Ξ(1690) as a $\bar{K}\Sigma$ molecular state

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1. Introduction
2. Formulation
3. Numerical results
4. Discussion
5. Summary and outlook

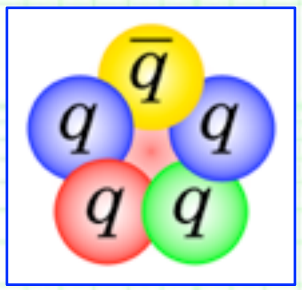
Key words: Ξ(1690), Hadronic molecules, Compositeness, Chiral unitary approach.

[1] T. S. , arXiv:1505.02849 [hep-ph].

1. Introduction

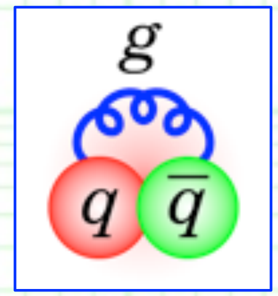
++ Exotic hadrons and their structure ++

- **Exotic hadrons --- not same quark component as ordinary hadrons**
  = not qqq nor $q\bar{q}$.

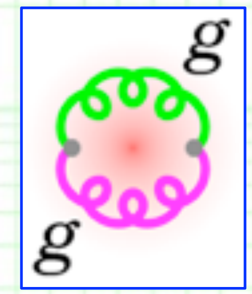


Penta-quarks

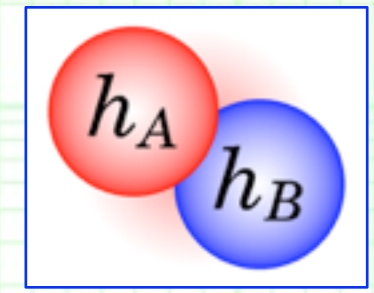
Tetra-quarks



Hybrids



Glueballs



Hadronic molecules

...

--- Actually some hadrons cannot be described by the quark model.

□ **Do exotic hadrons really exist ?**

□ **If they do exist, how are their properties ?**
--- Re-confirmation of quark models.
--- Constituent quarks in multi-quarks ? "Constituent" gluons ?

□ **If they do not exist, what mechanism forbids their existence ?**
<-- We know very few about hadrons (and dynamics of QCD).

1. Introduction

++ The Ξ(1690) resonance ++

- The Ξ(1690) resonance may be an exotic hadron.

--- Status: *** = existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

Citation: K.A. Olive et al. (Particle Data Group), Chin. Phys. C38, 090001 (2014) (URL: http://pdg.lbl.gov)

Ξ(1690) $I(J^P) = \frac{1}{2}(?^?)$ Status: ***

AUBERT 08AK, in a study of $\Lambda_c^+ \to \Xi^- \pi^+ K^+$, finds some evidence that the Ξ(1690) has $J^P = 1/2^-$.

DIONISI 78 sees a threshold enhancement in both the neutral and negatively charged $\Sigma \overline{K}$ mass spectra in $K^- p \to (\Sigma \overline{K}) K \pi$ at 4.2 GeV/c. The data from the $\Sigma \overline{K}$ channels alone cannot distinguish between a resonance and a large scattering length. Weaker evidence at the same mass is seen in the corresponding $\Lambda \overline{K}$ channels, and a coupled-channel analysis yields results consistent with a new Ξ.

BIAGI 81 sees an enhancement at 1700 MeV in the diffractively produced ΛK^- system. A peak is also observed in the $\Lambda \overline{K}^0$ mass spectrum at 1660 MeV that is consistent with a 1720 MeV resonance decaying to $\Sigma^0 \overline{K}^0$, with the γ from the Σ^0 decay not detected.

BIAGI 87 provides further confirmation of this state in diffractive dissociation of Ξ^- into ΛK^-. The significance claimed is 6.7 standard deviations.

ADAMOVICH 98 sees a peak of 1400 ± 300 events in the $\Xi^- \pi^+$ spectrum produced by 345 GeV/c Σ^--nucleus interactions.

Ξ(1690) MASSES

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID	
1690±10 OUR ESTIMATE		This is only an educated guess; the error given is larger than the error on the average of the published values.

Ξ(1690) WIDTHS

MIXED CHARGES

VALUE (MeV)	DOCUMENT ID
<30 OUR ESTIMATE	

Particle Data Group.

1. Introduction

++ Experiments of the Ξ(1690) resonance ++

- Historically Ξ(1690) was discovered as **a threshold enhancement in both the neutral and charged $\bar{K}\Sigma$ mass spectra** in the $K^{-} p \to (\bar{K}\Sigma) K \pi$ reaction at 4.2 GeV/c.

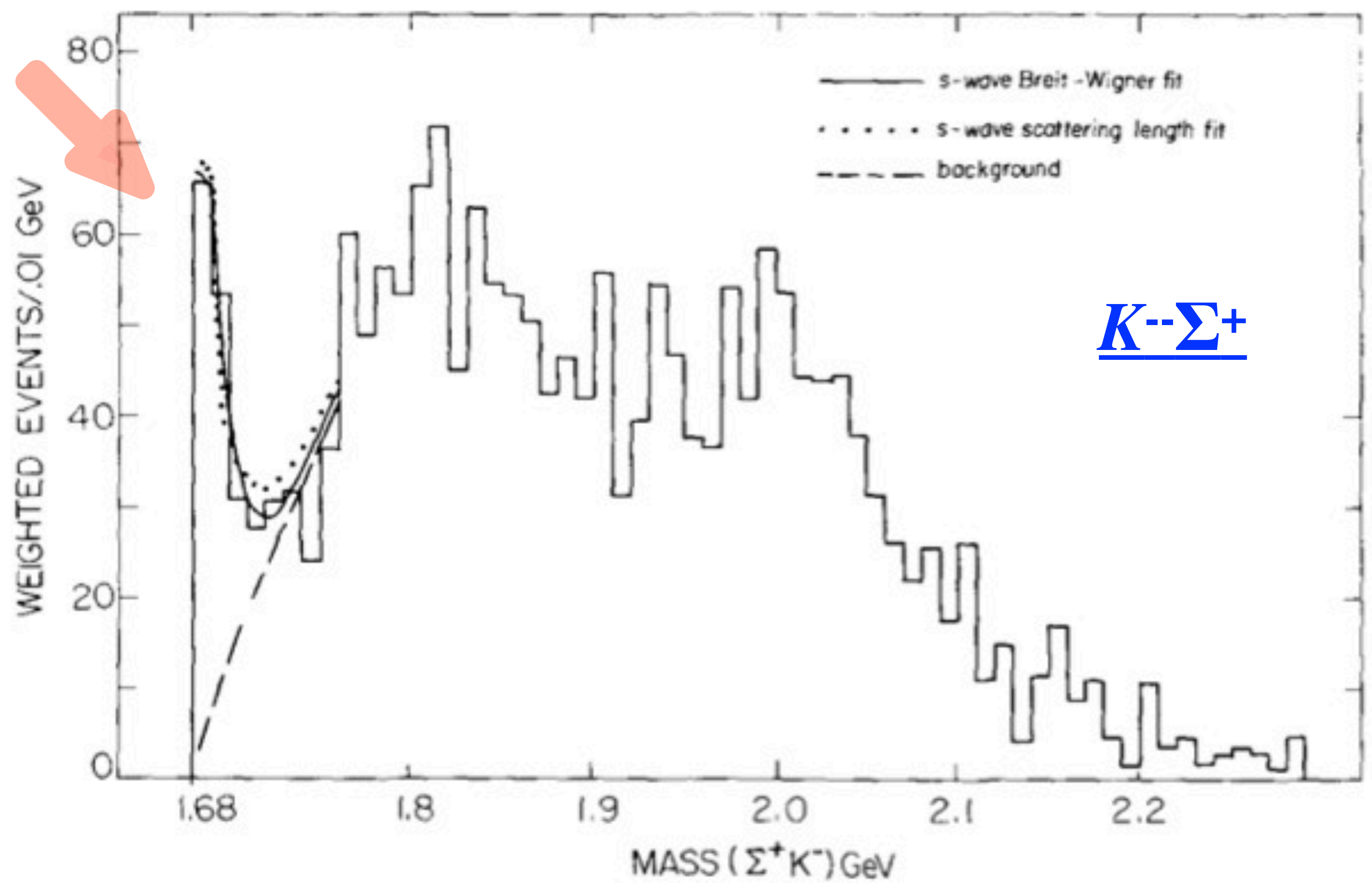


Fig. 1. The $\Sigma^{+}K^{-}$ mass spectrum for the reaction $K^{-}p \to \Sigma^{+}K^{-}K^{+}\pi^{-}$ after elimination of ϕ events mass ($K^{+}K^{-}$ less than 1.03 GeV). The origin of the curves is indicated.

C. Dionisi *et al.*, *Phys. Lett.* B80 (1978) 145.

1. Introduction

++ Experiments of the $\Xi(1690)$ resonance ++

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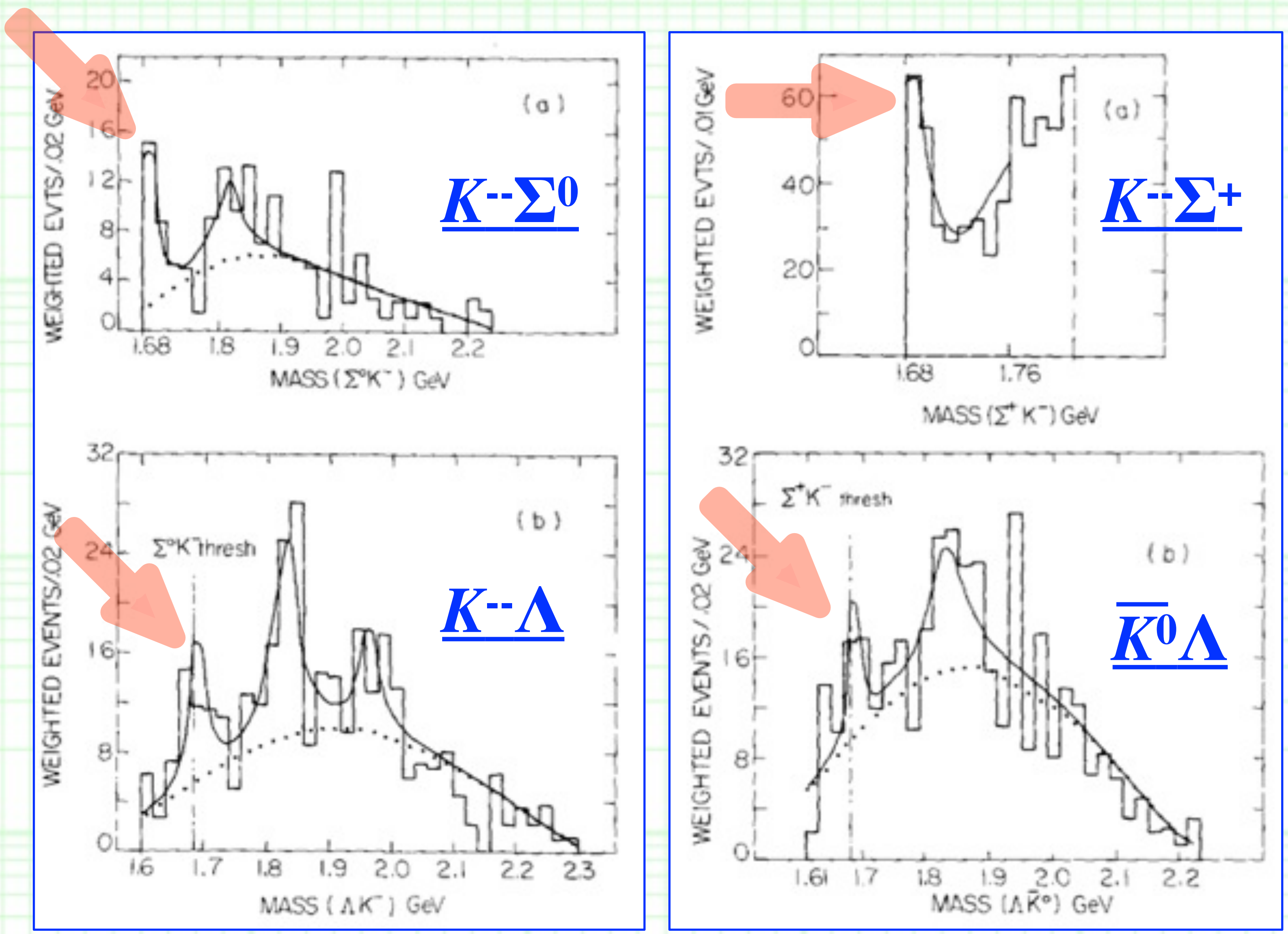


--- Rapid enhancement at the threshold of the $\bar{K}\Sigma$ mass spectra implies that this couples to the $\bar{K}\Sigma$ channel in s wave. $\Leftrightarrow J^P = 1/2^-$.

