

From charm mesons to doubly-charmed baryons

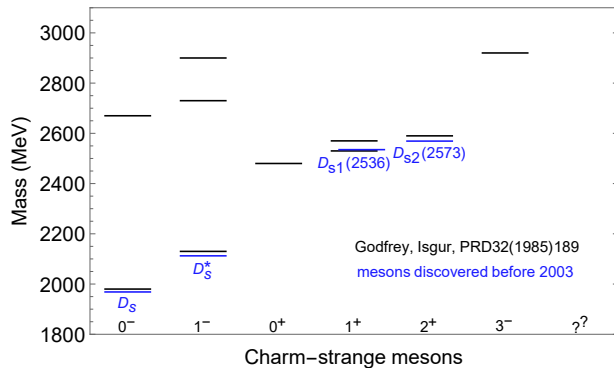
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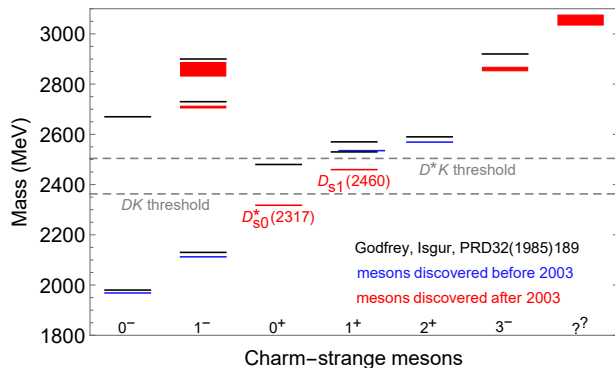
Peking University, Oct. 25, 2018

- Charm-strange mesons: $D_{s0}^*(2317)$, $D_{s1}(2460)$
- Charm-nonstrange mesons: $D_0^*(2400)$, $D_1(2430)$
- Predictions:
 - 👉 bottom-strange and nonstrange mesons
 - 👉 doubly-charmed baryons with $J^P = 1/2^-$
- Suggestions for experiments

Charm-strange mesons



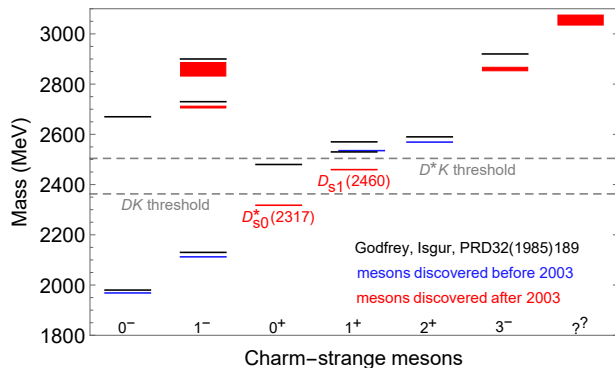
Charm-strange mesons



- $D_{s0}^*(2317)$: 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
 $\Rightarrow I = 0$

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

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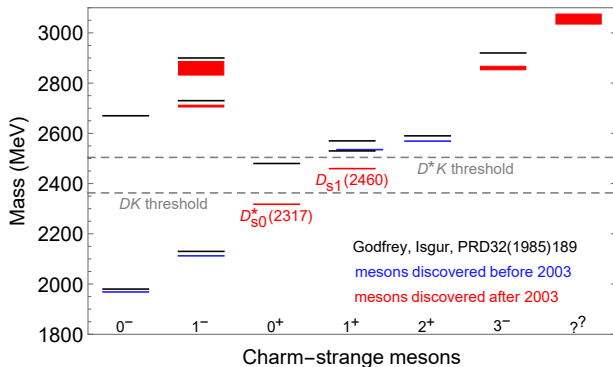


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Charm-nonstrange mesons (1)

Observations of charm-nonstrange excited mesons in 2003

$$B^- \rightarrow D^{(*)+} \pi^- \pi^-$$

Belle, PRD69(2004)112002 [hep-ex/0307021]

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

$$\Gamma = (267 \pm 40) \text{ MeV}$$

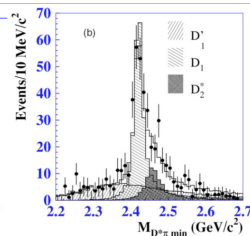
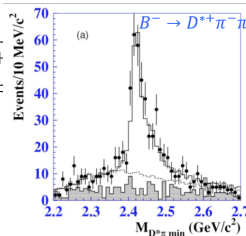
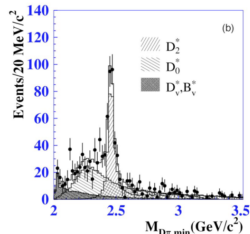
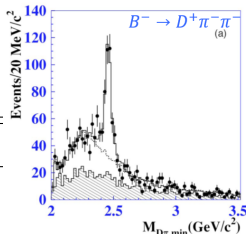
Mass (MeV):

