# Interactions of Charmed Mesons with Light Pseudoscalar Mesons from Lattice QCD


Liuming Liu
HISKP, Universität Bonn

in collaboration with
K. Orginos, F.-K. Guo, C. Hanhart and U.-G. Meißner



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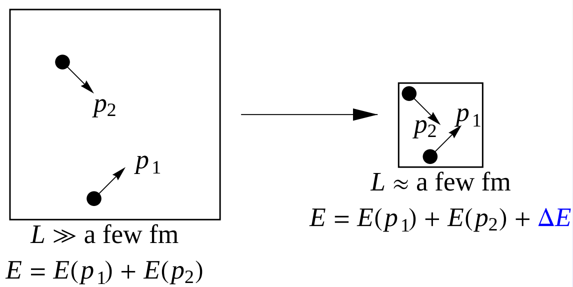
# Motivation

- In 2003 BaBar Collaboration discovered a positive-parity scalar charm strange meson $D_{s0}^*(2317)$ in $D_s\pi^0$ channel. The spin-1 partner $D_{s1}(2460)$ is also found in the $D_s^*\pi^0$ channel.
- These two states lie below $DK$ and $D^*K$ threshold respectively.
- Some proposals about their structure: molecule, chiral partner of the $(0^-, 1^-)$ doublet, tetraquark states...
- Study $DK$ interaction is important to understand the structure of $D_{s0}^*(2317)$.

# Lüscher's finite volume method




$$p \cot \delta(p) = \frac{1}{\pi L} \mathbf{S}\left(\left(\frac{pL}{2\pi}\right)^2\right)$$

The energy shift is obtained by fitting the ratio

$$R^{h_1-h_2}(t) = \frac{G^{h_1-h_2}(t,0)}{G^{h_1}(t,0)G^{h_2}(t,0)} \longrightarrow \exp(-\Delta E \cdot t) \qquad (1)$$

to a single exponential, where

$G^{h_1-h_2}(t) = \langle \mathcal{O}^{h_1}(t)\mathcal{O}^{h_2}(t)(\mathcal{O}^{h_1}(0)\mathcal{O}^{h_2}(0))^\dagger \rangle$ .

# Simulation details

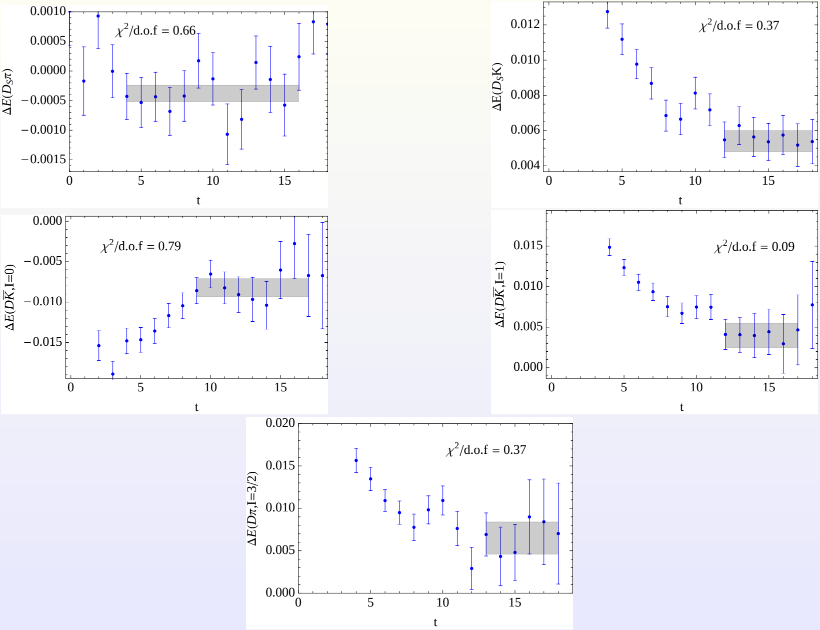
We use the gauge configurations generated by the MILC Collaboration (C. Aubin *et al*, Phys. Rev D70, 094505 (2004) ).

