Chiral dynamics for exotic resonances

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- ✔ Introduction and motivation
- ✔ Resonances and coupled-channel dynamics
- ✔ Predictions of chiral SU(3) symmetry
- ✔ Summary

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based on work with E.E. Kolomeitsev

Resonances and coupled-channel dynamics

✔ **Dynamic generation of resonances:** some good candidates

- $\Lambda(1405)$ resonance as $\bar{K}N$ quasi-bound state
  - Dalitz, Wyld, Rajasekaran, Weise, Siegel, ...
- $N(1535)$ resonance as $K\,\Sigma$ quasi-bound state
  - Dalitz, Wyld, Weise, Kaiser, Oset, ...
- $\Lambda(1520)$ resonance as $\bar{K}_\mu\,N$ quasi-bound state
  - Ball, Frazer, Aaron, Amado, ...
- $f_0(980)$ resonance as $K\,\bar{K}$ quasi-bound state
  - Van Beveren, Weinstein, Isgur, Janssen, Oller, Oset, Pelaez, ...

✔ **To be or not to be:** which resonances are generated by coupled channels ?

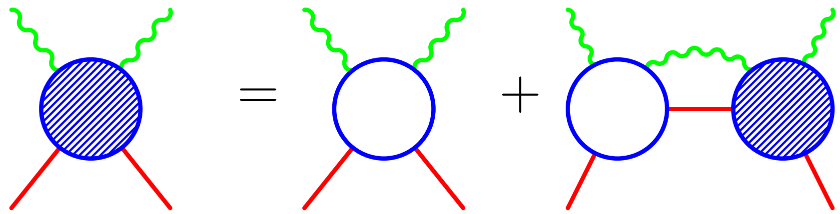
- if one member of a large-N_c multiplet is generated, so should be the full multiplet

✔ **Conjecture:**

excited baryon and meson resonances generated by coupled-channel dynamics

Coupled-channel Bethe-Salpeter equation

- **Scattering amplitude:**



- **Effective interaction kernel V:**

$$[1 - K \cdot G]^{-1} \cdot K \quad \longleftarrow \text{on-shell} \longrightarrow \quad [1 - V \cdot G]^{-1} \cdot V$$

defined by:

$$K = V + (1 - V \cdot G) \cdot V_L + V_R \cdot (1 - G \cdot V) + (1 - V \cdot G) \cdot V_{LR} \cdot (1 - G \cdot V) - V_R \cdot \frac{1}{1 - G \cdot V_{LR}} \cdot G \cdot V_L \,.$$

note: V_L and V_R vanish for on-shell kinematics

- **Strategy:** chiral and large-N_c expansion of effective interaction V

- **No dependence on choice of fields**

Solution of Bethe-Salpeter scattering equation

- **Decompose effective interaction V:**

$$V = \sum_{J,P} V^{(J,P)}(\sqrt{s}\,)\,\mathcal{Y}^{(J,P)}(\bar{q},q;w)$$

- **Unique covariant projection operators:**

$$\mathcal{Y}^{(J,P)}(\bar{q},q;w) \qquad \text{with} \quad \mathrm{w}^2 = \mathrm{s}$$

  - preserve total angular momentum J and parity P
  - regularity in q (initial meson) and $\bar{q}$ (final meson)
  - defined for any off-shell kinematics

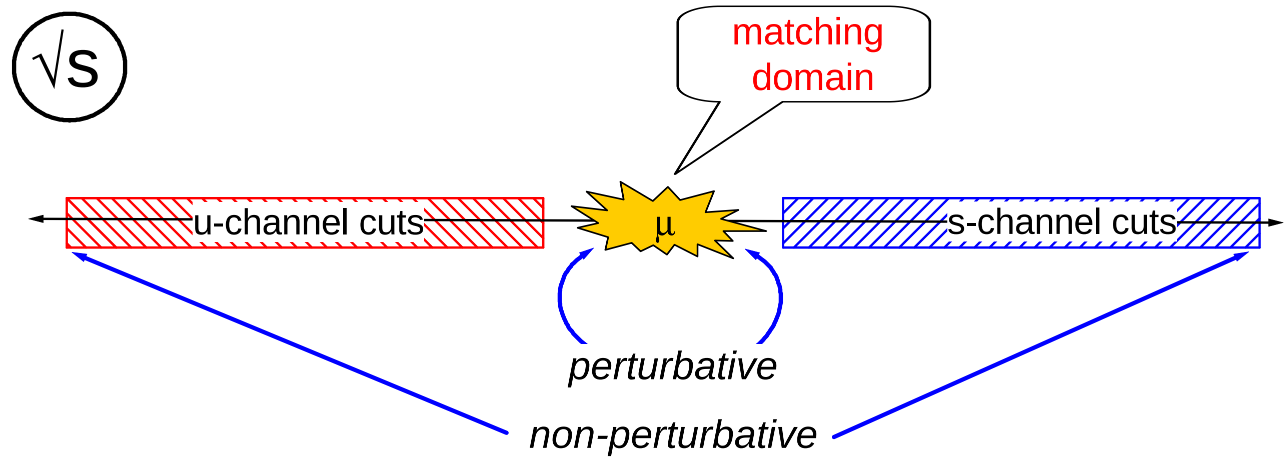
$$\Big(\mathcal{Y}^{(J,P)}\cdot G\cdot \mathcal{Y}^{(J',P')}\Big)(\bar{q},q;w) \overset{!}{=} \delta_{J,J'}\,\delta_{P,P'}\,J^{(J,P)}(\sqrt{s}\,)\,\mathcal{Y}^{(J,P)}(\bar{q},q;w)$$

$$\longrightarrow \text{divergent loop-functions } J^{(J,P)}(\sqrt{s}\,)$$

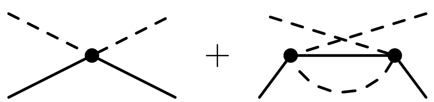
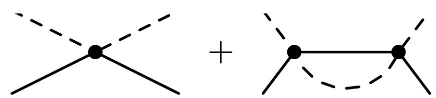
- **Scattering amplitude T:** algebraic matrix equation

$$T = \sum_{J,P}\Big(1 - V^{(J,P)}\,J^{(J,P)}\Big)^{-1} V^{(J,P)}\,\mathcal{Y}^{(J,P)} + \cdots$$

Gluing of s- and u-channel unitarized amplitudes



- **Approximated crossing symmetry:**

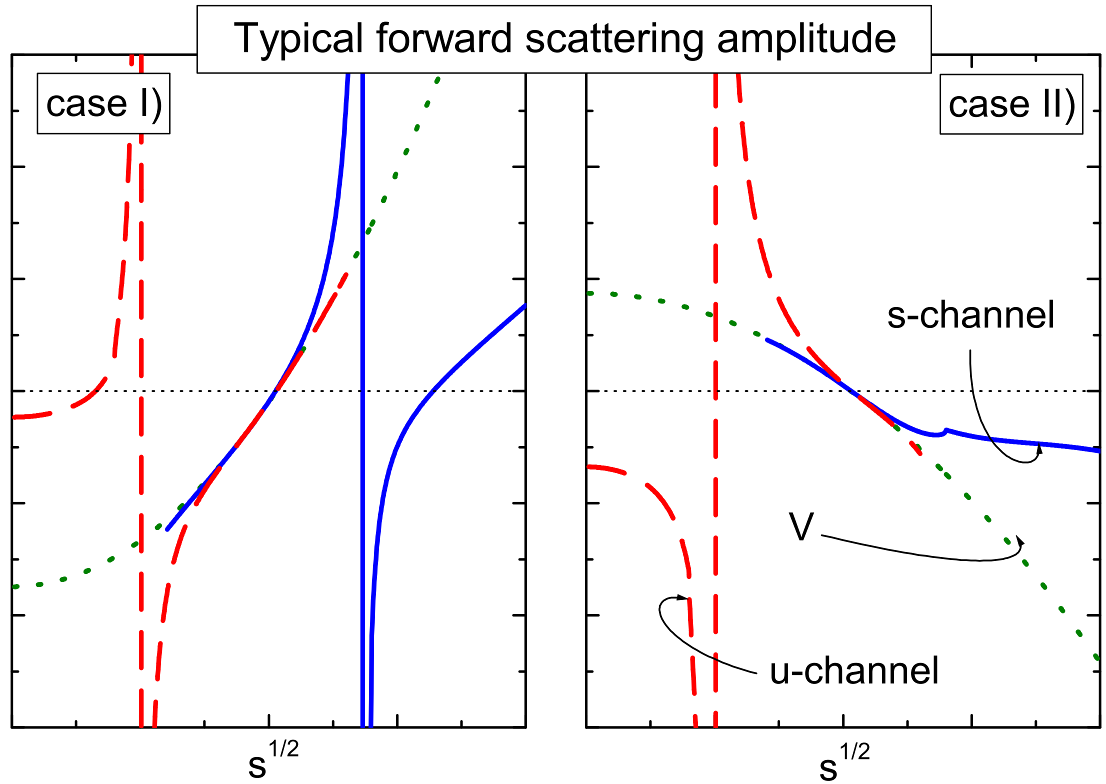
 $+ \cdots \Longrightarrow T_{\mathrm{u-chan.}}(\mu) \sim T_{\mathrm{s-chan.}}(\mu) \Longleftarrow$  $+ \cdots$

$$T = \begin{cases} T_{\mathrm{s-chan.}} & \text{if} \quad \sqrt{s} > \mu \\ T_{\mathrm{u-chan.}} & \text{if} \quad \sqrt{s} < \mu \end{cases}$$

- **Renormalization condition:** $T^{(J,P)}(\sqrt{s} = \mu) = V^{(J,P)}(\sqrt{s} = \mu)$

