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COMPATIBILITY OF LQCD PREDICTIONS FOR THE $T_{cc}(3875)^+$ WITH EXPERIMENT AND A COMPARATIVE STUDY WITH THE $\chi_{c1}(3872)^*$

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We perform a unified analysis of the $T_{cc}(3875)^+$ and $\chi_{c1}(3872)$ using an Effective Field Theory (EFT) based on local hidden gauge symmetry. Our model incorporates ρ- and ω-meson exchanges, one-pion exchange (OPE) with three-body dynamics, and a bare $c\bar{c}$ state for the $\chi_{c1}(3872)$. By fitting energy level data from multiple lattice QCD collaborations, we study the pion-mass dependence of the pole positions. While T_{cc}^+ results align with experimental data, a tension remains for the $\chi_{c1}(3872)$ at the physical point, highlighting the need for high-precision lattice simulations at low pion masses.

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1. Introduction

The exotic hadrons $T_{cc}(3875)^+$ and $\chi_{c1}(3872)$ are central to hadron physics as their properties challenge conventional quark models. The T_{cc}^+ is a doubly-charmed tetraquark candidate near the $D^{*+}D^0$ threshold [1], while the $\chi_{c1}(3872)$ sits at the $D^0\bar{D}^{*0}$ threshold [2]. Understanding whether they share a common molecular origin remains an open question [3]. Building on our previous EFT study of T_{cc}^+ [4], this work performs a unified analysis of lattice QCD (LQCD) data for both states [5–14]. By fitting the EFT to LQCD spectra, we quantify the light-quark mass dependence of their pole positions and extrapolate results to the physical point to elucidate their binding mechanisms.

2. Formalism

The $VP \to VP$ interaction is derived from local Hidden Gauge Symmetry Lagrangians extended to SU(4) [15, 16]

$$\mathcal{L}_{VPP} = -ig\langle [P, \partial_\mu P] V^\mu \rangle \,, \qquad \mathcal{L}_{VVV} = ig\langle (V^\nu \partial_\mu V_\nu - \partial_\mu V^\nu V_\nu) V^\mu \rangle \,, \quad (1)$$

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with $g = m_\rho/2f_\pi$. We analyze the $I = 0$ sector for DD^* (T_{cc}^+) and $D\bar{D}^*$ ($\chi_{c1}(3872)$). Tree-level potentials can be written as

$$V^{T_{cc}} = V_\rho + \frac{3}{2}V_\pi\,, \qquad V^{\chi_{c1}} = 2V_\rho + \frac{3}{2}V_\pi + V_{c\bar{c}}\,, \tag{2}$$

where the individual contributions are given by:

$$V_\rho = g^2\frac{(p_1+p_3)_\mu(p_2+p_4)^\mu}{(p_1-p_3)^2-m_\rho^2}\epsilon\cdot\epsilon^*\,, \tag{3}$$

$$V_\pi = g^2_{D^*D\pi}D_\pi(2p_4-p_1)_\mu\epsilon^\mu(2p_2-p_3)_\nu\epsilon^{*\nu}\,, \tag{4}$$

$$V_{c\bar{c}} = \frac{c^2}{s-m^2_{c\bar{c}}}\epsilon\cdot\epsilon^*\,. \tag{5}$$

The pion propagator D_π is treated via Time-ordered Perturbation Theory [17]. To compare with LQCD, we solve the Lippmann–Schwinger equation in a finite volume L, leading to the quantization condition [18]

$$\det\left[1-\frac{1}{L^3}\frac{\sqrt{s}}{P^0}\sum_{\vec{n}}^{q_{\max}}U^\Gamma V(\vec{q})I(\vec{q})\left(U^\Gamma\right)^\dagger\right]=0\,, \tag{6}$$

where $I(\vec{q})$ is the two-meson propagator function and U^Γ projects the potential onto the irreducible representations of the octahedral group O_h, such as the T_1^+ irrep for $J^P = 1^+$ [19, 20].

3. Results

We perform a global fit to LQCD data for the $T_{cc}(3875)^+$ [5, 7–10] and the $\chi_{c1}(3872)$ [11–14]. Table 1 summarizes the lattice setups and pion masses. Unlike in Ref. [4], we fit energy levels directly via the quantization condition in Eq. (6), incorporating ρ- and π-exchange potentials in finite volume. Experimental pole positions are included to better constrain the $\chi_{c1}(3872)$ near the physical point.

