Implication of chiral symmetry on the heavy-light meson spectroscopy

Resolving the $D_0^*(2400)$ puzzle and more

Meng-Lin Du

Helmholtz-Institut für Strahlen-und Kernphysik,
Universität Bonn

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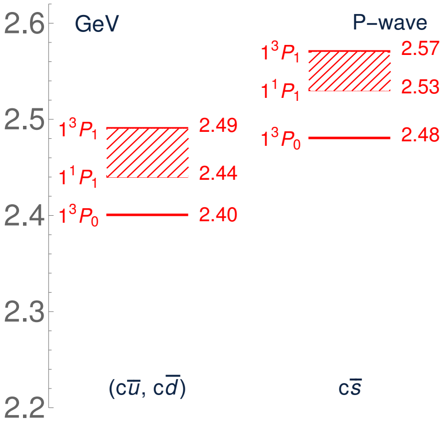
Outline

1. **Introduction**
2. **Implication of chiral symmetry on Breit-Wigner resonances**
3. **Status of Positive-Parity Charmed Mesons (Lattice QCD + EFTs)**
4. **Analysis on the experimental data of $B^+ \to D^+\pi^-\pi^-$**
5. **Summary and outlook**

Positive parity ground state charm mesons



S. Godfrey and N. Isgur, PRD **32**, 189 (1985)

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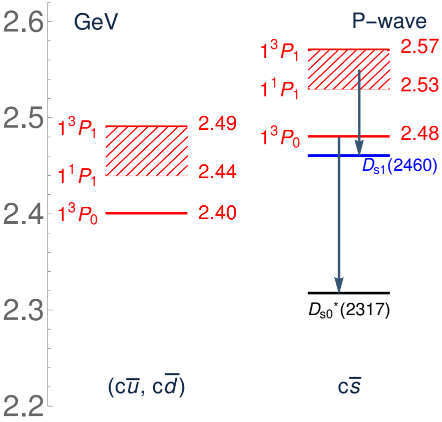

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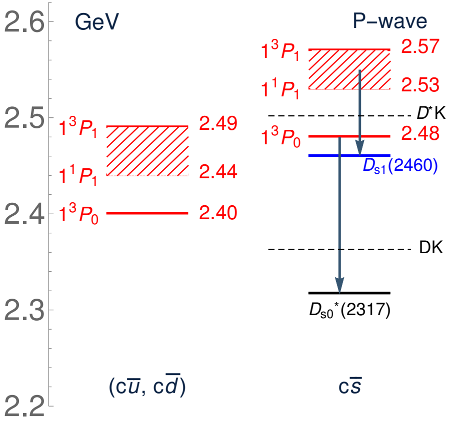

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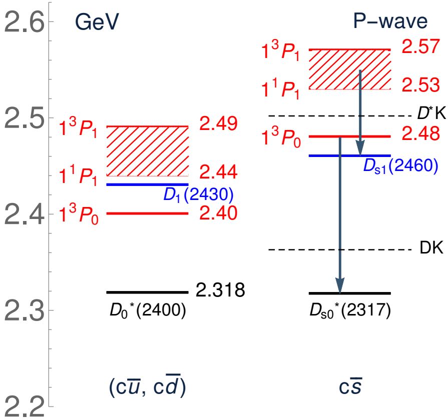

SU(3) partners

$$D_0^*(2400), D_1(2430)$$

$$D_{s0}^*(2317), D_{s1}(2460)$$

S. Godfrey and N. Isgur, PRD **32**, 189 (1985)

BaBar (2003), CLEO (2003); Belle (2004)

Puzzles

Puzzles in charm mesons:

1. Why are the masses of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ much lower than the quark model expectations for the lowest scalar and axial-vector charm-strange mesons?

2. Why is the mass difference between the $D_{s1}(2460)$ and the $D_{s0}^*(2317)$ equal to that between the ground state vector meson and pseudoscalar meson within 2 MeV?