C. Dionisi *et al.*, *Phys. Lett.* B80 (1978) 145.

1. Introduction

++ Experiments of the Ξ(1690) resonance ++

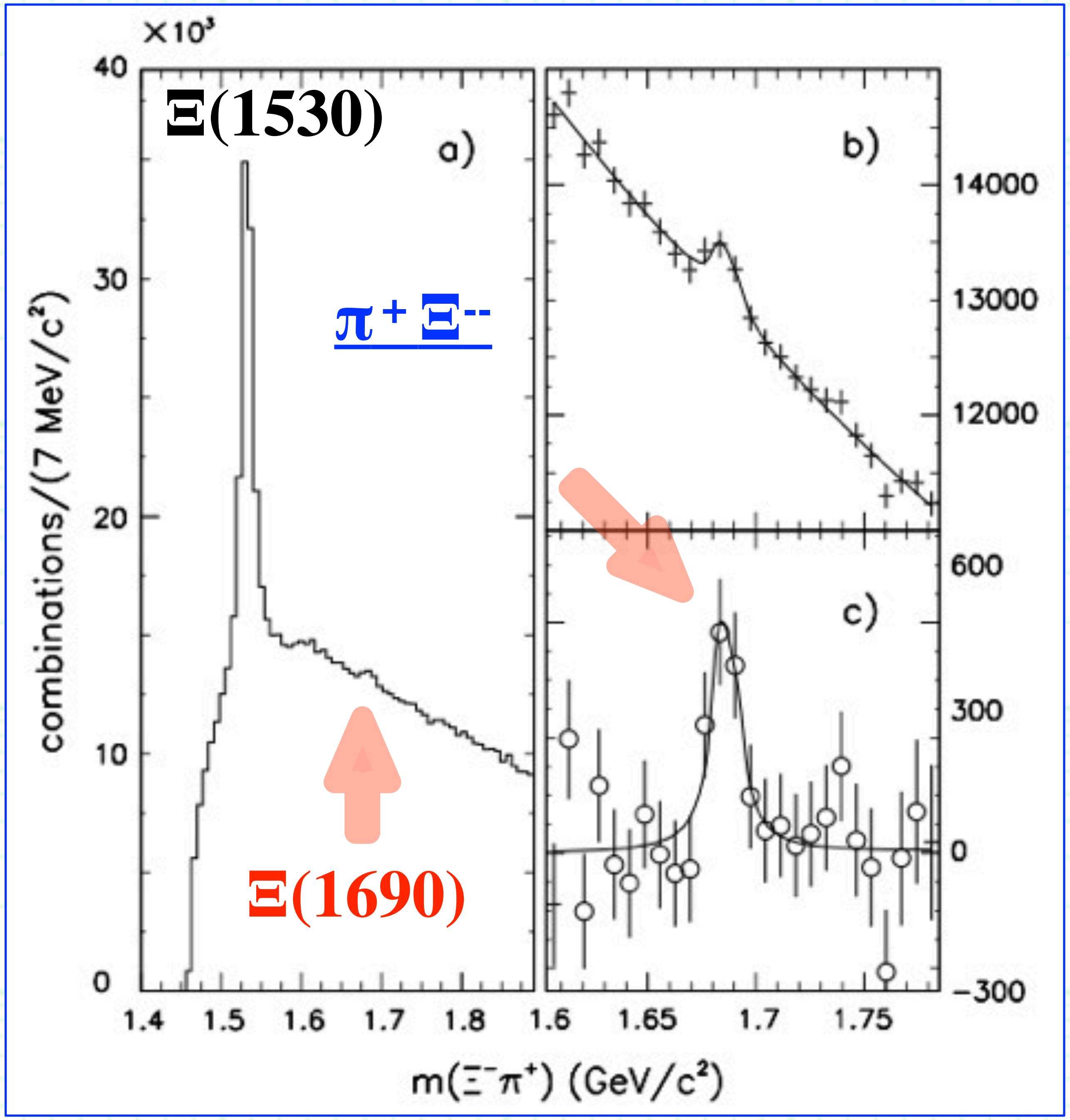
- Ξ(1690) has been observed and investigated in several experiments, for instance:
  - Small total decay width and tiny branching fraction to the πΞ state.

$$M = 1686 \pm 4\ \mathrm{MeV}/c^2\ , \Gamma = 10 \pm 6\ \mathrm{MeV}/c^2\ .$$

$$\frac{\sigma \cdot BR(\Xi^0(1690) \to \Xi^-\pi^+)}{\sigma \cdot BR(\Xi^0(1530) \to \Xi^-\pi^+)} = 0.022 \pm 0.005.$$

--- Using a Σ^{--} beam on nucleus.

M. I. Adamovich *et al.* [WA89 Collab.],
Eur. Phys. J. C5 (1998) 621.

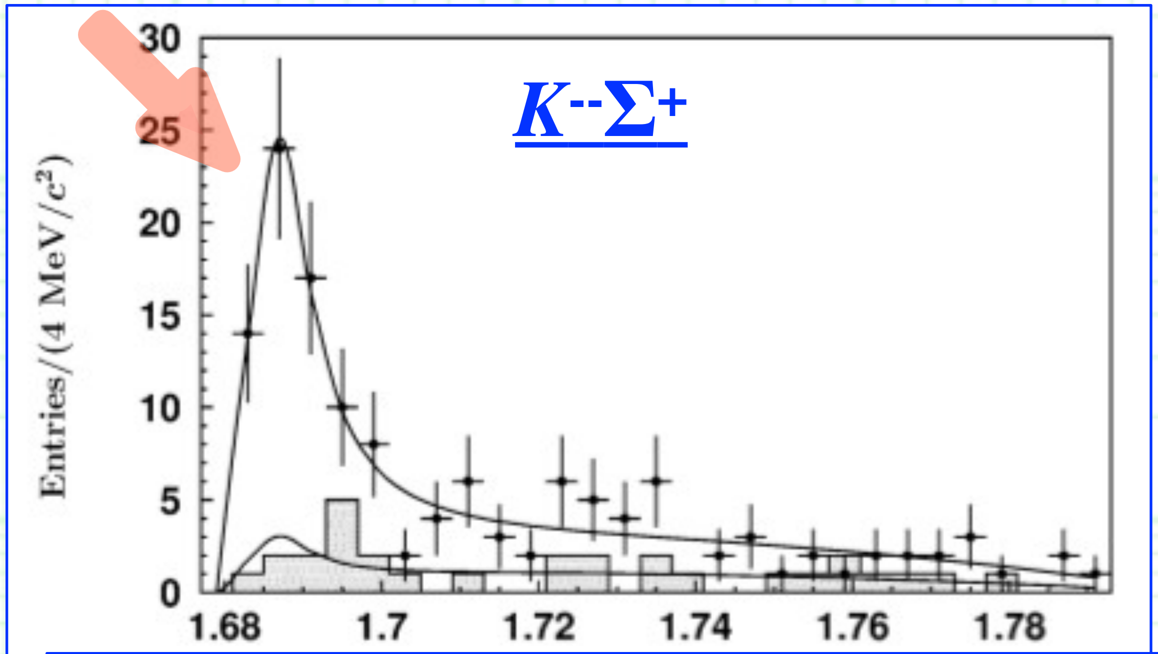


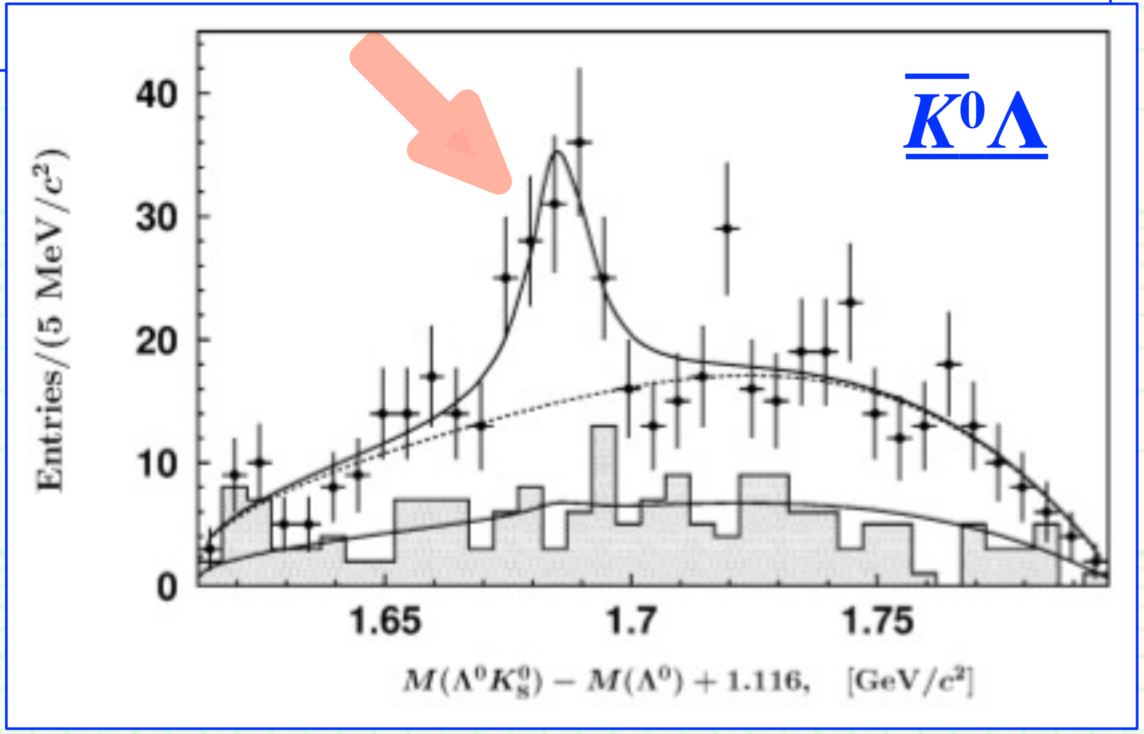
1. Introduction

++ Experiments of the Ξ(1690) resonance ++

- Ξ(1690) has been observed and investigated in several experiments, for instance:
  - Small total decay width and tiny branching fraction to the πΞ state.
  - Ξ(1690) can be observed in decay of heavy hadrons as well, giving mass spectra, branching fractions, and their ratios involving Ξ(1690).

$$\frac{\mathcal{B}(\Xi(1690)^0 \to \Sigma^+ K^-)}{\mathcal{B}(\Xi(1690)^0 \to \Lambda^0 \overline{K}^0)} = 0.50 \pm 0.26.$$





--- Using $e^+ e^-$ colliders.

K. Abe *et al.* [Belle Collab.], *Phys. Lett.* B524 (2002) 33;
M. Ablikim *et al.* [BES III], *Phys.Rev.* D91 (2015) 092006.

1. Introduction

++ Experiments of the Ξ(1690) resonance ++

- Ξ(1690) has been observed and investigated in several experiments, for instance:
  - Small total decay width and tiny branching fraction to the πΞ state.
  - Ξ(1690) can be observed in decay of heavy hadrons as well, giving mass spectra, branching fractions, and their ratios involving Ξ(1690).
  - A dip in the $P_0(\cos\theta)$ moment of the $\pi^+ \Xi^{--}$ mass spectrum appears in the vicinity of Ξ(1690), which implies that Ξ(1690) has $J^P = 1/2^{--}$.

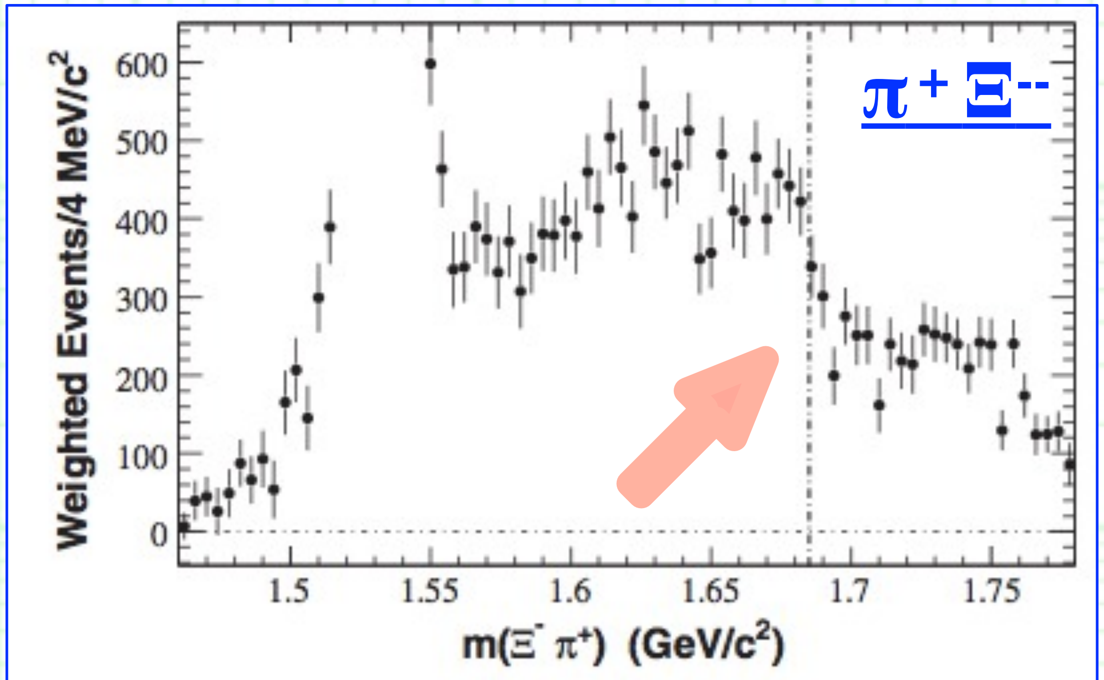
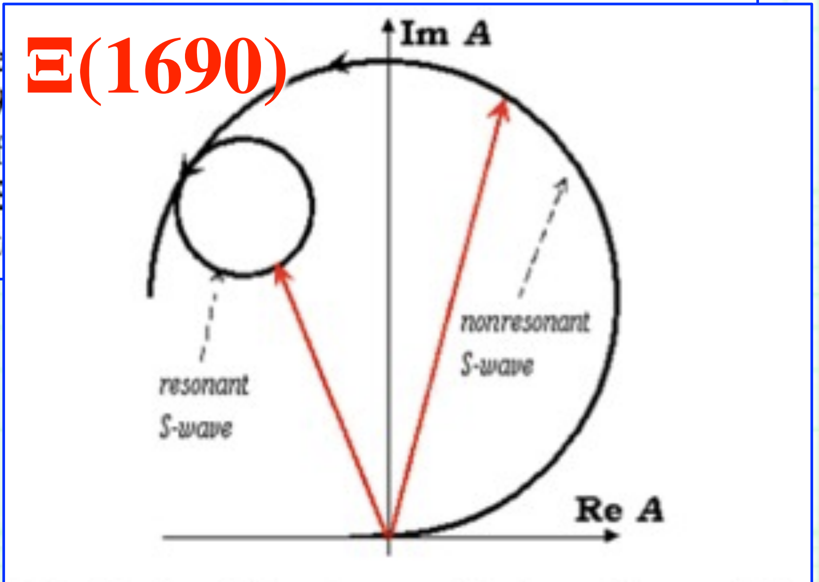


