

Exotics in meson-baryon dynamics with chiral symmetry



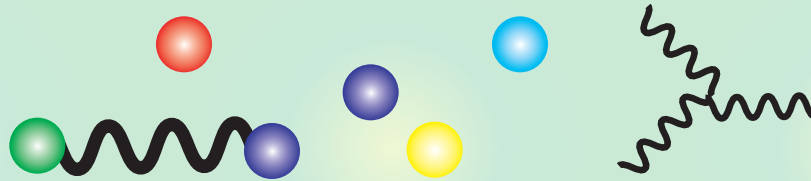
Tetsuo Hyodo^a

YITP, Kyoto^a

2006, Apr. 21st ₁

Introduction : QCD at low energy

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

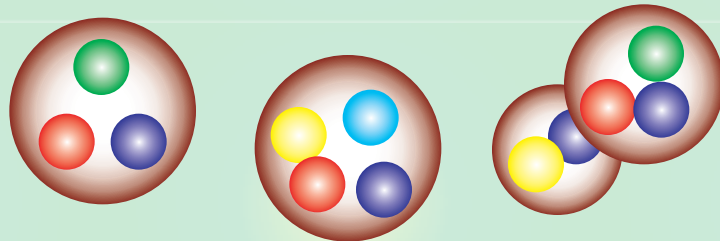


At low energies...

Color confinement

Chiral symmetry breaking

Mesons, baryons (Hadrons)

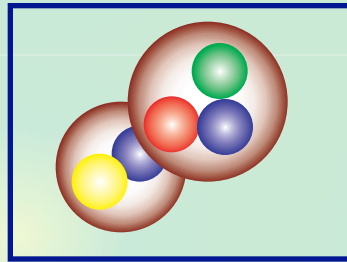
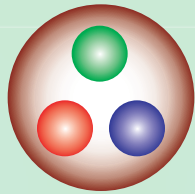


“exotics”

: elementary excitations of QCD vacuum

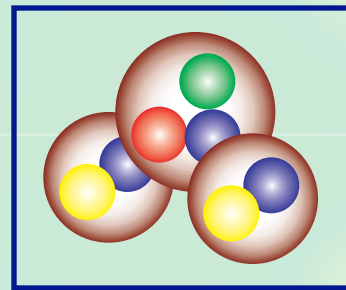
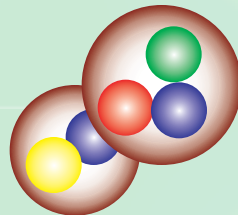
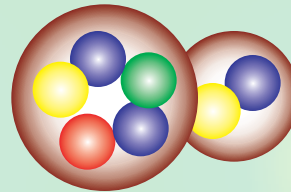
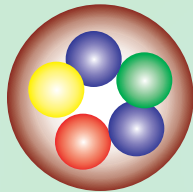
Introduction : Exotics

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



**meson-baryon
molecule**

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



**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

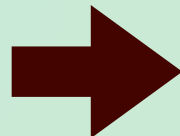
$$m_q \rightarrow 0$$

Flavor symmetry -> GMO formula

$$\Delta m_q \rightarrow 0$$

Symmetry

Hadrons



“exotics”

Contents

★ Introduction

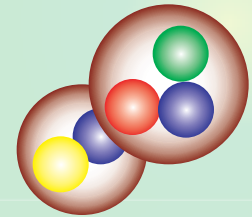
★ Part I : chiral unitary model

★ SU(3) breaking effect

★ Production of $\Lambda(1405)$

★ Magnetic moments of N(1535)

★ K^* coupling to $\Lambda(1520)$



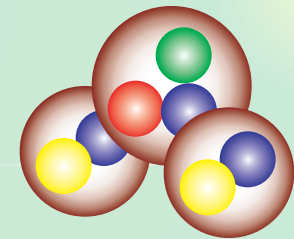
★ Part II : Pentaquarks

★ Spin parity determination

★ Two-meson cloud

★ 8–10 representation mixing

★ Meson induced Θ production



★ Summary

Introduction : $\Lambda(1405)$

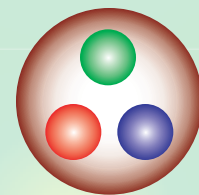
$$\Lambda(1405) : J^P = 1/2^-, I = 0$$

Mass : 1406.5 ± 4.0 MeV

Width : 50 ± 2 MeV

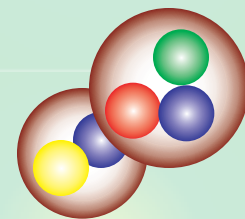
Decay mode : $\Lambda(1405) \rightarrow (\pi\Sigma)_{I=0}$ 100%

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)

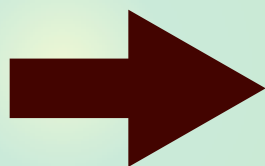
Chiral symmetry

**Low energy
behavior**



Unitarity of S-matrix

**Non-perturbative
resummation**



Scattering amplitude

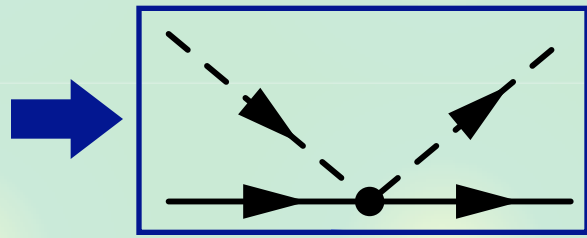
$J^P = 1/2^-$ resonances

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

Framework of the chiral unitary model : Interaction

Chiral perturbation theory

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



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.)

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

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

Framework of the chiral unitary model : Unitarization

Unitarization

N/D method : general form of amplitude

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

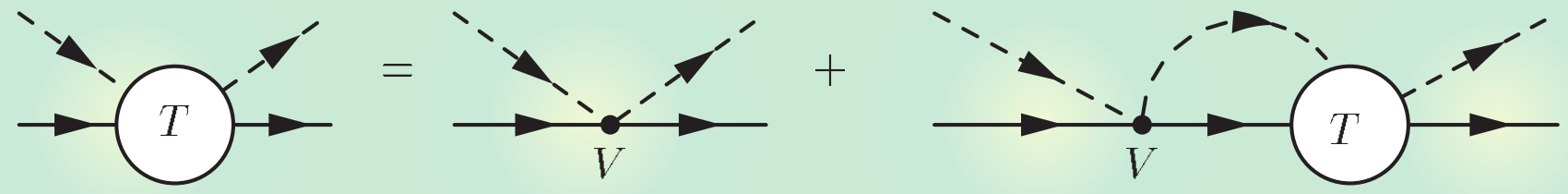
$$-G_i(\sqrt{s}) = -i \int \frac{d^4q}{(2\pi)^4} \frac{2M_i}{(P - q)^2 - M_i^2 + i\epsilon} \frac{1}{q^2 - m_i^2 + i\epsilon}$$

$$V^{(WT)}$$

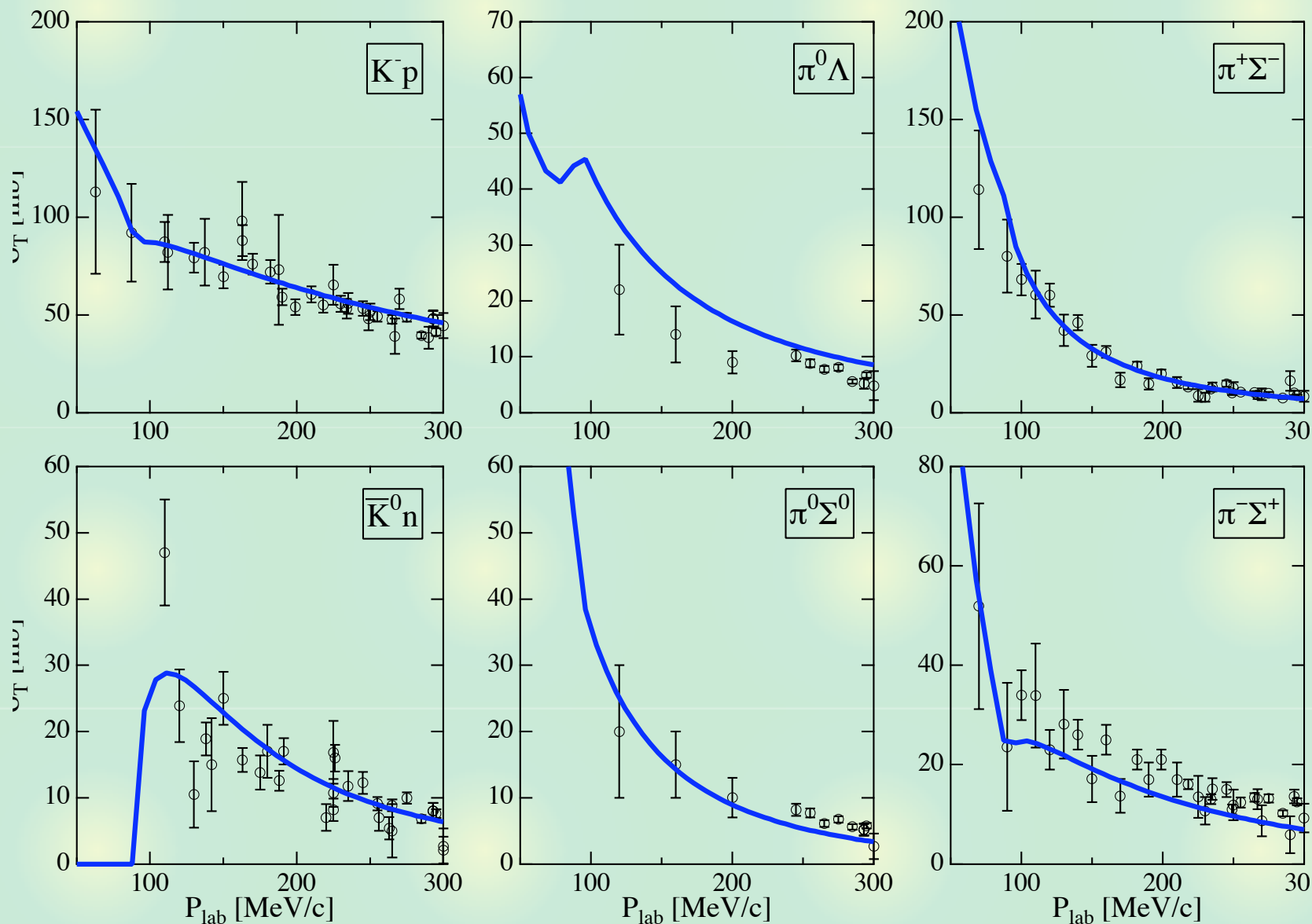
$$T^{-1} = -G + (V^{(WT)})^{-1}$$

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

physical masses
regularization of loop



Total cross sections of K^-p scattering

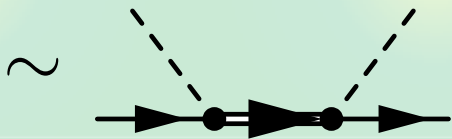


T. Hyodo, Nam, Jido, Hosaka, PRC (2003), PTP (2004), Chap. 4.

Two poles?

