Status of the Lambda(1405)

Maxim Mai
The George Washington University

ANNALS OF PHYSICS: 8, 100–118 (1959)

The Energy Dependence of Low Energy K^--Proton Processes*

R. H. DALITZ AND S. F. TUAN

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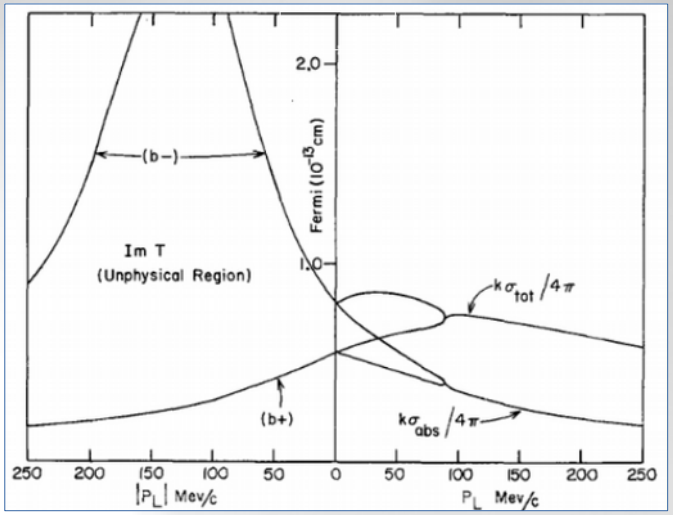


... 58 years later...

****** P D G (2017) ******

$$S = -1$$

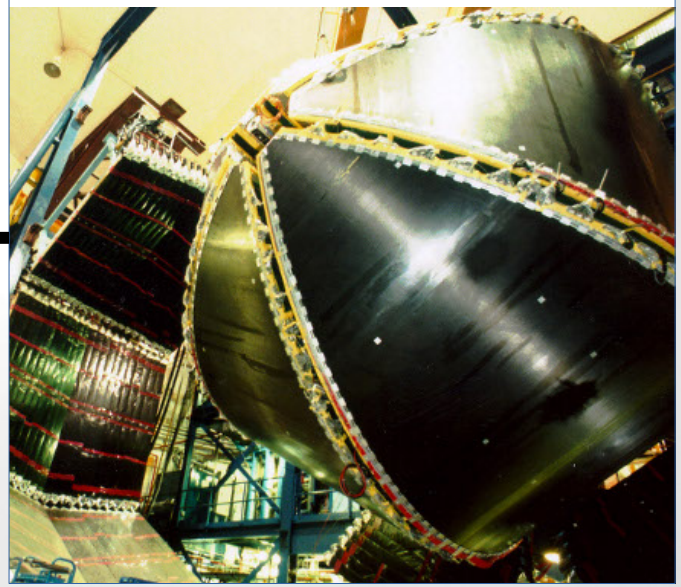
$$I = 0$$

$$J^p = \frac{1}{2}^-$$

$$M = 1405.1^{+1.3}_{-1.0}\ \text{MeV}$$

$$\Gamma = 50.5 \pm 2.0\ \text{MeV}$$

Experimental verification
CLAS@JLab (2014)



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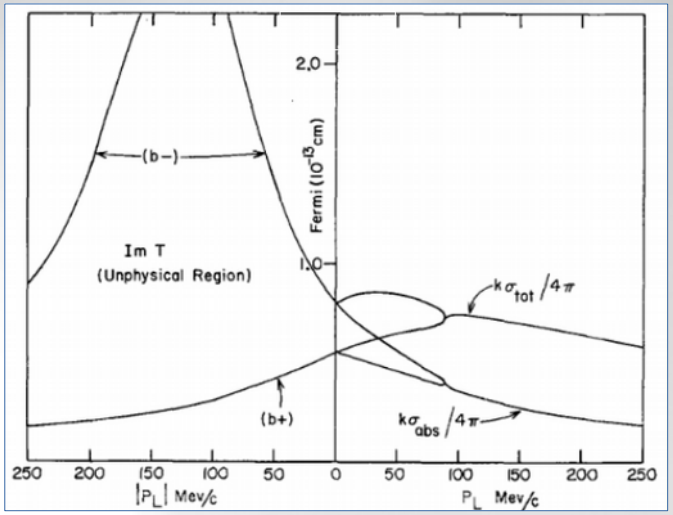

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But only one of two poles

Extrapolation below $\bar{K}N$ threshold

Major challenges

* Non-perturbative scattering amplitude required
* Isospin breaking has to be taken into account
* 10 channels w. same QNs
* Universality → interaction kernel & QCD

→ *PDG-note on Lambda(1405)* **Hyodo, Meißner (2015)**

Generation mechanism

Dynamically Generated State

* quasibound $\bar{K}N$ state in $\pi\Sigma$ continuum
* K-matrix — **Dalitz, Tuan (1960)**
* Unitarized ChPT amplitude — **Kaiser, Siegel, Weise (1995)**, **Oset, Ramos (1998)**

→ two-pole solution

Oller, Meißner (2001) Jido et al. (2003)

Genuine Quark State

* qqq state:
  $\Lambda(1405)$ **mass-degenerate** to $\Lambda(1520)$

Isgur, Karl (1978)

* Possible extensions:
  - active glue
  - hybrids: $qqq\bar{q}q$

*** presumably a mixture of both → ratio?**

Lattice QCD: strange magnetic form factor of s-quark vanishes

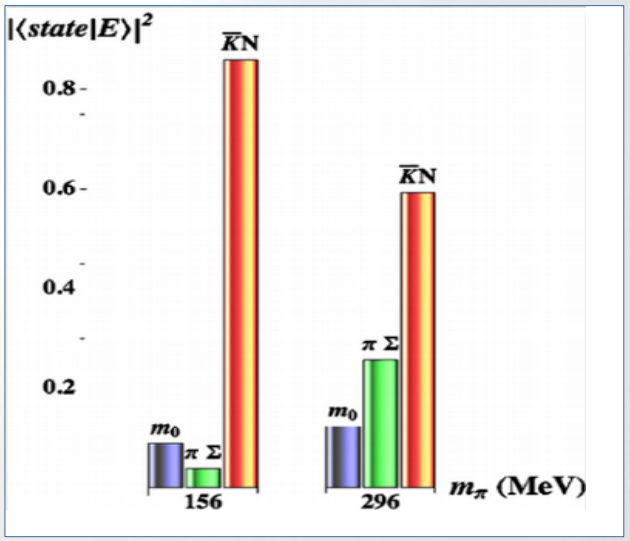
⇒ *Λ(1405) is dominated by a molecular $\bar{K}N$ state*