FIG. 10. The e
subtracted $P_0(\cos\theta$
mass distribution f
Fig. 3(a) with the Ξ
dashed line indicat



s-wave Argand diagram

B. Aubert *et al.* [BaBar Collab.], *Phys. Rev.* D78 (2008) 034008.

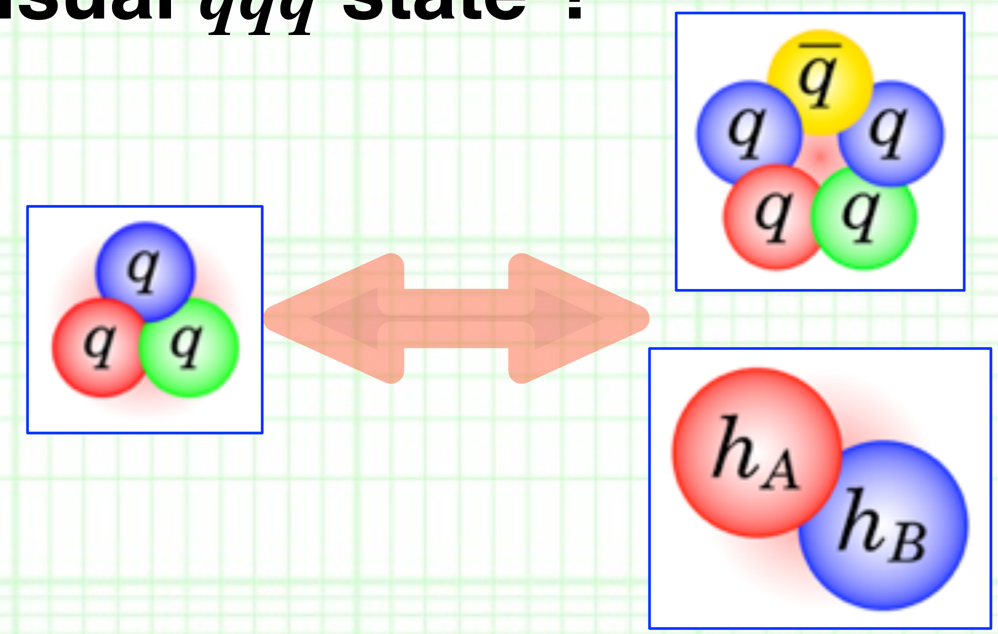
1. Introduction

++ Experiments of the Ξ(1690) resonance ++

- Ξ(1690) has been observed and investigated in several experiments, for instance:
  - Small total decay width and tiny branching fraction to the πΞ state.
  - Ξ(1690) can be observed in decay of heavy hadrons as well, giving mass spectra, branching fractions, and their ratios involving Ξ(1690).
  - A dip in the $P_0(\cos\theta)$ moment of the $\pi^+ \Xi^-$ mass spectrum appears in the vicinity of Ξ(1690), which implies that Ξ(1690) has $J^P = 1/2^-$.

- The small decay width and tiny branching fraction to the πΞ state are un-natural.

--> Ξ(1690) might have a some non-trivial structure than usual qqq state ?



-- But its properties and structure are still unclear.

1. Introduction

++ Theories of the Ξ(1690) resonance ++

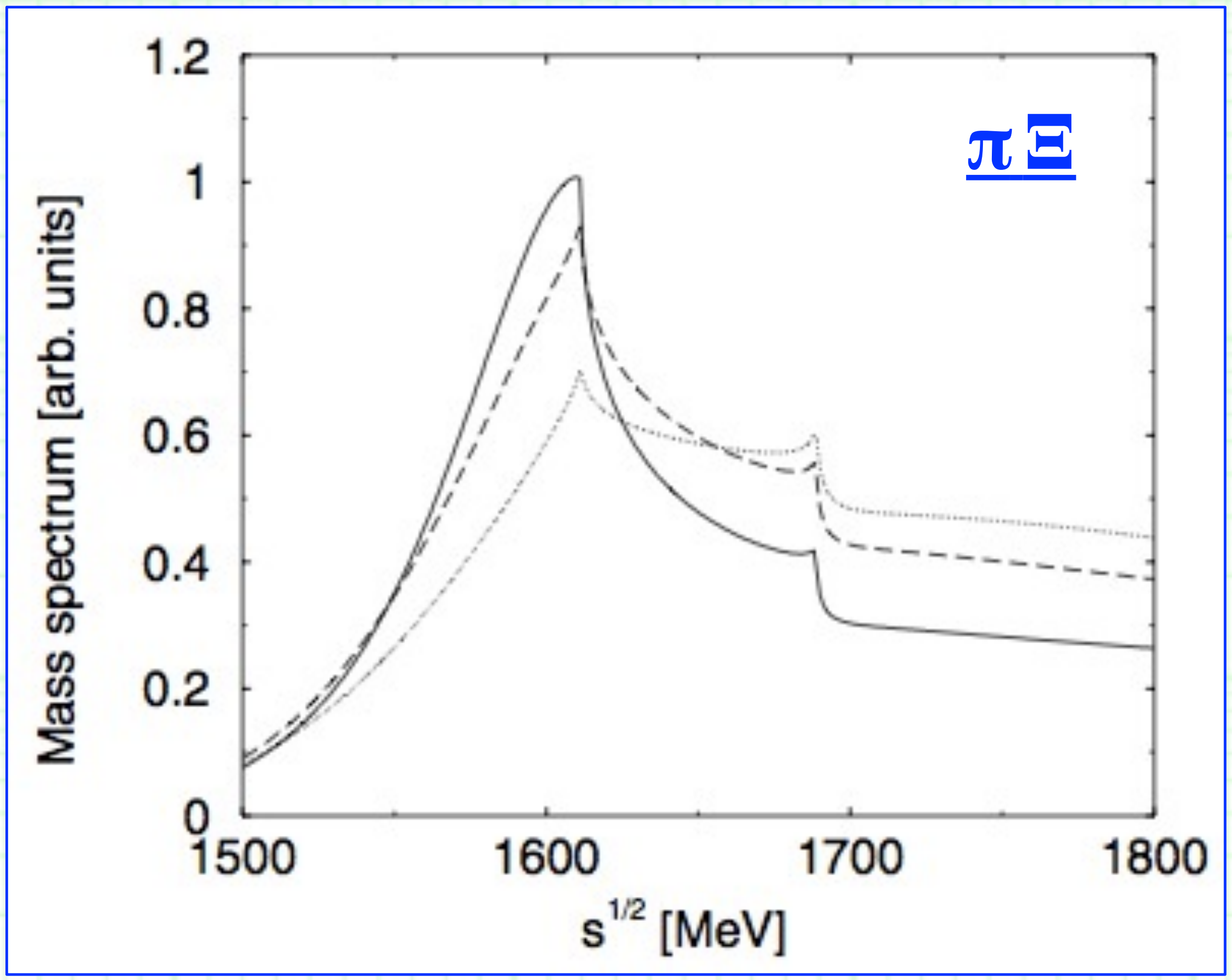
- Ξ(1690) and other Ξ* resonances has been investigated in several theoretical frameworks as well, for instance:
  - Quark models.
    K. T. Chao, N. Isgur and G. Karl, *Phys. Rev.* D23 (1981) 155;
    S. Capstick and N. Isgur, *Phys. Rev.* D34 (1986) 2809;
    M. Pervin and W. Roberts, *Phys. Rev.* C77 (2008) 025202;
    L. Y. Xiao and X. H. Zhong, *Phys. Rev.* D87 (2013) 094002;
    N. Sharma, A. Martinez Torres, K. P. Khemchandani and H. Dahiya, *Eur. Phys. J.* A49 (2013) 11;
    ...
  - Skyrme model.
    Y. Oh, *Phys. Rev.* D75 (2007) 074002.
  - Chiral unitary approach.
    A. Ramos, E. Oset and C. Bennhold, *Phys. Rev. Lett.* 89 (2002) 252001;
    C. Garcia-Recio, M. F. M. Lutz and J. Nieves, *Phys. Lett.* B582 (2004) 49;
    D. Gamermann, C. Garcia-Recio, J. Nieves and L. L. Salcedo, *Phys. Rev.* D84 (2011) 056017.

1. Introduction

++ Ξ* resonances in chiral unitary approach ++

- **Ξ* resonances in chiral unitary approach.**

--- Based on the combination of the chiral perturbation theory and the unitarization of the scattering amplitude.



- First, another Ξ* resonance, Ξ(1620), was studied in the s-wave $\pi\Xi$-$\bar{K}\Lambda$-$\bar{K}\Sigma$-$\eta\Xi$ coupled-channels scattering in the chiral unitary approach.

--- Ξ(1620) status: *

$J^P = 1/2^-$?

A. Ramos, E. Oset and C. Bennhold, *Phys. Rev. Lett.* 89 (2002) 252001.

1. Introduction

++ Ξ* resonances in chiral unitary approach ++

- **Ξ* resonances in chiral unitary approach.**

--- Based on the combination of the chiral perturbation theory and the unitarization of the scattering amplitude.

$(\frac{1}{2}, -2)$		$[\pi \Xi]$ 7.5	5.6	seen	2.6
$\Xi(1620)^{*}$		$[\bar{K}\Lambda]$ 5.2	2.8	seen	−1.5
$M \approx 1620$	1565	$[\bar{K}\Sigma]$ 0.7	2.6	0	−0.8
$\Gamma = 23$	247	$[\eta \Xi]$ 0.3	4.9	0	0.3
$(\frac{1}{2}, -2)$		$[\pi \Xi]$ 0.02	0.1	seen	−0.1
$\Xi(1690)^{***}$		$[\bar{K}\Lambda]$ 0.16	6.0	seen	0.9
$M = 1690 \pm 10$	1663	$[\bar{K}\Sigma]$ 5.15	3.1	seen	−2.5
$\Gamma = 10 \pm 6$	4	$[\eta \Xi]$ 2.28	3.2	0	−1.7

- Then, **systematic studies were done for several Ξ* states** together with many other resonances.

C. Garcia-Recio, M. F. M. Lutz and J. Nieves, *Phys. Lett.* B582 (2004) 49.

8 (1134)	2037−24i	0.6	0.6	0.3	0.2	0.3	↑0.5	1.5	0.6	**1.8**	**2.4**	1.1	0.2	1.0	**2.1**	
10 (70)	1729−46i	0.6	1.4	0.4	↑1.6	1.4	**2.1**	1.0	0.4	**3.3**	1.5	0.4	0.2	1.6	1.0	Ξ(1950) ★★★
8 (70)	1651−2i	0.2	0.3	↑**2.2**	1.3	1.0	**2.6**	0.2	0.6	0.9	0.4	0.2	**1.7**	0.4	0.2	Ξ(1690) ★★★
8 (56)	1577−139i	**2.6**	↑**1.7**	0.5	0.1	0.8	1.0	0.7	0.1	0.6	1.3	0.3	0.1	0.2	1.2	Ξ(1620) ★

--- Narrow width for Ξ(1690) ! But its mass is lower than Exp. value.

D. Gamermann, C. Garcia-Recio, J. Nieves and L. L. Salcedo, *Phys. Rev.* D84 (2011) 056017.

1. Introduction

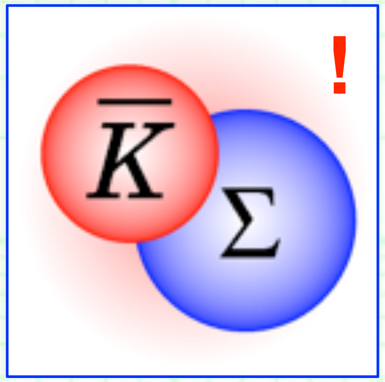
++ In this study ... ++

- In this study we concentrate on the phenomena near the $\bar{K}\Sigma$ threshold and on the $\Xi(1690)$ resonance.

