From lattice QCD to predictions of scattering phase shifts at the physical point

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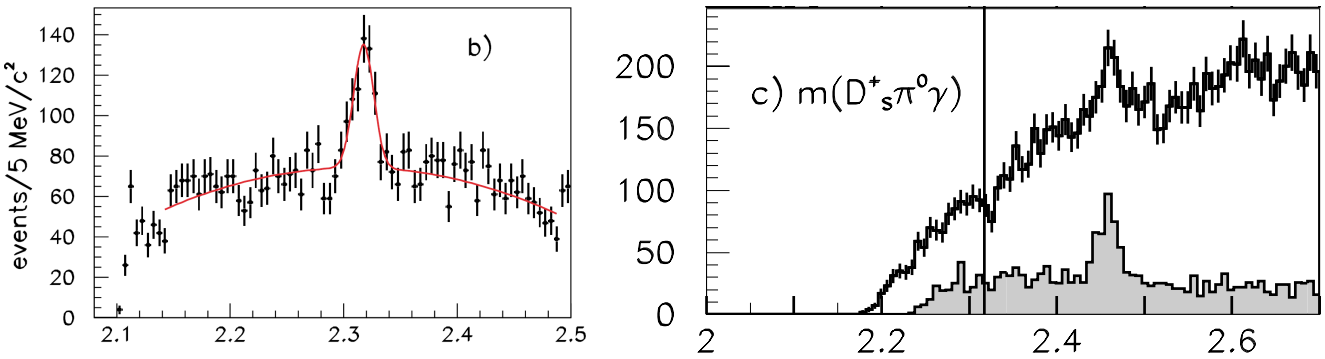
Outline

Exotic open-charm meson states

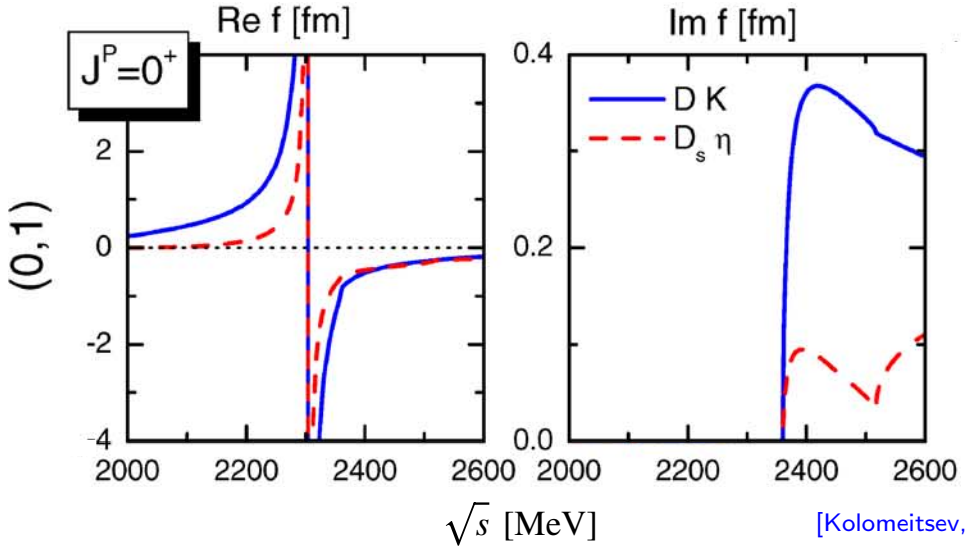
- quark model $\rightarrow$ an open-charm meson consists of a charm quark and a light (anti)quark
- the discovery of $D_{s0}^{*}(2317)$ and $D_{s1}(2460)$
  - isospin and strangeness $(I, S) = (0, 1)$
  - $D_{s0}^{*}(2317)$: $J^P = 0^+$ [BaBar (2003)]
  - $D_{s1}(2460)$: $J^P = 1^+$ [BaBar (2003)]
  - $\sim$ 150MeV lower than quark model [Godfrey, Isgur (1985)]



