Structure of $\Lambda(1405)$ and photoproduction

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2005, July 28th

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%**

(Naive) Quark model : ~1500 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)

Meson-Baryon or 3-quark?

Introduction : Λ(1405)

Recent works

Large Nc : LS partner of Λ(1520)

C.L. Schat, J.L. Goity and N.N. Scoccola PRL 88, 100202 (2002)

Lattice QCD with 3-quark operator

W. Melnitchouk, *et. al.*, PRD 67, 114506 (2003)
Y. Nemoto, *et. al.*, PRD 68, 094505 (2003)

--> not a 3-quark

F.X. Lee, *et. al.*, NP 119, 296 (2003)

--> 3-quark?

Chiral unitary approaches

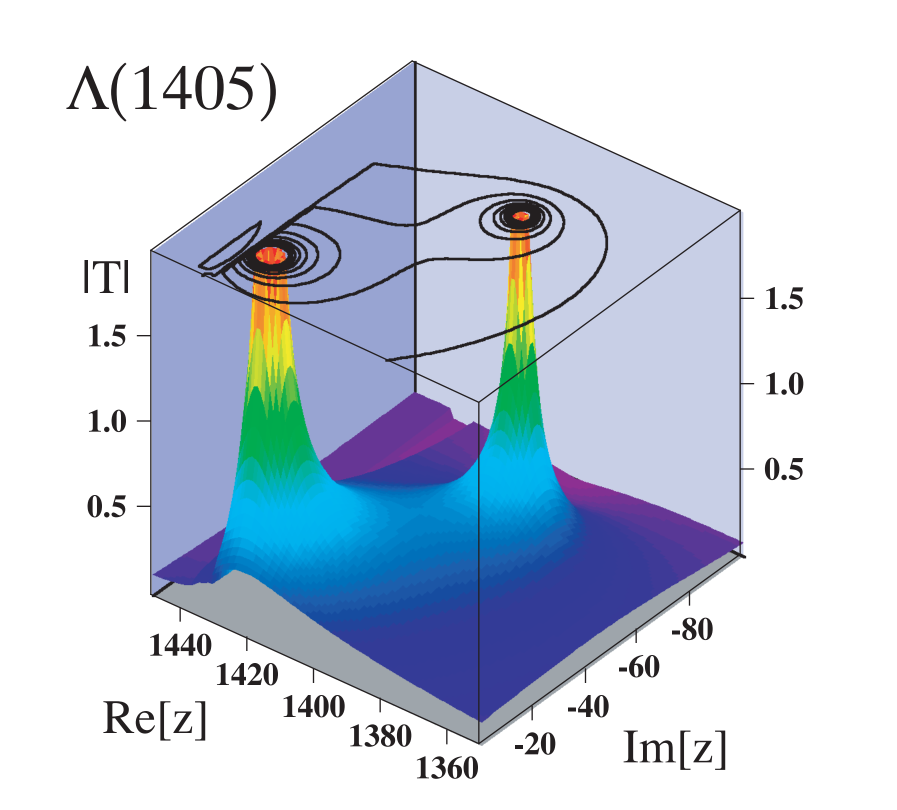
--> Meson-baryon picture

Motivation : Two poles?

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

- **Cloudy bag model**
  J. Fink, *et al.*, PRC41, 2720
- **Chiral unitary model**
  J. A. Oller, *et al.*, PLB500, 263
  E. Oset, *et al.*, PLB527, 99
  D. Jido, *et al.*, PRC66, 025203
  T. Hyodo, *et al.*, PRC68, 018201
  T. Hyodo, *et al.*, PTP112, 73
  C. Garcia-Recio, *et al.*, PRD67, 076009
  D. Jido, *et al.*, NPA725, 181
  T. Hyodo, *et al.*, PRC68, 065203
  C. Garcia-Recio, *et al.*, PLB582, 49
- **Correlated quark model**
  A. Zhang, *et al.*, hep-ph/0403210

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



ChU model, T. Hyodo

Chiral unitary model

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

Chiral symmetry

Low energy behavior

+

Unitarity of S-matrix

Non-perturbative resummation

Dynamical generation

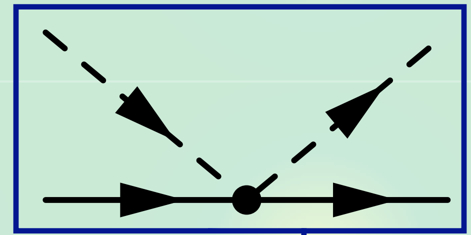
$$J^P = 1/2^- \text{ resonances}$$

$\Lambda(1405), \Lambda(1670),$
$\Sigma(1620), \Xi(1620),$
$N(1535)$

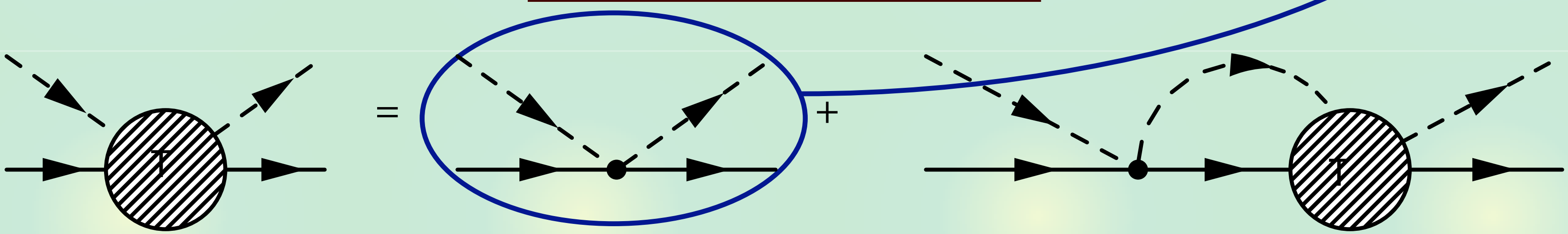
Framework of the chiral unitary model

Chiral perturbation theory

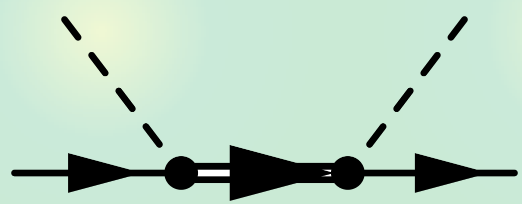
$$\mathcal{L}_{WT} = \frac{1}{4f^2}\mathrm{Tr}(\bar{B}i\gamma^{\mu}[(\Phi\partial_{\mu}\Phi - \partial_{\mu}\Phi\Phi), B])$$



