What we learn about charmed meson spectrum from $\bar{B} \to D\pi\pi$

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International Workshop on Partial Wave Analyses and Advanced Tools for Hadron Spectroscopy (PWA10/ATHOS5)

IHEP, 16 July – 20 July, 2018

Based on:

Meng-Lin Du et al., arXiv:1712.07957 [hep-ph]

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

- $D_0^*(2400)^0$: $J^P = 0^+$, $\Gamma = (247 \pm 67)$ MeV Belle (2004)

PDG2018:

2318 ± 29	**OUR AVERAGE** Error includes scale factor of 1.7.				
2297 ±8 ±20	3.4k	AUBERT	2009AB	BABR	$B^- \to D^+\pi^-\pi^-$
2308 ±17 ±32		ABE	2004D	BELL	$B^- \to D^+\pi^-\pi^-$
2407 ±21 ±35	9.8k	LINK	2004A	FOCS	γ A

Measurements by LHCb: (2360 ± 34) MeV LHCb, PRD92(2015)012012

- $D_1(2430)^0$: $J^P = 1^+$, $\Gamma = 384^{+130}_{-110}$ MeV

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2427 ±26 ±25	ABE	2004D	BELL	$B^- \to D^{*()0+}\pi^-\pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2477 ±28	[1] AUBERT	2006L	BABR	$\overline{B}^0 \to D^{*+}\omega\pi^-$

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

Charm-strange mesons

- $D^*_{s0}(2317)$: 0^+ BaBar (2003)

  $M = (2317.7 \pm 0.6)$ MeV,

  $\Gamma < 3.8$ MeV

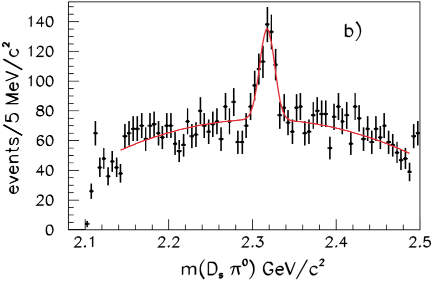
  The only hadronic decay: $D_s\pi$

- $D_{s1}(2460)$: 1^+ CLEO (2003)

  $M = (2459.5 \pm 0.6)$ MeV,

  $\Gamma < 3.5$ MeV

- no isospin partner observed, tiny widths $\Rightarrow I = 0$



BABAR, PRL90(2003)242001

Why are they interesting?

- Why $M_{D_0^*(2400)} \gtrsim M_{D_{s0}^*(2317)}$ and $M_{D_1(2430)} \sim M_{D_{s1}(2460)}$?
- Why are the masses of $D_{s0}^*(2317)$ and $D_{s1}(2460)$ much lower than quark model predictions for $c\bar{s}$ mesons ?
- Why $\underbrace{M_{D_{s1}(2460)^\pm} - M_{D_{s0}^*(2317)^\pm}}_{=(141.8\pm0.8)\ \text{MeV}} \simeq \underbrace{M_{D^{*\pm}} - M_{D^\pm}}_{=(140.67\pm0.08)\ \text{MeV}}$ within 2 MeV?

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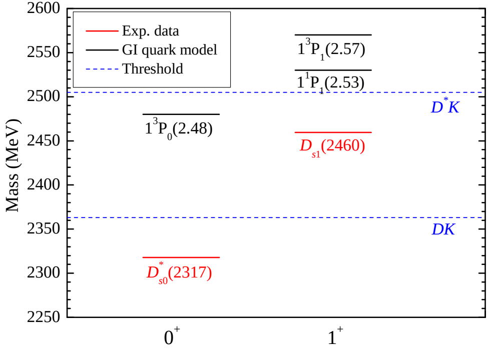

GI quark model: Godfrey, Isgur (1985)

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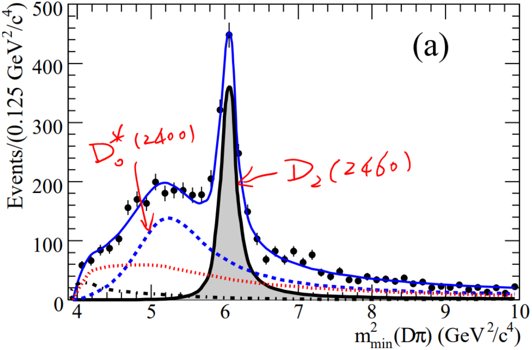
$D_0^*(2400)$ and $D_1(2430)$