The ultraviolet cutoff is fixed at $q_{\max} = 650$ MeV. The fit involves three parameters: the $D^*D\rho$ coupling (g), the $\chi_{c1}(3872)$ coupling to a bare $c\bar{c}$ state (c), and the global bare mass $m^0_{c\bar{c}}$. To account for charm-quark mass variations among lattice collaborations, we use $m_{c\bar{c}} = m^0_{c\bar{c}} + (m_D + m_{D^*} - m_D^{\text{phys}} - m_{D^*}^{\text{phys}})$. Best-fit values are $g = 2.52 \pm 0.32$, $c = 5.2 \pm 2.6$, and $m^0_{c\bar{c}} = 4025 \pm 36$ MeV ($\chi^2/\text{d.o.f.} = 4.2$). Figure 1 shows some representative results for the energy-level fit for each collaboration. We can see that the model accurately reproduces the energy spectra across collaborations.

Table 1. Lattice setups for DD^* (top) and $D\bar{D}^*$ (bottom) scattering. $M^{c\bar{c}}_{\text{avg}} = 1/4(m_{\eta_c} + 3m_{J\Psi})$.

Collaboration	a [fm]	L [fm]	m_π [MeV]	$M^{c\bar{c}}_{\text{avg}}$ [MeV]
Padmanath24 [5, 9]	0.086	2.07–2.76	280	3103
CLQCD22 [6]	0.152	2.4	349	3069
HSC24 [10]	0.120	1.9–2.9	391	3024
HALQCD23 [7]	0.0846	8	146	3097
HALQCD14 [8]	0.0907	2.9	411	3070
Prelovsek13 [11, 12]	0.1239	1.98	266	2387
Lee14 [13]	0.1527	2.44	305	2428
Li24 [14]	0.136	2.18	250–417	3069

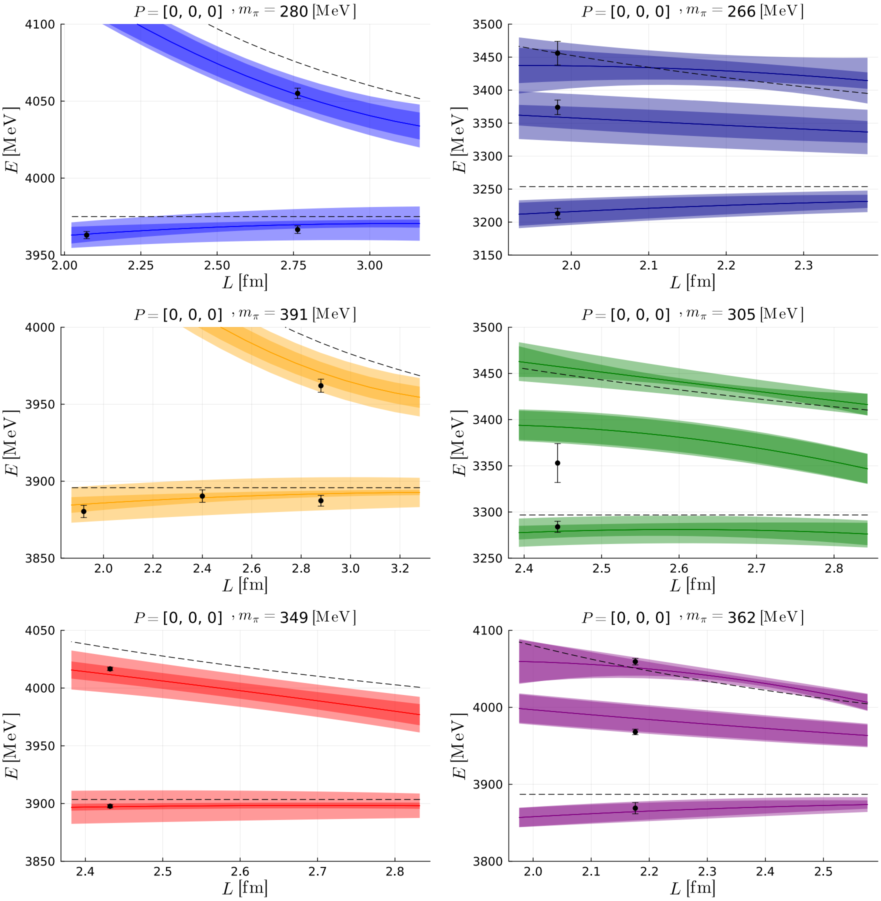

Fig. 1. Energy-level fit results for DD^* (left) and $D\bar{D}^*$ (right). Solid (dashed) lines represent (non)interacting levels.

