强子奇特态的一些重夸克有效场论研究

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第三届强子与重味物理
理论与实验联合研讨会

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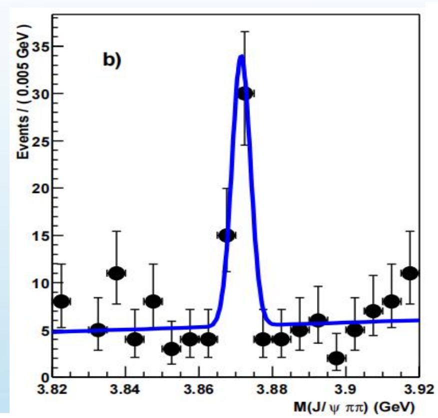
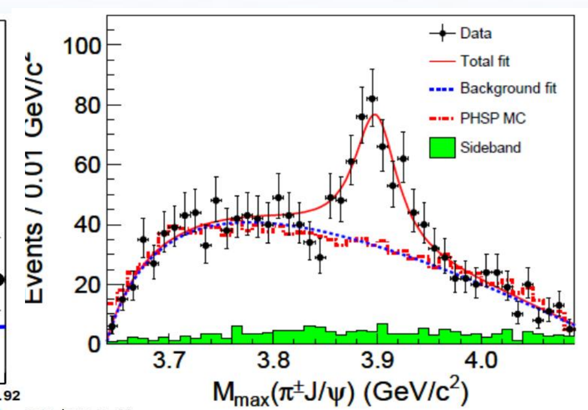
Outlines

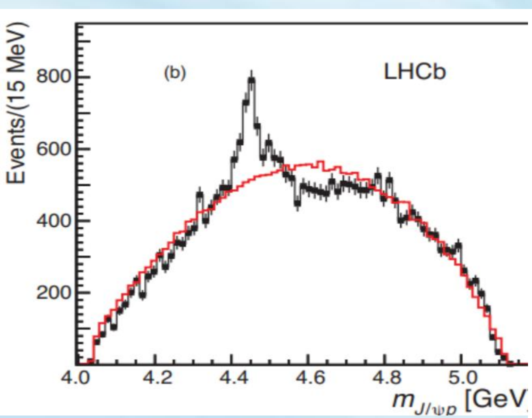
1. Introduction
2. Formalism
3. T_{cc} and X3872
4. Summary

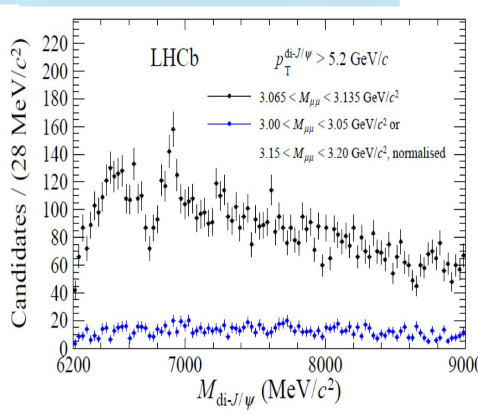
Introduction

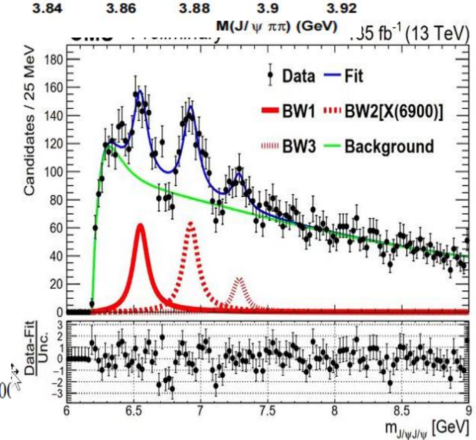
- X(3872) by Belle, in 2003
- Z_c(3900) by BESIII and Belle, in 2013
- P_c states by LHCb, in2015
- T_{cc}, X(6900)....
- Their nature?
  - Quantum number?
  - pole location?
  - The inner structure?

