Studies of Baryonic resonances in the chiral unitary approach

Eulogio Oset

---Unitary chiral approach to meson baryon interaction
-- Two dynamically generated Λ(1405) resonances: Experiments testing it
-- The Λ(1520) resonance
-- The Δ(1700) resonance
-- Λ(1520) and Σ*(1385) in the nuclear medium
-- Resonances of two mesons and one baryon

Unitarized Chiral Perturbation Theory

Skillful combination of the information of the Chiral Lagrangians and unitarity in coupled channels.

• Pioneering work of *Kaiser, Siegel, Waas, Weise 95-97* using Lipmann-Schwinger eq. and input from Chiral Lagrangians as potential.

• Subsequent work

Truong

- Inverse Amplitude Method (IAM)→ { *Dobado, Peláez '97* ; *Oller, E.O., Peláez '98* }

- (N/D) method→ { *Oller, E.O. '99* ; *Oller, Meissner '01* }

– Bethe-Salpeter eq.→ { *Oller, E.O. '97* ; *Nieves, Ruiz-Arriola '00* }

Hosaka, Hyodo ; Lutz, Kolomeitsev, Borasoy, Nißler, Weise

–Applications→ { *Ramos, Vicente, Marco, Parreño, Toki, Hirenzaki Hosaka, Oka, Nacher, Palomar, Jido, Inoue, Roca Cabrera, Okumura, Takahashi, Mizobe, Chiang Kamalov, Bennhold, Hernández, García Recio* }

Meson baryon Chiral Lagrangians

$$\mathcal{L}_1 =< \bar{B} i\gamma^\mu \bigtriangledown_\mu B > -M_B < \bar{B} B > \; + \frac{1}{2} D < \bar{B}\gamma^\mu\gamma_5 \{u_\mu, B\} > \\ + \frac{1}{2} F < \bar{B}\gamma^\mu\gamma_5 [u_\mu, B] >$$

$$\nabla_\mu B = \partial_\mu B + [\Gamma_\mu, B]$$
$$\Gamma_\mu = \tfrac{1}{2}(u^+\partial_\mu u + u\partial_\mu u^+)$$
$$U = u^2 = \exp(i\sqrt{2}\Phi/f)$$
$$u_\mu = iu^+\partial_\mu U u^+$$

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

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

Interaction of the meson octet with the baryon decuplet

Lutz and Kolomeitsev PL04

Sarkar,Oset,VicenteNPA05

$$\mathcal{L} = -i\bar{T}^{\mu}\not{D}T_{\mu} \tag{1}$$

where T^{μ}_{abc} is the spin decuplet field and D^{ν} the covariant derivative given by

$$\mathcal{D}^{\nu}T^{\mu}_{abc} = \partial^{\nu}T^{\mu}_{abc} + (\Gamma^{\nu})^{d}_{a}T^{\mu}_{dbc} + (\Gamma^{\nu})^{d}_{b}T^{\mu}_{adc} + (\Gamma^{\nu})^{d}_{c}T^{\mu}_{abd} \tag{2}$$

where μ is the Lorentz index, a, b, c are the $SU(3)$ indices. The vector current Γ^{ν} is given by

$$\Gamma^{\nu} = \frac{1}{2}(\xi\partial^{\nu}\xi^{\dagger} + \xi^{\dagger}\partial^{\nu}\xi) \tag{3}$$

with

$$\xi^2 = U = e^{i\sqrt{2}\Phi/f} \tag{4}$$

$T^{111} = \Delta^{++}$, $T^{112} = \frac{1}{\sqrt{3}}\Delta^{+}$, $T^{122} = \frac{1}{\sqrt{3}}\Delta^{0}$, $T^{222} = \Delta^{-}$, $T^{113} = \frac{1}{\sqrt{3}}\Sigma^{*+}$, $T^{123} = \frac{1}{\sqrt{6}}\Sigma^{*0}$, $T^{223} = \frac{1}{\sqrt{3}}\Sigma^{*-}$, $T^{133} = \frac{1}{\sqrt{3}}\Xi^{*0}$, $T^{233} = \frac{1}{\sqrt{3}}\Xi^{*-}$, $T^{333} = \Omega^{-}$.

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

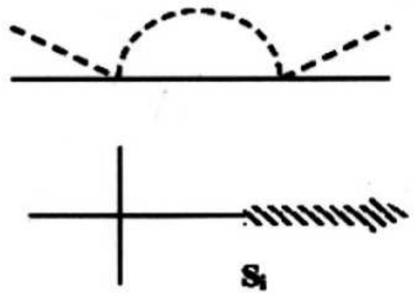
- **Unitarity** in coupled channels $\bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Sigma$, $\eta\Lambda$, $K\Xi$, in $S=-1$

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

- 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

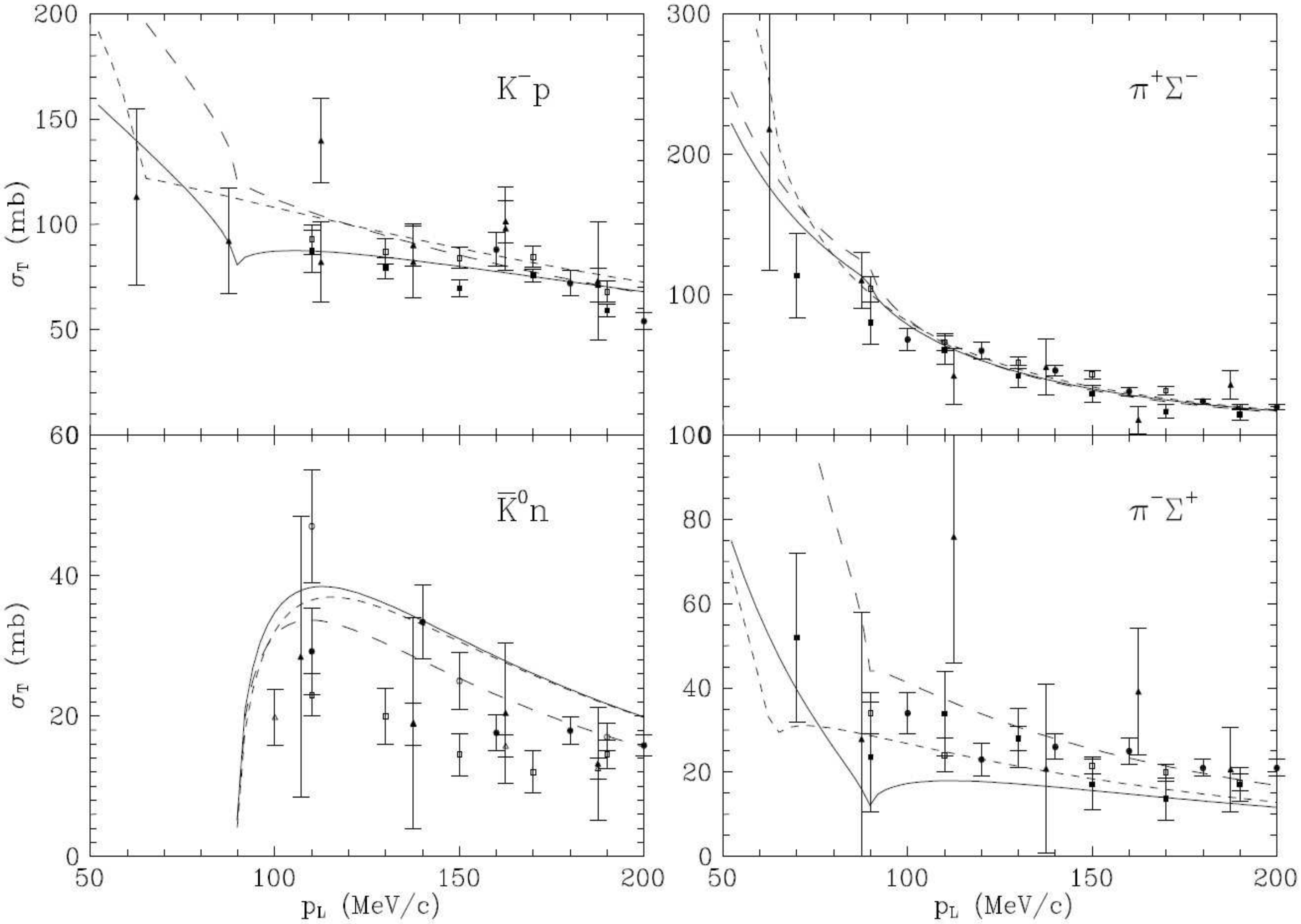
$$a_i(\mu) \simeq -2\ln\left[1 - \sqrt{1 + \frac{m_i^2}{\mu^2}}\right];$$

μ cut off

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

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

Oset, Ramos NPA98



The lowest order calculations have been improved recently in

Borasoy, Niessler and Weise, PRL (2005);Oller, Prades, Verbeni, PRL(2005); Oller (2006); Borasoy, Meissner and Niessler (2006) XXXX (2006)

Common features: two poles for the $\Lambda(1405)$, one around 1420 MeV with narrow width ($\sim 30 MeV$). The second one at lower energies, wider but changes much from model to model . Observation of the $\Lambda(1405)$ with different shapes in different reactions should further constraint the models.

Some differences: predictions for the scattering lenghts. More experimental work on $K^- p$ atoms is needed.

Results with lowest order Lagrangian compatible with theoretical band determined by Borasoy et al.

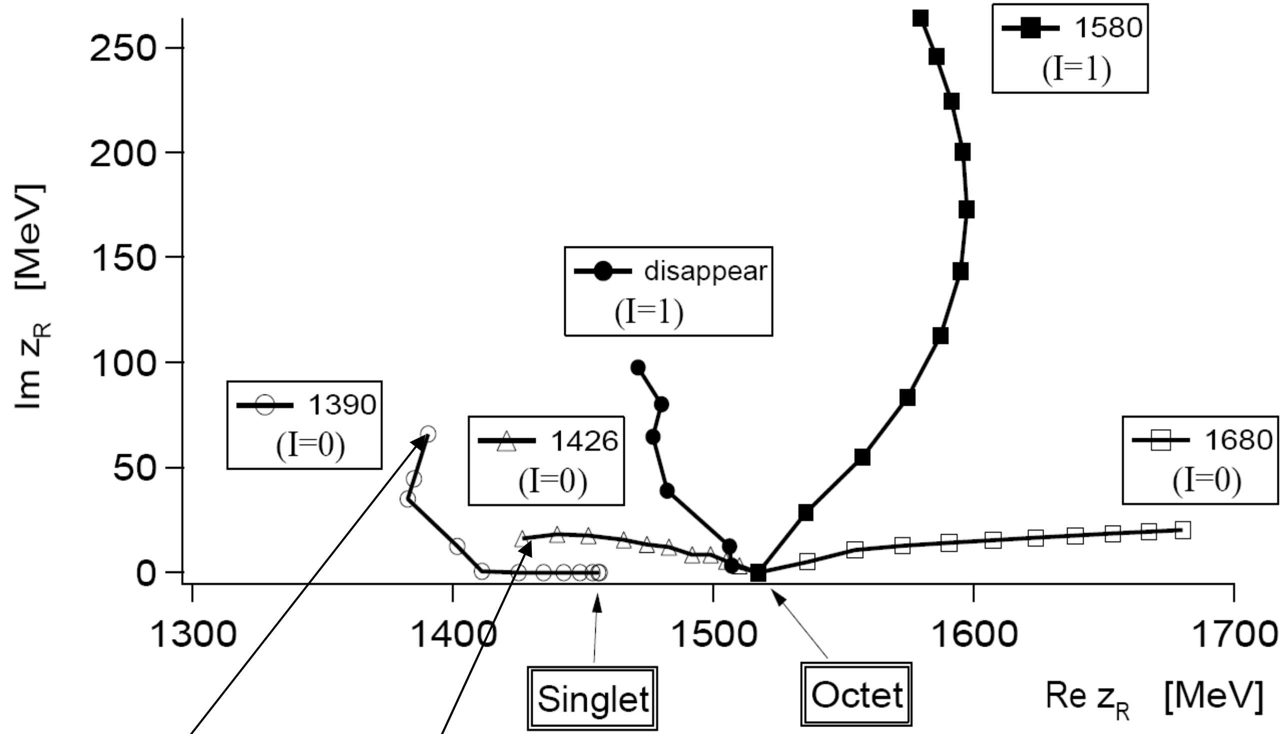
Poles of S=-1 $J^P = 1/2^-$ Resonances

Jido, Oller, Oset, Ramos, Meissner NPA03

$$8 \otimes 8 = 1 \oplus 8_s \oplus 8_a \oplus 10 \oplus \overline{10} \oplus 27$$

$$M_i(x) = M_0 + x(M_i - M_0),$$
$$m_i^2(x) = m_0^2 + x(m_i^2 - m_0^2),$$
$$a_i(x) = a_0 + x(a_i - a_0),$$

