第三届LHCb前沿物理研讨会

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国会学术厅

Decays of $D_{s0}^*(2317)$ and $D_{s1}(2460)$

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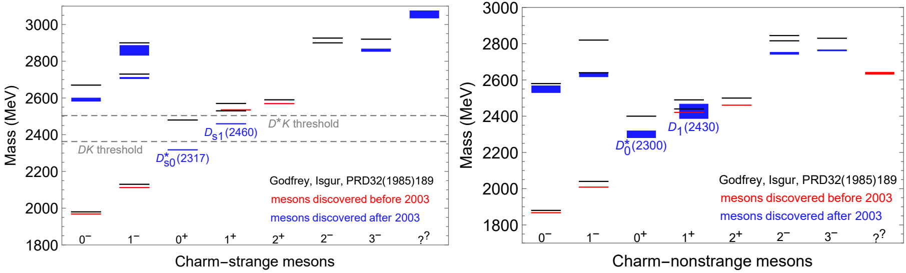
国科大雁栖湖校区, 2023.04.15–16

Puzzles of positive-parity charmed mesons



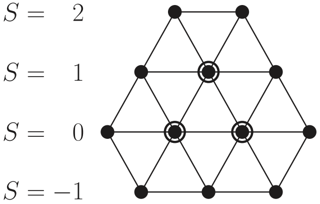
- Puzzle 1: Why are $D^*_{s0}(2317)$ and $D_{s1}(2460)$ so light?
- Puzzle 2: Why $\underbrace{M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)}}_{(141.8\pm0.8)\text{ MeV}} \simeq \underbrace{M_{D^{*\pm}} - M_{D^\pm}}_{(140.67\pm0.08)\text{ MeV}}$?
- Puzzle 3: Why $M_{D^*_0(2300)} \gtrsim M_{D^*_{s0}(2317)}$ and $M_{D_1(2430)} \sim M_{D_{s1}(2460)}$?

  $D^*_0(2300)$ was denoted as $D^*_0(2400)$ up to PDG2018

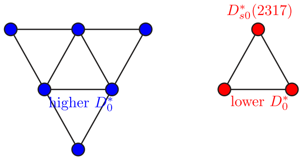
Solution to the puzzles in the hadronic molecular model

- Solution to Puzzle 1: not quark model $c\bar{s}$ mesons:
  $D^*_{s0}(2317)[\simeq DK(I=0)]$, $D_{s1}(2460)[\simeq D^*K(I=0)]$
  Barnes, Close, Lipkin (2003); van Beveren, Rupp (2003); Kolomeitsev, Lutz (2004); FKG et al. (2006); FKG, Hanhart, Meißner (2009); . . .
- Solution to Puzzle 2: HQSS $\Rightarrow$ similar binding energies
  $M_D + M_K - M_{D^*_{s0}} \simeq 45$ MeV

  $$M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)} \simeq M_{D^*} - M_D \text{ is natural}$$
- Solution to Puzzle 3: SU(3) irreps: $\bar{3} \otimes 8 = \overline{15} \oplus 6 \oplus \bar{3}$



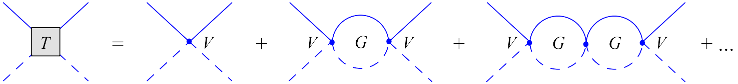
Albaladejo et al., PLB767(2017)465



two D^*_0, the SU(3) partner of $D^*_{s0}(2317)$ is the lower one

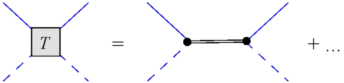
Unitarized chiral perturbation theory

- S-wave interactions between (D, D_s) and pseudo-Goldstone bosons (π, K, η)



- not far from the thresholds ⇒ chiral EFT for matter fields
- D^*_{s0}/D^*_0 should appear as poles in scattering amplitudes:

$$D^*_{s0} : DK, D_s\eta; \qquad D^*_0 : D\pi, D\eta, D_s\bar{K}$$



⇒ needs a nonperturbative treatment: ChPT + unitarization (UChPT)

Truong (1988); Oller, Oset (1997); Oller, Oset, Peláez (1998); Oller, Meißner (2001); . . .