Hall et al. (2014)

– statistics/operator basis is improvable

– contribution of the second pole neglected

Molina, Döring (2015)



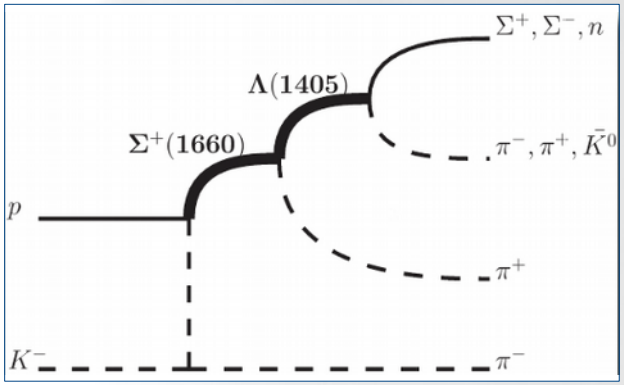
Experimental data

1) Cross sections **LNL (1960s), Rutherford Lab(1980s), ...**

* $K^- p \to K^- p,\ \bar{K}^0 n,\ \ldots$
* bubble chamber experiments
* huge error bars
* large deviations btw. experiments

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

* (2m) bubble chamber @ CERN
* low energy resolution
* multi-step production mechanism



3) SIDDHARTA **Bazzi et al.(2011)**

* Strong energy shift and width in $\bar{K}H$
* Very precise, but only determines $K^- p \to K^- p$ scattering length **Meißner, Raha, Rusetsky (2004)**

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

* high quality data, but theoretical analysis very intricate

Importance & Implications

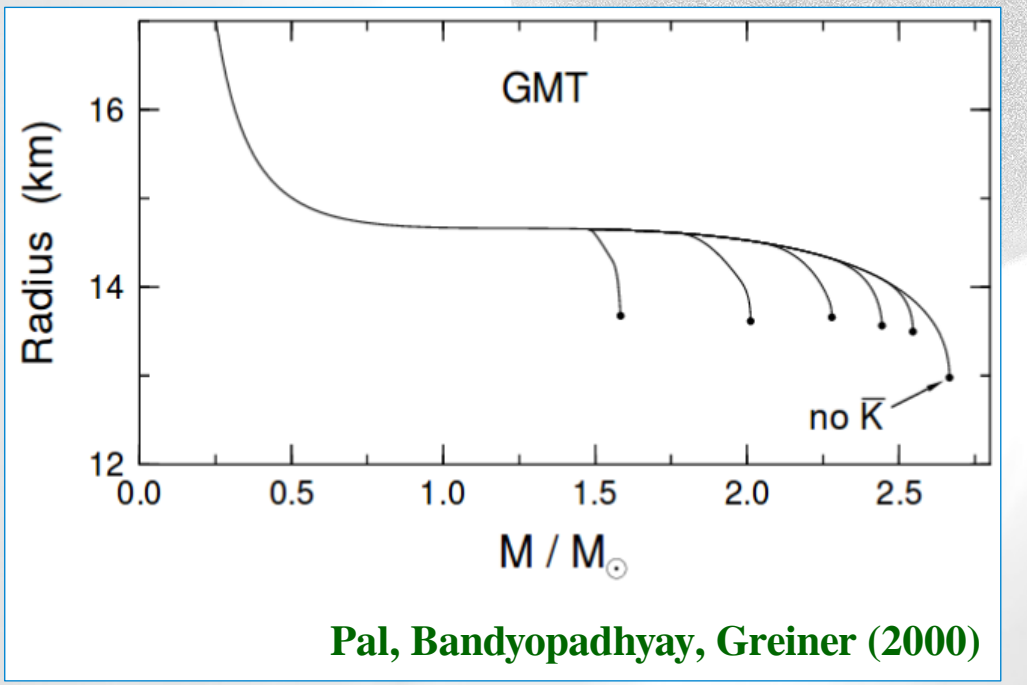
* Test of our understanding of QCD

* Possible $\bar{K}NN$ bound state dominated by $\bar{K}N$ interaction — **FINUDA/J-PARC/HADES**

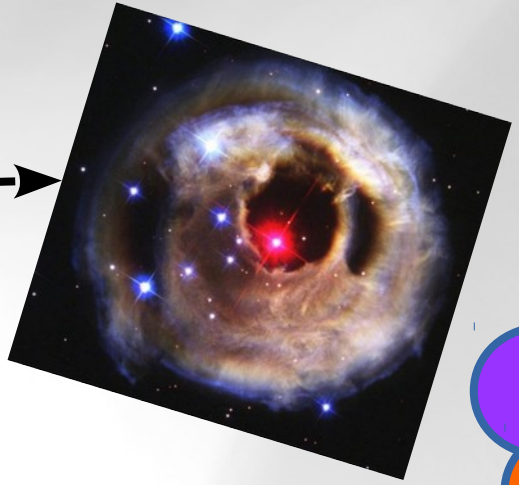
* **Observation of ~2$M_\odot$ neutron stars in *PSR J0348+0432*** — **Demorest et al. (Nature 2010)**, **Antoniadis et al.(Science 2013)**

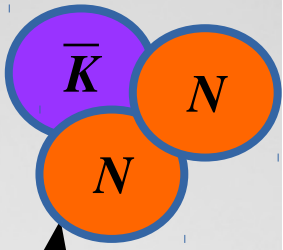
→ challenges our understanding of the EoS of NS