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

3. Why are the masses of the $D_0^*(2400)$ and $D_1(2430)$ almost equal to or even higher than their strange siblings?

Notice: all these experiments used a Breit–Wigner to extract the resonance

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Implication of chiral symmetry on Breit-Wigner resonances

1. Goldstone bosons: energy-dependent interactions
2. The standard Breit-Wigner: constant coupling. ~~chiral symmetry~~
3. S-wave BW parameterization: $F_0(s) \propto \frac{1}{s-m_0^2+im_0\Gamma}$

$$\frac{d}{ds}|F_0(s)|^2\Big|_{s=s_{\text{peak}}} = 0 \implies s_{\text{peak}} = m_0^2$$

4. Modified parameterization: $F_0(s) \propto \frac{E_\pi}{s-m_0^2+im_0\Gamma}$

$$s_{\text{peak}} = (m_0+\Delta)^2, \qquad \Delta = \frac{\Gamma^2 E_D}{4m_0E_\pi - \Gamma^2}$$

5. ? $D_0^*(2400)$, $D_1(2430)$

Coupled-channel $\implies$ chiral EFT + unitarization

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Lattice studies on the charmed scalar mesons: strange

- Early studies using only $c\bar{s}$-type interpolators
  $\hookrightarrow$ give mass significantly larger than $D_{s0}^*(2317)$ Bali (2003); UKQCD (2003); . . .
- $c\bar{s} + DK$ interpolators: right mass $M_\pi \approx 156$ MeV Mohler *et al.*, PRL111(2013)222001
  binding energy: 37 MeV, $M_{D_{s0}^*} - \frac{1}{4}\left(M_{D_s} + 3M_{D_s^*}\right)$:

Mohler et al.	PDG2017
(266 ± 16) MeV	(241.5 ± 0.8) MeV

- New calculation: $M_\pi = 150$ 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 on the charmed scalar mesons: nonstrange

$(S, I) = (0, 1/2)$:

- $c\bar{q} + D\pi$ interpolator — Mohler *et al.*, PRD87(2013)034501

$$M_\pi \approx 266 \text{ MeV}, \quad M_D \approx 1558 \text{ MeV}, \quad M_{D^*} \approx 1690 \text{ MeV}$$

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

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

	Mohler et al.	PDG2017
$M_{D_0^*} - \frac{1}{4}(M_D + 3M_{D^*})$	(351 ± 21) MeV	(347 ± 29) MeV
$M_{D_1} - \frac{1}{4}(M_D + 3M_{D^*})$	(380 ± 21) MeV	(456 ± 40) MeV

- Coupled-channel:

$\hookrightarrow c\bar{q} + D\pi + D\eta + D_s\bar{K}$ — Moir *et al.* [Hadron Spectrum Col.], JHEP1610(2016)011

$\hookrightarrow M_\pi \approx 391$ MeV, $M_D \approx 1885$ MeV: $D\pi$ threshold (2276.4 ± 0.9) MeV

K-matrix: a pole below threshold is found: 2275.9 ± 0.9 MeV ? $D_0^*(2400)$

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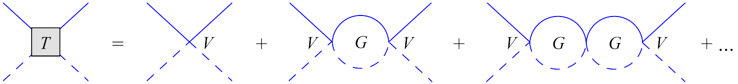
ChPT + unitarization

- Low-energy interactions between the charm and light pseudoscalar mesons: ChPT
- A nonperturbative treatment: unitarization Oller and Meißner, PLB**500**, 263 (2001)

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



$V(s)$: to be derived from SU(3) chiral effective Lagrangian

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

- NLO: 5 free parameters are determined by fit to lattice data on scattering lengths in 5 channels (no disconnected contribution)
  $D\bar{K}(I=1, I=0)$, D_sK, $D\pi(I=3/2)$, $D_s\pi$

L. Liu, Orginos, F.-K. Guo, Hanhart, Meißner, PRD86(2013)014508

$D^*_{s0}(2317)$ and $D_{s1}(2460)$ as hadronic molecules

- Hadronic molecular model: $D^*_{s0}(2317)[DK]$, $D_{s1}(2460)[D^*K]$

  Barnes, Close, Lipkin (2003); van Beveren, Rupp (2003); Kolomeitsev, Lutz (2004); Guo et al. (2006); ...