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

$V(s)$: from SU(3) chiral Lagrangian, 6 LECs up to NLO (fixed w/ lattice inputs)

L. Liu, Orginos, FKG, Hanhart, Meißner, PRD86(2013)014508

LO (universal from χ sym.): $\overline{15}$: repulsive; 6: attractive; $\bar{3}$: most attractive

Predictions for 0^+ & 1^+ heavy mesons

M.-L. Du et al., PRD98(2018)094018

- Heavy quark spin + flavor symmetry: more predictions, heavy-strange

meson	J^P	prediction (MeV)	PDG2022 (MeV)	lattice (MeV)
D_{s0}^*	0^+	2315^{+18}_{-28}	2317.8 ± 0.5	
D_{s1}	1^+	2456^{+15}_{-21}	2459.5 ± 0.6	
B_{s0}^*	0^+	5720^{+16}_{-23}	–	5711 ± 23[1]
B_{s1}	1^+	5772^{+15}_{-21}	–	5750 ± 25[1]

- Heavy-nonstrange, two $I = 1/2$ states $(M, \Gamma/2)$:

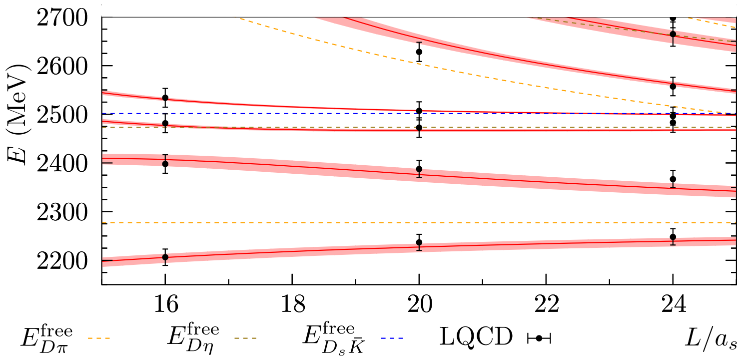
	Lower (MeV)	Higher (MeV)	PDG2022 (MeV)
D_0^*	$(2105^{+6}_{-8}, 102^{+10}_{-11})$	$(2451^{+36}_{-26}, 134^{+7}_{-8})$	$(2343 \pm 10, 115 \pm 8)$
D_1	$(2247^{+5}_{-6}, 107^{+11}_{-10})$	$(2555^{+47}_{-30}, 203^{+8}_{-9})$	$(2412 \pm 9, 157 \pm 15)$
B_0^*	$(5535^{+9}_{-11}, 113^{+15}_{-17})$	$(5852^{+16}_{-19}, 36 \pm 5)$	–
B_1	$(5584^{+9}_{-11}, 119^{+14}_{-17})$	$(5912^{+15}_{-18}, 42^{+5}_{-4})$	–

[1] Lang, Mohler, Prelovsek, Woloshyn, PLB750(2015)17

Agreements with lattice results (1)

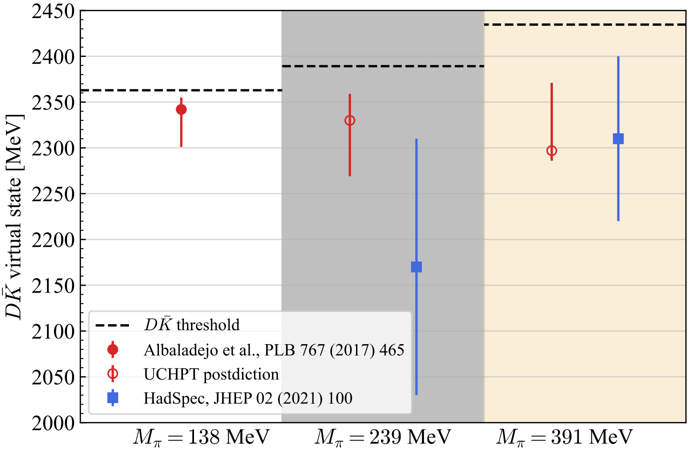
- Postdicted $I = 1/2\ D\pi, D\eta, D_s\bar{K}$ finite volume energy levels in c.m. frame v.s. lattice QCD results (more later) in [G. Moir *et al.* [HadSpec], JHEP1610(2016)011]

NOT a fit ! M. Albaladejo, P. Fernandez-Soler, FKG, J. Nieves, PLB767(2017)465



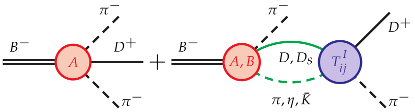
Agreements with lattice results (2)

- Predicted $(S, I) = (-1, 0)$ $D\bar{K}$ virtual state got support from lattice



Agreements with exp. (1)

M.-L. Du et al., PRD98(2018)094018



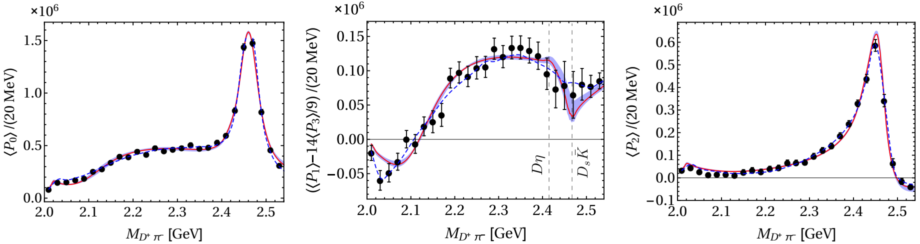
- SU(3) symmetry Savage, Wise (1989)
- S-wave: FSI, two new parameters
- P, D-wave: BWs from the LHCb fit

