Impact of New Results from CLAS on Baryonic Resonances

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WASHINGTON, DC

Jefferson Lab

7th Workshop of the APS Topical Group on Hadronic Physics

February 1-3, 2017, Washington, DC

Supported by

National Science Foundation

HPC support by JSC *jikp07*

JÜLICH FORSCHUNGSZENTRUM

DOE DE-AC05-06OR23177 & DE-SC0016582; NSF PIF 1415459 & CAREER PHY-1452055

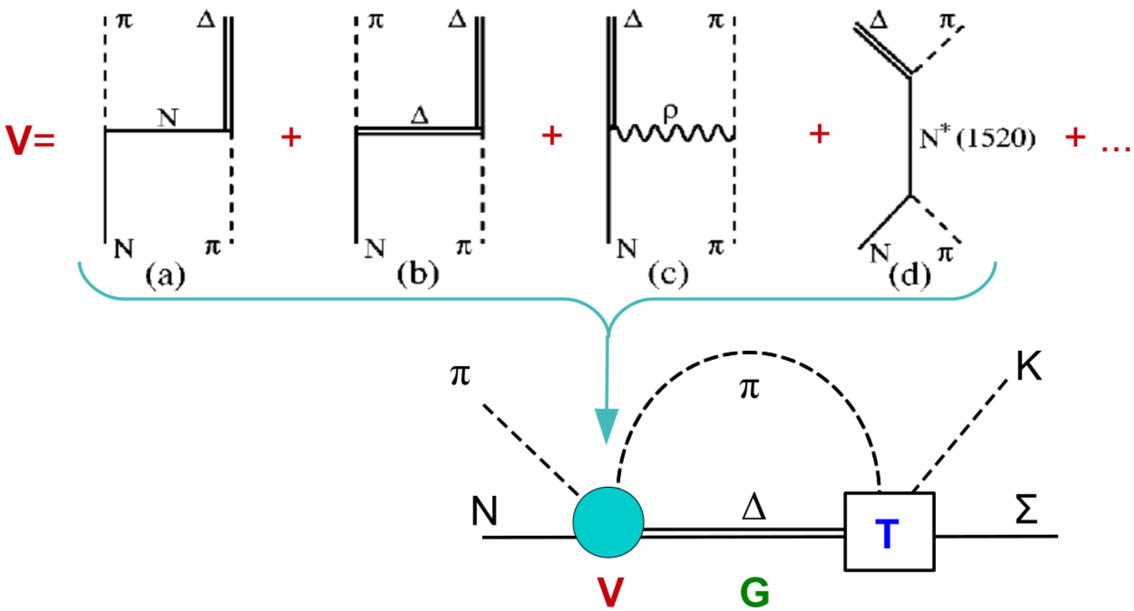
The Julich-Bonn Dynamical Coupled-Channel Approach

e.g. EPJ A 49, 44 (2013)

Dynamical coupled-channels (DCC): **simultaneous** analysis of different reactions

The scattering equation in partial-wave basis

$$\langle L'S'p'|T^{IJ}_{\mu\nu}|LSp\rangle = \langle L'S'p'|V^{IJ}_{\mu\nu}|LSp\rangle + \sum_{\gamma,L''S''}\int_0^\infty dq \quad q^2 \quad \langle L'S'p'|V^{IJ}_{\mu\gamma}|L''S''q\rangle \frac{1}{E-E_\gamma(q)+i\epsilon}\langle L''S''q|T^{IJ}_{\gamma\nu}|LSp\rangle$$



- potentials V constructed from effective $\mathcal{L}$
- s-channel diagrams: T^P

  genuine resonance states
- t- and u-channel: T^{NP}

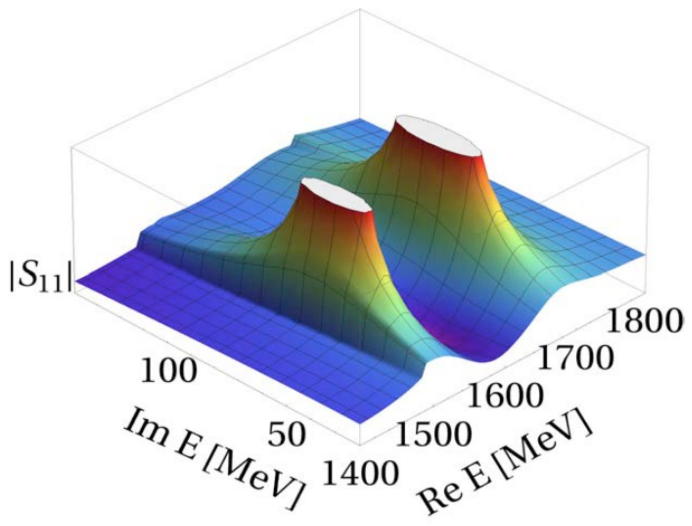
  dynamical generation of poles

  partial waves strongly correlated

Analytic structure

[M.D. et al, NPA (2009)]

Resonance states: **Poles in the T-matrix** on the 2^{nd} Riemann sheet

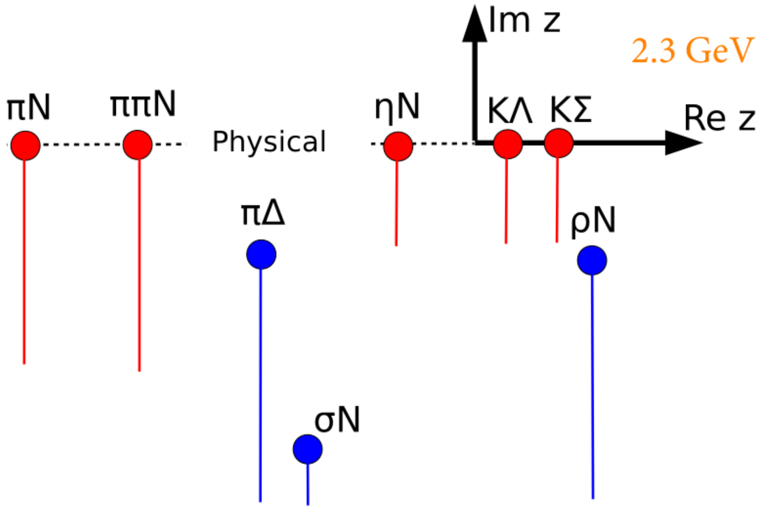


Re(E_0) = "mass", -2Im(E_0) = "width"

- pole position E_0 is the same in all channels
- residues→ branching ratios

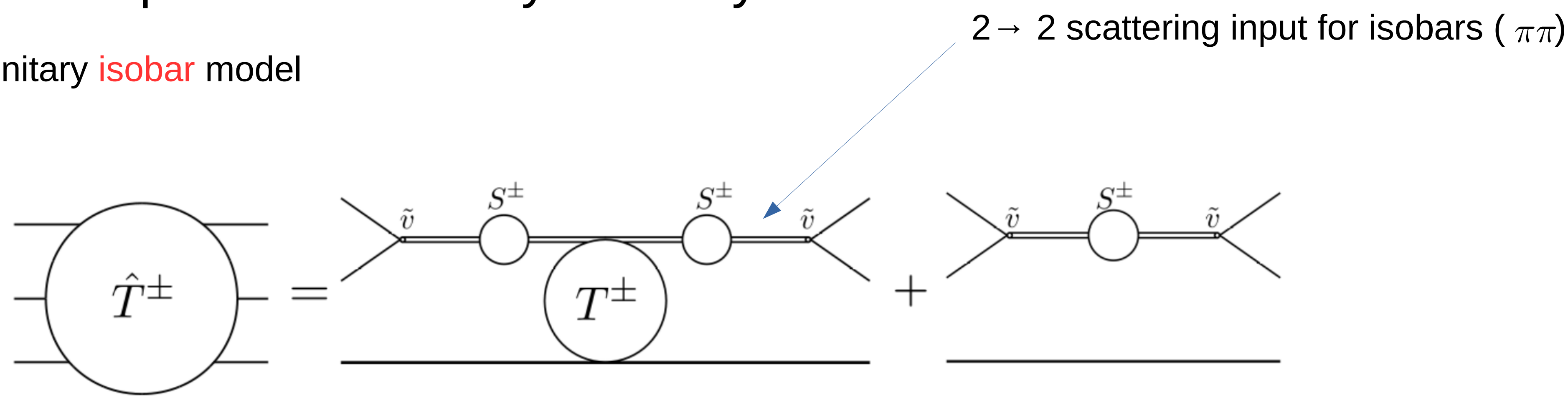
- (2-body) unitarity and analyticity respected
- 3-body $\pi\pi N$ channel:
  - parameterized effectively as $\pi\Delta$, σN, ρN
  - $\pi N/\pi\pi$ subsystems fit the respective phase shifts

  ↳ branch points move into complex plane



One aspect: Three-Body Unitarity

Unitary isobar model

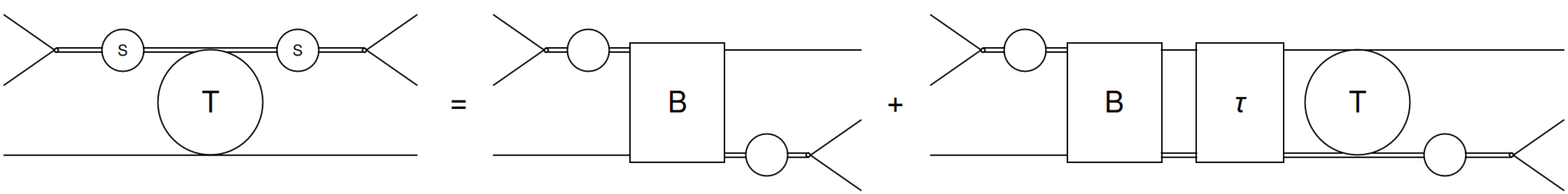


Unitarity

$$\langle q_1, q_2, q_3|(\hat{T}^+ - \hat{T}^-)|p_1, p_2, p_3\rangle = i\int\left(\prod_{\ell=1}^{3}\frac{\mathrm{d}^4k_\ell}{(2\pi)^4}(2\pi)\delta^+(k_\ell^2 - m^2)\right)(2\pi)^4\delta^4\left(P - \sum_{\ell=1}^{3}k_\ell\right)$$

