Towards a new paradigm of heavy-flavor hadron spectrum

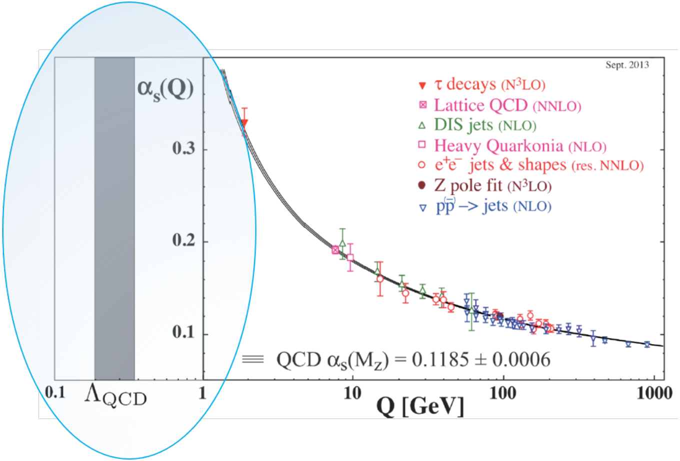
Revealing the mysteries of positive-parity charm mesons

Feng-Kun Guo

Institute of Theoretical Physics, Chinese Academy of Sciences

Seminar, USTC, Nov. 22, 2018

Low-energy QCD: big challenge

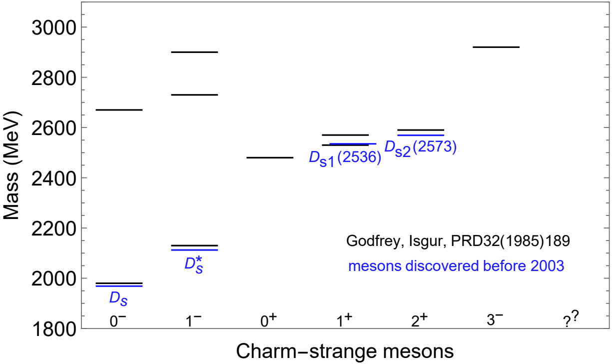


Confinement

nucleon structure

mysteries in hadron spectroscopy

Mysteries of charm mesons: Charm-strange



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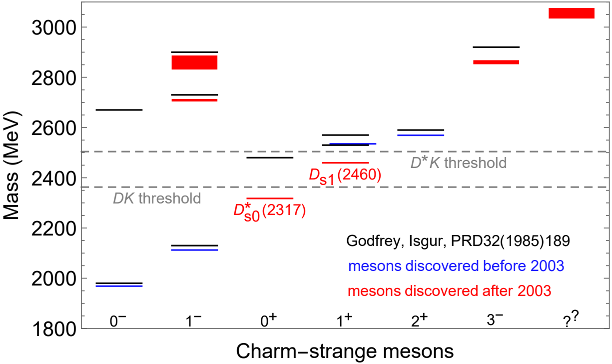

- $D^*_{s0}(2317)$: BaBar (2003)
  $J^P = 0^+$, $\Gamma < 3.8$ MeV
- $D_{s1}(2460)$: CLEO (2003)
  $J^P = 1^+$, $\Gamma < 3.5$ MeV
- no isospin partner observed, tiny widths
  $\Rightarrow I = 0$

- Mystery 1: Mass problem: Why are $D^*_{s0}(2317)$ and $D_{s1}(2460)$ so light?
- Mystery 2: Naturalness problem:

  Why $\underbrace{M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)}}_{(141.8\pm0.8)\text{ MeV}} \simeq \underbrace{M_{D^{*\pm}} - M_{D^\pm}}_{(140.67\pm0.08)\text{ MeV}}$?

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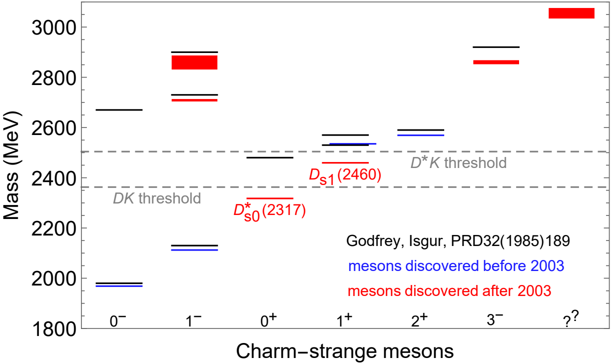

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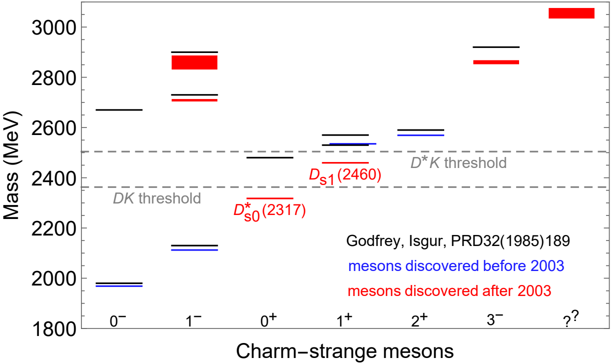

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Mysteries of charm mesons: Charm-nonstrange (1)

Obervations of charm-nonstrange excited mesons in 2003

$B^- \to D^{(*)+}\pi^-\pi^-$ Belle, PRD69(2004)112002 [hep-ex/0307021]

- $D_0^*(2400)$: $J^P = 0^+$

  $\Gamma = (267 \pm 40)$ MeV

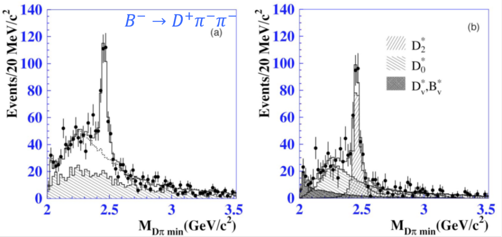
  Mass (MeV):

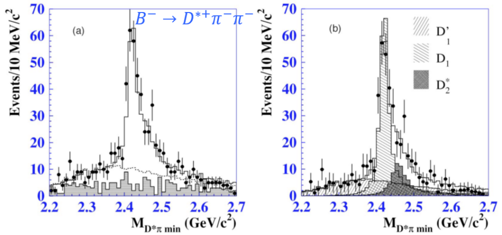
2318 ± 29	PDG18	
2297 ± 22	BaBar	B decays
2308 ± 36	Belle	B decays
2401 ± 41	FOCUS	γA
2360 ± 34	LHCb	$B^0 \to \bar{D}^0\pi^- K^+$

