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Identify the two-pole structures from an SU(3) flavor filter

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Outline

- **Brief review of $\Lambda(1405)$**
- **Two-pole structure**
- **An $SU(3)$ flavor filter**
- **Summary**

$\Lambda(1405)$: Puzzles in the quark model

PDG 2022

$$I(J^P) = 0(1/2^-)$$

$$M = 1405.1^{+1.3}_{-1.0} \text{ MeV}, \Gamma = 50.5 \pm 2.0 \text{ MeV}$$

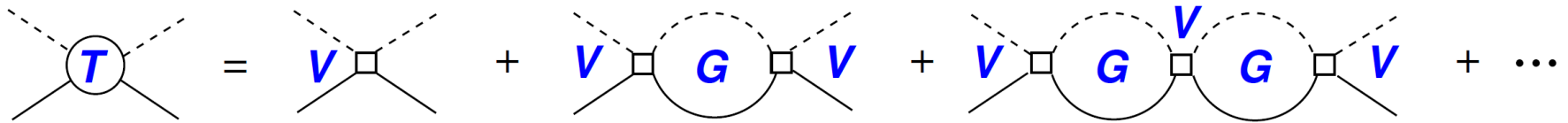
Quark model classification: a uds P-wave excitation, a few hundred MeV above the ground state $\Lambda(1116)$

- Much lower than its nucleon-counterpart $N(1535)$ ($J^P = 1/2^-$)
- Mass gap between $\Lambda(1405)$ and $\Lambda(1520)$ ($J^P = 3/2^-$) is much larger, compared with $N(1535)$ and $N(1520)$



$\Lambda(1405)$: Dynamically generated state

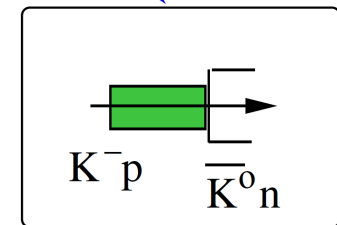
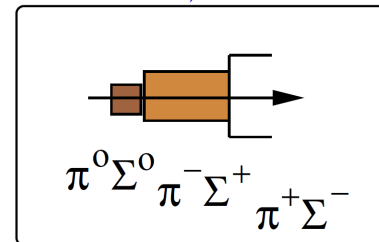
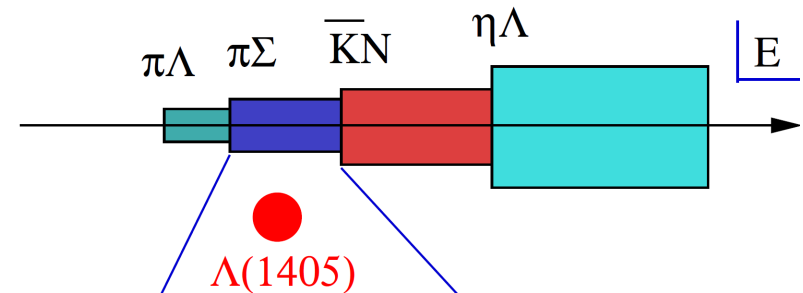
- Dynamically generated from the $\pi\Sigma - \bar{K}N$ coupled channel interaction in UChPT. (Hadronic molecule)



$$T = V + VGT$$

Bethe-Salpeter equation

Obtained from a chiral effective Lagrangian

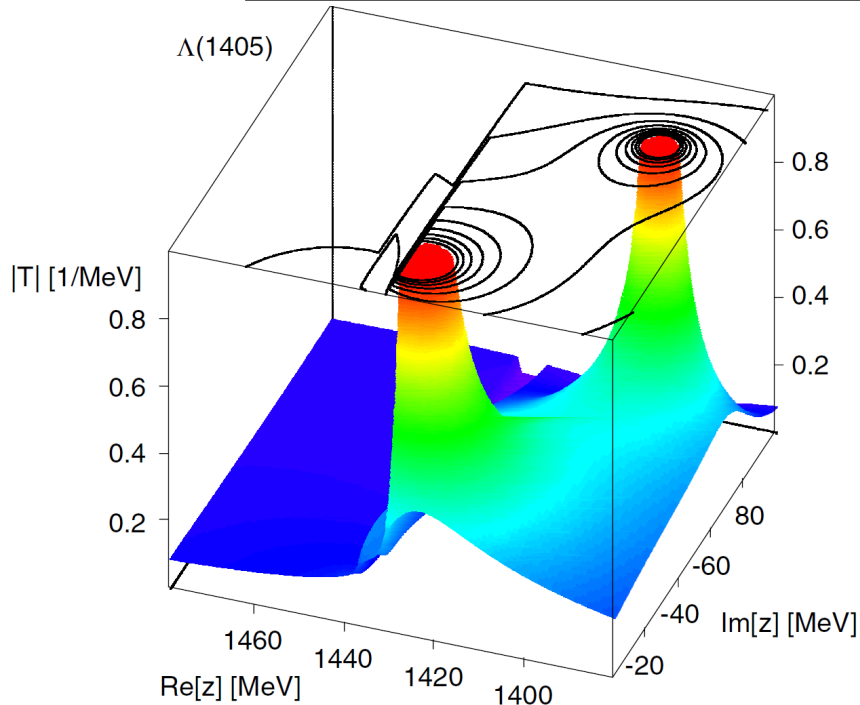


- Kaiser, Siegel, Weise, NPA594, 325(1995)
- Kaiser, Wass, Weise, NPA612, 297(1997)
- Oset & Ramos, NPA635, 99(1998)
- Oller, Oset, Ramos, PPNP45, 157(2000)
- Oller & Meissner, PLB500, 263(2001)
- **“first exotic hadron”**

$\Lambda(1405)$: Two-pole structure

| z_R | $1390 + \underline{66i}$ | | $1426 + \underline{16i}$ | |
|----------------|--------------------------|---------|--------------------------|---------|
| $(I = 0)$ | g_i | $ g_i $ | g_i | $ g_i $ |
| $\pi \Sigma$ | $-2.5 - 1.5i$ | 2.9 | $0.42 - 1.4i$ | 1.5 |
| $\bar{K} N$ | $1.2 + 1.7i$ | 2.1 | $-2.5 + 0.94i$ | 2.7 |
| $\eta \Lambda$ | $0.010 + 0.77i$ | 0.77 | $-1.4 + 0.21i$ | 1.4 |
| $K \Xi$ | $-0.45 - 0.41i$ | 0.61 | $0.11 - 0.33i$ | 0.35 |

Four
coupled-
channels



Oset, Ramos, Benthold, PLB527, 99(2002);
Jido, Oller, Oset, Ramos, Meissner,
NPA725, 181(2003)

- Oller & Meissner, PLB500, 263(2001)
- Jido, Hosaka, Nacher, Oset, Ramos, PRC66, 025203(2002)
- Garcia-Recio, Nieves, Arriola, Vacas, PRD67, 076009(2003)
- Jido, Oller, Oset, Ramos, Meissner, NPA725, 181(2003)

Hyodo & Jido, PPNP67, 55(2012)

➤ Understanding with group theory

Weinberg-Tomozawa (WT) term dominates the interaction

$$V_{ij}^{\text{WT}}(\sqrt{s}) = -\frac{C_{ij}}{4f^2} (2\sqrt{s} - M_i - M_j) \mathcal{N}_i \mathcal{N}_j$$

