

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

Xiao-Hai Liu

**Center for Joint Quantum Studies & Department of Physics,
Tianjin University**

**Based on: Y.B. He, XHL, L.S. Geng, F.K. Guo, J.J. Xie,
arXiv:2407.13486**

East Asian Workshop on Exotic Hadrons, Nanjing, 2024-12-10

Outline

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

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

PDG 2022

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

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

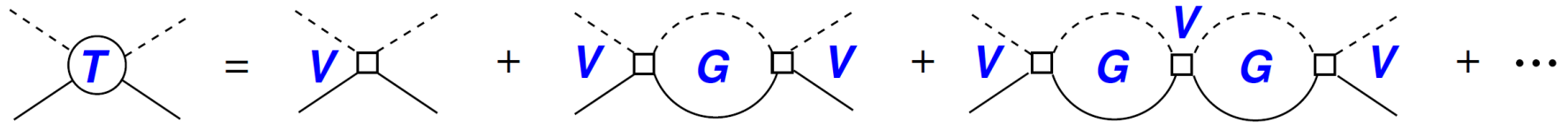
Quark model classification: a uds P-wave excitation, a few hundred MeV above the ground state $\Lambda(1116)$

- 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

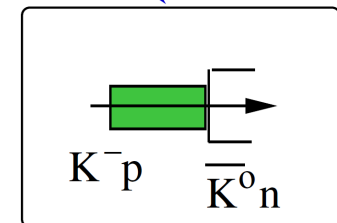
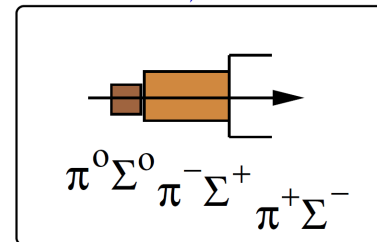
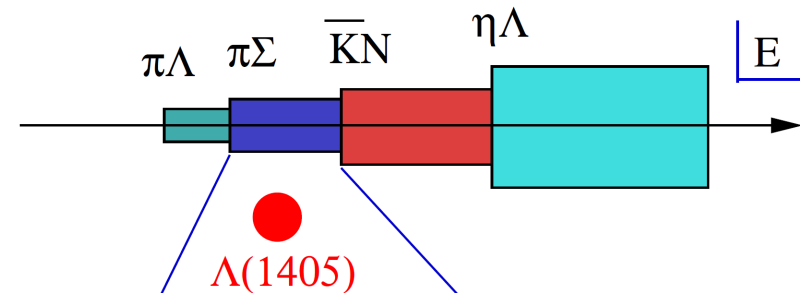
- Dynamically generated from the $\pi\Sigma - \bar{K}N$ coupled channel interaction in UChPT. (Hadronic molecule)



$$T = V + VGT$$

Bethe-Salpeter equation

Obtained from a chiral effective Lagrangian

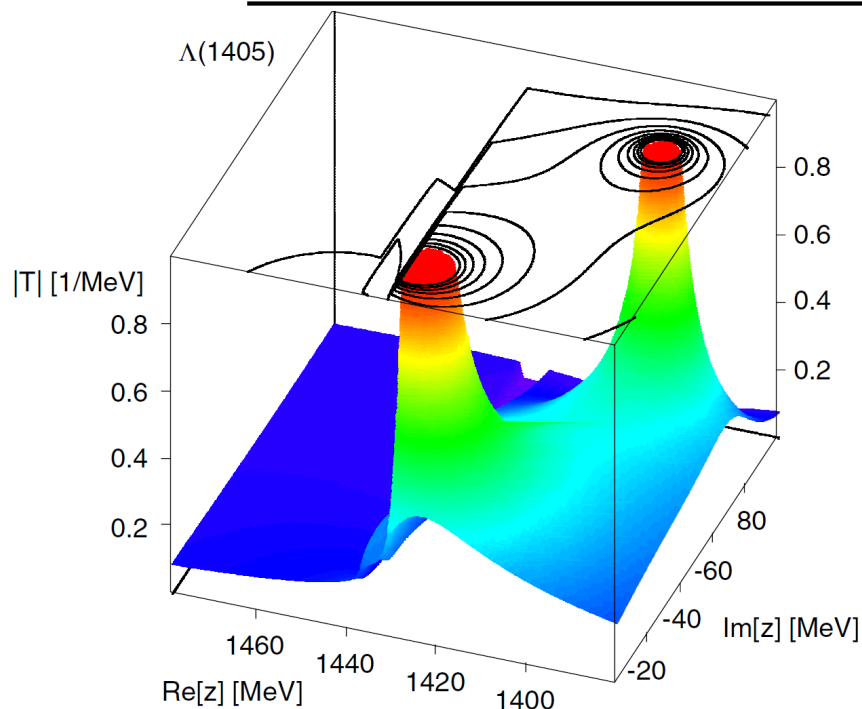


- Kaiser, Siegel, Weise, NPA594, 325(1995)
- Kaiser, Wass, Weise, NPA612, 297(1997)
- Oset & Ramos, NPA635, 99(1998)
- Oller, Oset, Ramos, PPNP45, 157(2000)
- Oller & Meissner, PLB500, 263(2001)
- **“first exotic hadron”**

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

Four
coupled-
channels

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	$\underline{-2.5 + 0.94i}$	<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



Oset, Ramos, Bennhold, 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  $\underbrace{\mathbf{1} \oplus \mathbf{8}_s \oplus \mathbf{8}_a}_{\text{attractive}} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27}$

In the SU(3) basis

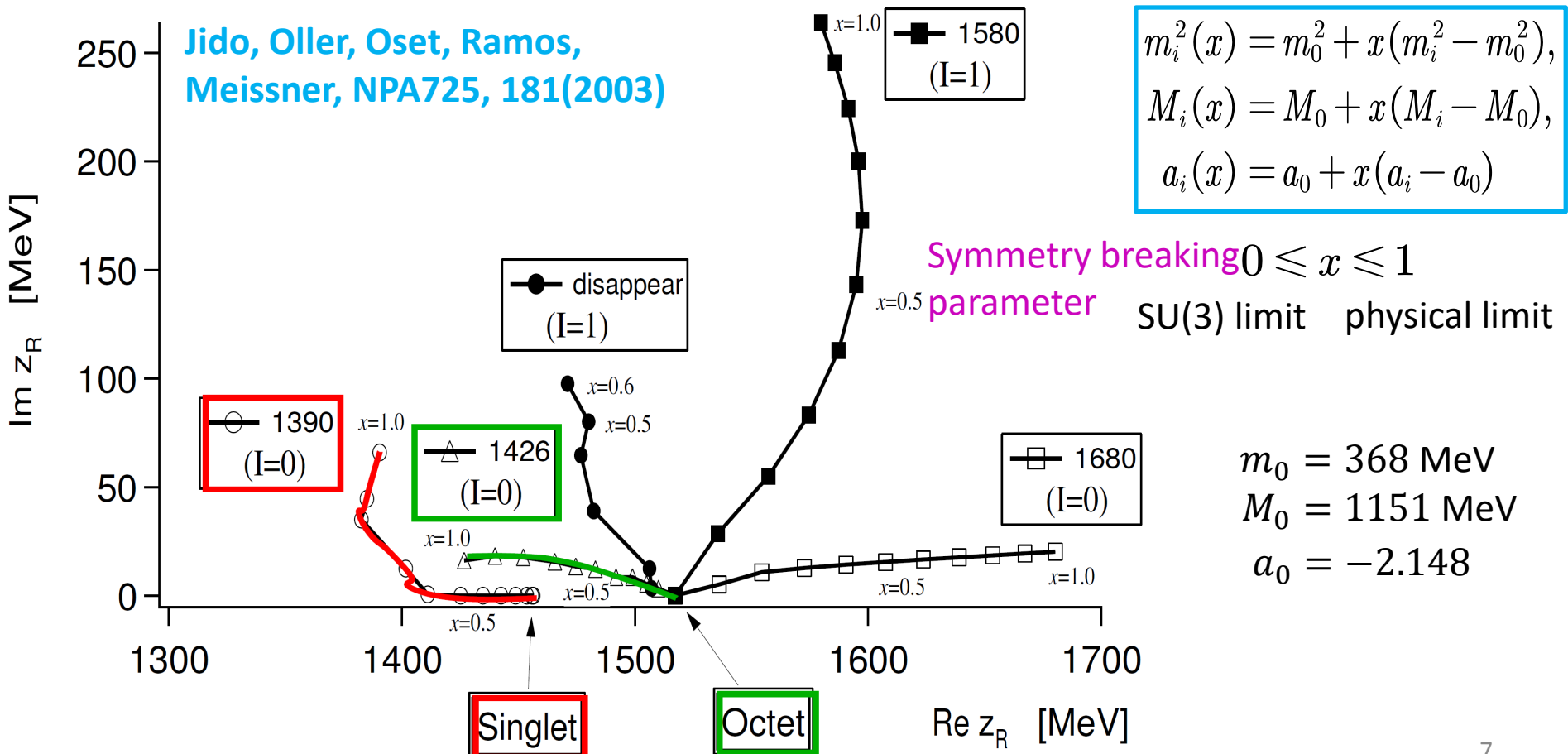
$$C_{\alpha\beta}^{\text{SU}(3)} = \sum_{i,j} \mathcal{D}_{\alpha i} C_{ij} \mathcal{D}_{\beta j} \quad \text{SU(3) C-G}$$

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

$\underbrace{\quad}_{\text{attractive}}$

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

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.

