



Exotic hadrons from an EFT perspective

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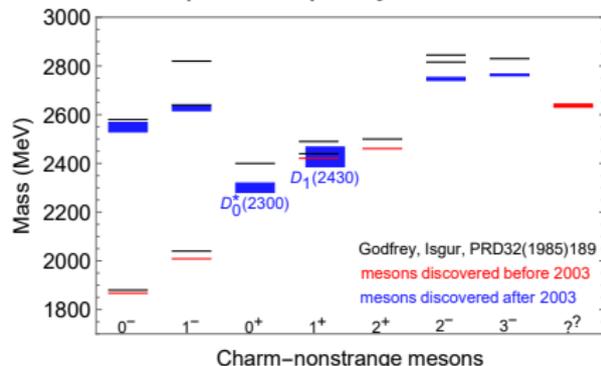
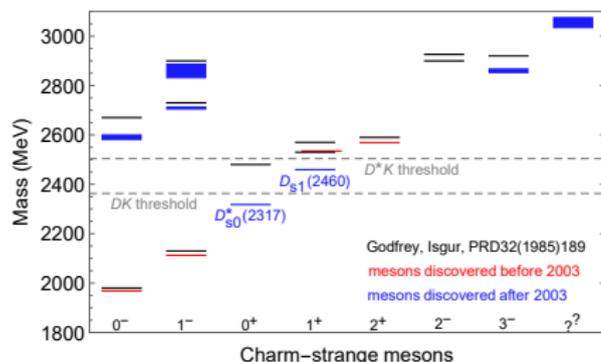
Experiments Lattice

08-13 August 2022

EFT, models

Introduction

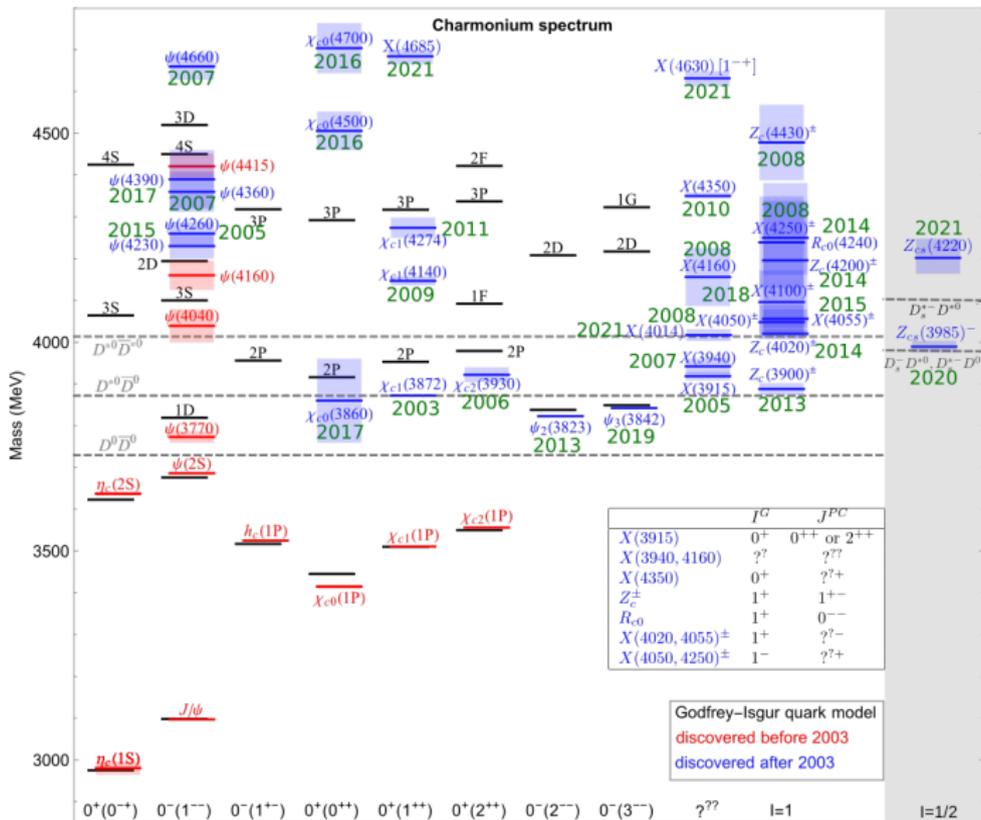
- Many hadron resonances containing heavy quarks observed since 2003
- Charm-strange and charm-nonstrange mesons with positive parity



- **Puzzle 1:** Why are $D_{s0}^*(2317)$ and $D_{s1}(2460)$ so light?
- **Puzzle 2:** Why $\underbrace{M_{D_{s1}(2460)} - M_{D_{s0}^*(2317)}}_{(141.8 \pm 0.8) \text{ MeV}} \simeq \underbrace{M_{D^{*\pm}} - M_{D^\pm}}_{(140.67 \pm 0.08) \text{ MeV}}$?
- **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

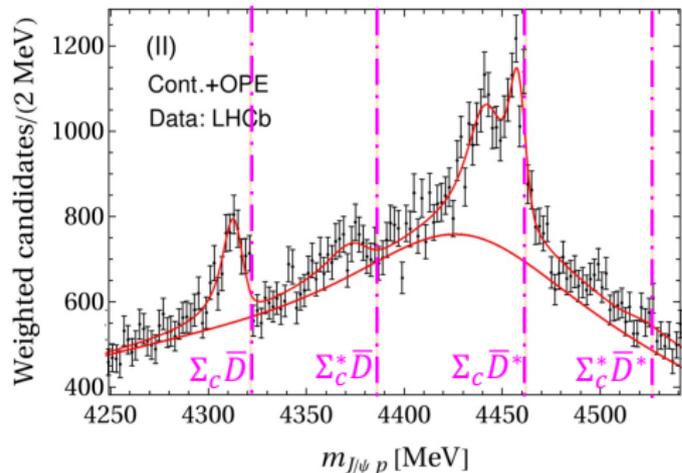
Introduction

- Charmonium and charmonium-like structures



Introduction

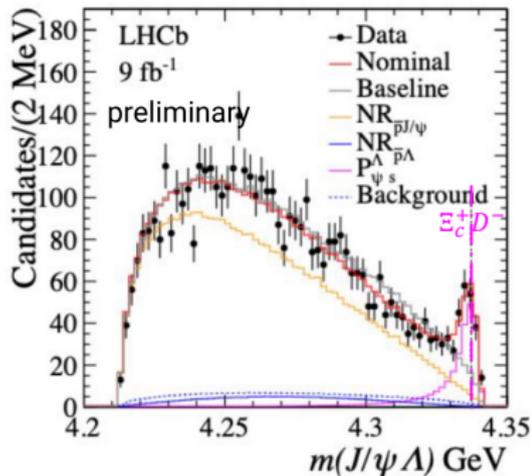
- Hidden-charm pentaquark states P_c and P_{cs}



