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

Pedro Fernandez-Soler

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M. Albaladejo – P. Fernandez-Soler – F-K Guo – J. Nieves

2 of June 2017

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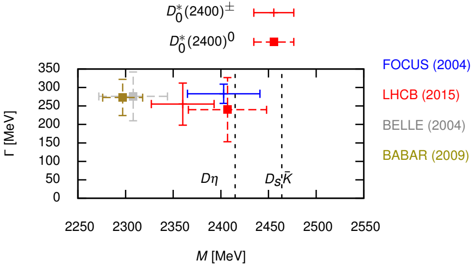
I Introduction
II Formalism: $D\pi$ $D\eta$ $D_s\bar{K}$ interaction
III Predictions: comparison with Lattice QCD
IV $SU(3)$ considerations
V Summary

- Lowest lying $(S, I) = (0, 1/2)$, $J^P = 0^+$



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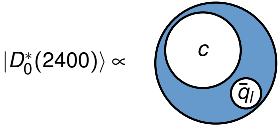

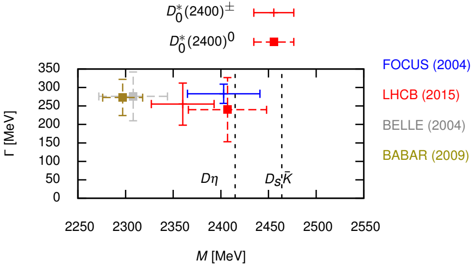

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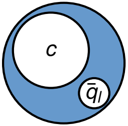
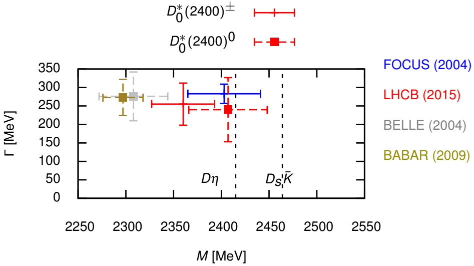
$|D_0^*(2400)\rangle \propto$ 



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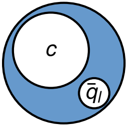
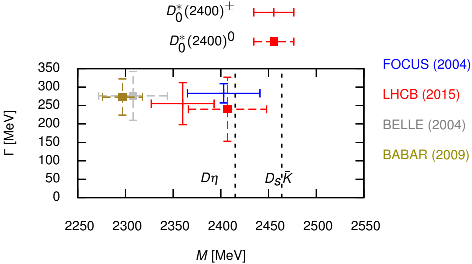
$|D_0^*(2400)\rangle \propto$ 



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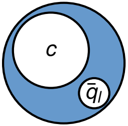
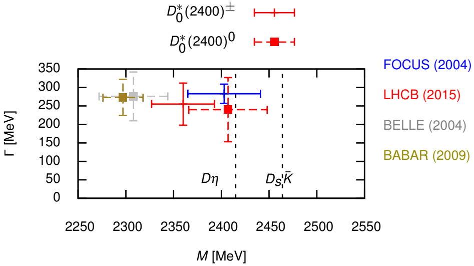
$|D_0^*(2400)\rangle \propto$ 



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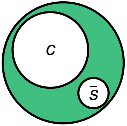
$|D_{s0}^*(2317)\rangle \propto$ 

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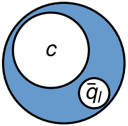

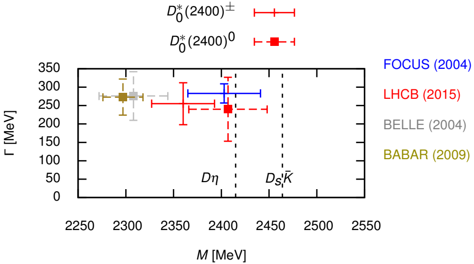

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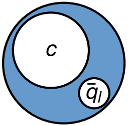
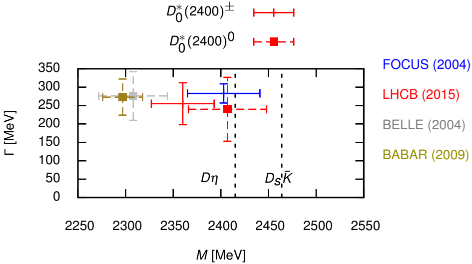
$|D_0^*(2400)\rangle \propto$ 



