Interactions between heavy and light mesons from chiral dynamics

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earlier papers since 2006: FKG, Shen, Chiang, Ping, Zou (2006); FKG, Hanhart, Krewald, Meißner (2008); FKG, Hanhart, Meißner (2009); Cleven et al. (2011); Liu et al. (2012); Yao, Du, FKG, Meißner (2015,2016); Du, FKG, Meißner (2016); . . .

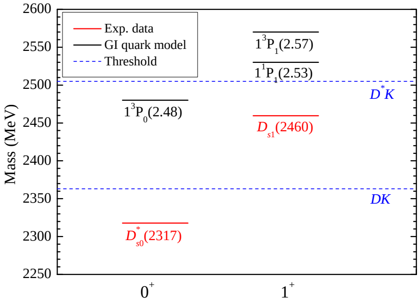
M. Albaladejo, P. Fernandez-Soler, FKG, C. Hidalgo-Duque, J. Nieves, arXiv:1610.06727 [hep-ph]

Charmed scalar and axial-vector mesons

- Most discussed: charm-strange $D_{s0}^*(2317)$ and $D_{s1}(2460)$

☞ $D_{s0}^*(2317)$: 0^+ BaBar (2003)
$M = (2317.7 \pm 0.6)$ MeV,
$\Gamma < 3.8$ MeV

☞ $D_{s1}(2460)$: 1^+ CLEO (2003)
$M = (2459.5 \pm 0.6)$ MeV,
$\Gamma < 3.5$ MeV



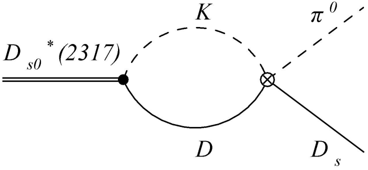
☞ Notable feature: $M_{D_{s1}(2460)} - M_{D_{s0}^*(2317)} = M_{D^*} + M_D$

$D_{s0}^*(2317)$

- One of the key hadron resonances since 2003, lots of models:
  $c\bar{s}$, tetraquark, or their mixture, ... recent review: H.-X. Chen et al., arXiv:1609.08928 [hep-ph]
- dominantly DK molecule Barnes, Close, Lipkin (2003); van Beveren, Rupp (2003); Kolomeitsev, Lutz (2004); FKG, Shen, Chiang, Ping, Zou (2006); Gamermann et al. (2007); ...
  - ☞ Heavy quark spin symmetry ⇒ spin partner: a D^*K molecule
    natural consequence: $M_{D_{s1}(2460)} - M_{D_{s0}^*(2317)} = M_{D^*} + M_D$
    FKG, Hanhart, Meißner, PRL102(2009)242004
  - ☞ large coupling to DK ⇒ large isospin breaking decay width:

$$\Gamma(D_{s0}^*(2317) \to D_s\pi) = \mathcal{O}\,(100\ \text{keV})$$

Faessler et al., PRD76(2007)014005; Lutz,Soyeur, NPA813(2008)14; FKG, Hanhart, Krewald, Meißner, PLB666(2008)251; Liu, Orginos, FKG et al., PRD87(2013)014508



$D_0^*(2400)$

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

PDG2016:

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

- New measurements by LHCb lie between: (2360 ± 15) MeV

LHCb, PRD92(2015)012012

- In all experiments, one Breit–Wigner resonance was assumed
- Question: why $M_{D_0^*(2400)} \gtrsim M_{D_{s0}^*(2317)}$?

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Lattice studies of the charmed scalar mesons

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

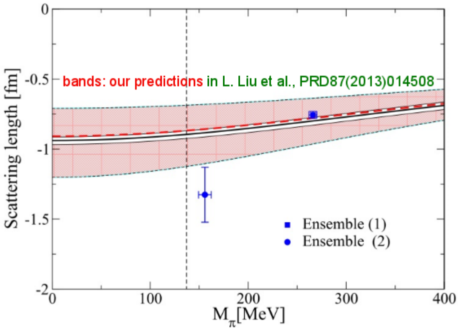
  Bali (2003); UKQCD (2003); . . .