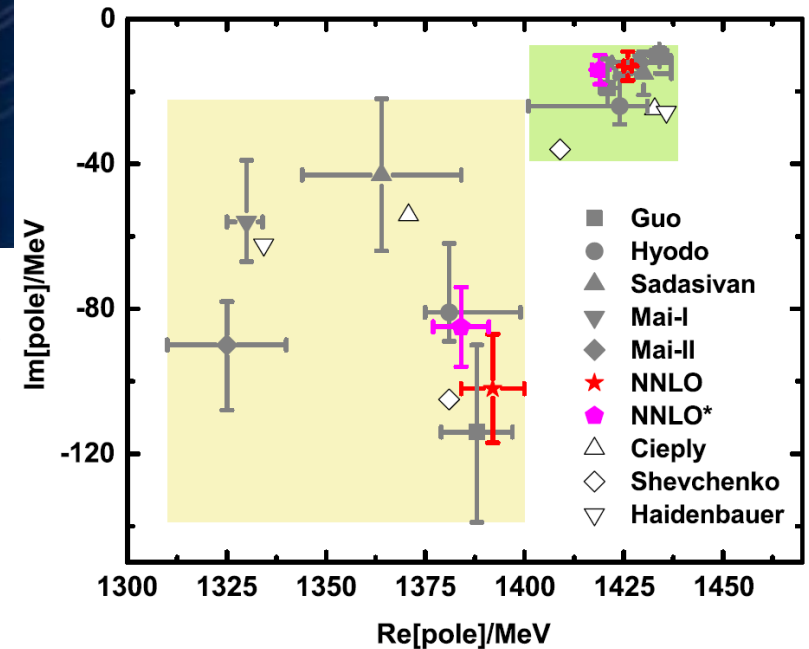
approach	pole 1 [MeV]	pole 2 [MeV]
Refs. [14, 15], NLO	$1424_{-23}^{+7} - i 26_{-14}^{+3}$	$1381_{-6}^{+18} - i 81_{-8}^{+19}$
Ref. [17], Fit II	$1421_{-2}^{+3} - i 19_{-5}^{+8}$	$1388_{-9}^{+9} - i 114_{-25}^{+24}$
Ref. [18], solution #2	$1434_{-2}^{+2} - i 10_{-1}^{+2}$	$1330_{-5}^{+4} - i 56_{-11}^{+17}$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

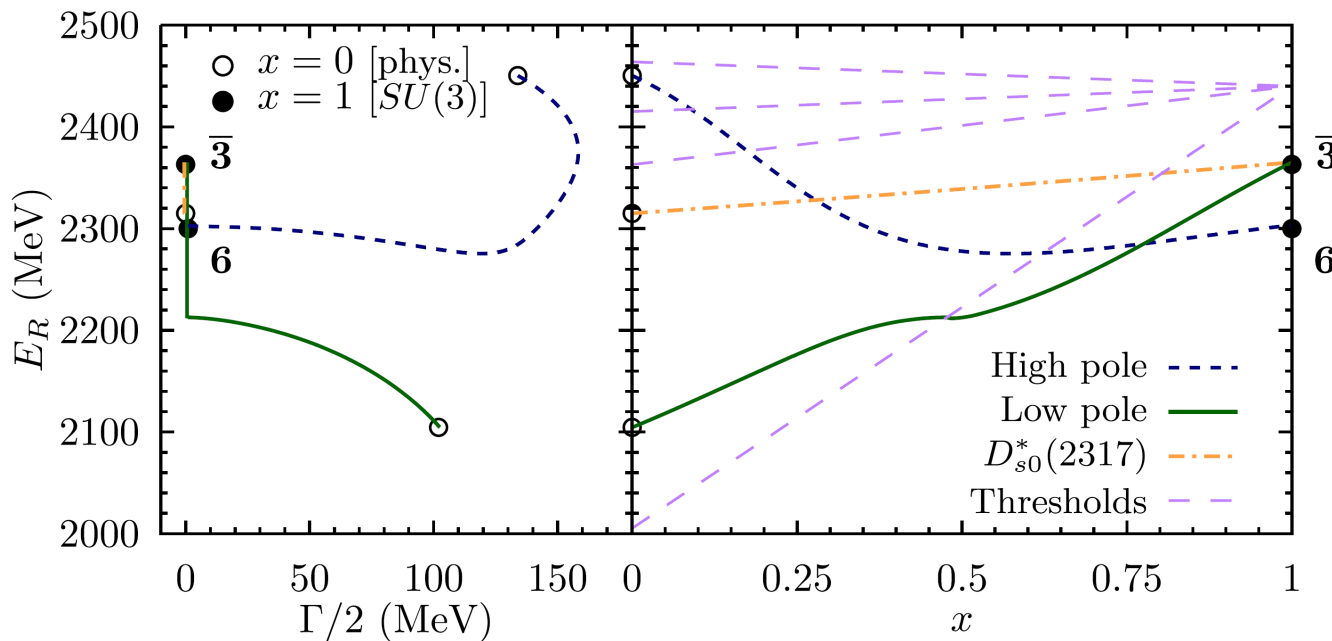
$D_0(J^P = 0^+)$: Analog in the heavy flavor sector

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)



$$(D^0, D^+, D_s^+) \quad \bar{3} \otimes 8 = \bar{15} \oplus \underbrace{6 \oplus \bar{3}}_{\text{attractive}}$$

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!