X Є [0,1]

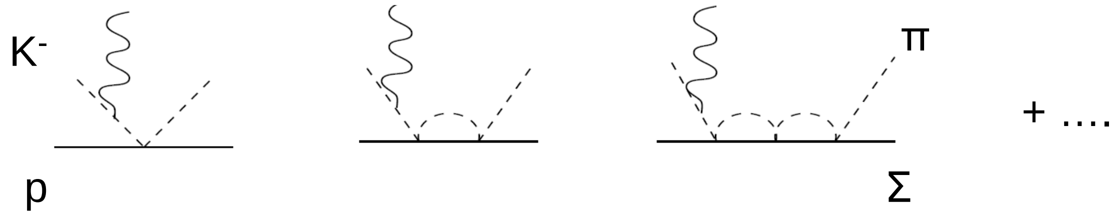


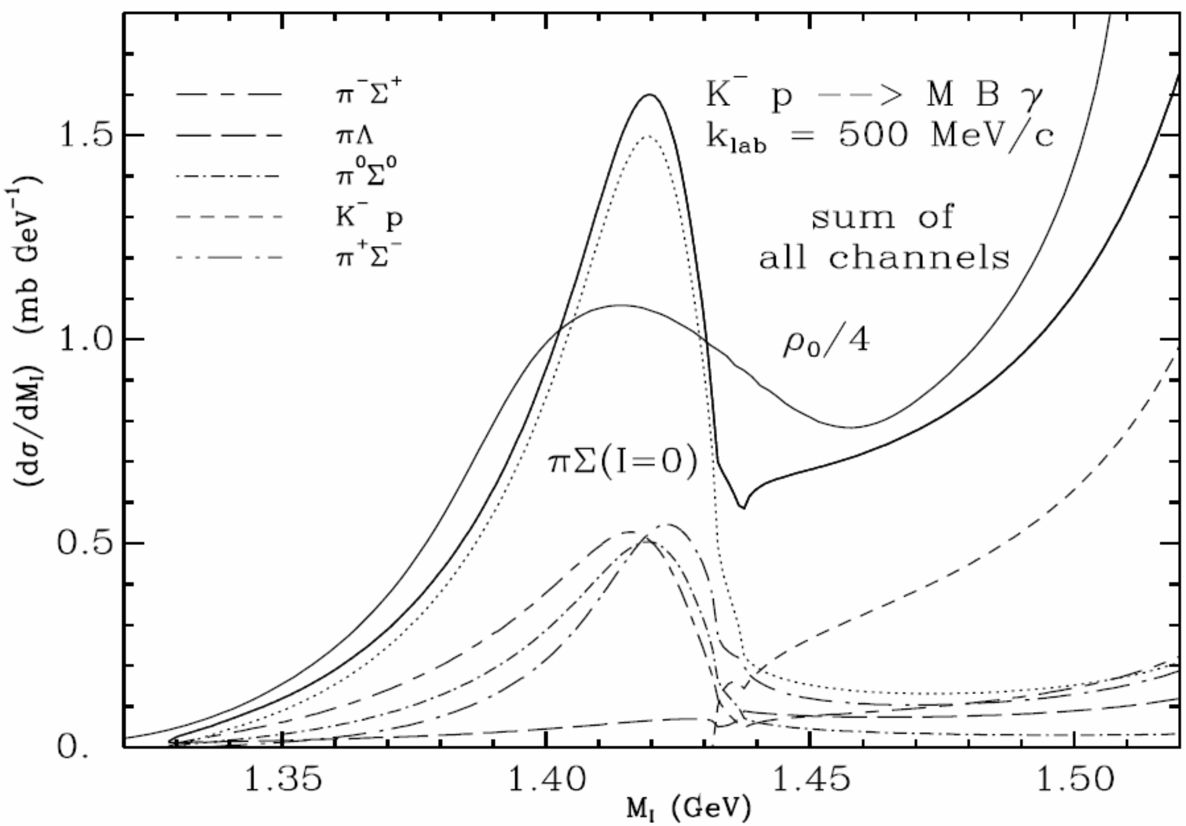
Couples strongly to Kbar N

Couples strongly to pi Sigma

The K⁻ p → γ Λ(1405) reaction

Nacher, Oset, Toki, Ramos PLB99



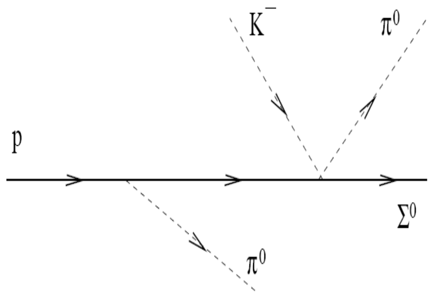


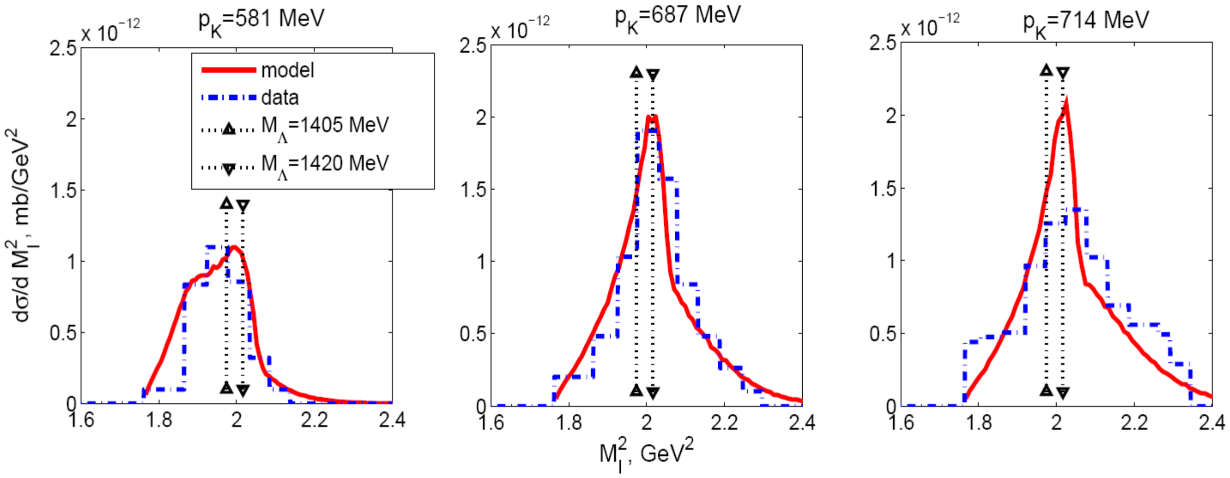
Note: photon removes energy from initial state → K^- p in the resonance region

K^- p couples strongly to narrow resonance
with a higher mass: 1420 MeV

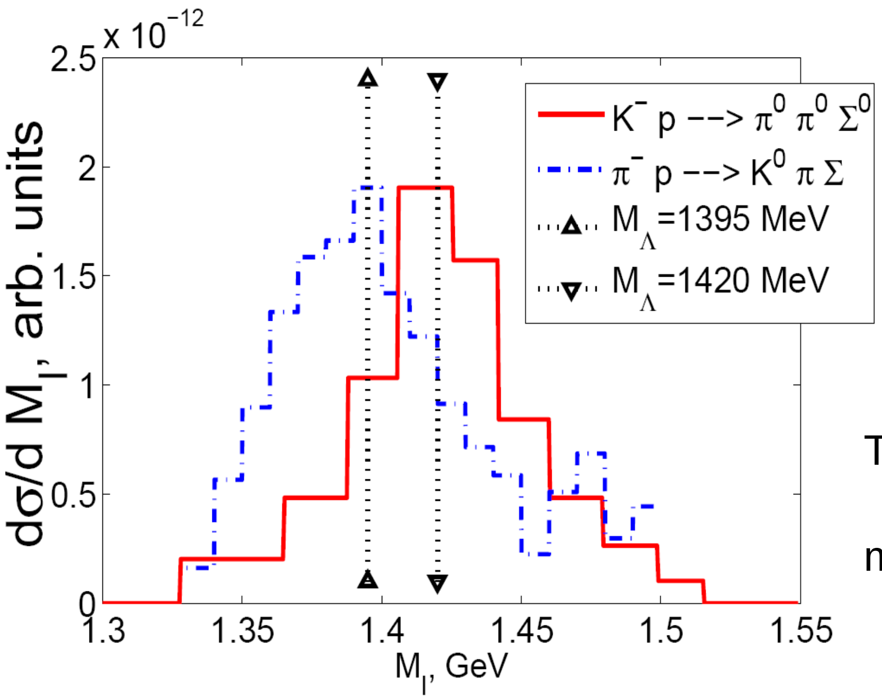
$K^- p \to \pi^0\pi^0\Sigma^0$ at $p_{K^-}=514-750$ MeV/c

Prakhov, Nefkens… PRC04





Theory : Magas, Oset, Ramos PRL05



The $K^- p \to \pi^0\pi^0\Sigma^0$ reaction selects mostly narrow pole

The $\pi^- p \to K^0 \pi\Sigma$ reaction selects mostly wide pole

Hyodo, Hosaka, Oset, Ramos Vicente Vacas PRC03

Alternative reactions

$K^- p \rightarrow \pi^0 \gamma \Lambda$ with $\gamma \Lambda$ in $\Lambda(1405)$ region

$K^- p \rightarrow \pi^0 \gamma \Sigma^0$ with $\gamma \Sigma$ in $\Lambda(1405)$ region

$\pi^- p \rightarrow K^0 \gamma \Lambda$ with $\gamma \Lambda$ in $\Lambda(1405)$ region

$\pi^- p \rightarrow K^0 \gamma \Sigma^0$ with $\gamma \Sigma$ in $\Lambda(1405)$ region

This would provide the radiative decay of the $\Lambda(1405)$ into $\gamma \Lambda$ and $\gamma \Sigma$

Possibility to see different results depending on the reaction because of the two $\Lambda(1405)$

JPARC candidates

Radiative decay of the Λ(1405) and its two pole structure

L.G. Geng, E. Oset and M. Doring Eur. Phys J. A 2007

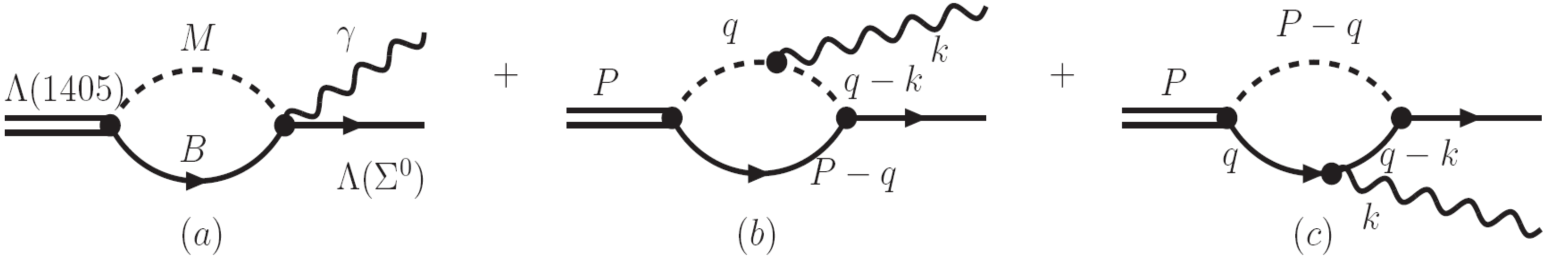


Fig. 1. The radiative decay mechanism of the $\Lambda(1405)$, where MB can be any of the four charged channels of the ten coupled channels: K^-p, $\bar{K}^0n$, $\pi^0\Lambda$, $\pi^0\Sigma^0$, $\eta\Lambda$, $\eta\Sigma^0$, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $K^+\Xi^-$, and $K^0\Xi^0$.

Decay channel	UχPT	χQM [35]	BonnCQM [36]	NRQM	RCQM [39]
$\gamma\Lambda$	16.1, 64.8	168	912	143 [37], 200, 154 [38]	118
$\gamma\Sigma^0$	73.5, 33.5	103	233	91 [37], 72, 72 [38]	46
Decay channel	MIT bag [38]	chiral bag [40]	soliton [41]	algebraic model [42]	isobar fit [23]
$\gamma\Lambda$	60, 17	75	44,40	116.9	27 ± 8
$\gamma\Sigma^0$	18, 2.7	1.9	13,17	155.7	10 ± 4 or 23 ± 7

How to see the effects of the two resonances?

