Identify the two-pole structures of Λ(1405) using an SU(3) flavor filter

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Outline

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

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

PDG 2022

$$\mathrm{I}\left(\mathrm{J^P}\right) = 0(1/2^-)$$

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

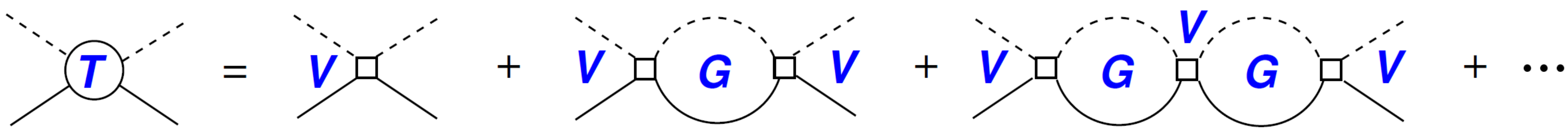
Quark model classification: a *uds* P-wave excitation, a few hundred MeV above the ground state $\Lambda(1116)$

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

?

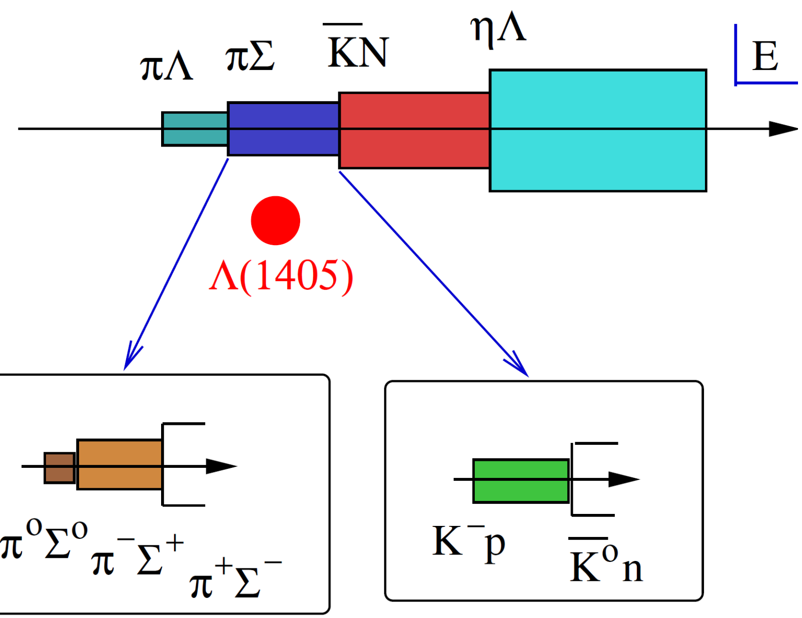
Λ(1405): Dynamically generated state

- 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

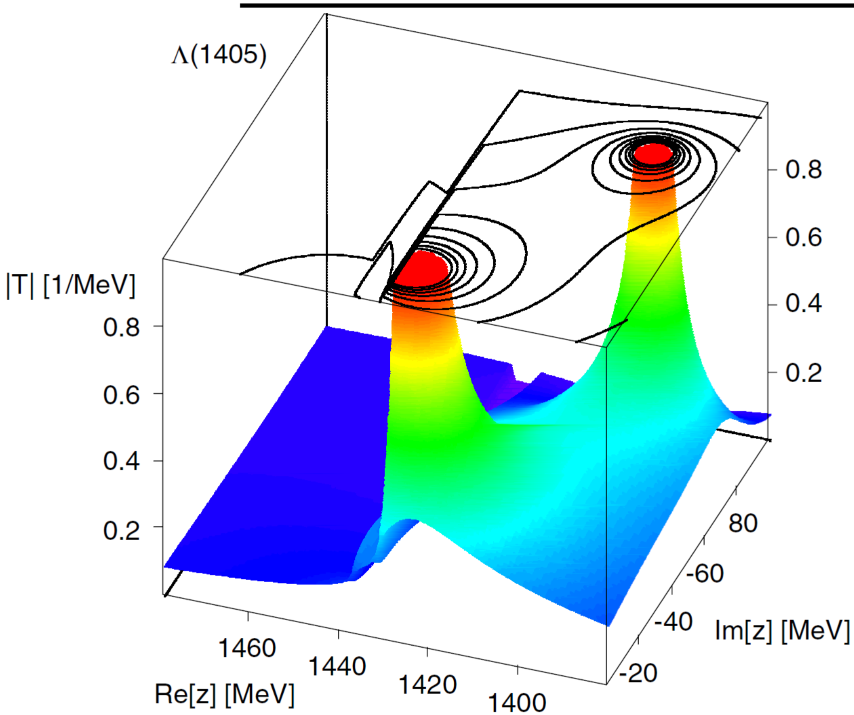


- Kaiser, Siegel, Weise, NPA594, 325(1995)
- Kaiser, Wass, Weise, NPA612, 297(1997)
- Oset & Ramos, NPA635, 99(1998)
- Oller, Oset, Ramos, PPNP45, 157(2000)
- Oller & Meissner, PLB500, 263(2001)
- …… **"first exotic hadron"**

Λ(1405): Two-pole structure

Four coupled-channels

z_R	$1390 + 66i$		$1426 + 16i$	
$(I = 0)$	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



Hyodo & Jido, PPNP67, 55(2012)

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)

➢ Understanding with group theory

Weinberg-Tomozawa (WT) term dominates the interaction

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

Decomposed into group irreducible representations

GB Octet

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

Baryon Octet

attractive ($\mathbf{1} \oplus 8_s \oplus 8_a$)

In the SU(3) basis

SU(3) C-G

$$C_{\alpha\beta}^{\mathrm{SU(3)}} = \sum_{i,j} \mathcal{D}_{\alpha i} C_{ij} \mathcal{D}_{\beta j}$$