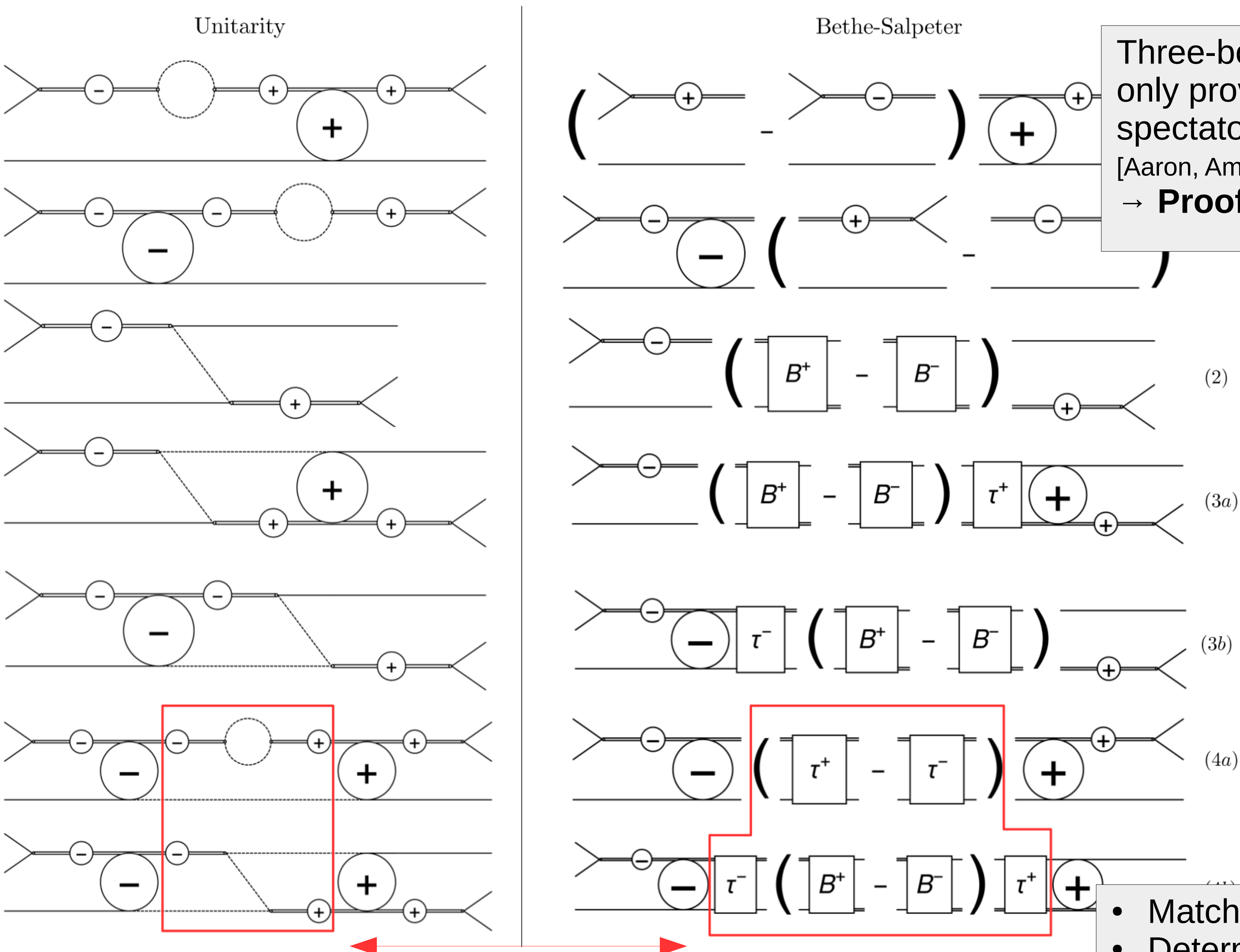
$$\times \langle q_1, q_2, q_3|\hat{T}^-|k_1, k_2, k_3\rangle \langle k_1, k_2, k_3|\hat{T}^+|p_1, p_2, p_3\rangle \,,$$

Bethe-Salpter Eq. ansatz



Strategy: To obtain a 3-body unitary amplitude, compare the right-hand sides of unitarity relation, both for generic isobar structure and BSE

Unitarity above breakup [M.D., M. Mai, A. Pilloni, A. Szczepaniak, in preparation]



Three-body unitarity for isobars only proven for bound state-spectator scattering
[Aaron, Amamdo, Young, PR (1969)]
→ **Proof above breakup needed**!

Bound-state particle scattering requires only comapring these.

- Match Ansatz to unitarity
- Determine three-body amplitude
- Consistency of matching relations shown.
- Proof finished

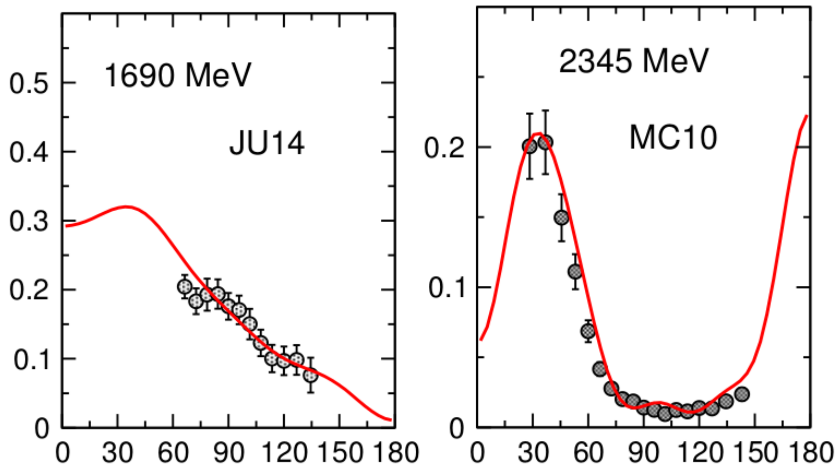
Results

Preliminary: $K^+\Lambda$ photoproduction in the JüBo model

simultaneous fit of $\gamma p \to \pi^0 p$, $\pi^+ n$, ηp, $K^+\Lambda$ and $\pi N \to \pi N$, ηN, $K\Lambda$, $K\Sigma$

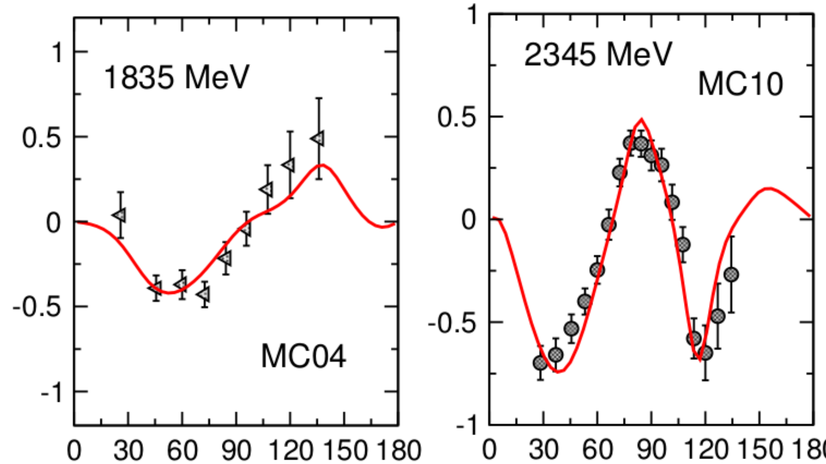
$\gamma p \to K^+\Lambda$:

- Differential cross section



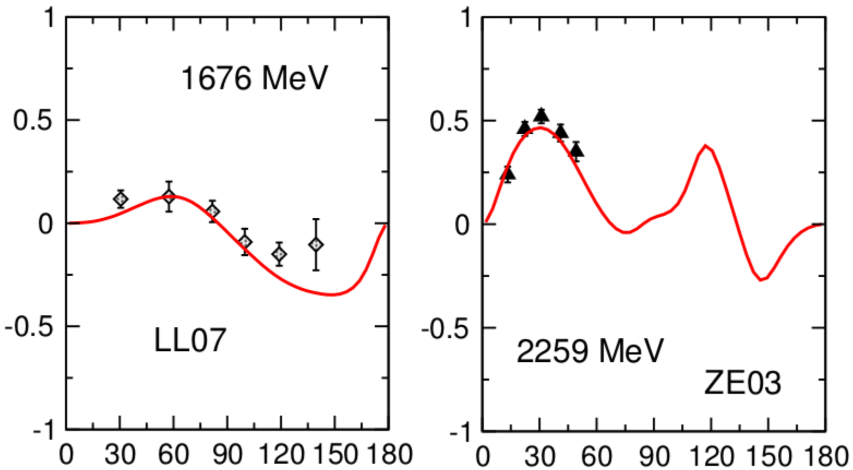
JU14: Jude PLB 735 (2014), MC10: McCracken PRC 81 (2010)

- Recoil polarization



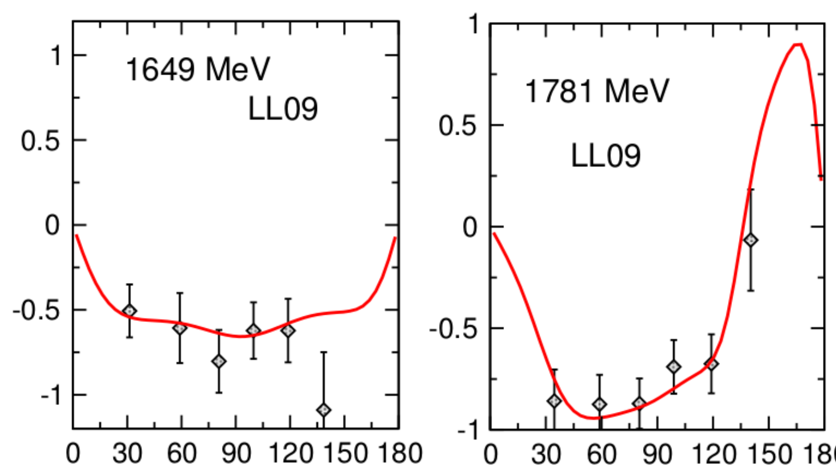
MC04: McNabb PRC 69 (2004), MC10: McCracken PRC 81 (2010)

- Beam asymmetry



LL07: Lleres EPJA 31 (2007), ZE03: Zegers PRL (2003)

- Target asymmetry



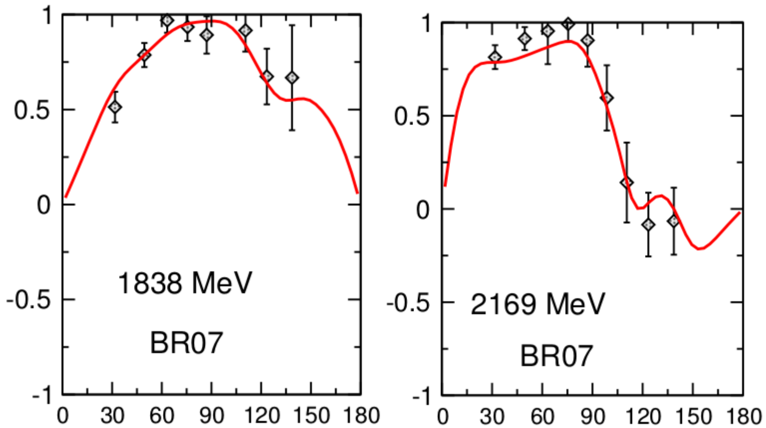
LL09: Lleres EPJA 39 (2009)

Preliminary: $K^+\Lambda$ photoproduction in the JüBo model

simultaneous fit of $\gamma p \to \pi^0 p$, $\pi^+ n$, ηp, $K^+\Lambda$ and $\pi N \to \pi N$, ηN , $K\Lambda$, $K\Sigma$