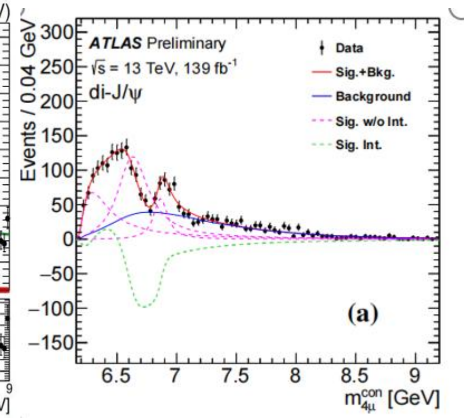












X3872 and T_{cc}^+

- Puzzle: are their masses below or above the threshold?

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

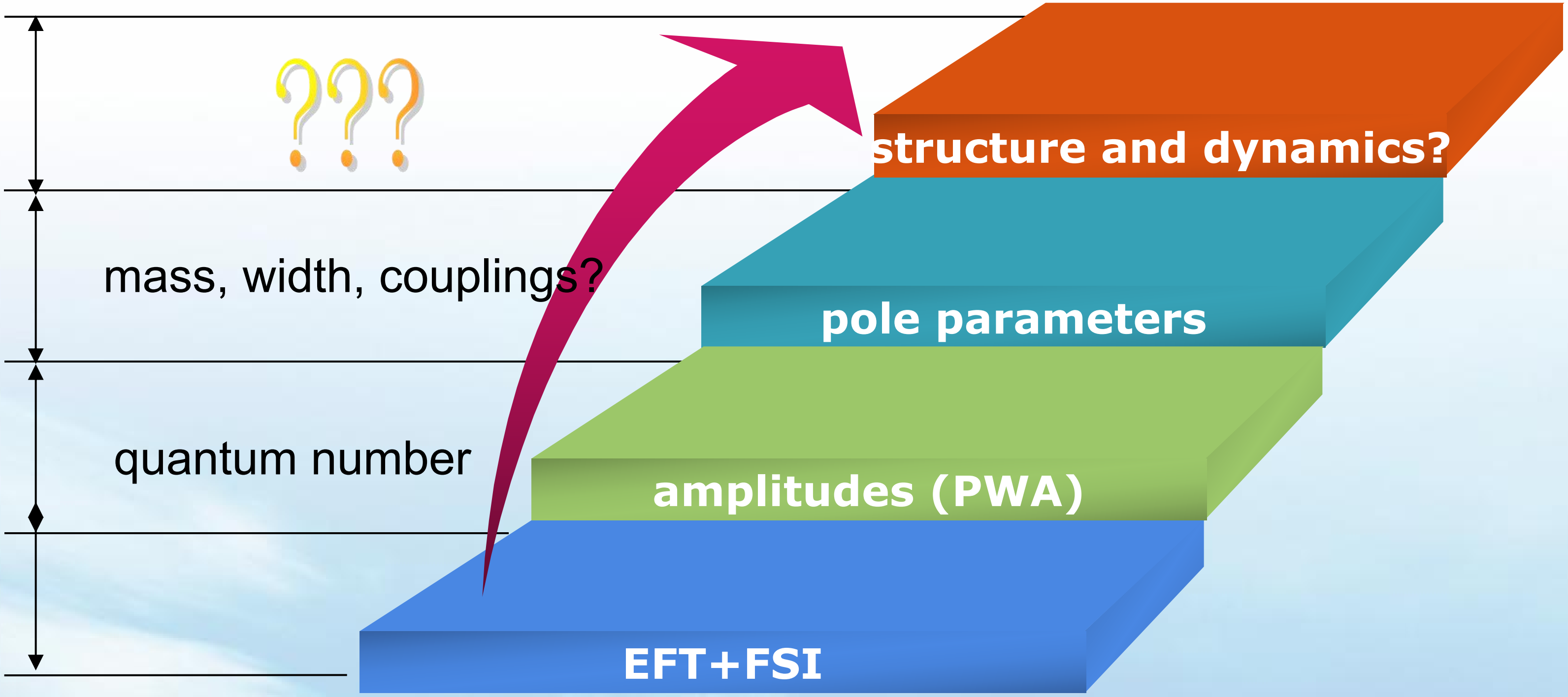
$$\Delta M = M_{T_{cc}^+} - (M_{D^{*+}} + M_{D^0}) = -237 \pm 61\ keV/c^2$$

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

- Charged partners?
  - not found yet

Strategy

- The property of the exotic states?



Formalism

HQEFT:

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

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

	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

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

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

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

$\chi_{c1}(3872)$	$c\bar{c}$	$u\bar{u}$	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
$\vdots$	$\vdots$	$\vdots$	$\vdots$

Isovector?

