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Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

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# Recent developments in chiral dynamics of hadrons and hadrons in a nuclear medium

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# *Recent developments in chiral dynamics of hadrons and hadrons in a nuclear medium*

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# 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 interaction

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

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

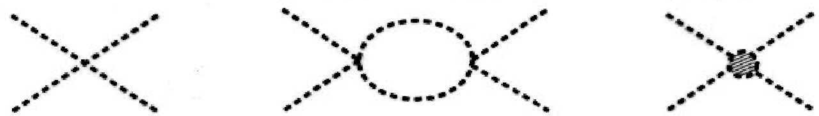
$$\nabla_\mu B = \partial_\mu B + [\Gamma_\mu, B] \; ; \; \Gamma_\mu = \frac{1}{2} (u^+ \partial_\mu u + u \partial_\mu u^+)$$

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

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

$\chi$ **PT:** (mesons)

$L_2$ $\qquad$ $L_2$ $\quad$ $L_2$ $\qquad$ $L_4$



Successful at low energies

Problems $\rightarrow$ { Limited energy range of applicability; Cannot deal with resonances }

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

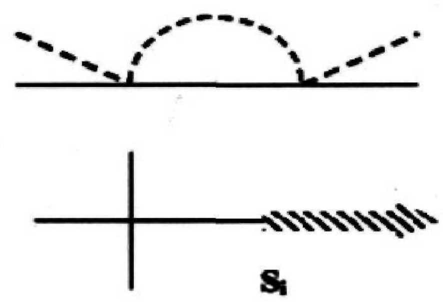
- **Unitarity** in coupled channels $\bar{K}N$, $\pi\Sigma$, $\pi\Lambda$, $\eta\Sigma$, $\eta\Lambda$, $K\Xi$, in $S=-1$

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

- 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 $\chi$PT expressions (usually at one loop level)

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

$\mu$ 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

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

$\mu$ 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

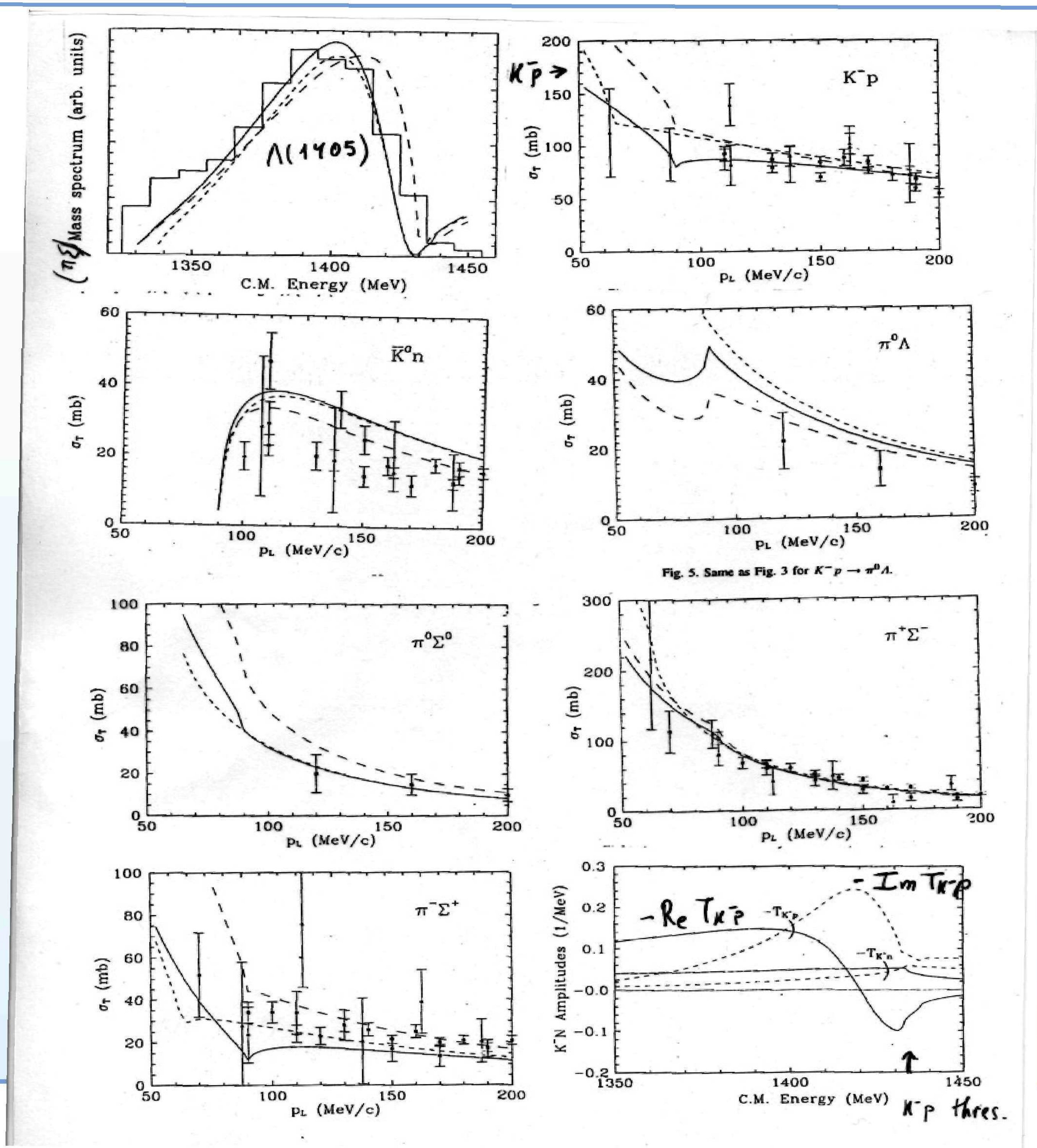


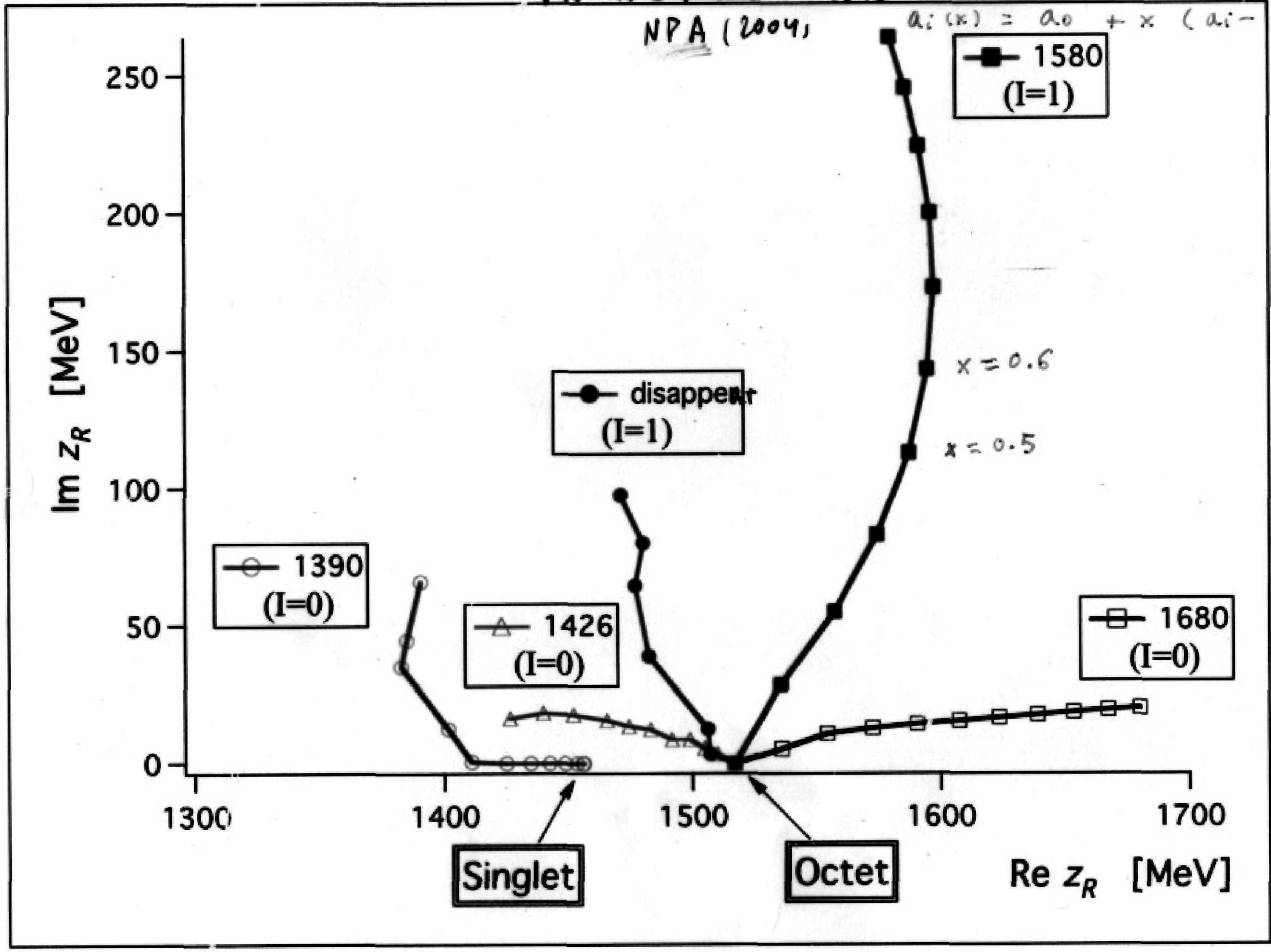

Fig. 5. Same as Fig. 3 for $K^- p \to \pi^0 \Lambda$.