Angular moments:

$$\langle P_0 \rangle \propto |\mathcal{A}_0|^2 + |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2, \quad \langle P_2 \rangle \propto \frac{2}{5}|\mathcal{A}_1|^2 + \frac{2}{7}|\mathcal{A}_2|^2 + \frac{2}{\sqrt{5}}|\mathcal{A}_0||\mathcal{A}_2|\cos(\delta_2 - \delta_0),$$

$$\langle P_{13} \rangle \equiv \langle P_1 \rangle - \frac{14}{9}\langle P_3 \rangle \propto \frac{2}{\sqrt{3}}|\mathcal{A}_0||\mathcal{A}_1|\cos(\delta_1 - \delta_0)$$

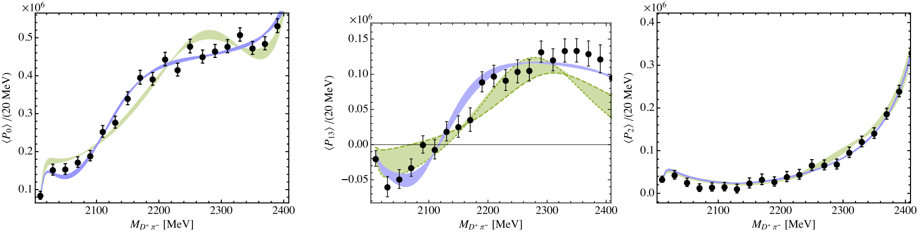
Data: LHCb, PRD94(2016)072001



- Fast variation in [2.4, 2.5] GeV in $\langle P_{13} \rangle$: cusps at $D\eta$ and $D_s\bar{K}$ thresholds

Agreements with exp. (2) M.-L. Du, FKG, Hanhart, Kubis, Meißner, PRL126(2021)192001

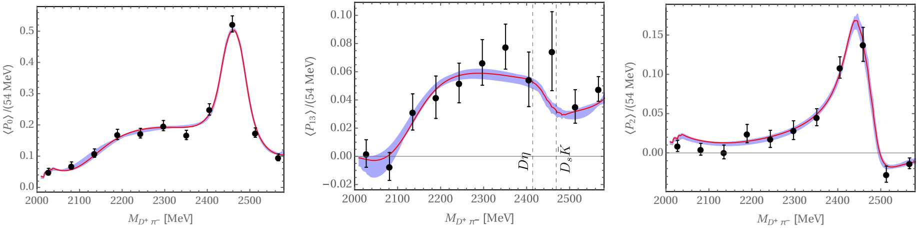
- Fits with the Khuri-Treiman equation taking into account three-body unitarity:
  - ⋆ using S-wave $D\pi$ scattering phase from UCHPT ($\chi^2/\text{d.o.f.} = 1.2$)
  - ⋆ from Breit-Wigner for $D_0^*(2300)$ w/ PDG parameters ($\chi^2/\text{d.o.f.} = 2.0$)



- The LHCb data are well described with UCHPT amplitude with two D_0^* states; the lower one has a mass about 2.1 GeV

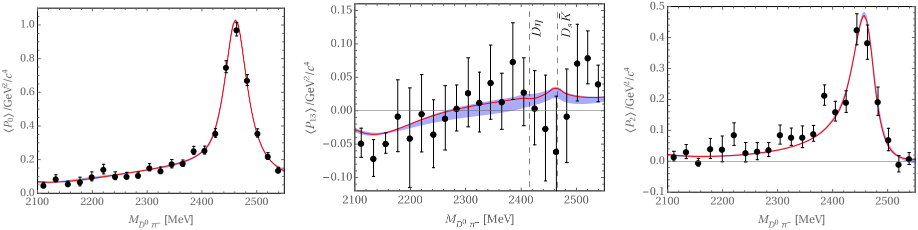
More B decays: $B^- \to D^+\pi^-K^-$

Data: LHCb, PRD91(2015)092002



$B^0 \to \bar{D}^0\pi^-\pi^+$

Data: LHCb, PRD92(2015)032002



and also $B^0 \to \bar{D}^0\pi^-K^+$, $B^- \to D^+\pi^-K^-$, $B_s^0 \to \bar{D}^0K^-\pi^+$