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

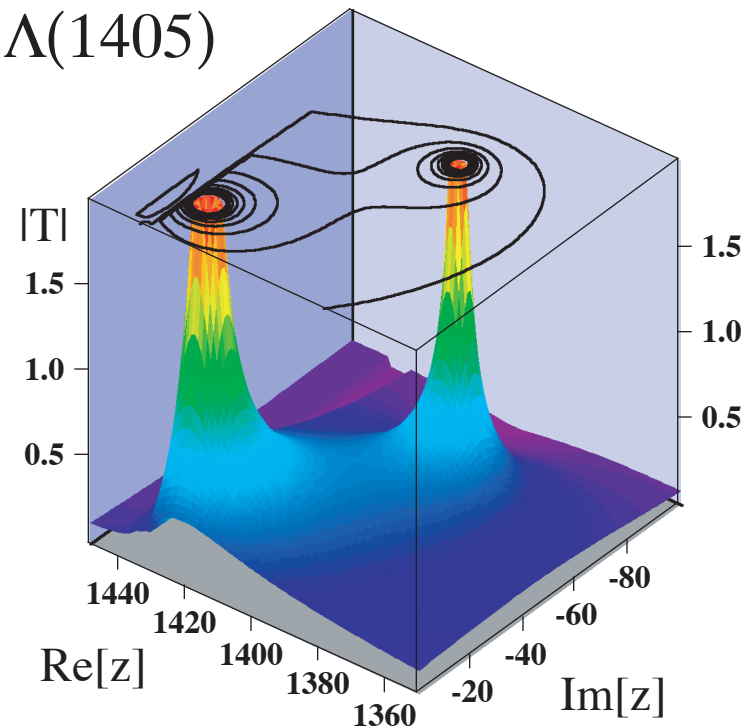
$$T_{ij}(\sqrt{s}) \sim \frac{g_i g_j}{\sqrt{s} - M_R + i\Gamma_R/2}$$



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

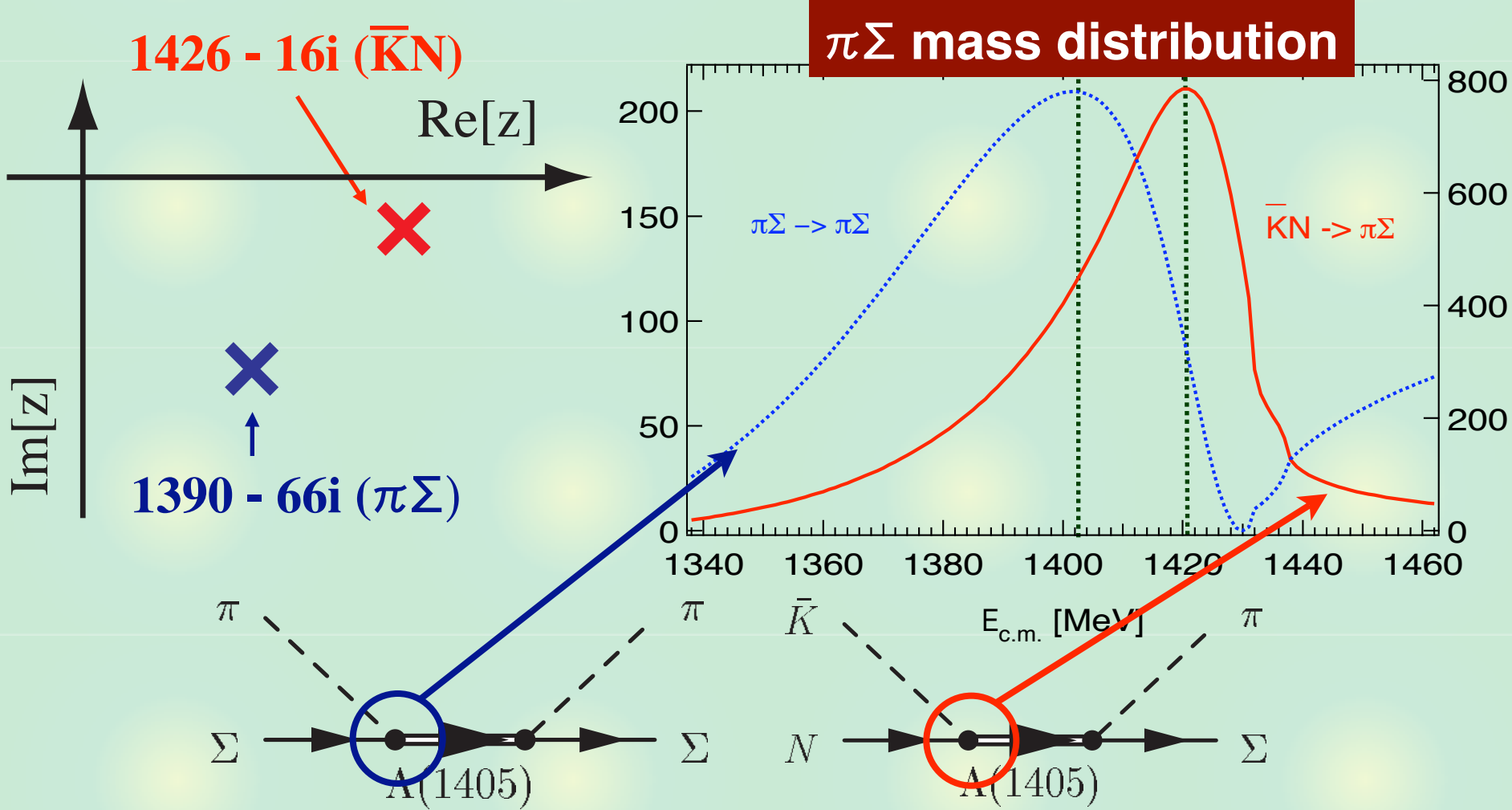
- Cloudy bag model
- Chiral unitary model

$\Lambda(1405)$



$\Lambda(1405)$ in the chiral unitary model

Real states? -> to be checked experimentally

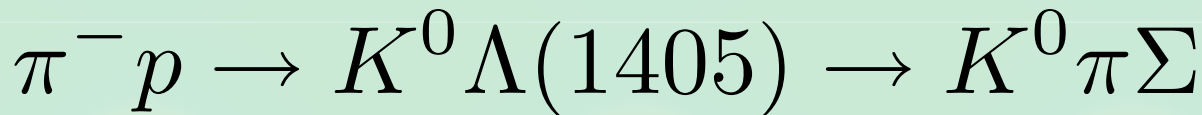


Shape of $\pi\Sigma$ spectrum depends on initial state

Production reaction for the $\Lambda(1405)$

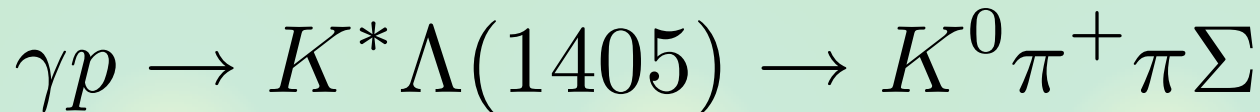
$$\frac{d\sigma}{dM_I} = C |t_{\pi\Sigma \rightarrow \pi\Sigma}|^2 p_{CM} \quad \longrightarrow \quad \frac{d\sigma}{dM_I} = \left| \sum_i C_i t_{i \rightarrow \pi\Sigma} \right|^2 p_{CM}$$