- Coupled to $D^{(*)}\pi$ in S-wave, analogous to the $K_0^*(700)$
- Notice: all these experiments used a Breit–Wigner to extract the resonance



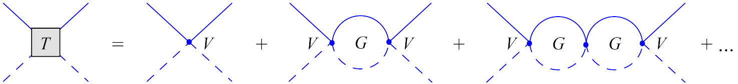
BaBar, PRD79(2009)112004

☞ $D^{(*)}\pi$-$D^{(*)}\eta$-$D_s^{(*)}\bar{K}$ coupled-channel effects are absent

☞ chiral symmetry constraint on soft pions is absent

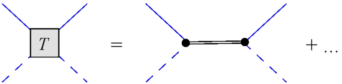
Interactions between charm and light mesons

- 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 $a(\mu)$

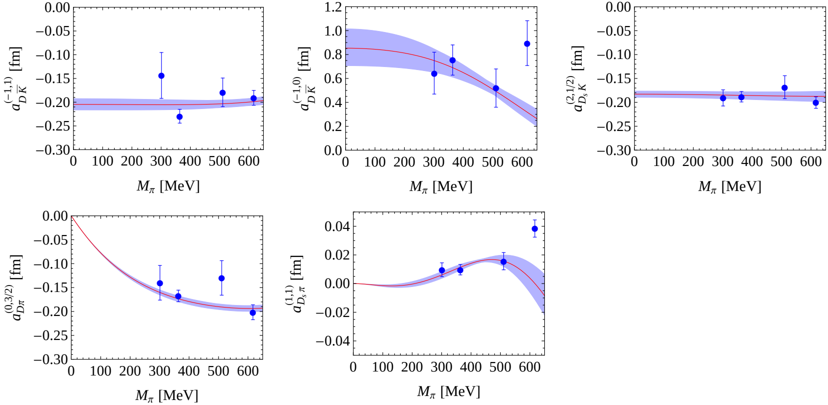
Fit to lattice data

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 $a(\mu)$

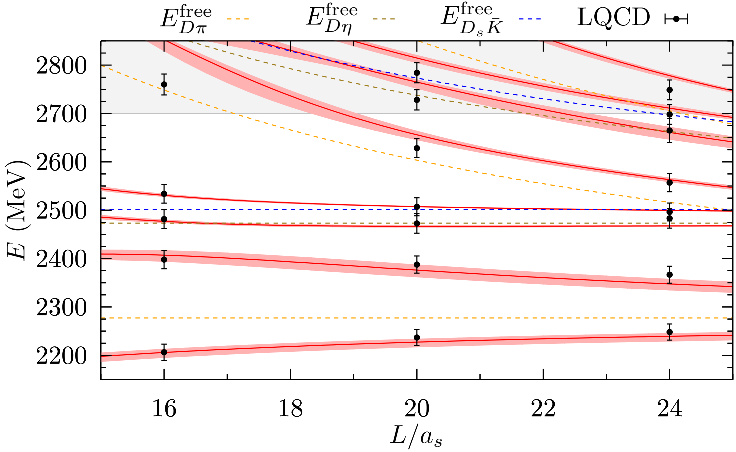


Postdictions versus recent lattice results: charm-nonstrange

- 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)	PDG2017 (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)	PDG2017 (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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B_{s0}^*	0^+	5720^{+16}_{-23}	–	5711 ± 23[2]
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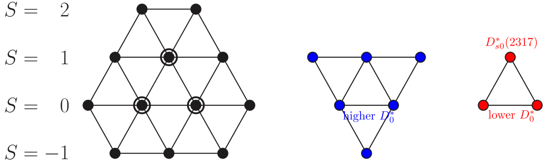
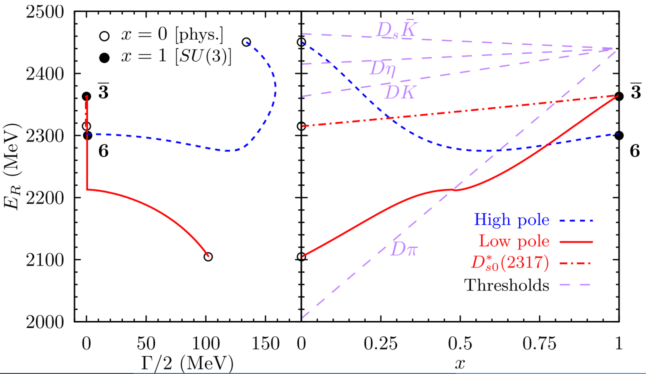
SU(3) analysis