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  - Its presence influences the shape of the f_0 and f_+ semileptonic form factors

Measurements

- C. Patrignani, et al., Particle Data Group, Chin. Phys. C 40 (2016) 100001
- B. Aubert, et al., BaBar Collaboration, Phys. Rev. Lett. 90 (2003) 242001
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Lattice QCD

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- A. Dougall, et al., UKQCD Collaboration, Phys. Lett. B 569 (2003) 41.
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  D. Mohler, C.B. Lang, L. Leskovec, S. Prelovsek, R.M. Woloshyn, Phys. Rev. Lett. 111 (2013) 222001 (include meson correlators)
- G. Moir, M. Peardon, S.M. Ryan, C.E. Thomas, D.J. Wilson, J. High Energy Phys. 1610 (2016) 011 (used here!)

Here

- E.E. Kolomeitsev, M.F.M. Lutz, Phys. Lett. B 582 (2004) 39
  F.-K. Guo, P.-N. Shen, H.-C. Chiang, R.-G. Ping, B.-S. Zou, Phys. Lett. B 641 (2006) 278
  F.-K. Guo, C. Hanhart, U.-G. Meißner, Eur. Phys. J. A 40 (2009) 171
- L. Liu, K. Orginos, F.-K. Guo, C. Hanhart, U.-G. Meißner, Phys. Rev. D 87 (2013) 014508

I. Introduction (3)

LQCD simulation of $(S, I) = (0, 1/2)$ sector J. High Energy Phys. 1610 (2016) 011.

- First principle calculations
- Quarks and gluons in a grid
- Periodic boundary conditions
  $\psi(\vec{x}_0 + \vec{n}L) = \psi(x_0)$
  $\vec{k} = \frac{2\pi}{L}(n_1, n_2, n_3) \rightarrow \vec{k}^2 = n\frac{4\pi^2}{L^2}$
- Produce hadron states $|D\pi(n)\rangle$
  - Volume dependence of energy levels

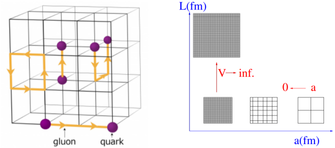

Figure: Taken from S.Ryan MESON2016

$$\omega_{D\pi}(n, L) = \sqrt{\vec{k}^2 + m_\pi} + \sqrt{\vec{k}^2 + m_D} \text{ vs } E_{D\pi}(L) \approx \omega_{D\pi}(n, L) + \Delta E(L)$$

  - m_i

	LQCD	Phys
m_π	391	138
m_K	550	496
m_η	588	548
m_D	1886	1867
m_{D_s}	1952	1968

Comparing with LQCD $L \rightarrow \infty$

- Lüscher formalism $\delta(L \rightarrow \infty) \leftrightarrow \Delta E(L)$ Commun. Math. Phys. 105, 153 (1986); Nucl. Phys. B354, 531 (1991)
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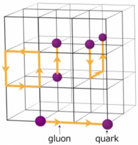

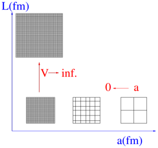

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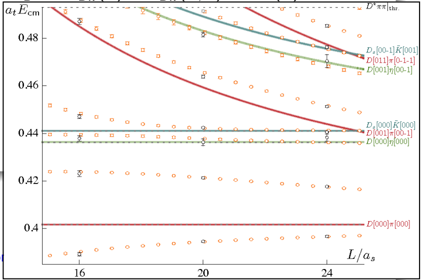

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II. Formalism (1): Unitarized scattering amplitudes

$$H(p_1)\phi(p_2) \to H'(p_3)\phi'(p_4)$$

$$H = \{D^0, D^+, D_s\},\ \phi = \begin{pmatrix} -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -2\frac{\eta}{\sqrt{6}} \end{pmatrix}$$

