Exotics in meson-baryon dynamics with chiral symmetry

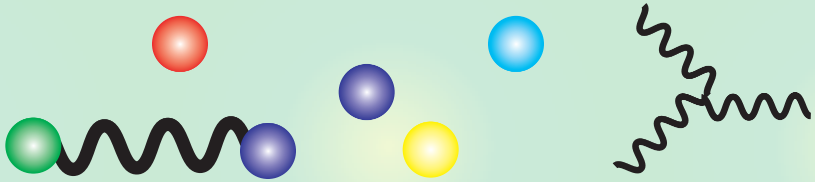
Tetsuo Hyodo[a]

RCNP, Osaka[a]

2006, Feb. 8th

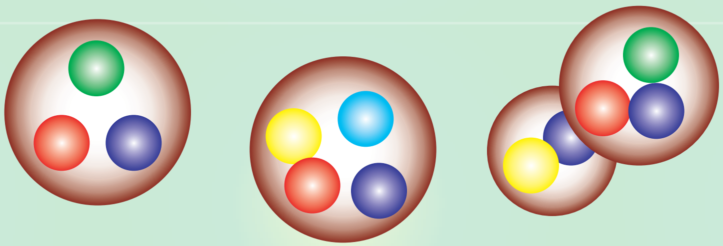
Introduction : QCD at low energy

Quantum chromodynamics (QCD)
: strong interaction of quarks and gluons



At low energies...
Color confinement
Chiral symmetry breaking

Mesons, baryons (Hadrons)

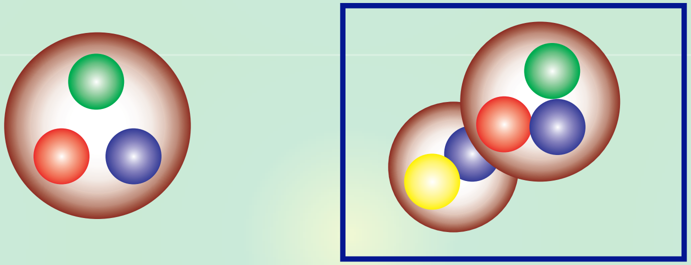


“exotics”

: elementary excitations of QCD vacuum

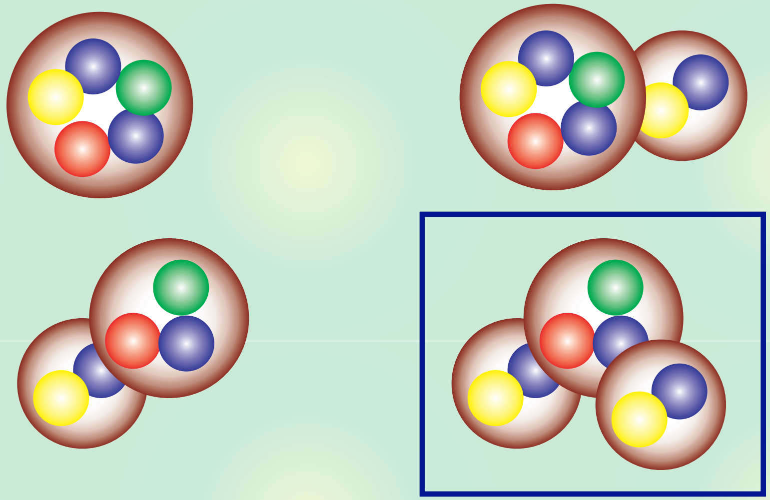
Introduction : Exotics

$$|\,B\,\rangle = |\,qqq\,\rangle + |\,qqq(q\bar{q})\,\rangle + \cdots$$



meson-baryon molecule

$$|\,P\,\rangle = |\,qqqq\bar{q}\,\rangle + |\,qqqq\bar{q}(q\bar{q})\,\rangle + \cdots$$



two-meson cloud

Hadron structure ↔ meson-baryon dynamics

Introduction : Hadronic description and symmetries

Hadronic description ↔ quark description

- **Observed in nature**
- **Interaction can be measured in experiments**

Guiding principle : symmetries of QCD

Chiral symmetry -> low energy theorem

$$m_q \to 0$$

Flavor symmetry -> GMO formula

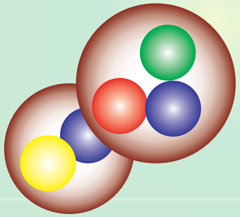
$$\Delta m_q \to 0$$

Symmetry

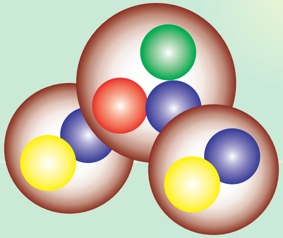
Hadrons ➡ **“exotics”**

Contents

- **Introduction**
- **Part I : chiral unitary model**
  - SU(3) breaking effect
  - Production of Λ(1405)
  - Magnetic moments of N(1535)
  - K* coupling to Λ(1520)



- **Part II : Pentaquarks**
  - Spin parity determination
  - Two-meson cloud
  - 8–$\overline{10}$ representation mixing
  - Meson induced Θ production



- **Summary**

Introduction : $\Lambda(1405)$

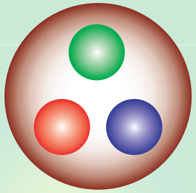
$\Lambda(1405) : J^P = 1/2^-, I = 0$

Mass : 1406.5 ± 4.0 MeV

Width : 50 ± 2 MeV

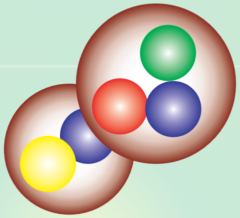
Decay mode : $\Lambda(1405) \rightarrow (\pi\Sigma)_{I=0}$ **100%**

Quark model : p-wave, ~1600 MeV?



N. Isgur, and G. Karl, PRD 18, 4187 (1978)

Coupled channel multi-scattering



R.H. Dalitz, T.C. Wong and G. Rajasekaran PR 153, 1617 (1967)

Chiral unitary model

Flavor SU(3) meson-baryon scatterings (s-wave)

Chiral symmetry

Low energy behavior

+

Unitarity of S-matrix

Non-perturbative resummation

→

Scattering amplitude

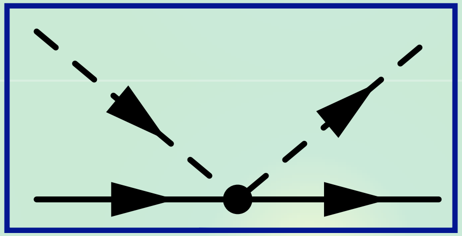
$J^P = 1/2^-$ resonances

- Theoretical foundation based on chiral symmetry
- Analytically solvable
  —> information of the complex energy plane

Framework of the chiral unitary model : Interaction

Chiral perturbation theory

$$\mathcal{L}_{WT} = \frac{1}{4f^2} \mathrm{Tr}(\bar{B} i\gamma^\mu [(\Phi\partial_\mu\Phi - \partial_\mu\Phi\Phi), B])$$



chiral symmetry

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

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

Ex.)

$$V^{(WT)}(\bar{K}N \to \bar{K}N, I=0) = -\frac{3}{4f^2}(2\sqrt{s} - M_N - M_N)\sqrt{\frac{E_N + M_N}{2M_N}}\sqrt{\frac{E_N + M_N}{2M_N}}$$

$$V^{(WT)}(\bar{K}N \to \pi\Sigma, I=0) = \sqrt{\frac{3}{2}}\frac{1}{4f^2}(2\sqrt{s} - M_N - M_\Sigma)\sqrt{\frac{E_N + M_N}{2M_N}}\sqrt{\frac{E_\Sigma + M_\Sigma}{2M_\Sigma}}$$

Framework of the chiral unitary model : Unitarization

Unitarization

N/D method : general form of amplitude

$$T_{ij}^{-1}(\sqrt{s}) = \delta_{ij}\left(\tilde{a}_i(s_0) + \frac{s-s_0}{2\pi}\int_{s_i^+}^{\infty} ds' \frac{\rho_i(s')}{(s'-s)(s'-s_0)}\right) + \mathcal{T}_{ij}^{-1}$$

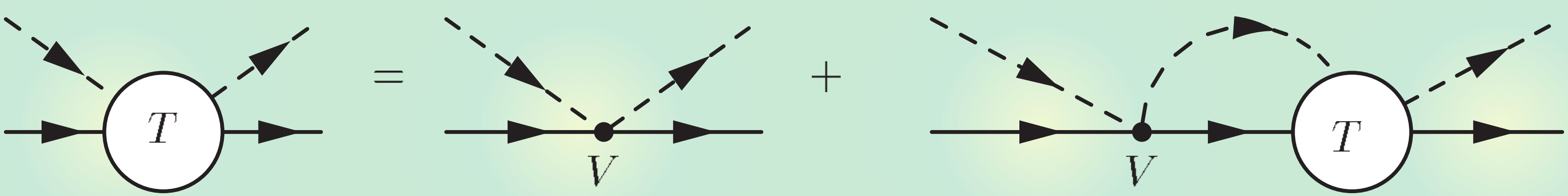
$$-G_i(\sqrt{s}) = -i\int \frac{d^4q}{(2\pi)^4}\frac{2M_i}{(P-q)^2-M_i^2+i\epsilon}\frac{1}{q^2-m_i^2+i\epsilon}$$

$$V^{(WT)}$$

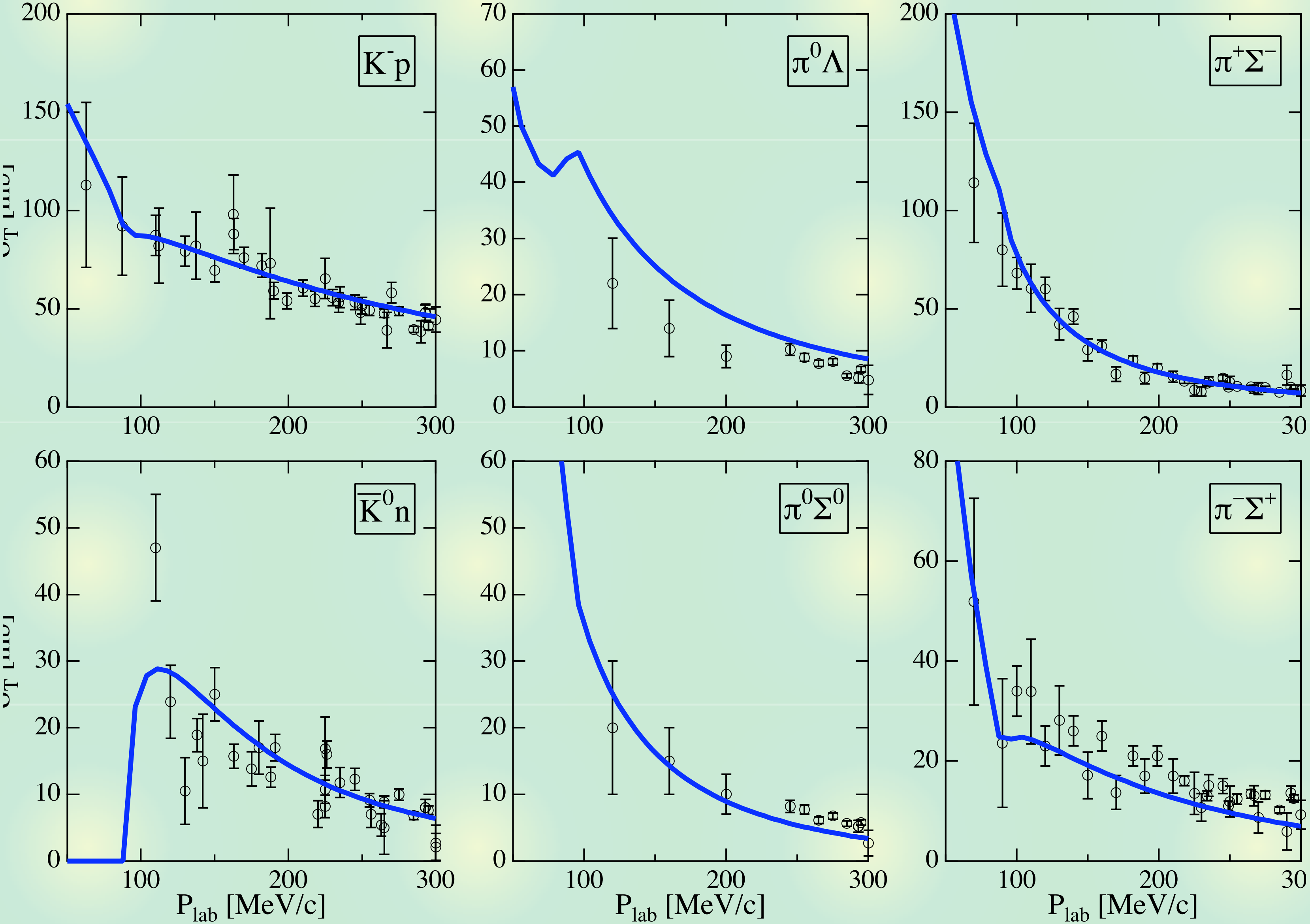
$$T^{-1} = -G + (V^{(WT)})^{-1}$$

$$T = V^{(WT)} + V^{(WT)}GT$$

physical masses
regularization of loop



Total cross sections of K⁻p scattering

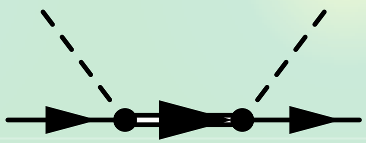


T. Hyodo, Nam, Jido, Hosaka, PRC (2003), PTP (2004), Chap. 4.

Two poles?