Look at different reactions

Suggested ones : K- induced and π induced

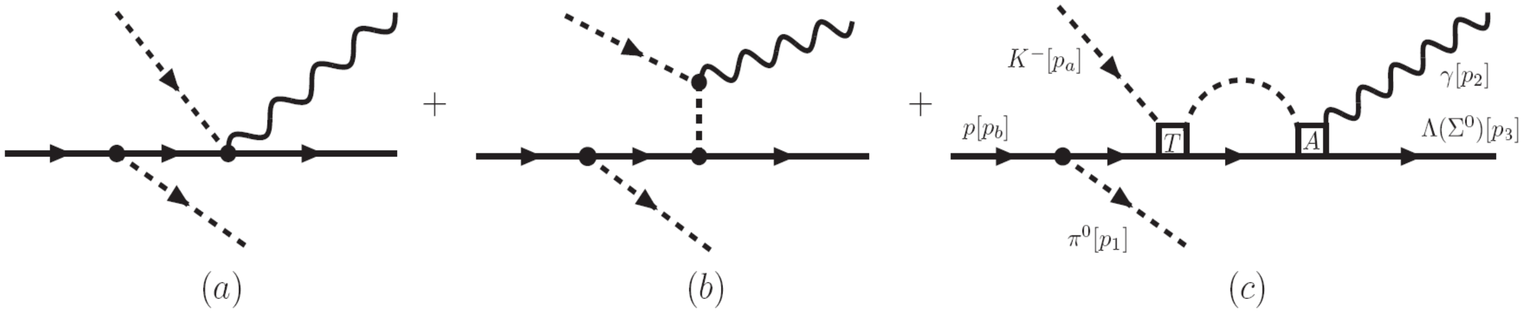


Fig. 3. The diagrams contributing to the reaction $K^- p \to \pi^0 \gamma \Lambda(\Sigma^0)$.

Fig. 4. The strong amplitude T.

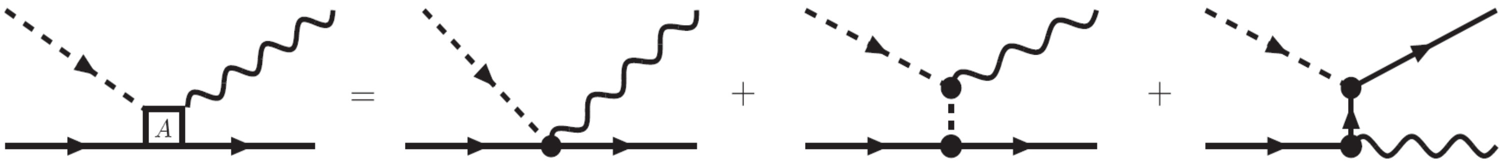


Fig. 5. The electromagnetic amplitude A.

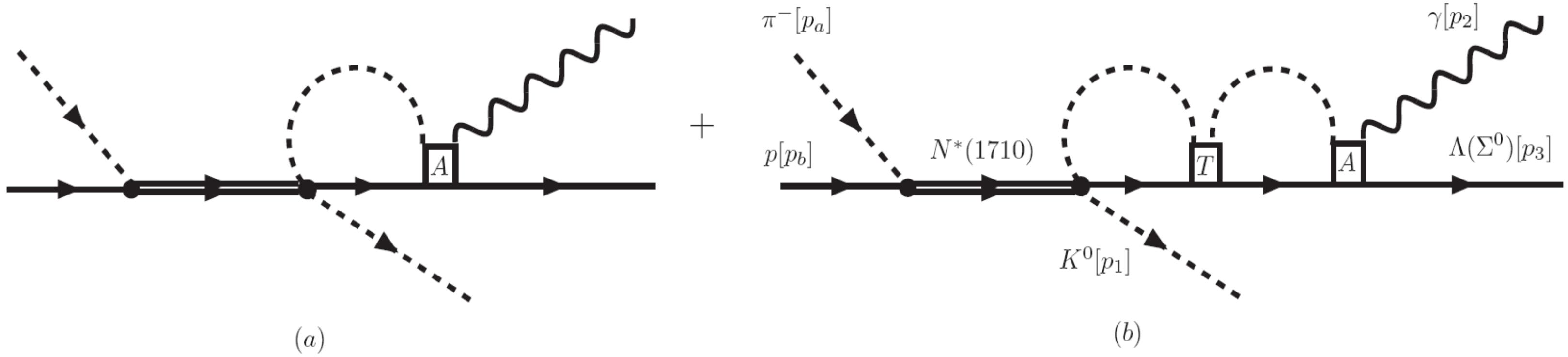


Fig. 8. The diagrams contributing to the reaction $\pi^- p \to K^0 \gamma \Lambda(\Sigma^0)$.

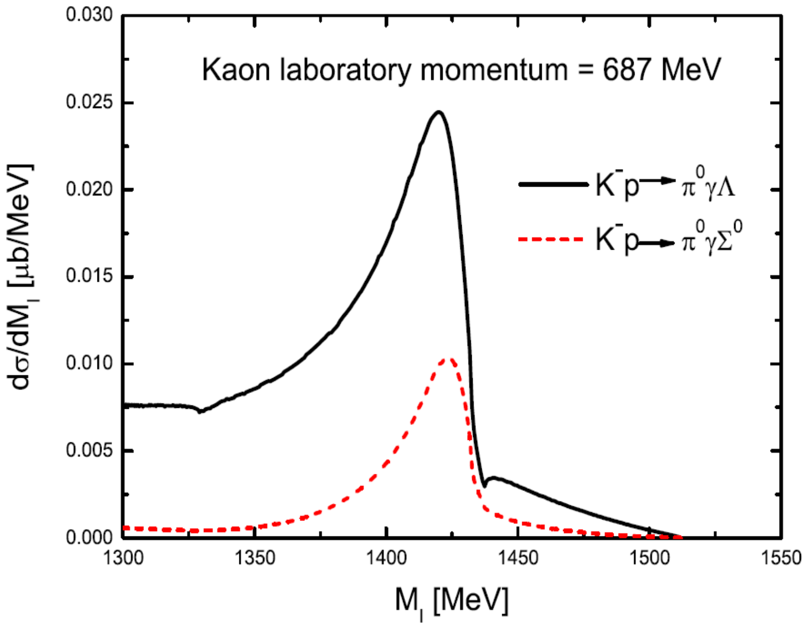


Fig. 6. The invariant mass distribution of $K^- p \to \pi^0 \gamma \Lambda(\gamma \Sigma^0)$ as a function of the invariant mass of the final $\gamma \Lambda(\gamma \Sigma^0)$ system.

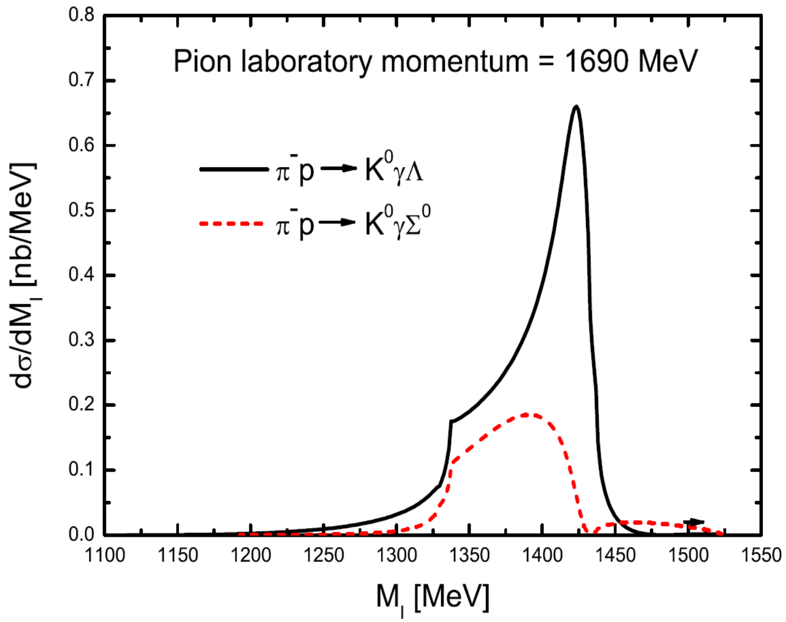


Fig. 9. The invariant mass distribution of $\pi^- p \to K^0 \gamma \Lambda(\gamma \Sigma^0)$ as a function of the invariant mass of the final $\gamma \Lambda(\gamma \Sigma^0)$ system.

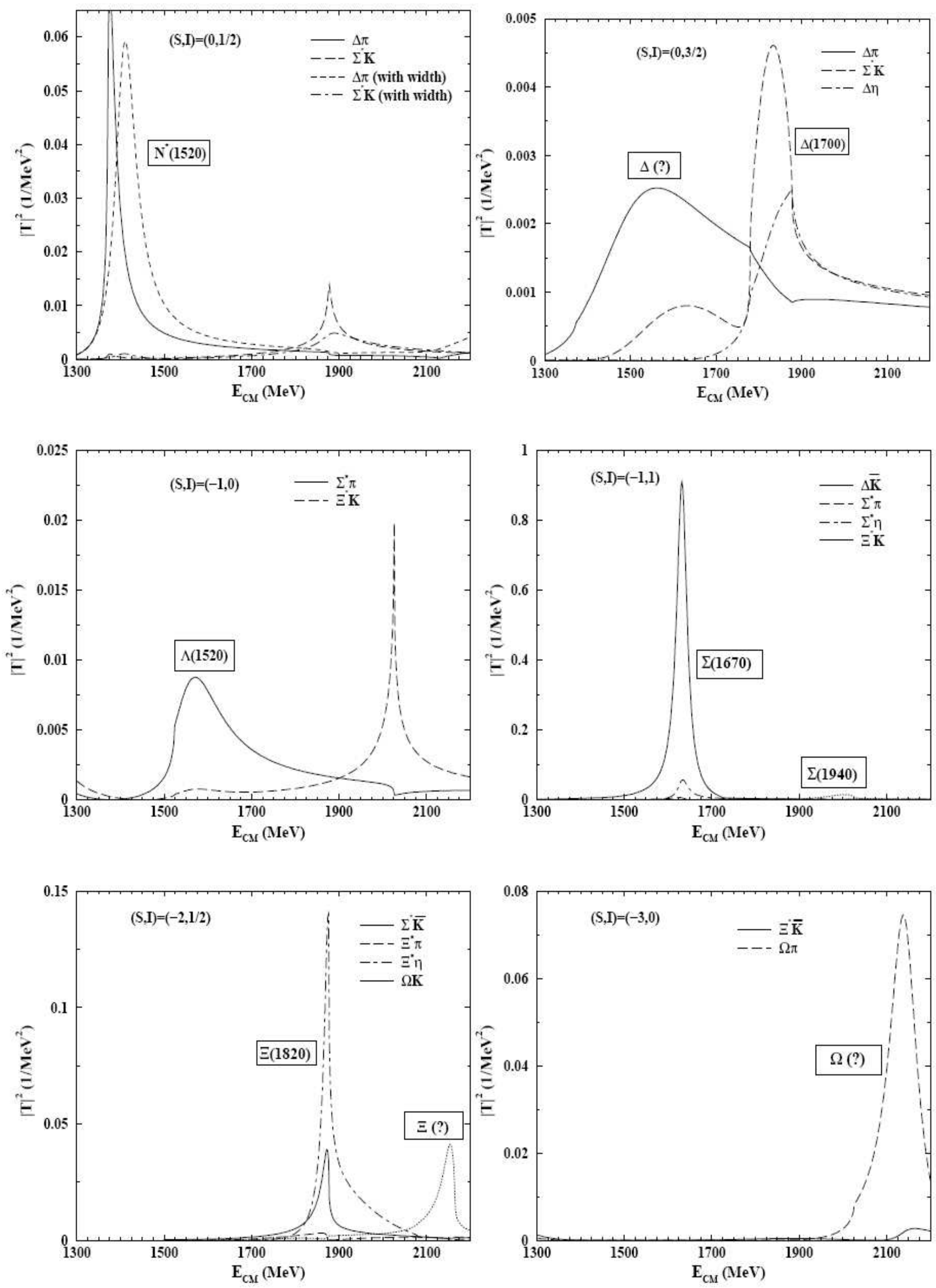
Do not stop there !

Bonn group Van Cauteren et al predict 912 eV for the radiative decay width of the $\Lambda(1405)$
and 1.6 eV for the $\Lambda(1670)$

The $\Lambda(1670)$ is also dynamically generated : unlikely to have such a small raditive width!

