Structure of Antikaon-Nucleon Scattering

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M. Mai and U. G. Meißner, Nucl. Phys. A **900** (2013)

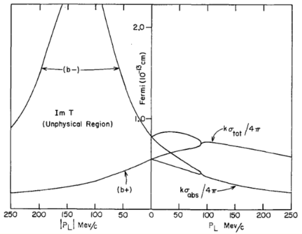
M. Mai and U.-G. Meißner, Eur. Phys. J. A **51** (2015)

L. Roca, M. Mai, E. Oset and U.-G. Meißner, Eur. Phys. J. C **75** (2015)

A. Cieplý, M. Mai, U.-G. Meißner and J. Smejkal, Nucl. Phys. A **954** (2016)

- *"Four sets of scattering amplitudes are obtained consistent with all the present data on K−-proton interactions and the possibilities for discrimination between them are discussed. Two of these amplitudes are found to correspond to a* ***resonance-like*** *behavior just within the unphysical region."*

  Dalitz, Tuan (1959)



⇒ ***What is this resonance?***

$$(S=-1;\ I=0;\ J^p=1/2^{-(?)};\ M\sim 1410-18i\text{ MeV})$$

A. Dynamically generated from coupled-channel effects

→ K-matrix — Dalitz, Tuan (1960!)

→ unitarized coupled-channel amplitude from ChPT — Kaiser,Siegel,Weise(1995)

⇒ **two-pole solution** — Oller, Meißner (2001)

B. Quark model → genuine qqq state — Capstick, Isgur (1986)

PDG favors A

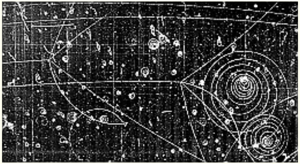
PDG MiniReview (2015)

Lattice QCD favors A

Hall et al. (2014)

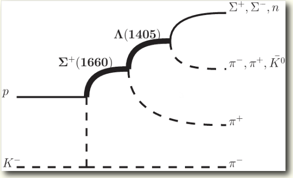
Experimental situation (no photons)

✓ **Total cross sections on** $K^-p \to K^-p, \bar{K}^0 n, \ldots$ LNL (1960s), Rutherford Lab(1980s), ...



- → bubble chamber experiments
- → huge error bars
- → large deviations btw. experiments

✓ $\pi\Sigma$ **mass distribution** Hemingway (1985)



- → 2m bubble chamber @ CERN
- → low energy resolution
- → multistep production ⇒ new parameter

✓ **Strong energy shift and width in** $\bar{K}H$ Bazzi et al.(2011)

⇒ a_{K^-p} from modified Deser-type relation Meißner, Raha, Rusetsky (2004)

✗ **Plans for an upgrade to** $\bar{K}D$

⇒ a_1, a_0 from *Faddeev equations/EFT* Shevchenko (2014).../MM et al.(2014)...

✗ pp **collisions** COSY (2008) HADES (2013)

⇒ high quality data, **but** theoretical analysis very intricate

Scattering amplitude - framework

- ChPT is an appropriate tool to study low-energy hadronic interactions.

  Weinberg (1979) Gasser, Leutwyler (1981)

  Here it has to fail! Because:

  1. Kaon mass is large → convergence
  2. Relevant thresholds are widely separated → convergence
  3. Resonance just below $\bar{K}N$ threshold → non-perturbative effect

- Non-perturbative methods:

  → Dispersion relations, N/D, Roy-Steiner equations
  → K-Matrix, JÜLICH-BONN model, ...
  → IAM, ***Chiral Unitary Models***, ...

- ***Chiral Unitary Models*** **- driving term**

$$V(\not{q}_2, \not{q}_1; p) = A_{WT}(\not{q}_1 + \not{q}_2) + Born(s) + Born(u)$$
$$+A_{14}(q_1 \cdot q_2) + A_{57}[\not{q}_1, \not{q}_2] + A_M + A_{811}\Big(\not{q}_2(q_1 \cdot p) + \not{q}_1(q_2 \cdot p)\Big)$$