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



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

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

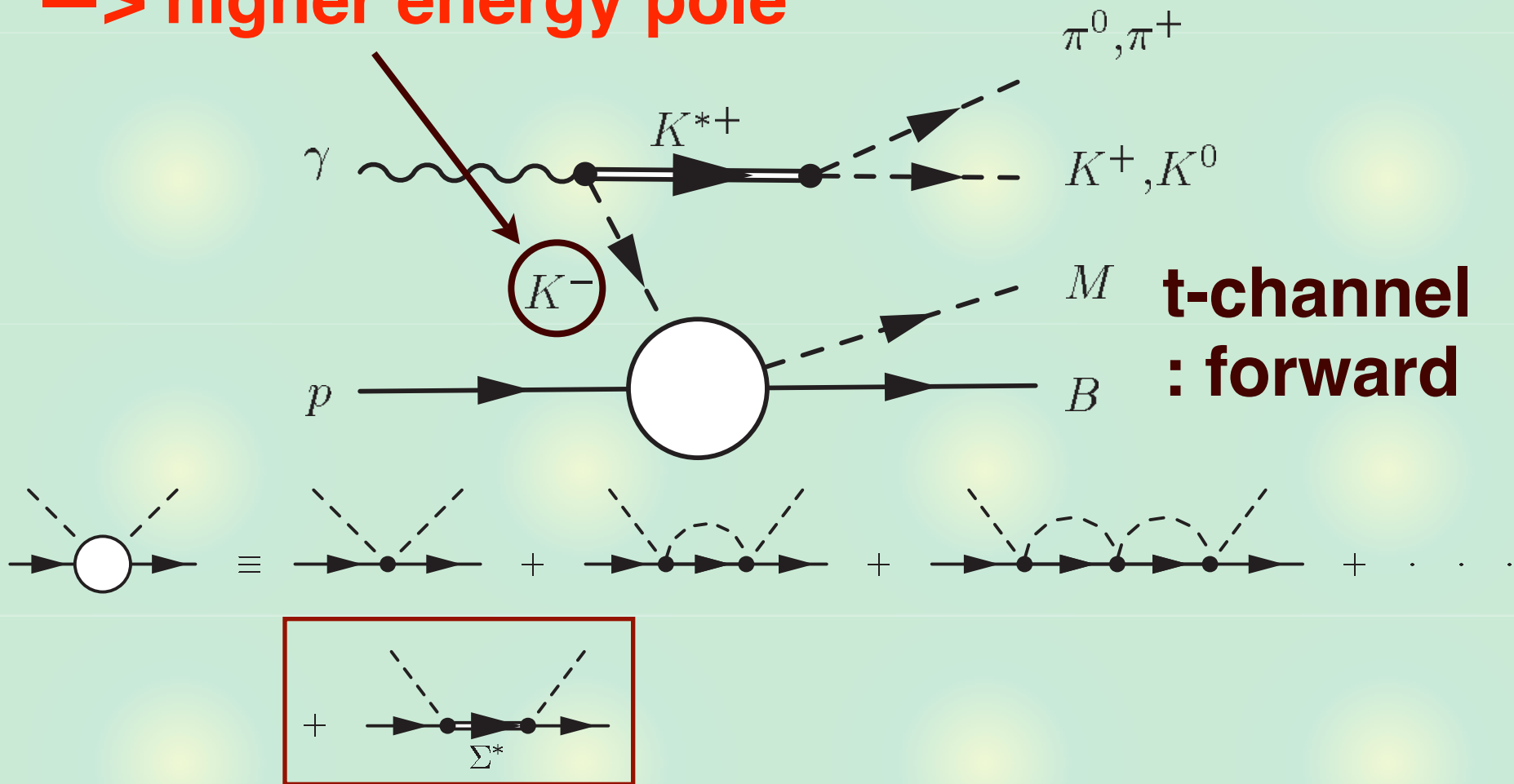


- **higher energy pole?**

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

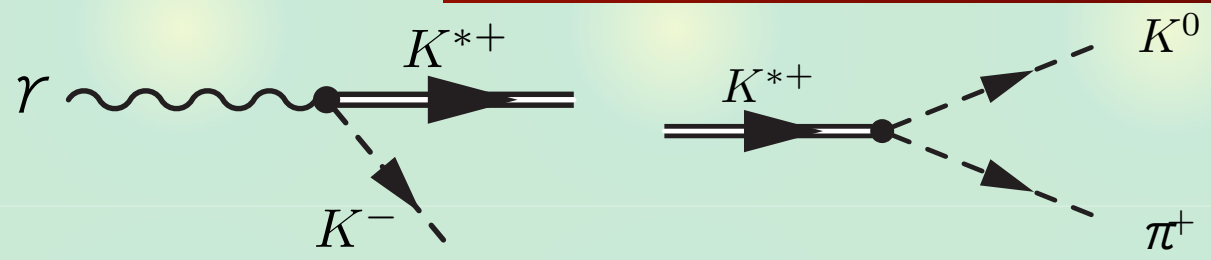
Photoproduction of K^* and $\Lambda(1405)$

Only $K^- p$ channel appears at the initial stage
→ higher energy pole



$\Sigma(1385)$ is included ← background estimation

Advantage of this reaction



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

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

**photon polarization \rightarrow K^* polarization
 \rightarrow $K\pi$ decay plane**

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

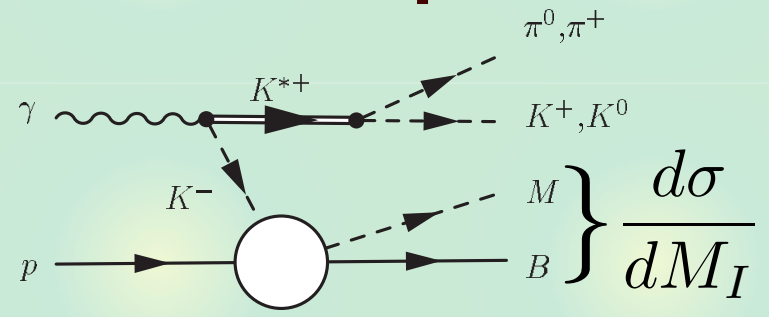
With polarized photon beam, the exchanged particle can be identified.

Clear mechanism

Isospin decomposition of final states

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

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



- **Pure $l=0$ amplitude $\leftarrow \Lambda(1405)$**

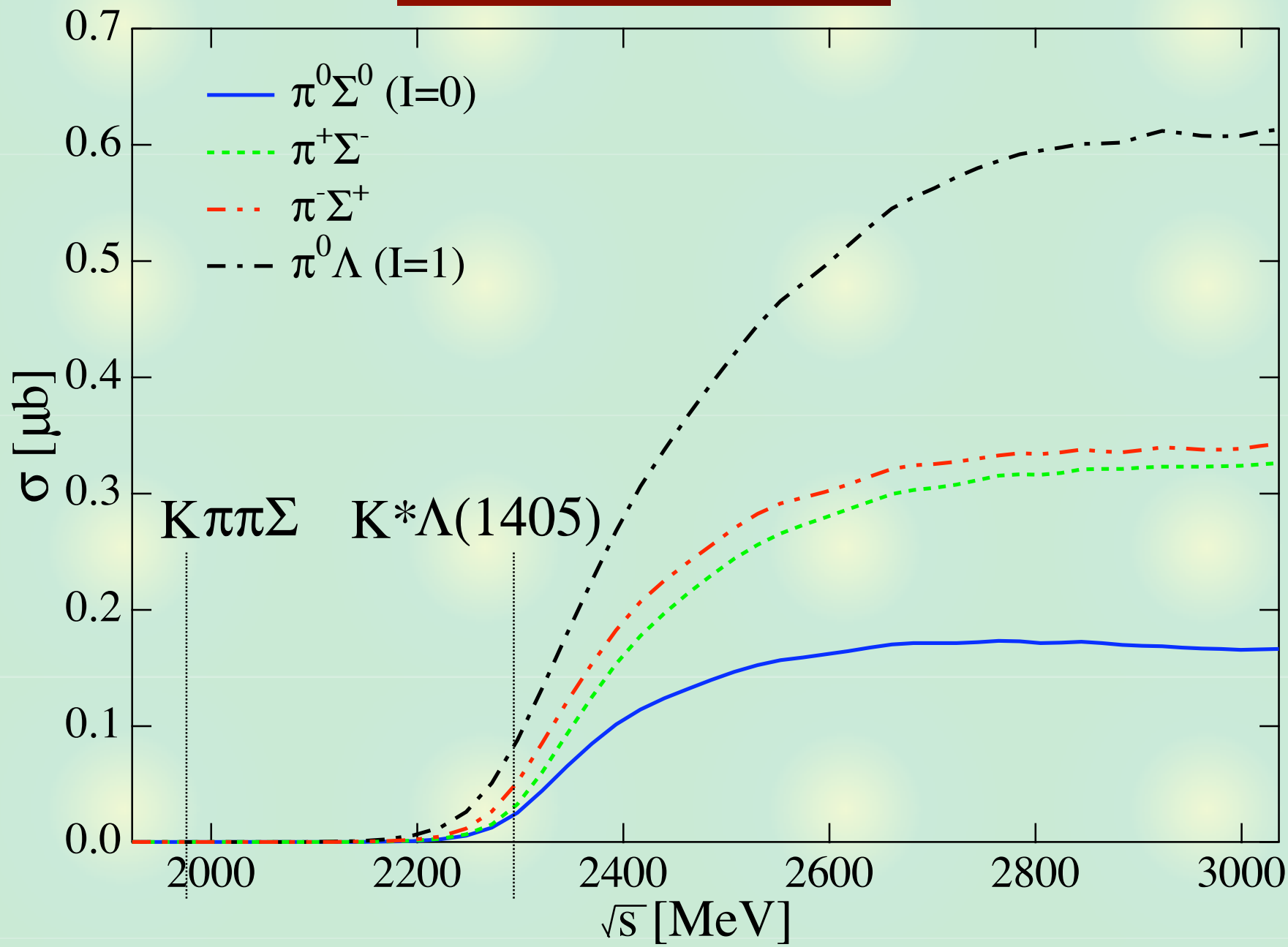
$$\sigma(\pi^0 \Lambda) \propto |T^{(1)}|^2$$

- **Pure $l=1$ amplitude $\leftarrow \Sigma(1385)$**

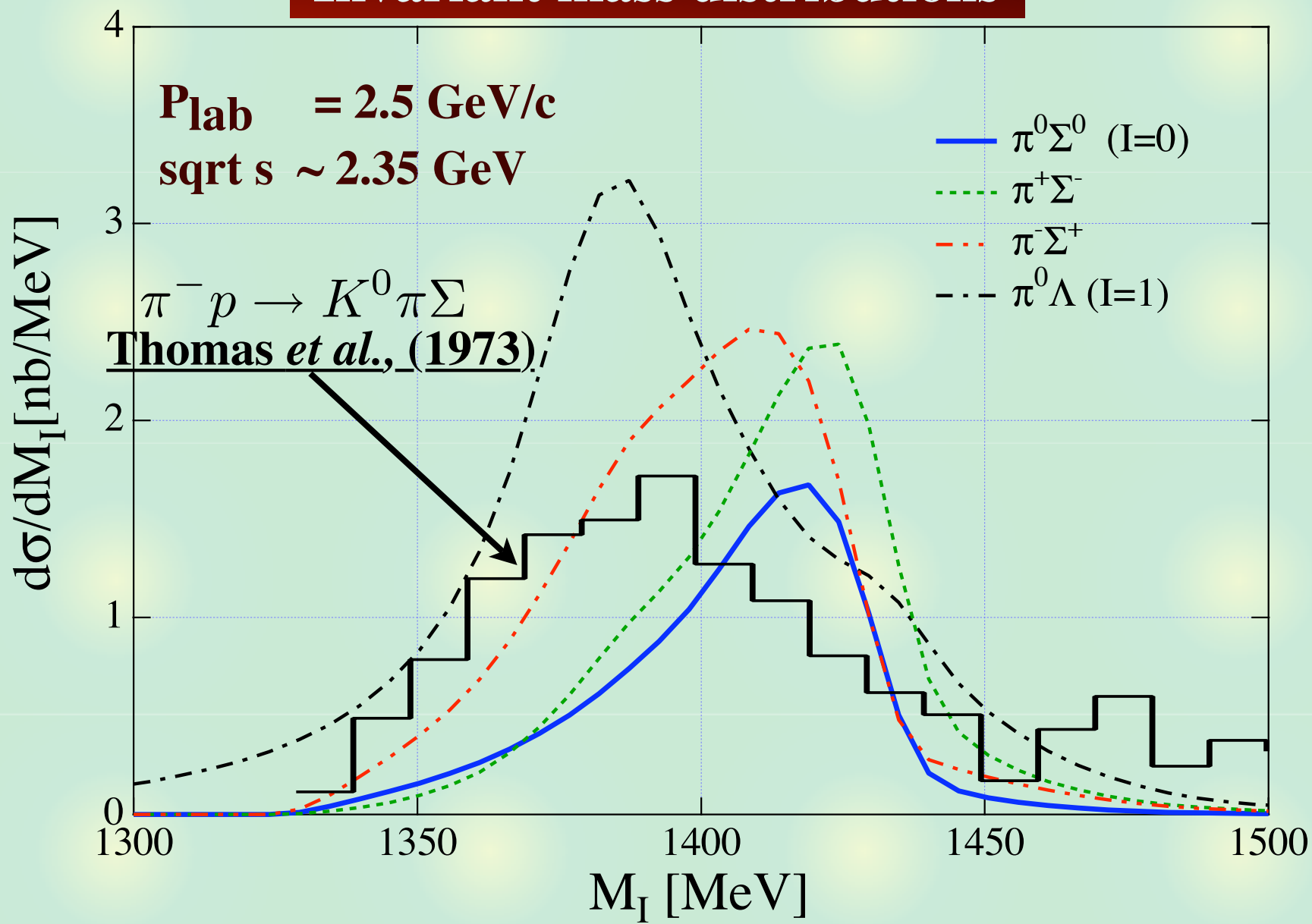
$$\sigma(\pi^\pm \Sigma^\mp) \propto \frac{1}{3} |T^{(0)}|^2 + \frac{1}{2} |T^{(1)}|^2 \pm \frac{2}{\sqrt{6}} \text{Re}(T^{(0)} T^{(1)*})$$