- $D_1(2430)$: $J^P = 1^+$

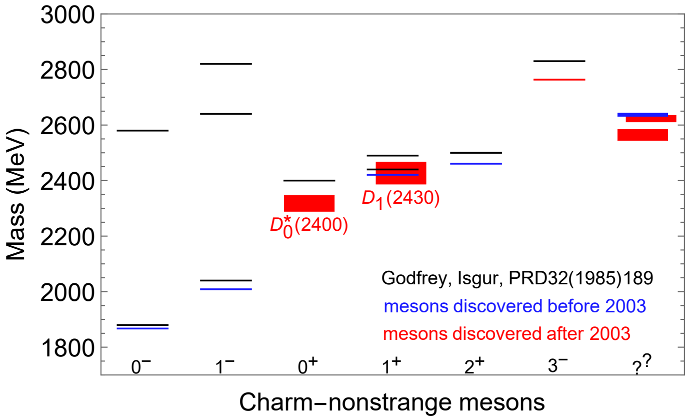
  $\Gamma = 384^{+130}_{-110}$ MeV

  $M = (2427 \pm 36)$ MeV





Mysteries of charm mesons: Charm-nonstrange (2)



- Mystery 3: Hierachy problem:

  Why $M_{D_0^*(2400)} \gtrsim M_{D_{s0}^*(2317)}$ and $M_{D_1(2430)} \sim M_{D_{s1}(2460)}$?

Theoretical tools

- Lattice QCD
- Symmetries:

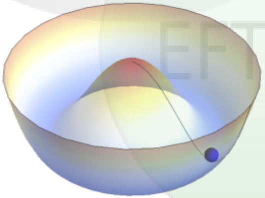
u	d	s		c	b	t
~2 MeV	~5 MeV	~100 MeV	$\ll \Lambda_{\rm QCD} \ll$	~1.3 GeV	~4.2 GeV	~173 GeV

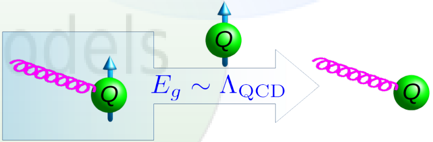
Light quarks (u, d, s) — Heavy quarks (c, b, t)

☞ Spontaneously broken chiral symmetry: π, K and η as the pseudo-Goldstone bosons

☞ Heavy quark spin symmetry

☞ Heavy quark flavor symmetry





- Quark model, QCD sum rules, . . .

Lattice studies of the charmed scalar mesons: strange

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

- $c\bar{s} + DK$ interpolators: ∼right mass Mohler et al., PRL111(2013)222001

  $M_{D_{s0}^*} - \frac{1}{4}\left(M_{D_s} + 3M_{D_s^*}\right)$:

Mohler et al.	PDG2018
(266 ± 16) MeV	(241.5 ± 0.8) MeV

- Calculation with $M_\pi = 150$ MeV Bali et al. [RQCD Col.], PRD96(2017)074501

	Energy [MeV]	Expt [MeV]
m_{0-}	1976.9(2)	1966.0(4)
m_{1-}	2094.9(7)	2111.3(6)
m_{0+}	2348(4)(+6)	2317.7(0.6)(2.0)
m_{1+}	2451(4)(+1)	2459.5(0.6)(2.0)

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

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

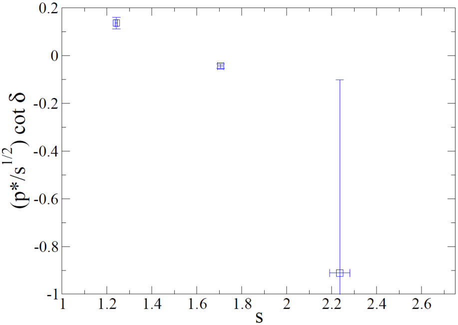
  Mohler et al., PRD87(2013)034501

  $M_\pi \approx 266$ MeV,

  $M_D \approx 1558$ MeV,

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

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



$\Rightarrow$ BW parameters of $D_0^*(2400)$ consistent with PDG values

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

Lattice studies of the charmed scalar mesons: nonstrange (2)

- $(S, I) = (0, \frac{1}{2})$: first coupled-channel lattice calculation including interpolating fields for $c\bar{q} + D\pi + D\eta + D_s\bar{K}$: Moir et al. [Hadron Spectrum Col.], JHEP1610(2016)011
- $M_\pi = 391$ MeV, $M_D = 1885$ MeV: $D\pi$ threshold (2276.4 ± 0.9) MeV
- for coupled channels:

  parametrizing the T-matrix with the K-matrix formalism

$$T_{ij}^{-1}(s) = K_{ij}^{-1}(s) + I_{ij}(s)$$

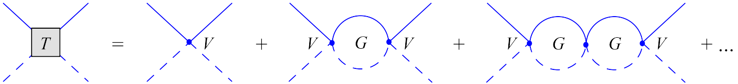
  $I_{ij}(s)$: 2-point loop function evaluated with a subtracted dispersion integral
  $K_{ij}(s)$: different forms of the K-matrix were used, summarized as

$$K_{ij}(s) = \left(g_i^{(0)} + g_i^{(1)} s\right)\left(g_j^{(0)} + g_j^{(1)} s\right)\frac{1}{m^2 - s} + \gamma_{ij}^{(0)} + \gamma_{ij}^{(1)} s$$

- $\Rightarrow$ a pole below threshold (2275.9 ± 0.9) MeV. relation to $D_0^*(2400)$?

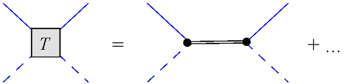
Interactions between charm and light mesons

- 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 field
- D_{s0}^*/D_0^* should appear as poles in scattering amplitudes:

$$D_{s0}^* : DK, D_s\eta; \qquad D_0^* : D\pi, D\eta, D_s\bar{K}$$



$\Rightarrow$ needs a nonperturbative treatment: ChPT + unitarization

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

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

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

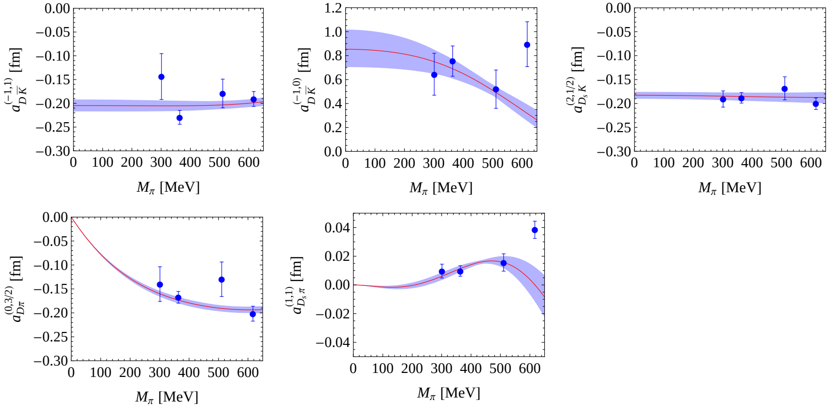
Fit to lattice data

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

- Fit to lattice data on scattering lengths in 5 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 $a(\mu)$