Theoretical work for this resonance suggested, similar to that for the $\Lambda(1405)$

Interaction of the meson Octet with baryon decuplet



Sarkar,Oset,VicenteNPA05

S=-1 , I=0, the Λ(1520) case

$$V_{ij} = -\frac{1}{4f^2} C_{ij} (k^0 + k'^0)$$

$$\begin{aligned} |\pi\Sigma^*;\ I=0\rangle &= \frac{1}{\sqrt{3}}\,|\pi^-\Sigma^{*+}\rangle - \frac{1}{\sqrt{3}}\,|\pi^0\Sigma^{*0}\rangle - \frac{1}{\sqrt{3}}\,|\pi^+\Sigma^{*-}\rangle \\ |K\Xi^*;\ I=0\rangle &= -\frac{1}{\sqrt{2}}\,|K^0\Xi^{*0}\rangle + \frac{1}{\sqrt{2}}\,|K^+\Xi^{*-}\rangle\ . \end{aligned} \tag{7}$$

	$\Sigma^*\pi$	$\Xi^* K$
$\Sigma^*\pi$	4	$\sqrt{6}$
$\Xi^* K$		3

Table 1: C_{ij} coefficients for $S=-1$, $I=0$.

The interaction is attractive and sufficient to produce a bound state or resonance with $\Sigma^*\pi$ as the main building block.

Introduction of the $\bar{K}N$ and $\pi\Sigma$ channels

$\bar{K}N$ and $\pi\Sigma$ couple to $\pi\Sigma(1385)$ in D-wave

$$-it_{\bar{K}N\to\pi\Sigma^*} = -i\beta_{\bar{K}N}\ |\vec{k}|^2\ \mathcal{C}(1/2\ 2\ 3/2; m, M-m)Y_{2,m-M}(\hat{k})(-1)^{M-m}\sqrt{4\pi}. \quad (8)$$

$$-it_{\pi\Sigma\to\pi\Sigma^*} = -i\beta_{\pi\Sigma}\ |\vec{k}|^2\ \mathcal{C}(1/2\ 2\ 3/2; m, M-m)Y_{2,m-M}(\hat{k})(-1)^{M-m}\sqrt{4\pi}. \quad (9)$$

$$V = \left|\begin{array}{cccc} C_{11}(k_1^0+k_1^0) & C_{12}(k_1^0+k_2^0) & \gamma_{13}\ q_3^2 & \gamma_{14}\ q_4^2 \\ C_{21}(k_2^0+k_1^0) & C_{22}(k_2^0+k_2^0) & 0 & 0 \\ \gamma_{13}\ q_3^2 & 0 & \gamma_{33}\ q_3^4 & \gamma_{34}\ q_3^2\ q_4^2 \\ \gamma_{14}\ q_4^2 & 0 & \gamma_{34}\ q_3^2\ q_4^2 & \gamma_{44}\ q_4^4 \end{array}\right|, \quad (10)$$

We chose a to get the pole at the physical position. β and γ chosen to reproduce the partial decay widths of the $\Lambda(1520)$ into $\bar{K}N(45\%)$ and $\pi\Sigma(42\%)$ and $\bar{K}N$ phase shifts.

From residues at pole $|g_{\pi\Sigma^*}| = 0.91, |g_{K\Xi^*}| = 0.29,\ |g_{\bar{K}N}| = 0.54$ and $|g_{\pi\Sigma}| = 0.45$.

The coupling to $\pi\ \Sigma$ * is the strongest

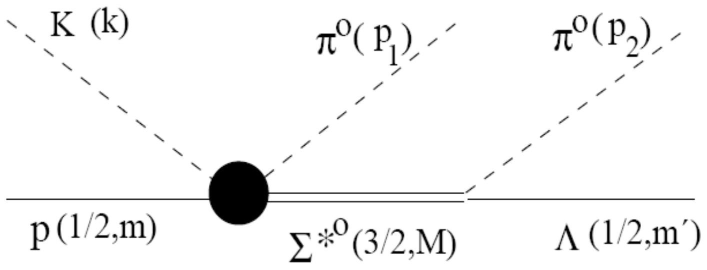
The β' s are γ_{13} and γ_{14}

Reaction $K^- p \to \pi^0 \pi^0 \Lambda$ from p_{K^-}=514 to 750 MeV/c

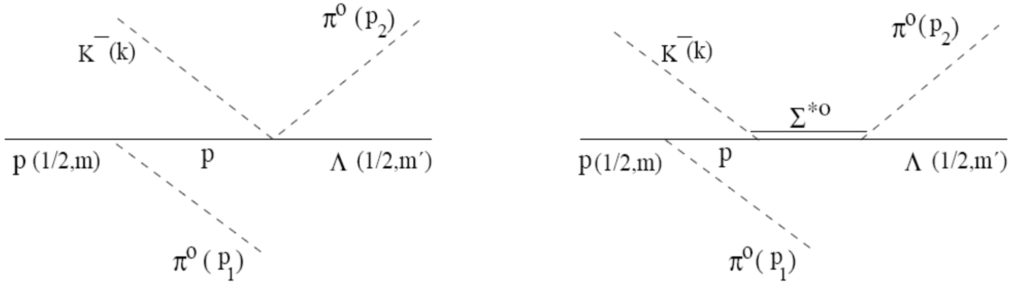
Prakhov …PRC04

Theoretical approach, Sarkar, Oset , Vicente Vacas PRC05

Roca, Magas, Sarkar, Oset PRC06

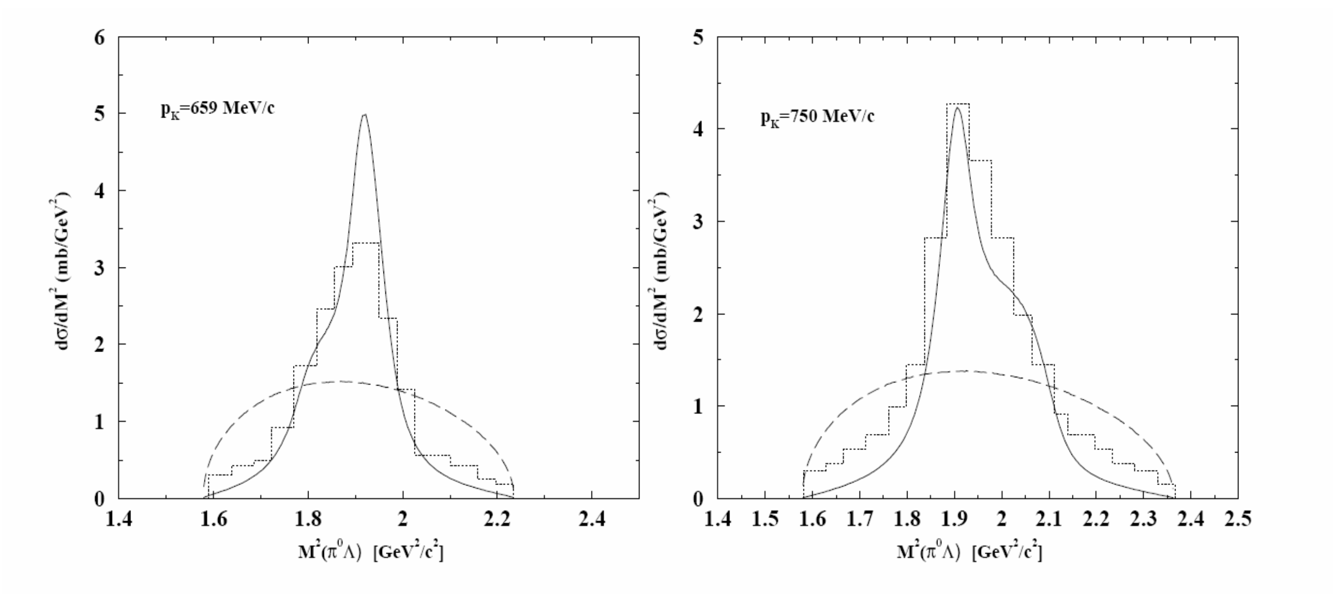


Λ(1520) mediated

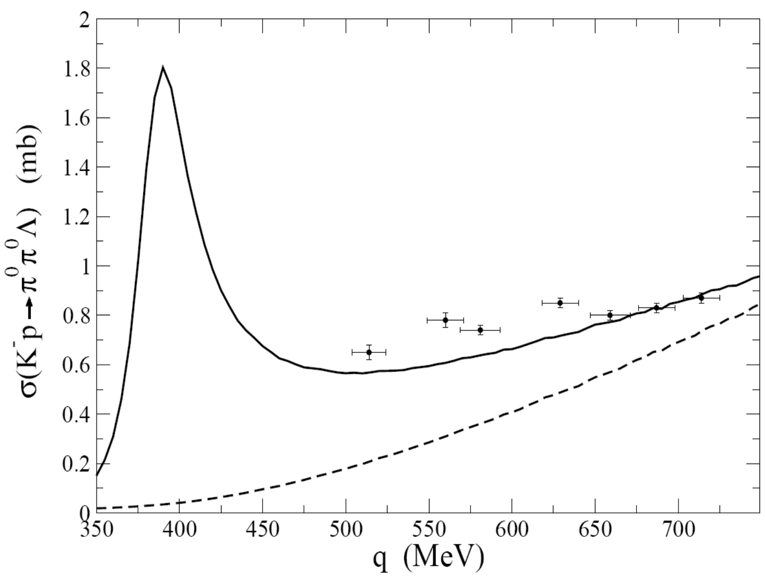


(a) (b)

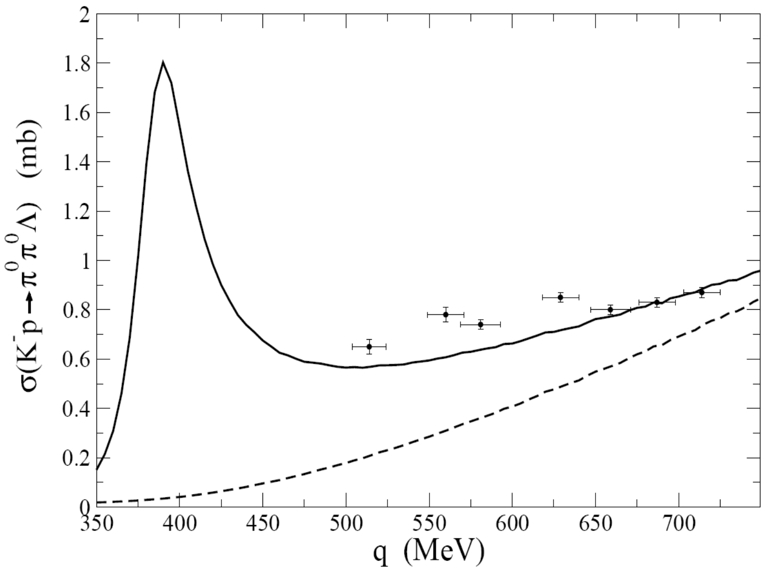
Background

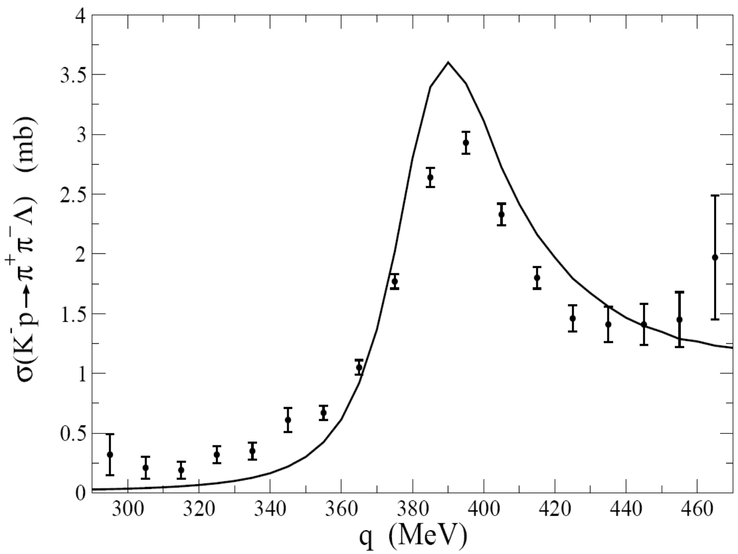


p_K=659 MeV/c
dσ/dM² (mb/GeV²)
M²(π⁰Λ) [GeV²/c²]
p_K=750 MeV/c
dσ/dM² (mb/GeV²)
M²(π⁰Λ) [GeV²/c²]



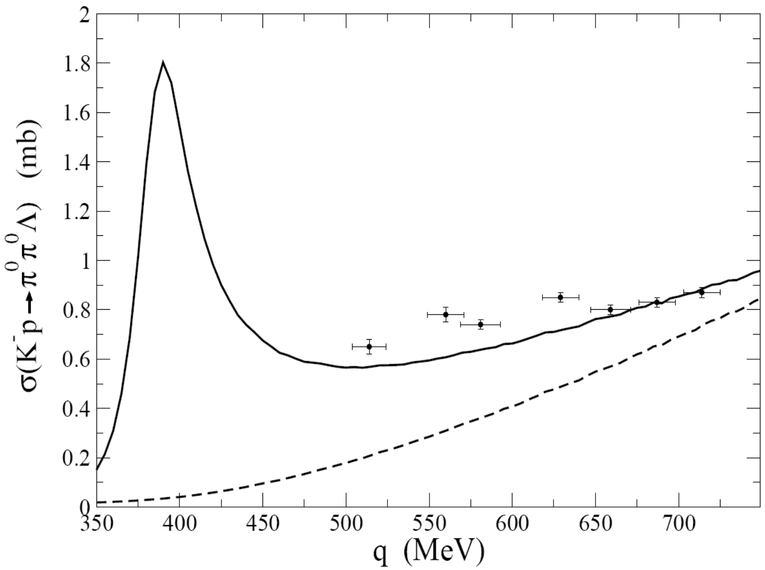
σ(K⁻p→π⁰π⁰Λ) (mb)
q (MeV)

