

T_{cc} 和 $X(3872)$ 研究

吴佳俊 (中国科学院大学)

合作者: 王广娟, 杨智, 朱世琳, Makoto Oka

[hep-ph] 2306.12406

第三届强子与重味物理理论与实验联合研讨会 2024.04.06 华中科技大学 武汉



中国科学院大学
University of Chinese Academy of Sciences



目录

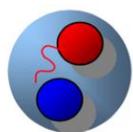
- 背景
- HEFT介绍, 单玻色子交换, 3P0模型
- T_{cc} 的产生
- X(3872)的性质
- 小结和展望



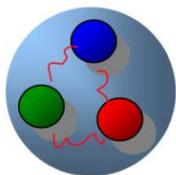
背景介绍

传统夸克模型

conventional hadron



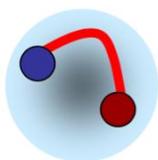
$(q \bar{q})$



(qqq)

奇特态

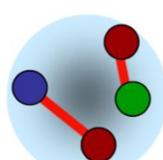
Hybrid



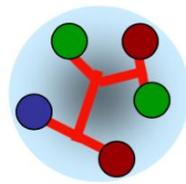
Glueball



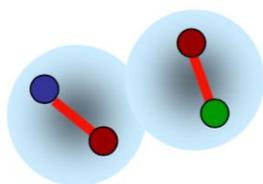
Tetraquark



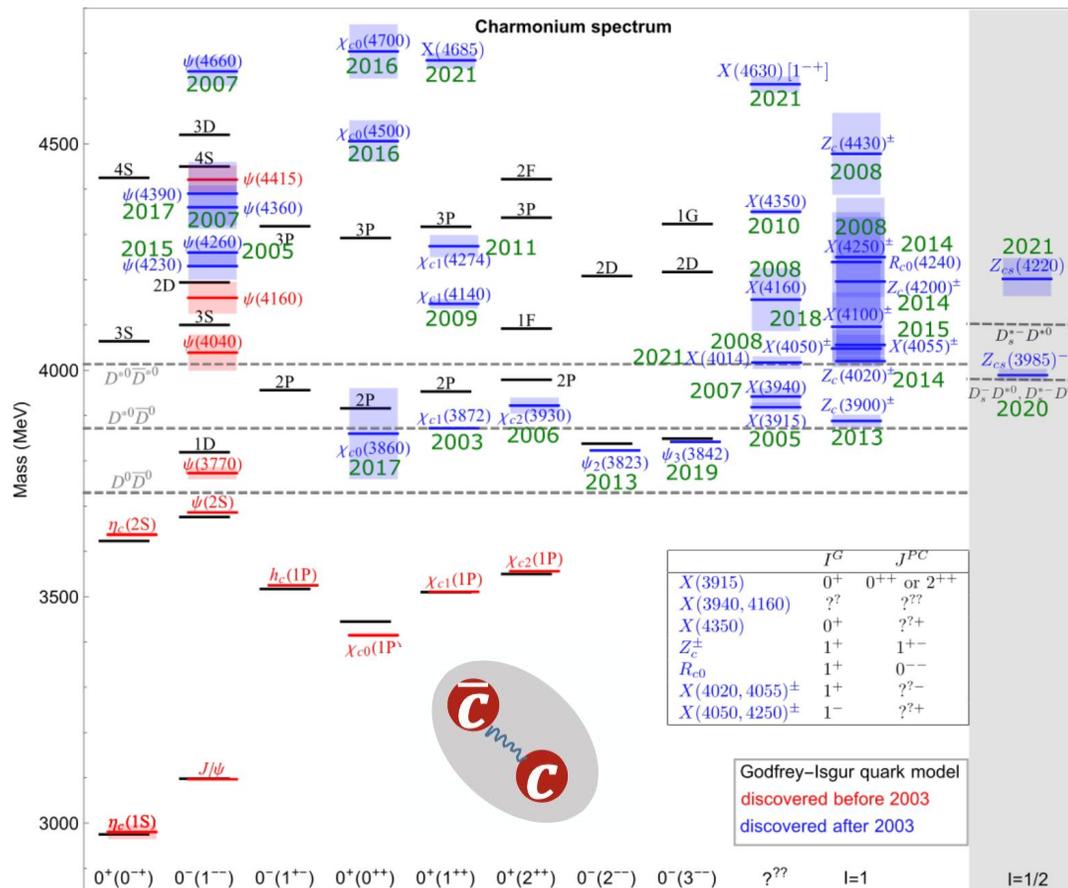
Pentaquark



Hadronic molecule



问题：对于一个强子而言，究竟是如何由这些可能的成分组成的？



背景介绍

问题：对于一个强子而言，究竟是如何由这些可能的成分组成的？

能够描述一系列强子，不是一个两个

相互作用的完整性

能够系统描述强子的较为完整的框架

夸克胶子层次

强子层次



背景介绍

问题：对于一个强子而言，究竟是如何由这些可能的成分组成的？

能够描述一系列强子，不是一个两个

相互作用的完整性

能够系统描述强子的较为完整的框架

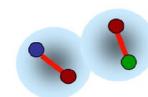
夸克胶子层次



$(q \bar{q})$

强子层次

Hadronic molecule



背景介绍

问题：对于一个强子而言，究竟是如何由这些可能的成分组成的？

能够描述一系列强子，不是一个两个

相互作用的完整性

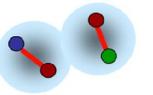
夸克胶子层次



(q q̄)

强子层次

Hadronic molecule



能够系统描述强子的较为完整的框架

$$H = H_0 + H_I = H_0 + \hat{g} + \hat{v}$$

$|B_i\rangle$ 裸态 \longleftrightarrow 夸克胶子层次

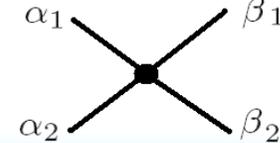
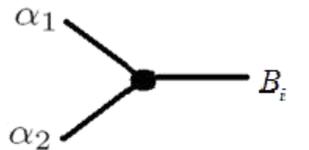
$|\alpha(k_\alpha)\rangle$ 无相互作用耦合道

\longleftrightarrow 强子层次

$$H_0 = \sum_{i=1,n} |B_i\rangle m_i \langle B_i| + \sum_{\alpha} |\alpha(k_\alpha)\rangle \left[\sqrt{m_{\alpha 1}^2 + k_\alpha^2} + \sqrt{m_{\alpha 2}^2 + k_\alpha^2} \right] \langle \alpha(k_\alpha)|$$

$$\hat{g} = \sum_{\alpha} \sum_{i=1,n} \left[|\alpha(k_\alpha)\rangle g_{i,\alpha}^+ \langle B_i| + |B_i\rangle g_{i,\alpha} \langle \alpha(k_\alpha)| \right]$$

$$\hat{v} = \sum_{\alpha,\beta} |\alpha(k_\alpha)\rangle v_{\alpha,\beta} \langle \beta(k_\beta)|$$

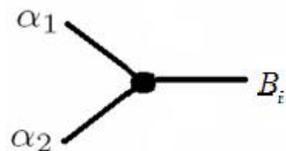


HEFT介绍

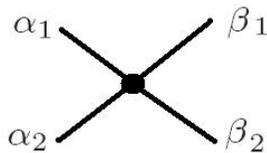
$$H = H_0 + H_I = H_0 + \hat{g} + \hat{v}$$

$$H_0 = \sum_{i=1,n} |B_i\rangle m_i \langle B_i| + \sum_{\alpha} |\alpha(k_{\alpha})\rangle \left[\sqrt{m_{\alpha 1}^2 + k_{\alpha}^2} + \sqrt{m_{\alpha 2}^2 + k_{\alpha}^2} \right] \langle \alpha(k_{\alpha})|$$

$$\hat{g} = \sum_{\alpha} \sum_{i=1,n} \left[|\alpha(k_{\alpha})\rangle g_{i,\alpha}^+ \langle B_i| + |B_i\rangle g_{i,\alpha} \langle \alpha(k_{\alpha})| \right]$$



$$\hat{v} = \sum_{\alpha,\beta} |\alpha(k_{\alpha})\rangle v_{\alpha,\beta} \langle \beta(k_{\beta})|$$