- Gauge action : one loop tadpole-improved gauge action. $\mathcal{O}(a^2)$ and $\mathcal{O}(g^2a^2)$ errors are removed.
- Fermion actions
  - Asqtad improved Kogut-Susskind action for sea quark.
  - Domain-wall fermion for light valence quark $(u, d, s)$.
  - Fermilab action for charm quark.
- lattice size: $20^3 \times 64$, lattice spacing $\sim 0.125$fm
- $M_\pi \sim 290, 350, 490, 590$MeV.

- The channels we studied on lattice:

$$\mathcal{O}^{I=1}_{D_s\pi} = D_s^-\pi^+, \quad \mathcal{O}^{I=3/2}_{D\pi} = D^+\pi^+, \quad \mathcal{O}^{I=1/2}_{D_sK} = D_s^+K^+,$$
$$\mathcal{O}^{I=1}_{D\bar{K}} = D^+\bar{K}^0, \quad \mathcal{O}^{I=0}_{D\bar{K}} = D^+K^- - D^0\bar{K}^0,$$

  where all the one particle operators are of the form $\bar{\psi}_1\gamma_5\psi_2$. $\pi$, $D$, $K$ and $\bar{K}$ represent the isospin triplet ($\pi^+$, $\pi^0$, $\pi^-$) and doublets ($D^+$, $D^0$), ($K^+$, $K^0$) and ($\bar{K}^0$, $K^-$), respectively.
- The channels we did not calculate directly on lattice: $D\pi(I=1/2)$, $DK(I=1)$, $DK(I=0)$ and $D_s\bar{K}(I=1/2)$.

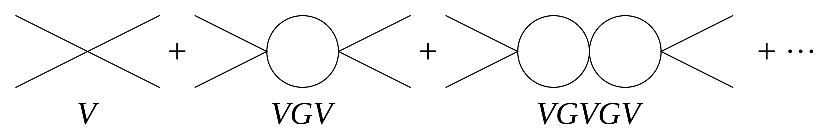


ΔE(D_S π)
χ²/d.o.f = 0.66
ΔE(D_S K)
χ²/d.o.f = 0.37
ΔE(DK̄,I=0)
χ²/d.o.f = 0.79
ΔE(DK̄,I=1)
χ²/d.o.f = 0.09
ΔE(Dπ,I=3/2)
χ²/d.o.f = 0.37
t

# Chiral extrapolations

Resum the chiral amplitude up to $\mathcal{O}(p^2)$:

$$T(s) = V(s)[1 - G(s)V(s)]^{-1},$$




G is regularized by a subtraction constant $\tilde{a}(\lambda)$.

$$V(s,t,u) = \frac{1}{F^2}\left[\frac{C_{\rm LO}}{4}(s-u) - 4C_0 h_0 + 2C_1 h_1 - 2C_{24}H_{24}(s,t,u) + 2C_{35}H_{35}(s,t,u)\right],$$

$$H_{24}(s,t,u) = 2h_{24}p_2\cdot p_4 + h_4\left(p_1\cdot p_2 p_3\cdot p_4 + p_1\cdot p_4 p_2\cdot p_3 - 2\bar{M}_D^2 p_2\cdot p_4\right),$$

and

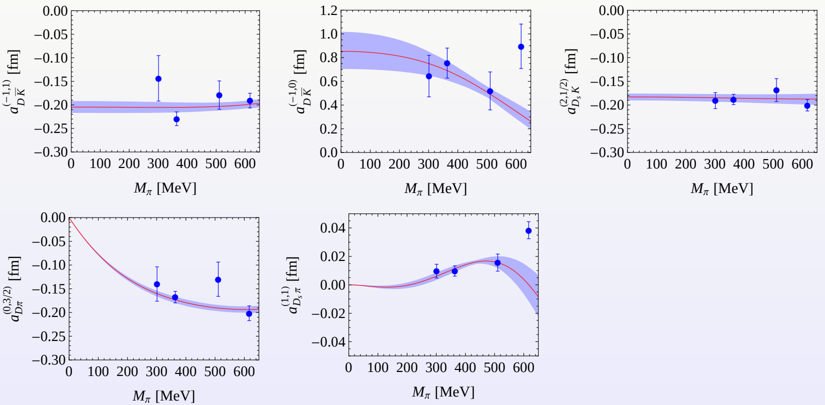
$$H_{35}(s,t,u) = h_{35}p_2\cdot p_4 + h_5\left(p_1\cdot p_2 p_3\cdot p_4 + p_1\cdot p_4 p_2\cdot p_3 - 2\bar{M}_D^2 p_2\cdot p_4\right),$$