$\mathscr{L}$ at NLO: $\mathscr{O}(p^2)$

S	I	channels
-1	0	$D\bar{K}$
-1	1	$D\bar{K}$
2	$1/2$	D_sK
0	$3/2$	$D\pi$
1	1	$D_s\pi$, DK
1	0	DK, $D_s\eta$
0	$1/2$	$D\pi$, $D\eta$, $D_s\bar{K}$

$$\mathscr{M}(s,t,u) = \frac{C_0}{4F^2}(s-u) + \mathscr{F}(s,t,u)$$

$$\mathscr{F}(s,t,u) = h_0\mathscr{F}_0(s,t,u) + h_1\mathscr{F}_1(s,t,u) + \cdots + h_5\mathscr{F}_5(s,t,u)$$

- 6 LEC describe all (S,I) sectors
- S-wave amplitudes unitarized

$$\mathscr{T}(s) = \mathscr{M}(s) + \mathscr{M}(s)G(s)\mathscr{M}(s) + \mathscr{M}(s)G(s)\mathscr{M}(s)G(s)\mathscr{M}(s) + \ldots$$

$$= (1 - \mathscr{M}(s)G(s))^{-1}\mathscr{M}(s) \Rightarrow \boxed{\mathscr{T}^{-1}(s) = \mathscr{M}(s)^{-1} - G(s)}$$

- h_{1-5} LECS constrained by LQCD [PHYSICAL REVIEW D 87, 014508 (2013)]

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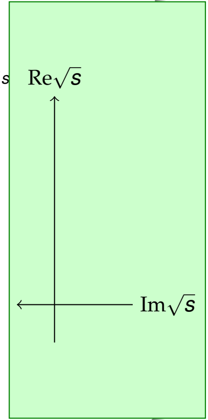

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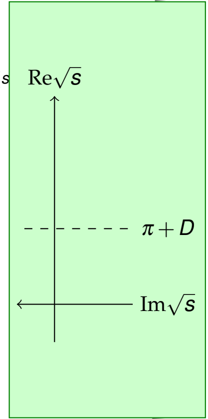

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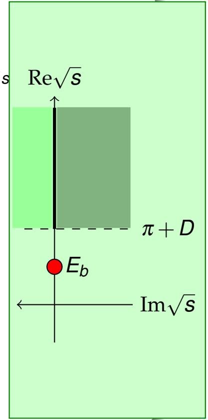

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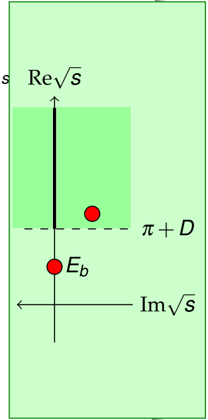

Analytical continuation

- $G_{D\pi}(s)\to G^{\mathrm{II}}_{ii}(s)=G_{D\pi}(s)+\mathrm{i}\frac{k}{4\pi\sqrt{s}}$

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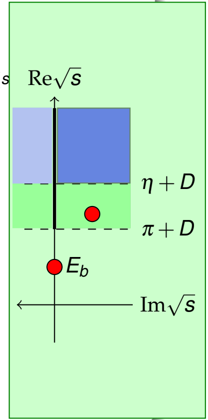

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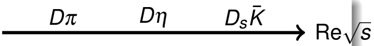

- $G_{D\pi}(s) \to G^{\mathrm{II}}_{ii}(s) = G_{D\pi}(s) + \mathrm{i}\frac{k}{4\pi\sqrt{s}}$
- $\xi = 0, 1$ $G_{j,j} \to G_{j,j}(s) + \mathrm{i}\frac{k}{4\pi\sqrt{s}}\xi_j$, (ξ_1, ξ_2, ξ_3) $(0,0,0) - (1,0,0) - (1,1,0) - (1,1,1)$

II. Formalism (4): finite volume

- In finite volume

$$G_j(s) = \int_{\mathbb{R}^3} \frac{d^3q}{(2\pi)^3} \frac{f(\vec{q})}{s-\omega_j(\vec{q})^2} \to \tilde{G}_j(s,L) = \sum_{\vec{q}(L)} \frac{1}{L^3} \frac{f(\vec{q})}{s-\omega_j(\vec{q})^2}$$

