Kaonic Systems

E. Oset, T. Sekihara, D. Jido, J. Yamagata, M. Bayar, A. Martinez,
T. Hyodo, A. Dote, M. Oka

Chiral dinamical approach to Kbar N interaction.
Recent results. The K^- d -> n Σ π reaction.
Chiral dinamical approach Kbar Nucleus interaction
Kaonic atoms. Deeply bound Kaonic states?
The K^- pp system
New challenging kaonic systems: K Kbar N, Kbar KbarN.
Extrapolation to charm: the DNN system!!

Chiral Lagrangian for pseudoscalar-baryon interaction

At lowest order in momentum the interaction Lagrangian reduces to

$$L_1^{(B)} = \langle \bar{B} i \gamma^\mu \frac{1}{4f^2} [(\Phi \partial_\mu \Phi - \partial_\mu \Phi \Phi) B - B (\Phi \partial_\mu \Phi - \partial_\mu \Phi \Phi)] \rangle$$

: $K^- p$ scattering

there are 10 channels, namely K^-p, $\bar{K}^0 n$, $\pi^0\Lambda$, $\pi^0\Sigma^0$, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\eta\Lambda$, $\eta\Sigma^0$, $K^+\Xi^-$ and $K^0\Xi^0$. In the case of K^-n scattering the coupled channels are: K^-n, $\pi^0\Sigma^-$, $\pi^-\Sigma^0$, $\pi^-\Lambda$, $\eta\Sigma^-$ and $K^0\Xi^-$. These amplitudes have the form

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

One solves the Bethe- Salpeter equation in coupled channels

T= (1-VG) $^{-1}$ V

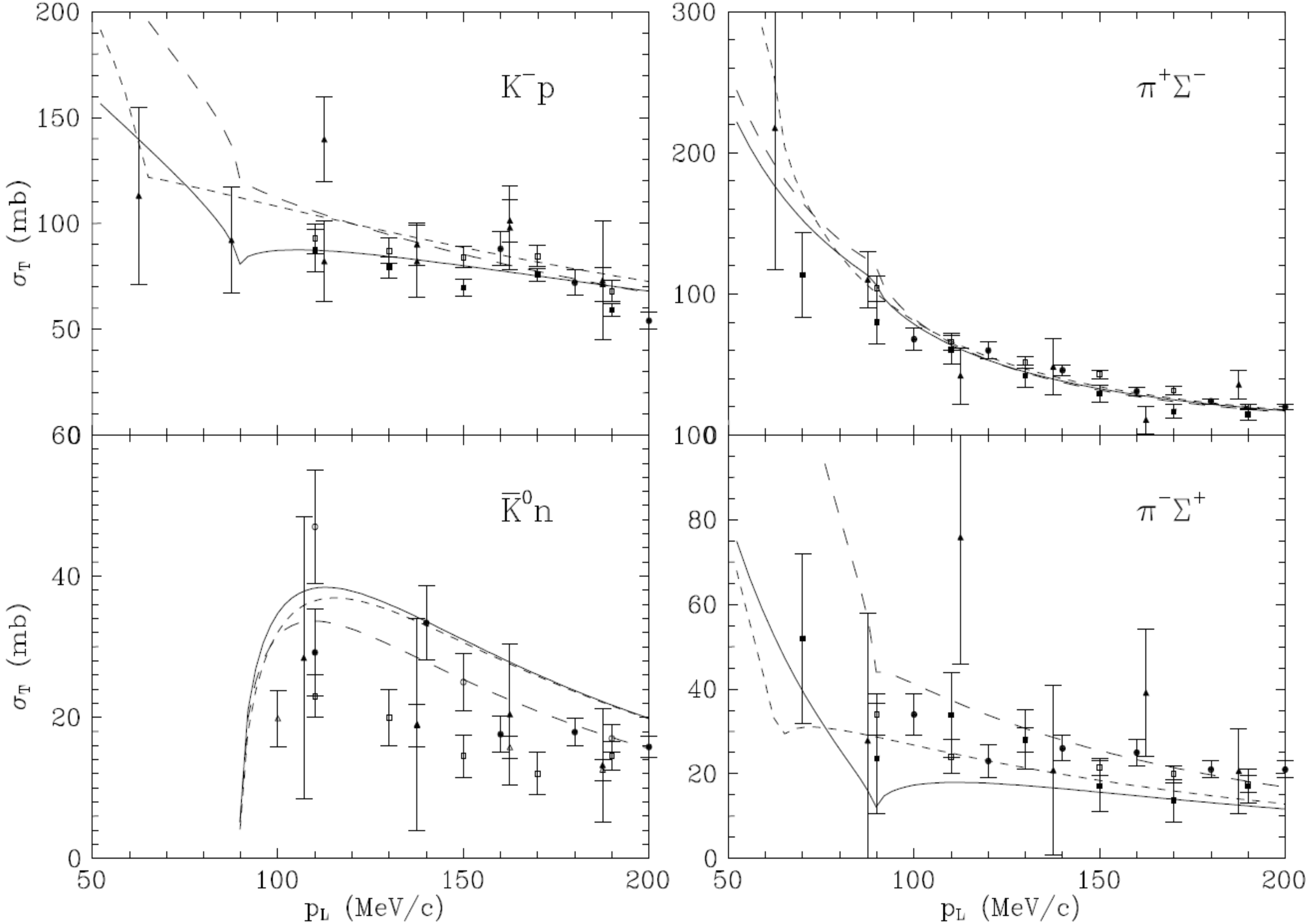
This produces transition amplitudes from K^- p to any other channel. Gives rise to resonances, Λ(1405), Λ(1670), ∑(1650)…

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix}$$

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

$$\begin{aligned} G_l &= i2M_l \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon} \\ &= \frac{2M_l}{16\pi^2} \Big\{ a_l(\mu) + \ln \frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s} \ln \frac{m_l^2}{M_l^2} + \\ &\qquad + \frac{\bar{q}_l}{\sqrt{s}} \left[\ln(s - (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) + \ln(s + (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) \right. \\ &\qquad \left. - \ln(-s + (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) - \ln(-s - (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) \right] \Big\} \end{aligned}$$