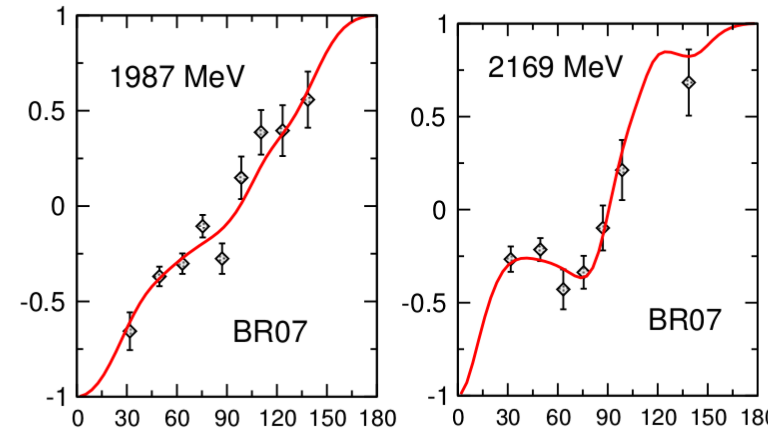
$\gamma p \to K^+\Lambda$:

- C_x



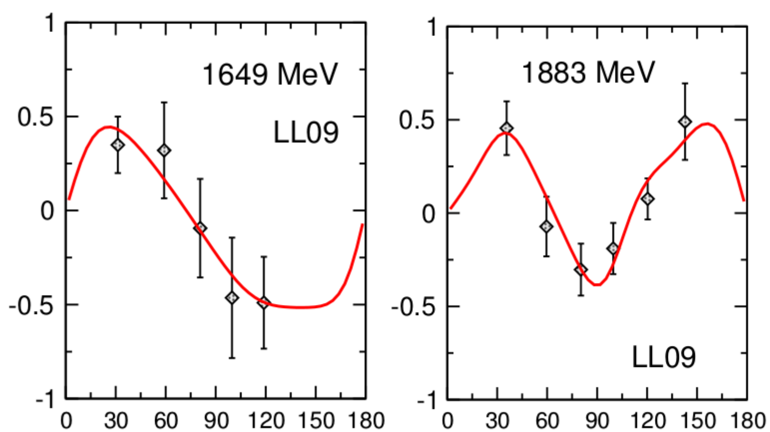
BR07: Bradford PRC 75 (2007)

- C_z



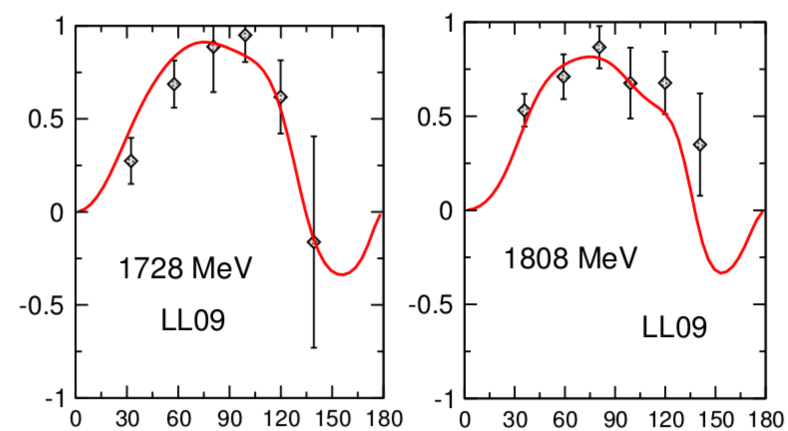
BR07: Bradford PRC 75 (2007)

- O_x



LL09: Lleres EPJA 39 (2009)

- O_z



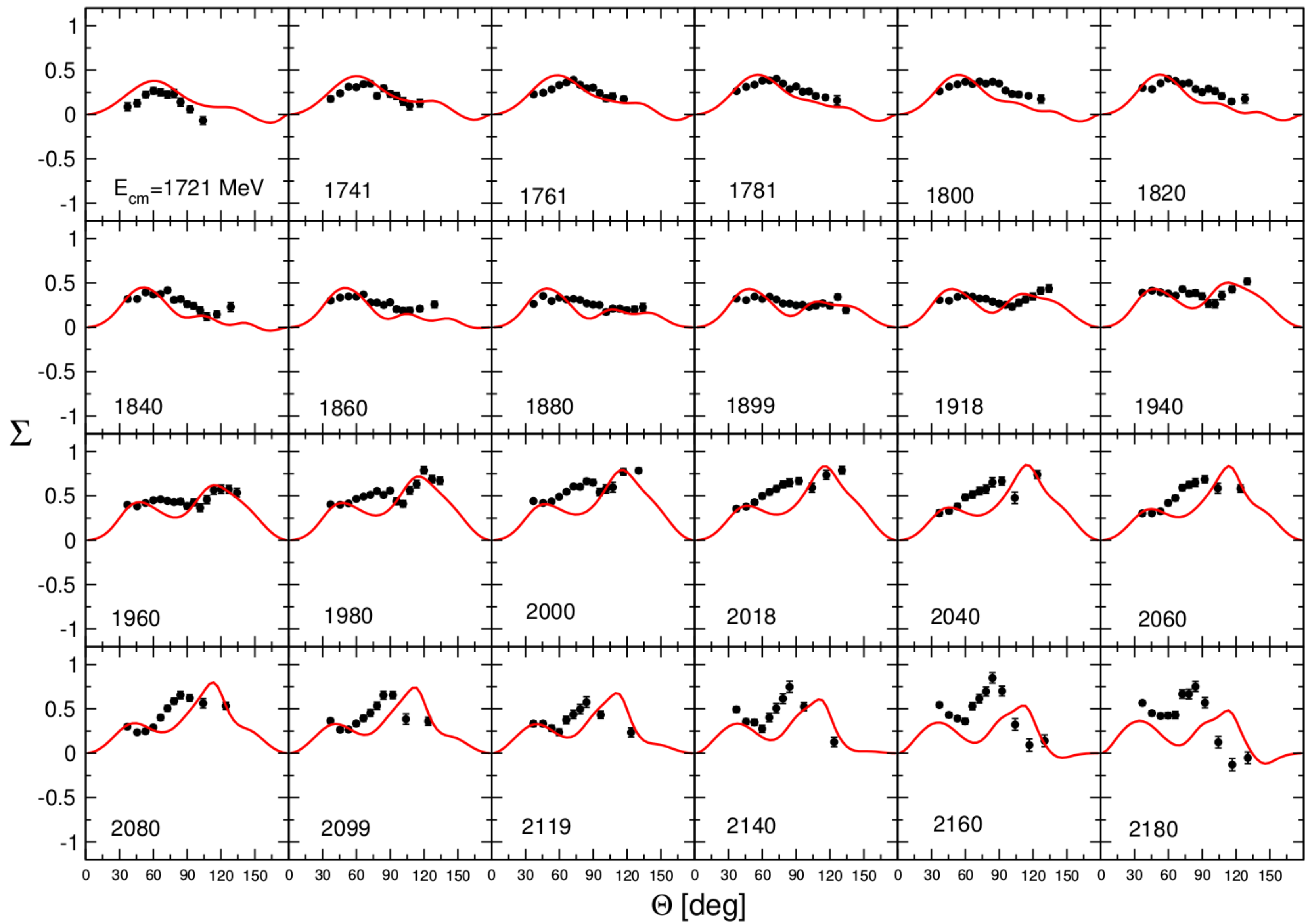
LL09: Lleres EPJA 39 (2009)

P_{13}(1900) resonance claimed by BnGa definitely improves our fit significantly, as well.

Preliminary: $K^+\Lambda$ photoproduction in the JüBo model

simultaneous fit of $\gamma p \to \pi^0 p$, $\pi^+ n$, ηp, $K^+\Lambda$ and $\pi N \to \pi N$, ηN, $K\Lambda$, $K\Sigma$

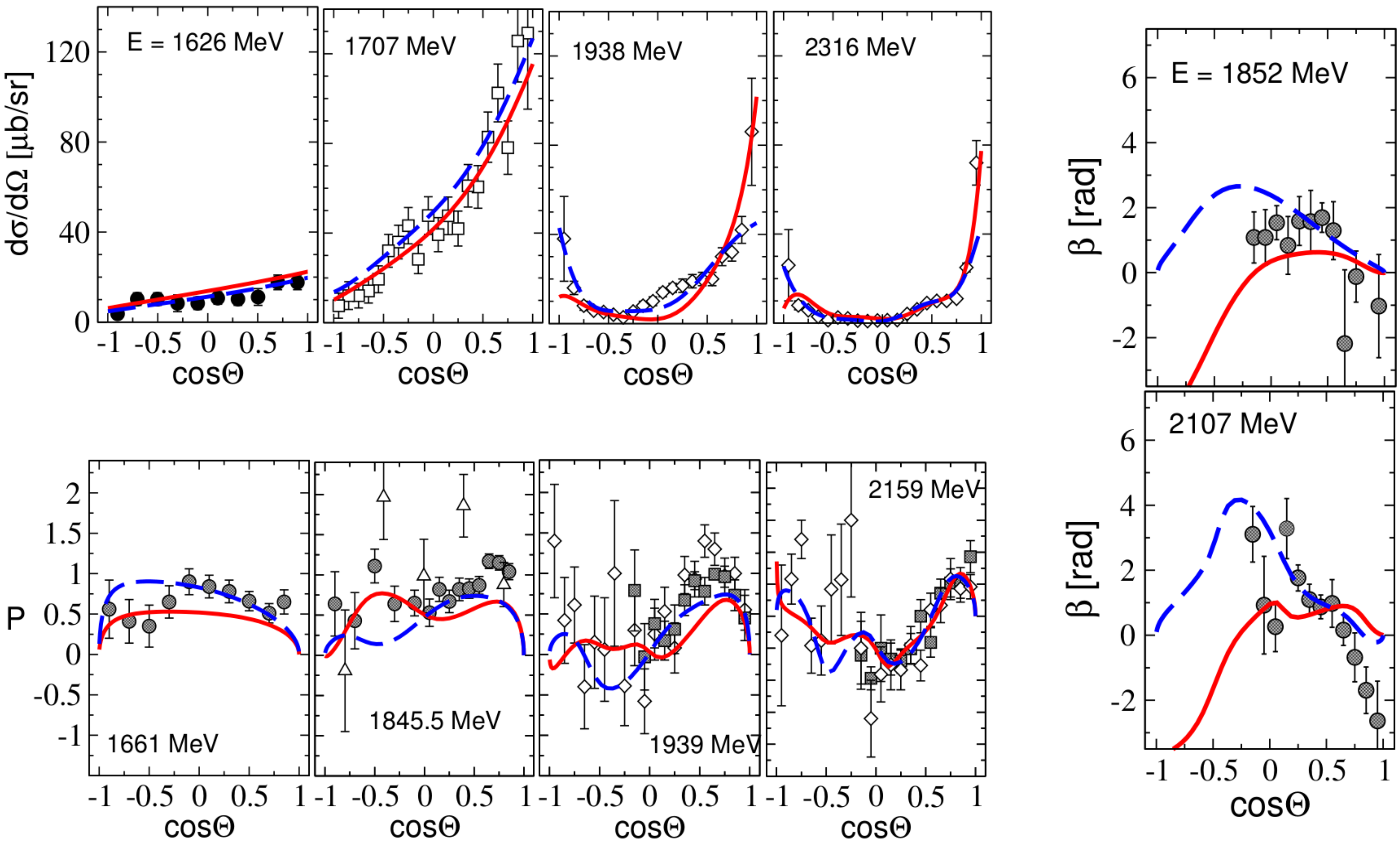
- Prediction for new CLAS data (Paterson *et al.* Phys. Rev. C 93, 065201 (2016)):