- By using the chiral unitary approach and adjusting parameters, we show the $\Xi(1690)$ state, which was studied in the previous studies, can exist near the $\bar{K}\Sigma$ threshold with $J^P = 1/2^-$, and it reproduces experimental mass spectra qualitatively well.

- We investigate and clarify properties of the $\Xi(1690)$ state, including its small decay width, molecular structure, etc.

--- We especially show that the $\Xi(1690)$ resonance can be indeed an s-wave $\bar{K}\Sigma$ molecular state in terms of the compositeness.



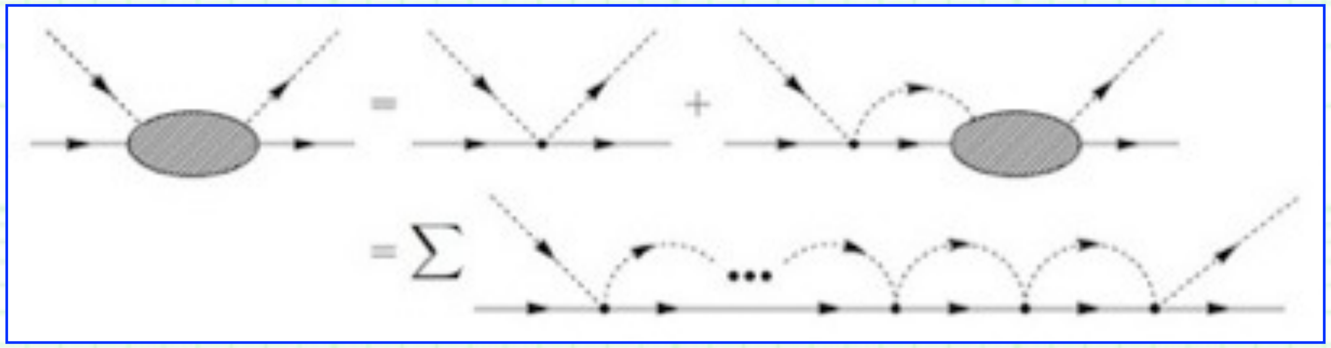
Hyodo-Jido-Hosaka (2012), Aceti-Oset (2012), Nagahiro-Hosaka (2014), ...
See Hyodo, *Int. J. Mod. Phys.* A28 (2013) 1330045;
also T. S. , Hyodo and Jido, *PTEP* (2015) 063D04.

2. Formulation

++ Chiral unitary approach ++

- We employ **the chiral unitary approach** for the s-wave $\bar{K}\Sigma$-$\bar{K}\Lambda$-$\pi\Xi$-$\eta\Xi$ coupled-channels scattering.

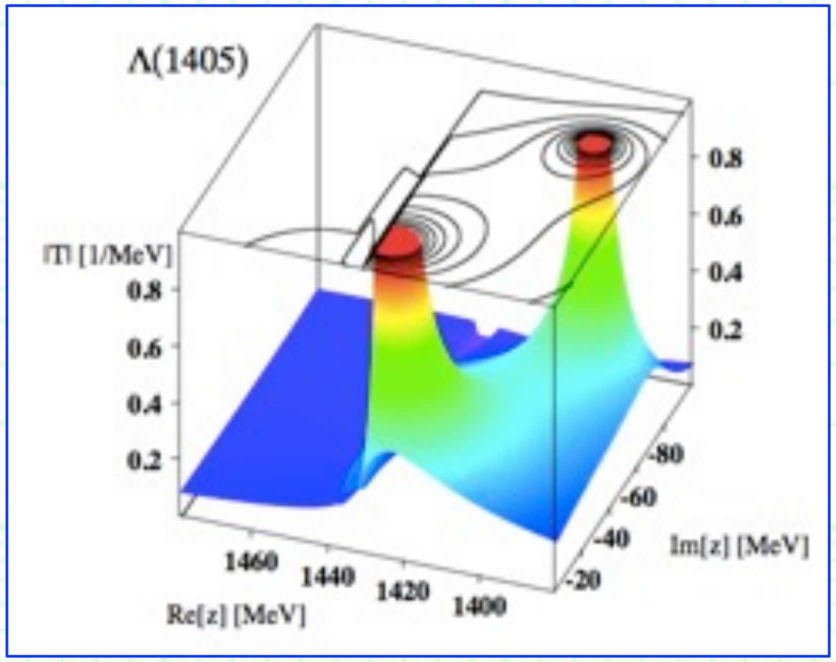
$$T_{jk}(w) = V_{jk}(w) + \sum_{l} V_{jl}(w) G_l(w) T_{lk}(w)$$



  - T is the scattering amplitude which we want to obtain.
  - V is the interaction kernel taken from the chiral perturbation theory projected to s-wave.
  - G is the loop function for the meson-baryon two-body system.

- The chiral unitary approach is **most successful in the $\bar{K}N$ interaction and $\Lambda(1405)$**.

  Kaiser-Siegel-Weise (1995), Oset-Ramos (1998), Oller-Meissner (2001), Lutz-Kolomeitsev (2002), Jido *et al.* (2003), ...



Hyodo and Jido (2012).

2. Formulation

++ Interaction kernel ++

- In this study we use the Weinberg-Tomozawa interaction for V.

--- The leading order term in s wave:

$$V_{jk}(w) = -\frac{C_{jk}}{4f_j f_k}(2w - M_j - M_k)\sqrt{\frac{E_j + M_j}{2M_j}}\sqrt{\frac{E_k + M_k}{2M_k}}$$

- The meson decay constant f_i is chosen at their physical values:

$$f_\pi = 92.2 \text{ MeV}, \quad f_K = 1.2 f_\pi, \quad f_\eta = 1.3 f_\pi$$

Particle Data Group.

- The Clebsch-Gordan coefficient C_{jk} is determined from the group structure of the flavor $SU(3)$ symmetry:

	$K^-\Sigma^+$	$\bar{K}^0\Sigma^0$	$\bar{K}^0\Lambda$	$\pi^+\Xi^-$	$\pi^0\Xi^0$	$\eta\Xi^0$
$K^-\Sigma^+$	1	$-\sqrt{2}$	0	0	$-1/\sqrt{2}$	$-\sqrt{3/2}$
$\bar{K}^0\Sigma^0$	$-\sqrt{2}$	0	0	$-1/\sqrt{2}$	$-1/2$	$\sqrt{3/4}$
$\bar{K}^0\Lambda$	0	0	0	$-\sqrt{3/2}$	$\sqrt{3/4}$	$-3/2$
$\pi^+\Xi^-$	0	$-1/\sqrt{2}$	$-\sqrt{3/2}$	1	$-\sqrt{2}$	0
$\pi^0\Xi^0$	$-1/\sqrt{2}$	$-1/2$	$\sqrt{3/4}$	$-\sqrt{2}$	0	0
$\eta\Xi^0$	$-\sqrt{3/2}$	$\sqrt{3/4}$	$-3/2$	0	0	0

--- We have no free parameters in the interaction kernel.

2. Formulation

++ Loop function ++

- For the loop function we take **a covariant expression**:

$$G_j(w) = i \int \frac{d^4 q}{(2\pi)^4} \frac{1}{(P/2+q)^2 - m_j^2 + i0} \frac{2M_j}{(P/2-q)^2 - M_j^2 + i0}$$

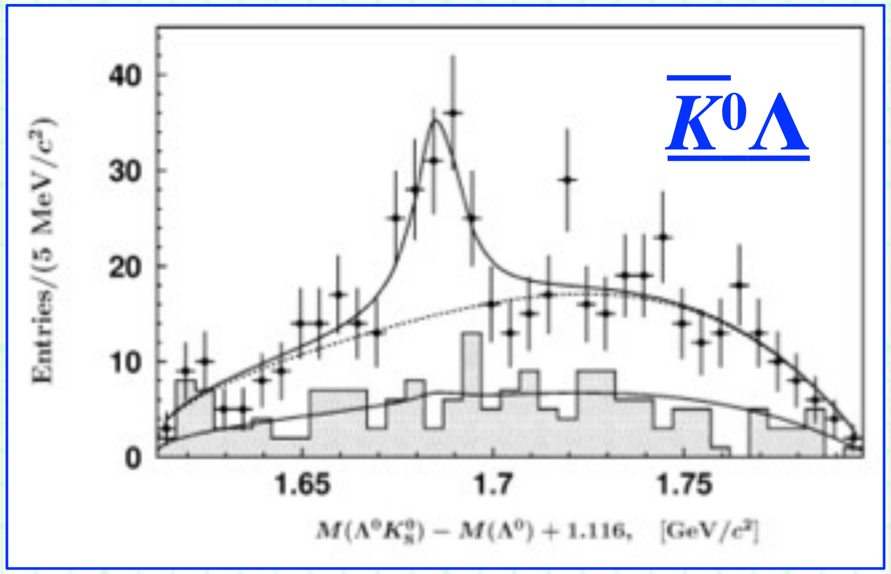
  - The integral is calculated with the dimensional regularization, and an infinite constant is replaced with a subtraction constant in each channel.

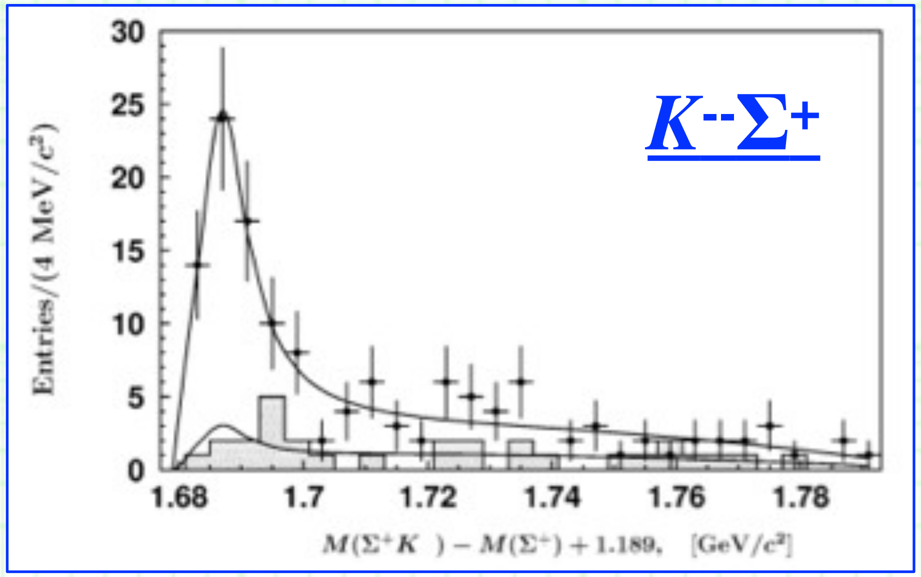
--> **Subtraction constants are free parameters.**

  - We assume the isospin symmetry for the subtraction constants, so we have **4 free parameters** ($a_{K\Sigma}$, $a_{K\Lambda}$, $a_{\pi\Xi}$, and $a_{\eta\Xi}$), which are fixed so as to reproduce the mass spectra by Belle.

--- **Neutral Ξ(1690).**

K. Abe *et al.* [Belle Collab.], *Phys. Lett.* B524 (2002) 33.

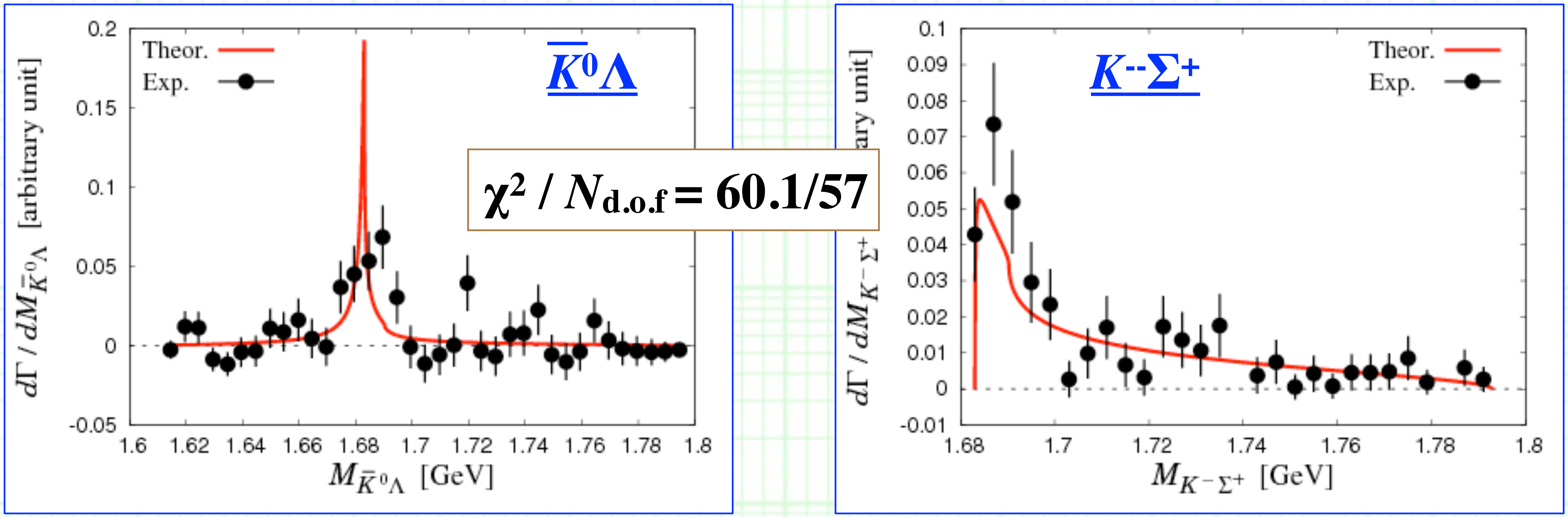




3. Numerical results

++ Fitting to the Belle data ++

- We fix **4 free parameters** ($a_{K\Sigma}$, $a_{K\Lambda}$, $a_{\pi\Xi}$, and $a_{\eta\Xi}$) **so as to reproduce the mass spectra by Belle**. The result of the best fit is:



- Background of the Belle data is subtracted.
- Relative scale between $\bar{K}^0\Lambda$ and $K^-\Sigma^+$ is fixed with the branching fractions:

$$\mathcal{B}[\Lambda_c^+ \to \Xi(1690)^0 K^+ \to (K^-\Sigma^+)K^+] = (1.3 \pm 0.5) \times 10^{-3}$$

$$\mathcal{B}[\Lambda_c^+ \to \Xi(1690)^0 K^+ \to (\bar{K}^0\Lambda)K^+] = (8.1 \pm 3.0) \times 10^{-4}$$

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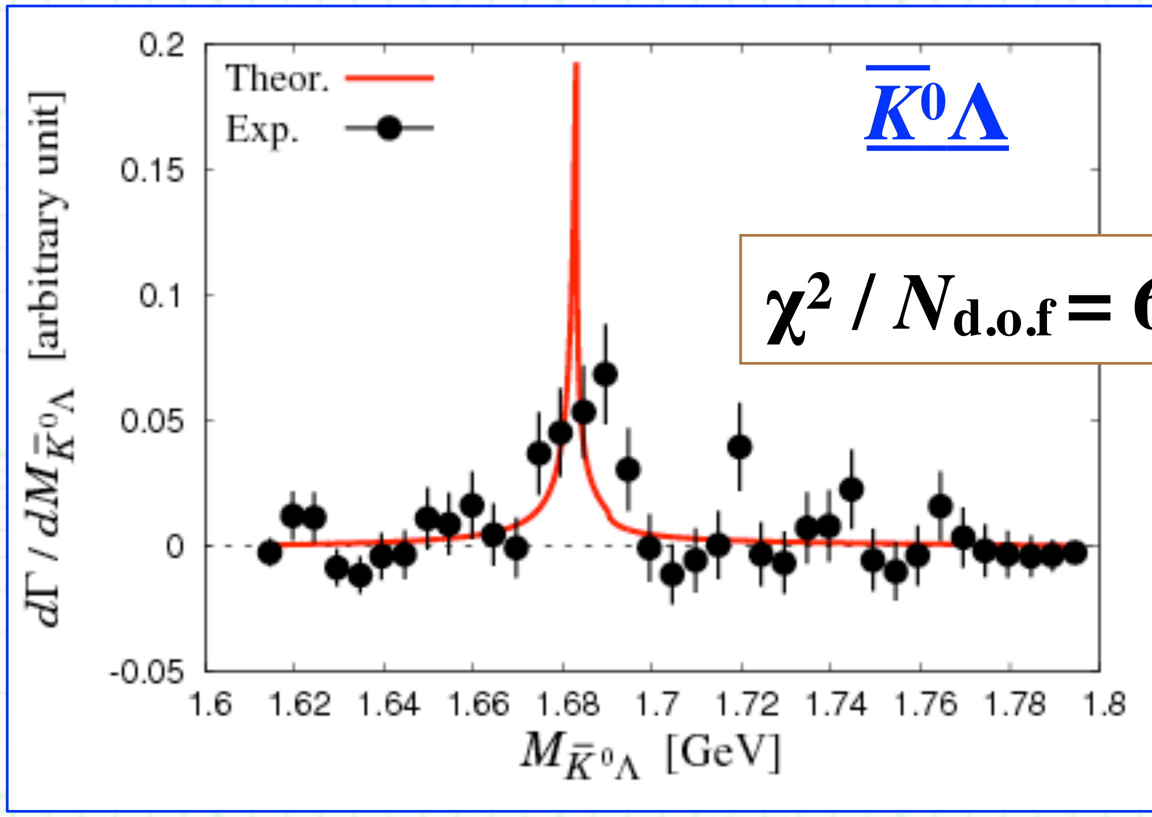
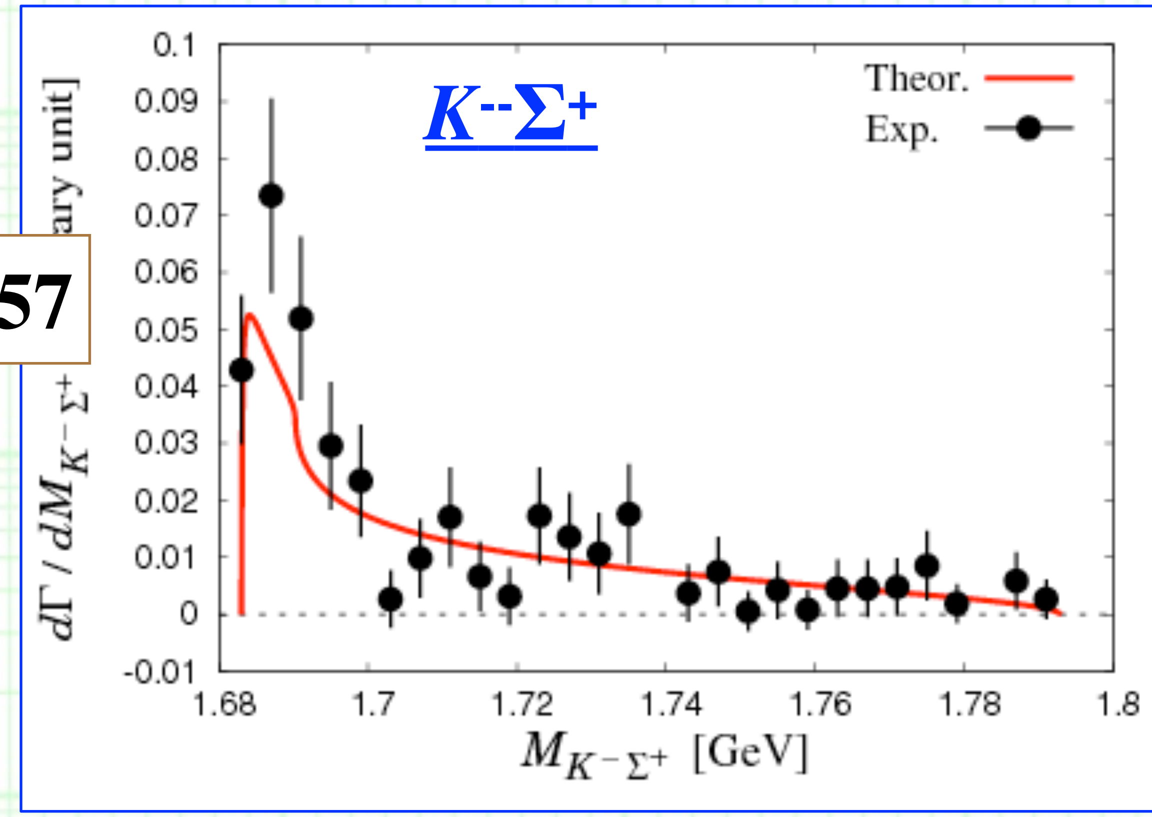


$\chi^2 / N_{d.o.f} = 60.1/57$



1. The Belle data on $\Xi(1690)$ are **reproduced qualitatively well**.

--- We can calculate the ratio

$$R \equiv \frac{\mathcal{B}[\Lambda_c^+ \to \Xi(1690)^0 K^+ \to (K^-\Sigma^+)K^+]}{\mathcal{B}[\Lambda_c^+ \to \Xi(1690)^0 K^+ \to (\bar{K}^0\Lambda)K^+]}$$

$R_{th} = 1.16$ <=> $R_{exp} = 0.62 \pm 0.33$.

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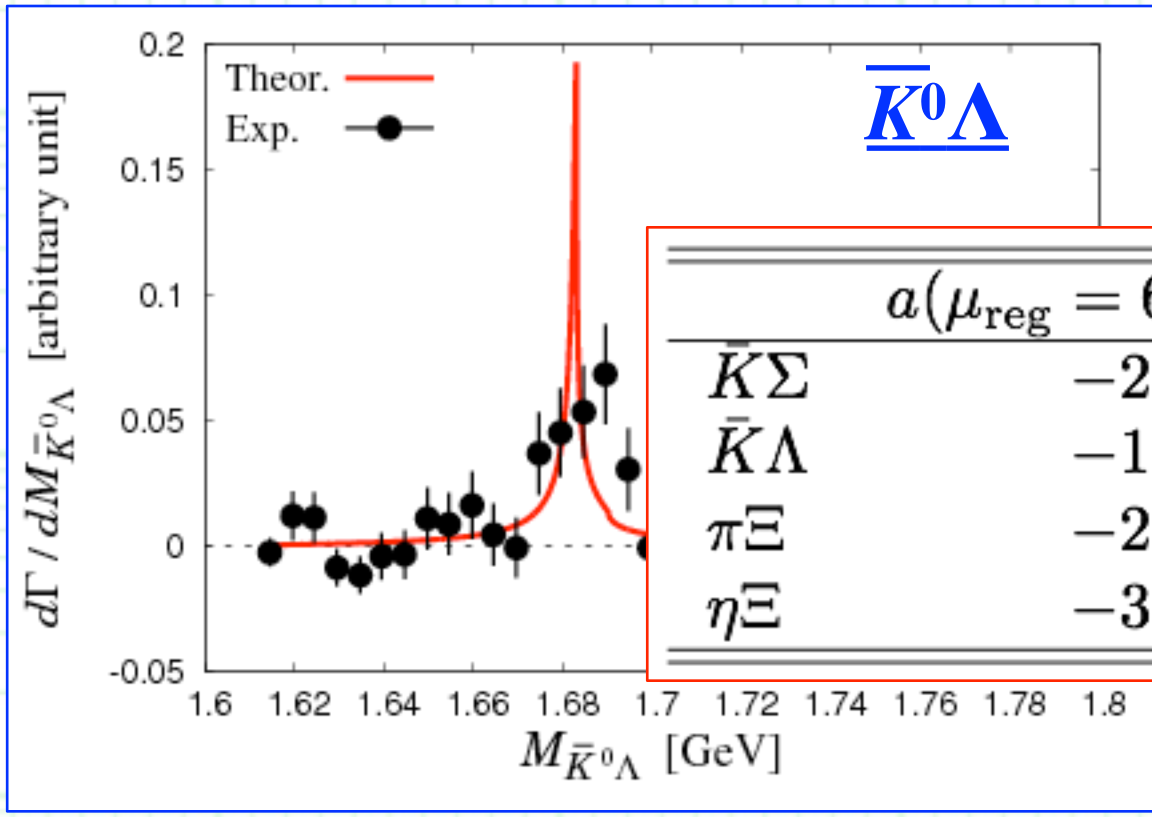

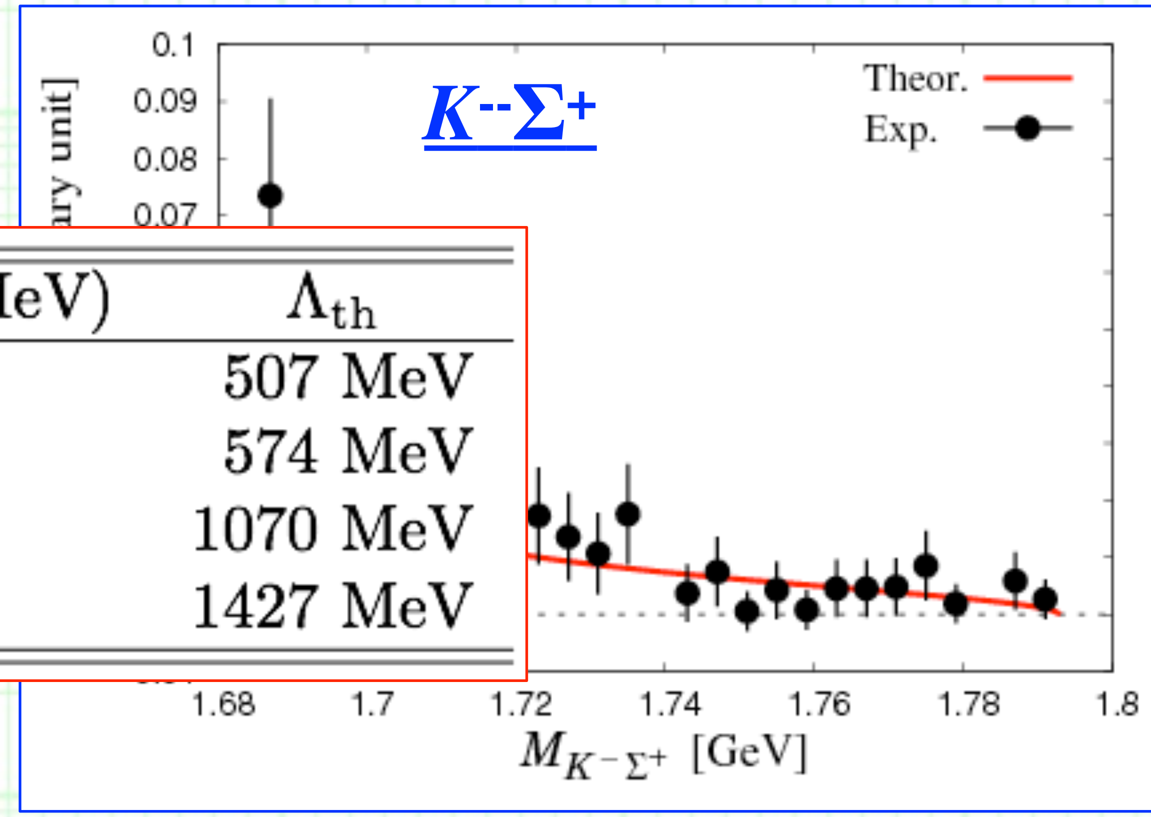

	$a(\mu_{\rm reg} = 630 \text{ MeV})$	$\Lambda_{\rm th}$
$\bar{K}\Sigma$	-2.00	507 MeV
$\bar{K}\Lambda$	-1.80	574 MeV
$\pi\Xi$	-2.91	1070 MeV
$\eta\Xi$	-3.28	1427 MeV

1. The Belle data on Ξ(1690) are reproduced qualitatively well.

2. Subtraction constants are "natural", as the values of the corresponding three-dimensional cut-off at the threshold, $\Lambda_{\rm th}$, is about 500 - 1500 MeV.