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

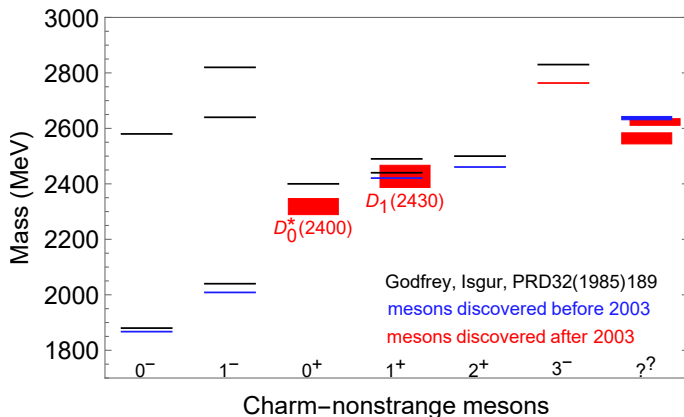
- $D_1(2430): J^P = 1^+$

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

$$M = (2427 \pm 36) \text{ MeV}$$



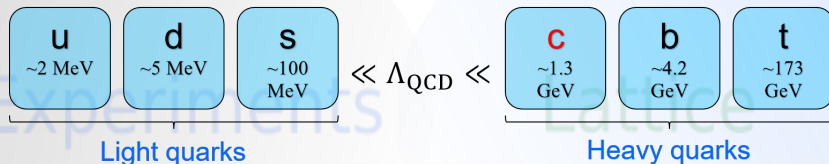
Charm-nonstrange mesons (2)



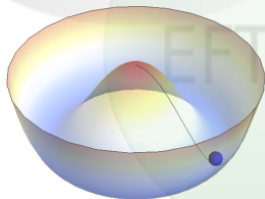
- Puzzle 3: Why $M_{D_0^*(2400)} \gtrsim M_{D_{s0}^*(2317)}$ and $M_{D_1(2430)} \sim M_{D_{s1}(2460)}$?

Theoretical tools

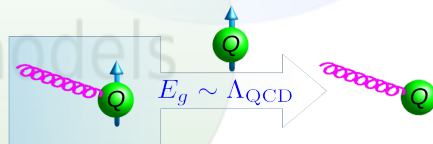
- Lattice QCD
- Symmetries:



☞ 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: $\sim$ right mass Mohler et al., PRL111(2013)222001

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

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

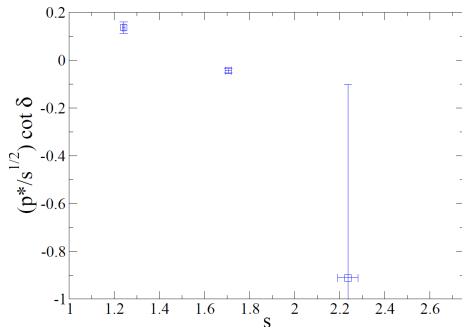
$$M_\pi \approx 266 \text{ MeV},$$

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

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

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

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



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

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

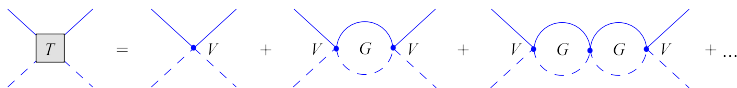
$K_{ij}(s)$: different forms of the K -matrix were used, summarized as

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

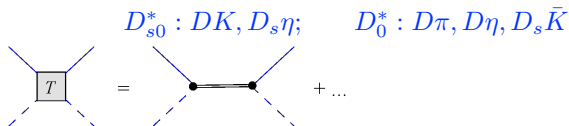
- $\Rightarrow$ a pole below threshold (2275.9 ± 0.9) MeV. relation to $D_0^*(2400)$?

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:



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

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

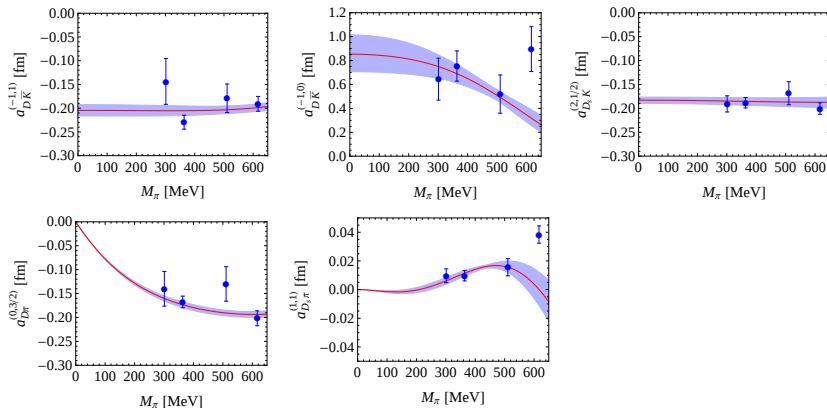
$V(s)$: to be derived from SU(3) chiral Lagrangian, 6 LECs up to NLO