→ $\bar{K}$-condensate changes EoS-stiffness significantly

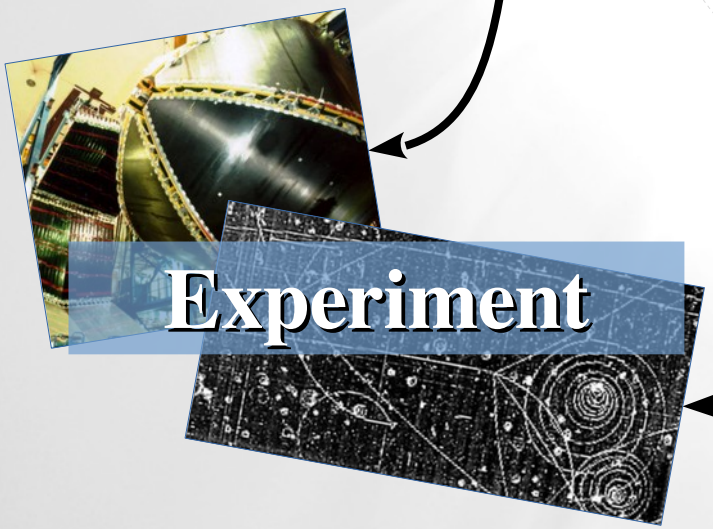


Pal, Bandyopadhyay, Greiner (2000)





Theoretical developments



Experiment

From QCD to scattering amplitude

ChPT = EFT of QCD **Weinberg (1979) Gasser, Leutwyler (1981)**

- is an appropriate tool for low-energy hadronic interactions
- Here it fails (perturbatively)!
  - * Kaon mass is large → *convergence*
  - * Relevant thresholds are widely separated → *convergence*
  - * Resonance just below $\bar{K}N$ threshold → *non-perturbative effect*

SU(3) ChPT

$$a_{\bar{K}N}^{I=0} = +0.53\ (LO) + 0.97\ (NLO) - (0.40 - 0.22i)\ (NNLO) = +1.11 + 0.22i\ \text{fm}$$

M.M. et al. (2008)

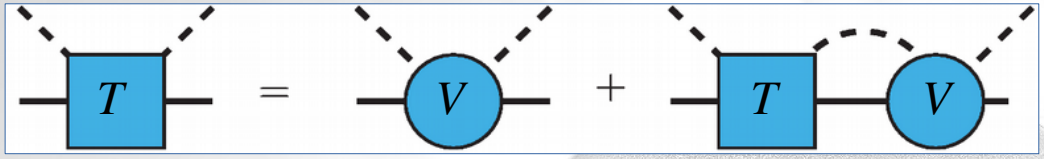
Non-perturbative methods:

- * Dispersion relations, N/D, Roy-Steiner equations
- * K-Matrix, JÜLICH-BONN model, …
- * **Chiral Unitary Approaches**

Chiral Unitary Approach(es)

Common features

* Unitarity is exact, e.g. via Bethe-Salpeter equation — **Salpeter et al.(1951)**



* Driving term from ChPT at LO or NLO — **Gasser, Leutwyler (1981)**

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

Variations

* Choice of V
  → Free parameters: low-energy-constants (0-14) & regularization scales (6)
* Solution of the BSE
  → Off-shell BSE analytically solvable, **if(f)** V ~ local terms — **Bruns, M.M., Meißner (2011)**
  → Off-shell effects are moderate for $\bar{K}N$ — **M.M., Meißner (2013)**
  → On-shell approximation technically advantageous

Typical features

* Two poles in the channel of $\Lambda(1405)$ — **Oller, Meißner (2001)**
  → Narrow @ ~1410 MeV — **.../Ikeda et al.(2013)/Roca, Oset(2013)**
  → Broad @ ~1350 ...?? — **.../MM, Meissner(2015)/Guo, Oller(2015)**

NLO kernel with s- & p-waves

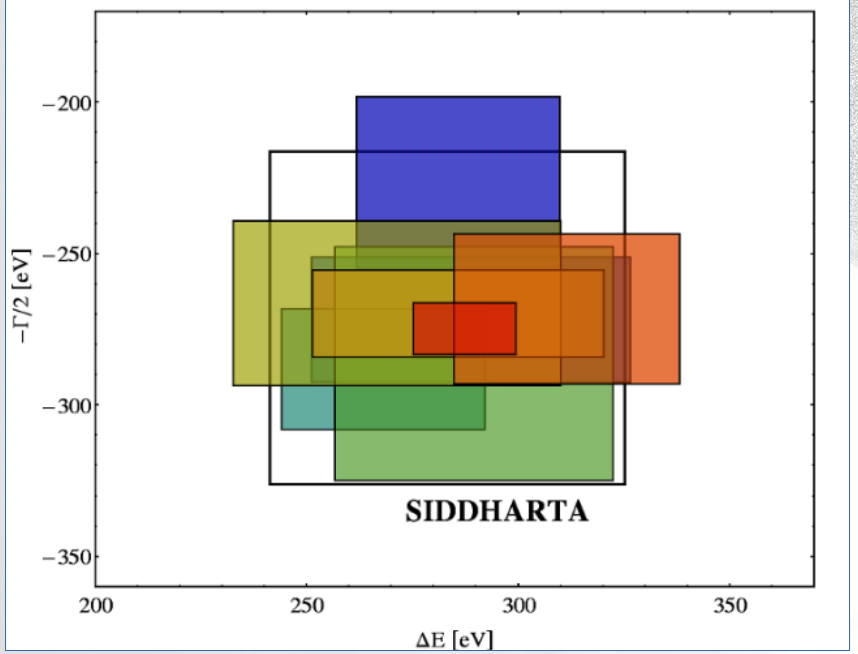
M.M., Meißner (2015)

