$Z_c(3900)$ Relevant $J/\psi\pi - D\bar{D}^*$ Coupled Channel Effects

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Abstract

- Since its discovery in 2013, the nature of $Z_c(3900)^{\pm}$ has been studied by phenomenological [6, 4, 2, 8] and lattice QCD studies [3, 7] .
- We employ the finite volume scattering formalism to extract the scattering amplitudes from the energy levels of interacting two-meson systems from $N_f = 2$ anisotropic lattice QCD at $m_\pi \approx 350$ MeV.
- This study explores the coupled-channel effects of $J/\psi\pi$ and $D\bar{D}^*$, with preliminary results presented by extracting phase-shifts and scattering amplitudes on two lattice volumes.

Feature of this study

- Two Volume ✓
- Multi irreps (moving frame) ✓
- Energy level stability ✓
- Realistic Coupled-Channel analysis ✓
- Best Fitting χ^2 ☐
- Partial-wave mixing effects: $L_{max} = 0$ ☐

Lattice setup

distillation method + anisotropic lattice

ens.	size	m_π(MeV)	LapH N_V	N_{cfg}
L16	$16^3 \times 128$	348.5(1.0)	70	6991
L24	$24^3 \times 192$	345.6(0.8)	160	489

m_D(GeV)	m_{D^*}(GeV)	$m_{J/\psi}$(GeV)	m_π(GeV)
1.8819(5)	2.0216(9)	3.0991(1)	0.3471(4)

Wave function

$$\mathcal{O}^{(I=1)}_{D\bar{D}^*}(\vec{p}) = \sum_{\vec{p}_1,\vec{p}_2} \frac{1}{\sqrt{2}} \left(\mathcal{O}_{D^+}\mathcal{O}_{\bar{D}^{*0}} - \mathcal{O}_{\bar{D}^0}\mathcal{O}_{D^{*+}}\right).$$

$$\mathcal{O}^{(I=1)}_{J/\psi\pi} = \sum_{\vec{p}_1,\vec{p}_2} \mathcal{O}_{J/\psi}\mathcal{O}_\pi.$$

Lattice irreps.

$T_1^+(\boldsymbol{d} = (0,0,0)) : O = P(\vec{p})V_z(-\vec{p}),$

$A_2^-(\boldsymbol{d} = (0,0,1)) : O = P(\vec{0})V_z(\vec{p}), P(\vec{p})V_z(0),$

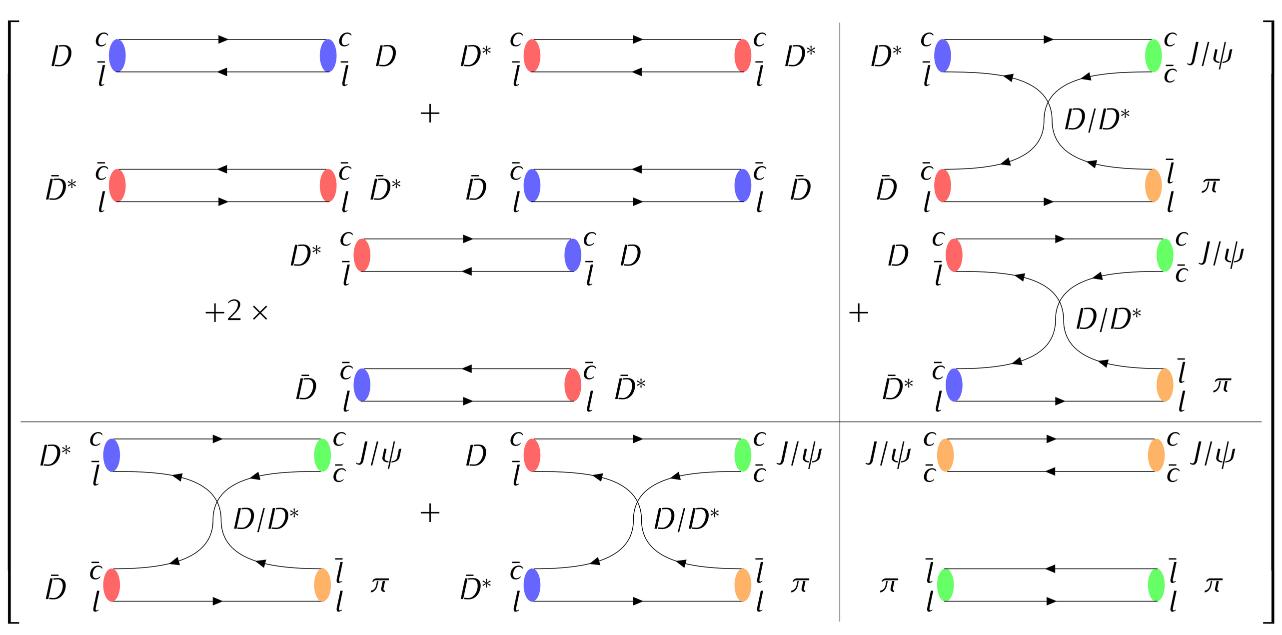
$A_2^-(\boldsymbol{d} = (1,1,0)) : O = P(\vec{0})[V_x(\vec{p}) + V_y(\vec{p})].$