- $c\bar{s} + DK$ interpolators:

  Mohler et al., PRL111(2013)222001

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

  Mohler et al., PRD87(2013)034501



  Lüscher's formula ⇒ $D\pi$ phase shifts ($M_\pi \approx 266$ MeV)
  ⇒ BW parameters of $D^*_0(2400)$ consistent with PDG values

- $(S, I) = (0, \frac{1}{2})$: 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
  found a bound state pole at (2275.9 ± 0.9) MeV
  slightly below $D\pi$ threshold (2276.4 ± 0.9) MeV (at $M_\pi \approx 391$ MeV)

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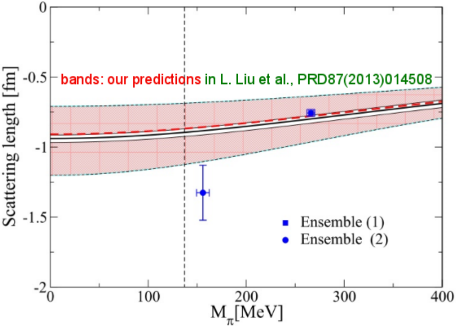

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Setup of the lattice calculation by Moir et al. JHEP1610(2016)011

- Meson masses: $M_\pi = 391$ MeV, $M_D = 1885$ MeV, ...
- three volumes: $16^3 \times 128$, $20^3 \times 128$, $24^3 \times 128$
- for coupled channels: they parametrize the T-matrix with the K-matrix formalism

$$T^{-1}_{ij}(s) = K^{-1}_{ij}(s) + I_{ij}(s)$$

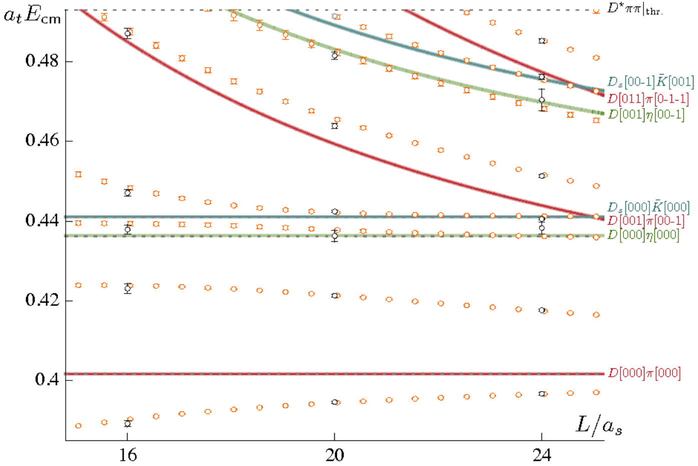
$I_{ij}(s)$: in fact loop function evaluated with a subtracted dispersion integral

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

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

- fit to computed energy levels with the parametrized T-matrix, then extract its poles: model dependence enters

- Meson masses: $M_\pi = 391$ MeV, $M_D = 1885$ MeV, ...
- three volumes: $16^3 \times 128$, $20^3 \times 128$, $24^3 \times 128$
- For the $I = 1/2$, $J^P = 0^+$ sector: one pole at (2275.9 ± 0.9) MeV



Necessity to study interactions between charm and light mesons

- These positive-parity charmed mesons couple to the ground state charm and light pseudoscalar mesons (ϕ) in S-wave
- scattering phase shifts $\Rightarrow$ Omnès representation of heavy-light form factors $\Rightarrow$ accurate determination of CKM matrix elements from $D(\bar{B}) \to \pi\ell\nu$

Flynn, Nieves (2001,2007)

- 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: unitarized ChPT

Oller, Oset (1997); Oller Meißner (2001); ...

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

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

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

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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, PLB666(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 D.-L. Yao, M.-L. Du, FKG, U.-G. Meißner, JHEP1511(2015)058

  renormalization: M.-L. Du, FKG, U.-G. Meißner, arXiv:1607.00822 [hep-ph], J.Phys.G., in print

  PCB-term subtraction in EOMS scheme using path integral:

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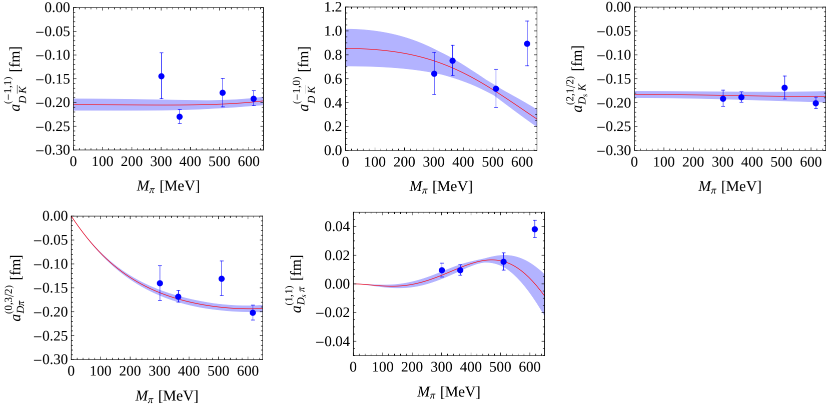
Fit to lattice data

