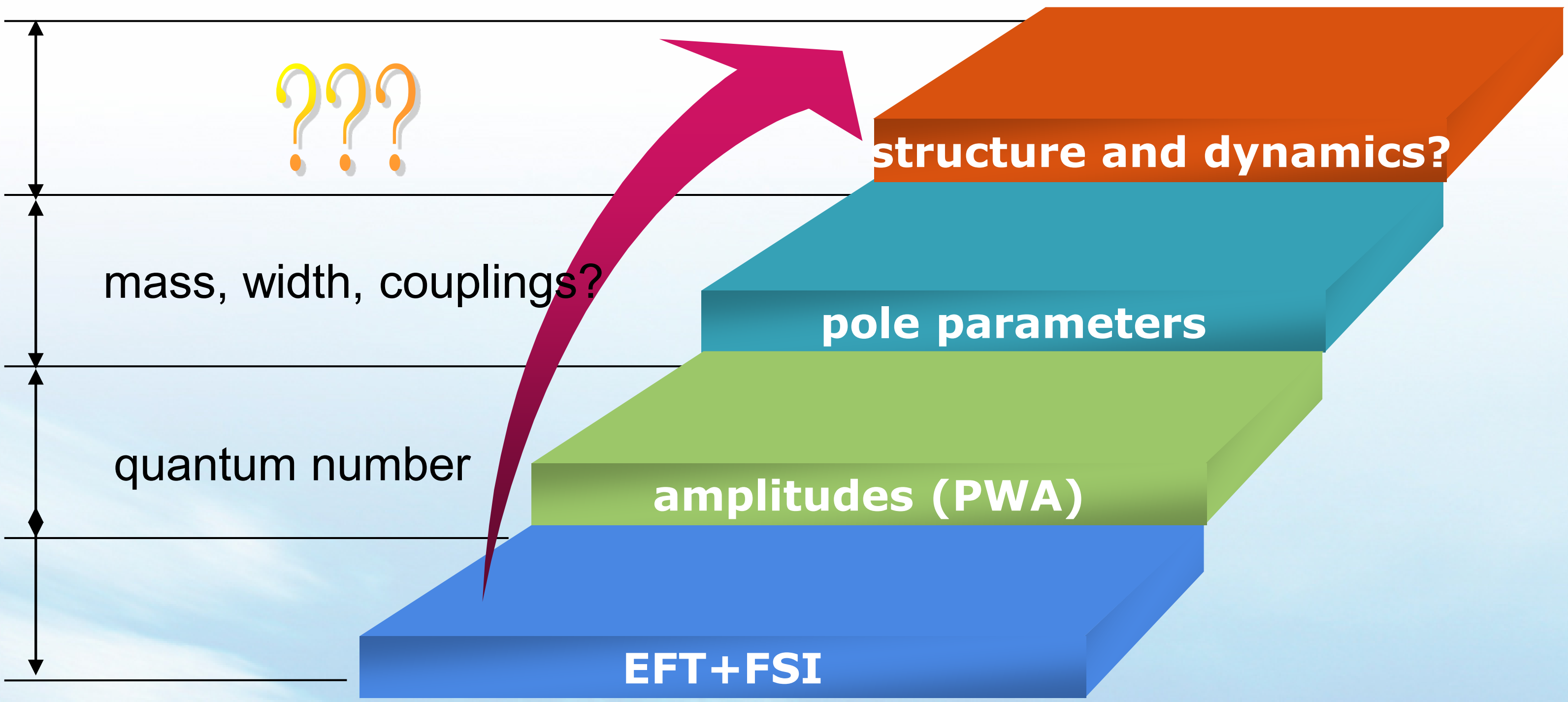
$$\Delta M = M_{\chi^0_{c1}} - (m_{D^0} + m_{\bar{D}^{*0}}) = -35 \pm 60 \text{ keV}$$

$$\Delta M = M_{T^+_{cc}} - (M_{D^{*+}} + M_{D^0}) = -237 \pm 61 \ keV/c^2,$$

- Inner structure?
- Charged partners?
  - not found yet

Strategy

- The property of the exotic states?



Formalism

HQEFT:

- Treat $c\bar{c}$, cc as static,

$$\left(\bar{u}_{(\alpha)}\,\Gamma_l u^{(\alpha)}\right)\left(\bar{h}_{(\beta)}\Gamma_h h^{(\beta)}\right) \qquad \left(\bar{u}^{(\alpha)}\,\Gamma_1 h_{(\alpha)}\right)\left(\bar{h}^{(\beta)}\,\Gamma_2 u_{(\beta)}\right)$$

- Interaction Lagrangians for isoscalars
  - Experiment has not found charged partners yet!

$$\mathcal{L}^{\rm singlet}_{\chi_{c1}} = i\,\tilde{g}_1 \epsilon_{\mu\nu\alpha\beta} v^\alpha \chi^\beta_{c1} \langle \gamma^\nu \bar{\mathcal{H}}_a \frac{1-\not{v}}{2}\gamma^\mu \frac{1+\not{v}}{2}\mathcal{H}_a\rangle + \tilde{g}_2 \left(\langle \mathcal{H}_a\,\Gamma_1 \frac{1+\not{v}}{2}\rangle\langle\Gamma_2 \bar{\mathcal{H}}_a \frac{1-\not{v}}{2}\rangle\chi^\mu_{c1} - \langle\Gamma_1\,\bar{\mathcal{H}}_a \frac{1+\not{v}}{2}\rangle\langle\mathcal{H}_a\Gamma_2 \frac{1-\not{v}}{2}\rangle\chi^\mu_{c1}\right).$$

$$\mathcal{L}^{\rm singlet}_{T_{cc}} = i g_1 \epsilon^{ab}\epsilon_{\mu\nu\alpha\beta} v^\alpha T^\beta \langle \frac{1+\not{v}}{2}\bar{\mathcal{H}}_a \gamma^\nu \bar{\mathcal{H}}^C_b \frac{1-\not{v}}{2}\gamma^{\mu C}\rangle + g_2 \epsilon^{ab} T^\mu \langle \Gamma_1 \frac{1+\not{v}}{2}\bar{\mathcal{H}}_a\rangle\langle\Gamma_2 \frac{1+\not{v}}{2}\,\bar{\mathcal{H}}_b\rangle + h.c..$$