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

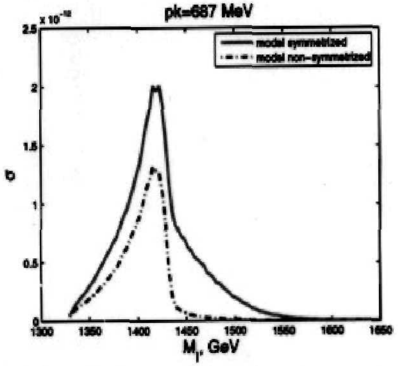
$M_i(x) = M_0 + x\,(M_i - M_0)$

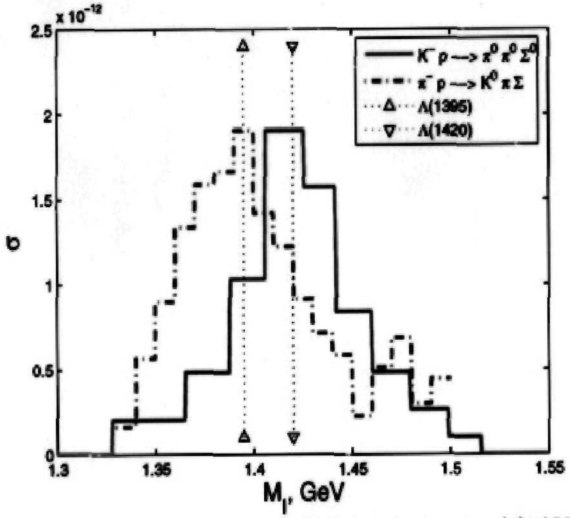
$m_i^2(x) = m_0^2 + x\,(m_i^2 - m_0^2)$

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



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




Γ ≃ 30 MeV
M ≃ 1420 Me

Γ ≃ 65 MeV
M ≃ 1396 Me

Puri, March 2005

Evidence for the two pole structure of the $\Lambda(1405)$ resonance and the nature of the $\Lambda(1520)$ – p.6/1

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

Interaction of the meson octet with the baryon decuplet S. Sarkar, E. O, M.J. Vicente Vacas, PRC

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

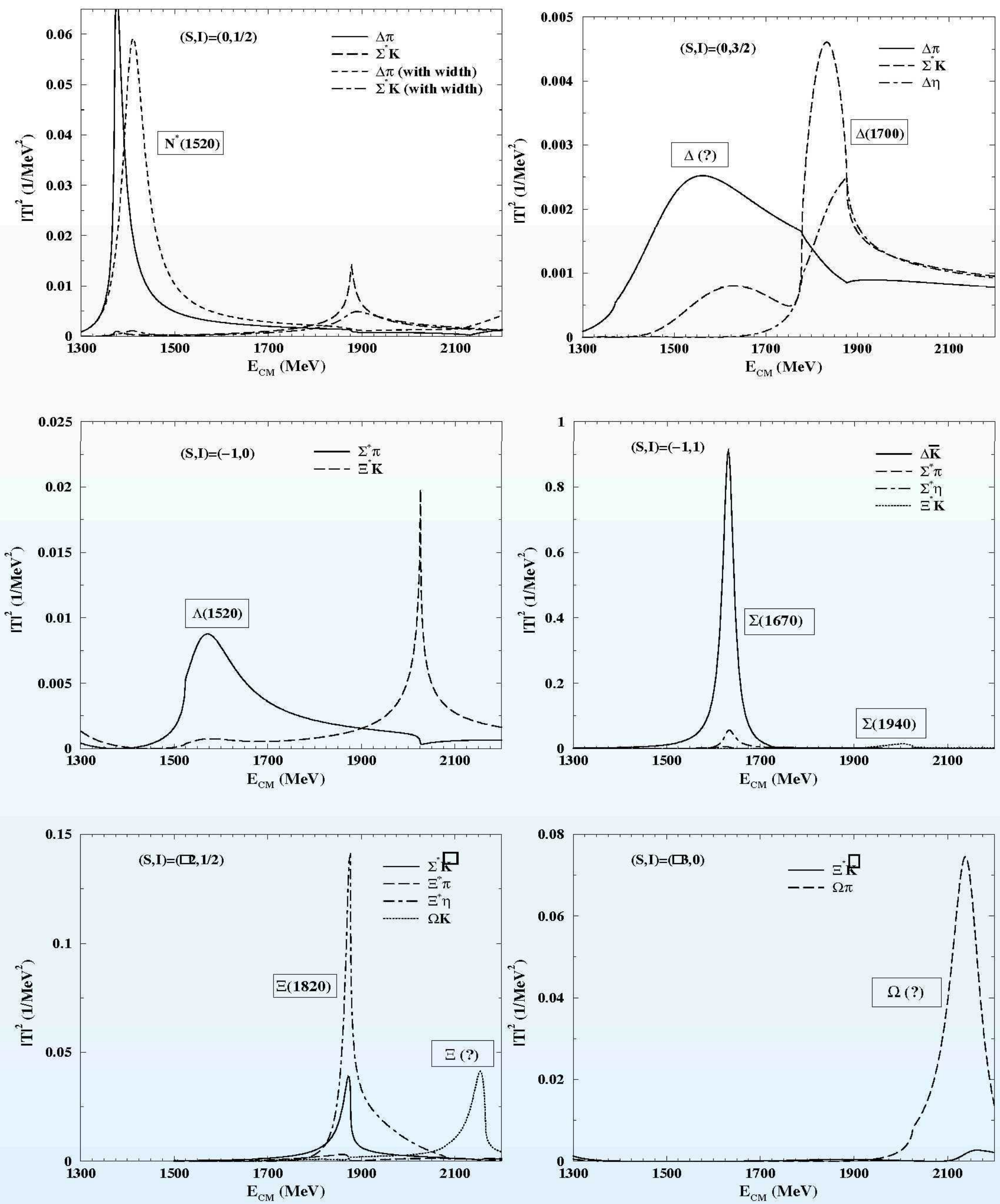
$$\mathcal{D}^{\nu} T^{\mu}_{abc} = \partial^{\nu} T^{\mu}_{abc} + (\Gamma^{\nu})^{d}_{a} T^{\mu}_{dbc} + (\Gamma^{\nu})^{d}_{b} T^{\mu}_{adc} + (\Gamma^{\nu})^{d}_{c} T^{\mu}_{abd} \tag{2}$$

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

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

$$V_{ij} = -\frac{1}{4f^2} C_{ij}(k^0 + k'^0). \tag{5}$$

$$\begin{aligned} |\pi\Sigma^*;\ I=0\rangle &= \frac{1}{\sqrt{3}}\,|\pi^-\Sigma^{*+}\rangle - \frac{1}{\sqrt{3}}\,|\pi^0\Sigma^{*0}\rangle - \frac{1}{\sqrt{3}}\,|\pi^+\Sigma^{*-}\rangle \\ |K\Xi^*;\ I=0\rangle &= -\frac{1}{\sqrt{2}}\,|K^0\Xi^{*0}\rangle + \frac{1}{\sqrt{2}}\,|K^+\Xi^{*-}\rangle\,. \end{aligned} \tag{6}$$