- **Optimal matching point:** e.g., for πH-scattering $\rightarrow \mu = m_H$

Crossing-symmetric scattering amplitudes



✔ **Gluing of s- and u-channel unitarized amplitudes:**

- requires good matching properties
- by construction: exact crossing symmetry in physical region
- approximate crossing symmetry at subthreshold energies

Chiral SU(3) interaction terms and large-N_c QCD

- **Large-N_c ground states:**
  - Goldstone boson octet $\Phi_{[8]} = \Big(\pi\,,K\,,\overline{K}\,,\eta\Big)$
  - Vector meson nonet $\Phi^{\mu}_{[9]} = \Big(\rho^{\mu}\,,K^{\mu}\,,\overline{K}^{\mu}\,,\omega^{\mu}\,,\phi^{\mu}\Big)$
  - Baryon octet $B_{[8]} = \Big(N\,,\Sigma\,,\Lambda\,,\Xi\Big)$
  - Baryon decuplet $B_{[10]} = \Big(\Delta\,,\Sigma^{*}\,,\Xi^{*}\,,\Omega\Big)$
- **Systematic approximation strategy:**

expand in *powers* of the small current quark masses, momenta and $1/N_c$

$$\frac{m_{\rm quark}}{\Lambda_{\chi SB}} \ll 1\,, \qquad \frac{1}{N_c} \ll 1$$

- heavy fields: $M_{[8,9,10]} \sim \Lambda_{\chi SB}$ but $M_{[10]} - M_{[8]} \sim \frac{1}{N_c}$
- light Goldstone bosons: $m_{[8]} \sim m^{1/2}_{\rm quark}$

Leading-order chiral interaction

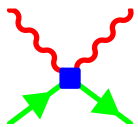
- **Leading-order interaction**

  use covariant derivative D_μ (local chiral SU(3) rotations) in kinetic term:

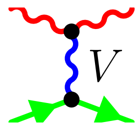
  e.g. $\mathrm{Tr}(\bar{B}_{[8]}\, i\, \gamma_\mu\, D^\mu B_{[8]})$ for baryon octet

- **Weinberg–Tomazawa term for meson-baryon interaction**

$$\mathcal{L}_{\mathrm{WT}} = \frac{i}{8\, f^2}\,\mathrm{tr}\;\bar{B}_{[8]}\,\gamma_\mu \left[\left[\Phi_{[8]}, (\partial^\mu \Phi_{[8]})\right]_-, B_{[8]}\right]_- + \frac{3\, i}{8\, f^2}\,\mathrm{tr}\; g_{\alpha\beta}\left(\bar{B}^\alpha_{[10]}\,\gamma^\mu\; B^\beta_{[10]}\right)\cdot\left[\Phi_{[8]}\,, (\partial_\mu \Phi_{[8]})\right]_-$$



$$= \frac{C_{\alpha,\beta}}{4\, f^2}\left(\not{k}_\alpha + \not{k}_\beta\right) \qquad \longleftarrow \text{ linear in meson 4-momentum}$$

- vector meson t-channel exchange $\qquad \sum_{\text{vector mesons}}$  $\Longrightarrow \quad \mathcal{K}\, C_{\alpha,\beta}\left(\not{k}_\alpha + \not{k}_\beta\right)$

- **Pion-decay constant** $\quad f \Longleftrightarrow f_\pi / f \simeq 1.07 \pm 0.12 \qquad f_\pi \simeq 92.42 \pm 0.33$ MeV

Parity-flip reactions in s-wave

- meson-baryon

$$\mathbf{0}^- + \frac{\mathbf{1}}{\mathbf{2}}^+ \longrightarrow \frac{\mathbf{1}}{\mathbf{2}}^- \longrightarrow \mathbf{0}^- + \frac{\mathbf{1}}{\mathbf{2}}^+$$

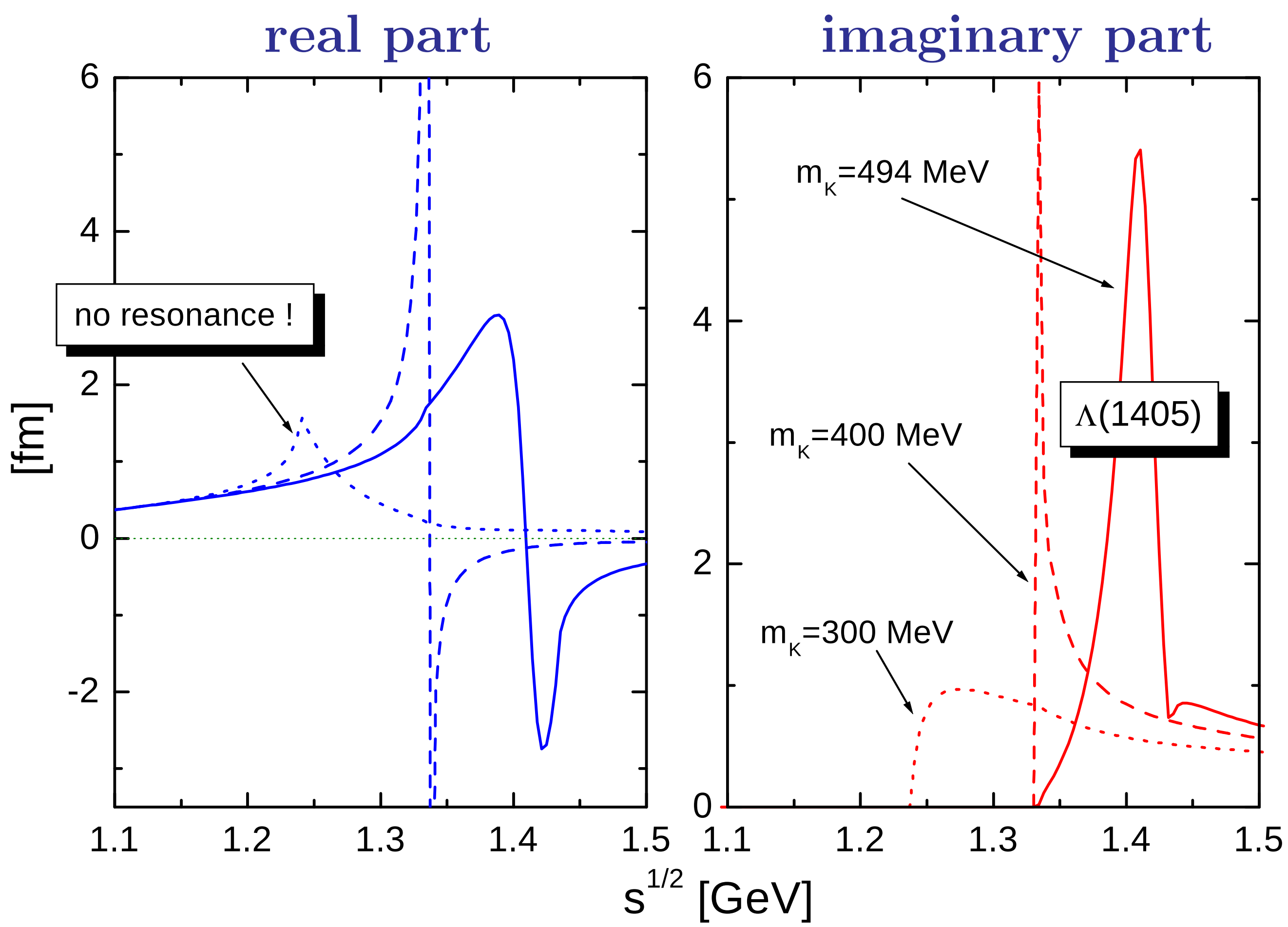
$$\mathbf{0}^- + \frac{\mathbf{3}}{\mathbf{2}}^+ \longrightarrow \frac{\mathbf{3}}{\mathbf{2}}^- \longrightarrow \mathbf{0}^- + \frac{\mathbf{3}}{\mathbf{2}}^+$$

- meson-meson

$$\mathbf{0}^- + \mathbf{0}^- \longrightarrow \mathbf{0}^+ \longrightarrow \mathbf{0}^- + \mathbf{0}^-$$

$$\mathbf{0}^- + \mathbf{1}^- \longrightarrow \mathbf{1}^+ \longrightarrow \mathbf{0}^- + \mathbf{1}^-$$