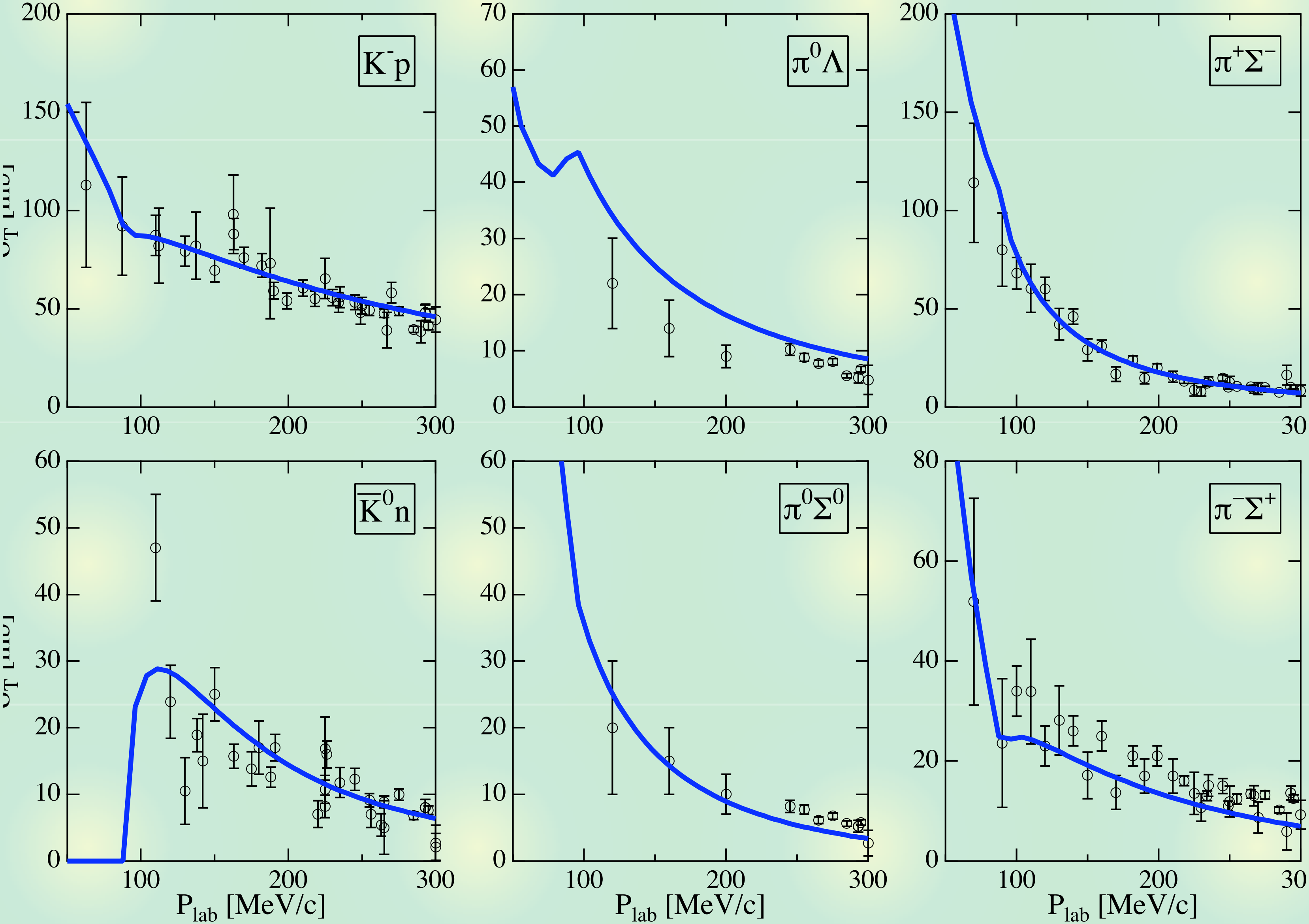
Unitarization



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

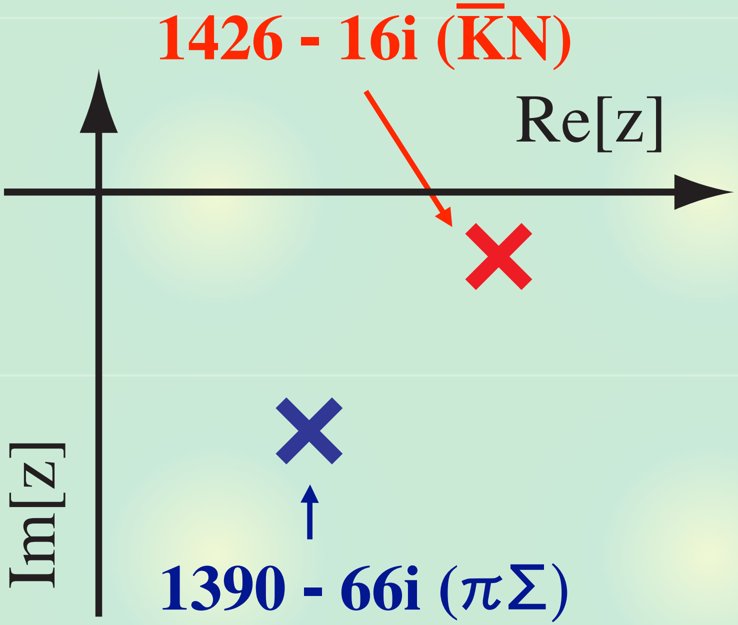
$\sim$ 

Total cross sections of K-p scattering

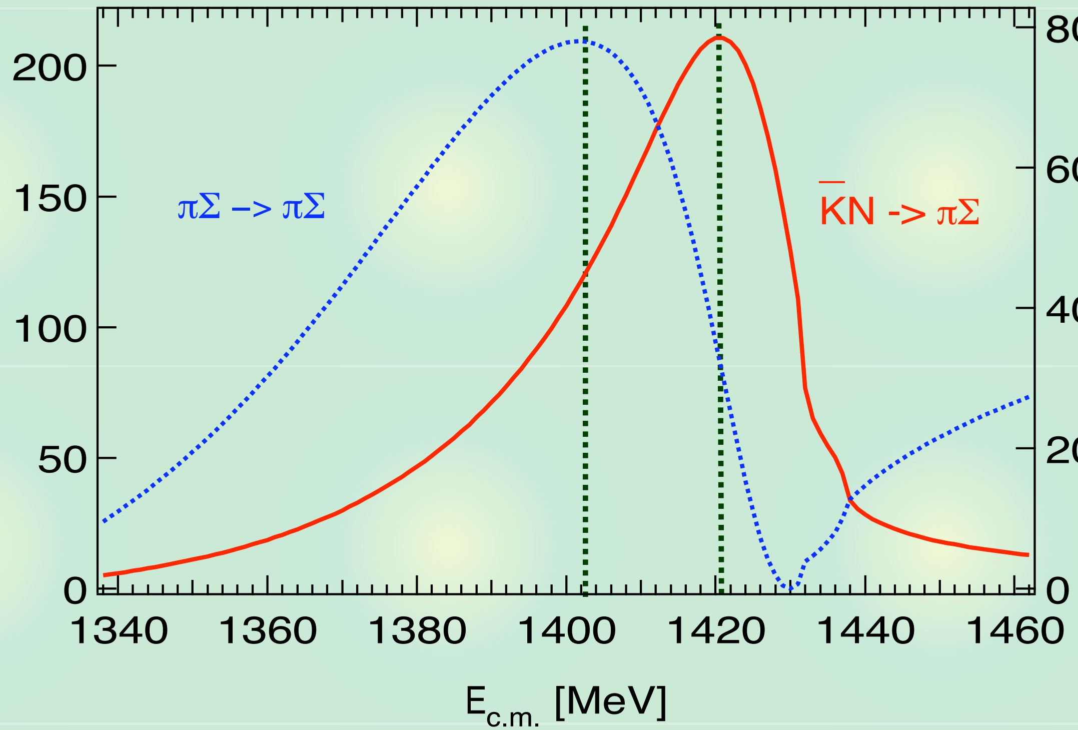


T. Hyodo, *et al.*, Phys. Rev. C 68, 018201 (2003)

