Evidence for the two pole structure of the $\Lambda(1405)$ resonance and the nature of the $\Lambda(1520)$

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Meson-Baryon interaction

$$\mathcal{L}_1^{(B)} = \langle \overline{B} i\gamma^\mu \nabla_\mu B\rangle - M_B\langle \overline{B}B\rangle + \\ + \frac{D}{2}\langle \overline{B}\gamma^\mu\gamma_5\{u_\mu, B\}\rangle + \frac{F}{2}\langle \overline{B}\gamma^\mu\gamma_5[u_\mu, B]\rangle$$

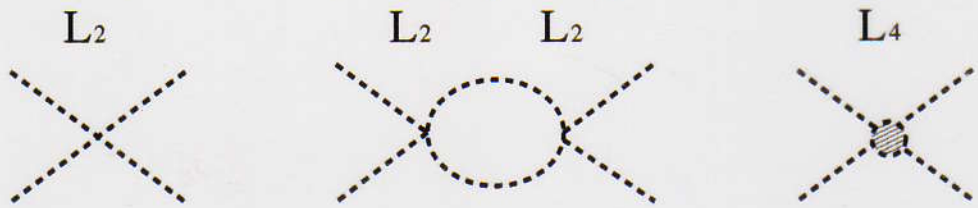
$$u_\mu = iu^\dagger\partial_\mu U u^\dagger \quad ; u^2 = U = e^{i\frac{\sqrt{2}}{f}\Phi}$$

$$\nabla_\mu B = \partial_\mu B + [\Gamma_\mu, B] \; ; \; \Gamma_\mu = \frac{1}{2}(u^+\partial_\mu u + u\partial_\mu u^+)$$

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

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

χ PT: (mesons)



Successful at low energies

Problems→
- Limited energy range of applicability
- Cannot deal with resonances

General scheme *Oller, Meissner PL '01* (meson baryon as exemple)

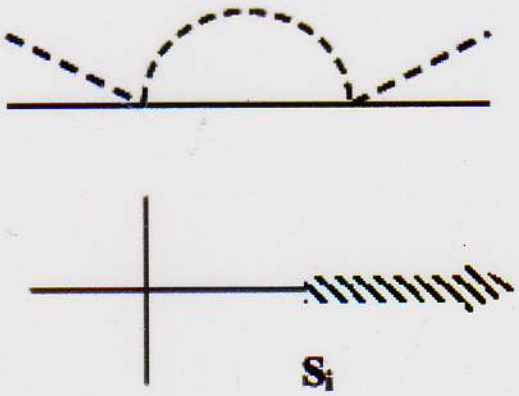
- **Unitarity** in coupled channels $\bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Sigma$, $\eta\Lambda$, $K\Xi$, in $S=-1$

$$\begin{aligned} \mathrm{Im}T_{ij} &= T_{il}\sigma_{ll}T^*_{lj} \\ \sigma_l &\equiv \sigma_{ll} \equiv \frac{2Mq_l}{8\pi\sqrt{s}} \\ \sigma &= -\mathrm{Im}T^{-1} \end{aligned}$$

- Dispersion relation

$$\begin{aligned} T^{-1}_{ij} &= -\delta_{ij}\left\{\hat{a}_i(s_0) + \frac{s-s_0}{\pi}\int_{s_i}^{\infty} ds' \frac{\sigma(s')_i}{(s-s')(s'-s_0)}\right\} + \\ &+ V^{-1}_{ij} \equiv -g(s)_i\delta_{ij} + V^{-1}_{ij} \end{aligned}$$

g(s) accounts for the right hand cut



V accounts for local terms, pole terms and crossed dynamics. V is determined by matching the general result to the χPT expressions (usually at one loop level)

$$g(s) = \frac{2M_i}{16\pi^2}\left\{a_i(\mu) + \log\frac{m_i^2}{\mu^2} + \frac{M_i^2 - m_i^2 + s}{2s}\log\frac{M_i^2}{m_i^2} + \right.$$
$$\left. + \frac{q_i}{\sqrt{s}}\log\frac{m_i^2 + M_i^2 - s - 2q_i\sqrt{s}}{m_i^2 + M_i^2 - s + 2q_i\sqrt{s}}\right\}$$

μ regularization mass
a_i subtraction constant

Inverting T^{-1}:

$$T = [1 - Vg]^{-1}V$$

Example 1: Take $V \equiv$ lowest order chiral amplitude

In meson-baryon S-wave

$$[1 - V\,g]\,T = V \rightarrow T = V + V\,g\,T$$

Bethe Salpeter eqn. with kernel V

This is the method of *E. O., Ramos '98* using cut off to regularize the loops

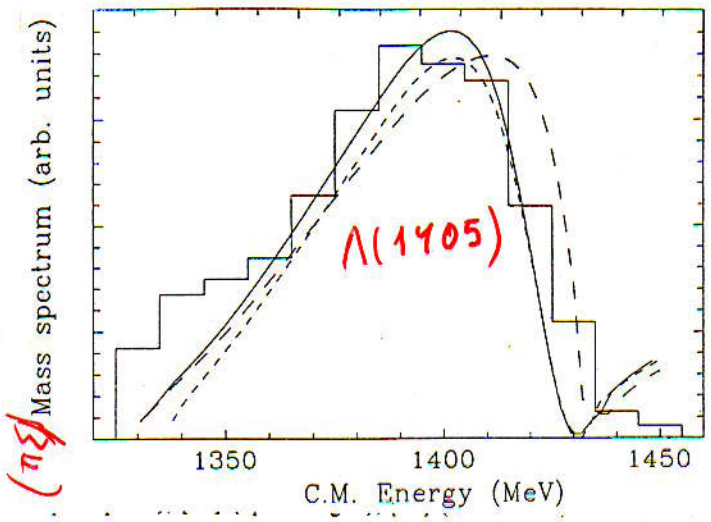
Oller, Meissner show equivalence of methods with