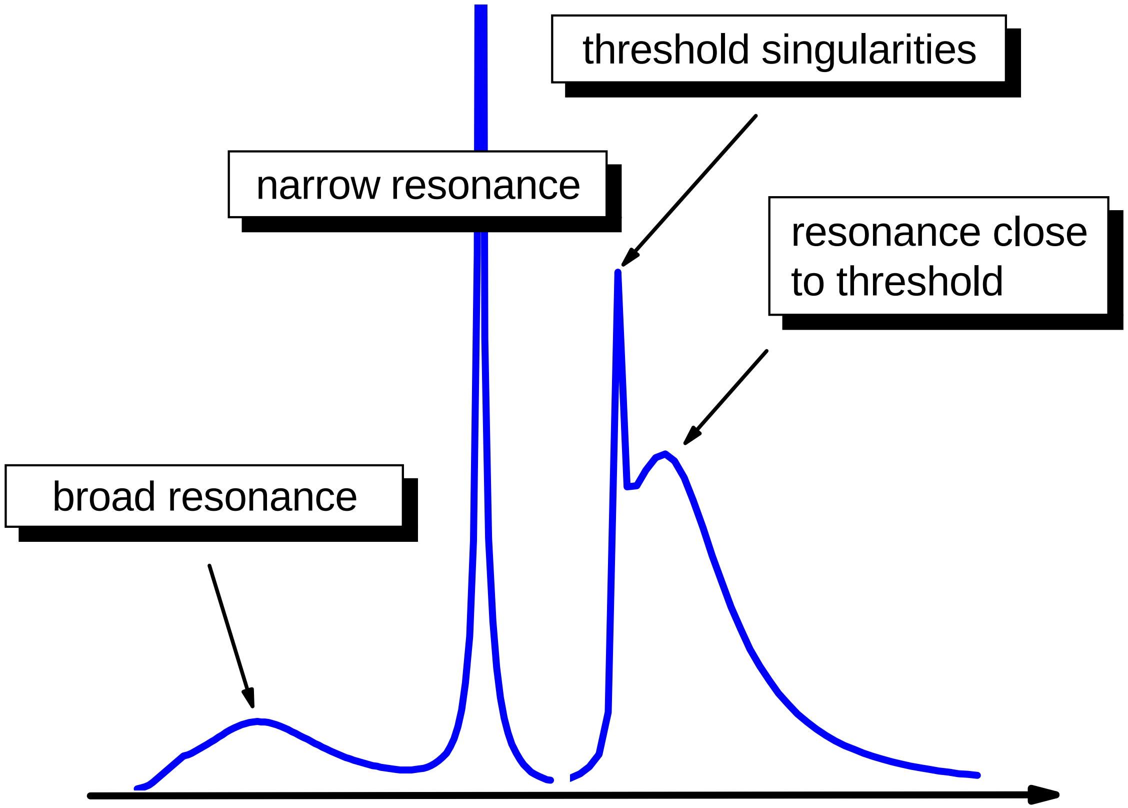
Antikaon-Nucleon S-wave amplitude (Q^1)



Found. Phys. **31** (2001)

- **Parameter free result** : use $f_\pi = 90$ MeV !
- $\Lambda(1405)$ **resonance dynamically generated** : disappears at $m_K = 300$ MeV !
- **Strong dependence on current quark masses:** see lattice QCD

Speed plots for multichannel scattering

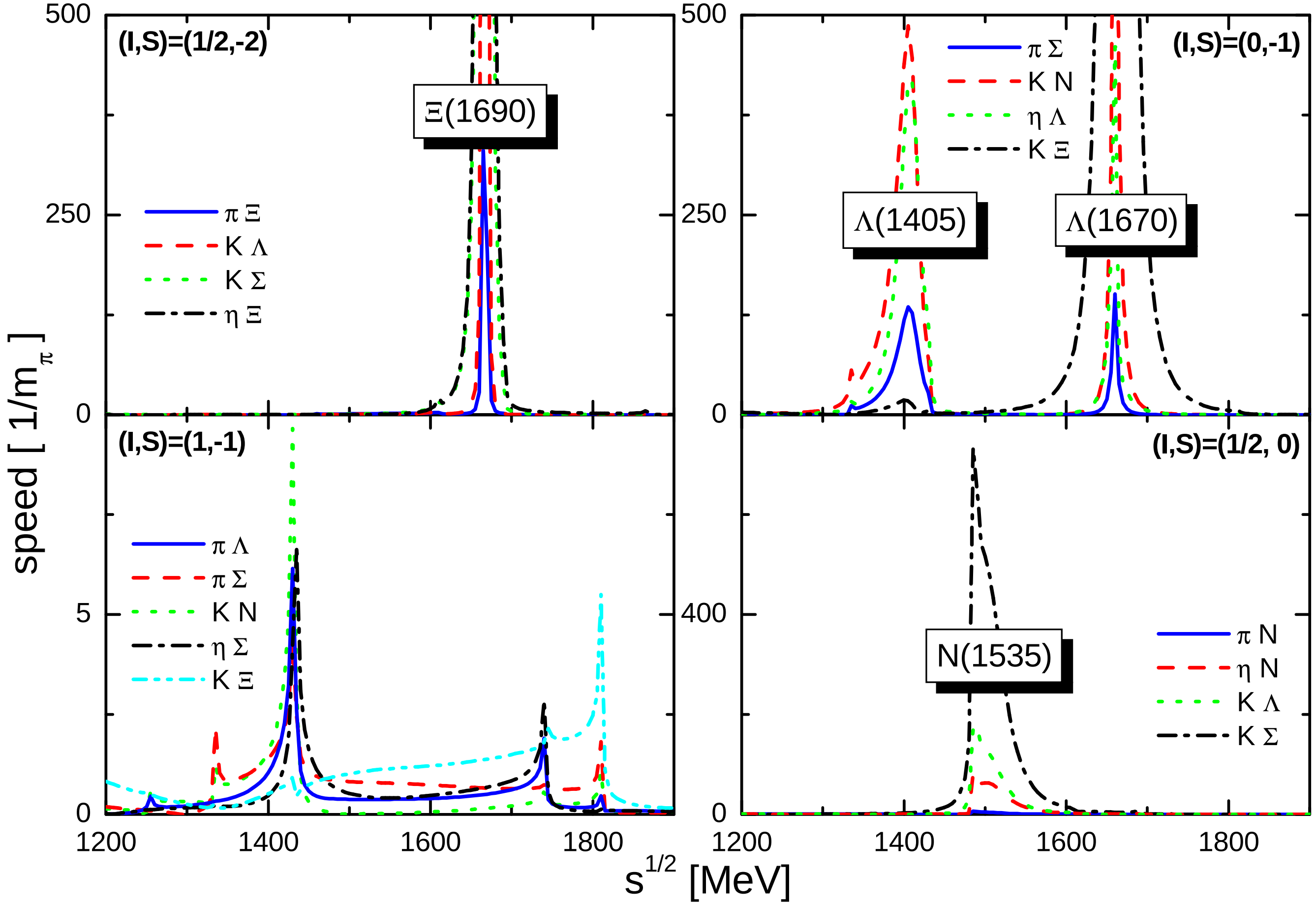


- generalization of time-delay for closed/open channels $\dfrac{\mathrm{d}\delta(E)}{\mathrm{d}E}$
- resonance position $\longleftarrow$ local maximum of the Speed
- for s-wave resonances - cusp effects at thresholds

- **analytic continuation of the S-matrix:** $\quad S_{ab} = \delta_{ab} + 2\,i\,T_{ab}$

$$\mathrm{Speed}_{ab}^{(I,S)}(\sqrt{s}) = \left| \sum_c \left[\frac{\mathrm{d}}{\mathrm{d}\sqrt{s}} S_{ac}^{(I,S)}(\sqrt{s}) \right] \left(S_{cb}^{(I,S)}(\sqrt{s}) \right)^* \right|$$

$J^P = \frac{1}{2}^-$ baryon resonances ($\mathbf{Q}^1$)



- no adjustable parameter:
  $f = 90$ MeV
- two octets and one singlet
- strong signals: $N(1535)$, $\Lambda(1405)$, $\Lambda(1670)$ and $\Xi(1690)$
- weak signals: $N(1650)$, $\Xi(1620)$ and $\Sigma(1620), \Sigma(1750)$

Chiral SU(3) symmetry predicts: $\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \overline{\mathbf{10}} \oplus \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}$

SU(3) limit

✔ **”heavy” SU(3) limit:** $m_\pi = m_\eta = m_K = 495$ MeV

- resonances turn into bound states

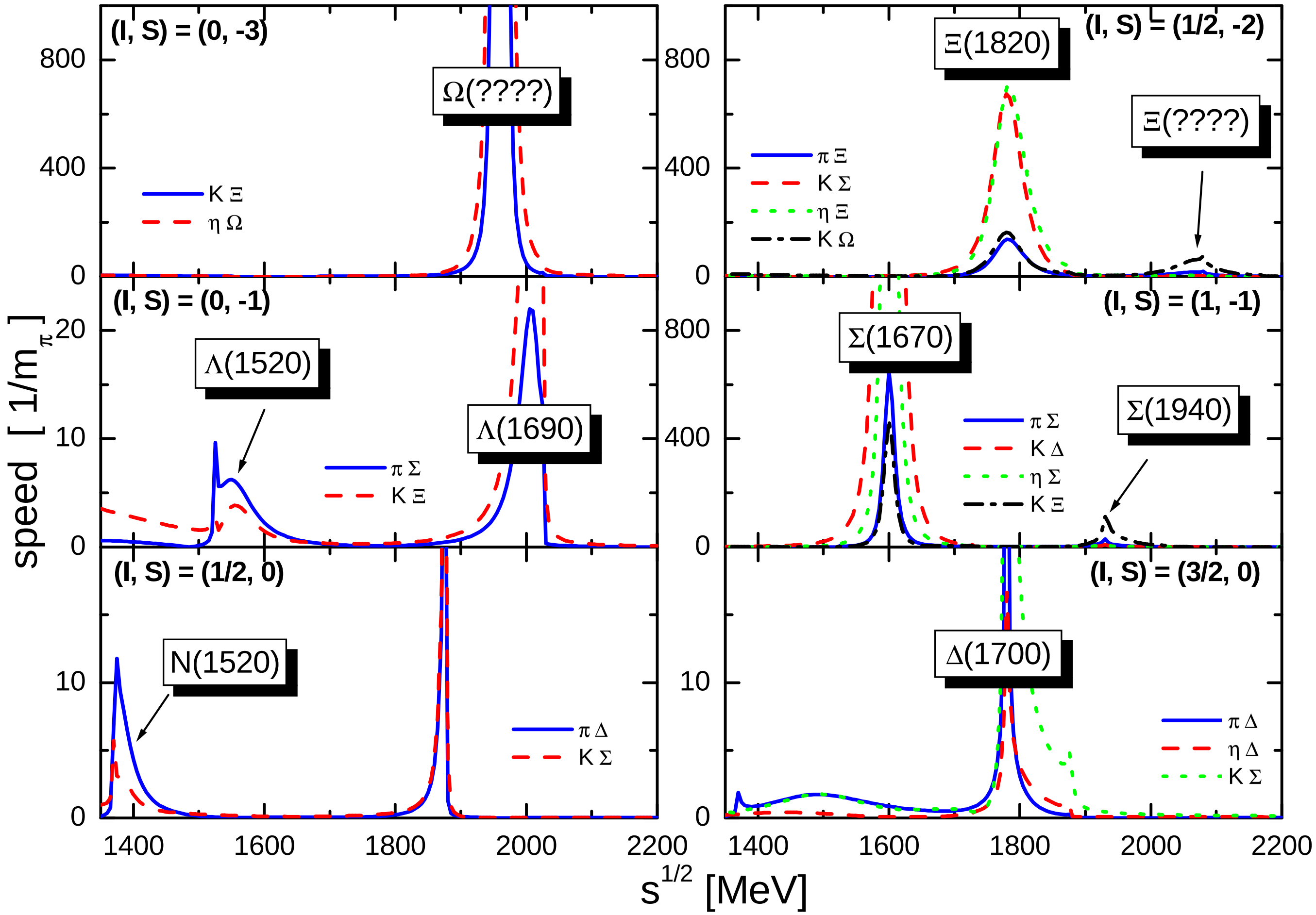
✔ **”light” SU(3) limit:** $m_\pi = m_\eta = m_K = 139$ MeV

