Constraints on the chiral unitary $\bar{K}N$ amplitude from $\pi\Sigma K^+$ photoproduction data

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Why is $\bar{K}N$ interaction so important?

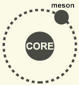
- Test of our understanding of low-energy SU(3) dynamics:
  ChPT is the right tool to study meson-baryon scattering, but
  - **1) new mass scale:** IR, EOMS reg. scheme ✓
  - **2) large kaon mass, strong coupling, resonance:**

    $a_{K^-p} = +0.63^{+0.43}_{-0.51} + 0.20i$ fm (NNLO ChPT[1])

    $a_{K^-p} = -0.66^{+0.16}_{-0.16} + 0.81^{+0.18}_{-0.18}i$ fm (EXP[2])

  $\rightarrow$ non-perturbative techniques IAM, N/D, BSE ...

- In-medium $\bar{K}N$ amplitudes for $\bar{K}$-nuclear states

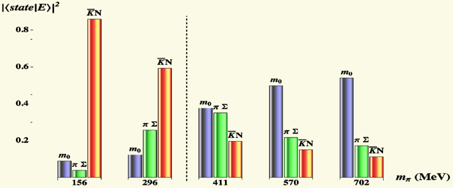


- Understanding of CLAS data: $\gamma^{(*)}p \rightarrow \pi\Sigma K^+$

[1] M.M., Bruns, Kubis, Meissner (2009)
[2] Bazzi et al. (2011)

Nature of $\Lambda(1405)$?

- Quark model genuine qqq state — Capstick, Isgur (1986)
  - or even more exotic states: hybrids, active glue, ...
- Dynamically generated from coupled-channel effects — Dalitz, Tuan (1960**!**)
- Lattice QCD: $\Lambda(1405)$ is dominated by a molecular $\bar{K}N$ state — Hall et al. (2014)



- Unitarized coupled-channel amplitude from ChPT
  - (N)LO chiral potential within BSE — Kaiser, Siegel, Weise (1995); Oset, Ramos (1998); ...
  - two pole solution — Oller, Meissner (2001); ...

Experimental situation

- Total cross sections on $K^- p \to K^- p, \bar{K}^0 n, \dots$ 1960s-1980s
  - old and not very restrictive[3]
- $\pi\Sigma$ mass distribution Hemingway (1985)
  - multistep production: $K^- p \to (\pi^-)\Sigma^+(1660) \to (\pi^+)\Lambda(1405) \to \Sigma\pi$
  - low resolution
- SIDDHARTA experiment Bazzi (2011)
  - $\bar{K}H$ strong energy shift and width $\to a_{K^- p}$
  - Plans for an upgrade to $\bar{K}D \to A_{Kd} \Rightarrow$ extract a_1, a_0 directly[4]
- pp collisions COSY (2008); HADES (2013)
  - Theoretically very complicated[5]
- $\pi\Sigma$ mass distribution CLAS (2012)
  - electro- and photoproduction: $\gamma p \to (K^+)\Lambda(1405) \to \pi\Sigma$
  - high statistics and good angular resolution
  - $J^P = \frac{1}{2}^-$ "confirmed"

[3] MM, Meißner (2012), Guo, Oller (2013)
[4] Kamalov, Oset, Ramos (2001); MM, Baru, ... (2014)
[5] ulf-oset-ref

Meson-baryon scattering ($S = -1$)

Framework

- Unitarity → BSE:

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

  - Passarino-Veltman reduction → I_B, I_M, $I_{MB}(s)$
    $\Rightarrow$ *dim. reg. in* $d = 4$ *and* $\bar{M}S$ *subtraction scheme*
  - $T \sim$ bubble chain in s direction → topologies are missing
    $\Rightarrow$ *scale dependence* μ_i *does* ***not*** *cancel out*
    $\Rightarrow$ *free model parameters*
  - (Off-shell) T corresponds to a set of Feynman diagrams
    → *can be solved exactly, if* $V \sim$ *set of local terms*
    → *on-shell solution:* $T_{on} = \frac{V}{1-GV} \,\hat{=}\, T|_{I_M \to 0}$

