UNIVERSIDAD DE **MURCIA**

Two-pole (two-state) structure of $D_0^*(2400)$

Based on: Phys. Lett. B **767**, 465 (2017)
[arXiv:1610.06727]

Miguel Albaladejo (U. Murcia)

In collaboration with:
P. Fernández-Soler, F. K. Guo, J. Nieves

Salamanca
HADRON 2017
XVII International Conference on Hadron Spectroscopy and Structure

Outline

1. **Introduction**
   - Why is $D_0^*(2400)$ interesting?
   - Theoretical interpretations
   - Experimental situation, LQCD simulations
2. **Formalism: T-matrix for $D\pi$, $D\eta$, $D_s\overline{K}$**
   - Scattering in infinite volume
   - Energy levels in a finite volume
3. **Results**
   - Comparison with LQCD
   - Spectroscopy
   - Amplitudes
4. **$SU(3)$ light–flavor limit and other predictions (charm & bottom)**
   - $SU(3)$ light–flavor limit
   - Predictions for other sectors
5. **Conclusions**
   - Chiral dynamics and two-state structure(s)
   - Conclusions

Outline

1. **Introduction**
   - Why is $D_0^*(2400)$ interesting?
   - Theoretical interpretations
   - Experimental situation, LQCD simulations
2.
   - Scattering in infinite volume
   - Energy levels in a finite volume
3.
   - Comparison with LQCD
   - Spectroscopy
   - Amplitudes
4.
   - $SU(3)$ light–flavor limit
   - Predictions for other sectors
5.
   - Chiral dynamics and two-state structure(s)
   - Conclusions

Introduction: Why is $D_0^*(2400)$ interesting?

- Lightest open-charm $J^P = 0^+$ states: $\begin{cases} D_{s0}^*(2317)\,, & (S,I) = (1,0) \\ D_0^*(2400)\,, & (S,I) = \left(0,\frac{1}{2}\right) \end{cases}$.
- Lightest systems to test **ChPT with heavy mesons**, besides $D^* \to D\pi$.
- $D\pi$ interactions (where it shows up) are relevant, since $D\pi$ appears as a final state in many reactions that are being considered now (*i.e.*, $Z_c(3900)$ and $\bar{D}^* D\pi$)
- **Problems** with simple quark models expectations:
  - $D_{s0}^*(2317)$ is around **150 MeV below** the predicted mass.
    Godfrey, Isgur, Phys. Rev. D **32**, 189 (1985); Godfrey, Moats, Phys. Rev. D **93**, 034035 (2016)
    Lakhina, Swanson, Phys. Lett. B **650**, 159 (2007); Ortega *et al.*, Phys. Rev. D **94**, 074037 (2016)
  - Naively, one would expect D_{s0}^* ($\sim c\bar{s}$) to be **heavier** than D_0^* ($\sim c\bar{n}$).
- $D_0^*(2400)$ is important in **weak interactions and CKM** parameters:
  Flynn, Nieves, Phys. Rev. D **76**, 031302 (2007)
  MA, P. Fernandez-Soler, F.K. Guo, J. Nieves, D.L. Yao, *in preparation*
  See De-Liang Yao's talk [Thursday, 15:35, Aula 2.3]
  - It determines the shape of the scalar form factor $f_0(q^2)$ in semileptonic $D \to \pi$ decays.
  - Relation to $|V_{cd}|$: $f_+(0) = f_0(0)$ and $d\Gamma \propto |V_{cd} f_+(q^2)|^2$.
  - Even more interesting: the bottom analogue $|V_{ub}|$.

Introduction: Theoretical interpretations

$c\bar{q}$ states

Dai *et al*. Phys. Rev. D **68**, 114011 (2003)

Narison, Phys. Lett. B **605**, 319 (2005)

Bardeen *et al*., Phys. Rev. D **68**, 054024 (2003)

Lee *et al*., Eur. Phys. J. C **49**, 737 (2007)

Wang, Wan, Phys. Rev. D **73**, 094020 (2006)

$c\bar{q}$+ tetraquarks or meson–meson

Browder *et al*., Phys. Lett. B **578**, 365 (2004)

van Beveren, Rupp, Phys. Rev. Lett. **91**, 012003 (2003)

Pure tetraquarks

Cheng, Hou, Phys. Lett. B **566**, 193 (2003)

Terasaki, Phys. Rev. D **68**, 011501 (2003)

Chen, Li, Phys. Rev. Lett. **93**, 232001 (2004)

Maiani *et al*,, Phys. Rev. D **71**, 014028 (2005)

Bracco *et al*., Phys. Lett. B **624**, 217 (2005)

Wang, Wan, Nucl. Phys. A **778**, 22 (2006)

Heavy-light meson–meson molecules

Barnes *et al*., Phys. Rev. D **68**, 054006 (2003)

Szczepaniak, Phys. Lett. B **567**, 23 (2003)

Kolomeitsev, Lutz, Phys. Lett. B **582**, 39 (2004)

Hofmann, Lutz, Nucl. Phys. A **733**, 142 (2004)

Guo *et al*., Phys. Lett. B **641**, 278 (2006)

Gamermann *et al*., Phys. Rev. D **76**, 074016 (2007)

Faessler *et al*., Phys. Rev. D **76**, 014005 (2007)

Flynn, Nieves, Phys. Rev. D **75**, 074024 (2007)

Albaladejo *et al*., Eur. Phys. J. C **76**, 300 (2016)

Introduction: Experimental situation, LQCD simulations

Experimental situation:

	Collab.	M (MeV)	$\Gamma/2$ (MeV)	Ref.
Neu.	Belle	2308 ± 36	138 ± 33	Phys. Rev. D **69**, 112002 (2004)
	BaBar	2297 ± 22	137 ± 25	Phys. Rev. D **79**, 112004 (2009)
	FOCUS	2407 ± 41	120 ± 40	Phys. Lett. B **586**, 11 (2004)
Char.	LHCb	2360 ± 33	128 ± 29	Phys. Rev. D **92**, 012012 (2015)
	FOCUS	2403 ± 38	142 ± 21	Phys. Lett. B **586**, 11 (2004)

Lattice QCD:

- Masses larger than the physical ones if using $c\bar{s}$ interpolators only.