Schematic diagrams and off-diagonal coupling

- We calculate the two-point correlation function matrix between S-wave $J/\psi\pi$ and $D\bar{D}^*$ operators, where the related momentum mode remains the specific lattice irrep. Then we solve the gevp for the exact energy level. The off-diagonal correlation function also can be extracted in the following form.

$$C_{mn}(t) = \sum_\tau \langle 0|\mathcal{O}_m(t+\tau)\mathcal{O}_n^\dagger(\tau)|0\rangle = \begin{bmatrix} C_{D\bar{D}^*-D\bar{D}^*} & C_{J/\psi\pi-D\bar{D}^*} \\ C_{D\bar{D}^*-J/\psi\pi} & C_{J/\psi\pi-J/\psi\pi} \end{bmatrix}$$

⇓



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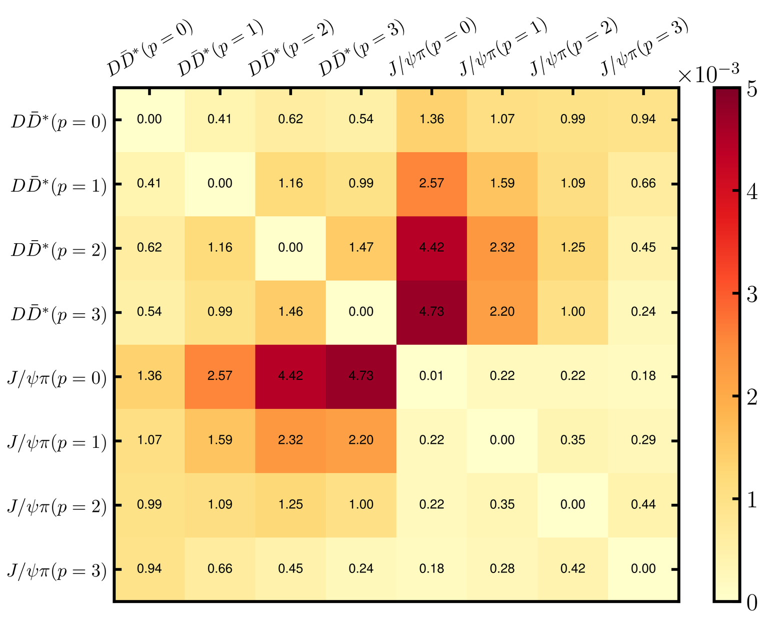
solving GEVP : $C(t)v(t) = \lambda_n(t)C(t_0)v(t)$