Fit to world data on $\pi N \to \pi N, \eta N, K\Lambda, K\Sigma$ ($\sim 10^5$ exp. points)

[Rönchen, M.D. *et al.*, EPJA 49 (2013)]

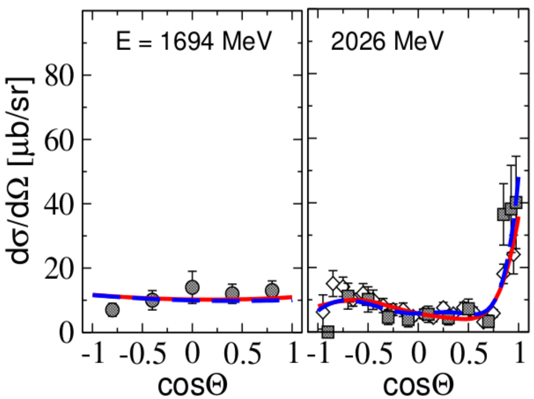
Selected results for $\pi^- p \to K^0 \Lambda$ [almost complete experiment]

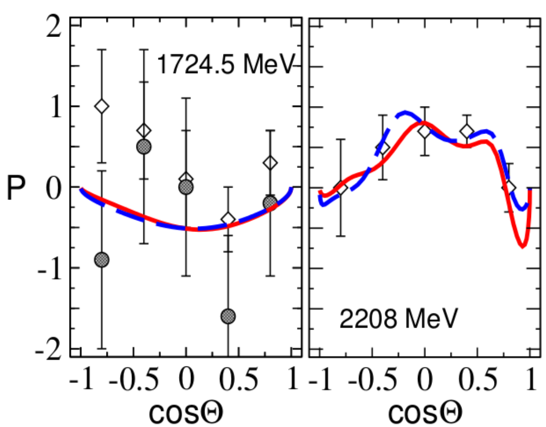


Re-measuring hadron-induced reactions

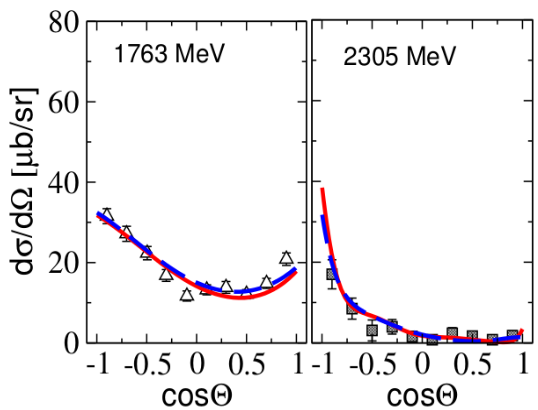
Fits: D. Rönchen, M.D., et al., EPJ A**49** (2013)

$\pi^- p \to K^0 \Sigma^0$



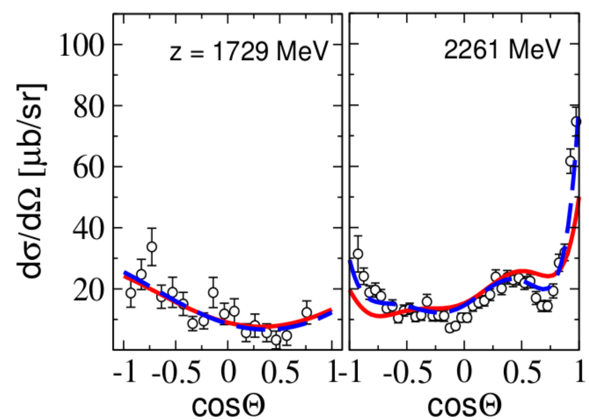


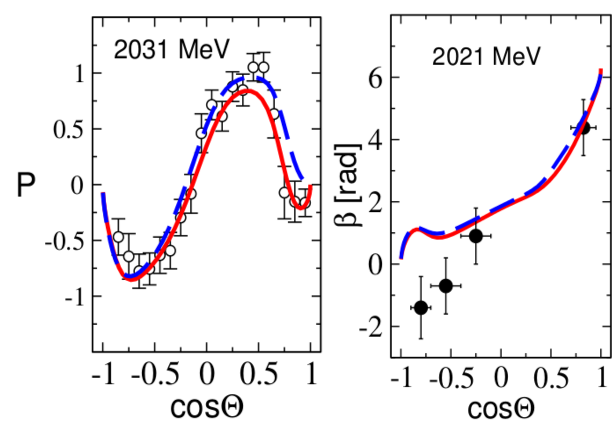
$\pi^- p \to K^+ \Sigma^-$



No polarization data!

$\pi^+ p \to K^+ \Sigma^+$



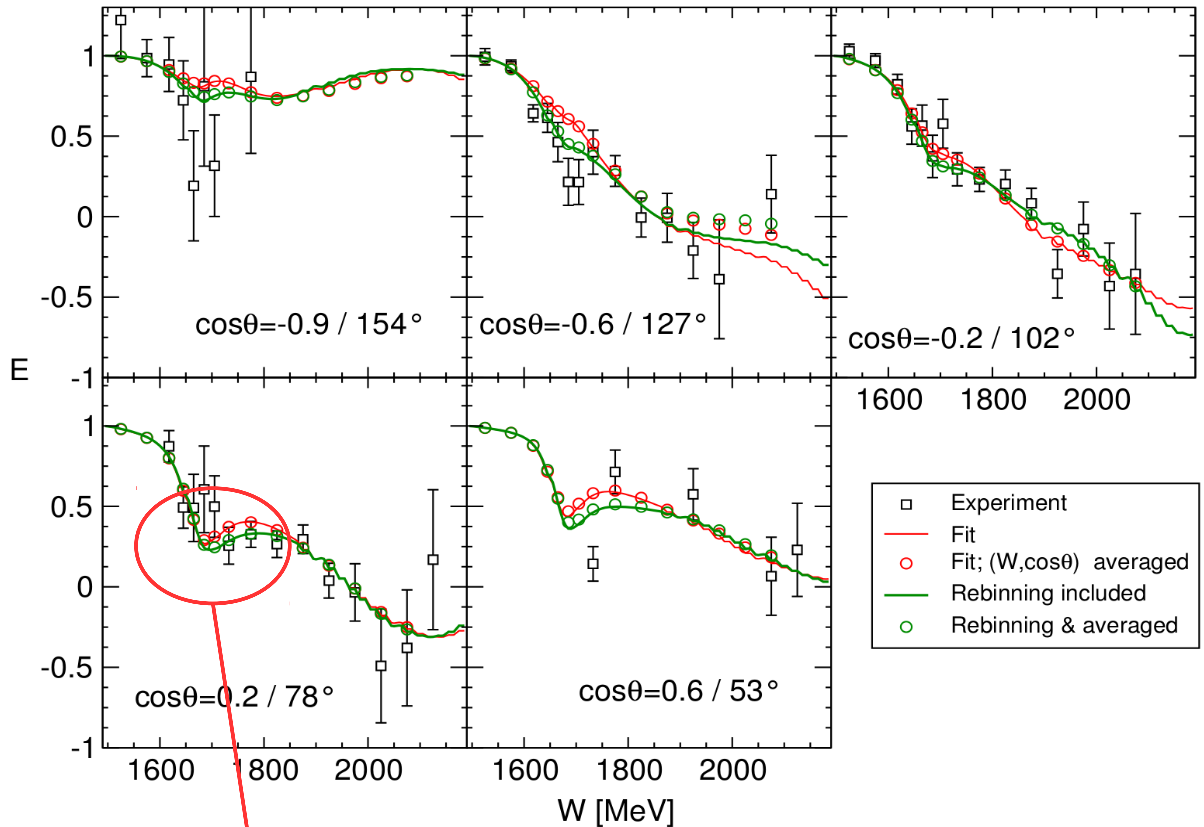


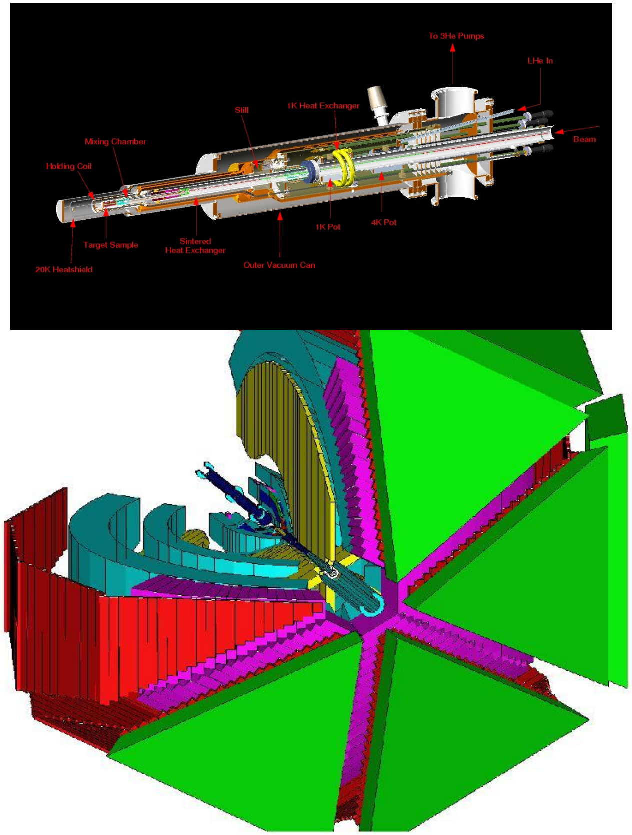
→ *Physics Opportunities with meson beams*,
Briscoe, M.D., Haberzettl, Manley, Naruki, Strakovsky, Swanson, EPJ A**51** (2015)

FROST/CLAS (II)