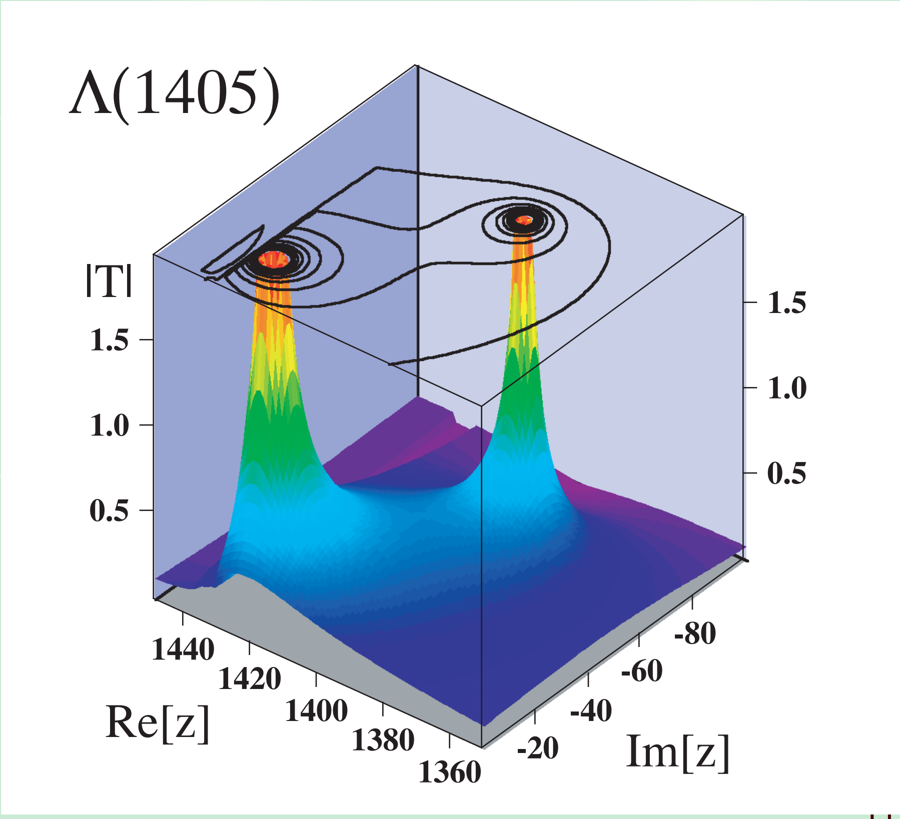
If there is a sufficient attraction, resonances can be dynamically generated.

$$T_{ij}(\sqrt{s}) \sim \frac{g_i g_j}{\sqrt{s} - M_R + i\Gamma_R/2}$$

$\sim$ 

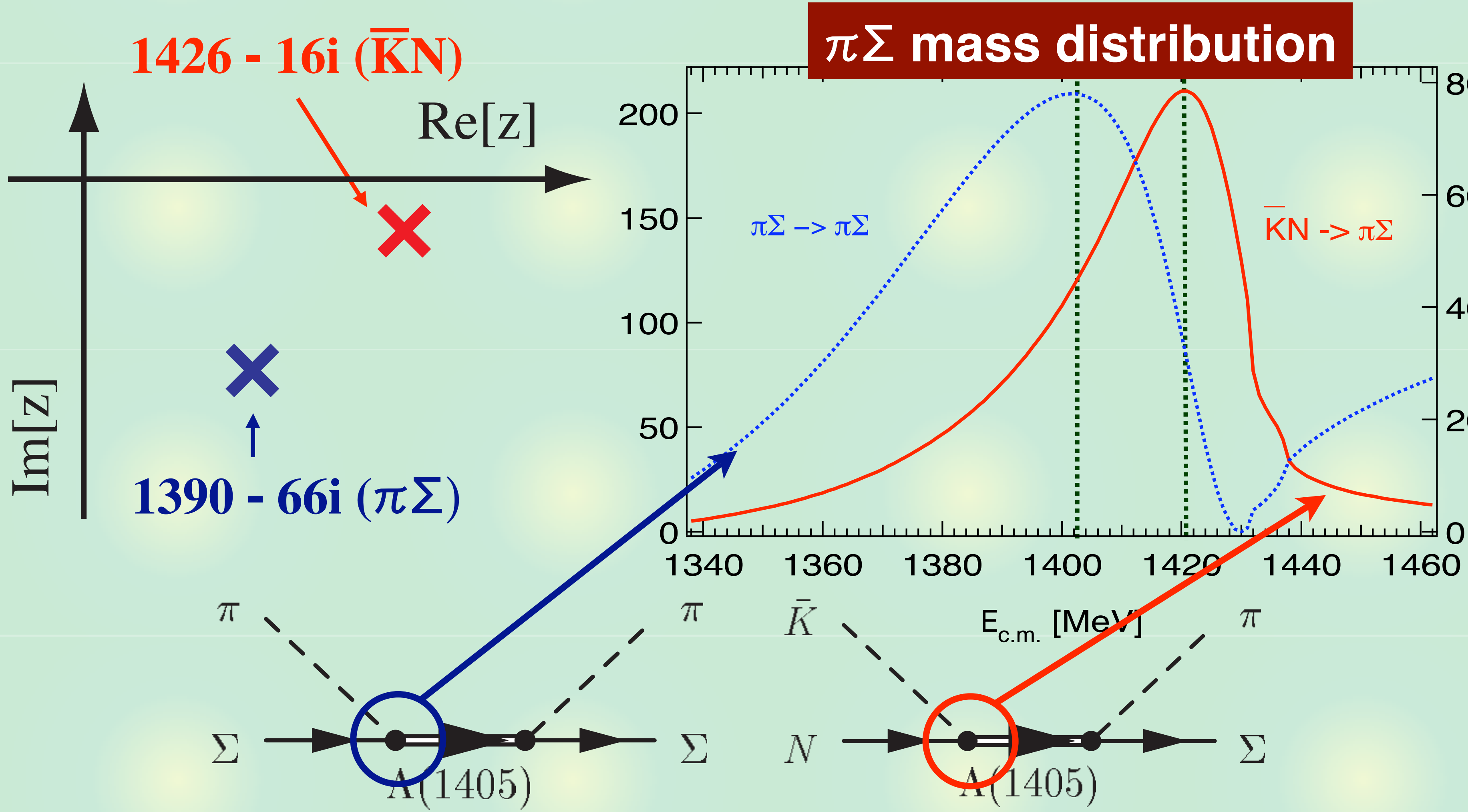
There are two poles of the scattering amplitude around nominal Λ(1405) energy region.

- **Cloudy bag model**
- **Chiral unitary model**



Λ(1405) in the chiral unitary model

Real states? -> to be checked experimentally



Shape of πΣ spectrum depends on initial state

Production reaction for the $\Lambda(1405)$

$$\frac{d\sigma}{dM_I} = C|t_{\pi\Sigma\to\pi\Sigma}|^2 p_{CM} \Rightarrow \frac{d\sigma}{dM_I} = |\sum_i C_i t_{i\to\pi\Sigma}|^2 p_{CM}$$

In order to clarify the two-pole structure, we study two reactions.

$$\pi^- p \to K^0 \Lambda(1405) \to K^0 \pi\Sigma$$

- **Experimental result -> lower energy pole**

T. Hyodo, Hosaka, Oset, Ramos, Vacas, PRC (2003), Section 5.2

$$\gamma p \to K^* \Lambda(1405) \to K^0 \pi^+ \pi\Sigma$$

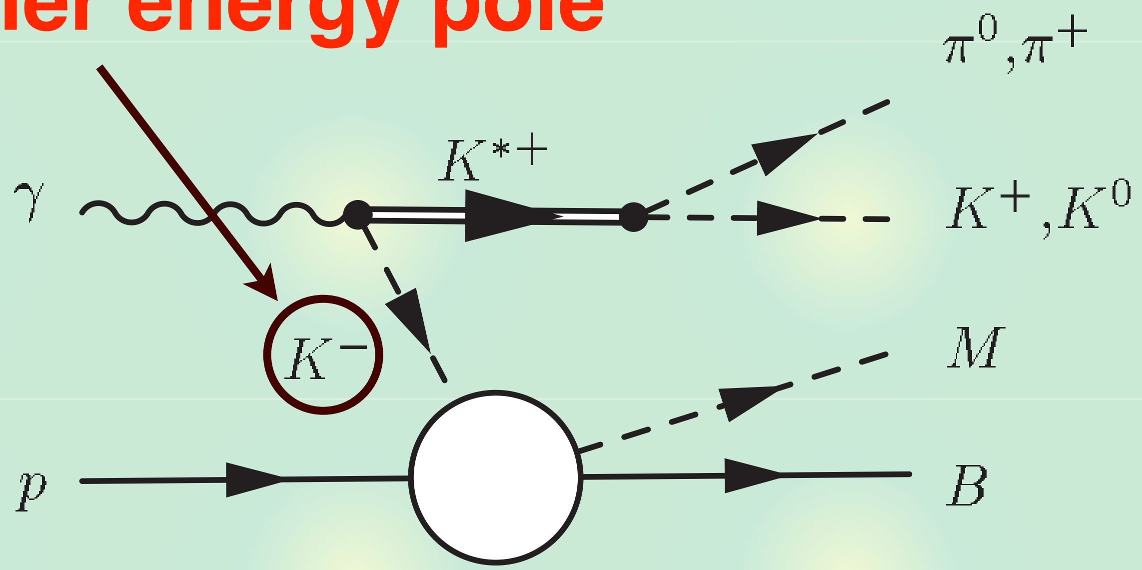
- **higher energy pole?**

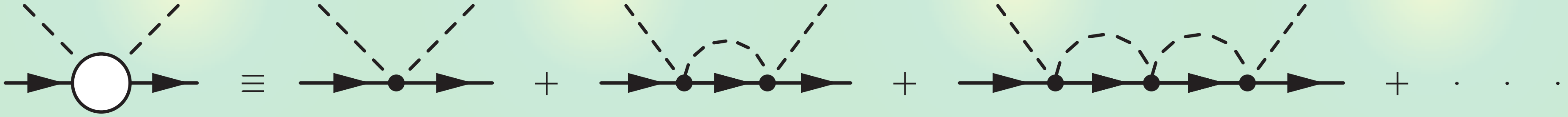
T. Hyodo, Hosaka, Vacas, Oset, PLB (2004), Section 5.3

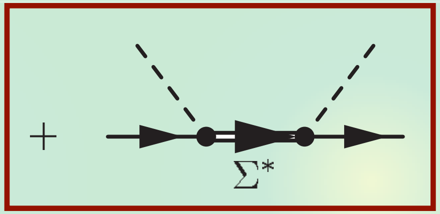
Photoproduction of K* and Λ(1405)

Only K⁻p channel appears at the initial stage

—> higher energy pole

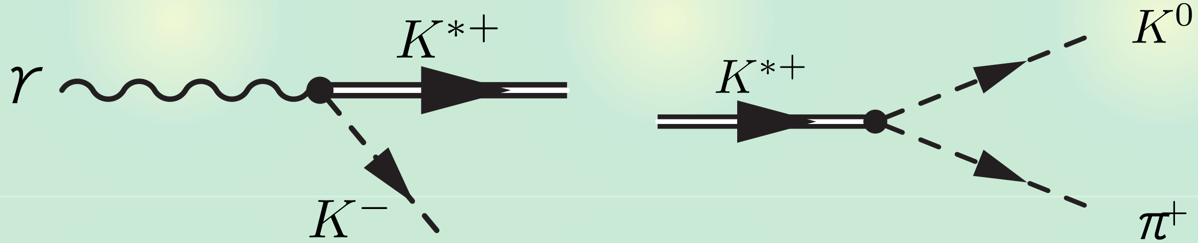






Σ(1385) is included <- background estimation

Advantage of this reaction



$$\mathcal{L}_{K^*K\gamma} = g_{K^*K\gamma}\epsilon^{\mu\nu\alpha\beta}\partial_\mu A_\nu(\partial_\alpha K^{*-}_\beta K^+ + \partial_\alpha \bar{K}^{*0}_\beta K^0) + \text{h.c.}$$

$$\mathcal{L}_{VPP} = -\frac{ig_{VPP}}{\sqrt{2}}\text{Tr}(V^\mu[\partial_\mu P, P])$$

photon polarization —> K* polarization
—> Kπ decay plane

For 0+ meson emission, $\epsilon^{\mu\nu\alpha\beta}$ is absent.