$P_c(4312)$, $P_c(4380)$, $P_c(4440)$, $P_c(4457)$

data: LHCb, PRL122(2019)222001; fit: Du, Baru, FKG, Hanhart,

Meißner, Oller, Wang, PRL124(2020)072001

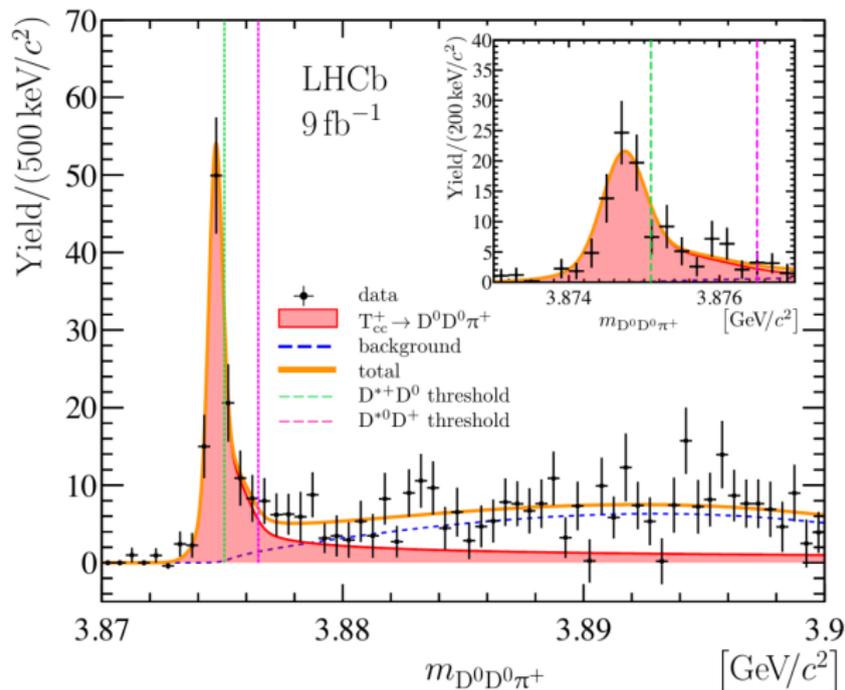


$P_{cs}(4338)$

LHCb seminar, E. Spadaro Norella and Chen

Chen (for LHCb), July 5, 2022

- Double-charm tetraquark T_{cc}^+



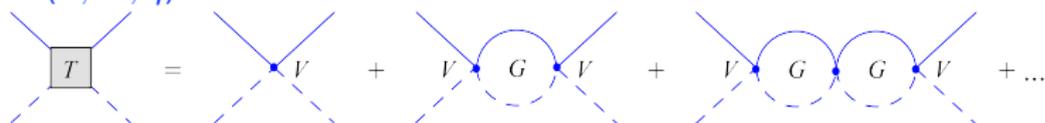
LHCb, Nature Phys.18(2022)751

- New facilities brought unexpected discoveries: **exotic hadron candidates; many structures are close to thresholds**
- Lattice QCD Plenary talk by L. Liu, and many more parallel talks
 - direct calculations of some systems
 - varying parameters (e.g., quark masses) to get more insights
 - determining low-energy constants in effective field theory (EFT)
- EFT provides a tool for combined analysis of lattice and experimental results.
Examples
 - Positive-parity charmed mesons
 - Hidden-charm and double-charm near-threshold states

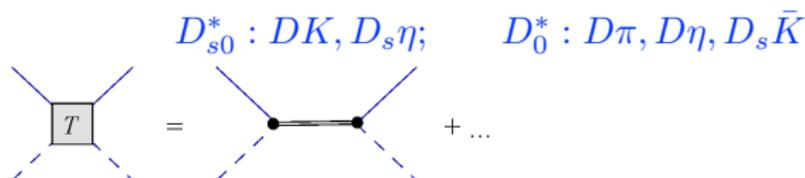
Positive-parity heavy mesons

Interactions between charm mesons (D, D_s) and light pseudoscalar mesons (π, K, η)

- S -wave interactions between charm mesons (D, D_s) and light pseudoscalar mesons (π, K, η)



- not far from the thresholds \Rightarrow chiral EFT for matter fields
- D_{s0}^*/D_0^* should appear as poles in scattering amplitudes:



\Rightarrow needs a nonperturbative treatment: ChPT + unitarization (UChPT)

Truong (1988); Oller, Oset (1997); Oller, Oset, Peláez (1998); Nieves, Ruiz Arriola (1999); Oller, Meißner (2001); ...

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

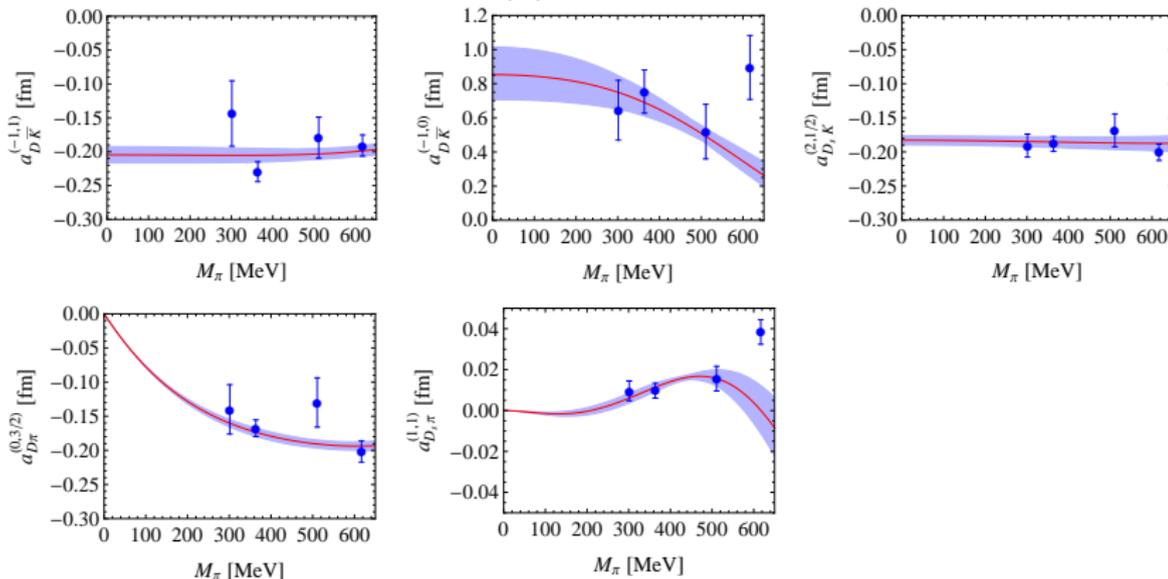
$V(s)$: from SU(3) chiral Lagrangian, 6 LECs up to NLO

$G(s)$: 2-point scalar loop functions, regularized with a subtraction constant $a(\mu)$

- Fit to lattice data on scattering lengths in 5 simpler channels:

$D\bar{K}(I=1, I=0)$, $D_s K$, $D\pi(I=3/2)$, $D_s\pi$: no disconnected contribution

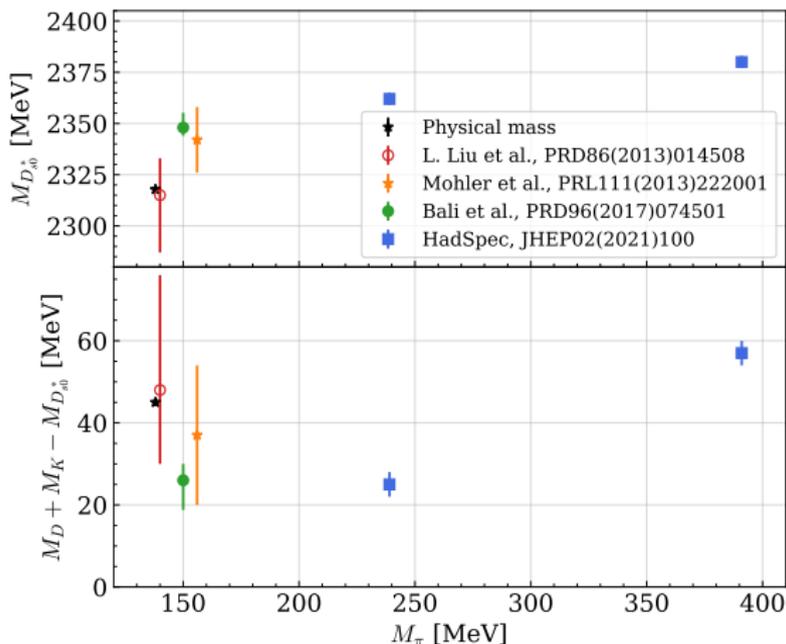
5 parameters: h_2, h_3, h_4, h_5 and $a(\mu)$



- N_c counting fulfilled: $h_2 \simeq 0.2$, $h_4 M_D^2 \simeq -0.3$, $h_3 \simeq 2.1$, $h_5 M_D^2 \simeq -1.9$
- $\underbrace{\hspace{15em}}_{\mathcal{O}(N_c^{-1})}$
 $\underbrace{\hspace{15em}}_{\mathcal{O}(N_c^0)}$