$\chi_{c1}(3872)$	$c\bar{c}$	$u\bar{u}$	L
1^{++}	$^1S_0(0^{-+})$	$^3P_0(0^{++})$	1
1^{++}	$^1S_0(0^{-+})$	$^3P_1(1^{++})$	1
1^{++}	$^3S_1(1^{--})$	$^3S_1(1^{--})$	0
1^{++}	$^3S_1(1^{--})$	$^1P_1(1^{+-})$	1
1^{++}	$^1P_1(1^{+-})$	$^1P_1(1^{+-})$	0
1^{++}	$^3P_0(0^{++})$	$^3P_1(1^{++})$	0
1^{++}	$^3S_1(1^{--})$	$^3D_1(1^{--})$	0
1^{++}	$^1P_1(1^{+-})$	$^3D_1(1^{--})$	1
1^{++}	$^1P_1(1^{+-})$	$^3D_2(2^{--})$	1
1^{++}	$^1P_1(1^{+-})$	$^3D_3(3^{--})$	1
$\vdots$	$\vdots$	$\vdots$	$\vdots$

	cc	$\bar{l}_1\bar{l}_2$
$j_h=1,\ j_l=1,\ L=0$		
$\psi_{\rm spin}$	symmetric	symmetric
$\psi_{\rm flavor}$	symmetric	symmetric
$\psi_{\rm space}$	symmetric	symmetric
$\psi_{\rm color}$	anti-symmetric	anti-symmetric
$j_h=0, j_l=0,\ L=1$		
$\psi_{\rm spin}$	anti-symmetric	anti-symmetric
$\psi_{\rm flavor}$	symmetric	symmetric
$\psi_{\rm space}$	symmetric	symmetric
$\psi_{\rm color}$	symmetric	symmetric

Isovector?

- It does not exclude the possibility of isovector.

$$\begin{pmatrix} \frac{\chi_{c1}^{0,\mu}}{\sqrt{2}} & \chi_{c1}^{+,\mu} \\ \chi_{c1}^{-,\mu} & -\frac{\chi_{c1}^{0,\mu}}{\sqrt{2}} \end{pmatrix} \qquad \begin{pmatrix} T_{cc}^{0,\mu} & -\frac{T_{cc}^{+,\mu}}{\sqrt{2}} \\ -\frac{T_{cc}^{+,\mu}}{\sqrt{2}} & T_{cc}^{++,\mu} \end{pmatrix}$$

- Lagrangians within HQEFT and chiral symmetry

$$\begin{aligned} \mathcal{L}_{\chi_{c1}} &= i\,\tilde{g}_1 \epsilon_{\mu\nu\alpha\beta} v^\mu \chi^\nu_{c1\,ab} \langle \gamma^\nu \bar{\mathcal{H}}_a \frac{1-\not{v}}{2} \gamma^\mu \frac{1+\not{v}}{2} \mathcal{H}_b \rangle \\ &+ \tilde{g}_2 \Big(\langle \mathcal{H}_a\, \Gamma_1 \frac{1+\not{v}}{2} \rangle \langle \Gamma_2 \bar{\mathcal{H}}_b \frac{1-\not{v}}{2} \rangle \chi^\mu_{c1\,ab} \\ &- \langle \Gamma_1\, \bar{\mathcal{H}}_a \frac{1+\not{v}}{2} \rangle \langle \mathcal{H}_b \Gamma_2 \frac{1-\not{v}}{2} \rangle \chi^\mu_{c1\,ba} \Big) . \end{aligned}$$

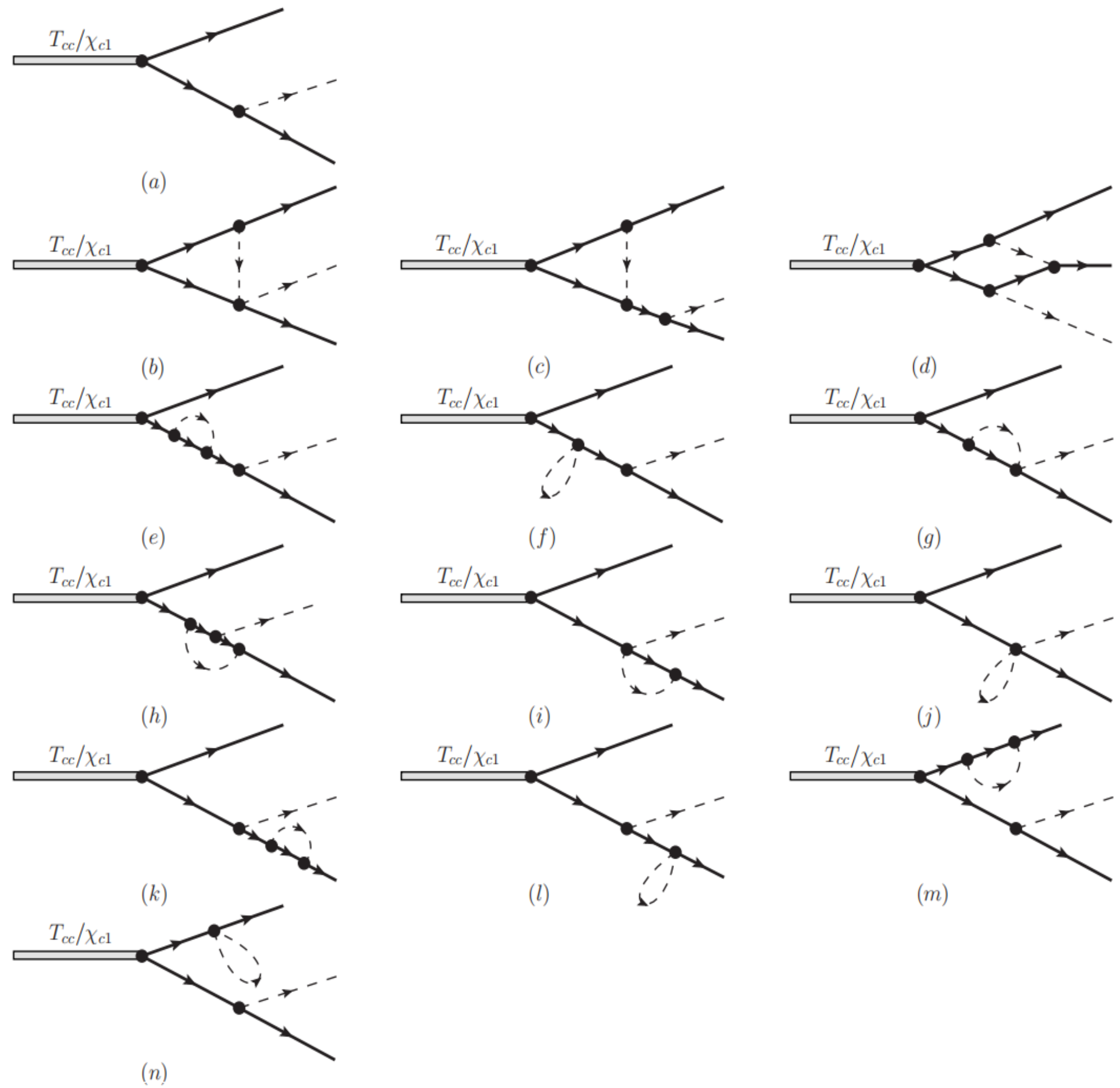
$$\begin{aligned} \mathcal{L}_{T_{cc}} &= i\, g_1 \epsilon_{\mu\nu\alpha\beta} v^\alpha T^\beta_{ab} \langle \frac{1+\not{v}}{2} \bar{\mathcal{H}}_b \gamma^\nu \bar{\mathcal{H}}^C_a \frac{1-\not{v}}{2} \gamma^\mu C \rangle \\ &+ g_2 T^\mu_{ab} \langle \Gamma_1 \frac{1+\not{v}}{2} \bar{\mathcal{H}}_a \rangle \langle \Gamma_2 \frac{1+\not{v}}{2} \bar{\mathcal{H}}_b \rangle + h.c. , \end{aligned}$$