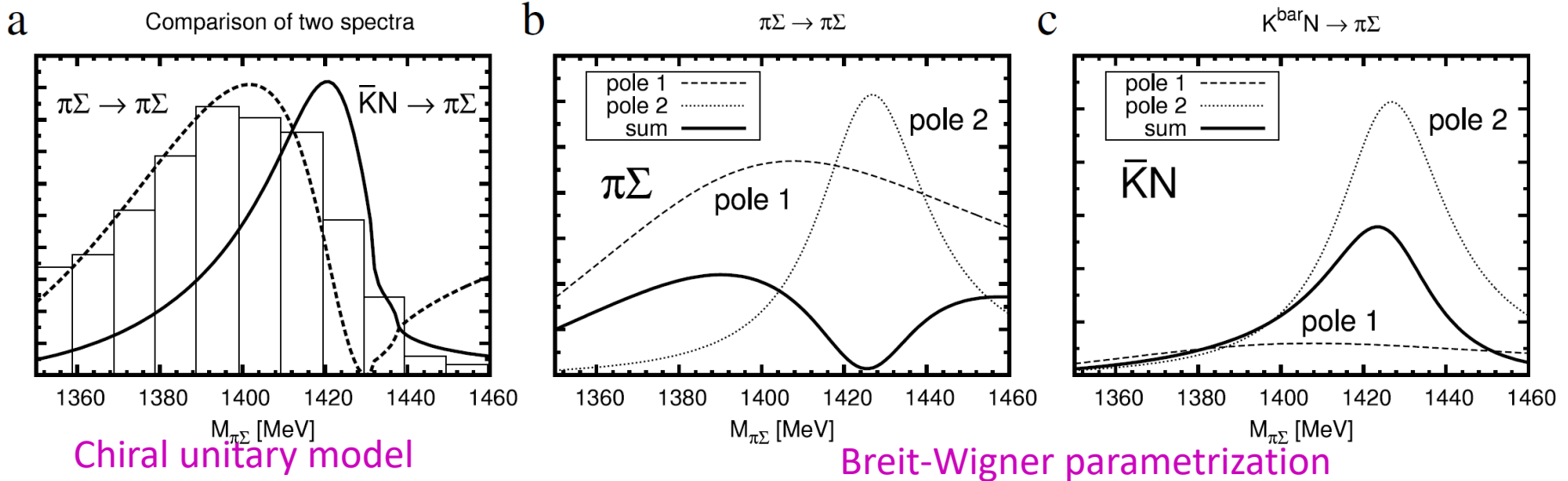
Ulf-G. Meißner ^{1,2,3}

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

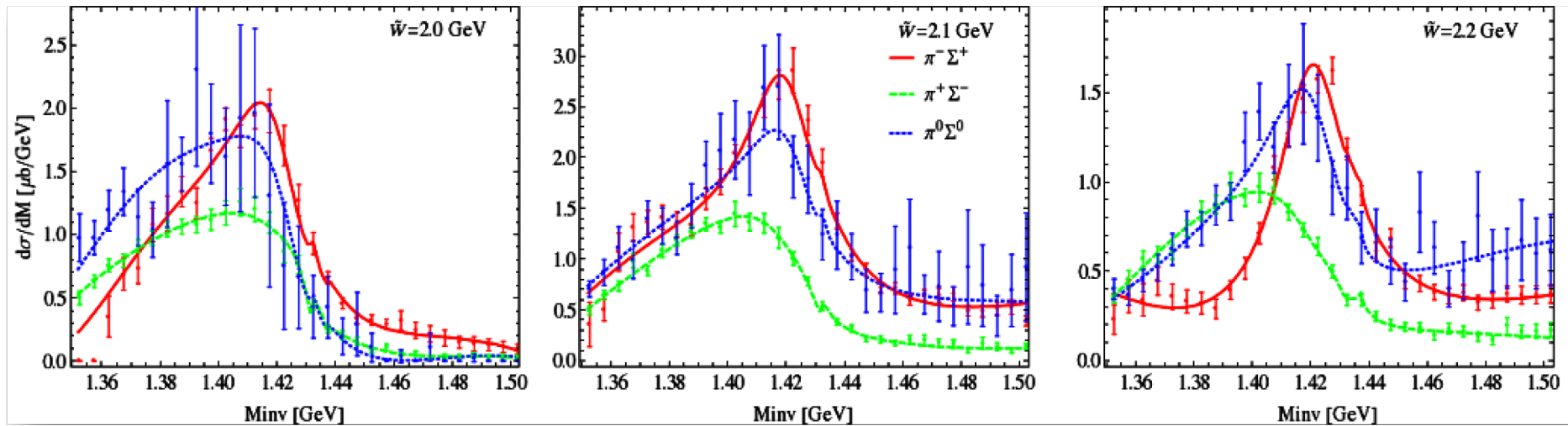


Jido et al., NPA725, 181(2003); NPA835, 59(2010)

z_R ($I = 0$)	1390 + 66i		1426 + 16i	
	g_i	$ g_i $	g_i	$ g_i $
$\pi\Sigma$	$-2.5 - 1.5i$	<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
$K\Sigma$	$-0.45 - 0.41i$	0.61	$0.11 - 0.33i$	0.35

Identify the two-pole structures

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

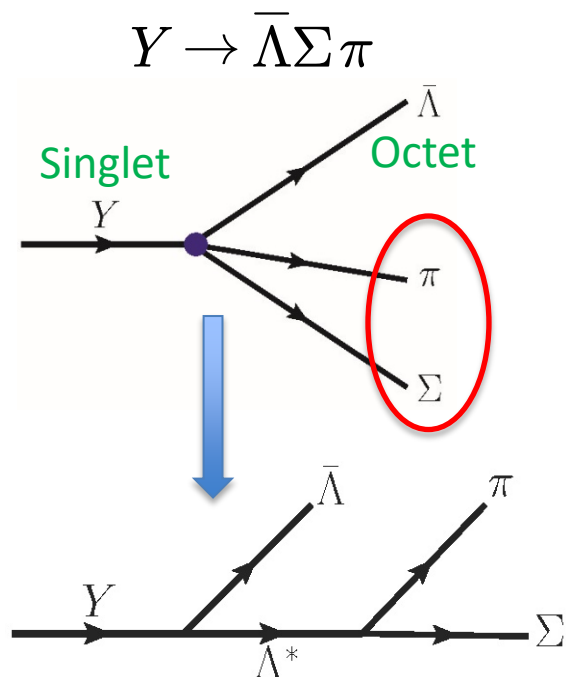


Result of the fits to the CLAS photoproduction data in three channels
A chiral unitary model adopted

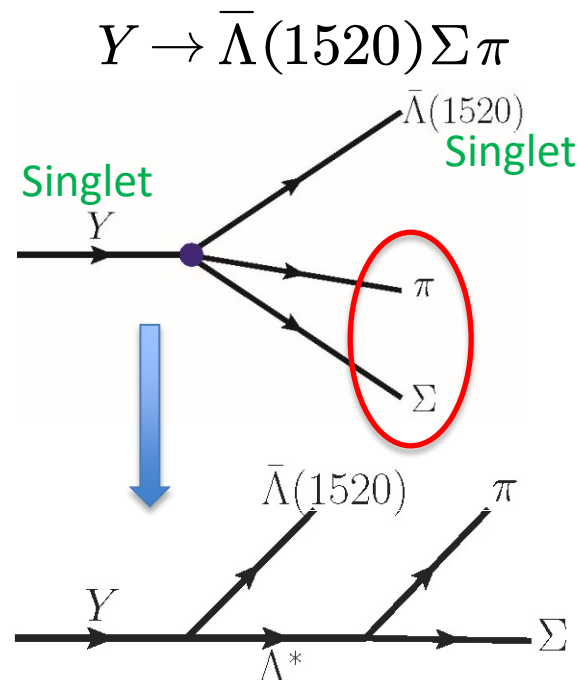
Solution	Pole 1	Pole 2
#2	$1434^{+2}_{-2} - i 10^{+2}_{-1}$	$1330^{+4}_{-5} - i 56^{+17}_{-11}$
#4	$1429^{+8}_{-7} - i 12^{+2}_{-3}$	$1325^{+15}_{-15} - i 90^{+12}_{-18}$