Lattice studies of the charmed scalar mesons: strange

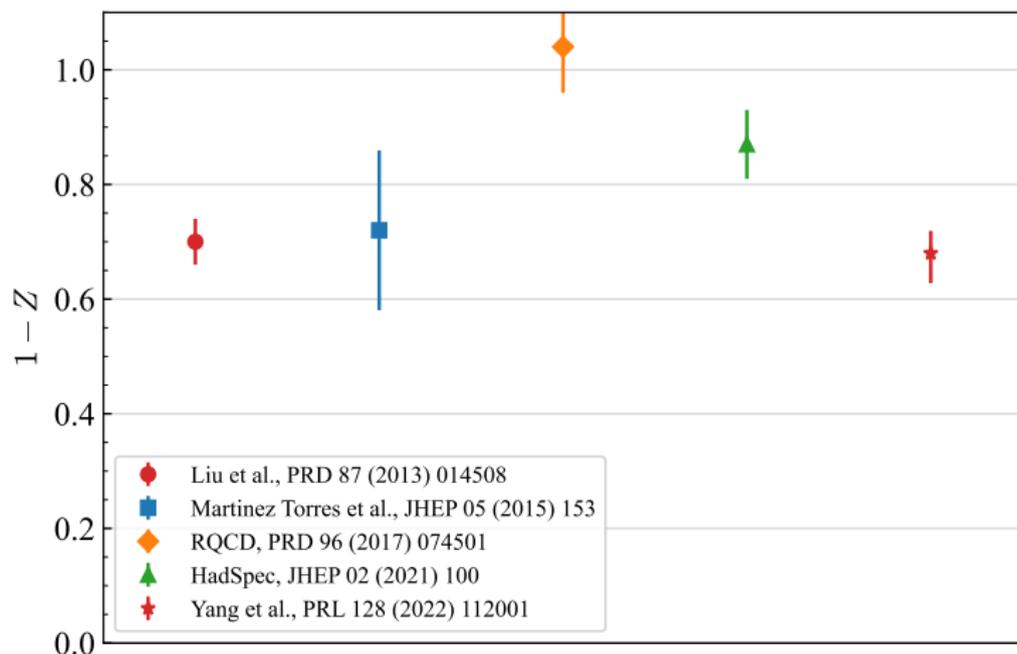
- $SU(3) \Rightarrow M_{D_{s0}^*} = 2315_{-28}^{+18} \text{ MeV}$ Liu, Orginos, FKG, Hanhart, Meißner, PRD86(2013)014508
- Lattice results with $c\bar{s} + DK$ interpolators: \sim right mass



- 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); ...

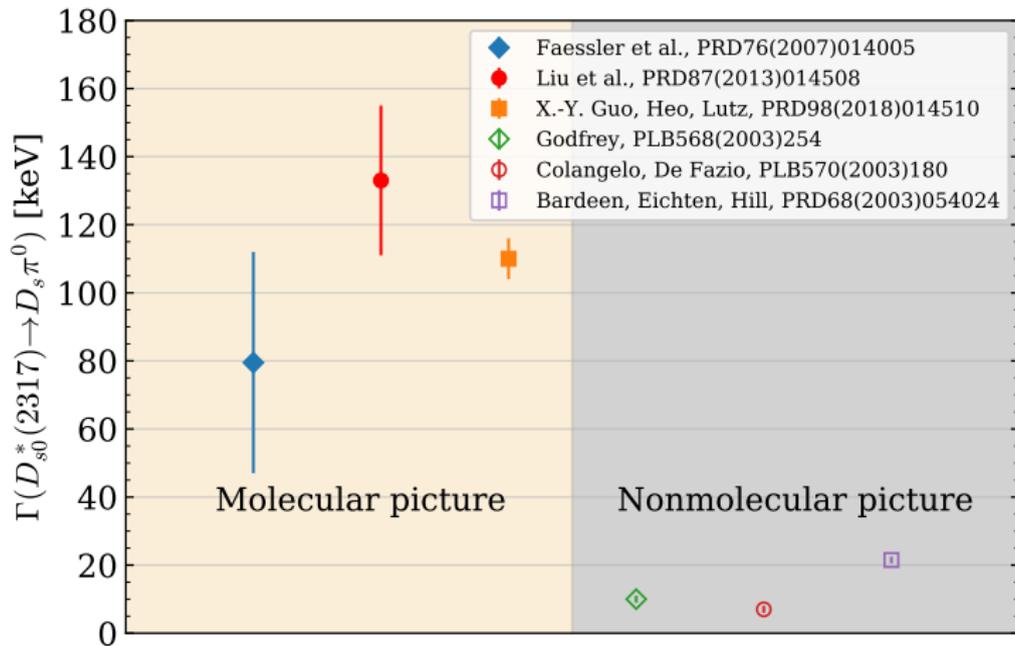
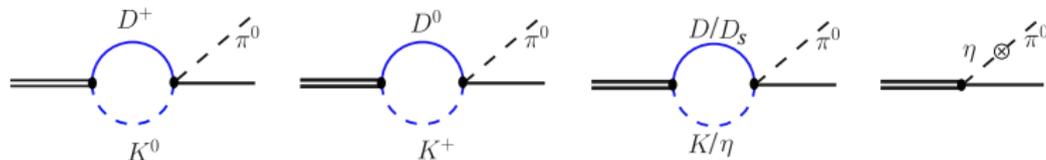
DK component from lattice QCD

- Compositeness (DK component) for $D_{s0}^*(2317)$ from (in)direct lattice calculations: DK as the **main** component, it is in this sense we recognize it as a **hadronic molecule**



Decay width of the $D_{s0}^*(2317)$ in light of lattice calculations

Crucial observable: $\Gamma[D_{s0}^*(2317)]$ measurement planned at PANDA



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

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

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

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

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

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Lattice studies of the charmed scalar mesons: nonstrange (1)

- $(S, I) = (0, \frac{1}{2})$: $c\bar{q} + D\pi$

interpolators:

Mohler et al., PRD87(2013)034501

$$M_\pi \approx 266 \text{ MeV},$$

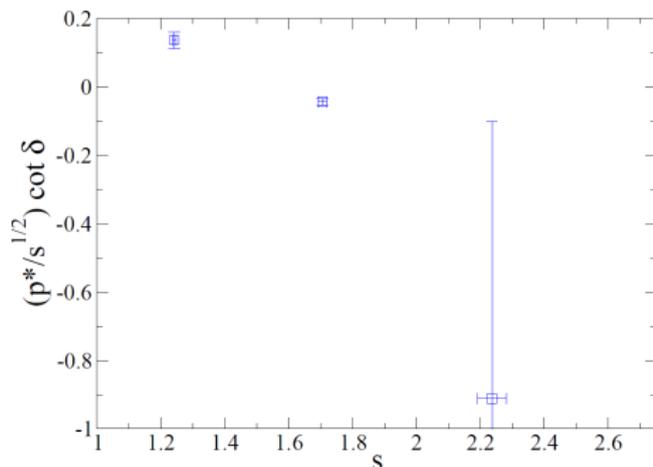
$$M_D \approx 1558 \text{ MeV},$$

$$M_{D^*} \approx 1690 \text{ MeV}$$

Lüscher's formula $\Rightarrow D\pi$ phase

shifts

\Rightarrow BW parameters of $D_0^*(2400)$ [the name of $D_0^*(2300)$ up to PDG2018]



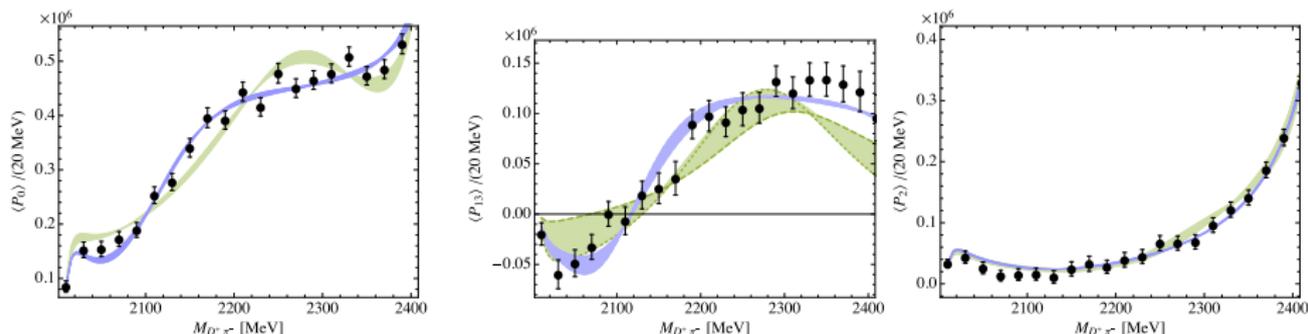
	Mohler et al.	PDG2018
$M_{D_0^*} - \frac{1}{4}(M_D + 3M_{D^*})$	$(351 \pm 21) \text{ MeV}$	$(347 \pm 29) \text{ MeV}$
$M_{D_1} - \frac{1}{4}(M_D + 3M_{D^*})$	$(380 \pm 21) \text{ MeV}$	$(456 \pm 40) \text{ MeV}$