  Bali, Phys. Rev. D **68**, 071501 (2003)

  UKQCD Collab., Phys. Lett. B **569**, 41 (2003)

- Masses consistent with $D_0^*(2400)$ and $D_{s0}^*(2317)$ obtained when "meson-meson" interpolators are employed.

  Mohler, Prelovsek, Woloshyn, Phys. Rev. D **87**, 034501 (2013)

  Mohler *et al.*, Phys. Rev. Lett. **111**, 222001 (2013)

Recent LQCD study with $D\pi$, $D\eta$ and $D_s\bar{K}$ coupled-channel scattering.
A bound state with large coupling to $D\pi$ is identified with $D_0^*(2400)$.

Hadron Spectrum Collab., JHEP **1610**, 011 (2016)

cf. talks: Ch. Thomas on Monday, R. Briceño on Tuesday

Outline

1

- Why is $D_0^*(2400)$ interesting?
- Theoretical interpretations
- Experimental situation, LQCD simulations

2 **Formalism: T-matrix for $D\pi$, $D\eta$, $D_s\overline{K}$**

- Scattering in infinite volume
- Energy levels in a finite volume

3

- Comparison with LQCD
- Spectroscopy
- Amplitudes

4

- $SU(3)$ light–flavor limit
- Predictions for other sectors

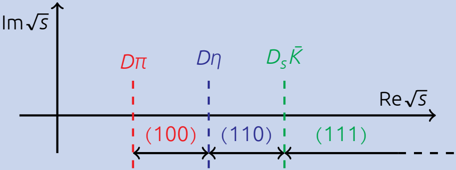
5

- Chiral dynamics and two-state structure(s)
- Conclusions

$D\pi$, $D\eta$, $D_s\overline{K}$ scattering: infinite volume

- **Coupled channel T-matrix:** $D\pi$, $D\eta$, $D_s\overline{K}$ scattering $[J^P = 0^+, (S,I) = (0, \frac{1}{2})]$.
- **Unitarity:** $T^{-1}(s) = V^{-1}(s) - \mathcal{G}(s)$
  - Normalization: $-ip_{ii}(s)T_{ii}(s) = 4\pi\sqrt{s}\left(\eta_i(s)e^{2i\delta_i(s)} - 1\right)$.
  - $\mathcal{G}_{ii}(s) = G(s, m_i, M_i)$, regularized with a subtraction constant $a(\mu)$ ($\mu = 1$ GeV).
- **Analytical continuations:** Riemann sheets (RS) denoted as $(\xi_1\xi_2\xi_3)$:

$$\mathcal{G}_{ii}(s) \to \mathcal{G}_{ii}(s) + i\frac{p_i(s)}{4\pi\sqrt{s}}\xi_i$$



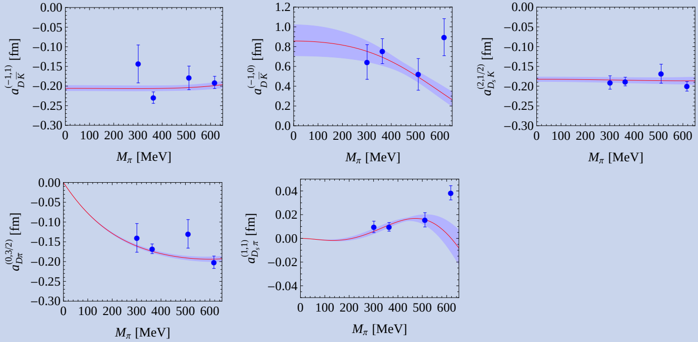
$D\pi$, $D\eta$, $D_s\overline{K}$ scattering: infinite volume (II)

- **Chiral symmetry** used to compute the $\mathcal{O}(p^2)$ potential:

$$f^2 V_{ij}(s,t,u) = C^{ij}_{\text{LO}} \frac{s-u}{4} + \sum_{a=0}^{5} h_a C^{ij}_a(s,t,u)$$

Guo *et al.*, Phys. Lett. B **666**, 251 (2008)
Liu *et al.*, Phys. Rev. D **87**, 014508 (2013)

- Values of h_a and $a(\mu)$ have been **previously fixed**:
  - Fitted to reproduce scattering lengths obtained in a LQCD simulation
  - They are not fitted in this work. We make **"predictions"**