Decomposed into group irreducible representations

GB Octet →

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

Baryon Octet →

attractive

In the SU(3) basis

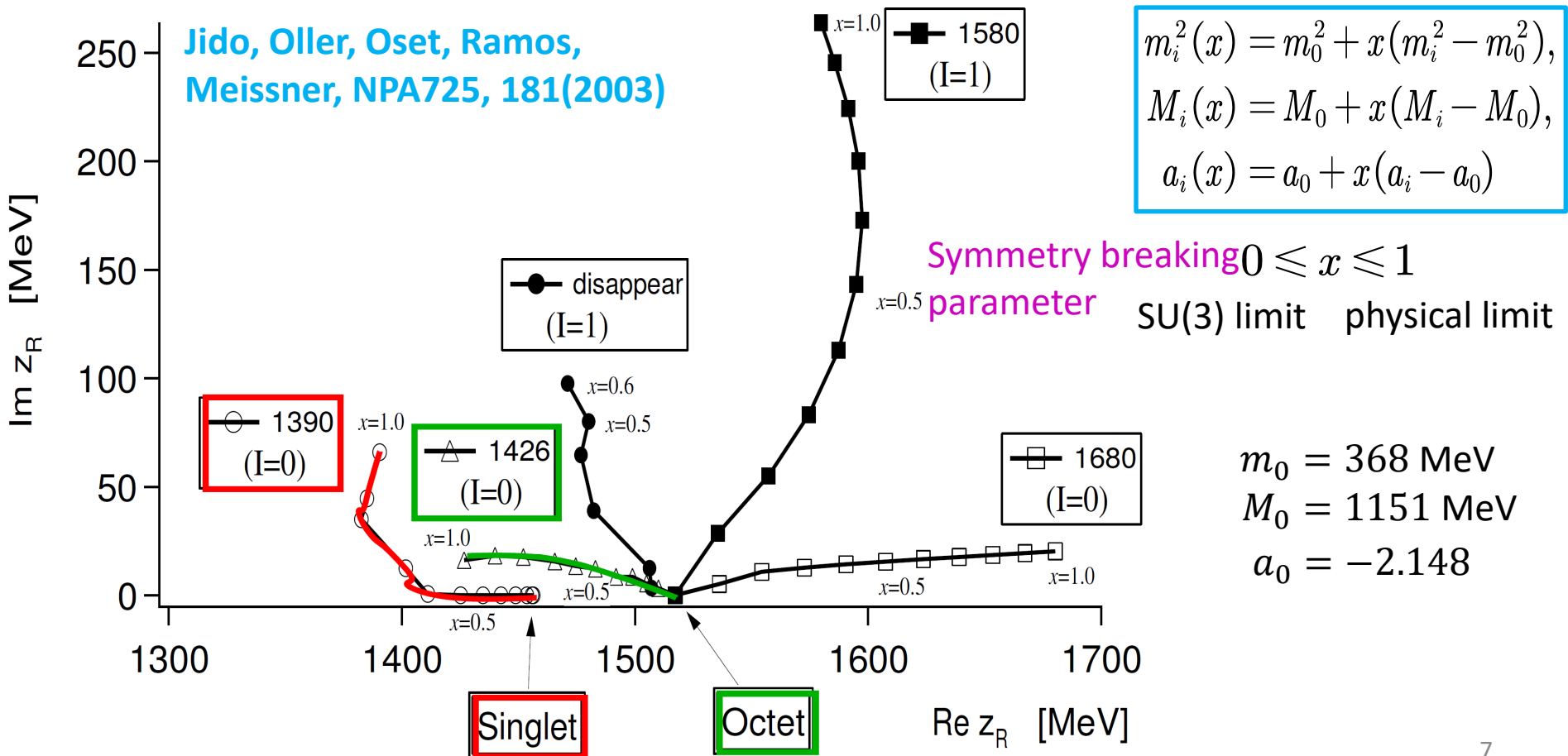
$$C_{\alpha\beta}^{\text{SU}(3)} = \sum_{i,j} \mathcal{D}_{\alpha i} C_{ij} \mathcal{D}_{\beta j} \quad \leftarrow \text{SU(3) C-G}$$

$$= \text{diag}(6, 3, 3, 0, 0, -2)$$

attractive

➤ Understanding with group theory

| z_R ($I=0$) | 1390 + 66i | | 1426 + 16i | | 1680 + 20i | |
|--------------------|-----------------|---------|----------------|---------|------------------|---------|
| | g_i | $ g_i $ | g_i | $ g_i $ | g_i | $ g_i $ |
| $\pi\Sigma$ | $-2.5 - 1.5i$ | 2.9 | $0.42 - 1.4i$ | 1.5 | $-0.003 - 0.27i$ | 0.27 |
| $\bar{K}N$ | $1.2 + 1.7i$ | 2.1 | $-2.5 + 0.94i$ | 2.7 | $0.30 + 0.71i$ | 0.77 |
| $\eta\Lambda$ | $0.010 + 0.77i$ | 0.77 | $-1.4 + 0.21i$ | 1.4 | $-1.1 - 0.12i$ | 1.1 |
| $K\Xi$ | $-0.45 - 0.41i$ | 0.61 | $0.11 - 0.33i$ | 0.35 | $3.4 + 0.14i$ | 3.5 |



$\Lambda(1405)$: Two-pole structure

Λ BARYONS ($S = -1, I = 0$)
 $\Lambda^0 = u d s$

Λ and Σ Resonances PDF

Pole Structure of the $\Lambda(1405)$ Region PDF

| Λ | | |
|-----------------|---------|------|
| Λ | $1/2^+$ | **** |
| $\Lambda(1380)$ | $1/2^-$ | ** |
| $\Lambda(1405)$ | $1/2^-$ | **** |
| $\Lambda(1520)$ | $3/2^-$ | **** |
| $\Lambda(1600)$ | $1/2^+$ | **** |
| $\Lambda(1670)$ | $1/2^-$ | **** |

Table 83.1: Comparison of the pole positions of $\Lambda(1405)$ in the complex energy plane from next-to-leading order chiral unitary coupled-channel approaches including the SIDDHARTA constraint. The lower two results also include the CLAS photoproduction data.

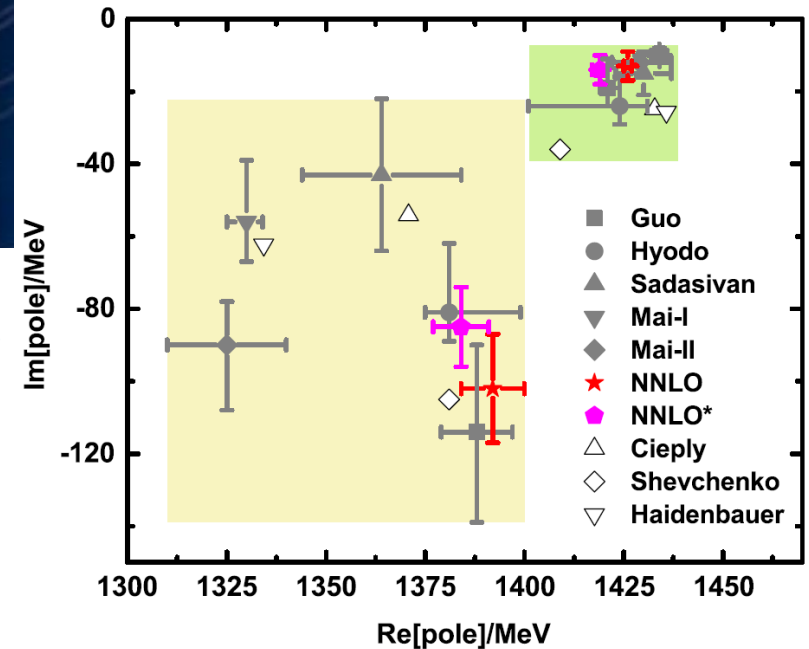
| approach | pole 1 [MeV] | pole 2 [MeV] |
|------------------------|-------------------------------------|---------------------------------------|
| Refs. [14, 15], NLO | $1424_{-23}^{+7} - i 26_{-14}^{+3}$ | $1381_{-6}^{+18} - i 81_{-8}^{+19}$ |
| Ref. [17], Fit II | $1421_{-2}^{+3} - i 19_{-5}^{+8}$ | $1388_{-9}^{+9} - i 114_{-25}^{+24}$ |
| Ref. [18], solution #2 | $1434_{-2}^{+2} - i 10_{-1}^{+2}$ | $1330_{-5}^{+4} - i 56_{-11}^{+17}$ |
| Ref. [18], solution #4 | $1429_{-7}^{+8} - i 12_{-3}^{+2}$ | $1325_{-15}^{+15} - i 90_{-18}^{+12}$ |