⇒ $A_{..}$ depend on low energy constants ⇒ free parameters

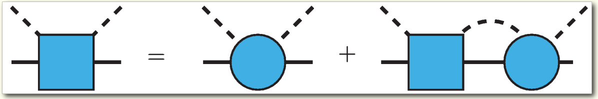
Scattering amplitude - re-summation

- **Bethe-Salpeter equation** Salpeter et al.(1951)

$$T(\not{q}_2,\not{q}_1;p) = V(\not{q}_2,\not{q}_1;p) + i\int \frac{d^dl}{(2\pi)^d}\frac{V(\not{q}_2,\not{l};p)T(\not{l},\not{q}_1;p)}{((\not{p}-\not{l})-m+i\epsilon)(l^2-M^2+i\epsilon)}$$

→ Intermediate particles are *off-shell*

⇒ exactly corresponding to a series of Feynman loop diagrams



⇒ BSE can be solved analytically, **if(f)** $V \sim$ local terms Bruns, MM, Meißner (2011)

⇒ drop the Born graphs

→ *Bubble chain* in s direction ⇒ topologies are missing

⇒ scale dependence **does not** cancel out ⇒ additional model parameters

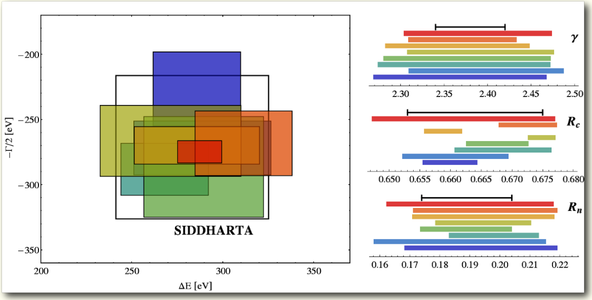
→ Off-shell effects are moderate MM, Meißner (2013)

⇒ use on-shell approximation first (scan of 20-dim. parameter space)

Fits and results

- Randomly chosen sets of starting values ($\# \approx 10000$)
- Solutions having poles on I. RS sorted out
- **Results**: 8 best fits obtained with similar $\chi^2_{\mathrm{d.o.f.}}$

Fit #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
$\chi^2_{\mathrm{d.o.f.}}$	1.35	1.14	0.99	0.96	1.06	1.02	1.15	0.90

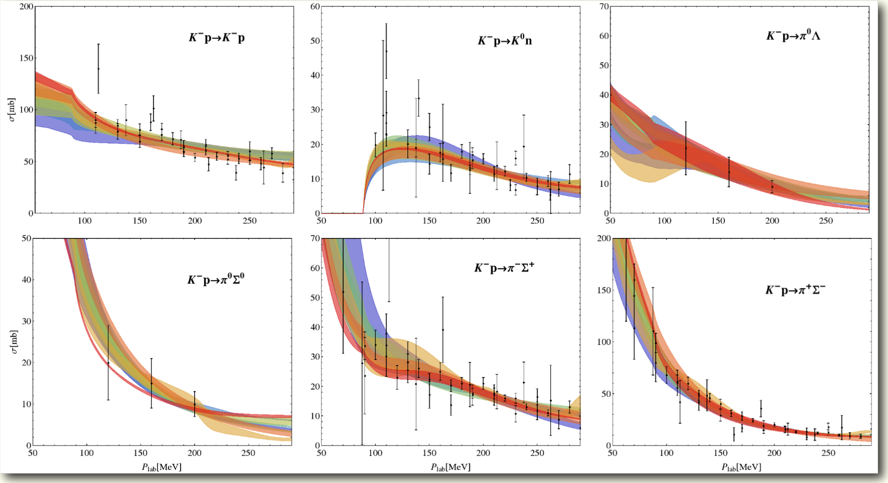


$\rightarrow$ error bars are twofold

1. parameter: variation of best fit parameters, such that $\Delta\chi^2_{\mathrm{d.o.f.}} < 1.15$
2. systematic: spread of solutions