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

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

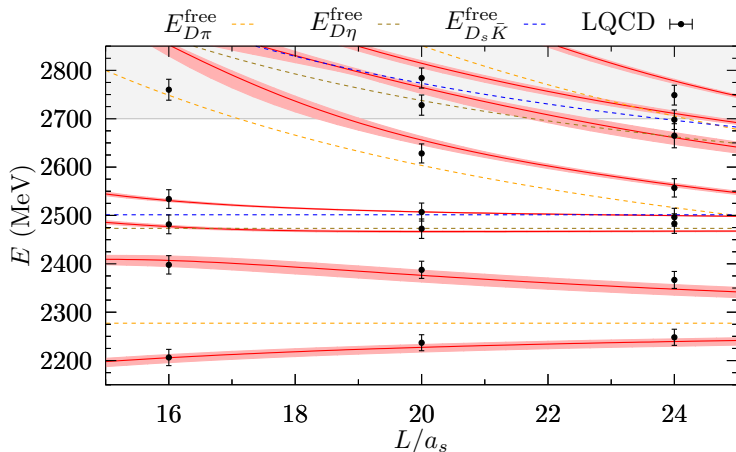


Postdictions versus recent lattice results: charm-nonstrange

- In a finite volume: $\vec{q} = \frac{2\pi}{L}\vec{n}$, $\vec{n} \in \mathbb{Z}^3$; loop integral $G(s)$: $\int d^3\vec{q} \rightarrow \frac{1}{L^3} \sum_{\vec{q}}$
- 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



- Heavy-strange

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

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

	Lower (MeV)	Higher (MeV)	PDG2018 (MeV)
D_0^*	$(2105_{-8}^{+6}, 102_{-11}^{+10})$	$(2451_{-26}^{+36}, 134_{-8}^{+7})$	$(2318 \pm 29, 134 \pm 20)$
D_1	$(2247_{-6}^{+5}, 107_{-10}^{+11})$	$(2555_{-30}^{+47}, 203_{-9}^{+8})$	$(2427 \pm 40, 192_{-55}^{+65})$
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] 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}	—	$5711 \pm 23[2]$
B_{s1}	1^+	5772^{+15}_{-21}	—	$5750 \pm 25[2]$

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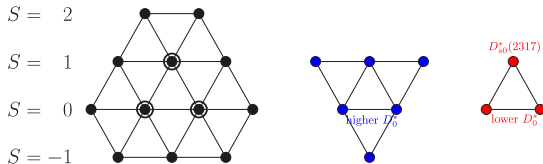
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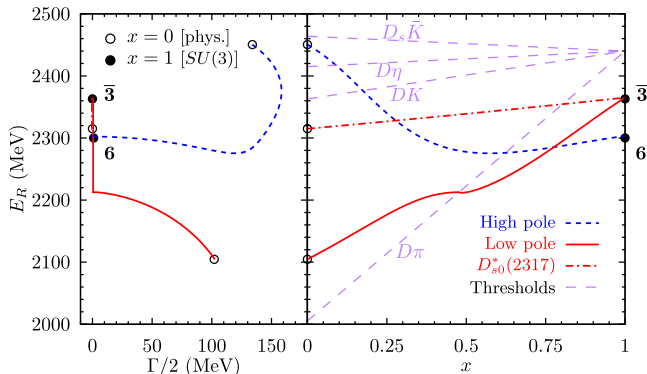
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SU(3) analysis

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



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



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

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

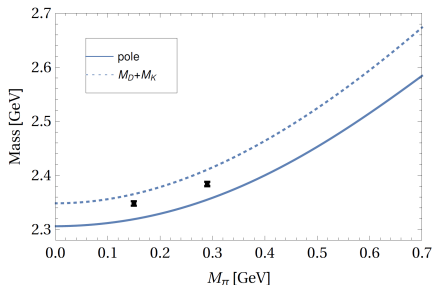
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 $D_{s0}^*(2317)$ contains $\sim 70\%$ DK Martínez Torres, Oset, Prelovsek, Ramos, JHEP1505,053
- Latest lattice results in G. Bali et al., PRD96(2017)074501

DK component from lattice QCD

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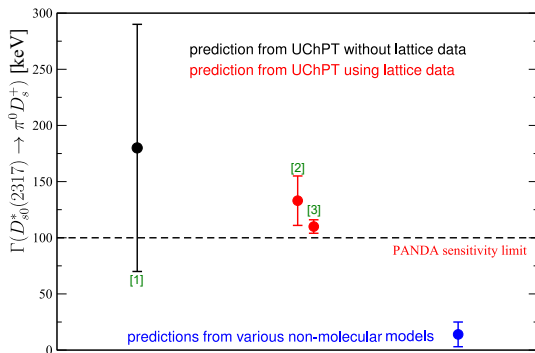
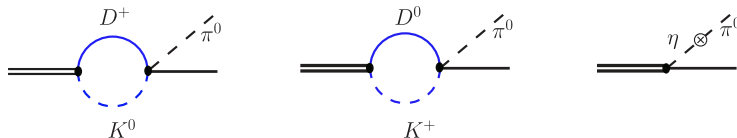
$$1 - Z = 1.04(0.08)(+0.30)$$