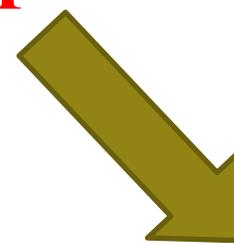
共振态
(质量, 宽度, 极点位置, 耦合强度)



HEFT



T 矩阵
(相移, 非弹
系数)



格点能谱

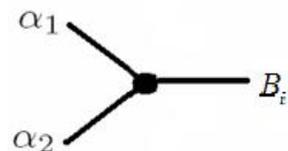


HEFT介绍

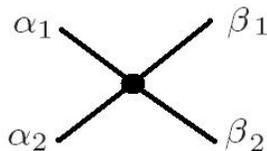
$$H = H_0 + H_I = H_0 + \hat{g} + \hat{v}$$

$$H_0 = \sum_{i=1,n} |B_i\rangle m_i \langle B_i| + \sum_{\alpha} |\alpha(k_{\alpha})\rangle \left[\sqrt{m_{\alpha 1}^2 + k_{\alpha}^2} + \sqrt{m_{\alpha 2}^2 + k_{\alpha}^2} \right] \langle \alpha(k_{\alpha})|$$

$$\hat{g} = \sum_{\alpha} \sum_{i=1,n} \left[|\alpha(k_{\alpha})\rangle g_{i,\alpha}^+ \langle B_i| + |B_i\rangle g_{i,\alpha} \langle \alpha(k_{\alpha})| \right]$$



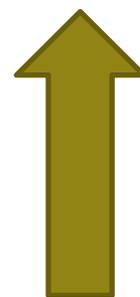
$$\hat{v} = \sum_{\alpha,\beta} |\alpha(k_{\alpha})\rangle v_{\alpha,\beta} \langle \beta(k_{\beta})|$$



**问题：两种相互作用怎么办？
a+b=5的解有太多了**

以T_{cc}和X(3872)给出方案

共振态
(质量, 宽度, 极点位置, 耦合强度)



HEFT



T 矩阵
(相移, 非弹性系数)



格点能谱

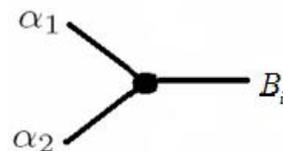


HEFT---3P0模型和单玻色子交换模型

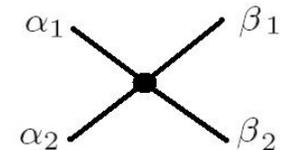
$$H_I = \hat{g} + \hat{v}$$

$$\hat{g} = \sum_{\alpha} \sum_{i=1,n} \left[|\alpha(k_{\alpha})\rangle g_{i,\alpha}^+ \langle B_i| + |B_i\rangle g_{i,\alpha} \langle \alpha(k_{\alpha})| \right]$$

$$\hat{v} = \sum_{\alpha,\beta} |\alpha(k_{\alpha})\rangle v_{\alpha,\beta} \langle \beta(k_{\beta})|$$

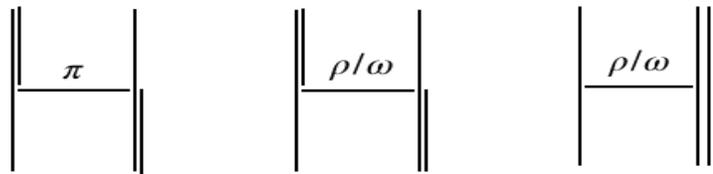


3P0模型，利用从夸克模型中得到的裸态波函数。



自主选择适当的模型

D介子和D*介子的相互作用,OBE



$$D^{(*)} D^{(*)} \quad H_a^{(Q)} = \frac{1+\not{v}}{2} [P_a^{*\mu} \gamma_{\mu} - P_a \gamma_5]$$

$$\bar{H}_a^{(Q)} \equiv \gamma_0 H_a^{(Q)\dagger} \gamma_0 = [P_a^{*\dagger\mu} \gamma_{\mu} + P_a^{\dagger} \gamma_5] \frac{1+\not{v}}{2}$$

$$P = (D^0, D^+, D_s^+) \& P^* = (D^{*0}, D^{*+}, D_s^{*+})$$

$$\mathcal{L}_{MH^{(Q)}H^{(Q)}} = ig \text{Tr} \left[H_b^{(Q)} \gamma_{\mu} \gamma_5 A_{ba}^{\mu} \bar{H}_a^{(Q)} \right]$$

$$\mathcal{L}_{VH^{(Q)}H^{(Q)}} = i\beta \text{Tr} \left[H_b^{(Q)} v_{\mu} (V_{ba}^{\mu} - \rho_{ba}^{\mu}) \bar{H}_a^{(Q)} \right] \\ + i\lambda \text{Tr} \left[H_b^{(Q)} \sigma_{\mu\nu} F^{\mu\nu}(\rho)_{ba} \bar{H}_a^{(Q)} \right]$$

$$H_a^{(\bar{Q})} \equiv C \left(\mathcal{C} H_a^{(Q)} \mathcal{C}^{-1} \right)^T C^{-1} = [P_{a\mu}^{(\bar{Q})*} \gamma^{\mu} - P_a^{(\bar{Q})} \gamma_5] \frac{1-\not{v}}{2} D^{(*)} \overline{D^{(*)}}$$

$$\bar{H}_a^{(\bar{Q})} \equiv \gamma_0 H_a^{(\bar{Q})\dagger} \gamma_0 = \frac{1-\not{v}}{2} [P_{a\mu}^{(\bar{Q})*\dagger} \gamma^{\mu} + P_a^{(\bar{Q})\dagger} \gamma_5]$$

$$\tilde{P} = (\bar{D}^0, D^-, D_s^-) \& \tilde{P}^* = (\bar{D}^{*0}, D^{*-}, D_s^{*-})$$

$$\mathcal{L}_{MH^{(\bar{Q})}H^{(\bar{Q})}} = ig \text{Tr} \left[\bar{H}_a^{(\bar{Q})} \gamma_{\mu} \gamma_5 A_{ab}^{\mu} H_b^{(\bar{Q})} \right]$$

$$\mathcal{L}_{VH^{(\bar{Q})}H^{(\bar{Q})}} = -i\beta \text{Tr} \left[\bar{H}_a^{(\bar{Q})} v_{\mu} (V_{ab}^{\mu} - \rho_{ab}^{\mu}) H_b^{(\bar{Q})} \right] \\ + i\lambda \text{Tr} \left[\bar{H}_a^{(\bar{Q})} \sigma_{\mu\nu} F^{\mu\nu}(\rho)_{ab} H_b^{(\bar{Q})} \right]$$

- $g = 0.57$ is determined by the strong decays $D^* \rightarrow D\pi$.
- undetermined λ & β .