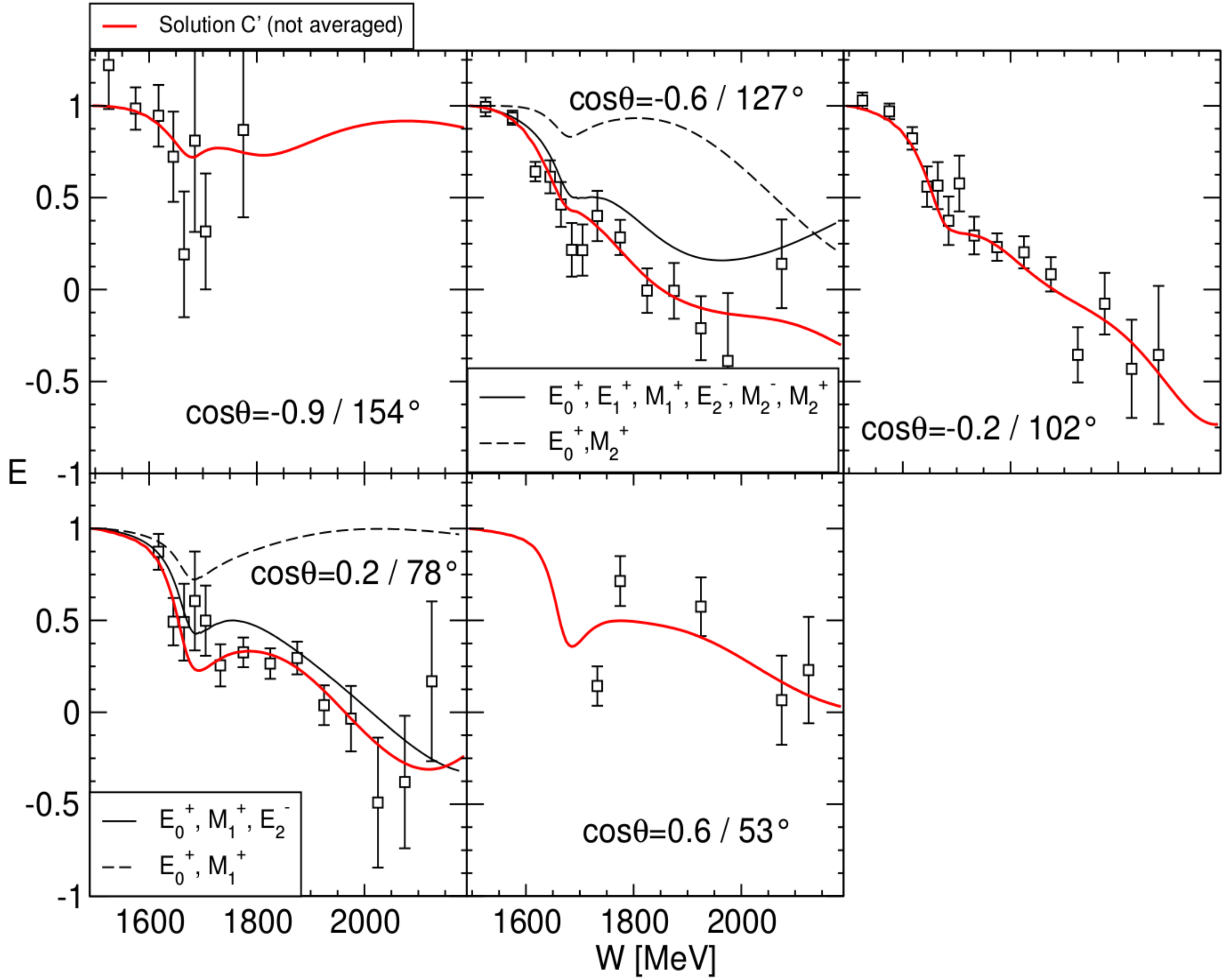
CLAS/JuBo (M. D., D. Rönchen), Phys.Lett. B755 (2016)

- First-ever measurement of observable E in η photo-production, enabled through the FROST target





Is this a new narrow baryonic resonance?
→ Conventional explanation in terms of interference effects.



NO additional structure (non-exotic pentaquark) at $W = 1.68$ GeV $\rightarrow$ interferences & $K\Sigma$ threshold.

→ How can we automatize/ blindfold resonance spectroscopy?

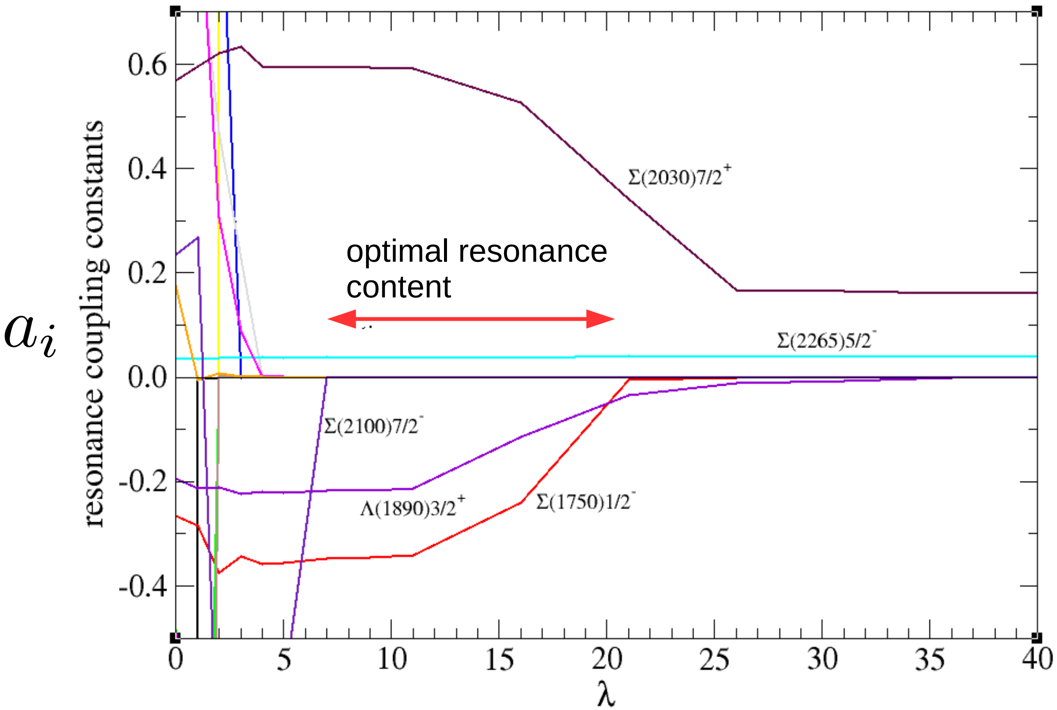
New developments

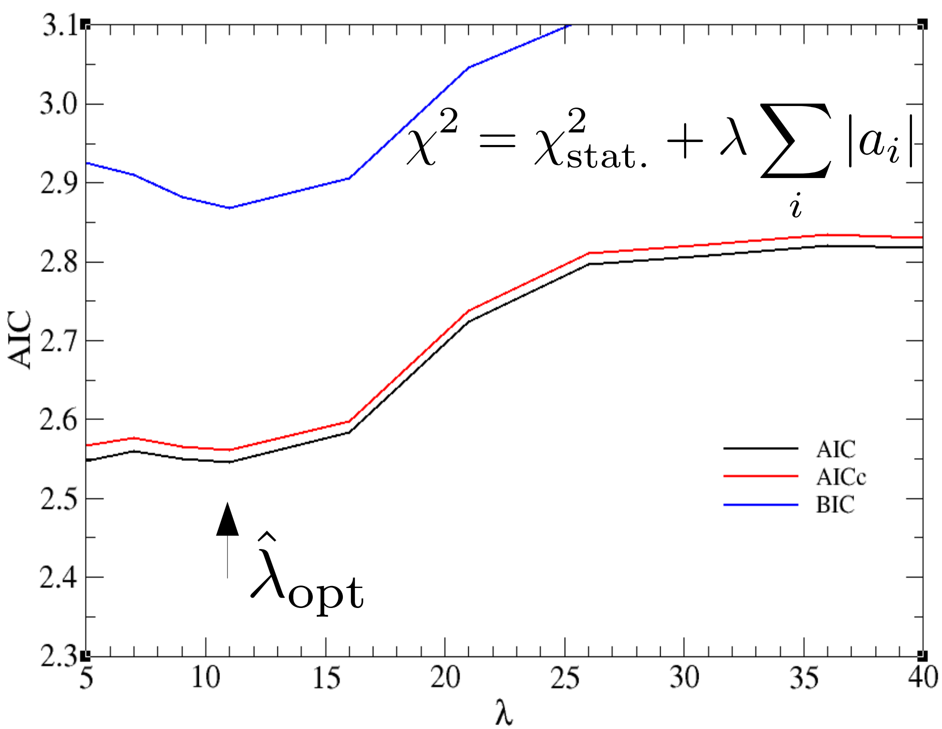
- Blindfolding spectroscopy [see also Guegan, Williams *et al.*, JINST 10 (2015)]
  - More detailed talk by Justin Landay (next)
- Toward (entirely) data-driven multi-channel analyses
- Preparing for CLAS12 electroproduction experiments
- Quantifying the impact of new measurements

Blindfolding spectroscopy

[M.D., J. Landay, H. Haberzettl, K. Nakayama, in preparation]

- New statistics tools: Automatized LASSO technique + goodness of fit criteria from information theory/ cross validation
- Model reaction $\bar{K}N \to K\Xi$ scrutinized [based on B. Jackson, Y. Oh, H. Haberzettl, K. Nakayama, Phys.Rev. C91 (2015)]
- Selection of model with minimal resonance content



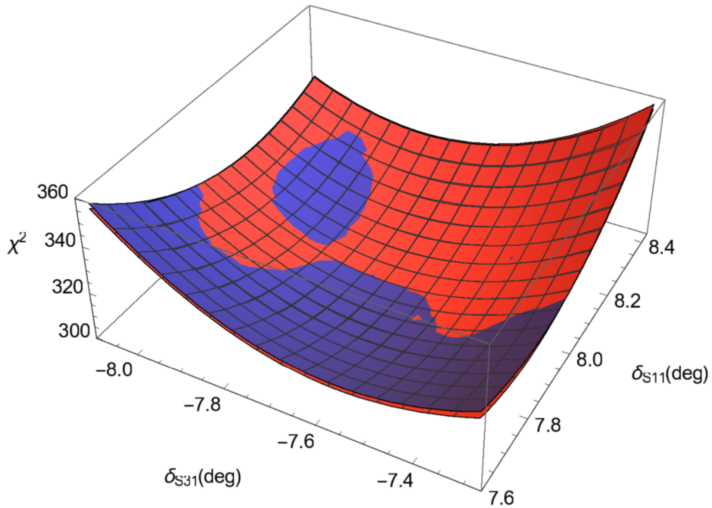


Toward Data-driven Analyses

[M.D., Revier, Rönchen, Workman, arXiv:1603.07265, PRC 2016]