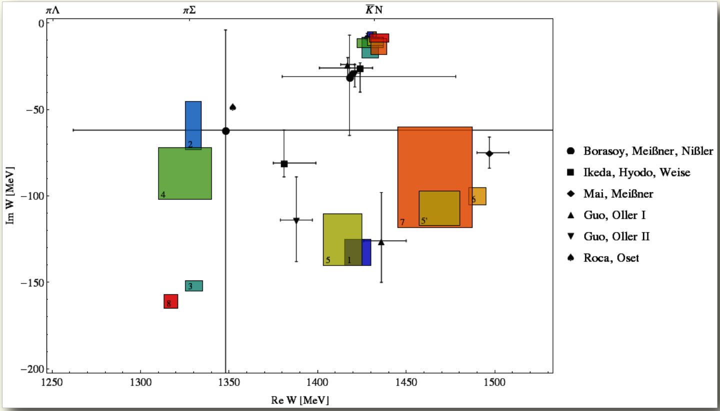
Results

→ similar cross sections



Results - complex plane

- Analytic continuation to the complex energy plane



→ two poles in all solutions on II. RS
→ stable position of the narrow pole
→ position of the second pole is rather unstable

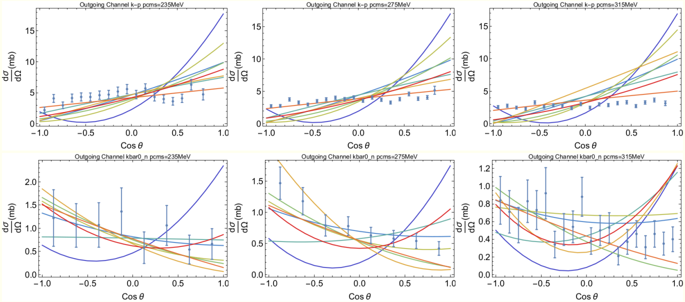
Can we reduce this ambiguity? PART 1

1) **Differential cross sections** Mast et al. (1976)

→ Chiral Unitary Meson-Baryon amplitude has a genuine P-wave part
→ Does the prediction agree with data? [analyzed by D. Sadasivan]

$K^- p \to K^- p$

$K^- p \to \bar{K}^0 n$



→ solution #1 seems to deviate strongly from data
→ further constraints require a refit

Can we reduce this ambiguity? PART 2

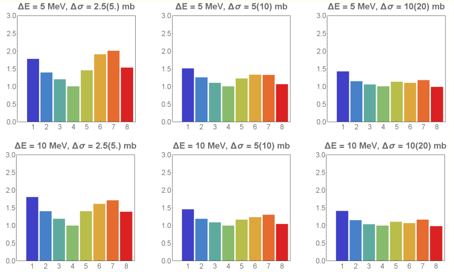
2) **New data on total cross sections** - synthetic data from fit #4:

$p_{lab} = 100...300$ MeV, $\Delta E = 5, 10$ MeV, $\Delta\sigma = 2.5, 5, 10$

Compare $\chi^2_{\text{d.o.f.}}/\chi^2_{\text{d.o.f.}}(\#4)$

→ threshold ratios, SIDDHARTA

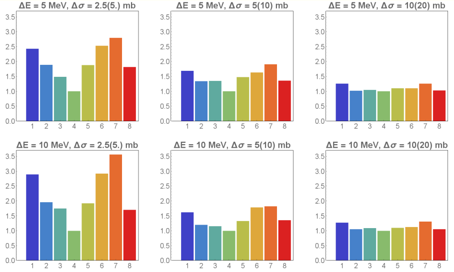
→ pseudo and real scattering data



⇒ $\Delta\sigma < 5(10)$ mb and $\Delta E < 10$ MeV desired

→ threshold ratios, SIDDHARTA

→ pseudo scattering data



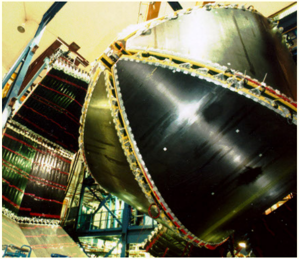
⇒ much larger values of $\Delta\sigma$ and ΔE are sufficient

Can we reduce this ambiguity? PART 3

3) **CLAS data on $\gamma p \to K^+ \pi\Sigma$**

- $\to$ $\pi\Sigma$ mass distribution
- $\to$ electro- and photoproduction:
  $\gamma p \to (K^+)\Lambda(1405) \to \pi\Sigma$
- $\to$ $J^P = \frac{1}{2}^-$ "*confirmed*" experimentally
- $\to$ high statistics and good angular resolution