D_0^* in PDG2022

$D_0^*(2300)$

$I(J^P) = 1/2(0^+)$

was $D_0^*(2400)$

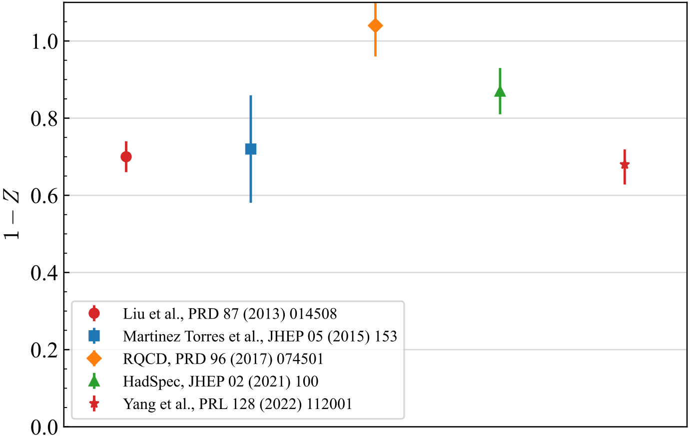
There is a strong evidence that recent data on $B \to D\pi\pi$ (AAIJ 2015Y, AAIJ 2016AH) and $B \to D\pi K$ (AAIJ 2014BH, AAIJ 2015V, AAIJ 2015X) call for two poles in the scalar $I = 1/2\ \pi D$ amplitude in this mass range. The data are consistent with a lower pole at $(2105\ ^{+6}_{-8}) - i(102\ ^{+10}_{-11})$ MeV and a higher pole at $(2451\ ^{+35}_{-26}) - i(134\ ^{+7}_{-8})$ MeV (DU 2018A, DU 2019 , DU 2021). For details see review on "Heavy Non-$q\bar{q}$ Mesons."

Independent analyses of data from other groups are called for to change the PDG entry!!

D_{s0}^* as DK molecule from lattice QCD

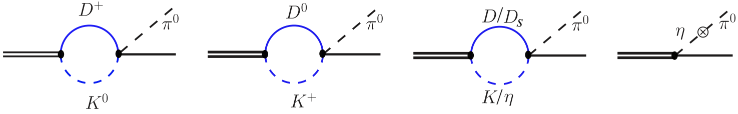
- $1-Z$: compositeness (DK component) for $D_{s0}^*(2317)$ from (in)direct lattice QCD calculations: DK as the main component, $\Rightarrow$ hadronic molecule

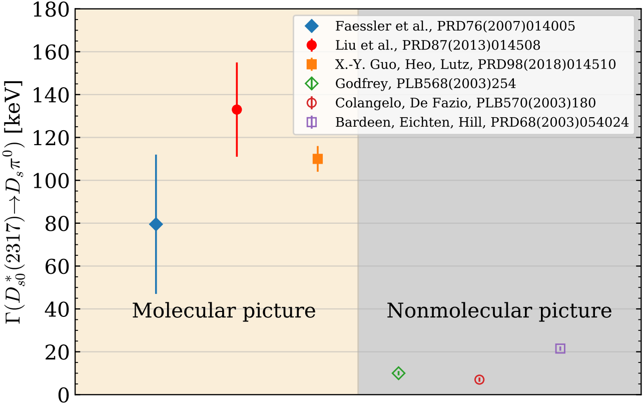
  reviews of compositeness: Hyodo, IJMPA28(2013)1330045; FKG, Hanhart, Meißner, Wang, Zhao, Zou, RMP90(2018)015004



Decays of $D_{s0}^*(2317)$

- Dominant channel: $D_{s0}^*(2317) \to D_s\pi^0$
- Measurement of total width planned at PANDA





Hadronic decays of $D_{s1}(2460)$

- Experimental measurement:

$$\frac{\Gamma\left(D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-\right)}{\Gamma\left(D_{s1}(2460)^+ \to D_s^{*+}\pi^0\right)} = \begin{cases} 0.14 \pm 0.04 \pm 0.02 & \text{Belle, PRL 92(2004)012002} \\ 0.09 \pm 0.02 & \text{PDG fit} \end{cases}$$

- Isospin breaking $D_{s1} \to D_s^*\pi^0$: (111 ± 15) keV — H.-L. Fu et al., EPJA58(2022)70
- How about $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$?
  - CHPT result from — S. Fajfer, A. Prapotnik Brdnik, PRD92(2015)074047

$$\Gamma\left(D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-\right) = 0.25(4)(7)\left({}^{+2}_{-4}\right)\,\mathrm{keV}$$

    Both D_s and D_{s1} were treated statically, P-wave happens between π^+ and $\pi^- \Rightarrow I(\pi^+\pi^-) = 1$, isospin breaking

  - But isospin is conserved (!!) for P-wave between D_s and isoscalar $\pi^+\pi^-$

$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ (1)

M.-N. Tang, Y.-H. Lin, FKG, C. Hanhart, U.-G. Meißner, arXiv:2303.18225 [hep-ph] (CTP, in print)

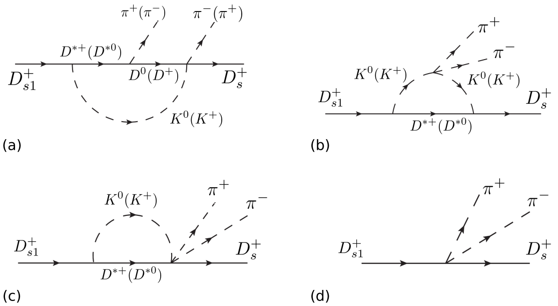
- Hadronic molecule v.s. other (compact) components