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^***

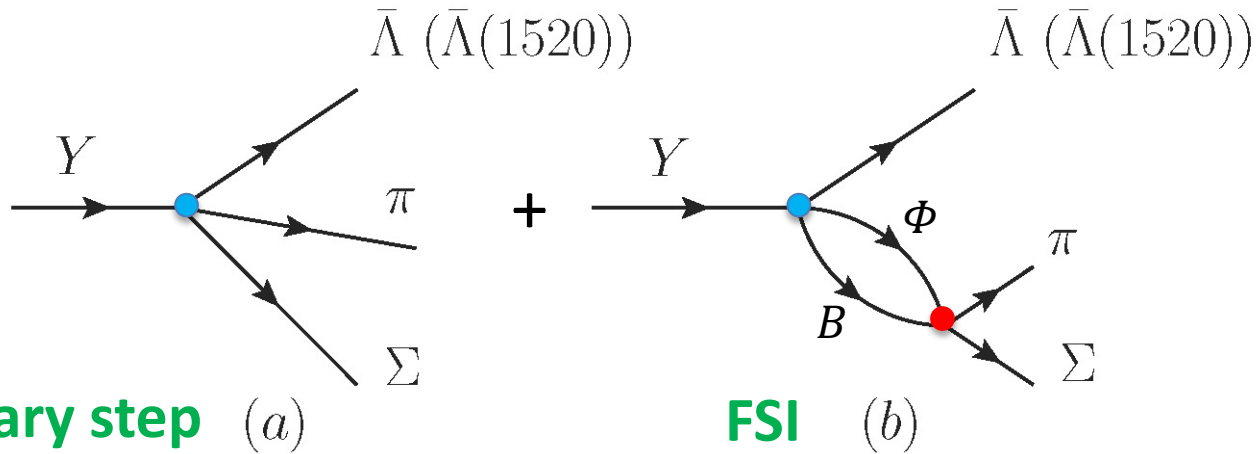
SU(3) symmetry requirement

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

Formalism



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

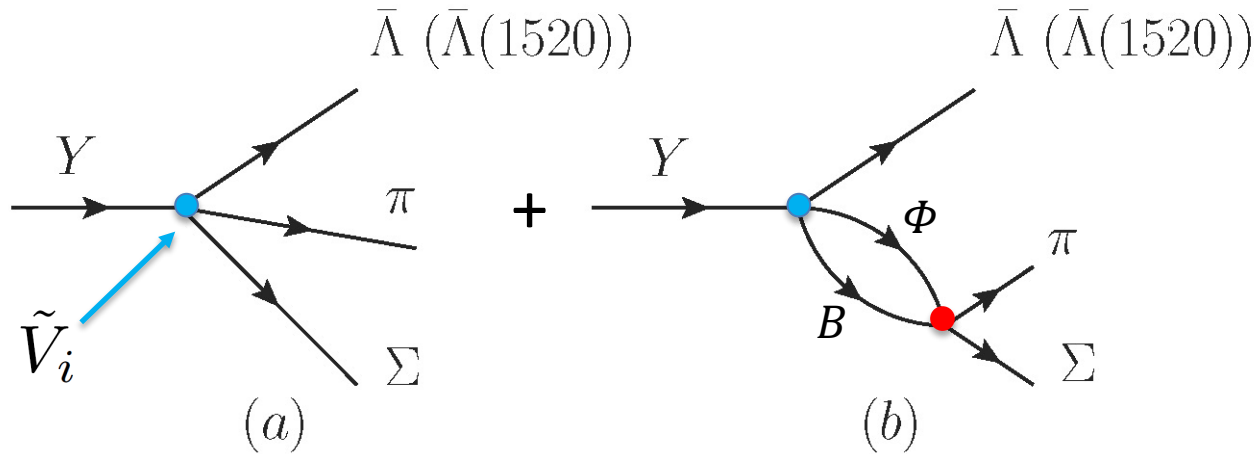
$$\mathcal{L}'_\psi = g_0 \bar{\Lambda}_\mu \gamma_5 \langle \Phi, B \rangle \psi^\mu$$

Four coupled channels

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

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

Formalism



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

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

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

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

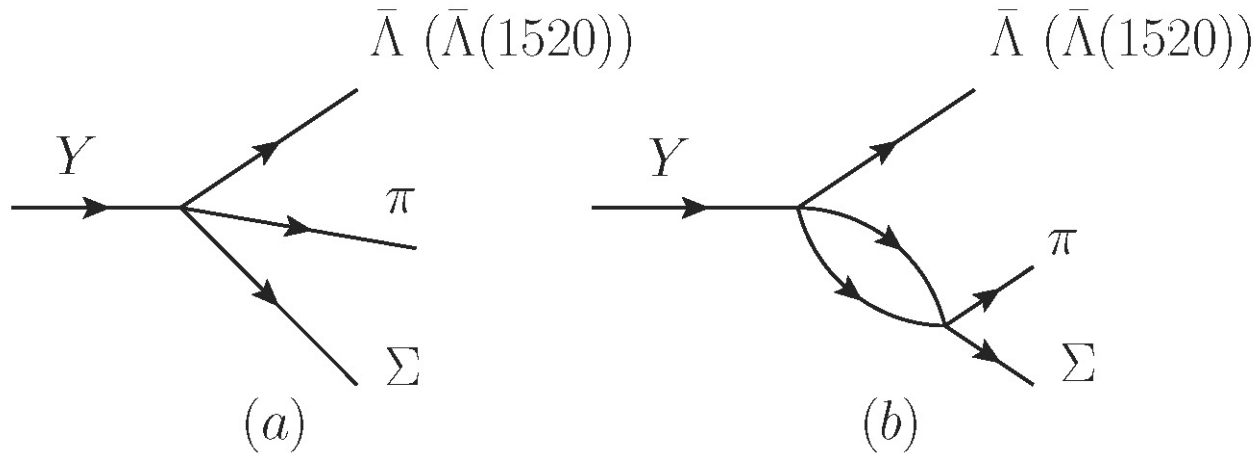
$$\left. - \ln(-s + (M_l^2 - m_l^2) + 2q_l\sqrt{s}) - \ln(-s - (M_l^2 - m_l^2) + 2q_l\sqrt{s})] \right\}$$

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

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

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

Formalism



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

Coefficient in $\tilde{V}_i$
$$h_{\pi\Sigma} = -\sqrt{2}\tilde{D}, \quad h_{\bar{K}N} = -\sqrt{\frac{1}{3}}\tilde{D} - \sqrt{3}\tilde{F},$$

$$h_{\eta\Lambda} = -\sqrt{\frac{2}{3}}\tilde{D}, \quad h_{K\Xi} = \sqrt{\frac{1}{3}}\tilde{D} - \sqrt{3}\tilde{F}.$$

$$h_{\pi\Sigma} = -\sqrt{3}g_0, \quad h_{\bar{K}N} = \sqrt{2}g_0,$$

$$h_{\eta\Lambda} = g_0, \quad h_{K\Xi} = -\sqrt{2}g_0.$$

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

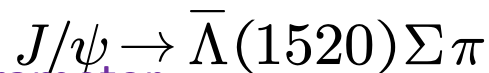
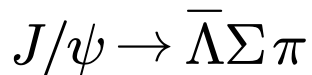
$$\mathcal{R}_{F/D} \equiv \frac{\tilde{F}}{\tilde{D}} = 0.18 \pm 0.03$$

- For $\psi(3686)$ decays

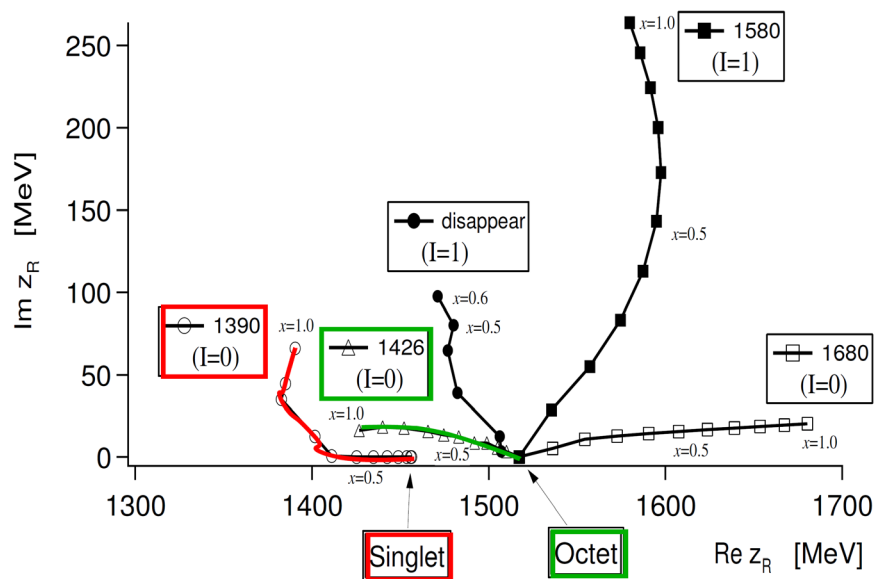
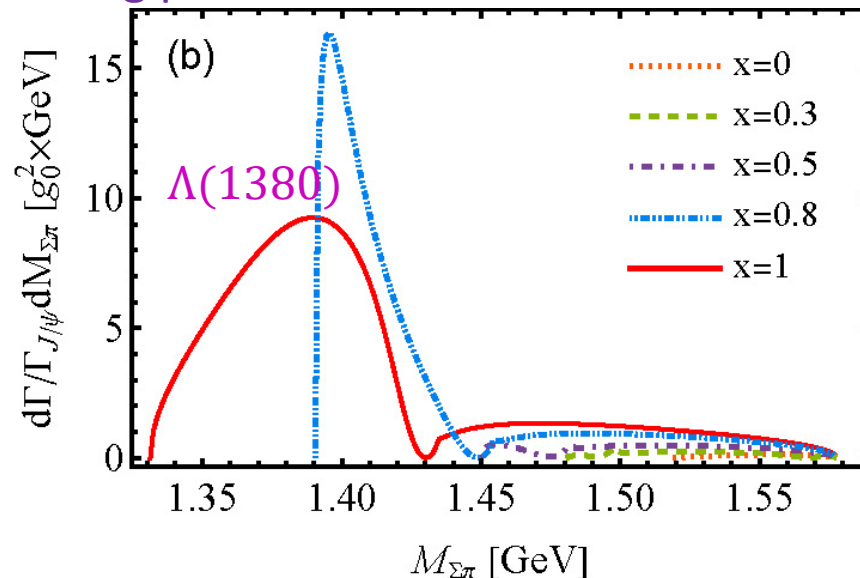
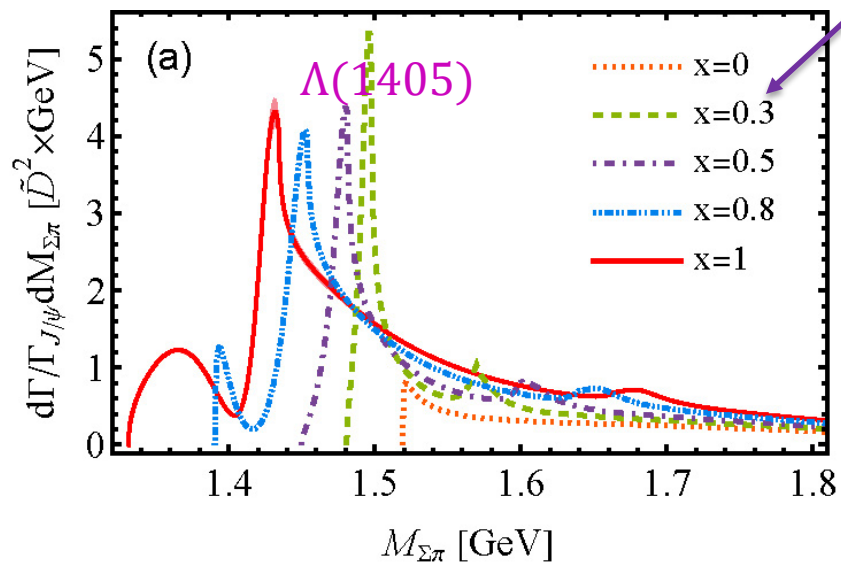
$$\mathcal{R}_{F/D} \equiv \frac{\tilde{F}}{\tilde{D}} = 0.50 \pm 0.06$$