Pole given in 2022: $(2.12 \pm 0.03) \text{ MeV}$

talk by D. Mohler; J. Bulava et al., arXiv:2203.03230

- $(S, I) = (0, \frac{1}{2})$: first coupled-channel lattice calculation including interpolating fields for $c\bar{q} + D\pi + D\eta + D_s\bar{K}$: Moir et al. [HadSpec], JHEP1610(2016)011
 - $M_\pi = 391$ MeV, $M_D = 1885$ MeV: $D\pi$ threshold (2276.4 ± 0.9) MeV
 - Coupled-channel T matrix: a pole below threshold (2275.9 ± 0.9) MeV
- More recent results with $M_\pi \simeq 239$ MeV: Gayer et al. [HadSpec], JHEP07(2021)123
Pole at $((2196 \pm 64) - \frac{i}{2}(425 \pm 224))$ MeV

- Fits with the Khuri-Treiman equation taking into account three-body unitarity: using S -wave $D\pi$ scattering phase from UCHPT ($\chi^2/\text{d.o.f.} = 1.2$) and from BW ($\chi^2/\text{d.o.f.} = 2.0$)

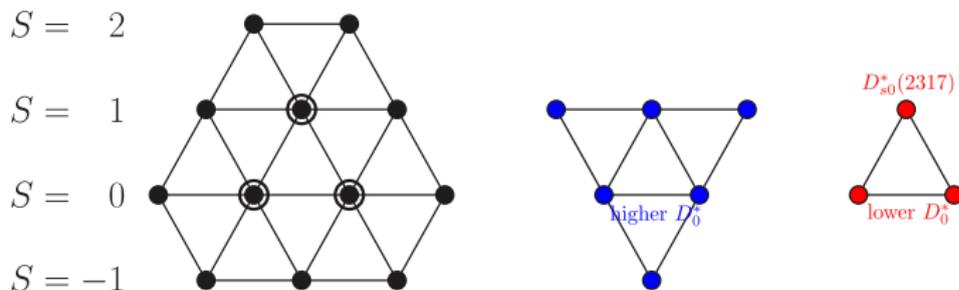


- The LHCb data are well described with UCHPT amplitude with two D_0^* states; the lower one has a mass about 2.1 GeV

SU(3) analysis (1)

- SU(3) irreps: $\bar{\mathbf{3}} \otimes \mathbf{8} = \bar{\mathbf{15}} \oplus \mathbf{6} \oplus \bar{\mathbf{3}}$

Albaladejo et al., PLB767(2017)465

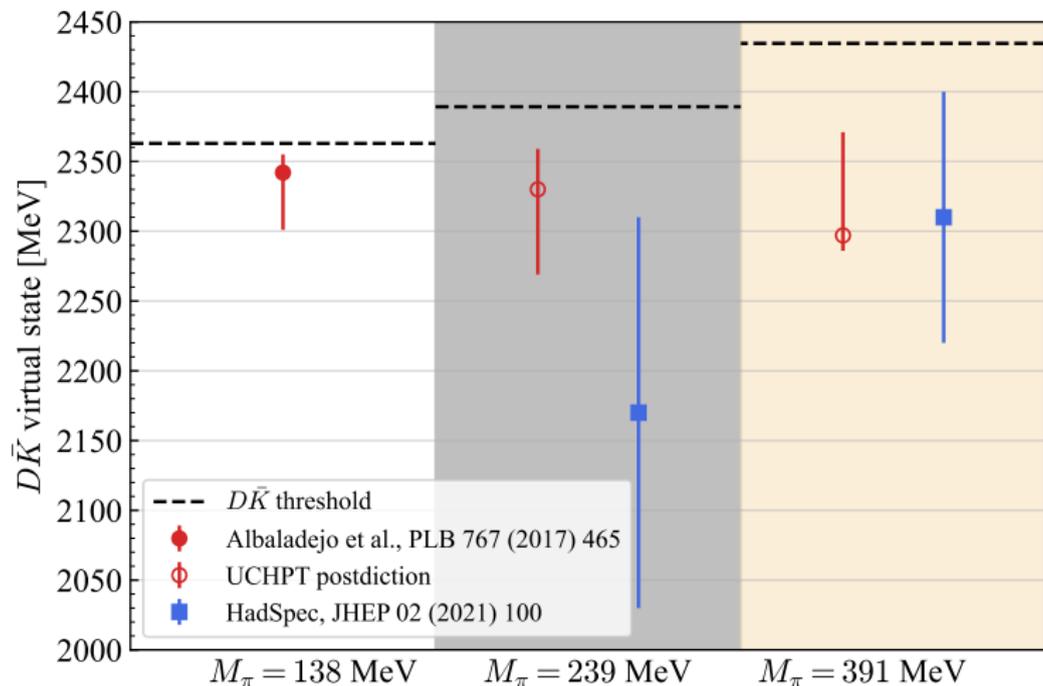


- WT term: $\bar{\mathbf{15}}$: repulsive; $\mathbf{6}$: attractive; $\bar{\mathbf{3}}$: most attractive
- $(S, I) = (1, 1)$: deep in the complex plane on wrong Riemann sheets
- $(S, I) = (-1, 0)$: virtual state at 2342_{-41}^{+13} MeV at the physical mass

SU(3) analysis (2)

- Virtual state $(S, I) = (-1, 0) D\bar{K}$ from lattice

HadSpec, JHEP02(2021)100



Solution to the positive-parity charmed meson puzzles

- **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

$$M_D + M_K - M_{D_{s0}^*} \simeq 45 \text{ MeV}$$

$$M_{D_{s1}(2460)} - M_{D_{s0}^*(2317)} \simeq M_{D^*} - M_D \text{ is natural}$$

- **Solution to puzzle 3:** the SU(3) nonstrange partner of $D_{s0}^*(2317)$ is the lower D_0^* state with a mass of about 2.1 GeV

Hidden-charm and double-charm near-threshold states

General rule for near-threshold structures

Coupled-channel NREFT: there must be nontrivial (near-)threshold structures for a pair of particles with an **S-wave attraction** X.-K. Dong, FKG, B.-S. Zou, PRL126,152001(2021)

• 2-channel T-matrix from unitarity

$$T(E) = 8\pi\Sigma_2 \begin{pmatrix} -\frac{1}{a_{11}} + ik_1 & \frac{1}{a_{12}} \\ \frac{1}{a_{12}} & -\frac{1}{a_{22}} - \sqrt{-2\mu_2 E - i\epsilon} \end{pmatrix}^{-1}$$

$$= -\frac{8\pi\Sigma_2}{\det} \begin{pmatrix} \frac{1}{a_{22}} + \sqrt{-2\mu_2 E - i\epsilon} & \frac{1}{a_{12}} \\ \frac{1}{a_{12}} & \frac{1}{a_{11}} - ik_1 \end{pmatrix}$$

$$\det = \left(\frac{1}{a_{11}} - ik_1 \right) \left(\frac{1}{a_{22}} + \sqrt{-2\mu_2 E - i\epsilon} \right) - \frac{1}{a_{12}^2}$$

$a_{11,12,22}$: three parameters

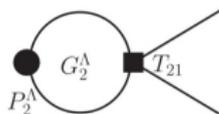
- Expanded around the higher threshold (ch-2), E defined relative to that threshold
- The nonanalytic piece: $\sqrt{-2\mu_2 E - i\epsilon}$

$$T_{21}(E) \propto \left[\frac{1}{a_{22, \text{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E) \right]^{-1}$$

$$|T_{21}(E)|^2 \propto |T_{22}(E)|^2 \propto$$

$$\begin{cases} \left[\left(\text{Re} \frac{1}{a_{22, \text{eff}}} \right)^2 + \left(\text{Im} \frac{1}{a_{22, \text{eff}}} - \sqrt{2\mu_2 E} \right)^2 \right]^{-1} & \text{for } E \geq 0 \\ \left[\left(\text{Im} \frac{1}{a_{22, \text{eff}}} \right)^2 + \left(\text{Re} \frac{1}{a_{22, \text{eff}}} + \sqrt{-2\mu_2 E} \right)^2 \right]^{-1} & \text{for } E < 0 \end{cases}$$