[BaBar (2003)]

- $D_{s0}^*(2317)$ and $D_{s1}(2460)$
  - a few MeV below DK/ D^*K thresholds
- dynamical generation from s-wave DK (D^*K) scattering
  - scattering coupled with $D_s\eta$ ($D_s^*\eta$)
  - from leading order chiral SU(3) Lagrangian [Kolomeitsev, Lutz (2003), Guo et al (2009)]
    $\rightarrow$ implemented with s-wave unitarity via resummation
  - stable against higher order chiral corrections

    [Lutz, Soyeur (2008), Liu et al (2012), Altenbuchinger et al (2013), Du et al (2017), XYG et al (2018)]



[Kolomeitsev, Lutz (2003)]

Scalar resonance with isospin-strangeness $(I, S) = (1/2, 0)$

- experimentalists have observed one resonance, as $D_0^*(2300)$
  - broad, with a measured mass ranging $2300 \sim 2400$ MeV [Belle, BaBar, Focus]
  - significantly heavier than expected as an SU(3) partner of $D_{s0}^*(2317)$
  - two-pole structure can be compatible with data [Du et al (2017)]
- from $D\pi$ scattering applying the chiral Lagrangian
  - three-channel coupled system with $D\pi$, $D\eta$, $D_s\bar{K}$
  - a two-pole structure in the scattering amplitude

    [Kolomeitsev, Lutz (2003), Lutz, Soyeur (2008), Albaladejo et al (2018), XYG et al (2018), Du et al (2021)]
  - pole masses (central values):

    LO chiral interaction (with unitarization from GSI):
    $(2117 - 151i)$ MeV, $(2390 - 38i)$ MeV [Kolomeitsev, Lutz (2003)]

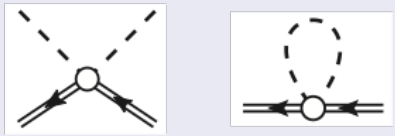
    including NLO chiral interactions (with unitarization from Bonn):
    $(2105 - 102i)$ MeV, $(2451 - 134i)$ MeV [Du et al (2017)]

    including NLO chiral interactions (with unitarization from GSI):
    $(2082 - 187i)$ MeV and $(2439 - 92i)$ MeV [XYG, Heo, Lutz PRD98(2018)014510]

Global fit to lattice data with the chiral Lagrangian

- we applied the NLO chiral Lagrangian to the lattice data set on D-meson masses and scattering observables

NLO Lagrangian



$$\mathcal{L}^{(2)} = -(4c_0 - 2c_1)D\bar{D}\,\mathrm{tr}\chi_+ - 2c_1 D\chi_+\bar{D} + 4(2c_2 + c_3)D\bar{D}\,\mathrm{tr}(U_\mu U^{\mu\dagger})$$
$$-4c_3 DU_\mu U^{\mu\dagger}\bar{D} + \frac{1}{M^2}(4\,c_4 + 2\,c_5)\,(\hat{\partial}_\mu D)(\hat{\partial}_\nu \bar{D})\mathrm{tr}\big[U^\mu, U^{\nu\dagger}\big]_+$$
$$-\frac{1}{M^2}\,2\,c_5\,(\hat{\partial}_\mu D)\big[U^\mu,\ U^{\nu\dagger}\big]_+(\hat{\partial}_\nu \bar{D})$$

  - 64 data points for D-masses, from ETMC, HPQCD, PACS, LHPC, HSC $\rightarrow$ in the chiral mass correction: internal masses are set to on-shell masses
  - scattering observables with LHPC and HSC ensembles at unphysical quark masses

