Direct access to charmonium decay parameters

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Introduction

- In lattice studies, it is common to relate the decay width of a baryon or meson to its spectrum [1, 2] at several volumes, which drives up the computational cost.
- We follow an alternative approach, first introduced in [3], to compute the decay width using ratios of four-point, three-point and two-point functions.
- The method requires to tune the energy on the lattice of the initial and final states and make them coincide. In our study, we employ partially twisted boundary conditions to achieve this condition.
- We apply this method to compute the decay width

$$\Gamma(\psi(3770) \to \bar{D}D)$$

which constitutes $\sim 90\%$ of the branching ratio. This means that we need to compute the hadronic mixing

$$x_{31} \equiv \langle \psi(3770) | \bar{D}D \rangle$$

Lattice simulations

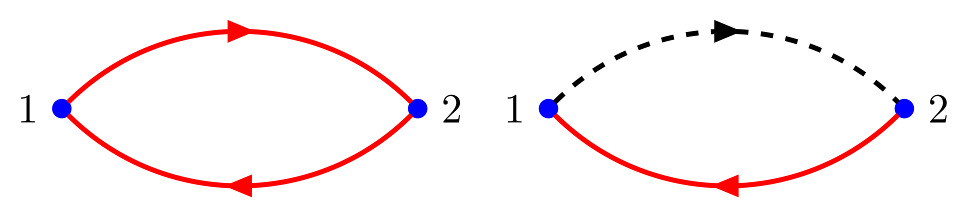
We employ two $N_f = 2$ CLS ensembles [4, 5]

id	β	a	L/a	m_π [MeV]	$m_\pi L$	Stat.
D5	5.3	0.0658(7)(7)	24	449	3.6	150
E5			32	437	4.7	192

We tune the D-meson momentum with partially twisted boundary conditions [6] on the charm quark.

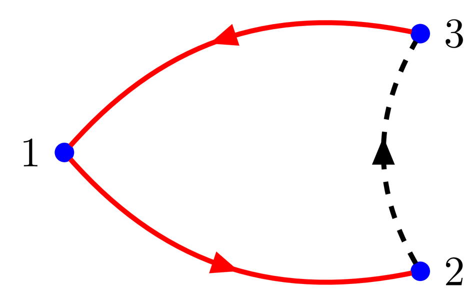
The charmonium states remain at rest

We require the D and $\psi(3770)$ propagators P^D, P^ψ

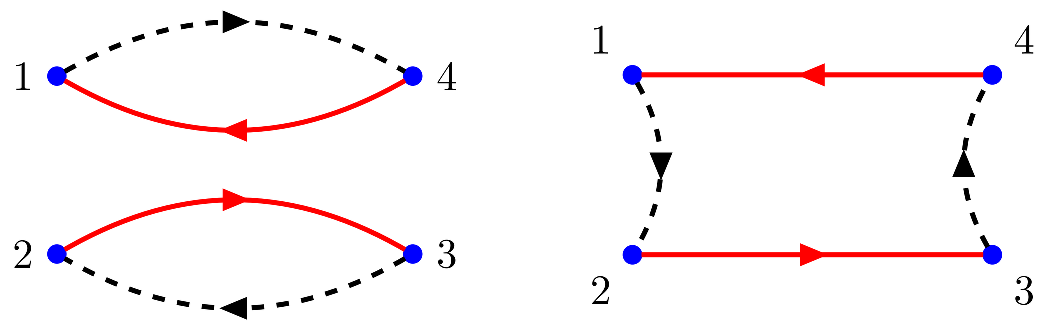


Red: charm quarks; black: light quarks.