PDG 2022

$\Lambda(1380)$
 $\Lambda(1405)$

Pole positions up to NNLO

| Pole positions (MeV) | |
|----------------------|------------------------------|
| $\Lambda(1380)$ | $1392 \pm 8 - i(102 \pm 15)$ |
| $\Lambda(1405)$ | $1425 \pm 1 - i(13 \pm 4)$ |



Lu, Geng, Doering, Mai,
PRL130, 071902(2023)

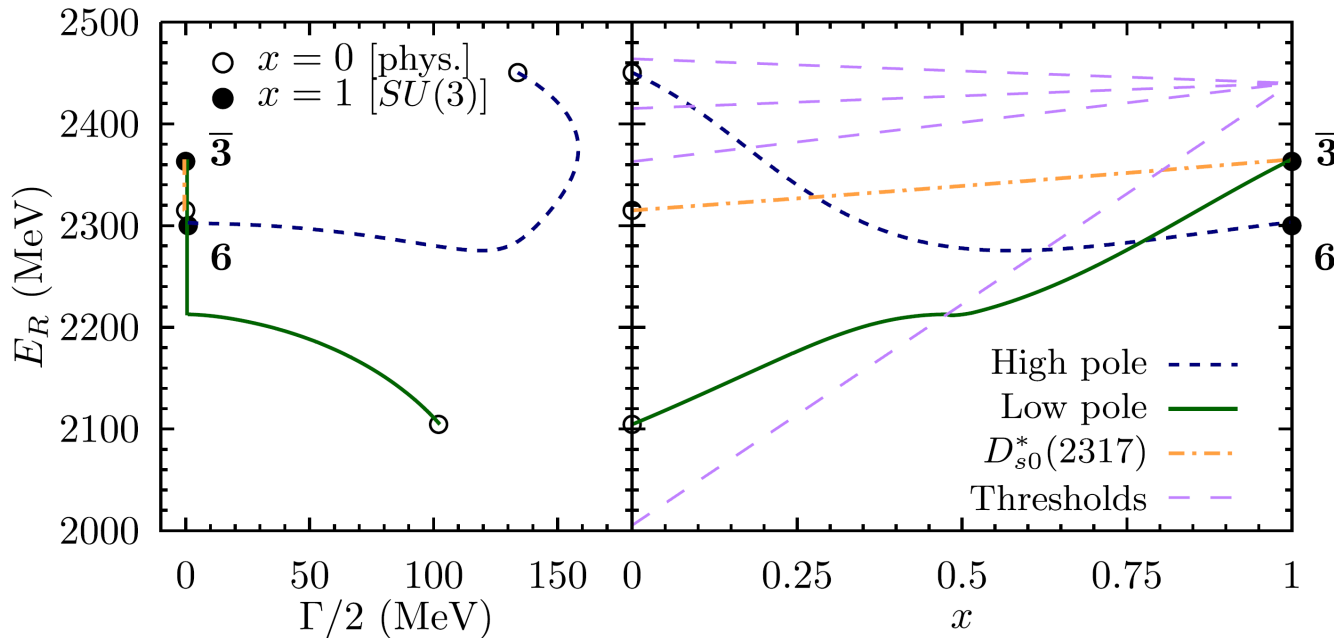
$D_0(J^P = 0^+)$: Analog in the heavy flavor sector

PDG 2022 $D_0^*(2300)$: $M = 2343 \pm 10$ MeV; $\Gamma = 229 \pm 16$ MeV

| 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) | $5.2^{+0.6}_{-0.4}$ | $6.7^{+0.6}_{-0.4}$ | $13.2^{+0.6}_{-0.5}$ |
| 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) | $5.0^{+0.7}_{-0.4}$ | $6.3^{+0.8}_{-0.5}$ | $12.8^{+0.8}_{-0.6}$ |

Moir *et al.*, JHEP1610, 011(2016)

Albaladejo, Fernandes-Soler, Guo, Nieves, PLB767, 465(2017)



(D^0, D^+, D_s^+)

$$\bar{3} \otimes 8 = \bar{15} \oplus \underbrace{6 \oplus \bar{3}}_{\text{attractive}}$$

GB Octet

Two-pole structure

Analog in the heavy flavor sector

| | lower pole | higher pole | RPP |
|---------|--------------------------------------|-------------------------------------|--|
| D_0^* | $(2105_{-8}^{+6}, 102_{-11}^{+10})$ | $(2451_{-26}^{+35}, 134_{-8}^{+7})$ | $(2300 \pm 19, 137 \pm 20)$ |
| D_1 | $(2247_{-6}^{+5}, 107_{-10}^{+11})$ | $(2555_{-30}^{+47}, 203_{-9}^{+8})$ | $(2427 \pm 26 \pm 25, 192_{-38}^{+54} \pm 37)$ |
| B_0^* | $(5535_{-11}^{+9}, 113_{-17}^{+15})$ | $(5852_{-19}^{+16}, 36 \pm 5)$ | - |
| B_1 | $(5584_{-11}^{+9}, 119_{-17}^{+14})$ | $(5912_{-18}^{+15}, 42_{-4}^{+5})$ | - |

Guo, Shen, Chiang, PLB647, 133(2007)

Cleven, Guo, Hanhart, Meissner, EPJA47, 465(2011)



Article

Two-Pole Structures in QCD: Facts, Not Fantasy!

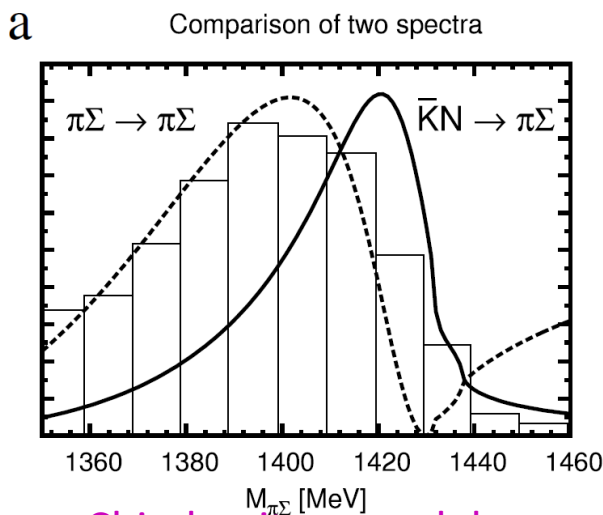
Ulf-G. Meißner ^{1,2,3}

The two-pole structure refers to the fact that particular single states in the spectrum as listed in the PDG tables are often two states.