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

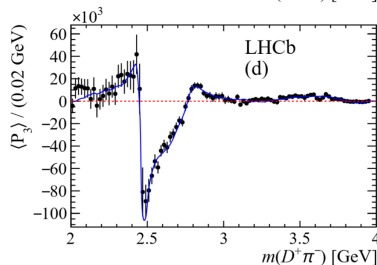
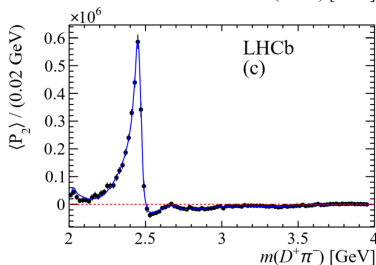
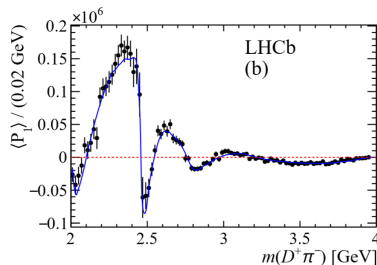
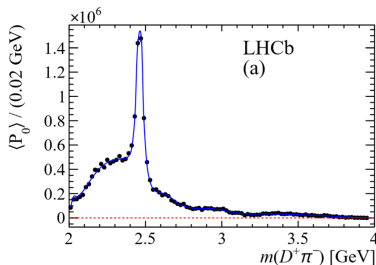


measurement planned at PANDA

[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

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

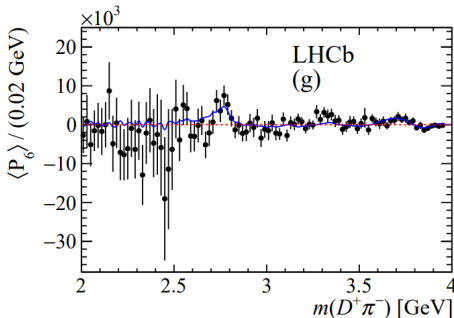


- Consider only S , P , D waves, up to around 2.5 GeV:

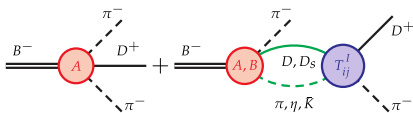
$$\mathcal{A}(B^- \rightarrow D^+ \pi^- \pi^-) = \mathcal{A}_0(s) + \sqrt{3}\mathcal{A}_1(s)P_1(z) + \sqrt{5}\mathcal{A}_2(s)P_2(z);$$

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 Blatt–Weisskopf barrier factors, one constant phase for each as free parameters



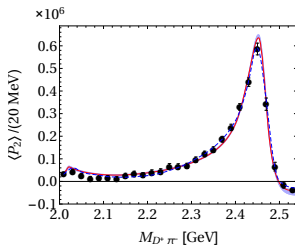
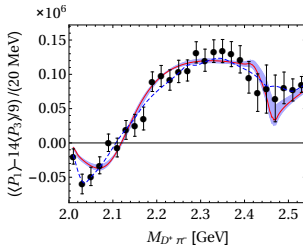
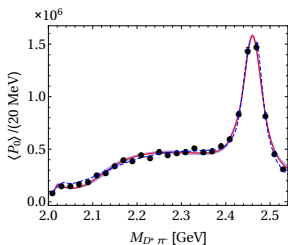
- *S*-wave: FSI, two new parameters
- *P*, *D*-wave: BWs from the LHCb fit

Angular moments:

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

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

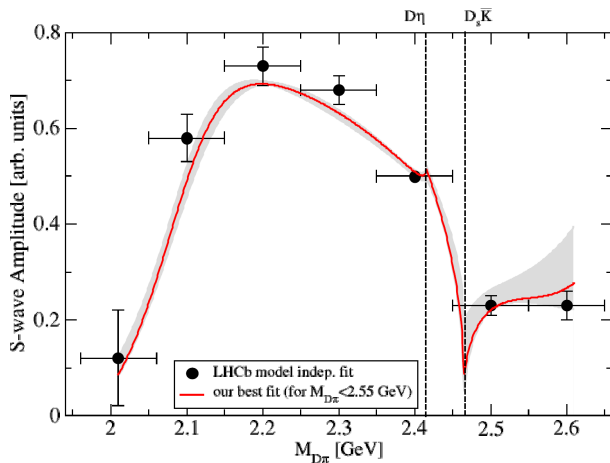
Data: LHCb, PRD94(2016)072001



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

$$B^- \rightarrow D^+ \pi^- \pi^- \quad (4)$$

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



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

Thanks for the recent experiment, lattice and EFT developments

⇒ likely resolution to all 3 puzzles 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 $M_{D_0^*(2400)} \lesssim M_{D_{s0}^*(2317)}$ and $M_{D_{s1}(2460)} \sim M_{D_{s1}(2460)}$?

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

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A: Two D_0^* and two D_1^* , the SU(3) partners of D_{s0}^* have smaller masses.

Thanks for the recent experiment, lattice and EFT developments

⇒ likely resolution to all 3 puzzles 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 $M_{D_{s1}(2460)^\pm} - M_{D_{s0}^*(2317)^\pm} \simeq M_{D^{*\pm}} - M_{D^\pm}$?