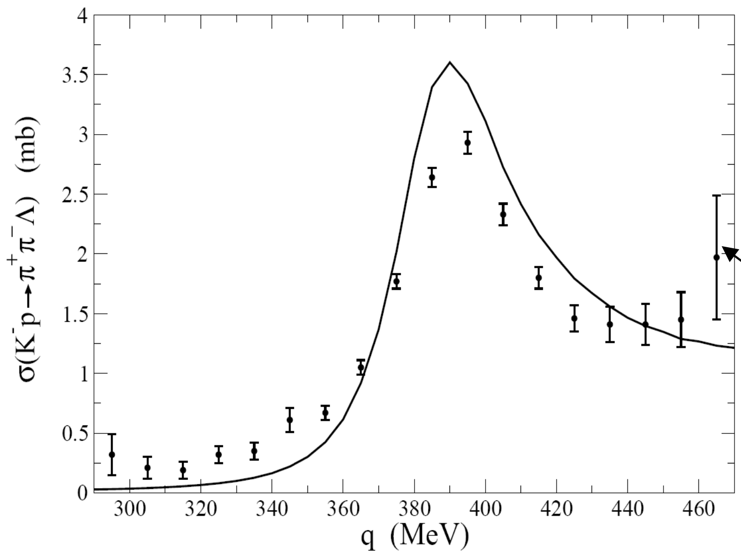




Cross section double than for $\pi^0 \pi^0 \Lambda$

Mast, PRD 73





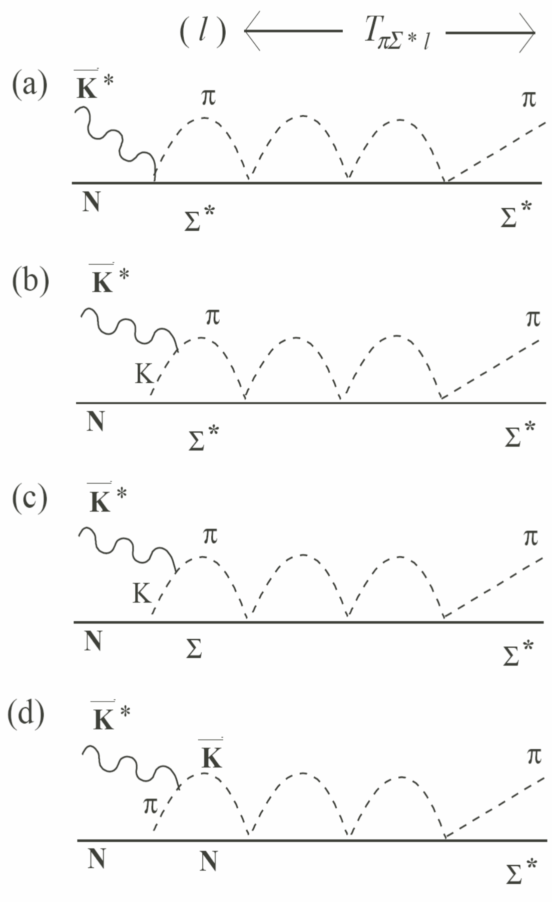
Cross section double than for $\pi^0 \pi^0 \Lambda$

Mast, PRD 73

Is the rise of σ at 465 MeV/c genuine or a statistical fluctuation????

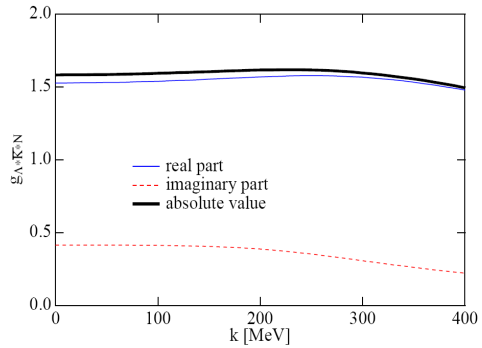
Coupling of $\bar{K}^*N$ to the $\Lambda(1520)$

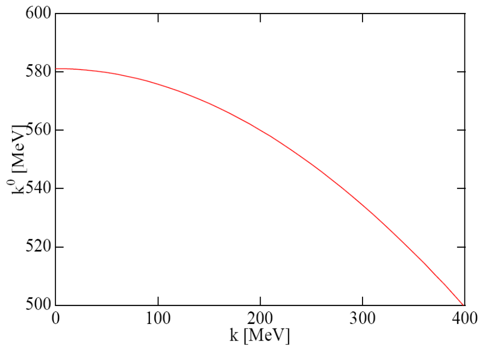
Hyodo, Sarkar, Hosaka, Oset PRC06



Dominated by Λ(1520)

The K* is coupled to the Meson baryon components of the Λ(1520)





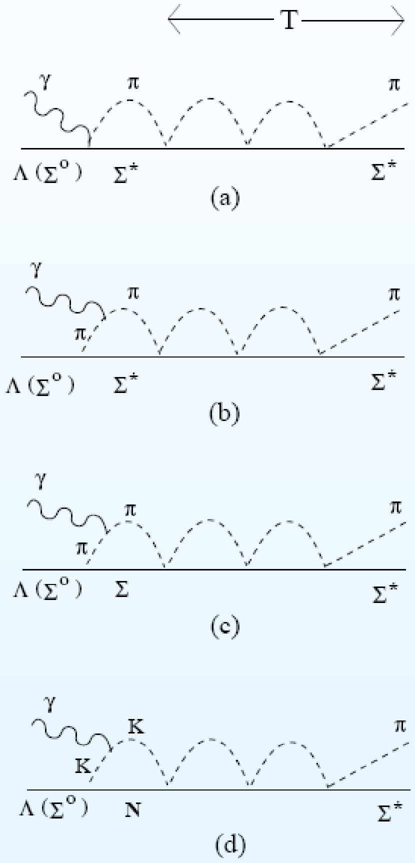
Parallel study done in quark models

g $_{\Lambda^*\ \mathrm{Kbar\ N}}$ =2.5

This coupling is Important in studies of pentaquark Production

Hosaka et al

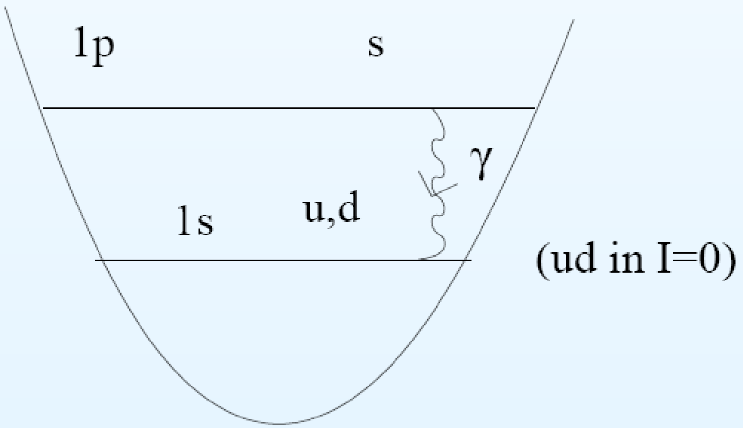
$\Lambda(1520)$ radiative decay, M. Doering, E. O., S. Sarkar PRC07



Coupling of the photon to the $\Lambda^*(1520)$. Diagrams (a) and (b) show the coupling to a $\pi\Sigma^*$ loop. The rescattering series that generates the pole of the $\Lambda^*(1520)$ in the complex scattering plane is symbolized by T. Diagrams (c) and (d) show the γ coupling to the d-waves of the resonance.

Quark model picture for $\Lambda(1520)$ radiative decay

Quark Model simplest wave function for the Lambda(1520) and radiation scheme



This model gives a large radiative decay width for $\Lambda(1520) \rightarrow \Lambda(1115)\gamma$ and zero for for $\Lambda(1520) \rightarrow \Sigma(1197)\gamma$

Results $\Lambda(1520)$ radiative decay

Experimental data, quark model results from Ref. Kaxiras:1985, and results for the partial decay width of the $\Lambda^*(1520)$ into $\gamma\Lambda$ and $\gamma\Sigma^0$.

	$\Gamma\left(\Lambda^*(1520) \to \gamma\Lambda\right)$ [keV]	$\Gamma\left(\Lambda^*(1520) \to \gamma\Sigma^0\right)$ [keV]
From Bertini:1987	33 ± 11	47 ± 17
From Mast:1969	134 ± 23	
From Antipov:2004	$159 \pm 33 \pm 26$	
From Taylor:2005	$167 \pm 43^{+26}_{-12}$	
From Ref. Kaxiras:1985	46	17
This study	3	71
		(60, with empirical $\Sigma^* \to \pi\Lambda, \pi\Sigma$ couplings)
From Van Cauteren et al. 05	258	157

Quark model radiative amplitude is inversely proportional to the radius of the quark core

A small admixture (5-10 %) of a compact 3q wave function (as in chiral quark models)

with s-quark in 1p, and u, d in 1s, can provide good Λ γ radiative decay without modifying

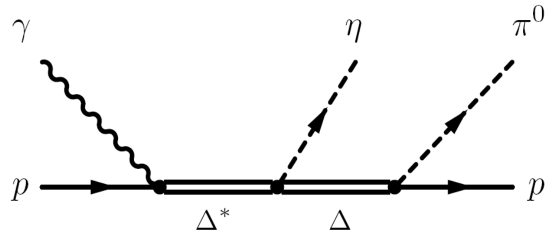
the Σ γ decay.

Λ(1520) would be a hybrid, mostly meson baryon state, with small genuine component showing up in some particular cases.

More detailed work should be done

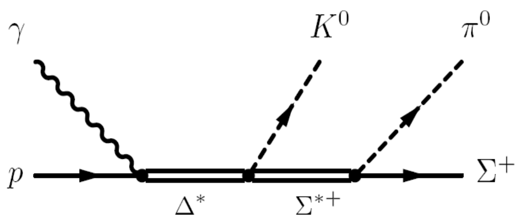
Clues to the nature of the $\Delta^*(1700)$ resonance from pion- and photon-induced reactions

Doering, Oset Strottman PLB06

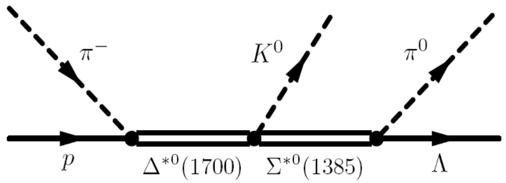


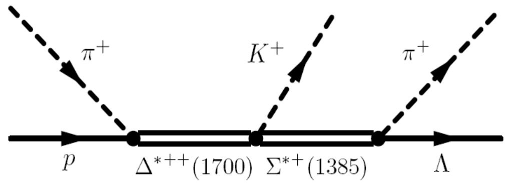
Nanova, Metag …

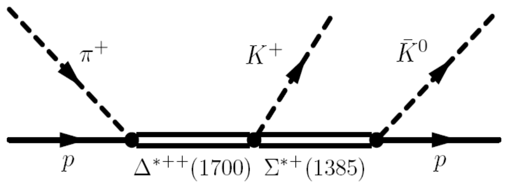
coupled channels $\Delta\pi, \Sigma^* K$, and $\Delta\eta$

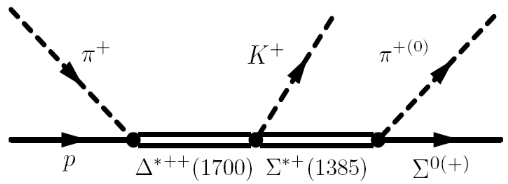


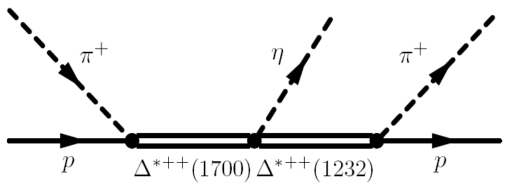
Nanova, Metag ….











should we assume that the $\Delta^*(1700)$ belongs to an $SU(3)$

decuplet as suggested in the PDG

it is easy to see that the couplings to the $\Delta\pi$, $\Sigma^* K$, $\Delta\eta$ states in