- Energy levels $\leftrightarrow$ eigen-energies

$$S_{i,j}(s) \to \tilde{S}_{i,j}(s,L)$$
$$\mathscr{T}_{i,j}(s) \to \tilde{\mathscr{T}}_{i,j}(s,L)$$

Let us denote them as $E(L)$,

$$\det \tilde{\mathscr{T}}^{-1}\left(s = E(L)^2, L\right) = 0, \; i.e., \; \det(\mathscr{M}^{-1}(s) - \tilde{G}(s,L)) = 0$$

II. Formalism (4): finite volume

- In finite volume

$$G_j(s) = \int_{\mathbb{R}^3} \frac{d^3q}{(2\pi)^3} \frac{f(\vec{q})}{s-\omega_j(\vec{q})^2} \to \tilde{G}_j(s,L) = \sum_{\vec{q}(L)} \frac{1}{L^3} \frac{f(\vec{q})}{s-\omega_j(\vec{q})^2}$$

- Energy levels $\leftrightarrow$ eigen-energies

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No interaction

Take $\mathscr{M}_{i,j} \to 0$. Recall $\omega_i(n,L) = \sqrt{n(\frac{2\pi}{L})^2 + M_i^2} + \sqrt{n(\frac{2\pi}{L})^2 + m_i^2}$

- $\tilde{G}_{i,i}(s,L) \sim \sum_{\vec{q}(L)} \frac{\cdots}{s-[\omega_i(\vec{q}(L))]^2} = \frac{\cdots}{s-\omega_i(0)^2} + \frac{\cdots}{s-\omega_i(1)^2} + \frac{\cdots}{s-\omega_i(2)^2} + \ldots$
- $\det(\mathscr{M}^{-1} - \tilde{G}(s,L)) = 0 \Rightarrow s = \omega_i(n,L)^2$

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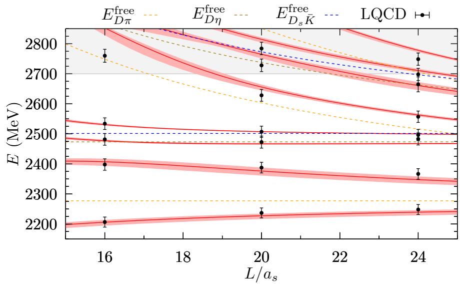
- $\det(\mathscr{M}^{-1} - \tilde{G}(s,L)) = 0 \Rightarrow s = \omega_i(n,L)^2$
- $\mathscr{M} \neq 0$: deviation of $E(L)$ from $\omega_i(n,L)$

III. Results (1)

Energy levels and poles

No fit is performed here!



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)	$7.7^{+1.2}_{-1.1}$	$0.3^{+0.5}_{-0.3}$	$4.2^{+1.1}_{-1.0}$
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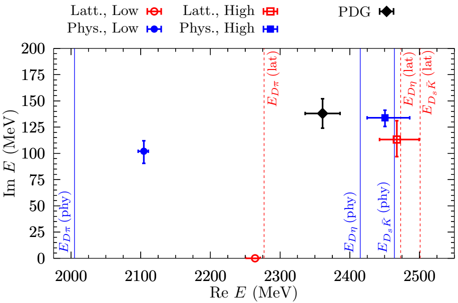

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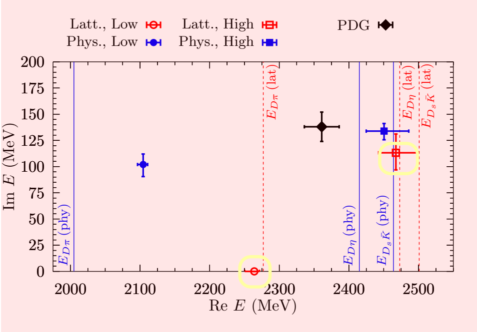

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	LQCD	Phys
m_π	391	138
m_K	550	496
m_η	588	548
m_D	1886	1867
m_{D_s}	1952	1968