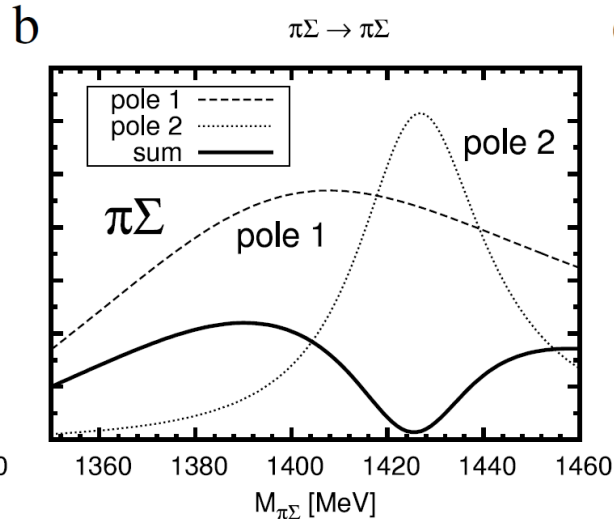
A comprehensive review by Ulf-G. Meissner
Symmetry 2020, 12(6), 981

Identify the two-pole structures

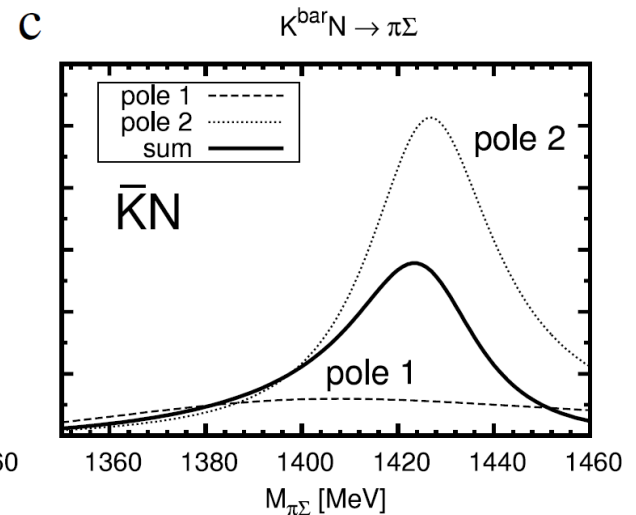
- Due to different couplings, the shape of the $\Lambda(1380/1405)$ spectrum can be different depending on the initial and final channels



Chiral unitary model



Breit-Wigner parametrization

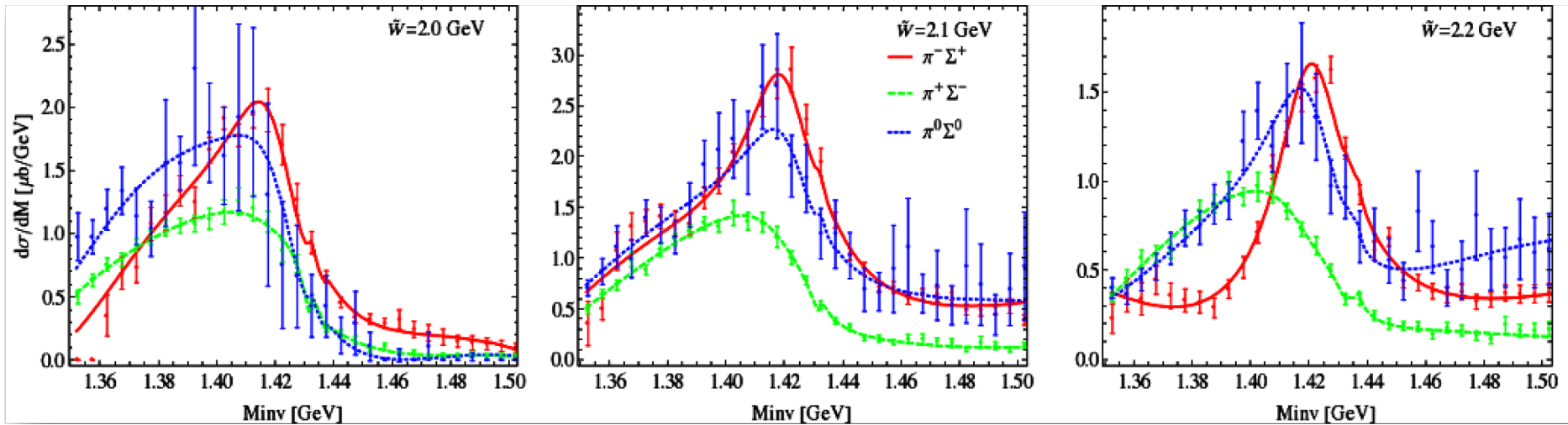


Jido et al., NPA725, 181(2003); NPA835, 59(2010)

| z_R | 1390 + 66i | | 1426 + 16i | |
|---------------|-----------------|------------|----------------|------------|
| | g_i | $ g_i $ | g_i | $ g_i $ |
| $(I = 0)$ | | | | |
| $\pi\Sigma$ | $-2.5 - 1.5i$ | <u>2.9</u> | $0.42 - 1.4i$ | 1.5 |
| $\bar{K}N$ | $1.2 + 1.7i$ | 2.1 | $-2.5 + 0.94i$ | <u>2.7</u> |
| $\eta\Lambda$ | $0.010 + 0.77i$ | 0.77 | $-1.4 + 0.21i$ | 1.4 |
| $K\Xi$ | $-0.45 - 0.41i$ | 0.61 | $0.11 - 0.33i$ | 0.35 |

Identify the two-pole structures

Mai & Meissner, EPJA51, 30(2015) $\gamma p \rightarrow \pi \Sigma K^+$

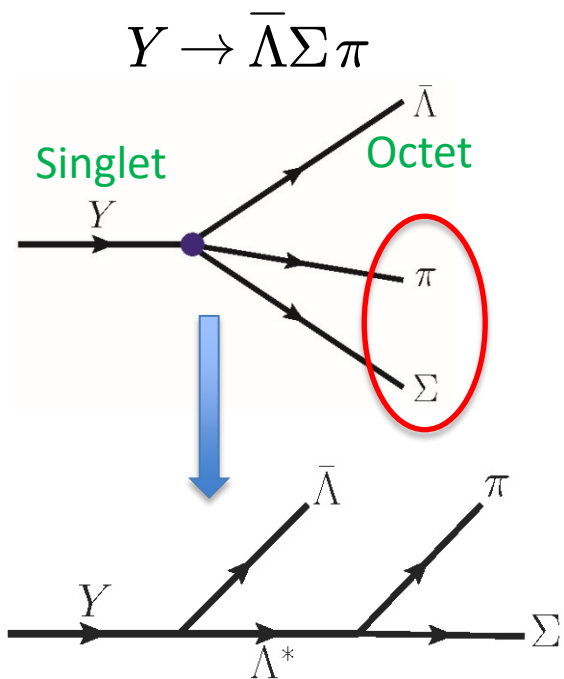


Result of the fits to the CLAS photoproduction data in three channels
A chiral unitary model adopted