| | $M_\pi$ | $M_K$ | $M_D$ | $M_{D_s}$ |
|---|---|---|---|---|
| m007 | 0.1842(7) | 0.3682(5) | 1.2081(13) | 1.2637(10) |
| m010 | 0.2238(5) | 0.3791(5) | 1.2083(11) | 1.2635(10) |
| m020 | 0.3113(4) | 0.4058(4) | 1.2226(13) | 1.2614(12) |
| m030 | 0.3752(5) | 0.4311(5) | 1.2320(11) | 1.2599(12) |

- $h_1$ is determined by the $SU(3)$ flavor mass splitting.
- We will use

$$\begin{aligned} M_K &= \mathring{M}_K + M_\pi^2/(4\mathring{M}_K), \\ M_D &= \mathring{M}_D + (h_1 + 2h_0)\frac{M_\pi^2}{\mathring{M}_D}, \\ M_{D_s} &= \mathring{M}_{D_s} + 2h_0\frac{M_\pi^2}{\mathring{M}_{D_s}}. \end{aligned}$$

| $\chi^2$/dof | $\tilde{a}(\lambda = 1\ \text{GeV})$ | $h_{24}$ | $h'_4$ | $h_{35}$ | $h'_5$ |
|---|---|---|---|---|---|
| 1.06 | $-1.88^{+0.07}_{-0.09}$ | $-0.10^{+0.05}_{-0.06}$ | $-0.32^{+0.35}_{-0.34}$ | $0.25 \pm 0.13$ | $-1.88^{+0.63}_{-0.61}$ |



The scattering lengths extrapolated to the physical light quark masses:

| Channels | $D\bar{K}(I=1)$ | $D\bar{K}(I=0)$ | $D_sK$ | $D\pi(I=3/2)$ | $D_s\pi$ |
|---|---|---|---|---|---|
| $a$ (fm) | $-0.20(1)$ | $0.84(15)$ | $-0.18(1)$ | $-0.100(2)$ | $-0.002(1)$ |

The other channels can be predicted from the LEC's determined from the fit:

| Channels | $a$ (fm) |
|---|---|
| $D\pi(I=1/2)$ | $0.37^{+0.03}_{-0.02}$ |
| $DK(I=0)$ | $-0.84^{+0.17}_{-0.22}$ |
| $DK(I=1)$ | $0.07\pm0.03+i(0.17^{+0.02}_{-0.01})$ |
| $D_s\bar{K}$ | $-0.09^{+0.06}_{-0.05}+i(0.44\pm0.05)$ |