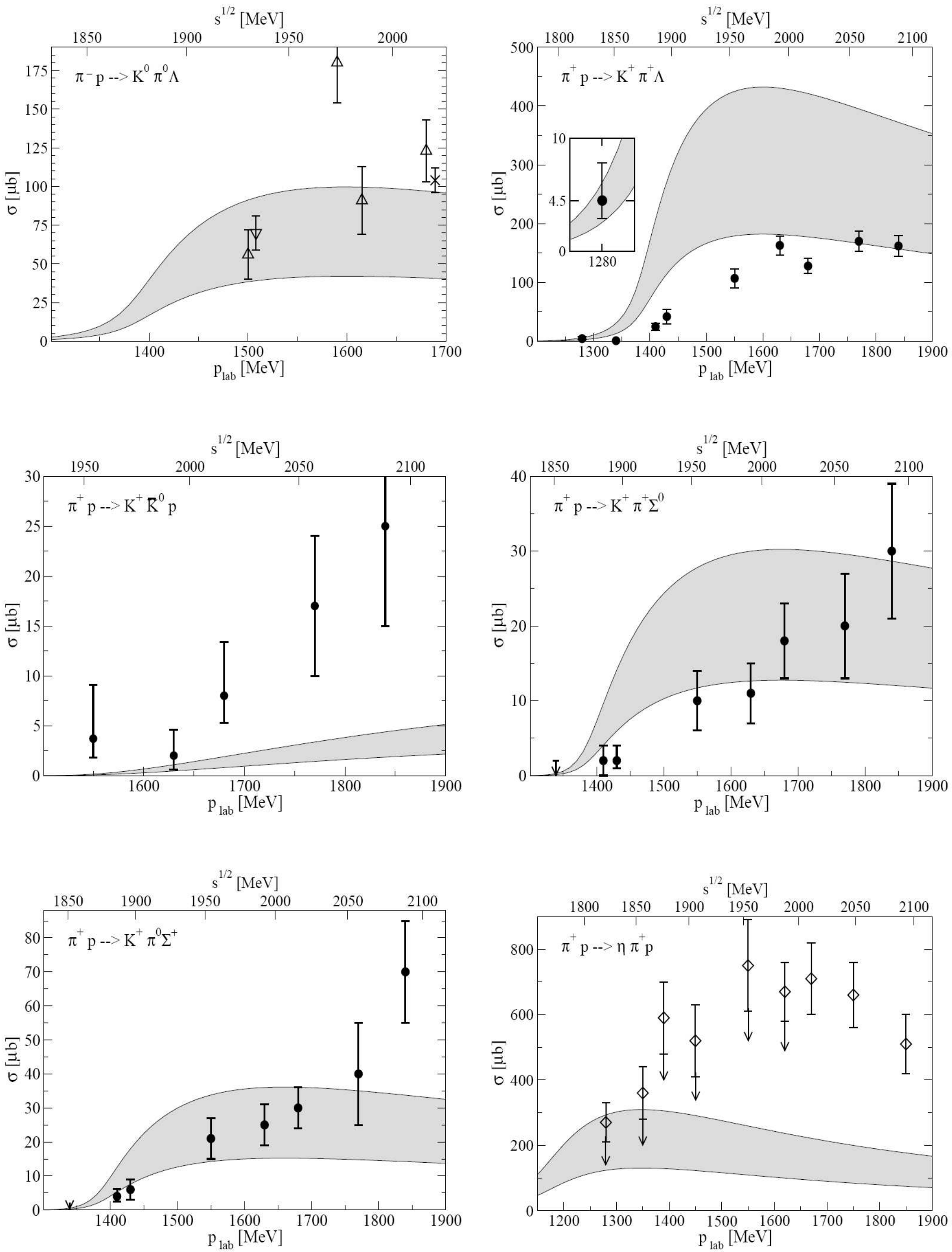
$I = 3/2$ are proportional to $\sqrt{5/8}$, $\sqrt{1/4}$, $\sqrt{1/8}$, respectively.

The squares of these coefficients are proportional to 1, 2/5, 1/5, respectively

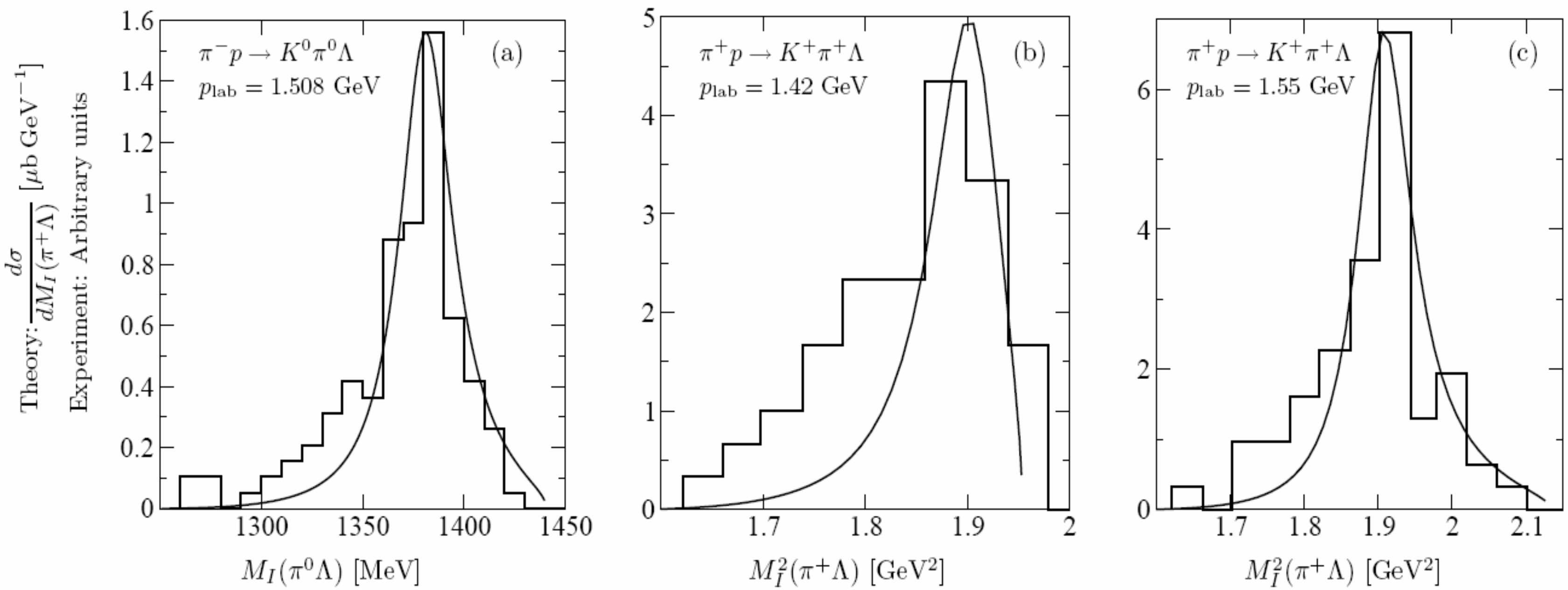
dynamically generated resonance, 1, 11.56, 4.84.

Huge differences: factor 20-30 in amplitudes , 400-900 in cross sections

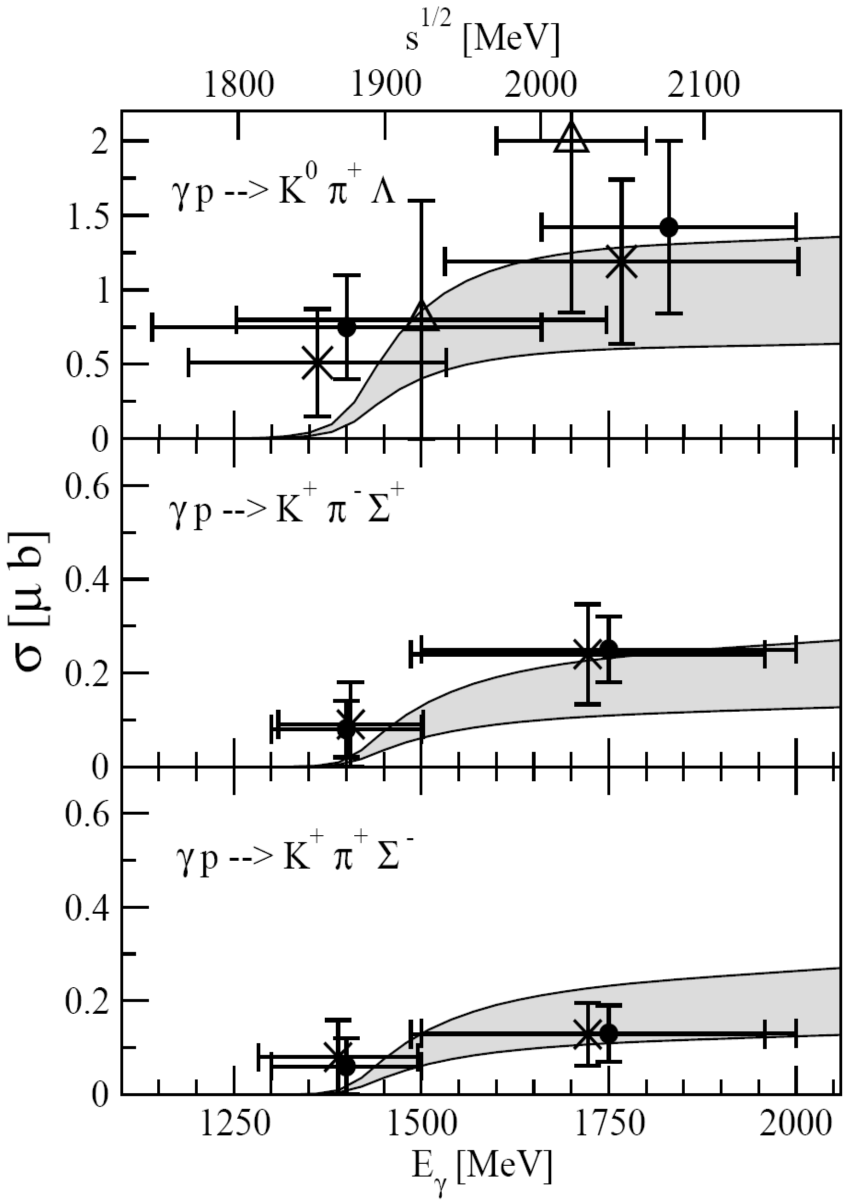
Very large differences: challenging predictions of the theory

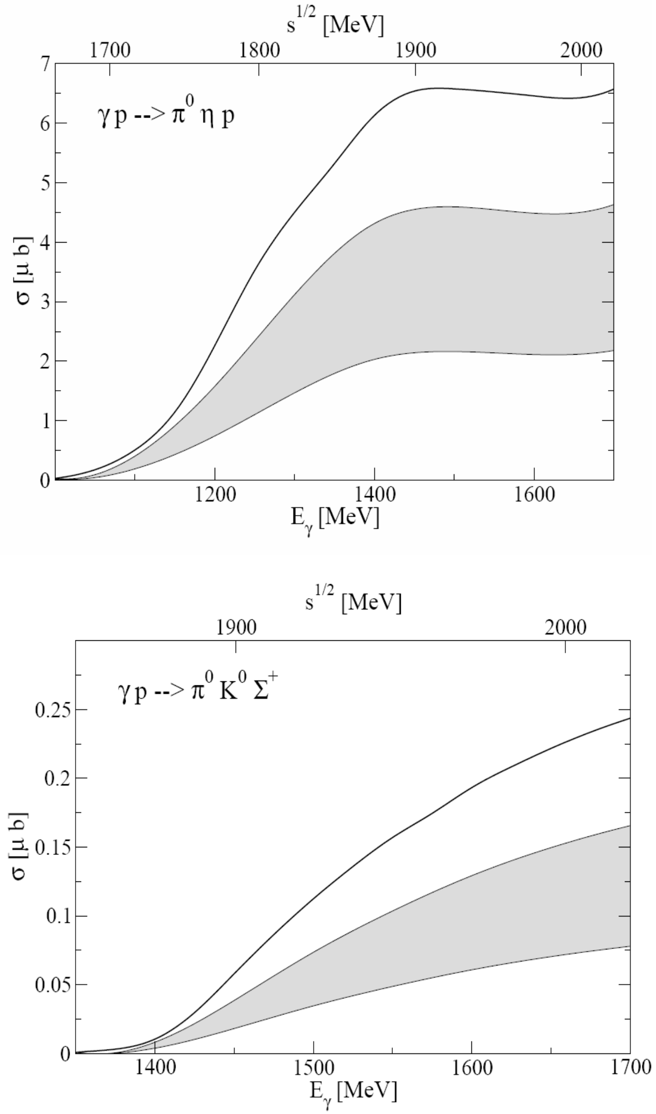


π⁻ p --> K⁰ π⁰ Λ
π⁺ p --> K⁺ π⁺ Λ
π⁺ p --> K⁺ K̄⁰ p
π⁺ p --> K⁺ π⁺ Σ⁰
π⁺ p --> K⁺ π⁰ Σ⁺
π⁺ p --> η π⁺ p
s^{1/2} [MeV]
p_lab [MeV]
σ [μb]