(S,I)=(0,1/2)
Δπ
Σ*K
Δπ (with width)
Σ*K (with width)
N*(1520)
(S,I)=(0,3/2)
Δπ
Σ*K
Δη
Δ (?)
Δ(1700)
(S,I)=(−1,0)
Σ*π
Ξ*K
Λ(1520)
(S,I)=(−1,1)
ΔK̄
Σ*π
Σ*η
Ξ*K
Σ(1670)
Σ(1940)
Σ*K̄
Ξ*π
Ξ*η
ΩK
Ξ(1820)
Ξ (?)
Ξ*K̄
Ωπ
Ω (?)
|T|² (1/MeV²)
E_CM (MeV)

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

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

$$-it_{\bar{K}N\to\pi\Sigma^*} = -i\beta_{\bar{K}N}\,|\vec{k}|^2\,\mathcal{C}(1/2\;2\;3/2;m,M-m)Y_{2,m-M}(\hat{k})(-1)^{M-m}\sqrt{4\pi}. \quad (7)$$

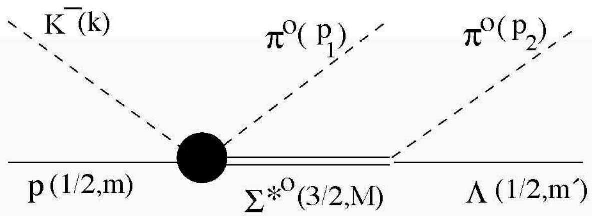
$$-it_{\pi\Sigma\to\pi\Sigma^*} = -i\beta_{\pi\Sigma}\,|\vec{k}|^2\,\mathcal{C}(1/2\;2\;3/2;m,M-m)Y_{2,m-M}(\hat{k})(-1)^{M-m}\sqrt{4\pi}. \quad (8)$$

$$V = \left|\begin{array}{cccc} C_{11}(k_1^0+k_1^0) & C_{12}(k_1^0+k_2^0) & \gamma_{13}\,q_3^2 & \gamma_{14}\,q_4^2 \\ C_{21}(k_2^0+k_1^0) & C_{22}(k_2^0+k_2^0) & 0 & 0 \\ \gamma_{13}\,q_3^2 & 0 & \gamma_{33}\,q_3^4 & \gamma_{34}\,q_3^2\,q_4^2 \\ \gamma_{14}\,q_4^2 & 0 & \gamma_{34}\,q_3^2\,q_4^2 & \gamma_{44}\,q_4^4 \end{array}\right|, \quad (9)$$

We chose $a$ to get the pole at the physical position. $\beta$ and $\gamma$ 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 $|g_{\pi\Sigma}| = 0.45$.

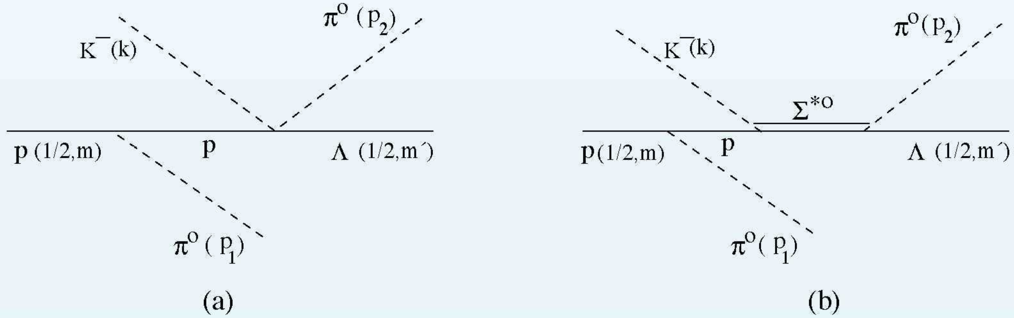
## The reaction $K^- p \to \pi^0 \Sigma^{*0}(1385) \to \pi^0 \pi^0 \Lambda(1116)$

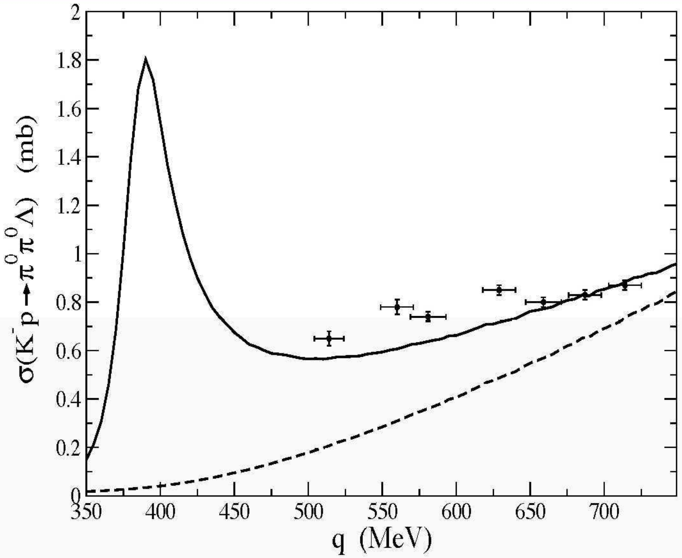
Prakhov...PRD04

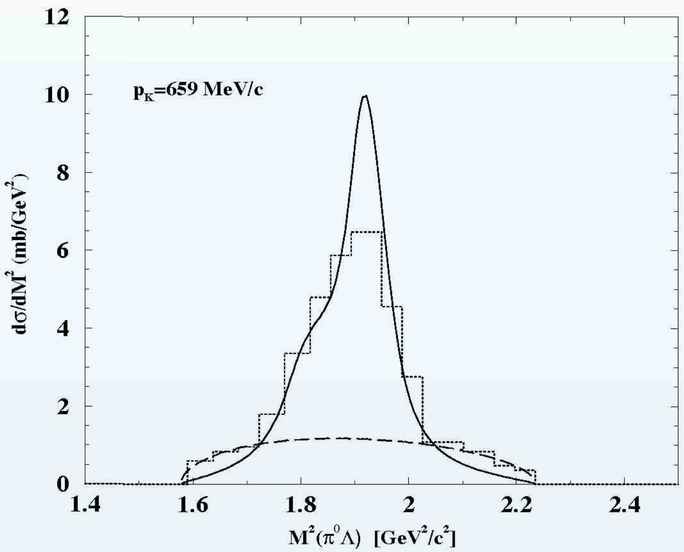


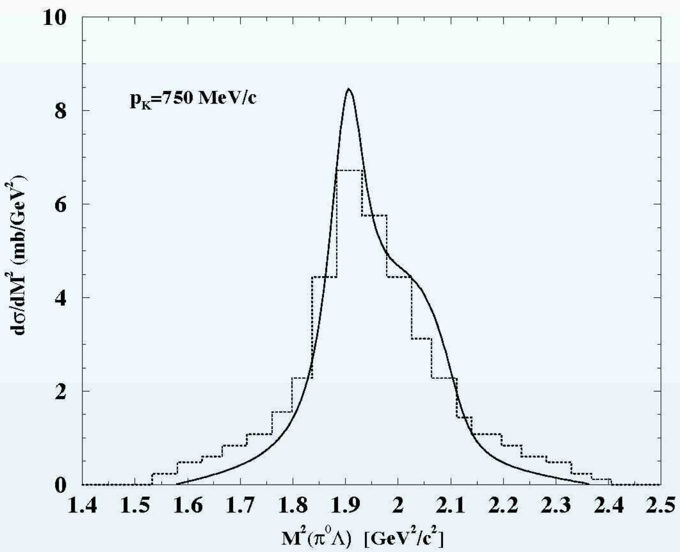

$$-it(\vec{p}_1, \vec{p}_2) = \frac{-iT_{\bar{K}N \to \pi\Sigma^*}}{3\sqrt{2}} \frac{f_{\Sigma^*\pi\Lambda}/m_\pi}{M_R - M_{\Sigma^*} + i\Gamma_{\Sigma^*}(M_R)/2} \left\{ \begin{array}{ll} -2p'_{2z} & m' = +1/2 \\ p'_{2x} + ip'_{2y} & m' = -1/2 \end{array} \right\}. \quad (10)$$