Oset, Ramos NPA98



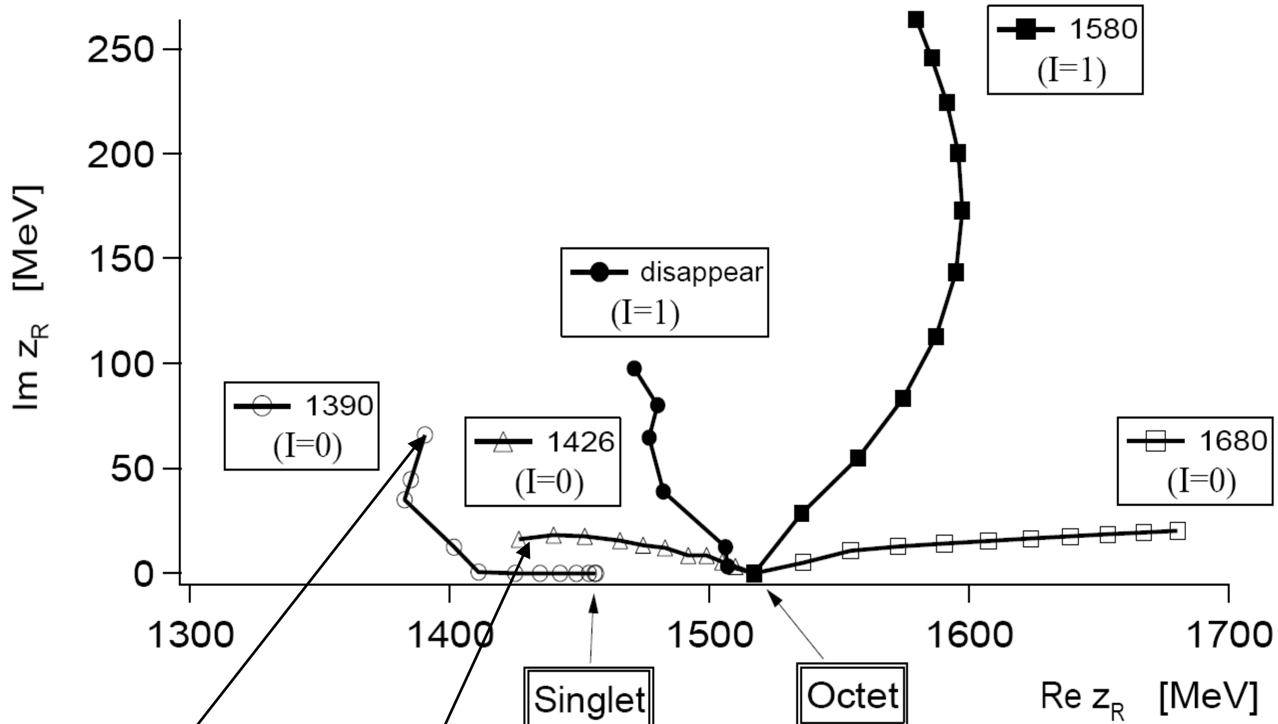
Poles of S=-1 $J^P = 1/2^-$ Resonances

Jido, Oller, Oset, Ramos, Meissner NPA03

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

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

$x \in [0,1]$



Couples strongly to Kbar N

Couples strongly to pi Sigma

DEAR motivated work: All calculations incompatible with DEAR measurement of K^- p atom (the data turned out to be incorrect)

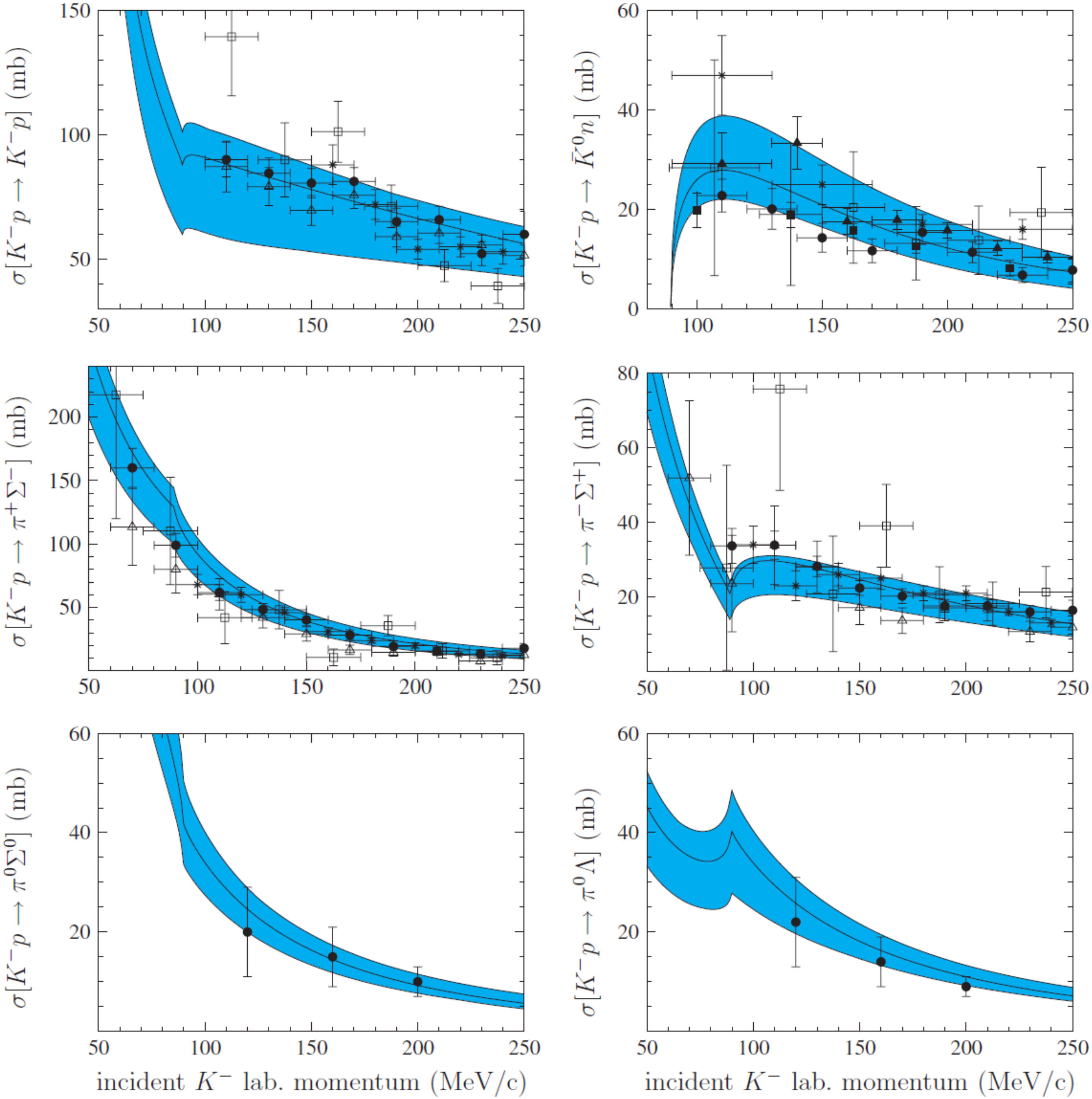
The lowest order calculations have been improved recently in

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

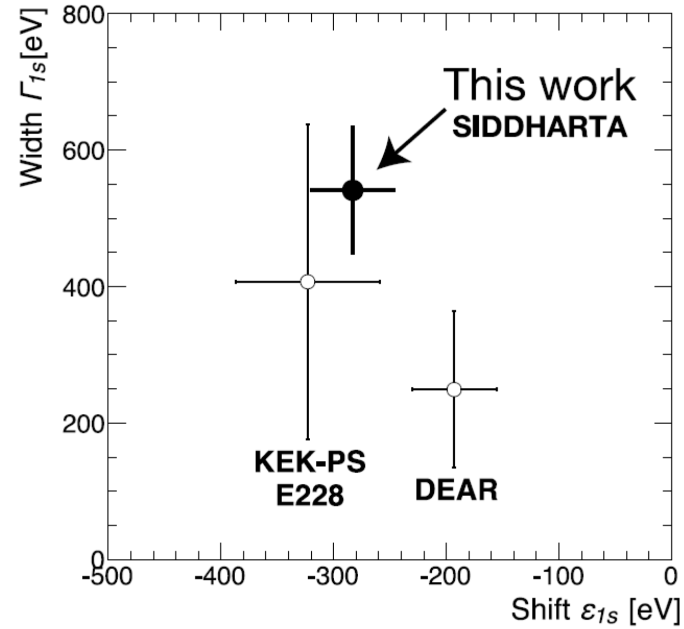
Some differences: predictions for the scattering lenghts. More experimental work on $K^- p$ atoms is needed.