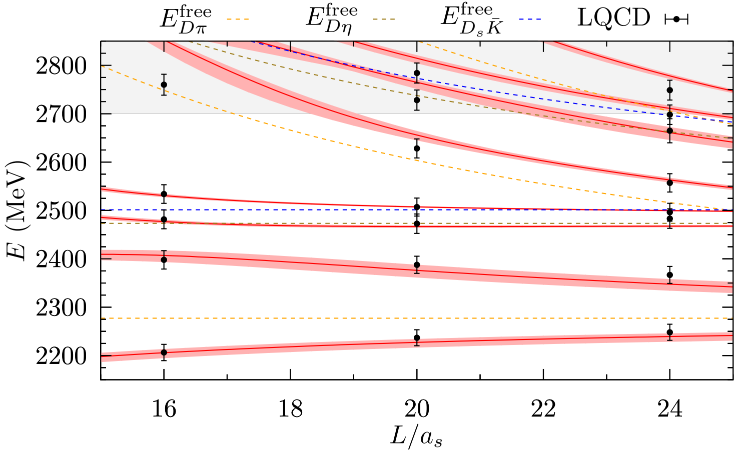


Postdictions versus recent lattice results: charm-nonstrange

- In a finite volume: $\vec{q} = \frac{2\pi}{L}\vec{n}, \vec{n} \in \mathbb{Z}^3$; loop integral $G(s)$: $\int d^3\vec{q} \to \frac{1}{L^3}\sum_{\vec{q}}$
- Postdicted $I = 1/2\ D\pi, D\eta, D_s\bar{K}$ finite volume energy levels versus lattice QCD results by [G. Moir *et al.* [Hadron Spectrum Collaboration], JHEP1610(2016)011]

NOT a fit !

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



Predictions for 0^+ & 1^+ heavy mesons

Du et al., arXiv:1712.07957

- Heavy-strange

meson	J^P	prediction (MeV)	PDG2018 (MeV)	lattice (MeV)
D_{s0}^*	0^+	2315^{+18}_{-28}	2317.7 ± 0.6	2348^{+7}_{-4}[1]

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

	Lower (MeV)	Higher (MeV)	PDG2018 (MeV)
D_0^*	$(2105^{+6}_{-8}, 102^{+10}_{-11})$	$(2451^{+36}_{-26}, 134^{+7}_{-8})$	$(2318 \pm 29, 134 \pm 20)$
D_1	$(2247^{+5}_{-6}, 107^{+11}_{-10})$	$(2555^{+47}_{-30}, 203^{+8}_{-9})$	$(2427 \pm 40, 192^{+65}_{-55})$
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] Bali, Collins, Cox, Schäfer, PRD96(2017)074501

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

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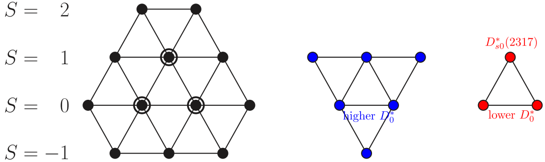
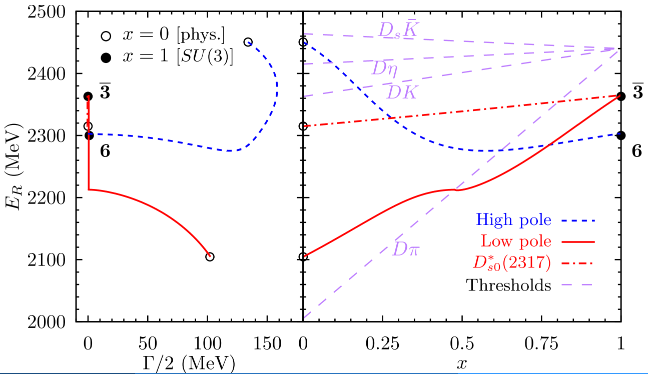
- In the SU(3) limit, irreps: $\overline{\mathbf{3}} \otimes \mathbf{8} = \overline{\mathbf{15}} \oplus \mathbf{6} \oplus \overline{\mathbf{3}}$



- Evolution of the two poles from the physical to the SU(3) symmetric case



DK component from lattice QCD

- Compositeness $(1 - Z)$ related to the S-wave scattering length: Weinberg (1965)

$$a \simeq -2\frac{1-Z}{2-Z}\frac{1}{\sqrt{2\mu E_B}}$$

- From the lattice energy levels in C. Lang et al., PRD90(2014)034510
  $D_{s0}^*(2317)$ contains ∼70% DK Martínez Torres, Oset, Prelovsek, Ramos, JHEP1505,053
- Latest lattice results in G. Bali et al., PRD96(2017)074501

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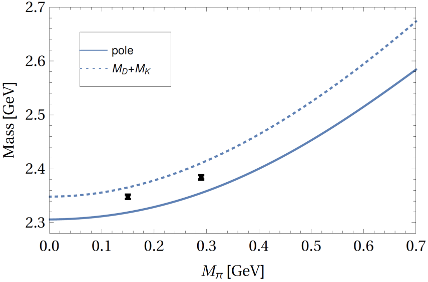


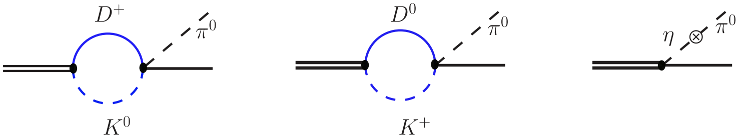
$1-Z = 1.04(0.08)(+0.30)$

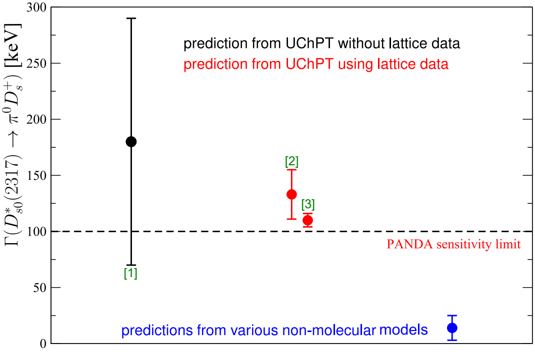
M_π [MeV]	150	290
$M_{D^*_{s0}(2317)}$ [MeV]	2348 ± 4	2384 ± 3
M_{D_s} [MeV]	1977 ± 1	1980 ± 1

strong M_π dependence!