- resonances are gone

✔ **Predictions that can be tested with lattice QCD:**

- requires unquenched QCD
- no quark-hadron duality here
- constituent-quark model does not predict such behavior

$J^P = \frac{3}{2}^-$ baryon resonances ($\mathbf{Q}^1$)

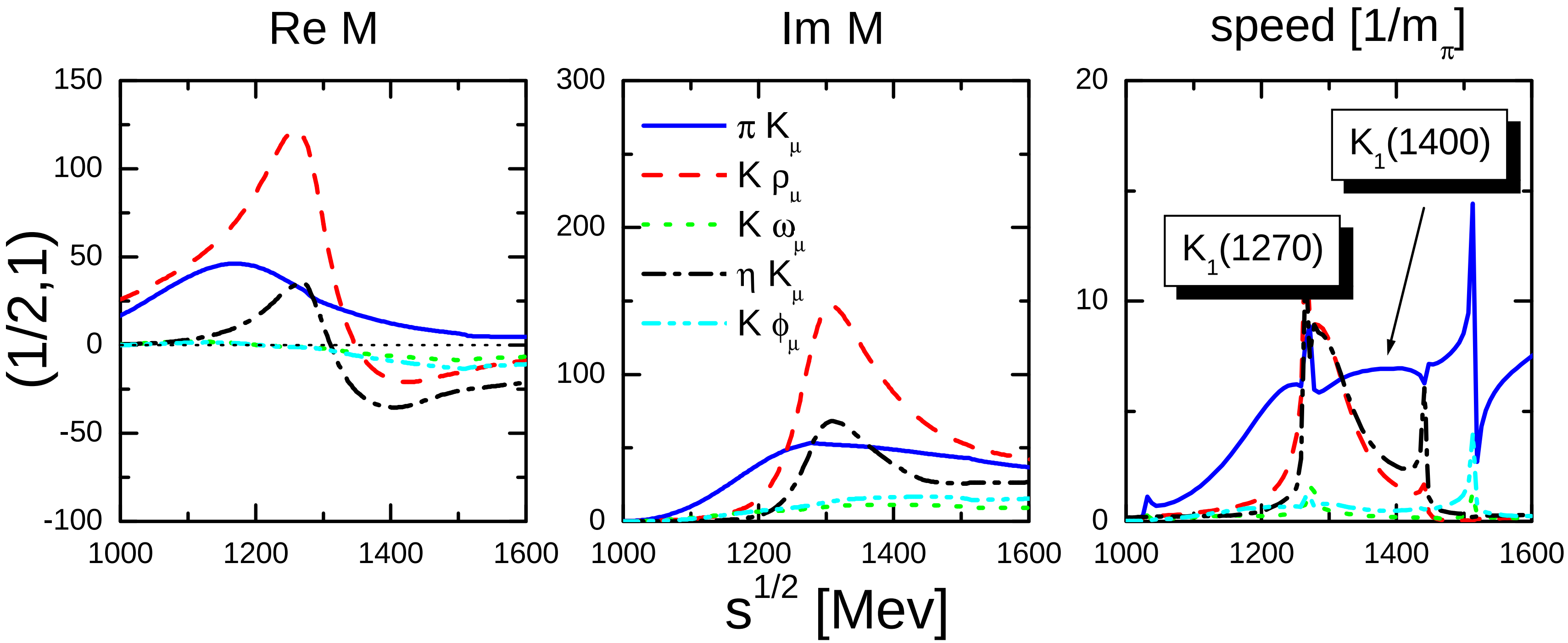


- no adjustable parameter:
  $f = 90$ MeV
- decuplet and octet
- bound state in $(0, -3)$-sector
- 27-plet state in $(0, -1)$-sector
- $\Lambda(1520)$–$\Lambda(1690)$ singlet-octet ??

Chiral SU(3) symmetry predicts: $8 \otimes 10 = 35 \oplus 27 \oplus 10 \oplus 8$

$J^P = 1^+$ meson resonances ($\mathbf{Q}^1$)

- **channel** $(I,S) = (1/2,1)$**:** two octet states



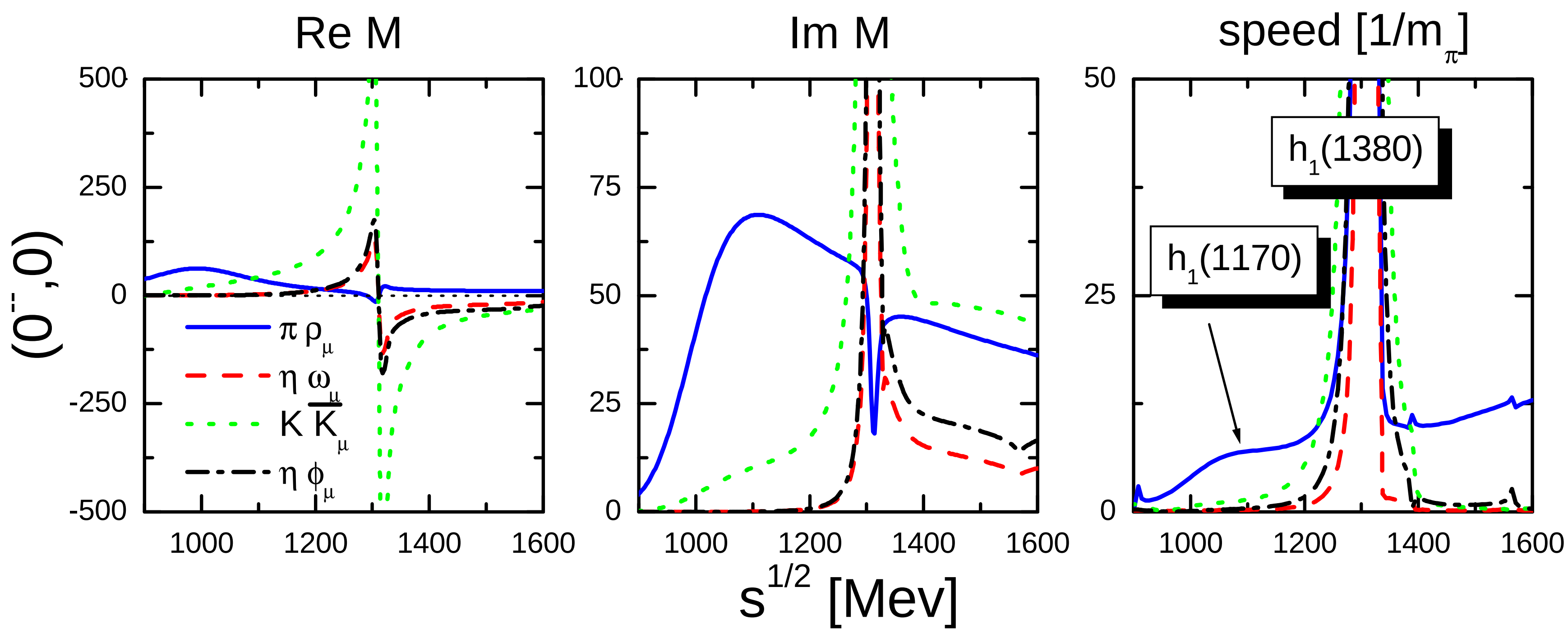
- **experimental pattern:**

$K_1(1270)$**:** dominant decay into $K\,\rho_\mu$ $\Gamma \simeq 90$ MeV

$K_1(1440)$**:** dominant decay into $K_\mu\,\pi$ $\Gamma \simeq 175$ MeV

$J^P = 1^+$ meson resonances ($\mathbf{Q}^1$)