  Effective coupling contains crucial information — S. Weinberg, PR137(1965)B672

$$g^2 \propto (1-Z)\sqrt{2\mu E_B}$$

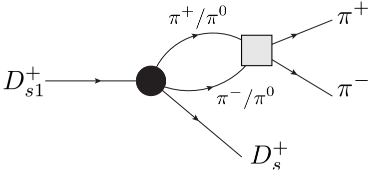
  is maximized for a pure molecular state

- Diagrams for $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$: (a,b,c): leading for molecular state



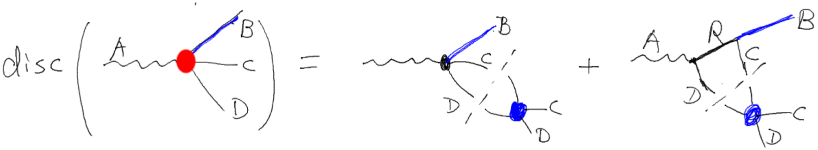
$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ (2)

- Phase space: $m_{\pi^+\pi^-} \in [2M_{\pi^\pm}, 0.49\ \text{GeV}]$
- $\pi\pi$ final state interaction (FSI) is important in S-wave: $f_0(500)$ (σ) meson



Black filled circle: all the one-loop diagrams in the previous page, $\hat{\mathcal{A}}_L(s)$

- Unitarity $\Rightarrow$ dispersion relation



$$\frac{1}{2i}\,\text{disc}\left[\mathcal{A}_L(s) + \underbrace{\hat{\mathcal{A}}_L(s)}_{\text{no right-hand cut}}\right] = \mathcal{A}_L(s)\rho(s)T_L^*(s) + \hat{\mathcal{A}}_L(s)\rho(s)\underbrace{T_L^*(s)}_{\pi\pi\ \text{scattering}}$$

$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ (3)

Solution to the dispersive equation, δ_L L-wave phase shift:

$$\frac{1}{2i}\,\text{disc}\,\mathcal{A}_L(s) = \left[\mathcal{A}_L(s) + \hat{\mathcal{A}}_L(s)\right]\sin\delta_L(s)e^{-i\delta_L(s)}$$

- Rewrite the unitarity relation using $\text{disc}\,\mathcal{A}_L(s) = \mathcal{A}_L(s+i\epsilon) - \mathcal{A}_L(s-i\epsilon)$:

$$\frac{1}{2i}\left[\mathcal{A}_L(s+i\epsilon)e^{-i\delta_L(s)} - \mathcal{A}_L(s-i\epsilon)e^{i\delta_L(s)}\right] = \hat{\mathcal{A}}_L(s)\sin\delta_L(s)$$

- Using properties of the Omnès function:

$$|\Omega_L(s)| = \Omega_L(s+i\epsilon)e^{-i\delta_L(s)} = \Omega_L(s-i\epsilon)e^{i\delta_L(s)},$$

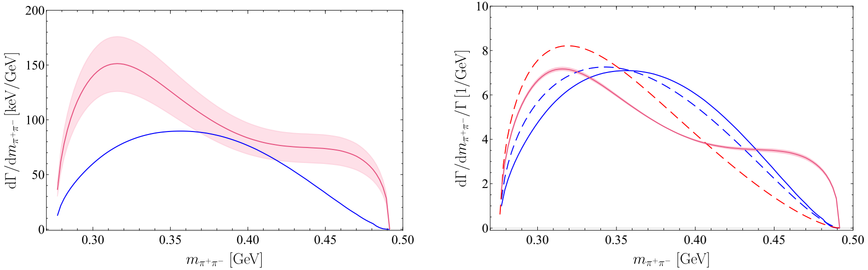
$$\frac{1}{2i}\left[\frac{\mathcal{A}_L(s+i\epsilon)}{\Omega_L(s+i\epsilon)} - \frac{\mathcal{A}_L(s-i\epsilon)}{\Omega_L(s-i\epsilon)}\right] = \frac{\hat{\mathcal{A}}_L(s)\sin\delta_L(s)}{|\Omega_L(s)|}$$

- Writing down the dispersion relation for $\mathcal{A}_L(s)/\Omega_L(s)$, one gets the total decay amplitude: $\mathcal{A}_{\text{tot}}(s,\cos\theta) = \sum_L\left[\mathcal{A}_L(s) + \hat{\mathcal{A}}_L(s)\right]P_L(\cos\theta)$

$$\mathcal{A}_L(s) = \Omega_L(s)\left[P_{n-1}(s) + \frac{s^n}{\pi}\int_{s_{\text{th}}}^{\infty} dz\,\frac{\hat{\mathcal{A}}_L(z)\sin\delta_L(z)}{z^n(z-s)|\Omega_L(z)|}\right]$$