Braching fractions of J/ψ decay modes
PDG 2022

An $SU(3)$ flavor filter



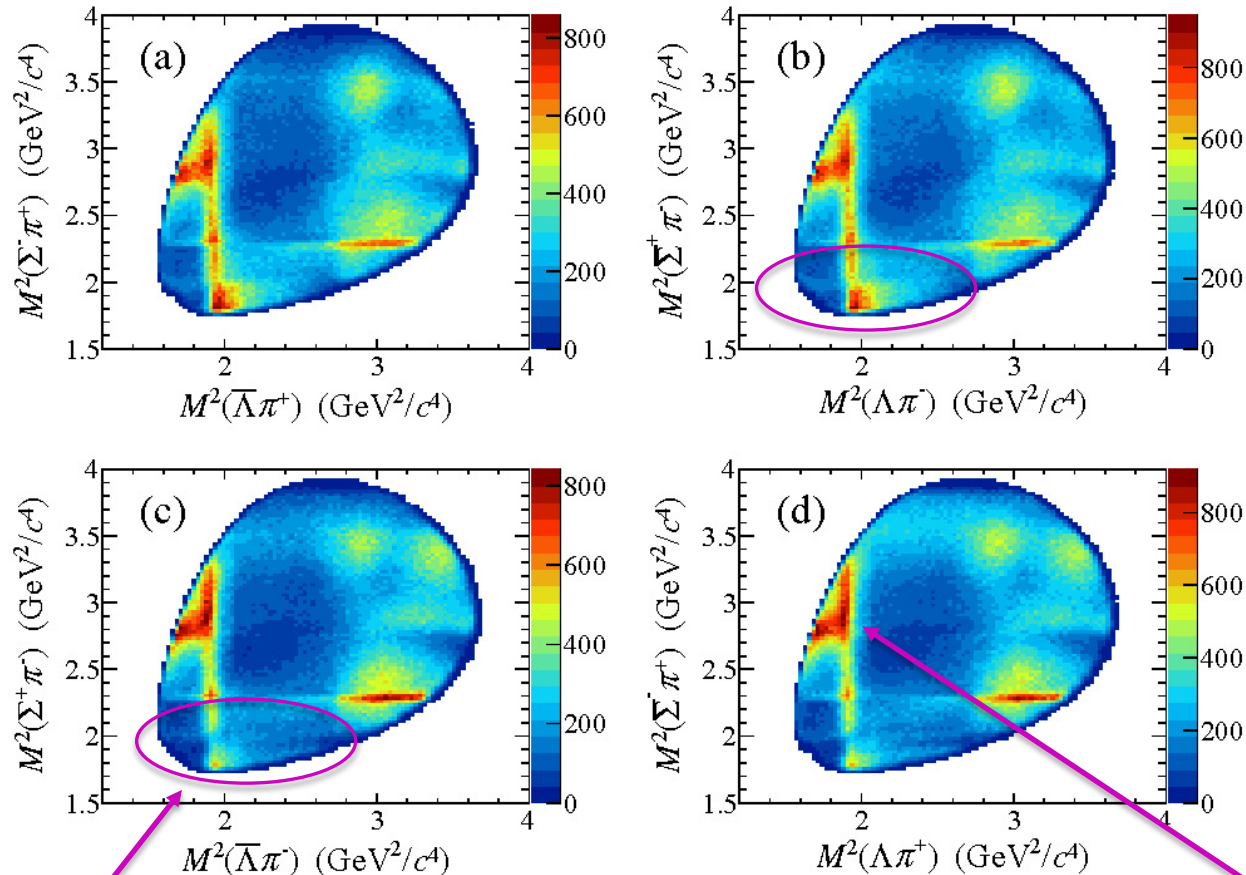
Symmetry breaking parameter



$$\begin{aligned} m_0 &= 368 \text{ MeV} \\ M_0 &= 1151 \text{ MeV} \\ a_0 &= -2.148 \end{aligned}$$

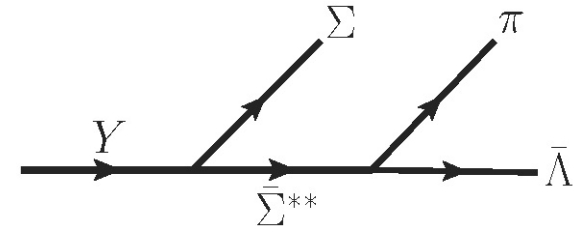
Background

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



$\Lambda(1405)$ region

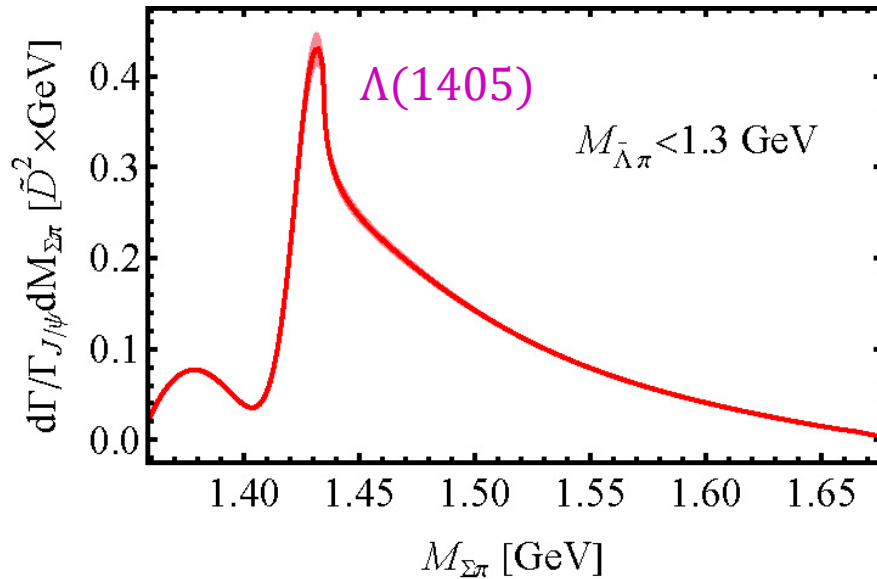
$\Sigma(1385)$?