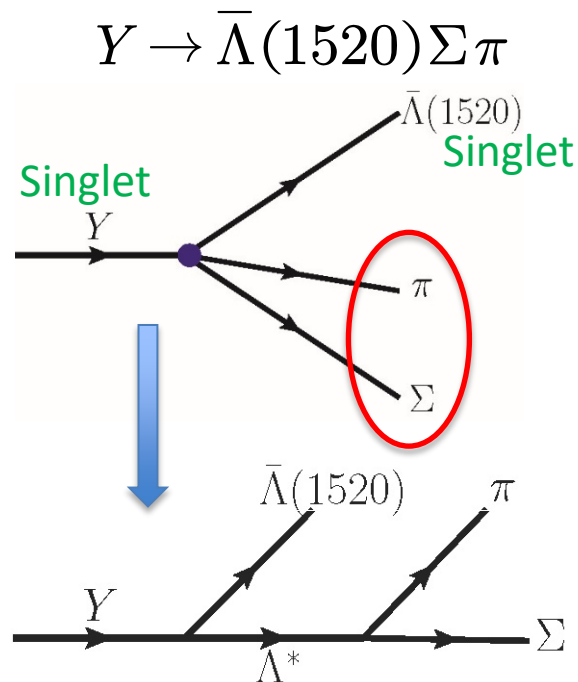
| Solution | Pole 1 | Pole 2 |
|----------|-----------------------------------|---------------------------------------|
| #2 | $1434_{-2}^{+2} - i 10_{-1}^{+2}$ | $1330_{-5}^{+4} - i 56_{-11}^{+17}$ |
| #4 | $1429_{-7}^{+8} - i 12_{-3}^{+2}$ | $1325_{-15}^{+15} - i 90_{-18}^{+12}$ |

The two-pole puzzle has still not been satisfactorily experimentally solved.

An SU(3) flavor filter



$\Sigma\pi$ produced from an **SU(3) octet Λ^***



$\Sigma\pi$ produced from an **SU(3) singlet Λ^***

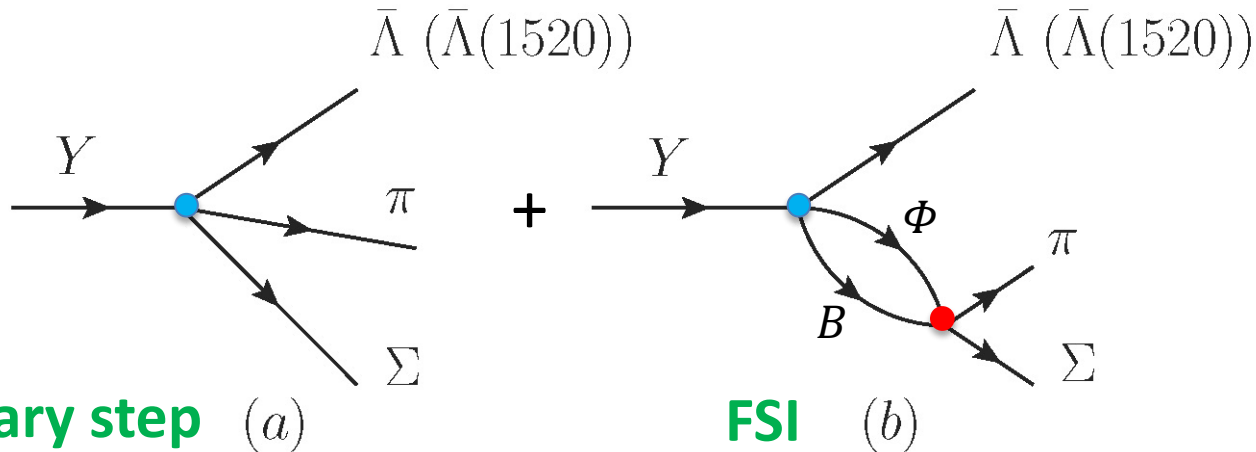
SU(3) symmetry requirement

Y : A heavy quarkonium state J/ψ , $\psi(3686)$, χ_{cJ} , $\Upsilon(ns)$...

- SU(3) singlet
- Huge data samples, more than 10 billion J/ψ events and 3 billion $\psi(3686)$ events in BESIII

$\Lambda(1520)$: SU(3) singlet with $J^P = 3/2^-$ generally supposed to be

An SU(3) flavor filter



$$\mathcal{L}_\psi = \tilde{D} \langle \bar{B} \gamma_\mu \gamma_5 \{ \Phi, B \} \rangle \psi^\mu + \tilde{F} \langle \bar{B} \gamma_\mu \gamma_5 [\Phi, B] \rangle \psi^\mu$$

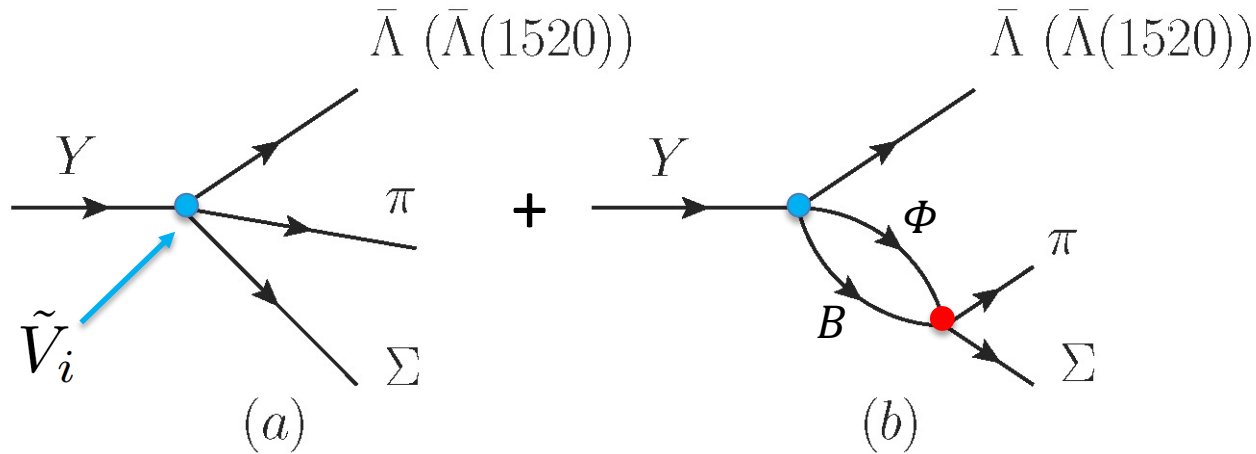
$$\mathcal{L}'_\psi = g_0 \bar{\Lambda}_\mu \gamma_5 \langle \Phi, B \rangle \psi^\mu$$

Four coupled channels

$\Phi B: \pi\Sigma, \bar{K}N, \eta\Lambda, K\Xi$

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix} \quad B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

An SU(3) flavor filter



Unitary model $t_i = \tilde{V}_i + \sum_j \tilde{V}_j G_j T_{ji}$ $T_{ij} = V_{ij} + V_{ik} G_k T_{kj}$

$$G_l = i2M_l \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon}$$

$$= \frac{2M_l}{16\pi^2} \left\{ a_l(\mu) + \ln \frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s} \ln \frac{m_l^2}{M_l^2} \right.$$

$$+ \frac{q_l}{\sqrt{s}} [\ln(s - (M_l^2 - m_l^2) + 2q_l\sqrt{s}) + \ln(s + (M_l^2 - m_l^2) + 2q_l\sqrt{s})$$

$$\left. - \ln(-s + (M_l^2 - m_l^2) + 2q_l\sqrt{s}) - \ln(-s - (M_l^2 - m_l^2) + 2q_l\sqrt{s}) \right\}$$

$$a_{\bar{K}N} = -1.84, \quad a_{\pi\Sigma} = -2.00, \quad a_{\pi\Lambda} = -1.83,$$

$$a_{\eta\Lambda} = -2.25, \quad a_{\eta\Sigma} = -2.38, \quad a_{K\Xi} = -2.67$$

