Structure of the antikaon-nucleon scattering amplitude

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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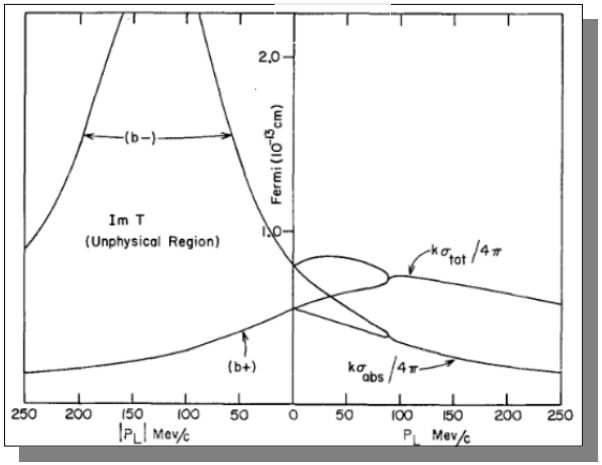

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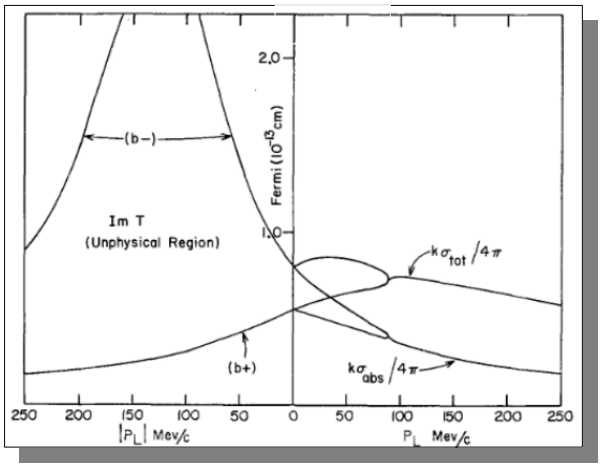

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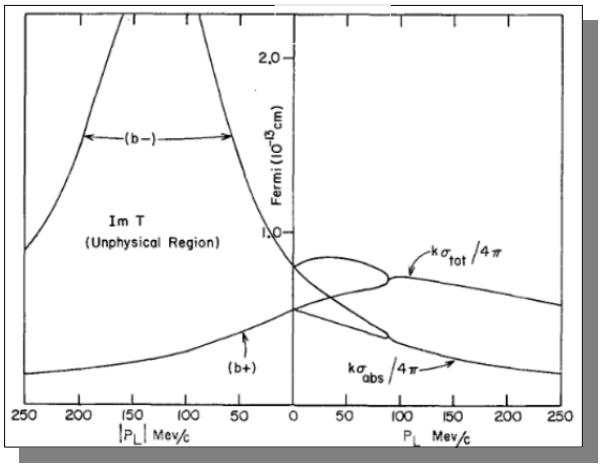

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Quantum Numbers

$S = -1$ $I = 0$ $J^p = 1/2^-$ **(CLAS (2012))**

Mass

~1410-18*i* MeV

Λ(1405)

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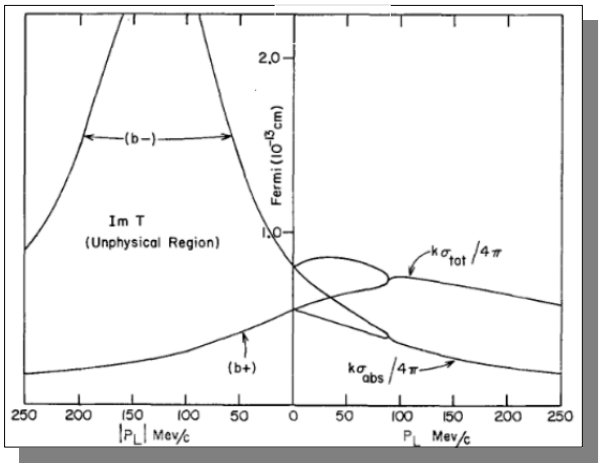

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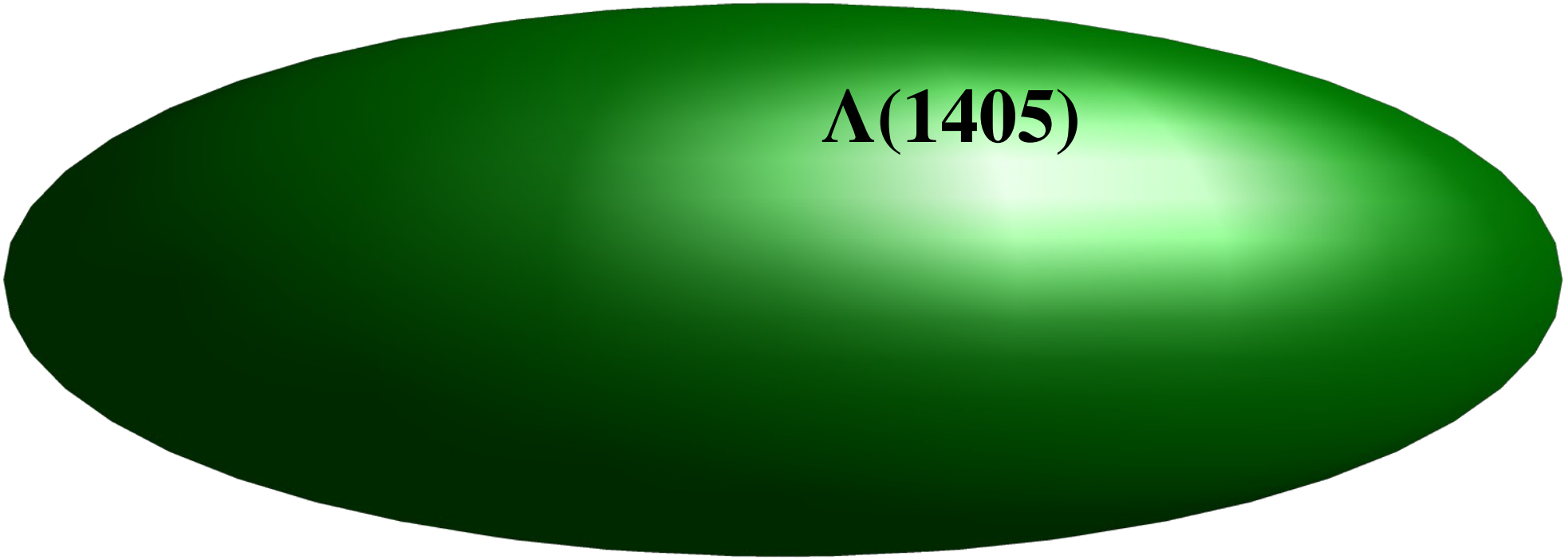
Production mechanism

→ genuine qqq state?
→ dynamical effect?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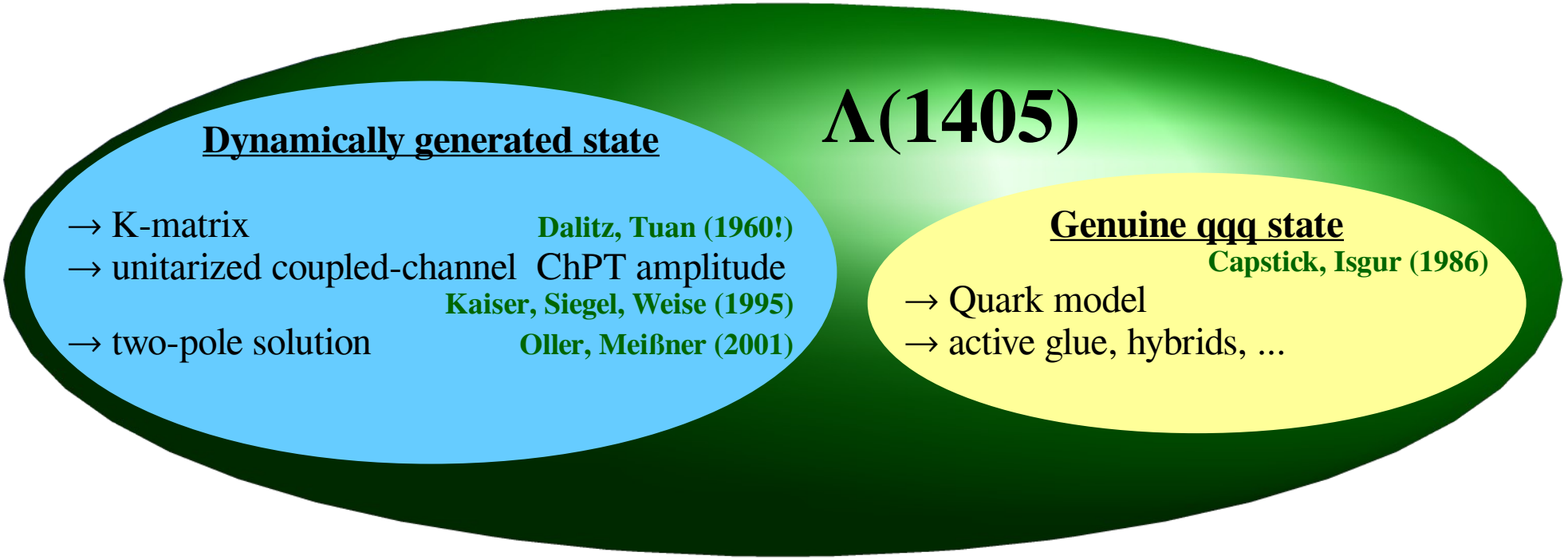
Genuine qqq state

Capstick, Isgur (1986)

→ Quark model

→ active glue, hybrids, ...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Dynamically generated state
→ K-matrix
Dalitz, Tuan (1960!)
→ unitarized coupled-channel ChPT amplitude
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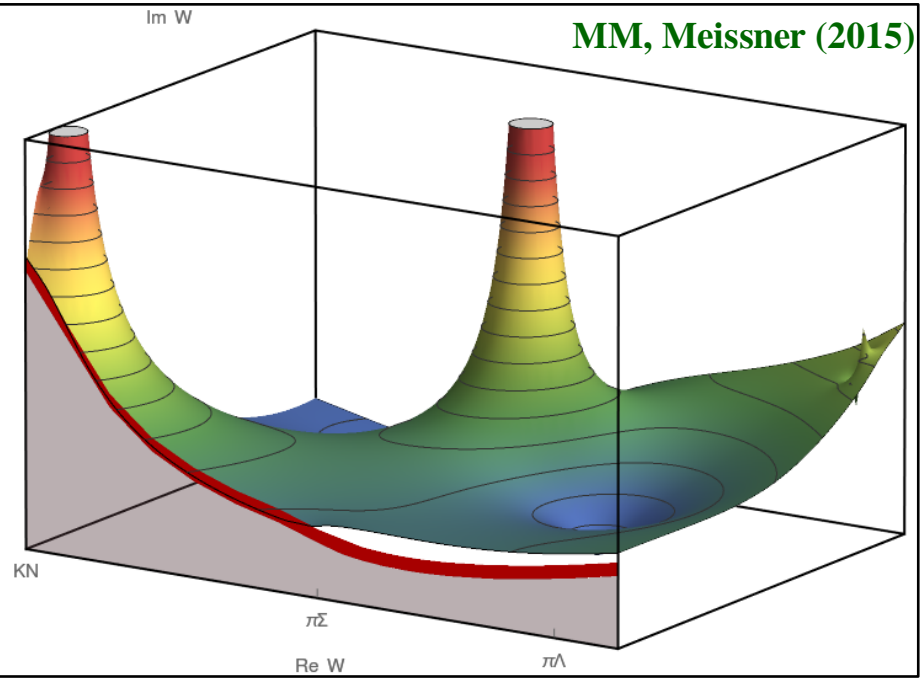
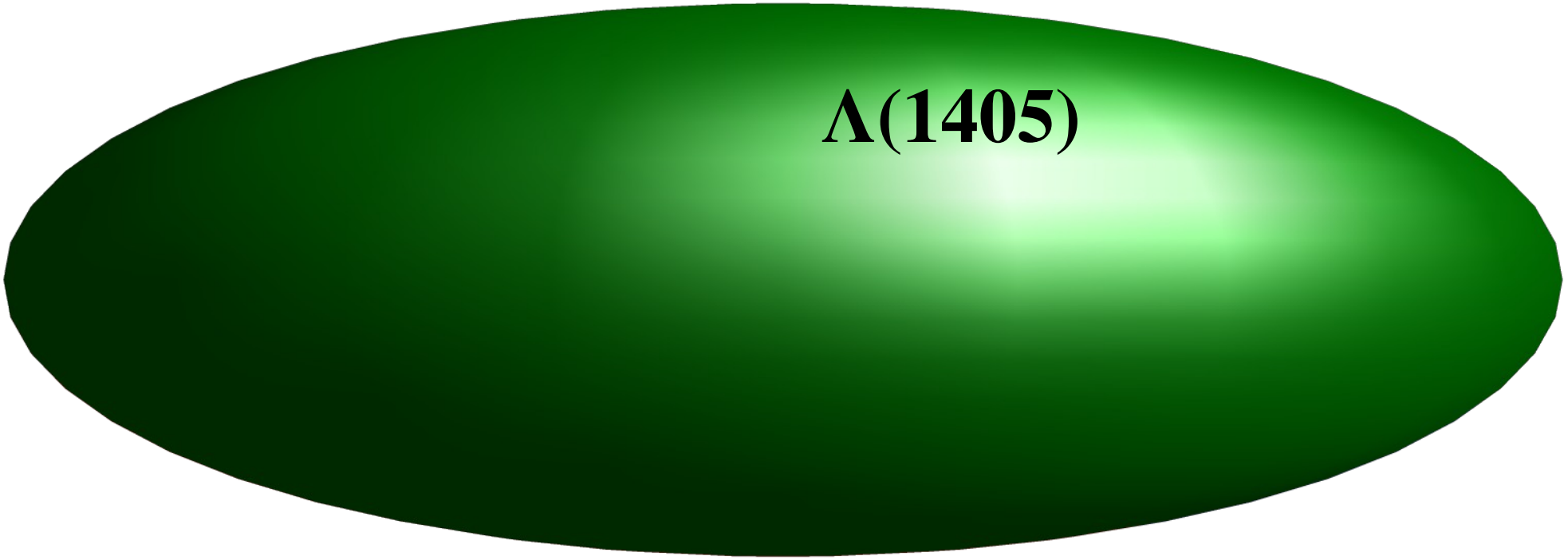
- Evaluate the scattering amplitude in the complex energy plane
- **Riemann surface** emerges with 2^(open channels) sheets