- **Mixture of $l=0$ and $l=1$**

Total cross sections



Invariant mass distributions



• dominance of higher pole -> different shape

Isospin decomposition of charged $\pi\Sigma$ states

Charged $\pi\Sigma$ states

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

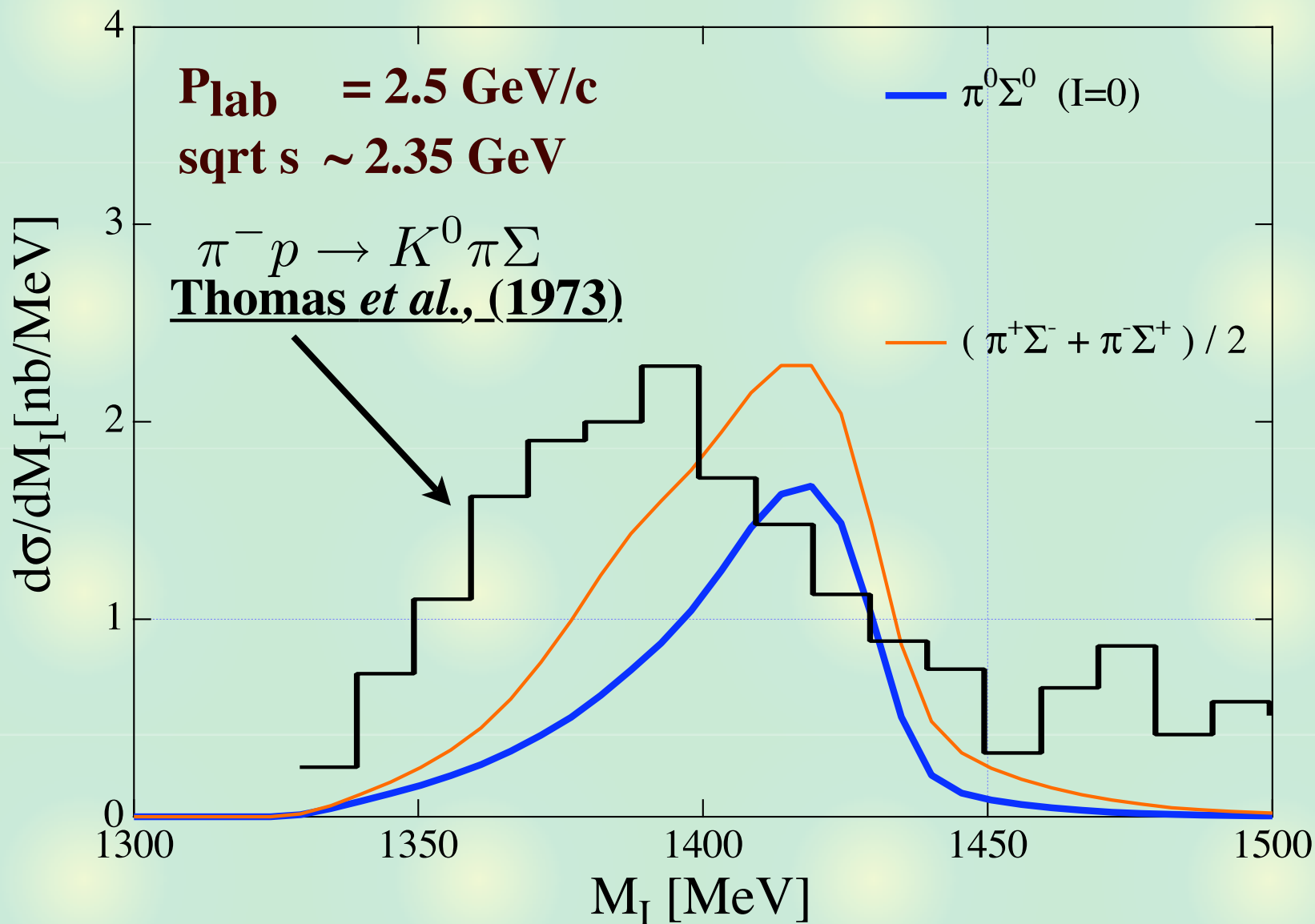
- **Difference between charged states**
 -> **interference term of l=0 and 1**

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 : l=1, $\Sigma(1385)$


Invariant mass distributions 2



$\Sigma(1385)$ contribution is small

Conclusion for part I

We study the **structure of $\Lambda(1405)$** using the chiral unitary model.



 In the chiral unitary model, $\Lambda(1405)$ is generated as a **quasi-bound state** in coupled channel meson-baryon scattering.

 There are **two poles** of the scattering amplitude around nominal $\Lambda(1405)$.

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

Pole 2 (1390–66i) : strongly couples to $\pi\Sigma$ state

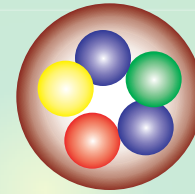
Conclusion for part I

-  We propose the $\gamma p \rightarrow K^* \Lambda(1405)$ 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 $\Sigma(1385)$ in $l=1$ channel, which is found to be **small for the $\pi\Sigma$ 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

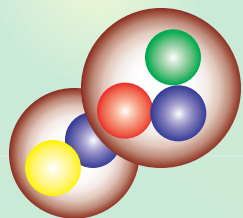
$$M_{\Theta} \sim 4m_{ud} + m_s \sim 1700 \text{ MeV}$$

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?



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

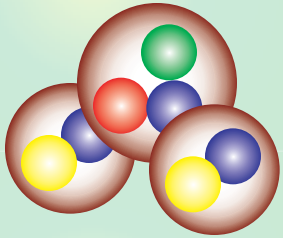
- > no interaction for s-wave
- > Chiral unitary model ×

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
 \rightarrow p-wave excitation \rightarrow **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)

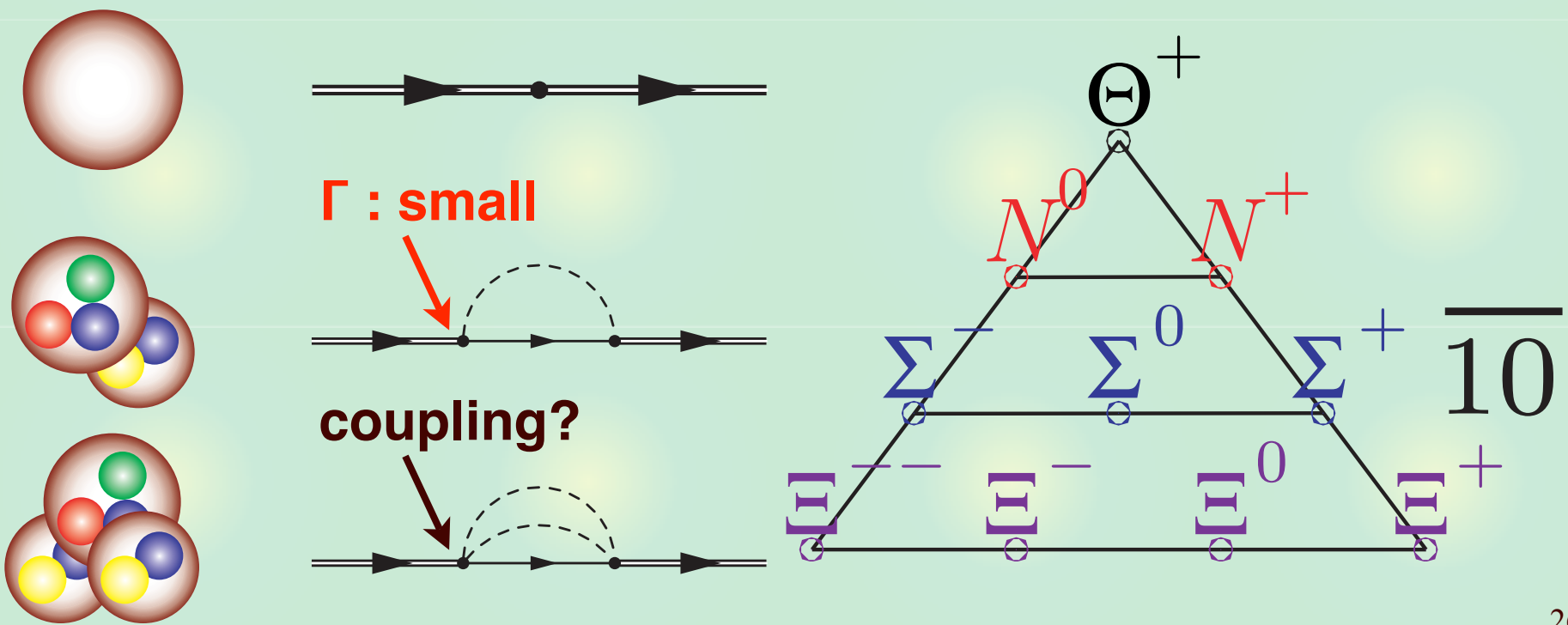
An attraction was found, but **not strong enough to bind the system.**

Two-meson cloud effect

How large the π KN effects in Θ ?

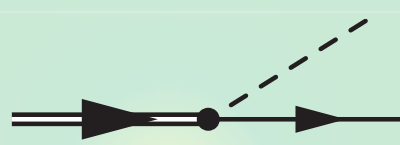
Hosaka, Hyodo, Estrada, Oset, Peláez, Vacas, PRC (2005), Chap. 9.