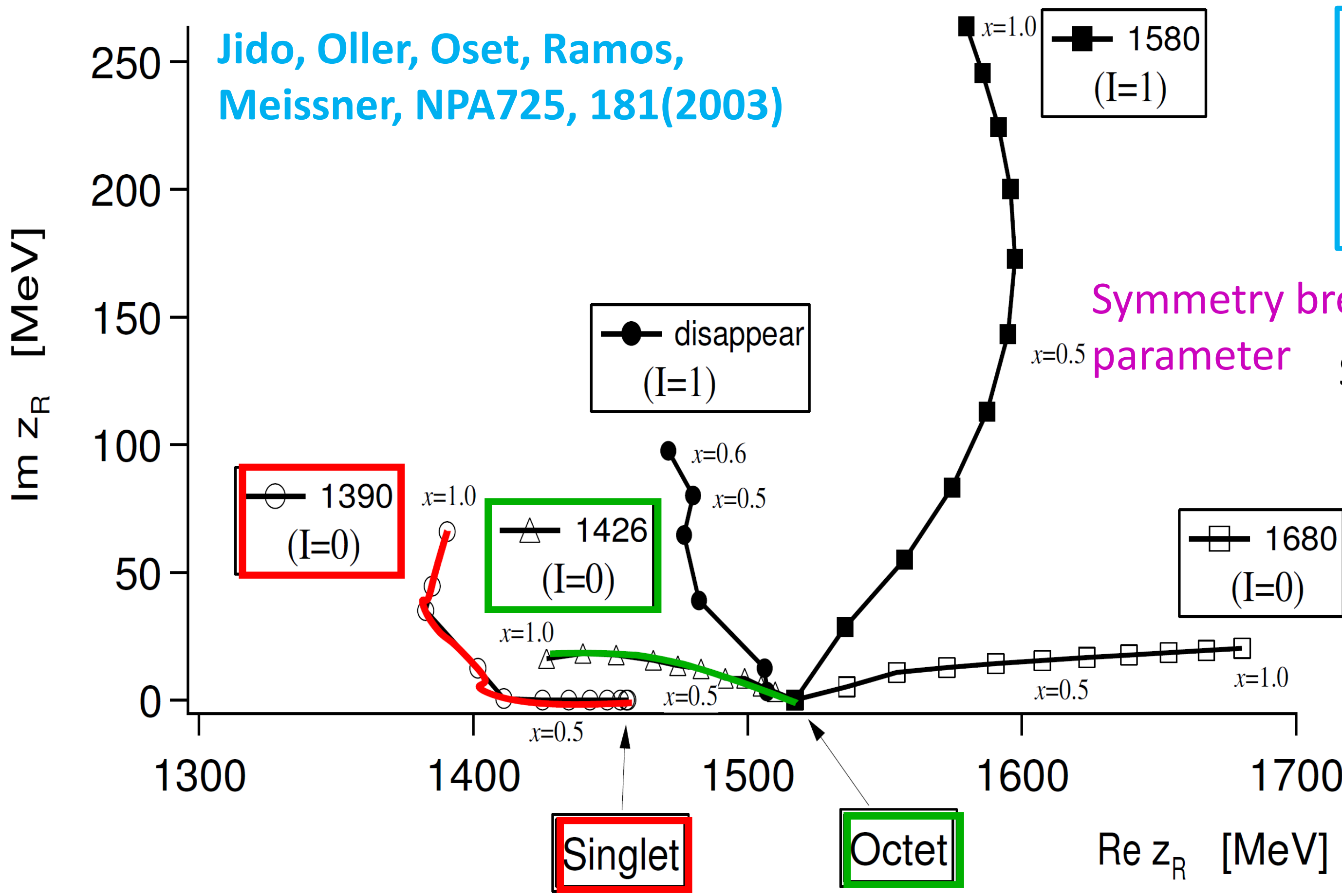
$$= \mathrm{diag}(6, 3, 3, 0, 0, -2)$$

attractive ($6, 3, 3$)

Two-pole Structure

➢ Understanding with group theory

z_R	$1390+66i$		$1426+16i$		$1680+20i$	
$(I=0)$	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$
$\pi\Sigma$	$-2.5-1.5i$	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



$$m_i^2(x) = m_0^2 + x(m_i^2 - m_0^2),$$
$$M_i(x) = M_0 + x(M_i - M_0),$$
$$a_i(x) = a_0 + x(a_i - a_0)$$

Symmetry breaking parameter $0 \leqslant x \leqslant 1$

SU(3) limit physical limit

$m_0 = 368$ MeV
$M_0 = 1151$ MeV
$a_0 = -2.148$

Λ(1405): Two-pole structure

PDG 2022

Λ(1380)
Λ(1405)

Λ BARYONS (S = −1, I = 0)

$\Lambda^0 = u\,d\,s$

Λ and Σ Resonances PDF

Pole Structure of the Λ(1405) Region PDF

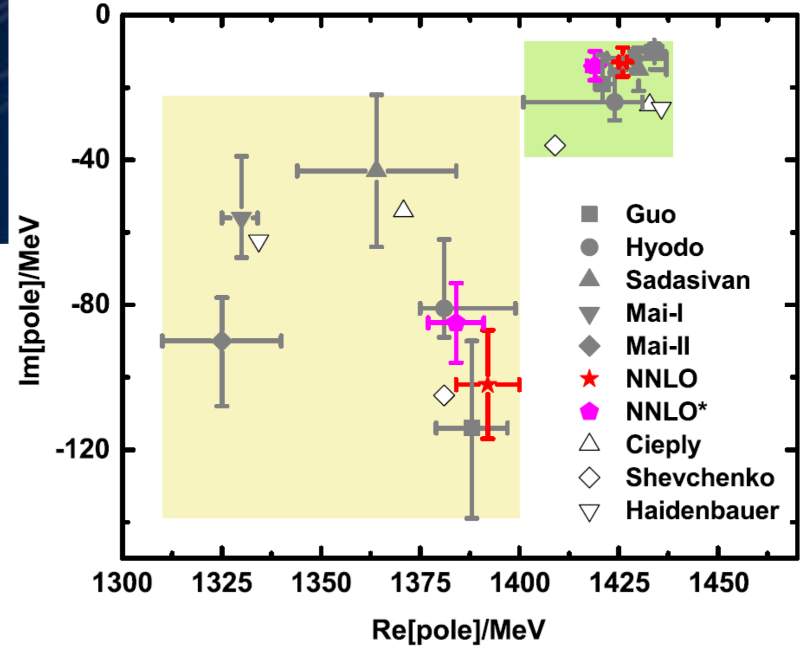
Λ	1/2+	****
Λ(1380)	1/2−	**
Λ(1405)	1/2−	****
Λ(1520)	3/2−	****
Λ(1600)	1/2+	****
Λ(1670)	1/2−	****

Table 83.1: Comparison of the pole positions of Λ(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	$1424^{+7}_{-23} - i\,26^{+3}_{-14}$	$1381^{+18}_{-6} - i\,81^{+19}_{-8}$
Ref. [17], Fit II	$1421^{+3}_{-2} - i\,19^{+8}_{-5}$	$1388^{+9}_{-9} - i\,114^{+24}_{-25}$
Ref. [18], solution #2	$1434^{+2}_{-2} - i\,10^{+2}_{-1}$	$1330^{+4}_{-5} - i\,56^{+17}_{-11}$
Ref. [18], solution #4	$1429^{+8}_{-7} - i\,12^{+2}_{-3}$	$1325^{+15}_{-15} - i\,90^{+12}_{-18}$