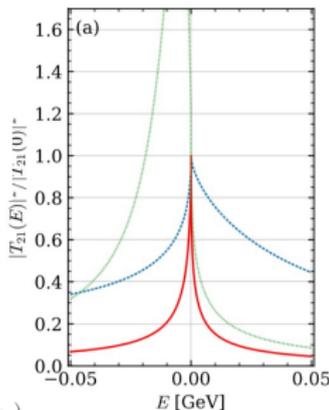
≥ 0 due to unitarity



- Maximal at threshold for **positive $\text{Re}(a_{22, \text{eff}})$** (attraction), $\text{FWHM} \propto 1/\mu$, virtual state-like pole
- Peaking at pole for negative $\text{Re}(a_{22, \text{eff}})$

$$\frac{1}{\mu} \left(\frac{4}{|a_0|^2} - \sum_x x \sqrt{\frac{3}{|a_0|^2} + x^2} \right),$$

the sum runs over $x = \text{Im}(1/a_0)$ and $\text{Re}(1/a_0)$



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• 2-channel T-matrix from unitarity

$$T(E) = 8\pi\Sigma_2 \begin{pmatrix} -\frac{1}{a_{11}} + ik_1 & \frac{1}{a_{12}} \\ \frac{1}{a_{12}} & -\frac{1}{a_{22}} - \sqrt{-2\mu_2 E - i\epsilon} \end{pmatrix}^{-1} \quad \det = \left(\frac{1}{a_{11}} - ik_1\right) \left(\frac{1}{a_{22}} + \sqrt{-2\mu_2 E - i\epsilon}\right) - \frac{1}{a_{12}^2}$$

$$= -\frac{8\pi\Sigma_2}{\det} \begin{pmatrix} \frac{1}{a_{22}} + \sqrt{-2\mu_2 E - i\epsilon} & \frac{1}{a_{12}} \\ \frac{1}{a_{12}} & \frac{1}{a_{11}} - ik_1 \end{pmatrix}$$

$a_{11,12,22}$: three parameters

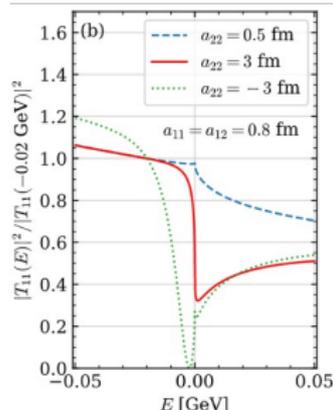
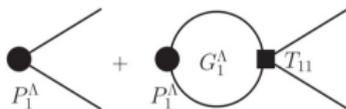
- Expanded around the higher threshold (ch-2), E defined relative to that threshold
- The nonanalytic piece: $\sqrt{-2\mu_2 E - i\epsilon}$

$$T_{11}(E) = \frac{-8\pi\Sigma_2 \left(\frac{1}{a_{22}} - i\sqrt{2\mu_2 E}\right)}{\left(\frac{1}{a_{11}} - ik_1\right) \left[\frac{1}{a_{22,\text{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E)\right]}$$

➤ The same pole can behave distinctly in different reactions

➤ One pole and one zero

➤ For strongly interacting channel-2 (large a_{22}), there will be a dip around threshold (zero close to threshold)



Hidden-charm P_c pentaquarks (1)

Heavy quark spin symmetry (HQSS)

P_c states: $\Sigma_c^{(*)} \bar{D}^{(*)}$ molecules, $P_c(4312) \sim \Sigma_c \bar{D}$, $P_c(4440, 4457) \sim \Sigma_c \bar{D}^*$?

Consider S -wave pairs of $\Sigma_c^{(*)} \bar{D}^{(*)}$ [$J_{\Sigma_c} = \frac{1}{2}$, $J_{\Sigma_c^*} = \frac{3}{2}$]:

$$J^P = \frac{1}{2}^- : \Sigma_c \bar{D}, \Sigma_c \bar{D}^*, \Sigma_c^* \bar{D}^*$$

$$J^P = \frac{3}{2}^- : \Sigma_c^* \bar{D}, \Sigma_c \bar{D}^*, \Sigma_c^* \bar{D}^*$$

$$J^P = \frac{5}{2}^- : \Sigma_c^* \bar{D}^*$$

Spin of the light degrees of freedom s_ℓ : $s_\ell(D^{(*)}) = \frac{1}{2}$, $s_\ell(\Sigma_c^{(*)}) = 1$. Thus, $s_L = \frac{1}{2}, \frac{3}{2}$

For each isospin, 2 independent terms

$$\left\langle 1, \frac{1}{2}, \frac{1}{2} \left| \hat{\mathcal{H}}_I \right| 1, \frac{1}{2}, \frac{1}{2} \right\rangle, \quad \left\langle 1, \frac{1}{2}, \frac{3}{2} \left| \hat{\mathcal{H}}_I \right| 1, \frac{1}{2}, \frac{3}{2} \right\rangle$$

Thus, the 7 pairs are in two spin multiplets: 3 with $s_L = \frac{1}{2}$ and 4 with $s_L = \frac{3}{2}$

Hidden-charm P_c pentaquarks (2)

Seven P_c generally expected in this hadronic molecular model

Xiao, Nieves, Oset, PRD88(2013)056012; Liu et al., PRD98(2018)114030, PRL122(2019)242001; Sakai, Jing, FKG, PRD100(2019)074007; ...

Pionless NREFT predictions using the masses of $P_c(4440, 4457)$ as inputs Liu et al.,

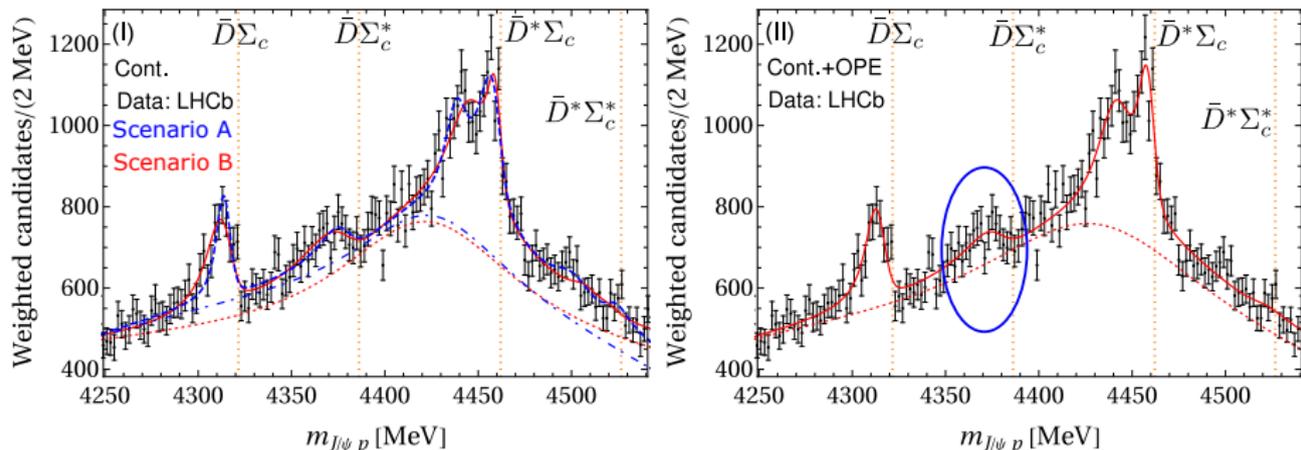
PRL122(2019)242001

Scenario	Molecule	J^P	B (MeV)	M (MeV)
A	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	7.8 – 9.0	4311.8 – 4313.0
A	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	8.3 – 9.2	4376.1 – 4377.0
A	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4440.3
A	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4457.3
A	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	25.7 – 26.5	4500.2 – 4501.0
A	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	15.9 – 16.1	4510.6 – 4510.8
A	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	3.2 – 3.5	4523.3 – 4523.6
B	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	13.1 – 14.5	4306.3 – 4307.7
B	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	13.6 – 14.8	4370.5 – 4371.7
B	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4457.3
B	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4440.3
B	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	3.1 – 3.5	4523.2 – 4523.6
B	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	10.1 – 10.2	4516.5 – 4516.6
B	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	25.7 – 26.5	4500.2 – 4501.0

Hidden-charm P_c pentaquarks (3)

Pionful EFT: fits to the LHCb $J/\psi p$ data using hadronic molecular model with HQSS: coupled channels ($\bar{D}^{(*)}\Sigma_c^{(*)}$, $J/\psi p$), complex (modeling $\Lambda_c \bar{D}^{(*)}$) contact terms + OPE