- It does not exclude the possibility of isovector.

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

- Lagrangians within HQEFT and chiral symmetry

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

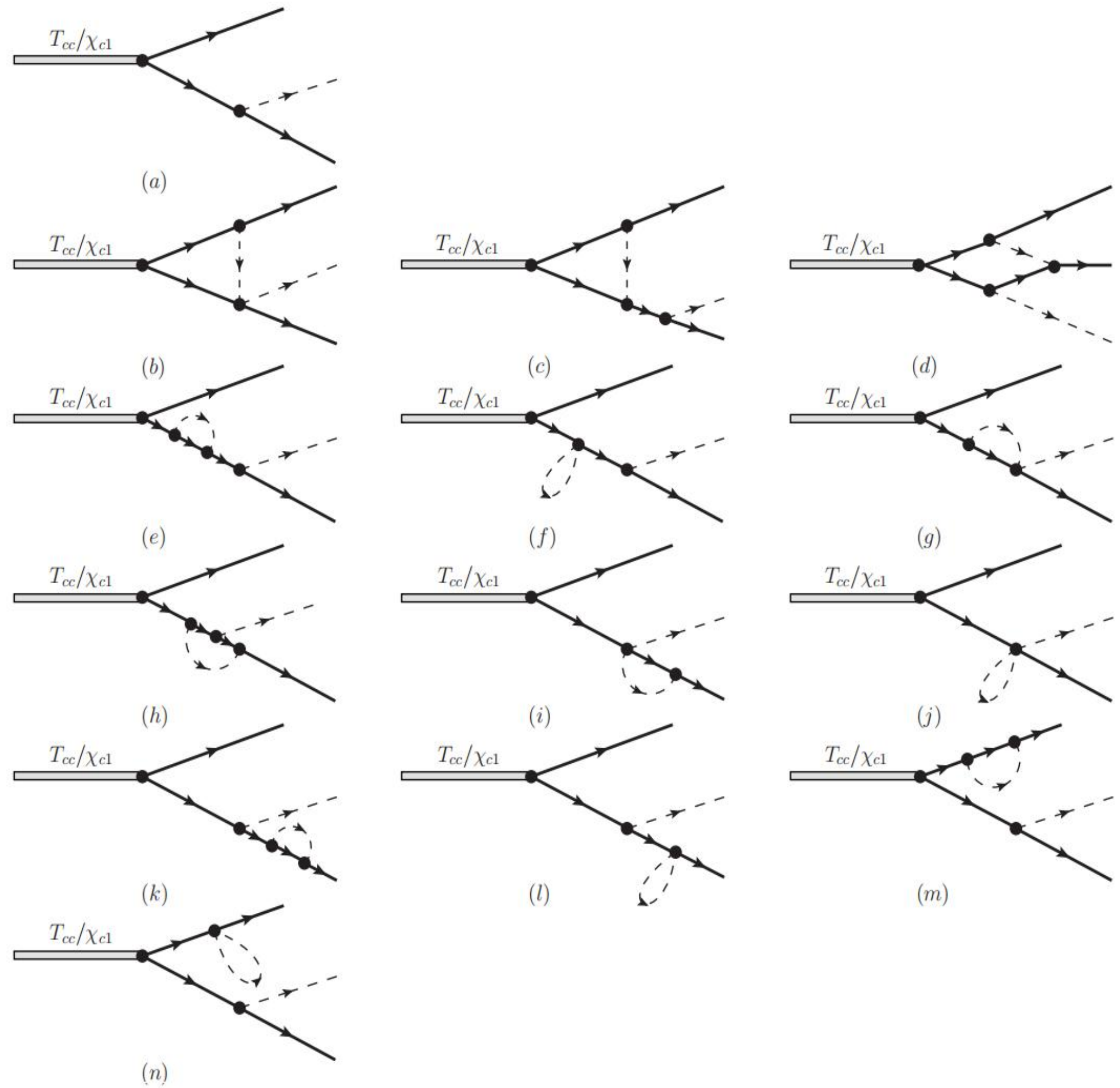
$$\begin{aligned} \mathcal{L}_{\chi_{c1}}^{\text{singlet}} &= i\, \tilde{g}_1 \epsilon_{\mu\nu\alpha\beta} v^\mu \chi_{c1}^\nu \langle \gamma^\nu \bar{\mathcal{H}}_a \, \frac{1-\not{v}}{2} \gamma^\mu \, \frac{1+\not{v}}{2} \mathcal{H}_a \rangle \\ &+ \tilde{g}_2 \Big(\langle \mathcal{H}_a \, \Gamma_1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