- NLO prediction for $D^*_{s0}(2317)$: 2315^{+18}_{-28} MeV

  L. Liu, Orginos, F.-K. Guo, Hanhart, Meißner, PRD86(2013)014508

  $\hookrightarrow$ one possible solution to the 1st puzzle

- Solution to the 2nd puzzle: heavy quark spin symmetry

  DK and D^*K interaction almost same $\Rightarrow$ similar bingding energies

  $M_D + M_K - M_{D^*_{s0}(2317)} \simeq M_{D^*} + M_K - M_{D_{s1}(2460)} \pm 4$ MeV

  Uncertainty: binding energy (45 MeV) $\times \frac{\Lambda_{QCD}}{m_c} \frac{M_K}{\Lambda_\chi}$

  $\Rightarrow \quad M_{D_{s1}(2460)^\pm} - M_{D^*_{s0}(2317)^\pm} \simeq M_{D^{*\pm}} - M_{D^\pm}$ is understood

  F.-K. Guo, C.Hanhart and U.-G.Meißner, PRL102(2009)242004

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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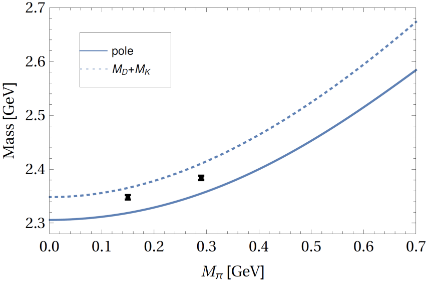


$$1 - Z = 1.04(0.08)(+0.30)$$

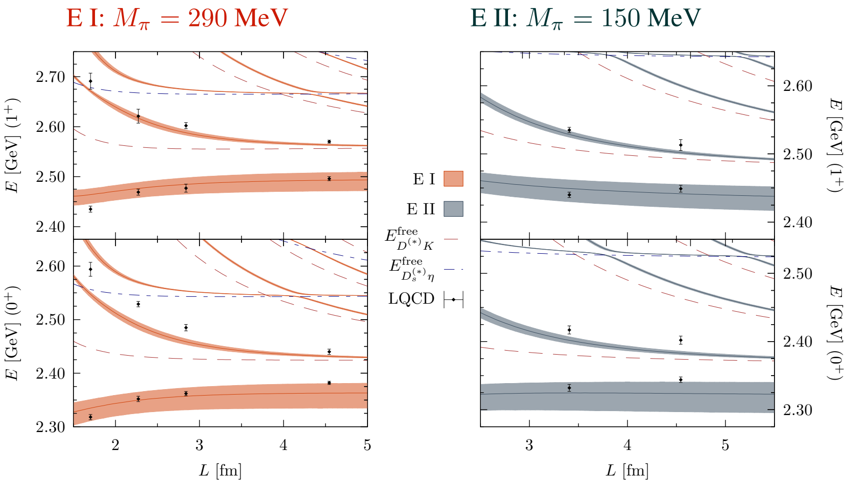
M_π [MeV]	150	290
$M_{D_{s0}^*(2317)}$ [MeV]	2348 ± 4	2384 ± 3
M_{D_s} [MeV]	1977 ± 1	1980 ± 1

strong M_π dependence!

curves: prediction in M. L. Du, F. K. Guo, U. G. Meißner and D. L. Yao, EPJC77(2017)728

Predictions versus recent lattice results: charm-strange

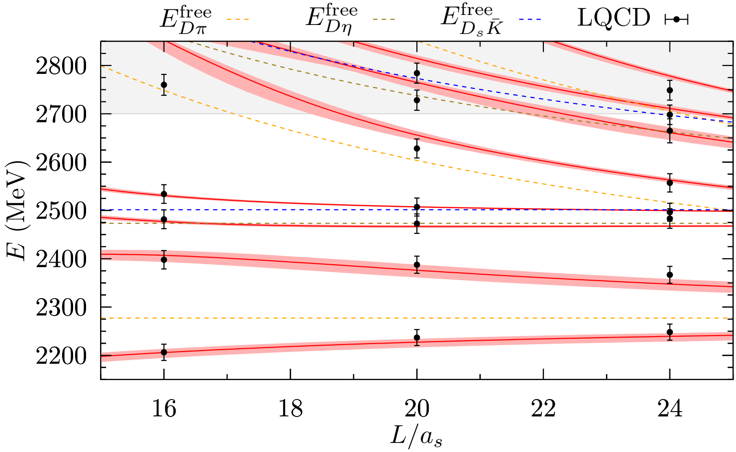
- Postdicted finite volume energy levels for $(S, I) = (1, 0)$, $J^P = 1^+$ & 0^+ versus lattice results by G. Bali, S. Collins, A. Cox, A. Schäfer, PRD96(2017)074501



M. Albaladejo *et al.*, arXiv:1805.07104

- Postdicted finite volume energy levels for $I = 1/2$ agree very well with lattice results by G. Moir *et al.* [Hadron Spectrum Collaboration], JHEP1610(2016)011

NOT a fit !