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



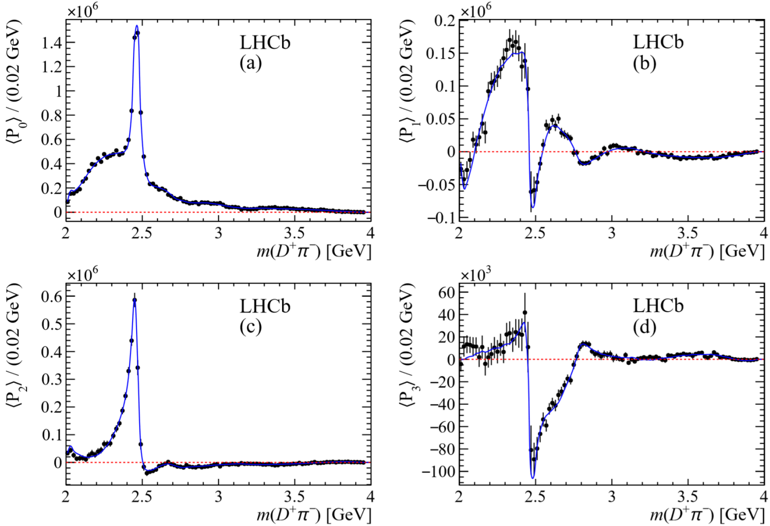
- Evolution of the two poles from the physical to the SU(3) symmetric case



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

LHCb, PRD94(2016)072001

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



Fit to LHCb data (1)

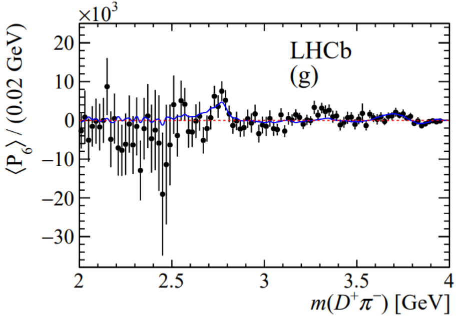
Du et al., arXiv:1712.07957 [hep-ph]

- 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:

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

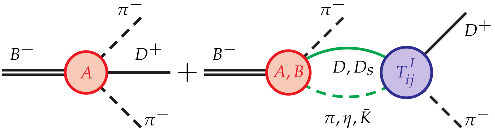


- P-wave: D^*, $D^*(2680)$ [$M = 2681$ MeV, $\Gamma = 187$ MeV]; D-wave: $D_2(2460)$ parametrized (with the same masses and widths) as in the LHCb paper: Breit–Wigner with Bleit–Weisskopf barrier factors, one constant phase for each as free parameters

Fit to LHCb data (2)

Du et al., arXiv:1712.07957 [hep-ph]

- S-wave: use the coupled-channel (1: $D\pi$; $2 : D\eta$; $3 : D_s\bar{K}$) amplitudes with all parameters fixed before



- For the production vertex:

  soft pion: pseudo-Goldstone boson; fast pion: matter field M

$$b \to c\,\bar{u}d \quad \Rightarrow \quad \text{spurion field: } H = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad t \equiv uHu^\dagger$$

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

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

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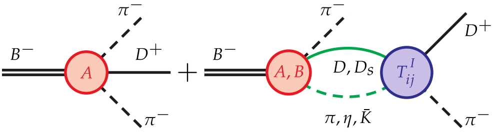

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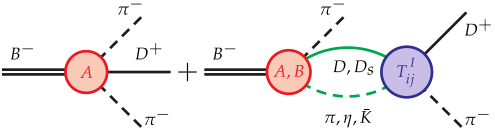