3. Numerical results

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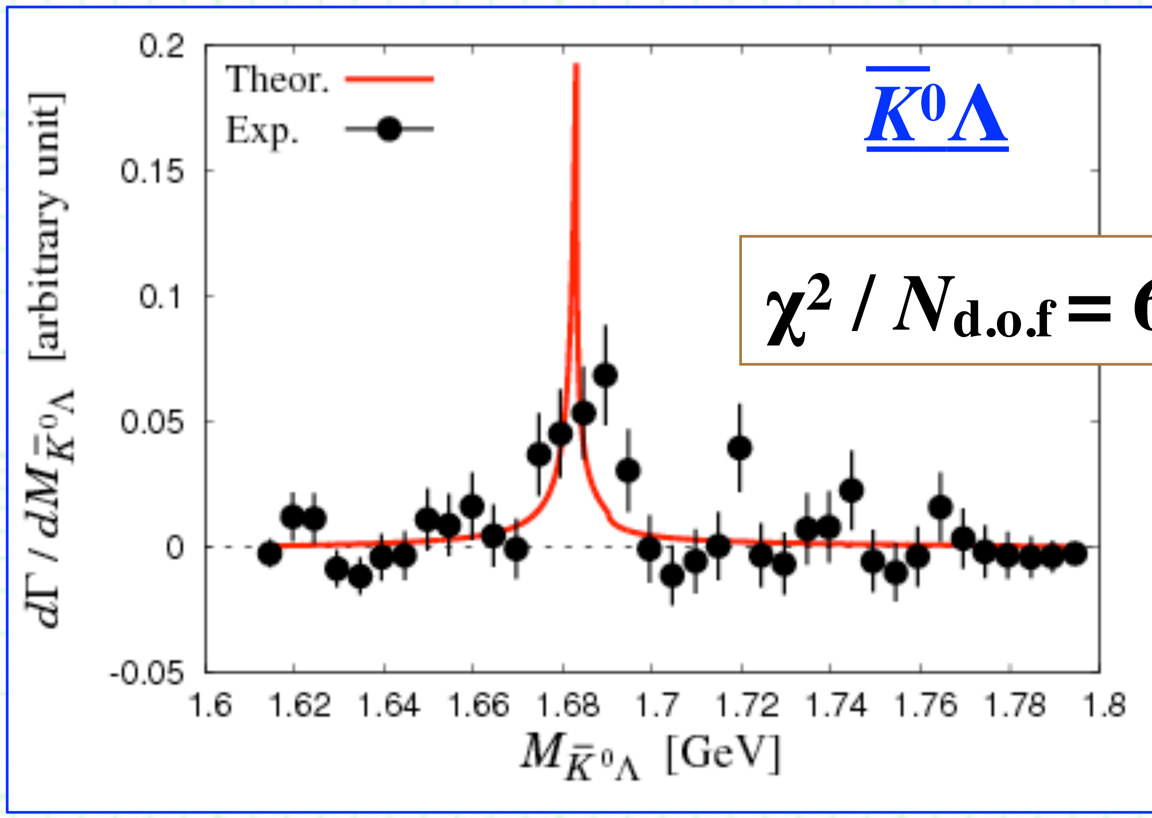

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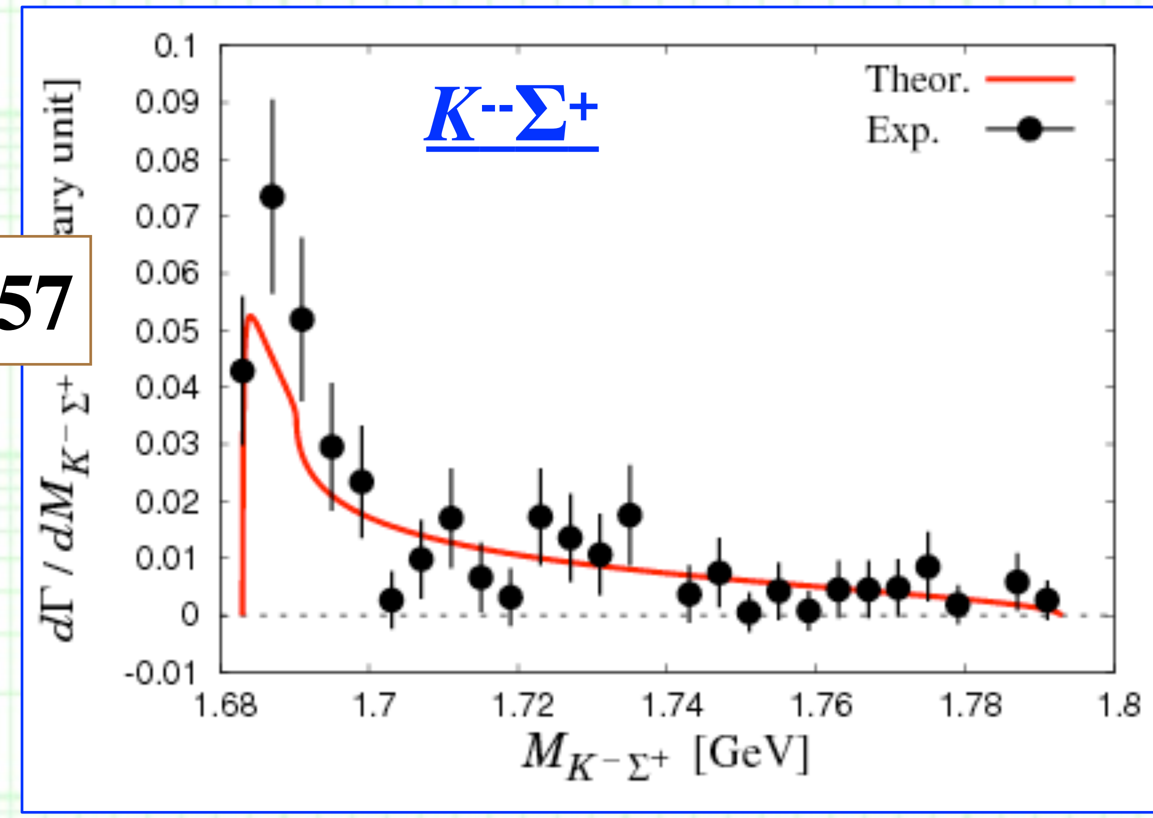


1. The Belle data on Ξ(1690) are **reproduced qualitatively well**.

2. Subtraction constants are **"natural"**.

3. **The Ξ(1690) pole is dynamically generated** at 1684.0 -- 0.6 *i* MeV, whose real part is between the $K^-\Sigma^+$ and the $\bar{K}^0\Sigma^0$ thresholds.

--- This pole exists in the first Riemann sheet of both $\bar{K}\Sigma$ channels.

4. Discussions

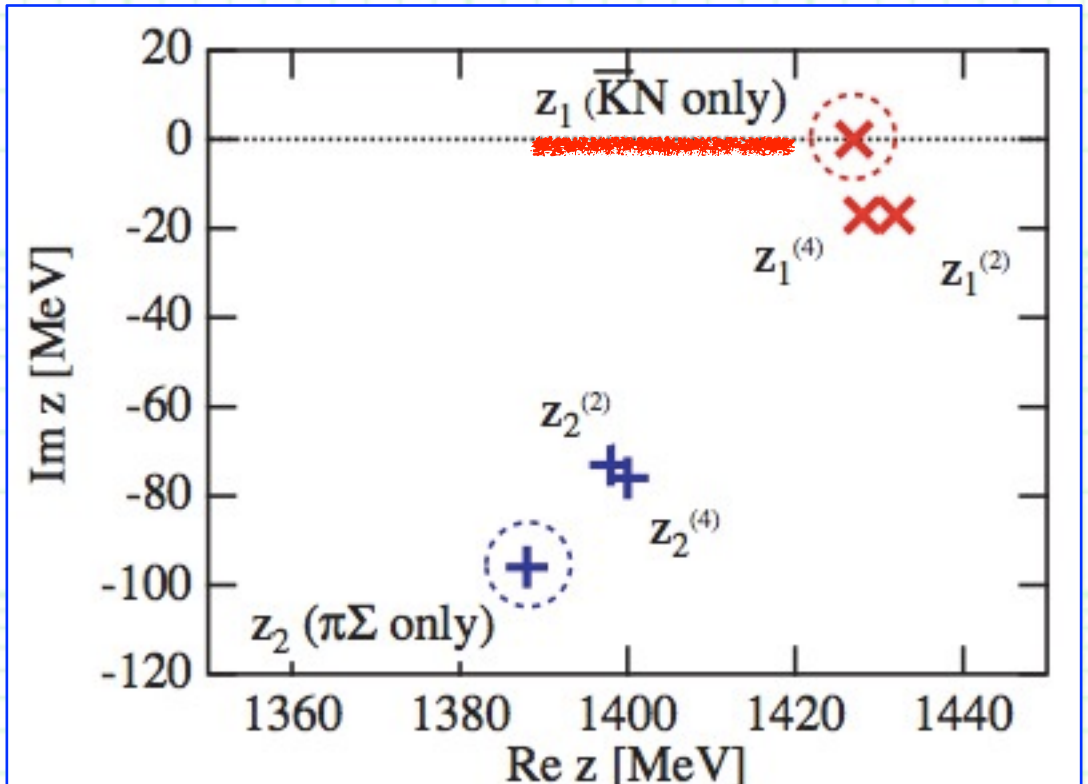
++ Origin of Ξ(1690) ++

- We naively expect that **the $\Xi(1690)^0$** (pole at 1684.0 -- 0.6 i MeV) **would originate from the $\bar{K}\Sigma(I=1/2)$ bound state** generated by the strongly attractive interaction between $\bar{K}\Sigma(I=1/2)$.

--- *cf.* The strongly attractive $\bar{K}N(I=0)$ interaction for Λ(1405).

- Thus we consider **a $\bar{K}\Sigma(I=1/2)$ single channel problem** (isospin basis), in which a bound state would appear at the energy of $V^{-1} = G$.

C_{jk}	$\bar{K}\Sigma$	$\bar{K}\Lambda$	$\pi\Xi$	$\eta\Xi$
$\bar{K}\Sigma$	2	0	$-1/2$	$3/2$
$\bar{K}\Lambda$	0	0	$-3/2$	$-3/2$
$\pi\Xi$	$-1/2$	$-3/2$	2	0
$\eta\Xi$	$3/2$	$-3/2$	0	0



For Λ(1405).