  → NO POLES on first Riemann Sheet

  → Poles on other sheets ~ **Resonances**

MM, Meissner (2015)

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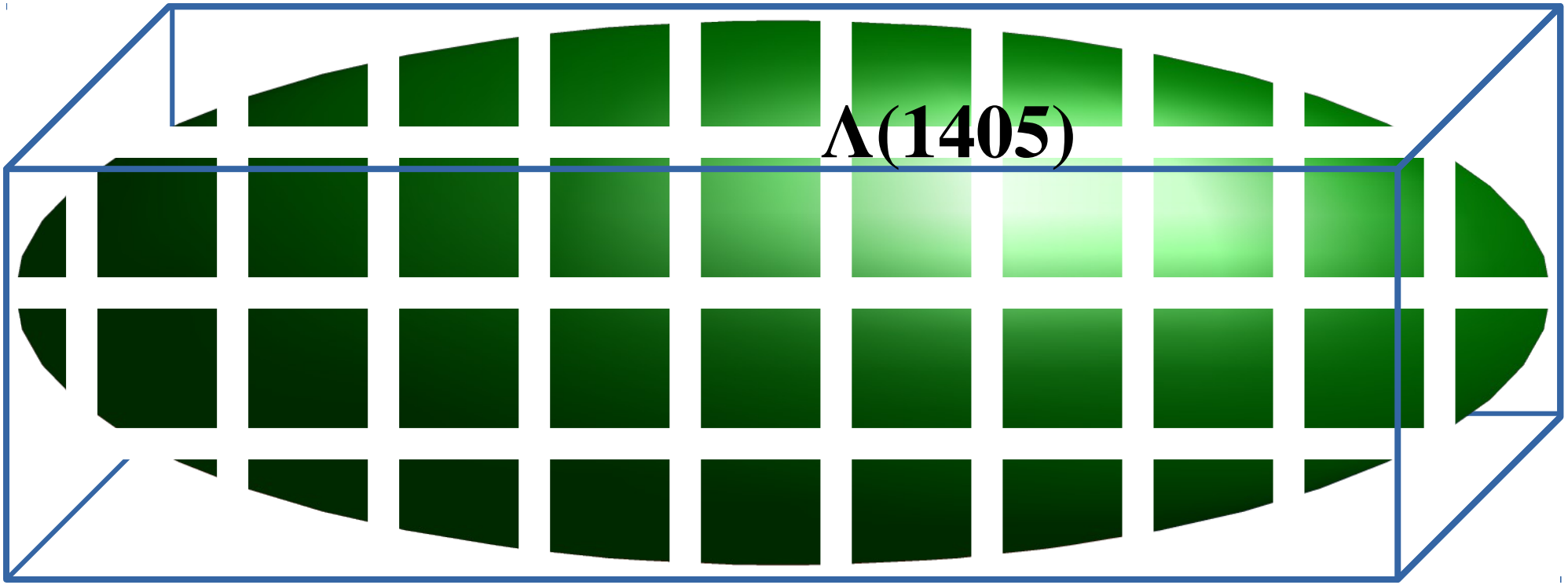

Lattice QCD

- Numerical simulations on ***discretized***, ***Eucledean*** space-time

$\Lambda(1405)$

$\bar{K}N$ molecule ~90%

Genuine qqq state ~10%

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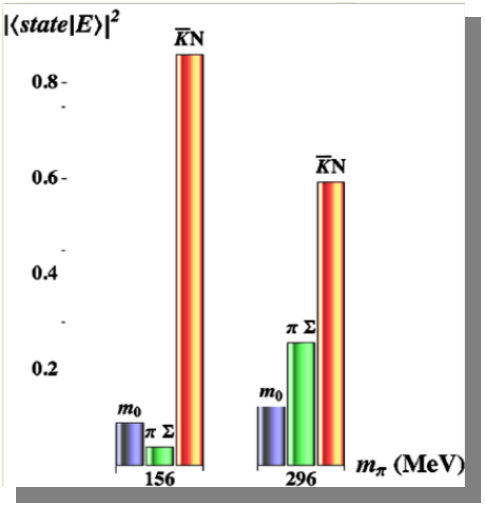
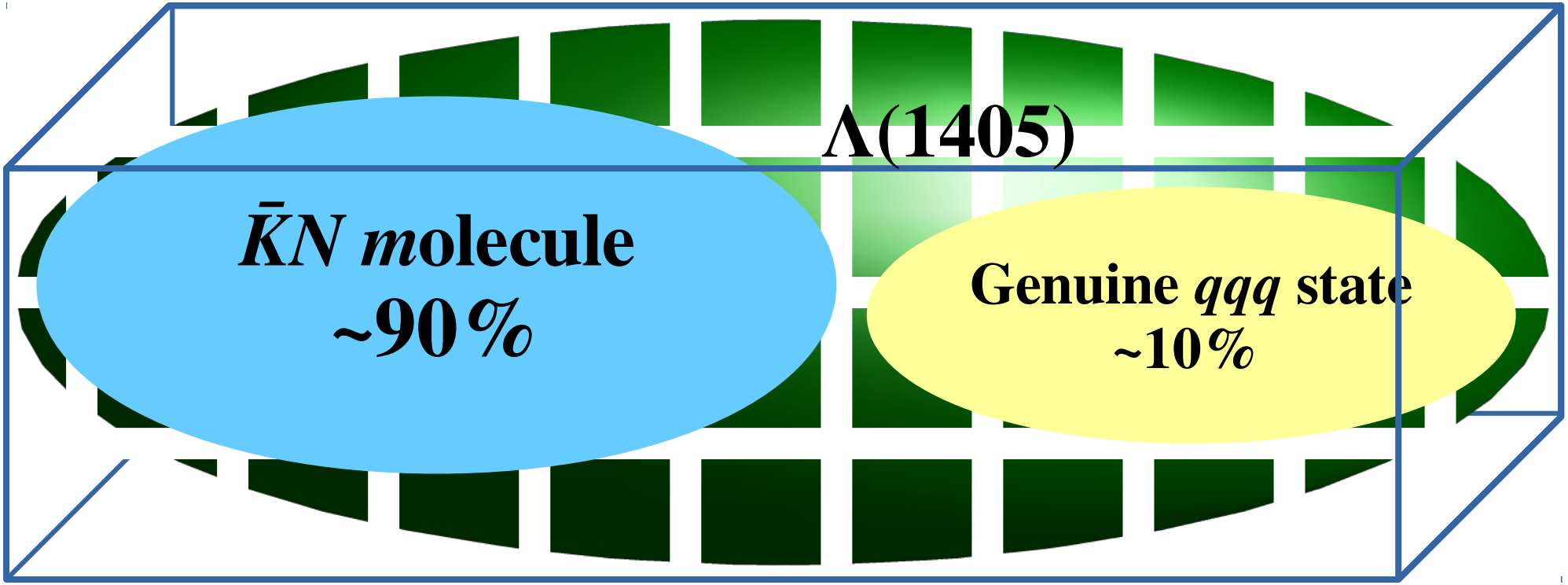
- Magnetic form factor of s-quark vanishes

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

Hall et al. (2014)





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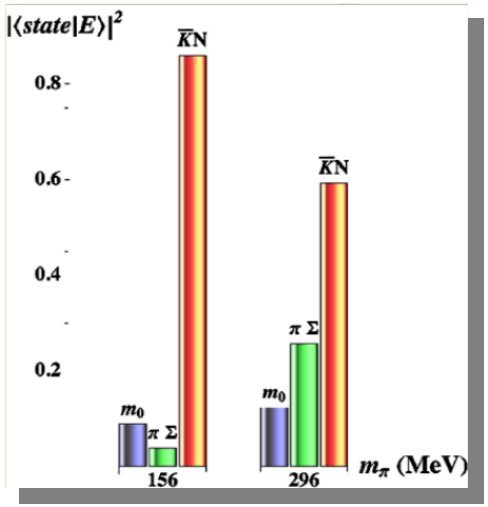

PDG

- Favors dynamically generated state scenario

PDG MiniReview (2015)

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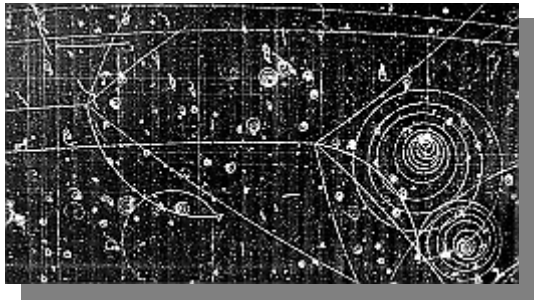
- huge error bars
- large deviations btw. Experiments

LNL (1960s), Rutherford Lab(1980s), ...



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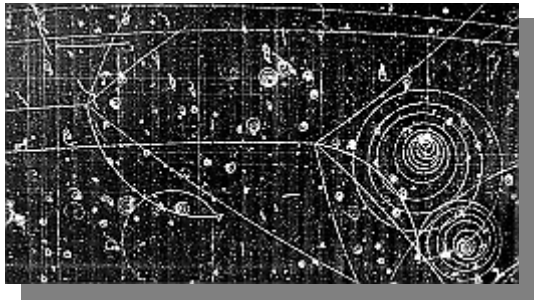

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- 2m bubble chamber @ CERN
- low energy resolution
- Multi-step production ⇒ new parameter

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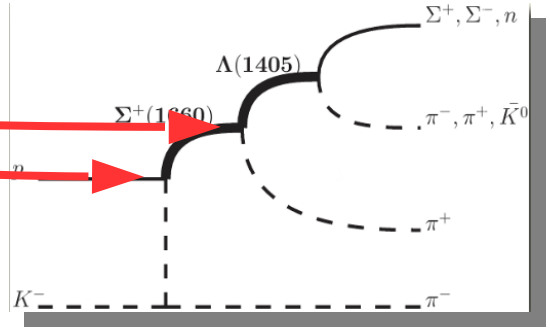

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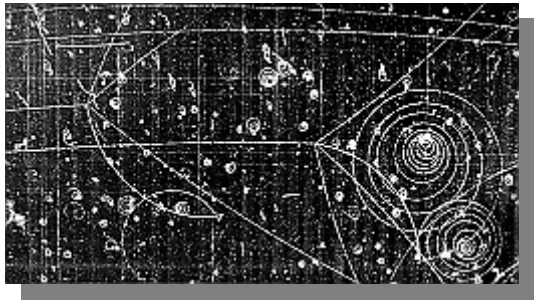

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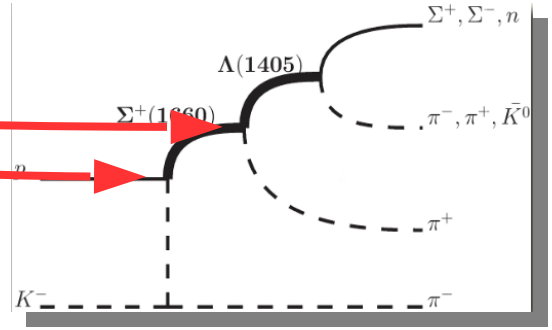

3) Strong energy shift and width in $\bar{K}H$ (SIDDHARTA exp.)