$D\pi$, $D\eta$, $D_s\overline{K}$ energy levels in a finite volume

- Periodic boundary conditions imposes **momentum quantization**
- Lüscher formalism:
  Commun. Math. Phys. **105**, 153 (1986)
  Nucl. Phys. B **354**, 531 (1991)

infinite volume	finite volume
$\vec{q} \in \mathbb{R}^3$	$\vec{q} = \frac{2\pi}{L}\vec{n}, \quad \vec{n} \in \mathbb{Z}^3$
$\int_{\mathbb{R}^3} \frac{d^3 q}{(2\pi)^3}$	$\frac{1}{L^3} \sum_{\vec{n}\in\mathbb{Z}^3}$

- In practice, changes in the T-matrix: $T(s) \to \widetilde{T}(s,L)$:

Döring *et al.*, Eur. Phys. J. **A** 47, 139 (2011)

$$\mathcal{G}_{ii}(s) \to \tilde{\mathcal{G}}_{ii}(s,L) = \mathcal{G}_{ii}(s) + \lim_{\Lambda\to\infty} \left(\frac{1}{L^3} \sum_{\vec{n}}^{|\vec{q}|<\Lambda} I_i(\vec{q}\,) - \int_0^\Lambda \frac{q^2 dq}{2\pi^2} I_i(\vec{q}\,) \right),$$

$$V(s) \to \tilde{V}(s,L) = V(s)\,,$$

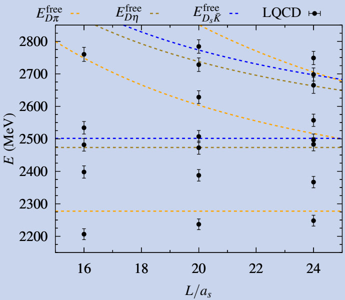
$$T^{-1}(s) \to \widetilde{T}^{-1}(s,L) = V^{-1}(s) - \tilde{\mathcal{G}}(s,L)\,,$$

- **Free** energy levels: $E^{(i)}_{n,\text{free}}(L) = \omega_{i1}((2\pi n/L)^2) + \omega_{i2}((2\pi n/L)^2)$
- **Interacting** energy levels $E_n(L)$: $\widetilde{T}^{-1}(E_n^2(L),L) = 0$ (poles of the $\widetilde{T}$-matrix).

Outline

1.
   - Why is $D_0^*(2400)$ interesting?
   - Theoretical interpretations
   - Experimental situation, LQCD simulations
2.
   - Scattering in infinite volume
   - Energy levels in a finite volume
3. **Results**
   - Comparison with LQCD
   - Spectroscopy
   - Amplitudes
4.
   - $SU(3)$ light–flavor limit
   - Predictions for other sectors
5.
   - Chiral dynamics and two-state structure(s)
   - Conclusions

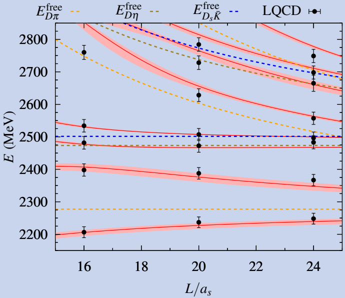
Results: Comparison with LQCD



M (MeV)	Latt.	Phys.
π	391	138
K	550	496
η	588	548
D	1886	1867
D_s	1952	1968

- LQCD: [G. Moir *et al.*, JHEP 1610, 011 (2016)]
- Bands: [M. A. *et al.*, Phys. Lett. B **767**, 465 (2017)]
- $E_n(L)$ are provided for $D\pi$, $D\eta$, $D_s\bar{K}$ in a recent LQCD simulation.
- We compute $E_n(L)$ and compare. **No fit** is performed.
- $E > 2.7$ GeV is probably beyond the range of validity for our T-matrix.
- Level below threshold, associated with a **bound state** (see below).
- Second level has large shifts w. r. t. thresholds: **Resonance?** (see below).

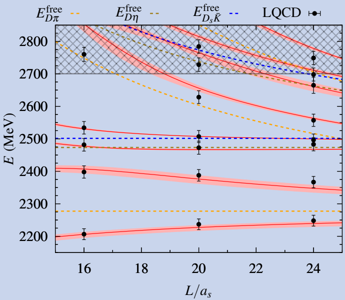
Results: Comparison with LQCD



M (MeV)	Latt.	Phys.
π	391	138
K	550	496
η	588	548
D	1886	1867
D_s	1952	1968

- LQCD: [G. Moir *et al.*, JHEP 1610, 011 (2016)]
- Bands: [M. A. *et al.*, Phys. Lett. B **767**, 465 (2017)]
- $E_n(L)$ are provided for $D\pi$, $D\eta$, $D_s\bar{K}$ in a recent LQCD simulation.
- We compute $E_n(L)$ and compare. **No fit** is performed.
- $E > 2.7$ GeV is probably beyond the range of validity for our T-matrix.
- Level below threshold, associated with a **bound state** (see below).
- Second level has large shifts w. r. t. thresholds: **Resonance?** (see below).

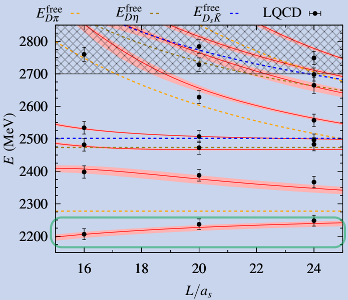
Results: Comparison with LQCD



M (MeV)	Latt.	Phys.
π	391	138
K	550	496
η	588	548
D	1886	1867
D_s	1952	1968

- LQCD: [G. Moir *et al.*, JHEP 1610, 011 (2016)]
- Bands: [M. A. *et al.*, Phys. Lett. B **767**, 465 (2017)]
- $E_n(L)$ are provided for $D\pi$, $D\eta$, $D_s\bar{K}$ in a recent LQCD simulation.
- We compute $E_n(L)$ and compare. **No fit** is performed.
- $E > 2.7$ GeV is probably beyond the range of validity for our T-matrix.
- Level below threshold, associated with a **bound state** (see below).
- Second level has large shifts w. r. t. thresholds: **Resonance?** (see below).