The quark-connected diagram $\bar{T}_3$ for $\psi(3770) \to \bar{D}D$



And the $\bar{D}D \to \bar{D}D$ propagator P^{DD}



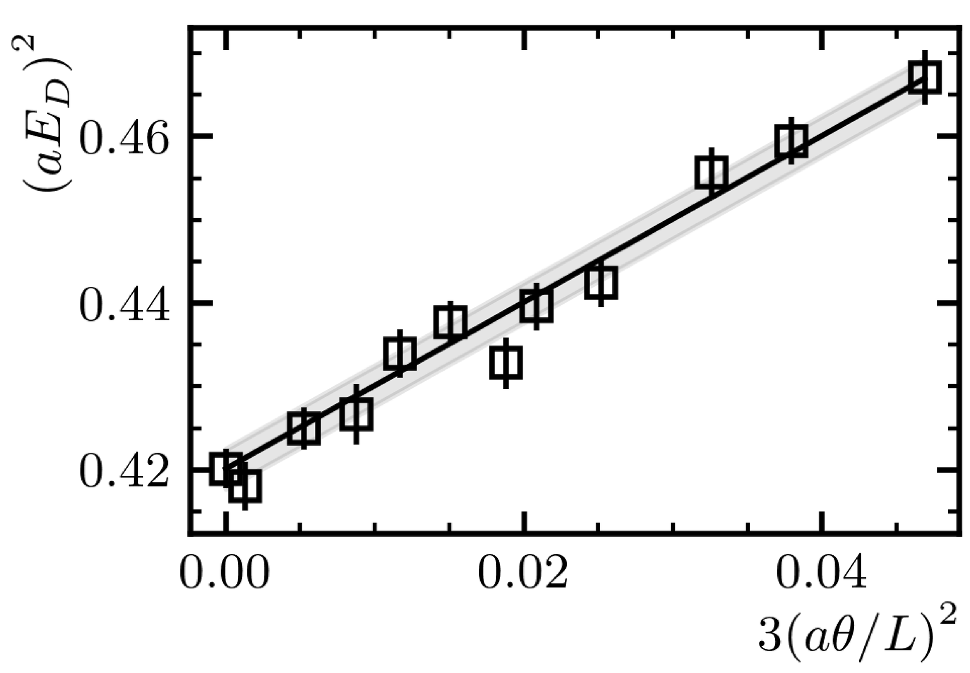
We exclude charm annihilation diagrams

Spectrum

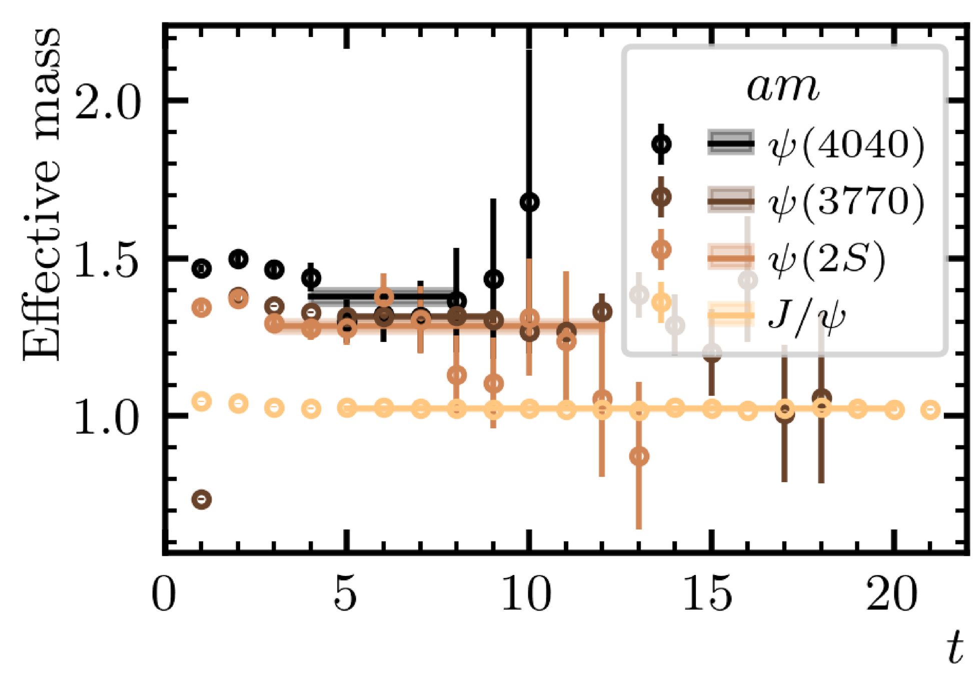
The isotropic partially-twisted boundary conditions boost the D-meson in the x, y and z directions

$$(aE_D)^2 = (am_D)^2 + 3\left(\frac{a\theta}{L}\right)^2$$

The energies are extracted with a single-exponential fit



We compute the vector-charmonium spectrum using an 8×8 GEVP with four $J^{PC} = 1^{--}$ interpolators, two Gaussian smearings, and 8 times the normal statistics. We are able to disentangle the two narrow states $\psi(2S)$ and $\psi(3770)$.