Bazzi et al.(2011)

Meißner, Raha, Rusetsky (2004)

- aK-p from modified Deser-type relation
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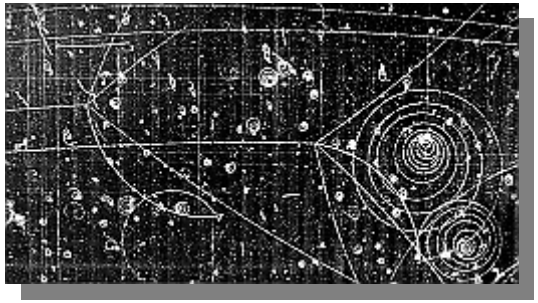

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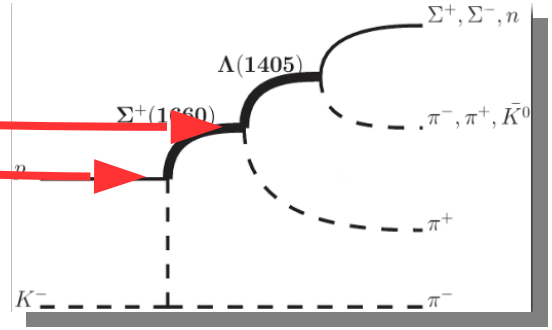

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4) *pp* collisions

COSY (2008) HADES (2013)

- high quality data, but theoretical analysis very intricate

Scattering amplitude

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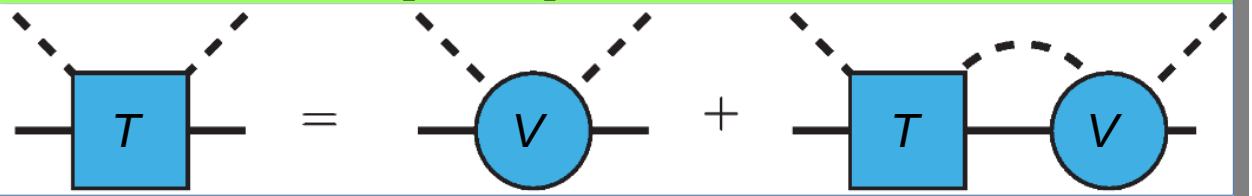
Bethe-Salpeter equation **Salpeter et al.(1951)**



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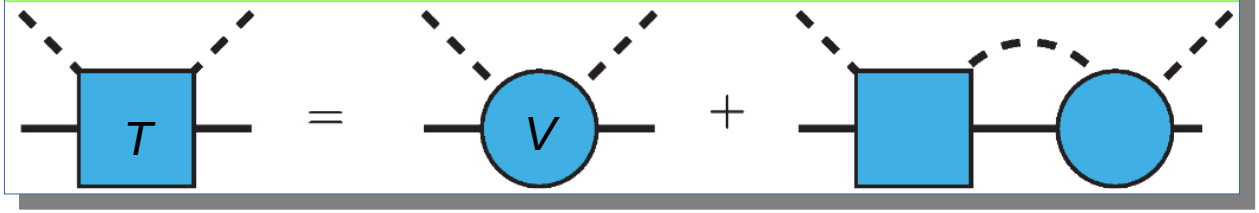

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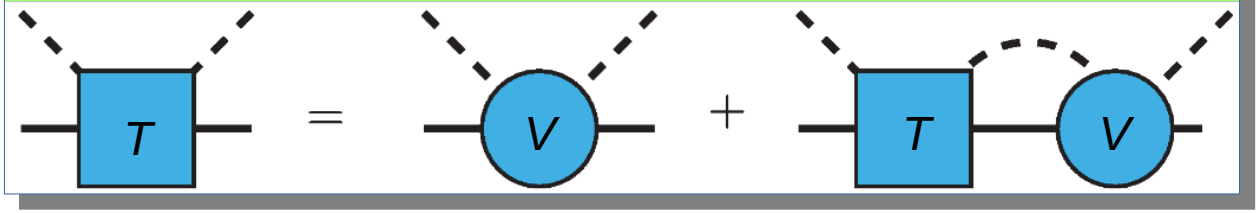

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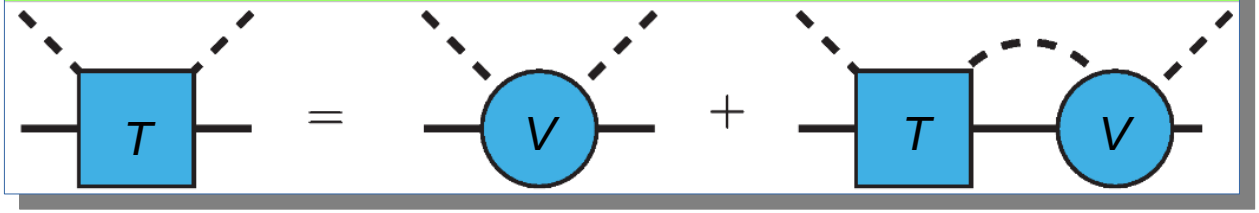

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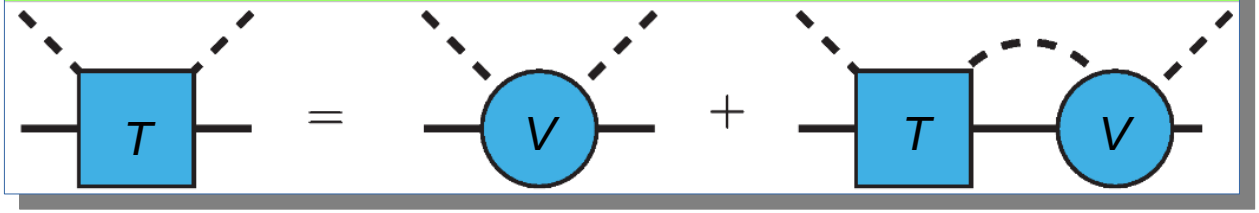

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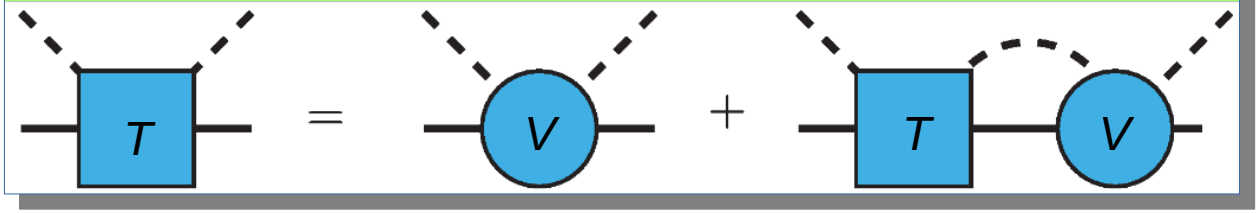

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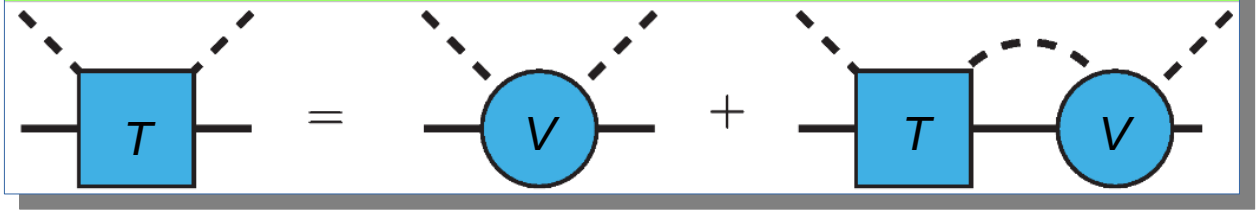

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- Bubble chain in *s* direction
  ⇒ topologies are missing ⇒ reg. scale dependence ⇒ 6 new parameters
- Off-shell effects are moderate — **MM, Meißner (2013)**
  ⇒ use on-shell approximation first (scan of 20-dim. parameter space)

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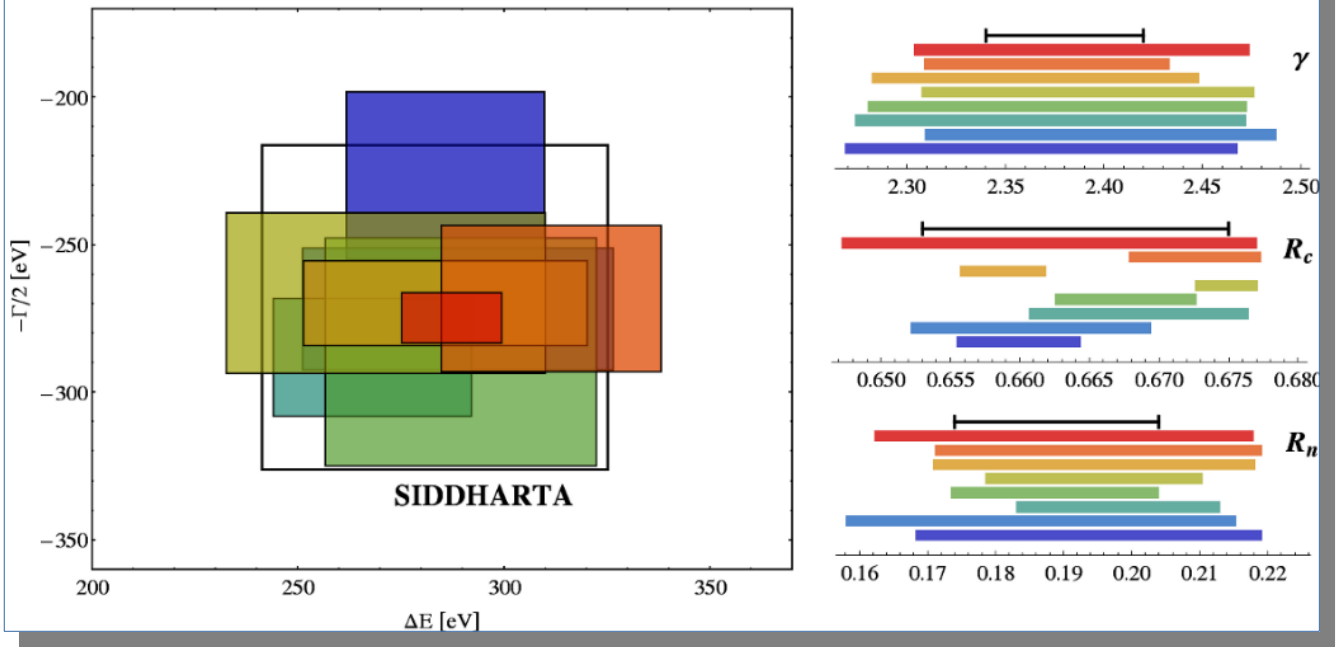
$\chi^2_{\text{d.o.f.}}$	1.35	1.14	0.99	0.96	1.06	1.02	1.15	0.90

Threshold ratios

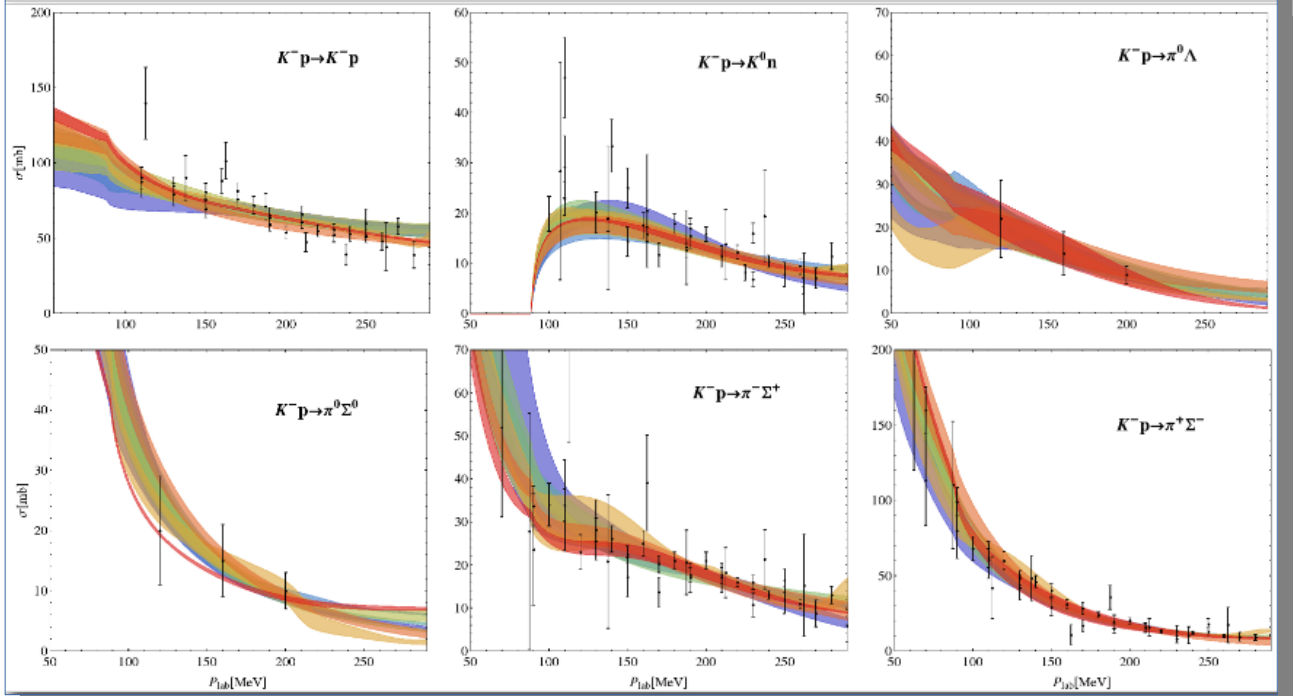


Fit to available data

- Randomly chosen sets of starting values (# ≈ 10,000) in a fit to *155* data points
- Solutions with poles on I. RS sorted out
- Results: **8** best fits obtained with similar $\chi^2_{\text{d.o.f.}}$
- Error bars: variation of fit parameters ($\Delta\chi^2_{\text{d.o.f}} < 1.15$) & spread of solutions