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



Borasoy, Niessler, Meissner PRC 2006

A New Measurement of Kaonic Hydrogen X rays



M. Bazzi et al. SIDHARTA, PLB 2011

Ikeda, Hyodo, Weise

	TW	TWB	NLO
pole positions [MeV]	1422 − 16 i 1384 − 90 i	1421 − 17 i 1385 − 105 i	1424 − 26 i 1381 − 81 i

M. Mai and U.G. Meissner

$$\mathcal{R}_{\Sigma\pi} : \; W_1 = 1428^{+2}_{-1} - i\, 8^{+2}_{-2}\ \text{MeV} .$$

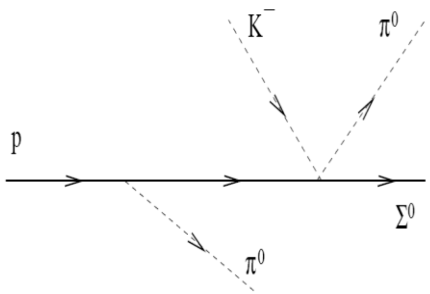
$$\mathcal{R}_{KN} : \; W_2 = 1467^{+11}_{-7} - i\, 75^{+9}_{-9}\ \text{MeV} .$$

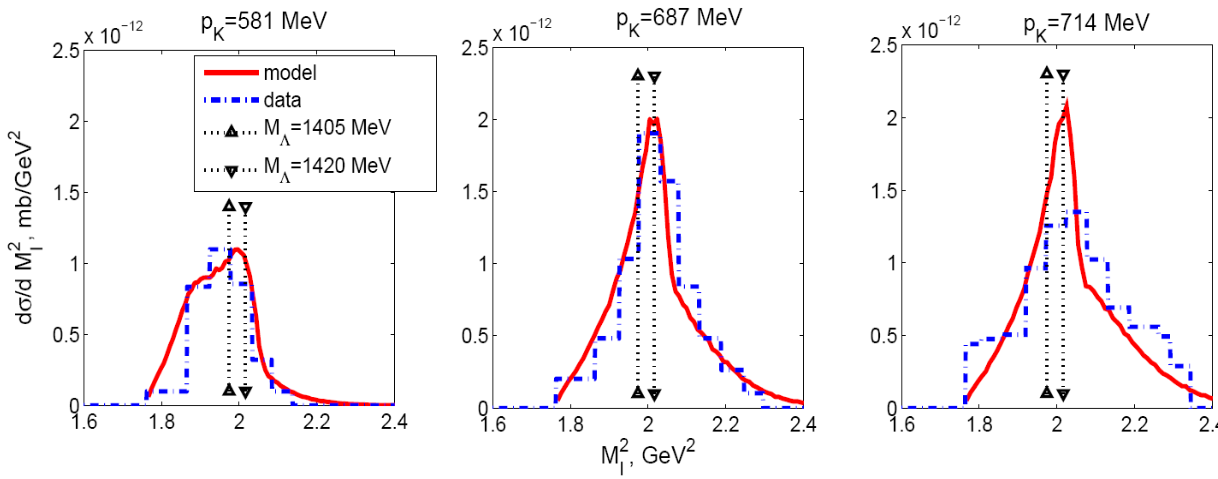
P_{klab}=235 MeV/c

General recommendation: If one wants to know where the poles of the resonances are, better use reactions where the resonances are produced and are clearly seen.

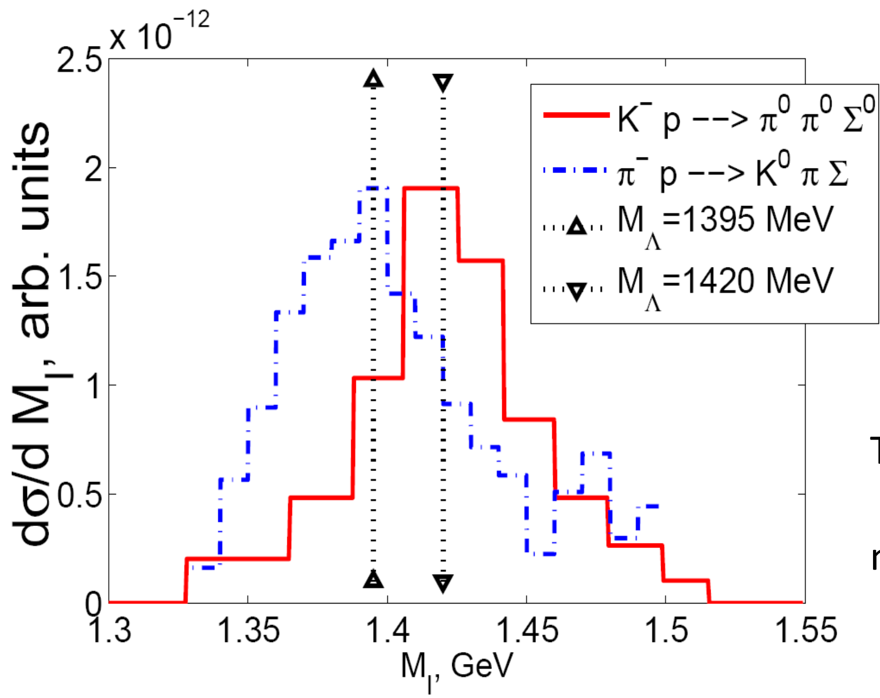
$K^- p \to \pi^0 \pi^0 \Sigma^0$ at $p_{K^-} = 514-750$ MeV/c