III. Results (1)

Energy levels and poles

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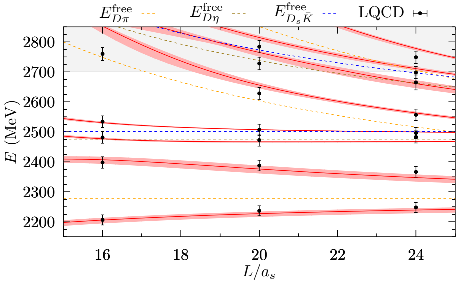

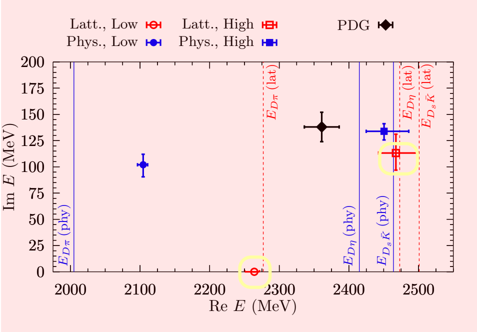

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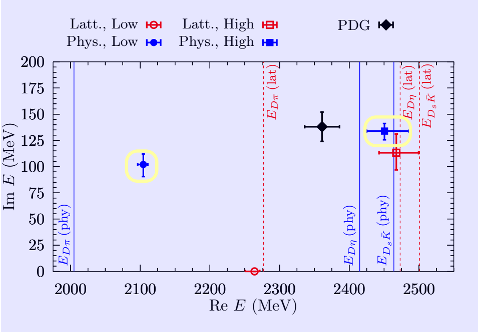

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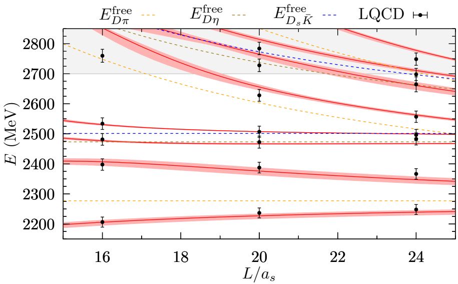

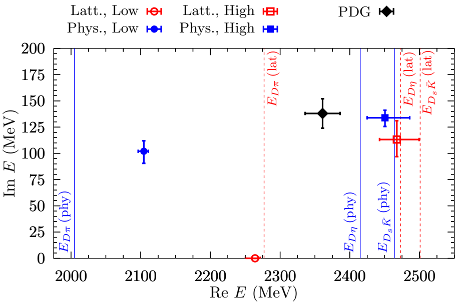

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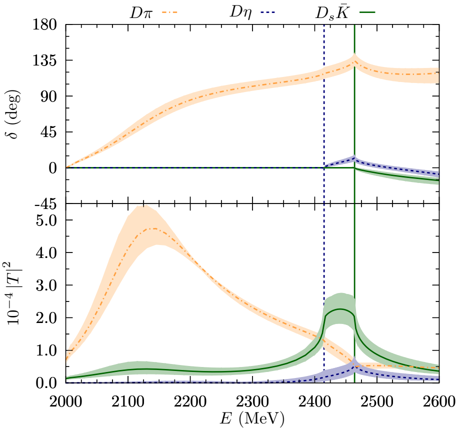

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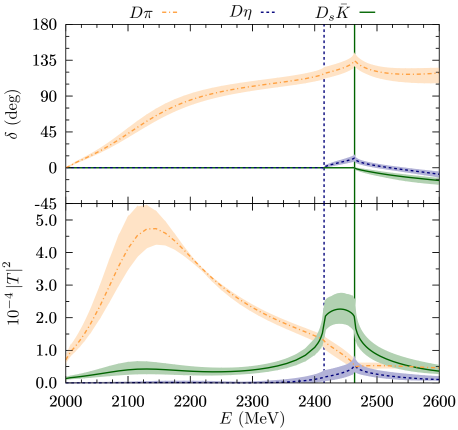