We assume the energy of the $\bar{D}D$ system is approximately $2E_D$ and we choose the momentum θ such that

$$am_{\psi(3770)} = 2E_D(\theta) \;\to \frac{\theta}{L} = \sqrt{\frac{1}{12}\left[m^2_{\psi(3770)} - (2m_D)^2\right]}$$

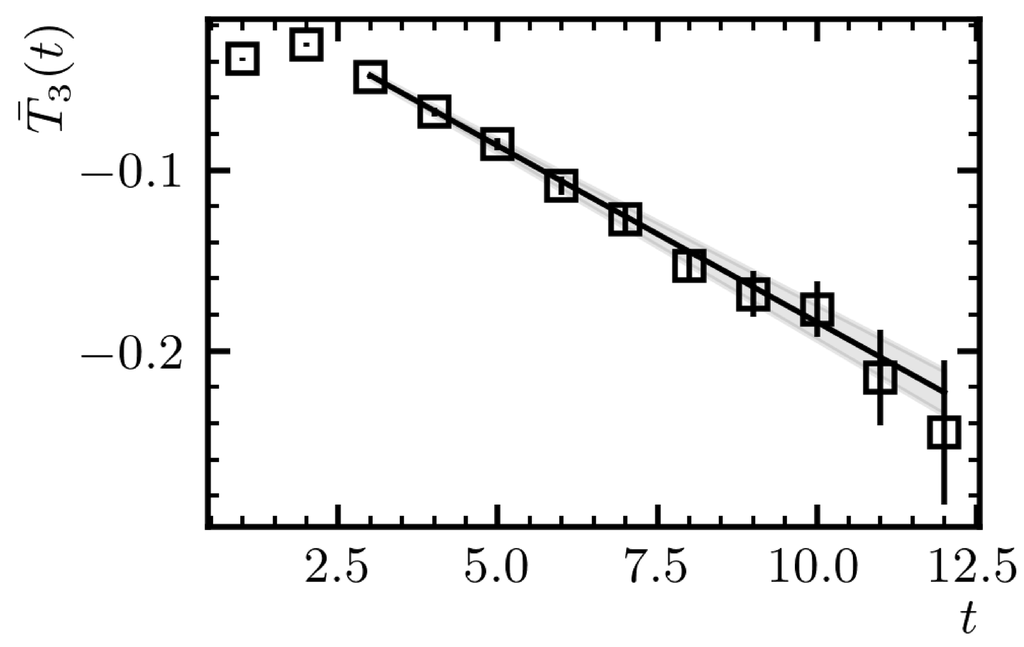
The energy of the states $\psi(3770)$ and $\bar{D}D$ is modified by the hadronic mixing x_{31} through the transfer matrix. To see this, one may solve the eigenvalue problem of the two-state transfer matrix

$$e^{-ma}\begin{pmatrix} e^{-a\Delta/2} & ax_{31} \\ ax_{31} & e^{a\Delta/2}\end{pmatrix} \quad \text{where} \quad \begin{matrix} 2m = m_{\psi(3770)} + 2m_D \\ 2\Delta = m_{\psi(3770)} - 2m_D \end{matrix} \quad \to \quad \begin{matrix} m_{\psi(3770)} = m + \sqrt{x^2 + \Delta^2} \\ 2m_D = m - \sqrt{x^2+\Delta^2}\end{matrix}$$

The decay width

It is possible to extract the hadronic mixing $x_{31} \equiv \langle \psi(3770) | \bar{D}D \rangle$ if $m_{\psi(3770)} = E_{DD}$,