## Conventional scheme for $K^- p \to \pi^0 \pi^0 \Lambda$

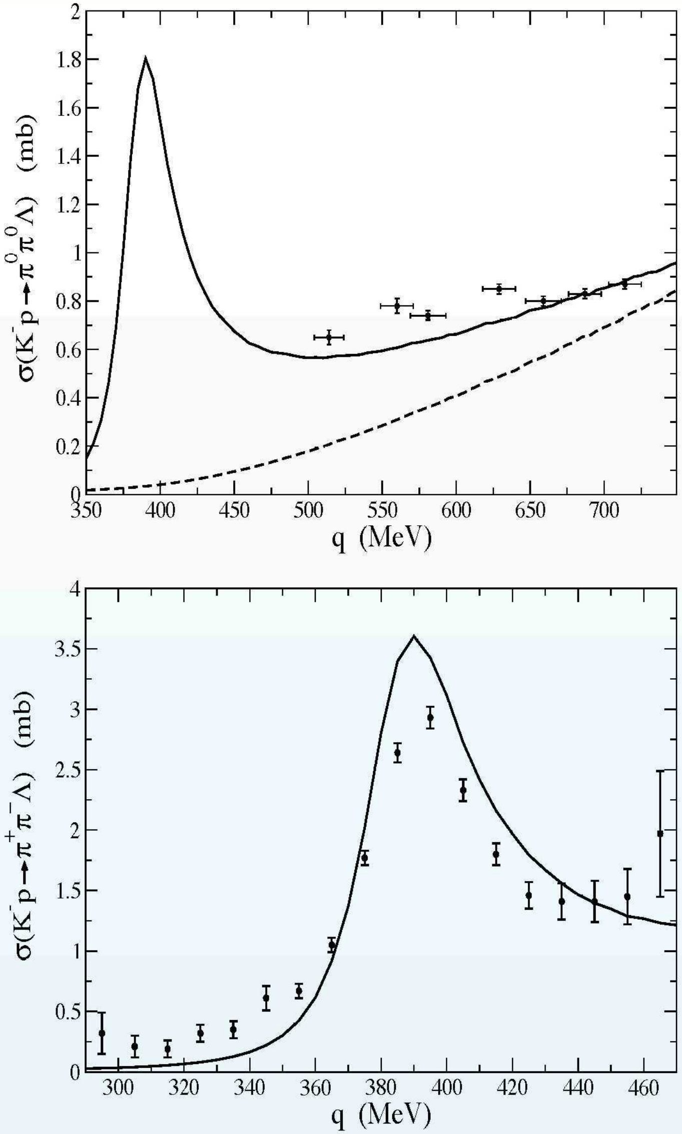





$K^- p \rightarrow \pi^0 \pi^0 \Lambda$, Prakhov,




$K^- p \to \pi^0\pi^0\Lambda$, Prakhov, $K^- p \to \pi^+\pi^-\Lambda$, Mast

## Hadron in a nuclear medium

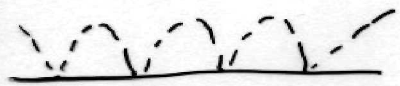
Talks of Mosel and Metag tuesday
Good review on the topic
M. Post, S. Leupold and U. Mosel , Nucl. Phys. A 741 (2004) 81
I present here examples closely linked to the chiral dynamics of the hadrons

- Kaons in a nuclear medium
- Kaon atoms
- $\Lambda(1520)$ in the medium

One does many body corrections in the $\bar{K}N$ amplitude

$$t(s) \longrightarrow \tilde{t}(\underset{K\uparrow}{q}, \underset{\uparrow N}{\rho})$$

$$\Rightarrow \quad \Pi_{\bar{K}}(q^0, \vec{q}, \rho) = 2\int \frac{d^3p}{(2\pi)^3}\, n(\vec{p}) \left[ \tilde{t}_{\bar{K}p}(q, \rho) + \tilde{t}_{\bar{K}n}(q, \rho) \right]$$

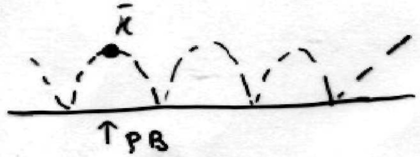


$$N \rightarrow \frac{1-n(\vec{p})}{p^0 - \varepsilon(p) + i\epsilon} + \frac{n(\vec{p})}{p^0 - \varepsilon(p) - i\epsilon}$$

Pauli blocking

Koch 94
Waas, Weise 97

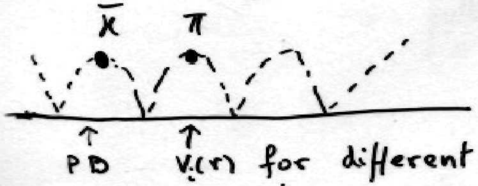
Shifts the $\Lambda(1405)$ at higher energies




Selfconsistent use of $\bar{K}$ selfenergy in the loops

Lutz 98

Brings back the $\Lambda(1405)$ to the free position

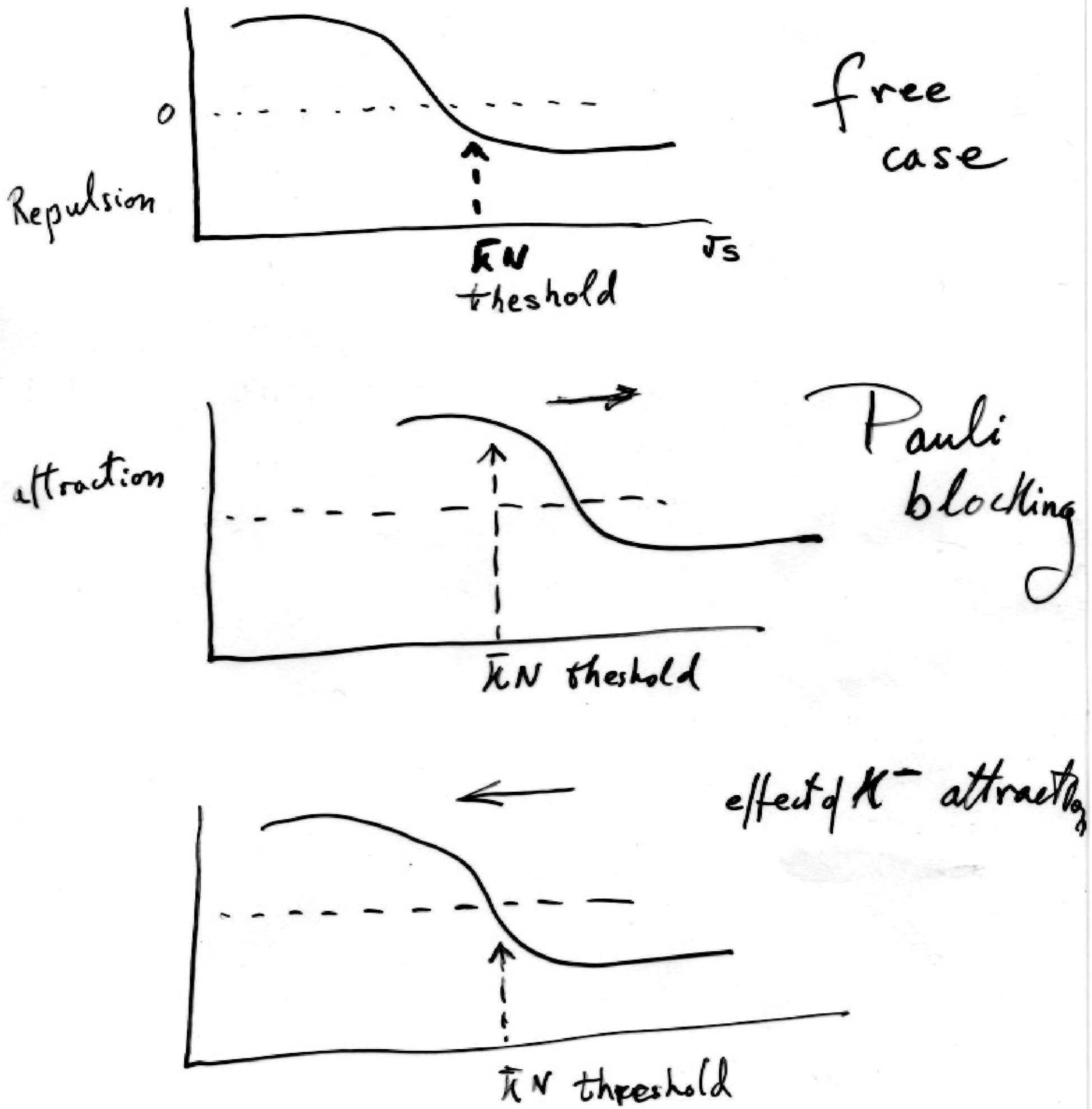



for different baryons

Selfcons. $\bar{K}$ + $\pi$ selfenergy + mean field baryon potential

Ramos, E.-O. NPA (2000)