Λ(1405) in the chiral unitary model



πΣ mass distribution



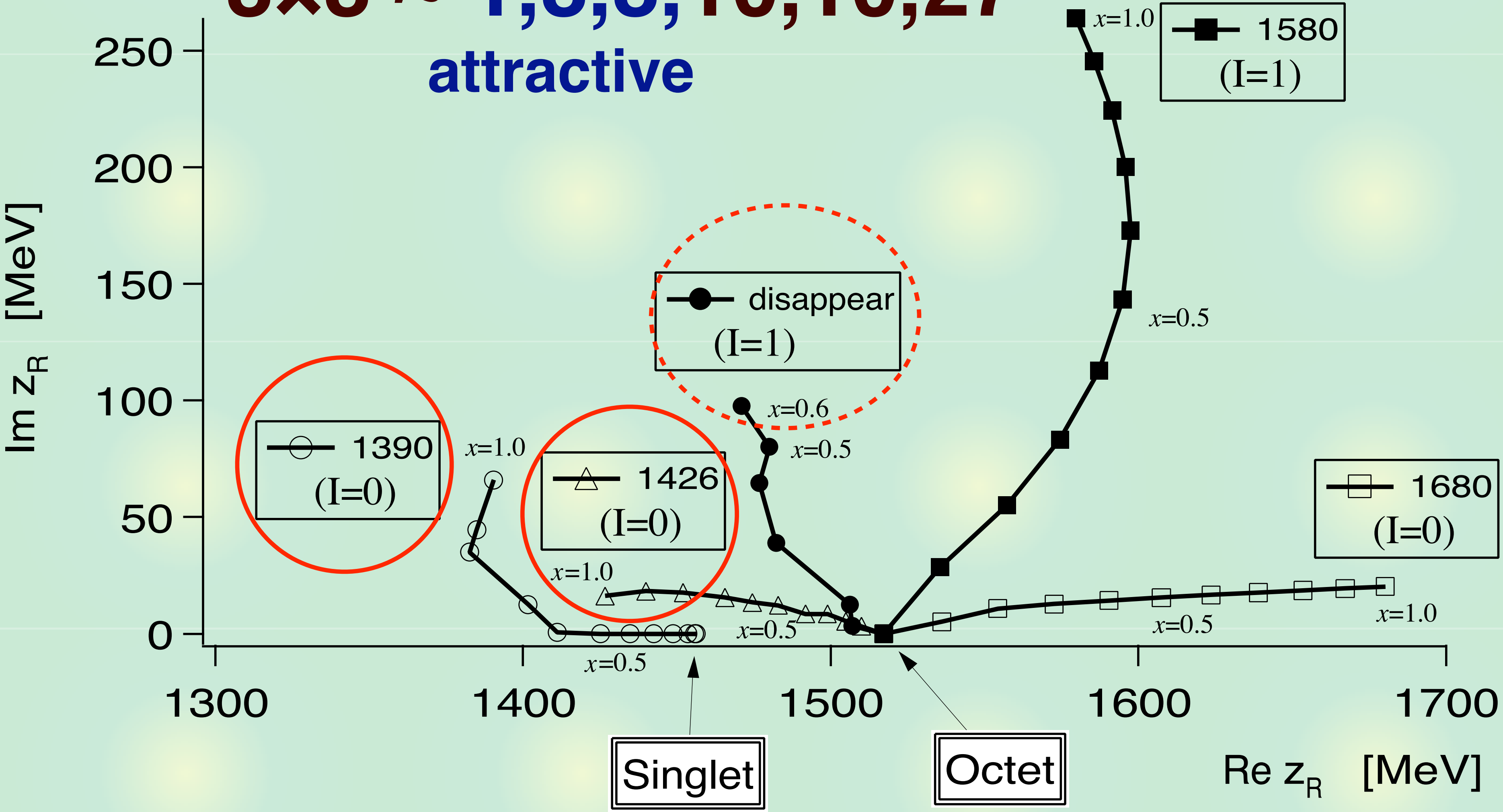
$$\frac{d\sigma}{dM_I} = C|t_{\pi\Sigma\to\pi\Sigma}|^2 p_{CM} \quad \Rightarrow \quad \frac{d\sigma}{dM_I} = |\sum_i C_i t_{i\to\pi\Sigma}|^2 p_{CM}$$