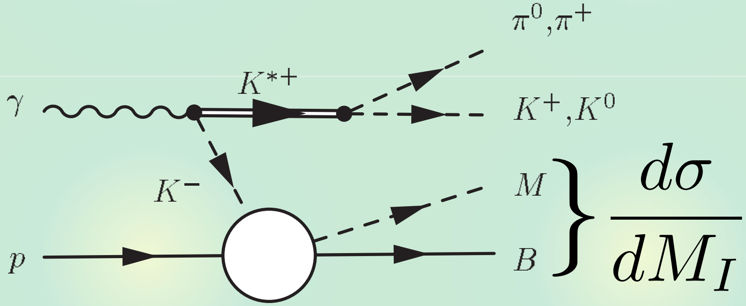
With polarized photon beam, the exchanged particle can be identified.

Clear mechanism

Isospin decomposition of final states

Since initial state is $\overline{K}N$, no I=2 component.

$$\sigma(\pi^0\Sigma^0) \propto \frac{1}{3}|T^{(0)}|^2$$



- **Pure I=0 amplitude <— Λ(1405)**

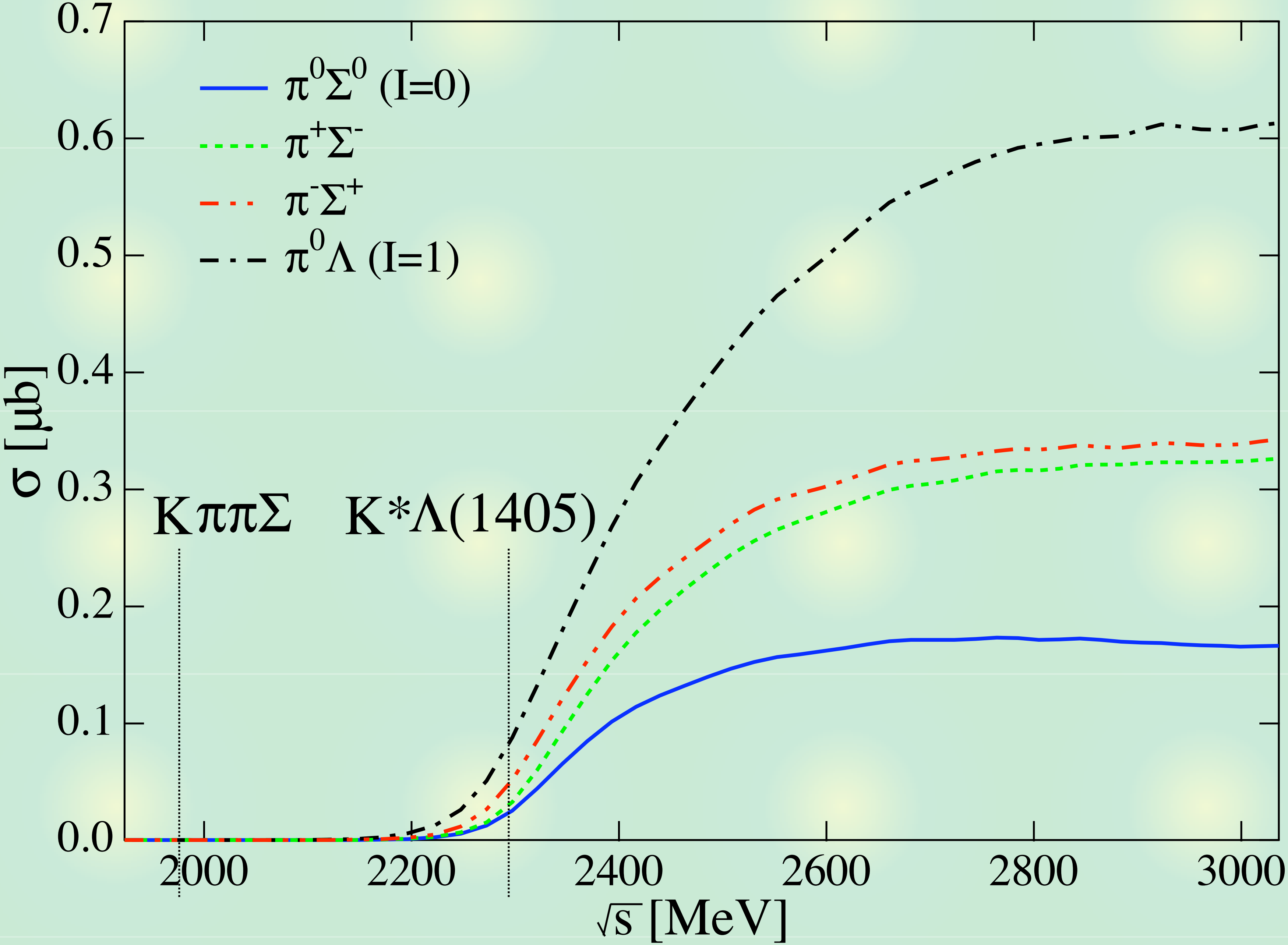
$$\sigma(\pi^0\Lambda) \propto |T^{(1)}|^2$$

- **Pure I=1 amplitude <— Σ(1385)**

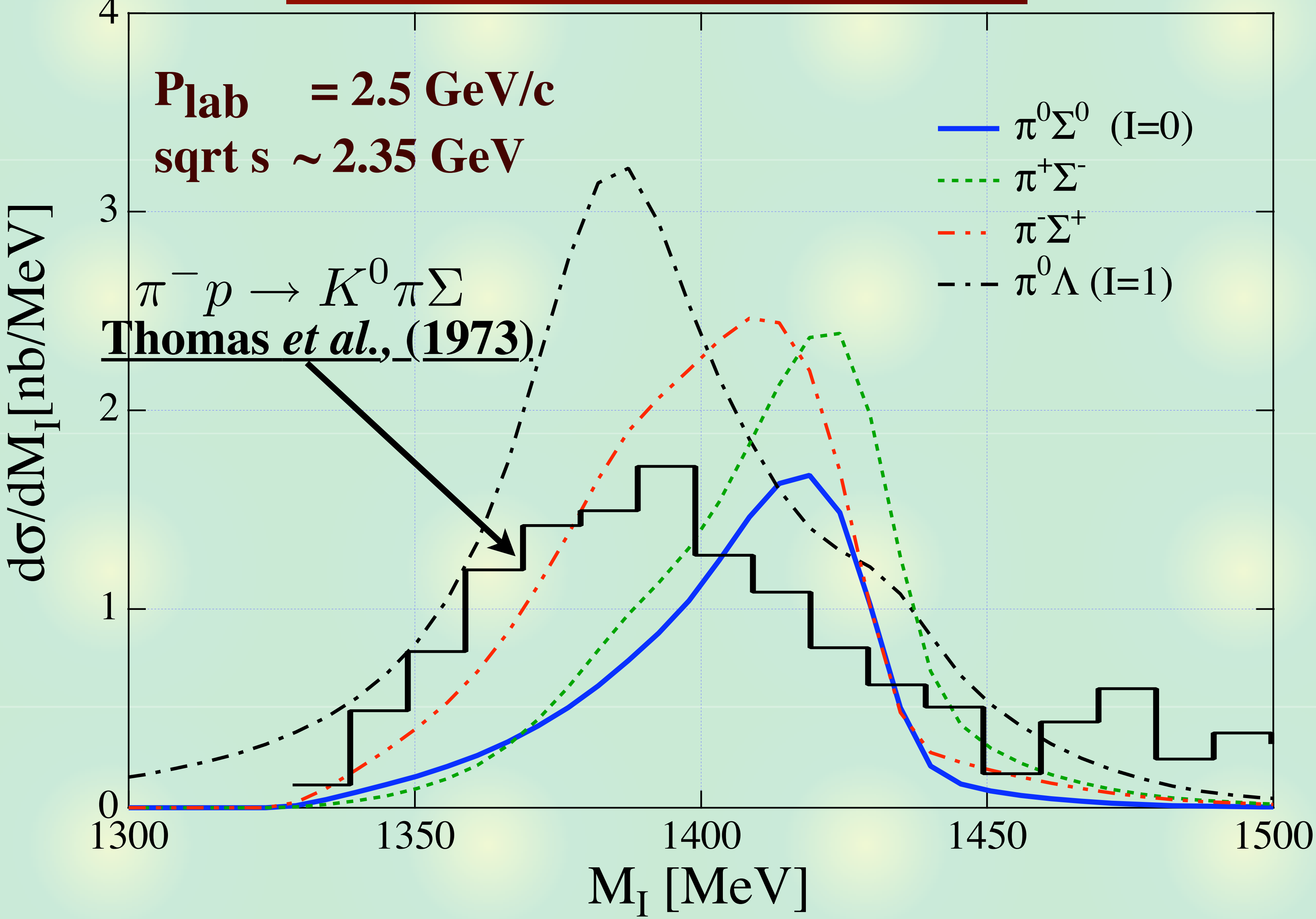
$$\sigma(\pi^\pm\Sigma^\mp) \propto \frac{1}{3}|T^{(0)}|^2 + \frac{1}{2}|T^{(1)}|^2 \pm \frac{2}{\sqrt{6}}\mathrm{Re}(T^{(0)}T^{(1)*})$$

- **Mixture of I=0 and I=1**

Total cross sections



Invariant mass distributions



- dominance of higher pole -> different shape

Isospin decomposition of charged πΣ states

Charged πΣ states

$$\frac{d\sigma(\pi^{\pm}\Sigma^{\mp})}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2 + \frac{1}{2}|T^{(1)}|^2 \pm \frac{2}{\sqrt{6}}\mathrm{Re}(T^{(0)}T^{(1)*})$$