- Lagrangians between D and π mesons

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

Feynman daigrams

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

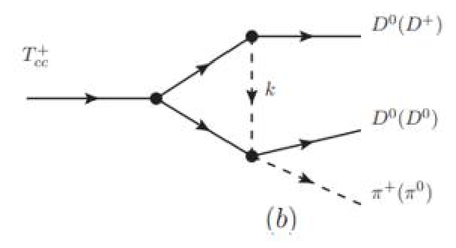


amplitudes

- Some examples

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

- This diagram is zero in the heavy quark limit



$$DD\pi v\cdot\partial\pi$$

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

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 $D\overline{D}^0\pi^0$ width and the Br from PDG

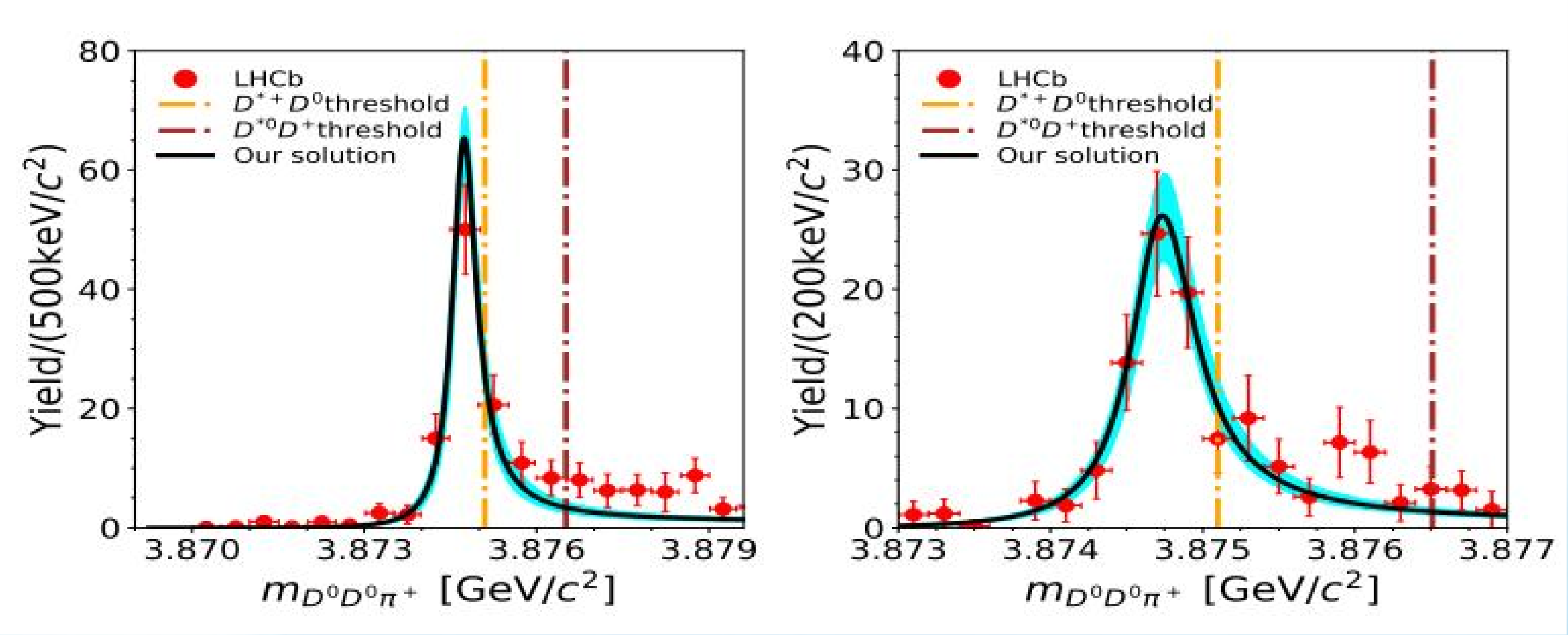
$$\Gamma^{tot}_{\chi^0_{c1}}(Q) = \frac{\Gamma^{(D^0\bar{D}^0\pi^0)}(Q)}{\mathrm{BR}(\chi^0_{c1} \to \mathrm{D}^0\bar{\mathrm{D}}^0\pi^0)}$$