Opens new decay channels and widens spectral function



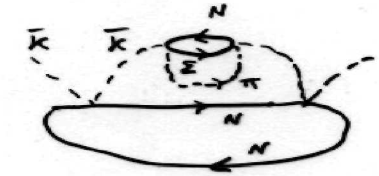
free case
0
Repulsion
$\bar{K}N$ theshold
$\sqrt{s}$
Pauli blocking
attraction
$\bar{K}N$ theshold
effect of $K^-$ attraction
$\bar{K}N$ threshold

# Medium decay channels

Koch
Waas, Weise

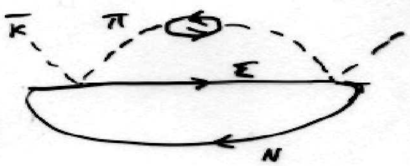

$\bar K \Rightarrow (\Sigma h)\,\pi \quad , (\Lambda h)\,\pi$

Lutz

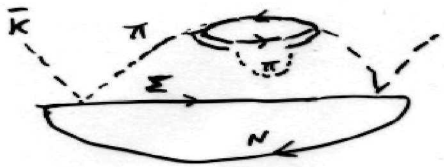



$+ \ \bar K \to (\Sigma h)(ph)\pi, (\Lambda h)(ph)\pi$

Ramos

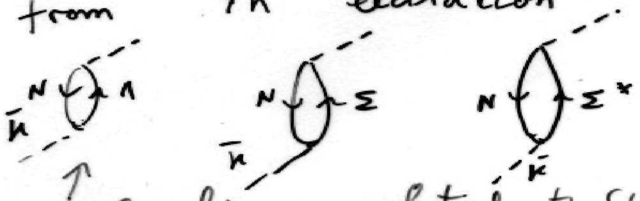



$+ \ \bar K \to (\Sigma h)(ph), (\Lambda h)(ph)$

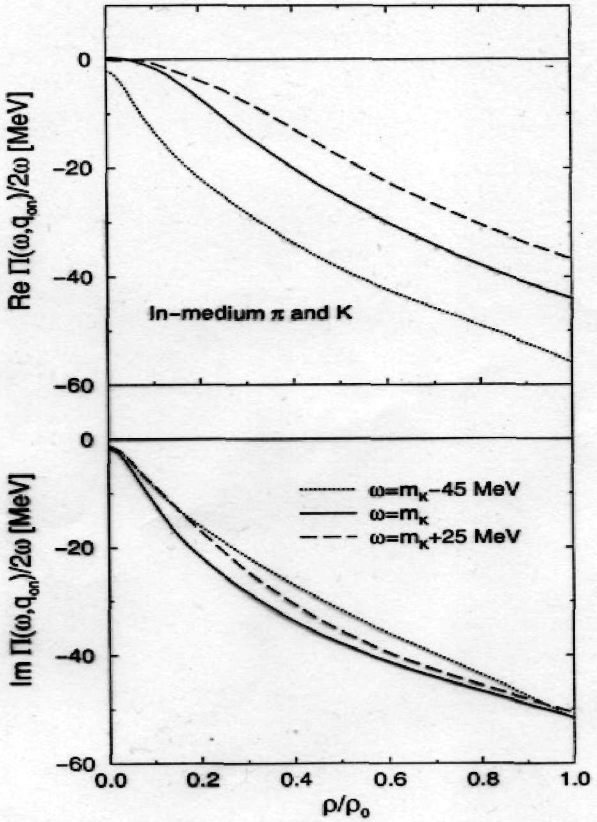



$+$ extra $(\Sigma h)(ph)\pi, (\Lambda h)(ph)\pi$

In addition we have p-wave $\bar K$ selfenergy from $Yh$ excitation




Couplings related to SU(3) coeff. D, F of original chiral Lagrangian




Re Vopt

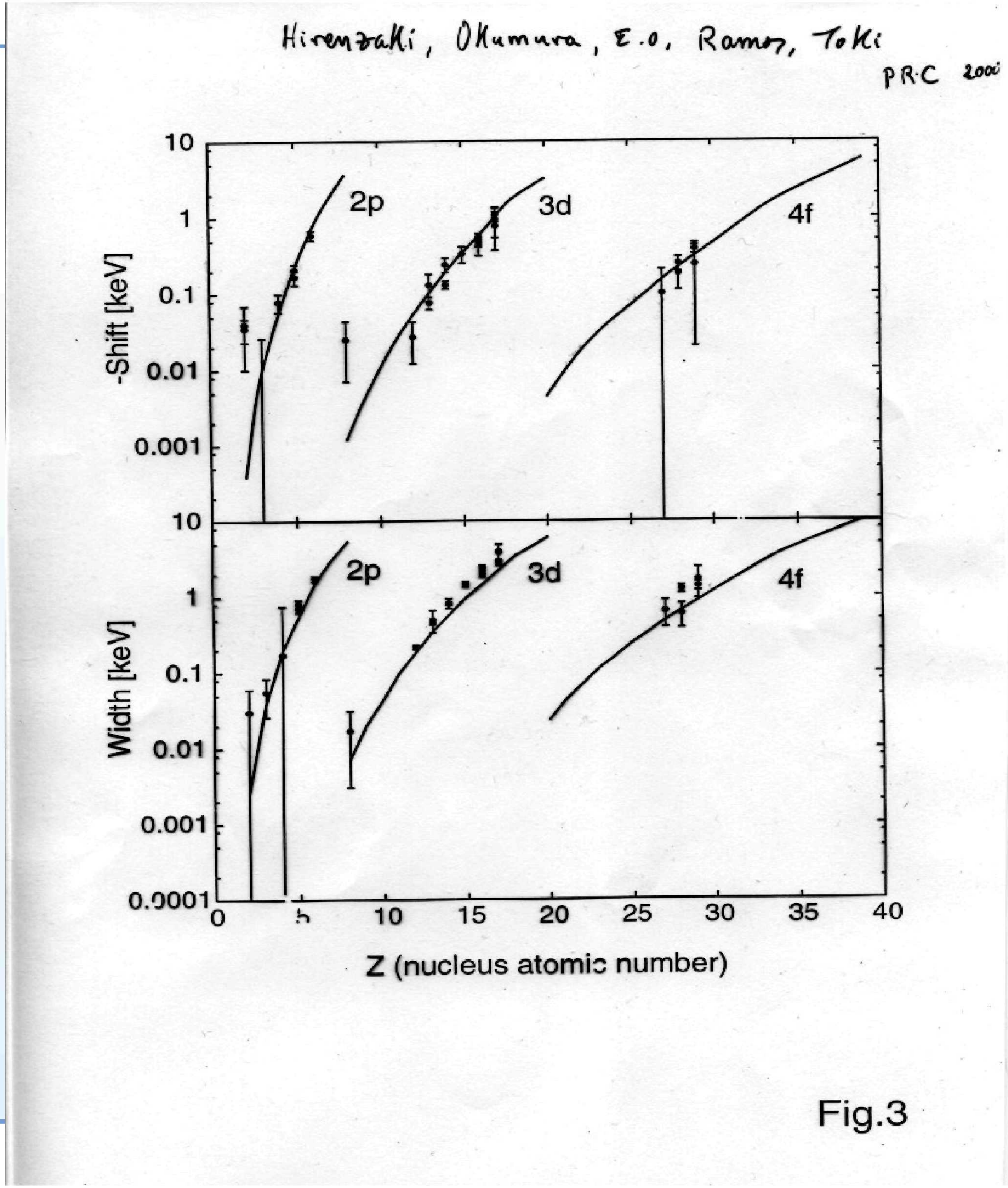
Im Vopt $\equiv -\frac{\Gamma}{2}$

FIG. 7. Real (top) and imaginary (bottom) parts of the $K^-$ optical potential as a function of density obtained from the *In-medium pions and kaons* approximation. Results are shown for three different $K^-$ energies: $\omega = m_K - 45$ MeV (dotted lines), $\omega = m_K$ (solid lines) and $\omega = m_K + 20$ MeV (dashed lines).