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

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

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

attractive



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

Application to the reaction

Theory | **Experiment**

$$\gamma p \to K^- \pi \Sigma$$

LEPS

J.C. Nacher, *et al.*, PLB445, 55 | J.K. Ahn, *et al.*, NPA721, 715

$$K^- p \to \gamma \pi \Sigma$$

J.C. Nacher, *et al.*, PLB461, 299

$$\pi^- p \to K^0 \pi \Sigma$$

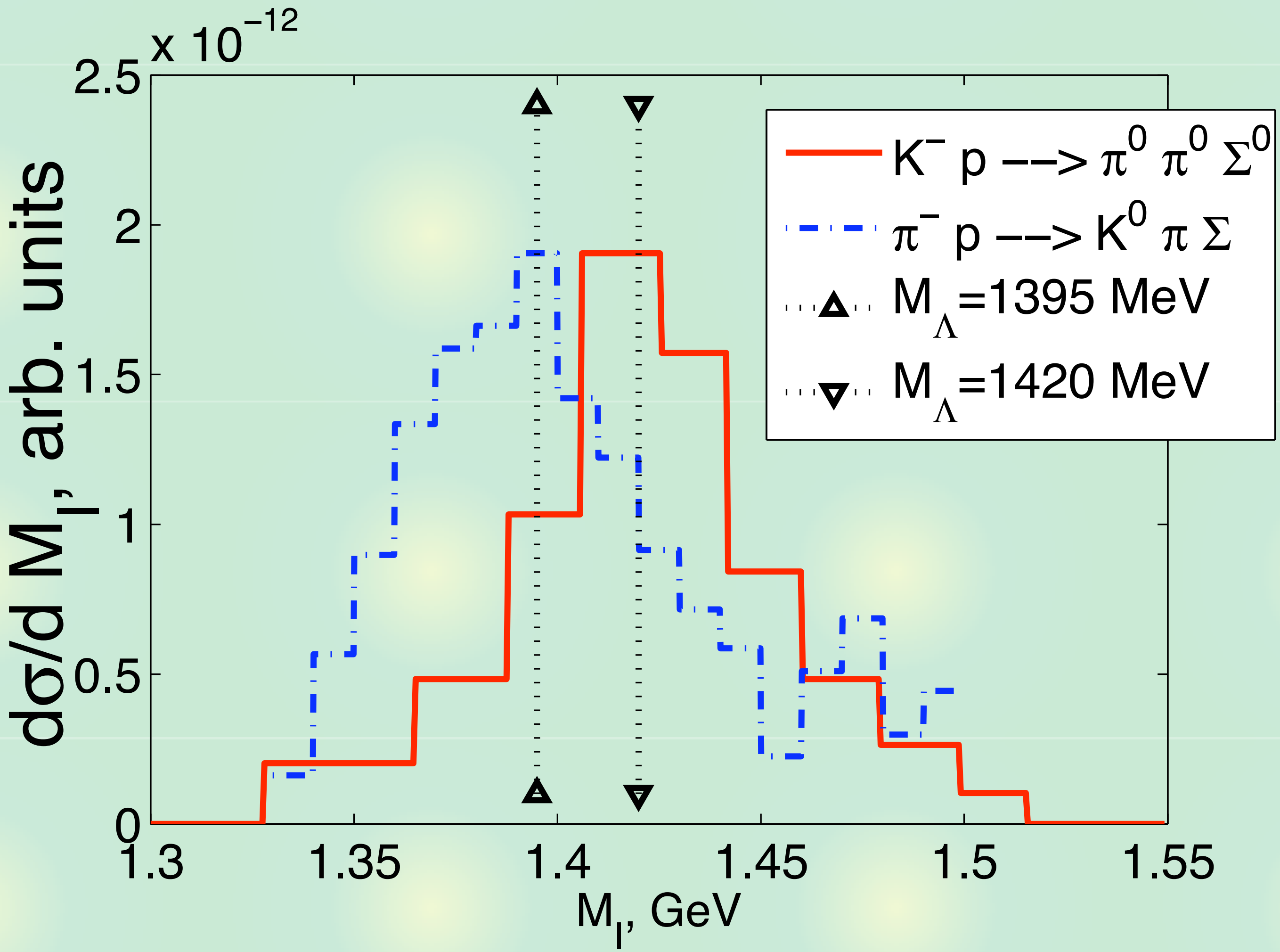
T. H., *et al.*, PRC68, 065203 | D.W. Thomas, *et al.*, NPB56, 15

$$K^- p \to \pi^0 \pi^0 \Sigma^0$$

Crystal ball

V.K. Magas, *et al.*, hep-ph/0503043 | S. Prakhov, *et al.*, PRC70, 034605

Application to the reaction



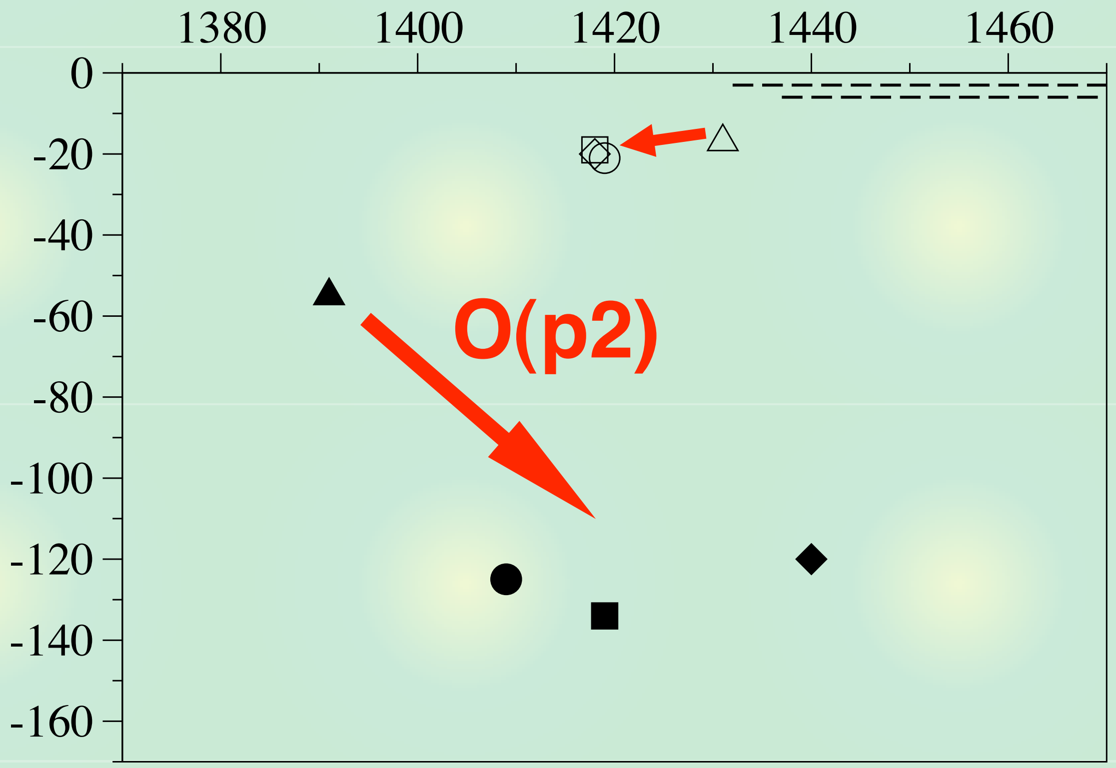
<u>V.K. Magas, *et al.*, hep-ph/0503043</u>