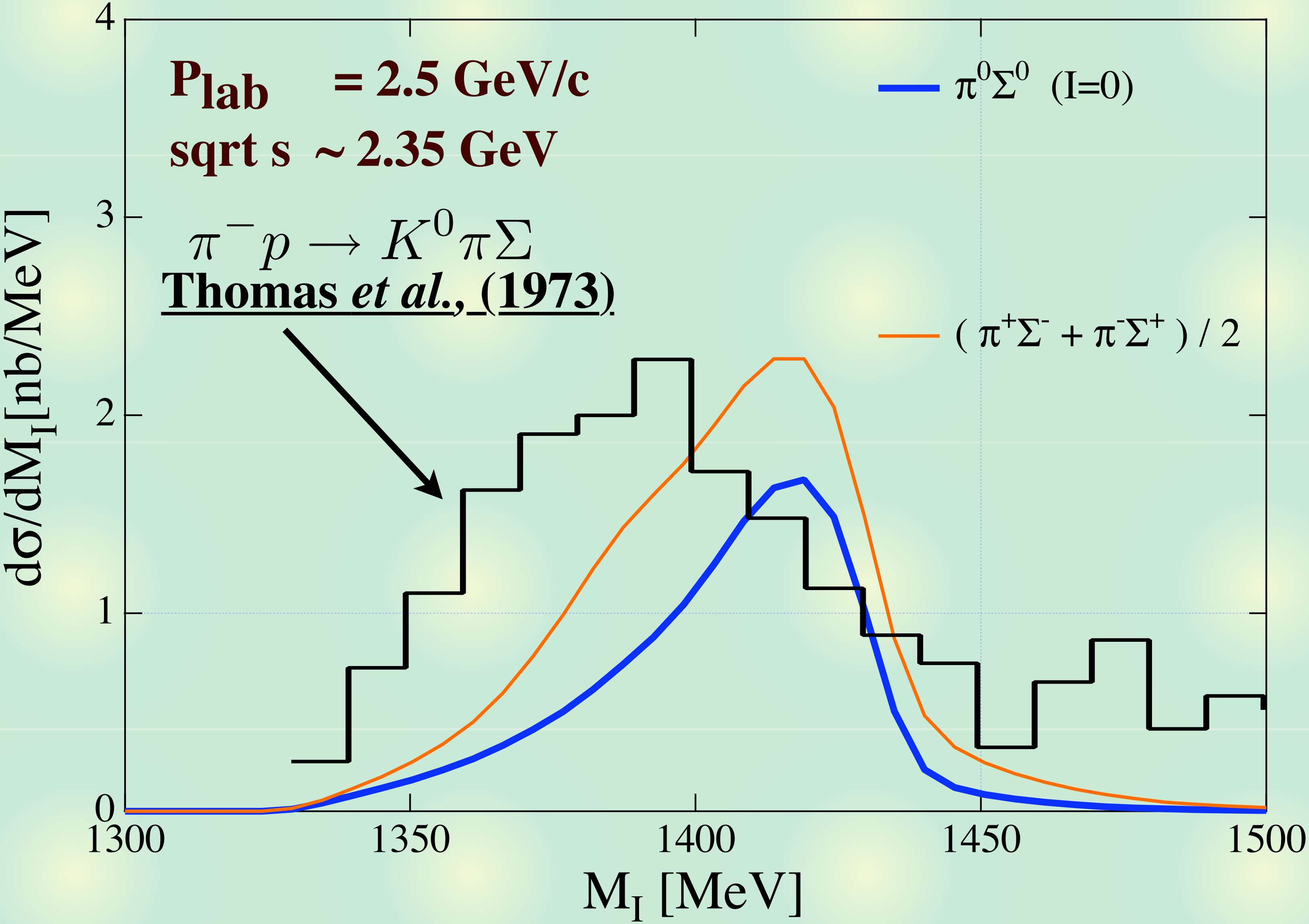
- **Difference between charged states**
  -> interference term of I=0 and 1

Taking average of two states, this term vanishes.

$$\frac{d\sigma(\pi^{0}\Sigma^{0})}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2$$

Difference from neutral channel : I=1, Σ(1385)

Invariant mass distributions 2



Σ(1385) contribution is small

Conclusion for part I

We study the structure of Λ(1405) using the chiral unitary model.

- In the chiral unitary model, Λ(1405) is generated as a quasi-bound state in coupled channel meson-baryon scattering.
- There are two poles of the scattering amplitude around nominal Λ(1405).

Pole 1 (1426–16i) : strongly couples to $\bar{K}N$ state
Pole 2 (1390–66i) : strongly couples to πΣ state

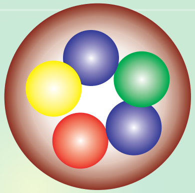
Conclusion for part I

- We propose the $\gamma p \longrightarrow K^* \Lambda(1405)$ reaction, which provides a **different shape** of spectrum from the nominal one. Observation of this feature give a support of the two-pole structure.
- We estimate the effect of **Σ(1385)** in I=1 channel, which is found to be **small for the πΣ spectrum.**

Properties of the Θ

LEPS, T. Nakano, *et al.*, Phys. Rev. Lett. 91, 012002 (2003)

$$|\,\Theta\,\rangle = |\,uudd\bar{s}\,\rangle$$



S = +1, manifestly exotic

light mass 1540 MeV

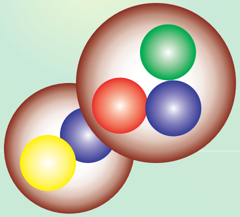
$$M_{\Theta} \sim 4m_{ud} + m_s \sim 1700 \text{ MeV}$$

narrow width < 15 MeV (1 MeV)

$$\Gamma_{B^*} \sim 100 \text{ MeV}$$

Is it possible to describe the Θ by hadrons?

Hadronic description : Two-body molecule?



$$V_{WT} = 0 \text{ for } I = 0, S = +1$$

—> no interaction for s-wave

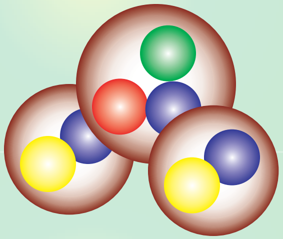
—> Chiral unitary model ×

In order to have the narrow width, it must be in d-wave or higher.

States in higher partial waves are expected to be heavy, and unnatural for the ground state.

It is difficult to reproduce the Θ properties.

Three-body molecule



$$M_K + M_\pi + M_N \sim 1570 \text{ MeV}$$

Only 30 MeV attraction can form the Θ.

Decay into KN requires the absorption of π —> p-wave excitation —> suppressed

Narrow and light state?

P. Bicudo, *et al.*, Phys. Rev. C69, 011503 (2004)
T. Kishimoto, *et al.*, hep-ex/0312003
F. J. Llanes-Estrada, *et al.*, Phys. Rev. C69, 055203 (2004)

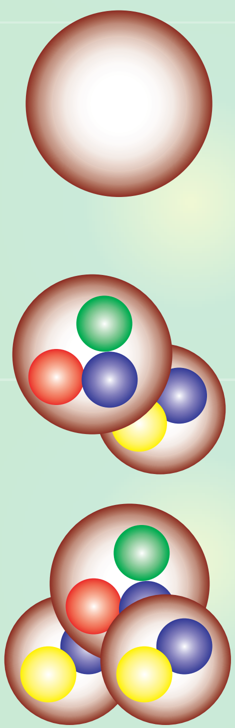
An attraction was found, but not strong enough to bind the system.

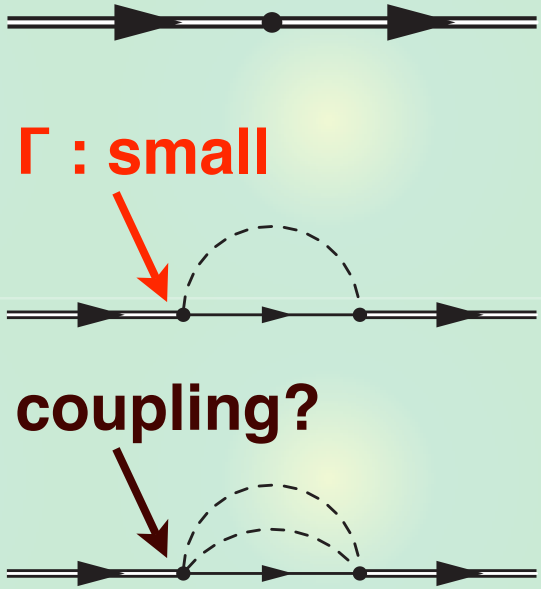
Two-meson cloud effect

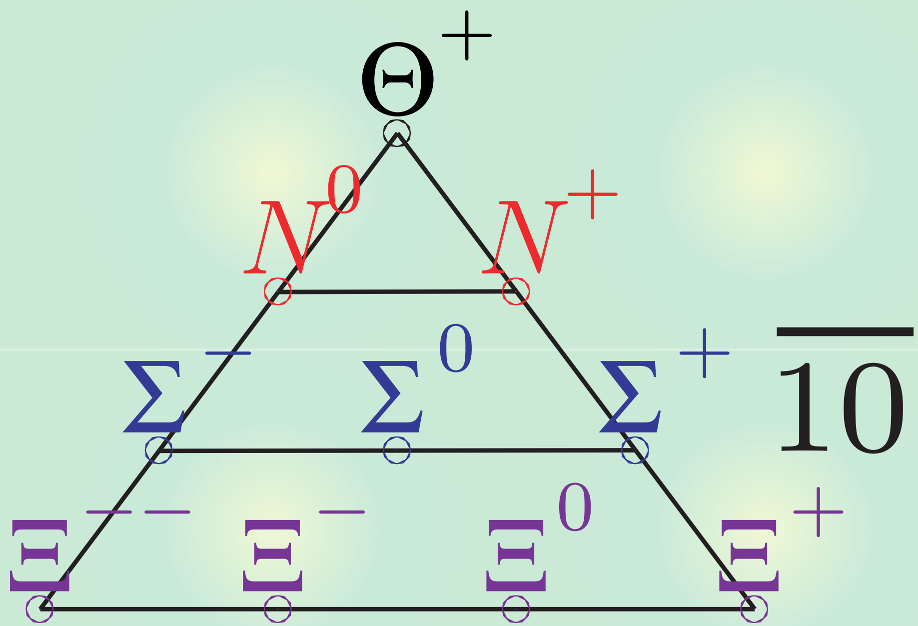
How large the πKN effects in Θ?

Hosaka, Hyodo, Estrada, Oset, Peláez, Vacas, PRC (2005), Chap. 9.

- Evaluate self-energy around “core”
- Coupling constant <— antidecuplet + SU(3)

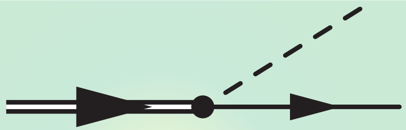






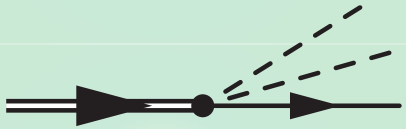
Two-meson coupling

N(1710) is assumed to be a partner of Θ.



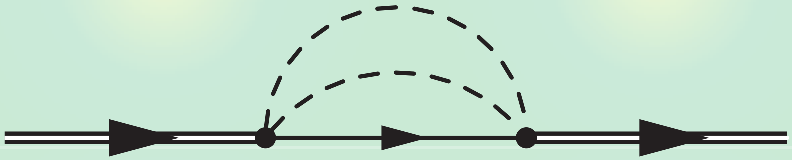
$\Theta^+ \to KN$ **Very narrow**

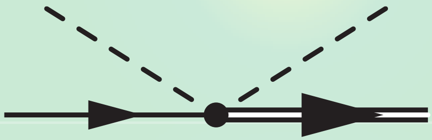
$N(1710) \to \pi N$ **10–20 %**



$\Theta^+ \to K\pi N$ **Forbidden**

$N(1710) \to \pi\pi N$ **40–90 %**

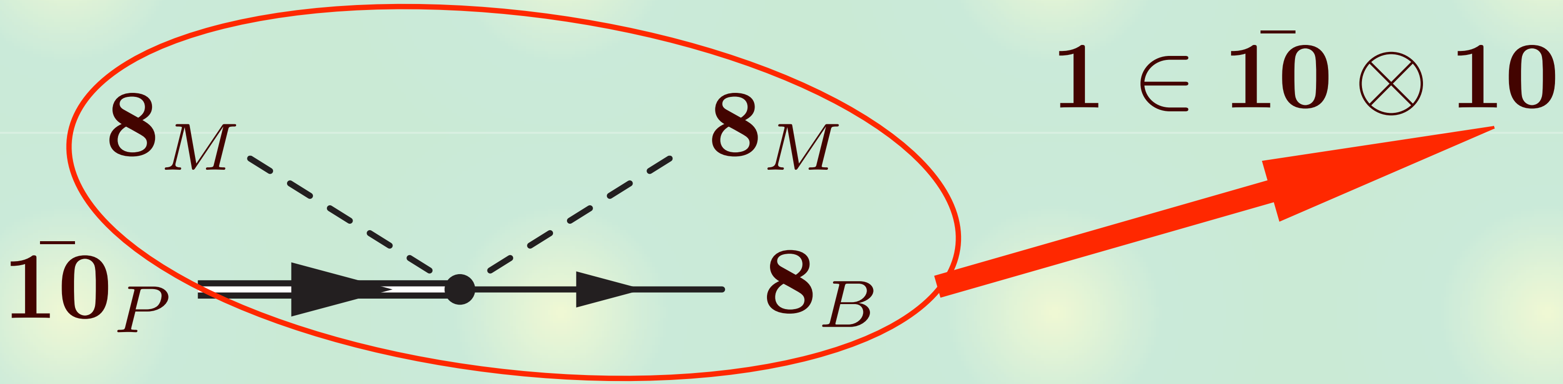




Large??