- only 2 parameters in S-wave: C and a subtraction constant in $G_i(s)$

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

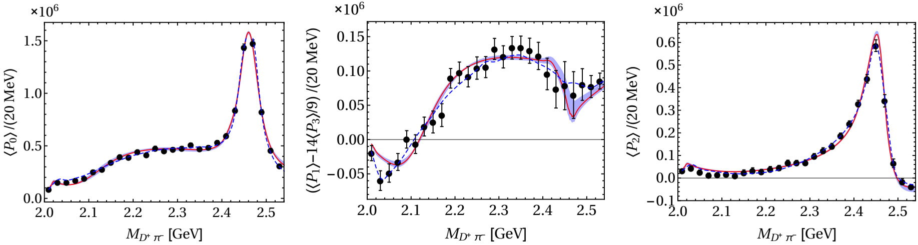
where $C = 2(c_2 + c_6)/(c_1 + c_4)$

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

Fit to LHCb data (3)

Du et al., arXiv:1712.07957 [hep-ph]

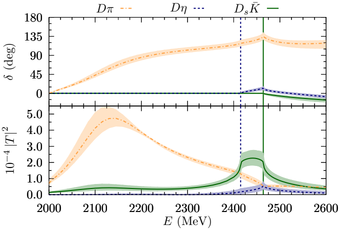
$$\langle P_0\rangle \propto |\mathcal{A}_0|^2 + |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2\,,$$
$$\langle P_2\rangle \propto \frac{2}{5}|\mathcal{A}_1|^2 + \frac{2}{7}|\mathcal{A}_2|^2 + \frac{2}{\sqrt{5}}|\mathcal{A}_0||\mathcal{A}_2|\cos(\delta_2-\delta_0)\,,$$
$$\langle P_{13}\rangle \equiv \langle P_1\rangle - \frac{14}{9}\langle P_3\rangle \propto \frac{2}{\sqrt{3}}|\mathcal{A}_0||\mathcal{A}_1|\cos(\delta_1-\delta_0)$$



- The S-wave $D\pi$ well described using our amplitudes with pre-fixed LECs (the same as before)
- Fast variation in [2.4, 2.5] GeV in $\langle P_{13}\rangle$: cusps at $D\eta$ and $D_s\bar{K}$ thresholds

Searching for the higher nonstrange state

- Near-threshold enhancement in $D_s\bar{K}$?



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

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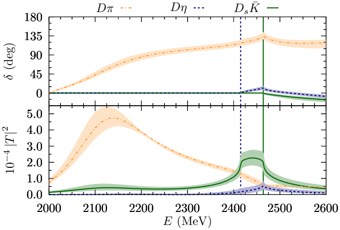

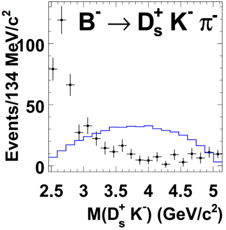

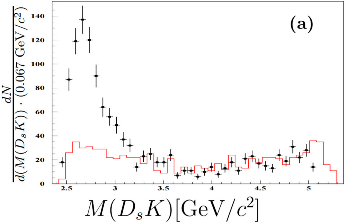

BaBar, PRL100(2008)171803; Belle, PRD80(2009)052005

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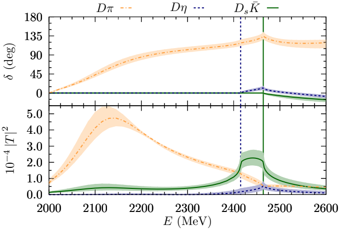

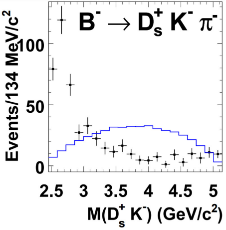

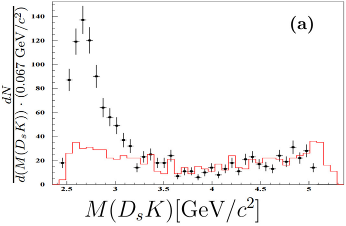

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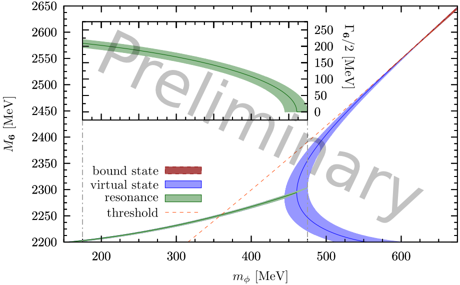

DK component from lattice QCD

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

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

$\Rightarrow D^*_{s0}(2317)$: ~70% DK Liu, Orginos, FKG, Hanhart, Meißner, PRD86(2013)014508