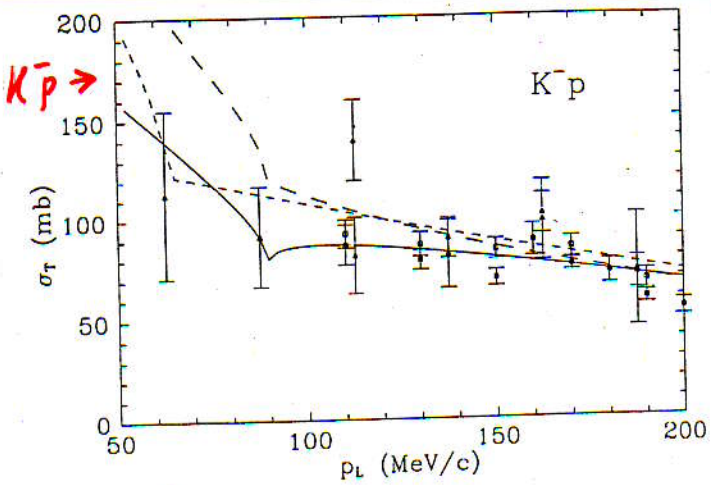
$$a_i(\mu) \simeq -2\ln\left[1 - \sqrt{1 + \frac{m_i^2}{\mu^2}}\right];$$

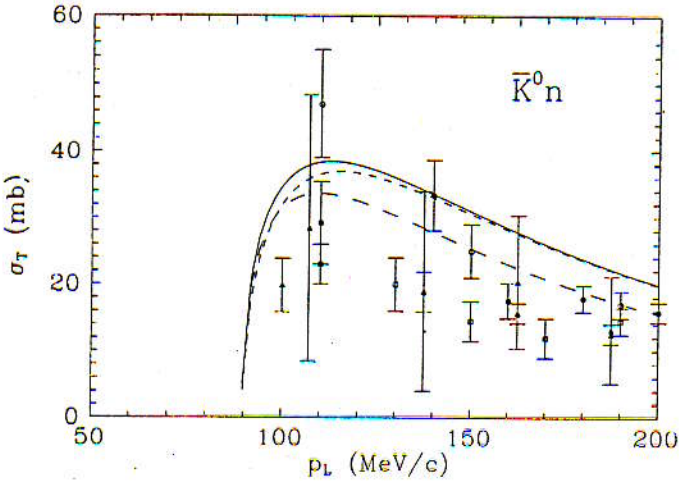
μ cut off

$a_i \simeq -2 \rightarrow \mu \simeq 630$ MeV in $\bar{K}N$

If higher order Lagrangians not well determined then fit a_i to the data







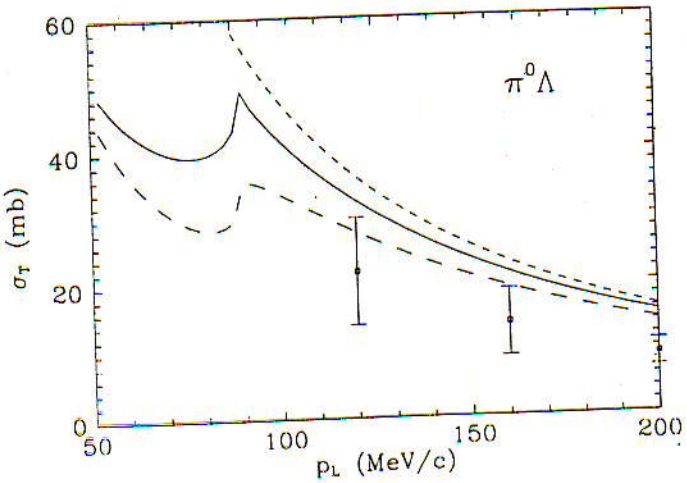
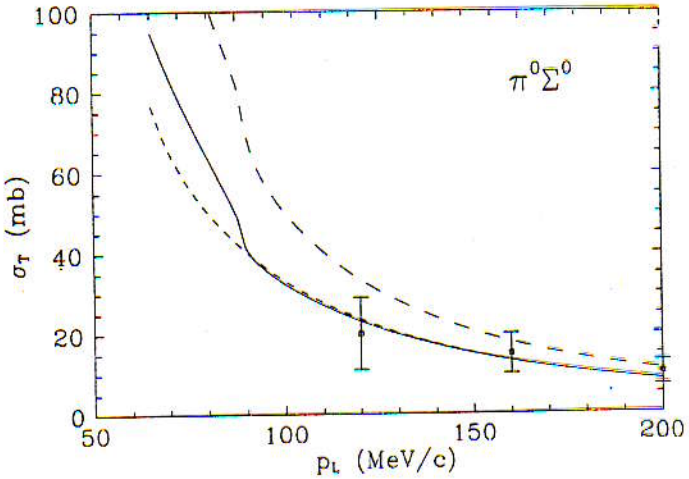
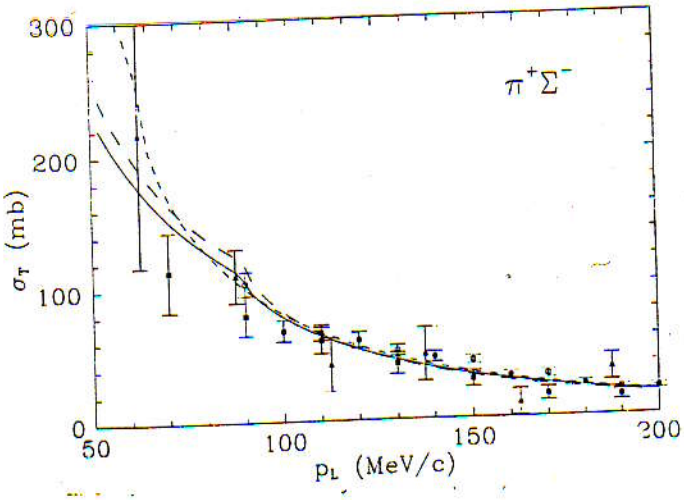
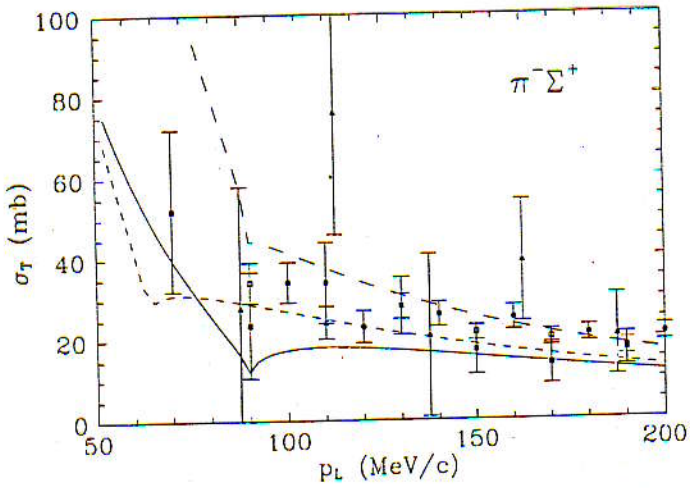
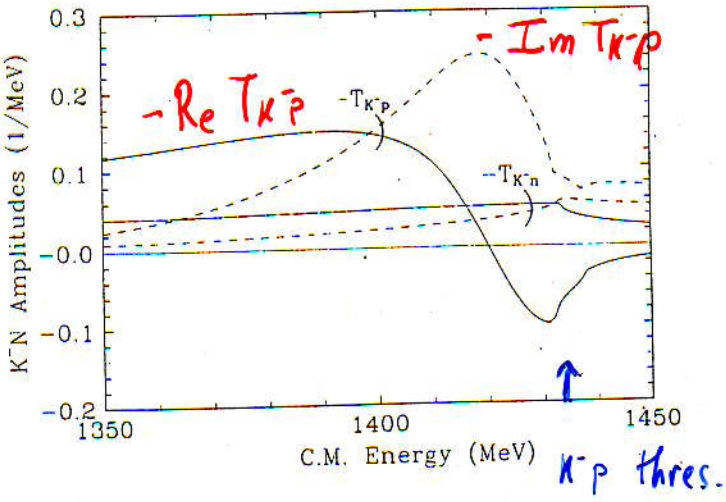