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

Photoproduction of K* and Λ(1405)

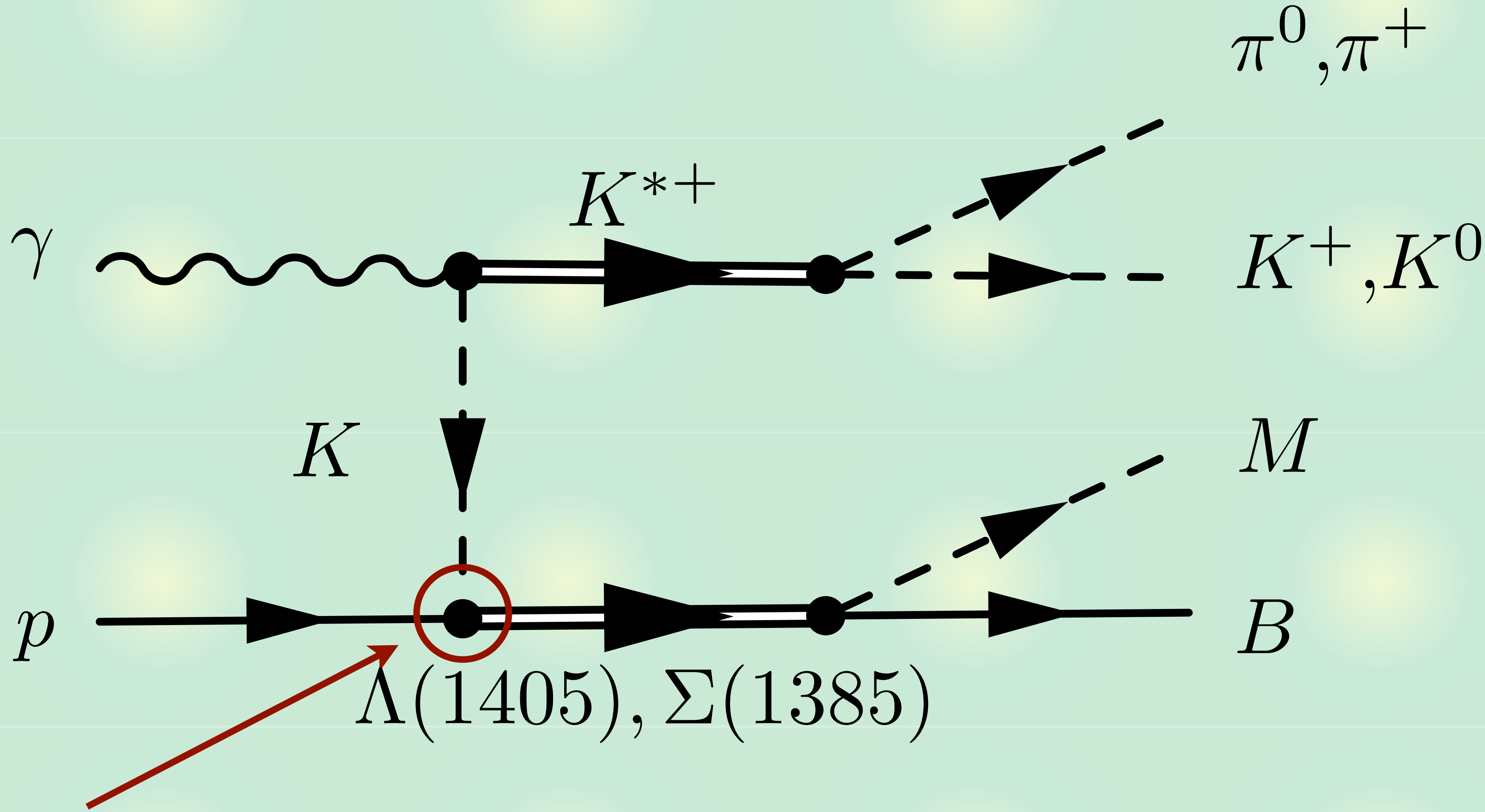
In order to study

- S = -1, I = 0, s-wave : Λ(1405)
  - two poles?
  - *1426 - 16i* : $\bar{K}N$
  - *1390 - 66i* : πΣ
- S = -1, I = 1, s-wave
  - pole? bump?

we calculate

$$\gamma p \longrightarrow K^* \Lambda(1405)$$

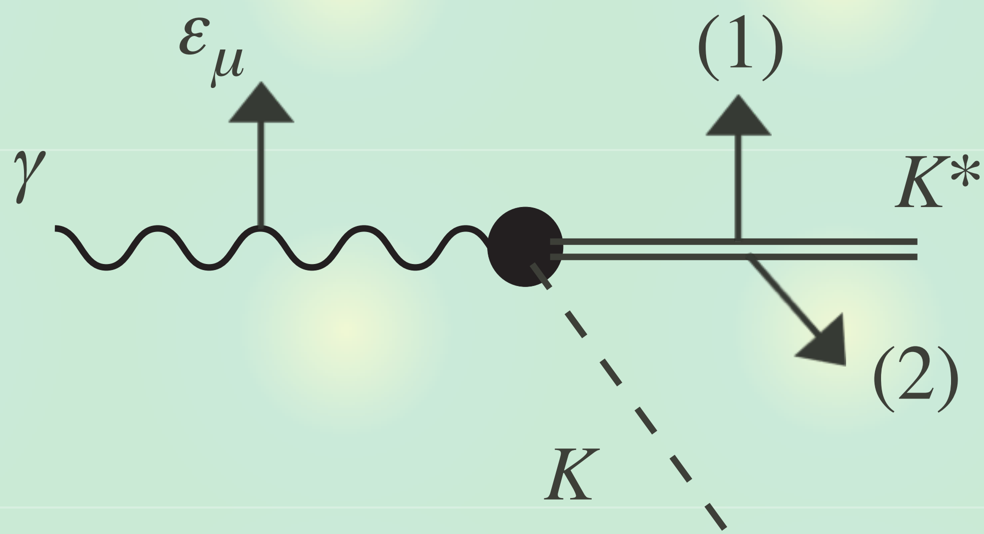
Photoproduction of K* and Λ(1405)



Only K^-p channel appears at the initial stage

Higher energy pole ??