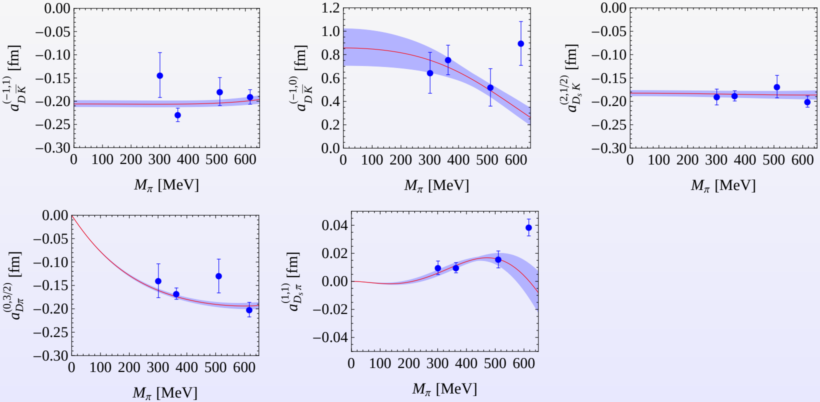
- The interaction in $DK(I=0)$ channel is so strong that the a pole emerges in the resummed amplitude.
- An pole on the real axis can be found in the first Riemann sheet, which correspond to a bound state. The pole position is $2315^{+18}_{-28}$ MeV.
- If there is an $S$-wave shallow bound state, the scattering length is related to the binding energy, and to the wave function renormalization constant $Z$, with $1-Z$ being the probability of finding the molecular component in the physical state (S. Weinberg, Phys.Rev. 137, B672 (1965).

$$a = -2\left(\frac{1-Z}{2-Z}\right)\frac{1}{\sqrt{2\mu\epsilon}}\left(1+\mathcal{O}(\sqrt{2\mu\epsilon}/\beta)\right).$$

$1-Z$ is found to be in the range [0.66, 0.73].
If $Z=0$, $a=-1.05$fm

Fix the pole position at the physical mass of $D^*_{s0}(2317)$ at the first Riemann sheet.

| $\chi^2$/d.o.f | $h_{24}$ | $h'_4$ | $h_{35}$ | $h'_5$ |
|---|---|---|---|---|
| 0.97 | $-0.10^{+0.05}_{-0.06}$ | $-0.30^{+0.31}_{-0.28}$ | $0.26^{+0.09}_{-0.10}$ | $-1.94^{+0.46}_{-0.38}$ |



| Channels | $a$(fm) |
|---|---|
| $D\bar{K}(I=1)$ | $-0.21(1)$ |
| $D\bar{K}(I=0)$ | $0.84(15)$ |
| $D_sK$ | $-0.18(1)$ |
| $D\pi(I=3/2)$ | $-0.100(1)$ |
| $D_s\pi$ | $-0.002(1)$ |
| $D\pi(I=1/2)$ | $0.37\pm0.01$ |
| $DK(I=0)$ | $-0.86\pm0.03$ |
| $DK(I=1)$ | $0.04^{+0.05}_{-0.01}+i(0.16^{+0.02}_{-0.01})$ |
| $D_s\bar{K}$ | $-0.06^{+0.01}_{-0.05}+i(0.45\pm0.05)$ |

# Isospin breaking decay width of the $D^*_{s0}(2317)$

- The decay width of the $D^*_{s0}(2317) \to D_s\pi^0$ can be a good criterion for testing the nature of the $D^*_{s0}(2317)$. In the $c\bar{s}$ meson picture, the decay width is of order 10 keV. In the molecular picture, it is of order 100keV.
- With the LEC's obtained from the fit, and the isospin breaking quark mass ratio $(m_d - m_u)/(m_s - \hat{m}) = 0.0299 \pm 0.0018$, we have:

$$\Gamma(D^*_{s0}(2317) \to D_s\pi) = (133 \pm 22)\ \text{keV}.$$

- Conclusions
  - We calculate the scattering lengths of five channels, $D\bar{K}(I=1)$, $D\bar{K}(I=0)$, $D_sK$, $D\pi(I=3/2)$ and $D_s\pi$ on lattices.
  - Chiral extrapolation is performed in a unitarized approach. The LEC's are determined.
  - The scattering length of the other channels, $D\pi(I=1/2)$, $DK(I=1)$, $DK(I=0)$ and $D_s\bar{K}$, are predicted from the LEC's.
  - We find that the attractive interaction in the $DK(I=0)$ channel is strong enough so that a pole is generated in the unitarized scattering amplitude. The pole position is close to $D^*_{s0}(2317)$.
  - The isospin breaking decay width is calculated and the result support the molecule interpretation of $D^*_{s0}(2317)$.
- In the future: disconnected diagrams, coupled channels, volume dependence...

*Thank you!*