The charm quark states $X(3872)$ and $Z_c(3900)$ on HISQ lattices

The FERMILAB LATTICE and MILC Collaborations

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1. Motivation

As part of our ongoing study of charmonium levels, we are currently studying the $X(3872)$ and the $Z_c(3900)$ using chiral quark compactification and HISQ light-quark actions on the MILC configurations with $2.7^3$ flavors of HISQ sea quarks. Here, we present new results from a preliminary study.

The $X(3872)$ state with $J^P = 1^+$ is one of the better established charmonium states found in $B$-meson decays by both Belle [1] and CDF [2] and studied with more precision by CDF [3], B, and Babar [6-8] Belle [7] and LHCb [9]. Its mass is remarkably close to the $D \bar{D}$ threshold with $M(D \bar{D}) = (3872) \pm 2 \text{ MeV}$. The $X(3872)$ is a charmed quark-antiquark state, produced in $B$-decays, and is studied at the LHCb experiment [9].

The $Z_c(3900)$, with $J^P = 1^-$, is a charged, open-charm quark-antiquark state observed by the BESIII collaboration [10] at an intermediate resonance in an analysis of $e^+e^-$ annihilations into $J/\psi \pi^+$ at $\sqrt{s} = 3.77$ GeV. This observation has been confirmed by the Belle Collaboration [11]. As an open-charm-like state, it is expected to undergo weak decay and would be a apt candidate for study at the LHCb experiment [9].

2. Technical lattice challenges

• Managing a variational calculation with both open charm and excited charmed components.

• Choosing interpolating operators that couple well to these states.

• Extending variational methods to cover systems with staggered fermions.

• Managing hadron correlators that require all-to-all methods.

3. What is new here?

• HISQ fermions with lighter light quarks.

• Larger box size. Important for weakly bound states.

4. Ensemble analysis

For this preliminary study we work with an ensemble of $3^3 \times 6$ lattices with $4.2$ fm lattice spacing. In addition, we use $2.7$ flavors of HISQ sea quarks.

5. Staggered variational method

A variational approach helps to determine multiple eigenvalues of the transfer matrix [22, 24]. We extend the method to staggered fermions [23].

Define

\[ C_{\mu}(\mathbf{x}) = \sum_{\mathbf{p}} \langle \mathbf{p} \mid \mathbf{x} \rangle \chi_{\mu}^{\mathbf{p}}(\mathbf{x}) \]

where \( \chi^{\mathbf{p}}(\mathbf{x}) \) is the interpolating operator.

In terms of a pseudo-transfer matrix \( T \) with eigenvalues \( \gamma_i \),

\[ C_{\mu}(\mathbf{x}) = \sum_i \gamma_i \langle \mathbf{p} \mid \mathbf{x} \rangle \chi_i^{\mathbf{p}}(\mathbf{x}) \]

where \( \chi_i^{\mathbf{p}}(\mathbf{x}) \) is the interpolating operator.

With a sufficiently complete interpolating operator basis, we get eigenvalues \( \gamma_i \) from highest states and often from oppositely charged states.

6. $X(3872)$ interpolating operators

= Interpolating operators $(\mathbf{S} \otimes \mathbf{1})$:

\[ C_{\mu}(\mathbf{x}) = \sum_{\mathbf{p}} \langle \mathbf{p} \mid \mathbf{x} \rangle \chi^{\mathbf{p}}(\mathbf{x}) \]

= D0 interpolating operators $(\mathbf{P} \otimes \mathbf{1})$:

\[ \langle \mathbf{p} \mid \mathbf{x} \rangle = \left[ -\delta_0 - D_0^{\mathbf{p}} - D_0^{\mathbf{p}+\mathbf{i}} - D_0^{\mathbf{p}-\mathbf{i}} \right] \]