$$x_{mn} \equiv \langle m|\hat{H}_I|n\rangle \approx V_{mn}$$

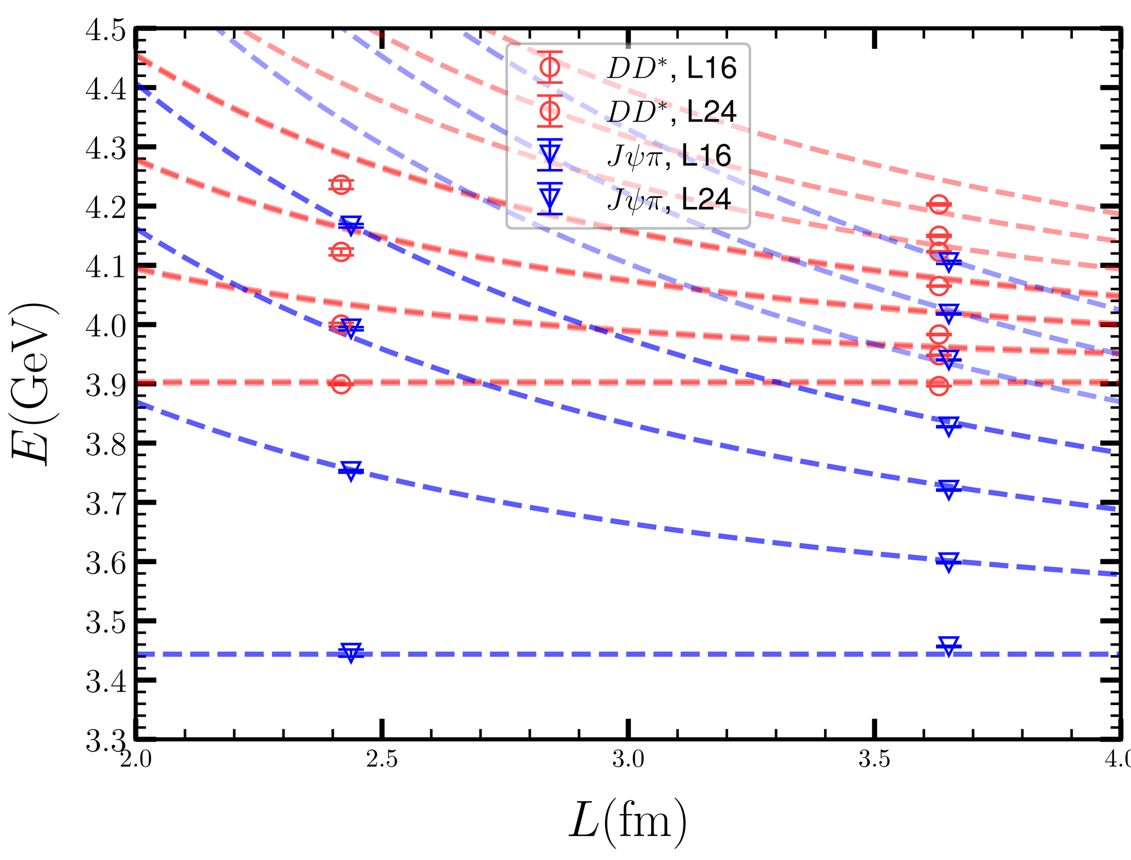
from

$$\frac{C_{DD^*\to J/\psi\pi}}{\sqrt{C_{DD^*}\times C_{J/\psi\pi}}} \sim xt\left(1 + \frac{1}{24}(\Delta E t)^2\right)$$

- The off-diagonal coupling $J/\psi\pi - D\bar{D}^*$ is important and strongly momentum dependent .
- Therefore, a constant contact term interaction is not enough, which favors to the results of study [1?] .