Effective interactions which account for the $N(1710) \to \pi\pi N$ decay

SU(3) structure of effective Lagrangian



$$
\begin{aligned}
\mathbf{8}_M \otimes \mathbf{8}_M \otimes \mathbf{8}_B =& (\mathbf{1} \oplus \mathbf{8}^s \oplus \mathbf{8}^a \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27})_{MM} \otimes \mathbf{8}_B \\
=& \mathbf{8} \quad \leftarrow \text{from } \mathbf{1}_{MM} \otimes \mathbf{8}_B \\
& \oplus (\mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27}) \quad \leftarrow \text{from } \underline{\mathbf{8}^s_{MM}} \otimes \mathbf{8}_B \\
& \oplus (\mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27}) \quad \leftarrow \text{from } \underline{\mathbf{8}^a_{MM}} \otimes \mathbf{8}_B \\
& \oplus (\mathbf{8} \oplus \mathbf{10} \oplus \mathbf{27} \oplus \mathbf{35}) \quad \leftarrow \text{from } \underline{\mathbf{10}_{MM}} \otimes \mathbf{8}_B \\
& \oplus (\mathbf{8} \oplus \overline{\mathbf{10}} \oplus \mathbf{27} \oplus \mathbf{35}') \quad \leftarrow \text{from } \overline{\mathbf{10}}_{MM} \otimes \mathbf{8}_B \\
& \oplus (\mathbf{8} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27} \oplus \mathbf{27} \oplus \mathbf{35} \oplus \mathbf{35}'' \oplus \mathbf{64}) \quad \leftarrow \text{from } \underline{\mathbf{27}_{MM}} \otimes \mathbf{8}_B
\end{aligned}
$$

Construction of interaction Lagrangians

Ex.) Construction of 8s Lagrangian

$$D_i{}^j[\mathbf{8}^s_{MM}] = \phi_i{}^a\phi_a{}^j + \phi_i{}^a\phi_a{}^j - \frac{2}{3}\delta_i{}^j\phi_a{}^b\phi_b{}^a$$
$$= 2\phi_i{}^a\phi_a{}^j - \frac{2}{3}\delta_i{}^j\phi_a{}^b\phi_b{}^a$$

$$T^{ijk}[\bar{\mathbf{10}}_{BMM(8s)}] = 2\phi_l{}^a\phi_a{}^i B_m{}^j\epsilon^{lmk} + (i,j,k \text{ symmetrized})$$

$$\Rightarrow \quad \mathcal{L}^{8s} = \frac{g^{8s}}{2f}\bar{P}_{ijk}\epsilon^{lmk}\phi_l{}^a\phi_a{}^i B_m{}^j + h.c.$$

Interaction Lagrangians

Terms without derivative

$$\mathcal{L}^{8s} = \frac{g^{8s}}{2f}\bar{P}_{ijk}\epsilon^{lmk}\phi_l{}^a\phi_a{}^i B_m{}^j + h.c.$$

8s

$$\mathcal{L}^{8a} = 0$$
$$\mathcal{L}^{10} = 0$$

<- symmetry under exchange of mesons

$$\mathcal{L}^{27} = \frac{g^{27}}{2f}\left[4\bar{P}_{ijk}\epsilon^{lbk}\phi_l{}^i\phi_a{}^j B_b{}^a - \frac{4}{5}\bar{P}_{ijk}\epsilon^{lbk}\phi_l{}^a\phi_a{}^j B_b{}^i\right] + h.c.$$

Experimental information

$N(1710) \to \pi\pi(s\text{-wave},\ I=0)N$

$N(1710) \to \pi\pi(p\text{-wave},\ I=1)N$

With one derivative

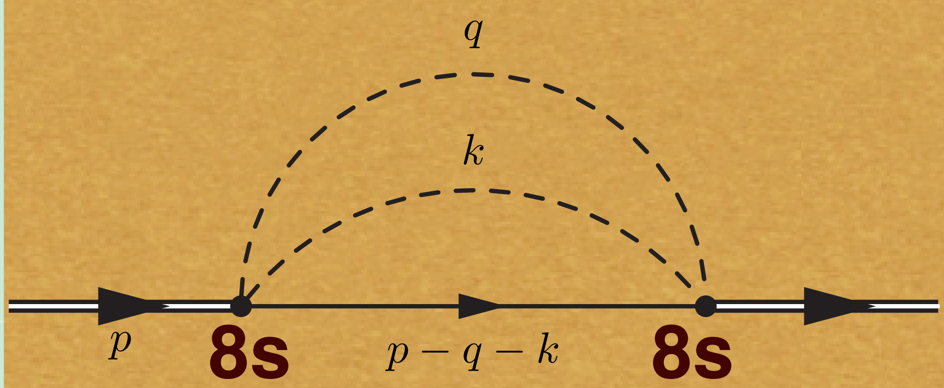
8a

$$\mathcal{L}^{8a} = i\frac{g^{8a}}{4f^2}\bar{P}_{ijk}\epsilon^{lmk}\gamma^\mu(\partial_\mu\phi_l{}^a\phi_a{}^i - \phi_l{}^a\partial_\mu\phi_a{}^i)B_m{}^j + h.c.$$

Diagrams for self-energy

Imaginary part : decay width

SU(3) breaking : masses of particles



Evaluate in the rest frame

N.R. approx. for baryon

$$-\int \frac{d^4k}{(2\pi)^4}\int \frac{d^4q}{(2\pi)^4}|t^{(j)}|^2\frac{1}{k^2-m_1^2+i\epsilon}\frac{1}{q^2-m_2^2+i\epsilon}\frac{M}{E}\frac{1}{p^0-k^0-q^0-E+i\epsilon}$$

$$=\int \frac{d^3k}{(2\pi)^3}\int \frac{d^3q}{(2\pi)^3}|t^{(j)}|^2\frac{1}{2\omega_1}\frac{1}{2\omega_2}\frac{M}{E}\frac{1}{p^0-\omega_1-\omega_2-E+i\epsilon}$$

↑ **vertex**

N(1710) decay ⇒ $g^{8s}=1.88\ ,\quad g^{8a}=0.315$

Diagrams for self-energy

Real part : Principle value integral for mass shift.

$$I^{(j)}(p^0; B, m_1, m_2) = \int \frac{d^3k}{(2\pi)^3} \int \frac{d^3q}{(2\pi)^3} |t^{(j)}|^2 \frac{1}{2\omega_1} \frac{1}{2\omega_2} \frac{M}{E} \frac{1}{p^0 - \omega_1 - \omega_2 - E + i\epsilon}$$

divergent <— cutoff

$q_{max} = k_{max} =$ 700–800 MeV

p^0 = energy of antidecuplet

$$\Sigma_P^{(j)}(p^0) = \sum_{B,m_1,m_2} \left(F^{(j)} C^{(j)}_{P,B,m_1,m_2}\right) I^{(j)}(p^0; B, m_1, m_2) \left(F^{(j)} C^{(j)}_{P,B,m_1,m_2}\right)$$

$$\Sigma_\Theta^{8a}(p^0) = \left(F^{8a}\right)^2 \left[18 I^{8a}(p^0; N, K, \pi) + 18 I^{8a}(p^0; N, K, \eta)\right]$$

Coupled channel summation

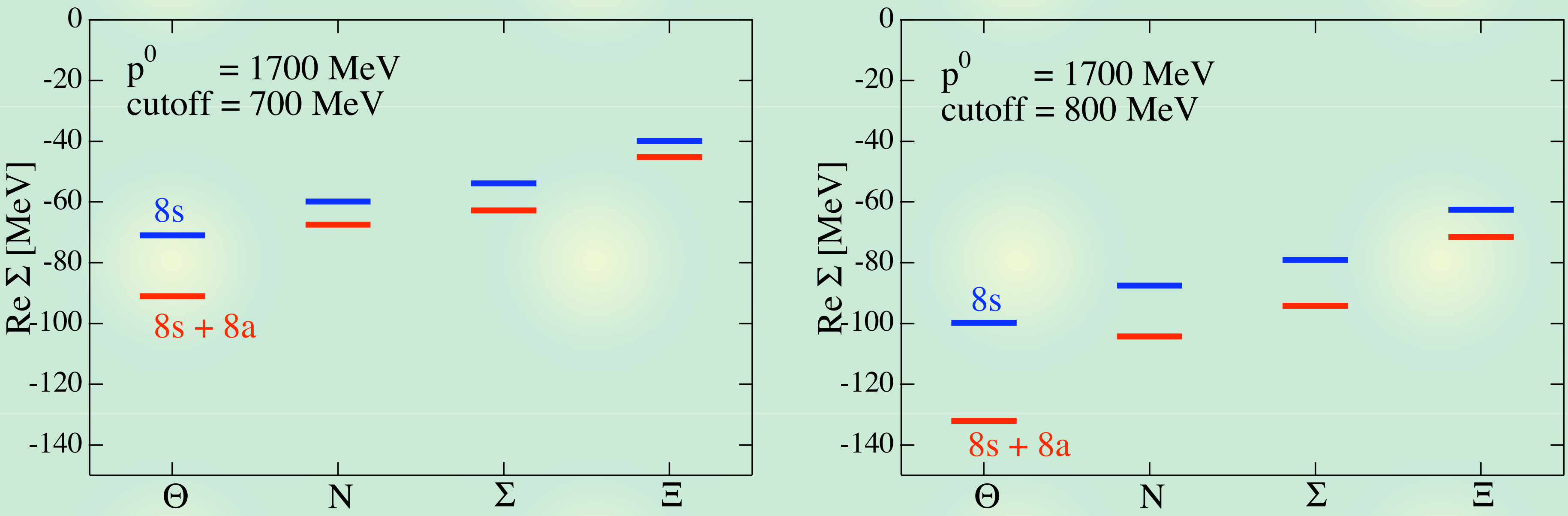
P	α	$8s$	$8a$
$\Theta_{\overline{10}}$	$NK\pi$	18	18
	$NK\eta$	2	18

P	α	$8s$	$8a$
$N_{\overline{10}}$	$NK\bar{K}$	4	12
	$N\pi\pi$	3	6
	$N\pi\eta$	2	-
	$N\eta\eta$	1	-
	$\Lambda K\pi$	$\frac{9}{2}$	$\frac{9}{2}$
	$\Lambda K\eta$	$\frac{1}{2}$	$\frac{9}{2}$
	$\Sigma K\pi$	$\frac{9}{2}$	$\frac{9}{2}$
	$\Sigma K\eta$	$\frac{1}{2}$	$\frac{9}{2}$

P	α	$8s$	$8a$
$\Sigma_{\overline{10}}$	$N\bar{K}\pi$	3	3
	$N\bar{K}\eta$	$\frac{1}{3}$	3
	$\Lambda K\bar{K}$	3	3
	$\Lambda\pi\eta$	2	-
	$\Lambda\pi\pi$	-	6
	$\Sigma K\bar{K}$	3	11
	$\Sigma\pi\pi$	3	4
	$\Sigma\pi\eta$	$\frac{4}{3}$	-
	$\Sigma\eta\eta$	1	-
	$\Xi K\pi$	3	3
	$\Xi K\eta$	$\frac{1}{3}$	3

P	α	$8s$	$8a$
$\Xi_{\overline{10}}$	$\Sigma\bar{K}\pi$	9	9
	$\Sigma\bar{K}\eta$	1	9
	$\Xi K\bar{K}$	6	6
	$\Xi\pi\eta$	4	-
	$\Xi\pi\pi$	-	12

Results of self-energy : Real part (mass shift)



All mass shifts are attractive (~100 MeV for Θ).