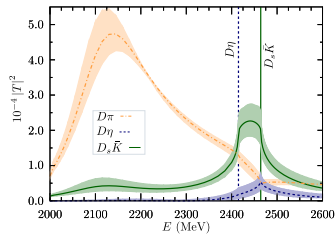
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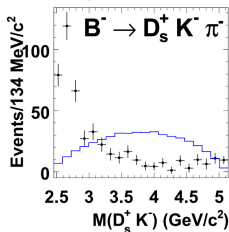
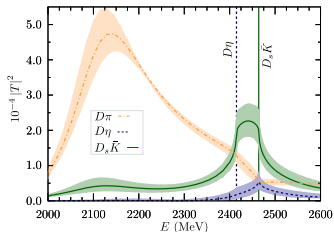
Searching for the higher nonstrange state

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

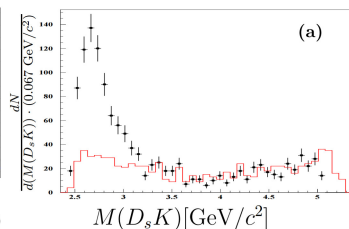


Searching for the higher nonstrange state

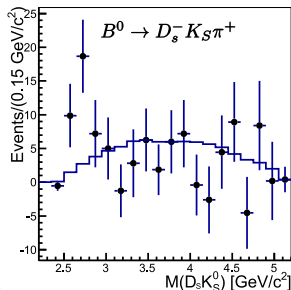
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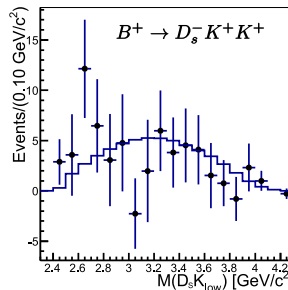
BaBar, PRL100(2008)171803;



Belle, PRD80(2009)052005

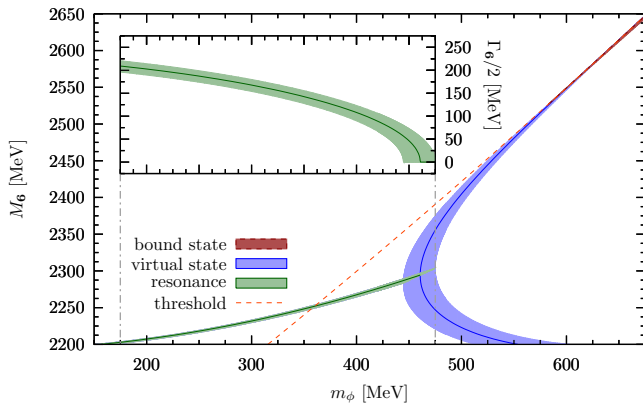


Belle, PRD91(2015)032008



Searching for the higher nonstrange state: lattice

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



Doubly-charmed baryons

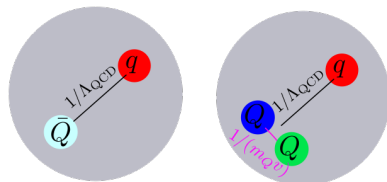
- Heavy anti-quark–diquark symmetry (HADS):

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

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

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

Savage, Wise (1990)



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

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

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

Doubly-charmed baryons

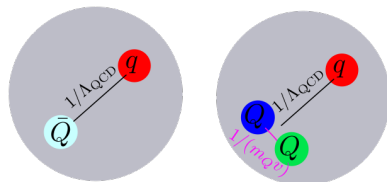
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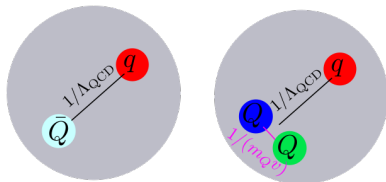
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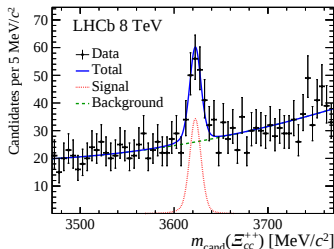
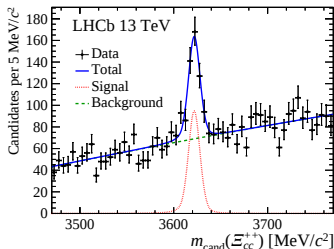
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Doubly-charmed baryons with $J^P = 1/2^-$

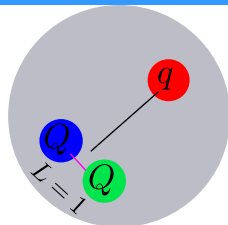
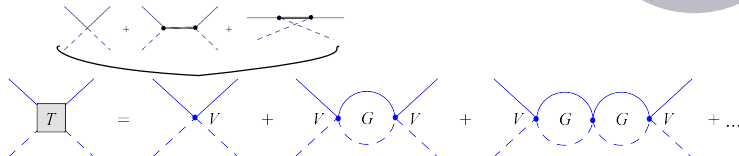
- P -wave QQ

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 $s_{QQ} = 0$

$$\Xi_{cc}^P \lambda = \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_Q}\right)$$

The diagram shows a doubly-charmed baryon Ξ_{cc}^P (represented by a double line) decaying into a charm meson Ξ_{cc} and a pion π . The decay is mediated by a parameter λ , which is shown in red.