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

Decay width of $D_{s0}^*(2317)$: smoking gun





measurement planned at PANDA

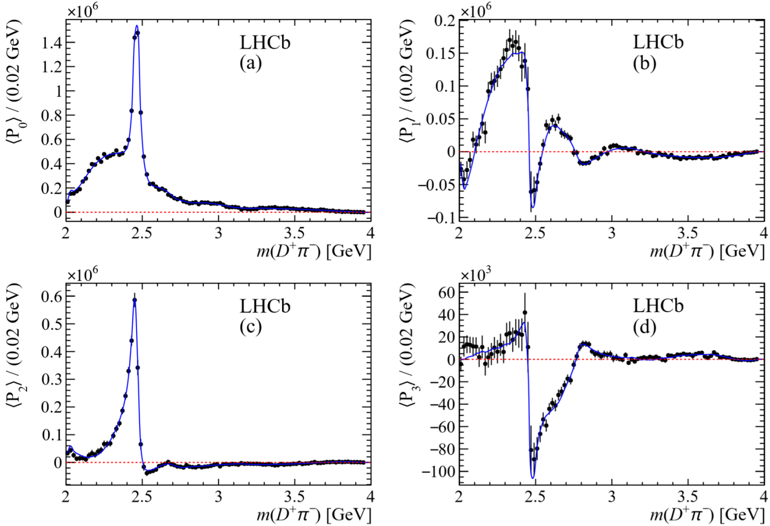
[1] FKG et al.,PLB666(2008)251; [2] L. Liu et al.,PRD87(2013)014508; [3] X. Guo et al.,PRD98(2018)014510

non-molecular: e.g., P. Colangelo and F. De Fazio, PLB570(2003)180

$B^- \to D^+\pi^-\pi^-$ (1)

LHCb, PRD94(2016)072001

Angular moments: $\langle P_L \rangle \propto \int_{-1}^{+1} d\cos\theta \, P_L(\cos\theta) \, \frac{d\Gamma}{dm_{D\pi}\, d\cos\theta}$

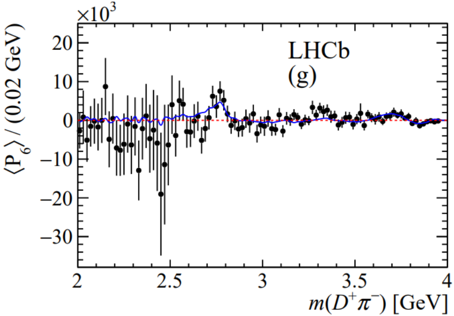


- Consider only S, P, D waves, up to around 2.5 GeV:

$$\mathcal{A}(B^- \to D^+\pi^-\pi^-) = \mathcal{A}_0(s) + \sqrt{3}\mathcal{A}_1(s)P_1(z) + \sqrt{5}\mathcal{A}_2(s)P_2(z);$$

higher partial waves negligible:

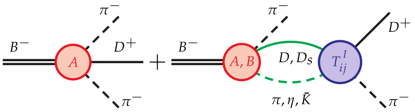
$$\langle P_6 \rangle \propto |\mathcal{A}_3|^2$$



- P-wave: D^*, $D^*(2680)$ [$M = 2681$ MeV, $\Gamma = 187$ MeV]; D-wave: $D_2(2460)$ parametrized (with the same masses and widths) as in the LHCb paper: Breit–Wigner with Bleit–Weisskopf barrier factors, one constant phase for each as free parameters

$B^- \to D^+\pi^-\pi^-$ (3)

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



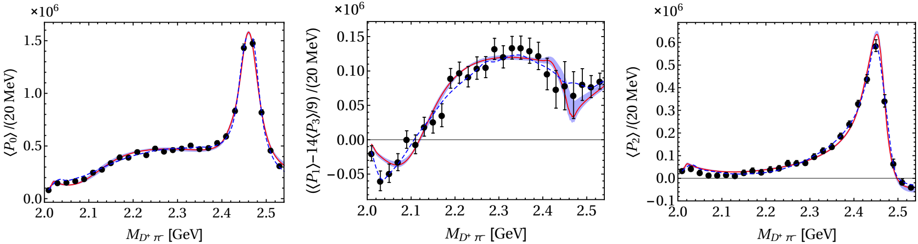
- S-wave: FSI, two new parameters
- P, D-wave: BWs from the LHCb fit

Angular moments:

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

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

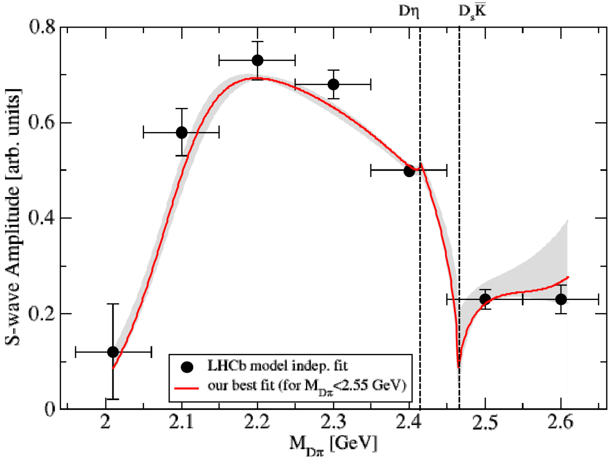
Data: LHCb, PRD94(2016)072001



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

$B^- \to D^+\pi^-\pi^-$ (4)

$D\pi$ S-wave amplitude: comparison with the LHCb determination



Coupled-channel thresholds, effects enhanced by the pole at $(2.45 - i\,0.13)$ GeV

Puzzles solved

Thanks for the recent experiment, lattice and EFT developments

⇒ likely resolution to all 3 myteriess of positive-parity charm mesons:

- Q: Why are $D^*_{s0}(2317)$ and $D_{s1}(2460)$ much lighter than quark model predictions for $c\bar{s}$ mesons ?

  A: They are dominantly DK and D^*K molecular states, respectively.

- Q: Why $M_{D_{s1}(2460)^\pm} - M_{D^*_{s0}(2317)^\pm} \simeq M_{D^{*\pm}} - M_{D^\pm}$?

  A: Consequence of HQSS as dominantly DK and D^*K molecules.

- Q: Why $M_{D_0^*(2400)} \gtrsim M_{D^*_{s0}(2317)}$ and $M_{D_1(2430)} \sim M_{D_{s1}(2460)}$?

  A: Two D_0^* and two D_1, the SU(3) partners of D_{sJ} have smaller masses.