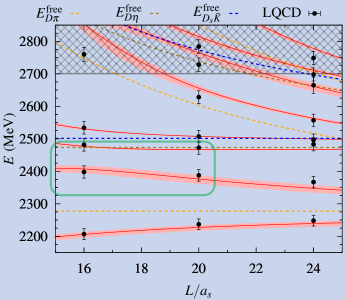
Results: Comparison with LQCD



M (MeV)	Latt.	Phys.
π	391	138
K	550	496
η	588	548
D	1886	1867
D_s	1952	1968

- LQCD: [G. Moir *et al.*, JHEP 1610, 011 (2016)]
- Bands: [M. A. *et al.*, Phys. Lett. B **767**, 465 (2017)]
- $E_n(L)$ are provided for $D\pi$, $D\eta$, $D_s\bar{K}$ in a recent LQCD simulation.
- We compute $E_n(L)$ and compare. **No fit** is performed.
- $E > 2.7$ GeV is probably beyond the range of validity for our T-matrix.
- Level below threshold, associated with a **bound state** (see below).
- Second level has large shifts w. r. t. thresholds: **Resonance?** (see below).

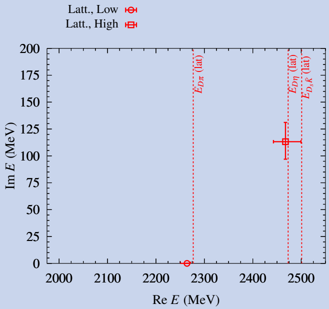
Results: Comparison with LQCD



M (MeV)	Latt.	Phys.
π	391	138
K	550	496
η	588	548
D	1886	1867
D_s	1952	1968

- LQCD: [G. Moir *et al.*, JHEP 1610, 011 (2016)]
- Bands: [M. A. *et al.*, Phys. Lett. B **767**, 465 (2017)]
- $E_n(L)$ are provided for $D\pi$, $D\eta$, $D_s\bar{K}$ in a recent LQCD simulation.
- We compute $E_n(L)$ and compare. **No fit** is performed.
- $E > 2.7$ GeV is probably beyond the range of validity for our T-matrix.
- Level below threshold, associated with a **bound state** (see below).
- Second level has large shifts w. r. t. thresholds: **Resonance?** (see below).

Results: Spectroscopy

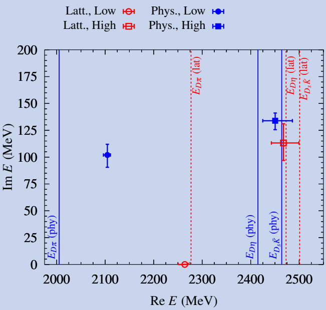


Meson Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$\lvert g_{D\pi}\rvert$	$\lvert g_{D\eta}\rvert$	$\lvert g_{D_s\bar{K}}\rvert$
lattice	$2264^{+\ 8}_{-14}$	0	(000)	$7.7^{+1.2}_{-1.1}$	$0.3^{+0.5}_{-0.3}$	$4.2^{+1.1}_{-1.0}$
	2468^{+32}_{-25}	113^{+18}_{-16}	(110)	$5.2^{+0.6}_{-0.4}$	$6.7^{+0.6}_{-0.4}$	$13.2^{+0.6}_{-0.5}$
physical	2105^{+6}_{-8}	102^{+10}_{-12}	(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)	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$

- We also study DK, $D_s\eta$, $(S,I)=(1,0)$ $D^*_{s0}(2317)$: $M = 2315^{+18}_{-28}$ MeV.

- For lattice masses, we find a **bound state** (000) and a **resonance** (110)
- For physical masses:
  - The bound state evolves into a **resonance** (100) above $D\pi$ threshold.
  - The resonance varies very little, and is still a **resonance** (110).
  - For both states, the coupling pattern is similar.
- PDG includes only one resonance, “suspiciously” lying between both.

Results: Spectroscopy

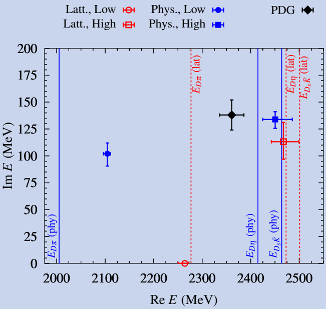


Meson Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$\lvert g_{D\pi}\rvert$	$\lvert g_{D\eta}\rvert$	$\lvert g_{D_s\bar{K}}\rvert$
lattice	$2264^{+\ 8}_{-14}$	0	(000)	$7.7^{+1.2}_{-1.1}$	$0.3^{+0.5}_{-0.3}$	$4.2^{+1.1}_{-1.0}$
	2468^{+32}_{-25}	113^{+18}_{-16}	(110)	$5.2^{+0.6}_{-0.4}$	$6.7^{+0.6}_{-0.4}$	$13.2^{+0.6}_{-0.5}$
physical	2105^{+6}_{-8}	102^{+10}_{-12}	(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)	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$

- We also study DK, $D_s\eta$, $(S,I)=(1,0)$ $D^*_{s0}(2317)$: $M = 2315^{+18}_{-28}$ MeV.