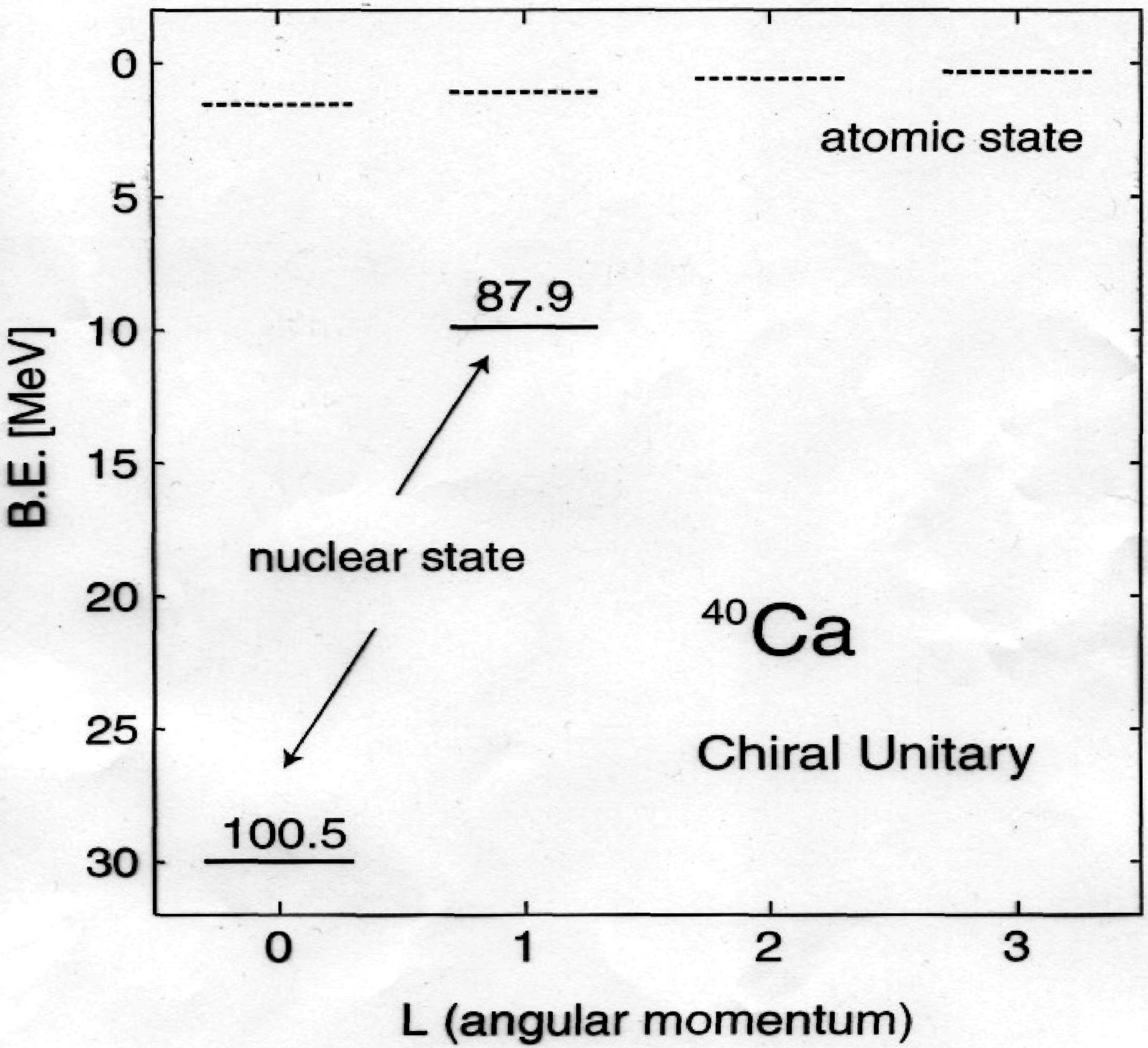
Similar results in

Schaffner-Bielich, Koch, Effenberg NPA 2000

Cieply, Friedman, Gal, Mares NPA 2001



Hirenzaki, Okumura, E.O., Ramos, Toki
PRC 2000
-Shift [keV]
Width [keV]
2p
3d
4f
Z (nucleus atomic number)
Fig.3



0
5
10
15
20
25
30
B.E. [MeV]
atomic state
87.9
nuclear state
40Ca
Chiral Unitary
100.5
0
1
2
3
L (angular momentum)

## Claims of narrow deeply bound kaon atoms

Akaishi and Yamazaki made rough estimates of the kaon nucleus optical potential ignoring the selfconsistency and predicted narrow bound states For the A=3 and 4 systems

leads to binding energies of the kaon of the order of 70 MeV with widths around 75 MeV, ( from $K^- N \to \pi\Sigma$).

Next, the nucleus is allowed to shrink to densities $\rho = 10\rho_0$

Then, $K^-$ bound in $^3He$ by 108 MeV and in $^4He$ by 86 MeV
Experimentalist "find" a possible deeply bound $K^-$ state. Suzuki et al. PLB597 (2004)

$K^- \, ^4He \to Sp$, S(3115) Strange tribaryon.
But I=1, and if $K^-$ state, B=195 MeV

Contradiction with AY with I=0 and 108 MeV!!

KEK Suzuki et al



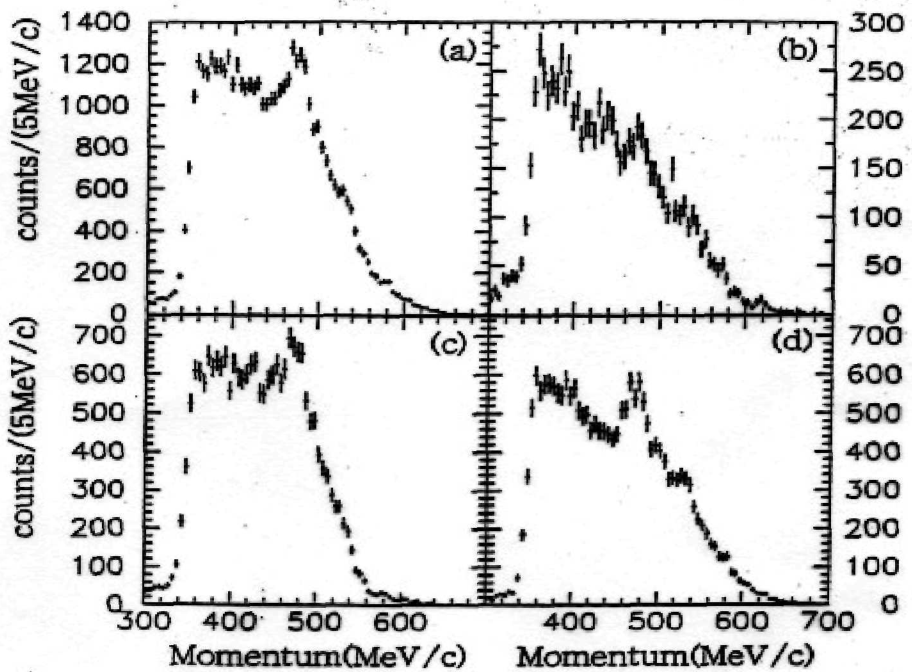



**Fig. 5.** Proton momentum spectra without energy-loss correction, with cut conditions defined in Fig. 4: (a) with the "$\pi$"-cut, (b) with the "$p$"-cut, (c) with "fast-$\pi$"-cut, and (d) with "$\pi$"-cut excluding the fast pions.

## The saga continues

AY strike back:

Introduce relativistic corrections (use Klein Gordon equation) ( The chiral theories always did)

some spin orbit corrections

Increase ad hoc the $\bar{K}N$ interaction

B=195 comes out then

At this point the $K^-$ potential in the center of the nucleus has become 618 MeV!!!

Experimental reconversion: ..... Sato in BadHonnef, PANIC05... claim the state seen is indeed a $K^-$ bound state.