- **channel** $(I^G, S) = (0^-, 0)$**:** octet and singlet states



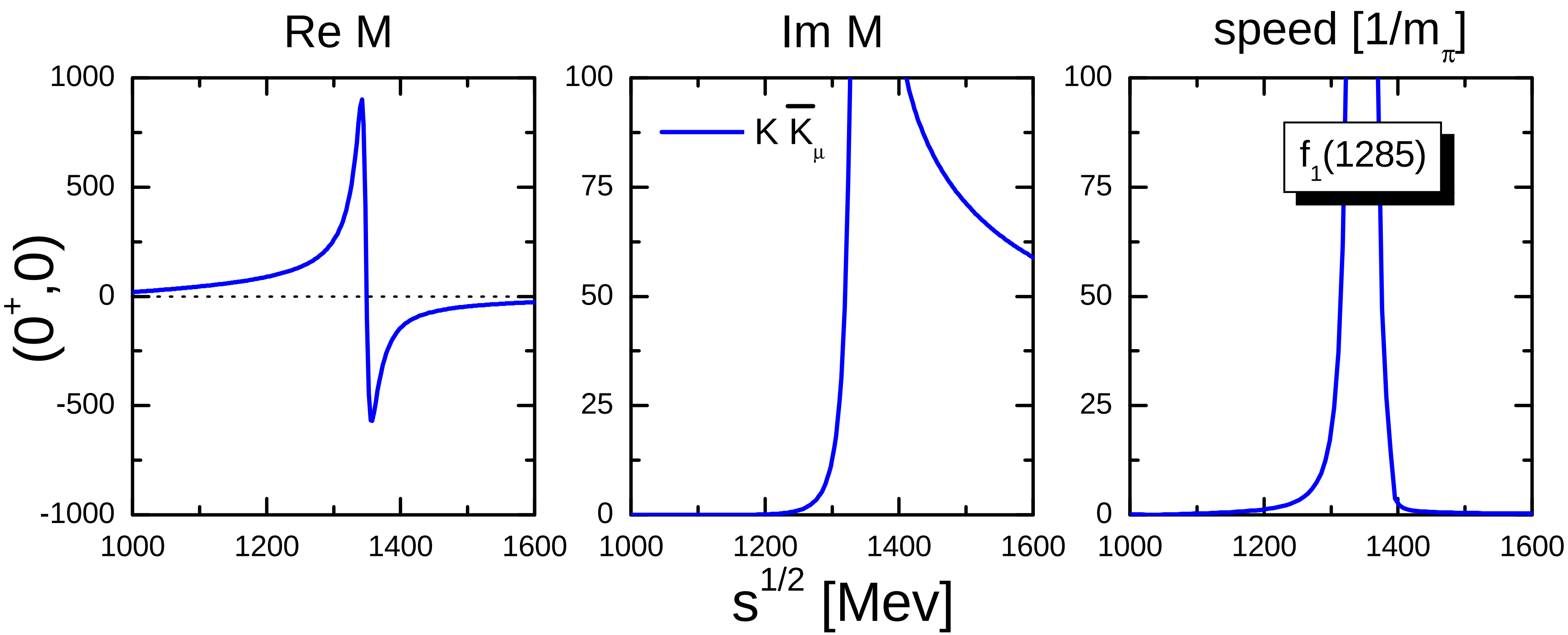
- **experimental pattern:**

$h_1(1170)$**:** seen only through $\pi\,\rho_\mu$ channel $\Gamma \simeq 360$ MeV

$h_1(1380)$**:** dominant decay into $K_\mu\,\bar{K}$ and $K\,\bar{K}_\mu$ $\Gamma \simeq 80$ MeV

$J^P = 1^+$ meson resonances ($\mathbf{Q}^1$)

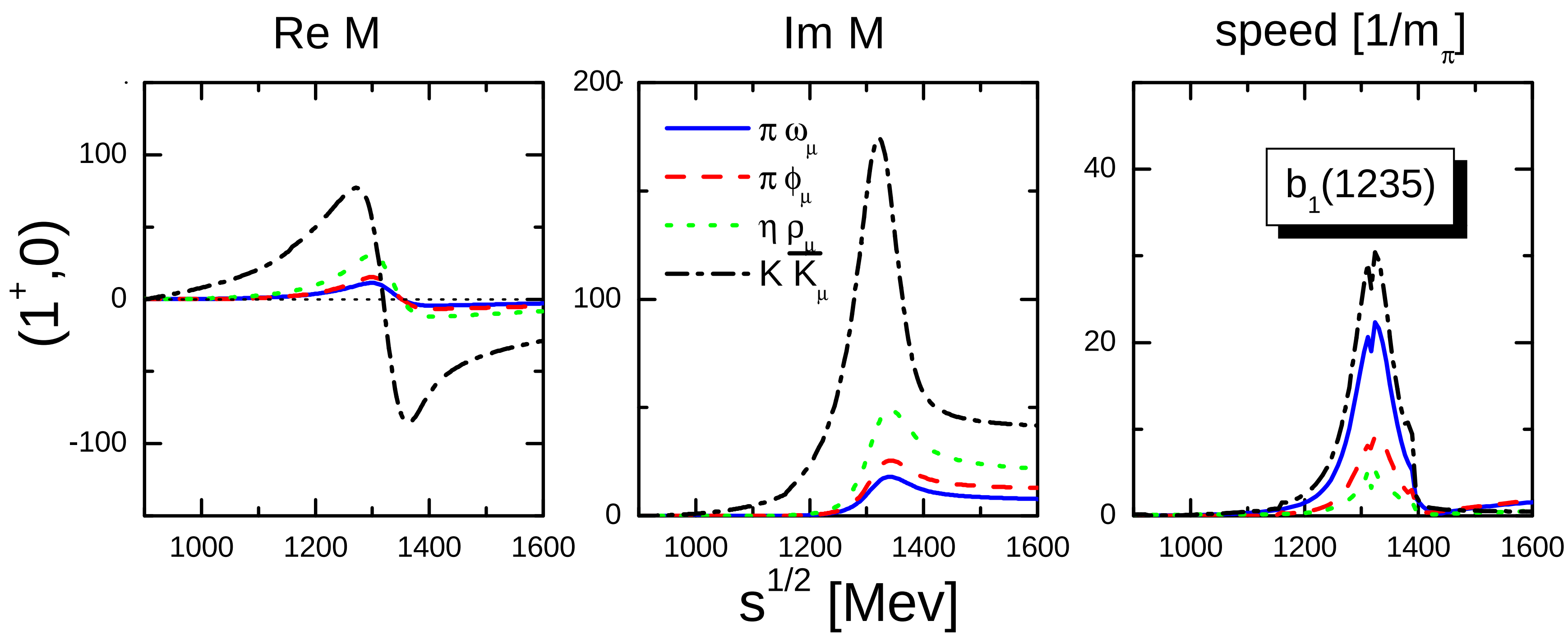
- **channel** $(0^+, 0)$**:** octet state



- **experimental widh:** $\Gamma \simeq 20$ MeV

$J^P = 1^+$ meson resonances ($\mathbf{Q}^1$)

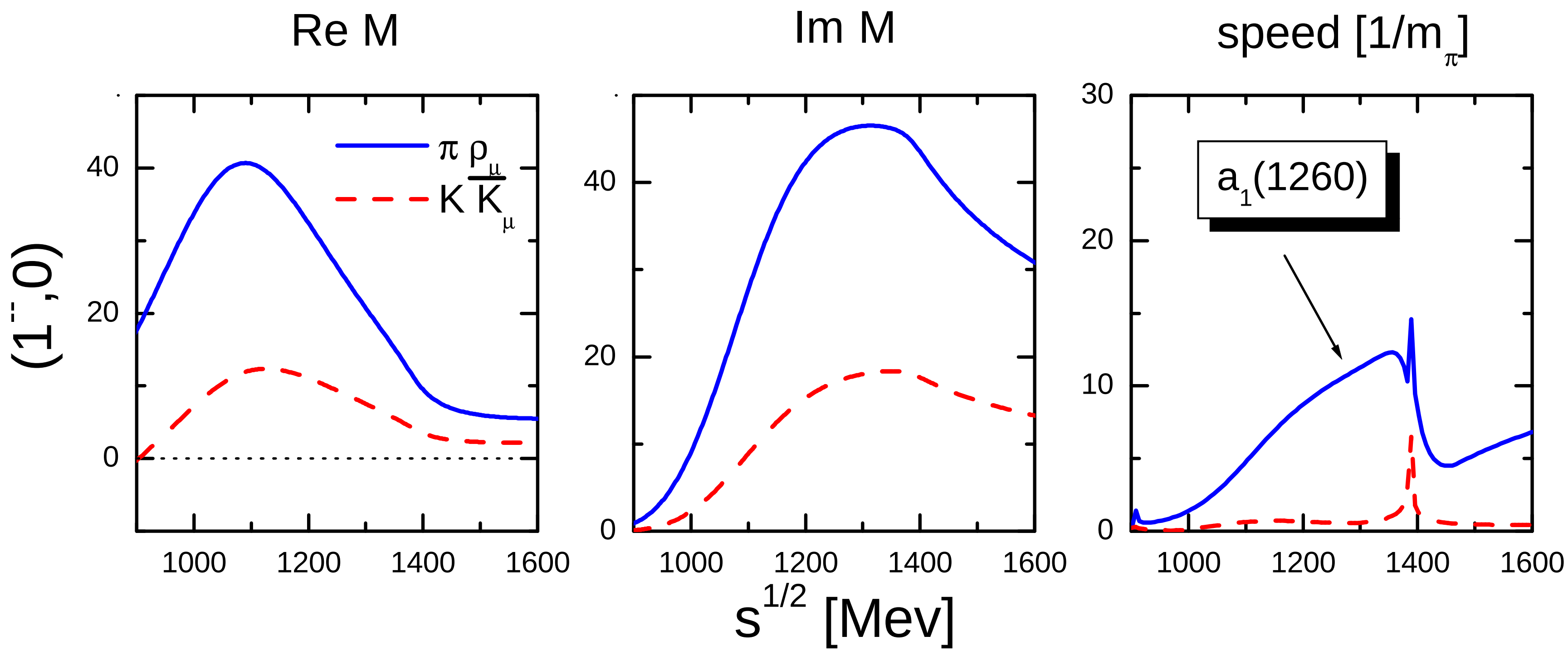
- **channel** $(I^G, S) = (1^+, 0)$**:** octet state