Fig. 5. Same as Fig. 3 for $K^- p \to \pi^0 \Lambda$.









- Further work

$SU(3)$ $\quad 8 \otimes 8 \rightarrow 1 + 8^S + 8^A + 10 + \overline{10} + 27$

M B

One should be getting two octets of dynamically generated mesons in $L = 0$

so far $\Lambda(1405)$ $(I = 0)$ seen in

Weise et al, Lutz, E.O., Ramos, Oller, Meissner

$$\left.\begin{array}{l}\Lambda(1670)(I=0)\\ \\ \Sigma(1620)(I=1)\end{array}\right\}\text{seen in}$$ *E.O., Ramos, Benhold PL '02*

$\Sigma(1620)$ not visible in amplitudes. Must be searched as a pole in the 2nd Riemann sheet of the complex plane

- T in complex plane: close to a pole

$$T_{ij} \approx \frac{g_i g_j}{z - z_R} \qquad : \qquad \sqrt{s} \to \text{z complex}$$

$z_R \approx M_R + i\frac{\Gamma}{2}$ (2nd Riemann sheet)

g_i: coupling of resonance to i channel

$g_i \to \Gamma_i$ partial decay width in channel i

- **Search for a $S = -2$ resonance:** Ramos, Bennhold E.O PRL 02

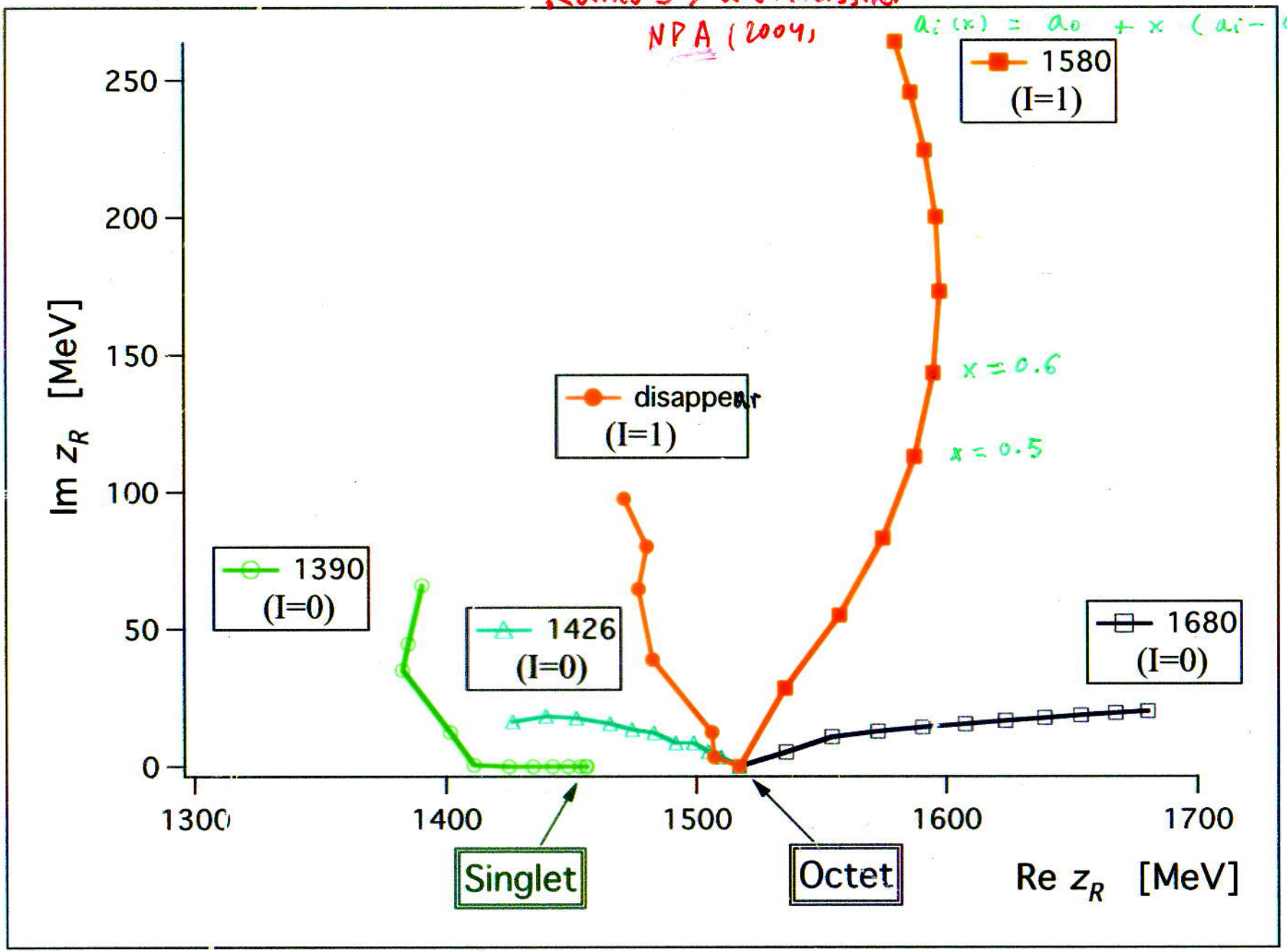
Pole found around $z_R = (1605 + i\,65)\,MeV$ with natural size values of a_i