Mass splitting is nearly equal spacing.

Mass difference between Ξ and Θ
-> 60 MeV : ~20% of 320 = 1860–1540 MeV

Discussion

All mass shifts are attractive.

-> Existence of attraction is consistent with previous attempts.

Mass splitting is nearly equal spacing.

-> Deviation from GMO formula due to two-meson cloud is not very large.

Two-meson cloud also provides substantial effect for N and Σ.

-> It originates in the large coupling of the N(1710) to the three-body channels.

Conclusion for part II

We study the two-meson virtual cloud effect to the self-energy of baryon antidecuplet.

- **Two types of interaction Lagrangians (8s, 8a) are derived in order to estimate the two-meson cloud.**

$$\mathcal{L}^{8s} = \frac{g^{8s}}{2f}\bar{P}_{ijk}\epsilon^{lmk}\phi_l{}^a\phi_a{}^i B_m{}^j + h.c.$$

$$\mathcal{L}^{8a} = i\frac{g^{8a}}{4f^2}\bar{P}_{ijk}\epsilon^{lmk}\gamma^\mu(\partial_\mu\phi_l{}^a\phi_a{}^i - \phi_l{}^a\partial_\mu\phi_a{}^i)B_m{}^j + h.c.$$

Conclusion for part II

- Two-meson cloud effects are always **attractive**, of the order of 100 MeV for the Θ. It plays an important role to understand the nature of the Θ.
- Mass difference shows **nearly equal spacing**, and two-meson cloud provides **20%** of the empirical one.

Summary

We study the "exotics" in hadron dynamics based on chiral and flavor symmetries.

- Chiral unitary model provides a good description of the Λ(1405) as meson-baryon molecule.
- The two-pole structure of the Λ(1405) can be tested experimentally.
- The two-meson cloud provides ~100 MeV attraction for the Θ and about 20% of the mass splitting for $\overline{10}$.

Summary

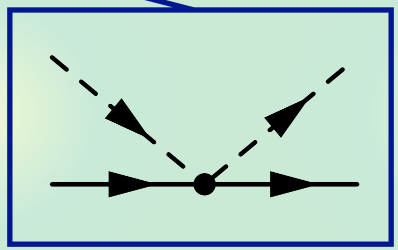
- There are appreciable meson cloud (higher Fock components) effects in baryons and pentaquarks due to meson-baryon dynamics, which complement the valence quarks.
- It is important to test the hadron properties experimentally.
- Symmetries provide a way to study hadrons systematically.

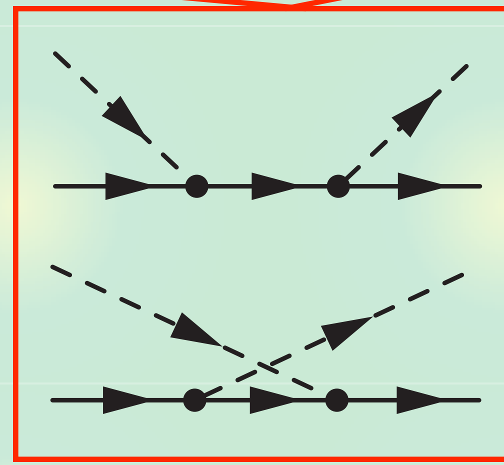
Appendix

ChU

Appendix : ChPT Lagrangian

$$\mathcal{L}^{(1)} = \mathrm{Tr}\Big(\bar{B}(i\not{\mathcal{D}} - M_0)B - D(\bar{B}\gamma^\mu\gamma_5\{A_\mu, B\}) - F(\bar{B}\gamma^\mu\gamma_5[A_\mu, B])\Big)$$





$$\mathcal{D}_\mu B = \partial_\mu B + i[V_\mu, B]$$

$$\xi(\Phi) = \exp\{i\Phi/\sqrt{2}f\}$$

$$D + F = g_A$$

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

$$V_\mu = -\frac{i}{2}(\xi^\dagger\partial_\mu\xi + \xi\partial_\mu\xi^\dagger) = \frac{i}{4f^2}(\Phi\partial_\mu\Phi - \partial_\mu\Phi\Phi) + \cdots$$

$$A_\mu = -\frac{i}{2}(\xi^\dagger\partial_\mu\xi - \xi\partial_\mu\xi^\dagger) = -\frac{1}{f}\partial_\mu\Phi + \cdots$$

Two-pole structure

Are they real states?
—> need to check experimentally

- **Experimental results available so far:**

Thomas *et al.*, (1973)

$$\pi^- p \to K^0 \Lambda(1405) \to K^0 \pi \Sigma$$

Hemingway *et al.*, (1984)

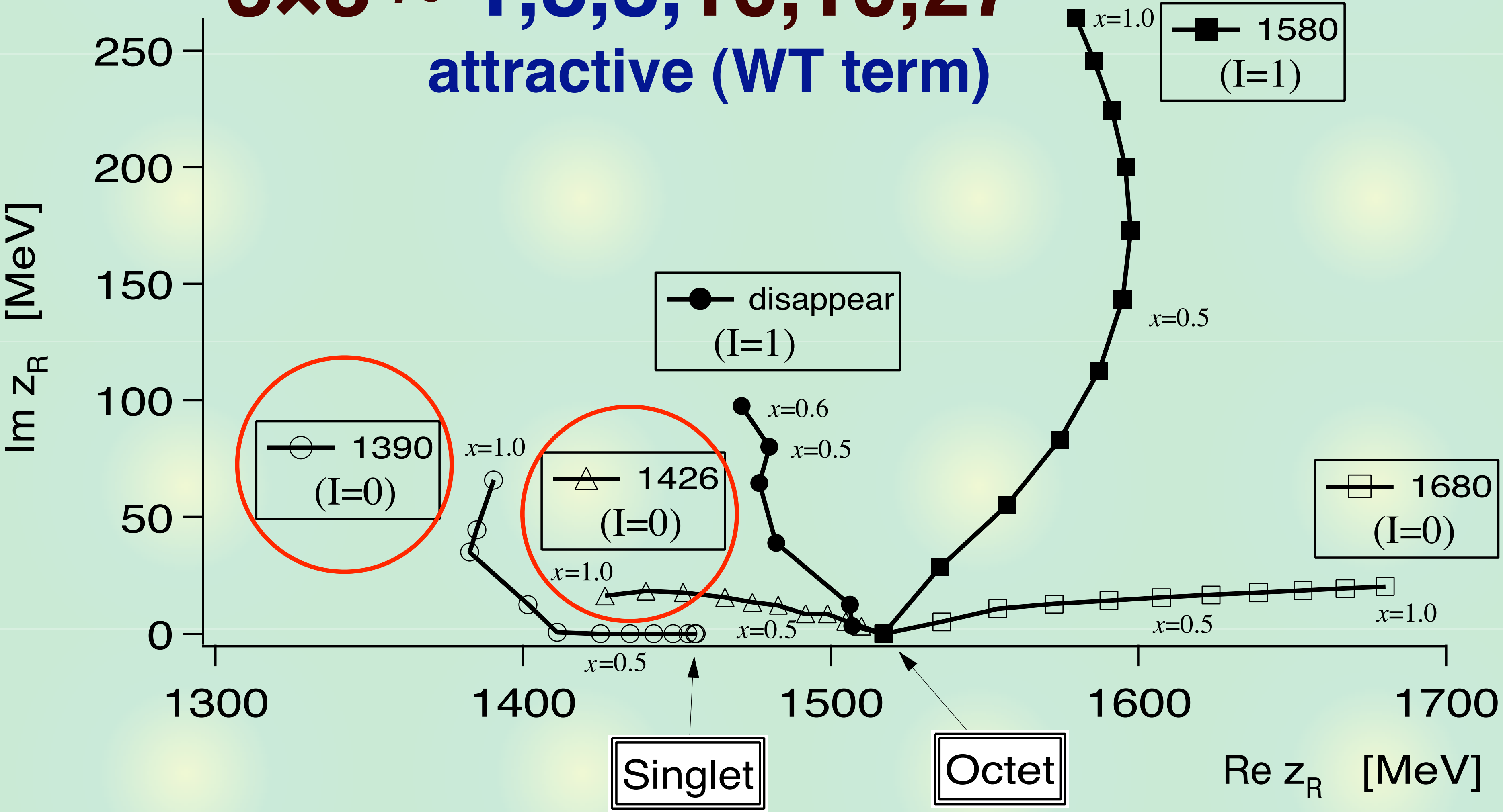
$$\Sigma^*(1660)^+ \to \pi^+ \Lambda(1405) \to \pi^+ \pi \Sigma$$

- **PDG : analysis based on the Hemingway data assuming one state**

Trajectories of the poles with SU(3) breaking (S = -1)

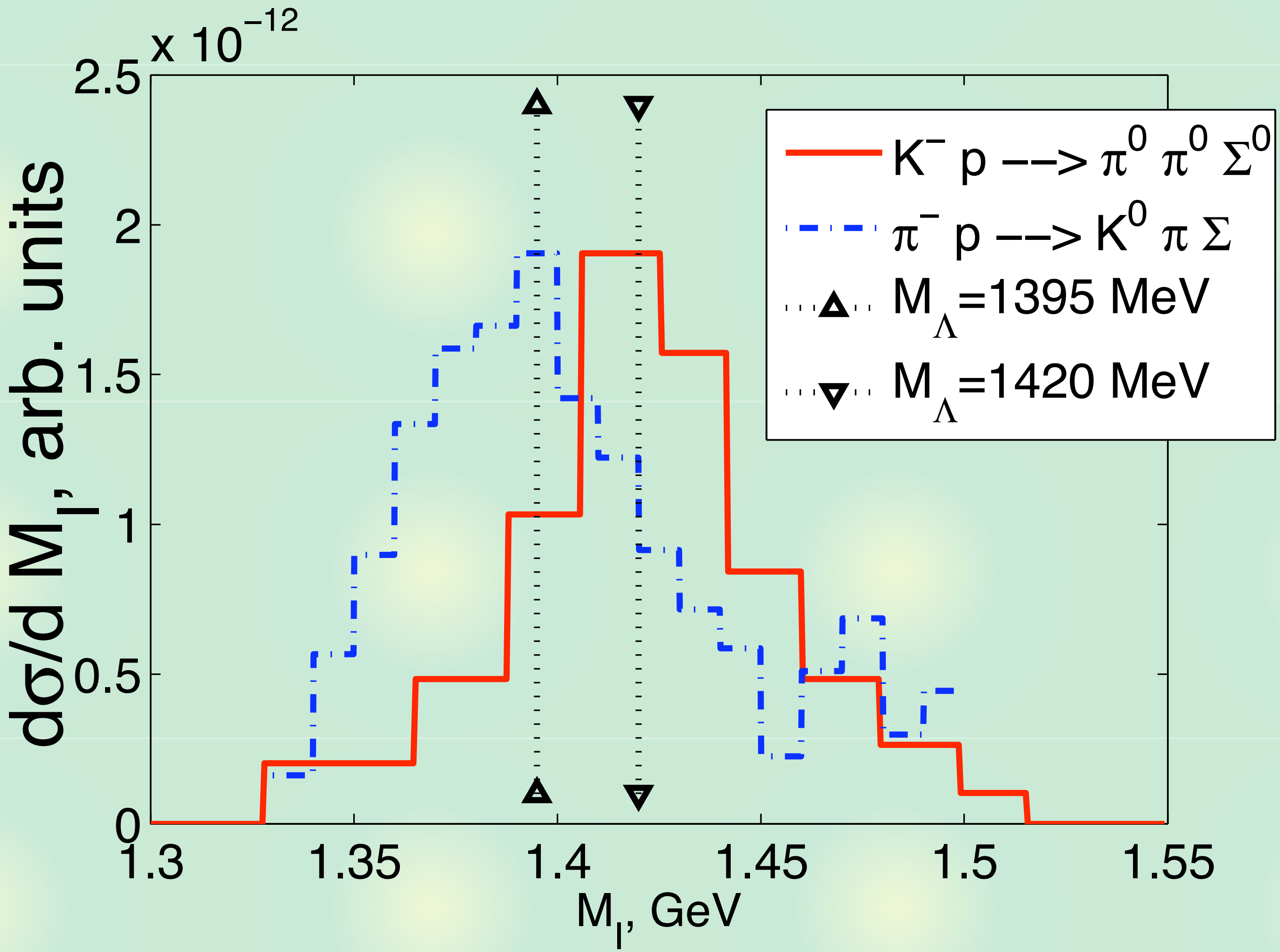
$8\times8 \sim 1,8,8,10,\overline{10},27$

attractive (WT term)