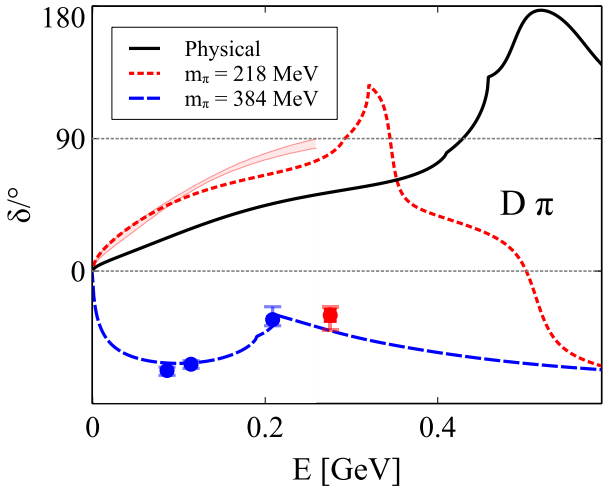
[XYG, Heo, Lutz, PRD98(2018)014510]

Global fit to lattice data with the chiral Lagrangian

- the validity of our approach needs to be tested against further lattice data
  - in 2018, all s-wave D-meson two-body scattering phase shifts were predicted for two HSC ensembles with $m_\pi \simeq 220\,\text{MeV}$ and $380\,\text{MeV}$
    [XYG, Heo, Lutz (2018)]
- this year HSC presented new results on those two ensembles
  [HSC 2008.06432, 2102.04973]
  - this talk: dedicated to the comparison of our prediction and the lattice results

Open-charm phase shifts: compared with HSC results

- $(I, S) = (1/2, 0)$ $D\pi$ scattering phase shifts for the physical case and the two HSC ensembles



[XYG, Heo, Lutz PRD98(2018)014510]

[HSC JHEP10(2016)011]

[HSC 2102.04973]

- plotted as functions of kinetic energy in the c.m. frame $E = \sqrt{s} - \sqrt{s}_{\rm thr}$
- striking dependence on light-quark mass from both our predictions and lattice
- for physical case: the black line shaped by the two-pole structure

Open-charm phase shifts: compared with HSC results

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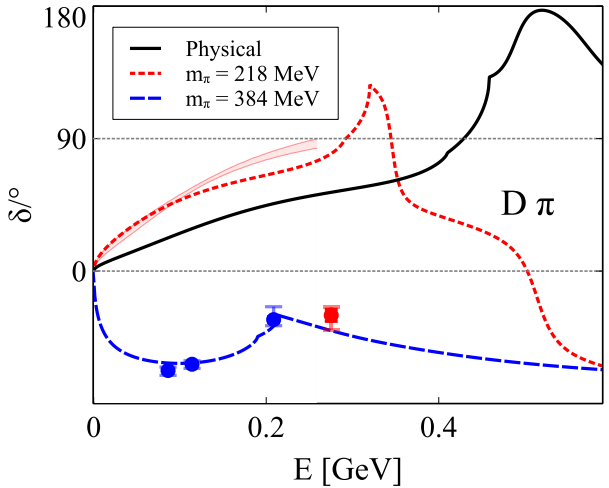


[XYG, Heo, Lutz PRD98(2018)014510]

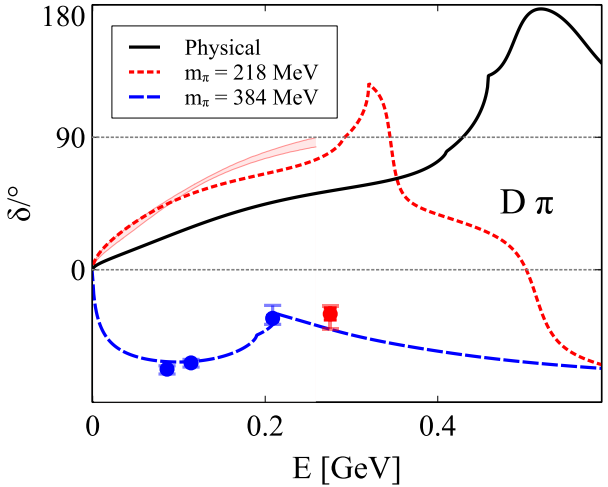
[HSC JHEP10(2016)011]