D. Jido, Oller, E.O, Ramos, U.G. Meissner NPA (2004)

$M_i(x) = M_0 + x\,(M_i - M_0)$

$m_i^2(x) = m_0^2 + x\,(m_i^2 - m_0^2)$

$a_i(x) = a_0 + x\,(a_i - a_0)$



TWO Λ(1405) STATES

D. Jido, J.A. Oller, E. Oset, A. Ramos and U.G. Meissner, nucl-th/0303062

Pole positions and couplings to $I = 0$ physical states

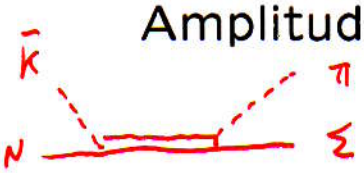
z_R ($I = 0$)	$1390 + 66i$		$1426 + 16i$		$1680 + 20i$	
	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$
$\pi\Sigma$	$-2.5 - 1.5i$	2.9	$0.42 - 1.4i$	1.5	$-0.003 - 0.27i$	0.27
$\bar{K}N$	$1.2 + 1.7i$	2.1	$-2.5 + 0.94i$	2.7	$0.30 + 0.71i$	0.77
$\eta\Lambda$	$0.010 + 0.77i$	0.77	$-1.4 + 0.21i$	1.4	$-1.1 - 0.12i$	1.1
$K\Xi$	$-0.45 - 0.41i$	0.61	$0.11 - 0.33i$	0.35	$3.4 + 0.14i$	3.5

–SU(3) decomposition:Couplings of the $I = 0$ bound states to the meson–baryon SU(3) basis states

z_R	$1390 + 66i$ (evolved singlet)		$1426 + 16i$ (evolved octet 8_s)		$1680 + 20i$ (evolved octet 8_a)	
	g_γ	$\lvert g_\gamma \rvert$	g_γ	$\lvert g_\gamma \rvert$	g_γ	$\lvert g_\gamma \rvert$
1	$2.3 + 2.3i$	3.3	$-2.1 + 1.6i$	2.6	$-1.9 + 0.42i$	2.0
8_s	$-1.4 - 0.14i$	1.4	$-1.1 - 0.62i$	1.3	$-1.5 - 0.066i$	1.5
8_a	$0.53 + 0.94i$	1.1	$-1.7 + 0.43i$	1.8	$2.6 + 0.59i$	2.7
27	$0.25 - 0.031i$	0.25	$0.18 + 0.092i$	0.21	$-0.36 + 0.28i$	0.4

–Influence of the poles on the physical observables

Amplitudes for $\bar{K}N \to \pi\Sigma$ and $\pi\Sigma \to \pi\Sigma$



$$g^{R_1}_{\bar{K}N}\frac{1}{W-M_{R_1}+i\Gamma_{R_1}/2}g^{R_1}_{\pi\Sigma}+g^{R_2}_{\bar{K}N}\frac{1}{W-M_{R_2}+i\Gamma_{R_2}/2}g^{R_2}_{\pi\Sigma}\ ,$$

$$g^{R_1}_{\pi\Sigma}\frac{1}{W-M_{R_1}+i\Gamma_{R_1}/2}g^{R_1}_{\pi\Sigma}+g^{R_2}_{\pi\Sigma}\frac{1}{W-M_{R_2}+i\Gamma_{R_2}/2}g^{R_2}_{\pi\Sigma}\ .$$

(1)

Normally for the description of the $\Lambda(1405)$ one looks at the $\pi\Sigma$ invariant mass and assumes

$$\frac{d\sigma}{dM_i} = C|T_{\pi\Sigma\to\pi\Sigma}|^2 q_{\text{c.m.}}\ , \qquad (2)$$

In the presence of the two $\Lambda(1405)$ states this is not justified. One has

$$\frac{d\sigma}{dM_i} = \left|\sum_i C_i T_{i\to\pi\Sigma}\right|^2 q_{\text{c.m.}}\ , \qquad (3)$$

Example

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

Thomas et al.