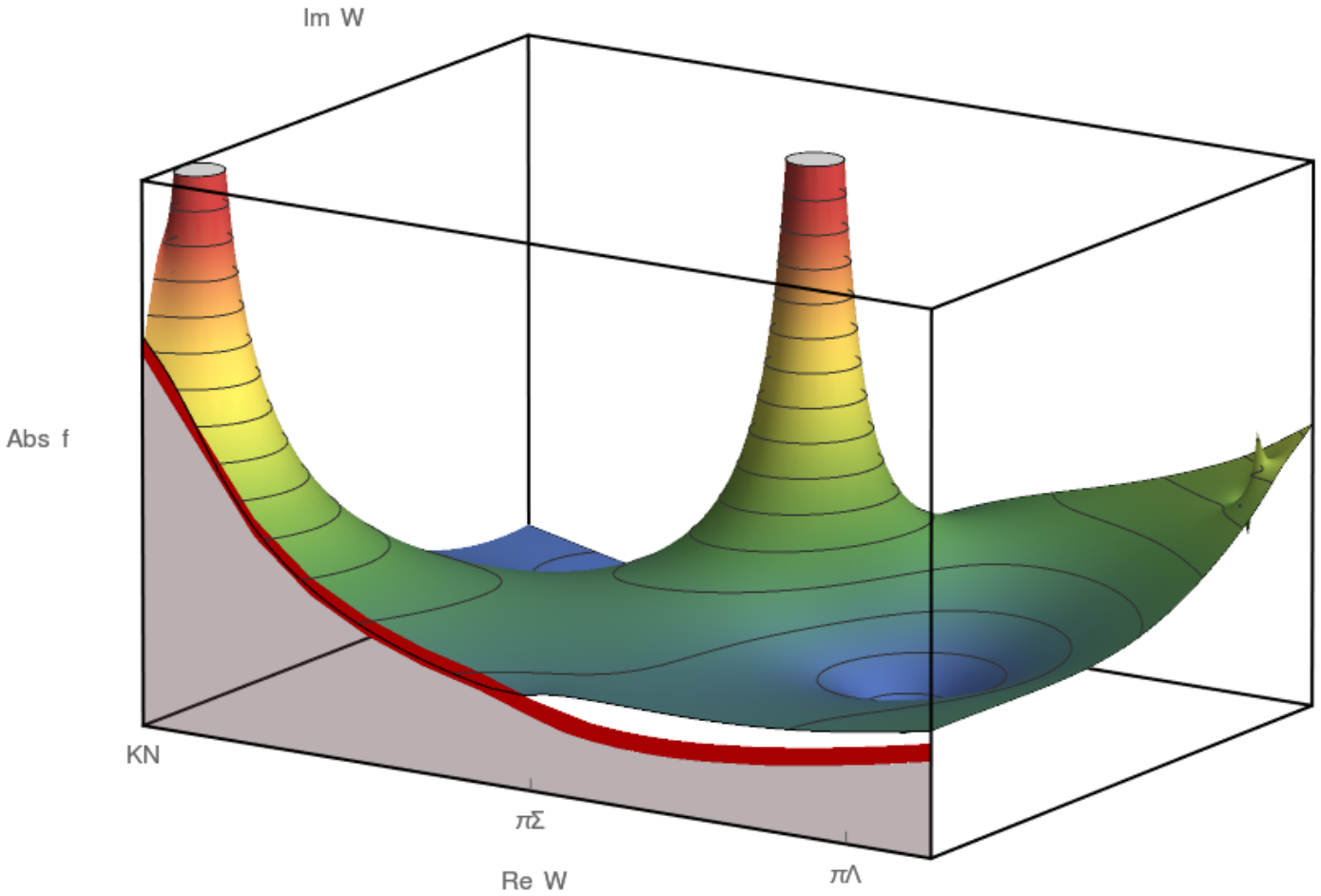
Fit #	1	2	3	4	5	6	7	8
$\chi^2_{\text{d.o.f.}}$	1.35	1.14	0.99	0.96	1.06	1.02	1.15	0.90

Total cross sections



Mass/width of Λ(1405)

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



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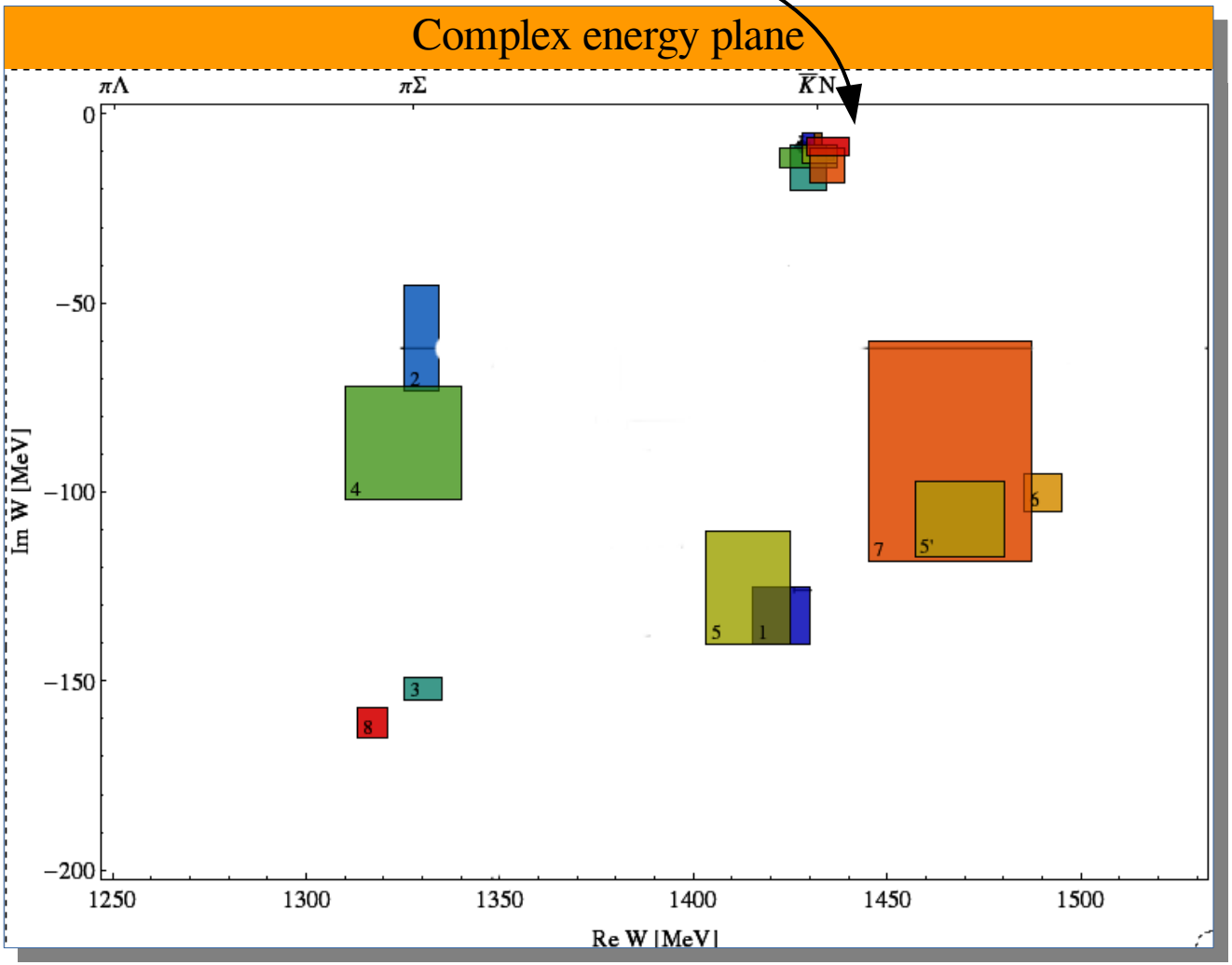
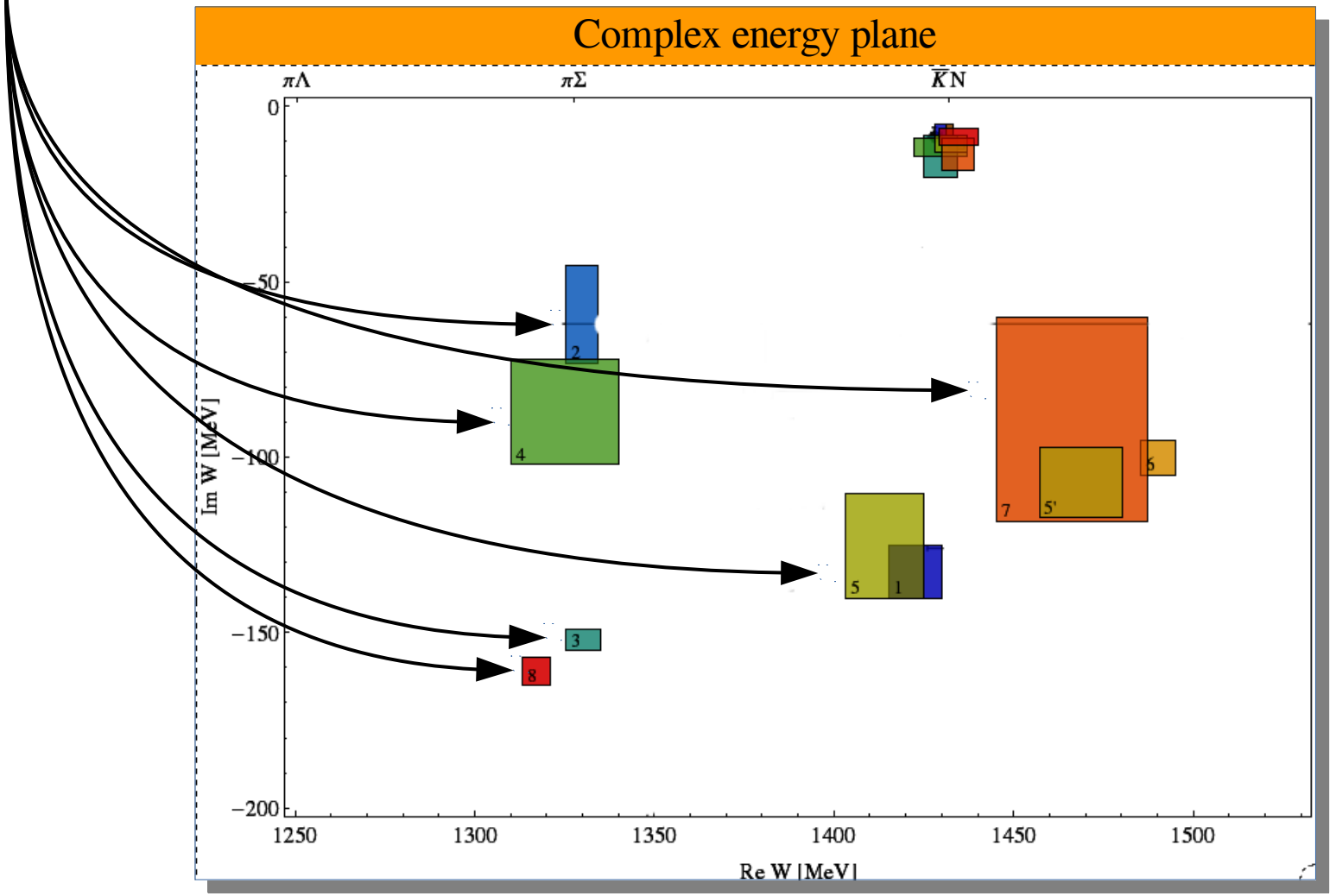


Mass/width of Λ(1405)

- 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 certain**



Other models

Is this ambiguity specific for this approach?

- First direct comparison of most recent UChPT model **MM, Cieply, Meissner, Smejkal (2016)**

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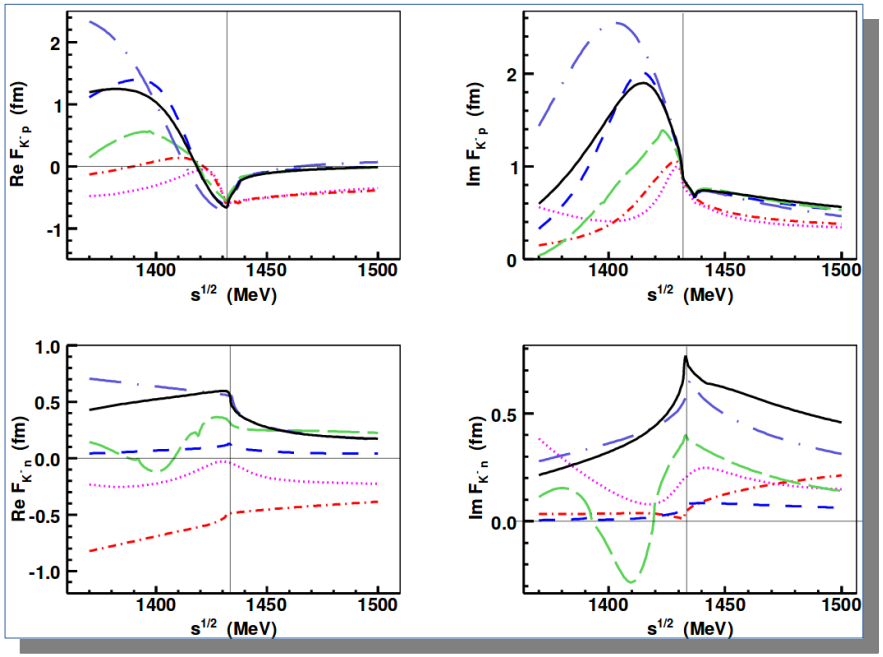
S-wave amplitude



- agreement at the threshold in the K^-p channel
  $\Rightarrow$ SIDDHARTA!
- large spread in the $I=1$ channel
  $\Rightarrow$ **SIDDHARTA 2 needed!!!**