- Similar result in Martínez Torres, Oset, Prelovsek, Ramos, JHEP1505,053 by analyzing the lattice energy levels in C. Lang et al., PRD90(2014)034510

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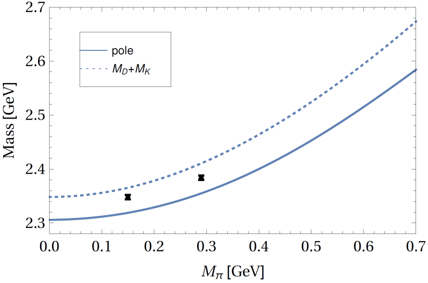

$1-Z = 1.04(0.08)(+0.30)$

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

Solutions to all three puzzles

- 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: hadronic molecules, main components: $D_{s0}^*(2317)[DK]$, $D_{s1}(2460)[D^*K]$

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

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

  A: HQSS $\Rightarrow$ DK and D^*K interactions almost the same $\Rightarrow$

  Chen, Li, PRL93(2004)232001; FKG et al., PRL102(2009)242004

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

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

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Solutions to all three puzzles

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  Chen, Li, PRL93(2004)232001; FKG et al., PRL102(2009)242004

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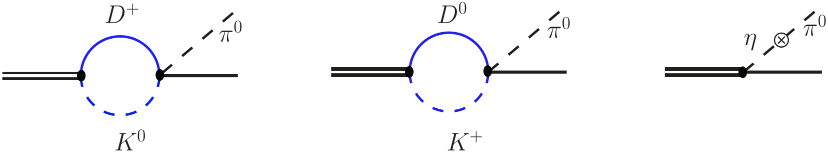
Direct experimental consequences?

Decay width of $D^*_{s0}(2317)$



- Large isospin decay width $\Gamma(D^*_{s0}(2317)^+ \to D_s^+\pi^0) \sim 100$ keV

  Faessler *et al.* (2007); Lutz, Soyeur (2007); FKG *et al.* (2008); Cleven *et al.* (2014)

- $\Gamma(D^*_{s0}(2317)) = (133 \pm 22)$ keV — L. Liu *et al.*, PRD86(2013)014508
- Recent result with terms up to $O(p^4)$ in chiral expansion

  X.-Y. Guo, Y. Heo, M. F. M. Lutz, arXiv:1801.10122

  ☞ LECs from fitting to the lattice results of masses and phase shifts

  ☞ $\Rightarrow \Gamma(D^*_{s0}(2317)) = (110 \pm 6)$ keV
- To be measured at $\overline{\text{P}}$ANDA

Summary

- Precise angular moments data on $B^- \to D^+\pi^-\pi^-$ (in particular $\langle P_1 \rangle - \frac{14}{9}\langle P_3 \rangle$) are consistent with two D_0^* resonances in $D\pi$ S-wave
- support from agreement with lattice results
- Puzzles of positive-parity charmed mesons naturally understood
- To-do: more decays systematically

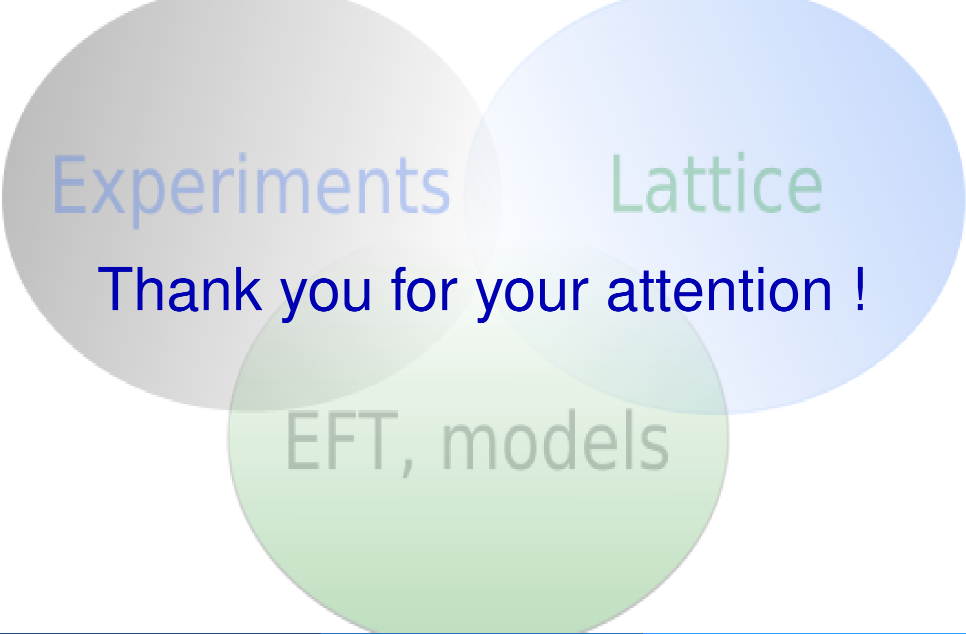
  $$B \to D^{(*)}\pi\pi/D^{(*)}\eta\pi/D_s^{(*)}\bar{K}\pi, \quad B_s \to D^{(*)}K\pi/D_s^{(*)}\eta\pi, \ldots$$