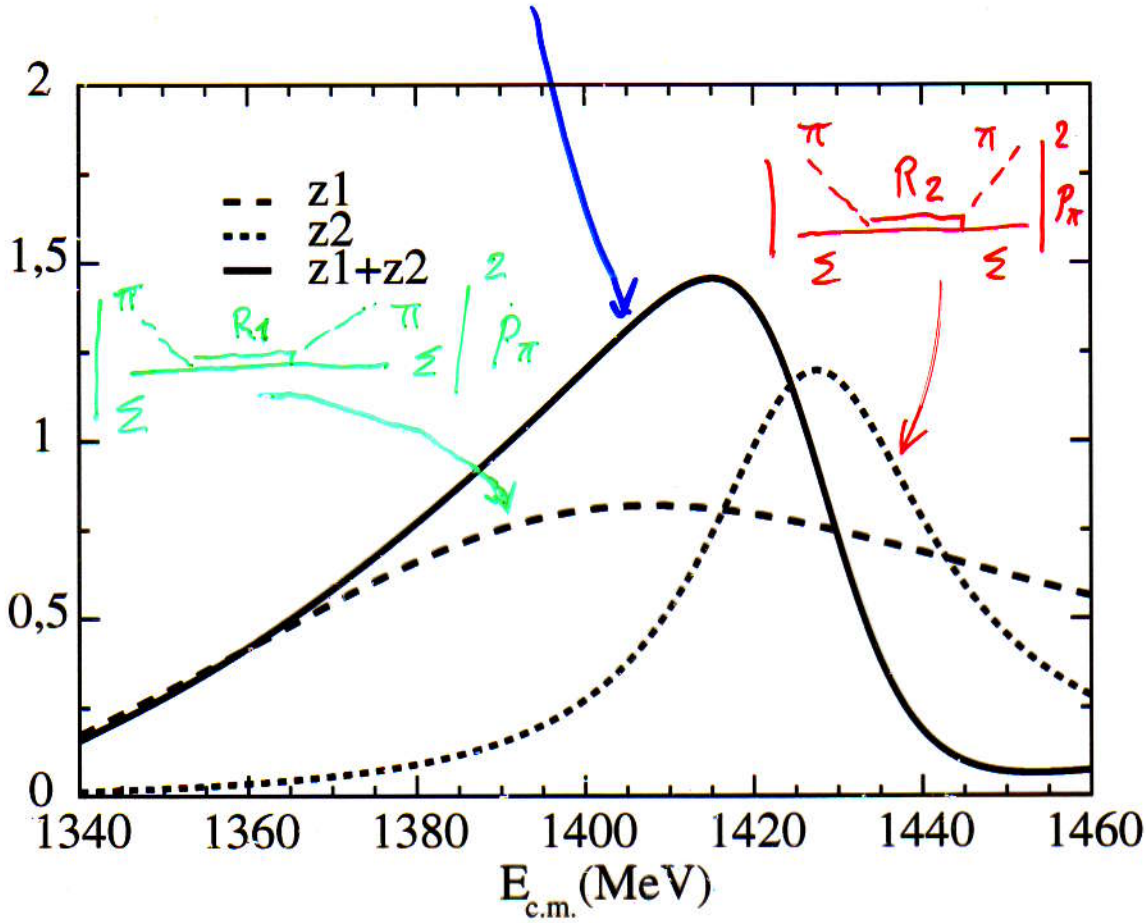
MB ≡ $\bar{K}N$

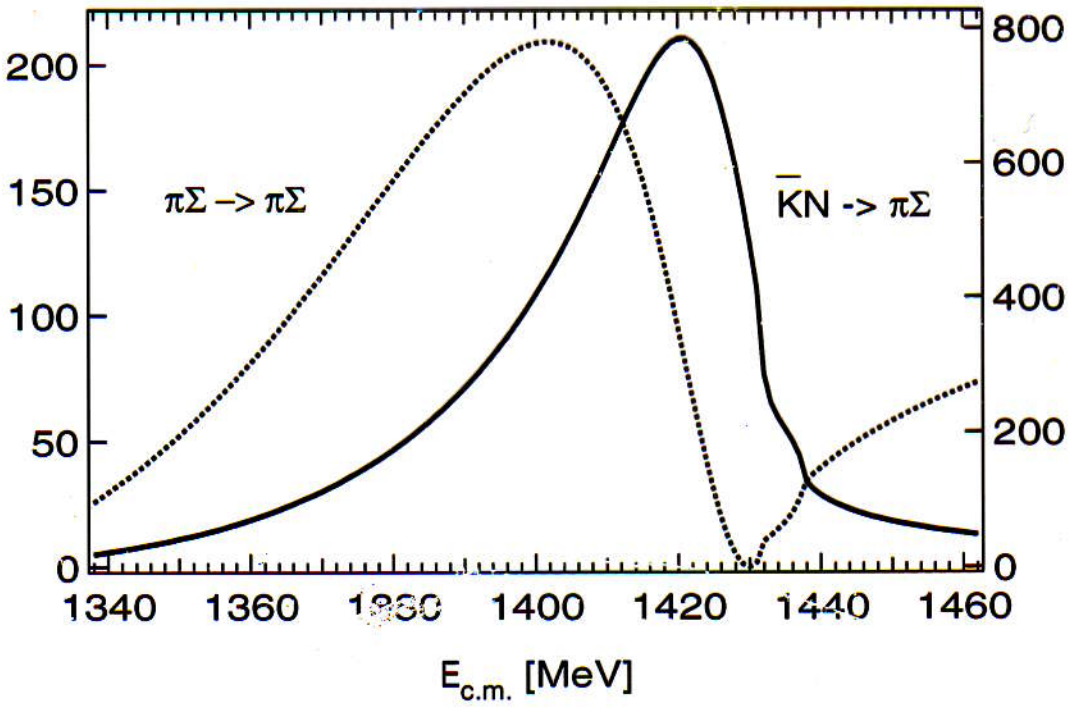
$\pi\Sigma$

?