Pole positions up to NNLO

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



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

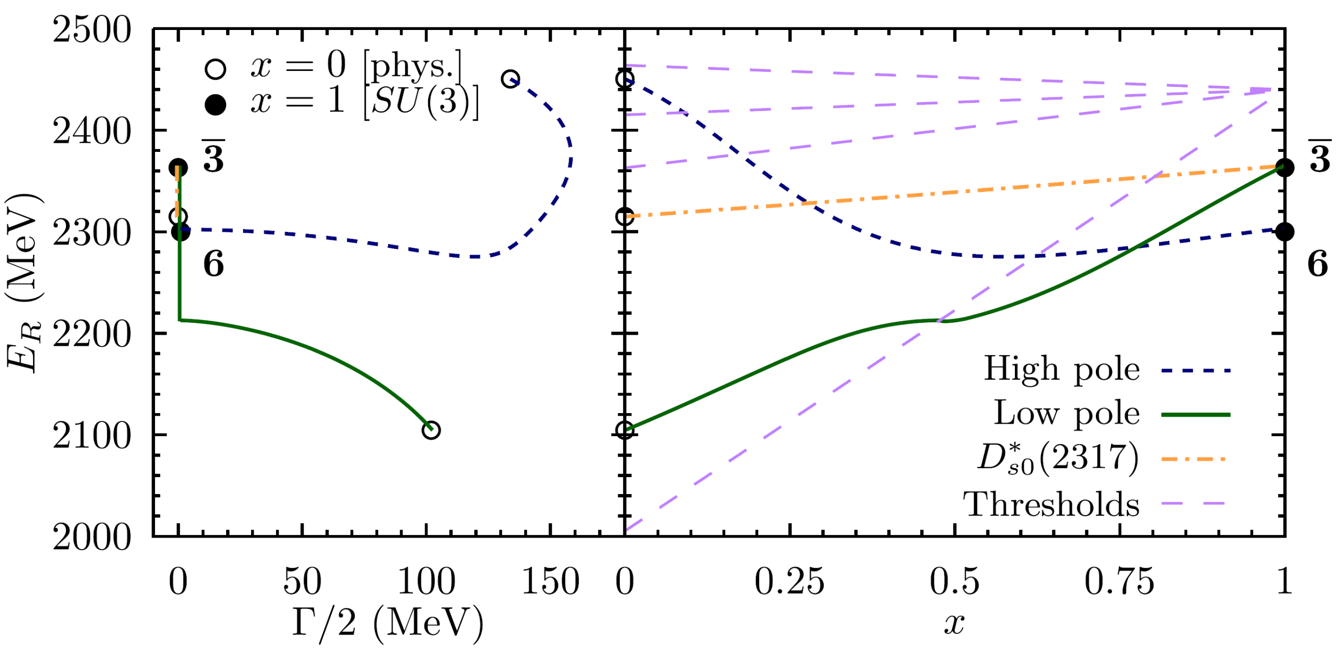
$D_0(J^P = 0^+)$: Analog in the heavy flavor sector

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

Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$\lvert g_{D\pi}\rvert$	$\lvert g_{D\eta}\rvert$	$\lvert g_{D_s\bar{K}}\rvert$
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)	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$

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

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



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

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

GB Octet

attractive

Two-pole structure

Analog in the heavy flavor sector

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

Guo, Shen, Chiang, PLB647, 133(2007)
Cleven, Guo, Hanhart, Meissner, EPJA47, 465(2011)

symmetry

MDPI

Article

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

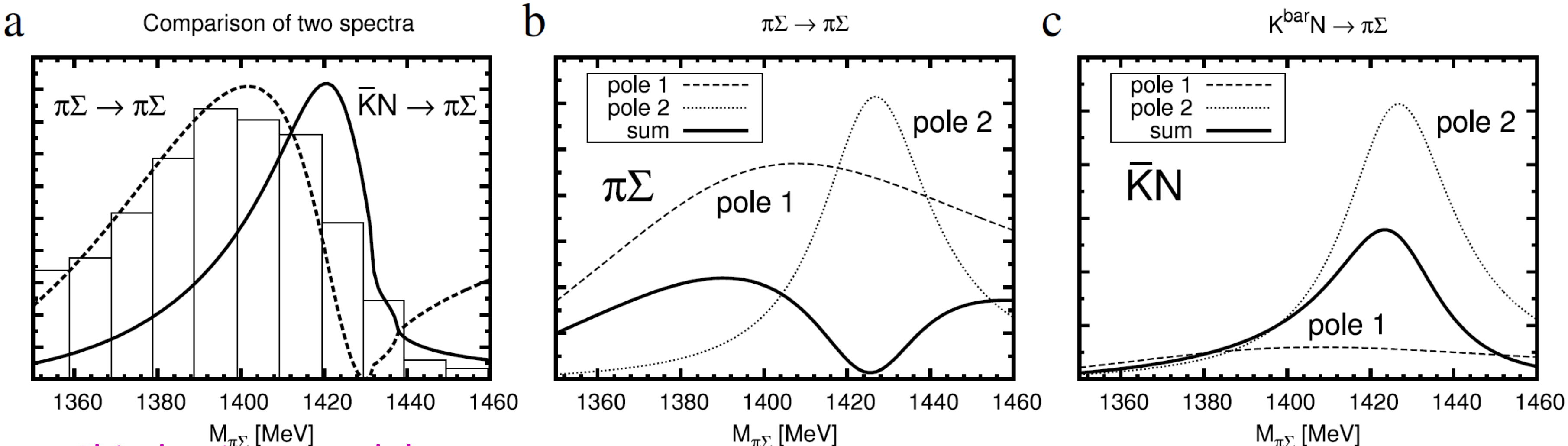
Ulf-G. Meißner [1,2,3]