- 8 best fits obtained with similar $\chi^2_{\text{d.o.f.}}$

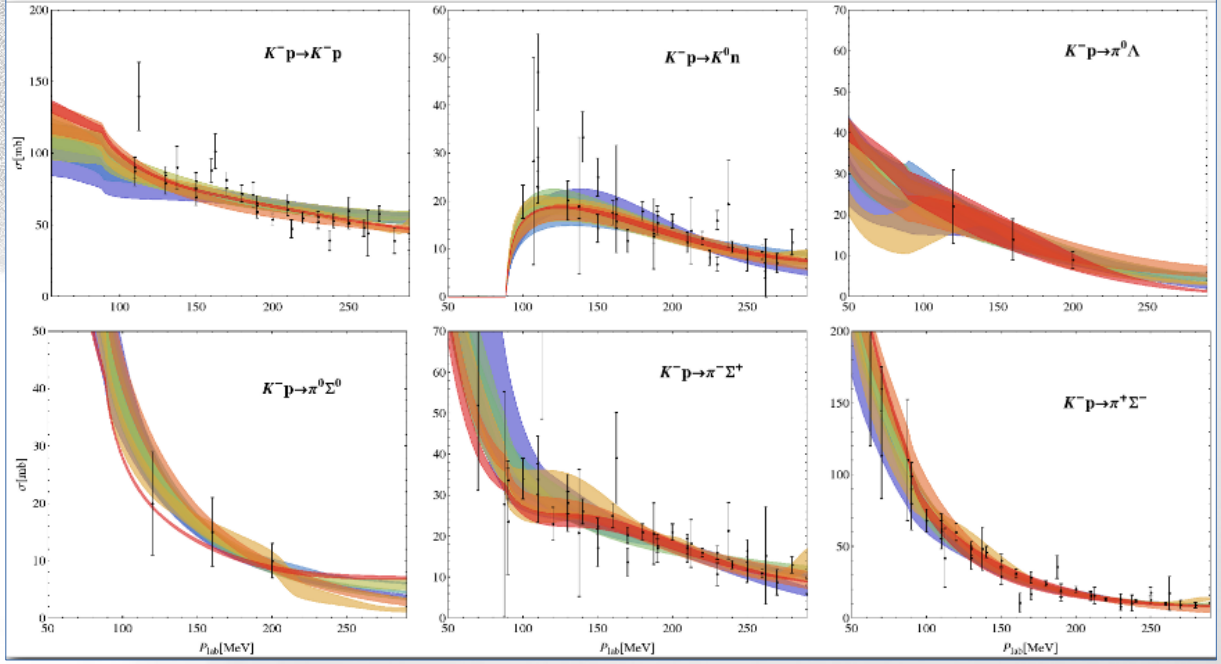
Fit #	1	2	3	4	5	6	7	8
$\chi^2_{\text{d.o.f.}}$	1.35	1.14	0.99	0.96	1.06	1.02	1.15	0.90

- **Error bars: variation of fit parameters ($\Delta\chi^2_{\text{d.o.f}} < 1.15$) & spread of solutions**

Threshold ratios



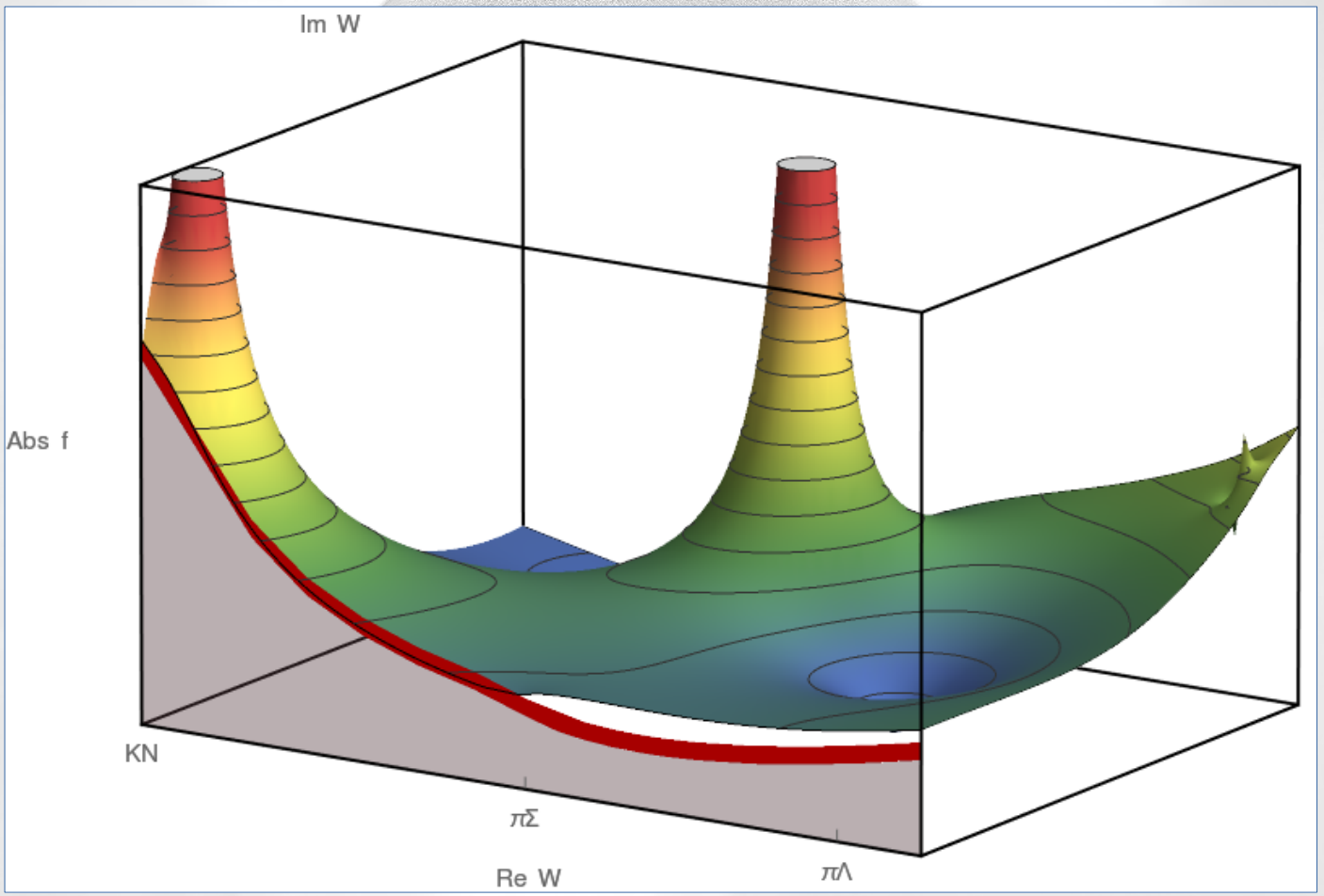
Total cross sections



NLO kernel with s- & p-waves

M.M., Meißner (2015)