- For lattice masses, we find a **bound state** (000) and a **resonance** (110)
- For physical masses:
  - The bound state evolves into a **resonance** (100) above $D\pi$ threshold.
  - The resonance varies very little, and is still a **resonance** (110).
  - For both states, the coupling pattern is similar.
- PDG includes only one resonance, "suspiciously" lying between both.

Results: Spectroscopy

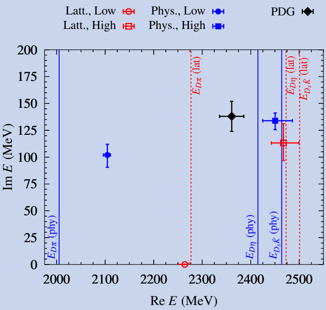


Meson Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$\lvert g_{D\pi}\rvert$	$\lvert g_{D\eta}\rvert$	$\lvert g_{D_s\bar{K}}\rvert$
lattice	$2264^{+\ 8}_{-14}$	0	(000)	$7.7^{+1.2}_{-1.1}$	$0.3^{+0.5}_{-0.3}$	$4.2^{+1.1}_{-1.0}$
	2468^{+32}_{-25}	113^{+18}_{-16}	(110)	$5.2^{+0.6}_{-0.4}$	$6.7^{+0.6}_{-0.4}$	$13.2^{+0.6}_{-0.5}$
physical	2105^{+6}_{-8}	102^{+10}_{-12}	(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)	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$

- We also study DK, $D_s\eta$, $(S, I) = (1, 0)$ $D^*_{s0}(2317)$: $M = 2315^{+18}_{-28}$ MeV.

- For lattice masses, we find a **bound state** (000) and a **resonance** (110)
- For physical masses:
  - The bound state evolves into a **resonance** (100) above $D\pi$ threshold.
  - The resonance varies very little, and is still a **resonance** (110).
  - For both states, the coupling pattern is similar.
- PDG includes only one resonance, “suspiciously” lying between both.

Results: Spectroscopy



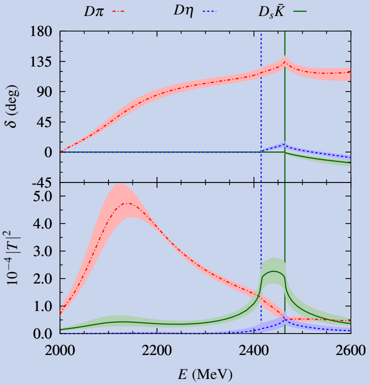
Meson Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$\lvert g_{D\pi}\rvert$	$\lvert g_{D\eta}\rvert$	$\lvert g_{D_s\bar{K}}\rvert$
lattice	2264^{+8}_{-14}	0	(000)	$7.7^{+1.2}_{-1.1}$	$0.3^{+0.5}_{-0.3}$	$4.2^{+1.1}_{-1.0}$
	2468^{+32}_{-25}	113^{+18}_{-16}	(110)	$5.2^{+0.6}_{-0.4}$	$6.7^{+0.6}_{-0.4}$	$13.2^{+0.6}_{-0.5}$
physical	2105^{+6}_{-8}	102^{+10}_{-12}	(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)	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$

- We also study DK, $D_s\eta$, $(S,I)=(1,0)$ $D^*_{s0}(2317)$: $M = 2315^{+18}_{-28}$ MeV.

- The $D^*_0(2400)$ structure is actually produced by **two different states** (poles), together with complicated interferences with thresholds.
- This two-state structure was previously reported, and receives now a robust support.

Kolomeitsev, Lutz, Phys. Lett. B **582**, 39 (2004)
Guo *et al.*, Phys. Lett. B **641**, 278 (2006)
Guo *et al.*, Eur. Phys. J. A **40**, 171 (2009)

Results: Amplitudes



- $-ip_i(s)\,T_{ii}(s) = 4\pi\sqrt{s}\left(\eta_i(s)e^{2i\delta_i(s)} - 1\right)$
- Lower pole at $\sqrt{s} = 2.1 - 0.1\,i$ GeV:
  - $|T_{11}(s)|^2$ peaks at $\sqrt{s} \simeq 2.1$ GeV
  - $\delta_{11}(s) = \pi/2$ at $\sqrt{s} \simeq 2.2$ GeV.
- Higher pole at $\sqrt{s} = 2.45 - 0.13\,i$ GeV:
  - Small enhancement in $|T_{D\pi}(s)|^2$.
  - Clear peak in the $D_s\bar{K}$ amplitude. Narrow, non-conventional shape, stretched between thresholds cusps.
- Possible tests in $B \to DPP'$ decays?