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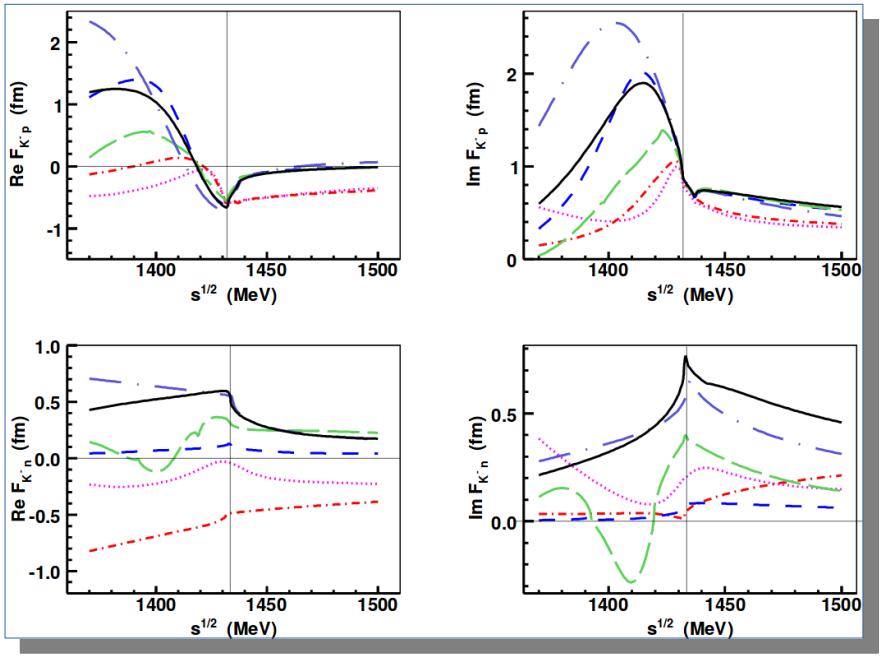

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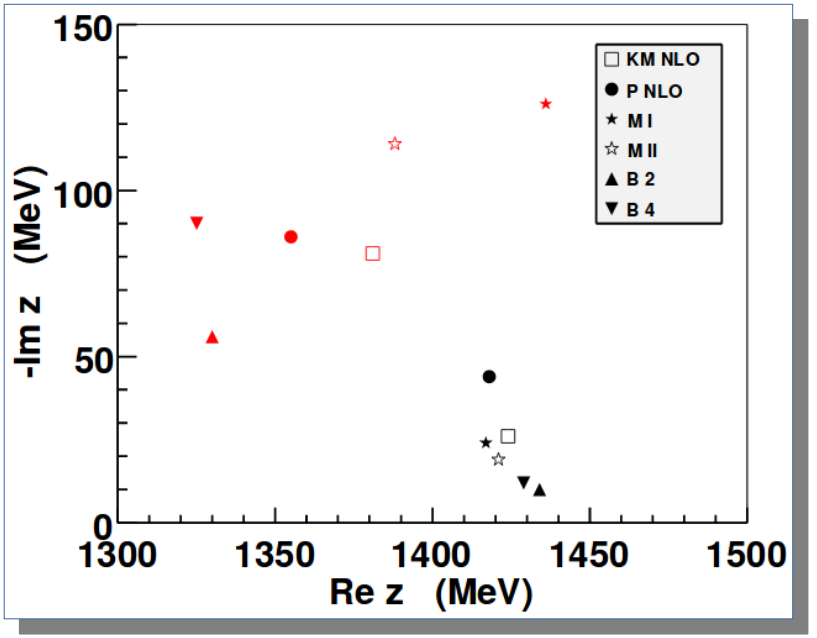
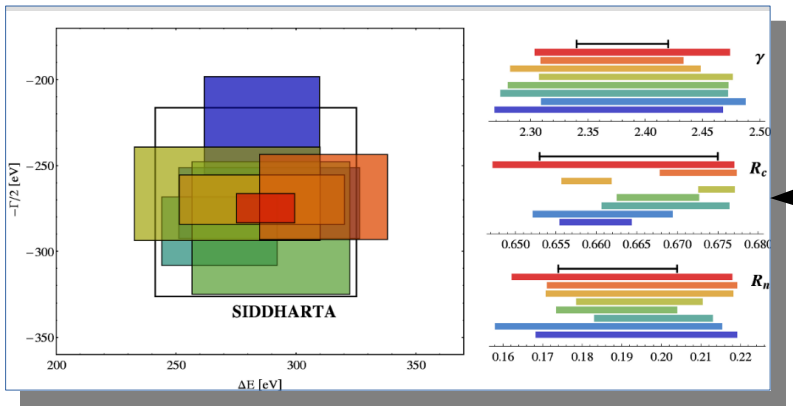
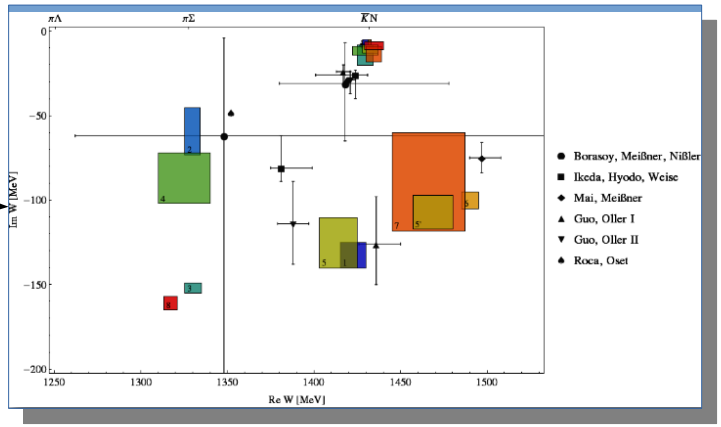
Pol positions



- Large spread of the position of the broader pol

multiple solutions agree with data but make different predictions of $\Lambda(1405)$ properties





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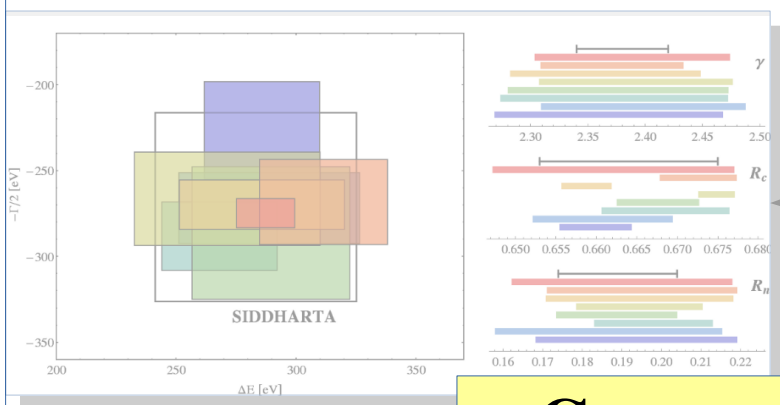

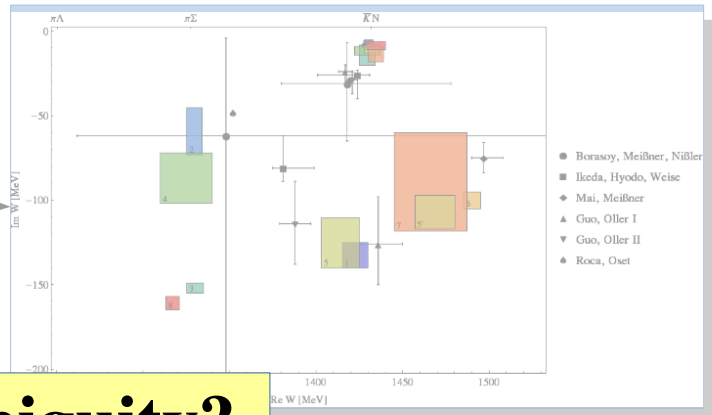

Can one reduce this ambiguity?

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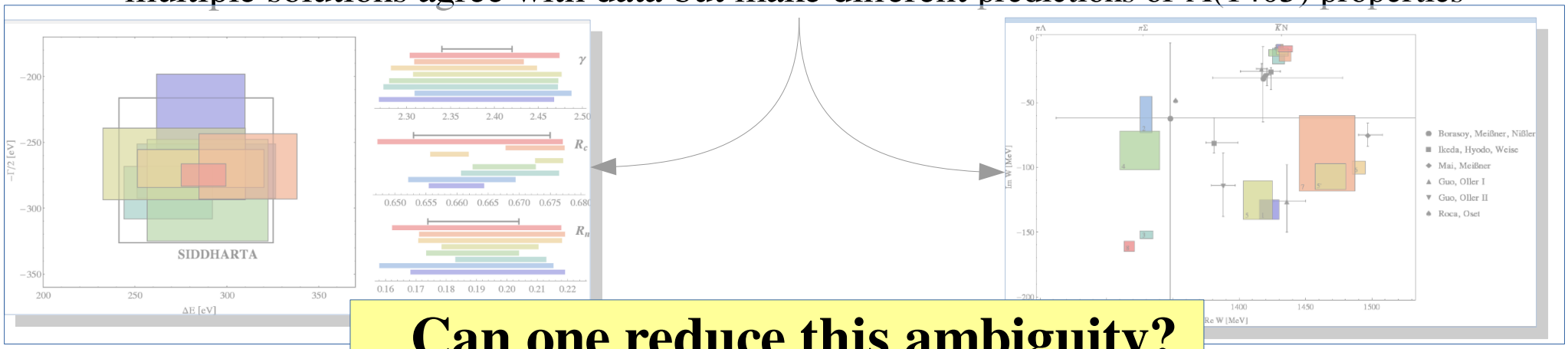

Can one reduce this ambiguity?

Differential cross sections

Mast et al.(1976)

- Data: Old and not too many
- Theoretical analysis:
  Simple - present framework has explicit p-waves

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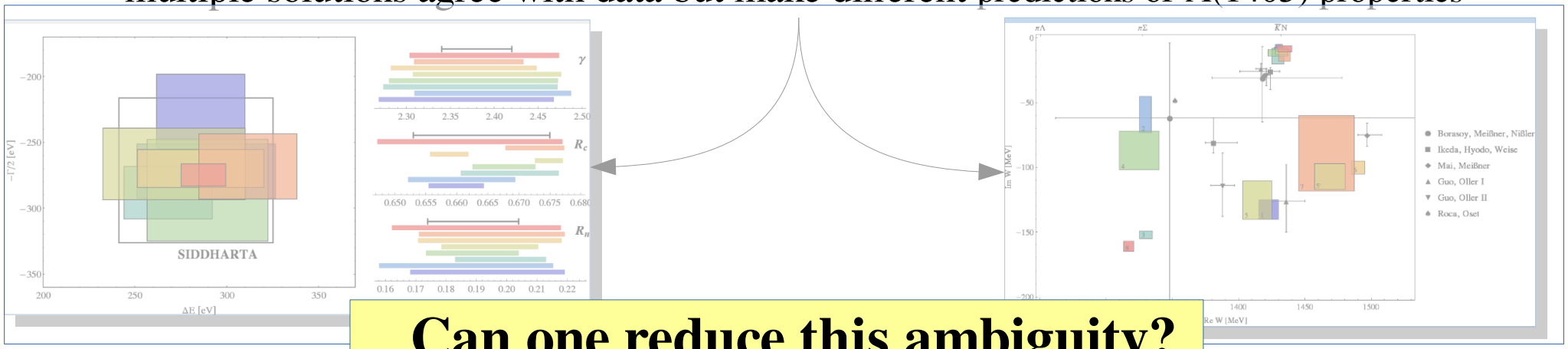

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New data on total cross sections

Proposed experiment with Klong(20xx)

- Data: ...
- Theoretical analysis: same as before

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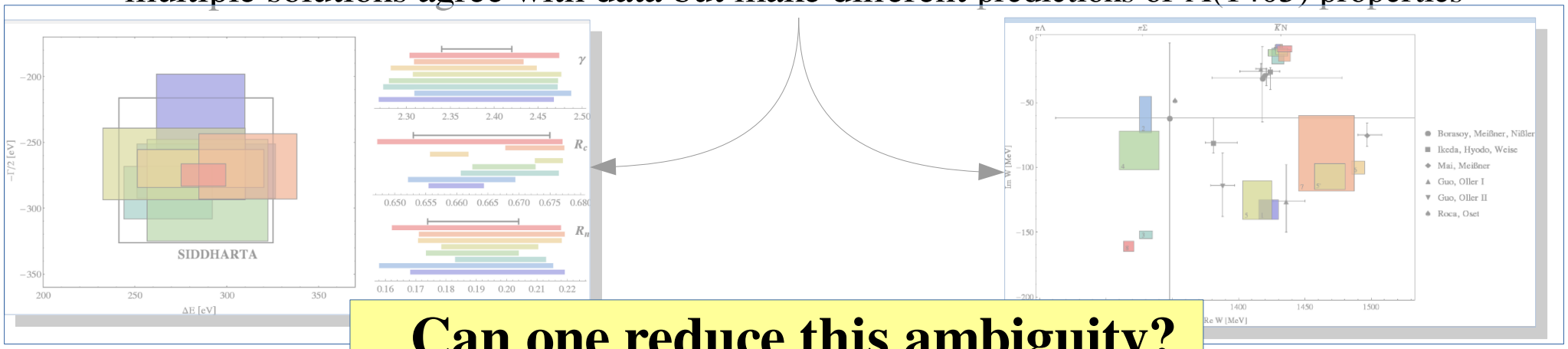

Can one reduce this ambiguity?

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

Moriya et al. (2012)

- Data: high quality
- Theoretical analysis:
  Two-meson photoproduction mechanism?