Prakhov, Nefkens... PRC04





Theory : Magas, Oset, Ramos PRL05

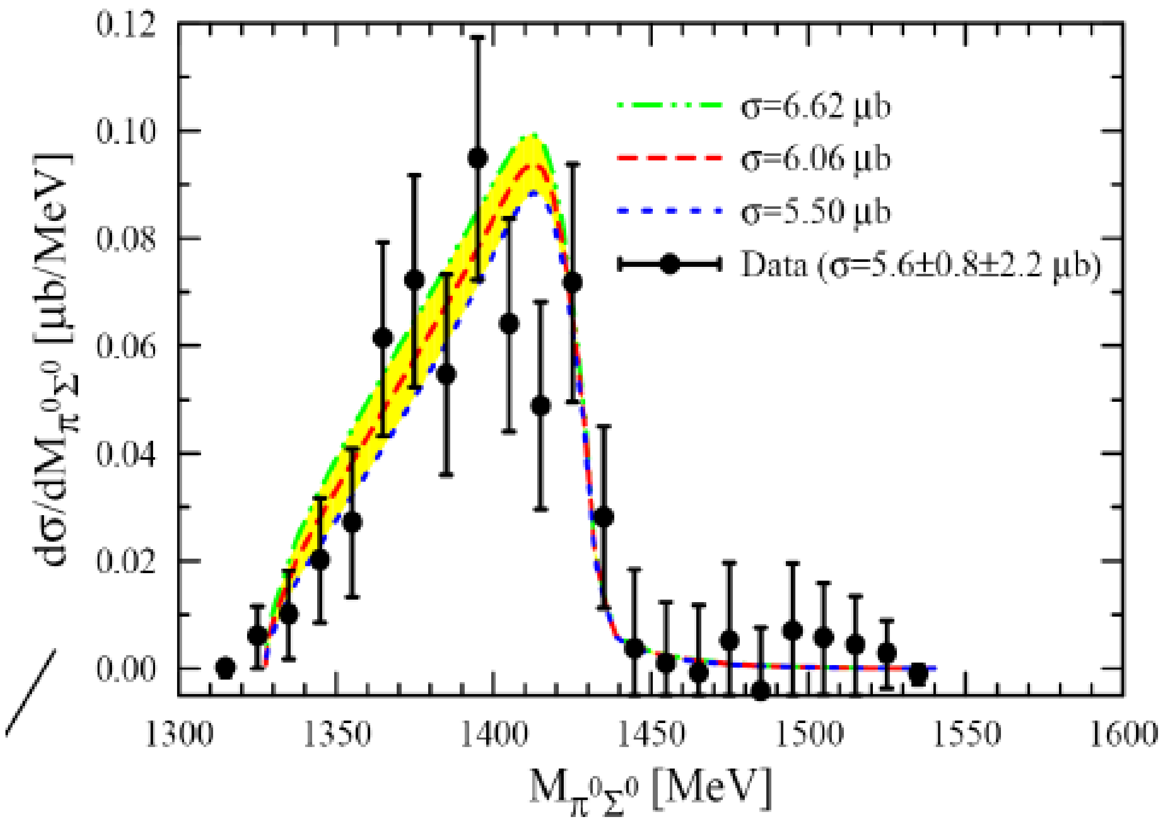


The $K^- p \to \pi^0 \pi^0 \Sigma^0$ reaction selects mostly narrow pole

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

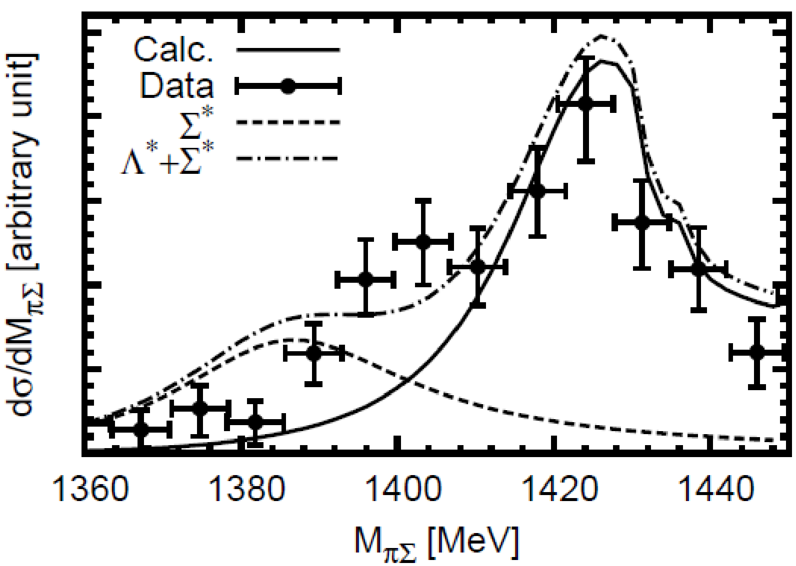
Hyodo, Hosaka, Oset, Ramos Vicente Vacas PRC03

ANKE data on the $pp \rightarrow pK^+Y^0$ → P K^+ π^0 Σ^0 reaction, Zychor PLB 2008



Kaonic production of $\Lambda(1405)$ off deuteron target in chiral dynamics

D. Jido[1], E. Oset[2], and T. Sekihara[3] PRC 2010



$K^- d \rightarrow \pi\Sigma n$

O. Braun *et al.*, Nucl. Phys. B **129**, 1 (1977)

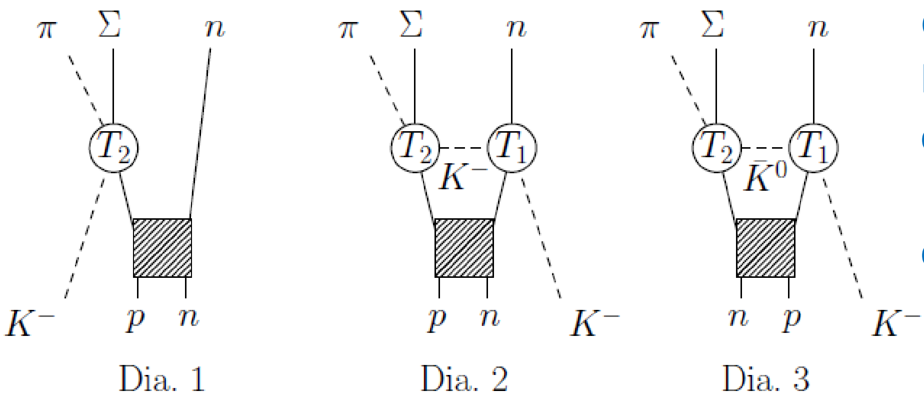


Fig. 2. Diagrams for the calculation of the $K^- d \to \pi\Sigma n$ reaction. T_1 and T_2 denote the scattering amplitudes for $\bar{K}N \to \bar{K}N$ and $\bar{K}N \to \pi\Sigma$, respectively.

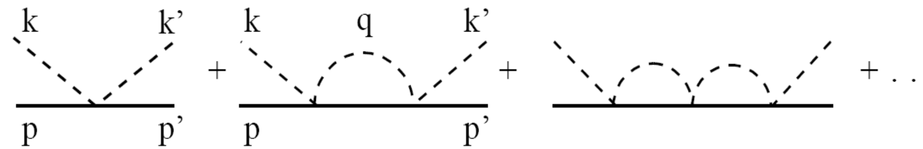
Recent work of Miyagawa, Haidenbauer question this approach **arXiv:1202.4272**
But it neglects the potential energy of the nucleons.
New results with Watson formalism or spectral functions support Jido's results

Ramos, E.O. 2000

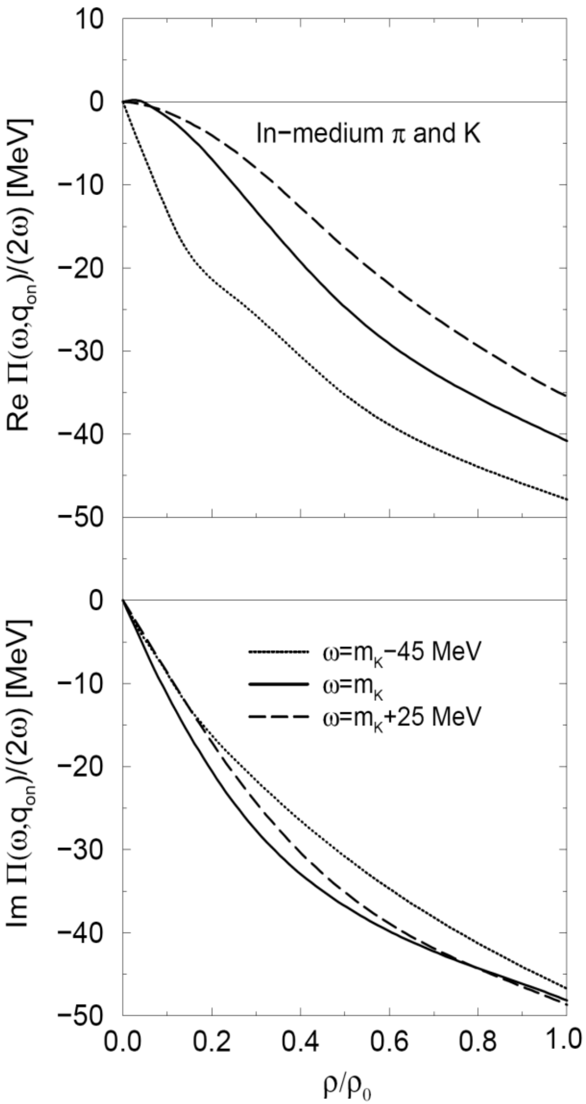
$2\,\omega\, V_{opt}=$ $$\Pi^s_{\bar K}(q^0,\vec q,\rho) = 2\int \frac{d^3p}{(2\pi)^3}\, n(\vec p)\left[T^{\bar K p}_{\rm eff}(P^0,\vec P,\rho)+T^{\bar K n}_{\rm eff}(P^0,\vec P,\rho)\right]$$

Kaons in nuclei

T(Kbar N)=



In the medium Pauli blocking effect on the nucleons is considered, plus baryon selfenergy, and K selfenergy is accounted for selfconsistently