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

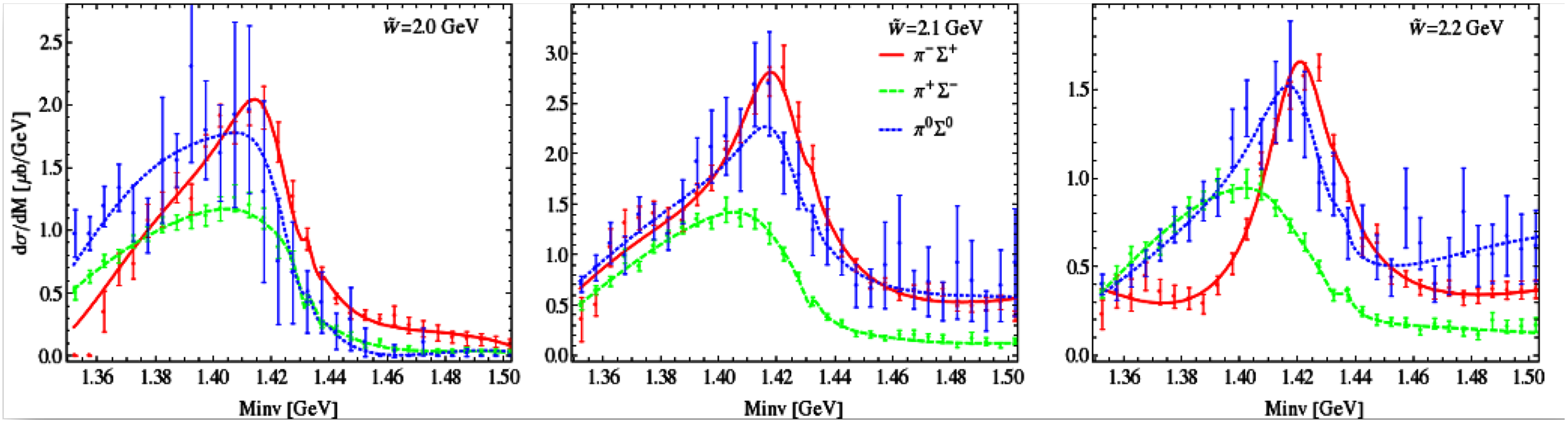
Breit-Wigner parametrization

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

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

Identify the two-pole structures

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



Result of the fits to the CLAS photoproduction data in three channels

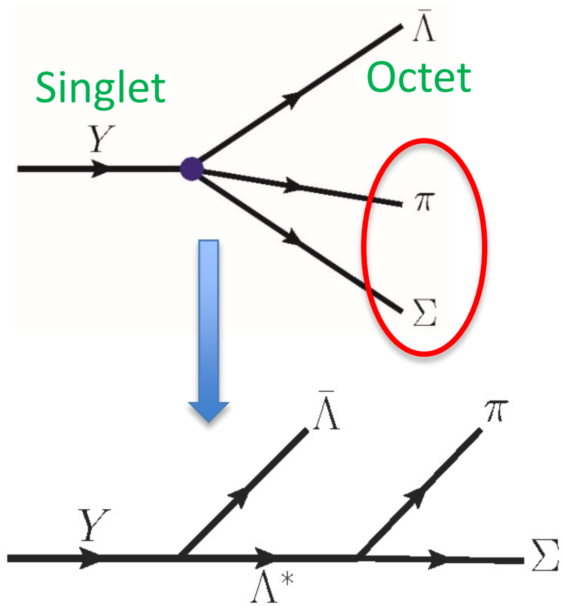
A chiral unitary model adopted

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.

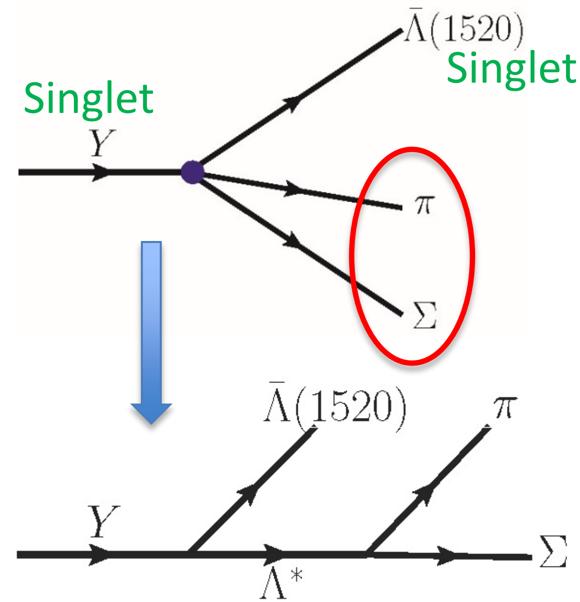
An SU(3) flavor filter

$Y \to \bar{\Lambda}\Sigma\pi$



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

$Y \to \bar{\Lambda}(1520)\Sigma\pi$



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

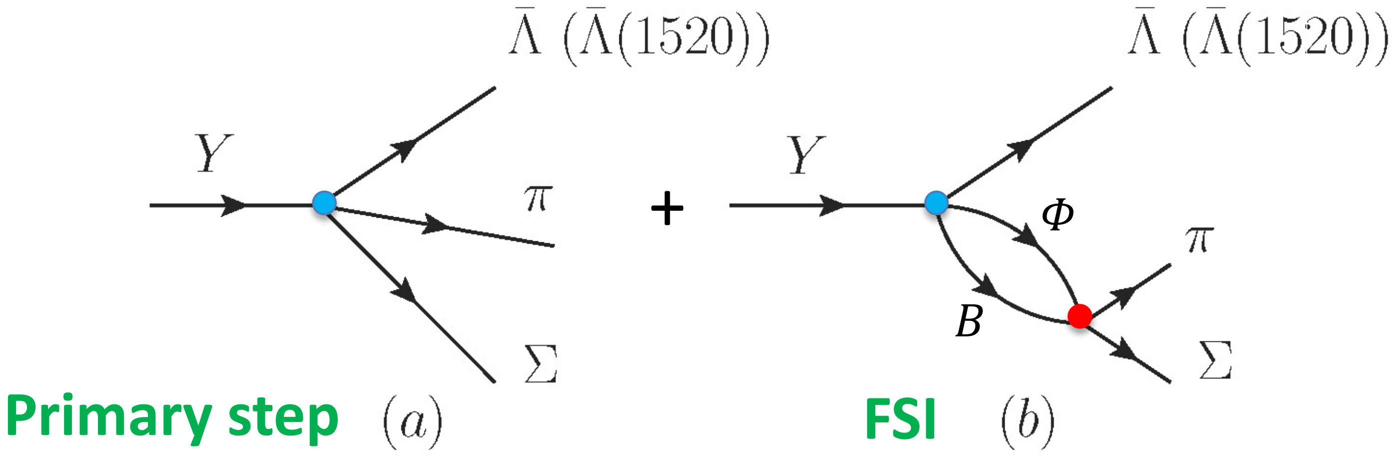
SU(3) symmetry requirement

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



$$\mathcal{L}_{\psi} = \tilde{D}\left\langle \bar{B}\gamma_{\mu}\gamma_{5}\{\Phi, B\}\right\rangle \psi^{\mu} + \tilde{F}\left\langle \bar{B}\gamma_{\mu}\gamma_{5}[\Phi, B]\right\rangle \psi^{\mu}$$

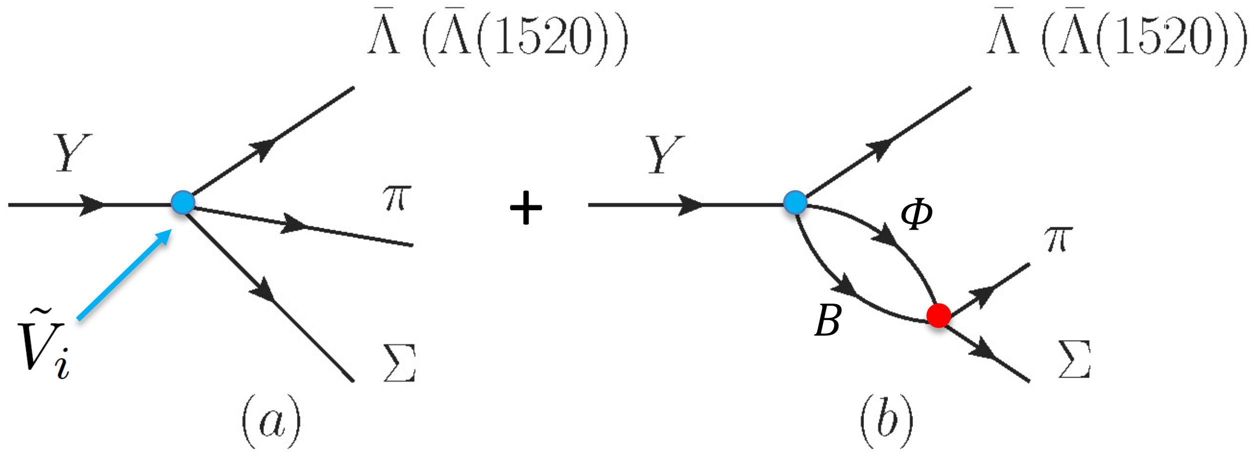
$$\mathcal{L}'_{\psi} = g_0 \bar{\Lambda}_{\mu}\gamma_5 \langle \Phi, B\rangle \psi^{\mu}$$