- **experimental width dominated by** $\pi\,\omega_\mu$ **channel:** $\Gamma \simeq 140$ MeV
- **couples strongly to** $K_\mu\,\bar{K}$ **and** $K\,\bar{K}_\mu$ **states**
- **strangeness channels crucial for generation of resonances**

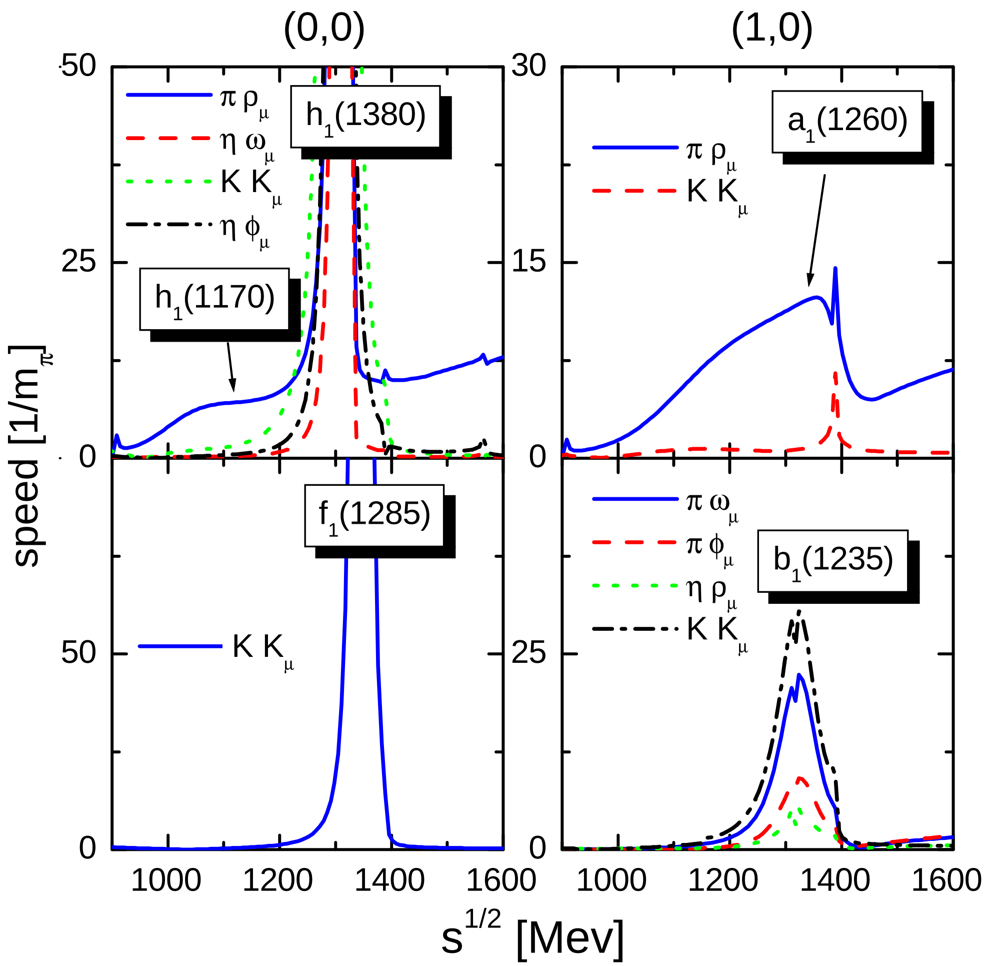
$J^P = 1^+$ meson resonances (Q^1)

- **channel** $(1^-, 0)$**:** octet state



- **couples strongly to** $\pi\,\rho_\mu$ **state**

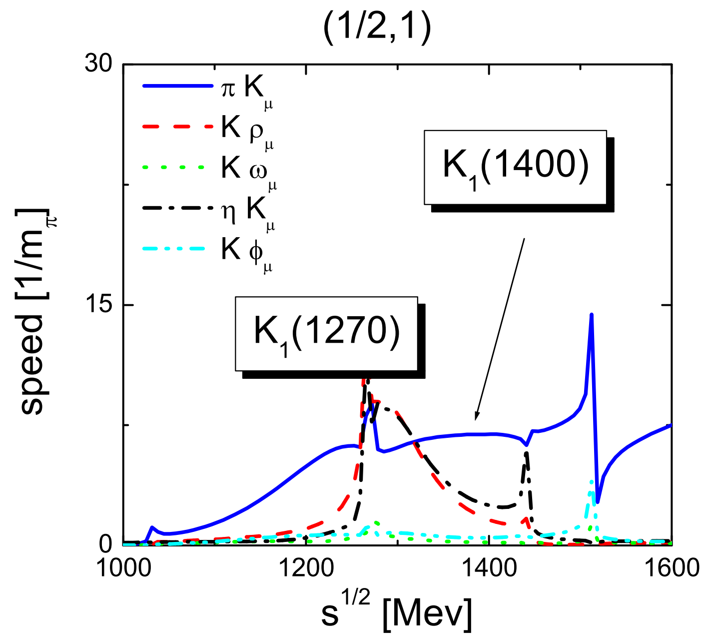
$J^P = 1^+$ meson resonances ($\mathbf{Q^1}$)



- **Chiral SU(3) symmetry:**

  2 octets and singlet

  $$8 \otimes 8 = 27 \oplus \overline{10} \oplus 10 \oplus 8 \oplus 8 \oplus 1$$



- **Predictions:**
  - $h_1(1380)$, $f_1(1285)$ and $b_1(1235)$ couples strongly to $K\bar{K}_\mu$–channel
  - $h_1(1380) \leftrightarrow (I^G = 0^+)$ state

Charmed meson and baryon resonances

- **Heavy-light mesons:** $(c\,\bar{q}_i)$ – SU(3) anti-triplet $[\bar{3}]$
  - 0^- mesons $\quad H = (D_0(1867), D_+(1867), D_s(1969))$
  - 1^- mesons $\quad H^\mu = (D_0^\mu(2008), D_+^\mu(2008), D_s^\mu(2110))$
- **Heavy-light baryons:** $(c\,q_i\,q_j)$ – SU(3) anti-triplet $[\bar{3}]$ or sextet $[6]$
  - $\frac{1}{2}^+$ $[\bar{3}]$-baryons $\quad B_{[\bar{3}]} = (\Xi_c(2470), \Lambda_c(2284))$
  - $\frac{1}{2}^+$ $[6]$-baryons $\quad B_{[6]} = (\Sigma_c(2453), \Xi'_c(2580), \Omega_c(2704))$
- **Chiral SU(3) symmetry predicts:**

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

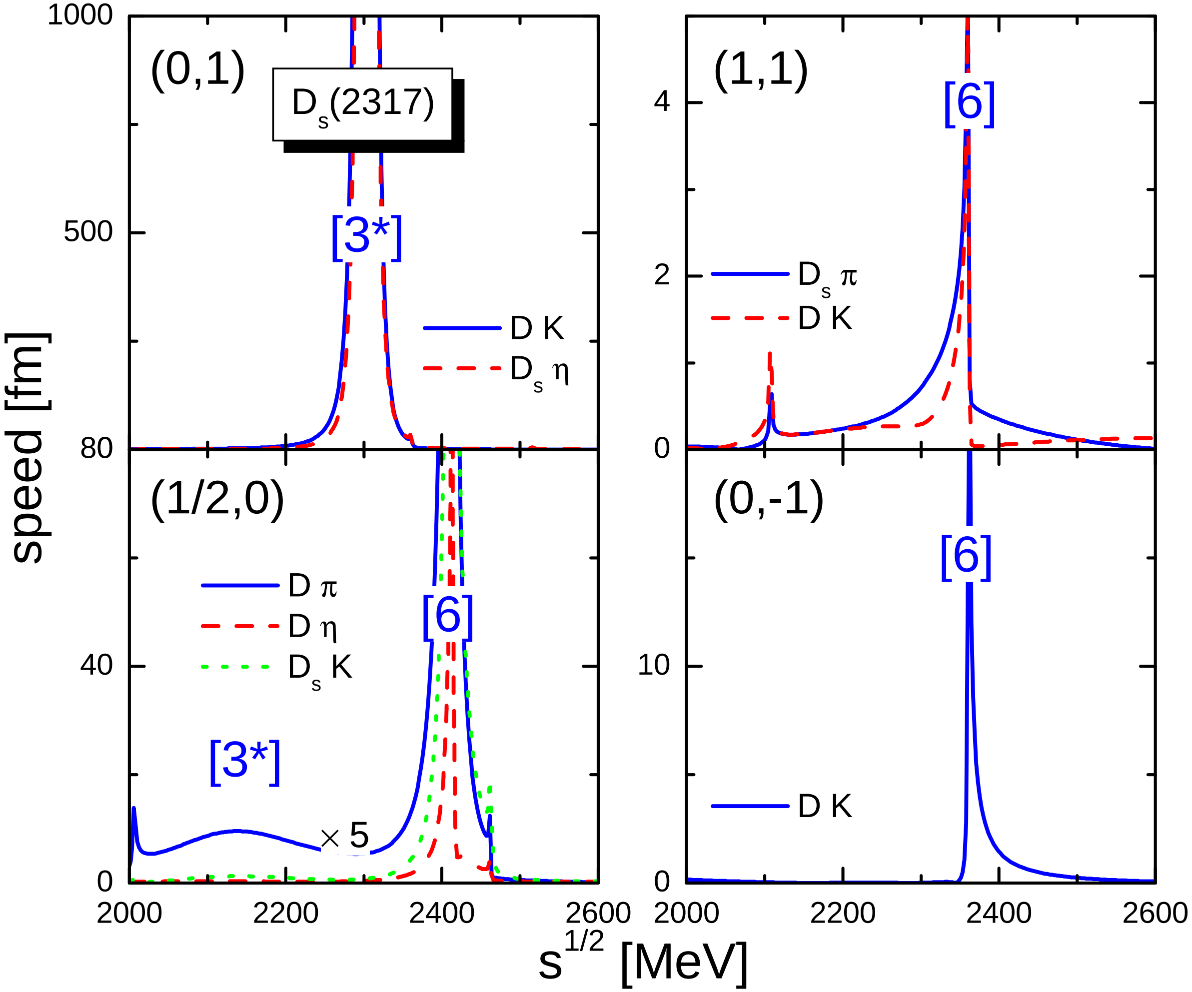
  - attraction in $[\bar{3}]$ and $[6]$ but repulsion in $[\overline{15}]$

$$6 \otimes 8 = \bar{3} \oplus 6 \oplus \overline{15} \oplus 24$$

  - attraction in $[\bar{3}]$, $[6]$, and $[\overline{15}]$ but repulsion in $[24]$