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



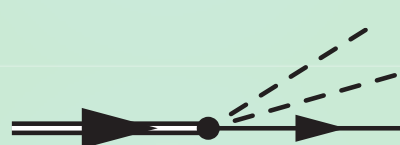
Two-meson coupling

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




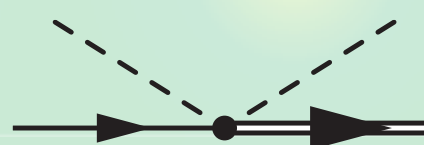
$\Theta^+ \rightarrow KN$ **Very narrow**

$N(1710) \rightarrow \pi N$ **10–20 %**



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

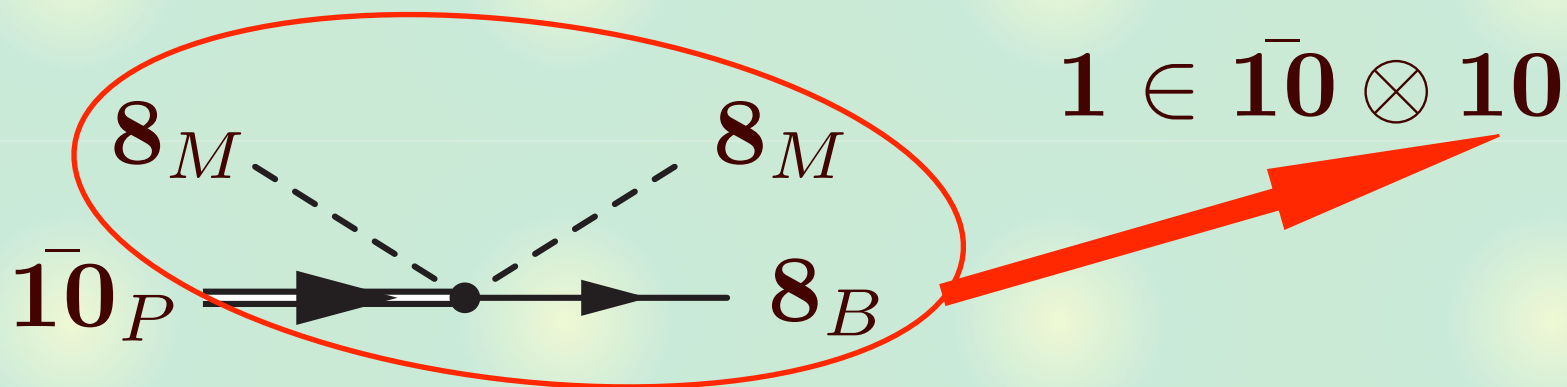
$N(1710) \rightarrow \pi\pi N$ **40–90 %**

Large??

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

SU(3) structure of effective Lagrangian



$$8_M \otimes 8_M \otimes 8_B = (1 \oplus 8^s \oplus 8^a \oplus 10 \oplus \bar{10} \oplus 27)_{MM} \otimes 8_B$$

$$= 8 \quad \leftarrow \text{from } 1_{MM} \otimes 8_B$$

$$\oplus (1 \oplus 8 \oplus 8 \oplus \mathbf{10} \oplus \bar{10} \oplus 27) \quad \leftarrow \text{from } \underline{8^s_{MM}} \otimes 8_B$$

$$\oplus (1 \oplus 8 \oplus 8 \oplus \mathbf{10} \oplus \bar{10} \oplus 27) \quad \leftarrow \text{from } \underline{8^a_{MM}} \otimes 8_B$$

$$\oplus (8 \oplus \mathbf{10} \oplus 27 \oplus 35) \quad \leftarrow \text{from } \underline{10_{MM}} \otimes 8_B$$

$$\oplus (8 \oplus \bar{10} \oplus 27 \oplus 35') \quad \leftarrow \text{from } \bar{10}_{MM} \otimes 8_B$$


$$\oplus (8 \oplus \mathbf{10} \oplus \bar{10} \oplus 27 \oplus 27 \oplus 35 \oplus 35'' \oplus 64) \quad \leftarrow \text{from } \underline{27_{MM}} \otimes 8_B$$

Construction of interaction Lagrangians

Ex.) Construction of 8_s Lagrangian

$$\begin{aligned}
 D_i^j[\mathbf{8}_{MM}^s] &= \phi_i^a \phi_a^j + \phi_i^a \phi_a^j - \frac{2}{3} \delta_i^j \phi_a^b \phi_b^a \\
 &= 2\phi_i^a \phi_a^j - \frac{2}{3} \delta_i^j \phi_a^b \phi_b^a
 \end{aligned}$$

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



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

Interaction Lagrangians

Terms without derivative

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

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

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

← 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

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

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

With one derivative

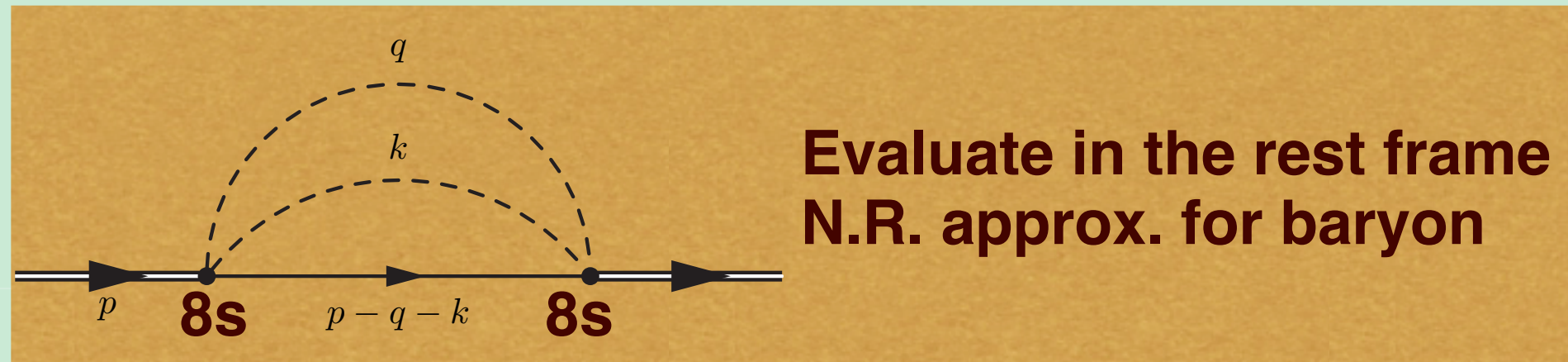
8a

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

Diagrams for self-energy

Imaginary part : decay width

SU(3) breaking : masses of particles



$$\begin{aligned}
 & - \int \frac{d^4 k}{(2\pi)^4} \int \frac{d^4 q}{(2\pi)^4} |t^{(j)}|^2 \frac{1}{k^2 - m_1^2 + i\epsilon} \frac{1}{q^2 - m_2^2 + i\epsilon} \frac{M}{E} \frac{1}{p^0 - k^0 - q^0 - E + i\epsilon} \\
 & = \int \frac{d^3 k}{(2\pi)^3} \int \frac{d^3 q}{(2\pi)^3} |t^{(j)}|^2 \frac{1}{2\omega_1} \frac{1}{2\omega_2} \frac{M}{E} \frac{1}{p^0 - \omega_1 - \omega_2 - E + i\epsilon}
 \end{aligned}$$

↑ vertex

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

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

$$\mathbf{q}_{\max} = \mathbf{k}_{\max} = 700\text{--}800 \text{ MeV}$$

p^0 = energy of antidecuplet

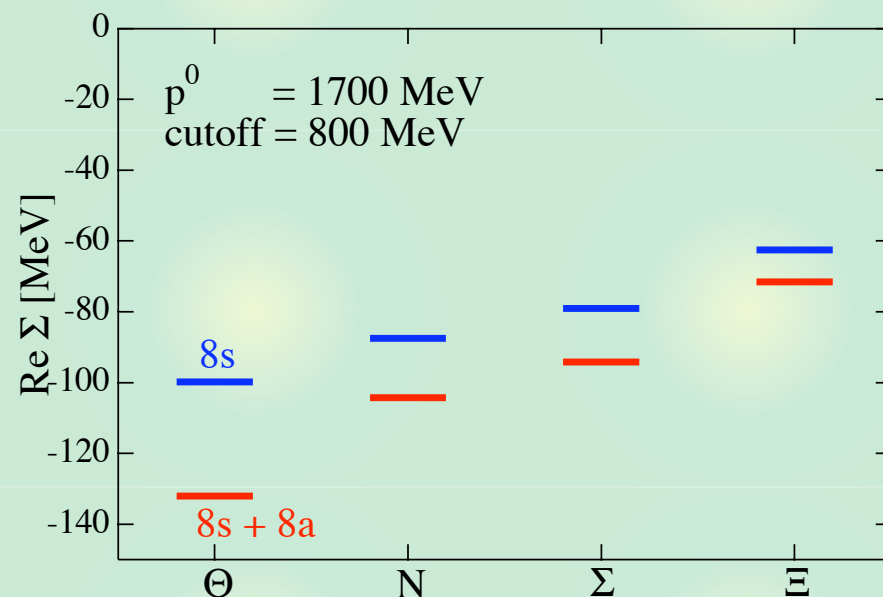
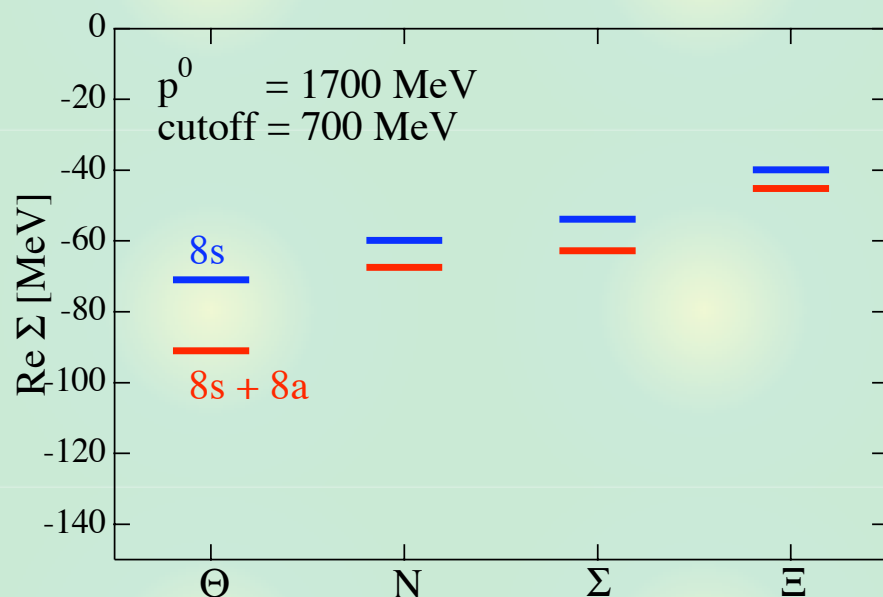
$$\Sigma_P^{(j)}(p^0) = \sum_{B, m_1, m_2} \left(F^{(j)} C_{P, B, m_1, m_2}^{(j)} \right) I^{(j)}(p^0; B, m_1, m_2) \left(F^{(j)} C_{P, B, m_1, m_2}^{(j)} \right)$$

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

Coupled channel summation

P	α	$8s$	$8a$	P	α	$8s$	$8a$	P	α	$8s$	$8a$
Θ_{10}	$NK\pi$	18	18	N_{10}	$NK\bar{K}$	4	12	Σ_{10}	$N\bar{K}\pi$	3	3
	$NK\eta$	2	18		$N\pi\pi$	3	6		$N\bar{K}\eta$	$\frac{1}{3}$	3
					$N\pi\eta$	2	-		$\Lambda K\bar{K}$	3	3
					$N\eta\eta$	1	-		$\Lambda\pi\eta$	2	-
					$\Lambda K\pi$	$\frac{9}{2}$	$\frac{9}{2}$		$\Lambda\pi\pi$	-	6
					$\Lambda K\eta$	$\frac{1}{2}$	$\frac{9}{2}$		$\Sigma K\bar{K}$	3	11
					$\Sigma K\pi$	$\frac{9}{2}$	$\frac{9}{2}$		$\Sigma\pi\pi$	3	4
					$\Sigma K\eta$	$\frac{1}{2}$	$\frac{9}{2}$		$\Sigma\pi\eta$	$\frac{4}{3}$	-
Ξ_{10}	$\Sigma\bar{K}\pi$	9	9						$\Sigma\eta\eta$	1	-
	$\Sigma\bar{K}\eta$	1	9						$\Xi K\pi$	3	3
	$\Xi K\bar{K}$	6	6						$\Xi K\eta$	$\frac{1}{3}$	3
	$\Xi\pi\eta$	4	-								
	$\Xi\pi\pi$	-	12								

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



All mass shifts are **attractive** ($\sim 100 \text{ MeV}$ for Θ).