M. Albaladejo *et al.*, PLB767(2017)465

Two states in $I = 1/2$ sector

- The amplitudes are based on QCD
- Two states in $I = 1/2$ sector were found in Kolomeitsev, Lutz (2004); Guo, Shen, Chiang, Ping, Zou (2006); F.-K. Guo, Hanhart, Meißner (2009); Z.-H. Guo, Meißner, D.-L. Yao (2015)
- remarkable agreement with lattice data $\Rightarrow$ a strong support
- two states also in heavy meson sectors $(M, \Gamma/2)$ in MeV:

	lower pole	higher pole	RPP
D_0^*	$\left(2105^{+6}_{-8}, 102^{+10}_{-11}\right)$	$\left(2451^{+35}_{-26}, 134^{+7}_{-8}\right)$	$(2318 \pm 29, 134 \pm 20)$
D_1	$\left(2247^{+5}_{-6}, 107^{+11}_{-10}\right)$	$\left(2555^{+47}_{-30}, 203^{+8}_{-9}\right)$	$(2427 \pm 40, 192^{+65}_{-55})$
B_0^*	$\left(5535^{+9}_{-11}, 113^{+15}_{-17}\right)$	$\left(5852^{+16}_{-19}, 36 \pm 5\right)$	–
B_1	$\left(5584^{+9}_{-11}, 119^{+14}_{-17}\right)$	$\left(5912^{+15}_{-18}, 42^{+5}_{-4}\right)$	–

$\hookrightarrow$ solution to the third puzzle

- But is there any experimental support?

  to compare with the most precise measurement of $B^- \to D^+\pi^-\pi^-$ by LHCb PRD94(2016)072001

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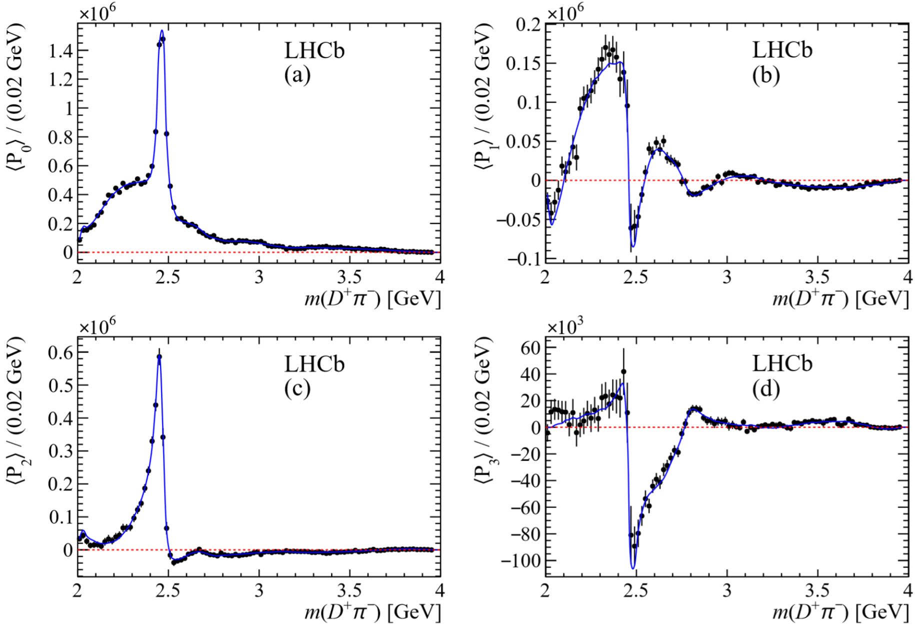
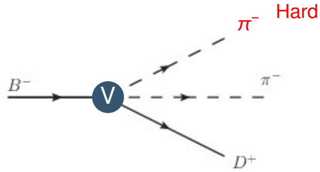
  PRD94(2016)072001

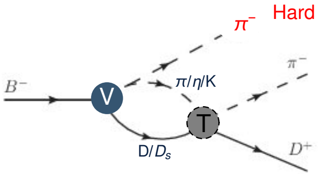
Angular moments of $B^- \to D^+\pi^-\pi^-$