- Lagrangians between D and π mesons

$$\begin{aligned} \mathscr{L}_{DD} &= i \langle H_b v^\mu D_{\mu ba} \bar{H}_a \rangle + ig \langle H_b \gamma_\mu \gamma_5 \mathcal{A}^\mu_{ba} \bar{H}_a \rangle \\ &+ \frac{f_\pi^2}{4} \partial_\mu \Sigma_{ab} \partial^\mu \Sigma^\dagger_{ba} . \end{aligned}$$

Feynman daigrams

- up to NLO
- Ignoring the rescattering of the pions, as they will only affect the F_π

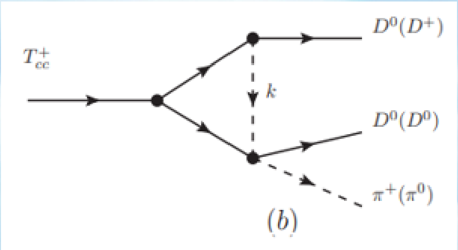


amplitudes

- Some examples

$$
\begin{aligned}
i\mathscr{M}^{(\beta)}_{T^+_{cc}} &= g_x M_{T^+_{cc}} \sqrt{m_{D^0} m_{D^+}}\; p_3 \cdot \epsilon(q) \Big\{ \frac{g(1+\delta Z D^0(g)/2 + \delta Z D^+(g)/2)(\Delta_5 - \Delta_4')}{2 f_\pi^2 \Delta_4' \Delta_5} \\
&+ \frac{g^3}{128\pi^2 f_\pi^4} \Big[\frac{[2C_1(m_{\pi^-}, \Delta_2, \Delta_2') - C_1(m_{\pi^0}, \Delta_3, \Delta_3')]}{\Delta_5} - \frac{[2C_1(m_{\pi^+}, \Delta, \Delta') - C_1(m_{\pi^0}, \Delta_1, \Delta_1')]}{\Delta_4'} \\
&+ \frac{4J_1(m_{\pi^+}, \Delta_4)\Delta_4}{\Delta_4'^2} - \frac{4J_1(m_{\pi^+}, \Delta_5')\Delta_5'}{\Delta_5^2} + \frac{4J_1(m_{\pi^0}, \Delta_4')}{\Delta_4'} - \frac{4J_1(m_{\pi^+}, \Delta_5)}{\Delta_5} \\
&+ \frac{8C_1(m_{\pi^+}, -\Delta_2', \Delta_5)}{\Delta_4'} - \frac{8C_1(m_{\pi^+}, -\Delta', \Delta_2)}{\Delta_5} - \frac{4C_1(m_{\pi^0}, -\Delta_3', \Delta_4')}{\Delta_4'} + \frac{4C_1(m_{\pi^+}, -\Delta_1', \Delta_5)}{\Delta_5} \\
&- \frac{4I_1(m_{\pi^+})}{g^2 \Delta_5} + \frac{4I_1(m_{\pi^+})}{g^2 \Delta_5} - \frac{2I_1(m_{\pi^0})}{g^2 \Delta_4'} + \frac{2I_1(m_{\pi^0})}{g^2 \Delta_5} + 2D_1(m_{\pi^+}, \Delta_6, \Delta', \Delta)
\end{aligned}
$$

- This diagram is zero in the heavy quark limit



$$D D \pi v \cdot \partial \pi$$

$$
\begin{aligned}
i\mathscr{M}_{b1} &= \int \frac{d^d k}{(2\pi)^d} \frac{i\sqrt{2} M_{T^+_{cc}} m_{D^0} g g_x}{8 f_\pi^3} (p_3 \cdot v + k \cdot v)(k \cdot v \quad v \cdot \epsilon(p) - k \cdot \epsilon(p)) \\
&\left(\frac{1}{k^2 - m_{\pi^+}^2} \frac{1}{k \cdot v - (p \cdot v - p_1 \cdot v + \frac{3}{4} m_{D^{*0}} - \frac{7}{4} m_{D^0})} \frac{1}{k \cdot v - (-p_1 \cdot v + \frac{5}{4} m_{D^{*+}} - \frac{1}{4} m_{D^+})} \right) \\
&= \frac{\sqrt{2} M_{T^+_{cc}} m_{D^0} g g_x}{8 f_\pi^4} (v^\mu (v \cdot \epsilon(p)) - \epsilon^\mu(p)) v_\mu \Big(p_3 \cdot v \frac{1}{16\pi^2 \Delta'} (C_1(\Delta, \Delta', m) + C_2(\Delta, \Delta', m) \\
&+ I_1(m) + I_2(m, \Delta)) v_\mu + \frac{1}{16\pi^2} (C_1(\Delta, \Delta', m) + C_2(\Delta, \Delta', m)) \Big) \\
&= 0\,.
\end{aligned}
$$