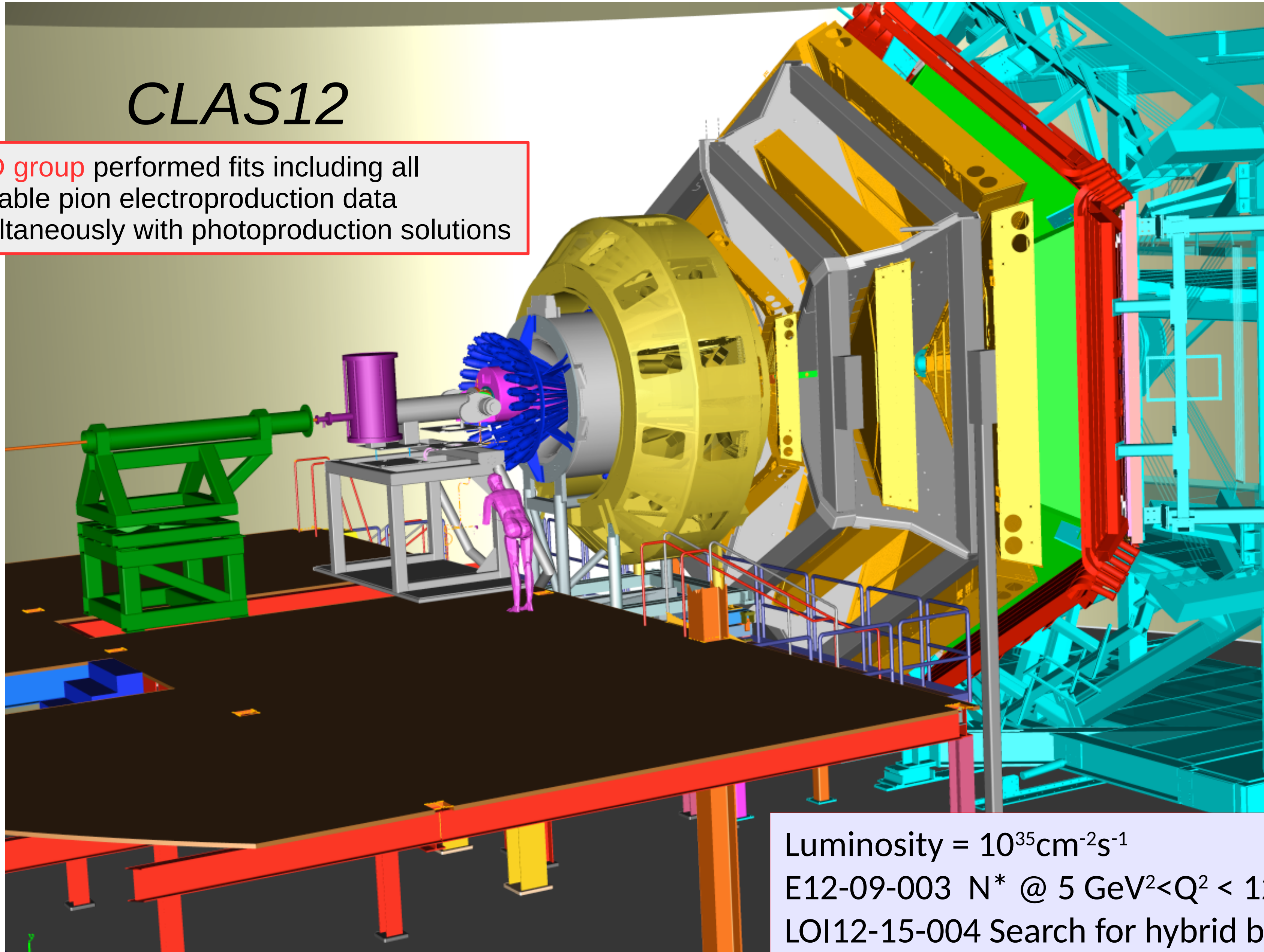
- Multi-channel analyses to detect faint resonance signals
- All groups use GW/SAID partial waves for $\pi N \to \pi N$
  - The chi-square obtained in fits to single-energy solutions is not related to chi-square of a fit to data → Statistical interpretation of resonance signals difficult.
- Provide online covariance matrices etc. to allow other groups to perform *correlated chi-square* fits.

Slight adaptation of their code allows other groups to obtain a χ^2 (almost) as if they fitted to $\pi N \to \pi N$ directly.



$$\chi^2(\mathbf{A}) = \chi^2(\hat{\mathbf{A}}) + (\mathbf{A} - \hat{\mathbf{A}})^T \hat{\Sigma}^{-1} (\mathbf{A} - \hat{\mathbf{A}}) + \mathcal{O}(\mathbf{A} - \hat{\mathbf{A}})^3$$

Transition form factors @ CLAS 12



SAID group performed fits including all available pion electroproduction data simultaneously with photoproduction solutions

Luminosity = $10^{35} cm^{-2} s^{-1}$

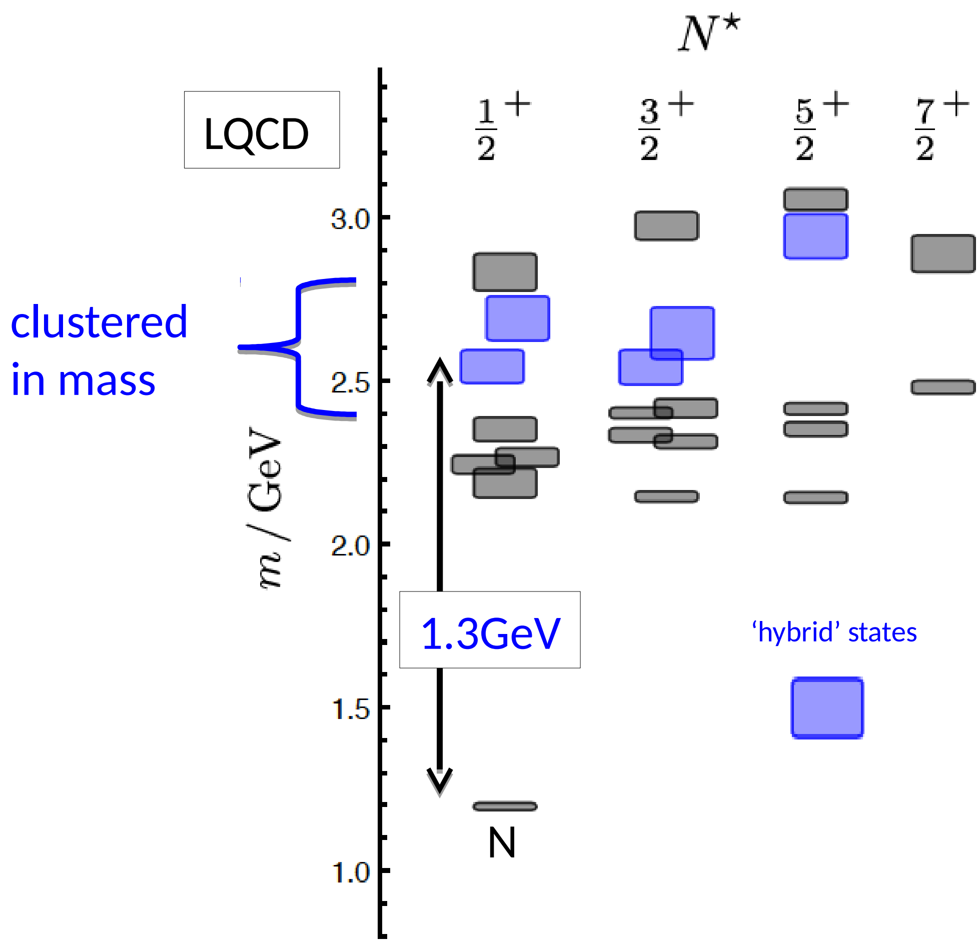
E12-09-003 N* @ 5 $GeV^2 < Q^2 < 12 \ GeV^2$

LOI12-15-004 Search for hybrid baryons

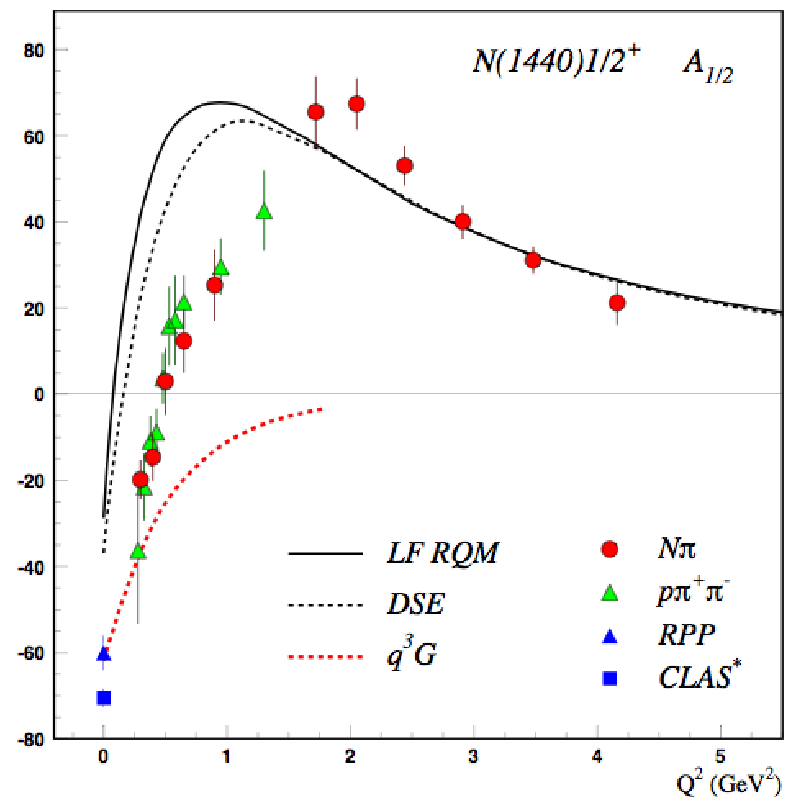
E12-06-108A KY Electroproduction with CLAS

Hybrid Baryons

J.J. Dudek and R.G. Edwards, PRD85 (2012) 054016



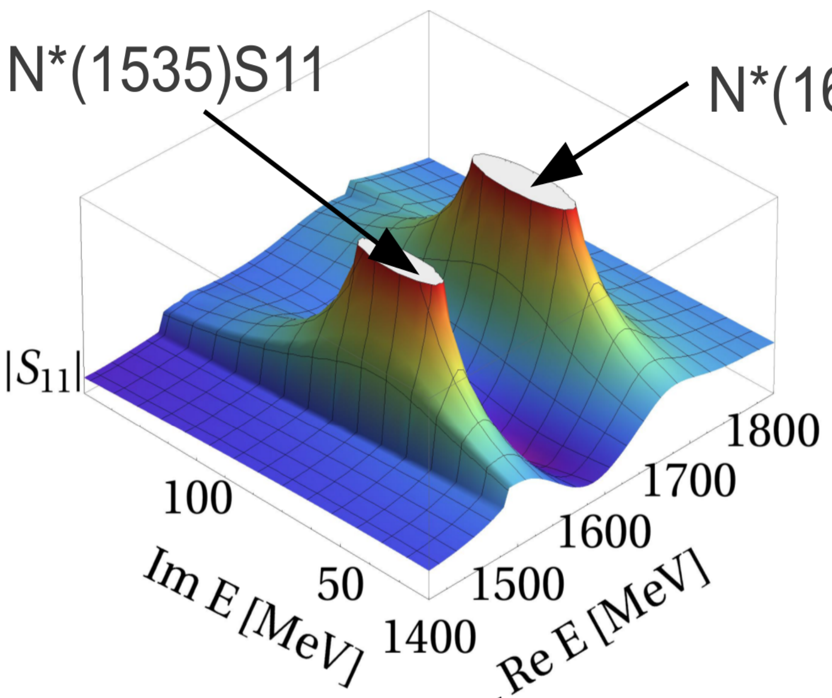
Unusual transition FF?