Advantage of this reaction



(1) $\varepsilon_\mu(K^*) \,//\, \varepsilon_\mu(\gamma)$: J^P = natural

(2) $\varepsilon_\mu(K^*) \perp \varepsilon_\mu(\gamma)$: J^P = unnatural

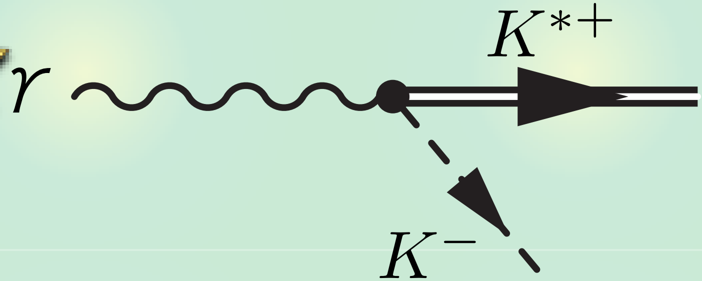
With polarized photon beam, the exchanged particle can be identified.

Clear mechanism

Effective interaction for meson part

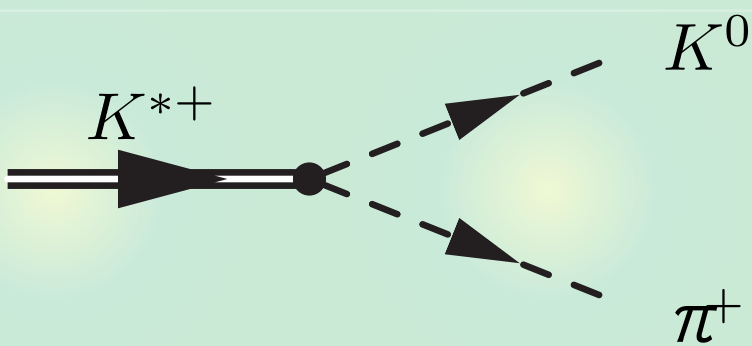
γKK* coupling

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

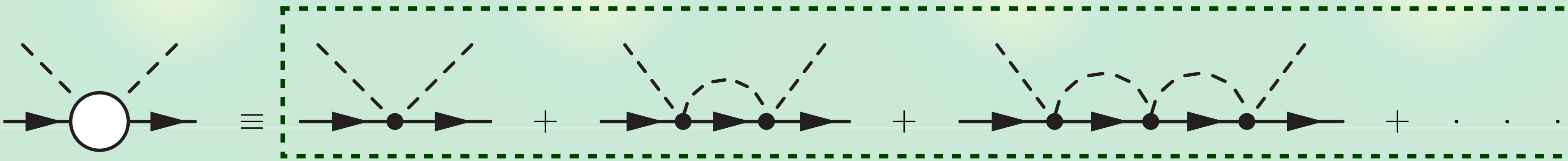


VPP coupling

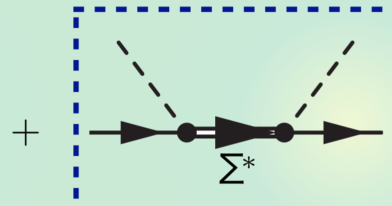
$$\mathcal{L}_{VPP} = -\frac{ig_{VPP}}{\sqrt{2}}\text{Tr}(V^\mu[\partial_\mu P, P])$$