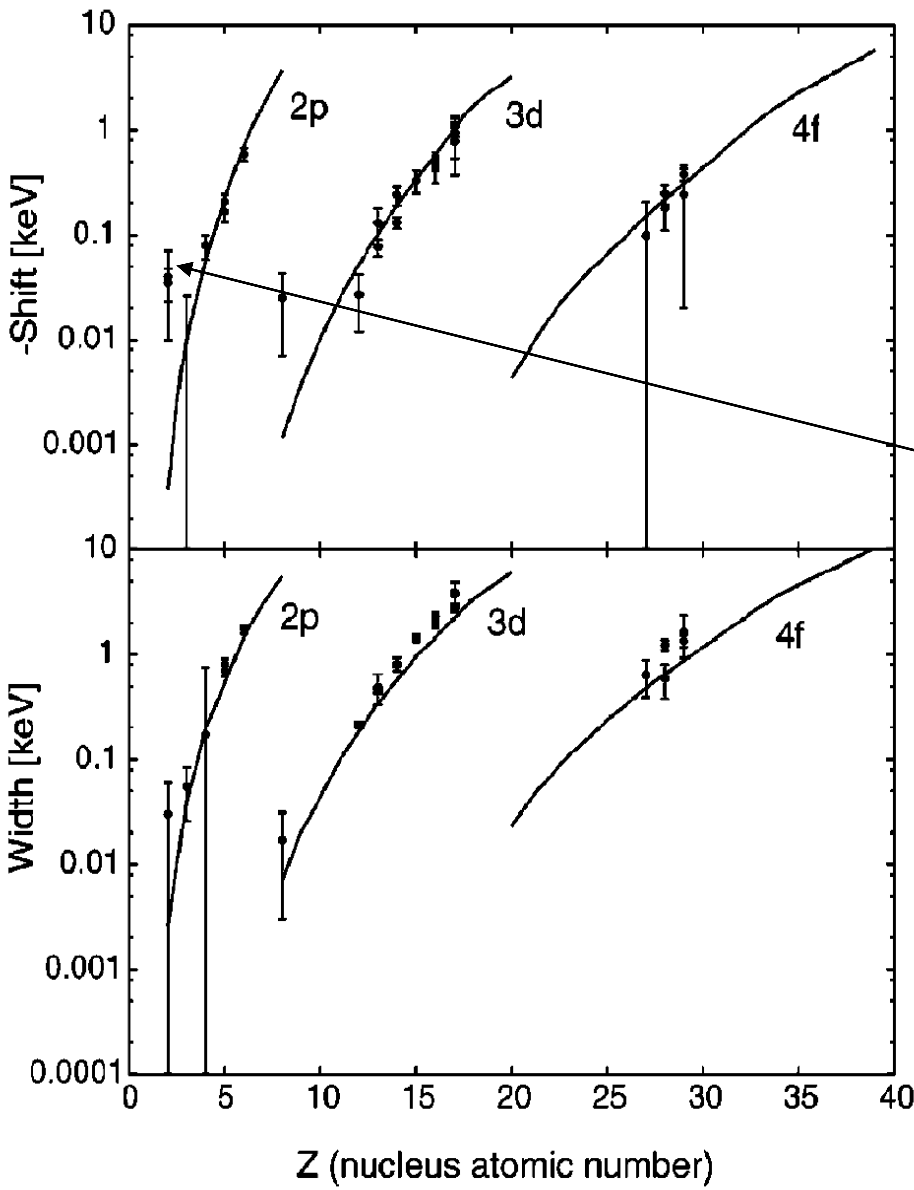


Re V_{opt}

Im V_{opt} = - Γ / 2

Similar results in Schaffner-Bielig, Koch, Effenberger, 2000
Lutz 98
Cieply, Friedman, Gal, Mares, 2001

Atomic orbits, Coulomb plus strong K optical potential



Hirenzaki, Okumura et al.
Phys Rev C (2000)

This discrepancy recently solved by Hayano et al.
New experiment in agreement with theory

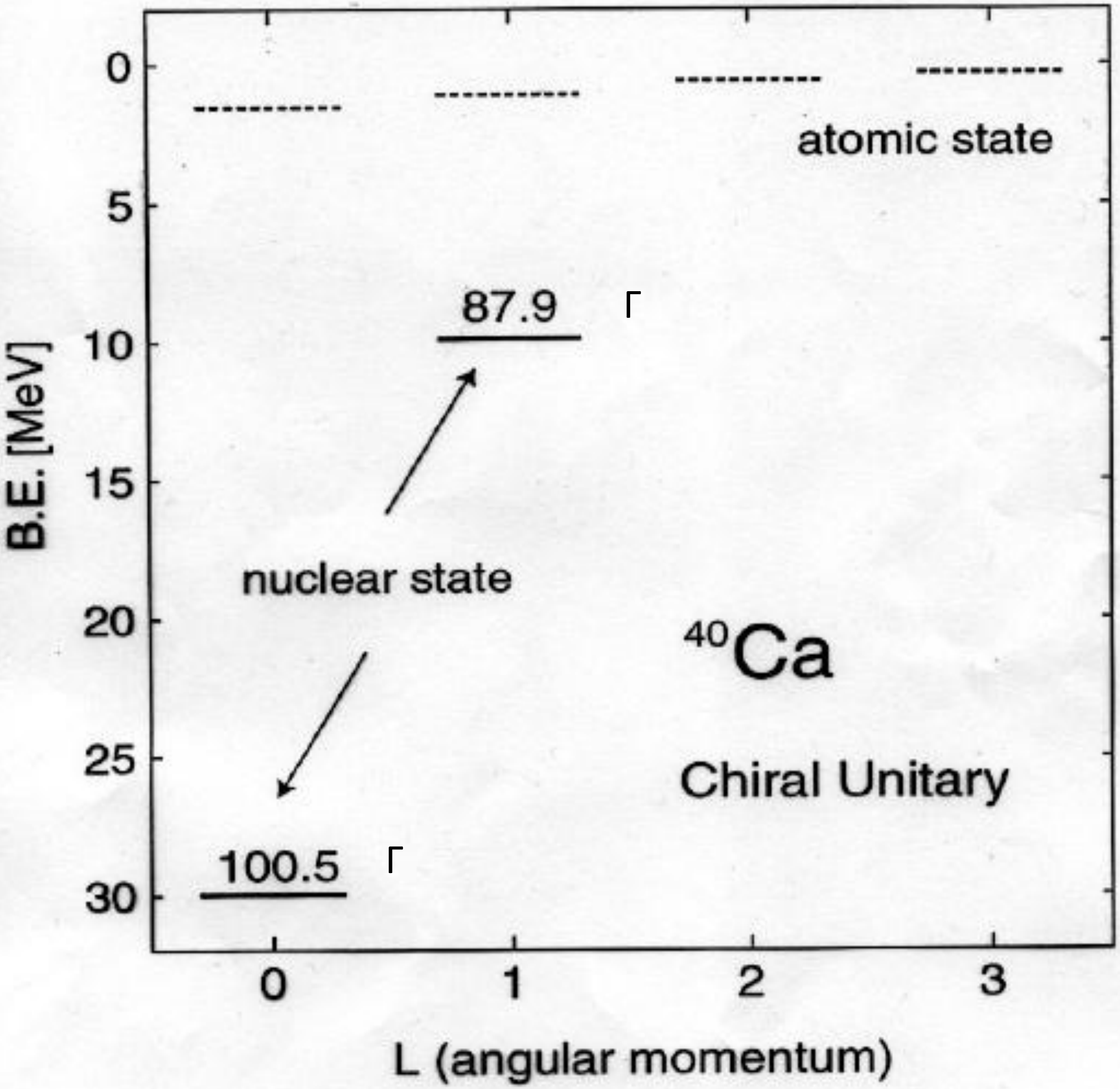
Okada, PLB 2007
Bazzi, PLB 2009
Shift: 0±6 (stat)±2 (syst) eV

SIDHARTA: arXiv:1205.0640

$$\Gamma_{2p}\left({}^4\mathrm{He}\right) = 14 \pm 8\ (\mathrm{stat.}) \pm 5\ (\mathrm{syst.})\ \mathrm{eV}$$

Talk of Tatsuno in Krakow 2012

Nuclear deeply bound states



Phenomenological potentials with 200 MeV attraction reproduce atom data and lead to more deeply bound states
Gal et al,
Akaishi, Yamazaki