## Discussion of the KEK experiment, Suzuki et al.

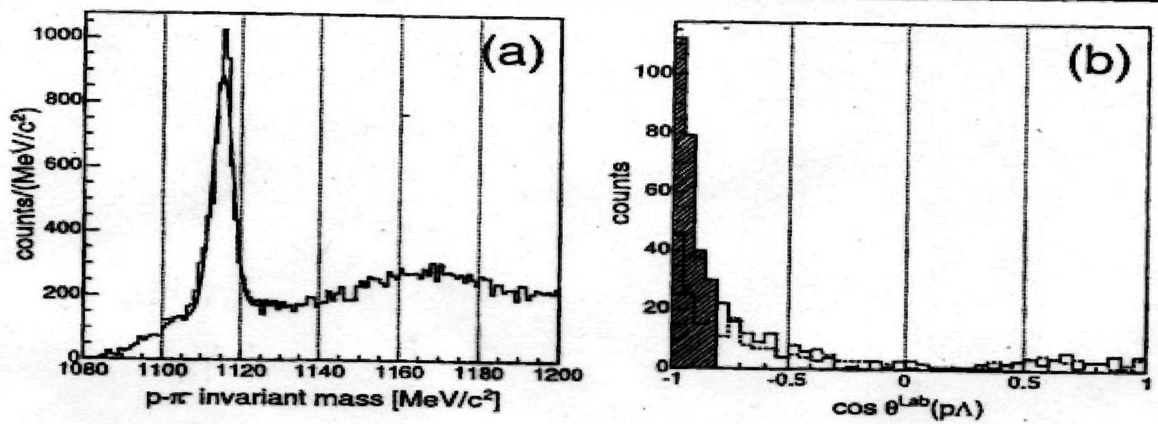
- Kaons at rest absorbed: $K^- \, {}^4He \to S \, p$, They see a peak in the p spectrum around 500 MeV/c.
- Auger emission of the p. Binding energy taken by $K^-$.
- Alternative explanation
  .. E. O. and H. Toki (2005)
  .. Many possible conventional mechanisms studied and discarded
- The one passing all tests
- $K^- NN \to \Lambda N \qquad p_N = 562 MeV/c$
- $K^- NN \to \Sigma N \qquad p_N = 488 MeV/c$
  The other nucleons left as spectators
- exp. peak seen at $p_p = 475 MeV/c$ (some energy loss in thick target)
  But what about a peak at $p_p = 562 MeV/c$ from $K^- pp \to \Lambda p$?

## FINUDA experiment, M. Agnello et al. PRL 94 (2005)

- $K^-$ absorption at rest from $^6Li,^7Li,^{12}C....$
  They look for events back to back. Find two peaks in $\Lambda p$ invariant mass: a narrow one at higher energies and a broad one at lower energies. The latter is identified with a bound $K^-$ state.
- Cuts: $p_\Lambda > 300MeV/c$ to eliminate $K^-p \rightarrow \Lambda\pi$
  $|cos(\theta)| > 0.8$
- Narrow peak identified as $K^-pp \rightarrow \Lambda p$ removing binding energy
  Broad one at lower energies: "bound $K^-$ state in pp " with B=115 MeV.
- Questions:
  where does the binding energy of the kaon go?
  Where is the strength if $K^-pp \rightarrow \Lambda p$ exciting the nucleus (largest part)?

FINUDA Agnello et al






ı) Invariant-mass distribution of a proton and a $\pi^-$ for all the events in which these two particles are observed, ssian together with a linear background in the invariant-mass range of 1100–1130 MeV/$c^2$. (b) Opening angle Λ and a proton: solid line, $^6$Li, $^7$Li, and $^{12}$C; dashed line, $^{27}$Al and $^{51}$V. The shaded area ($\cos\theta^{\mathrm{Lab}} < -0.8$) is sel ck event.

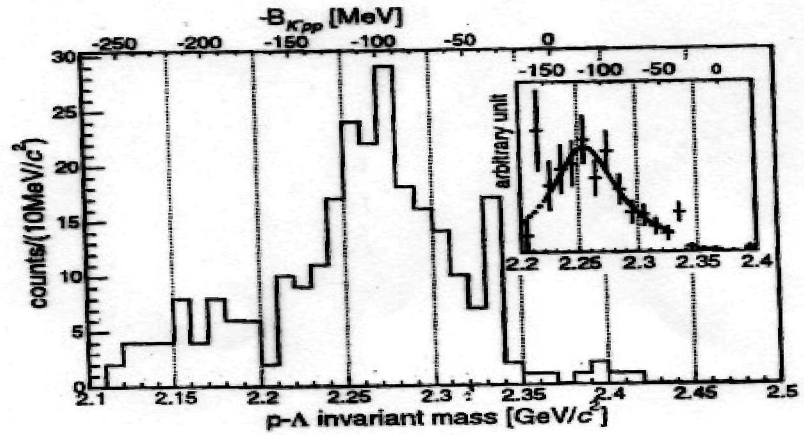
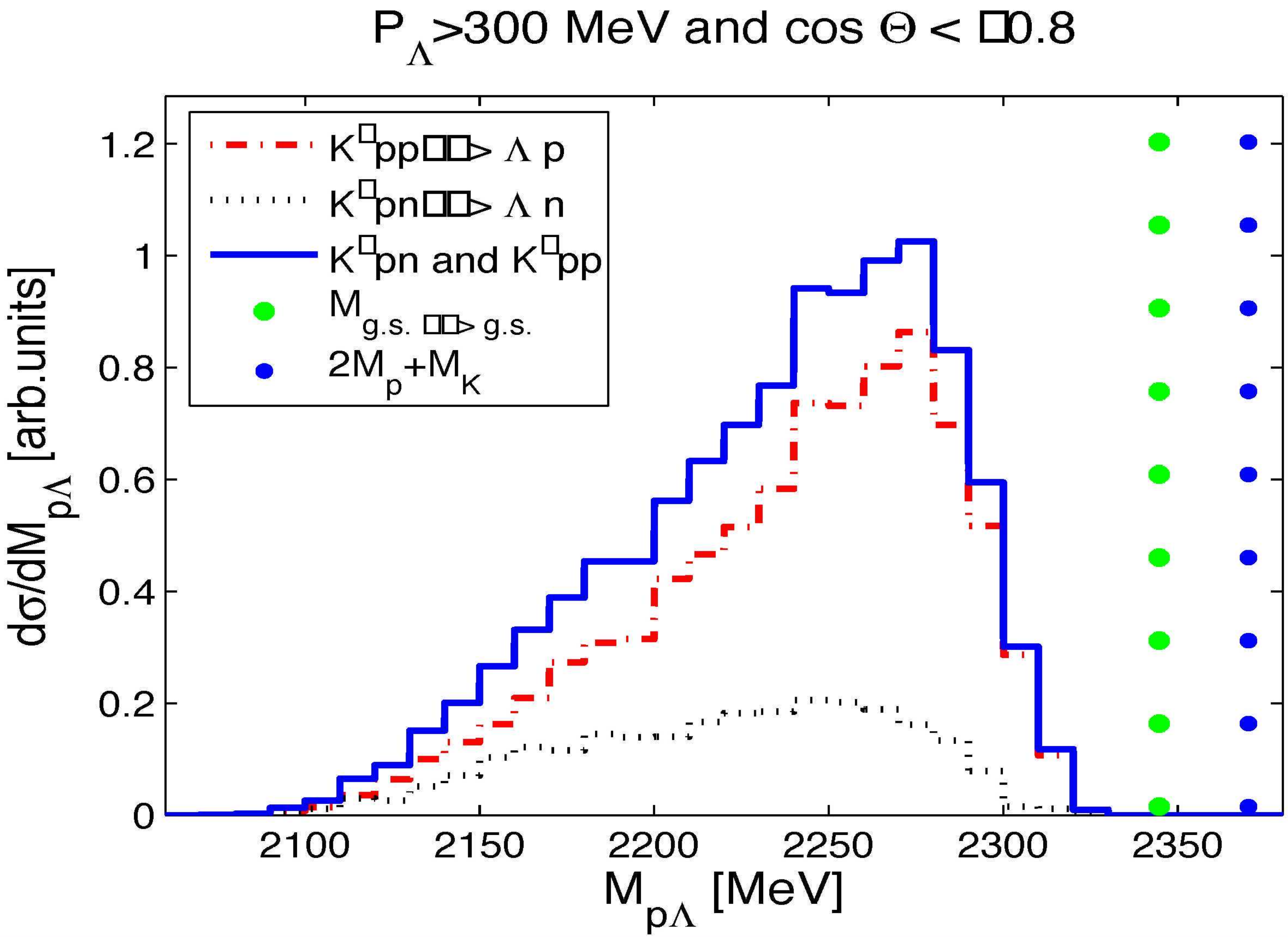



FIG. 3. Invariant mass of a Λ and a proton in back-to-back correlation ($\cos\theta^{\mathrm{Lab}} < -0.8$) from light targets before the acceptance correction. The inset shows the result after the acceptance correction for the events which have two protons with well-defined good tracks. Only the bins between 2.22 and