Framework

- Kernel → NLO ChPT potential (contact terms):

$$\mathcal{L}_{\phi B}^{(1)} = \langle \bar{B}(i\gamma_\mu D^\mu - m_0)B\rangle + \frac{D/F}{2}\langle \bar{B}\gamma_\mu\gamma_5[u^\mu, B]_\pm\rangle$$

$$\mathcal{L}_{\phi B}^{(2)} = b_0\langle \bar{B}B\rangle\langle\chi_+\rangle + ... + b_1\langle \bar{B}\Big[u_\mu, [u^\mu, B]\Big]\rangle + ... + ib_5\langle \bar{B}\sigma^{\mu\nu}\Big[[u_\mu, u_\nu], B\Big]\rangle + ...$$
$$+ \frac{i\, b_{11}}{2m_0}\Big(2\langle \bar{B}\gamma^\mu[D_\nu, B]\rangle\langle u_\mu u^\nu\rangle + \langle \bar{B}\gamma^\mu B\rangle\langle [D_\nu, u_\mu]u^\nu + u_\mu[D_\nu, u^\nu]\rangle\Big)$$

$$\Rightarrow V^{(2)} = A_{WT}(\not{q}_1 + \not{q}_2) + A_{14}(q_1\cdot q_2) + A_{57}[\not{q}_1, \not{q}_2] + A_M + A_{811}\Big(\not{q}_2(q_1\cdot p) + \not{q}_1(q_2\cdot p)\Big)$$

  - 14 low energy constants → free parameters
  - s and u channel BORN graphs:

→ off-shell inclusion not feasible

→ $V \mapsto V_{on-shell}$ lead to unphys. singularities below threshold[6]

[6] **Nissler, PhD thesis (2007)**

Fit strategy

- Fit to SIDDHARTA, thr. ratios and tot. cross sections:

  MM, Meißner, Nucl. Phys. A **900**, 51 (2013)

  - Full offshell six channel problem
  - Two pole solution: - first (narrow) pole as expected
    - second pole at a significantly different position
  - No contradiction to $\pi\Sigma$ inv. mass distribution by Hemingway (1985)
  - Offshell effects are moderate

$\Rightarrow$ Redo the analysis:

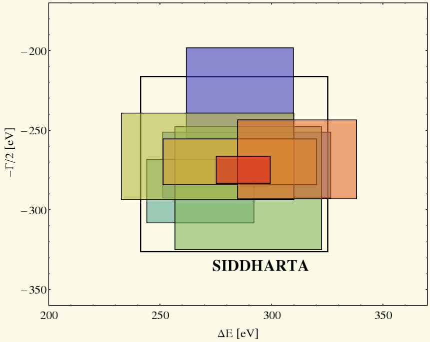
  - Take all 10 channels into account
  - Put NLO potential onshell $\to$ performance $\times$ 30
  - Improve fitting strategy:
    1) Random start values $\to$ fast ($N = 19$) fit
    2) Evaluate complex s plane $\to$ sort out unphysical solutions
    3) Final, full ($N = 158$) fit

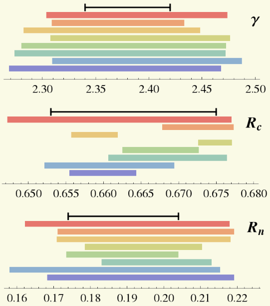
Fit results

⇒ 8 best fits are obtained:

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

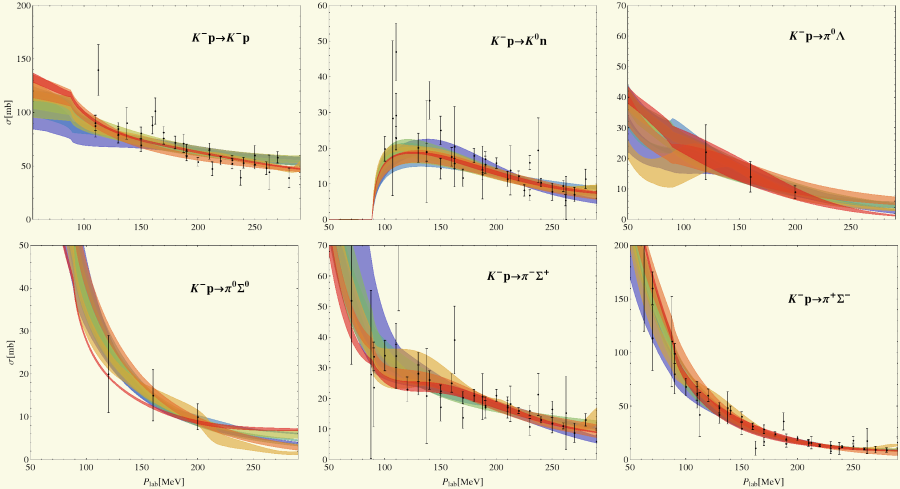
... with similar threshold values:





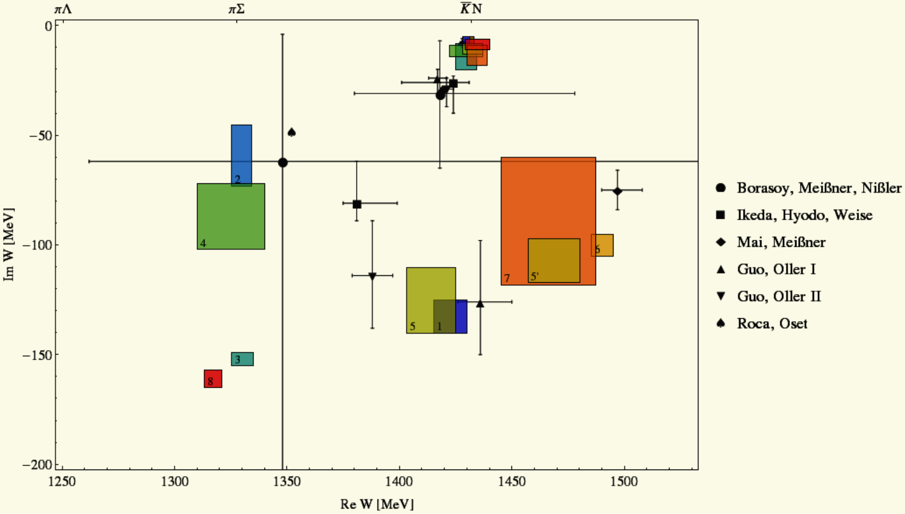
Fit results

... with similar cross sections:



Fit results

..., but different pole positions:



Intermediate conclusion

- 8 best solutions for the $\bar{K}N$ amplitude found
  $\rightarrow$ good description of hadronic data
- Scattering amplitudes are very different
  $\rightarrow$ e.g. (second) pole positions

$\Rightarrow$ Hadronic data does **not** fix the scattering amplitude fully

- ~~Constrain the free parameters of the model~~
- Low-momentum kaon beam experiments are being debated
  $\rightarrow$ still some time to wait

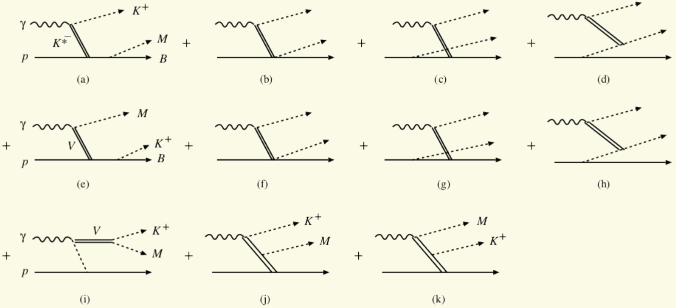
$\Rightarrow$ Use high-quality data on invariant mass distribution of $\pi\Sigma$ from $\gamma p \rightarrow K^+\pi\Sigma$ by the CLAS collaboration

$K^+\pi\Sigma$ photoproduction

Framework

- Gauge invariant amplitude:[7]
  1. hadronic skeleton (two-particle unitarity)
  2. couple photon to any possible place

✓LO chiral potential and vector mesons exchange diagrams[8]



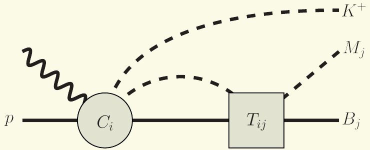
$+\ldots$

⇒ Good fit with additional parameters (15 per energy bin !)