See also recent papers Cieply et al. PRC11, NPA12

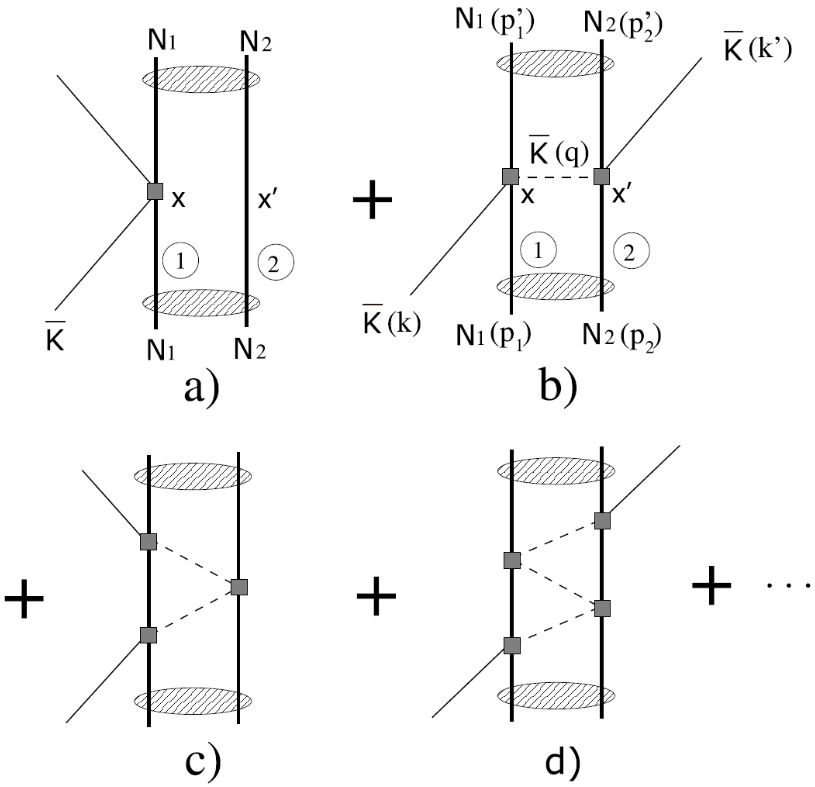
Simplest cluster: K^- pp system

	Method	properties	B[MeV]	Γ[MeV]
Schevchenko et al. PRC 2007	Faddeev	coupled channels	50-70	100
Sato, Ikeda PRC 2007	Faddeev	coupled channels	79	74
Sato, Ikeda 2009	Faddeev	Chiral constraints	47	50
Akaishi, Yamazaki	Variational	phenomenological	48	60
Dote, Hyodo, Weise NPA 2008	Variational	Chiral amplitudes pp short range repulsion	19	40-70
Dote, Hyodo, Weise PRC2009	Variational	Chiral amplitudes pp short range repulsion	20-40	100

Chiral dynamics → small binding, large width (larger than binding)

Fixed Center Approximation to Faddeev equations

M. Bayar, E. O , NPA 2012



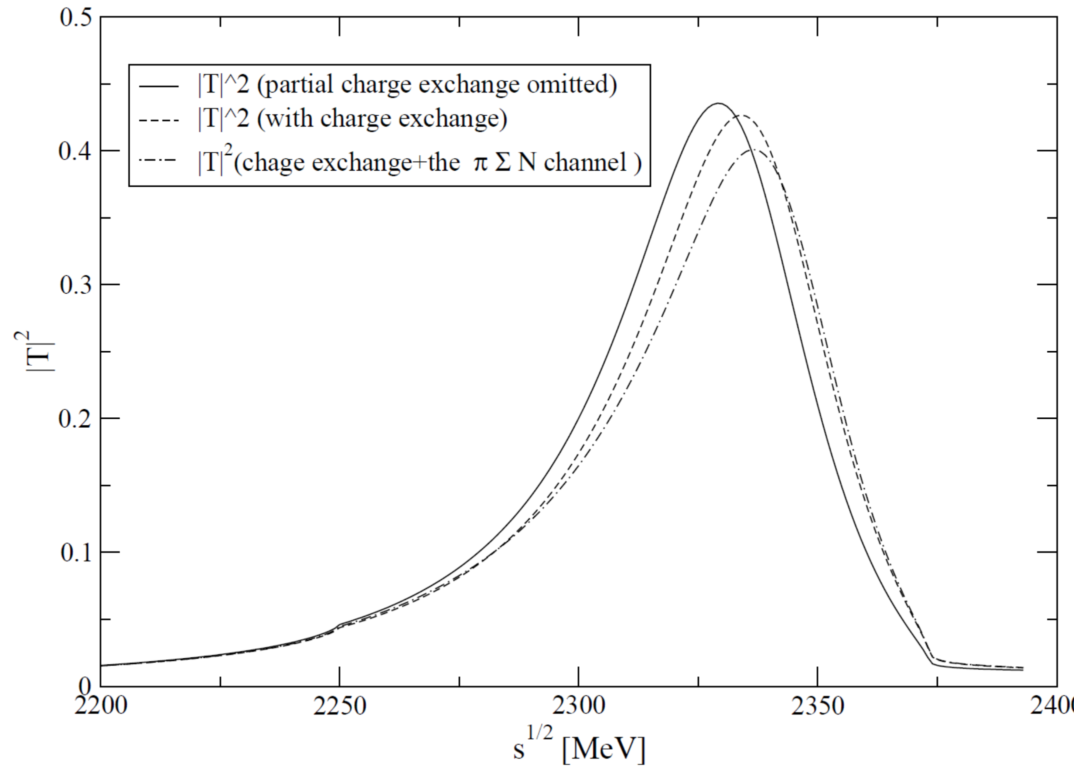
$$T^{(1/2)} = \frac{\frac{3}{2}t^{(0)} + \frac{1}{2}t^{(1)} + 2G_0 t^{(0)} t^{(1)}}{1 + \frac{1}{2}(t^{(1)} - t^{(0)})G_0 - G_0^2 t^{(0)} t^{(1)}}$$

$$G_0 = \int \frac{d^3 q}{(2\pi)^3} F_{NN}(q) \frac{1}{q^{0\,2} - \vec{q}^{\,2} - m_{\bar{K}}^2 + i\epsilon}.$$

We find a binding of about 27-35 MeV and Γ= 50 MeV

Hyodo, Weise , Dote   B around 20 MeV

Recent , Barnea, Gal, Liverts, PLB 2012, B around 16 MeV with full Faddeev.



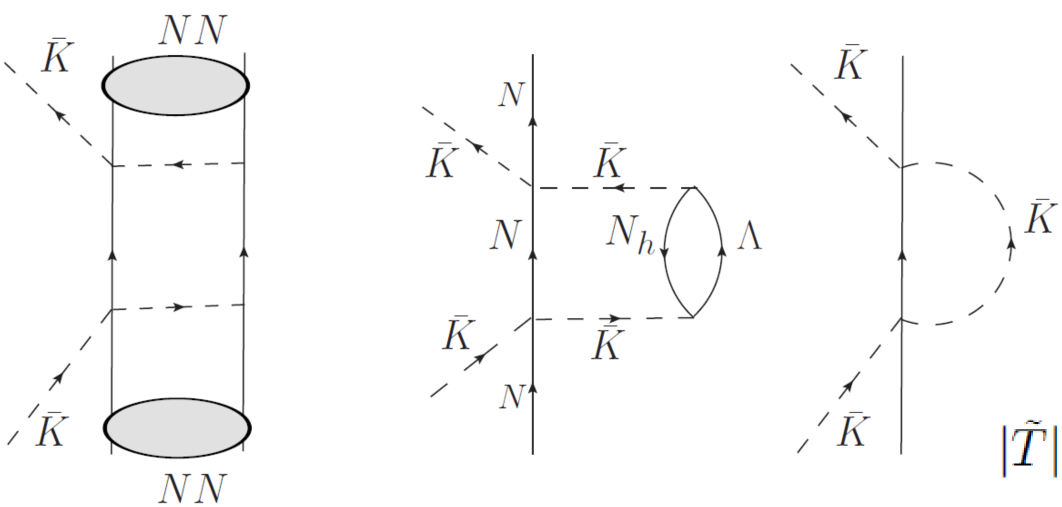
Recent advances in K⁻ NN absorption

Branching ratios of mesonic and nonmesonic antikaon absorptions in nuclear medium

Takayasu Sekihara, Junko Yamagata-Sekihara, Daisuke Jido, Yoshiko Kanada En'yo

arXiv:1204.3978

Absorption in the K⁻ NN system: M. Bayar, E. O., done not perturbatively by modifying the Kbar N amplitudes and using them in the unitary formula of the FCA.