[HSC 2102.04973]

- ensemble at $m_\pi \simeq 380\,\text{MeV}$: binned lattice data [HSC (2016)]
  $\rightarrow$ blue/red points are fitted/unfitted
  $\rightarrow$ the blue line from our best fit
- both the lattice and our fit show a real pole below the $D\pi$ threshold
- we predict a second (complex) pole at around the $D_s\bar{K}$ threshold
  $\rightarrow$ affect the $D\pi$ phase-shift very little

Open-charm phase shifts: compared with HSC results

- $(I, S) = (1/2, 0)$ $D\pi$ scattering phase shifts for the physical case and the two HSC ensembles



[XYG, Heo, Lutz PRD98(2018)014510]

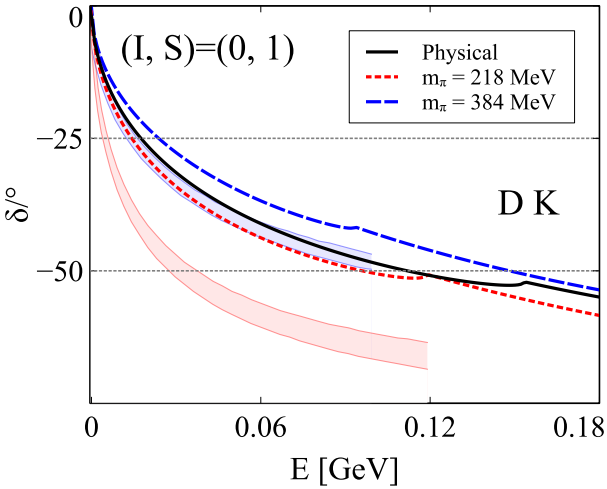
[HSC JHEP10(2016)011]

[HSC 2102.04973]

- ensemble at $m_\pi \simeq 220\,\text{MeV}$:
  $\rightarrow$ our prediction in red line
  $\rightarrow$ lattice result in red band [HSC (2021)]
- one pole from both lattice and us: between the $D\pi$ and $D\eta$ threshold, far away from the real axis
- we predict another pole slightly above the $D\eta$ threshold

DK scattering phase shifts

- DK scattering phase shifts with $(I, S) = (0, 1)$

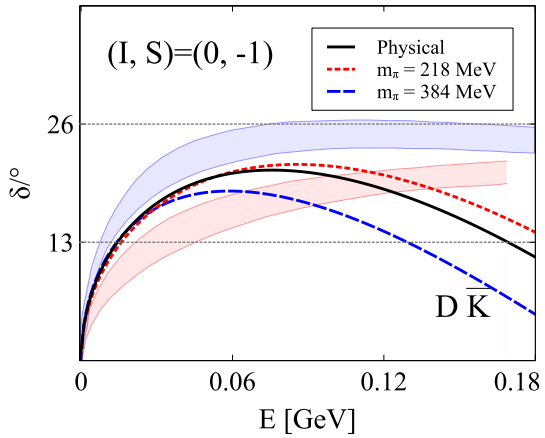


[XYG, Heo, Lutz PRD98(2018)014510]

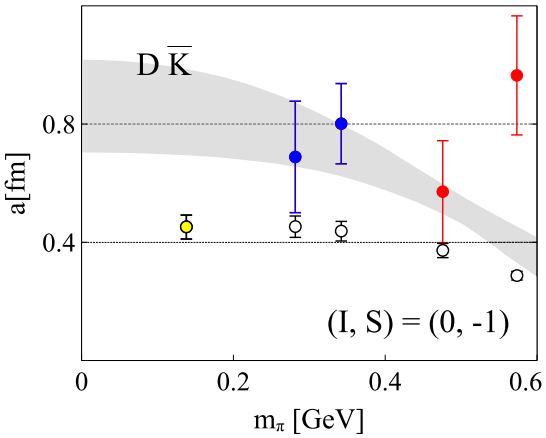
[HSC 2008.06432]