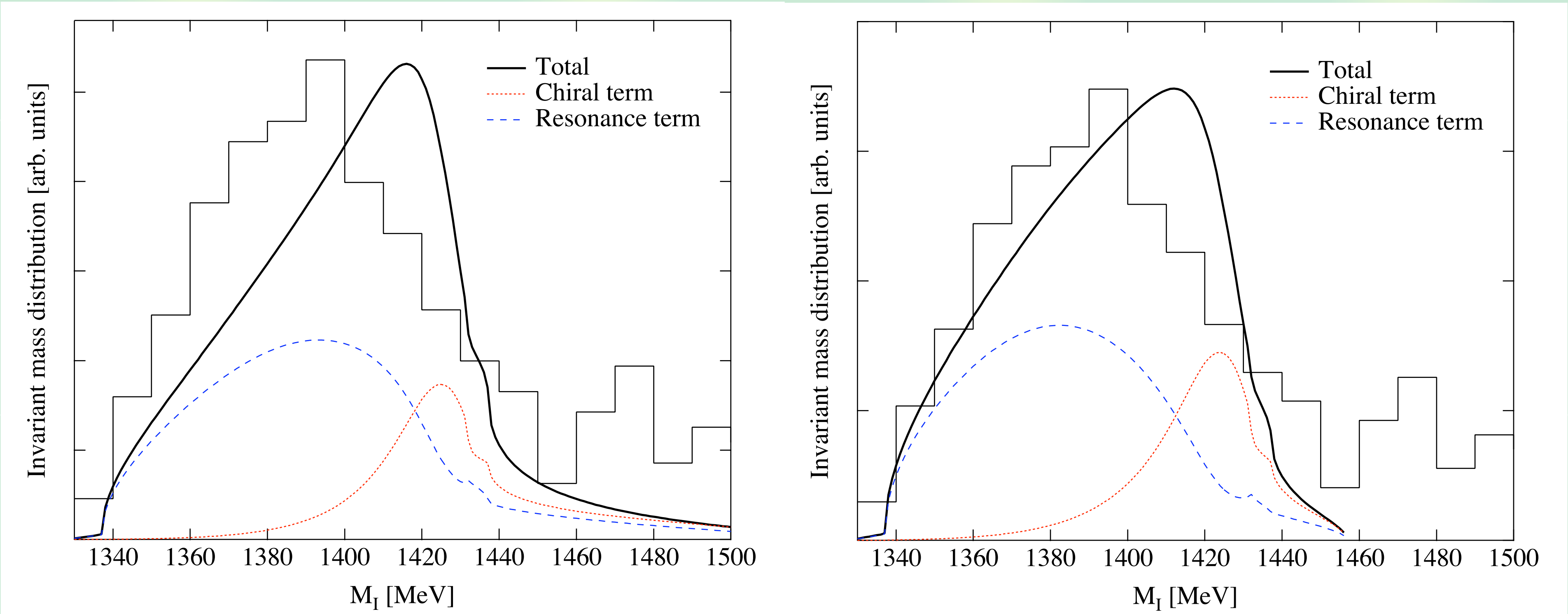
D. Jido, *et al.*, Nucl. Phys. A 723, 205 (2003)

Application to the reaction



V.K. Magas, *et al.*, hep-ph/0503043

Improvement of mass distributions



P_{lab} = 1.66 GeV/c P_{lab} = 1.55 GeV/c

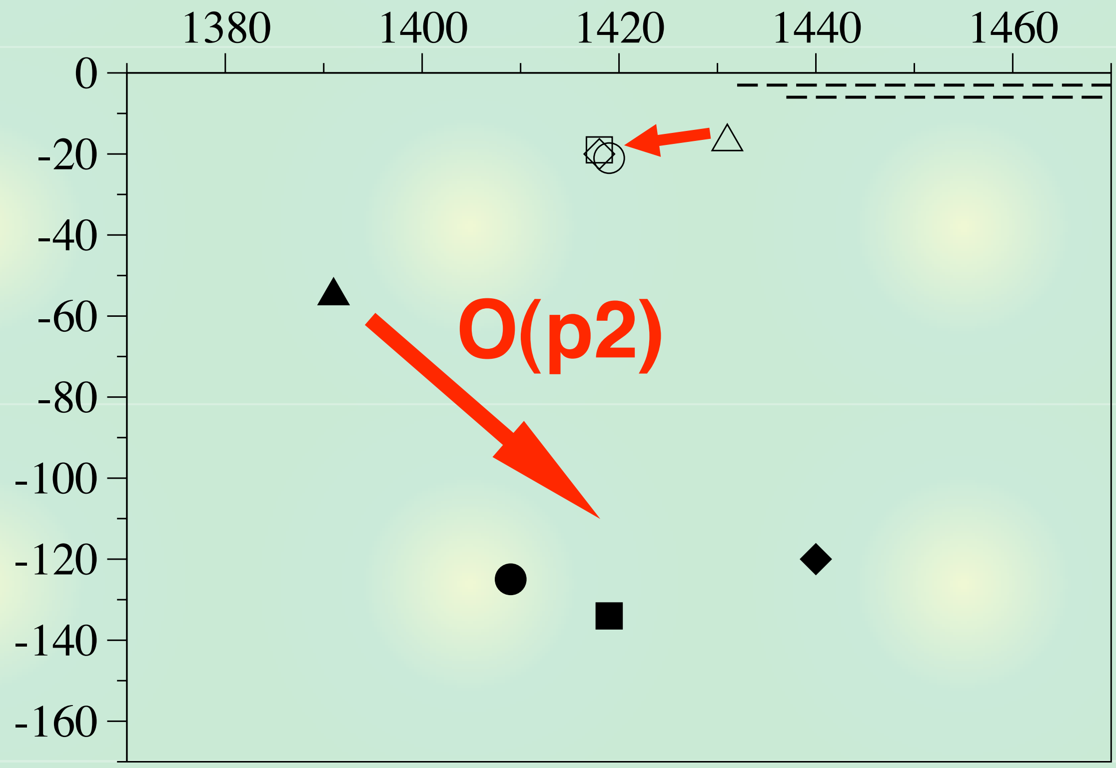
- Consistency between amplitude and phase space
- Σ(1385) contribution
- Approximation for loop

Controversial?

B. Borasoy., *et al.*, hep-ph/0505239

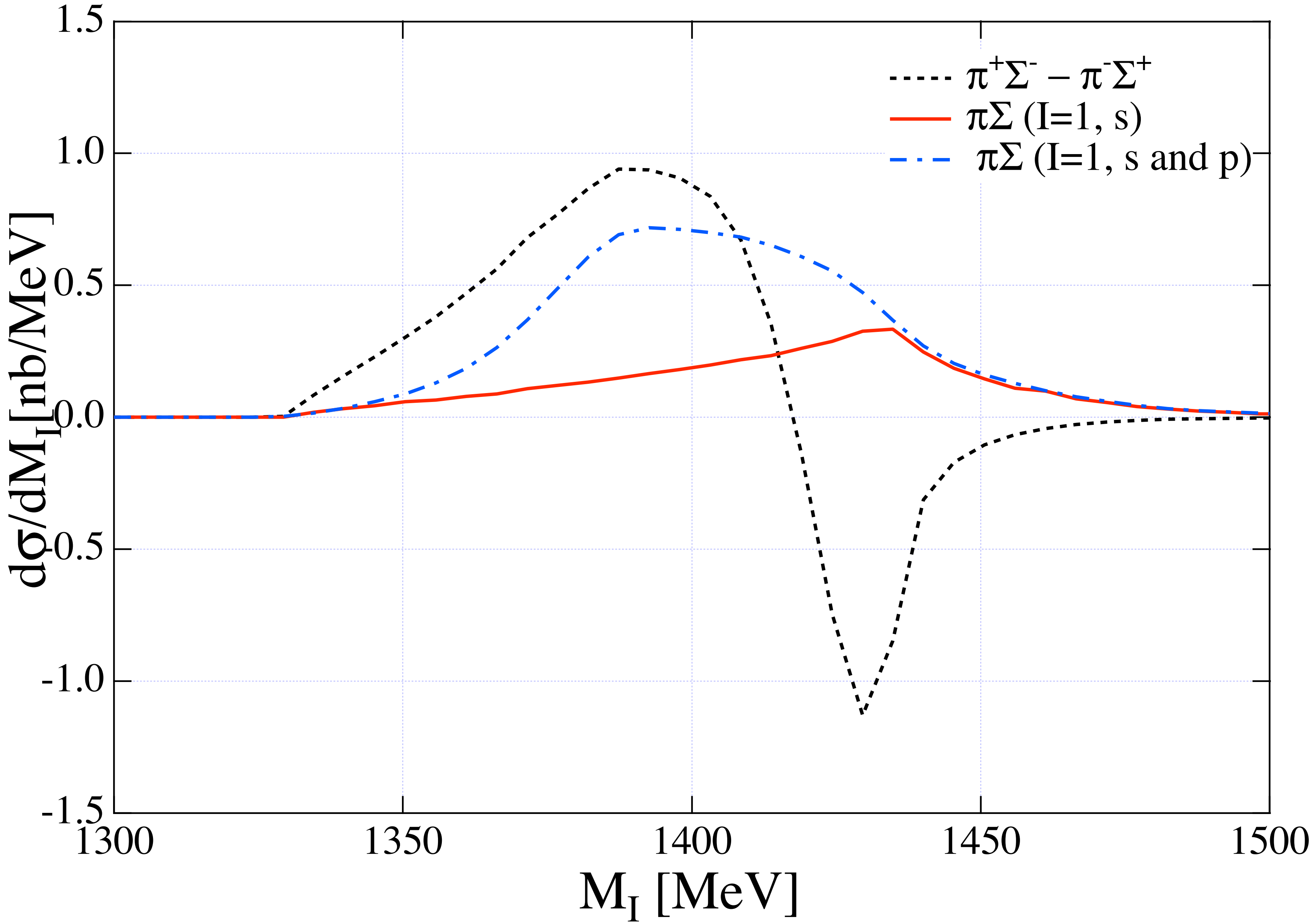
Similar study but with O(p2) terms

DEAR experiment
: kaonic hydrogen



Inclusion of O(p2) terms
: one pole moves far away from the real axis

I=1, s-wave amplitude



Appendix

PENTA

Pentaquarks : Importance

QCD does not forbid it.

- Rather, existence was implied;
- Exotics <- Duality in scattering theory
- Heavy pentaquark <- large Nc and heavy M_Q

Test for inter-quark correlation

- meson ($\bar{q}q$) $\ni$ only $q\bar{q}$
- baryon (qqq) $\ni$ only qq(color $\bar{3}$)
- pentaquark ($qqqq\bar{q}$) $\ni$ qq(color 6), ...

multi-quark states, quark matter, ...