- Analytic continuation to the complex energy plane
  → two poles in all 8 solutions on the II. RS



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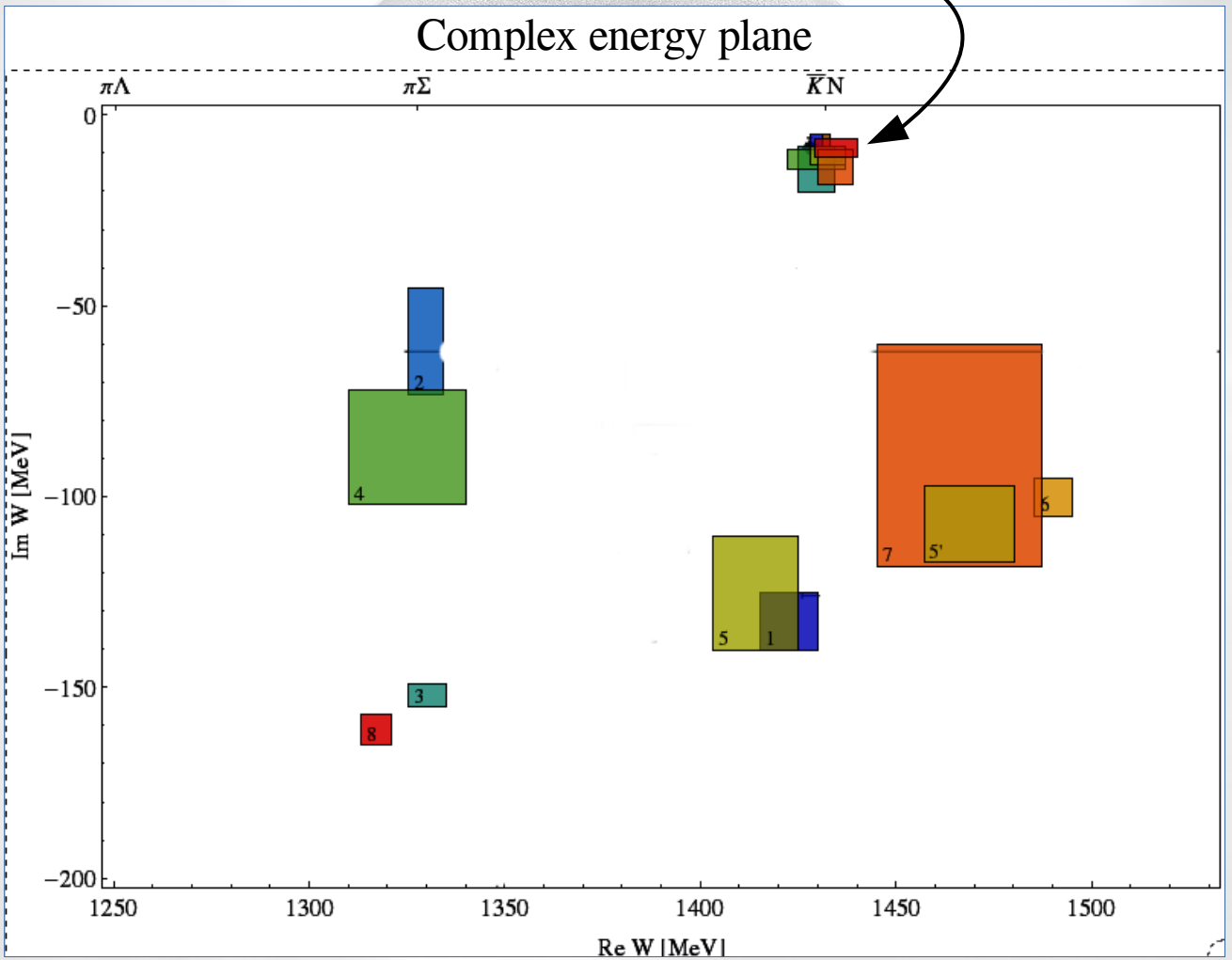