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

$$G_l = i2M_l \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon}$$
$$= \frac{2M_l}{16\pi^2} \Big\{ a_l(\mu) + \ln\frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s} \ln\frac{m_l^2}{M_l^2}$$
$$+ \frac{q_l}{\sqrt{s}} [\ln(s - (M_l^2 - m_l^2) + 2q_l\sqrt{s}) + \ln(s + (M_l^2 - m_l^2) + 2q_l\sqrt{s})$$
$$- \ln(-s + (M_l^2 - m_l^2) + 2q_l\sqrt{s}) - \ln(-s - (M_l^2 - m_l^2) + 2q_l\sqrt{s})] \Big\}$$

$a_{\bar{K}N} = -1.84, \quad a_{\pi\Sigma} = -2.00, \quad a_{\pi\Lambda} = -1.83,$
$a_{\eta\Lambda} = -2.25, \quad a_{\eta\Sigma} = -2.38, \quad a_{K\Xi} = -2.67$

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

Parameters of the model

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

Γ_{210}	$\Lambda\bar{\Lambda}\pi^0$		$(3.8 \pm 0.4) \times 10^{-5}$
Γ_{211}	$\Lambda\bar{\Lambda}\pi^+\pi^-$		$(4.3 \pm 1.0) \times 10^{-3}$
Γ_{212}	$\Lambda\bar{\Lambda}\eta$		$(1.62 \pm 0.17) \times 10^{-4}$
Γ_{213}	$\Lambda\bar{\Sigma}^-\pi^+$ (or c.c.)	[2]	$(8.3 \pm 0.7) \times 10^{-4}$
Γ_{214}	$pK^-\bar{\Lambda}$ +c.c.		$(8.6 \pm 1.1) \times 10^{-4}$
Γ_{215}	$pK^-\bar{\Sigma}^0$		$(2.9 \pm 0.8) \times 10^{-4}$
Γ_{216}	$\bar{\Lambda}nK^0_S$ + c.c.		$(6.5 \pm 1.1) \times 10^{-4}$
Γ_{217}	$\Lambda\bar{\Sigma}$ + c.c.		$(2.83 \pm 0.23) \times 10^{-5}$
Γ_{218}	$\Sigma^+\bar{\Sigma}^-$		$(1.07 \pm 0.04) \times 10^{-3}$
Γ_{219}	$\Sigma^0\bar{\Sigma}^0$		$(1.172 \pm 0.032) \times 10^{-3}$
Γ_{220}	$\Sigma^+\bar{\Sigma}^-\eta$		$(6.3 \pm 0.4) \times 10^{-5}$
Γ_{221}	$\Xi^-\bar{\Xi}^+$		$(9.7 \pm 0.8) \times 10^{-4}$

Braching fractions of J/ψ decay modes
PDG 2022

- 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

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

- For $\psi(3686)$ decays

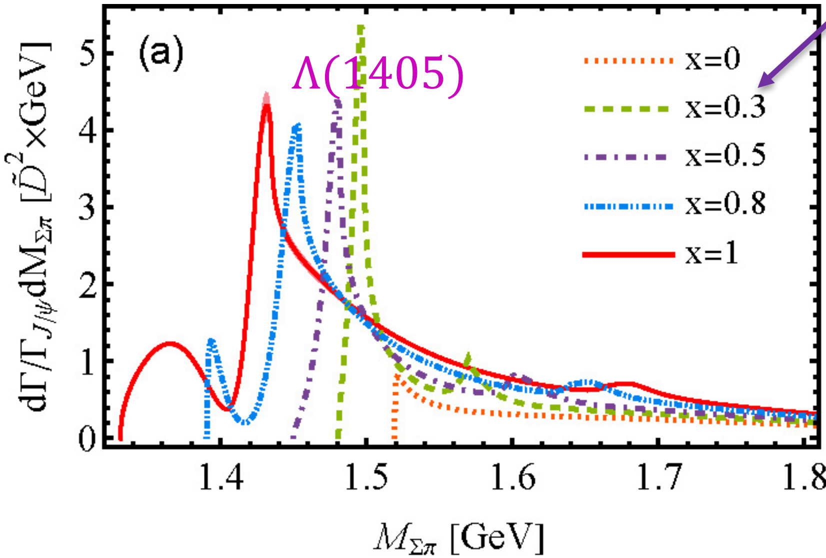
$$\mathcal{R}_{F/D} \equiv \frac{\widetilde{F}}{\widetilde{D}} = 0.50 \pm 0.06$$