New data on total cross sections

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

- Chiral Unitary Meson-Baryon amplitude has a genuine *p*-wave part

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

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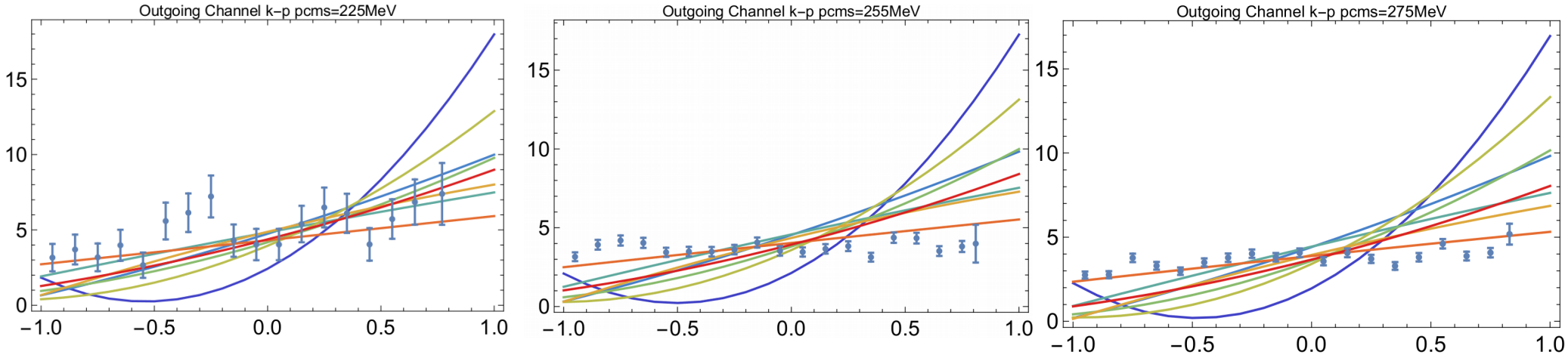

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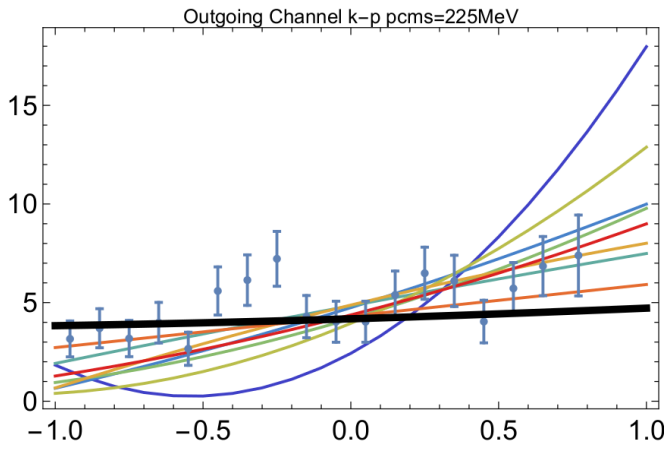
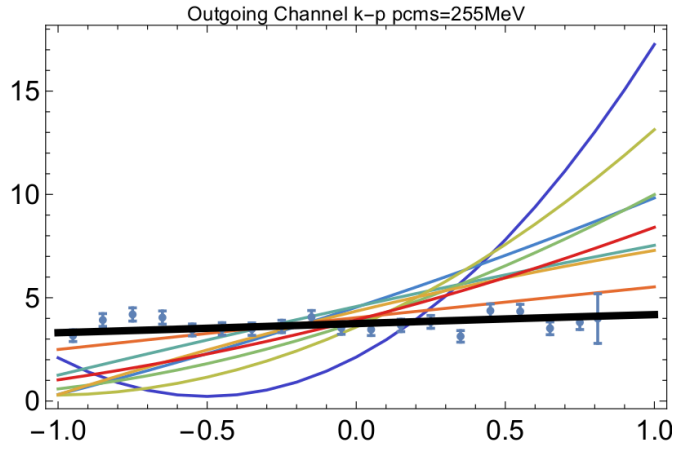
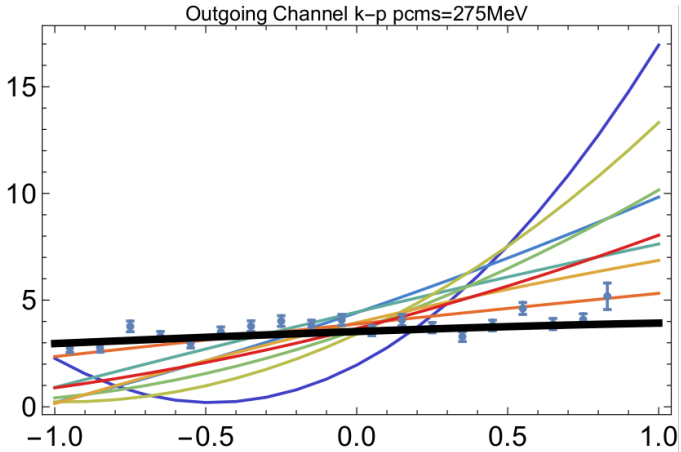






Prediction: solution #1 deviates strongly from these data → new constraint on *T*-matrix?
Re-fit: nice agreement & parameters do not change significantly

Can we reduce this ambiguity? PART 2

New data on total cross sections **proposed experiment @JLAB (20xx)**

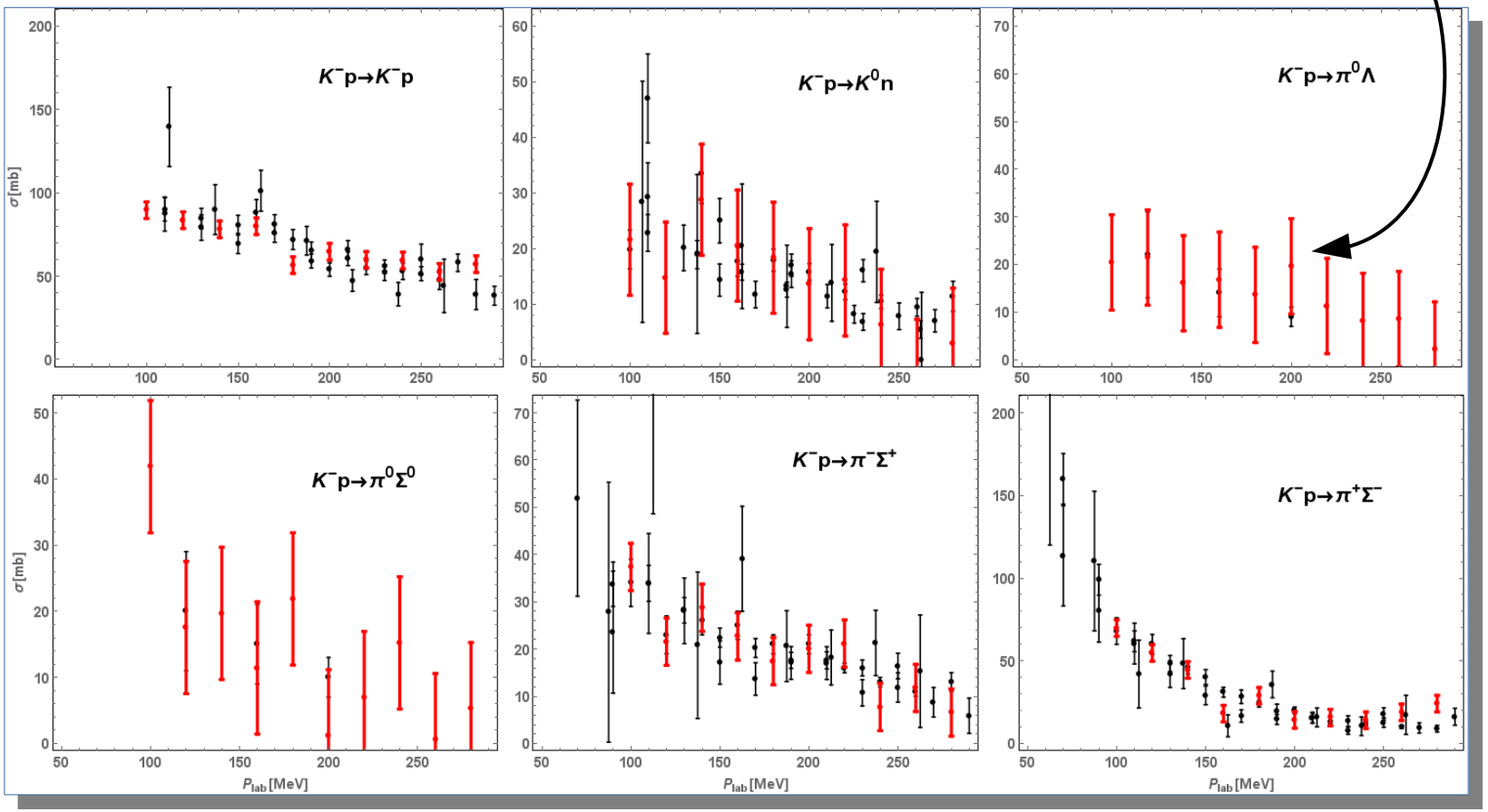
- Test requirements on data for a new constraint on *T*-matrix

Can we reduce this ambiguity? PART 2

New data on total cross sections

proposed experiment @JLAB (20xx)

- Test requirements on data for a new constraint on T-matrix → *synthetic data from fit #4*



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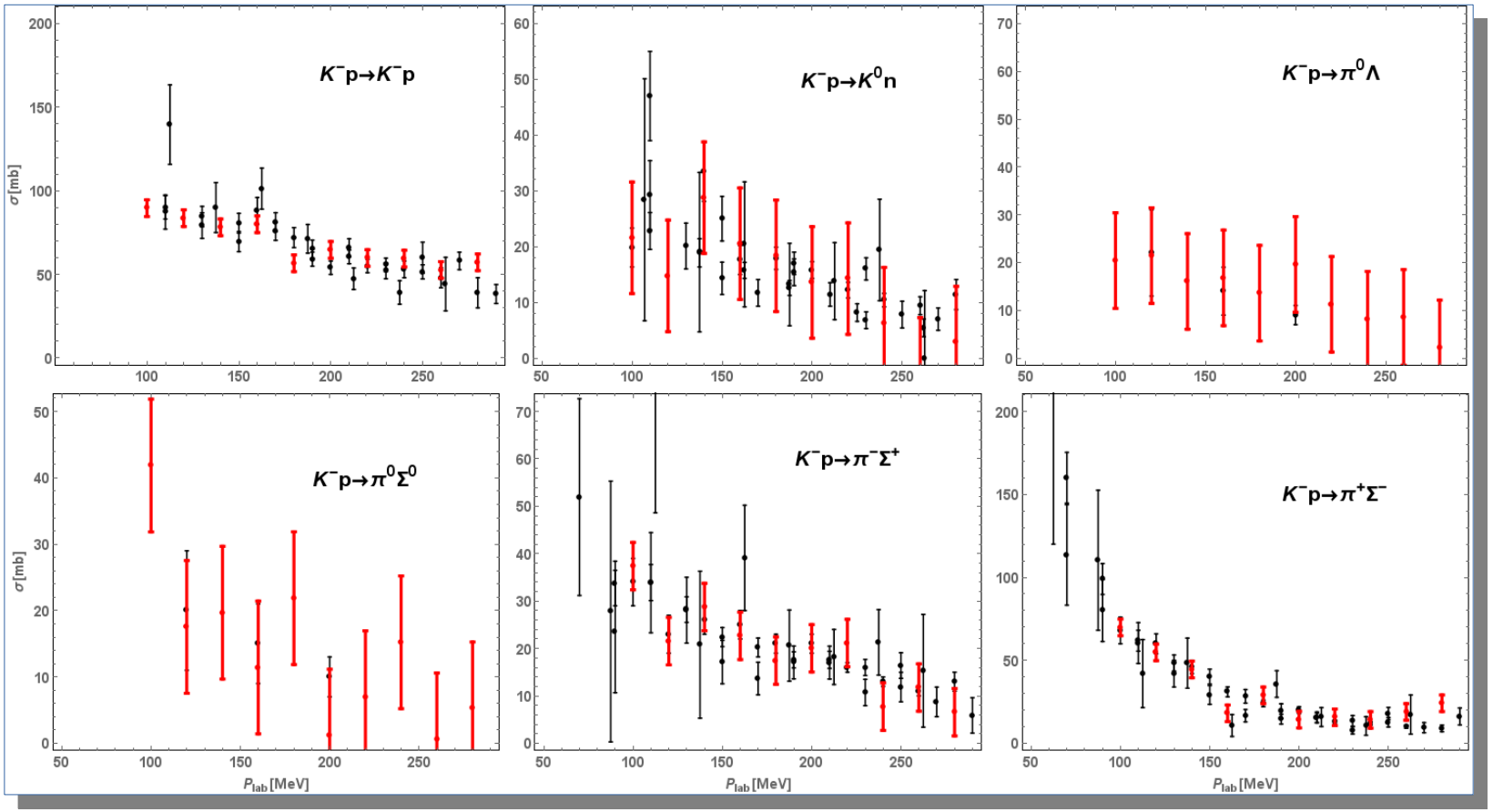