Widths

- T_{cc}: sum of the three body decays

$$\Gamma^{tot}(Q) = \sum_j \Gamma^{(j)}(Q) \qquad \Gamma^{(j)}(Q) = \int_{\gamma(Q)} dsdt \frac{\overline{|\mathscr{M}^{(j)}|^2}}{32Q^3}$$

- X(3872): use the $D\bar{D}^0\pi^0$ width and the Br from PDG

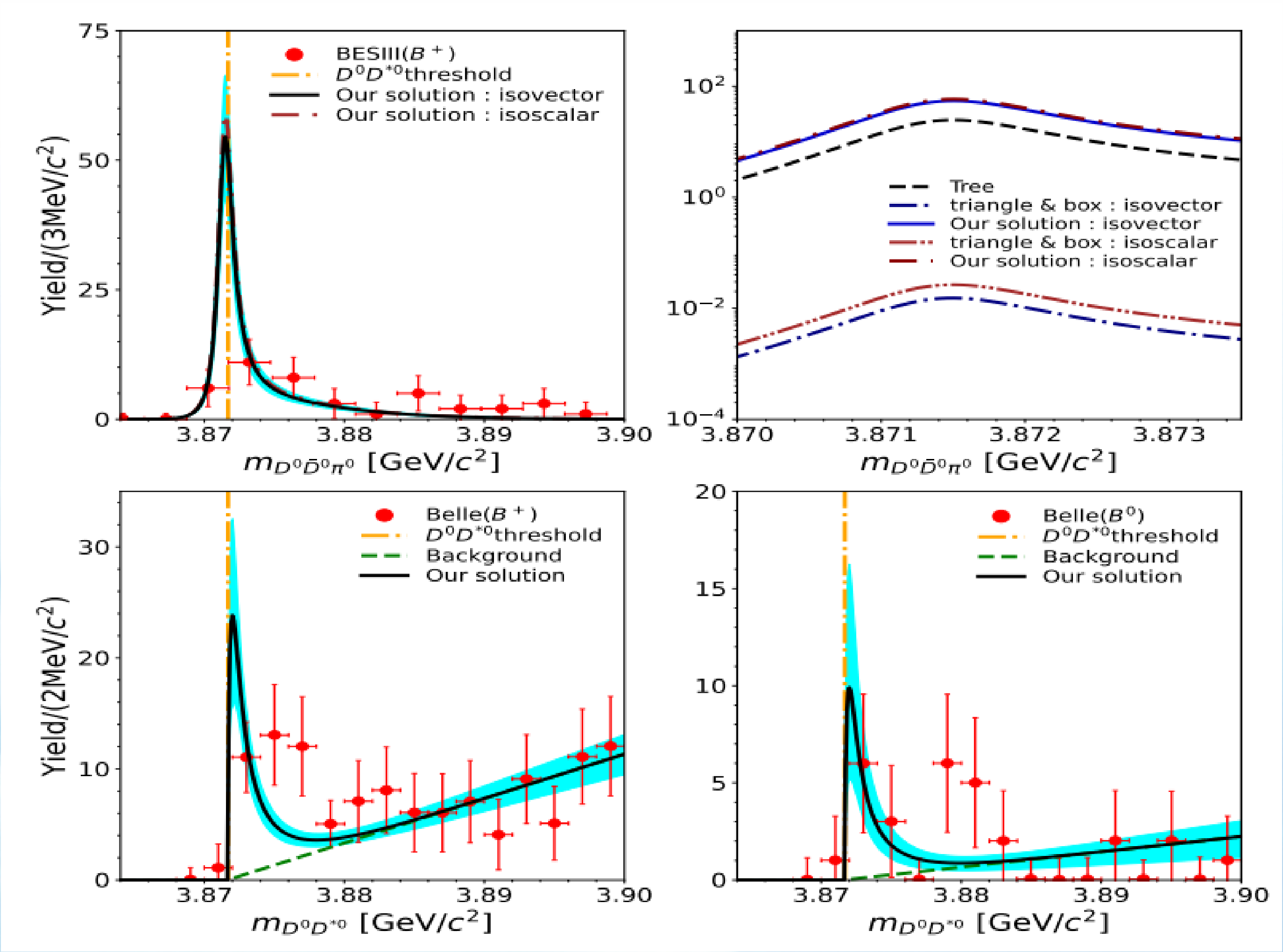
$$\Gamma^{tot}_{\chi^0_{c1}}(Q) = \frac{\Gamma^{(D^0\bar{D}^0\pi^0)}(Q)}{\mathrm{BR}(\chi^0_{c1} \to \mathrm{D}^0\bar{\mathrm{D}}^0\pi^0)}$$

- For narrow resonance, BW is good enough to extract the resonance parameters

$$\frac{dY^{(j)}_{T_{cc},\chi_{c1}}}{dQ} = N^{(j)}\left[\frac{\Gamma^{(j)}(Q)}{(Q^2-M^2)^2+[M\Gamma_{tot}(Q)]^2}\right]$$

Fit resultsX(3872)