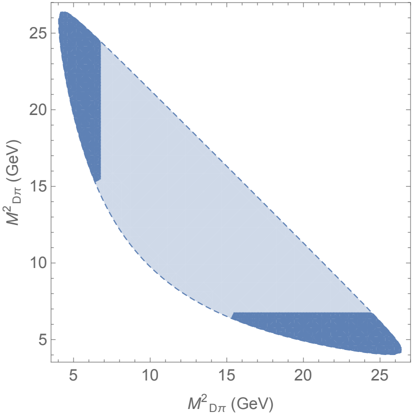
LHCb, PRD94(2016)072001



$B^+ \to D^+\pi^-\pi^-$ kinematics







Chiral effective Lagrangian

1. Effective weak Hamiltonian H_{eff} for $\Delta b = 1$ and $\Delta c = 1$:

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ud} (C_1 \mathcal{O}_1^d + C_2 \mathcal{O}_2^d) + (b \to s) + h.c.,$$

$$\mathcal{O}_1^d = (\bar{c}_a b_b)_L (\bar{d}_b u_a)_L, \qquad \mathcal{O}_2^d = (\bar{c}_a b_a)_L (\bar{d}_b u_b)_L.$$

2. Transforming under $g_L \times g_R \in SU(3)_L \times SU(3)_R$, $h \in SU(3)_V$

Goldstone fields: $u \mapsto g_R u h^\dagger = h u g_L^\dagger, \quad u_\mu \mapsto h u_\mu h^\dagger,$

Matter fields: $B \mapsto B h^\dagger, \quad D \mapsto D h^\dagger, \quad M \mapsto h M h^\dagger$

3. Introducing $t = u H u^\dagger$, $t \mapsto h t h^\dagger$

$$\mathcal{L}_{\text{eff}} = B\Big(c_1(u_\mu t M + M t u_\mu) + c_2(u_\mu M + M u_\mu)t + c_3 t(u_\mu M + M u_\mu)$$
$$+ c_4(u_\mu \langle M t\rangle + M\langle u_\mu t\rangle) + c_5 t\langle M u_\mu\rangle + c_6\langle (M u_\mu + u_\mu M)t\rangle\Big)\partial^\mu D^\dagger$$

Chiral effective Lagrangian

1. Introducing a spurion H: $H_i^j \mapsto H_{i'}^{j'} (g_L)_i^{i'} (g_L^\dagger)_{j'}^j$

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb}^* H_i^j C(\bar{c}b)_L(\bar{q}^i q_j)_L, \quad H = \begin{pmatrix} 0 & 0 & 0 \\ V_{ud} & 0 & 0 \\ V_{us} & 0 & 0 \end{pmatrix}$$

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$$\mathcal{L}_{\text{eff}} = B\Big(c_1(u_\mu t M + M t u_\mu) + c_2(u_\mu M + M u_\mu)t + c_3 t(u_\mu M + M u_\mu)$$
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Chiral effective Lagrangian

1. Introducing a spurion H: $H_i^j \mapsto H_{i'}^{j'} (g_L)_i^{i'} (g_L^\dagger)_{j'}^j$

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb}^* H_i^j C (\bar{c}b)_L (\bar{q}^i q_j)_L, \quad H = \begin{pmatrix} 0 & 0 & 0 \\ V_{ud} & 0 & 0 \\ V_{us} & 0 & 0 \end{pmatrix}$$

2. Transforming under $g_L \times g_R \in SU(3)_L \times SU(3)_R$, $h \in SU(3)_V$

Goldstone fields: $u \mapsto g_R u h^\dagger = h u g_L^\dagger, \quad u_\mu \mapsto h u_\mu h^\dagger,$

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Amplitudes

Amplitudes up to D-wave:

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

- S-wave: ($C = (c_2 + c_6)/(c_1 + c_4)$),

$$\mathcal{A}_0(s) \propto \left\{E_\pi\left[2 + G_1(s)\left(\frac{5}{3}T_{11}^{1/2}(s) + \frac{1}{3}T^{3/2}(s)\right)\right] + \frac{1}{3}E_\eta G_2(s)T_{21}^{1/2}(s) + \sqrt{\frac{2}{3}}E_K G_3(s)T_{31}^{1/2}(s)\right\} + C E_\eta G_2(s)T_{21}^{1/2}(s)$$