Σ* (1385) dominated reactions





F. Klein et al. at ELSA, preliminary
Results in good agreement

V. Metag, M. Navova …..
Preliminary results in good agreement

Three body resonances in two meson-one baryon systems

Alberto Martinez, Kanchan Khemchandani, Eulogio Oset

Chiral dynamics of meson baryon interaction
The N/D method and the on shell factorization of V and T in the Bethe Salpeter Equation
Three body Faddeev equations
On shell T matrix factorization in Faddeev equations. New reformulation of F.E.
Results for the system of two mesons and one baryon in S=-1, I=0, I=1
Comparison with the low lying Λ and Σ $J^P = 1/2^+$ states of the PDG

Then the Faddeev equations result

$$T = T^1 + T^2 + T^3$$

$$\begin{aligned} T^i &= t^i \delta^3(\vec{k}_i' - \vec{k}_i) + T_R^{(ij)} + T_R^{(ik)} \\ &= t^i \delta^3(\vec{k}_i' - \vec{k}_i) + t^i \tilde{G}[T^j + T^k] \end{aligned}$$

t^i is the two body t matrix for the pair (j,k) with j, k indices complementary to i
Example, t^1 is the interaction between particles 2,3 and so on

T^i accounts for all diagrams where the last interaction is t^i

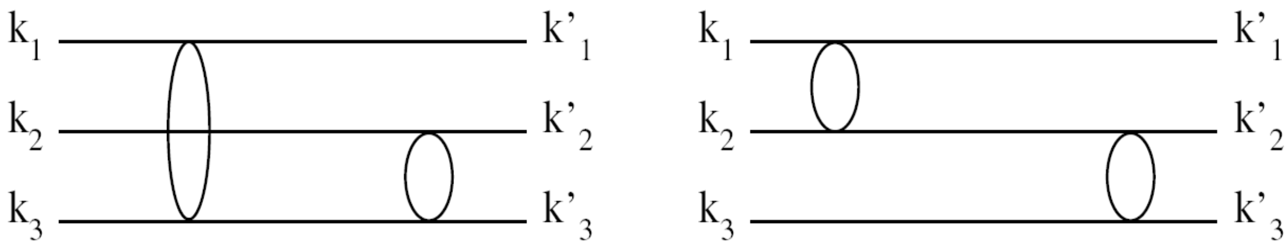
G stands for the three body propagator 1/(E-H)
H stands for the energy of the three intermediate particles prior to the last interaction, t^i

Coupled channels used

We start by taking all combinations of a pseudoscalar meson of the 0^- SU(3) octet and a baryon of the $1/2^+$ octet that couple to $S = -1$ with any charge. This is the system where a large attraction develops which is responsible for the generation of the two $\Lambda(1405)$ states. To this system we add an extra pion and hence the three body system contains twenty-two coupled channels : $\pi^0 K^- p$, $\pi^0 \bar{K}^0 n$, $\pi^0 \pi^0 \Sigma^0$, $\pi^0 \pi^+ \Sigma^-$, $\pi^0 \pi^- \Sigma^+$, $\pi^0 \pi^0 \Lambda$, $\pi^0 \eta \Sigma^0$, $\pi^0 \eta \Lambda$, $\pi^0 K^+ \Xi^-$, $\pi^0 K^0 \Xi^0$, $\pi^+ K^- n$, $\pi^+ \pi^0 \Sigma^-$, $\pi^+ \pi^- \Sigma^0$, $\pi^+ \pi^- \Lambda$, $\pi^+ \eta \Sigma^-$, $\pi^+ K^0 \Xi^-$, $\pi^- \bar{K}^0 p$, $\pi^- \pi^0 \Sigma^+$, $\pi^- \pi^+ \Sigma^0$, $\pi^- \pi^+ \Lambda$, $\pi^- \eta \Sigma^+$, $\pi^- K^+ \Xi^0$.

So, we have 22 channels and 6 coupled equations. The evaluation of all two body t-matrices and the G^{ijk} propagators is as lengthy as one may imagine, or more!!

The equations (2) at second order in t, for the case $i = 1$, corresponds to diagrams like



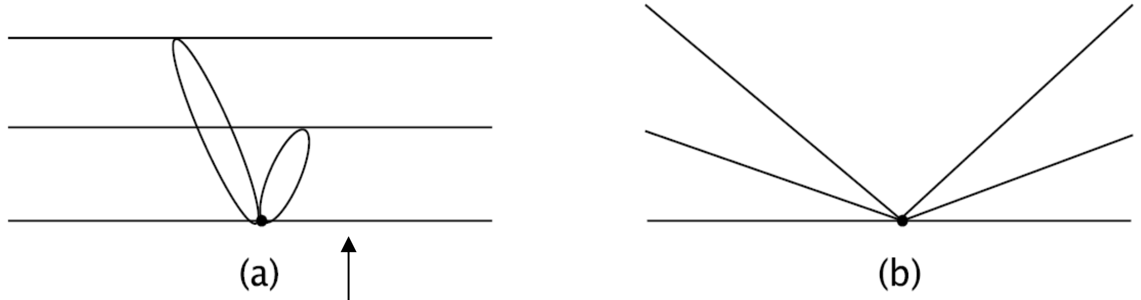
(a) (b)

which can be expressed mathematically as $t^1 g^{(12)} t^2$ and $t^1 g^{(13)} t^3$, respectively, where

$$g^{(ij)} = \frac{N_k}{2E_k} \frac{1}{\sqrt{s} - E_i(\vec{k}'_i) - E_j(\vec{k}_j) - E_k(\vec{k}'_i + k_j) + i\epsilon}$$

The variables are all specified from the external Momenta. We call these “on shell amplitudes”

$$N_l = \begin{cases} 1 & \text{meson-meson interaction} \\ 2M_l & \text{meson-baryon interaction.} \end{cases}$$



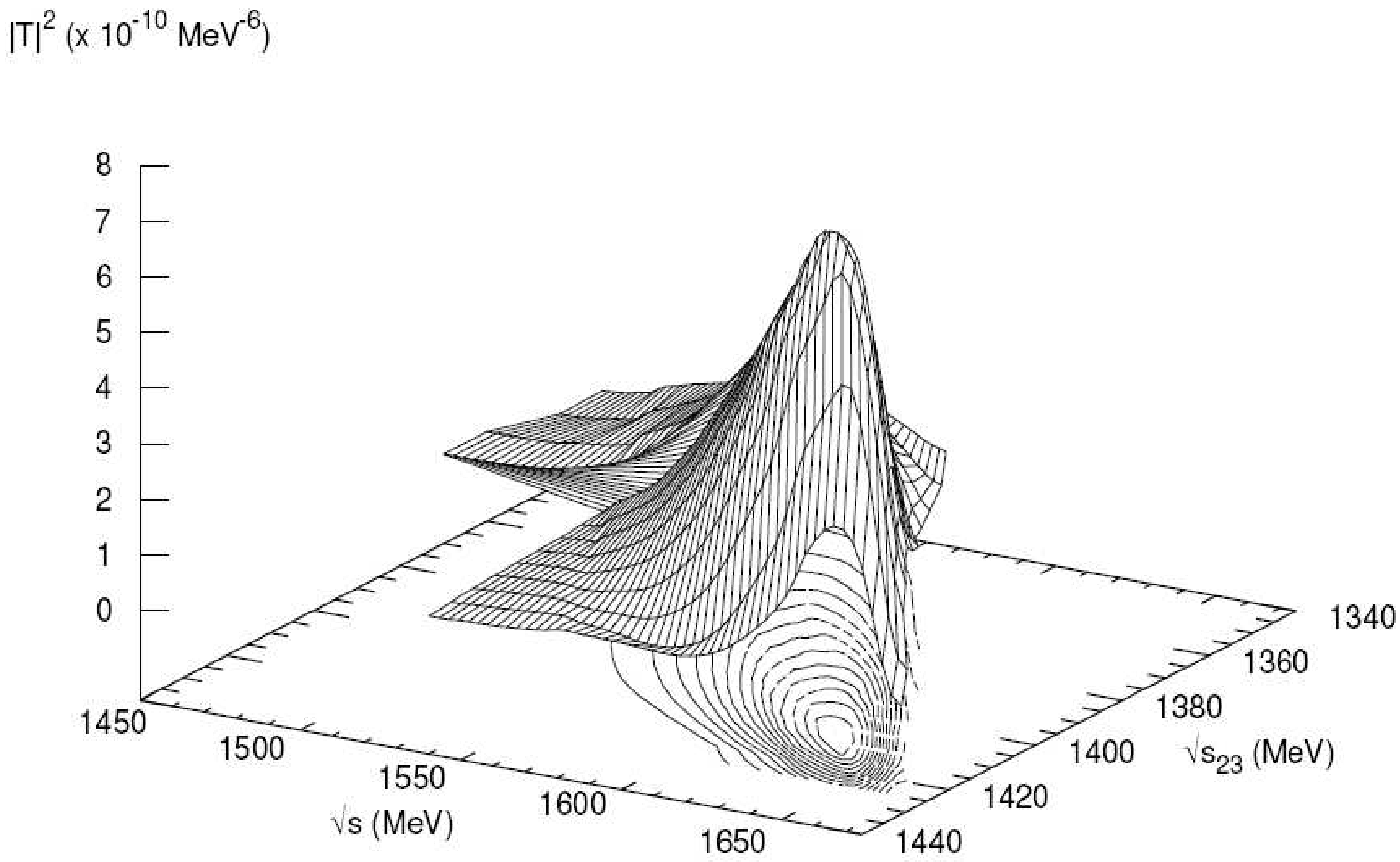
$V_{off} = \beta\,(q^2 - m^2)$ for mesons $V_{off} = \gamma\,(E - E' + k^0 - k'^0)$
They kill a meson or baryon propagator and generate a three body force

There are other three body forces from the chiral Lagrangian

The total contribution of such kind of diagrams is zero in the limit of SU(3) and zero momentum transfer of the baryon. Less than 3% in the realistic case.

One must take only the two body amplitudes “on shell”. They depend on s_{ij} for s-waves

This allows us to write the F.E. as algebraic equations



$\pi^0\ \pi^0\ \Sigma^0 \rightarrow \pi^0\ \pi^0\ \Sigma^0$

$\Sigma(1620)$

We find two Lambda states and six Sigma states . We search in the channels:
$\pi^0 \pi^0 \Lambda$ I= 0 (Lambda state) $\pi^0 \pi^0 \Sigma^0$ I=1 (Sigma state)

We find

$\Lambda(1584)$ $\Gamma = 30$ MeV
$\Lambda(1751)$ $\Gamma = 95$ MeV
$\Sigma(1480)$ $\Gamma = 30$ MeV
$\Sigma(1551)$ $\Gamma = 25$ MeV ?
$\Sigma(1612)$ $\Gamma = 63$ MeV
$\Sigma(1662)$ $\Gamma = 60$ MeV
$\Sigma(1750)$ $\Gamma= 30$ MeV
$\Sigma(1780)$ $\Gamma= 30$ MeV

The width obtained is only from three body decay
Should be smaller than the total width

These energies are close by to existing resonances of $J^P=1/2^+$

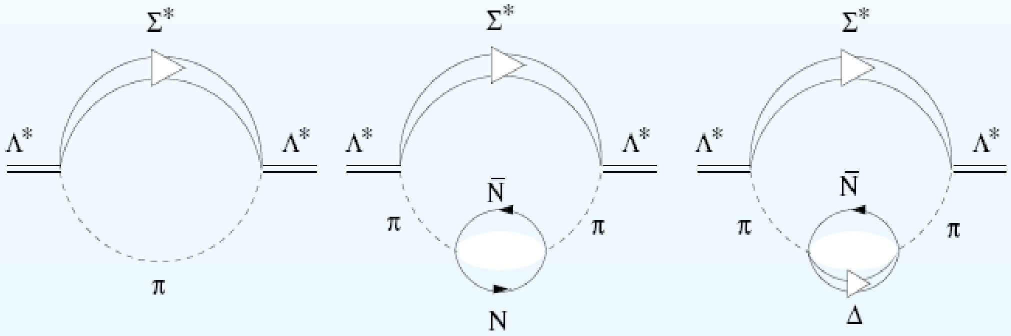
The results obtained indicate that the low lying $J^P = 1/2^+$ resonances can be obtained as Resonances of two mesons and a baryon.
Which means that in the real world this three body component could be the dominant one

These findings should stimulate research looking for three body decay channels of resonances and search for new ones looking at invariant masses of three particles in the final state

$\Lambda(1520)$ in the nuclear medium

Kaskulov, Oset PRC06

The coupling of the $\Lambda(\overset{1520}{\cancel{1495}})$ to $\pi\Sigma(1385)$ is very large but decay into this channel practically suppressed because of lack of phase space.
In nuclei a π can excite ph. Plenty of phase space. Large width.