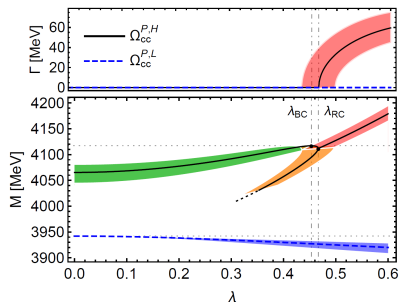
Doubly-charmed strange baryons with $J^P = 1/2^-$: Ω_{cc}^P

M.-J. Yan, X.-H. Liu, S. González-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 $\dot{M}_{\Xi_{cc}^P} = 3838$ MeV from quark model D. Ebert et al., PRD96(2002)024008

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



- Tiny widths due to isospin breaking:

$$\Omega_{cc}^P \rightarrow \Omega_{cc}\pi^0$$

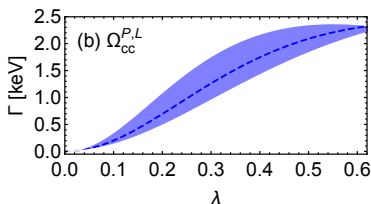
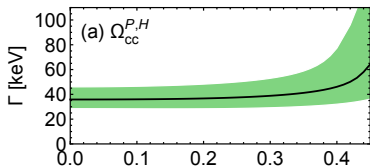
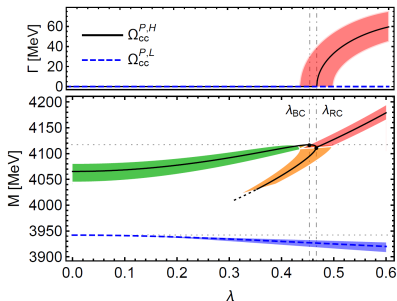
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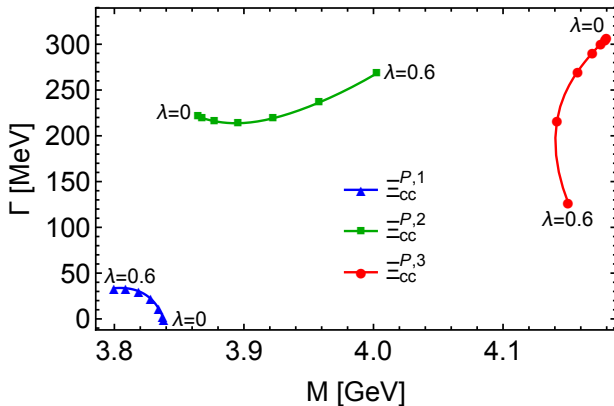
- Tiny widths due to **isospin breaking**:

$$\Omega_{cc}^P \rightarrow \Omega_{cc}\pi^0$$

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

M.-J. Yan, X.-H. Liu, S. González-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:

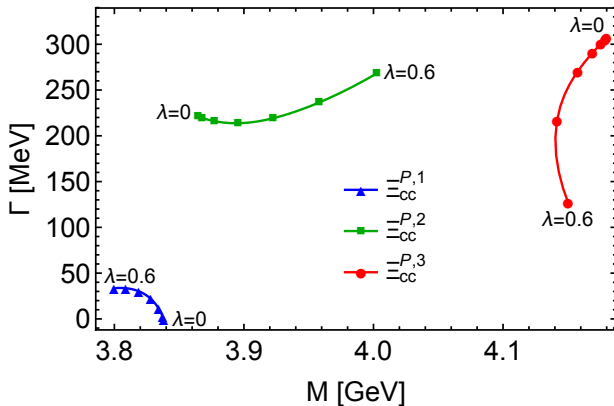


- $\mathcal{B}(\Xi_{cc}^{P,1}, \Xi_{cc}^{P,2} \rightarrow \Xi_{cc}\pi) \simeq 100\%$, searching for $\Xi_{cc}^{P,1}$ in $\Xi_{cc}^{++}\pi^- \Rightarrow \lambda$