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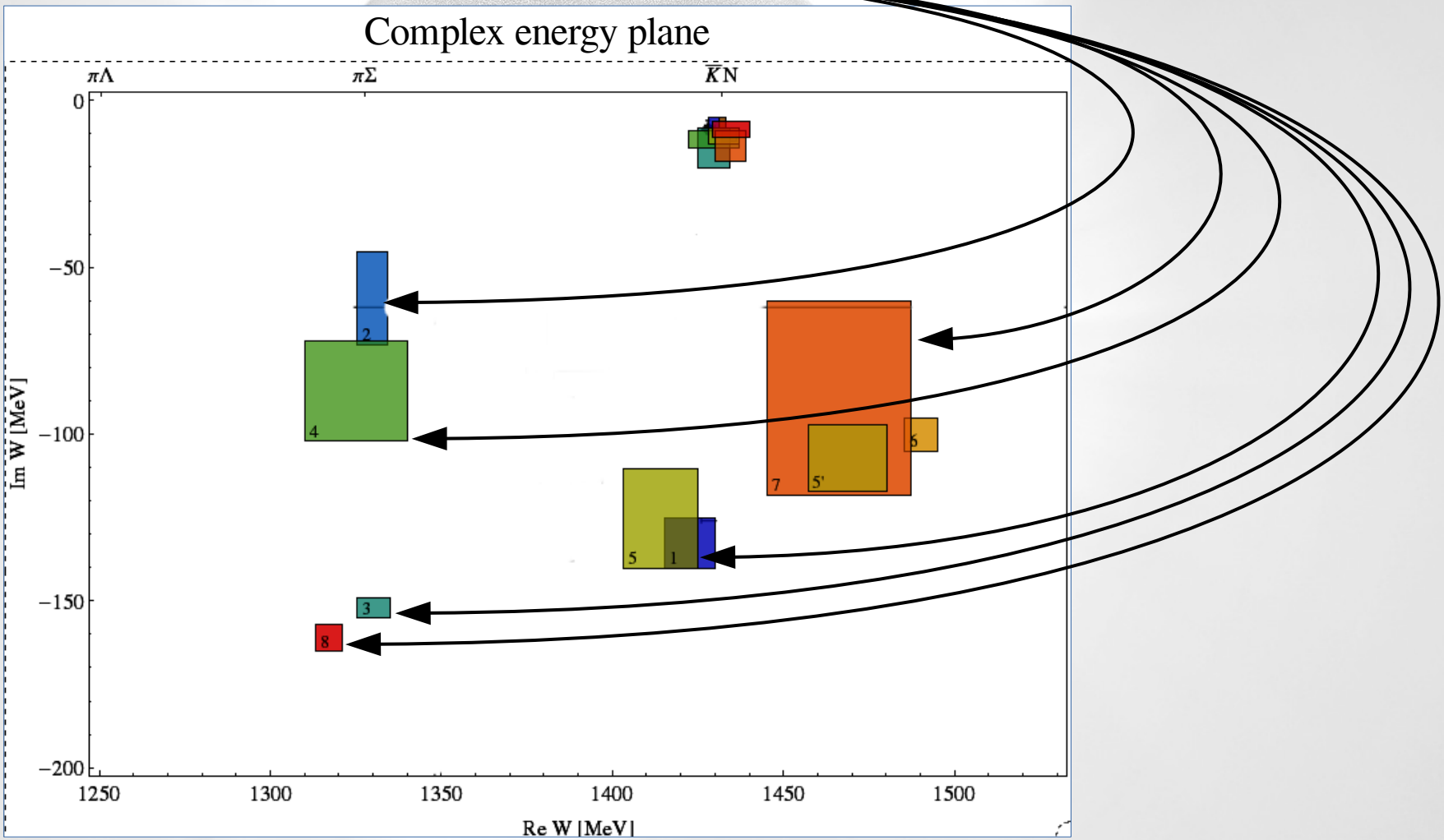
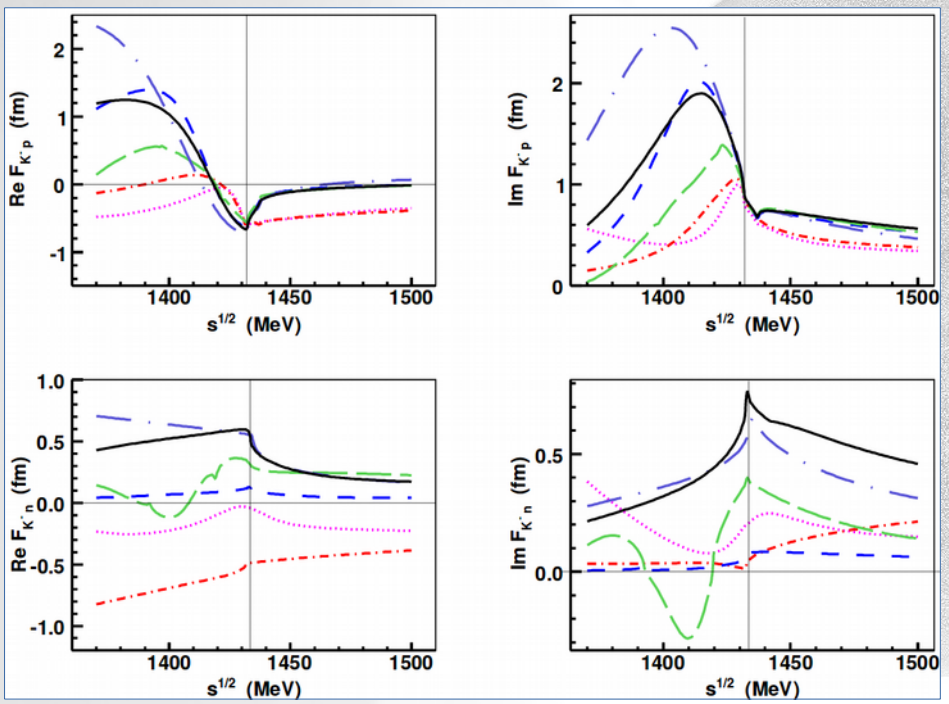
- Analytic continuation to the complex energy plane
  → two poles in all 8 solutions on the II. RS
  → position of the narrow pole stable
  → **position of the broad pole not!**