- Chiral symmetry ✓
- Unitarity ✓

$$\text{Im}\mathcal{A}(s) = -T^\dagger(s)\rho(s)\mathcal{A}(s)$$
$$\text{Im}G(s) = -\rho(s)$$

- P- and D-wave: Breit-Wigner

$$\mathcal{A}_i = |\mathcal{A}_i|e^{i\delta_i}$$

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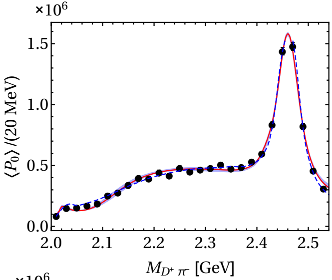
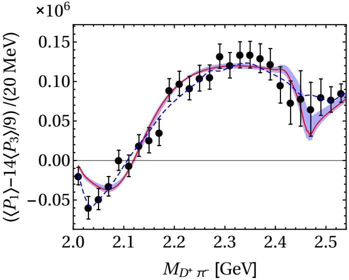
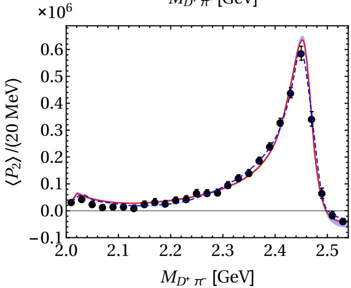
Numerical result (angular moments)







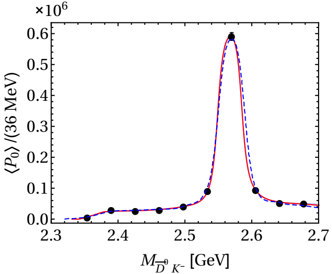
$$\langle P_0 \rangle \propto |\mathcal{A}_0|^2 + |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2,$$

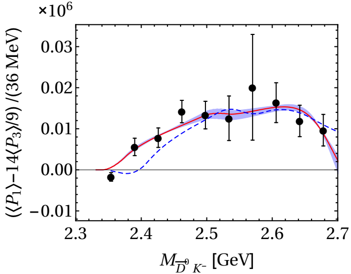
$$\langle P_2 \rangle \propto \frac{2}{5}|\mathcal{A}_1|^2 + \frac{2}{7}|\mathcal{A}_2|^2 + \frac{2}{\sqrt{5}}|\mathcal{A}_0||\mathcal{A}_2|\cos(\delta_0 - \delta_2),$$

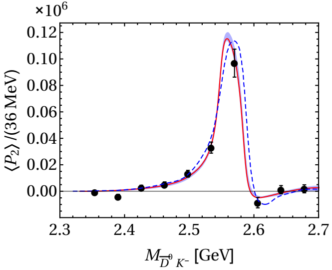
$$\langle P_{13} \rangle \equiv \langle P_1 \rangle - \frac{14}{9}\langle P_3 \rangle \propto \frac{2}{\sqrt{3}}|\mathcal{A}_0||\mathcal{A}_1|\cos(\delta_0 - \delta_1)$$

M. L. Du, M. Albaladejo, P. Fernández-Soler, F. K. Guo, C. Hanhart, U. G. Meißner, J. Nieves and D. L. Yao, arXiv:1712.07957 [hep-ph].

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







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Summary and outlook (I)

Thanks to the recent experiment, lattice and EFT developments

$\Rightarrow$ likely resolution to all 3 puzzles of positive-parity charm mesons:

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

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

- Q: Why $M_{D_{s1}(2460)^\pm} - M_{D^*_{s0}(2317)^\pm} \simeq M_{D^{*\pm}} - M_{D^\pm}$ within 2 MeV ?

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

- Q: Why are the masses of the $D_0^*(2400)$ and $D_1(2430)$ almost equal to or even higher than their strange siblings?

  A: There are two D_0^* and two D_1, and the lower ones have smaller masses.

Summary and outlook (II)

- Chiral symmetry

  ↪ a shift of the BW peak

- Two-pole structures of $D_0^*(2400)$ and $D_1(2430)$
- Fully consistent with the high quality LHCb data on B decays
- Call for a change of paradigm for the positive-parity mesons:

  ↪ dynamically generated for ground states

  ↪ already have been established for the scalars made from light quarks

- More data with accuracy for the $B \to D^{(*)}\pi\pi$ and $B \to D_s^{(*)} K\pi$
- Hadronic width of the $D_{s0}^*(2317)$
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Thank you very much for your attention!