Puzzles solved

Experiments

Lattice

EFT, models

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Puzzles solved

Thanks for the recent experiment, lattice and EFT developments

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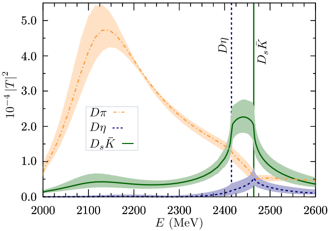

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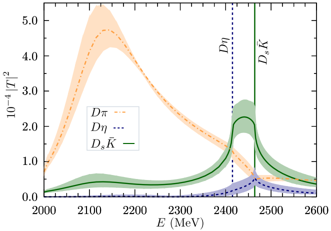
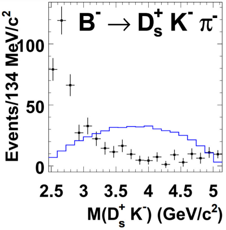
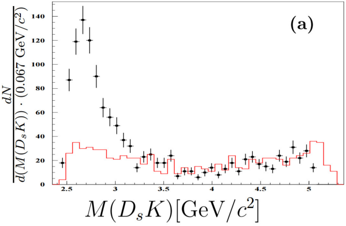
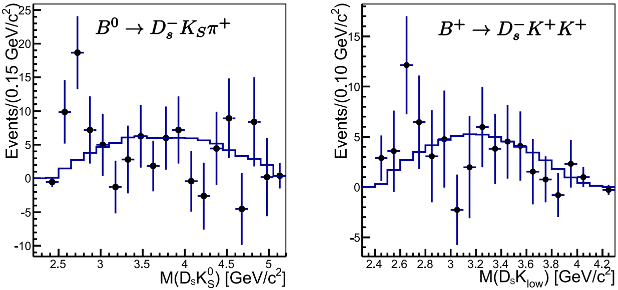




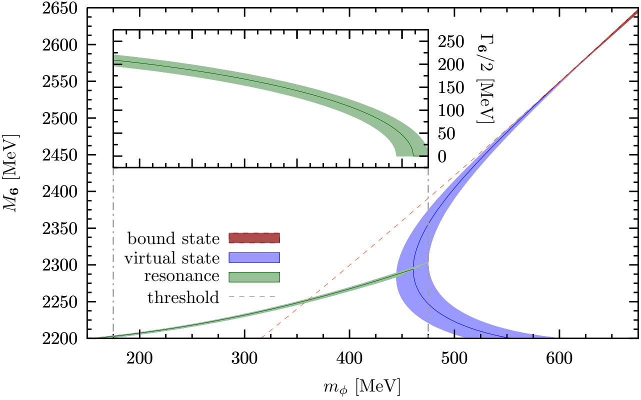


BaBar, PRL100(2008)171803; Belle, PRD80(2009)052005



Belle, PRD91(2015)032008

- Lattice QCD calculation with a SU(3) symmetric large quark mass:



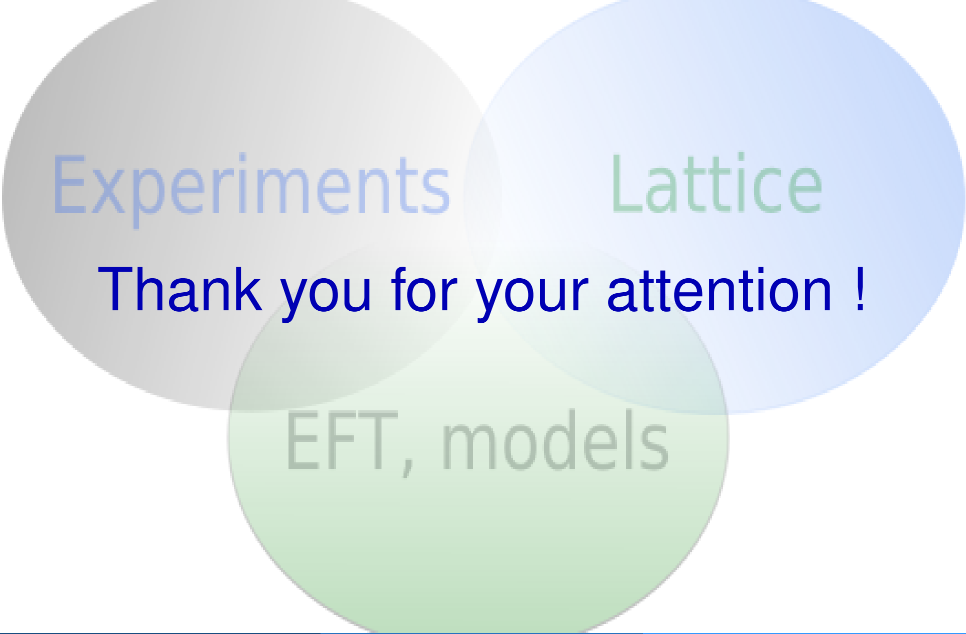
Summary and suggestions

- Mysteries of positive-parity charmed mesons naturally understood
- There will be further experimental and lattice checks
- π, K, η are pseudo-Goldstone bosons, interactions for other hadrons could be more strong

  $\Rightarrow$ importance of S-wave multi-hadron channels should be generally expected

  $\Rightarrow$ new paradigm shifted from quark model (old paradigm)
- Suggestion for PDG:

  to reconsider the D_0^* parameters



Thank you for your attention !

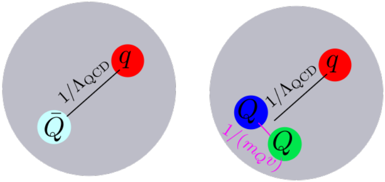
Doubly-charmed baryons

- Heavy anti-quark–diquark symmetry (HADS): Savage, Wise (1990)

  $m_Q v \gg \Lambda_{\text{QCD}}$,

  the diquark serves as a point-like color-$\bar{3}$ source, like a heavy anti-quark.

  doubly-heavy baryons $\Leftrightarrow$ anti-heavy mesons



- HADS + CHPT with virtual photons: Brodsky, FKG, Hanhart, Meißner, PLB698(2011)251

  $M_{D^+} - M_{D^0} \Rightarrow M_{\Xi_{cc}^{++}} - M_{\Xi_{cc}^{+}} = (1.5 \pm 2.7)$ MeV

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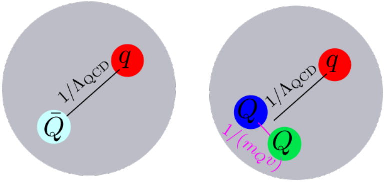

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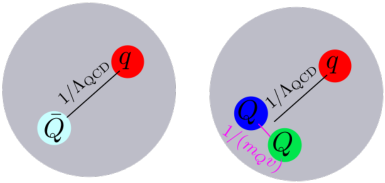

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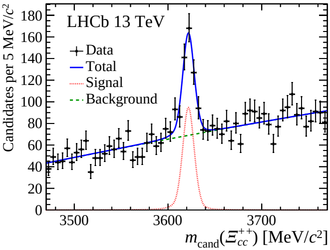
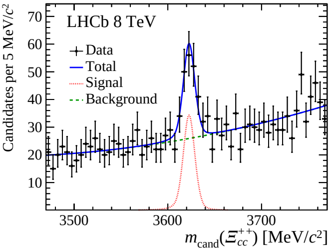


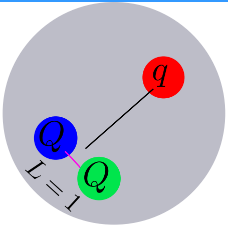


Doubly-charmed baryons with $J^P = 1/2^-$

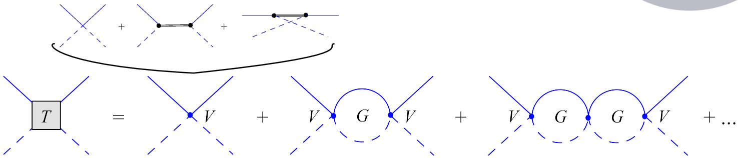
- P-wave QQ

  excitation energy   Mehen, PRD96(2017)094028

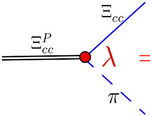
  $$\sim \frac{1}{2}(M_{h_c} - M_{J/\psi}) = \mathcal{O}\,(200 \text{ MeV})$$