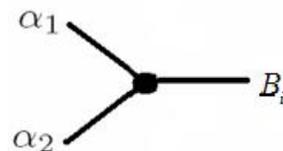


HEFT---3P0模型和单玻色子交换模型

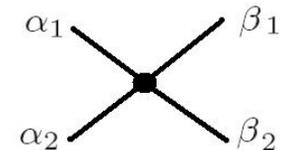
$$H_I = \hat{g} + \hat{v}$$

$$\hat{g} = \sum_{\alpha} \sum_{i=1,n} \left[|\alpha(k_{\alpha})\rangle g_{i,\alpha}^+ \langle B_i| + |B_i\rangle g_{i,\alpha} \langle \alpha(k_{\alpha})| \right]$$

$$\hat{v} = \sum_{\alpha,\beta} |\alpha(k_{\alpha})\rangle v_{\alpha,\beta} \langle \beta(k_{\beta})|$$

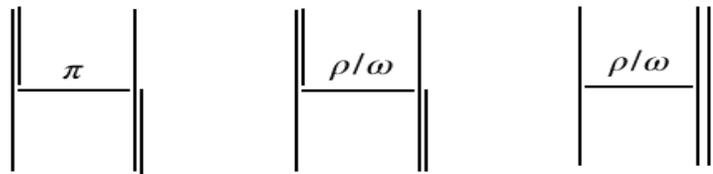


3P0模型，利用从夸克模型中得到的裸态波函数。



自主选择适当的模型

D介子和D*介子的相互作用,OBE



问题：两种相互作用怎么办？
a+b=5的解有太多了
用Tcc定v，研究X(3872)

$$D^{(*)}D^{(*)} \quad H_a^{(Q)} = \frac{1+\not{v}}{2} [P_a^{*\mu} \gamma_{\mu} - P_a \gamma_5]$$

$$\bar{H}_a^{(Q)} \equiv \gamma_0 H_a^{(Q)\dagger} \gamma_0 = [P_a^{*\dagger \mu} \gamma_{\mu} + P_a^{\dagger} \gamma_5] \frac{1+\not{v}}{2}$$

$$P = (D^0, D^+, D_s^+) \& P^* = (D^{*0}, D^{*+}, D_s^{*+})$$

$$\mathcal{L}_{MH^{(Q)}H^{(Q)}} = ig \text{Tr} [H_b^{(Q)} \gamma_{\mu} \gamma_5 A_{ba}^{\mu} \bar{H}_a^{(Q)}]$$

$$\mathcal{L}_{VH^{(Q)}H^{(Q)}} = i\beta \text{Tr} [H_b^{(Q)} v_{\mu} (V_{ba}^{\mu} - \rho_{ba}^{\mu}) \bar{H}_a^{(Q)}]$$

$$+ i\lambda \text{Tr} [H_b^{(Q)} \sigma_{\mu\nu} F^{\mu\nu}(\rho)_{ba} \bar{H}_a^{(Q)}]$$

$$H_a^{(\bar{Q})} \equiv C (CH_a^{(Q)} C^{-1})^T C^{-1} = [P_{a\mu}^{(\bar{Q})*} \gamma^{\mu} - P_a^{(\bar{Q})} \gamma_5] \frac{1-\not{v}}{2} D^{(*)} \overline{D^{(*)}}$$

$$\bar{H}_a^{(\bar{Q})} \equiv \gamma_0 H_a^{(\bar{Q})\dagger} \gamma_0 = \frac{1-\not{v}}{2} [P_{a\mu}^{(\bar{Q})* \dagger} \gamma^{\mu} + P_a^{(\bar{Q}) \dagger} \gamma_5]$$

$$\bar{P} = (\bar{D}^0, D^-, D_s^-) \& \bar{P}^* = (\bar{D}^{*0}, D^{*-}, D_s^{*-})$$

$$\mathcal{L}_{MH^{(\bar{Q})}H^{(\bar{Q})}} = ig \text{Tr} [\bar{H}_a^{(\bar{Q})} \gamma_{\mu} \gamma_5 A_{ab}^{\mu} H_b^{(\bar{Q})}]$$

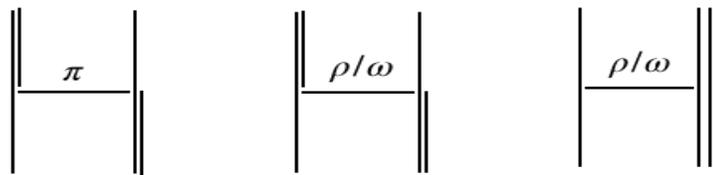
$$\mathcal{L}_{VH^{(\bar{Q})}H^{(\bar{Q})}} = -i\beta \text{Tr} [\bar{H}_a^{(\bar{Q})} v_{\mu} (V_{ab}^{\mu} - \rho_{ab}^{\mu}) H_b^{(\bar{Q})}]$$

$$+ i\lambda \text{Tr} [\bar{H}_a^{(\bar{Q})} \sigma_{\mu\nu} F^{\mu\nu}(\rho) H_b^{(\bar{Q})}]$$

- $g = 0.57$ is determined by the strong decays $D^* \rightarrow D\pi$.
- undetermined $\lambda \& \beta$.

HEFT---单玻色子交换模型

D介子和D*介子的相互作用,OBE



$$V_\pi = \frac{g^2}{f_\pi^2} \frac{(q \cdot \epsilon_\lambda)(q \cdot \epsilon_{\lambda'}^\dagger)}{q^2 - m_\pi^2},$$

$$V_{\rho/\omega}^u = -2\lambda^2 g_V^2 \frac{(\epsilon_{\lambda'}^\dagger \cdot q)(\epsilon_\lambda \cdot q) - q^2 (\epsilon_\lambda \cdot \epsilon_{\lambda'}^\dagger)}{q^2 - m_{\rho/\omega}^2},$$

$$V_{\rho/\omega}^t = \frac{\beta^2 g_V^2}{2} \frac{(\epsilon_\lambda \cdot \epsilon_{\lambda'}^\dagger)}{q^2 - m_{\rho/\omega}^2}.$$

仅考虑s波, 分波后的势能

$$\mathcal{V}(l, l', S, j) = \frac{1}{(2\pi)^3} \sqrt{\frac{1}{2E_D^i 2E_D^f 2E_K^i 2E_K^f}} 2\pi \int d\cos\theta V^v(\vec{p}_f, \vec{p}_i) \left(\frac{\Lambda^2}{\Lambda^2 + p_f^2}\right)^2 \left(\frac{\Lambda^2}{\Lambda^2 + p_i^2}\right)^2$$

