Reducing ambiguity of antikaon-nucleon amplitude using modern experimental data

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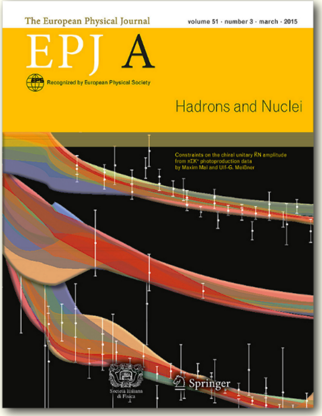
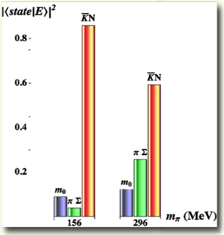


What is $\Lambda(1405)$ made of?

- **Quark model**
  - → genuine qqq state — Capstick, Isgur (1986)
  - → or even more exotic: hybrids, active glue, ...
- **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)
    - ⇒ many (confirming) works followed
    - ⇒ ***accepted by PDG in 2015!***
- **Lattice QCD**
  - → $32^2 \times 64$ full-QCD ensembles
  - → Magnetic form factor of s-quark vanishes
    - ⇒ $\Lambda(1405)$ is dominated by a molecular $\bar{K}N$ state

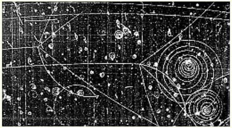
Hall et al. (2014)

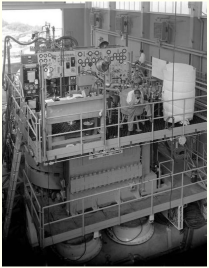


Experimental situation

- **Total cross sections on $K^-p \to K^-p, \bar{K}^0 n, \ldots$**
  - $\to$ various bubble chamber experiments

    LNL Berkeley (1960s), Rutherford Laboratory (1981s), ...





Bubble chamber @ Lawrence Radiation Laboratory

  - $\to$ huge error bars
  - $\to$ large deviations btw. experiments

    $\Rightarrow$ weak constraints on $\bar{K}N$ amplitude

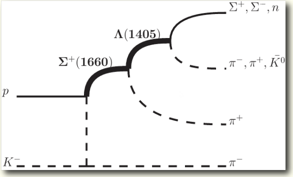
    MM, Meißner (2012), Guo, Oller (2013)

- **$\pi\Sigma$ mass distribution**

  Hemingway (1985)

  - $\to$ 2m bubble chamber @ CERN
  - $\to$ multistep production
  - $\to$ low energy resolution

    $\Rightarrow$ not very restictive



Experimental situation

- **Threshold amplitudes**
  - $\rightarrow$ $\bar{K}H$ strong energy shift and width in the SIDDHARTA exp. Bazzi et al. (2011)
    - $\Rightarrow$ a_{K^-p} from the Deser-type formula Meißner, Raha, Rusetsky (2004)
  - $\rightarrow$ plans for an upgrade to $\bar{K}D$ DAΦNE (????), J-PARC (????)
    - $\Rightarrow$ A_{Kd} from the Deser-type formula
    - $\Rightarrow$ a_1, a_0 from *Faddeev equations/ (Static Approximation + Recoil Corrections)*

      Shevchenko (2014), .../ Kamalov et al. (2001) MM et al. (2014)

- ***pp* collisions** COSY (2008) HADES (2013)
  - $\rightarrow$ high quality data
  - $\rightarrow$ theoretical analysis very intricate

- **$\pi\Sigma$ mass distribution** CLAS (2012)
  - $\rightarrow$ electro- and photoproduction: $\gamma p \to (K^+)\Lambda(1405) \to \pi\Sigma$
  - $\rightarrow$ $J^P = \frac{1}{2}^-$ "*confirmed*" experimentally
  - $\rightarrow$ high statistics and good angular resolution
    - $\Rightarrow$ **new contraints on $\bar{K}N$ amplitude (?)**

CLAS @ JLAB

I. Meson-baryon scattering

General 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

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

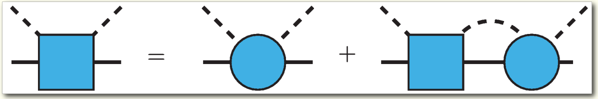
⇒ $A_{..}$ depend on low energy constants ⇒ free parameters

Resummation

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

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

→ 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

→ Loop integrals → *Passarino-Veltman* reduction → dim. reg.