M.-L. Du, V. Baru, FKG, C. Hanhart, U.-G. Meißner, J. A. Oller, Q. Wang, PRL124(2020)072001



- 7 P_c states in two spin multiplets
 - a narrow $P_c(4380)$
 - 3 states around 4.5 GeV

For analysis with more channels ($+\Lambda_c \bar{D}^{(*)} + \eta_c p$), see

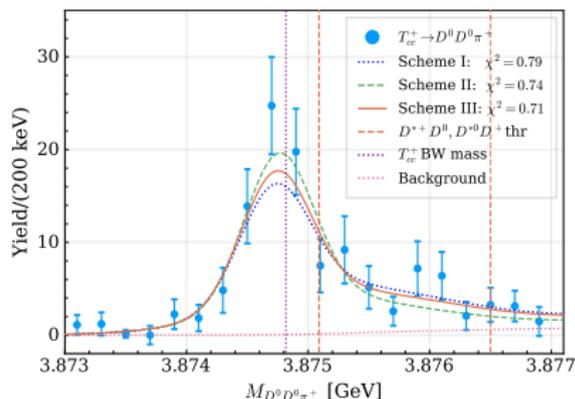
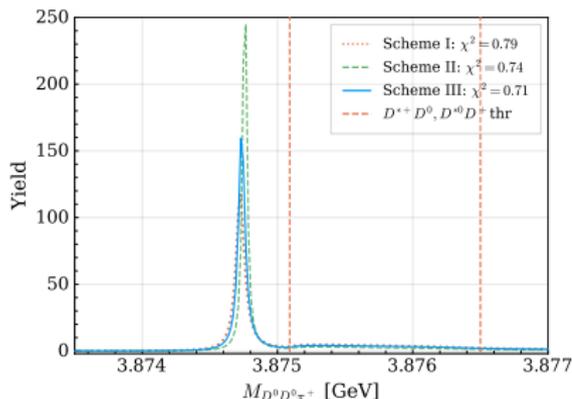
M.-L. Du et al., JHEP08(2021)157

Double-charm tetraquarks (1)

- $T_{cc}(3885)^+$: candidate of isoscalar DD^* hadronic molecule

N. Li et al., CPL38(2021)092001; Feijoo et al., PRD104(2021)114015; X.-K. Dong, FKG, B.-S. Zou, CTP73(2001)125201; Fleming, Hodges, Mehen, PRD104(2021)116010; M.-J. Yan, Pavon Valderrama, PRD105(2022)014007; Albaladejo, PLB829(2022)137052; ...

- Pionful EFT applied to the case of $T_{cc}(3885)^+$ M.-L. Du et al., PRD105(2022)014024 including $DD\pi$ three-body effects



- Pole below $D^{*+} D^0$ threshold: $-356_{-38}^{+39} - i(28 \pm 1)$ keV
- $D^* D$ hadronic molecule: compositeness = 0.84 ± 0.06 , derived from a_0, r_0

Double-charm tetraquarks (2)

- Low-energy D^*D scattering parameters

$$a_0 = \left(-6.72_{-0.45}^{+0.36} \pm 0.27\right) - i(0.10 \pm 0.03 \pm 0.03) \text{ fm}$$

$$r_0 = -2.40 \pm 0.01 \pm 0.85 \text{ fm}$$

Lattice results [$m_\pi \simeq 280\text{MeV}$, $m_c^{(h)}$]: [Padmanath, Prelovsek, PRL129\(2022\)032002;](#)

$a_0 = 1.04(29) \text{ fm}$, $r_0 = 0.96_{-0.20}^{+0.18} \text{ fm}$ [talks by M. Padmanath and S. Prelovsek](#)

- HQSS: 4 low-energy constants at LO for all S -wave $D^{(*)}D^{(*)}$ interactions

$$(I = 0, 1) \otimes (s_L = 0, 1)$$

$$\begin{aligned} \mathcal{L}_{HH} = & -\frac{D_{00}}{8} \text{Tr} \left(H_a^\dagger H_b H_b^\dagger H_a \right) - \frac{D_{01}}{8} \text{Tr} \left(\sigma^i H_a^\dagger H_b \sigma^i H_b^\dagger H_a \right) \\ & - \frac{D_{10}}{8} \text{Tr} \left(\tau_{aa'}^A H_{a'}^\dagger H_b \tau_{bb'}^A H_b^\dagger H_a \right) - \frac{D_{11}}{8} \text{Tr} \left(\tau_{aa'}^A \sigma^i H_{a'}^\dagger H_b \tau_{bb'}^A \sigma^i H_b^\dagger H_a \right) \end{aligned}$$

$$\begin{aligned} D_{s_L=1}^{I=0} &= 3D_{10} + 3D_{11} - D_{00} - D_{01}, & D_{s_L=1}^{I=1} &= D_{00} + D_{01} + D_{10} + D_{11}, \\ D_{s_L=0}^{I=0} &= D_{00} - 3D_{10} - 3D_{01} + 9D_{11}, & D_{s_L=0}^{I=1} &= 3D_{01} + 3D_{11} - D_{00} - D_{10}. \end{aligned}$$

- $I(J^P) = 0(1^+)$ D^*D^* bound state as a HQSS partner of $T_{cc}(3885)$

- Lattice results assisted with EFT provide invaluable inputs in understanding hadronic phenomena
- Experimental and lattice data need to be analyzed using EFT with symmetry constraints built in to reach a precision hadron spectroscopy

Thank you for your attention !

Experiments

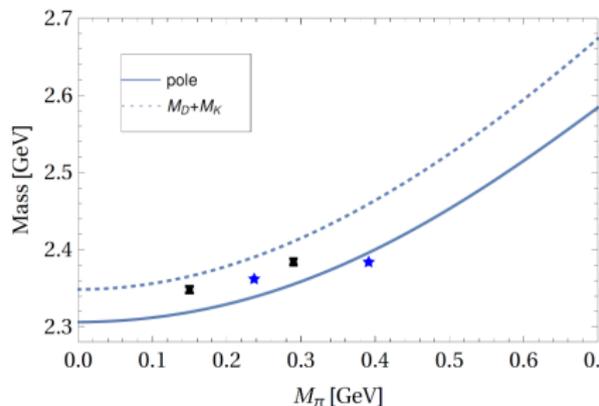
Lattice

Backup slides

EFT, models

DK component 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!

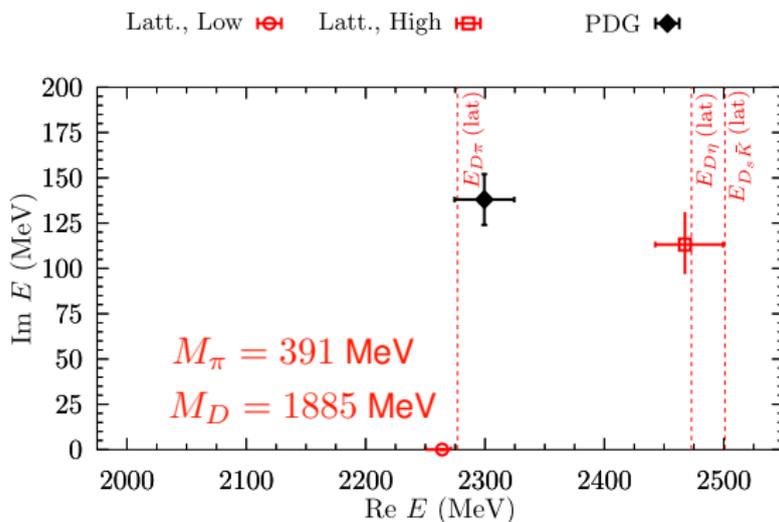
curves: prediction in [Du et al., EPJC77\(2017\)728](#)

- Lattice results in [HadSpec, JHEP 02 \(2021\) 100](#)