⋮

Coherent sum of $R_1 + R_2$

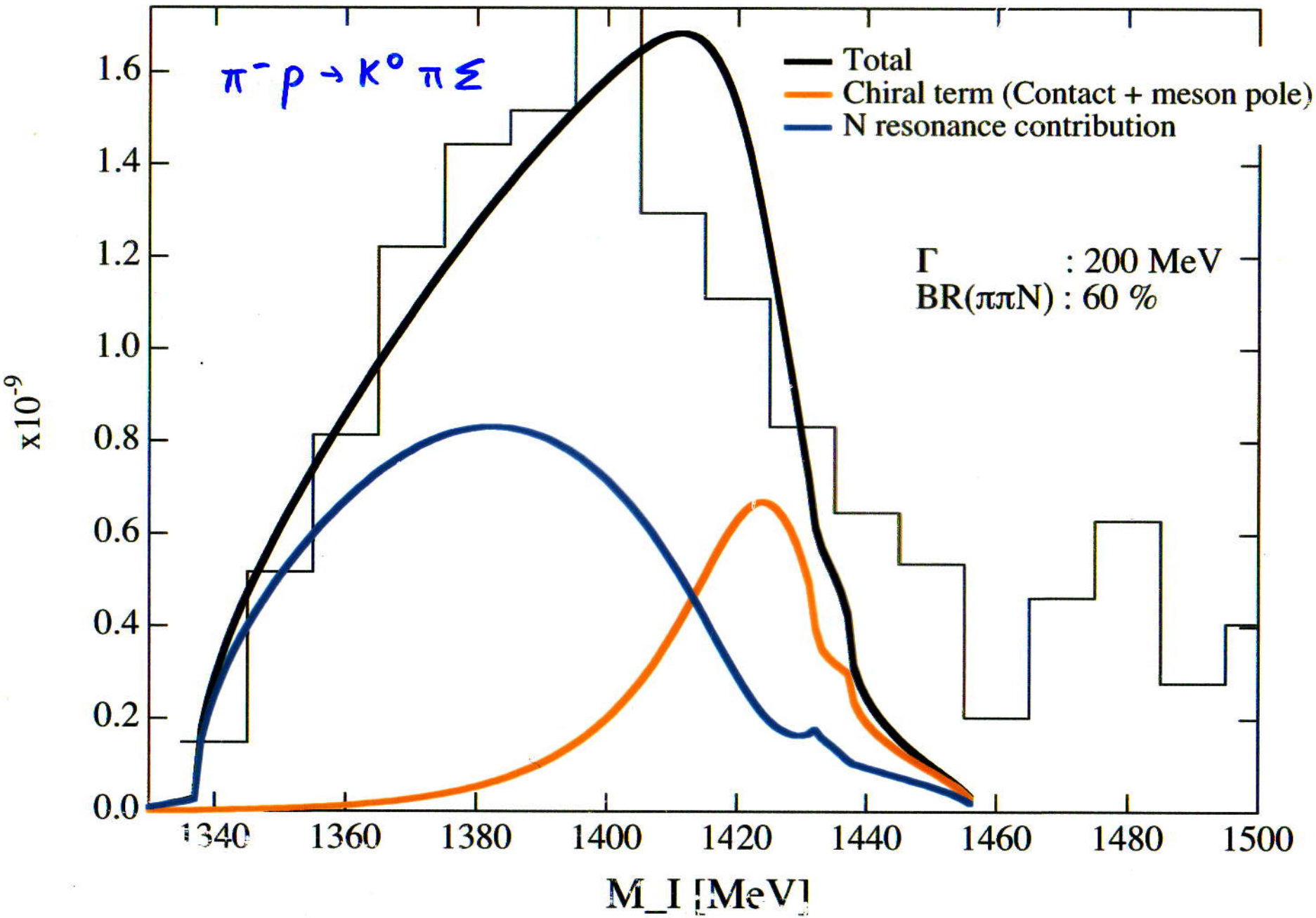


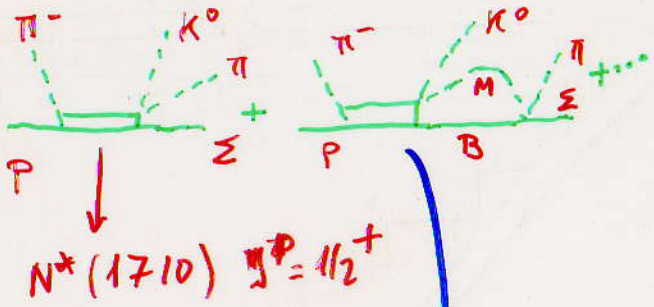


$|t_i|^2 p_\pi$ from E.O., A. Ramos Phys. Lett.

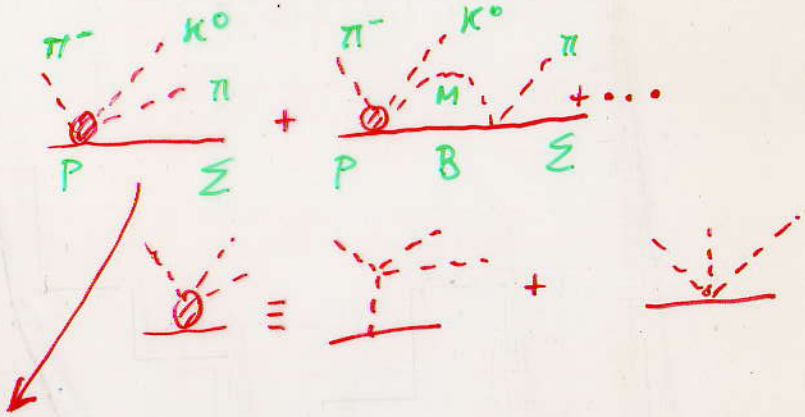
$\pi\Sigma$ invariant mass distribution

Hyodo, Hosaka, E.O, Ramos, Vicente Vacas
PRC (2003) 065203





$N^*(1710)\ J^P = 1/2^+$



Evidence for the two pole structure of the $\Lambda(1405)$

V.K. Magas, A. Ramos and E.O., Phys. Rev. Lett. 2005

Chiral dynamics of the meson baryon interaction for $S = -1, I = 0$ leads to two poles in the vicinity of the $\Lambda(1405)$

Table 1: Pole positions and couplings to $S = -1, I = 0$ physical states

z_R	$1390 + 66i$		$1426 + 16i$		$1680 + 20i$	
$(I = 0)$	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$
$\pi\Sigma$	$-2.5 - 1.5i$	2.9	$0.42 - 1.4i$	1.5	$-0.003 - 0.27i$	0.27
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$K\Xi$	$-0.45 - 0.41i$	0.61	$0.11 - 0.33i$	0.35	$3.4 + 0.14i$	3.5

First pole has large width and couples strongly to $\pi\Sigma$

Second pole has narrow width and clouples strongly to $\bar{K}N$

Evidence for the two pole structure of the $\Lambda(1405)$

The $\Lambda(1405)$ is always seen from the $\pi\Sigma$ invariant mass distribution.