→ *Bubble chain* in s direction → topologies are missing
⇒ scale dependence **does not** cancel out
⇒ additional model parameters

Fits and results

- Off-shell effects are moderate MM, Meißner (2013)
  $\Rightarrow$ for an efficient scan of parameter space (20 dim.!)
  use on-shell approximation $\rightarrow$ performance $\times$ 30
  $\Rightarrow$ later gradually turn on the off-shell effects
- Fit strategy
  - $\rightarrow$ Data: threshold amplitudes, cross sections - 155 data points
  - $\rightarrow$ Randomly chosen sets of starting values (# $\approx$ 10000)
  - $\rightarrow$ Solutions having poles on I. RS sorted out
- Results: 8 best fits obtained
  - $\rightarrow$ similar $\chi^2_{\text{d.o.f.}}$

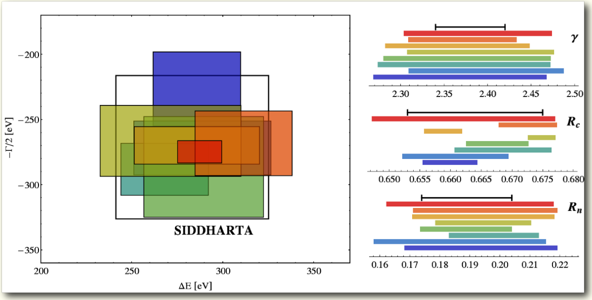
Fit #	1	2	3	4	5	6	7	8
$\chi^2_{\text{d.o.f.}}$	1.35	1.14	0.99	0.96	1.06	1.02	1.15	0.90

Fits and results

- Results: 8 best fits obtained

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

→ similar threshold ratios

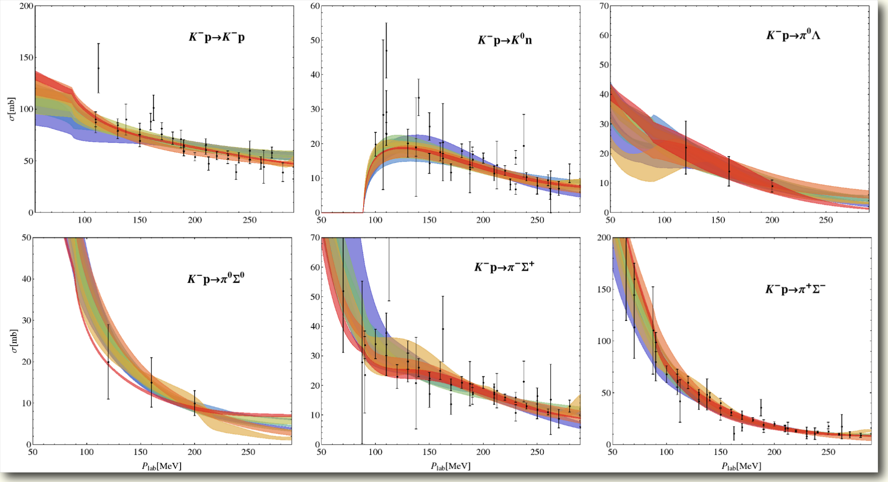


→ error bars are twofold

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

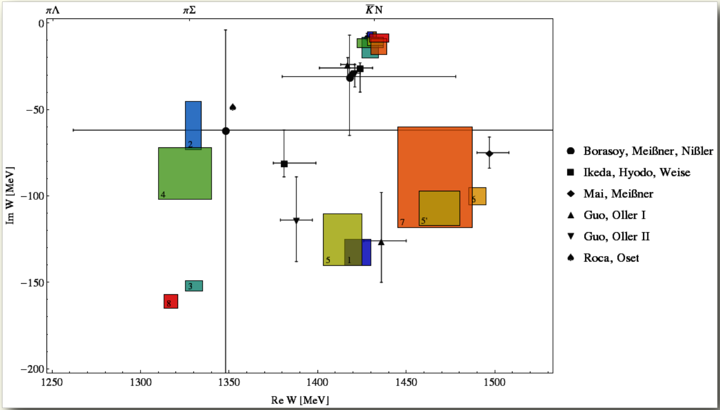
Results

$\rightarrow$ 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

II. CLAS data on $\gamma p \to K^+ \pi \Sigma$

Framework

Data

- $\Lambda(1405)$ lineshape from double meson photoproduction JLAB `CLAS (2012)`
  - → 9 energy bins
  - → 60 values of $M_{\pi\Sigma}$ - 5 MeV resolution
  - → three channels: $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\pi^0\Sigma^0$

Photoproduction amplitude

I Gauge invariant approaches

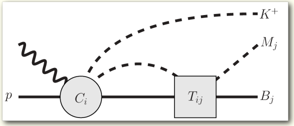
1. Turtle approximation
   - attach photon everywhere to *off-shell* hadronic amplitude
     `Gross, Riska (1987), Kvinikhidze, Blankleider (1999) and Borasoy et al. (2005)`
   - single meson case is done for the NLO-kernel `MM et al.(2012)`
   - double meson case is tidious ... *work in progress*
2.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