p_{lab} = 100...300 MeV ΔE = 5, 10 MeV $\Delta\sigma$ = 2.5, 5, 10 mb

Use either ***complementary*** *or* ***superseding***

Can we reduce this ambiguity? PART 2

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

	complementary	***superseding***

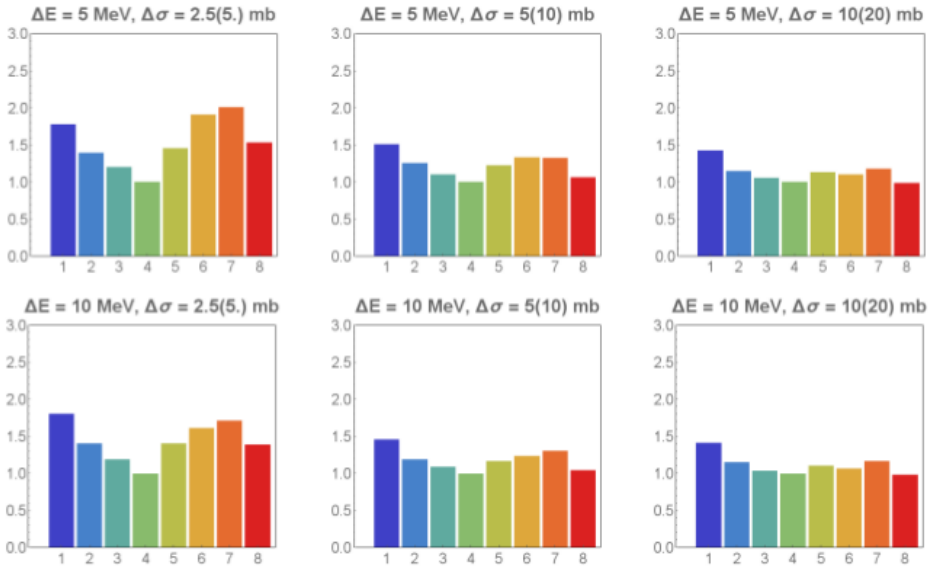
Can we reduce this ambiguity? PART 2

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

complementary

→ threshold ratios, SIDDHARTA

→ pseudo and real scattering data

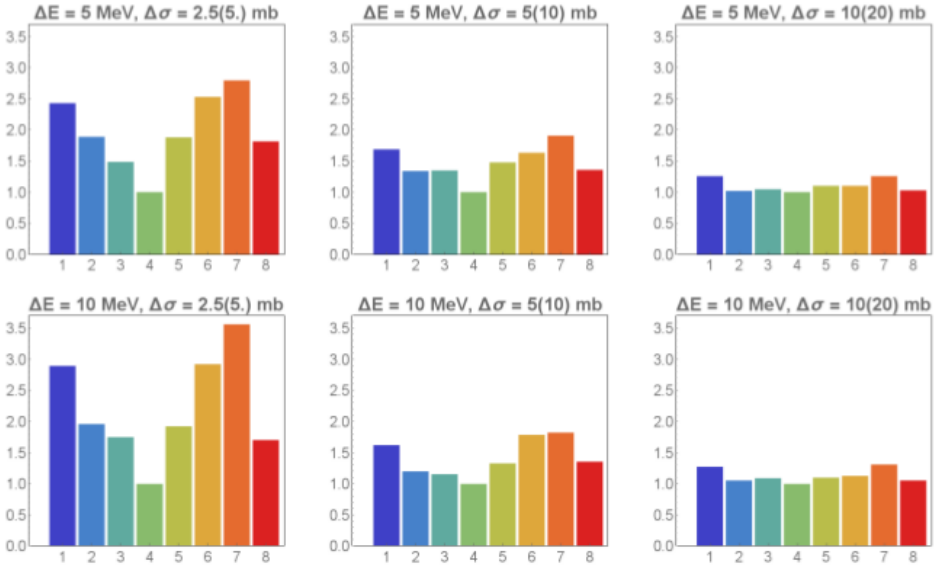


⇒ $\Delta\sigma < 5(10)$ mb and $\Delta E < 10$ MeV desired

superseding

→ threshold ratios, SIDDHARTA

→ pseudo scattering data

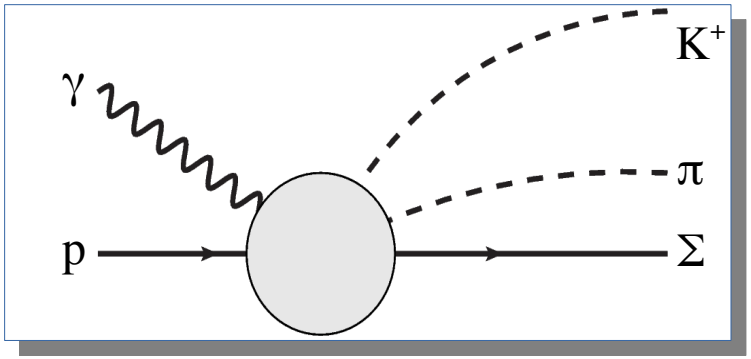


⇒ much larger values of $\Delta\sigma$ and ΔE are sufficient

Can we reduce this ambiguity? PART 3

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

Moriya et al. (2012)



- $\pi\Sigma$ mass distribution (lineshape)
  - → *9 energy bins*
  - → *60 values of $M(\pi\Sigma)$ - 5 MeV resolution*
  - → *three channels: $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\pi^0\Sigma^0$*
- $\mathbf{J^P = \frac{1}{2}^-}$ "confirmed" experimentally
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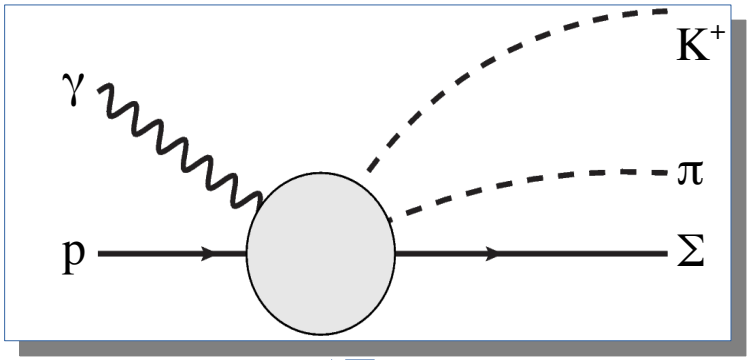


Test model

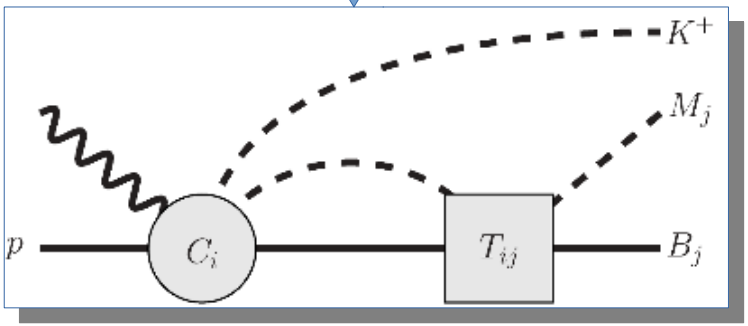
most simple Ansatz to test the hadronic solution

⇒ new free parameters

no gauge invariance, parameters are not physical

⇒ global fit is meaningless

⇒ no access to microscopic features of the spectrum



flexible enough for the CLAS data Oset, Roca (2013) MM, Meissner(2015)

⇒ **conservative** test of the hadronic solutions

Test results

Test of hadronic solutions

- Fit only new (generic) parameters

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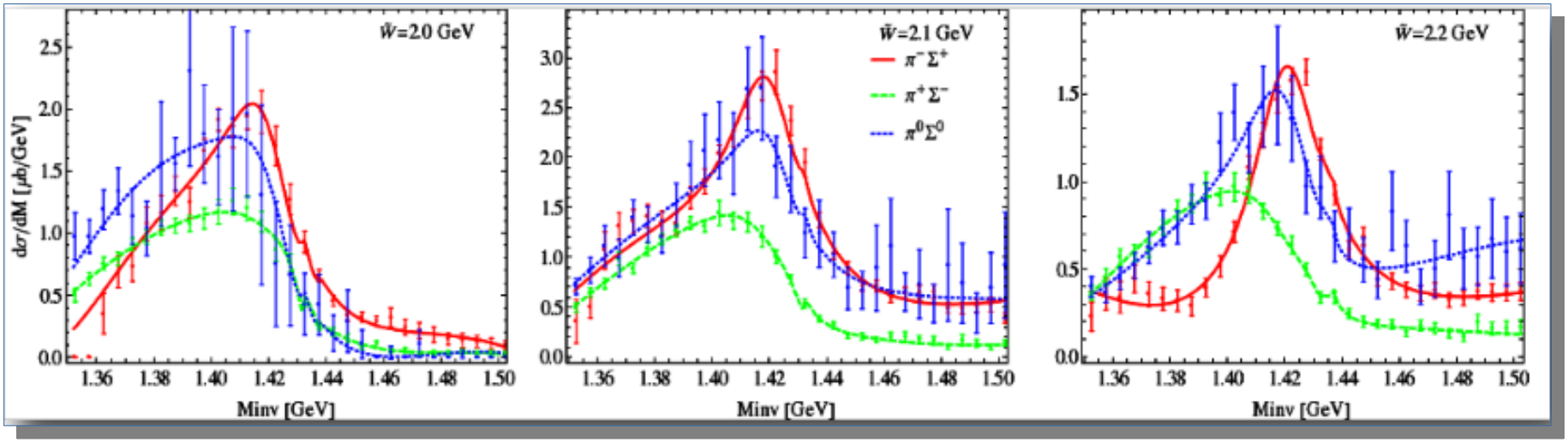
- Hadronic fits #2, #4 and #5 lead to good fits



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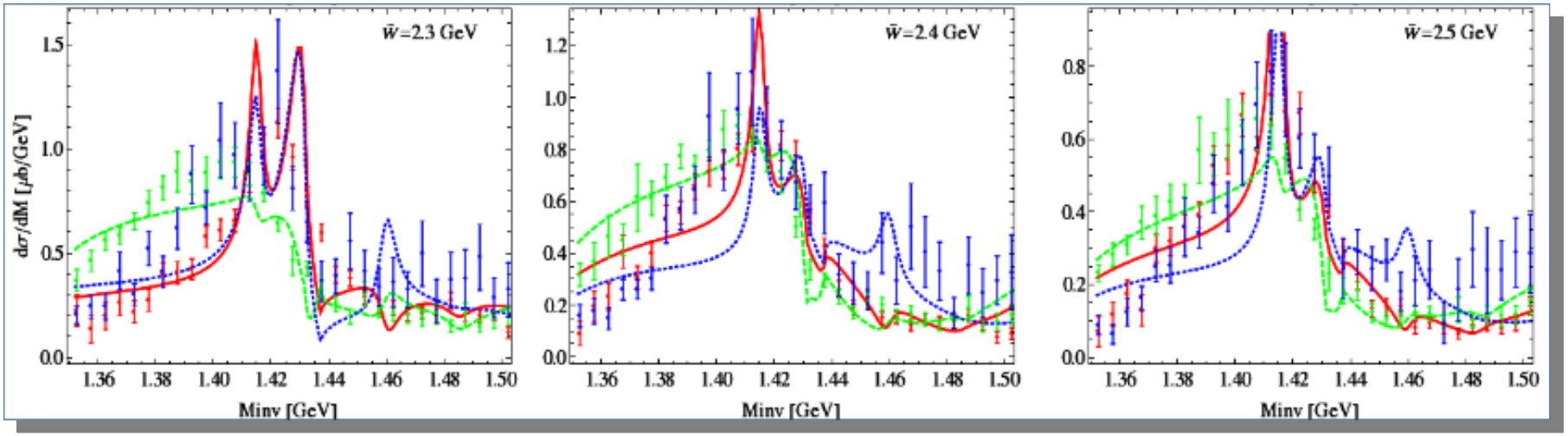
- Hadronic fits #1, #3, #6, #7 and #8 **do not lead to good fits!** **→ withdraw!**



Test results

- **8 solutions agree with hadronic data**

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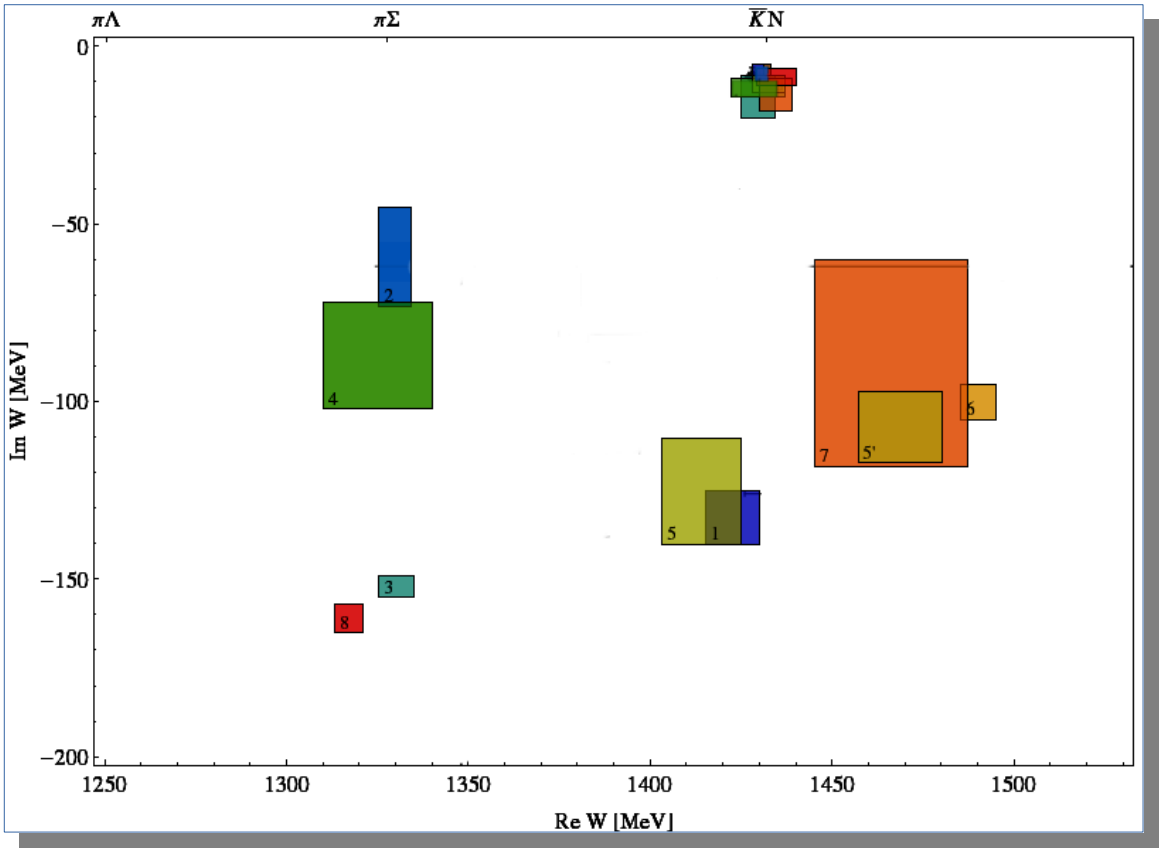