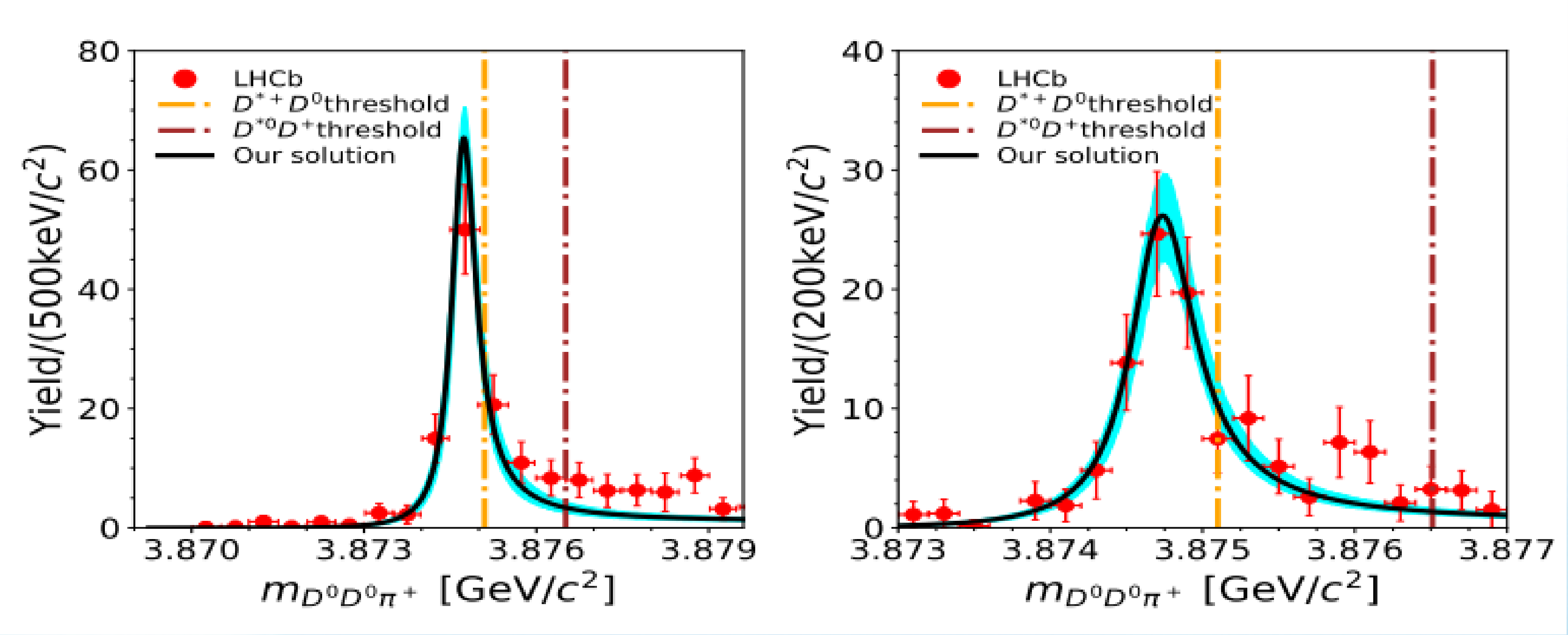
- Invariant mass spectra for X(3872)



They are not generated by triangle singularity!

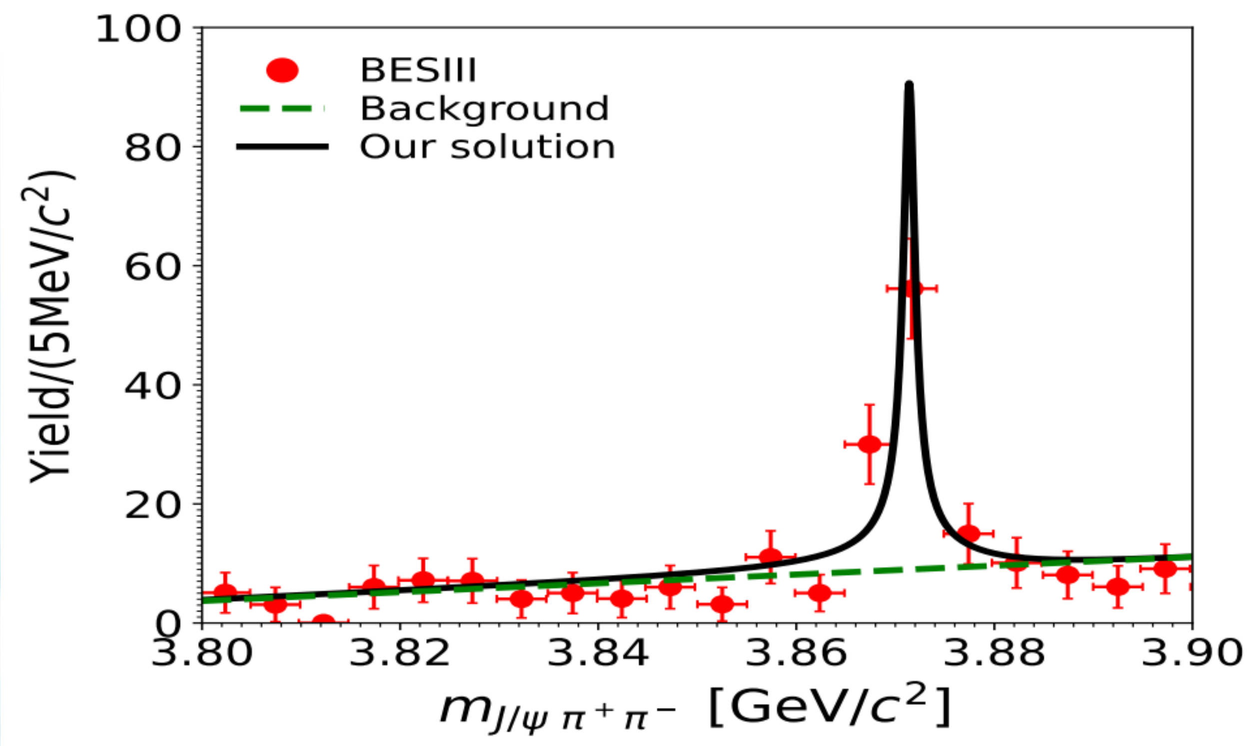
Fit results

- Invariant mass spectra of T_{cc}



X(3872)

- Prediction of J/ψππ invariant mass spectra



$$\mathscr{L}_{\chi_{c1}} = i\frac{g_J}{f_\pi^2}\epsilon^{\alpha\beta\mu\nu}\psi_\nu\chi_\mu^0(\partial_\beta\pi^-\partial_\alpha\pi^+ - \partial_\alpha\pi^-\partial_\beta\pi^+)$$

Pole loacttions

- Both of them locate below the thresholds

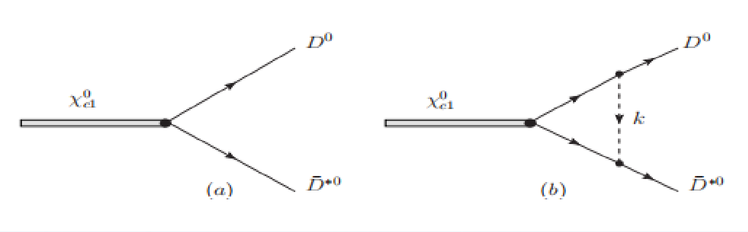
$$\Delta M = M_{T_{cc}^+} - (m_{D^0} + m_{D^{*+}}) = -342 \pm 55 \text{ keV}$$