$$\frac{\bar{T}_3}{\sqrt{P^{DD}P^\psi}} = x_{31}t + A$$



Then, apply Fermi's golden rule to find

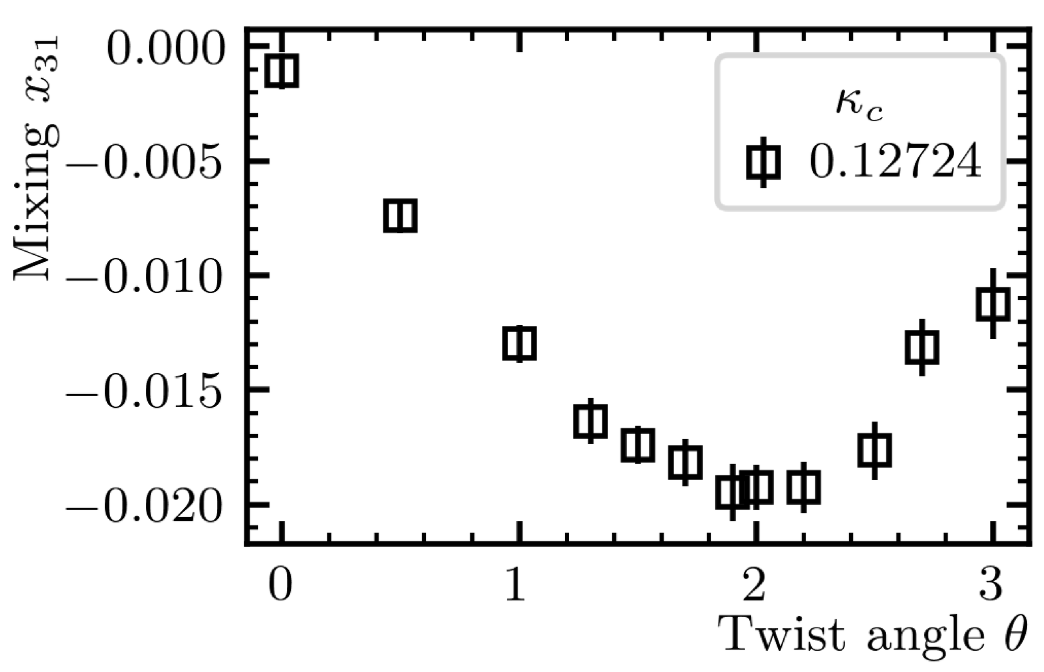
$$\Gamma\left[\psi(3770) \to \bar{D}D\right] = \frac{x^2 L^3 |\bar{p}| m_{\psi(3770)}}{24\pi}$$

Other relations to the decay width

We can explore the dependence on θ using

$$\frac{\bar{T}_3(t)}{\sqrt{P^{DD}P^\psi}} = \frac{x_{31}}{\Delta}\sinh(t\Delta) + Be^{-t\Delta}.$$

where $\Delta \equiv (m_{\psi(3770)} - E_{DD})/2 \neq 0$.



We can form a ratio that tends to the mixing directly,

$$x_{\mathrm{T}}(t) \equiv \frac{\bar{T}_3}{\sqrt{P^\psi P^{DD}}}\frac{\lambda^{t/2}}{1+\lambda+\cdots+\lambda^t} \underset{t\gg 1}{\to} x_{31}$$

where $\lambda \equiv \exp\big(m_{\psi(3770)} - E_{DD}\big)$

- Reduced precision $\to$ use as a crosscheck

If $m_{\psi(3770)} = E_{DD}$, the process $\bar{D}D \to \bar{D}D$ is also related to the mixing via virtual particles,

$$\frac{P^{DD,\text{box}}}{P^{DD}} = \frac{|x_{31}|^2}{2}t^2 + \sum_{i=1,2}\frac{|x^2_{i1}|}{\Delta_i^2}\big(-1-\Delta_i t + e^{t\Delta_i}\big)$$

where $\Delta_1 = E_{DD} - m_{J/\psi}$ and $\Delta_2 = E_{DD} - m_{\psi(2S)}$

- The mixings to J/ψ and $\psi(2S)$ also appear
- All mixings appear at $\mathcal{O}(t^2)$
- The J/ψ and $\psi(2S)$ terms dominate at long times

A further relation can be derived when the transition occurs between ground states [3], but it is not applicable here.

Next steps

- The $\bar{D}D$ correlator that we compute,

$$\langle \bar{D}^0(-\bar{p},t)D^0(\bar{p},t)\bar{D}^0(-\bar{p},0)D^0(\bar{p},0)\rangle$$

includes both $J^{PC} = 1^{--}$ and $J^{PC} = 1^{++}$. The ground state of the latter is $\chi_{c1}(1P)$, with mass 3510.67(5) MeV. We need to subtract the correlator

$$\langle \bar{D}^0(-\bar{p},t)D^0(\bar{p},t)\bar{D}^0(\bar{p},0)D^0(-\bar{p},0)\rangle$$

which cannot be computed via partially twisted boundary conditions
- Study the dependence of x_{31} on κ_c and compare to the expectation from quark models [7]
- Estimate systematics

Further reading

(1) M. Luscher, *Commun. Math. Phys.*, 1986, **104**, 177.
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