Outline

1.
   - Why is $D_0^*(2400)$ interesting?
   - Theoretical interpretations
   - Experimental situation, LQCD simulations
2.
   - Scattering in infinite volume
   - Energy levels in a finite volume
3.
   - Comparison with LQCD
   - Spectroscopy
   - Amplitudes
4. **$SU(3)$ light–flavor limit and other predictions (charm & bottom)**
   - $SU(3)$ light–flavor limit
   - Predictions for other sectors
5.
   - Chiral dynamics and two-state structure(s)
   - Conclusions

$SU(3)$ light–flavor limit

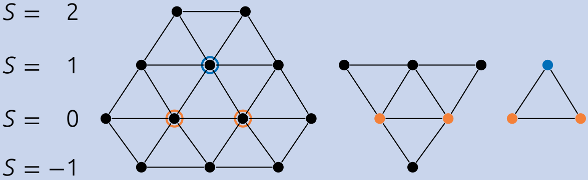
- $SU(3)$ flavor limit: $m_i \to m = 0.49$ GeV, $M_i \to M = 1.95$ GeV.
- Irrep decomposition: $\bar{\mathbf{3}} \otimes \mathbf{8} = \boxed{\overline{\mathbf{15}} \oplus \mathbf{6} \oplus \bar{\mathbf{3}}}$. T and V can be **diagonalized:**

$$V_d(s) = D^\dagger V(s) D = \text{diag}\left(V_{\overline{\mathbf{15}}}(s)\,, V_{\mathbf{6}}(s)\,, V_{\bar{\mathbf{3}}}(s)\right) = \boxed{A(s)\,\text{diag}\,(1,-1,-3)}\,,$$

$$T_d(s) = \text{diag}\left(T_{\overline{\mathbf{15}}}(s)\,, T_{\mathbf{6}}(s)\,, T_{\bar{\mathbf{3}}}(s)\right)\,.$$

$$T_A^{-1}(s) = V_A^{-1}(s) - G(s,m,M) \quad (\textit{e.g.}, \text{each } T_A(s) \text{ is “single channel”})\,.$$

- $\overline{\mathbf{15}}$ is repulsive. $\mathbf{6}$ and $\bar{\mathbf{3}}$ are attractive. “Curiously”, $\bar{\mathbf{3}}$ admits a **$c\bar{q}$ interpretation**.



State	Channels	(S,I)	$\overline{\mathbf{15}}$	$\mathbf{6}$	$\bar{\mathbf{3}}$
D_0^*	$D\pi$, $D\eta$, $D_s\bar{K}$	$\left(0,\frac{1}{2}\right)$	✓	✓	✓
$D_{s0}^*(2317)$	DK, $D_s\eta$	$(1,0)$	✓	✗	✓

$SU(3)$ light–flavor limit

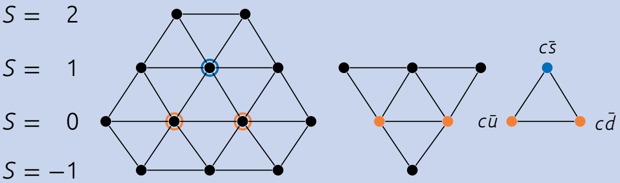
- $SU(3)$ flavor limit: $m_i \to m = 0.49$ GeV, $M_i \to M = 1.95$ GeV.
- Irrep decomposition: $\overline{\mathbf{3}} \otimes \mathbf{8} = \boxed{\overline{\mathbf{15}} \oplus \mathbf{6} \oplus \overline{\mathbf{3}}}$. T and V can be **diagonalized:**

$$V_d(s) = D^\dagger V(s) D = \text{diag}\left(V_{\overline{\mathbf{15}}}(s), V_{\mathbf{6}}(s), V_{\overline{\mathbf{3}}}(s)\right) = \boxed{A(s)\,\text{diag}\,(1,-1,-3)}\,,$$

$$T_d(s) = \text{diag}\left(T_{\overline{\mathbf{15}}}(s), T_{\mathbf{6}}(s), T_{\overline{\mathbf{3}}}(s)\right)\,.$$

$$T_A^{-1}(s) = V_A^{-1}(s) - G(s,m,M) \quad (\textit{e.g.}, \text{each } T_A(s) \text{ is "single channel"})\,.$$

- $\overline{\mathbf{15}}$ is repulsive. $\mathbf{6}$ and $\overline{\mathbf{3}}$ are attractive. "Curiously", $\overline{\mathbf{3}}$ admits a **$c\bar{q}$ interpretation**.

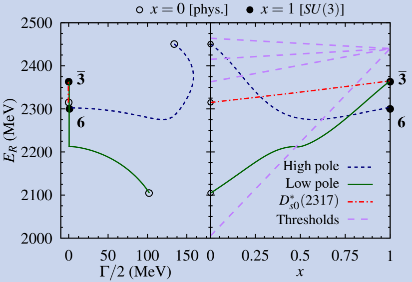


State	Channels	(S,I)	$\overline{\mathbf{15}}$	$\mathbf{6}$	$\overline{\mathbf{3}}$
D_0^*	$D\pi$, $D\eta$, $D_s\bar{K}$	$\left(0, \frac{1}{2}\right)$	✓	✓	✓
$D_{s0}^*(2317)$	DK, $D_s\eta$	$(1,0)$	✓	✗	✓

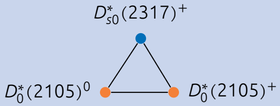
$SU(3)$ light–flavor limit (II)

Connecting **physical** ($x = 0$) and **flavor $SU(3)$** ($x = 1$) limits:

$$m_i = m_i^{\text{phy}} + x(m - m_i^{\text{phy}})\,, \quad (m = 0.49\ \text{GeV})\,,$$
$$M_i = M_i^{\text{phy}} + x(M - M_i^{\text{phy}})\,, \quad (M = 1.95\ \text{GeV})\,.$$



- The **high D_0^*** connects with a **6 virtual state** (unph. RS, below threshold).
- The **low D_0^*** connects with a **$\bar{3}$ bound state** (ph. RS, below threshold).
- The **$D_{s0}^*(2317)$** also connects with the **$\bar{3}$ bound state**.