Mass splitting is nearly **equal spacing**.

Mass difference between Ξ and Θ

$\rightarrow 60 \text{ MeV} : \sim 20\% \text{ of } 320 = 1860 - 1540 \text{ MeV}$

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 $\Lambda(1405)$ as **meson-baryon molecule**.
- The **two-pole structure** of the $\Lambda(1405)$ can be tested experimentally.
- The **two-meson cloud** provides ~ 100 MeV attraction for the Θ and about 20% of the mass splitting for $\bar{10}$.

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

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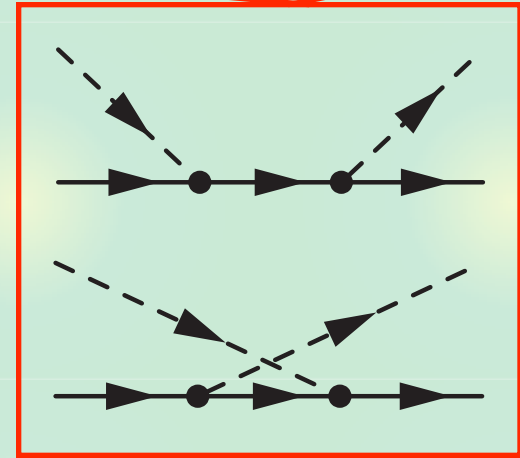
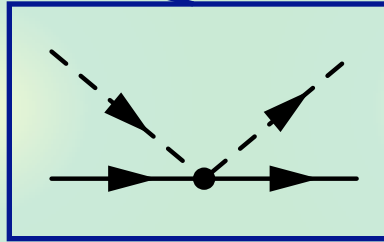
Appendix : ChPT Lagrangian

$$\mathcal{L}^{(1)} = \text{Tr} \left(\bar{B}(i\mathcal{D} - M_0)B - D(\bar{B}\gamma^\mu\gamma_5\{A_\mu, B\}) - F(\bar{B}\gamma^\mu\gamma_5[A_\mu, B]) \right)$$

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

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

$$D + F = g_A$$



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

$$\underline{V}_\mu = -\frac{i}{2}(\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger) = \frac{i}{4f^2} \underline{(\Phi \partial_\mu \Phi - \partial_\mu \Phi \Phi)} + \dots$$

$$\underline{A}_\mu = -\frac{i}{2}(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger) = -\frac{1}{f} \underline{\partial_\mu \Phi} + \dots$$

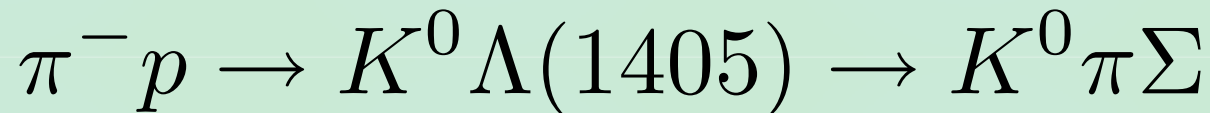
Two-pole structure

Are they real states?

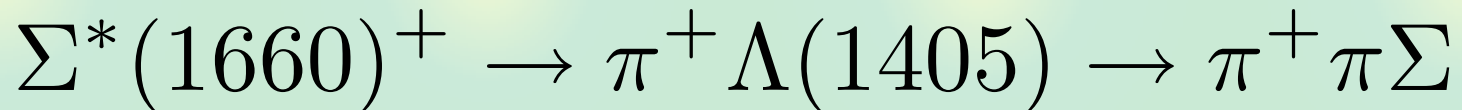
—> need to check experimentally

- Experimental results available so far:

Thomas et al., (1973)



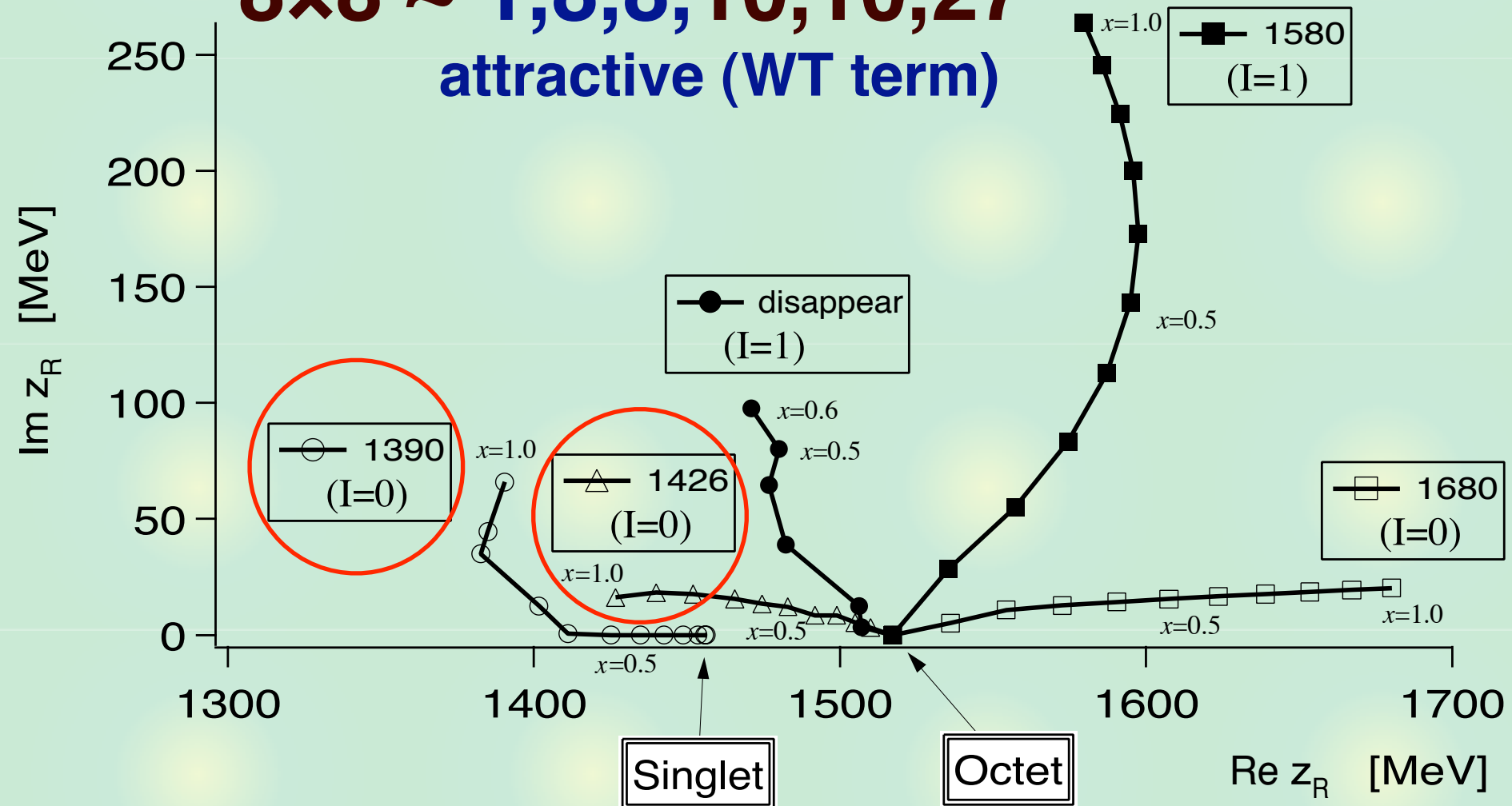
Hemingway et al., (1984)