$J^P = 0^+$ charmed meson resonances ($\mathbf{Q}^1$)

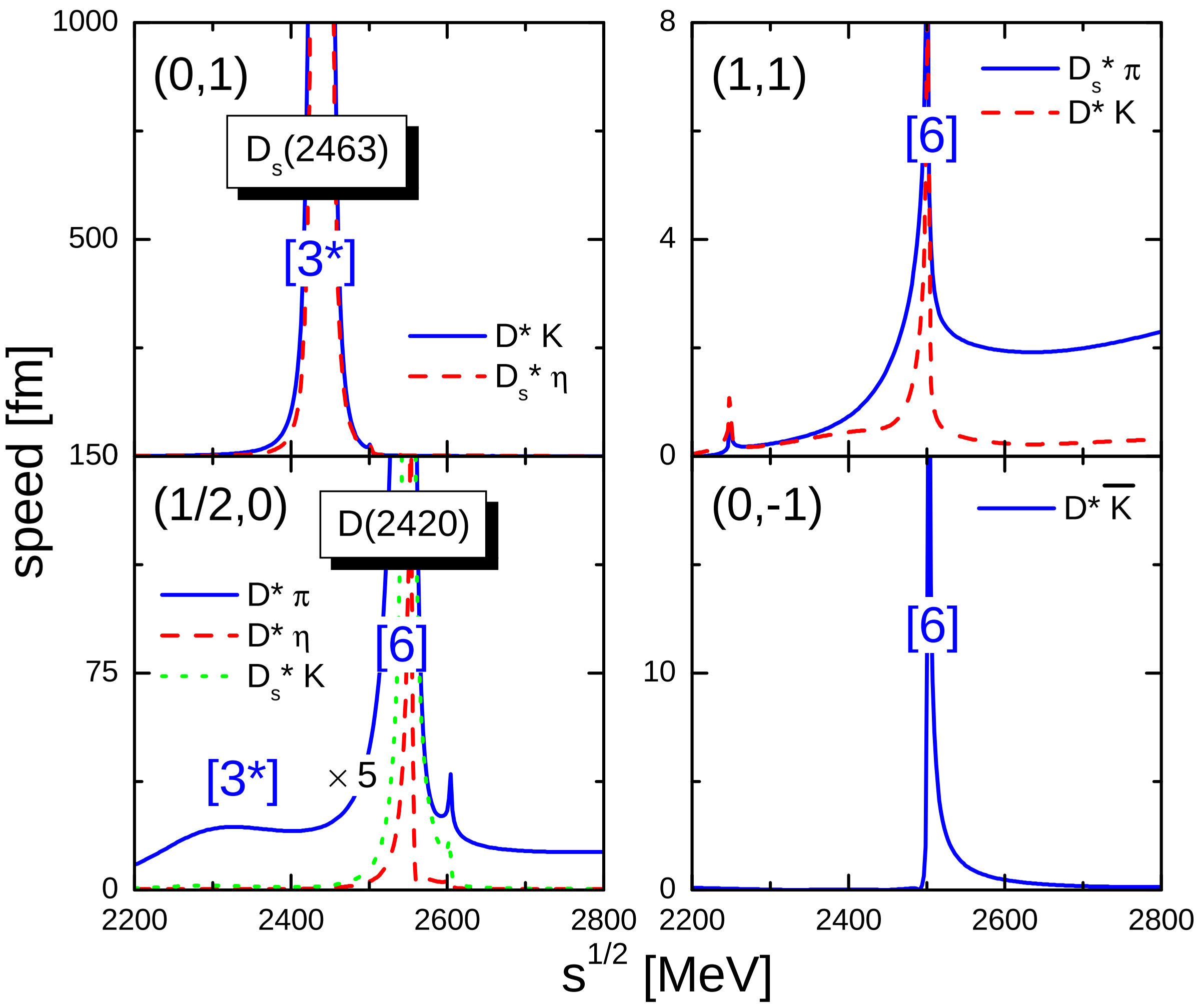
- **Chiral SU(3) predicts:** anti-triplet and sextet states $\quad \bar{3} \otimes 8 = \bar{3} \oplus 6 \oplus \overline{15}$



- bound $[\bar{3}]$ in $(0,1)$ at 2303 MeV
  [BABAR at 2317 MeV]
- broad $[\bar{3}]$ in $(\frac{1}{2},0)$ at 2138 MeV
- narrow $[6]$ in $(\frac{1}{2},0)$ at 2413 MeV
- cusp structures in $(0,-1)$ and $(1,1)$

$J^P = 1^+$ charmed meson resonances ($\mathbf{Q}^1$)

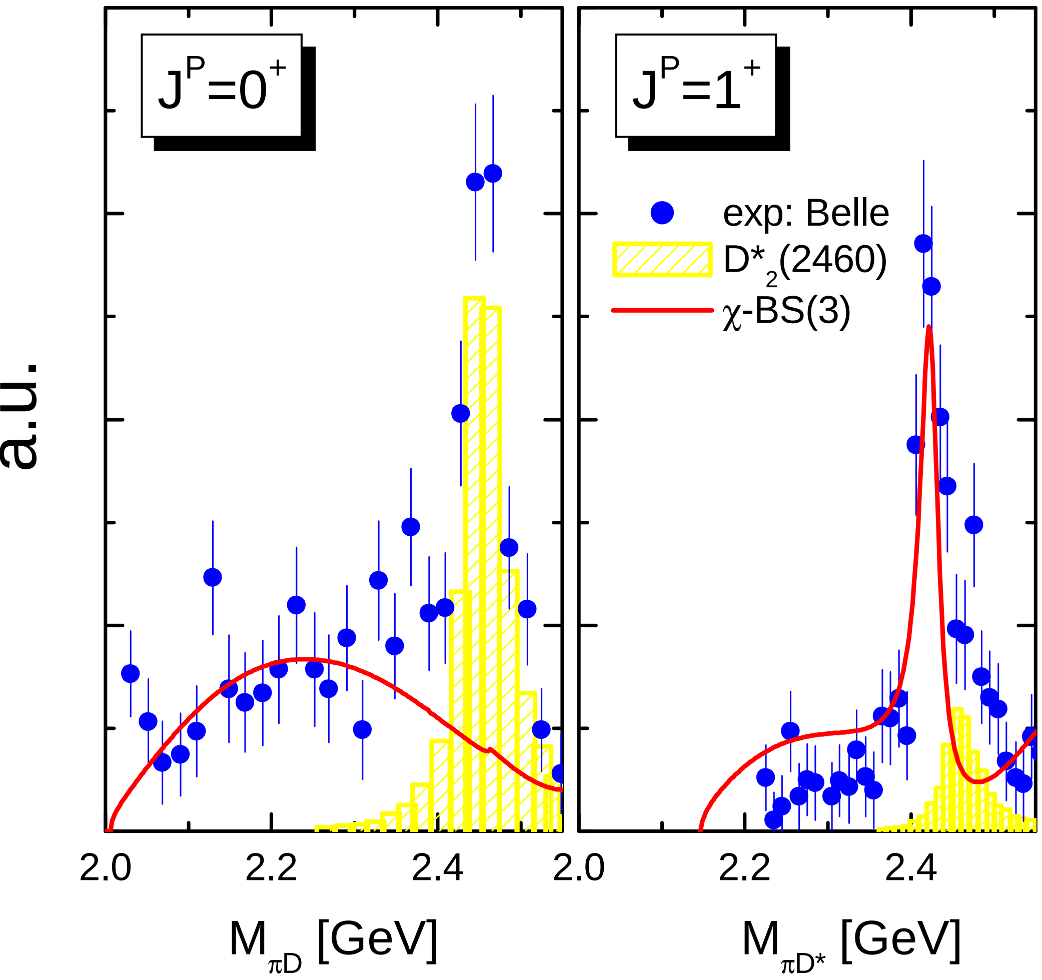
- **Chiral SU(3) predicts:** anti-triplet and sextet states $\bar{3} \otimes 8 = \bar{3} \oplus 6 \oplus \overline{15}$



- bound $[\bar{3}]$ in $(0,1)$ at 2440 MeV [CLEO at 2463 MeV]
- $M(1^+) - M(0^+) \simeq 140$ MeV
- broad $[\bar{3}]$ in $(\frac{1}{2},0)$ at 2325 MeV
- narrow $[6]$ in $(\frac{1}{2},0)$ at 2552 MeV [identify with D(2420)]
- cusp structures in $(0,-1)$ and $(1,1)$

Charmed meson resonance spectrum (Q^2)