$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ (4)

- Double bump structure in the $\pi\pi$ invariant mass distribution as a feature of the hadronic molecular picture
  - ⋆ Red: molecular, assuming the $D_{s1}D_s\pi\pi$ contact term to vanish
  - ⋆ Blue: compact, without D^*K loops



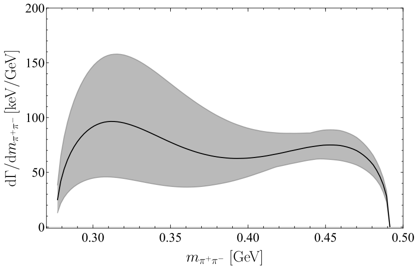
Dashed: without $\pi\pi$ FSI

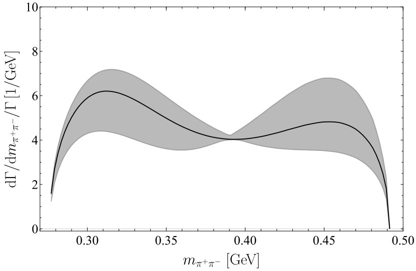
- agree with Belle measurement $0.14 \pm 0.04 \pm 0.02$:

$$\left.\frac{\Gamma\left(D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-\right)}{\Gamma\left(D_{s1}(2460)^+ \to D_s^{*+}\pi^0\right)}\right|_{\text{mol.}} = 0.19^{+0.07}_{-0.05}$$

$D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ (5)

- With the contact term fixed from reproducing the Belle measurement (consistent with zero)





- Prediction for the bottom analogue:

$$\Gamma\left(B_{s1}^0 \to B_s^0\pi^+\pi^-\right) = (3 \pm 1)\,\text{keV}$$

Summary

We are close to understanding the nature of the low-lying 0^+ and 1^+ charmed mesons.

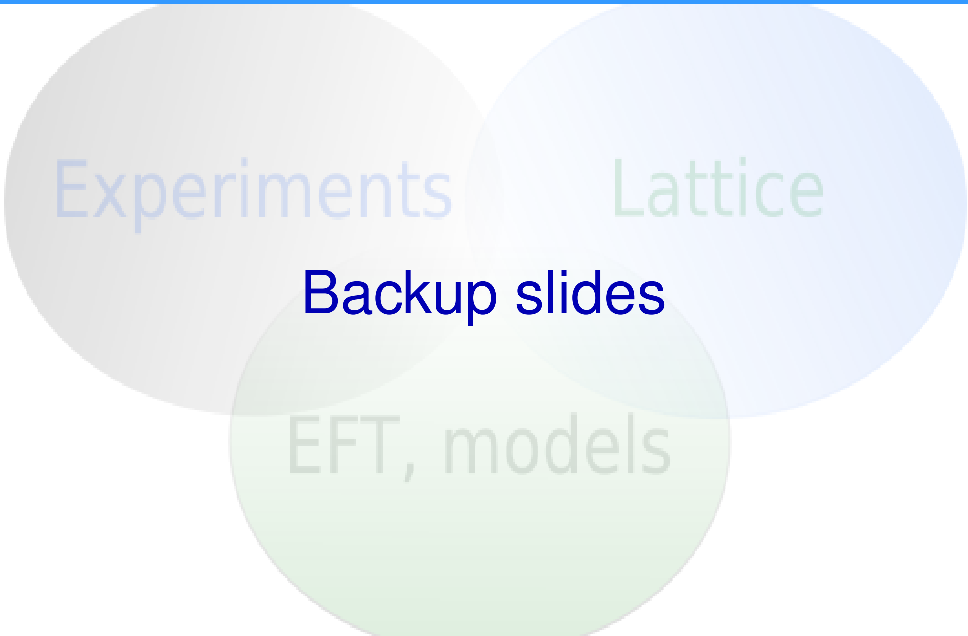
Missing building blocks: more measurements for $D_{s0}^*(2317)$ and $D_{s1}(2460)$:

- Full widths
- $\pi^+\pi^-$ invariant mass distribution of $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$

Looking forward to more achievements of LHCb!

Thank you for your attention !