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

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

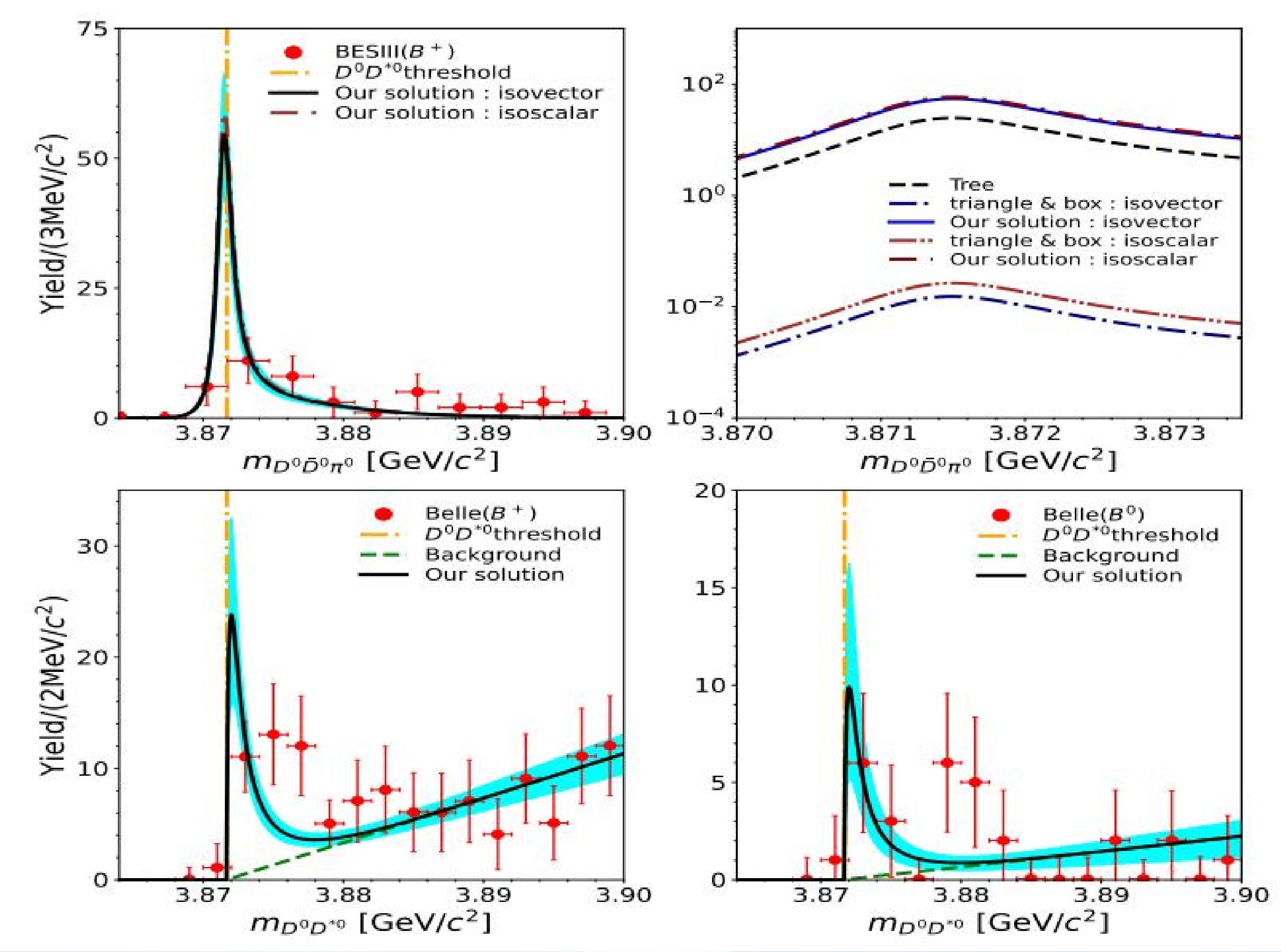
Fit results

- Invariant mass spectra of T_{cc}



X(3872)