一共三个参数, β , λ 和 Λ 。

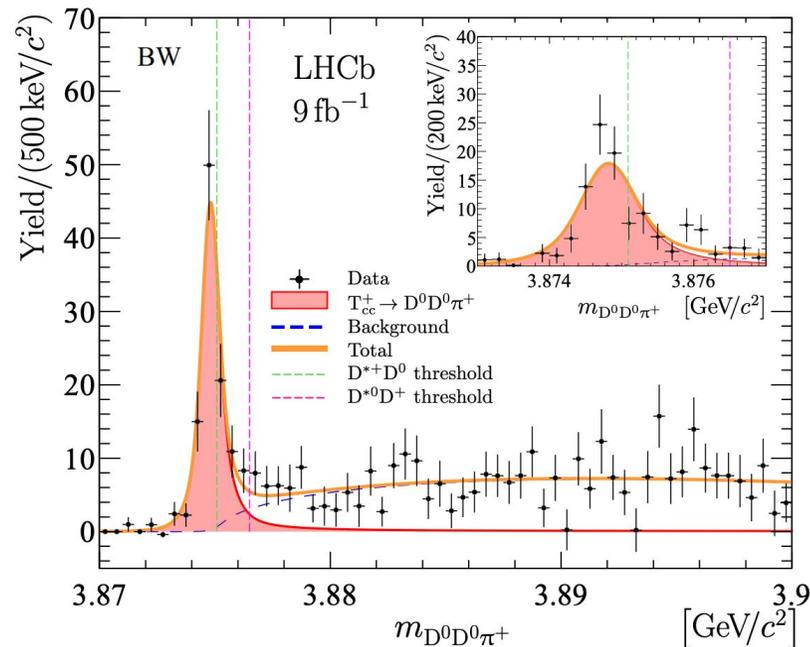
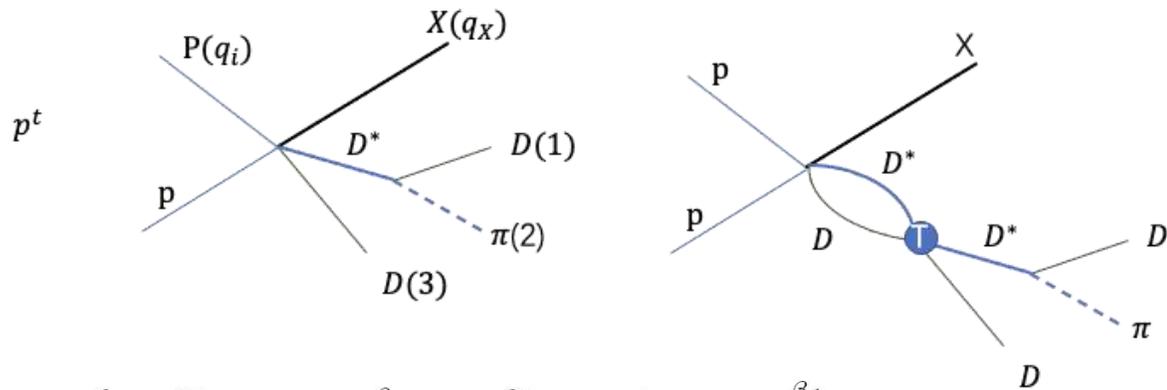
	wave function	$I(J^{PC})$	u -channel: π	u -channel: ρ/ω	t -channel: ρ/ω
DD^*	$\frac{1}{\sqrt{2}}(D^+D^{*0} - D^0D^{*+})$	$0(1^+) [T_{cc}^+]$	$\frac{3}{2}V_\pi$	$\frac{3}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t + \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}(D^+D^{*0} + D^0D^{*+})$	$1(1^+)$	$\frac{1}{2}V_\pi$	$\frac{1}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t + \frac{1}{2}V_\omega^t$
DD^*	$\frac{1}{\sqrt{2}}([D^+D^{*-}] + [D^0\bar{D}^{*0}])$	$0(1^{++})[X(3872)]$	$\frac{3}{2}V_\pi$	$-\frac{3}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}([D^+D^{*-}] - [D^0\bar{D}^{*0}])$	$1(1^{++})$	$-\frac{1}{2}V_\pi$	$\frac{1}{2}V_\rho^u - \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}(\{D^+D^{*-}\} + \{D^0\bar{D}^{*0}\})$	$0(1^{+-})[h_c]$	$-\frac{3}{2}V_\pi$	$\frac{3}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$-\frac{3}{2}V_\rho^t - \frac{1}{2}V_\omega^t$
	$\frac{1}{\sqrt{2}}(\{D^+D^{*-}\} - \{D^0\bar{D}^{*0}\})$	$1(1^{+-}) [Z_c(3900)]$	$\frac{1}{2}V_\pi$	$-\frac{1}{2}V_\rho^u + \frac{1}{2}V_\omega^u$	$\frac{1}{2}V_\rho^t - \frac{1}{2}V_\omega^t$

由于不同电荷态的质量不同会有同位旋破坏, 因此我们随后的计算是按照粒子的物理态来计算的。



T_{cc} 的产生

$$pp \rightarrow X D^0 D^0 \pi^+$$



$$t_{\alpha,\beta} = V_{\alpha,\beta} + \sum_{\gamma} V_{\alpha,\gamma} \frac{1}{E - \sqrt{m_{\gamma_1}^2 + k_{\gamma}^2} - \sqrt{m_{\gamma_2}^2 + k_{\gamma}^2} + i\epsilon} t_{\gamma,\beta}$$

$$t_{\alpha,\beta}(k_{\alpha}, k_{\beta}, E) = V_{\alpha,\beta}(k_{\alpha}, k_{\beta}) + \sum_{\gamma} \int k_{\gamma}^2 dk_{\gamma} \frac{V_{\alpha,\gamma}(k_{\alpha}, k_{\gamma}) t_{\gamma,\beta}(k_{\gamma}, k_{\beta}, E)}{E - \sqrt{m_{\gamma_1}^2 + k_{\gamma}^2} - \sqrt{m_{\gamma_2}^2 + k_{\gamma}^2} + i\epsilon}$$

$$|\mathcal{M}|^2 = |a_{pp \rightarrow DD^* X}|^2 \sum_{\lambda_X} \epsilon_{\mu}(p_X, \lambda_X) \epsilon_{\mu'}^{\dagger}(p_X, \lambda_X) \sum_j \mathcal{B}_{j\mu} \mathcal{B}_{j\mu'}^{\dagger}$$

$$\mathcal{B}_j^{\mu}(p_{12}, p_{23}) = g \left\{ \frac{-i(p_{\pi}^{\mu} - \frac{p_{12}^{\mu} p_{12} \cdot p_{\pi}}{m_{D^*}^2})}{p_{12}^2 - m_{D^*}^2 + im_{D^*} \Gamma_{D^*}} \right\}_j + \sum_{i=1,2} ig \left\{ \int dq_{D^*} q_{D^*}^2 \frac{d\Omega_{q_{D^*}}}{4\pi} \frac{\sqrt{2w_{D_2}}}{\sqrt{2w_{D^*}}} \frac{\sqrt{2w_{D_{12}^*}}}{\sqrt{2w_D}} \frac{T_{ij}^{J00}(M, |q_{D^*}|, |p_{12}|)}{(M - w_{D^*}^i) - w_D^i + i\epsilon} \frac{\epsilon_a^{*\mu}(w_{D^*}, q_{D^*}) \epsilon_a(p_{12}) \cdot p_{\pi}}{p_{12}^2 - m_{D^*}^2 + im_{D^*} \Gamma_{D^*}} \right\}_j + (p_{D_1} \rightarrow p_{D_2})$$

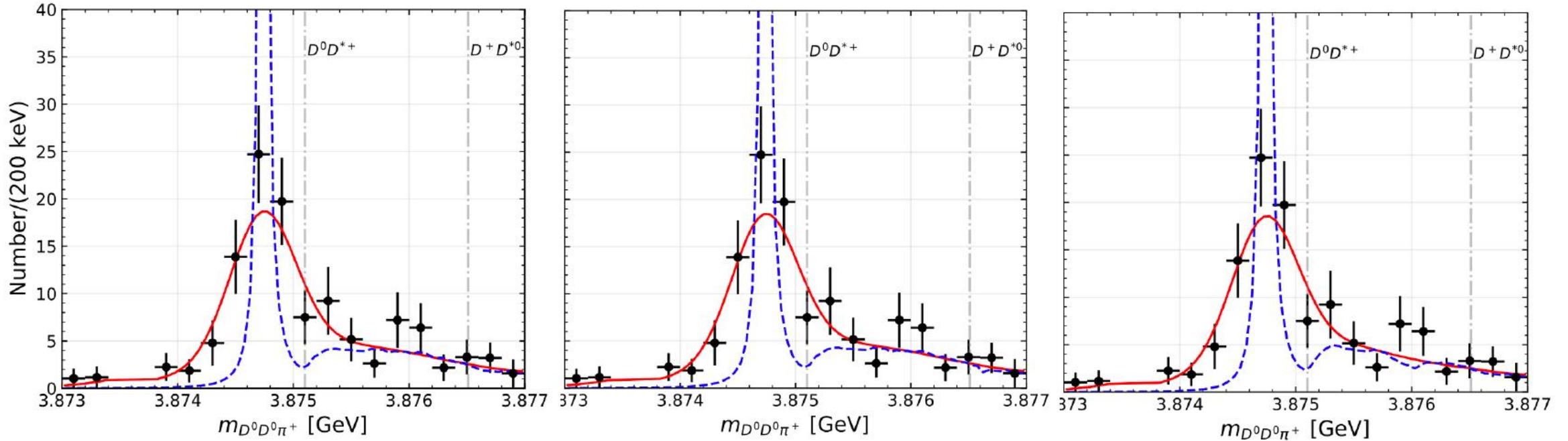


T_{cc} 的产生

$$pp \rightarrow X D^0 D^0 \pi^+$$

$\Lambda(\text{fixed})$	$\lambda (/ \text{GeV})$	β
0.8 GeV	0.890 ± 0.20	0.810 ± 0.11
1 GeV	0.683 ± 0.025	0.687 ± 0.017
1.2 GeV	0.587 ± 0.21	0.550 ± 0.12
1.17 GeV	0.56	0.9