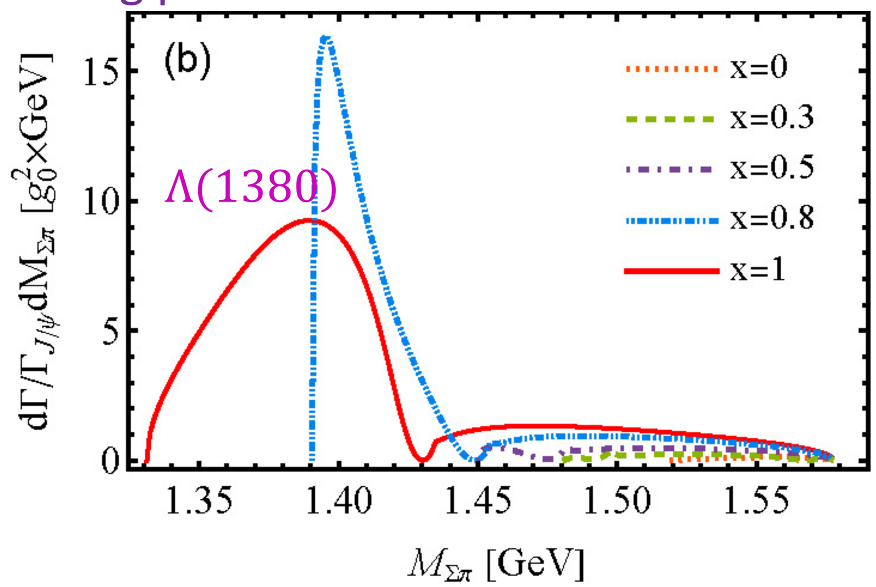
An SU(3) flavor filter

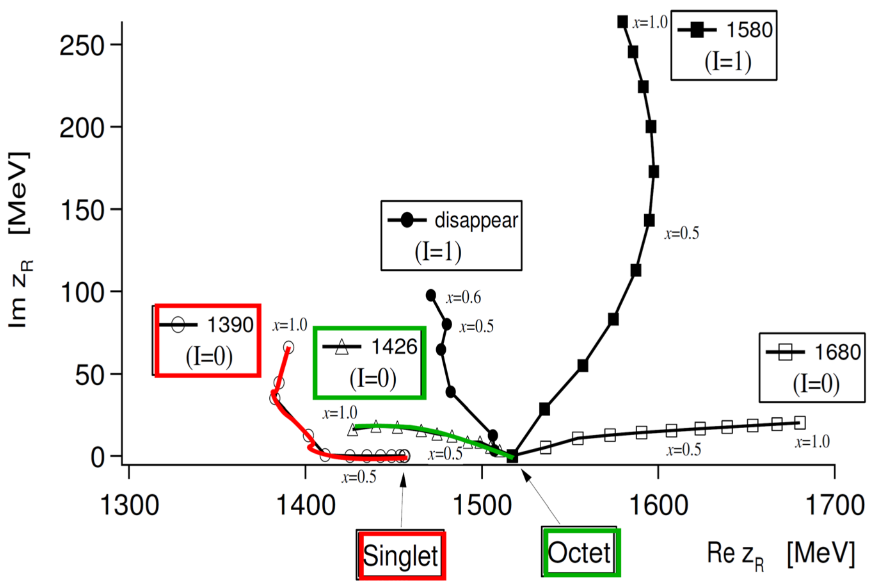
$J/\psi \to \bar{\Lambda}\Sigma\pi$

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

Symmetry breaking parameter







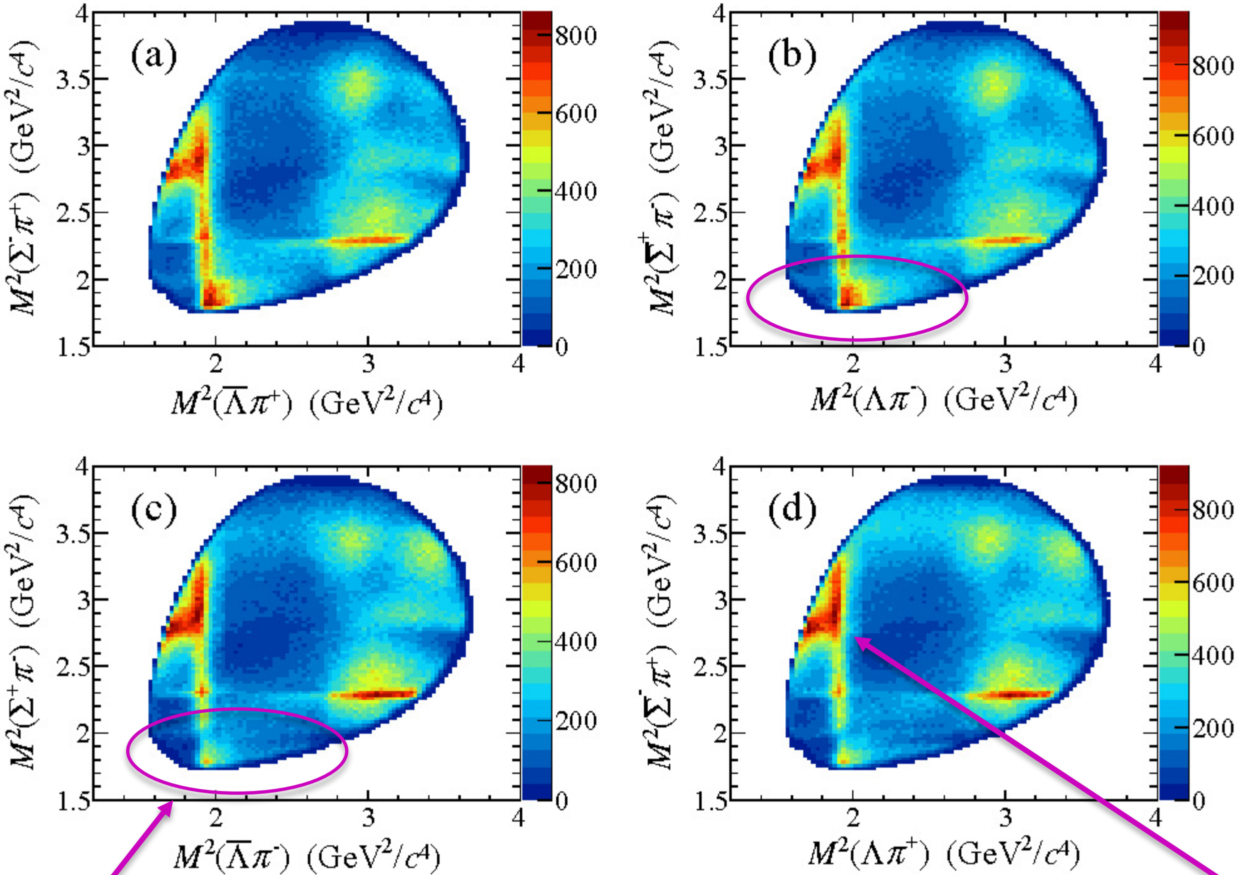
$m_0 = 368$ MeV

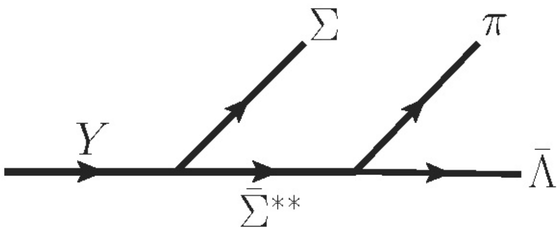
$M_0 = 1151$ MeV

$a_0 = -2.148$

Background

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





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

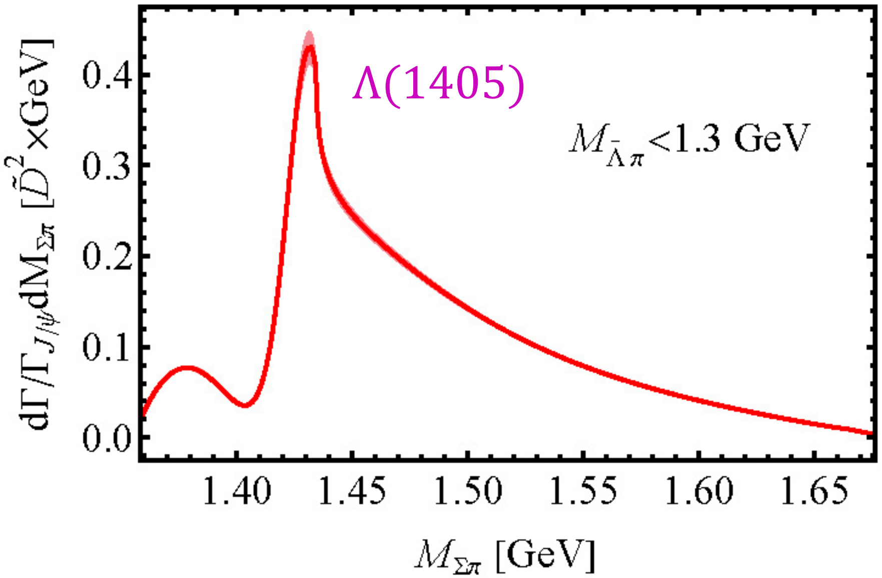
$\Lambda(1405)$ region

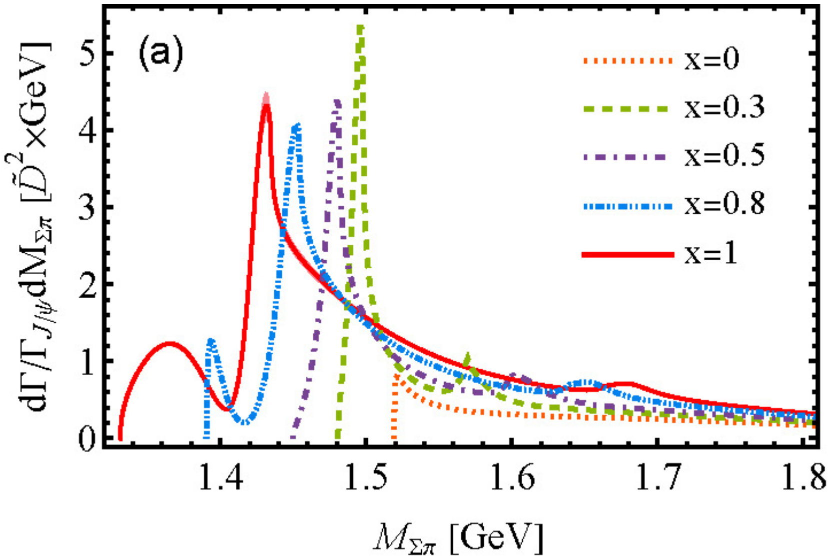
$\Sigma(1385)$?