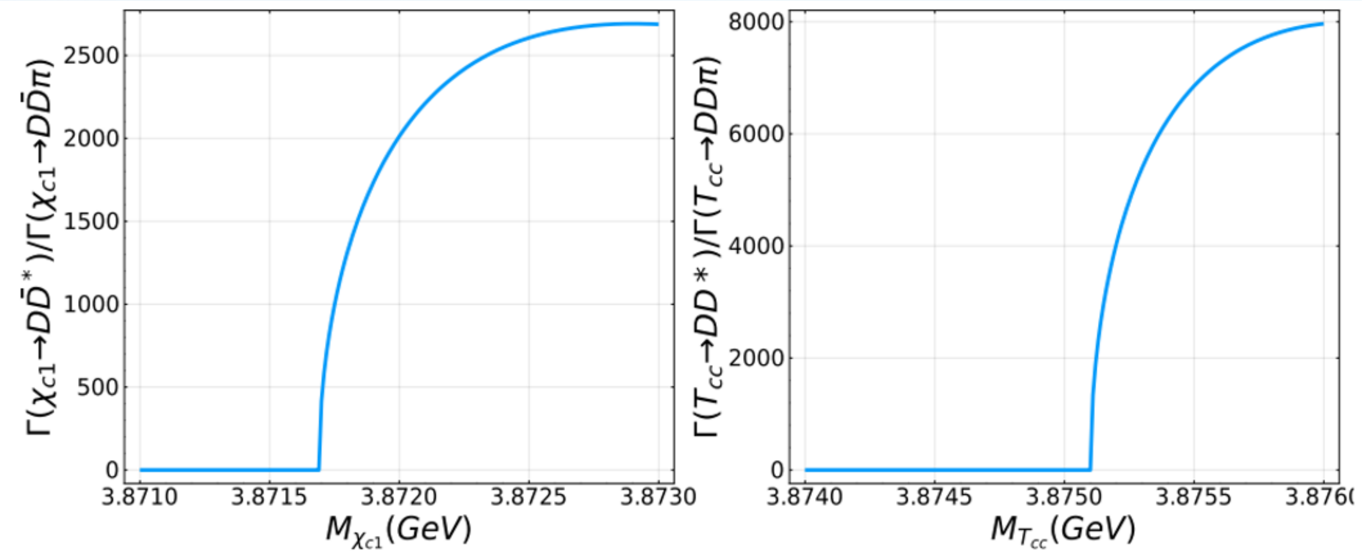
$$\Delta M = M_{\chi_{c1}^0} - (m_{D^0} + m_{\bar{D}^{*0}}) = -70 \pm 21 \text{ keV}$$

Parameters	T_{cc}^+	χ_{c1}^0
M (MeV)	3874.758 ± 0.055	3871.620 ± 0.021
Γ_{tot} (MeV)	0.541 ± 0.047	1.496 ± 0.084
g_x	2.12 ± 0.12	$\cdots$
$\tilde{g}_x$	$\cdots$	2.47 ± 0.75
$b_2(DD^*)(\text{GeV}^{-3})$	$\cdots$	619175 ± 145204
$b_3(D\bar{D}^*)(\text{GeV}^{-3})$	$\cdots$	175960 ± 73583
$\chi^2_{\text{d.o.f}}$	1.19	0.81

Mass

- If their masses are above the thresholds, the the $\Gamma(\chi_{c1} \to D\bar{D}^*)$ or $\Gamma(\mathrm{T}_{cc} \to DD^*)$ would have strong enhancement very close to the threshold.
  - Even much larger than the total widths!
- They should **below** the thresholds.





Partners of isovectors: X(3872)

- Most possible channels to discover them

$$\chi_{c1}^{\pm} \to D^0 \bar{D}^0 \pi^{\pm}$$

- Needs some luck!

- It is possible to find them!

$$X(3872) \to \pi^0 \chi_{c1}(1P)$$

$$\mathscr{B}(X(3872) \to \pi^0 \chi_{c1}) / \mathscr{B}(X(3872) \to \pi^+ \pi^- J/\psi) = 0.88^{+0.33}_{-0.27} \pm 0.10$$