  precise data needed
- Suggestions for PDG:

  reconsider $D_0^*(2400)$ and $D_1(2430)$ parameters
- Not mentioned:

  new spectrum of $J^P = \frac{1}{2}^-$ doubly charmed baryons M.-J. Yan et al., arXiv:1805.10972

  searching for Ξ_{cc}^P with a mass about 3.82 GeV in $\Xi_{cc}^{++}\pi^-$



Thank you for your attention !

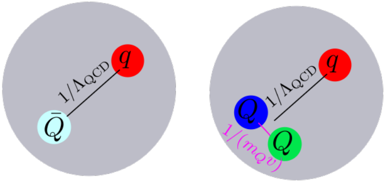
Doubly charmed baryons

- 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

- LHCb observation of Ξ_{cc}^{++}: $M = (3621.40 \pm 0.78)$ MeV LHCb, PRL119(2017)112001

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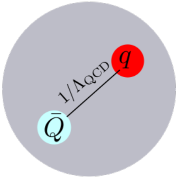

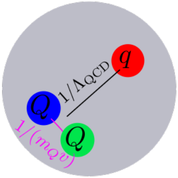

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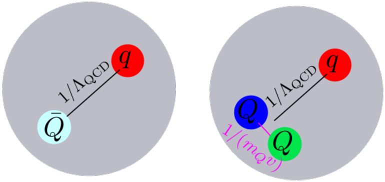

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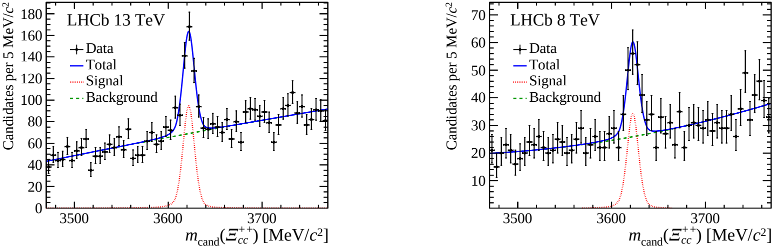
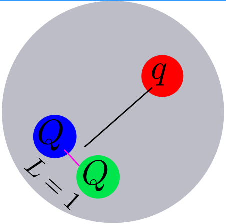


Doubly charmed baryons with $J^P = 1/2^-$

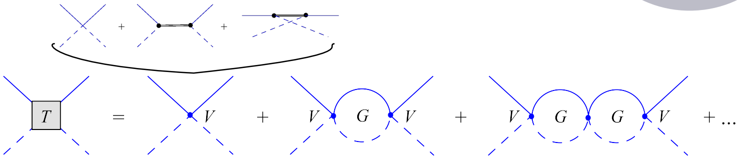


- P-wave QQ

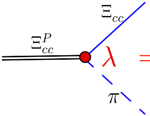
  excitation energy   Mehen, PRD96(2017)094028

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

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



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



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

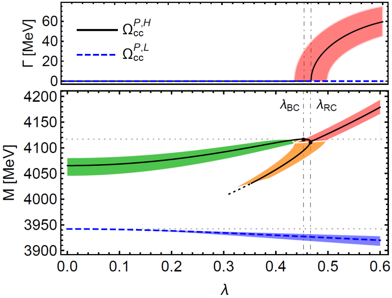
Doubly charmed strange baryons with $J^P = 1/2^-$: Ω_{cc}^P

M.-J. Yan, X.-H. Liu, S. Gonzàlez-Solís, FKG, C. Hanhart, U.-G. Meißner, B.-S. Zou, arXiv:1805.10972