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

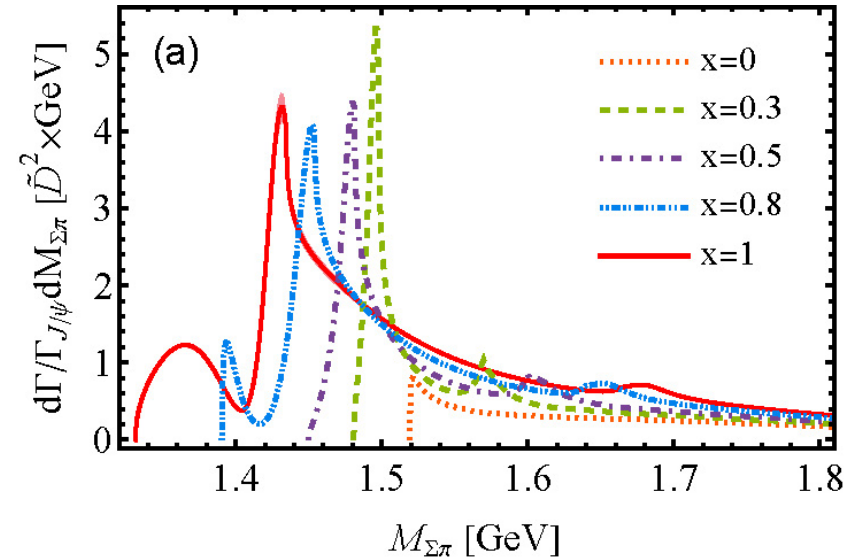
An SU(3) flavor filter

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



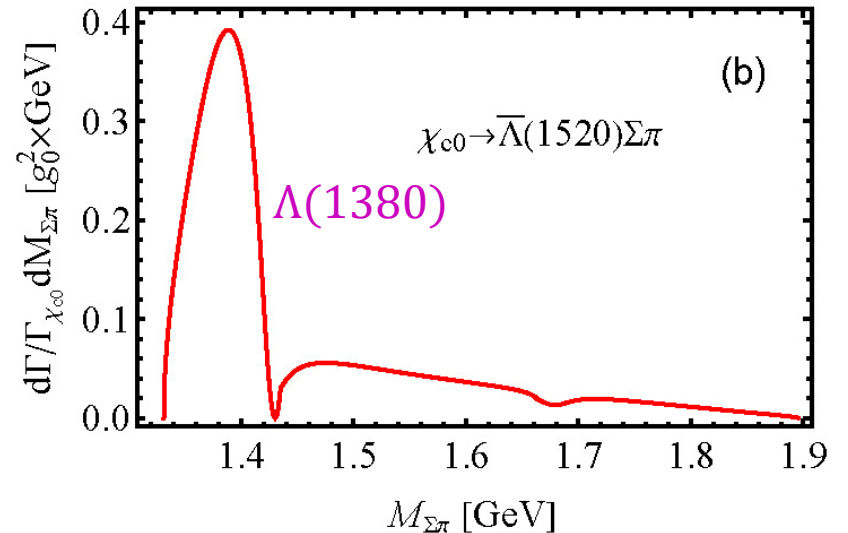
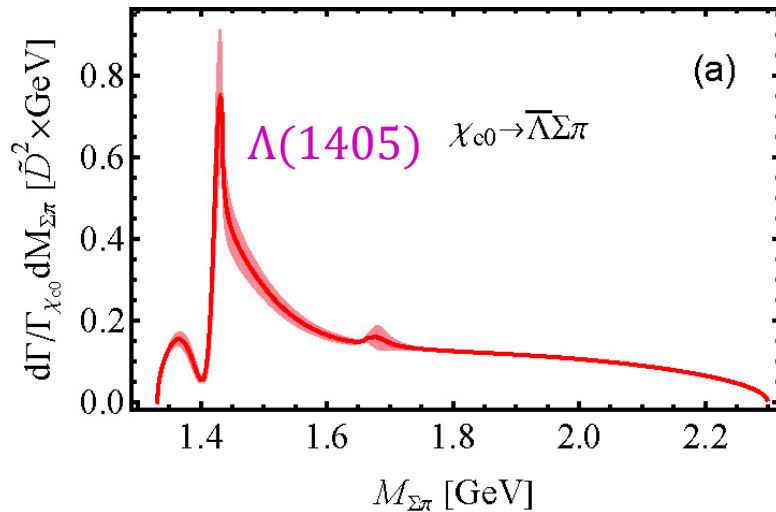
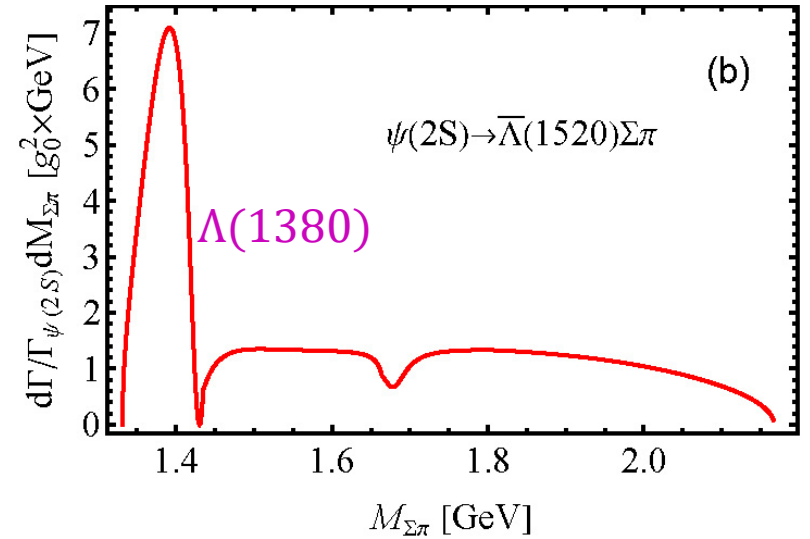
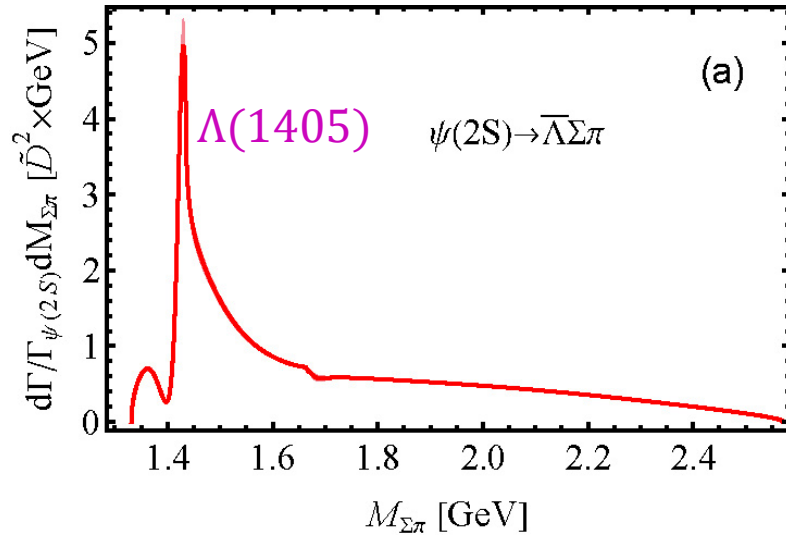
Invariant mass distribution of $\Sigma\pi$ by cutting