## Our description of the peaks

V. K. Magas, A. Ramos, E. O and H. Toki, (2006)

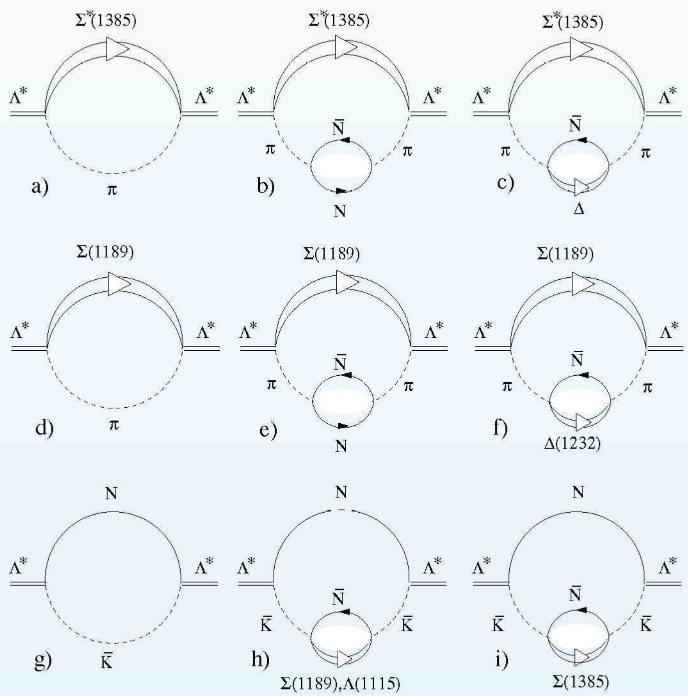
- We run a computer simulation code for $K^-$ absorption in nuclei by pp and pn pairs:
- $|\Psi(r)|^2$ distribution for $K^-$ peaked around surface of nucleus
- $K^-$ absorbed by pp or pn, with momenta randomly chosen from local Fermi sea.
- energy and momentum conservation including nuclear potential
- $\Lambda p$, $\Lambda n$ emitted according to phase space
- p, n have further collisions
  pN -> p' N    np -> pn    (fast n to fast p)
  done according to $\sigma\rho$ probability per unit length and experimental angular distributions ($\sigma_\Lambda = \frac{2}{3}\sigma_N$)
- $\Lambda p$ invariant mass reconstructed from final events.




$^{12}C$ Results imposing the experimental angle cut for back to back events, $\cos\Theta_{\vec{p}_\Lambda \vec{p}_p} < -0.8$, and up to three collisions.

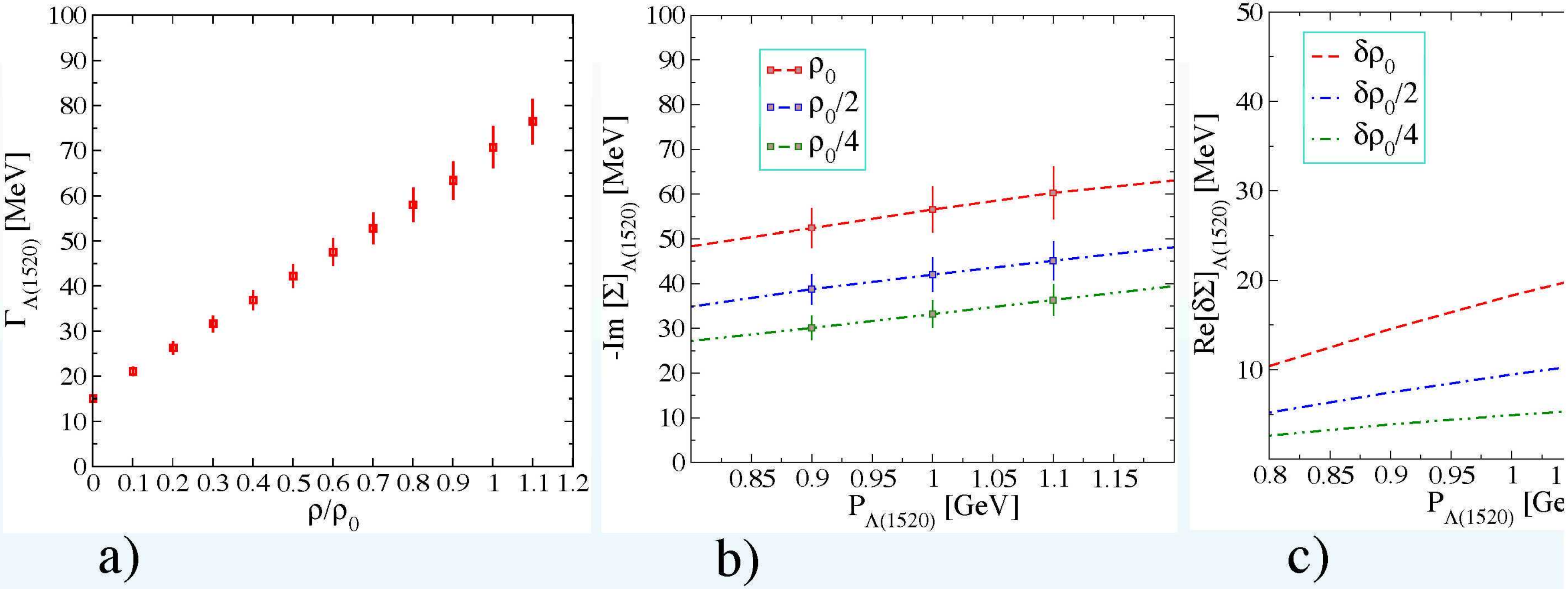
# $\Lambda(1520)$ in the nuclear medium

The coupling of the $\Lambda(1405)$ to $\pi\Sigma(1385)$ is very large but decay into this channel practically suppressed because of lack of phase space.
In nuclei a $\pi$ can excite $ph$. Plenty of phase space. Large width.




M.Kaskulov and E. O. , Phys Rev C (2006)

# Results for $\Lambda(1520)$ in the nuclear medium




These drastic changes could be observed experimentally suggestion made in Kaskulov, Roca, E. O, Eur. Phys. J. A (2206) by looking at the A dependence of the production cross section in

- proton induced $\Lambda(1520)$ production
- photon induced $\Lambda(1520)$ production (in progress at Spring8/Osaka)

## Conclusions

- Chiral dynamics is a powerful and ideal tool to face hadron interactions at intermediate energies in free space and in nuclei.
- It has shown as a side effect that some popular resonances qualify as dynamically generated or quasibound states of hadrons.
- It has predicted the existence on new resonances. Evidence for the second $\Lambda(1405)$ recently found.
- Chiral dynamics is important when dealing with hadrons in a nucleus.
- It makes prediction for kaon interaction with nuclei in good agreement with data of Kaon atoms. Predicts deeply bound kaon states but with a large width.
- strinking medium effects in some resonances, like the $\Lambda(1520)$

## Deeply bound kaon states

- The $K^-$ optical potential on which predictions of narrow deeply bound $K^-$ states was done is overly exagerated and incomplete in the decay channels.
- The KEK and FINUDA experiment do not have any support for the interpretation of the data as bound kaons except the " theoretical predictions" of the mentioned work.
- We have shown that all the peaks can be interpreted in terms of $K^-$ absorption on pairs of nucleons,
  in KEK with remnant nucleus as spectator
  in FINUDA, first peak with remnant nucleus as spectator
  second peak with nuclear excitation to the continuum
- These mechanisms passed all tests for which there were available data.

# Summary of DHD06 Workshop, Kyoto Feb 2006

- Akaishi strikes back, confusion of cut off in field theory and range of interaction. No selfconsistency yet, still $10\rho_0$ density.
- Yamazaki strikes back, makes wrong assumption on final state in $K^{-}\,{}^4He$ absorption going to $p\Sigma\, nn$ instead of $p\Sigma\, d$ ( small recoil energy of $d$, 10 MeV for 200 MeV/c of Fermi motion). Misses the experimental fact of the narrow signal in FINUDA for $K^-$ absorption without extra final state interaction. Disguised offer of compromise, peaks partly from $K^-$ absorption and partly from production of tribaryon. Compromise rejected: too much coincidence that the peaks appear in all nuclei at the $K^-$ absorption kinematics.
- No help from any body else of the japanese community.
- No claims in the experimental talks about deeply bound kaon atoms. Back to tribaryon claim.
- Iwasaki pledge "please understand all this is still preliminary, we are working to understand what happens"
- The paper of 2003 with claims for deeply bound K from the $K^-(at\ rest)$ absorption in ${}^4He$, $(K^-, n)$ has been withdrawn.

# Summary of DHD06 Workshop, Kyoto Feb 2006

- Y. Yamagata presents calculations of $(K^-, p)$ in flight and concludes that even if there are deeply bound kaon states the signal would be too weak to be seen in present experiments.
- S. Okada ( Hayano exp.) presents results for $3d \rightarrow 2p$ X-rays of Kaonic Helium. 2p shift: Old experiments 40 eV, chiral unitary model 0.2 eV, Akaishi potential 11 eV. New experiment compatible with zero with 3-4 eV precision.