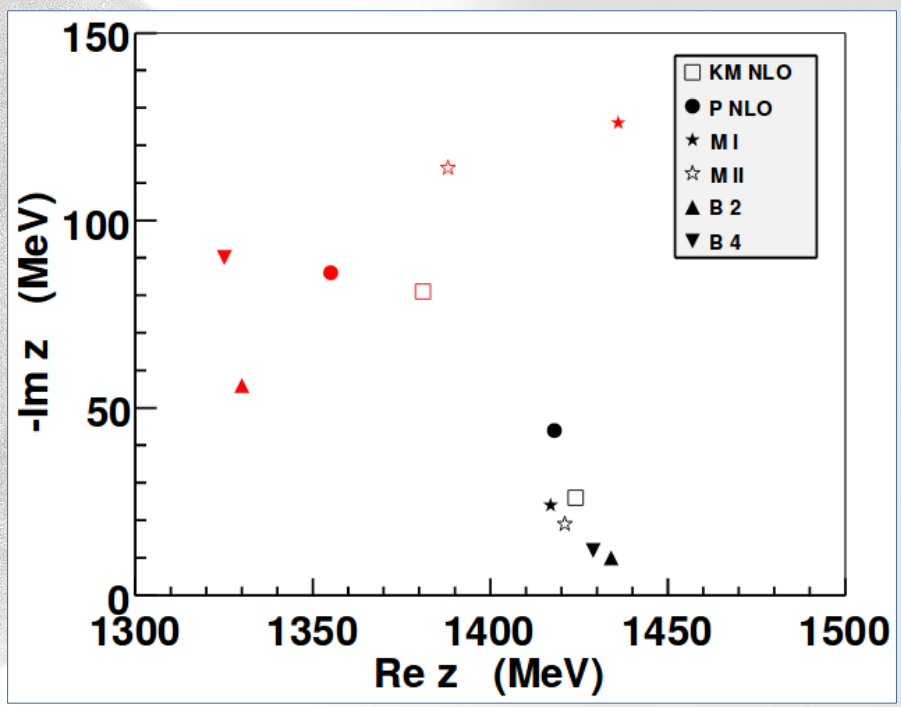
Inter-NLO-model comparison

* Direct comparison of most recent (NLO) UChPT approaches **Cieply, M.M., Meißner, Smejkal (2016)**

S-wave amplitude



Pol positions



* **agreement at the threshold in the K^-p channel**

* **large spread in the $I=1$ channel**

* Large spread of the position of the second (red) pole

Theoretical ambiguity

multiple solutions agree with data, but make different predictions for Λ(1405) properties

1) **New data on cross sections** — **Proposed experiment: Klong(20??)**

2) **Differential cross sections** — **Mast et al.(1976)**

→ requires an approach with angular dependence in the kernel — **M.M., Meißner(2015)**

→ **work in progress...** — **Sadasivan et al. (2017?)**

3) ***K̄NN, K̄d* measurements** — **Proposed experiments – SIDDHARTA2 / J-PARC**

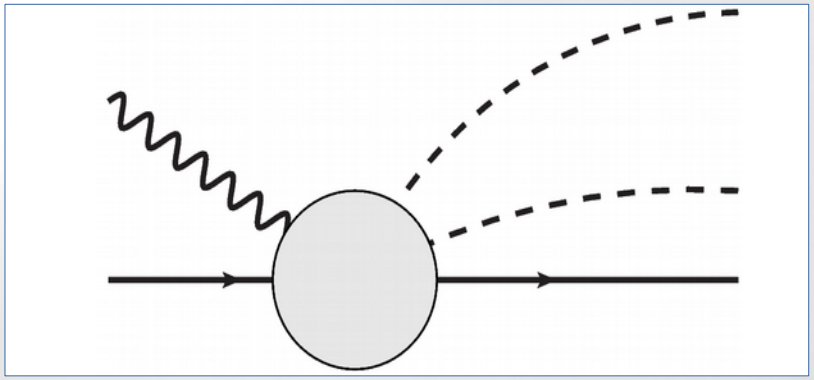
→ disentangle *I=0* and *I=1* contributions

→ require 3body scattering amplitude — **Shevchenko(2014), M.M. et al.(2015) Hoshino et al. (2017)**

4) **CLAS data on $\gamma p \to K^+\pi\Sigma$** — **Moriya et al. (2012)**

→ high precision data

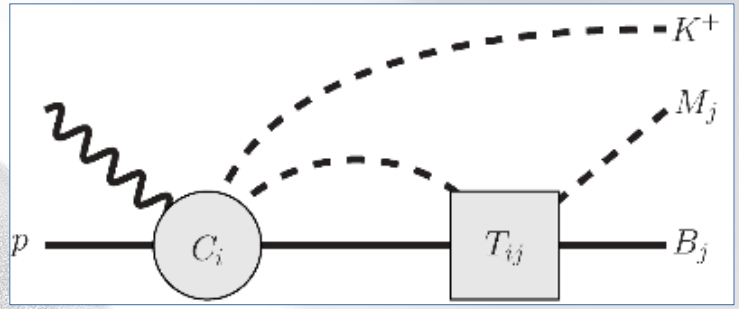
→ Two-meson photo-production mechanism?



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

Most simple ansatz to test the hadronic solution

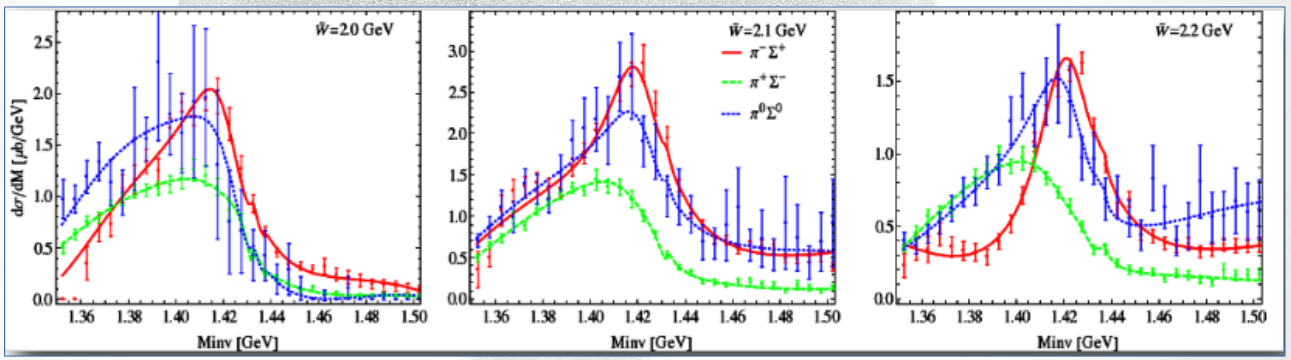
Oset, Roca (2013) MM, Meißner(2015)