- The low D_0^* and the $D_{s0}^*(2317)$ are $SU(3)$ **flavor partners**.
- This **solves the “puzzle”** of $D_{s0}^*(2317)$ being lighter than $D_0^*(2400)$: it is not, the lower D_0^* pole ($M = 2105$ MeV) is lighter.

Predictions for other sectors: charm

(S,I)	Channels	$\overline{\mathbf{15}}$	$\mathbf{6}$	$\overline{\mathbf{3}}$	0^+ M	0^+ $\Gamma/2$	1^+ M	1^+ $\Gamma/2$
$(0,\frac{1}{2})$	$D^{(*)}\pi, D^{(*)}\eta, D_s^{(*)}\bar{K}$	✓	✓	✓	(R) 2105^{+6}_{-8}	102^{+10}_{-12}	(R) 2240^{+5}_{-6}	93^{+9}_{-9}
					(R) 2451^{+36}_{-26}	134^{+7}_{-8}		
$(1,0)$	$D^{(*)}K, D_s^{(*)}\eta$	✓	✗	✓	(B) 2315^{+18}_{-28}		(B) 2436^{+16}_{-22}	
$(-1,0)$	$D^{(*)}\bar{K}$	✗	✓	✗	(V) 2342^{+13}_{-41}		–	
$(1,1)$	$D_s^{(*)}\pi, D^{(*)}K$	✓	✓	✗	–		–	

- **HQSS** relates 0^+ ($D_{(s)}P$) and 1^+ ($D^*_{(s)}P$) sectors: **similar resonance pattern.**
- Two pole structure: higher D_1 pole probably affected by ρ channels.
- $D\bar{K}$ $[0^+, (-1,0)]$: this virtual state (from **6**) has a large impact on the scattering length, $a^{D\bar{K}}_{(-1,0)} \simeq 0.8$ fm. (Rest of scattering lengths are $|a| \simeq 0.1$ fm.)

Predictions for other sectors: bottom

(S,I)	Channels	$\overline{\mathbf{15}}$	$\mathbf{6}$	$\overline{\mathbf{3}}$	0^+ M	0^+ $\Gamma/2$	1^+ M	1^+ $\Gamma/2$
$(0,\frac{1}{2})$	$\bar{B}^{(*)}\pi$, $\bar{B}^{(*)}\eta$, $\bar{B}_s^{(*)}\bar{K}$	✓	✓	✓	(R) 5537^{+9}_{-11} (R) 5840^{+12}_{-13}	116^{+14}_{-15} 25^{+6}_{-5}	(R) 5581^{+9}_{-11}	115^{+13}_{-15}
$(1,0)$	$\bar{B}^{(*)}K$, $\bar{B}_s^{(*)}\eta$	✓	✗	✓	(B) 5724^{+17}_{-24}		(B) 5768^{+17}_{-23}	
$(-1,0)$	$\bar{B}^{(*)}\bar{K}$	✗	✓	✗	(V–B) thr.		(V–B) thr.	
$(1,1)$	$\bar{B}_s^{(*)}\pi$, $\bar{B}^{(*)}K$	✓	✓	✗	–		–	

- **Heavy flavour symmetry** relates charm (D) and bottom ($\bar{B}$) sectors.
- $(0,\frac{1}{2})$: B_0^*, two-pole pattern also observed.
- $(-1,0)$: $[B^{(*)}\bar{K}]$: very close to threshold. Relevant prediction. Can be either **bound or virtual** (**6**) within our errors.
- $(1,1)$: $[\bar{B}_s\pi, \bar{B}K, 0^+]$, $X(5568)$ channel. No state is found: $\overline{\mathbf{15}}$ and **6**. If it exists, it is not dynamically generated in $B_s\pi$, $B\bar{K}$ interactions.

  M. A. *et al.*, Phys. Lett. B **757**, 515 (2016); Guo *et al.*, Commun. Theor. Phys. **65**, 593 (2016)
- $(1,0)$: Our results for B_{s0}^* and B_{s1} agree with **other results** from LQCD:

  Lang *et al.*, Phys. Lett. B **750**, 17 (2015); M. A. *et al.* Eur. Phys. J. C**77**, 170 (2017)

Outline

Chiral dynamics and two-state structure(s)

- Other famous two-poles structures rooted in **chiral dynamics:**

$\Lambda(1405)$ $[\Sigma\pi, N\bar{K}]$

Oller, Meißner, Phys. Lett. B **500**, 263 (2001)
Jido *et al.*, Nucl. Phys. A **725**, 181 (2003)
García-Recio *et al.*, Phys. Lett. B **582**, 49 (2004)
Magas *et al.*, Phys. Rev. Lett. **95**, 052301 (2005)

$K_1(1270)$

Roca *et al.*, Phys. Rev. D **72**, 014002 (2005)
Geng *et al.*, Phys. Rev. D **75**, 014017 (2007)
García-Recio *et al.*, Phys. Rev. D **83**, 016007 (2011)

- **Chiral dynamics:**
  - Incorporates the $SU(3)$ light-flavor structure,
  - Determines the strength of the interaction,
  - Ensures lightness of Goldstone bosons, which in turn separates generating channels from higher hadronic channels.