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

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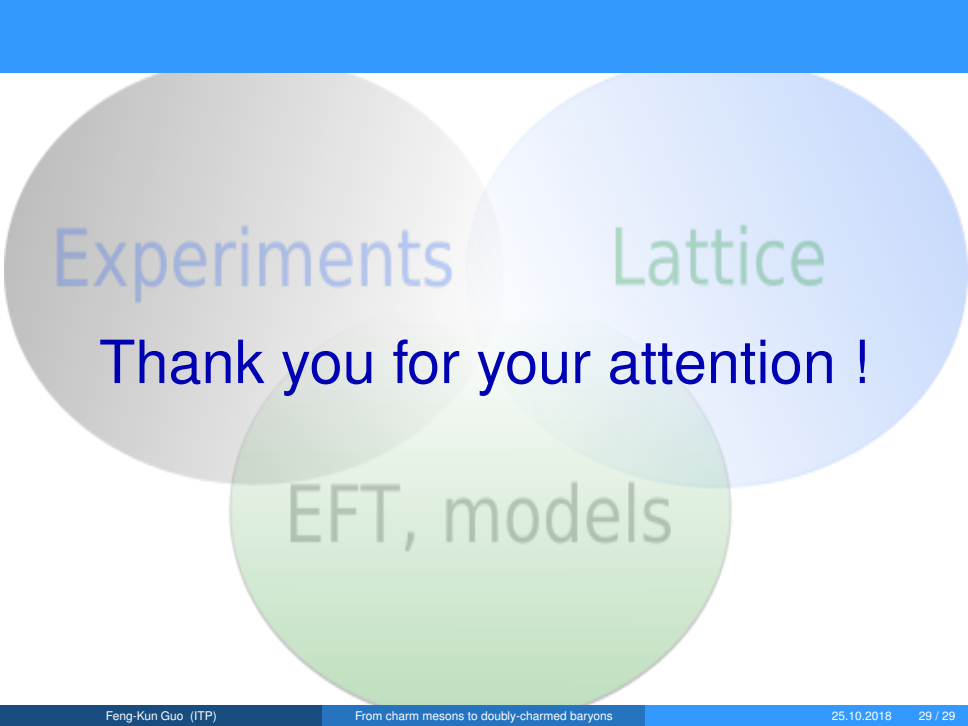
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Summary and suggestions

- Puzzles of positive-parity charmed mesons naturally understood
- Suggestion for lattice:
to study the flavor sextet at the SU(3) symmetric point at large quark masses
- Suggestions for exp.:
 - ✎ D_0^*, D_1 : precise measurements of $\langle P_1 \rangle - \frac{14}{9} \langle P_3 \rangle$ for $B^- \rightarrow D^+ \pi^- \pi^-$ and $B^- \rightarrow D^{*+} \pi^- \pi^-$
 - ✎ the higher D_0^*, D_1 : $D_s \bar{K}$ spectrum in processes such as $B^- \rightarrow D_s^{(*)+} K^- \pi^-$, $B^- \rightarrow D_s^{(*)+} K^- K^-$, $\bar{B}_s^0 \rightarrow D_s^{(*)+} \bar{K}^0 \pi^-$, ...
 - ✎ to search for B_{s0}^* ($M \approx 5.72$ GeV) in $B_s^* \gamma$,
 B_{s1} ($M \approx 5.77$ GeV) in $B_s^{(*)} \gamma$, not the $B_{s1}(5830)$
 - ✎ to search for $J^P = 1/2^-$ Ξ_{cc} ($M \approx 3.82$ GeV) in $\Xi_{cc}^{++} \pi^-$
- Suggestion for PDG:
to reconsider the D_0^* parameters



Experiments

Lattice

Thank you for your attention !

EFT, models

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

- Heavy quark flavor symmetry:

for a **singly**-heavy hadron, $M_{HQ} = m_Q + A + \mathcal{O}(m_Q^{-1})$

- 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 $\Delta_{b-c} \equiv m_b - m_c \simeq \overline{M}_{B_s} - \overline{M}_{D_s} \simeq 3.33 \text{ GeV}$, where

$\overline{M}_{B_s} = 5.403 \text{ GeV}$, $\overline{M}_{D_s} = 2.076 \text{ GeV}$: 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**

¹The 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 $m_Q \rightarrow \infty$: $\Delta v = \frac{\Delta p}{m_Q} = \frac{\Lambda_{\text{QCD}}}{m_Q}$
 $\Rightarrow$ 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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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: $\int d^3\vec{q} \rightarrow \frac{1}{L^3} \sum_{\vec{q}}$, and one gets

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

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

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

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

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

- 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

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

where $u_\mu = i [u^\dagger (\partial_\mu - i r_\mu) u + u (\partial_\mu - i l_\mu) u^\dagger]$, $u = e^{i \lambda_a \phi_a / (2 F_0)}$

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

- this gives the [Weinberg–Tomozawa term](#) for $P\phi$ scattering

- At the next-to-leading order $\mathcal{O}(p^2)$: FKG, Hanhart, Krewald, Meißner, PLB666(2008)251

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

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

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

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

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 $\mathcal{O}(p^3)$, see Y.-R. Liu, X. Liu, S.-L. Zhu, PRD79(2009)094026; L.-S. Geng et al., PRD82(2010)054022; D.-L. Yao, M.-L. Du, FKG, U.-G. Meißner, JHEP1511(2015)058;

M.-L. Du, FKG, U.-G. Meißner, D.-L. Yao, EPJC77(2017)728

renormalization:

M.-L. Du, FKG, U.-G. Meißner, JPG44(2017)014001

PCB-term subtraction in EOMS scheme using path integral:

M.-L. Du, FKG, U.-G. Meißner, JHEP1610(2016)122

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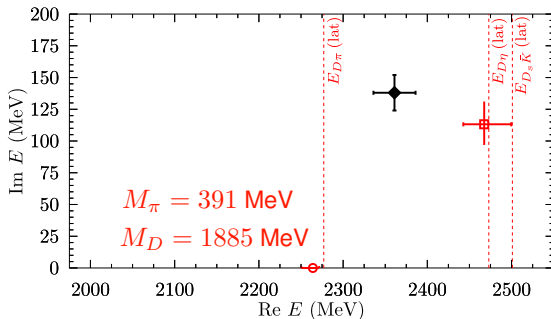
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Two $I = 1/2$ states !