Cheng, et al. PRD 106,016012



Λ (GeV)	BE (keV)	Γ (keV)	$\sqrt{\langle r^2 \rangle}$	$I = 0$	$I = 1$	$P(D^0 D^{*+})$	$P(D^+ D^{*0})$	$\frac{\text{Res}(D^0 D^{*+})}{\text{Res}(D^+ D^{*0})}$
0.8	-387.7	67.3	4.8 fm	95.8%	4.2%	70.0%	30.0%	$-1.063 + 0.001I$
1.0	-393.0	70.4	4.7 fm	95.8%	4.2%	70.0%	30.0%	$-1.055 + 0.001I$
1.2	-391.6	72.7	4.7 fm	95.7%	4.3%	70.3%	29.7%	$-1.052 + 0.001I$

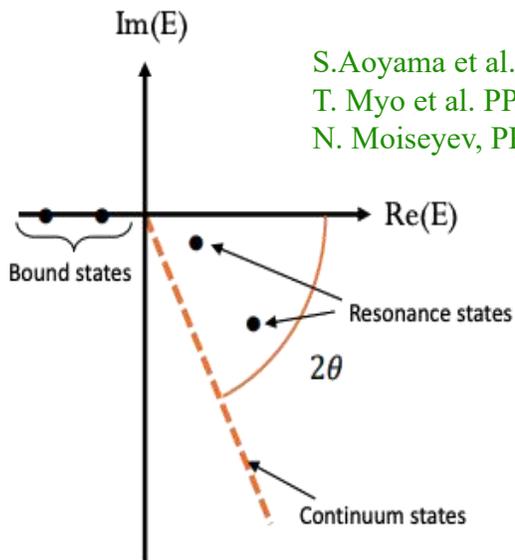


T_{cc} 的性质

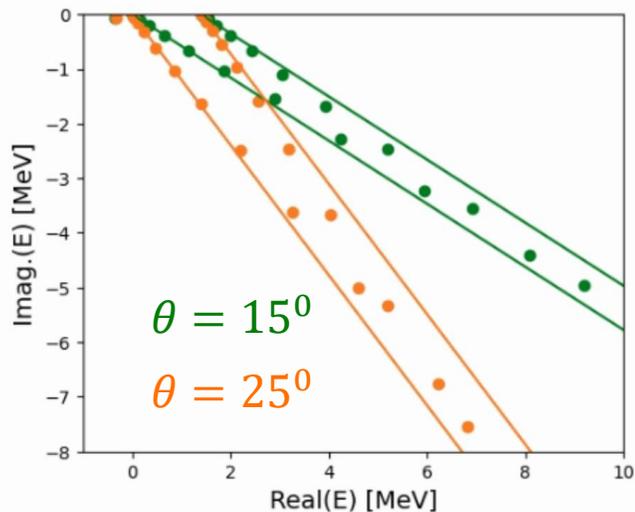
Complex scaling method

$$\mathbf{r} \rightarrow \mathbf{r}e^{i\theta}, \quad \mathbf{q} \rightarrow \mathbf{q}e^{-i\theta} \quad H_\theta \Phi_\theta = E_\theta \Phi_\theta,$$

$$\left[\begin{array}{l} \overline{D^{*0}}D^0 / \overline{D^0}D^{*0} \\ \dots \\ D^{*-}D^+ / D^{*+}D^- \end{array} \right. \text{Coupled-channel effect}$$



S.Aoyama et al. PTP. 116, 1 (2006).
T. Myo et al. PPNP. 79, 1 (2014)
N. Moiseyev, PR 302, 212 (1998)



• 束缚态

$$m_{T_{cc}} = 3874.7 \text{ MeV},$$

$$\Delta E = -393 \text{ keV}$$

$$\Gamma_{T_{cc}} = 70.4 \text{ keV}$$

$$\bullet \sqrt{\langle r^2 \rangle} = 4.7 \text{ fm}$$

$$\bullet 70.0\% D^{*+}D^0, \quad 30.0\% D^+D^{*0}$$

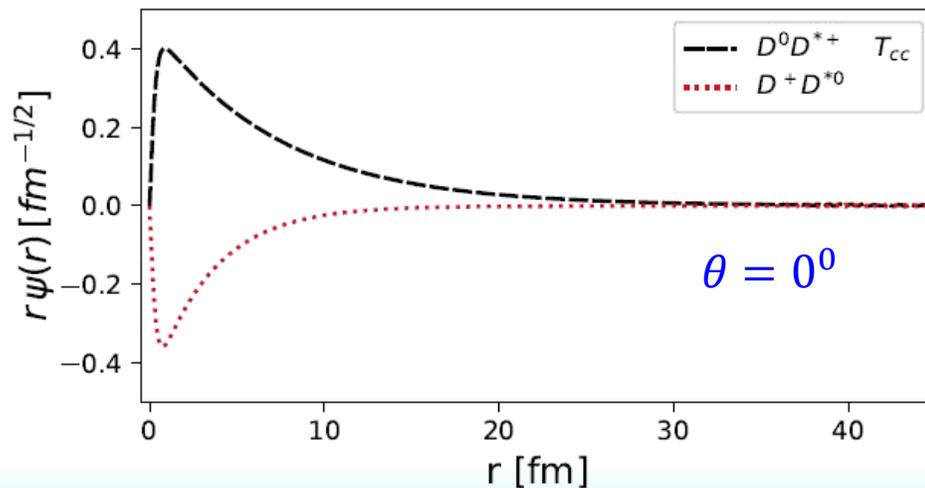
$$95.8\%, DD^*(I = 0)$$

$$4.2\% DD^*(I = 1)$$

两个道的质量不同

$$[I = 0] = \frac{1}{\sqrt{2}}(D^{*+}D^0 - D^{*0}D^+)$$

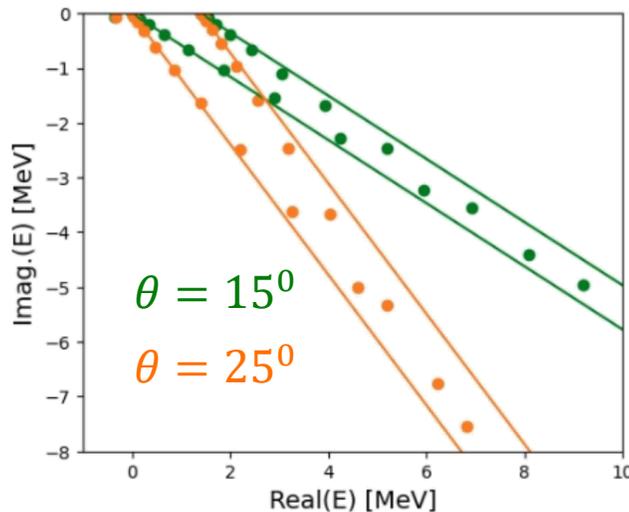
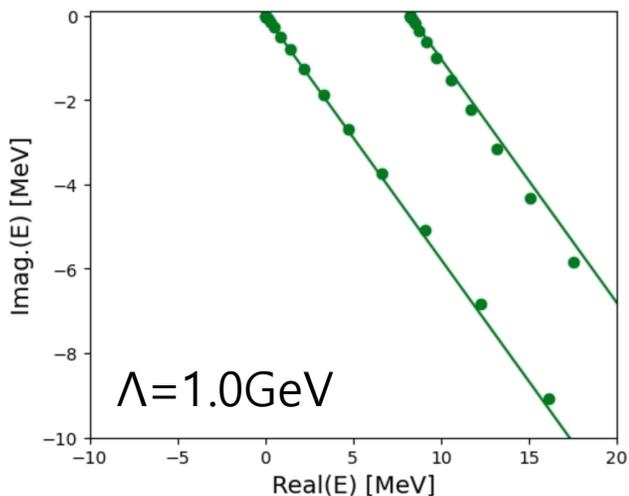
$$[I = 1] = \frac{1}{\sqrt{2}}(D^{*+}D^0 + D^{*0}D^+)$$