Effective interaction for baryon part



ChU amplitude

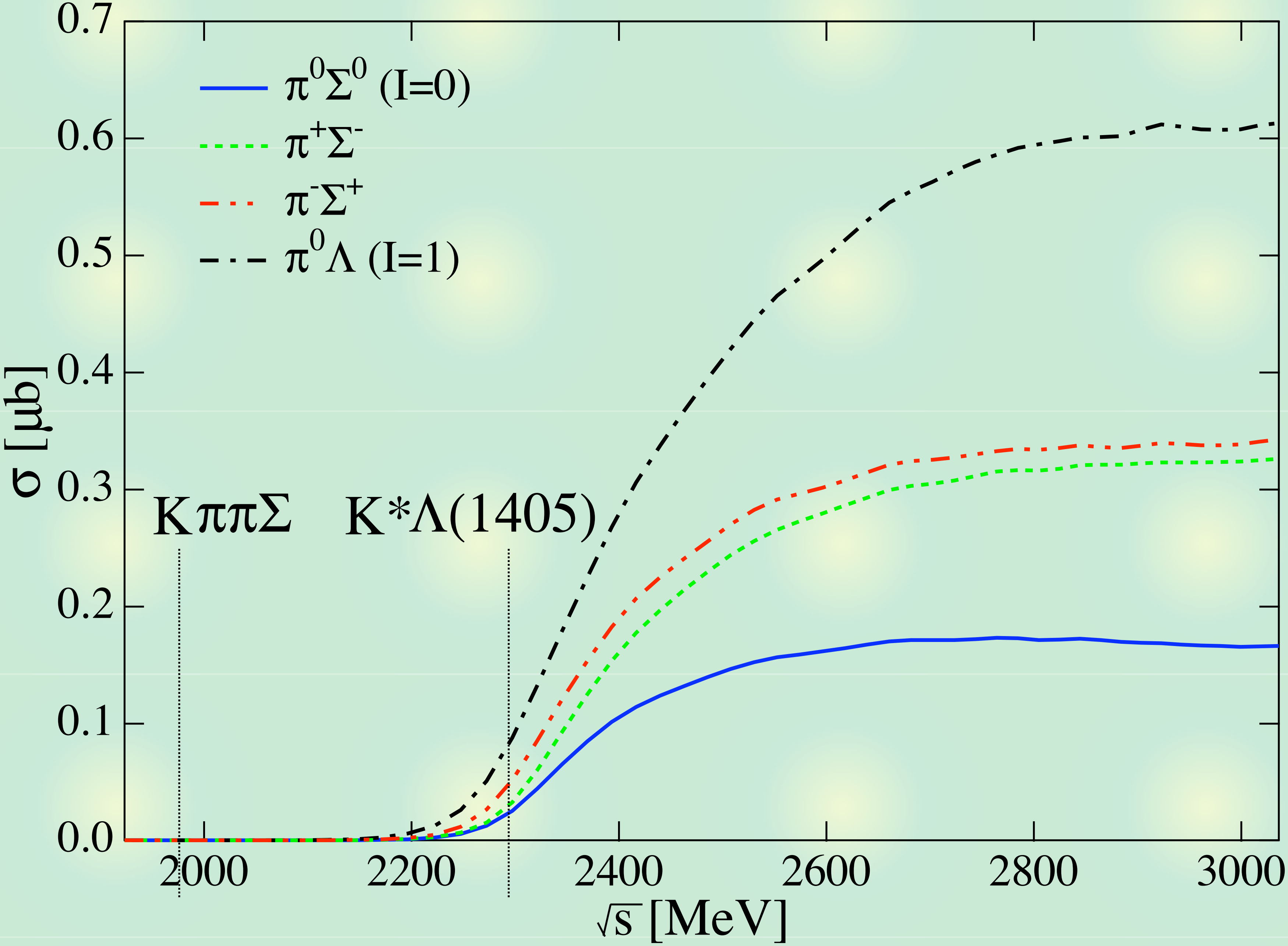


Σ(1385) pole term

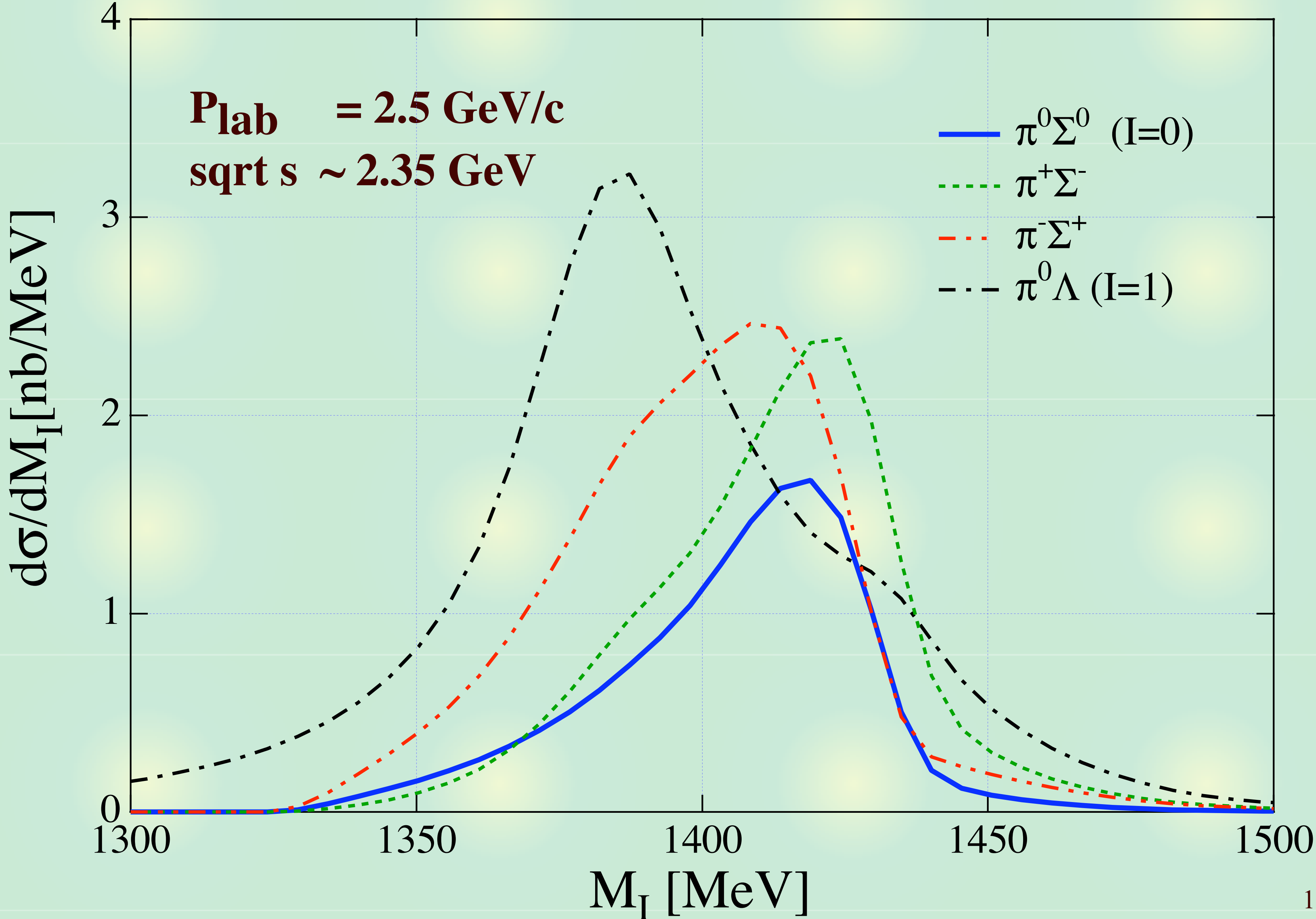
- **Σ(1385)MB coupling**
- $$-it_{\Sigma^* i} = c_i \frac{12}{5}\frac{D+F}{2f}\boldsymbol{S}\cdot\boldsymbol{k}_i$$
- **form factor**

$$F_f(k_1) = \frac{\Lambda^2 - m_K^2}{\Lambda^2 - (k_1)^2}$$

Total cross sections



Invariant mass distributions



Isospin decomposition of πΣ states

Since initial state is KN, we neglect the I=2.