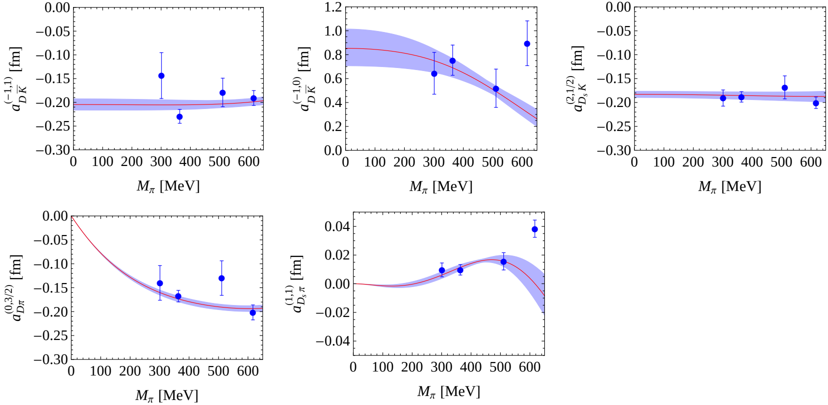
Backup slides



 L. Liu, Orginos, FKG, Hanhart, Meißner, PRD86(2013)014508

- Fit to lattice data on scattering lengths in 5 relatively simple channels: $D\bar{K}(I=1, I=0)$, D_sK, $D\pi(I=3/2)$, $D_s\pi$: no disconnected contribution

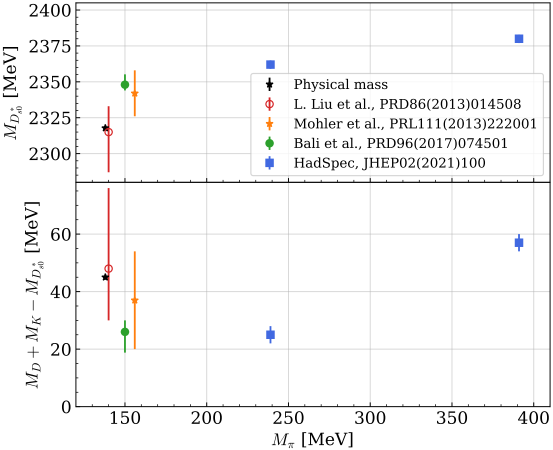
  5 parameters: h_2, h_3, h_4, h_5 and $a(\mu)$



- N_c counting fulfilled: $\underbrace{h_2 \simeq 0.2,\ h_4 M_D^2 \simeq -0.3,}_{\mathcal{O}(N_c^{-1})}$ $\underbrace{h_3 \simeq 2.1,\ h_5 M_D^2 \simeq -1.9}_{\mathcal{O}(N_c^{0})}$

Lattice studies of the charmed scalar mesons: strange

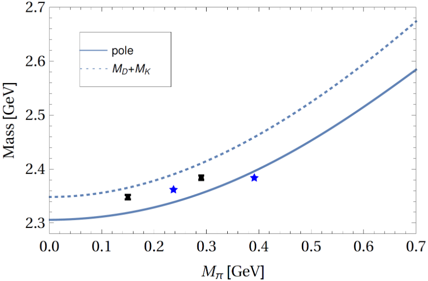
- SU(3) $\Rightarrow M_{D_{s0}^*} = 2315^{+18}_{-28}$ MeV   Liu, Orginos, FKG, Hanhart, Meißner, PRD86(2013)014508
- Lattice results with $c\bar{s} + DK$ interpolators: ∼right mass



- Early studies using only $c\bar{s}$-type interpolators typically give mass sizeably larger than that of $D_{s0}^*(2317)$ Bali (2003); UKQCD (2003); HadSpec (2013); . . .

D_{s0}^{*} as DK molecule from lattice QCD (2)

- Lattice results in G. Bali et al., PRD96(2017)074501



M_π [MeV]	150	290
$M_{D_{s0}^{*}(2317)}$ [MeV]	2348 ± 4	2384 ± 3
M_{D_s} [MeV]	1977 ± 1	1980 ± 1

strong M_π dependence!

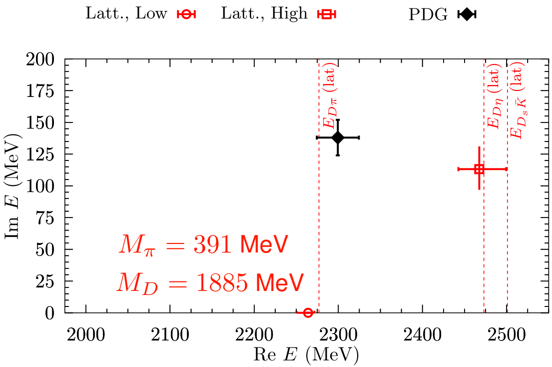
curves: prediction in Du et al., EPJC77(2017)728

- Lattice results in HadSpec, JHEP 02 (2021) 100

M_π [MeV]	239	391
$M_{D_{s0}^{*}(2317)}$ [MeV]	2362 ± 3	2380 ± 3

Pion mass dependence

Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$\lvert g_{D\pi}\rvert$	$\lvert g_{D\eta}\rvert$	$\lvert g_{D_s\bar{K}}\rvert$
lattice	$2264^{+\ 8}_{-14}$	0	$(+++)$	$7.7^{+1.2}_{-1.1}$	$0.3^{+0.5}_{-0.3}$	$4.2^{+1.1}_{-1.0}$
	2468^{+32}_{-25}	113^{+18}_{-16}	$(--+)$	$5.2^{+0.6}_{-0.4}$	$6.7^{+0.6}_{-0.4}$	$13.2^{+0.6}_{-0.5}$