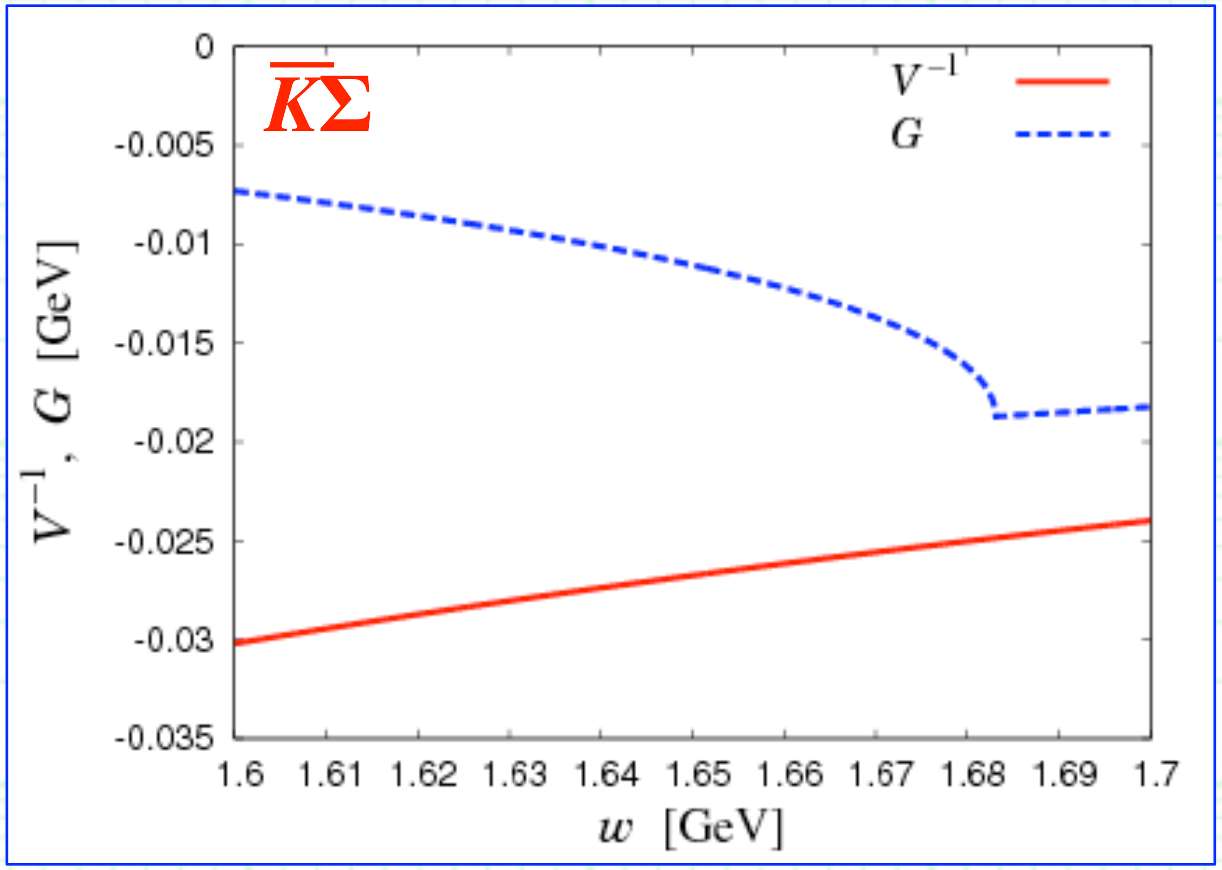
T. Hyodo and W. Weise, *Phys. Rev.* C77 (2008) 035204.

(isospin basis)

4. Discussions

++ Origin of Ξ(1690) ++

- We consider a $\bar{K}\Sigma(I=1/2)$ single channel problem (isospin basis), in which a bound state would appear at the energy of $V^{-1} = G$.



- V^{-1} is below G, which means that the chiral $\bar{K}\Sigma$ interaction is attractive but not strong enough to generate a bound state in a single channel case.

--- In contrast to the $\bar{K}N(I=0)$ Int. , which can solely generate a bound state for Λ(1405).

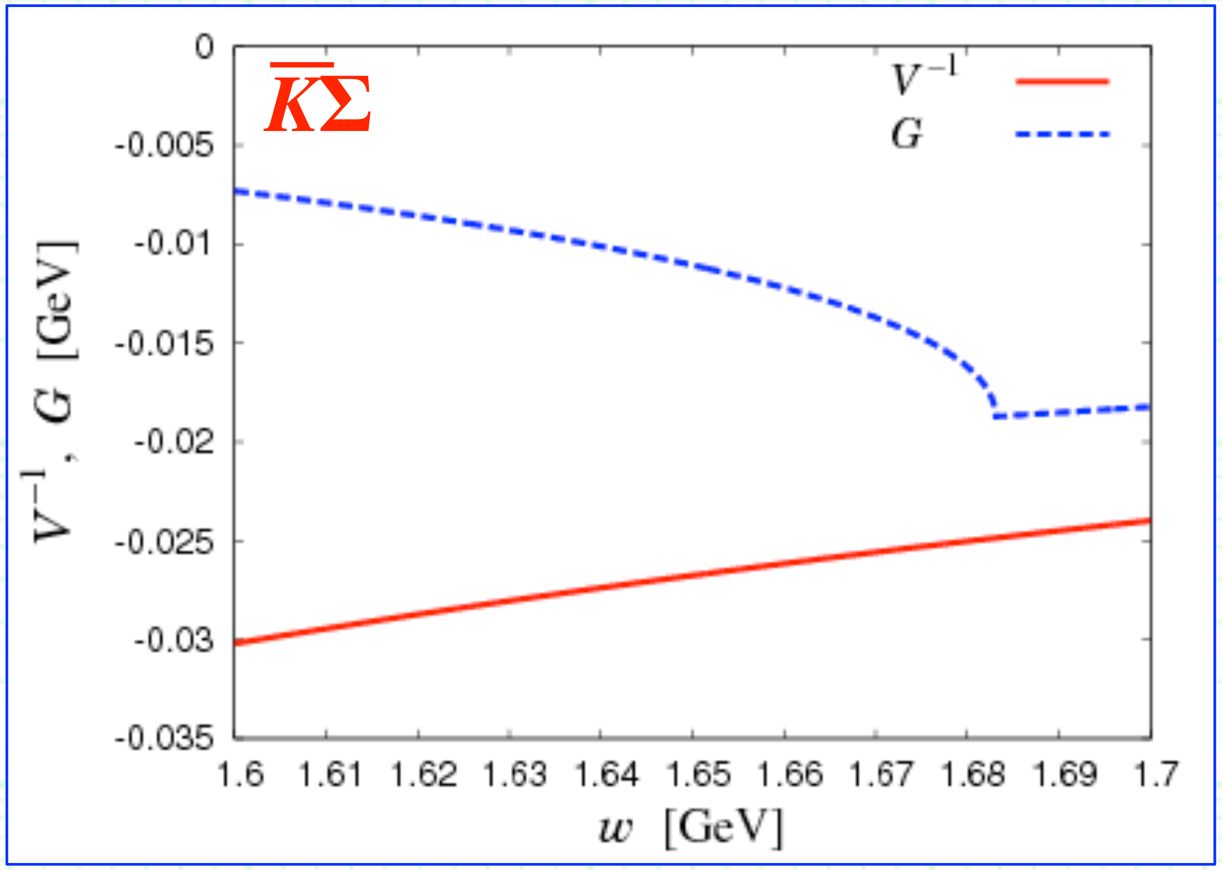
C_{jk}	$\bar{K}\Sigma$	$\bar{K}\Lambda$	$\pi\Xi$	$\eta\Xi$
$\bar{K}\Sigma$	2	0	$-1/2$	$3/2$
$\bar{K}\Lambda$	0	0	$-3/2$	$-3/2$
$\pi\Xi$	$-1/2$	$-3/2$	2	0
$\eta\Xi$	$3/2$	$-3/2$	0	0

C_{jk}	$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$K\Xi$
$\bar{K}N$	3	$-\sqrt{3/2}$	$3/\sqrt{2}$	0
$\pi\Sigma$	$-\sqrt{3/2}$	4	0	$\sqrt{3/2}$
$\eta\Lambda$	$3/\sqrt{2}$	0	0	$-3/\sqrt{2}$
$K\Xi$	0	$\sqrt{3/2}$	$-3/\sqrt{2}$	3

4. Discussions

++ Origin of Ξ(1690) ++

- We consider a $\bar{K}\Sigma(I=1/2)$ single channel problem (isospin basis), in which a bound state would appear at the energy of $V^{-1} = G$.



□ V^{-1} is below G, which means that the chiral $\bar{K}\Sigma$ interaction is attractive but not strong enough to generate a bound state in a single channel case.

--- In contrast to the $\bar{K}N(I=0)$ Int. , which can solely generate a bound state for Λ(1405).

- This fact implies that the multiple scatterings, such as $\bar{K}\Sigma$ --> ηΞ --> $\bar{K}\Sigma$, assist the $\bar{K}\Sigma$ interaction in dynamically generating Ξ(1690) as a $\bar{K}\Sigma$ quasi-bound state which is located very close to the $\bar{K}\Sigma$ threshold.

4. Discussions

++ Comparison with previous ChUA calculations ++

- This discussion on the $\bar{K}\Sigma$ interaction can be further utilized for **comparison of our result on Ξ(1690)** (pole at 1684.0 -- 0.6 *i* MeV) **with previous ones in chiral unitary approach.**

$(\frac{1}{2}, -2)$		$[\pi\Xi]$ 7.5	5.6	seen	2.6
$\Xi(1620)^{*}$		$[\bar{K}\Lambda]$ 5.2	2.8	seen	−1.5
$M \approx 1620$	1565	$[\bar{K}\Sigma]$ 0.7	2.6	0	−0.8
$\Gamma = 23$	247	$[\eta\Xi]$ 0.3	4.9	0	0.3
$(\frac{1}{2}, -2)$		$[\pi\Xi]$ 0.02	0.1	seen	−0.1
$\Xi(1690)^{***}$		$[\bar{K}\Lambda]$ 0.16	6.0	seen	0.9
$M = 1690 \pm 10$	1663	$[\bar{K}\Sigma]$ 5.15	3.1	seen	−2.5
$\Gamma = 10 \pm 6$	4	$[\eta\Xi]$ 2.28	3.2	0	−1.7

<--> Qualitatively similar, but **the mass** (= real part of the pole position) **of our result is 20 - 30 MeV larger than others.**

C. Garcia-Recio, M. F. M. Lutz and J. Nieves, *Phys. Lett.* B582 (2004) 49.

8 (1134)	2037–24i	0.6	0.6	0.3	0.2	0.3	↑0.5	1.5	0.6	**1.8**	**2.4**	1.1	0.2	1.0	**2.1**	
10 (70)	1729–46i	0.6	1.4	0.4	↑1.6	1.4	**2.1**	1.0	0.4	**3.3**	1.5	0.4	0.2	1.6	1.0	Ξ(1950) ★★★
8 (70)	1651–2i	0.2	0.3	↑**2.2**	1.3	1.0	**2.6**	0.2	0.6	0.9	0.4	0.2	**1.7**	0.4	0.2	Ξ(1690) ★★★
8 (56)	1577–139i	**2.6**	↑**1.7**	0.5	0.1	0.8	1.0	0.7	0.1	0.6	1.3	0.3	0.1	0.2	1.2	Ξ(1620) ★

D. Gamermann, C. Garcia-Recio, J. Nieves and L. L. Salcedo, *Phys. Rev.* D84 (2011) 056017.

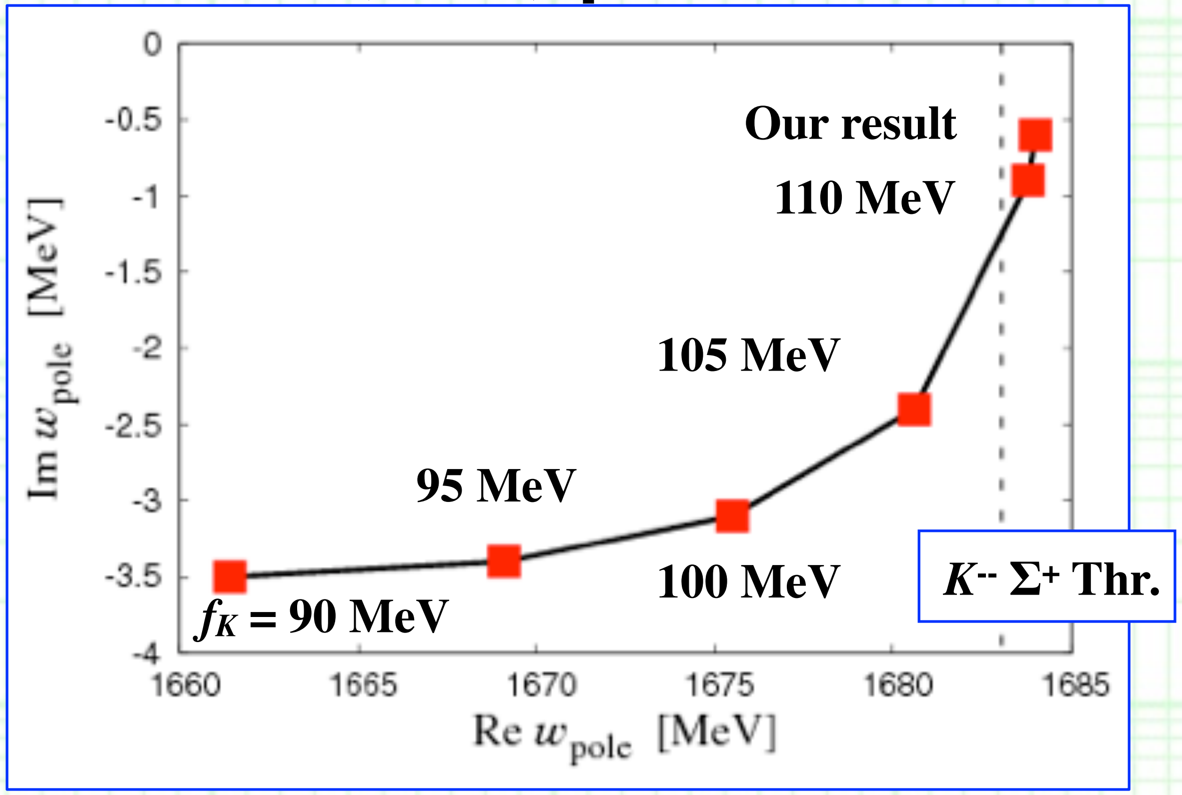
4. Discussions

++ Comparison with previous ChUA calculations ++

- This discussion on **the $\bar{K}\Sigma$ interaction** can be further utilized for **comparison of our result on Ξ(1690)** (pole at 1684.0 -- 0.6 *i* MeV) **with previous ones in chiral unitary approach**.