Properties of the Θ

$$|\,\Theta\,\rangle = |\,uudd\bar{s}\,\rangle$$

light mass 1540 MeV

$$M_\Theta \sim 4m_{ud} + m_s \sim 1700 \text{ MeV}$$

$$M_K + M_N \sim 1430 \text{ MeV}$$ **<— $q\bar{q}$ correlation**

narrow width < 15 MeV (1 MeV)

$$\Gamma_{B^*} \sim 100 \text{ MeV}$$

$$\Gamma_{\Lambda(1520)} \sim 20 \text{ MeV}$$ **<— spin 3/2 (d-wave)**

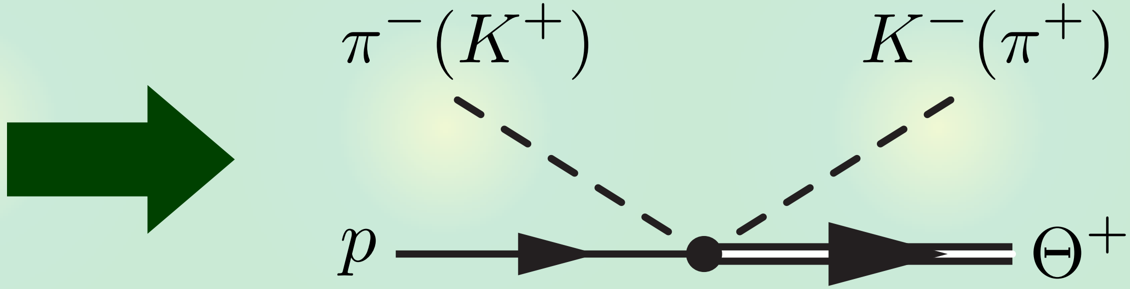
Motivations

Possibility of $\Theta^+ \sim K\pi N$ bound state

P. Bicudo, *et al.*, Phys. Rev. C69, 011503 (2004)
T. Kishimoto, *et al.*, hep-ex/0312003
F. J. Llanes-Estrada, *et al.*, Phys. Rev. C69, 055203 (2004)

Anomalies in production experiments

$\pi^- p \to K^- \Theta^+$ at KEK
$\gamma d \to \Lambda^* \Theta^+$ at SPring-8



Criteria to construct the Lagrangian

Interaction is flavor SU(3) symmetric

Chiral symmetric? -> later

Small number of derivatives

low energy : OK

Assumptions for Θ^+

N(1710) is the S=0 partner of antidecuplet
-> $J^P = 1/2^+$

No mixing with 8, 27,... <- decay width

T.D. Cohen, Phys. Rev. D70, 074023 (2004)
S. Pakvasa and M. Suzuki, Phys. Rev. D70, 036002 (2004)
T. H. and A. Hosaka, Phys. Rev. D71, 054017 (2005)

Two-meson cloud effect

How much the three-body components in Θ?

A. Hosaka, T. H., *et al.*, Phys. Rev. C71, 045205 (2005), Section 9.

Let us assume Θ belongs to the antidecuplet, and evaluate the self-enrgy coming from the two-meson cloud.

GMO rule

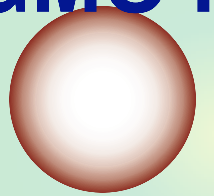
$$M_\Theta = M_0 + \mathrm{Re}\Sigma_\Theta$$

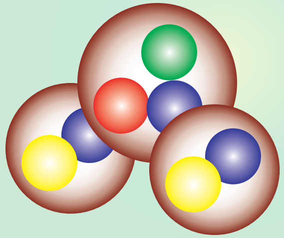
$$M_N = M_0 + \Delta + \mathrm{Re}\Sigma_N$$

$$M_\Sigma = M_0 + 2\Delta + \mathrm{Re}\Sigma_\Sigma$$

$$M_{\Xi_{3/2}} = M_0 + 3\Delta + \mathrm{Re}\Sigma_{\Xi_{3/2}}$$

Two-meson cloud





Interaction Lagrangians 1

Antidecuplet field

$$P^{333} = \sqrt{6}\Theta^{+}_{\overline{10}}$$

$$P^{133} = \sqrt{2}\,N^{0}_{\overline{10}} \qquad P^{233} = -\sqrt{2}\,N^{+}_{\overline{10}}$$

$$P^{113} = \sqrt{2}\,\Sigma^{-}_{\overline{10}} \qquad P^{123} = -\Sigma^{0}_{\overline{10}} \qquad P^{223} = -\sqrt{2}\,\Sigma^{+}_{\overline{10}}$$

$$P^{111} = \sqrt{6}\Xi^{--}_{\overline{10}} \qquad P^{112} = -\sqrt{2}\,\Xi^{-}_{\overline{10}} \qquad P^{122} = \sqrt{2}\,\Xi^{0}_{\overline{10}} \qquad P^{222} = -\sqrt{6}\Xi^{+}_{\overline{10}}$$

Meson and baryon fields

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

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

Other possible Lagrangians : detail

$$\mathcal{L}^{8s} = \frac{g^{8s}}{2f} \bar{P}_{ijk} \epsilon^{lmk} \phi_l{}^a \phi_a{}^i B_m{}^j + h.c.$$

Two-meson 27 interaction

$$\mathcal{L}^{27} = \frac{g^{27}}{2f} \left[4\bar{P}_{ijk} \epsilon^{lbk} \phi_l{}^i \phi_a{}^j B_b{}^a - \frac{4}{5} \bar{P}_{ijk} \epsilon^{lbk} \phi_l{}^a \phi_a{}^j B_b{}^i \right] + h.c.$$

Chiral symmetric interaction

$$\mathcal{L}^{\chi} = \frac{g^{\chi}}{2f} \bar{P}_{ijk} \epsilon^{lmk} (A_\mu)_l{}^a (A^\mu)_a{}^i B_m{}^j + h.c.$$

$$A_\mu = \frac{i}{2} \left(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger \right) = -\frac{\partial_\mu \phi}{\sqrt{2} f} + \mathcal{O}(p^3) \qquad \xi = e^{i\phi/\sqrt{2}f}$$

$$(A_\mu)_l{}^a (A^\mu)_a{}^i \to \frac{1}{2f^2} \partial_\mu \phi_l{}^a \partial^\mu \phi_a{}^i$$

SU(3) breaking interaction $M = \mathrm{diag}(\hat{m}, \hat{m}, m_s)$

$$\mathcal{L}^{M} = \frac{g^{M}}{2f} \bar{P}_{ijk} \epsilon^{lmk} S_l{}^i B_m{}^j$$

$$S = \xi M \xi + \xi^\dagger M \xi^\dagger = \mathcal{O}(\phi^0) - \frac{1}{2f^2} (2\phi M \phi + \phi\phi M + M \phi\phi) + \mathcal{O}(\phi^4)$$

Chiral symmetric Lagrangian

$$\mathcal{L}^{8s} = \frac{g^{8s}}{2f}\bar{P}_{ijk}\epsilon^{lmk}\phi_l{}^a\phi_a{}^i B_m{}^j + h.c.$$

$$\mathcal{L}^{\chi(2)} = \frac{g^{\chi}}{2f}\bar{P}_{ijk}\epsilon^{lmk}\frac{1}{2f^2}\partial_\mu\phi_l{}^a\partial^\mu\phi_a{}^i B_m{}^j + h.c.$$

SU(3) structure : Identical !

Only loop integral is changed
<- adjusting the cutoff, we would have the same results

N(1710) decay -> $g^{\chi} = 0.218$

Results of chiral Lagrangian

[MeV]

Re{Σ}	8s	χ(2)
Θ	-100	-99
N	-87	-83
Σ	-79	-70
Ξ	-63	-57
cutoff	800	525

Decay	8s	χ(2)
$N(1710) \to N\pi\pi$	25	25
$N(1710) \to N\eta\pi$	0.58	0.32
$\Sigma(1770) \to N\bar{K}\pi$	4.7	4.5
$\Sigma(1770) \to \Sigma\pi\pi$	10	3.6
$\Xi(1860) \to \Sigma\bar{K}\pi$	0.57	0.40

Almost the same results

Difference comes from the SU(3) breaking of momenta at the vertex

27 and mass Lagrangians

$$\mathcal{L}^{27} = \frac{g^{27}}{2f}\left[4\bar{P}_{ijk}\epsilon^{lbk}\phi_l{}^i\phi_a{}^j B_b{}^a - \frac{4}{5}\bar{P}_{ijk}\epsilon^{lbk}\phi_l{}^a\phi_a{}^j B_b{}^i\right] + h.c.$$

$$\mathcal{L}^{M} = \frac{g^{M}}{2f}\bar{P}_{ijk}\epsilon^{lmk}(-\frac{1}{2f^2})(2\phi M\phi + \phi\phi M + M\phi\phi)_l{}^i B_m{}^j + h.c.$$

Fitting couplings to the N(1710) decay
-> large binding energy of 1 GeV : unrealistic

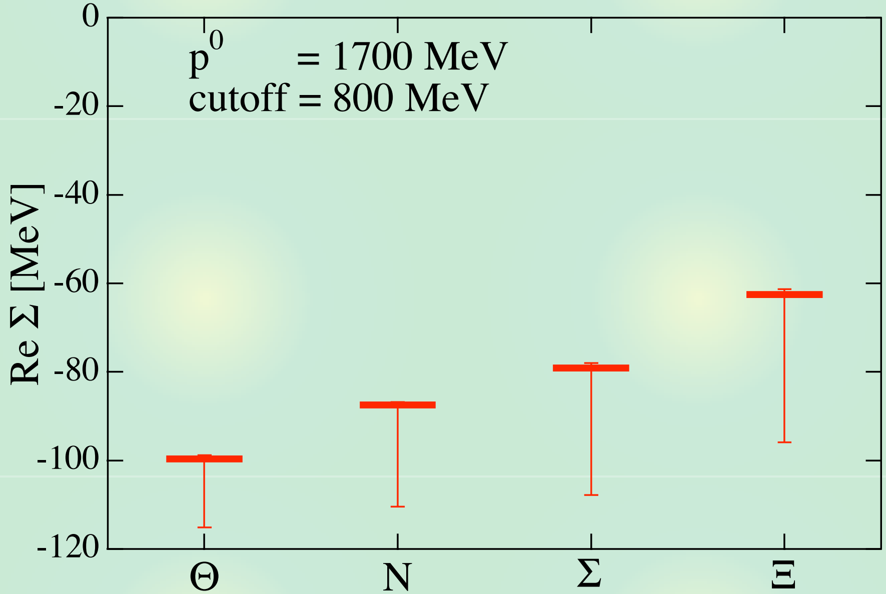
Treat them as a small perturbation to the 8s.

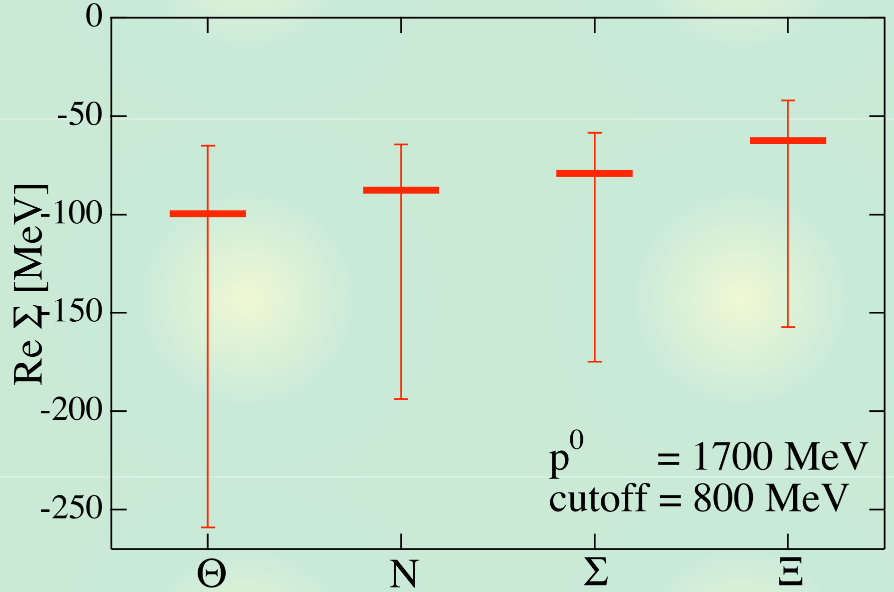
$$g^{27} = g^{M} = g^{8s} = 1.88\ , \quad b_{27} = -\frac{5}{4}(1-a)\ , \quad b_M = \frac{f^2}{m_\pi^2}(1-a)$$

$$\mathcal{L}^{int} = a\mathcal{L}^{8s} + b_{27,M}\mathcal{L}^{27,M}$$

Deviation from a = 1 : weight of new terms

Results of 27 and mass Lagrangians





27

0.90 < a < 1.06

M

0.76 < a < 1.06

Contributions of these terms are considered as a theoretical uncertainty in the analysis.