Adopt the same subtraction constants as those in [Jido *et al.*, NPA725, 181(2003)]

Parameters of the model

$$\mathcal{L}_\psi = \tilde{D} \langle \bar{B} \gamma_\mu \gamma_5 \{ \Phi, B \} \rangle \psi^\mu + \tilde{F} \langle \bar{B} \gamma_\mu \gamma_5 [\Phi, B] \rangle \psi^\mu$$

$$\Gamma_{210} \quad \Lambda \bar{\Lambda} \pi^0 \quad (3.8 \pm 0.4) \times 10^{-5}$$

$$\Gamma_{211} \quad \Lambda \bar{\Lambda} \pi^+ \pi^- \quad (4.3 \pm 1.0) \times 10^{-3}$$

$$\Gamma_{212} \quad \Lambda \bar{\Lambda} \eta \quad (1.62 \pm 0.17) \times 10^{-4}$$

$$\Gamma_{213} \quad \Lambda \bar{\Sigma}^- \pi^+ \text{ (or c.c.)} \quad [2] \quad (8.3 \pm 0.7) \times 10^{-4}$$

$$\Gamma_{214} \quad p K^- \bar{\Lambda} \text{ +c.c.} \quad (8.6 \pm 1.1) \times 10^{-4}$$

$$\Gamma_{215} \quad p K^- \bar{\Sigma}^0 \quad (2.9 \pm 0.8) \times 10^{-4}$$

$$\Gamma_{216} \quad \bar{\Lambda} n K_S^0 \text{ + c.c.} \quad (6.5 \pm 1.1) \times 10^{-4}$$

$$\Gamma_{217} \quad \Lambda \bar{\Sigma} \text{ + c.c.} \quad (2.83 \pm 0.23) \times 10^{-5}$$

$$\Gamma_{218} \quad \Sigma^+ \bar{\Sigma}^- \quad (1.07 \pm 0.04) \times 10^{-3}$$

$$\Gamma_{219} \quad \Sigma^0 \bar{\Sigma}^0 \quad (1.172 \pm 0.032) \times 10^{-3}$$

$$\Gamma_{220} \quad \Sigma^+ \bar{\Sigma}^- \eta \quad (6.3 \pm 0.4) \times 10^{-5}$$

$$\Gamma_{221} \quad \Xi^- \bar{\Xi}^+ \quad (9.7 \pm 0.8) \times 10^{-4}$$

- For J/ψ decays, branching fractions of four channels $\bar{\Lambda} \Sigma \pi$, $\bar{\Lambda} N \bar{K}$, $\bar{\Lambda} \Lambda \eta$ and $\bar{\Sigma} N \bar{K}$ are used for the fitting

$$\mathcal{R}_{F/D} \equiv \frac{\tilde{F}}{\tilde{D}} = 0.18 \pm 0.03$$

- For $\psi(3686)$ decays

$$\mathcal{R}_{F/D} \equiv \frac{\tilde{F}}{\tilde{D}} = 0.50 \pm 0.06$$

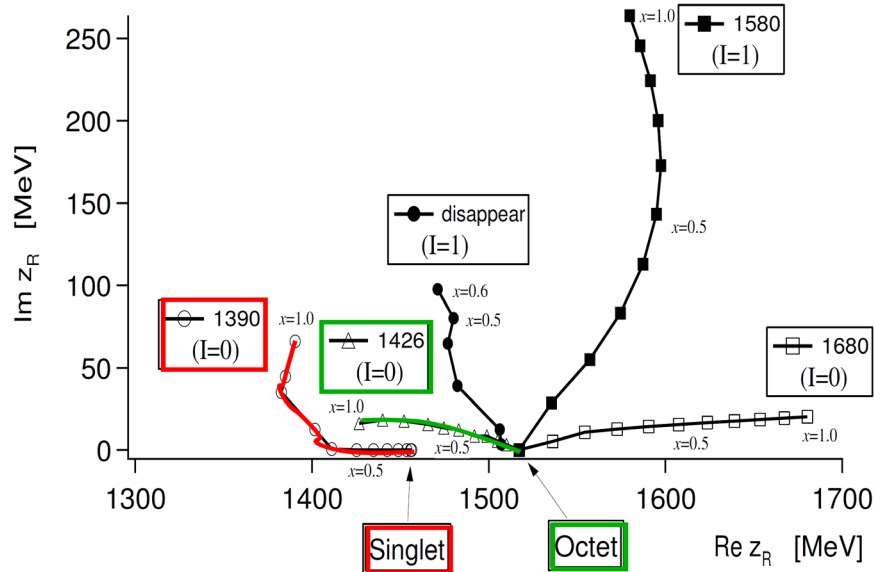
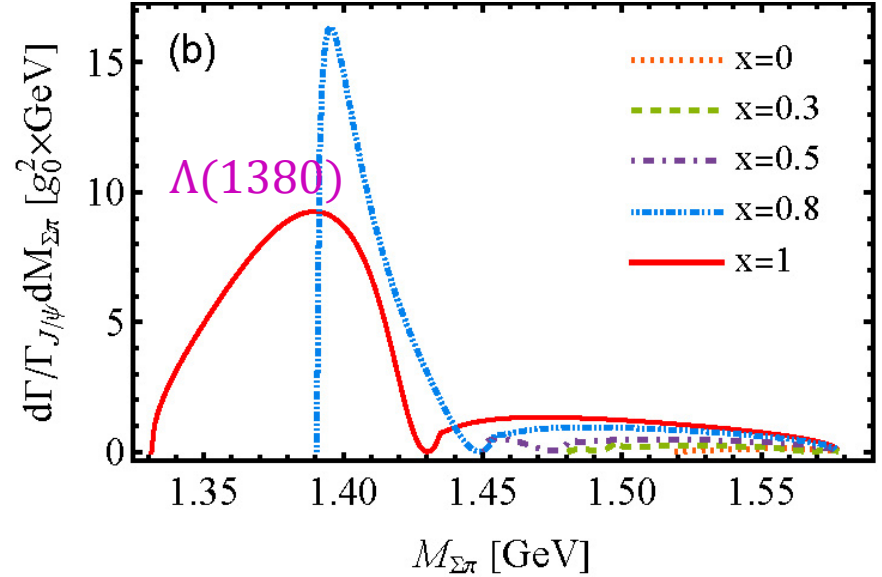
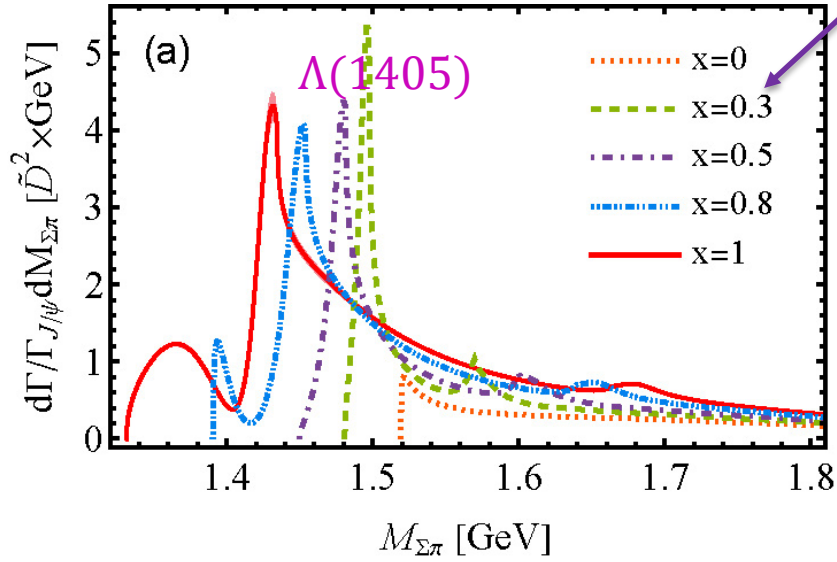
Branching fractions of J/ψ decay modes
PDG 2022