Framework

II Test model

- most simple ansatz to test the hadronic solution:

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



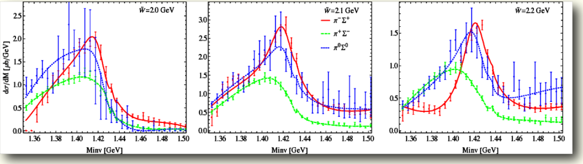
- flexible enough for the CLAS data Oset, Roca (2013)
  ⇒ less free parameters ($15 \mapsto 10$)
- no gauge invariance, parameters are not physical
  ⇒ global fit is meaningless
  ⇒ *no access* to microscopic features of the spectrum
  ⇒ **conservative** test of the hadronic solutions

Results

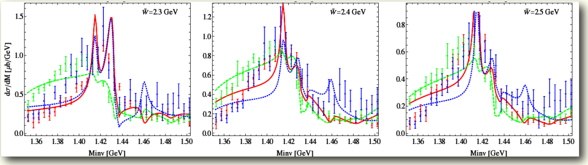
- Test of hadronic solutions

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

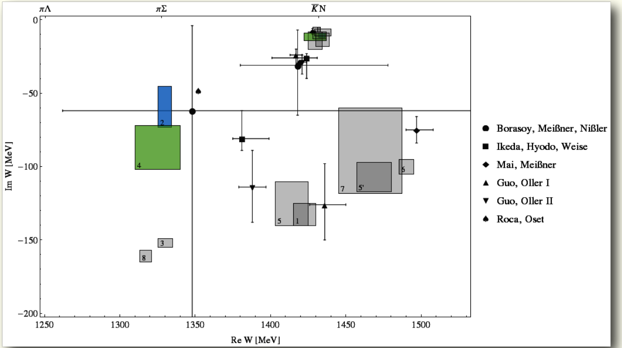


- Hadronic fits #1, #3, #6, #7 and #8 do not!!!



Results - comparison

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



$\Rightarrow$ both solutions have similar pole positions

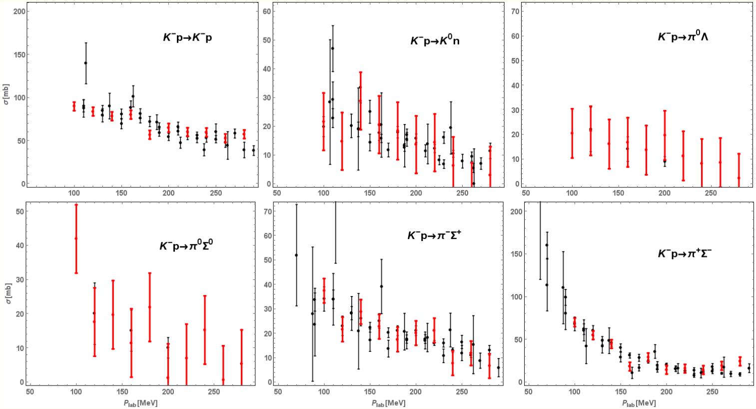
... also similar to the estimation by Oset and Roca (2013)

$\Rightarrow$ **universal feature** demanded by CLAS data!

III. New scattering data???

Pseudo scattering data

- What is the desired accuracy on $\sigma_{\bar{K}N\to\ldots}$ measurement?
- **Generate pseudodata: benchmark - fit #4**
  - → *Assume* uniformly distributed data for $p_{lab} = 100 \ldots 300$ MeV
    ... with energy bins of the size of $\Delta E = 5, 10, 20$ MeV
  - → *Assume* error bars of $\Delta\sigma = 2.5, 5, 10$ mb for charged
    ... and $\Delta\sigma = 5, 10, 20$ mb for neutral channels