X(3872)的性质

由 DD^* 相互作用得到 $DD^* + \bar{D}\bar{D}^*$ 的相互作用，因此可以类似考虑纯 $DD^* + \bar{D}\bar{D}^*$ 的相互作用产生的 T 矩阵，即没有 $c\bar{c}$ 态。

$$V'_{\bar{D}^*D} = \chi * V_{\bar{D}^*D}$$



• 束缚态

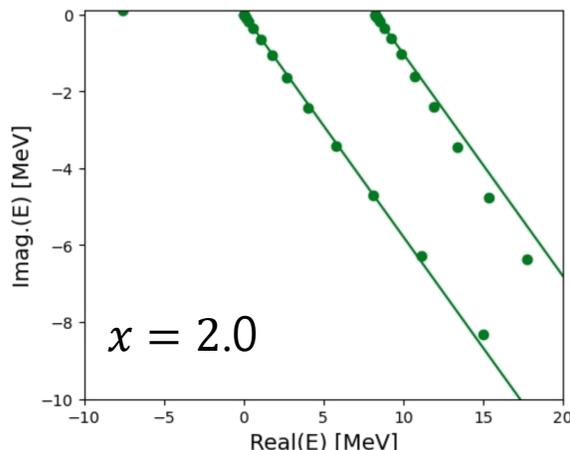
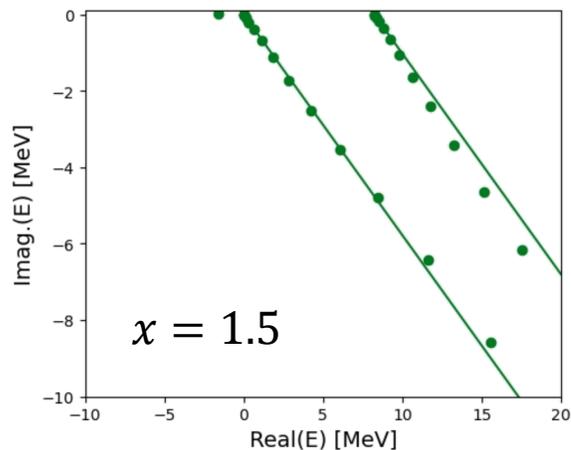
$$m_{T_{cc}} = 3874.7 \text{ MeV},$$

$$\Delta E = -393 \text{ keV}$$

$$\Gamma_{T_{cc}} = 70.4 \text{ keV}$$

$$\bullet \sqrt{\langle r^2 \rangle} = 4.7 \text{ fm}$$

$$\bullet 70.0\% D^{*+}D^0, \quad 30.0\% D^+D^{*0}$$



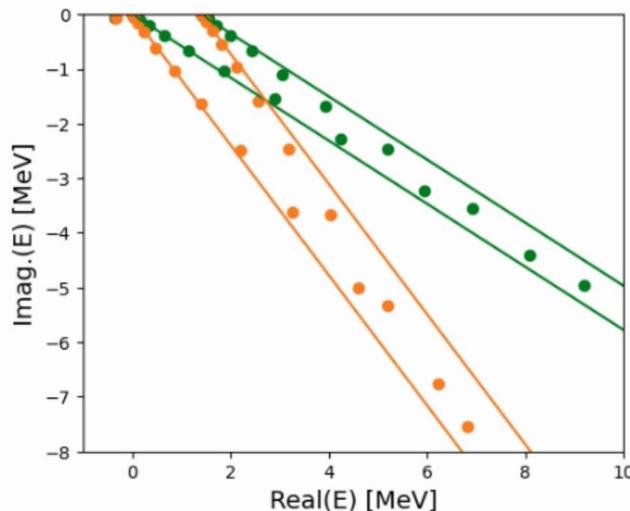
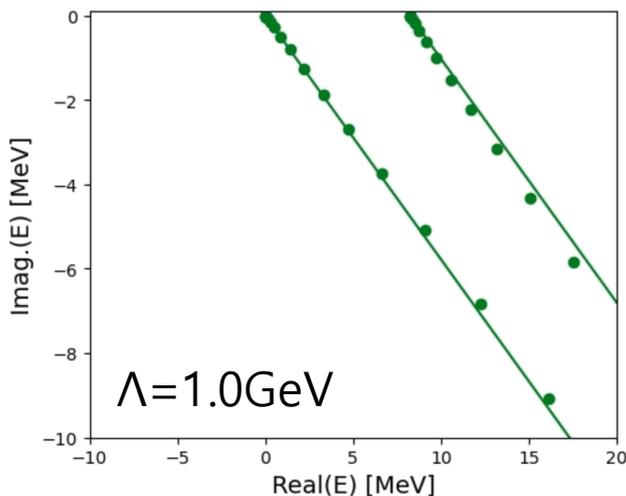
首先，这是一个吸引势能，其次这个吸引势能不足以形成一个束缚态

对于X(3872)，只找到一个虚态
 $3870.0 + 0.26 i \text{ MeV}$



X(3872)的性质

由 DD^* 相互作用得到 $D\bar{D}^* + \bar{D}D^*$ 的相互作用，因此可以类似考虑纯 $D\bar{D}^* + \bar{D}D^*$ 的相互作用产生的 T 矩阵，即没有 $c\bar{c}$ 态。

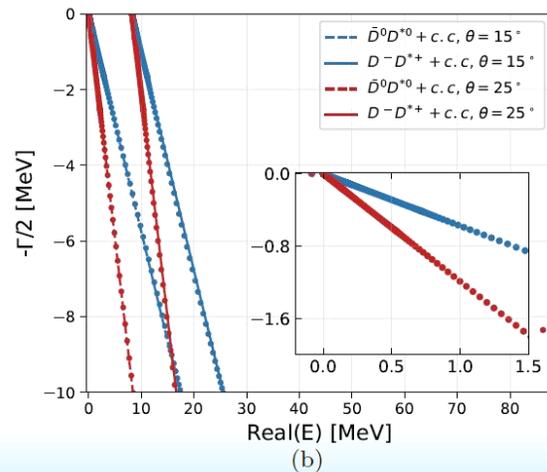


- 束缚态
 $\Delta E = -393 \text{ keV}$
 $\Gamma_{T_{cc}} = 70.4 \text{ keV}$
- $\sqrt{\langle r^2 \rangle} = 4.7 \text{ fm}$
- 70.0% $D^{*+}D^0$, 30.0% D^+D^{*0}

首先，这是一个吸引势能，其次这个吸引势能不足以形成一个束缚态

加入 $c\bar{c}$ 裸态的成分，需要一个裸态：

$\chi_{c1}(2P, 3940)$ 及其波函数，由夸克模型确定。
 $3P_0$ 的相互作用参数 $\gamma = 4.69$ 通过 $\psi(3770)$ 到 $D\bar{D}$ 确定，因此对X(3872)的分析没有增加任何参数。



- 束缚态
 $\Delta E = -80.4 \text{ keV}$
 $\Gamma_{T_{cc}} = 32.5 \text{ keV}$
- $\sqrt{\langle r^2 \rangle} = 11.2 \text{ fm}$
- 94.0% $\bar{D}^{*0}D^0$, 4.8% $D^{*-}D^+$, 1.2% $c\bar{c}$