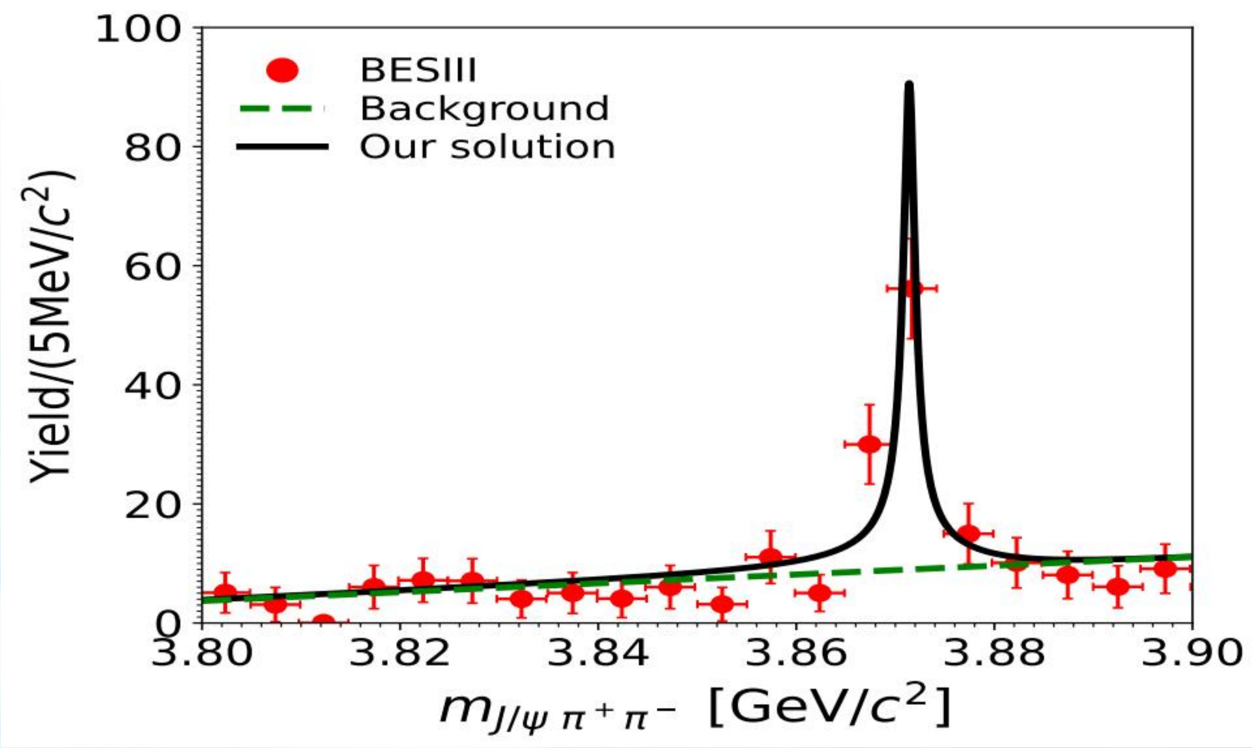
- Invariant mass spectra for X(3872)



They are not generated by triangle singularity!

X(3872)

- Prediction of J/ψππ invariant mass spectra



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

Pole loacttions

- Both of them locate below the thresholds

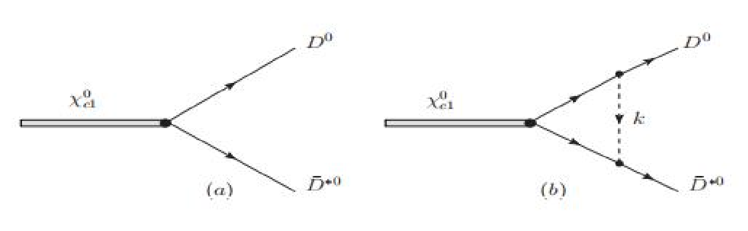
$$\Delta M = M_{T_{cc}^+} - (m_{D^0} + m_{D^{*+}}) = -342 \pm 55 \text{ keV}$$