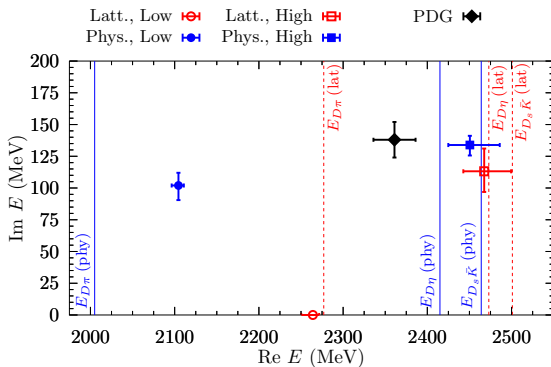
Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$ g_{D\pi} $	$ g_{D\eta} $	$ g_{D_s\bar{K}} $
lattice	2264^{+8}_{-14}	0	(000)	$7.7^{+1.2}_{-1.1}$	$0.3^{+0.5}_{-0.3}$	$4.2^{+1.1}_{-1.0}$
	2468^{+32}_{-25}	113^{+18}_{-16}	(110)	$5.2^{+0.6}_{-0.4}$	$6.7^{+0.6}_{-0.4}$	$13.2^{+0.6}_{-0.5}$

Latt., Low  Latt., High  PDG 



Two $I = 1/2$ states !

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



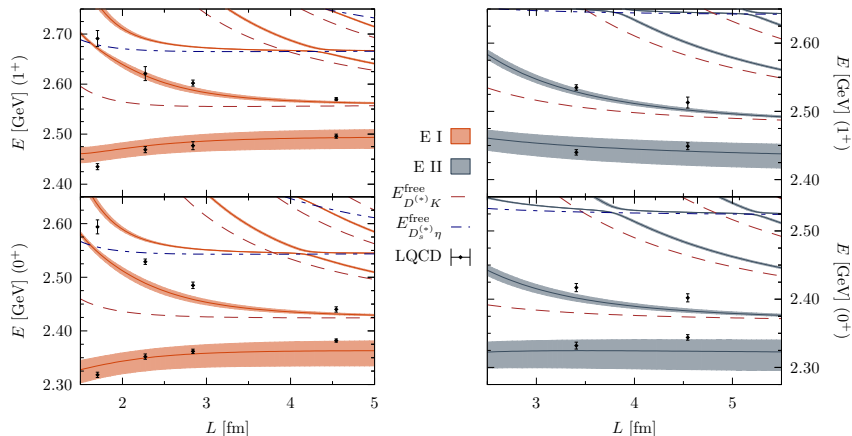
Postdictions versus recent lattice results: charm-strange

- **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]

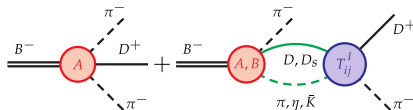
M. Albaladejo, P. Fernandez-Soler, J. Nieves, P. G. Ortega, arXiv:1805.07104

E I: $M_\pi = 290$ MeV

E II: $M_\pi = 150$ MeV



- $B^- \rightarrow D^+ \pi^- \pi^-$ contains **coupled-channel** $D\pi$ FSI
- consider S, P, D waves: $\mathcal{A}(B^- \rightarrow D^+ \pi^- \pi^-) = \mathcal{A}_0(s) + \mathcal{A}_1(s) + \mathcal{A}_2(s)$
 - 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**

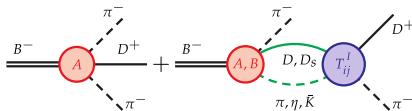


only 2 parameters in S -wave: C and a subtraction constant in $G_i(s)$

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

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More similar states?

FKG, U.-G. Meißner, PRD84(2011)014013

- Chiral symmetry $\Rightarrow$ universal Weinberg–Tomoza 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

$D_{sJ}(2860)$	$D_{sJ}(2860) \rightarrow DK$	$\frac{\Gamma(D_{sJ} \rightarrow D^*K)}{\Gamma(D_{sJ} \rightarrow DK)}$
$s_\ell^P = \frac{1}{2}^-, J^P = 1^-, n = 1$	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 $(2S, 1^-)$: $D_{s1}^*(2700)$ $\Gamma(D^*K)/\Gamma(DK) = 0.91 \pm 0.18$

$$M(2P, 2^+) \sim 3.16 \text{ GeV}$$

M. Di Pierro, E. Eichten, PRD64(2001)114004

- A natural explanation of the decay pattern:

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

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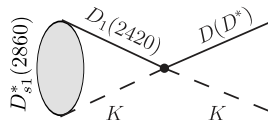
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