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

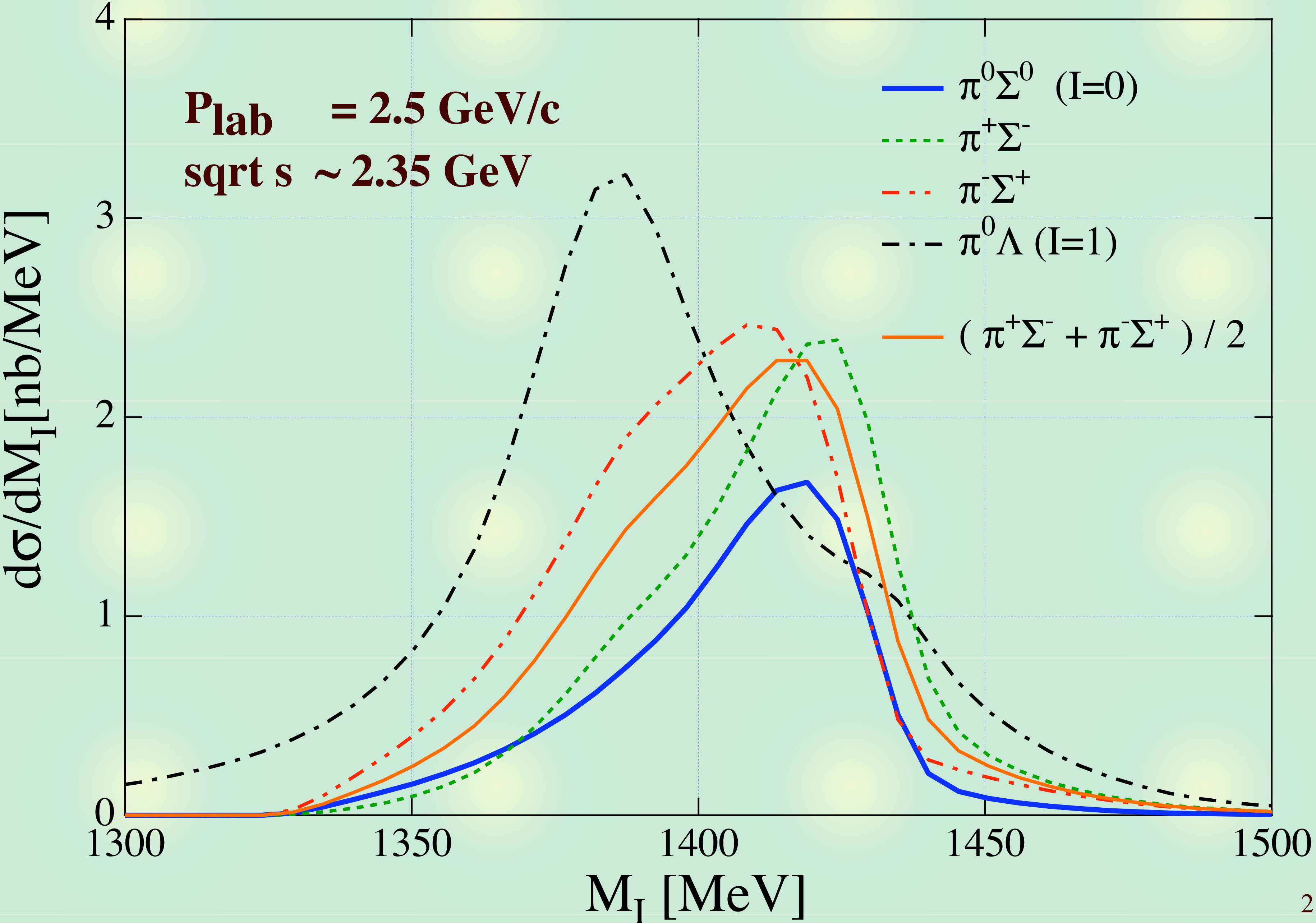
- **Pure I=0 amplitude**

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

- **Difference among charged states**
  -> when summed up, this term vanishes

- **No p-wave contribution**
  -> I=1 s-wave amplitude

Invariant mass distributions 2



Summary and conclusions 1

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

- 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
- By observing the charged πΣ states in the $\gamma p \to K^* \Lambda(1405)$ reaction, it is possible to isolate the higher energy pole.

Summary and conclusions 2

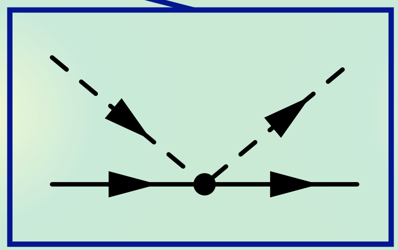
- If we observe neutral πΣ state, clear I=0 distribution is obtained.
-
- Combining three πΣ states, we can also study the s-wave I=1 amplitude, where the existence of another pole is argued.

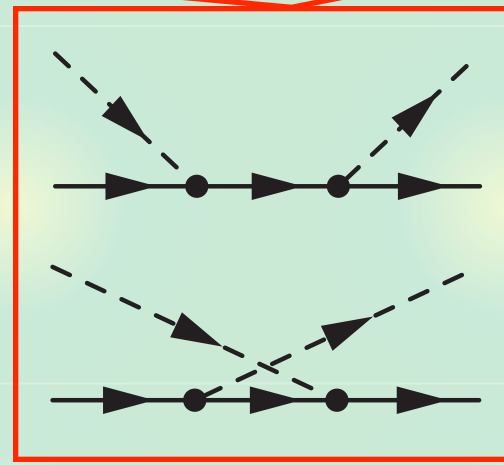
T. H., A. Hosaka, E. Oset, M. J. Vicente Vacas, PLB593, 75 (2004)

Appendix : ChPT Lagrangian

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

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





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

$$D + F = g_A$$

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

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

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

Appendix : Several treatments 1

N. Kaiser, P. B. Siegel and W. Weise, NPA594, 325, PLB362, 23 (1995)

(HB)ChPT p^2, Form factor (channel dep.)

S = -1,0, Λ(1405), N(1535)

E. Oset and A. Ramos, NPA635, 99 (1998)

WT term, 3-momentum cutoff (channel indep.)
S = -1, Λ(1405)

J. A. Oller and U. G. Meissner, PLB500, 263 (2001)

ChPT p, dimensional reg. (channel indep.)
S = -1, Λ(1405)

Analytic solution for BS eq.

-> pole structure in complex plane

Appendix : Several treatments 2

E. Oset, A. Ramos and C. Bennhold, PLB527, 99 (2002)
T. Inoue, E. Oset, and M. J. Vicente Vacas, PRC 65, 035204 (2002)
A. Ramos, E. Oset and C. Bennhold, PRL 89, 252001 (2002)

WT term, dimensional reg. (channel dep.)
Λ(1405), Λ(1670), Σ(1620), N(1535), Ξ(1620)
Scattering observables, S = -1, 0, analytic

M. F. M. Lutz and E. Kolomeitsev, NPA700, 193 (2002)

ChPT p^3, Optimal reno. (channel indep.)
Scattering observables, Numerical solution

C. Garcia-Recio, M. F. M. Lutz and J. Nieves, PLB582, 49 (2004)

WT term, Optimal reno. (channel indep.)
Λ(1405), Λ(1670), Σ(1620), N(1535), Ξ(1620), Ξ(1690)
Scattering observables?