Pion mass dependence

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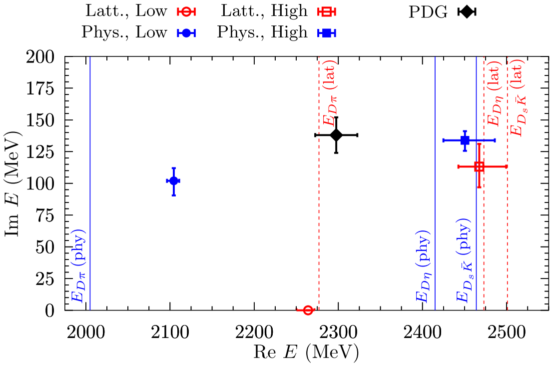
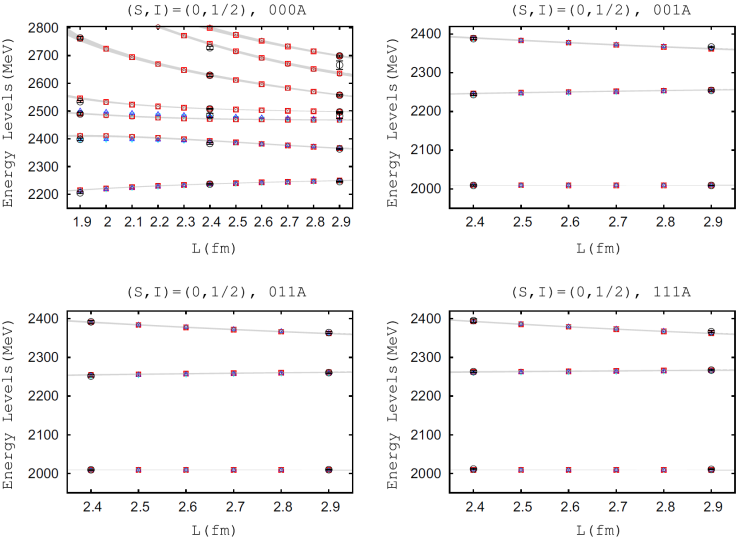
	2468^{+32}_{-25}	113^{+18}_{-16}	$(--+)$	$5.2^{+0.6}_{-0.4}$	$6.7^{+0.6}_{-0.4}$	$13.2^{+0.6}_{-0.5}$
physical	2105^{+6}_{-8}	102^{+10}_{-11}	$(-++)$	$9.4^{+0.2}_{-0.2}$	$1.8^{+0.7}_{-0.7}$	$4.4^{+0.5}_{-0.5}$
	2451^{+36}_{-26}	134^{+7}_{-8}	$(--+)$	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$



A more recent fit to lattice data including moving frame ones

Z.-H. Guo et al., EPJC79(2019)13



Determined parameters (from Fit IIB) are similar

Lattice data: Moir et al., JHEP1610,011

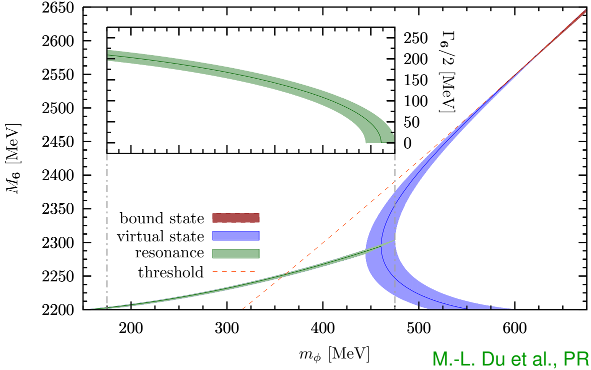
Searching for the higher nonstrange state: lattice

- Tuning interaction strength by varying quark masses:

  Expectation: WT term $\propto E_\pi$, increasing M_π leads to stronger interaction

  increasing S-wave interaction strength $\Rightarrow$ resonance $\rightarrow$ below-th. resonance $\rightarrow$ virtual state $\rightarrow$ bound state, then easier for lattice to get a signal
- SU(3) symmetric, then the sextet decouples from the triplet;

  prediction (qualitative for large m_q), to check with large m_q on lattice:



M.-L. Du et al., PRD98(2018)094018

E. B. Gregory, FKG, C. Hanhart, S. Krieg, T. Luu, arXiv.2106.15391

Lattice results of the energy shift at SU(3) symmetric point with $M_\pi = 612(90)$ MeV

- Evidence for a bound state in the **sextet**
- The $\overline{15}$ has a repulsive interaction (in a diquark-antidiquark tetraquark model, $\overline{15}$ would also exist)