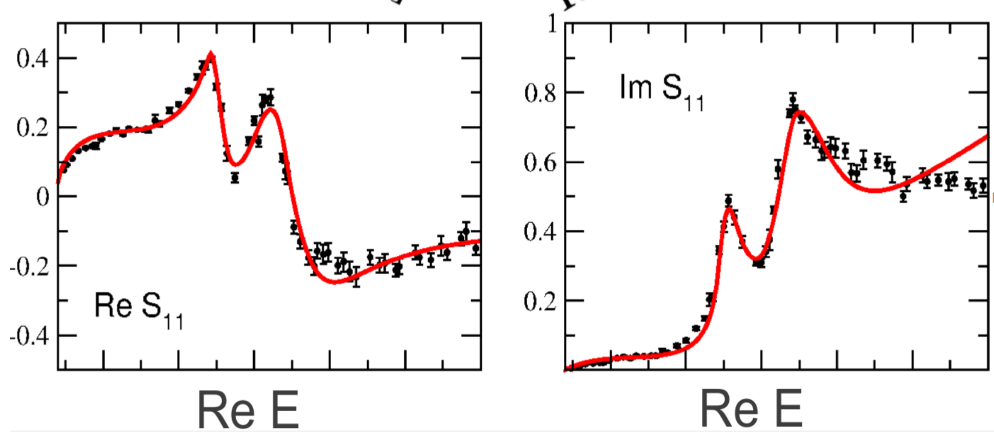
Hybrid states have same J^P values as q^3 baryons. How to identify them? → Measure Q^2 dependence of electro-couplings

Transition Form Factors at the Pole

Common effort MAID/SAID/Zagreb/JuBo
[Tiator, M.D., R. Workman, et al., PRC (2017)]



Definition of a resonance:
Pole in the complex plane of the scattering energy E (≡ z ≡ W);
- Pole position ("mass & width")
- Residues ("branching ratios")

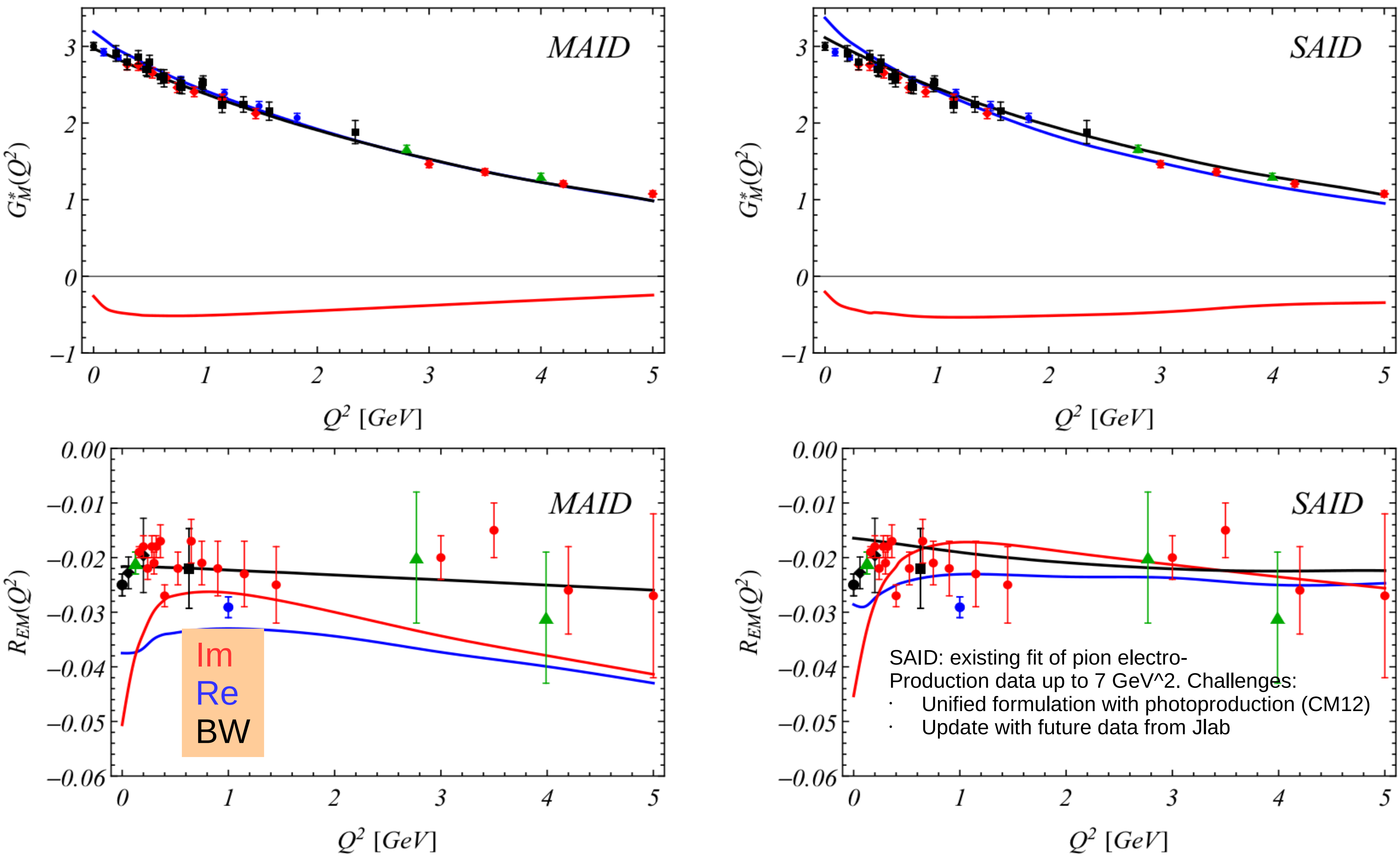


Also $\gamma^{(*)} N N^*$ transition form factors are complex quantities if defined at pole (background-independent definition)

Pole: point of comparison for (unitary) chiral models & lattice [Jido, M.D., Oset, PRC77 (2008); for lattice: A. Agadjanov, Bernard, Meissner, Rusetsky, NPB886 (2014)]

First Results for $\Delta(1232)P33$

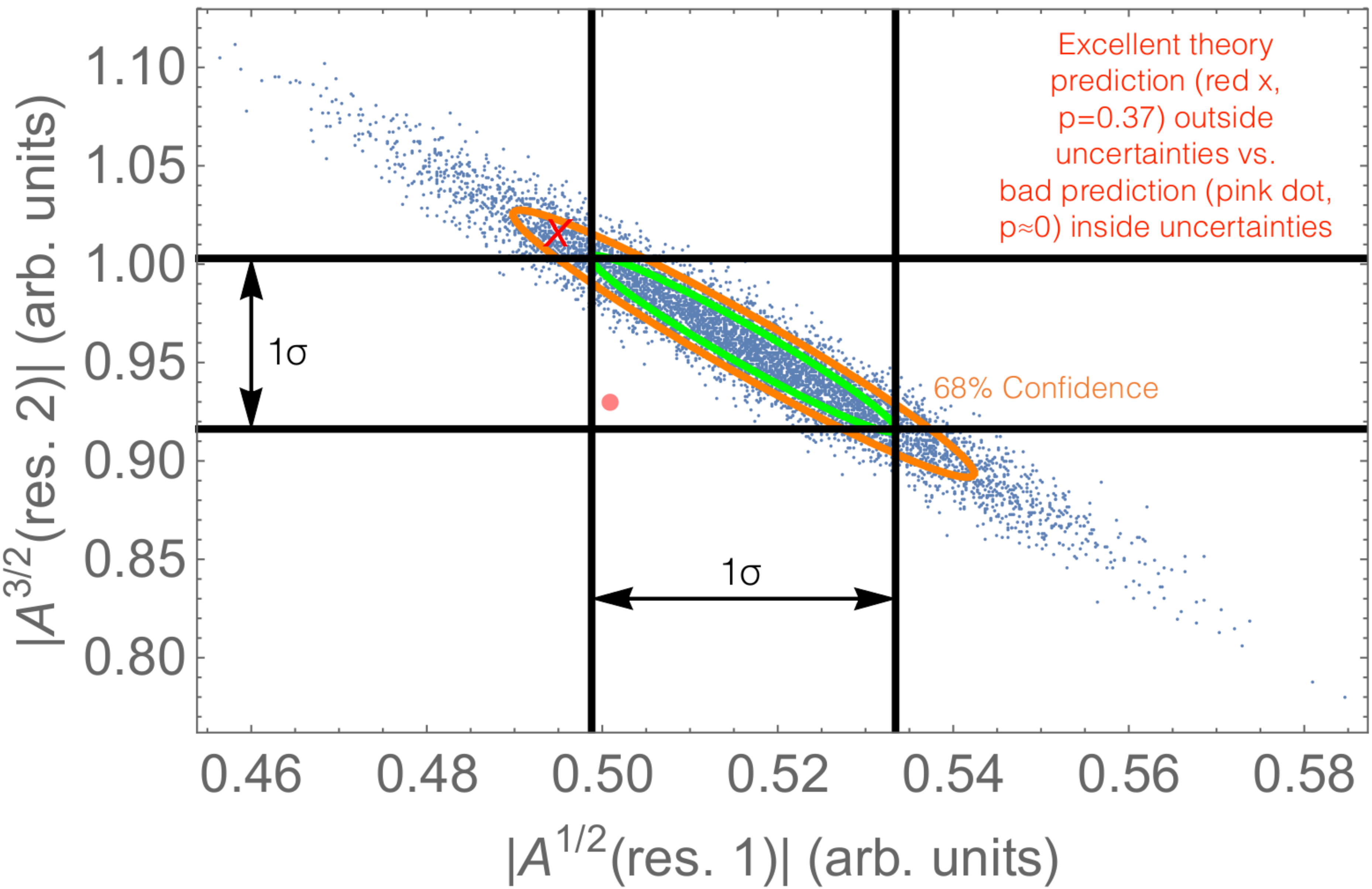
[Tiator, M.D., R. Workman, et al. PRC (2017)]



“Data points”: Aznauryan *et al.*

How to quantify the impact of new measurements?