$\Rightarrow$ theoretical analysis requires a **photoproduction amplitude**



Photoproduction amplitude

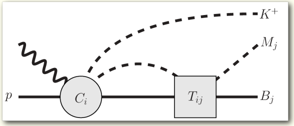
I Gauge invariant approaches

1. "Turtle" approximation Gross, Riska (1987), Kvinikhidze et al.(1999) Borasoy et al.(2005)
   - attach photon everywhere to *off-shell* hadronic amplitude
   - single meson case is done for the NLO-kernel MM et al.(2012)
2. Gauged vertices Nakamura, Jido (2014)
   - photon attached to meson production amplitude at the tree level
     ⇒ at the LO driving term no good fit to CLAS data
     ⇒ good fit with additional vector meson d.o.f. - ***15 per energy bin!***

II Test model

- most simple ansatz to test the hadronic solution:

$$\mathcal{M}_j(W, M_{\pi\Sigma}) = C_i(W) \cdot G_i(M_{\pi\Sigma}) \cdot T^{on}_{i\to j}(M_{\pi\Sigma})$$



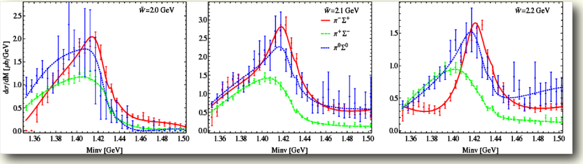
- flexible enough for the CLAS data Oset, Roca (2013)
  ⇒ less free parameters ($15 \mapsto 10$)
- no gauge invariance, parameters are not physical
  ⇒ global fit is meaningless
  ⇒ **conservative** test of the hadronic solutions

Results

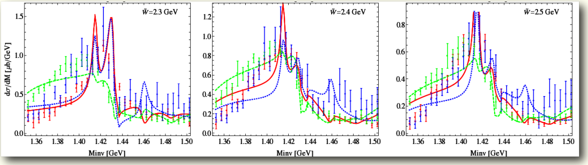
- Test of hadronic solutions

Fit #	1	2	3	4	5	6	7	8
$\chi^2_{\text{d.o.f.}}$ (hadr.)	1.35	1.14	0.99	0.96	1.06	1.02	1.15	0.90
$\chi^2_{\text{p.p.}}$ (CLAS)	3.18	1.94	2.56	1.77	1.90	6.11	2.93	3.14

- Hadronic fits #2, #4 and #5 lead to *good* fits

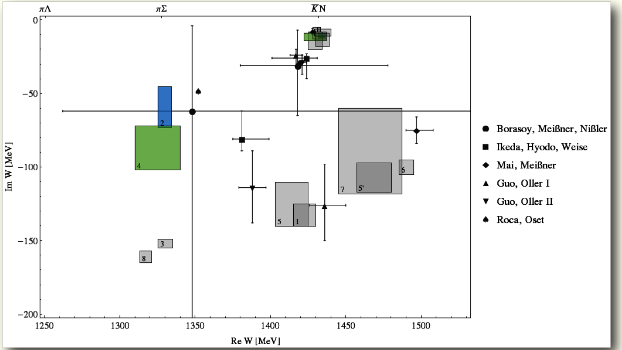


- Hadronic fits #1, #3, #6, #7 and #8 do not!!!



Results - comparison

⇒ after comparison with Hemingway data ($K^- p \to \Sigma^+ \pi^- \pi^+ \pi^-$) two solutions remain: #2 and #4



⇒ both solutions have similar pole positions

... also similar to the estimation by Oset and Roca (2013)

⇒ **universal feature** demanded by CLAS data!

Summary

- The NLO chiral unitary $\bar{K}N$ amplitude used to analyze hadronic data
- 8 solutions are found in the *on-shell* approximation
  → *the position of the narrow pole is quite certain*
  → *broad pole has large systematic uncertainty*
- Fit to differential cross section is possible ... work in progress
- Photoproduction amplitude constructed from the hadronic part
  → *simple, but very flexible ansatz ...* ***conservative test***
  → *5 solutions disagree with the CLAS data, 2 remain after all tests*
- New data can actually reduce the ambiguity of the $\bar{K}N$ amplitude
  → *desired accuracy is* ***not a part of science-fiction***