T_{cc} , X(3872)的性质

• T_{cc} 束缚态

$$\Delta E = -393 \text{ keV}$$

$$\Gamma_{T_{cc}} = 70.4 \text{ keV}$$

$$\bullet \sqrt{\langle r^2 \rangle} = 4.7 \text{ fm}$$

$$\bullet 70.0\% D^{*+}D^0, \quad 30.0\% D^+D^{*0}$$

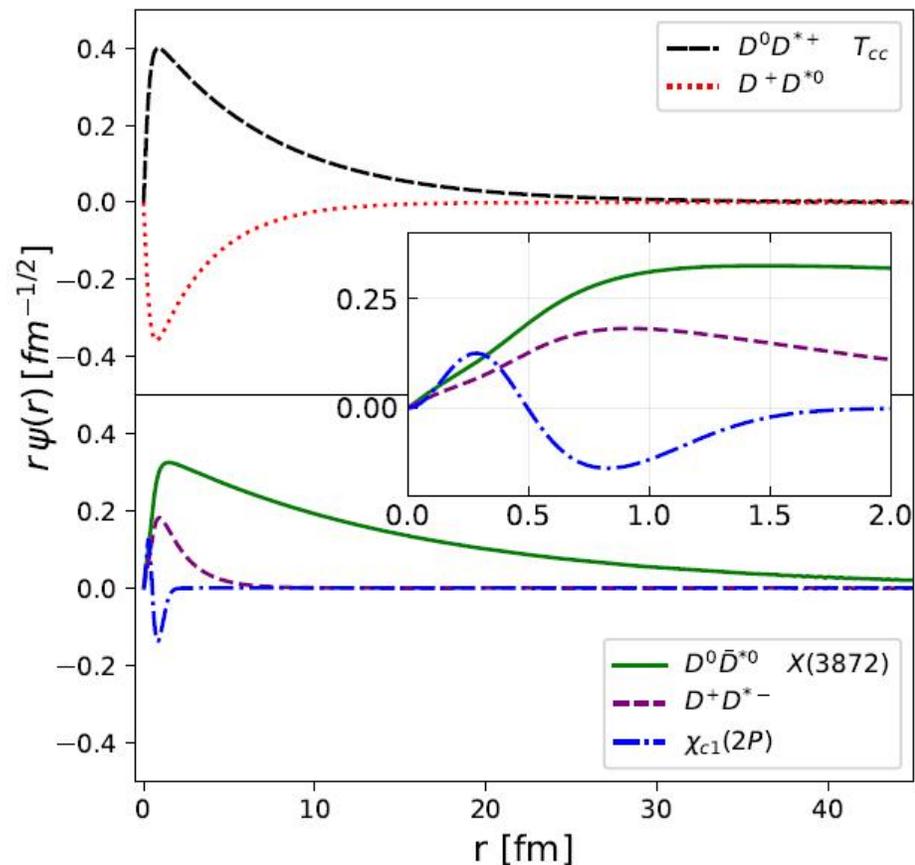
• X(3872)束缚态

$$\Delta E = -80.4 \text{ keV}$$

$$\Gamma_{T_{cc}} = 32.5 \text{ keV}$$

$$\bullet \sqrt{\langle r^2 \rangle} = 11.2 \text{ fm}$$

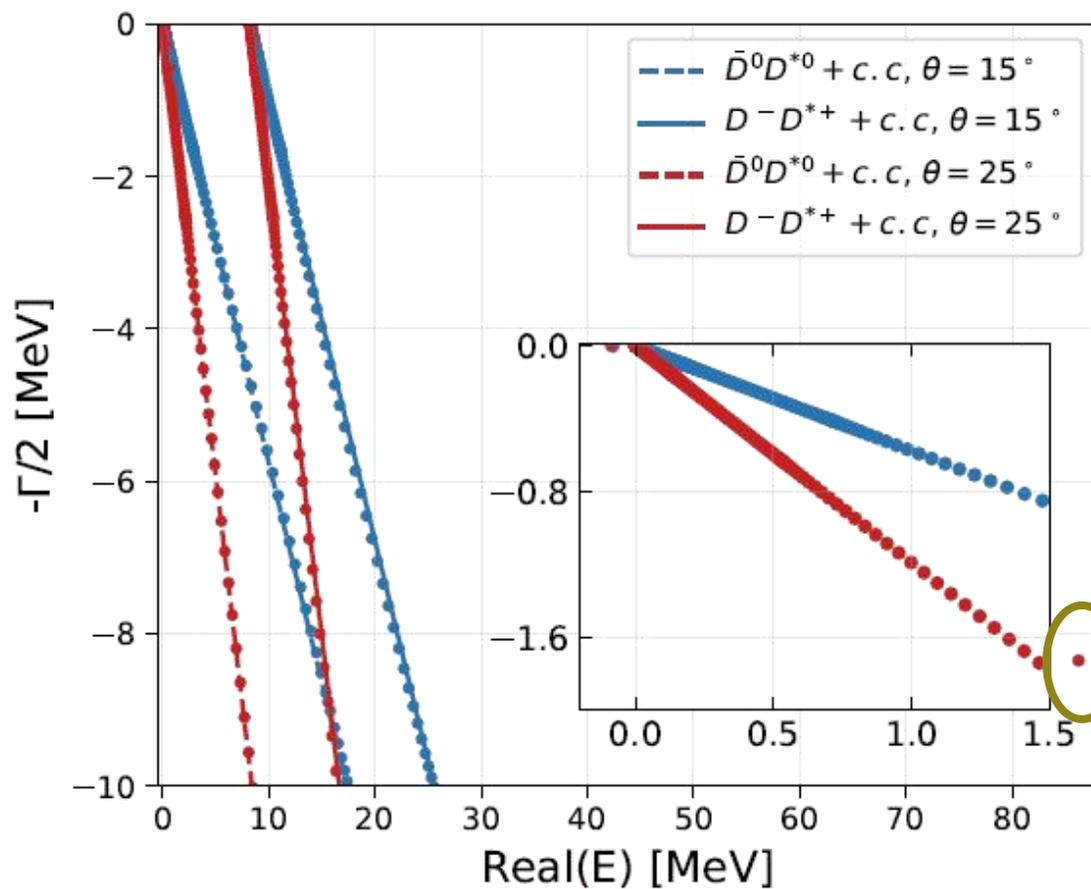
$$\bullet 94.0\% \bar{D}^{*0}D^0, \quad 4.8\% D^{*-}D^+, \quad 1.2\% c\bar{c}$$



由于X(3872)的束缚能极小，所以整个 $D^{*0}\bar{D}^0$ 波函数是一个尾巴很长很长的波函数，实际上这个很好理解，一旦这个态的质量大于 $D^{*0}\bar{D}^0$ 阈值，就变成共振态，而共振态是不归一的，就是长程上可以变成两个强子态。而这个长尾巴实际上就提供了大部分的复合度，而在短距离的成分中，还是以 $c\bar{c}$ 成分为主。而且在形成中，也体现出裸态的重要作用。



预言



(b)

J^{pc}	$Lq\bar{q}$	$Sq\bar{q}$		
0^{++}	0	0	$\eta_c(2980)$	$\eta_c(2S)$
1^{--}	0	1	$J/\psi(3096)$	$\psi(2S), \dots$
	2	1	$\psi(3770)$	
1^{+-}	1	0	$h_c(3525)$	z_c
0^{++}	1	1	$\chi_{c0}(3414)$	$\chi_{c0}(3860)$
1^{++}	1	1	$\chi_{c1}(3510)$?
2^{++}	1	1	$\chi_{c2}(3556)$	$\chi_{c2}(3930)$
2^{--}	2	1	$\psi_2(3823)$	
3^{--}	2	1	$\psi_3(3842)$	
2^{+-}	2	0	?	