If $\Lambda(1405)$ is formed from $\pi\Sigma \rightarrow$ weight to first resonance

If $\Lambda(1405)$ is formed from $\bar{K}N \rightarrow$ weight to second resonance

The $K^-p \rightarrow \gamma\Lambda(1405)$ reaction ideal to see second resonance, but not yet done

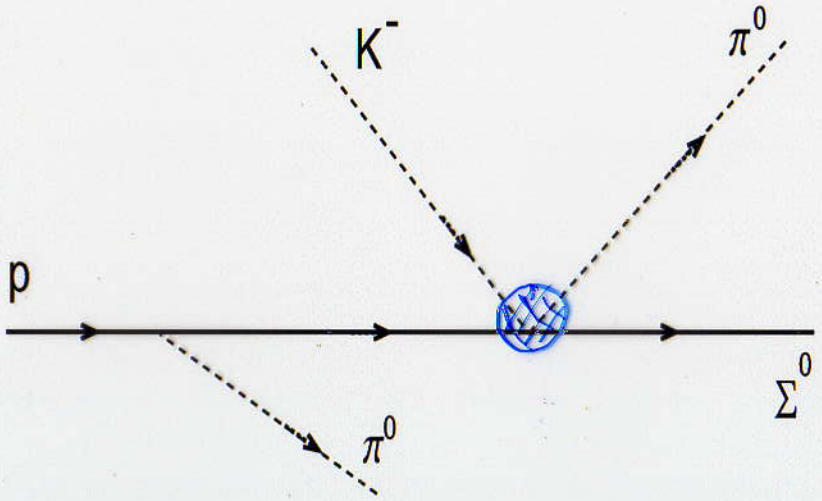
good luck! recent experiment $K^-p \rightarrow \pi^0\Lambda(1405)$

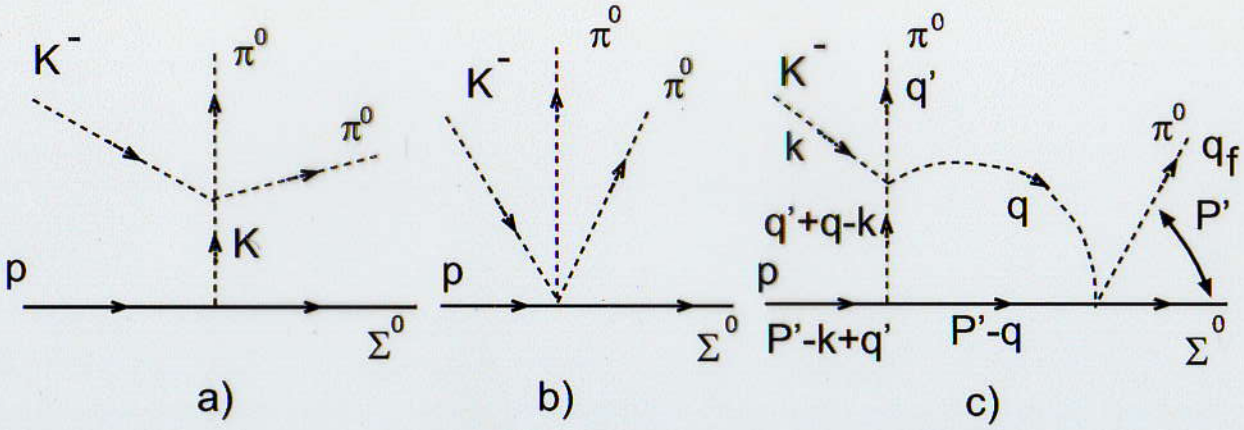
$K^-p \rightarrow \pi^0\pi^0\Sigma^0$ by S. Prakhov *et al.* [Crystall Ball Collaboration] Phys. Rev. C70 (2004) 034605

One π^0 can take energy away and then the residual $\pi^0\Sigma^0$ can form the $\Lambda(1405)$