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
  parameters: h_2, h_3, h_4, h_5 and $a(\mu)$



- Prediction: pole in the $(S, I) = (1, 0)$ channel: 2315^{+18}_{-28} MeV. DK dominant
  Exp.: $M_{D^*_{s0}(2317)} = (2317.7 \pm 0.6)$ MeV PDG2016

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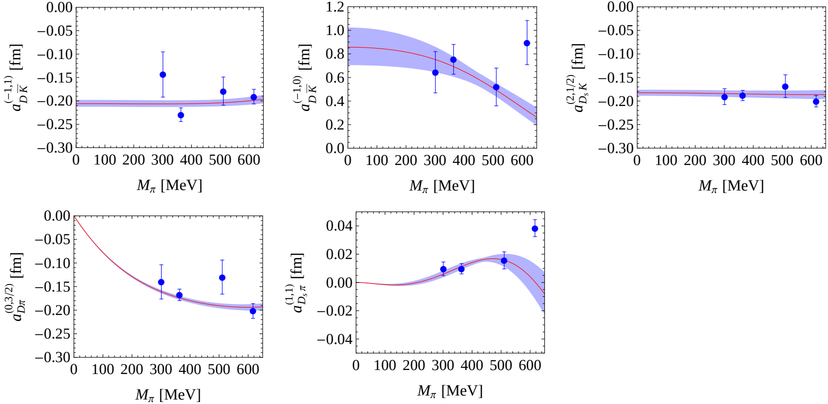


- Pole in the $(S, I) = (1, 0)$ channel fixed to $M_{D_{s0}^*(2317)} = 2317.8$ MeV by adjusting $a(\mu)$

Energy levels in a finite volume

- Goal: predict finite volume energy levels for $I = 1/2$, and compare with recent lattice data by the Hadron Spectrum Collaboration JHEP1610(2016)011
  $\Rightarrow$ insights into $D_0^*(2400)$
- In a finite volume, 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 et al., EPJA47(2011)139

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

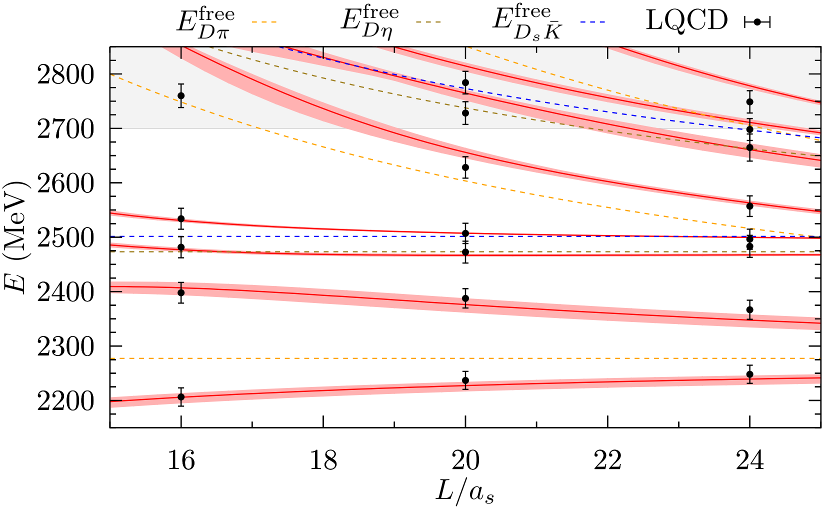
$I(\vec{q})$: loop integrand

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

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

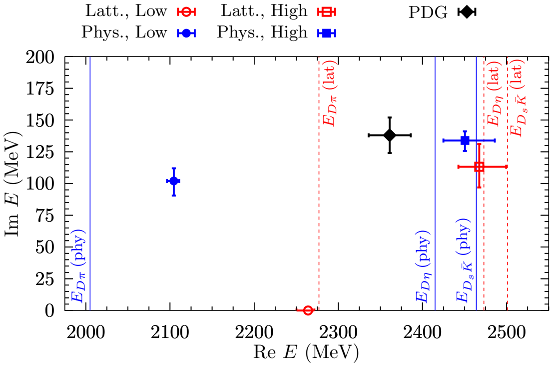
Predictions versus recent lattice results

- Postdicted finite volume energy levels for $I = /2$ agree very well with lattice results: (not a fit !)