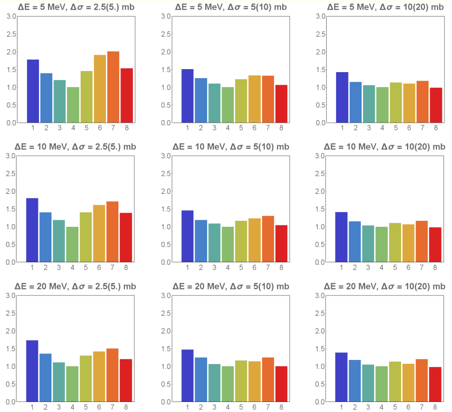


Pseudo scattering data

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

$\rightarrow$ threshold ratios, SIDDHARTA

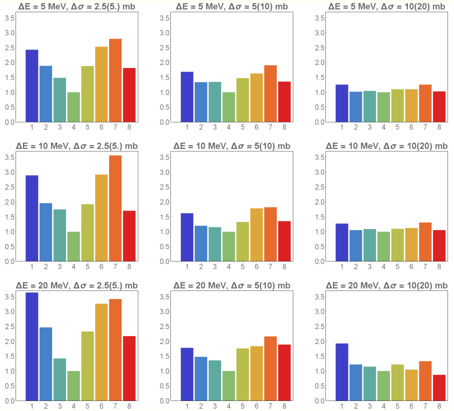
$\rightarrow$ pseudo and real scattering data



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

$\rightarrow$ threshold ratios, SIDDHARTA

$\rightarrow$ pseudo scattering data

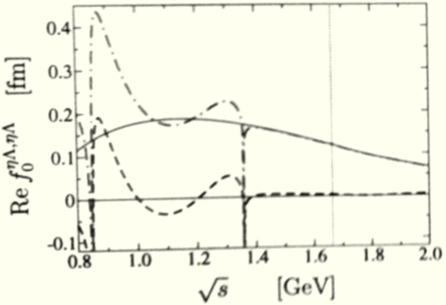


$\Rightarrow$ much larger values of $\Delta\sigma$ and ΔE are sufficient

Summary

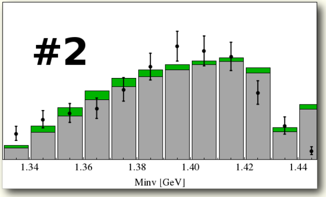
- The NLO chiral unitary $\bar{K}N$ amplitude used to analyze hadronic data
- 8 solutions are found in the *on-shell* approximation
  → *the position of the narrow pole is quite certain*
  → *broad pole has large systematic uncertainty*
- Photoproduction amplitude constructed from the hadronic part
  → *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*

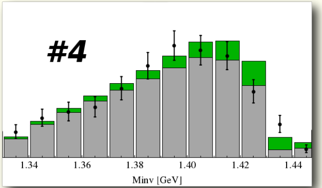
THANK YOU



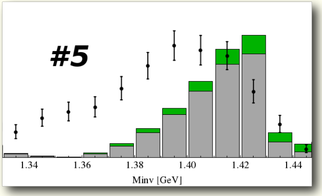
Re $f_0^{\eta\Lambda,\eta\Lambda}$ [fm]
$\sqrt{s}$ [GeV]
Im $f_0^{\eta\Lambda,\eta\Lambda}$ [fm]
$\sqrt{s}$ [GeV]

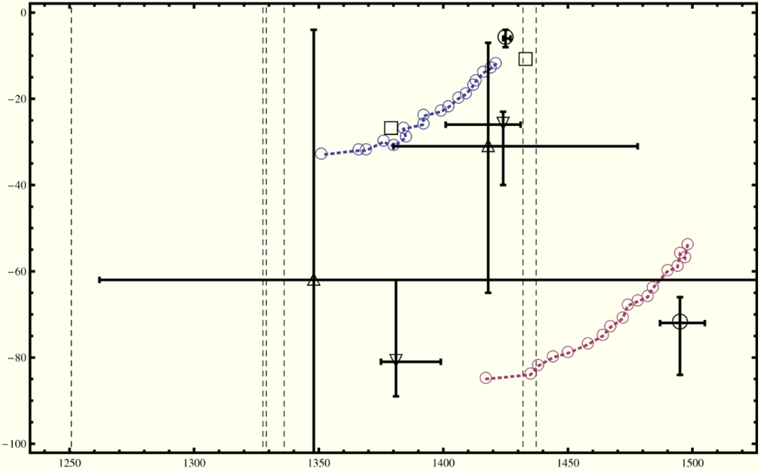
- Qualitative comparison with Hemingway data ($K^- p \to \Sigma^+ \pi^- \pi^+ \pi^-$)
  - → Fit #2 and #4 are fine



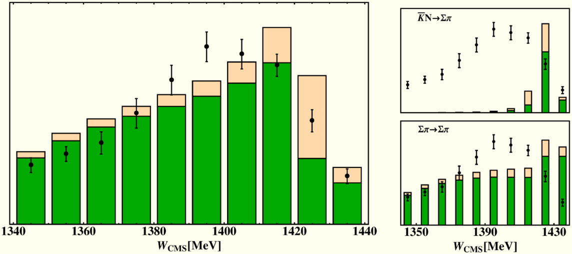


  - → Fit #5 is completely off





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]