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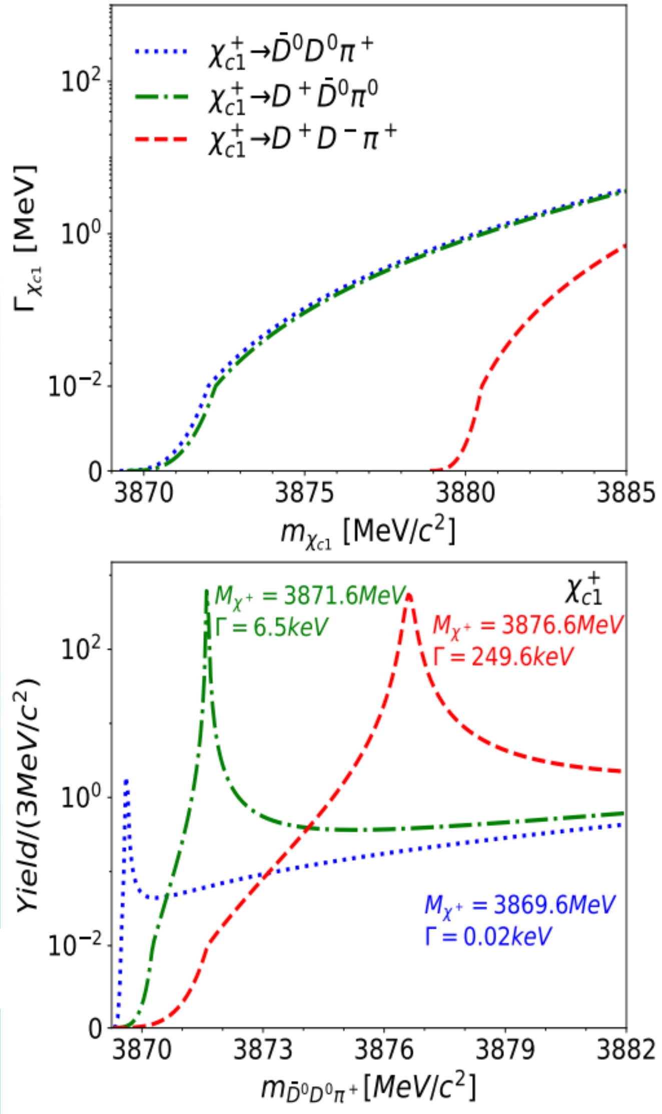
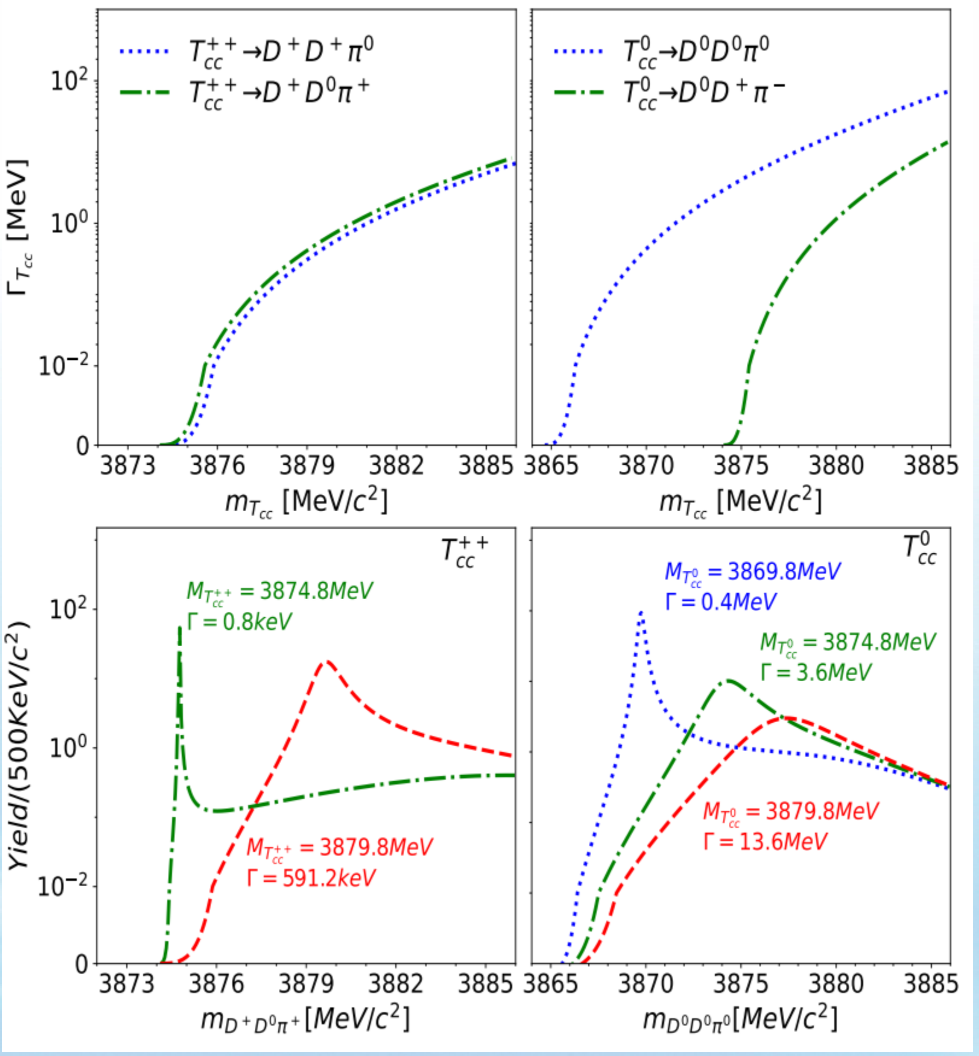


Partners of isovectors: T_{cc}

- Most possible channels to discover them

$$T_{cc}^{++} \to D^0 D^+ \pi^+,\ T_{cc}^0 \to D^0 D^0 \pi^0$$

- If the masses of the partners are too close to the threshold
  - their widths are rather small
  - need high statistics
- If too far away
  - their widths are large
  - get rid of the b.g.



Inner structure of X3872?

- Refit the amplitudes with K-matrix

$$T(s) = K(s)[1 - C(s)K(s)]^{-1} \qquad C_i(s) = \frac{s}{\pi}\int_{s_i}^{\infty} ds' \frac{\rho_i(s')}{s'(s'-s)}$$

- poles of X3872
  - RS-II: 3871.451 ± 0.010 –i 0.629 ± 0.004 MeV
  - RS-III: 3871.448 ± 0.011 –i 0.629±0.003

$c\bar{c}$+hadronic states?

- T_{cc}
  - RS-II: $3874.74^{+0.11}_{-0.04} - \mathrm{i}\ 0.30^{+0.05}_{-0.03}$

hadronic states?

A new method

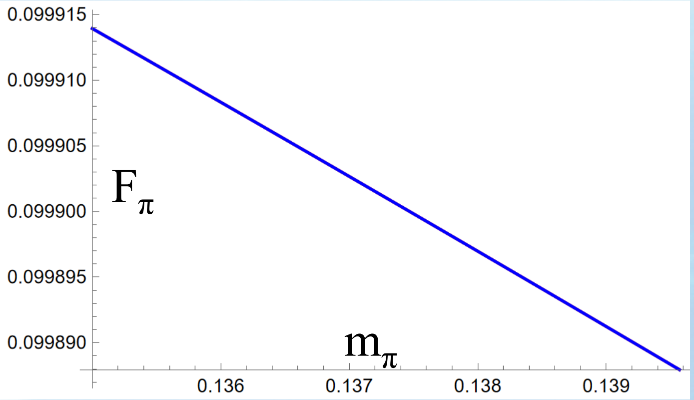
- A new method to study inner structure?
- The simplest way, satisfying intuition: For a molecule, its mass should increase/decrease as that of the constituent hadrons!
- How to make sure the trend of the amplitudes is right in unphysical region?
- In the physical region, constrained by data and also ensured by ChEFT.

$$
\begin{aligned}
\mathscr{L}_2 = \quad & \frac{f_0^2}{4}\langle \partial_\mu U^\dagger \partial^\mu U + \mathscr{M}(U + U^\dagger)\rangle, \\
\mathscr{L}_4 = \quad & L_1 \langle \partial_\mu U^\dagger \partial^\mu U\rangle^2 + L_2 \langle \partial_\mu U^\dagger \partial_\nu U\rangle \langle \partial^\mu U^\dagger \partial^\nu U\rangle \\
& + L_3 \langle \partial_\mu U^\dagger \partial^\mu U \partial_\nu U^\dagger \partial^\nu U\rangle + L_4 \langle \partial_\mu U^\dagger \partial^\mu U\rangle \langle U^\dagger \mathscr{M} + \mathscr{M}^\dagger U\rangle \\
& + L_5 \langle \partial_\mu U^\dagger \partial^\mu U (U^\dagger \mathscr{M} + \mathscr{M}^\dagger U)\rangle + L_6 \langle U^\dagger \mathscr{M} + \mathscr{M}^\dagger U\rangle^2 \\
& + L_7 \langle U^\dagger \mathscr{M} - \mathscr{M}^\dagger U\rangle^2 + L_8 \langle U^\dagger \mathscr{M} U^\dagger \mathscr{M} + \mathscr{M}^\dagger U \mathscr{M}^\dagger U\rangle,
\end{aligned}
$$