Finally, we analyze the pion-mass dependence of the $T_{cc}(3875)^+$ and $\chi_{c1}(3872)$ pole positions. For this extrapolation, we employ the NLO chiral perturbation theory formulas for charmed-meson masses from the fit of Ref. [21]. The resulting trajectories are shown in Fig. 2. While the model accurately describes the lattice poles and their evolution with m_π, we observe a remaining tension: the extrapolated pole for the $\chi_{c1}(3872)$ at the physical

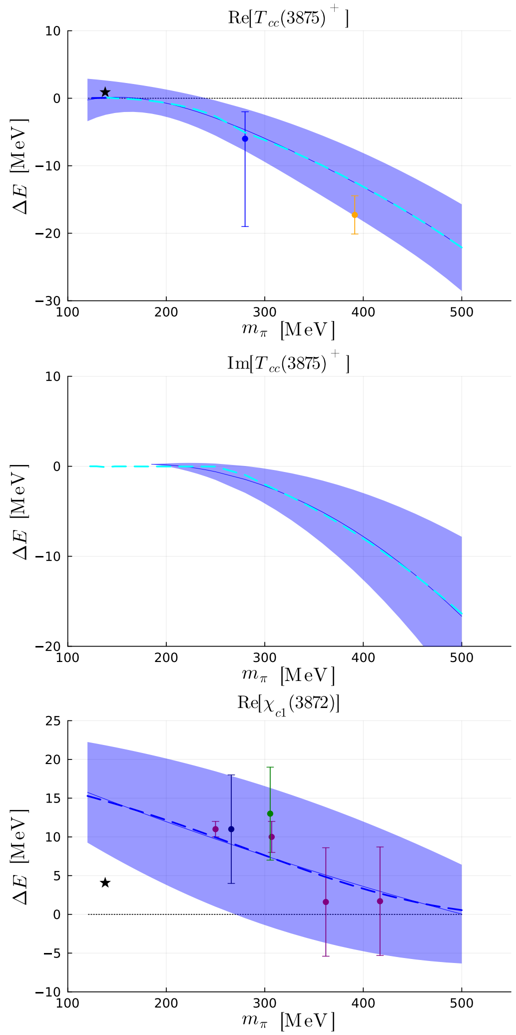

Fig. 2. (Color online) Pion-mass dependence of the $T_{cc}(3875)^+$ and $\chi_{c1}(3872)$ pole positions. Dashed blue (light blue/light gray) lines denote poles in the first (second) Riemann sheet. The physical point is represented with a black star.

point does not fully coincide with the experimental value. This discrepancy suggests that further investigation in this low-pion-mass regime is needed to better understand this discrepancy between lattice data and the experiment.

4. Conclusions

In this work, we have carried out a unified EFT study of the $T_{cc}(3875)^+$ and $\chi_{c1}(3872)$ states, focusing on their light-quark mass dependence. By solving the scattering equations in a finite volume, we have successfully described the energy levels from various lattice QCD collaborations. The global fit shows that a framework based on light-meson exchange can describe the attractive interaction in both DD^* and $D\bar{D}^*$ channels. Our best fit provides a good description of the lattice data. The analysis of the pole trajectories shows that the $T_{cc}(3875)^+$ properties align well with experimental observations. However, for the $\chi_{c1}(3872)$, there is a visible tension between the extrapolated lattice data and the experimental value at the physical point. While different theoretical interpretations can be explored, the current results are strictly driven by the available lattice data. We conclude that more simulations at near-physical pion masses are needed to determine if this discrepancy is a consequence of the current lattice setups or if it points toward a more complex structure of the $\chi_{c1}(3872)$.

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