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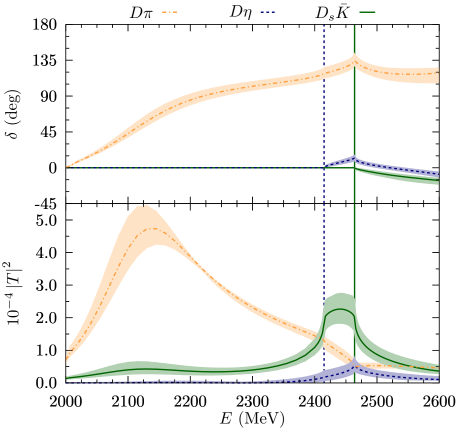
  Belle: Phys.Rev. D80 (2009) 052005



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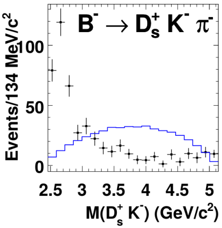

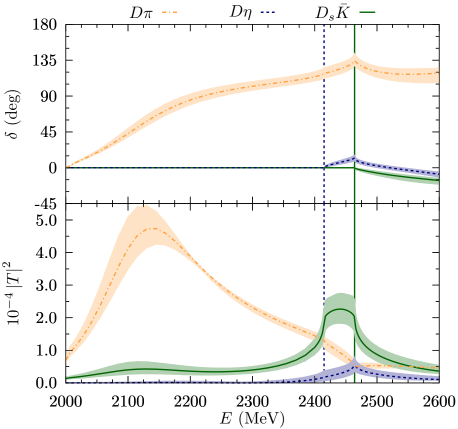

The two pole $SU(3)$ origin

- We take the $SU(3)$ limit

$$m_i \to m$$
$$M_i \to M$$

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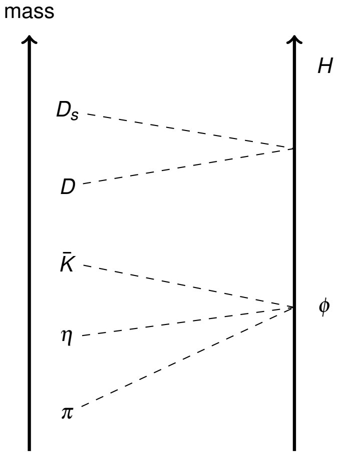

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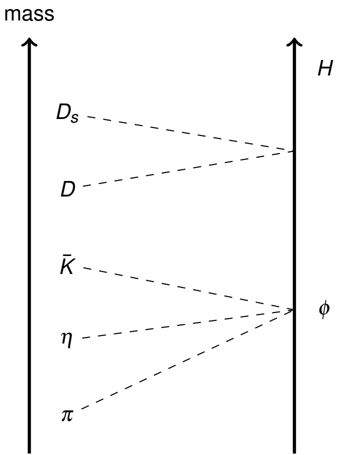

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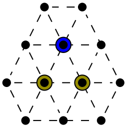
(S, I)
$(2, 1/2)$
$(1, \{1, 0\})$
$(0, \{3/2, 1/2\})$
$(-1, 1)$

$\bar{\mathbf{15}}$



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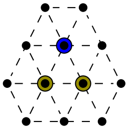

$\mathbf{6}$

$(1, 1)$

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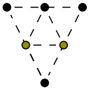

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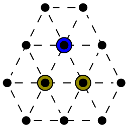

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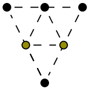

$\bar{\mathbf{3}}$

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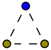

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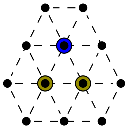

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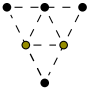

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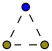

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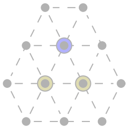

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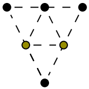

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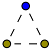

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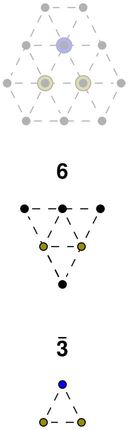
$(1, 0)$
$(0, 1/2)$