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

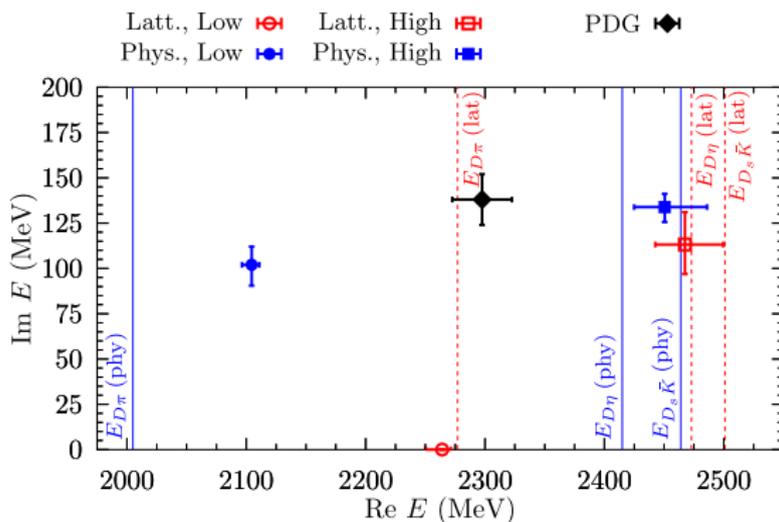
Pion mass dependence

Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$ g_{D\pi} $	$ g_{D\eta} $	$ g_{D_s\bar{K}} $
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}	(- - +)	$5.2^{+0.6}_{-0.4}$	$6.7^{+0.6}_{-0.4}$	$13.2^{+0.6}_{-0.5}$



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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}	(- - +)	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$

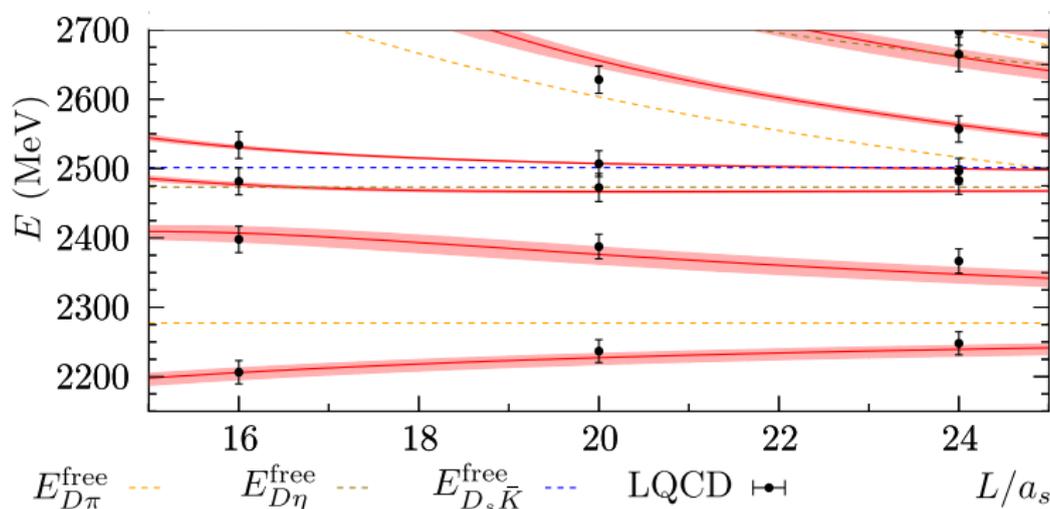


Postdictions versus recent lattice results: charm-nonstrange

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

NOT a fit!

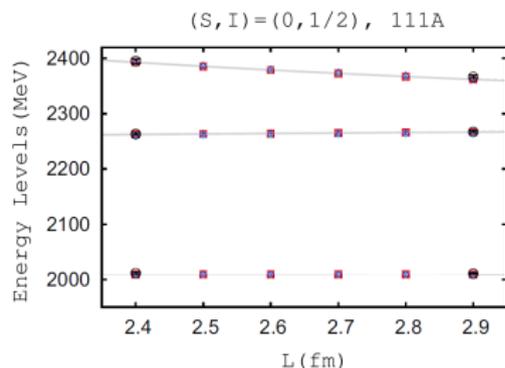
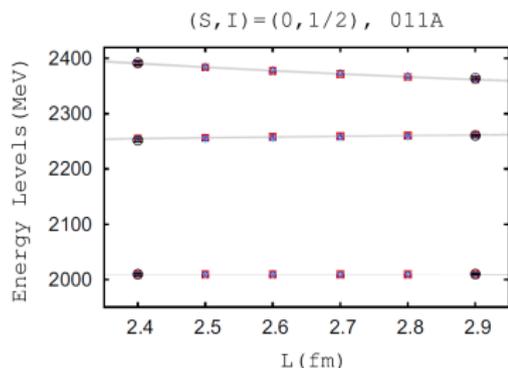
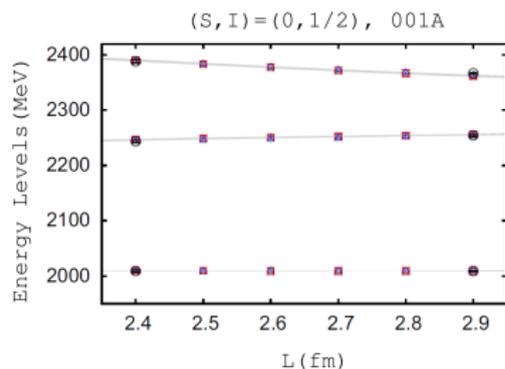
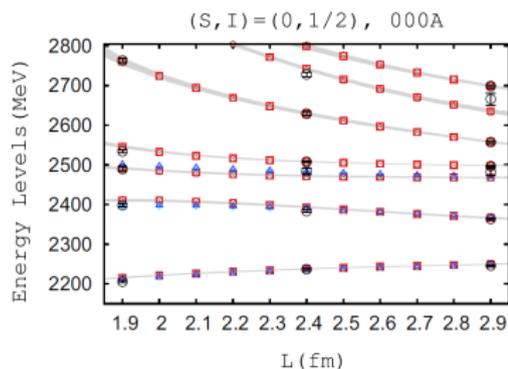
M. Albaladejo, P. Fernandez-Soler, FKG, J. Nieves, PLB767(2017)465



consequence of SU(3) + chiral

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

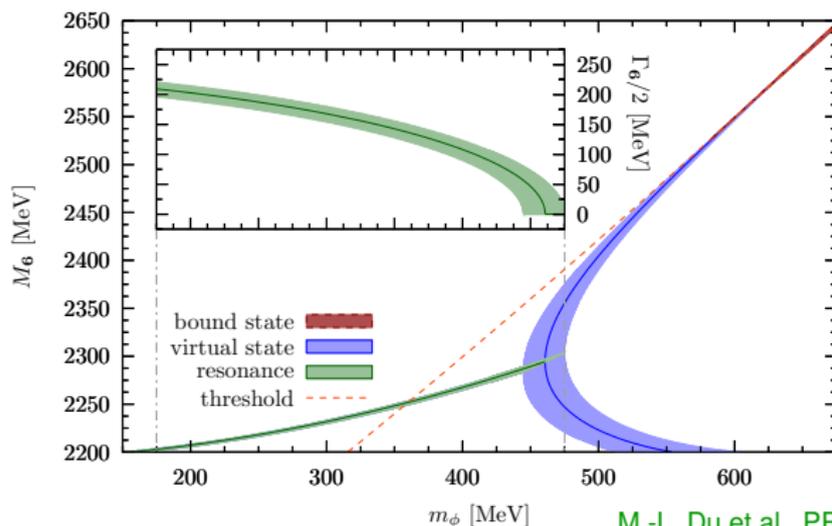
Searching for the higher nonstrange state: lattice