An SU(3) flavor filter

$$J/\psi \rightarrow \bar{\Lambda} \Sigma \pi$$

Symmetry breaking parameter

$$J/\psi \rightarrow \bar{\Lambda}(1520) \Sigma \pi$$



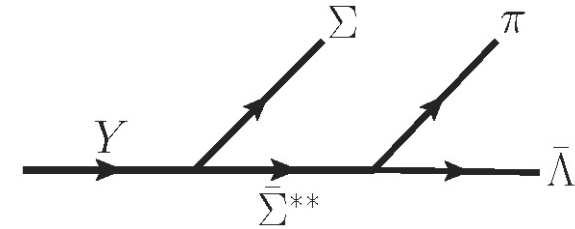
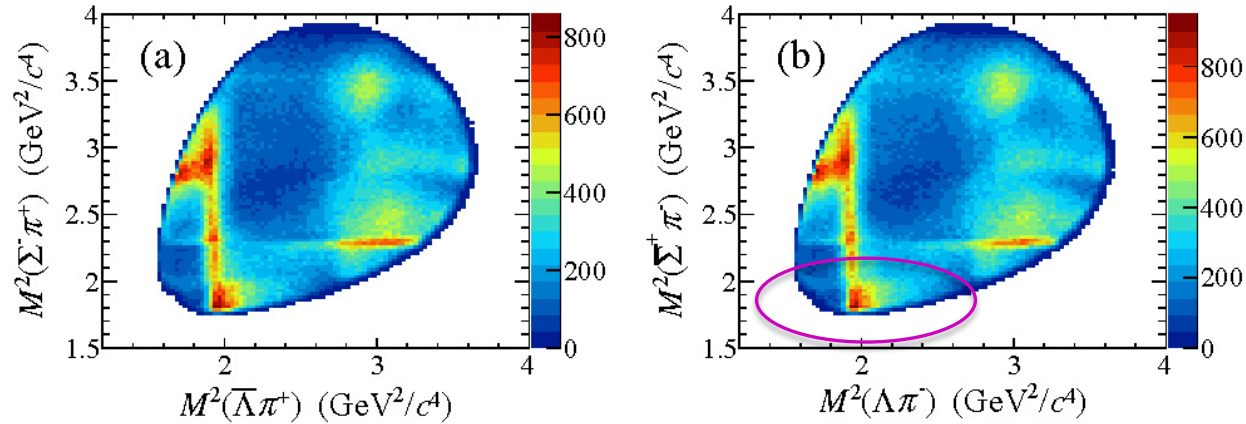
$$m_0 = 368 \text{ MeV}$$

$$M_0 = 1151 \text{ MeV}$$

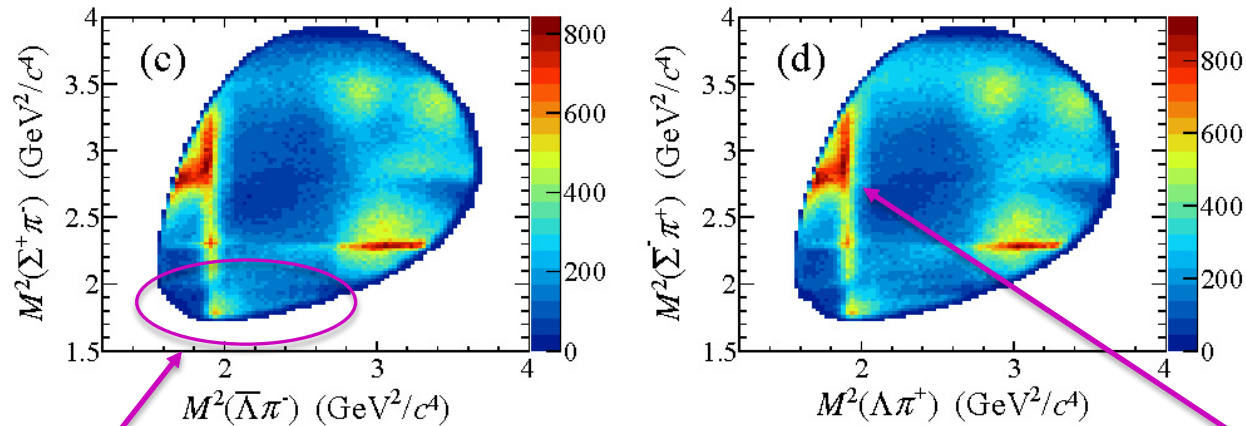
$$a_0 = -2.148$$

Background

Dalitz plots of $J/\psi \rightarrow \bar{\Lambda}\Sigma\pi, \bar{\Sigma}\Lambda\pi$



- Contributions from intermediate Σ^{**} resonances are ignored
- Eliminate the influence by proper cutting

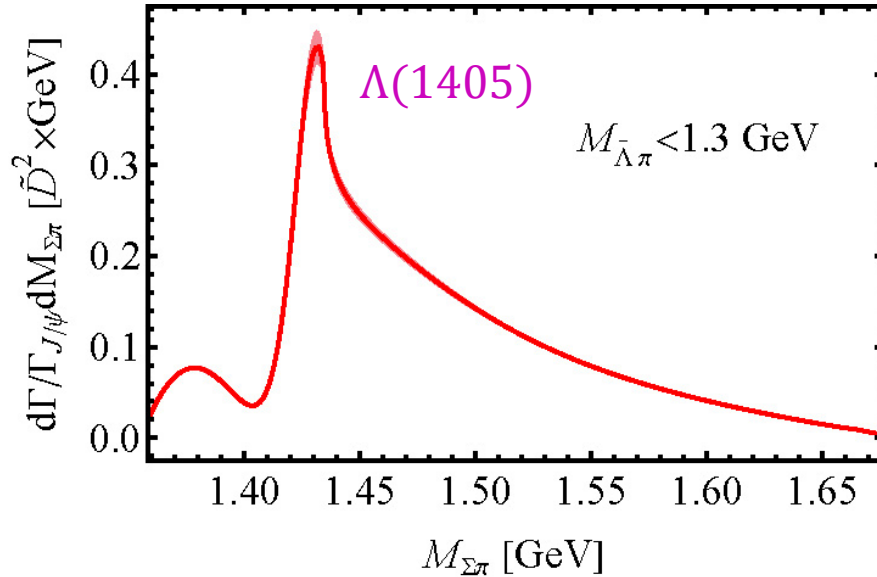


$\Lambda(1405)$ region

$\Sigma(1385)$?