Finite Volume Formalism

- After solving GEVP procedure, from two volumes, we use the precise energy level to implement the coupled-channel Lüscher formulae (or the Lüscher-Lellouch quantization condition), which involves the determinant of a 2×2 matrix that includes the inverse of the transition matrix $t(s)$ and other factors.



$$S = \begin{bmatrix} \eta e^{2i\delta_1} & i\sqrt{1-\eta^2}e^{i(\delta_1+\delta_2)} \\ i\sqrt{1-\eta^2}e^{i(\delta_1+\delta_2)} & \eta e^{2i\delta_2} \end{bmatrix}.$$

$$S_{ij} = I + 2i\rho_{ij}^{\frac{1}{2}} \cdot t \cdot \rho_{ij}^{\frac{1}{2}}$$

Lüscher-Lellouch formulism

$$\det\left[t_{ij}^{-1}(s) + i\rho_{ij} - \rho_{ij}\mathcal{M}^{\mathbf{d},\Lambda}(k)\right] = 0.$$

or

$$\det\left[\mathcal{F}^{\mathbf{d},-1}(k) - t(s)\right] = 0.$$

- In this study, We try two methods to parameterize the transition matrix $t(s)$, which reminds the unitarity of the scattering matrix S. The first method involves the inverse of another matrix $K(s)$. The second method involves the inverse of the matrix $K(s)$ with a different parameter.

K-Matrix Parameterization

$$t^{-1}(s) = K^{-1}(s) + \begin{bmatrix} I_1 & 0 \\ 0 & I_2 \end{bmatrix}(s),$$

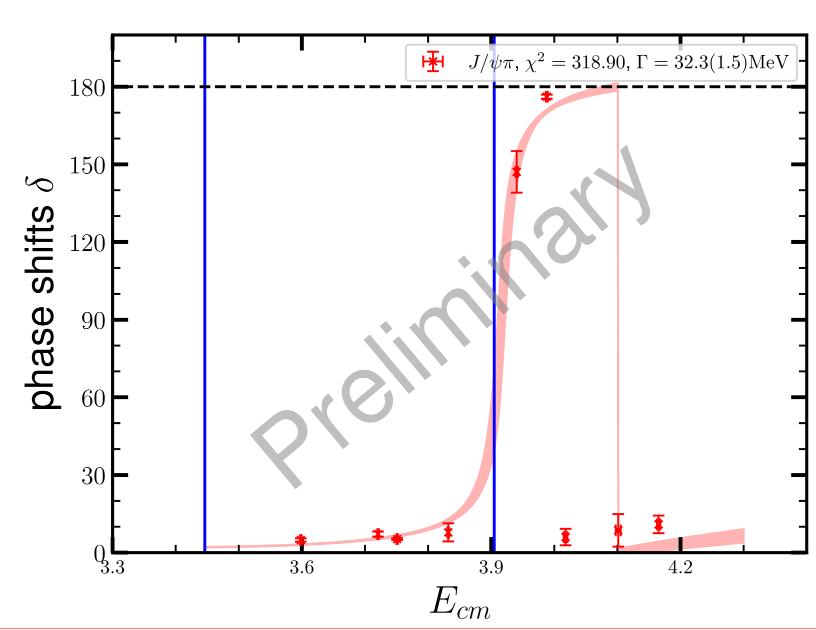
$$K(s) = \frac{1}{m^2 - s}\begin{bmatrix} g_1^2 & g_1 g_2 \\ g_1 g_2 & g_2^2 \end{bmatrix} + \begin{bmatrix} \gamma_{11}^2 & \gamma_{12} \\ \gamma_{12} & \gamma_{22}^2 \end{bmatrix}.$$

Single-Channel analysis

- Within $J/\psi\pi$ channel, though the single channel Lüscher formulae, the phase-shifts δ_0 are extracted from the scattering momentum q.

Single channel Lüscher formulae

$$p\cot\delta(q) = \frac{2}{\gamma L \pi^{\frac{1}{2}}} Z^{\boldsymbol{d}}_{00}(1, q^2).$$



- The possible phase-shift jump give a hint for a resonance near the $D\bar{D}^*$ threshold.
- However, more realible results should be give by coupled-channel analysis.

Outlook

- 1. We performed a preliminary single-channel analysis of the scattering amplitudes, yielding some insights into the resonance state.
- 2. Currently, the fitting of the coupled-channel analysis is still in progress .

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