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

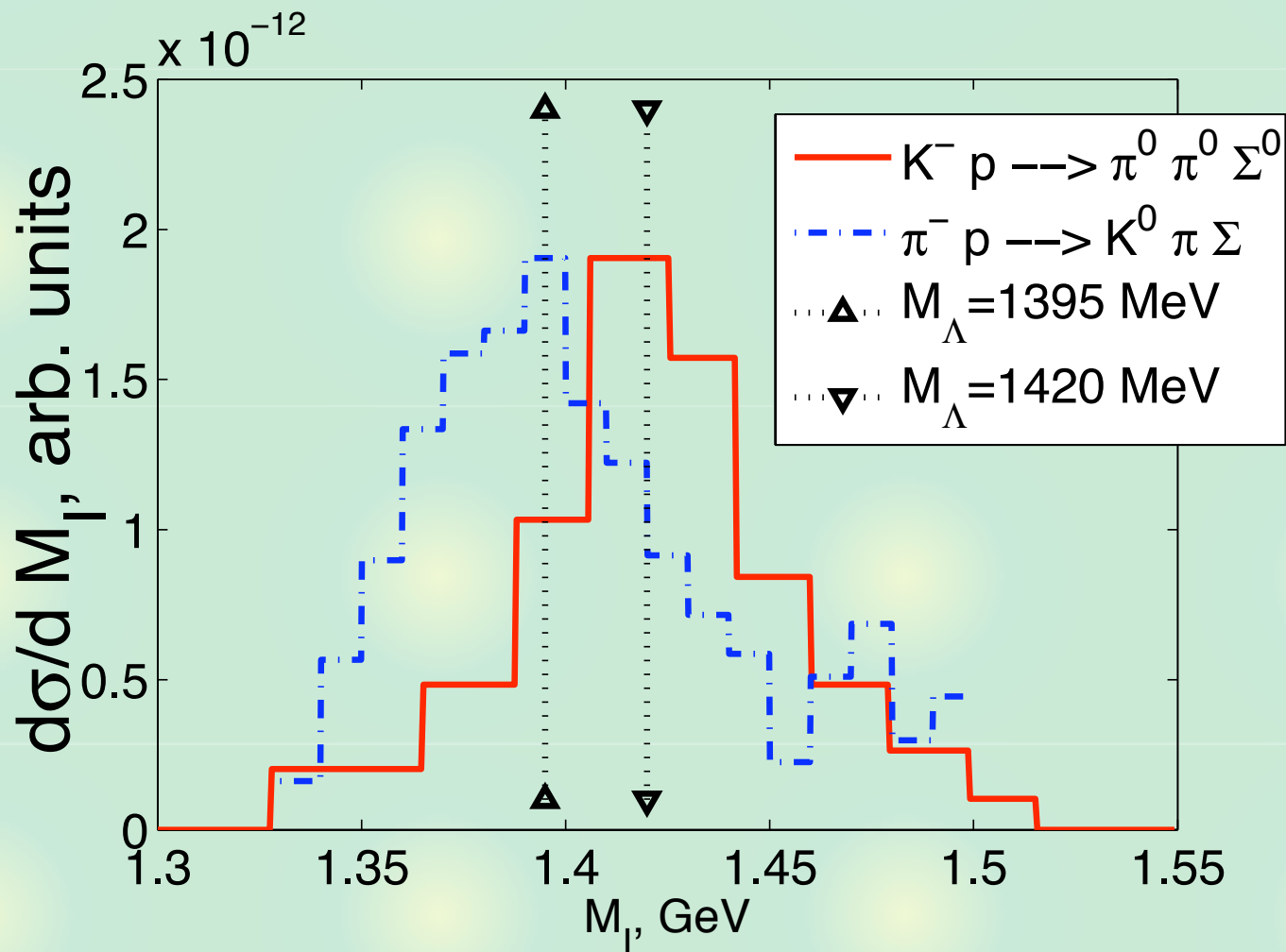
Trajectories of the poles with SU(3) breaking ($S = -1$)

$8 \times 8 \sim 1, 8, 8, 10, \overline{10}, 27$
attractive (WT term)



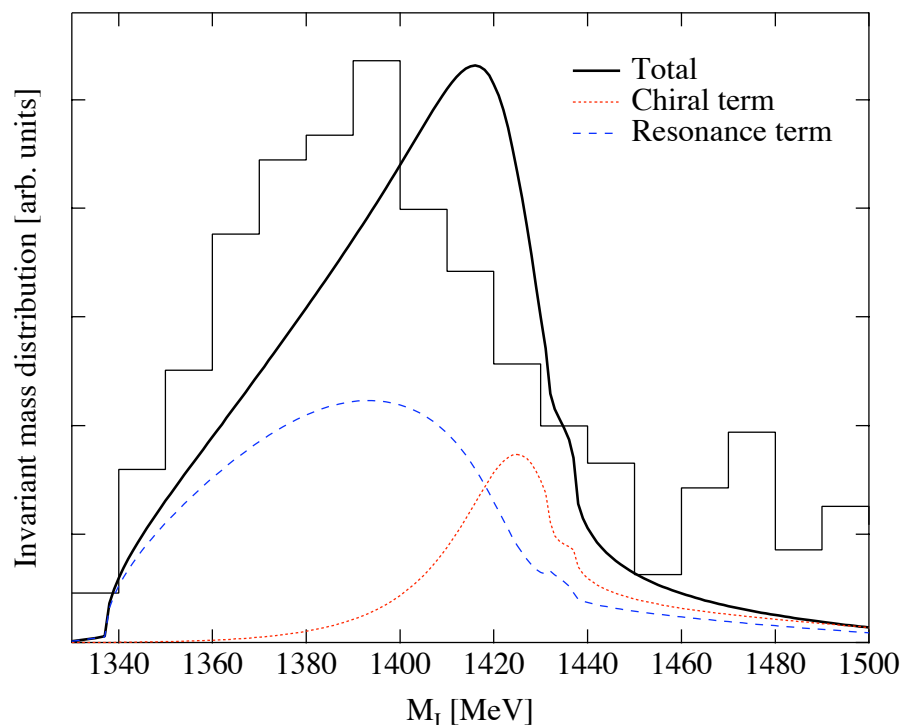
D. Jido, et al., Nucl. Phys. A 723, 205 (2003)

Application to the reaction

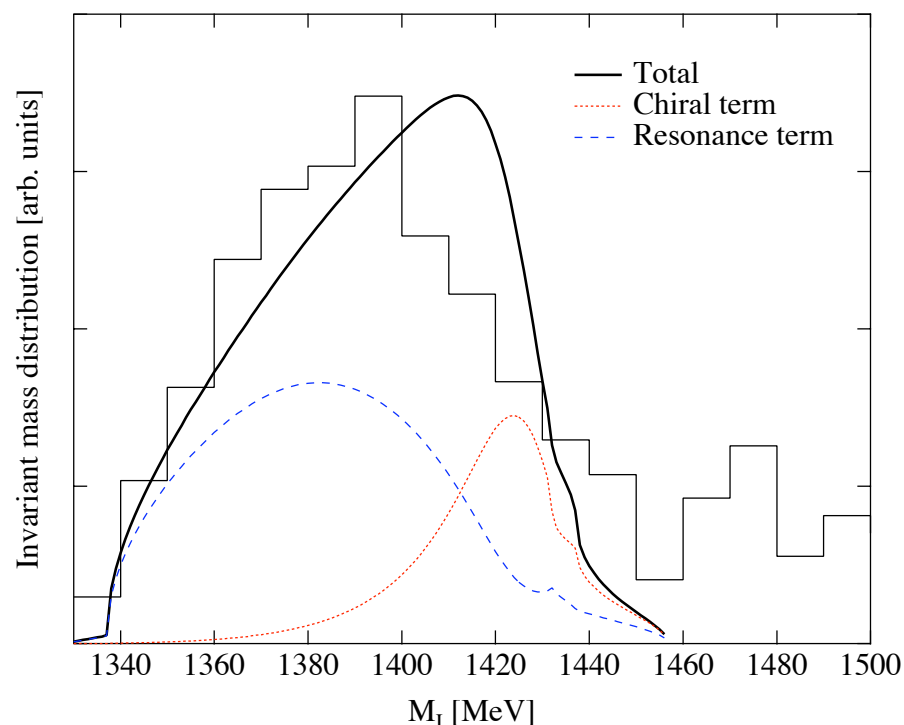


V.K. Magas, *et al.*, hep-ph/0503043

Improvement of mass distributions



$P_{\text{lab}} = 1.66 \text{ GeV}/c$



$P_{\text{lab}} = 1.55 \text{ GeV}/c$

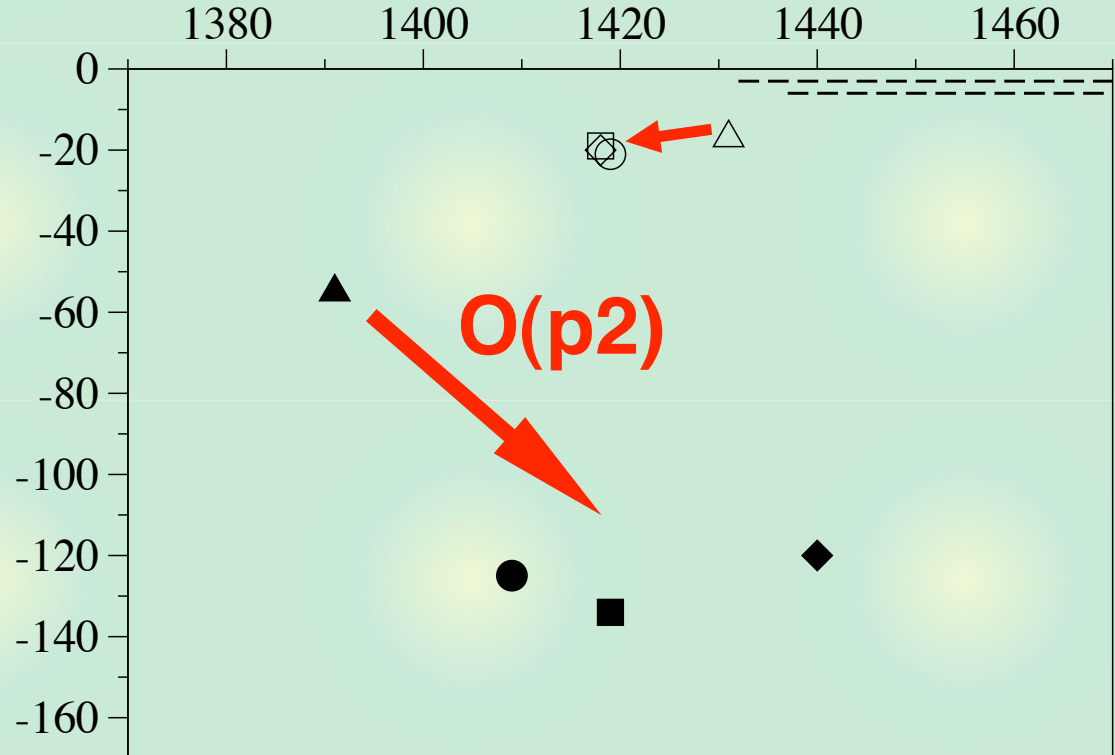
- **Consistency between amplitude and phase space**
- **$\Sigma(1385)$ contribution**
- **Approximation for loop**

Controversial?