- 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

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



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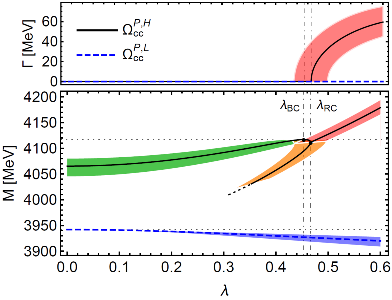
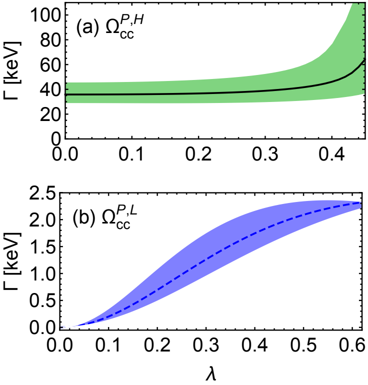


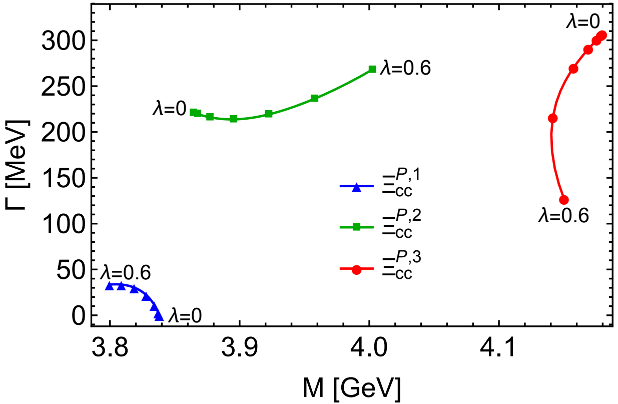


- Tiny width due to isospin breaking: $\Omega_{cc}^P \to \Omega_{cc}\pi^0$

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

M.-J. Yan, X.-H. Liu, S. Gonzàlez-Solís, FKG, C. Hanhart, U.-G. Meißner, B.-S. Zou, arXiv:1805.10972

- 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 $\Xi_{cc}^{++}\pi^- \Rightarrow \lambda$

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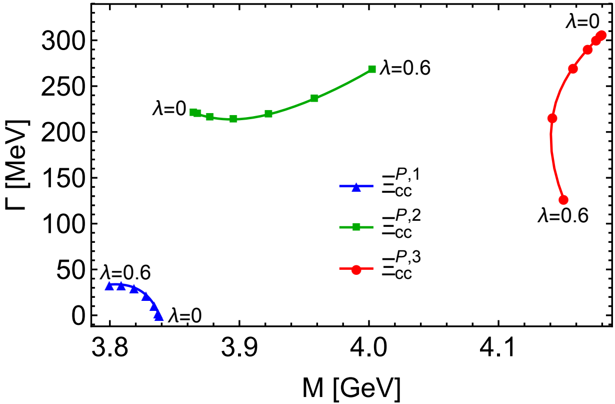

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Lattice studies of the charmed scalar mesons: strange

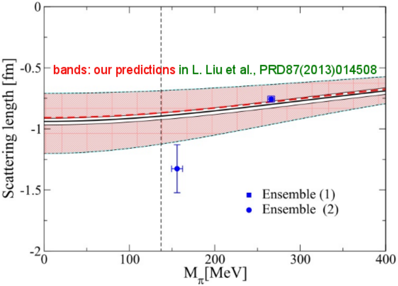
- Early studies using only $c\bar{s}$-type interpolators typically give mass larger than that for $D^*_{s0}(2317)$ Bali (2003); UKQCD (2003); ...

- $c\bar{s} + DK$ 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.	PDG2017
(266 ± 16) MeV	(241.5 ± 0.8) MeV



- New 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)

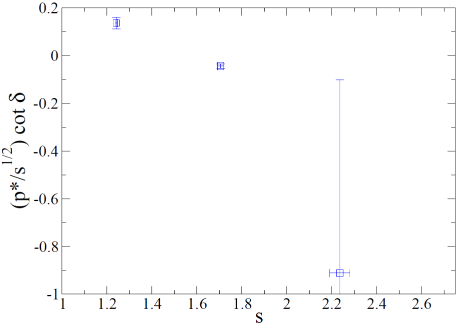
Lattice studies of the charmed scalar mesons: nonstrange (1)

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

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 $D_0^*(2400)$?