7 e.g. Borasoy et al. (2009)
8 Nakamura, Jido (2014)

Framework

- Simple model[9]
  - $\mathcal{M}_j(W, M_{\pi\Sigma}) = C_i(W) \cdot I_{MB_i}(M_{inv}) \cdot T^{on}_{MB_i \to MB_j}(M_{\pi\Sigma})$



  - $d\sigma/dM_{\pi\Sigma}(W, M_{\pi\Sigma}) = \frac{\alpha}{64\pi^3} \frac{\mathbf{p}_{\pi\Sigma}\mathbf{p}_{K^+}}{W^2 \mathbf{p}_i} |\mathcal{M}(W, M_{\pi\Sigma})|^2$
  - no gauge invariance, parameters are non-physical

    → *global fit is meaningless*

    → *microscopic features of the spectrum not accessible*
  - flexible enough for the CLAS data[10]

    → *less free parameters (15 ↦ 10)*

    → ***conservative** test for the hadronic solutions*

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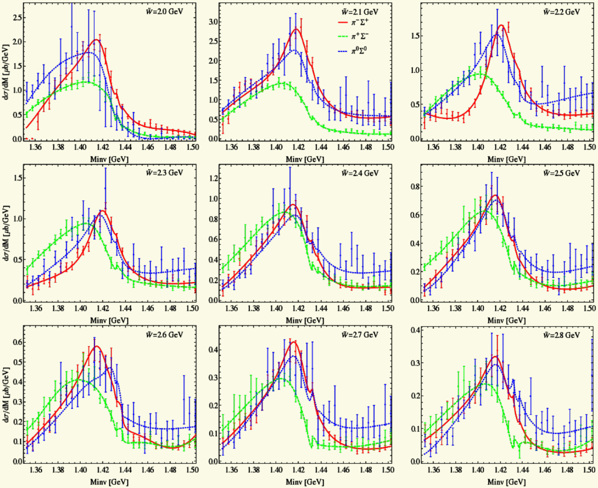
[9] **e.g. Oset, Roca (2013)**

[10] **Oset, Roca (2013)**

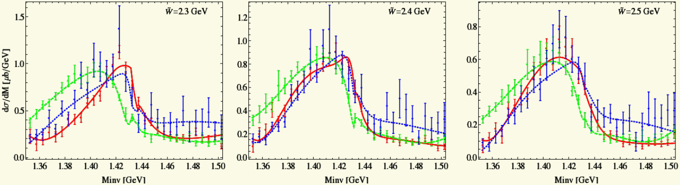
Results - best fit

- Best fit: $\chi^2_{\text{photo,p.p.}} \approx 1.77$ flexibility OK

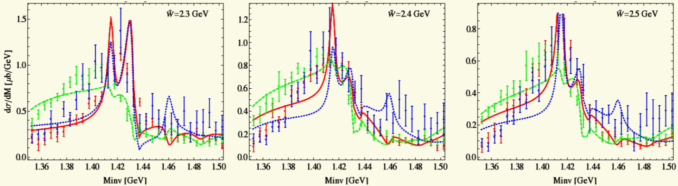


Results - comparison

- But not for every solution:
  - Solution #2:



  - Solution #6:

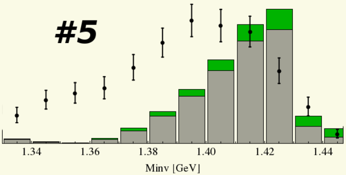


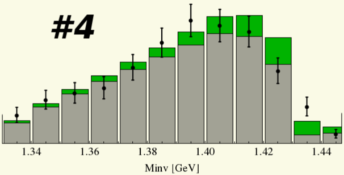
Results - comparison

- Test of hadronic solutions:

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

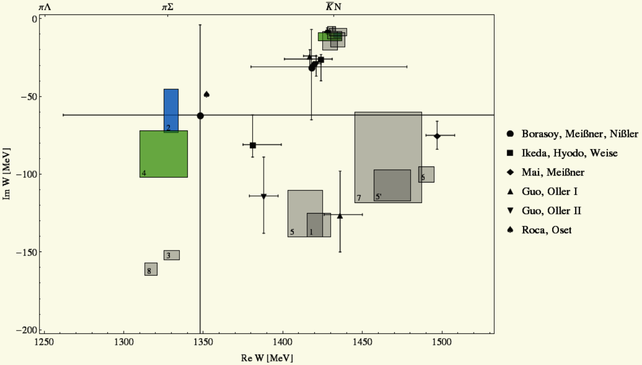
  - #2, #4 and #5 are *good* fits
  - #5 **disagrees** qualitatively with Hemingway ($K^-p \to \Sigma^+\pi^-\pi^+\pi^-$):





Results - conclusion

⇒ After comparison with CLAS and Hemingway two solutions remain:



→ Different ansatz for the hadronic part, but similar poles as Oset and Roca

⇒*photoproduction amplitude is too simple!*

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

Summary and Outlook

DONE

- The NLO chiral unitary $\bar{K}N$ amplitude used to analyze hadronic data
- 8 solutions are found in the onshell approximation:

  → *narrow pole at a fixed position*

  → *broad pole has large systematic uncertainty*

- Photoproduction amplitude constructed from the hadronic part:

  → *very flexible ansatz ... **conservative test***

  → *5 solutions disagree with the CLAS data*

  → *2 solutions remain after all tests*

TO DO

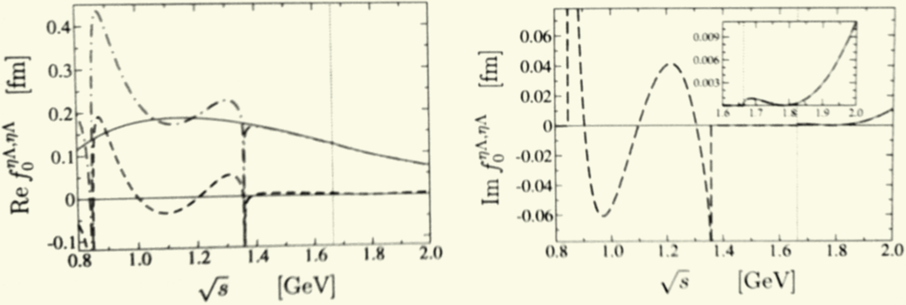
- Better ansatz is required for the photoproduction part

  → *physical parameters*

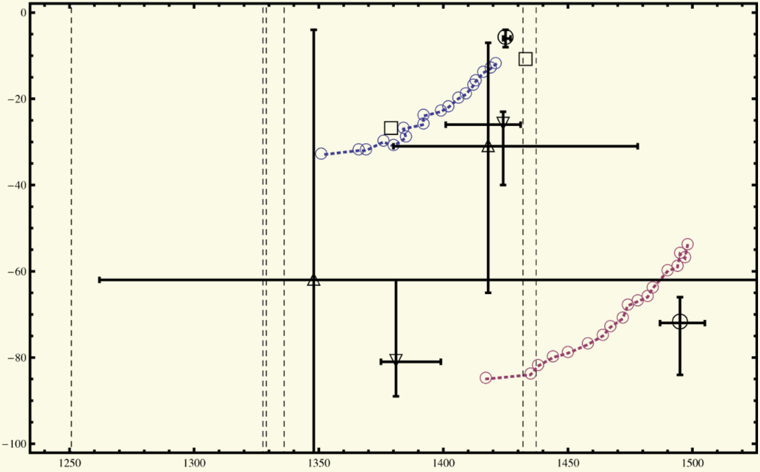
  → *microscopic features (electro vs. photoproduction?)*

  → *direct extraction of the $\bar{K}N$ amplitude*

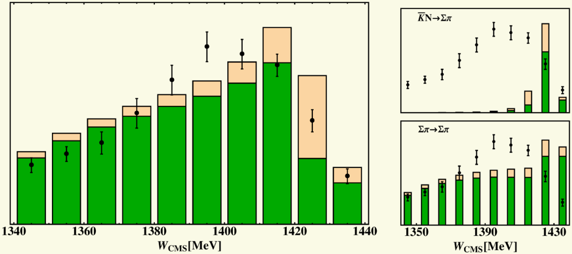
¡Gracias!



Re $f_0^{\eta\Lambda,\eta\Lambda}$ [fm]
0.4
0.3
0.2
0.1
0
-0.1
0.8
1.0
1.2
1.4
1.6
1.8
2.0
$\sqrt{s}$ [GeV]
Im $f_0^{\eta\Lambda,\eta\Lambda}$ [fm]
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
0.009
0.006
0.003
1.6
1.7
1.8
1.9
2.0
0.8
1.0
1.2
1.4
1.6
1.8
2.0
$\sqrt{s}$ [GeV]



0
−20
−40
−60
−80
−100
1250
1300
1350
1400
1450
1500



1340
1360
1380
1400
1420
1440
W_{CMS}[MeV]
$\bar{K}$N→Σπ
Σπ→Σπ
1350
1390
1430
W_{CMS}[MeV]