BESIII, arXiv:2306.10319

An SU(3) flavor filter

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



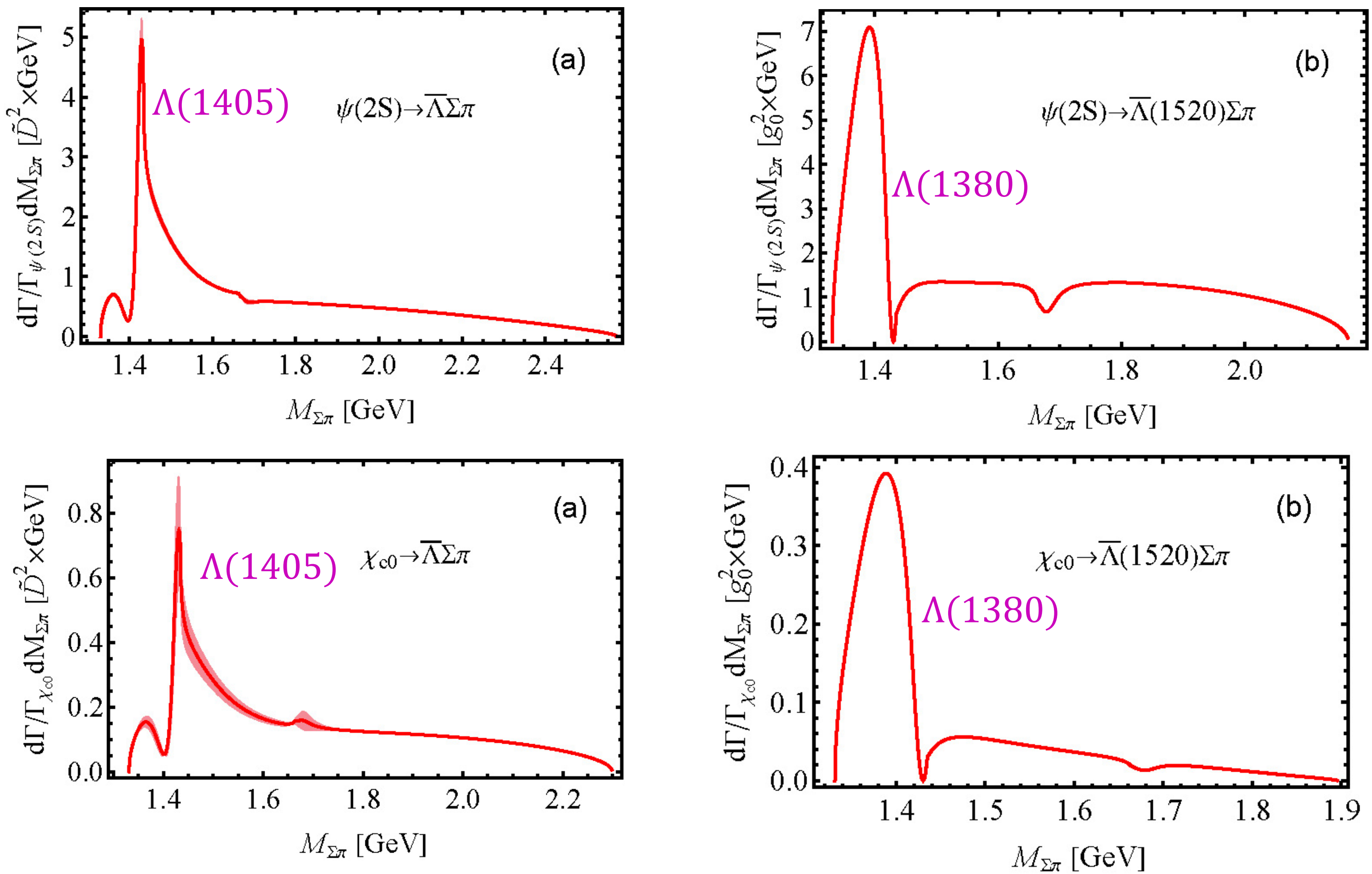


Invariant mass distribution of $\Sigma\pi$ by cutting

Interference with the background is not taken into account

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

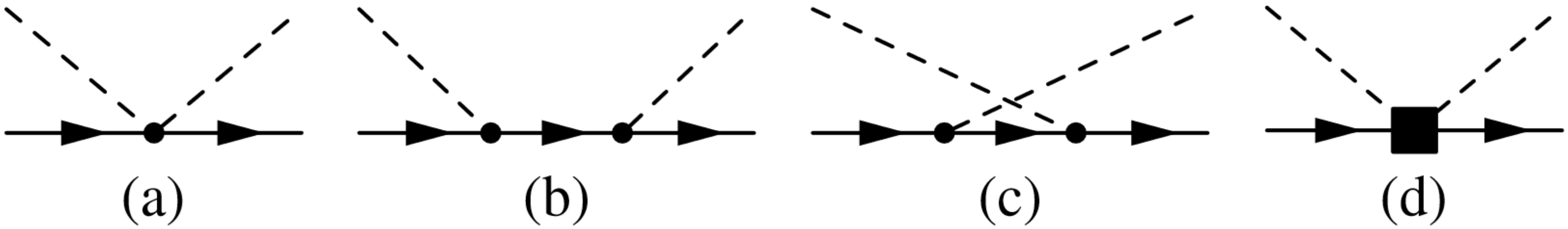
An SU(3) flavor filter



$\chi_{c0} \to \bar{\Lambda}\Sigma\pi$ 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



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

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

Scheme 1: Born terms + NLO contact terms (NLO1)
Scheme 2: NLO contact terms (NLO2)