- 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

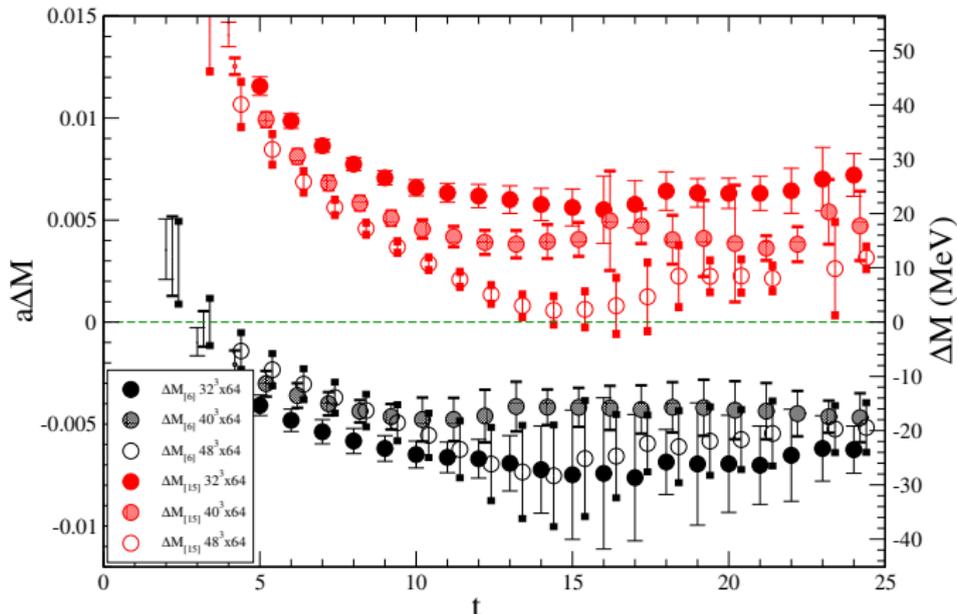
- $SU(3)$ symmetric, then the sextet decouples from the triplet;
prediction (qualitative for large m_q), to check with large m_q on lattice:

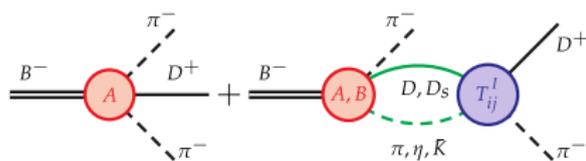


M.-L. Du et al., PRD98(2018)094018

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)





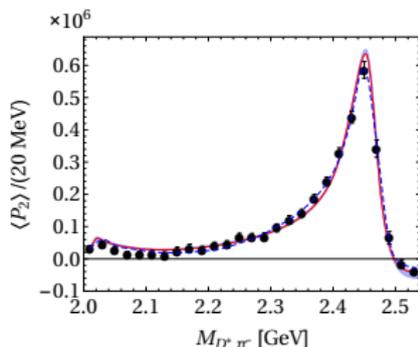
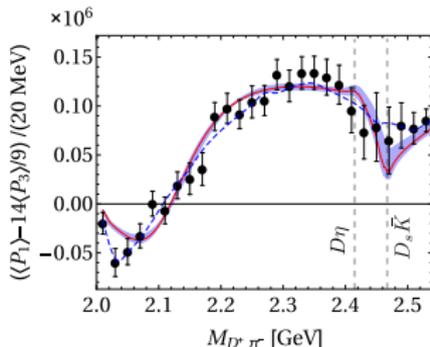
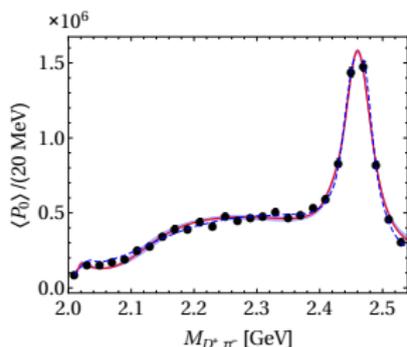
- SU(3) symmetry Savage, Wise (1989)
- S -wave: FSI, two new parameters
- P, D -wave: BWs from the LHCb fit

Angular moments:

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

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

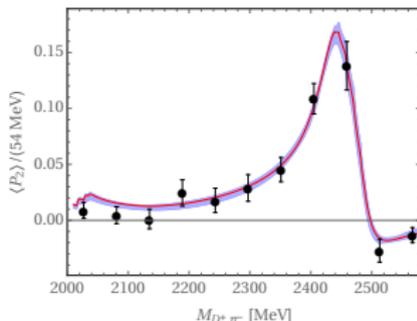
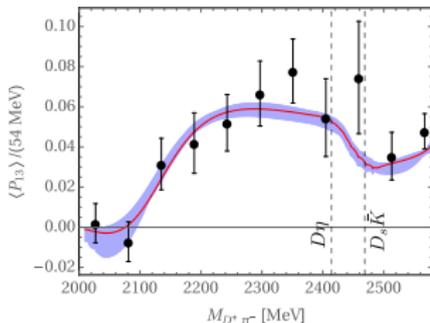
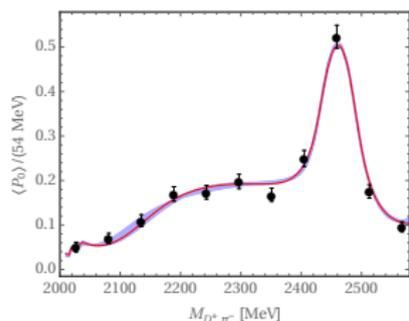
Data: LHCb, PRD94(2016)072001



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

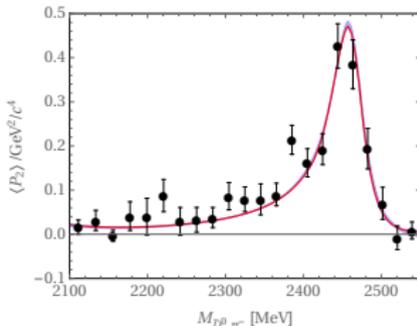
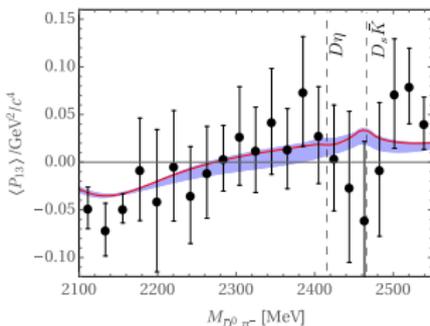
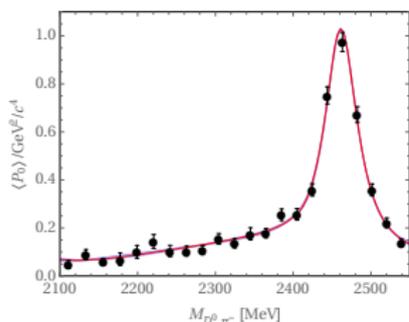
Fit to data of $B^- \rightarrow D^+ \pi^- K^-$

Data: LHCb, PRD91(2015)092002



Fit to data of $B^0 \rightarrow \bar{D}^0 \pi^- \pi^+$

Data: LHCb, PRD92(2015)032002



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

Hidden-charm P_c pentaquarks (4)

Scheme II	J^P	Pole [MeV]	DC (threshold [MeV])	Production
$P_c(4312)$	$\frac{1}{2}^-$	4314(2) - 5(2) i	$\Sigma_c \bar{D}$ (4321.6)	636(73) - 98(53) i
$P_c(4380)$	$\frac{3}{2}^-$	4378(2) - 13(3) i	$\Sigma_c^* \bar{D}$ (4386.2)	618(373) - 181(95) i
$P_c(4440)$	$\frac{3}{2}^-$	4441(2) - 11(3) i	$\Sigma_c \bar{D}^*$ (4462.1)	999(140) - 15(18) i
$P_c(4457)$	$\frac{1}{2}^-$	4459(2) - 4(1) i	$\Sigma_c \bar{D}^*$ (4462.1)	-918(68) + 159(78) i
P_c	$\frac{1}{2}^-$	4524(2) - 9(1) i	$\Sigma_c^* \bar{D}^*$ (4526.7)	-228(384) + 22(23) i
P_c	$\frac{3}{2}^-$	4518(2) - 11(2) i	$\Sigma_c^* \bar{D}^*$ (4526.7)	-156(517) - 58(43) i
P_c	$\frac{5}{2}^-$	4498(5) - 35(17) i	$\Sigma_c^* \bar{D}^*$ (4526.7)	-393(620) - 2(26) i

- Three additional P_c states $\gtrsim 4.5$ GeV: LHC Run-3, photoproduction?

- Production mechanism needs to be understood

- Different molecular model:

$$P_c(4440): \frac{3}{2}^- \Sigma_c \bar{D}^*; P_c(4457): \frac{1}{2}^+ \Lambda_c(2595) \bar{D} \quad \text{Burns, Swanson, PRD100(2019)114033}$$

- One way to distinguish the two models for $P_c(4457)$, isospin breaking decays into

$$J/\psi \Delta: \text{huge for } \Sigma_c \bar{D}^* \quad \text{FKG et al., PRD99(2019)091501; Burns, EPJA51(2015)152;}$$

$$\text{tiny for } \Lambda_c(2595) \bar{D} \quad \text{Burns, Swanson, PRD100(2019)114033}$$