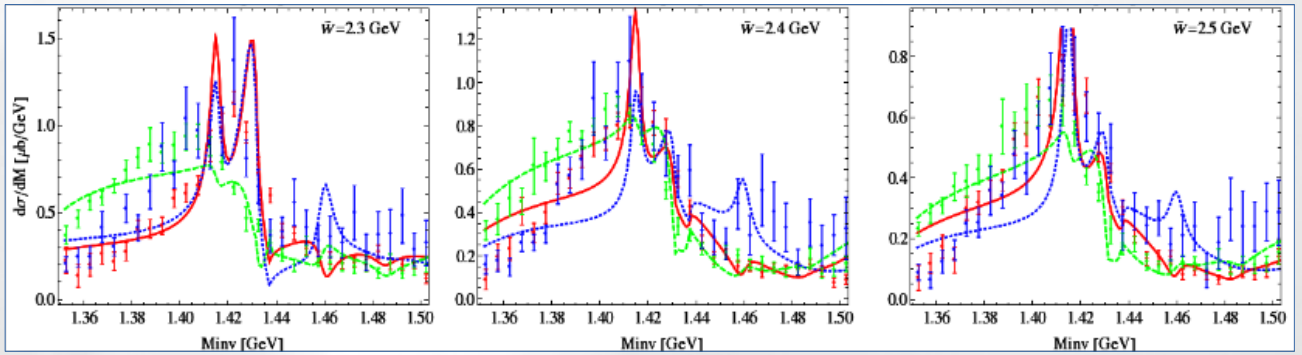
- new "generic" model parameters (C_i)
- T_{ij} from 8 previous (hadronic) fits
- conservative test of the hadronic solutions

Result

- Only 2 hadronic solutions allow for a good fit to CLAS data



- Others do not



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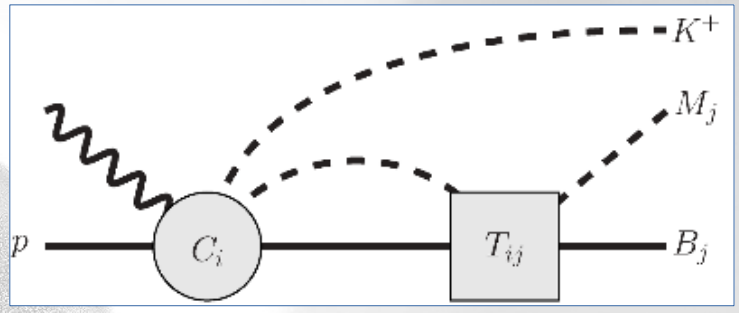

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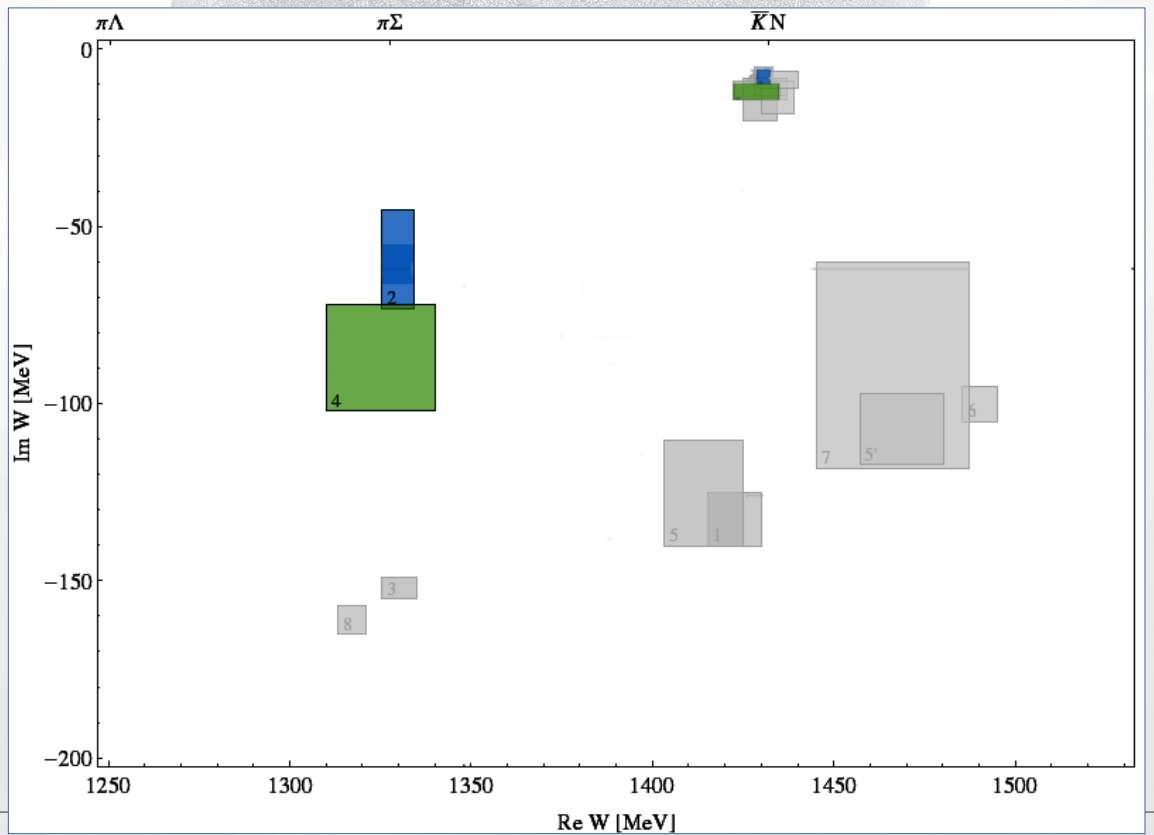

Summary & Outlook

- **$\Lambda(1405)$ is dominated by $\bar{K}N$ interaction**
- **$\bar{K}N$ physics has large implications**
  - Neutron Stars
  - $\bar{K}NN$ bound states
- **Modern theoretical approach**
  - Chiral potential + Bethe-Salpeter equation
- **Sizable systematic uncertainties btw variants of UChPT**
  - Available data old and imprecise
  - New sources will become available soon
  - High-precision CLAS data reduces theoretical uncertainty

Thank you