• $\chi_{c1}(2p)$ 束缚态

$M = 3957.9 \text{ MeV}$

$\Gamma_{Tcc} = 16.7 \text{ MeV}$

• 主要衰变道: $\bar{D}^* D$

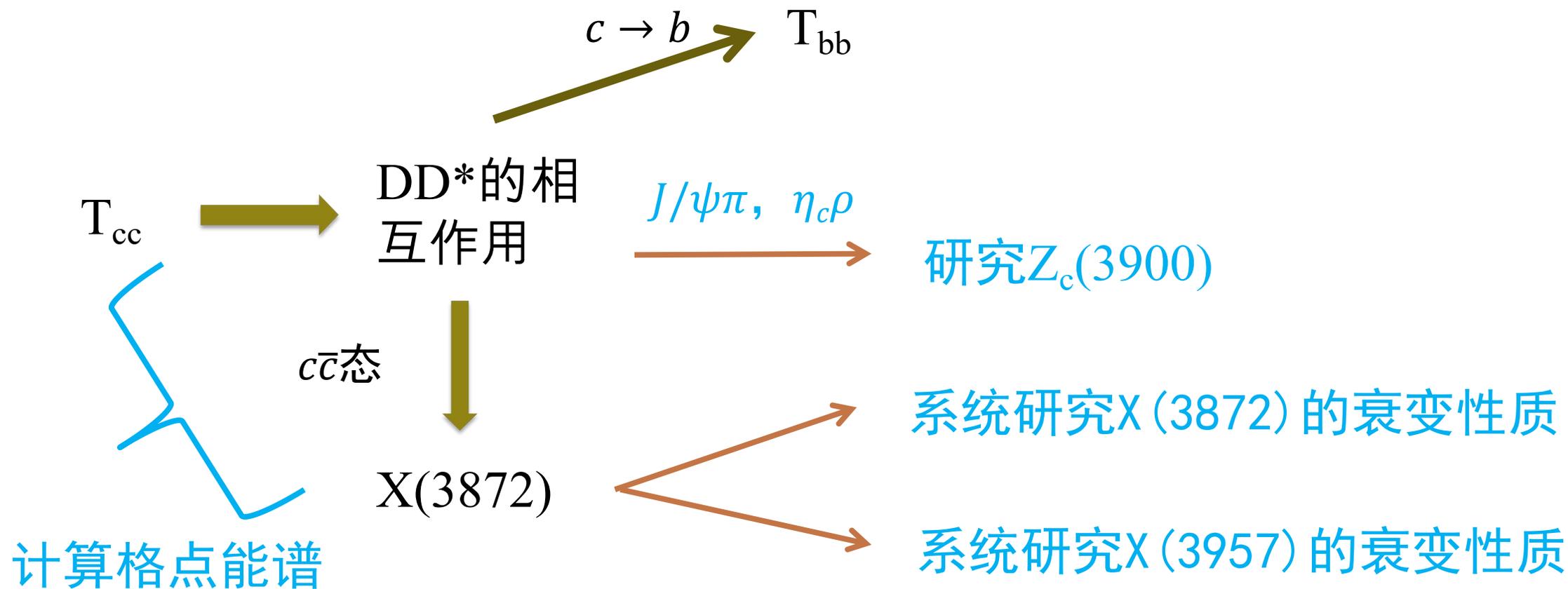


小结

- 通过Tcc的研究确定DD*的相互作用
- 由确定的DD*的相互作用和裸态可以研究X (3872)的性质
- 研究发现X (3872) 中DD*成分绝对主导，但是主要分布在长程部分，即大于1fm，裸态在短程部分依然主导。



展望



X(3872) Relevant $D\bar{D}^*$ Scattering in $N_f = 2$ Lattice QCD

Haozheng Li, Chunjiang Shi, Ying Chen, Ming Gong, Juzheng Liang et al. (Feb 22, 2024)

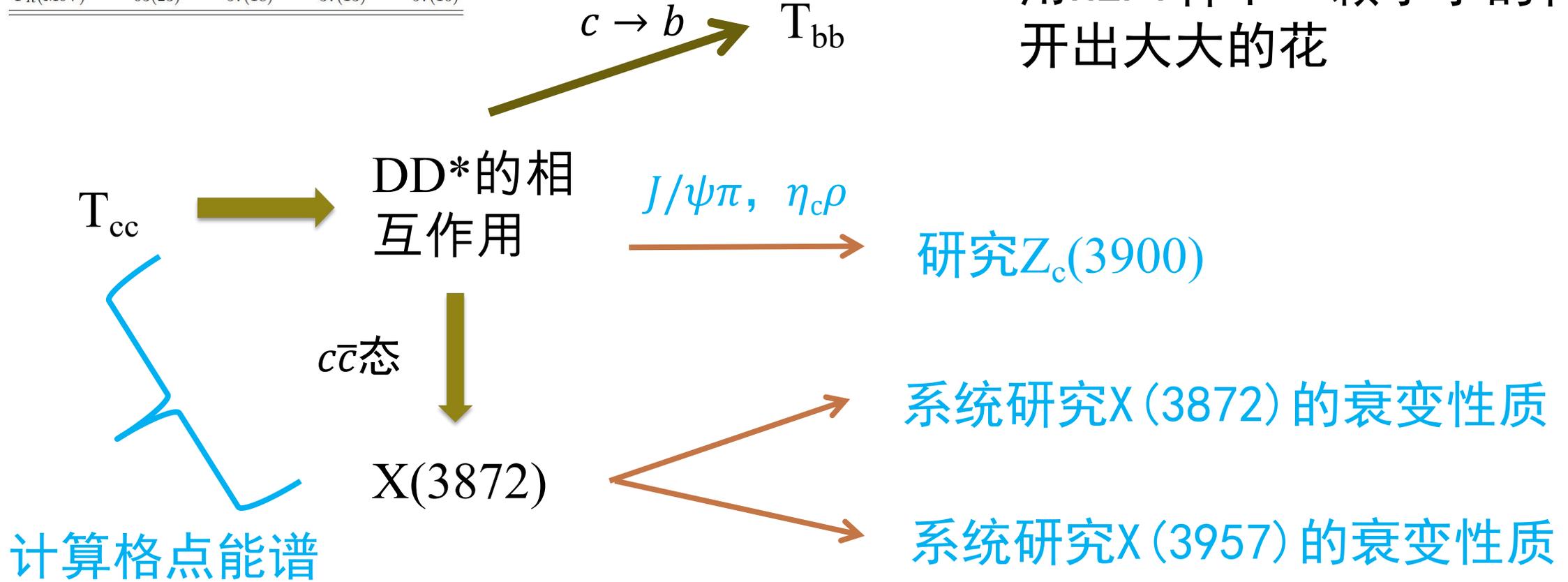
e-Print: 2402.14541 [hep-lat]

TABLE III. Resonance parameters (m_R, Γ_R).

	250(3)	307(2)	362(1)	417(1)
m_π (MeV)	250(3)	307(2)	362(1)	417(1)
m_R (MeV)	3924(5)	3926(6)	3969(4)	3995(4)
Γ_R (MeV)	63(23)	57(18)	37(13)	57(10)

展望

在强子的花园里挖呀挖呀挖
用HEFT种下一颗小小的种子
开出大大的花



谢谢大家!

广告时间



中国科学院大学
University of Chinese Academy of Sciences



第二届强子物理新发展研讨会 暨 强子物理在线论坛100期特别活动

2-6 July 2024

Asia/Shanghai timezone

会议概况

会议日程

会议注册

参会人员

往届会议

Travel Info

第二届强子物理新发展研讨会 暨 强子物理在线论坛100期特别活动



<https://indico.itp.ac.cn/event/225/>



中国科学院大学
University of Chinese Academy of Sciences