Interference with the background is not taken into account



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

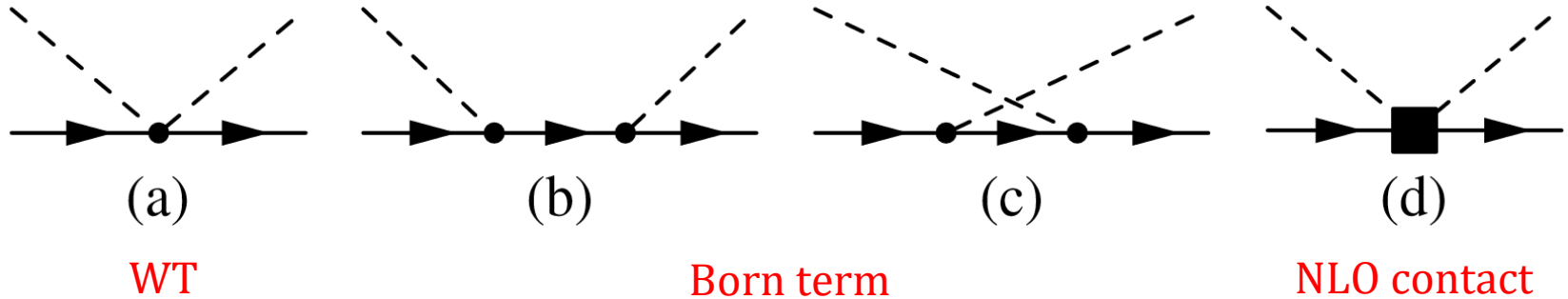
An SU(3) flavor filter



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

NLO Contributions

Pseudoscalar meson octet scattering off light baryon octet



$$\mathcal{L}_{MB}^{(1)} = \text{Tr}(\bar{\mathcal{B}}(i\gamma_\mu \mathcal{D}^\mu - M_0)\mathcal{B} - D\bar{\mathcal{B}}\gamma_\mu\gamma_5\{a^\mu, \mathcal{B}\} - F\bar{\mathcal{B}}\gamma_\mu\gamma_5[a^\mu, \mathcal{B}])$$

$$\begin{aligned} \mathcal{L}_{MB}^{(2)} = & b_0 \text{Tr}(\bar{\mathcal{B}}\mathcal{B}) \text{Tr}(\chi_+) + b_D \text{Tr}(\bar{\mathcal{B}}\{\chi_+, \mathcal{B}\}) + b_F \text{Tr}(\bar{\mathcal{B}}[\chi_+, \mathcal{B}]) \\ & + d_1 \text{Tr}(\bar{\mathcal{B}}\{u_\mu, [u^\mu, \mathcal{B}]\}) + d_2 \text{Tr}(\bar{\mathcal{B}}[u_\mu, [u^\mu, \mathcal{B}]]) \\ & + d_3 \text{Tr}(\bar{\mathcal{B}}u_\mu) \text{Tr}(\mathcal{B}u^\mu) + d_4 \text{Tr}(\bar{\mathcal{B}}\mathcal{B}) \text{Tr}(u_\mu u^\mu), \end{aligned}$$

Scheme 1: Born terms + NLO contact terms (NLO1)

Scheme 2: NLO contact terms

(NLO2)

Ikeda, Hyodo, Weise,
NPA881, 98(2012)

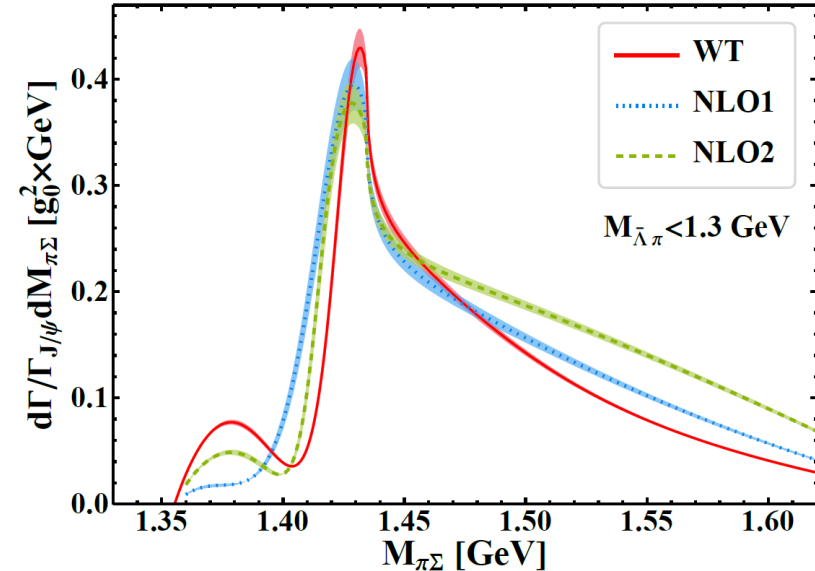
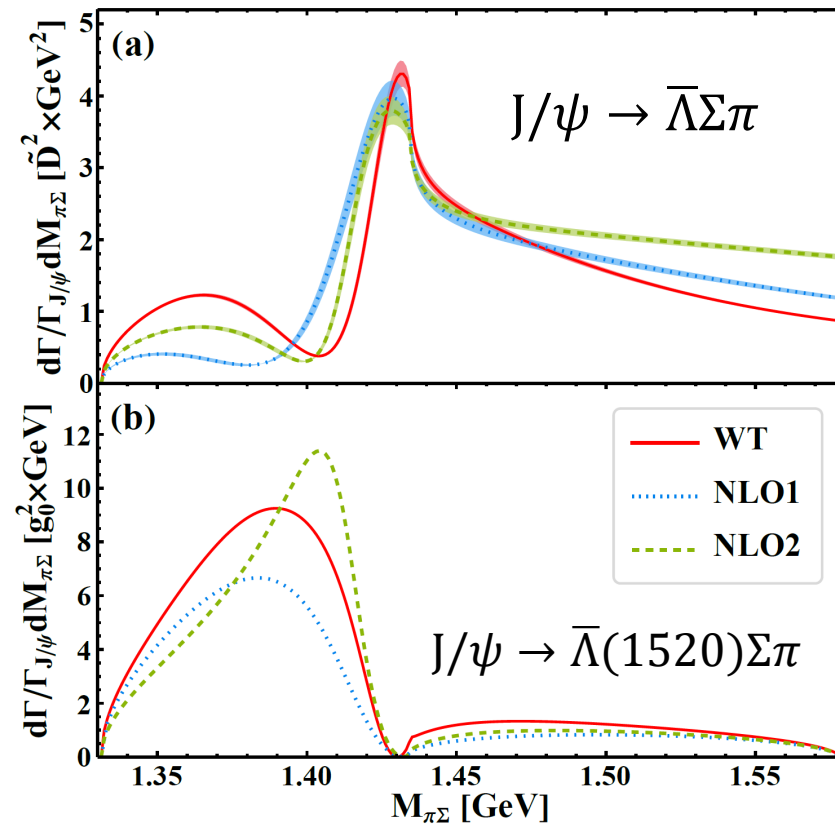
Guo, Kamiya, Mai, Meissner,
PLB846,138264(2023)