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

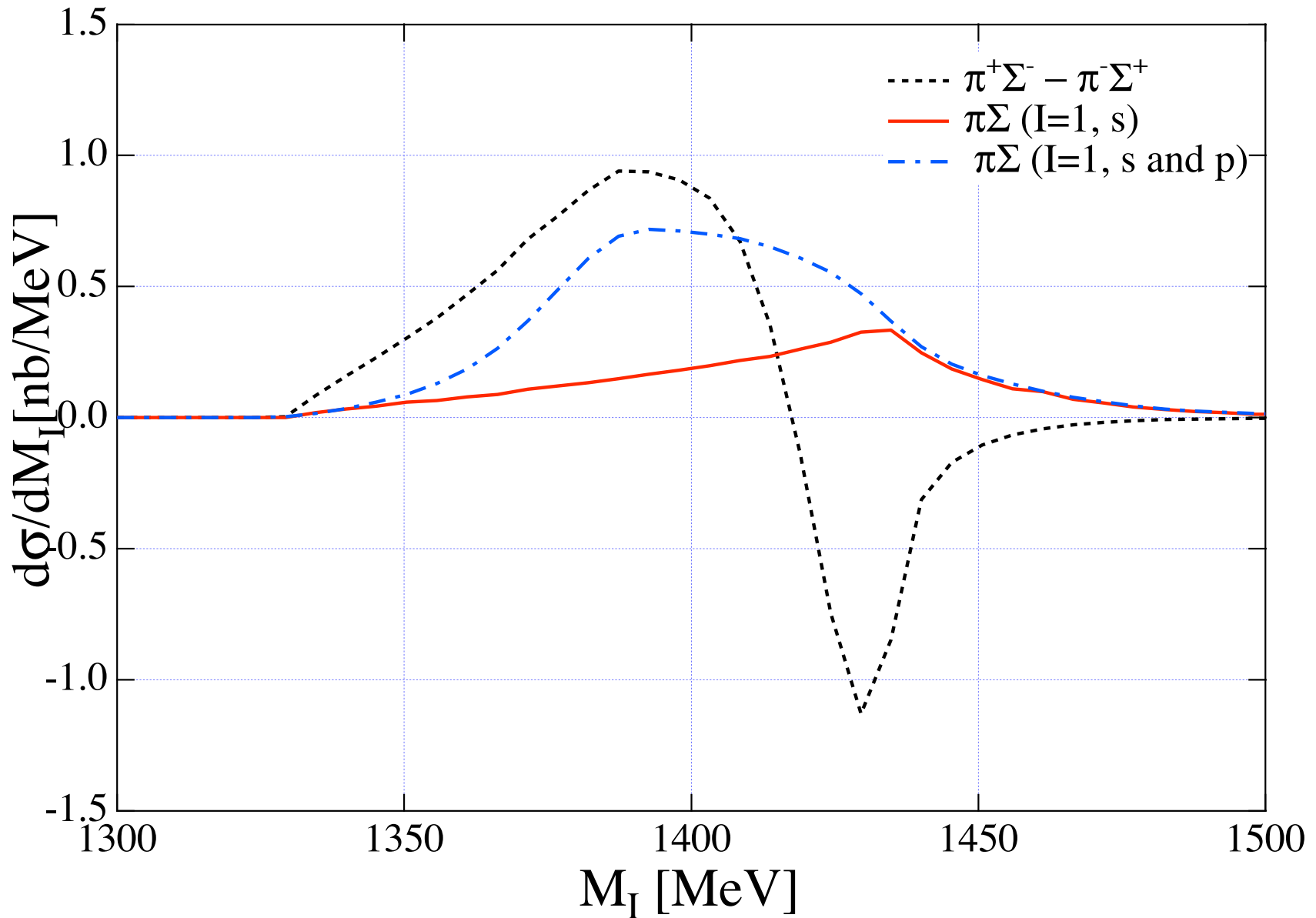
Similar study but
with $O(p^2)$ terms

DEAR experiment
: kaonic hydrogen



Inclusion of $O(p^2)$ 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 \leftarrow Duality in scattering theory

Heavy pentaquark \leftarrow large N_c and heavy M_Q

Test for inter-quark correlation

meson ($\bar{q}q$) \ni only $q\bar{q}$

baryon (qqq) \ni only $qq(\text{color } \bar{3})$

pentaquark ($qqqq\bar{q}$) \ni $qq(\text{color } 6), \dots$

multi-quark states, quark matter, ...

Properties of the Θ

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

light mass 1540 MeV

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

$$M_K + M_N \sim 1430 \text{ MeV} \leftarrow \text{q}\bar{\text{q}} \text{ correlation}$$

narrow width < 15 MeV (1 MeV)

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

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

Motivations

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

P. Bicudo, *et al.*, Phys. Rev. C69, 011503 (2004)

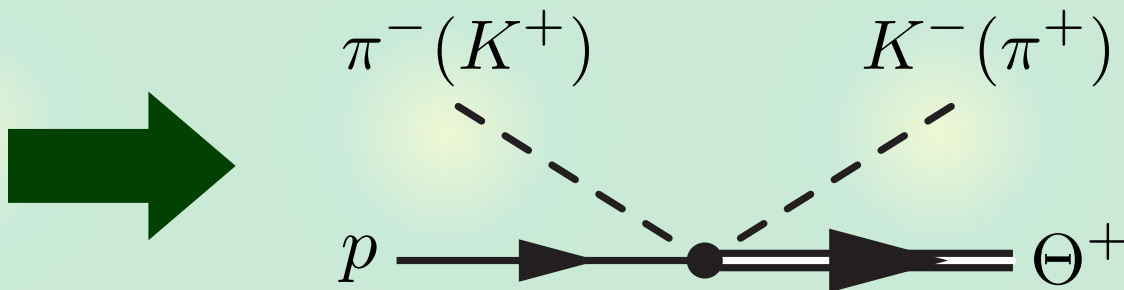
T. Kishimoto, *et al.*, hep-ex/0312003

F. J. Llanes-Estrada, *et al.*, Phys. Rev. C69, 055203 (2004)

Anomalies in production experiments

$\pi^- p \rightarrow K^- \Theta^+$ at KEK

$\gamma d \rightarrow \Lambda^* \Theta^+$ 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. C* **71**, 045205 (2005),
Section 9.

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

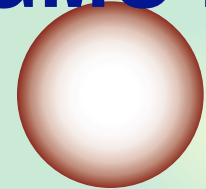
$$M_{\Theta} = M_0 + \text{Re}\Sigma_{\Theta}$$

$$M_N = M_0 + \Delta - \text{Re}\Sigma_N$$

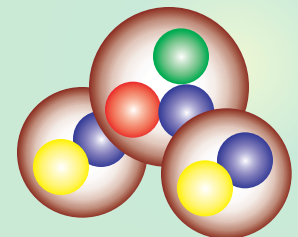
$$M_{\Sigma} = M_0 + 2\Delta - \text{Re}\Sigma_{\Sigma}$$

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

GMO rule



Two-meson cloud



Interaction Lagrangians 1

Antidecuplet field

$$P^{333} = \sqrt{6}\Theta_{10}^+$$

$$P^{133} = \sqrt{2}N_{10}^0 \quad P^{233} = -\sqrt{2}N_{10}^+$$

$$P^{113} = \sqrt{2}\Sigma_{10}^- \quad P^{123} = -\Sigma_{10}^0 \quad P^{223} = -\sqrt{2}\Sigma_{10}^+$$

$$P^{111} = \sqrt{6}\Xi_{10}^{--} \quad P^{112} = -\sqrt{2}\Xi_{10}^- \quad P^{122} = \sqrt{2}\Xi_{10}^0 \quad P^{222} = -\sqrt{6}\Xi_{10}^+$$

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

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

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

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

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

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

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

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	$\chi(2)$	Decay	8s	$\chi(2)$
Θ	-100	-99	$N(1710) \rightarrow N\pi\pi$	25	25
N	-87	-83	$N(1710) \rightarrow N\eta\pi$	0.58	0.32
Σ	-79	-70	$\Sigma(1770) \rightarrow N\bar{K}\pi$	4.7	4.5
Ξ	-63	-57	$\Sigma(1770) \rightarrow \Sigma\pi\pi$	10	3.6
cutoff	800	525	$\Xi(1860) \rightarrow \Sigma\bar{K}\pi$	0.57	0.40

Almost the same results

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

27 and mass Lagrangians

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

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

Fitting couplings to the N(1710) decay

-> large binding energy of 1 GeV : unrealistic

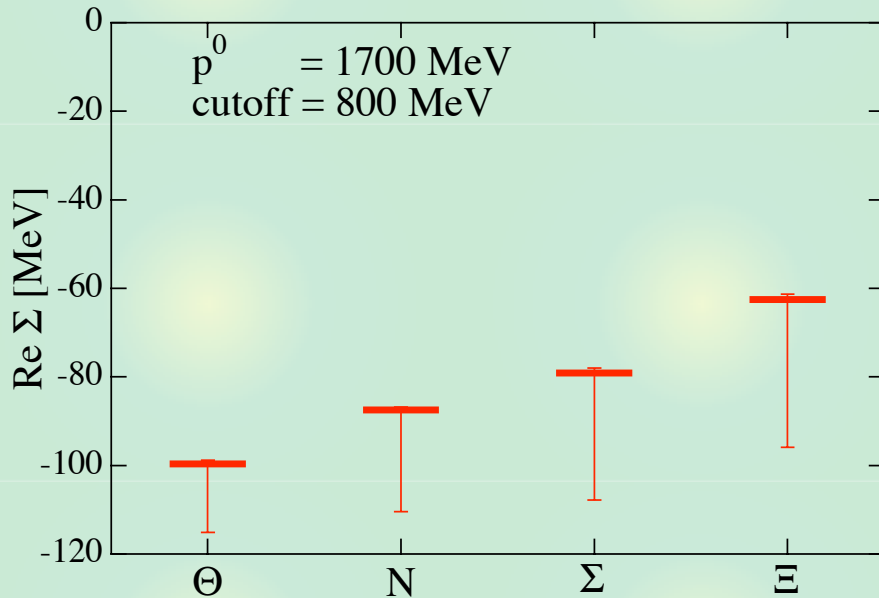
Treat them as a small perturbation to the 8s.

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

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

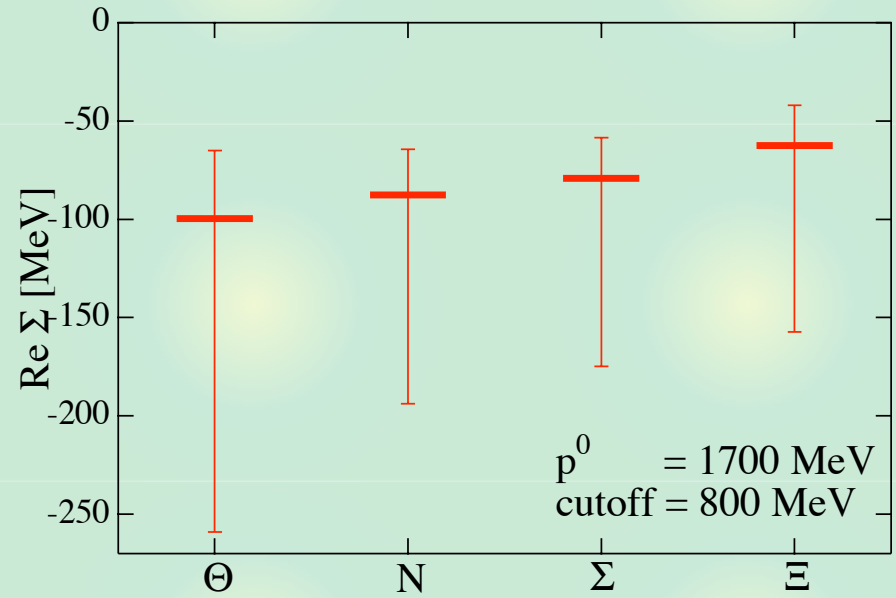
Deviation from a = 1 : weight of new terms

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.