(a) (b) (c)

$$i\mathrm{Im}\ \delta\tilde{g} = -i\frac{1}{2\pi}\frac{M_\Lambda M_N}{M_{NN\bar{K}}}p_\Lambda|\tilde{T}|^2$$

$$|\tilde{T}|^2 = V_y^2\vec{p}_\Lambda^{\,2}\frac{1}{[(q^0)^2 - p_\Lambda^2 - m_{\bar{K}^2}]^2}|\varphi(0)|^2$$

Γ increases from 50 MeV to about 75 MeV, recall B=16-35 MeV . Too wide for observation????

The structures are so neat that it looks easy to see them:

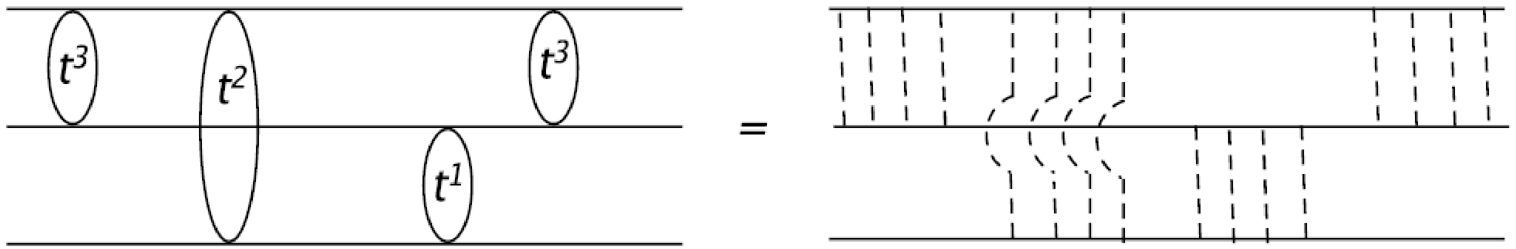
But in nuclei their formation requires removal of two occupied nucleons,
and Γ >> Energy separation of nuclear levels → different contributions overlap
and signal gets diluted over a large background !!!

Other Kaonic Systems: The K Kbar N System

Martinez Torres
Khemchandani

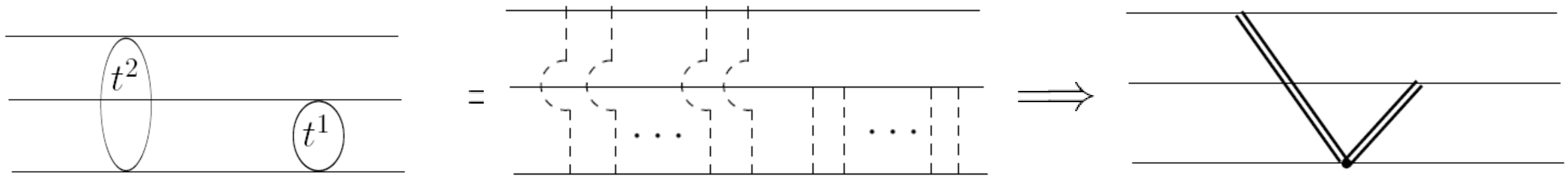
Three body Faddeev equations

One starts from a two nucleon potential and draws all possible diagrams with any amount of interactions between two particles

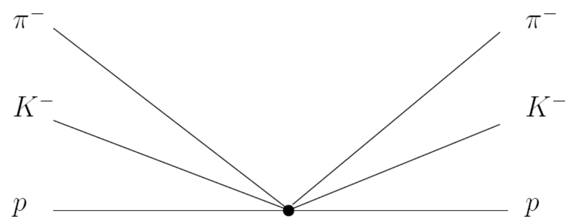


The iterative potential exchanges between two same lines sum up to give the two nucleon t-matrix

- Chiral amplitudes → "on-shell" part (c.m energy) $q^2=m^2$; "off-shell" part $\propto$ 1 / propagator ➡ three-body forces



From chiral Lagrangians



Cancel in the SU(3) limit

A. Martinez Torres, K. Khemchandani, E. O. PRC 2009

$\mathbf{I(J^P)}$	**Theory** channels	mass (MeV)	width (MeV)	**PDG data** name	mass (MeV)	width (MeV)
$1/2\,(1/2^+)$	only $\pi\pi N$	1704	375	$N^*(1710)$	1680-1740	90-500
	$\pi\pi N$, $\pi K\Sigma$, $\pi K\Lambda$, $\pi\eta N$	$\sim$ no change	$\sim$ no change			
$1/2\,(1/2^+)$	only $\pi\pi N$	2100	250	$N^*(2100)$	1885-2270	80-400
	$\pi\pi N$, $\pi K\Sigma$, $\pi K\Lambda$, $\pi\eta N$	2080	54			
$3/2\,(1/2^+)$	$\pi\pi N$, $\pi K\Sigma$, $\pi K\Lambda$, $\pi\eta N$	2126	42	$\Delta(1910)$	1870-2152	190-270
$1/2\,(1/2^+)$	$N\pi\pi$, $N\pi\eta$, $NK\bar{K}$	1924	20	$N^*(?)$	?	?

New state: mostly K Kbar N → This state first derived with variational calculation in Jido, Kanaka-En'yo PRC2008

Martinez Torres, Khemchandani, Meissner, Oset, EPJA 2009, claim this state is responsible for the peak of γ p → K+ Λ around 1920 MeV