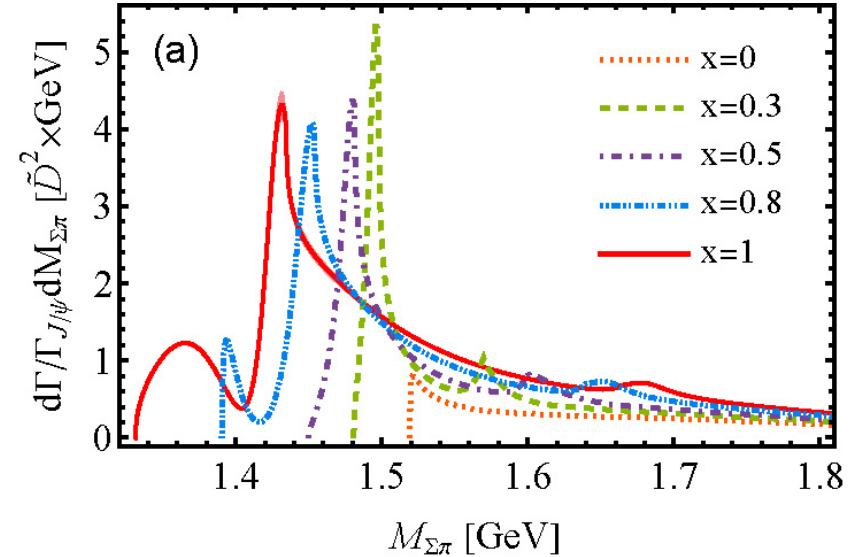
An SU(3) flavor filter

$$J/\psi \rightarrow \bar{\Lambda}\Sigma\pi$$



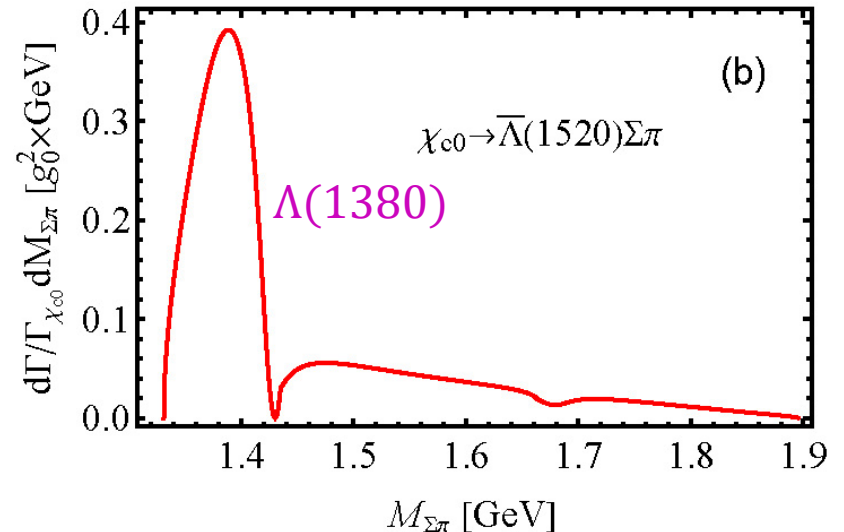
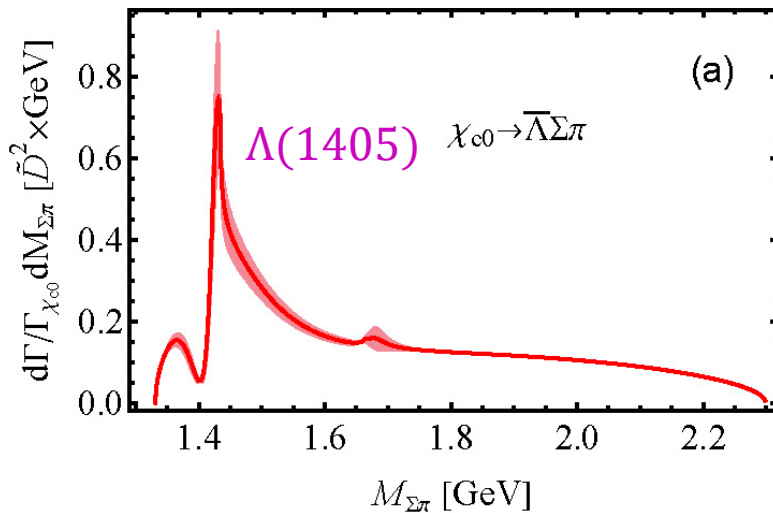
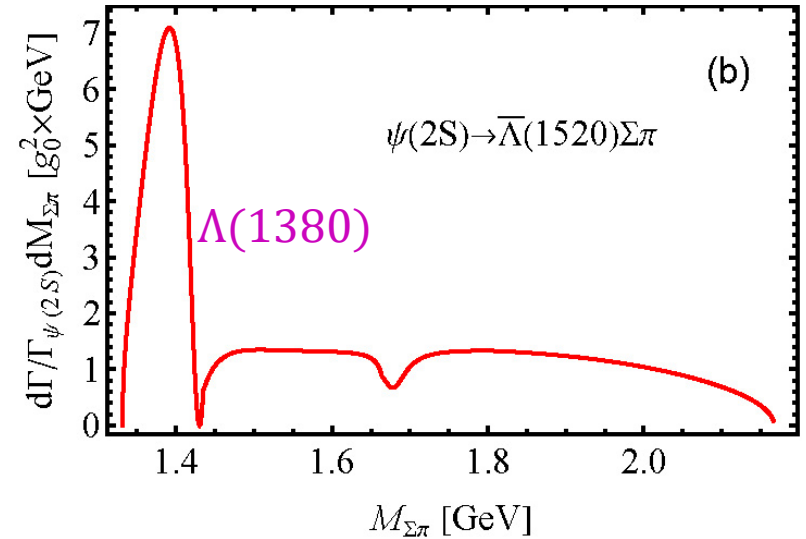
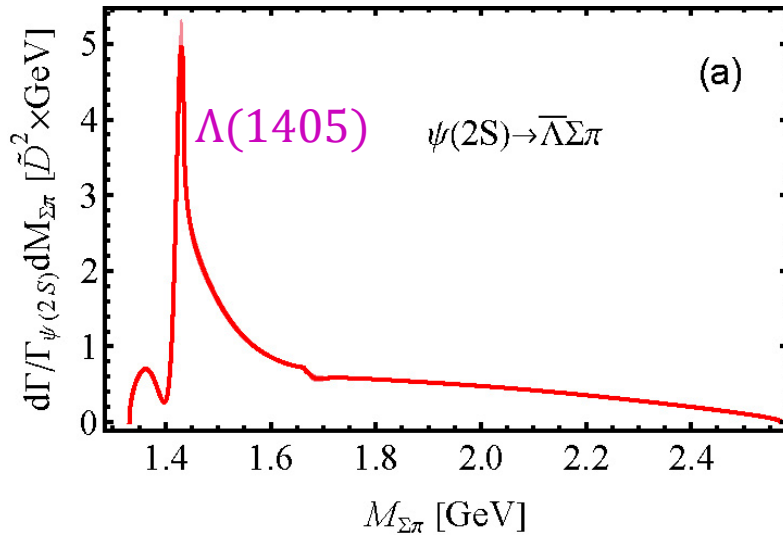
Invariant mass distribution of $\Sigma\pi$ by cutting

Interference with the background is not taken into account



No available data of $J/\psi \rightarrow \bar{\Lambda}(1520)\Sigma\pi$

An SU(3) flavor filter



$\chi_{c0} \rightarrow \bar{\Lambda}\Sigma\pi$ decay has ever been studied in [Liu, Wang, Xie, Song, Zhu, PRD98, 114017(2018)], the flavor filter is however ignored

Summary

- An SU(3) flavor filter is proposed to identify the two-pole structure of $\Lambda(1405/1380)$
 - The two poles are dynamically generated from different irreducible representations.
 - Huge data samples of heavy quarkonia accumulated in current experiments.
 - The spectator in the three-body decays is a good singlet/octet candidate.
- Other flavor filter
 - $Y \rightarrow \bar{D}^* D \pi$ decays, single out the triplet D_0^*

Thanks!