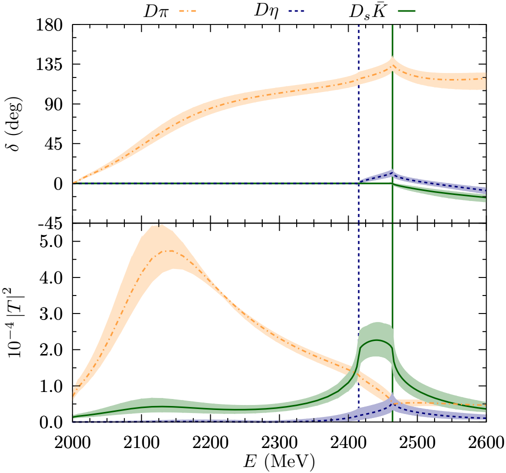
There are two poles!

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



Two poles in $I = 1/2$ sector

- Phase shifts and $|T_{ii}|^2$



- Two poles/states in $I = 1/2$ sector were found in Kolomeitsev, Lutz (2004); FKG, Shen, Chiang, Ping, Zou (2006); FKG, Hanhart, Meißner (2009); Z.-H. Guo, Meißner, D.-L. Yao (2015)
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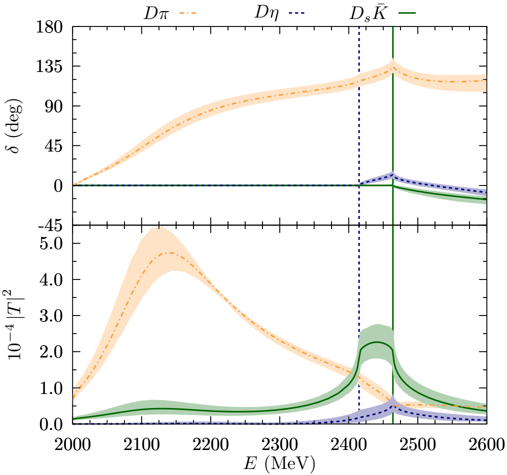

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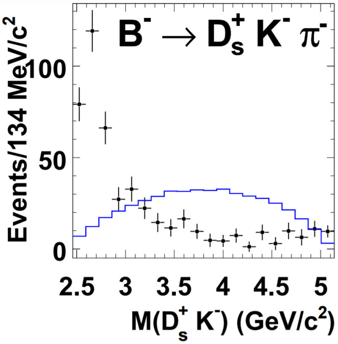
Experimental signal?

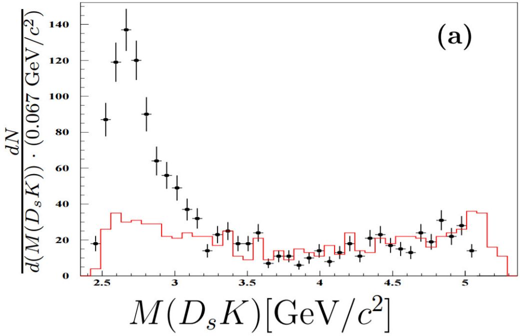
- The higher pole couples most strongly to the $D_s\bar{K}$

  & is close to the $D_s\bar{K}$ threshold

  $\Rightarrow$ near-threshold enhancement in $D_s\bar{K}$ invariant mass distribution

- Experimental signal? BaBar, PRL100(2008)171803; Belle, PRD80(2009)052005





Summary

- constructed unitarized chiral amplitudes for S-wave scattering between heavy and light pseudoscalar mesons
- with parameters (4 LECs and one subtraction constant) fixed from lattice data for scattering lengths in a few channels, other channels can be predicted
- predicted $D_{s0}^*(2317)$ mass correctly: dominantly DK
- predicted FV energy levels agree very well with lattice:
  strong evidence for two poles in the $(S,I)=(0,1/2)$ sector
  $\Rightarrow$ two states in the $D_0^*(2400)$ mass region
- Chiral dynamics + coupled channels $\Rightarrow$ two-pole structures:
  ☞ $\Lambda(1405)$: very well-known, couple dominantly to $\Sigma\pi$ and $N\bar{K}$, respectively
  Hyodo, Meißner, review in PDG2016; Oller, Meißner (2001); Jido et al. (2003); ...
  ☞ $K_1(1270)$: 2 poles couple most strongly to $K^*\pi$ and ρK L.-S. Geng et al (2007)

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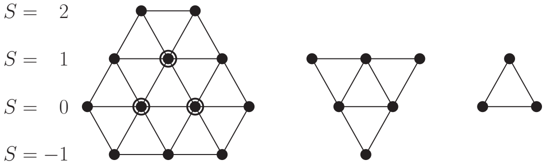
  ☞ $K_1(1270)$: 2 poles couple most strongly to $K^*\pi$ and ρK L.-S. Geng et al (2007)
  ☞ most famous: $f_0(500)$ and $f_0(980)$ in the $\pi\pi$–$K\bar{K}$ system

Thank you !

Backup slides

SU(3) analysis

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



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