- $\Rightarrow \Xi_{cc}^P, \Omega_{cc}^P$ as dynamical degrees of freedom



- S-wave QQ: spin $s_{QQ} = 1$, P-wave QQ: spin $s_{QQ} = 0$



$$\lambda = \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_Q}\right)$$

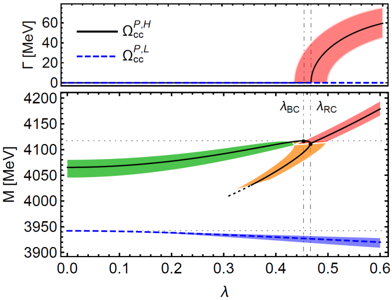
Doubly-charmed strange baryons with $J^P = 1/2^-$: Ω_{cc}^P

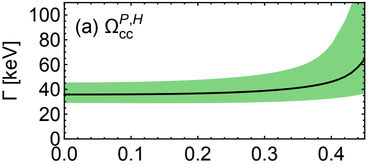
M.-J. Yan, X.-H. Liu et al., PRD98(2018)091502(R)

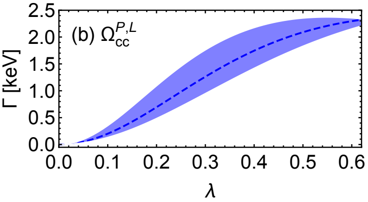
- Very likely two states below the $\Xi_{cc}\bar{K}$ threshold

  Inputs: bare $\mathring{M}_{\Xi_{cc}^P} = 3838$ MeV from quark model D. Ebert et al., PRD96(2002)024008

  $$M_{\Omega_{cc}} - M_{\Xi_{cc}} = M_{D_s} - M_D, \quad \mathring{M}_{\Omega_{cc}^P} - M_{\Omega_{cc}} = 217 \text{ MeV}$$





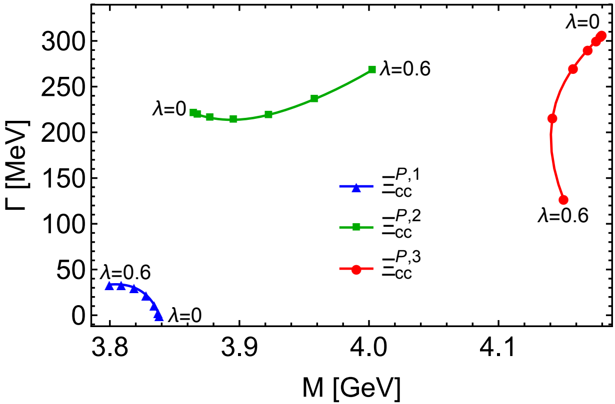


- Tiny widths due to isospin breaking: $\Omega_{cc}^P \to \Omega_{cc}\pi^0$

Doubly-charmed nonstrange baryons with $J^P = 1/2^-$: Ξ_{cc}^P

M.-J. Yan, X.-H. Liu et al., PRD98(2018)091502(R)

- Three $\frac{1}{2}^-$ Ξ_{cc}^P states below 4.2 GeV:



- $\mathcal{B}(\Xi_{cc}^{P,1}, \Xi_{cc}^{P,2} \to \Xi_{cc}\pi) \simeq 100\%$, searching for $\Xi_{cc}^{P,1}$ in $\Xi_{cc}^{++}\pi^- \Rightarrow \lambda$

HQS for $D_{s0}^*(2317)$ and $D_{s1}(2460)$

- Heavy quark flavor symmetry:
  for a singly-heavy hadron, $M_{H_Q} = m_Q + A + \mathcal{O}\left(m_Q^{-1}\right)$
- rough estimates of bottom analogues whatever the D_{sJ} states are

$$M_{B_{s0}^*} = M_{D_{s0}^*(2317)} + \Delta_{b-c} + \mathcal{O}\left(\Lambda_{\text{QCD}}^2\left(\frac{1}{m_c} - \frac{1}{m_b}\right)\right) \simeq (5.65 \pm 0.15)\ \text{GeV}$$

$$M_{B_{s1}} = M_{D_{s1}(2460)} + \Delta_{b-c} + \mathcal{O}\left(\Lambda_{\text{QCD}}^2\left(\frac{1}{m_c} - \frac{1}{m_b}\right)\right) \simeq (5.79 \pm 0.15)\ \text{GeV}$$

  here $\Delta_{b-c} \equiv m_b - m_c \simeq \overline{M}_{B_s} - \overline{M}_{D_s} \simeq 3.33$ GeV, where
  $\overline{M}_{B_s} = 5.403$ GeV, $\overline{M}_{D_s} = 2.076$ GeV: spin-averaged g.s. $Q\bar{s}$ meson masses

  ☞ both to be discovered [1]

- more precise predictions can be made in a given model, e.g. hadronic molecules

[1] The established meson $B_{s1}(5830)$ is probably the bottom partner of $D_{s1}(2536)$.

Easy predictions from HQFS

- Heavy quark flavor symmetry (HQFS) for any hadron containing one heavy quark: velocity remains unchanged in the limit $m_Q \to \infty$: $\Delta v = \frac{\Delta p}{m_Q} = \frac{\Lambda_{\text{QCD}}}{m_Q}$
  $\Rightarrow$ heavy quark is like a static color triplet source, m_Q is irrelevant
- Predicting the bottom-partner masses in 1 minute:

$$M_{B_{s0}^*} \simeq M_B + M_K - 45\,\text{MeV} \simeq 5.730\ \text{GeV}$$
$$M_{B_{s1}} \simeq M_{B^*} + M_K - 45\,\text{MeV} \simeq 5.776\ \text{GeV}$$

nice agreement with lattice results: Lang, Mohler, Prelovsek, Woloshyn, PLB750(2015)17

$$M_{B_{s0}^*}^{\text{lat.}} = (5.711 \pm 0.013 \pm 0.019)\ \text{GeV}$$
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Energy levels in a finite volume

- Goal: predict finite volume (FV) energy levels for $I = 1/2$, and compare with recent lattice data by the `Hadron Spectrum Col.` in JHEP1610(2016)011
  $\Rightarrow$ insights into $D_0^*(2400)$
- In a FV, momentum gets quantized: $\vec{q} = \frac{2\pi}{L}\vec{n},\ \vec{n} \in \mathbb{Z}^3$
- Loop integral $G(s)$ gets modified: $\int d^3\vec{q} \to \frac{1}{L^3}\sum_{\vec{q}}$, and one gets