$$
\Phi(x) = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}
$$

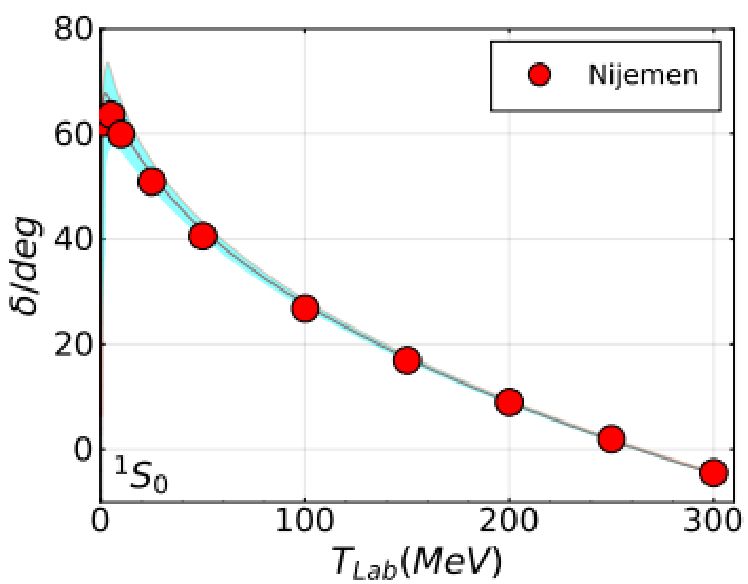
ChEFT

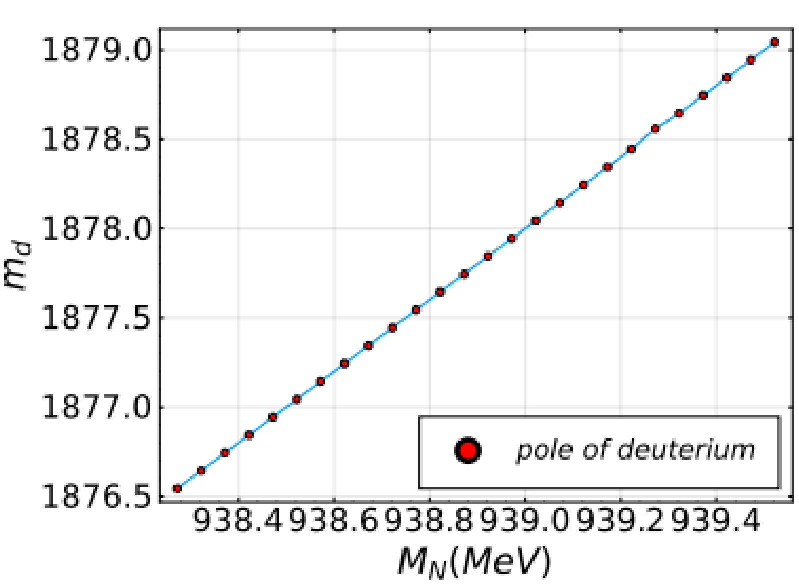
- Supplies dynamics
- Isospin symmetry: The mass difference between charged and neutral particles is ignored in ChEFT
- Describe the physics in low energy region successfully
- Isospin symmetry breking won't affect the couplings much!



deuteron

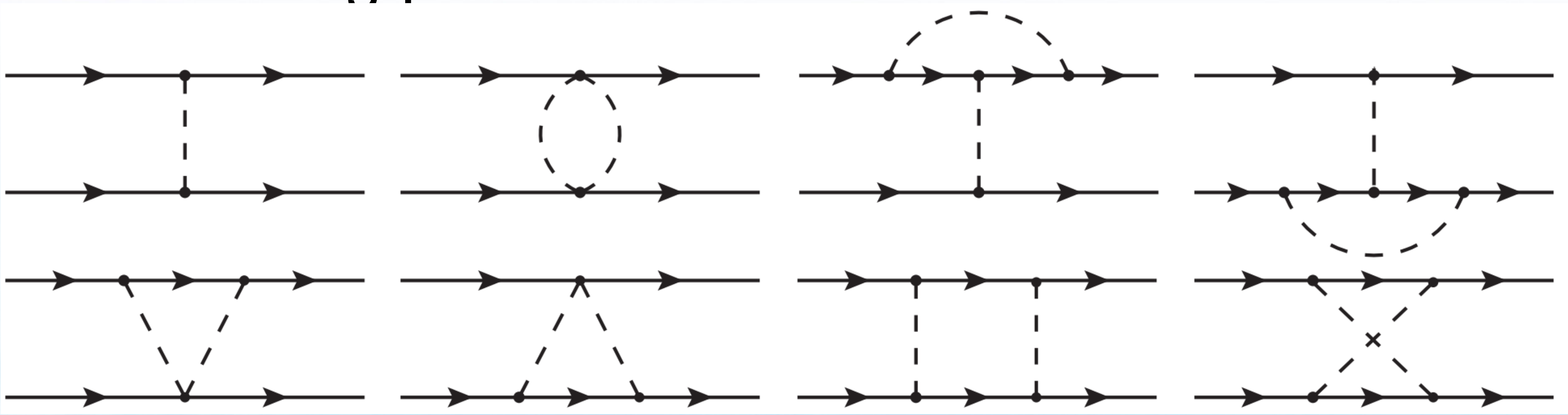
- Deuteron: Maybe the only undoubted molecule.
- Varying the masses within the range allowed by isospin symmetry. The amplitudes still fit rather well to the 'data'.
- Mass of deuteron increases as that of nucleons.





X3872?

- DD* scattering
- Long range interaction only?
- Searching poles



4、Summary

HQEFT

We propose a HQEFT to deal with the doublely charmed mesons coupling with D mesons

χ_{c1}, T_{cc}

The resonance parameters are extracted. Both of them should below the thresholds.

partners

The decay modes of their partners are predicted. The most possible channels to discover them are: $\chi_{c1}^{\pm} \to D^0 \bar{D}^0 \pi^{\pm}$

$T_{cc}^{++} \to D^0 D^+ \pi^+$, $T_{cc}^0 \to D^0 D^0 \pi^0$

Next?

Inner structures from EFT? Other resonances?

Thank You For your patience !