Conclusions

- We have studied $D\pi$, $D\eta$, $D_s\bar{K}$ scattering $[0^+, (S,I) = (0, \frac{1}{2})]$
- So far only one pole reported experimentally, but…
- We have presented a strong support for the **existence of two $D_0^*(2400)$ states** (different poles), based on a succesful, no-fitting comparison of our T-matrix with the energy levels of a recent LQCD simulation.
- A $SU(3)$ study shows that $D_{s0}^*(2317)$ and the lower $D_0^*(2400)$ are **flavour partners**: they complete a $\bar{\mathbf{3}}$ multiplet.
- The lower pole ($M = 2105^{+6}_{-8}$ MeV) is **lighter** than $D_{s0}^*(2317)$, solving this apparent contradiction.
- Predictions for **other sectors** (heavy vectors, bottom sector) have been also given. In particular:
  - The two-pole structure is also seen in the **bottom sector.**
  - A very **near-threshold** state (bound or virtual) is predicted for BK ($\bar{B}\bar{K}$).

UNIVERSIDAD DE **MURCIA**

Two-pole (two-state) structure of $D_0^*(2400)$

Based on: Phys. Lett. B **767**, 465 (2017) [arXiv:1610.06727]

Miguel Albaladejo (U. Murcia)

In collaboration with:
P. Fernández-Soler, F. K. Guo, J. Nieves

Salamanca
HADRON 2017
XVII International Conference on Hadron Spectroscopy and Structure

Connecting $SU(3)$ and physical limits Riemann sheets

Riemann sheets:

$$\mathcal{G}_{ii}(s) \to \mathcal{G}_{ii}(s) + i\frac{p_i(s)}{4\pi\sqrt{s}}\,\xi_i$$

$SU(3)$ limit:

$$m_i = m_i^{\rm phy} + x(m - m_i^{\rm phy})\,, \quad (m = 0.49\ \text{GeV})\,,$$
$$M_i = M_i^{\rm phy} + x(M - M_i^{\rm phy})\,, \quad (M = 1.95\ \text{GeV})\,.$$

- Physical case ($x = 0$): RS specified by $(\xi_1\xi_2\xi_3)$, $\xi_i = 0$ or 1.
- $SU(3)$ symmetric case ($x = 1$): all channels have the same threshold, so there are only two RS (000) and (111).
- To connect the **lower pole** with the $T_{\mathbf{6}}$ virtual state,

$$\xi_3 = x \qquad (1,1,0) \to (1,1,x)$$

- To connect the **lower pole** with the $T_{\bar{\mathbf{3}}}$ bound state,

$$\xi_1 = 1 - x \qquad (1,0,0) \to (1-x,0,0)$$

Lattice QCD parameterization

Parameters																			N_{pars}	χ^2/N_{dof}
m	$g_i^{(0)}$			$g_i^{(1)}$			$\gamma_{ij}^{(0)}$						$\gamma_{ij}^{(1)}$							
	1	2	3	1	2	3	11	12	13	22	23	33	11	12	13	22	23	33		
✓	✓	-	✓	-	-	-	✓	-	-	✓	-	✓	-	-	-	-	-	-	6	*3.35*
✓	✓	-	✓	-	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	7	*2.70*
✓	✓	-	✓	-	-	-	✓	-	✓	✓	-	✓	-	-	-	-	-	-	7	*3.14*
✓	✓	-	✓	-	-	-	✓	-	-	✓	✓	✓	-	-	-	-	-	-	7	*2.13*
✓	✓	✓	-	-	-	-	✓	-	-	✓	-	✓	-	-	-	-	-	-	6	*13.1*
✓	✓	✓	-	-	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	7	*11.7*
✓	✓	✓	-	-	-	-	✓	-	✓	✓	-	✓	-	-	-	-	-	-	7	*2.07*
✓	✓	✓	-	-	-	-	✓	-	-	✓	✓	✓	-	-	-	-	-	-	7	*2.07*
✓	✓	✓	✓	-	-	-	✓	-	-	✓	-	✓	-	-	-	-	-	-	7	1.76
✓	✓	✓	✓	-	-	-	✓	✓	-	✓	-	✓	-	-	-	-	-	-	8	1.71
✓	✓	✓	✓	-	-	-	✓	✓	✓	✓	-	✓	-	-	-	-	-	-	9	1.76
✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	5	*2.15*
✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	✓	-	-	✓	-	-	6	1.78
✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	✓	-	-	✓	-	✓	7	1.71
✓	✓	✓	✓	✓	-	-	✓	-	-	✓	-	-	-	-	-	-	-	-	8	1.68
✓	✓	✓	✓	✓	-	-	✓	-	-	-	-	✓	-	-	-	-	-	-	7	*2.01*
✓	✓	✓	✓	✓	-	-	✓	-	-	✓	-	✓	-	-	-	-	-	-	8	1.63
✓	✓	✓	✓	✓	✓	-	✓	-	-	✓	-	✓	-	-	-	-	-	-	9	1.66
✓	✓	✓	✓	✓	-	✓	✓	-	-	✓	-	✓	-	-	-	-	-	-	9	1.68

Table 11. The S-wave t-matrix parametrisations used in section 3.3.1 where "✓" denotes a free parameter and "-" a parameter fixed to zero. The channel labels are ordered by increasing mass, $1 = D\pi$, $2 = D\eta$ and $3 = D_s\bar{K}$. The forms shown also included a free P-wave part contributing an additional 3 parameters. Forms with $\chi^2/N_{\text{dof}} > 1.9$ (shown in italics) were not used in our final analysis as described in the text of section 3.3.1.

JHEP10(2016)011