NLO Contributions

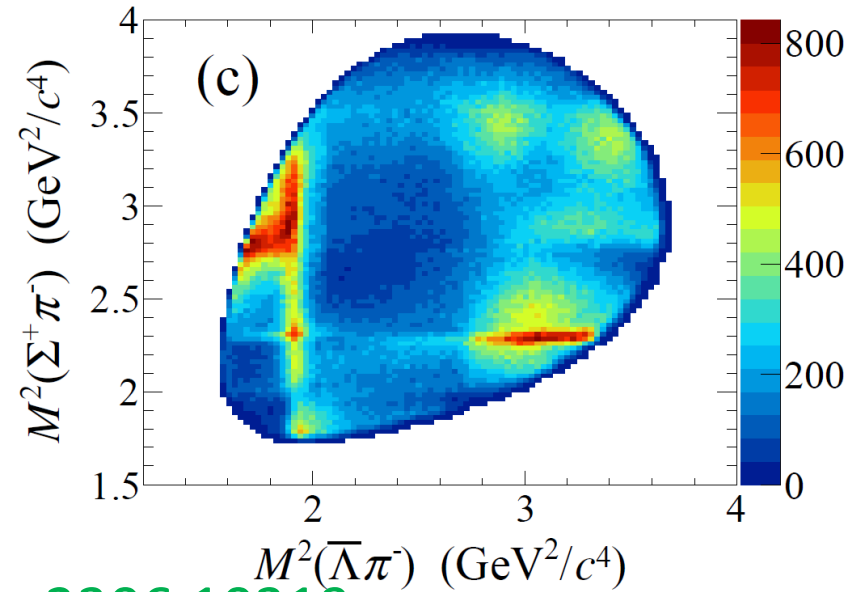
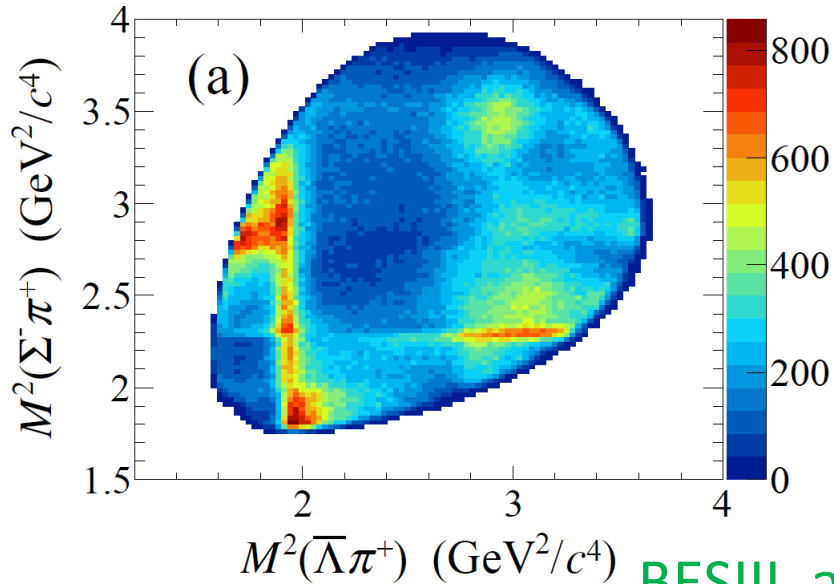
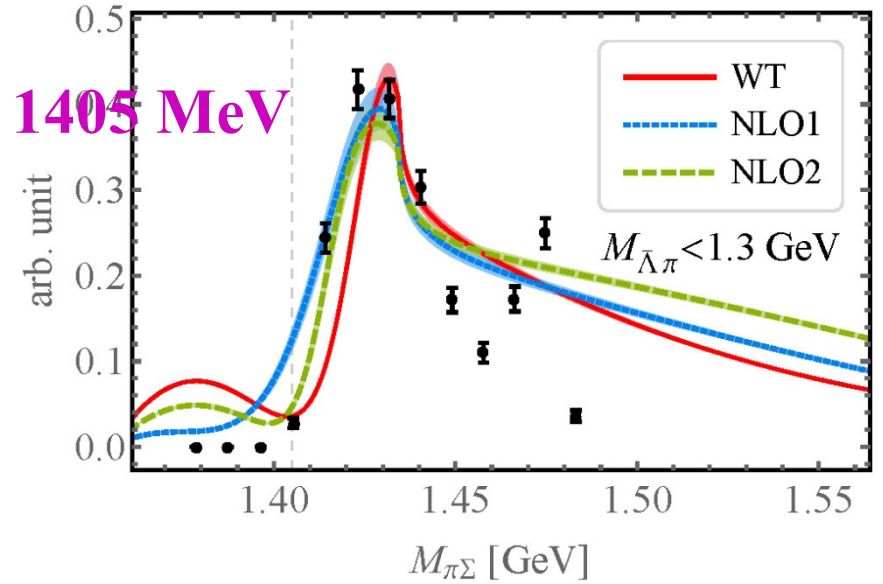
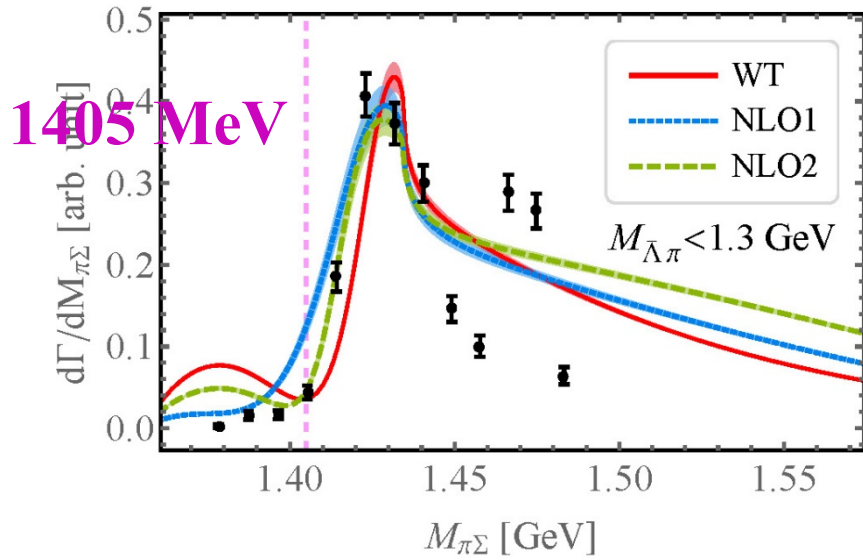
Pole positions (MeV)	$\Lambda(1380)$	$\Lambda(1405)$
WT	1390-i66	1426-i16
NLO1	1381-i81	1424-i26
NLO2	1415-i165.7	1417.9-i15.9

Ikeda, Hyodo, Weise, NPA881, 98(2012)

Guo, Kamiya, Mai, Meissner, PLB846, 138264(2023)

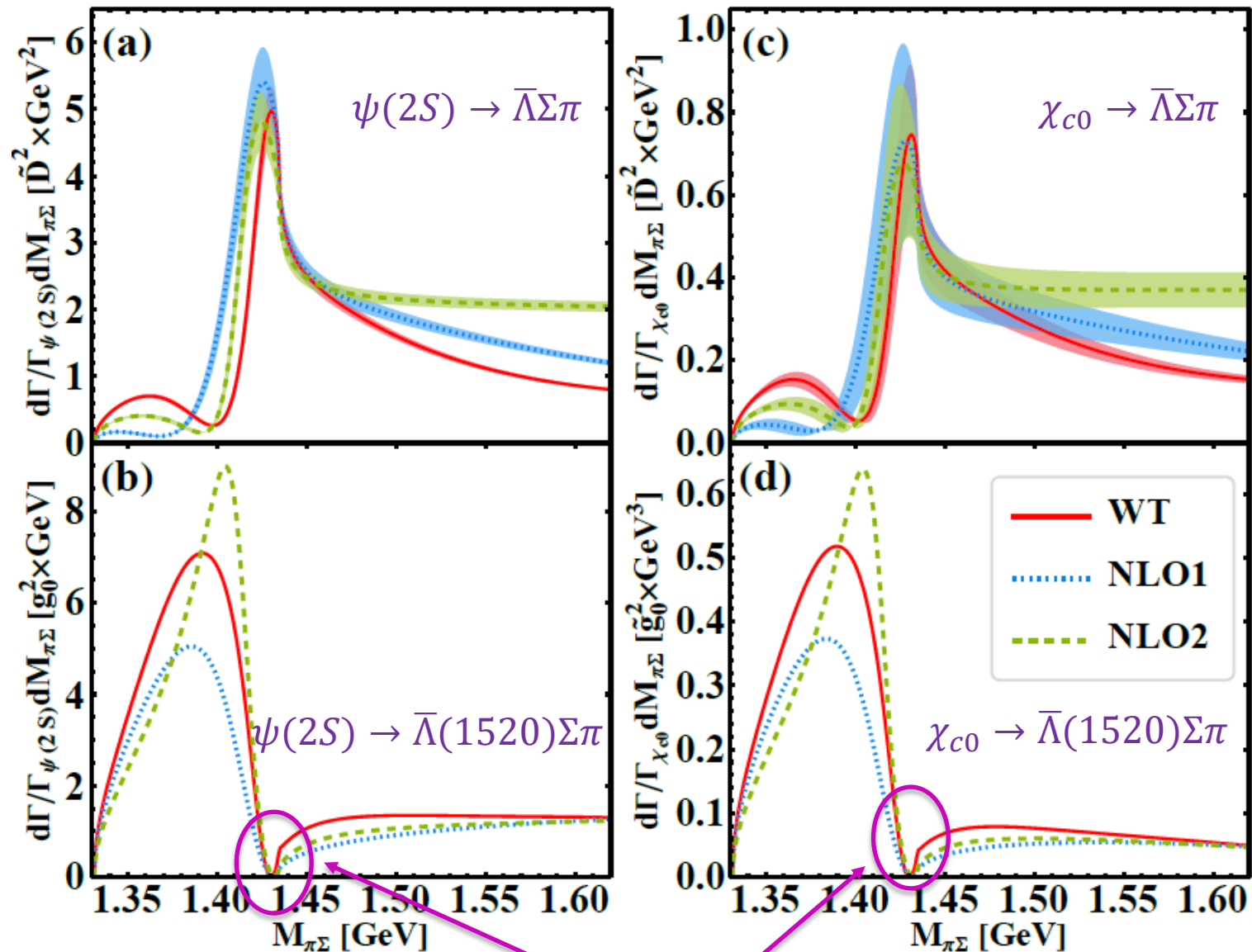


Data & Model



BESIII, arXiv:2306.10319

NLO Contributions



dips

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!