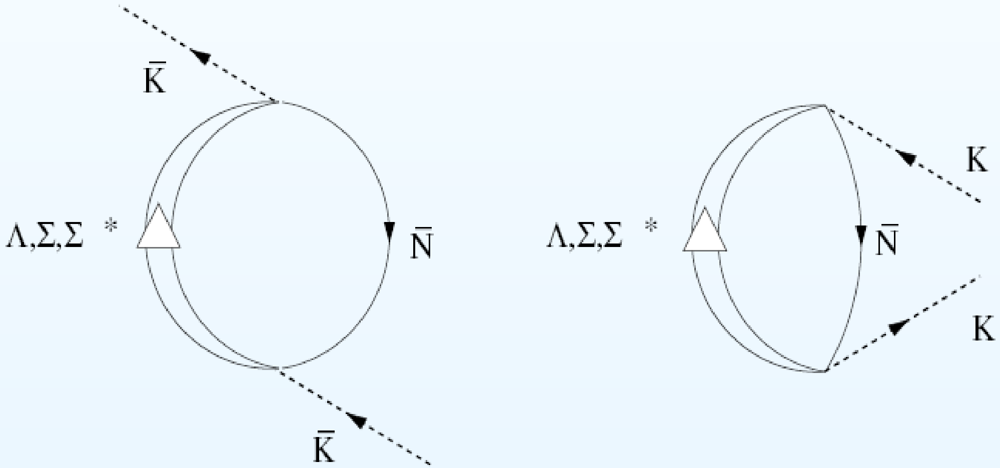
Analogy to mesonic and nonmesonic decay of $\Lambda(1115)$ in nuclei.
$\Lambda(1115) \rightarrow \pi N$ is forbidden by Pauli blocking in nuclear matter.
But π becomes ph and decay possible
$\rightarrow$ Non mesonic $\Lambda(1115)$ decay
$\Lambda(1115)N \rightarrow NN$

This is much more important than the mesonic decay in nuclei.

D-wave decay of $\Lambda(1520)$ in the nuclear medium

$$\Lambda(1520) \to \bar{K}N + \pi\Sigma$$

- In-medium $\bar{K}$ optical potential: $\bar{K} \to \Lambda$-h + Σ-h + $\Sigma(1385)$-h



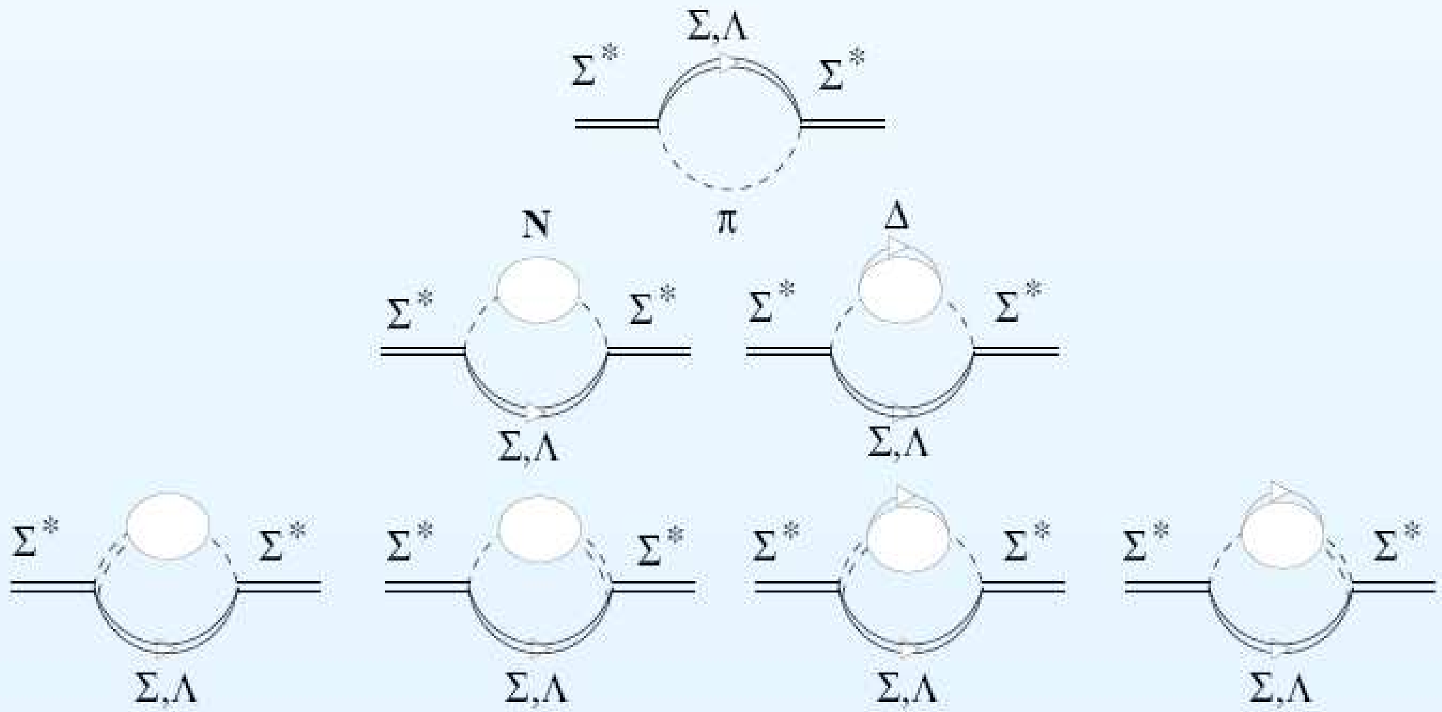
A.Ramos and E.Oset, Nucl. Phys. A 671 (2000) 481.

$\Sigma(1385)$ in the nuclear medium

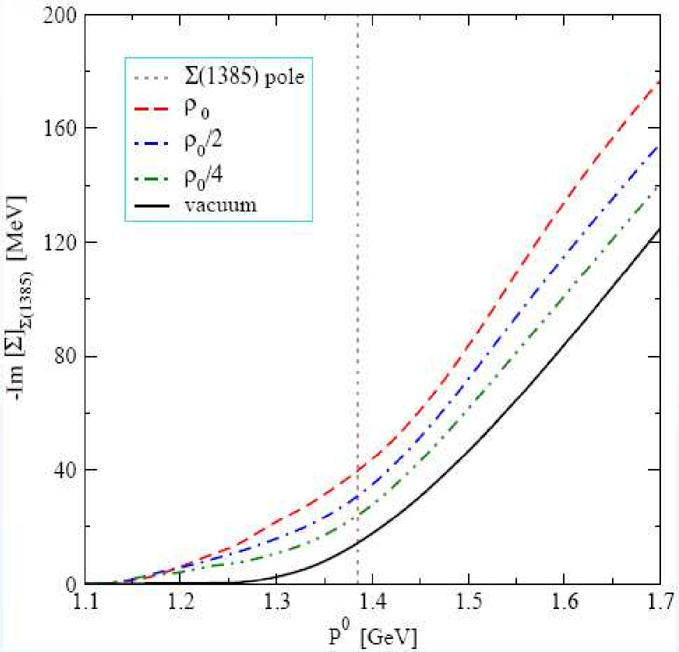
- The free width $\Gamma \simeq 30$ MeV
- Decay modes: $\Sigma(1385) \to \pi\Sigma + \pi\Lambda$

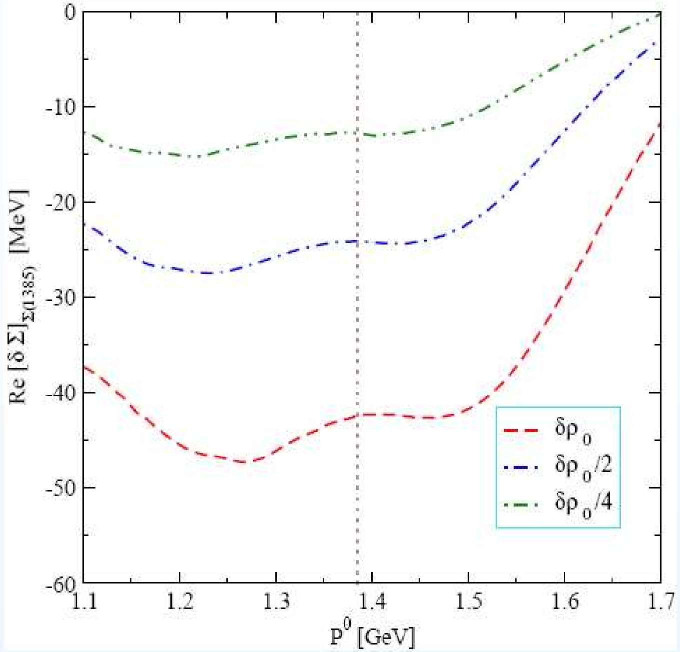
In-medium renormalization

- The pion decay $\pi \to \Delta - h + N - h$
- Short-range correlations



Results for the in-medium self energy of the $\Sigma(1385)$

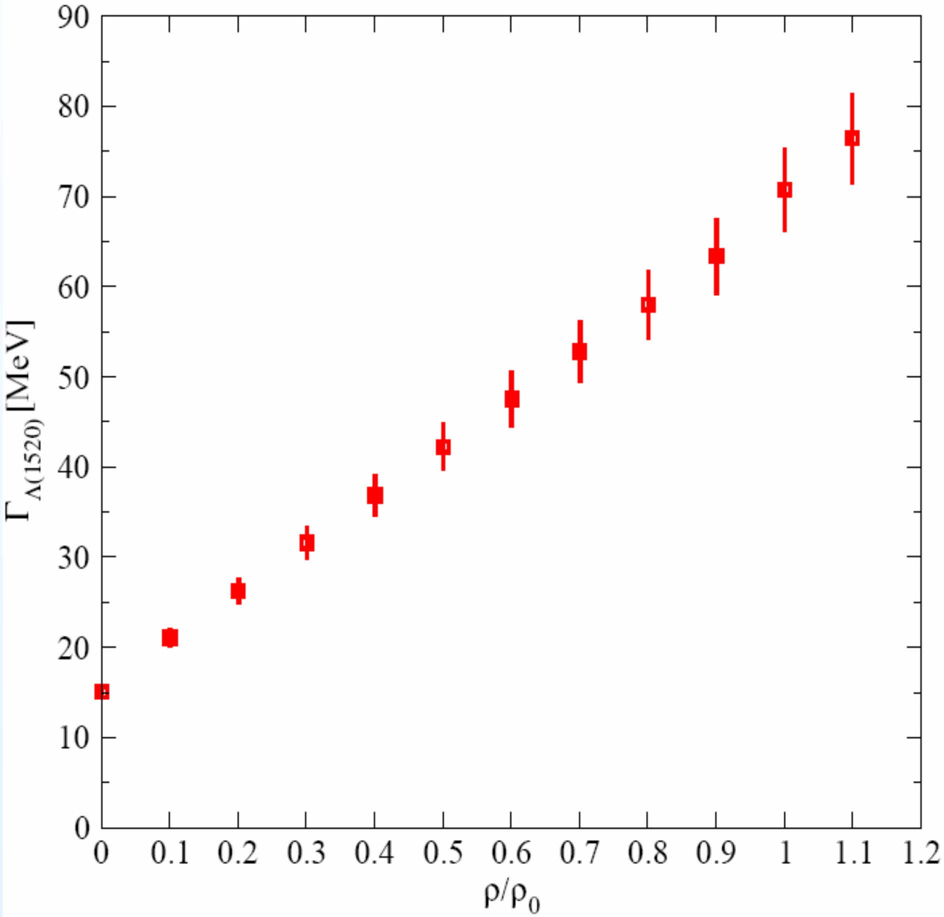




In-medium width of the $\Sigma(1385)$ at $\rho = \rho_0$: $\Gamma = -2\text{Im}\Sigma \simeq 80$ MeV

Results for the width of the $\Lambda(1520)$ in nuclear matter

$$\Gamma = -2Im\Sigma_\Lambda$$



Conclusions

- Chiral dynamics is becoming very helpful to correlate data so far disconnected.
- Makes clear predictions which can be confirmed: new resonances, cross sections for selected reactions….
- Challenging tests of predictions, many that can be done at JPARC.
- Three body resonances will likely become a new fronteer. Interesting to look for invariant masses of three particles in final states.
- Medium effects are very interesting: Λ(1520) has a width about 5 times bigger than free. Σ*(1385) about 2.5 times larger.
- Experiments to test these predictions welcome.