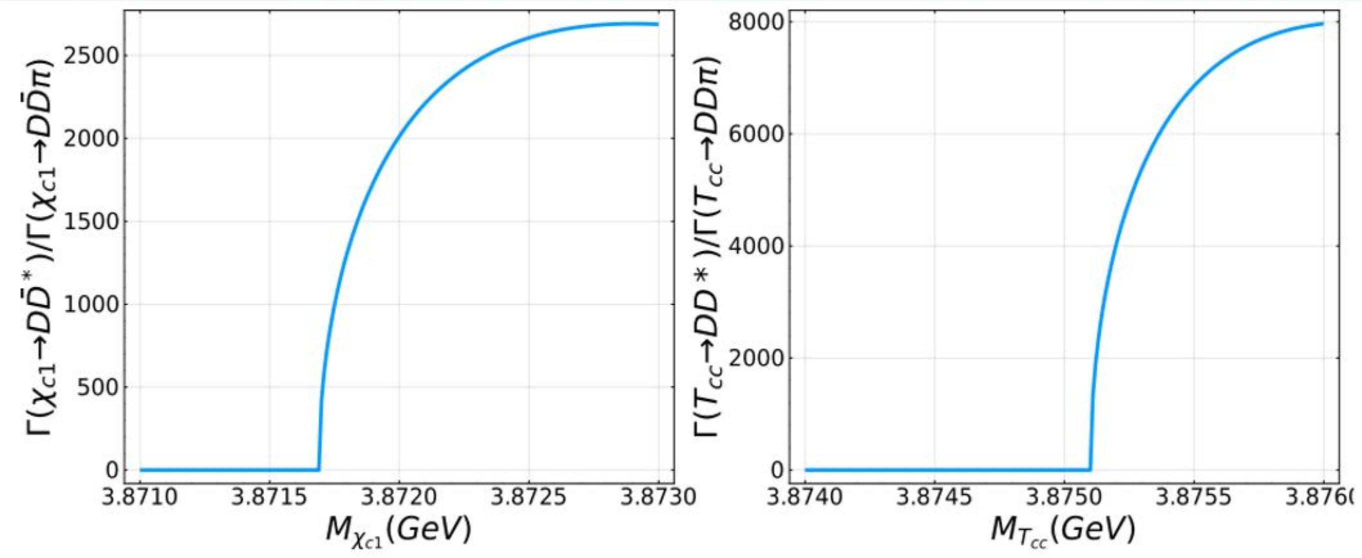
$$\Delta M = M_{\chi_{c1}^0} - (m_{D^0} + m_{\bar{D}^{*0}}) = -70 \pm 21 \text{ keV}$$

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	2.85 ± 0.12	$\cdots$
$\tilde{g}_x$	$\cdots$	2.53 ± 0.75
$b_2(D\bar{D}^*)(\text{GeV}^{-3})$	$\cdots$	604167 ± 145204
$b_3(D\bar{D}^*)(\text{GeV}^{-3})$	$\cdots$	172027 ± 73583
$\chi^2_{\text{d.o.f}}$	1.21	0.48

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.