  - In Ref. [1] they used the meson decay constant *f* = 90 MeV in all channels, while we use their physical values (f_K = 110.64 MeV).

--> The Ξ(1690) pole moves as:



  - In Ref. [2] they introduced channels with vector mesons, which would assist more the $\bar{K}\Sigma$ interaction, and hence the mass of Ξ(1690) shifted to lower energies.

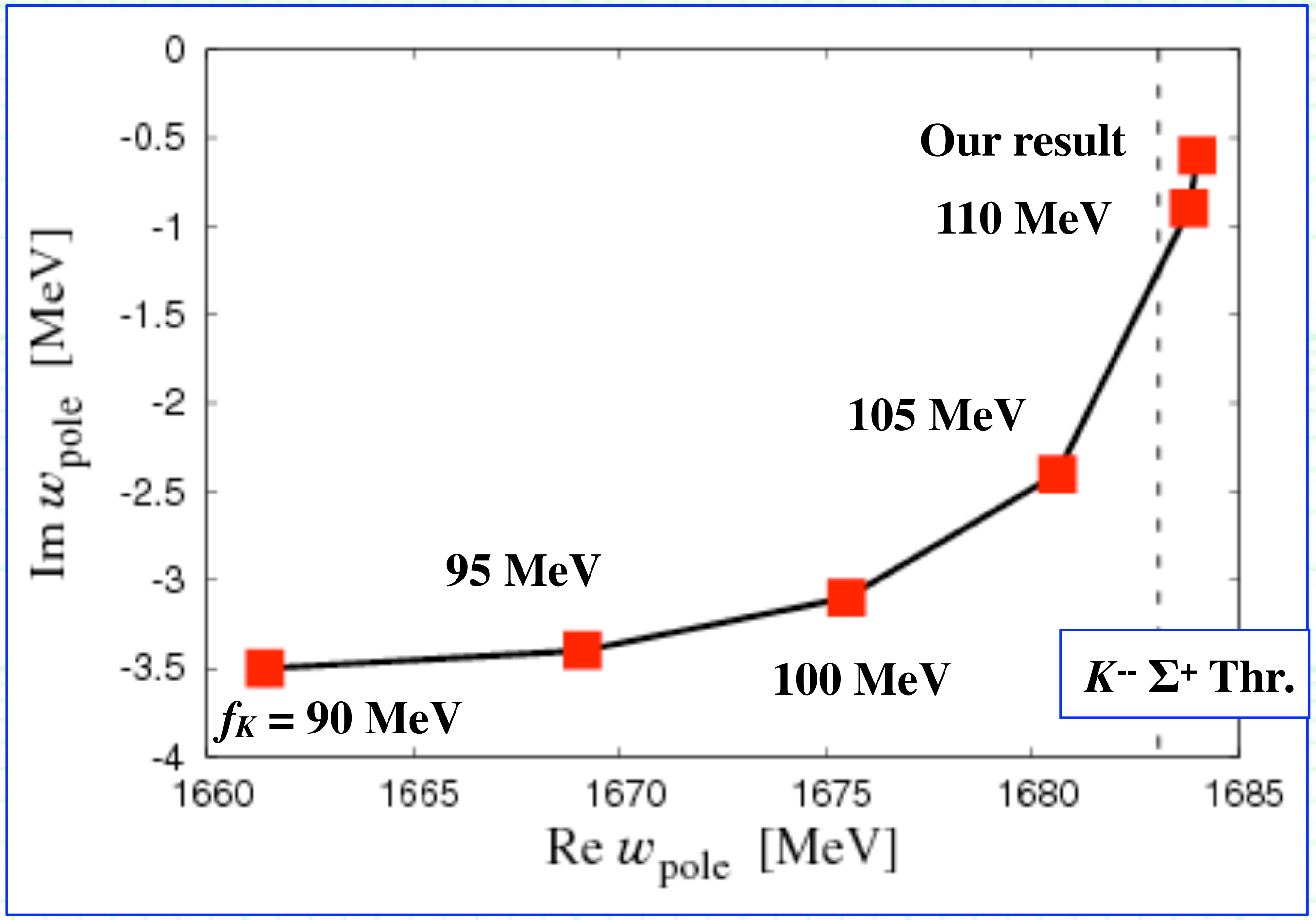
[1] C. Garcia-Recio, M. F. M. Lutz and J. Nieves, *Phys. Lett.* B582 (2004) 49.
[2] D. Gamermann, C. Garcia-Recio, J. Nieves and L. L. Salcedo, *Phys. Rev.* D84 (2011) 056017.

4. Discussions

++ Compositeness for Ξ(1690) ++

- **Our Ξ(1690) pole** exists at 1684.0 -- 0.6 i MeV, whose real part is **very close to the $K^- \Sigma^+$ threshold** (= 1863.1 MeV).

--- The pole exists in the first Riemann sheet of the $K^- \Sigma^+$ channel.



□ **Our Ξ(1690) state should be genuinely $\bar{K}\Sigma$ composite !** (coupled-channels version)

□ **"Theorem" (single channel)**: The bound state with **the field renormalization const. $Z \sim 0$** naturally appears when the state exists **near the threshold**, and especially **Z vanishes in the limit B --> 0**.

--> The state should be **genuinely composite**.

T. Hyodo, *Phys. Rev.* C90 (2014) 055208;
C. Hanhart, J. R. Pelaez and G. Rios, *Phys. Lett.* B739 (2014) 375.

4. Discussions

++ Compositeness for Ξ(1690) ++

- **Our Ξ(1690) pole exists at 1684.0 -- 0.6 *i* MeV, whose real part is very close to the $K^-\Sigma^+$ threshold (= 1863.1 MeV).**

--- The pole exists in the first Riemann sheet of the $K^-\Sigma^+$ channel.

- □ **Its $\bar{K}\Sigma$ component can be measured in terms of the compositeness, which is defined as the contribution of the two-body component to the normalization of the total wave function.**

Hyodo, *Int. J. Mod. Phys.* A28 (2013) 1330045; T. S. , Hyodo and Jido, *PTEP* (2015) 063D04.

$$\langle \Psi^* | \Psi \rangle = \sum_j X_j + Z = 1$$

$$X_j = -g_j^2 \left[\frac{dG_j}{dw} \right]_{w = w_{\mathrm{pole}}} , \quad Z = - \sum_{j,k} g_k g_j \left[G_j \frac{dV_{jk}}{dw} G_k \right]_{w = w_{\mathrm{pole}}}$$

$X_{K^-\Sigma^+}$	$0.84 - 0.27i$
$X_{\bar{K}^0\Sigma^0}$	$0.11 + 0.15i$
$X_{\bar{K}^0\Lambda}$	$-0.01 + 0.01i$
$X_{\pi^+\Xi^-}$	$0.00 + 0.00i$
$X_{\pi^0\Xi^0}$	$0.00 + 0.00i$
$X_{\eta\Xi^0}$	$0.01 + 0.02i$
Z	$0.06 + 0.09i$

- □ **From the result of compositeness, the $\bar{K}\Sigma$ compositeness really dominates the sum rule with small imaginary part.**

--> Strongly indicates that Ξ(1690) is indeed a $\bar{K}\Sigma$ molecular state.

4. Discussions

++ Small decay width ++

- One more remarkable property of $\Xi(1690)^0$ is its very small width: $\Gamma = -2\,\mathrm{Im}(w_{\rm pole}) \sim 1$ MeV.

--- This can be qualitatively understood by considering the structure of C_{jk} for a $\bar{K}\Sigma$ bound state.

1. Transition of $\bar{K}\Sigma$ <--> $\bar{K}\Lambda$ is forbidden at the leading order ($C_{jk} = 0$), so the decay of the $\bar{K}\Sigma$ quasi-bound state to the $\bar{K}\Lambda$ channel is highly suppressed.

C_{jk}	$\bar{K}\Sigma$	$\bar{K}\Lambda$	$\pi\Xi$	$\eta\Xi$
$\bar{K}\Sigma$	2	0	$-1/2$	$3/2$
$\bar{K}\Lambda$	0	0	$-3/2$	$-3/2$
$\pi\Xi$	$-1/2$	$-3/2$	2	0
$\eta\Xi$	$3/2$	$-3/2$	0	0

2. In addition, $\bar{K}\Sigma$ <--> $\pi\Xi$ is not strong compared to, *e.g.*, $\bar{K}N(I=0)$ <--> $\pi\Sigma$.

--- $C_{jk} = -0.5$ vs. $-\sqrt{1.5} = -1.22$ ... .

($I = 1/2$, isospin basis)

C_{jk}	$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$K\Xi$
$\bar{K}N$	3	$-\sqrt{3/2}$	$3/\sqrt{2}$	0
$\pi\Sigma$	$-\sqrt{3/2}$	4	0	$\sqrt{3/2}$
$\eta\Lambda$	$3/\sqrt{2}$	0	0	$-3/\sqrt{2}$
$K\Xi$	0	$\sqrt{3/2}$	$-3/\sqrt{2}$	3

--> As a consequence, $\Xi(1690)$ as a $\bar{K}\Sigma$ molecule cannot couple strongly to $\bar{K}\Lambda$ nor $\pi\Xi$.

--- This leads to small decay width and tiny branching fraction to $\pi\Xi$.

4. Discussions

++ Charged Ξ(1690) ++

- Finally we consider the charged Ξ(1690) in the same parameter set as the neutral one. As a result, we obtain the $\Xi(1690)^{-}$ pole as:

w_{pole}	$1692.5 - 10.7i$ MeV
$X_{\bar{K}^0\Sigma^-}$	$0.87 - 0.51i$
$X_{K^-\Sigma^0}$	$-0.33 + 0.36i$
$X_{K^-\Lambda}$	$0.00 + 0.04i$
$X_{\pi^-\Xi^0}$	$0.00 + 0.00i$
$X_{\pi^0\Xi^-}$	$0.00 + 0.00i$
$X_{\eta\Xi^-}$	$0.07 + 0.02i$
Z	$0.39 + 0.09i$

- The $\Xi(1690)^{-}$ pole is located between the $K^{-}\Sigma^0$ and $\bar{K}^0\Sigma^{-}$ thresholds; The pole is in the first Riemann sheet of the $\bar{K}^0\Sigma^{-}$ and $\eta\Xi^{-}$ channels and in the second Riemann sheet of the $K^{-}\Lambda$, $K^{-}\Sigma^0$, $\pi^{-}\Xi^0$, and $\pi^0\Xi^{-}$ channels.

- The pole position has a larger imaginary part ~ 10 MeV compared to the neutral case, since it exists above the $\bar{K}^0\Sigma^{-}$ threshold in its second Riemann sheet and hence the decay to $\bar{K}^0\Sigma^{-}$ is allowed.

- Although both $X_{K0\Sigma-}$ and $X_{K-\Sigma0}$ have large imaginary part, sum of them is the dominant contribution with its small imaginary part, which implies that the $\Xi(1690)^{-}$ state is also a $\bar{K}\Sigma$ molecular state.

5. Summary and outlook

++ Summary ++

- We have investigated dynamics of $\bar{K}\Sigma$ and its coupled channels in the chiral unitary approach.
  - We employ the simplest interaction: Weinberg-Tomozawa term.
  - Subtraction constants as free parameters are fixed by fitting the $\bar{K}^0\Lambda$ and $K^-\Sigma^+$ mass spectra to the experimental data.

- As a result, we have found that:
  - The obtained scattering amplitude can qualitatively reproduce the experimental data of the $\bar{K}^0\Lambda$ and $K^-\Sigma^+$ mass spectra.
  - Dynamically generates a Ξ^* pole near the $\bar{K}\Sigma$ threshold as a $\bar{K}\Sigma$ molecule, which can be identified with the $\Xi(1690)^0$ resonance.
  - However, the $\bar{K}\Sigma$ interaction alone is slightly insufficient to bring a $\bar{K}\Sigma$ bound state, so multiple scattering is important for $\Xi(1690)$.
  - The small or vanishing couplings of the $\bar{K}\Sigma$ channel to others can naturally explain small decay width of $\Xi(1690)$.

5. Summary and outlook

++ Outlook ++

- **Theoretical study**:
  - Propose reactions which can clarify properties of the $\Xi(1690)$ resonance in experiments, both neutral and charged states.
  - Predict the $\Xi(1690)$ production cross section.
  - Improvement of model by, *e.g.* , introducing s- and u-channel Born terms.

- **Experimental study**:
  - Determine J^P of the $\Xi(1690)^0$ resonance.
  - Measure the $\bar{K}\Lambda$ and $\bar{K}\Sigma$ mass spectra and ratio of their branching fractions.
  - Furthermore, precise determination of its pole position should be important to discuss the internal structure of $\Xi(1690)$.

--- Flatte parameterization may be necessary since it exists near the $\bar{K}\Sigma$ threshold.

Thank you very much for your kind attention !