Test results

- **2 solutions remain after comparison to CLAS/Hemingway data**

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$\chi^2_{\text{d.o.f.}}$ (hadr.)	1.35	1.14	0.99	0.96	1.06	1.02	1.15	0.90
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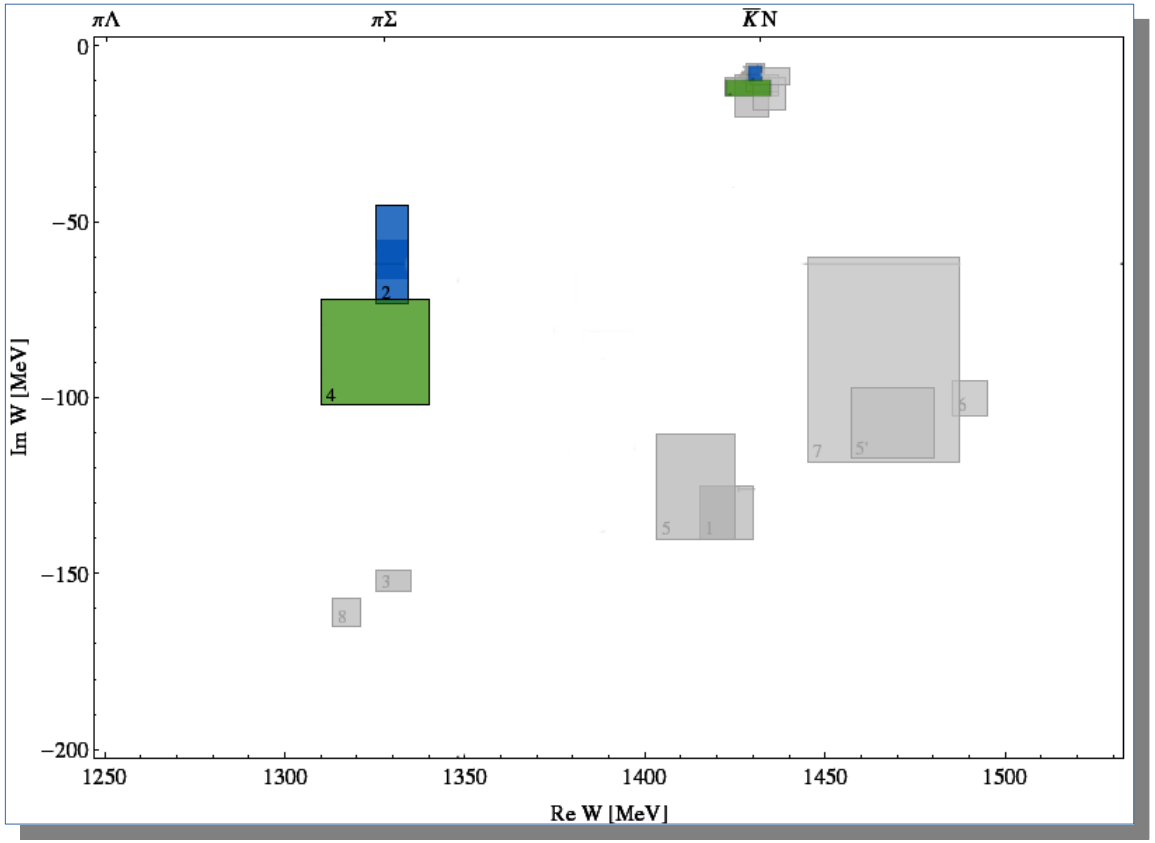

⇒ both solutions have similar pole positions ⇒ universal feature demanded by CLAS data!?

Summary

- **NLO chiral unitary $\bar{K}N$ amplitude for hadronic data**
  - → 8 solutions are found in the on-shell approximation
  - → the position of the narrow pole is 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 after all tests
- **New data can reduce the ambiguity of the $\bar{K}N$ amplitude**
  - → desired accuracy is not too high

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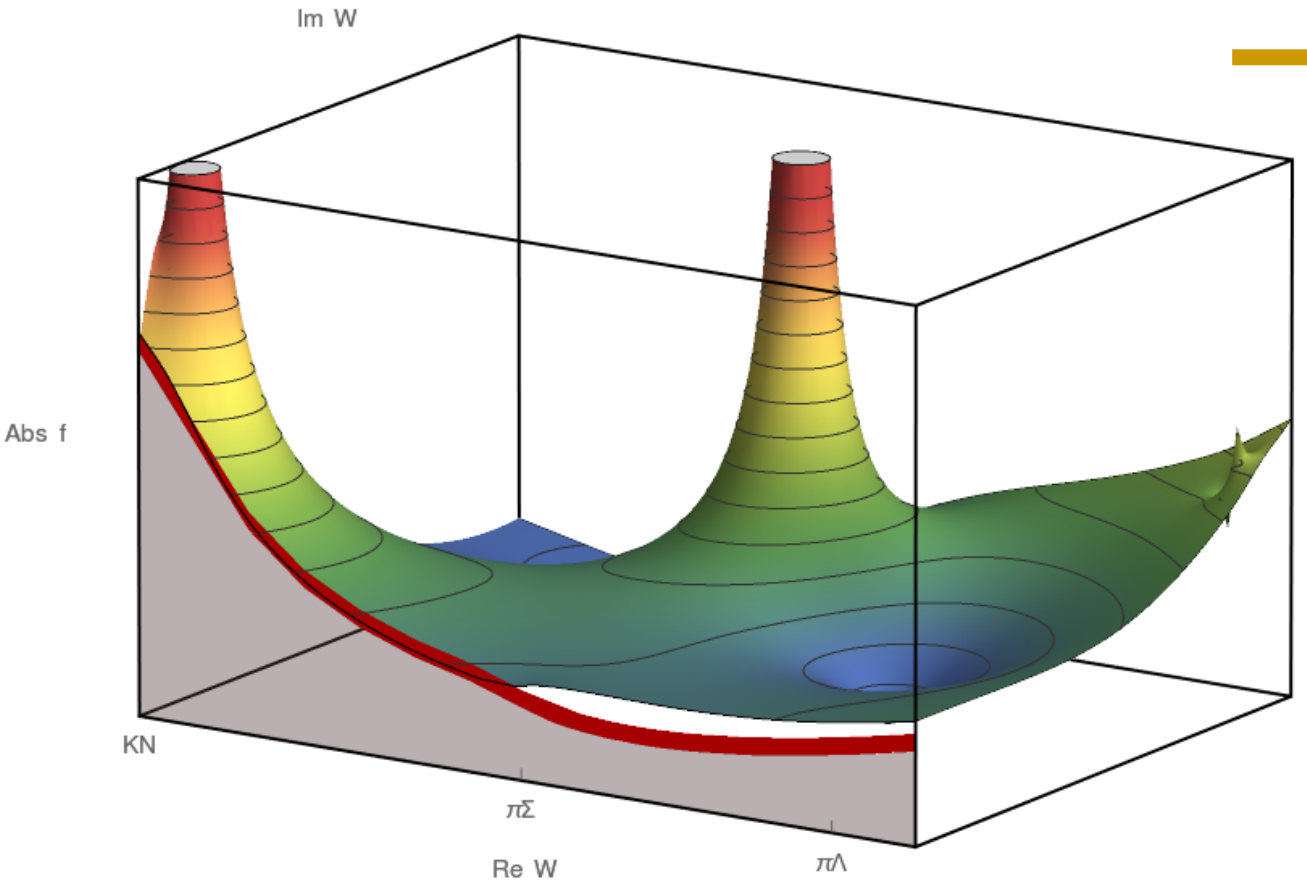
Outlook

- Fit to differential cross section
  - **→ work in progress**
- Full understanding of CLAS requires a microscopic model for two-meson photoproduction
  - **→ some steps are done, but needs more working hours**

Thank you
&
stay tuned



Test results

Test of hadronic solutions

- 3 solutions remain after comparison with CLAS data

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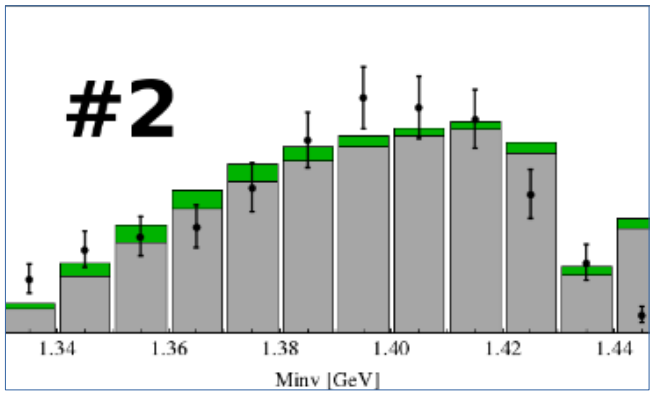
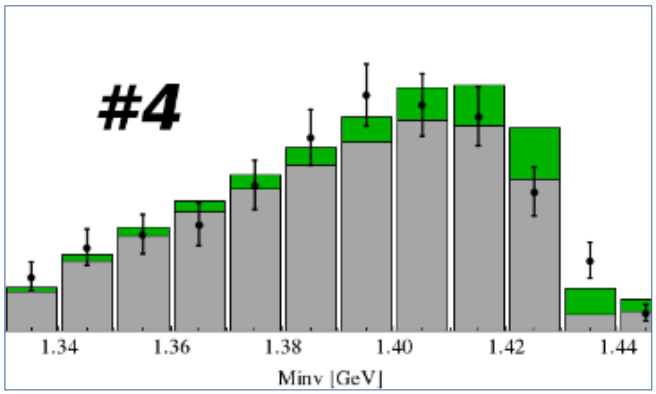
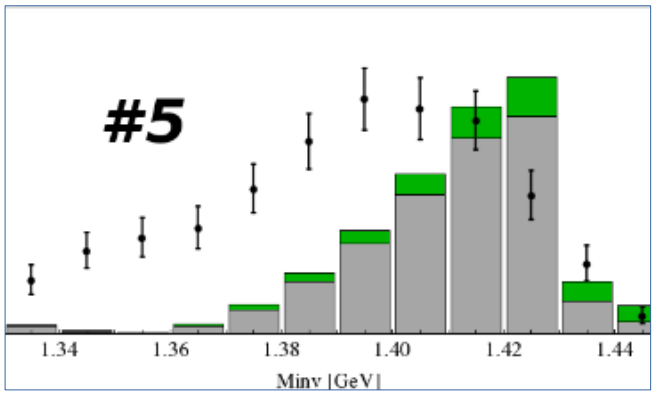
$\chi^2_{\text{p.p.}}$ (CLAS)	3.18	1.94	2.56	1.77	1.90	6.11	2.93	3.14

- Hemingway data on $(K^- p \to \Sigma^+ \pi^- \pi^+ \pi^-)$ as a second test







- Solutions #2 and #4 are fine
- Solution #5 is peaked to higher energies ← *second pole at high energy*

Photoproduction amplitude

I. Gauge invariant approaches

1) "Turtle" approximation — **Gross, Riska (1987) 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)**

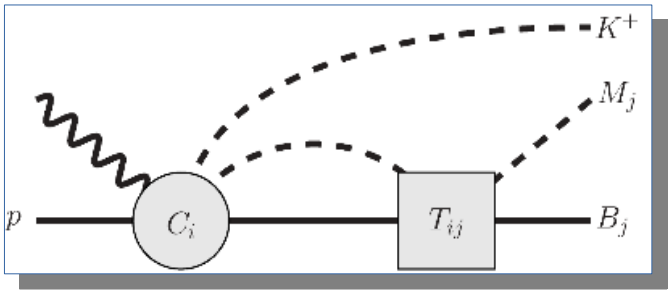
→ photon attached to meson production amplitude at the tree level

⇒ 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. Phenomenological models (*this work*)

1) Test model



→ most simple Ansatz to test the hadronic solution

⇒ less free parameters (10)

→ no gauge invariance, parameters are not physical

⇒ global fit is meaningless

⇒ no access to microscopic features of the spectrum

→ flexible enough for the CLAS data — **Oset, Roca (2013)**

⇒ **conservative** test of the hadronic solutions