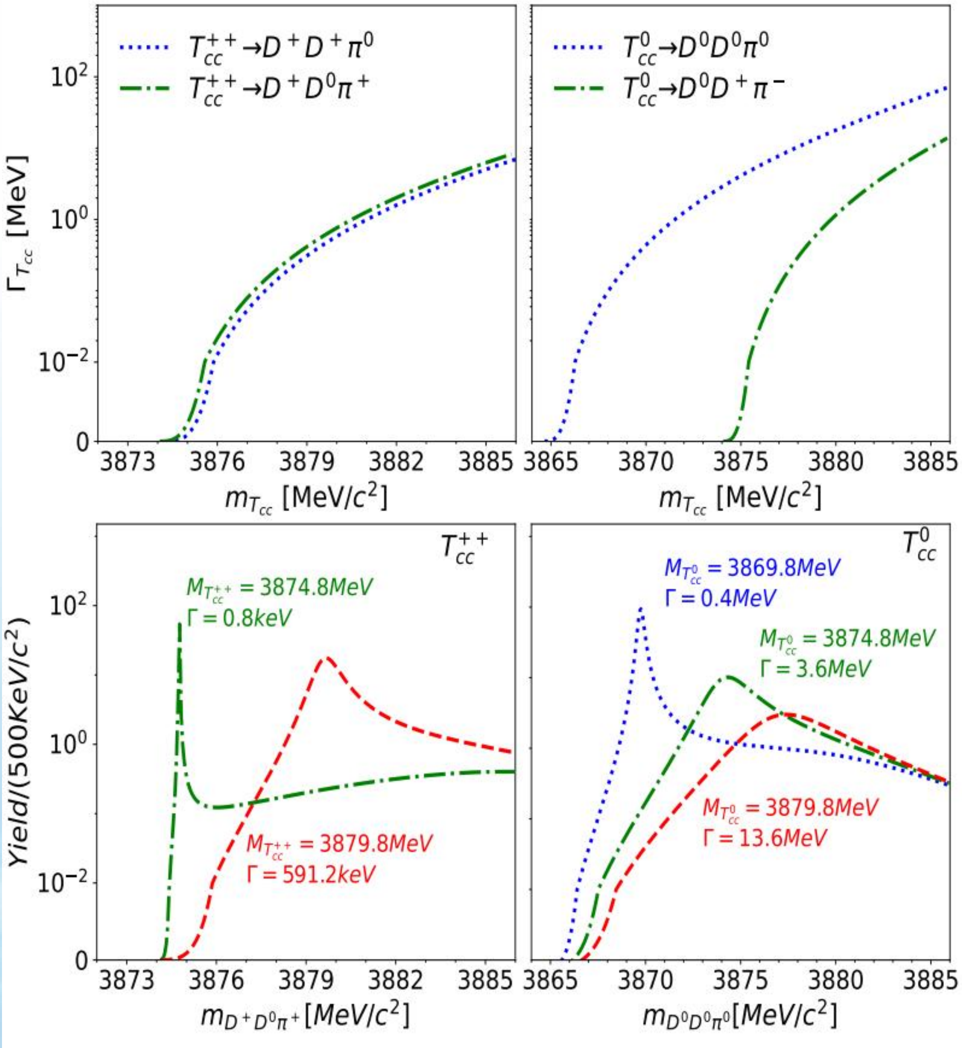


Partners of isovectors: T_{cc}

- 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 resolution
- If too far away
  - their widths are large
  - need high statistics



Partners of isovectors: X(3872)

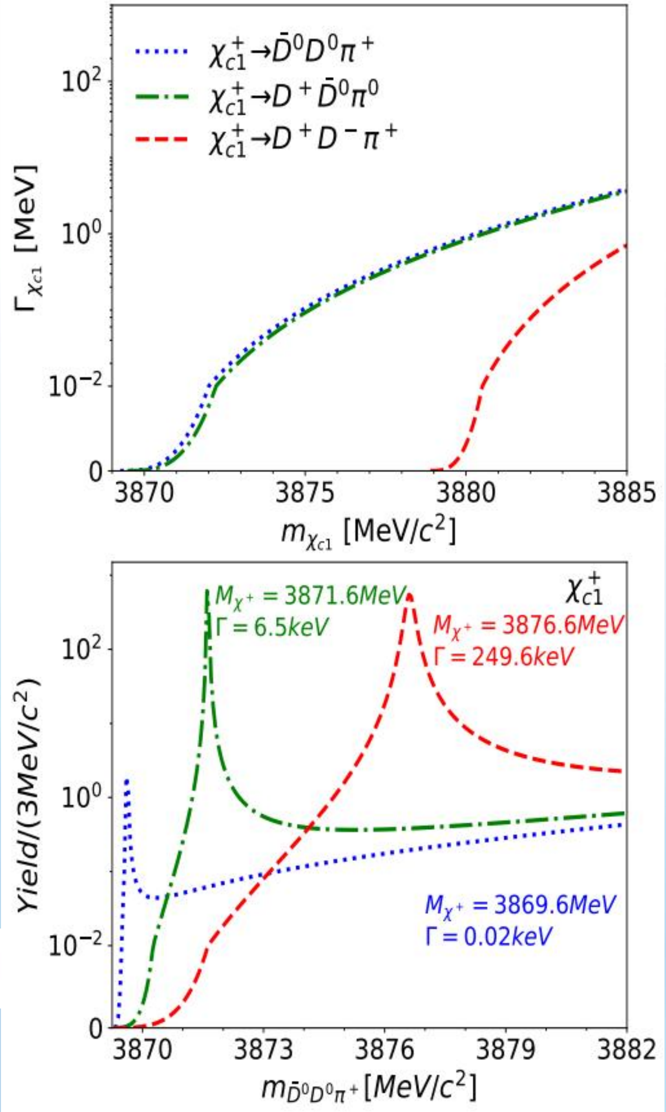
- Most possible channels to discover them

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

- 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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4、Summary

HQEFT

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

T_{cc}, χ_{c1}

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? Other resonances?

Thank You For your patience !