Evidence for the two pole structure of the $\Lambda(1405)$

Theoretical model

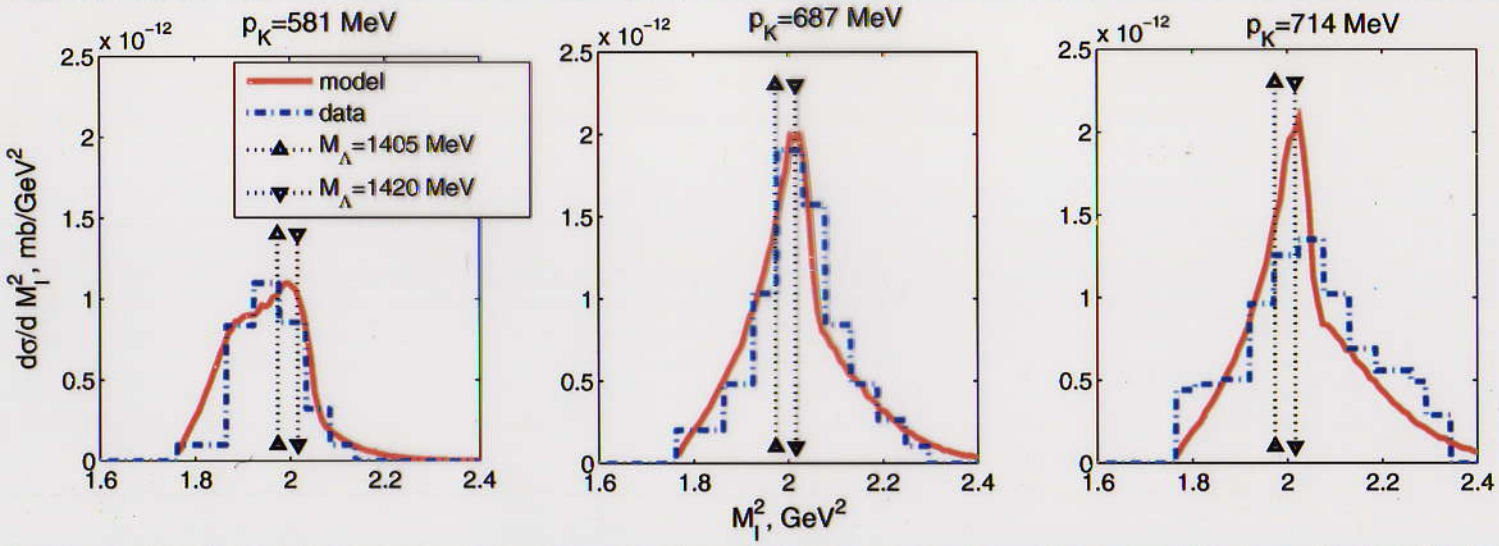




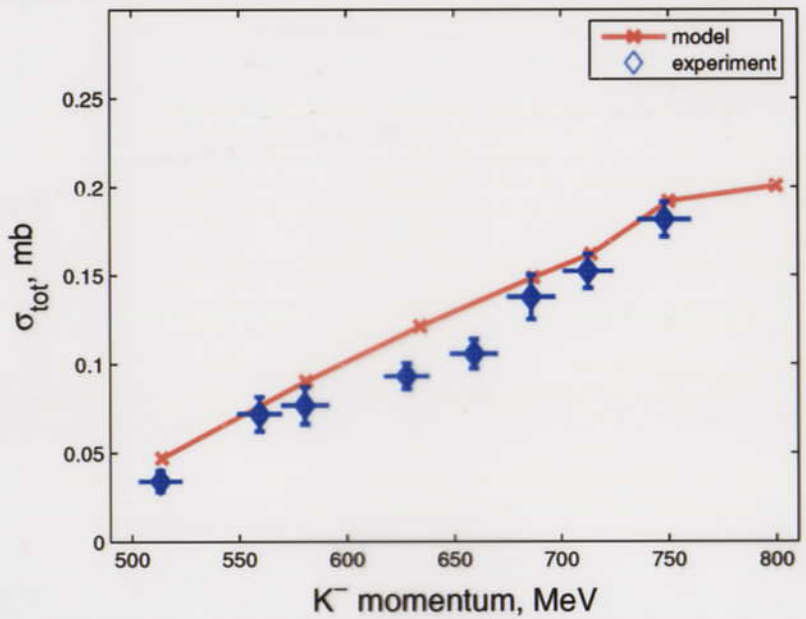
Evidence for the two pole structure of the $\Lambda(1405)$

$$-it^{(N-\mathrm{pole})} = -\frac{D+F}{2f}\vec{\sigma}\left[\vec{q}\,'(1+\frac{q^{0\,\prime}}{2M_N}) + \frac{q^{0\,\prime}}{M_N}\vec{k}\right] \times$$
$$\frac{M_N}{E_N(\vec{k}+\vec{q}\,')}\,\frac{1}{E_N(\vec{k}) - q'^{\,0} - E_N(\vec{k}+\vec{q}\,')}\,t_{K^-p\to\pi^0\Sigma^0}, \qquad (1)$$

Because of two identical π^0 one must symmetrize the amplitude.

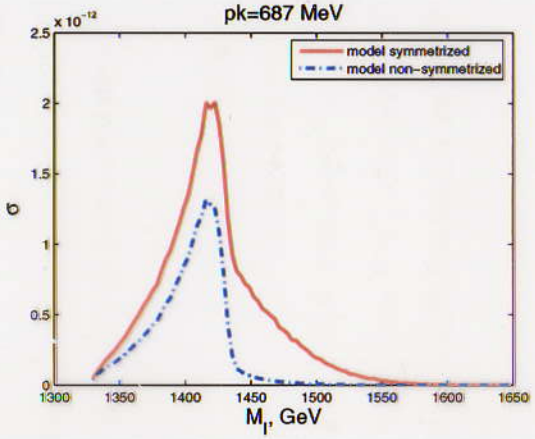


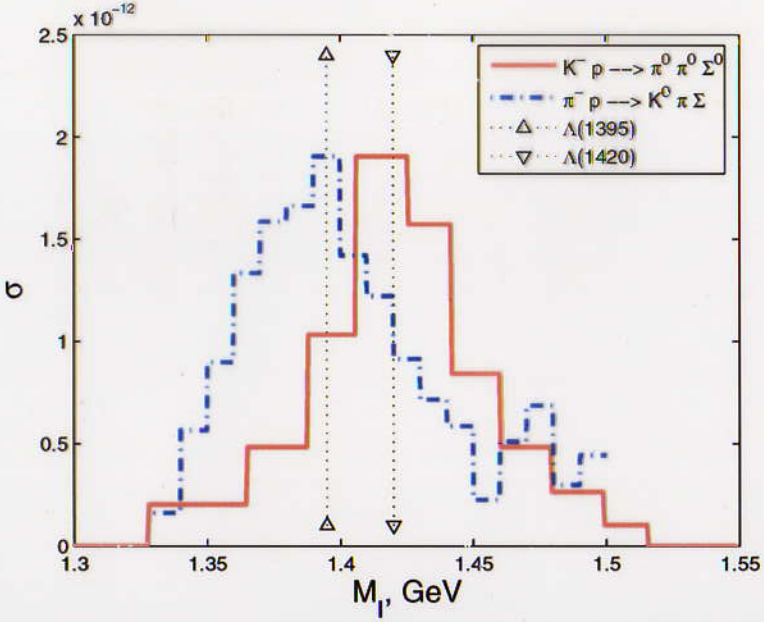
Total cross section



The theoretical model accurately describes the data, total cross sections and invariant mass distributions. We found two reactions that give more weight to either of the two states that form the $\Lambda(1405)$. The theoretical work together with the two experiments provide evidence of the existence of the two poles.

Evidence for the two pole structure of the $\Lambda(1405)$





$\Gamma \simeq 30$ MeV

$M \simeq 1420$ MeV

$\Gamma \simeq 65$ MeV

$M \simeq 1396$ MeV

CONCLUSIONS

- The interaction of baryon octet * meson octet leads to 1 singlet and Two octets of dynamically generated resonances.

Two nearby poles collaborate to create the experimental $\Lambda(1405)$

- 1st one, wide, at lower energies and couples mostly to $\pi\Sigma$

- 2n one, narrow, at higher energies and couples mostly to $\bar{K}N$

Experiments see only one shape, superposition of the Two resonances. It depends on the weight of each resonance, which is given by dynamics of the problem

Comparative analysis of $\pi^- p \to K^0 \pi \Sigma$
$K^- p \to \pi^0 \pi^0 \Sigma^0$

has provided experimental evidence of the existence of the Two $\Lambda(1405)$ states