III. Results (3)

$SU(3)$ limit

The two pole $SU(3)$ origin

- We take the $SU(3)$ limit

$$m_i \to m$$
$$M_i \to M$$

- $\bar{\mathbf{3}} \otimes \mathbf{8} = \bar{\mathbf{15}} \oplus \mathbf{6} \oplus \bar{\mathbf{3}}$

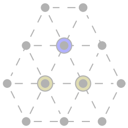
- $\mathscr{M}_{i,j} \to \mathrm{diag}(\mathscr{M}_{\bar{\mathbf{15}}}, \mathscr{M}_{\mathbf{6}}, \mathscr{M}_{\bar{\mathbf{3}}}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -3 \end{pmatrix} (\mathbb{I} + \hat{F}_{\mathrm{NLO}}(s))$

- $\mathscr{T}_{i,j} \to \mathrm{diag}(\mathscr{T}_{\bar{\mathbf{15}}}, \mathscr{T}_{\mathbf{6}}, \mathscr{T}_{\bar{\mathbf{3}}})$ 3 one-channel interactions!

- How do we relate the poles?

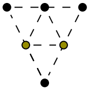
(S, I) — $\bar{\mathbf{15}}$

$(2, 1/2)$
$(1, \{1, 0\})$
$(0, \{3/2, 1/2\})$
$(-1, 1)$



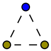
$\mathbf{6}$

$(1, 1)$
$(0, 1/2)$
$(-1, 0)$



$\bar{\mathbf{3}}$

$(1, 0)$
$(0, 1/2)$



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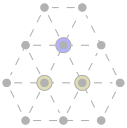
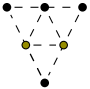
- How do we relate the poles?
- $\boxed{\tilde{m}(\mathbf{x}) = m_i + \mathbf{x}(m - m_i)}$

(S, I)	$\bar{\mathbf{15}}$
$(2, 1/2)$	
$(1, \{1, 0\})$	
$(0, \{3/2, 1/2\})$	
$(-1, 1)$	



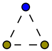
$\mathbf{6}$

$(1, 1)$
$(0, 1/2)$
$(-1, 0)$



$\bar{\mathbf{3}}$

$(1, 0)$
$(0, 1/2)$



The two pole $SU(3)$ origin

- We take the $SU(3)$ limit

$$m_i \to m$$
$$M_i \to M$$

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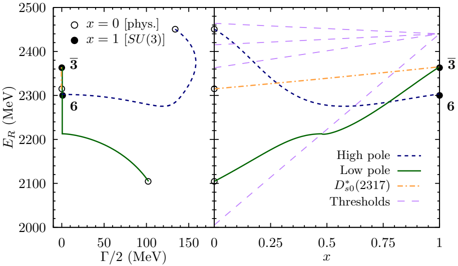
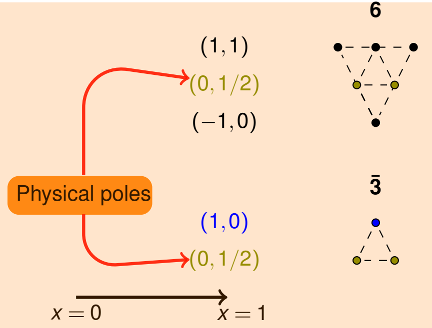
- How do we relate the poles?

- $\boxed{\tilde{m}(\mathbf{x}) = m_i + \mathbf{x}(m - m_i)}$





Summary

- We have used unitarized HM chiral amplitudes previously constrained in different channels and sectors (S, I) to compute the scattering in $(0, 1/2)$ $J^P = 0^+$
- The predictions in finite volume are in agreement with the results of a recent lattice simulation
- Our scattering amplitudes show a two-pole structure in the range of energies of the $D_0^*(2400)$ $(2.1 \sim 2.4)$ GeV
- We have studied the $SU(3)$ origin of the two-poles, finding that the lighter (2.1 GeV) and the $D_{s0}^*(2317)$ build the $\bar{3}$ triplet (mass puzzle)
- This two-pole structure also predicted in $J^P = 1^+$ and in the bottom 0^+ and 1^+ sectorss
- Thank you for your attention!!