- we predict a decline of the phase shift
- driven by a pole below DK threshold
  $\rightarrow$ physical case: recognized as $D_{s0}^*(2317)$
  $\rightarrow$ stable against a variation of light-quark masses
- the pole position heavily affects the shape of the phase shifts
- further improvements are requested

$D\bar{K}$ scattering phase shifts and lengths

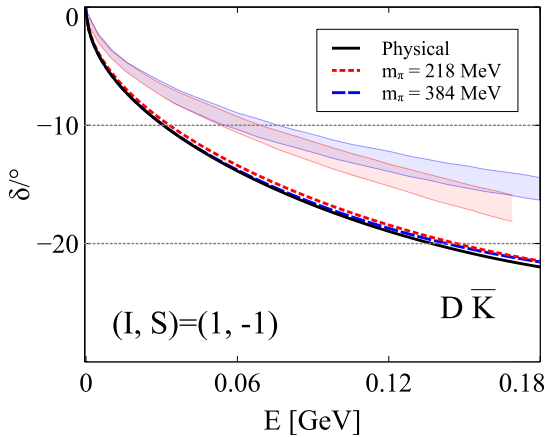


- for $m_\pi \simeq 220(380)$MeV, our predictions in red (blue) lines vs. lattice in red (blue) bands [HSC (2020)]
- close to the threshold, overshoot the lattice result for $m_\pi \simeq 220\,\text{MeV}$ $\rightarrow$ overestimate the scattering length at $m_\pi \simeq 220\,\text{MeV}$

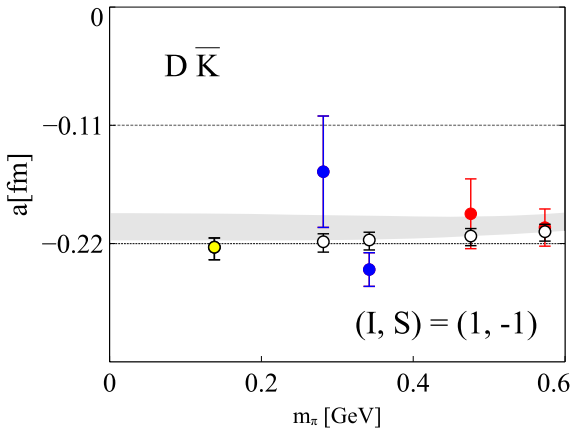


- LHPC data points in blue are included in our fit [Liu et al (2012)]
- our fit (white points) already undershoots those $\rightarrow$ driven by our global fit
- compare to fit from Bonn group (gray band) [Liu et al (2012)]

$D\bar{K}$ scattering phase shifts and lengths



- our predictions in red/blue lines vs. lattice in red/blue bands [HSC (2020)]
- both show little dependence on light-quark mass
- tension in the magnitude of the scattering length



- LHPC data points in blue are included in our fit [Liu et al (2012)]
- the second data point seems incompatible with HSC results
- a similar fit result from Bonn in gray band [Liu et al (2012)]

Summary

- a critical discussion of predictions we have made for D-meson systems in comparison with latest lattice results [HSC (2020,2021)]
  - the predictions were based on available global lattice data, in application of the chiral SU(3) Lagrangian
  - the latest lattice data are phase shifts for $D\pi$, DK, $D\bar{K}$ scatterings on HSC ensembles with $m_\pi \simeq 220,\ 380\,\mathrm{MeV}$
- the prediction on $D\pi$ phase shift at $m_\pi \simeq 220\mathrm{MeV}$ appears quite compatible with the HSC result
  - strong support for the two-pole structure in the scattering amplitude
- significant tension in the $D\bar{K}$ elastic scattering phase-shifts
  - further studies are called on this issue