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

$$M_{B_{s0}^*}^{\text{lat.}} = (5.711 \pm 0.013 \pm 0.019)\ \text{GeV}$$
$$M_{B_{s1}}^{\text{lat.}} = (5.750 \pm 0.017 \pm 0.019)\ \text{GeV}$$

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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

  renormalization: M.-L. Du, FKG, U.-G. Meißner, JPG**44**(2017)014001

  PCB-term subtraction in EOMS scheme using path integral:

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

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- 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

  renormalization: M.-L. Du, FKG, U.-G. Meißner, JPG**44**(2017)014001

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

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 $\widetilde{T}(s, L)$:

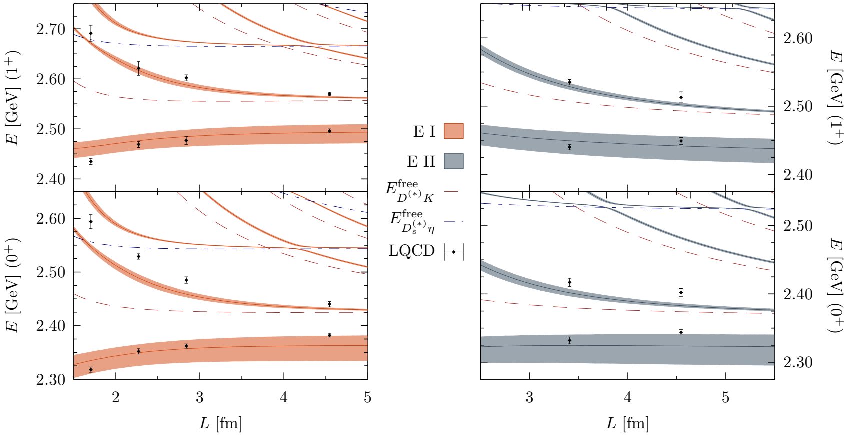
$$\widetilde{T}^{-1}(s, L) = V^{-1}(s) - \widetilde{G}(s, L)$$

- 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

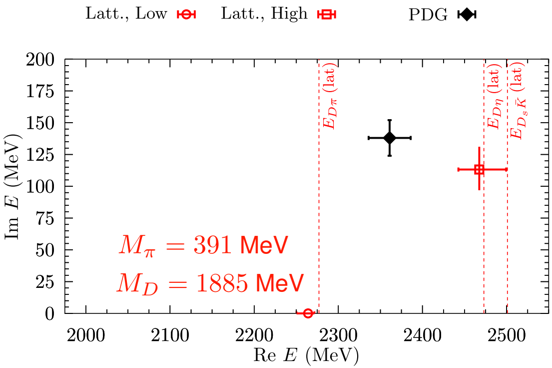
E I: $M_\pi = 290$ MeV

E II: $M_\pi = 150$ MeV



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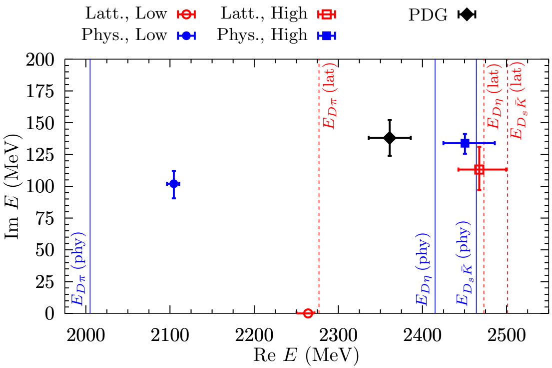
physical	2105^{+6}_{-8}	102^{+10}_{-11}	(100)	$9.4^{+0.2}_{-0.2}$	$1.8^{+0.7}_{-0.7}$	$4.4^{+0.5}_{-0.5}$
	2451^{+36}_{-26}	134^{+7}_{-8}	(110)	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$



More similar states?

FKG, U.-G. Meißner, PRD84(2011)014013

- Chiral symmetry $\Rightarrow$ 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
  $D_1(2420)K$ and $D_2(2460)K$ bound states

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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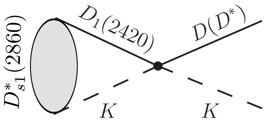

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