M. Döring, U.-G. Meißner, E. Oset, A. Rusetsky, EPJA47(2011)139

$$\widetilde{G}(s,L) = G(s) + \lim_{\Lambda\to+\infty}\underbrace{\left[\frac{1}{L^3}\sum_{\vec{n}}^{|\vec{q}|<\Lambda} I(\vec{q}) - \int_0^\Lambda \frac{q^2\mathrm{d}q}{2\pi^2}\, I(\vec{q})\right]}_{\text{finite volume effect}}$$

$I(\vec{q})$: loop integrand

- FV energy levels obtained by as poles of $\widetilde{T}(s,L)$:

$$\widetilde{T}^{-1}(s,L) = V^{-1}(s) - \widetilde{G}(s,L)$$

Chiral Lagrangian (I)

- The leading order Lagrangian:

$$\mathcal{L}_{\phi P}^{(1)} = D_\mu P D^\mu P^\dagger - m^2 P P^\dagger$$

with $P = (D^0, D^+, D_s^+)$ denoting the D–mesons, and the covariant derivative being

$$\begin{aligned} D_\mu P &= \partial_\mu P + P\Gamma_\mu^\dagger, \quad D_\mu P^\dagger = (\partial_\mu + \Gamma_\mu)P^\dagger, \\ \Gamma_\mu &= \frac{1}{2}\left(u^\dagger \partial_\mu u + u\partial_\mu u^\dagger\right), \end{aligned}$$

where $u_\mu = i\left[u^\dagger(\partial_\mu - ir_\mu)u + u(\partial_\mu - il_\mu)u^\dagger\right], \quad u = e^{i\lambda_a \phi_a/(2F_0)}$

Burdman, Donoghue (1992); Wise (1992); Yan et al. (1992)

- this gives the Weinberg–Tomozawa term for $P\phi$ scattering

Chiral Lagrangian (II)

- At the next-to-leading order $\mathcal{O}\left(p^2\right)$: FKG, Hanhart, Krewald, Meißner, PLB**666**(2008)251

$$\mathcal{L}_{\phi P}^{(2)} = P\left[-h_0\langle\chi_+\rangle - h_1\chi_+ + h_2\langle u_\mu u^\mu\rangle - h_3 u_\mu u^\mu\right]P^\dagger \\ +D_\mu P\left[h_4\langle u_\mu u^\nu\rangle - h_5\{u^\mu, u^\nu\}\right]D_\nu P^\dagger \ ,$$

$\chi_\pm = u^\dagger\chi u^\dagger \pm u\chi^\dagger u, \quad \chi = 2B_0\,\mathrm{diag}(m_u, m_d, m_s)$

- LECs: $h_{1,3,5} = \mathcal{O}\left(N_c^0\right), h_{2,4,6} = \mathcal{O}\left(N_c^{-1}\right)$

  $M_{D_s} - M_D \Rightarrow h_1 = 0.42$

  h_0: can be fixed from lattice results of charmed meson masses

  $h_{2,3,4,5}$: to be fixed from lattice results on scattering lengths

- Extensions to $\mathcal{O}\left(p^3\right)$, see Y.-R. Liu, X. Liu, S.-L. Zhu, PRD**79**(2009)094026; L.-S. Geng et al., PRD**82**(2010)054022; D.-L. Yao, M.-L. Du, FKG, U.-G. Meißner, JHEP**1511**(2015)058;

  M.-L. Du, FKG, U.-G. Meißner, D.-L. Yao, EPJC**77**(2017)728

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  PCB-term subtraction in EOMS scheme using path integral:

  M.-L. Du, FKG, U.-G. Meißner, JHEP**1610**(2016)122

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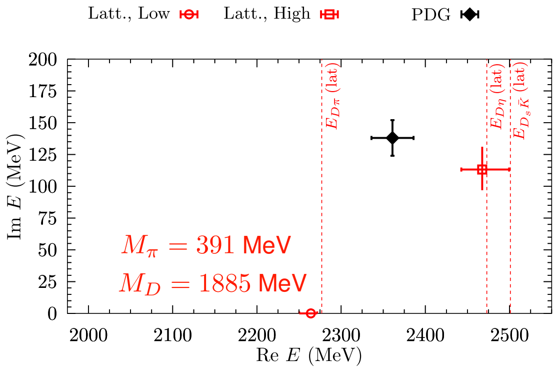
Two $I = 1/2$ states !

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	(000)	$7.7^{+1.2}_{-1.1}$	$0.3^{+0.5}_{-0.3}$	$4.2^{+1.1}_{-1.0}$
	2468^{+32}_{-25}	113^{+18}_{-16}	(110)	$5.2^{+0.6}_{-0.4}$	$6.7^{+0.6}_{-0.4}$	$13.2^{+0.6}_{-0.5}$



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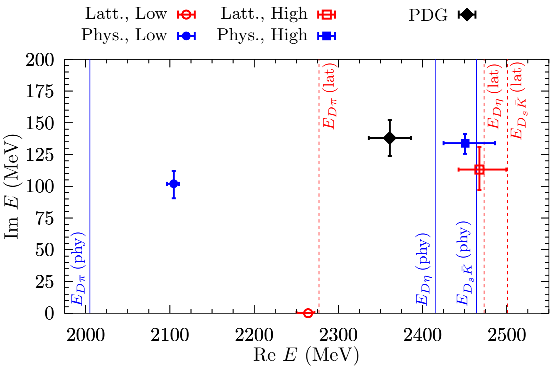
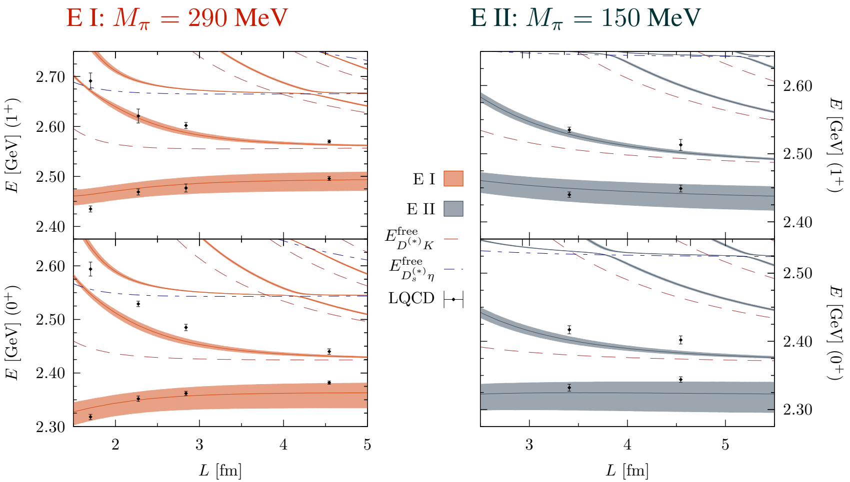
physical	2105^{+6}_{-8}	102^{+10}_{-11}	(100)	$9.4^{+0.2}_{-0.2}$	$1.8^{+0.7}_{-0.7}$	$4.4^{+0.5}_{-0.5}$
	2451^{+36}_{-26}	134^{+7}_{-8}	(110)	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$