Mart and Bennhold PRC 2000

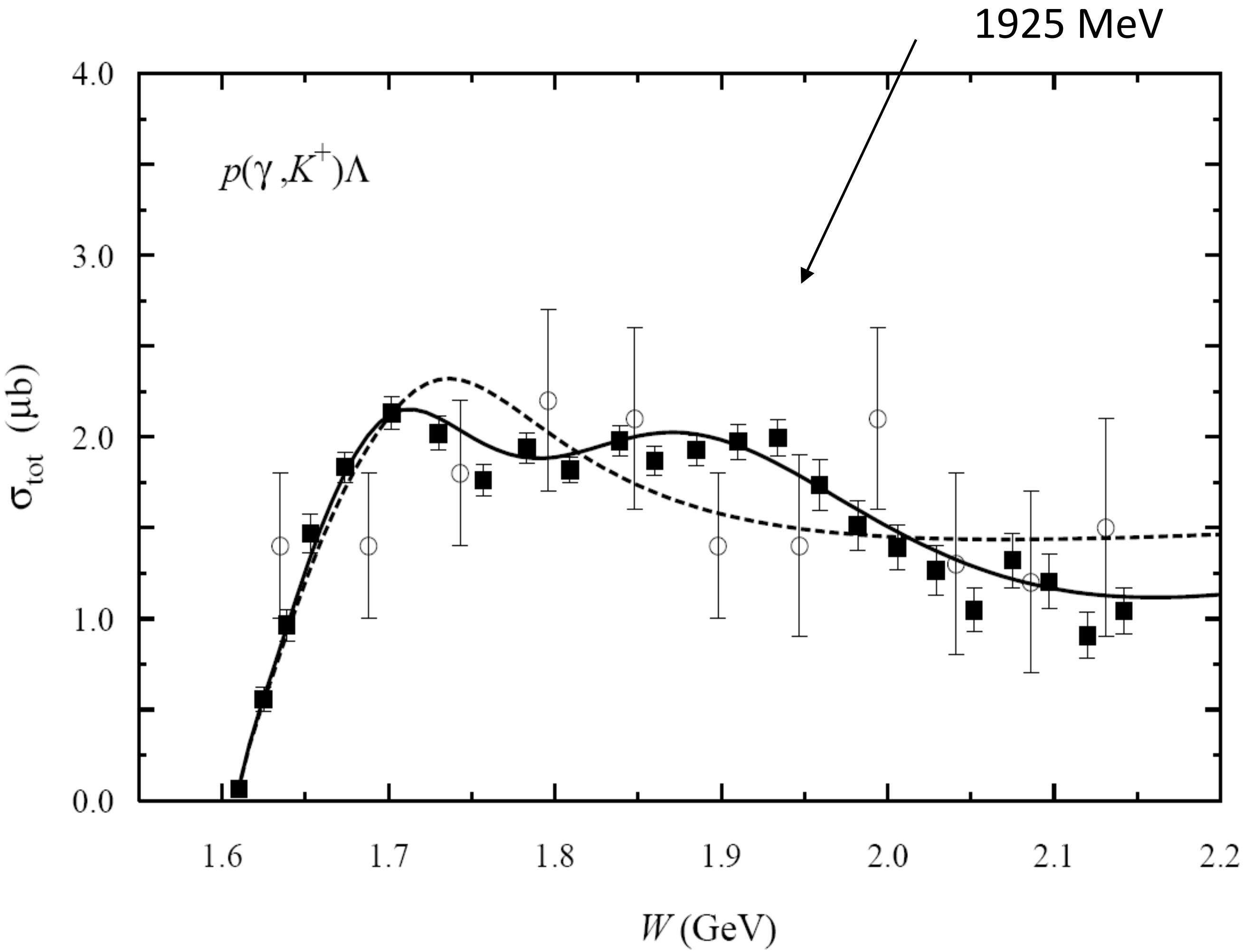


FIG. 1. Total cross section for $K^+\Lambda$ photoproduction on the proton. The dashed line shows the model without the $D_{13}(1960)$ resonance, while the solid line is obtained by including the $D_{13}(1960)$ state. The new SAPHIR data [6] are denoted by the solid squares, old data [22] are shown by the

$\gamma p \rightarrow K^+ \Lambda$

There are many analyses on this reaction with different conclusions: essentially one puts N resonances in the analysis and you get N back. Different conclusions: Sarantsev, Thoma, Mawwell, Mart .....

Recent work

A Bayesian analysis of kaon photoproduction with the Regge-plus-resonance model
Authors: Lesley De Cruz, Jan Ryckebusch, Tom Vrancx, Pieter Vancraeyveld **arXiv:1205.2195**

Talk of Vancraeyveld
In Krakow 2012

They advocate two new resonances $D_{13}(1900)$ $(3/2^-)$ (missing from PDG)
and $P_{11}(1900)$ $(1/2^+)$ (missing from PDG)

The DNN system

Similar to Kbar NN changing one quark sbar by a quark c.

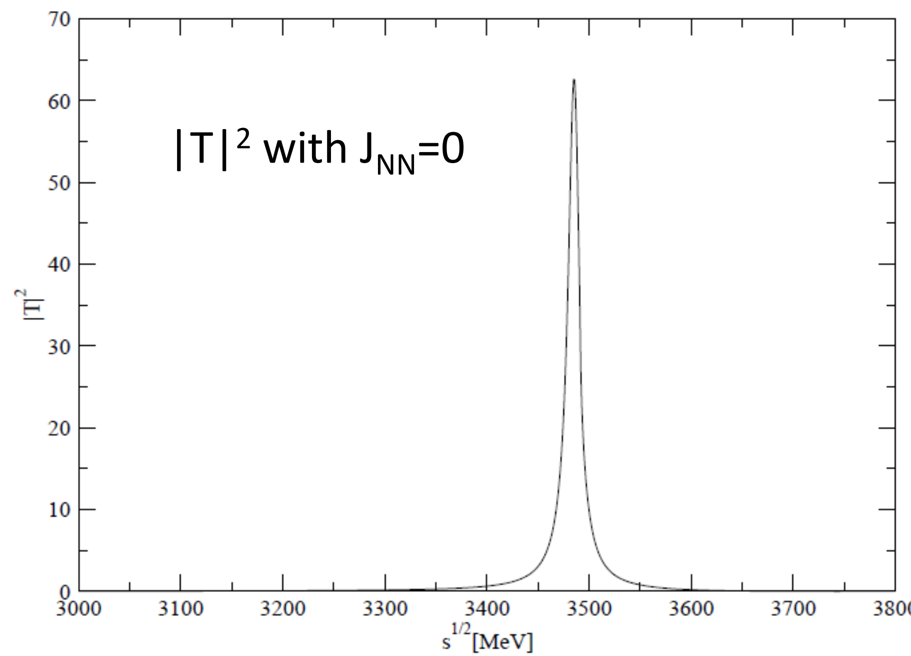
Analogy: Λ(1405) → Λ_c(2595) (Γ = 3.6 MeV) (Ramos, Mizutani, Lutz, Hofmann, Tolos, Nieves .....)

Recent work: Bayar, Xiao, Hyodo, Dote, Oka, E.O. **arXiv:1205.2275**

Two methods used: variational calculation and Faddeev Fixed Center Approximation

The two methods find a state ($1/2^-$) with I=1/2 with E = 3500 MeV, bound by about 250 MeV with Γ = 20- 40 MeV, including two body absorption.

Very promising for FAIR and JPARC



Conclusions

The Kbar N interaction keeps attracting interest. The new SIDHARTA data is very valuable

The two Λ(1405) states universally accepted and supported by experiments

It is important that new studies of the Kbar interaction demand to reproduce experiments where the Λ(1405) are produced.

The Kbar NN system is interesting. People converging to B=15-30 MeV, Γ around 75 MeV

K^- atoms are known and more could be measured. Deeply bound kaon atoms with B around 30 MeV or more have widths about 100 MeV.

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On the other hand, people are finding new Kaonic systems never mentioned two years ago. K Kbar N system , new state around 1920 MeV, possibly already seen in the $\gamma\, p \rightarrow K^+ \Lambda$ reaction
Predictions for Kbar Kbar N, a Ξ state around 1900, Jido and En'yo
A K Kbar Kbar state forming the K(1460) , Martinez Torres, Jido, En'yo .....

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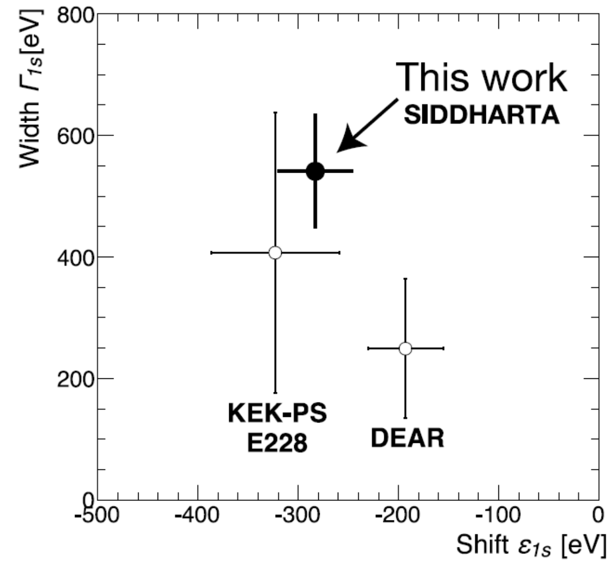
The dream of having kaons as a glue to drive clusters of particles bound is coming true but with systems very different to those originally envisaged.

Leave room for D driven bound states: THEY ARE COMING

A New Measurement of Kaonic Hydrogen X rays

M. Bazzi et al. SIDHARTA , PLB 2011



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$$\text{Re}(T(s)) = \text{Re}(T(s_0)) + \frac{(s-s_0)}{\pi}\int_{s_{\text{thr}}}^{\infty} ds' \frac{\text{Im}\,(T(s'))}{(s-s')(s-s_0)}$$

Problems with convergence unless Im T smoothed --> problems with unitarity. ??????