✔ **Chiral corrections:** 3 parameters tuned to data



✔ **"hidden" 0^+-resonance $(I,S) = (\frac{1}{2}, 0)$**

- narrow [6]-state at 2389 MeV
- couples weakly to $\pi D(1867)$ channel

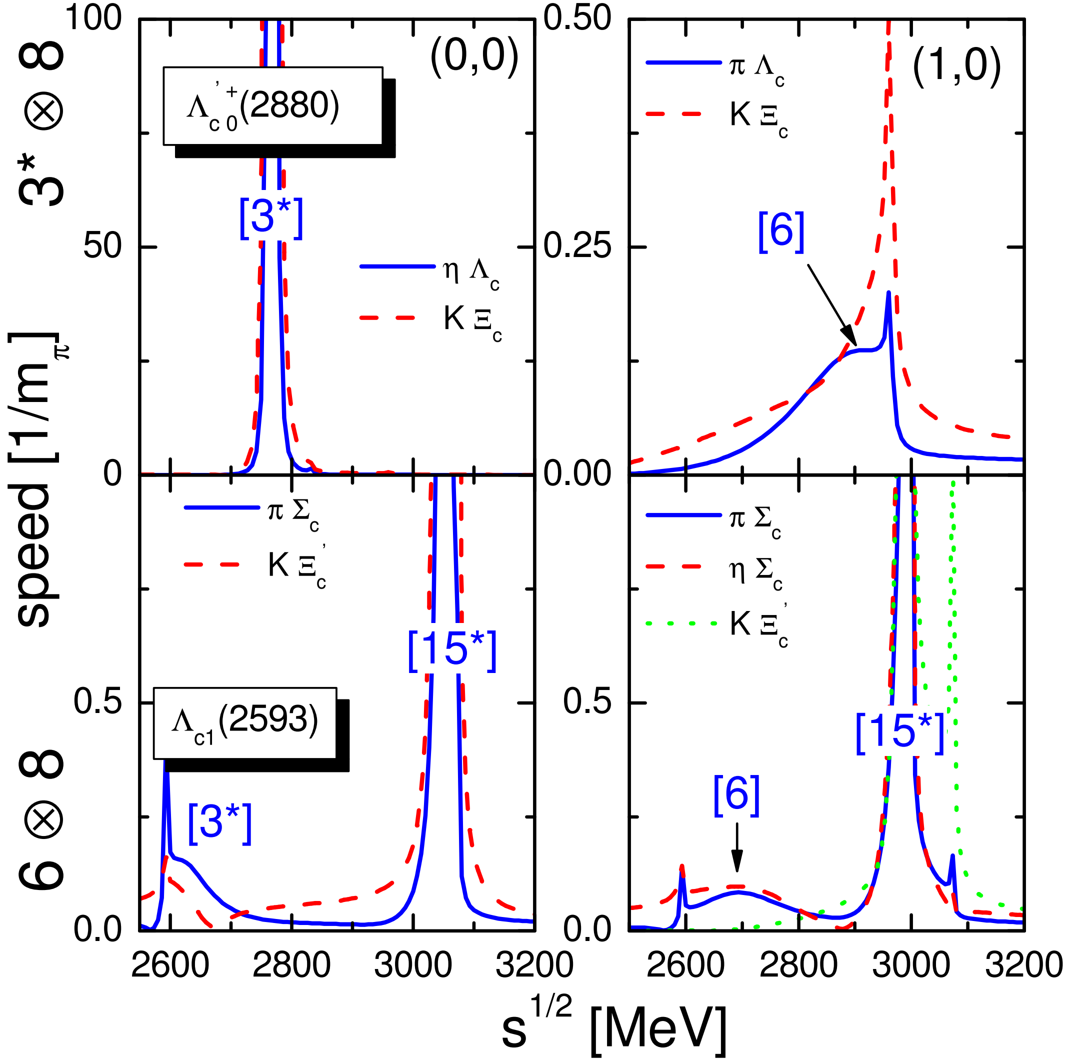
✔ **Is the $D(2420)$ a sextet state ?**

- where is the heavy-quark partner of the 2^+ $D(2460)$?

✔ **charmed mesons with negative strangeness**

- $\overline{K}$ bound at $D(1867)$ and $D_\mu(2008)$
- predict: 2352 MeV $(J^P = 0^+)$ and 2416 MeV $(J^P = 1^+)$

$J^P = \frac{1}{2}^-$ charmed baryon resonances



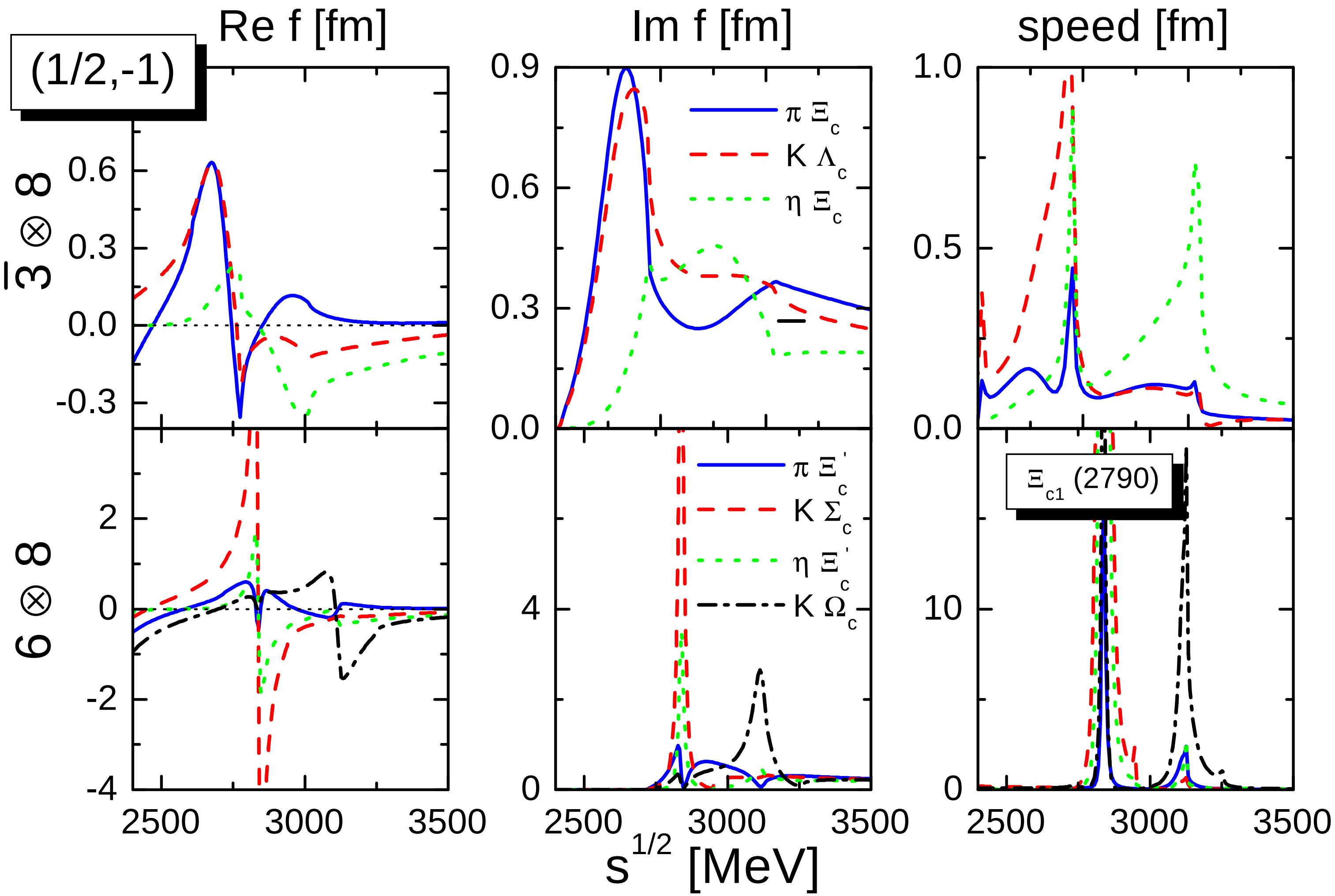
- ✔ **Chiral SU(3) dynamics predicts:**

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

  $6 \otimes 8 = \bar{3} \oplus 6 \oplus \overline{15} \oplus 24$

- ✔ **bound** $[\bar{3}]$ **in** $(0,0)_{[\bar{3}]}$ **at 2767 MeV**
  - identify with CLEO's $\Lambda_c(2880)$
- ✔ **broad** $[\bar{3}]$ **in** $(0,0)_{[6]}$ **at 2650 MeV**
  - identify with CLEO's $\Lambda_c(2593)$
- ✔ **mixing of** $(0,0)_{[\bar{3}]}$ **and** $(0,0)_{[6]}$ **sectors**
  - level-level repulsion $\rightarrow$ good!
- ✔ **predict exotic resonances**
  - states with $(\frac{1}{2},+1)$, $(\frac{3}{2},-1)$ and $(1,-2)$ systems of $K@\,\Sigma_c$, $\bar{K}@\,\Sigma_c$ and $\bar{K}@\,\Xi'_c$

$J^P = \frac{1}{2}^-$ charmed baryon resonances



✔ **recover CLEO's** $\Xi_c(2790)$ - complex coupled channel dynamics!

Summary

✔ meson and baryon resonances that do not belong to the large-N_c ground states are dynamically generated by coupled-channel dynamics

- degrees of freedom: large-N_c meson and baryon ground-state fields
- crossing symmetry constrains renormalization scheme
- independence on choice of chiral coordinates by covariant on-shell reduction
- at leading order: parameter-free prediction for baryon and meson resonances in light and heavy-light quark sectors
- prediction of new multiplets