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

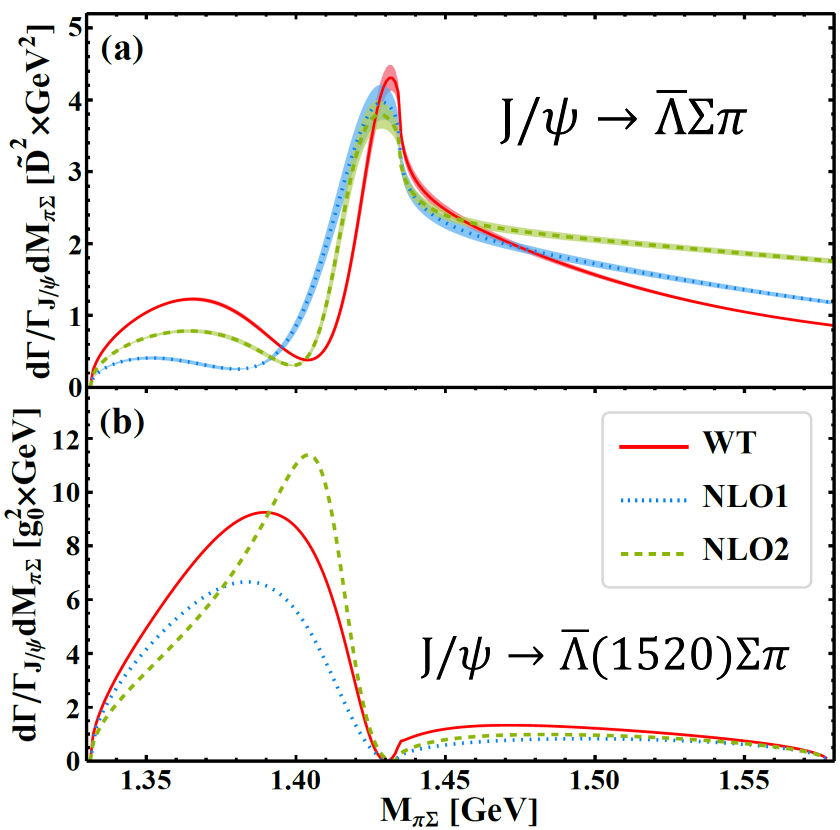
Guo, Kamiya, Mai, Meissner, PLB846,138264(2023)

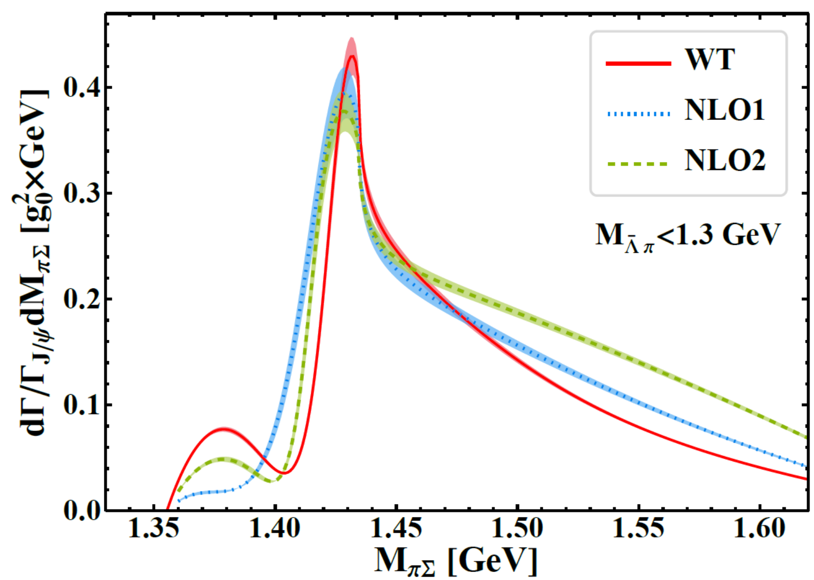
NLO Contributions

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

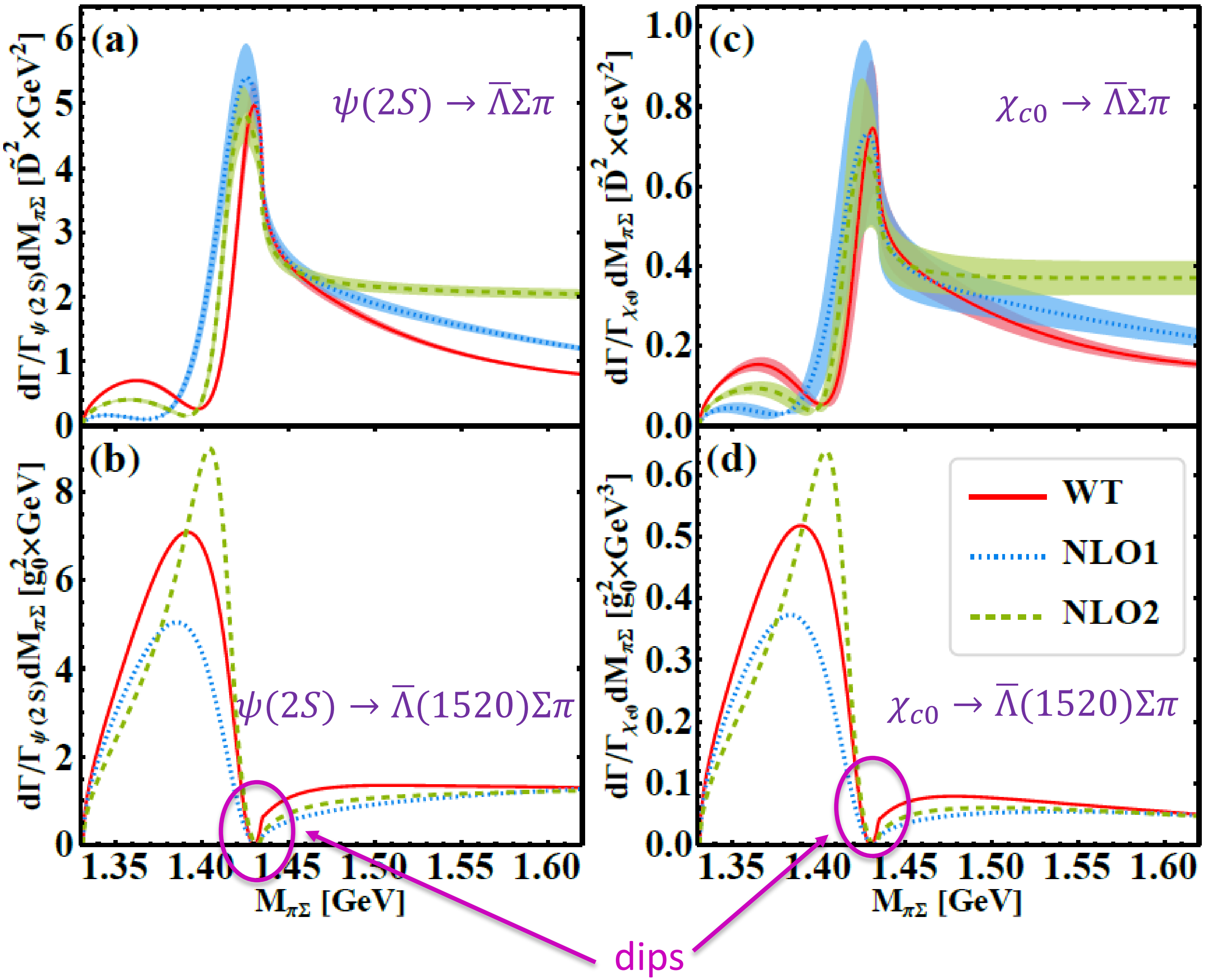
Ikeda, Hyodo, Weise, NPA881, 98(2012)

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





NLO Contributions



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**
  - $Y \to \bar{D}^* D\pi$ **decays, single out the triplet** D_0^*

Thanks!