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

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

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 $\mathcal{O}\left(p^2\right)$: Guo, Hanhart, Krewald, Meißner, PLB**666**(2008)251

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

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

- 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, F.-K. Guo, U.-G. Meißner, JHEP**1511**(2015)058; M.-L. Du, F.-K. Guo, U.-G. Meißner, D.-L. Yao, EPJC**77**(2017)728

  renormalization: Meißner, JPG**44**(2017)014001

  PCB-term subtraction in EOMS scheme using path integral: M.-L. Du, F.-K. Guo, U.-G. Meißner, JHEP**1610**(2016)122

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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

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

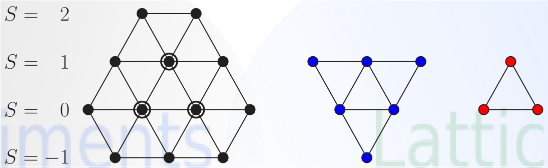
$I(\vec{q})$: loop integrand

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

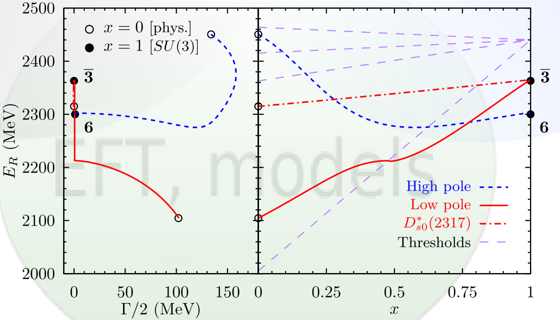
$$\widetilde{T}^{-1}(s,L) = V^{-1}(s) - \widetilde{G}(s,L)$$

SU(3) analysis

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

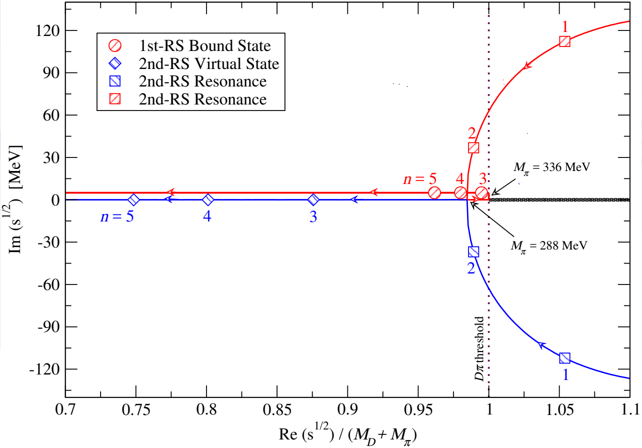


- Evolution of the two poles (LO) from the physical to the SU(3) symmetric case



Albaladejo *et al.*, PLB**767**, 465 (2017)

Trajectories of the (S=0,I=1/2) resonance at around 2.1 GeV



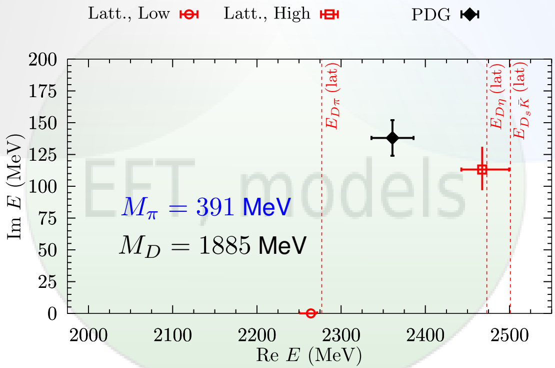
Trajectories of the $(S = 0, I = 1/2)$ resonance at around 2.1 GeV with varying M_π. n is defined by $M_\pi = n M_\pi^{\text{phys}}$.

Z. H. Guo *et al.*, PRD92 (2015) no.9, 094008

There are two poles (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)	$5.2^{+0.6}_{-0.4}$	$6.7^{+0.6}_{-0.4}$	$13.2^{+0.6}_{-0.5}$

Experiments Lattice



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