Postdictions versus recent lattice results: charm-strange

- Postdicted finite volume energy levels for $(S, I) = (1, 0)$ $D^{(*)}K$, $J^P = 1^+$ & 0^+ versus lattice QCD results by [G. Bali, S. Collins, A. Cox, A. Schäfer, PRD96(2017)074501]

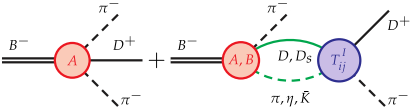
M. Albaladejo, P. Fernandez-Soler, J. Nieves, P. G. Ortega, arXiv:1805.07104



Fit to LHCb data

Du et al., PRD98(2018)094018

- $B^- \to D^+\pi^-\pi^-$ contains coupled-channel $D\pi$ FSI
- consider S, P, D waves: $\mathcal{A}(B^- \to D^+\pi^-\pi^-) = \mathcal{A}_0(s) + \mathcal{A}_1(s) + \mathcal{A}_2(s)$
  - ☞ P-wave: D^*, $D^*(2680)$; D-wave: $D_2(2460)$ as in the LHCb paper
  - ☞ S-wave: use the coupled-channel (1: $D\pi$; $2: D\eta$; $3: D_s\bar{K}$) amplitudes with all parameters fixed before



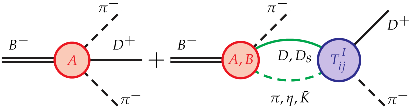
  - ☞ only 2 parameters in S-wave: C and a subtraction constant in $G_i(s)$

SU(3)+chiral $\Rightarrow$

$$\mathcal{A}_0(s) \propto E_\pi \left[2 + G_{D\pi}(s)\left(\frac{5}{3}T^{1/2}_{11}(s) + \frac{1}{3}T^{3/2}(s)\right)\right] + \frac{1}{3}E_\eta G_{D\eta}(s)T^{1/2}_{21}(s) + \sqrt{\frac{2}{3}}E_{\bar{K}}G_{D_s\bar{K}}(s)T^{1/2}_{31}(s) + C\,E_\eta G_{D\eta}(s)T^{1/2}_{21},$$

Im $G_i(s) = -\rho_i(s) \Rightarrow$ Unitarity: Im$\mathcal{A}_{0,i}(s) = -\sum_j T^*_{ij}(s)\rho_j(s)\mathcal{A}_{0,j}(s)$

- $B^- \to D^+\pi^-\pi^-$ contains coupled-channel $D\pi$ FSI
- consider S, P, D waves: $\mathcal{A}(B^- \to D^+\pi^-\pi^-) = \mathcal{A}_0(s) + \mathcal{A}_1(s) + \mathcal{A}_2(s)$
  - ☞ P-wave: D^*, $D^*(2680)$; D-wave: $D_2(2460)$ as in the LHCb paper
  - ☞ S-wave: use the coupled-channel (1: $D\pi$; $2:D\eta$; $3:D_s\bar{K}$) amplitudes with all parameters fixed before



  - ☞ only 2 parameters in S-wave: C and a subtraction constant in $G_i(s)$

SU(3)+chiral $\Rightarrow$ $$\mathcal{A}_0(s) \propto E_\pi \left[2 + G_{D\pi}(s)\left(\frac{5}{3}T^{1/2}_{11}(s) + \frac{1}{3}T^{3/2}(s)\right)\right] + \frac{1}{3}E_\eta G_{D\eta}(s)T^{1/2}_{21}(s) + \sqrt{\frac{2}{3}}E_{\bar{K}}G_{D_s\bar{K}}(s)T^{1/2}_{31}(s) + C\, E_\eta G_{D\eta}(s)T^{1/2}_{21},$$

Im $G_i(s) = -\rho_i(s) \Rightarrow$ Unitarity: Im$\mathcal{A}_{0,i}(s) = -\sum_j T^*_{ij}(s)\rho_j(s)\mathcal{A}_{0,j}(s)$

More similar states?

FKG, U.-G. Meißner, PRD84(2011)014013

- Chiral symmetry ⇒ universal Weinberg–Tomozawa term
  applicable to any hadrons with a small width $\Gamma \ll$ inverse of force range
- nice candidates: $D_1(2420)$ & $D_2(2460)$, $\Gamma \sim 30$ MeV
  more speculative (using the same subtraction constant) predictions of
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Constituents	$D_1(2420)K$	$D_2(2460)K$	$\bar{B}_1(5720)K$	$\bar{B}_2(5747)K$
J^P	1^-	2^-	1^-	2^-
Predictions	2870 ± 9	2910 ± 9	6151 ± 33	6169 ± 33
Decays	$D^{(*)}K, D_s^{(*)}\eta$	$D^*K, D_s^*\eta$	$\bar{B}^{(*)}K, \bar{B}_s^{(*)}\eta$	$\bar{B}^*K, \bar{B}_s^*\eta$

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What is $D_s^*(2860)$?

- $D_{s1}^*(2860)$: puzzling decay pattern: $\Gamma(D^*K)/\Gamma(DK) = 1.10 \pm 0.24$

  Predictions from HQSS: P.Colangelo et al.,PRD77(2008)014012

$D_{sJ}(2860)$	$D_{sJ}(2860) \to DK$	$\frac{\Gamma(D_{sJ}\to D^*K)}{\Gamma(D_{sJ}\to DK)}$
$s_\ell^P = \frac{1}{2}^-, J^P = 1^-, n = 1$	p-wave	1.23
$s_\ell^P = \frac{1}{2}^+, J^P = 0^+, n = 1$	s-wave	0
$s_\ell^P = \frac{3}{2}^+, J^P = 2^+, n = 1$	d-wave	0.63
$s_\ell^P = \frac{3}{2}^-, J^P = 1^-, n = 0$	p-wave	0.06
$s_\ell^P = \frac{5}{2}^-, J^P = 3^-, n = 0$	f-wave	0.39

  but, better candidate for $(2S, 1^-)$: $D_{s1}^*(2700)$ $\Gamma(D^*K)/\Gamma(DK) = 0.91 \pm 0.18$

  $M(2P, 2^+) \sim 3.16$ GeV M. Di Pierro, E. Eichten, PRD64(2001)114004

- A natural explanation of the decay pattern:

  $$: \quad \frac{\Gamma(D_{s1}^*(2860) \to D^*K)}{DK} \simeq 2\frac{M_{D^*}}{M_D}\left|\frac{\vec{k}_{D^*}}{\vec{k}_D}\right|^3 = 1.23$$

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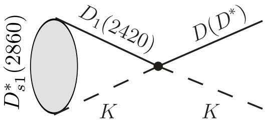

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