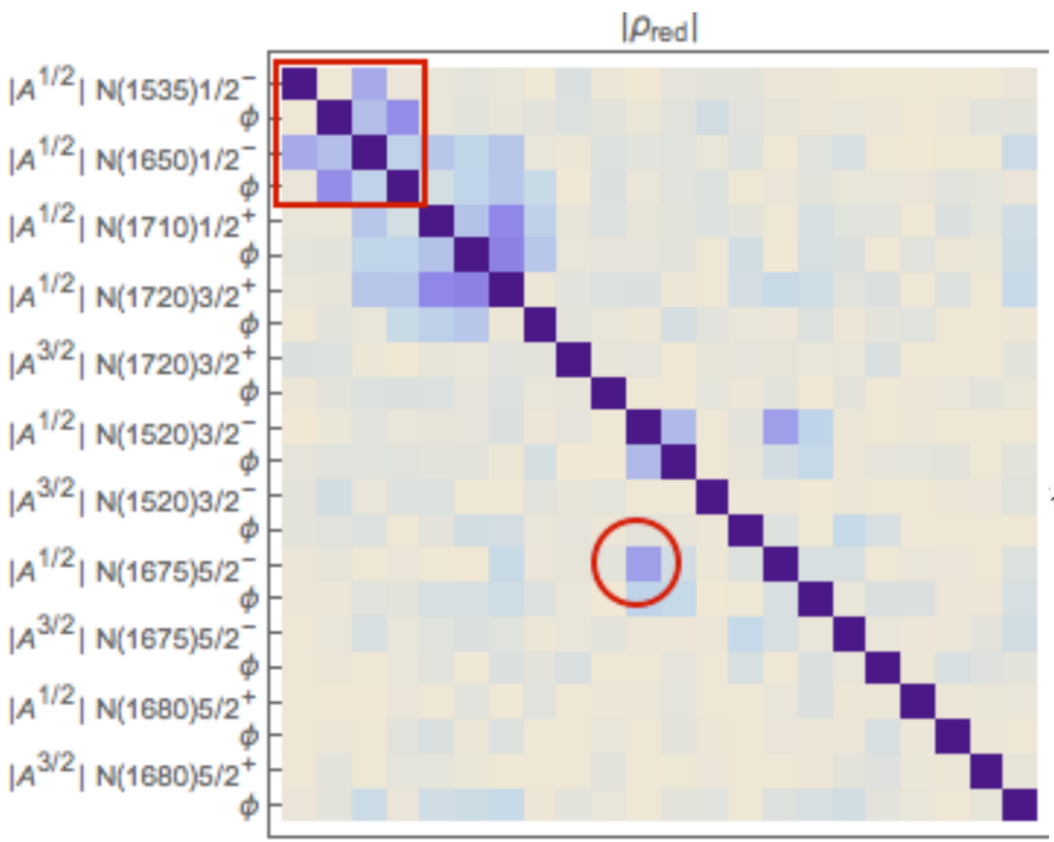
Consider correlations of helicity couplings extracted from experiment

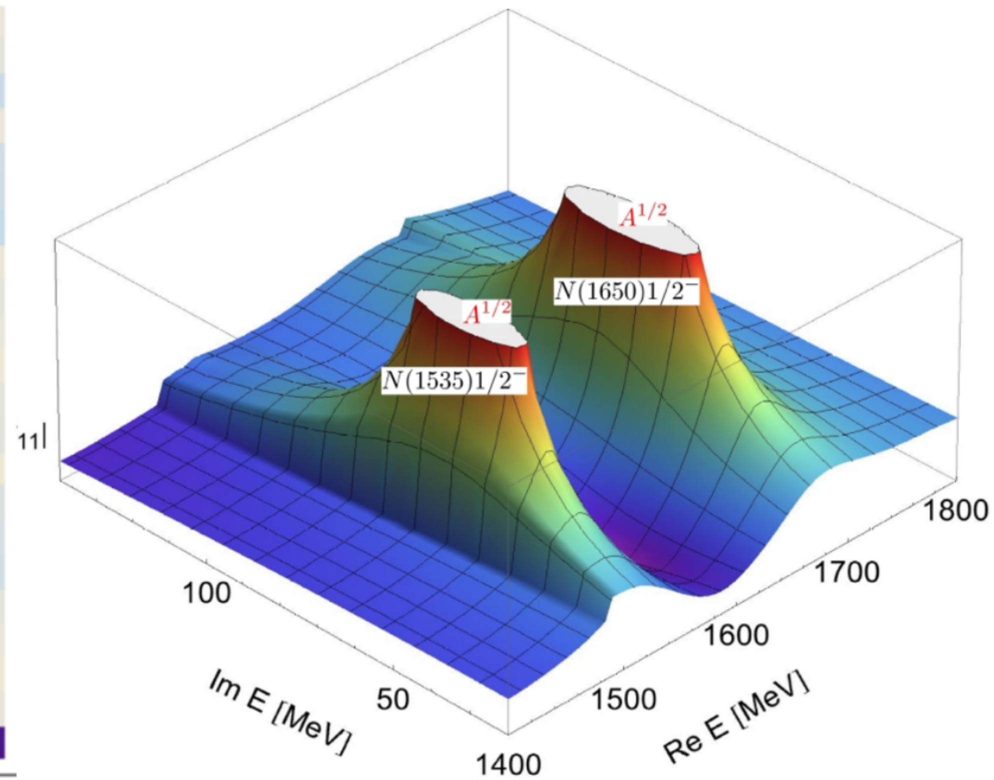


Results from analysis of world data of η photoproduction

[M.D., D. Sadasivan, in preparation]

Here $A = |A|e^{i\phi}$ defined at the resonance pole.





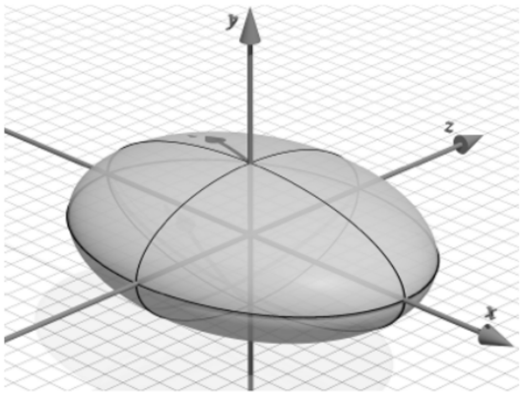
Bulk properties of uncertainties from different data sets

Helicity Coupling	All	No E	No F	No T	No Σ
Number of Data Points	6425	6369	6281	6281	6022
Generalized Variance	0.0494	0.0521	0.1288	0.1239	6.664
$\sqrt{\mathrm{Tr}\, C}$	10.4965	10.51	12.00	11.423	19.85
Multicollinearity	8.173	8.203	9.280	9.5323	10.371
Condition number	133.61	132.10	173.664	164.1	322.66

C=Covariance Matrix

Generalized Variance = Det[C] ~Volume of the Error Ellipsoid

Helicity Coupling	No artificial data	Cx	Cz	Cx and Cz
Number of Data Points	6425	6569	6569	6713
Generalized Variance	0.0494	0.03758	0.0362	0.0132
$\sqrt{\mathrm{Tr}\, C}$	10.4965	10.72	10.487	10.102
Multicollinearity	8.173	7.599	6.770	6.157
Condition number	133.61	112.47	109.69	107.683



- Allows to trace quantitatively the impact of data sets and observables
- Helpful in design of new measurements
- Correlations allow to assess quality of theory predictions

Outlook

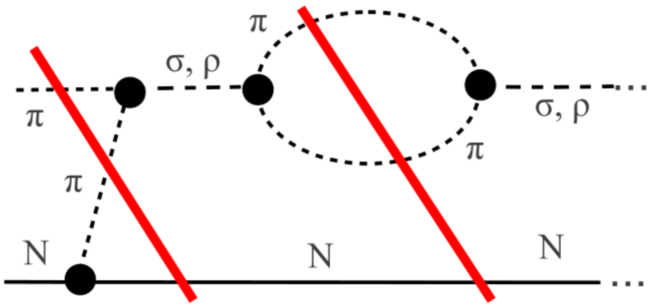
- High-precision (double) polarization observables from CLAS, ELSA, MAMI,... in unprecedented quality
- Precision spectroscopy requires
  - Systematic search for new resonances (model selection techniques)
  - Entirely data-driven analyses
  - Quantitative answers to impact of data
  - Extension to Electroproduction planned building on existing SAID analyses.
- First lattice-QCD results on baryons emerging

→ Generalize analysis effort to make connection to first-principle calculations.

$$S = \mathbb{1} + iT$$

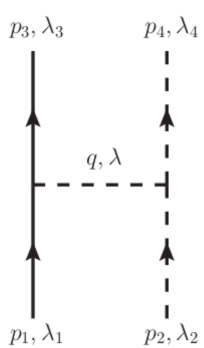
Unitarity: $SS^\dagger = 1 \Leftrightarrow -i(T - T^\dagger) = T\,T^\dagger$

- 3-body unitarity:
  discontinuities from t-channel exchanges
  $\rightarrow$ Meson exchange from requirements of the S-matrix

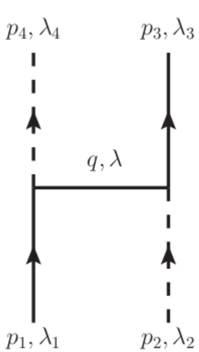


Other cuts

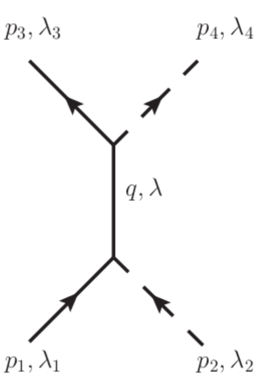
- to approximate left-hand cut $\rightarrow$ Baryon u-channel exchange
- σ, ρ exchanges from crossing plus analytic continuation.



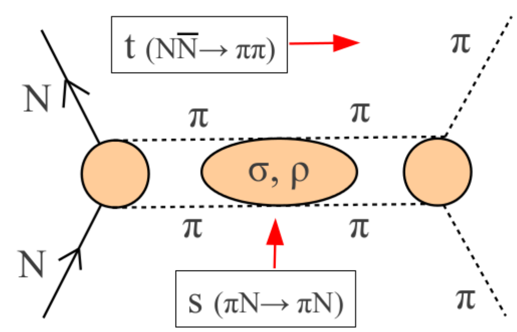
$\vec{q} = \vec{p}_1 - \vec{p}_3$



$\vec{q} = \vec{q}_1 - \vec{p}_4$



$\vec{q} = \vec{p}_1 + \vec{p}_2 = 0$



Amplitude reconstruction from complete experiments and truncated partial-wave expansions

[Workman, Tiator, Wunderlich, M.D., H. Haberzettl, PRC (2017)]

How do complete experiment and truncated partial wave complete experiment compare. Depending on which partial-wave content is admitted in the amplitude?

Set	Included Partial Waves	CEA	TPWA	Complete Sets for TPWA
1	$L = 0\ (E_{0+})$	1(1)	1(1)1	$I[1]$
2	$J = 1/2\ (E_{0+}, M_{1-})$	4(4)	4(4)1	$I[1]\,,\check{P}[1]\,,\check{C}_x[1]\,,\check{C}_z[1]$
			4(3)2	$I[2]\,,\check{P}[1]\,,\check{C}_x[1]$
3	$L = 0,1\ (E_{0+}, M_{1-}, E_{1+})$	6(6)	6(6)1	$I[1]\,,\check{\Sigma}[1]\,,\check{T}[1]\,,\check{P}[1]\,,\check{F}[1]\,,\check{G}[1]$
			6(4)2	$I[2]\,,\check{\Sigma}[1]\,,\check{T}[2]\,,\check{P}[1]$
			6(3)3	$I[3]\,,\check{\Sigma}[1]\,,\check{T}[2]$
4	$L = 0,1\ (E_{0+}, M_{1-}, E_{1+}, M_{1+})$	†		TPWA at 1 angle not possible
	full set of 4 S, P wave multipoles		8(5)2	$I[2]\,,\check{\Sigma}[1]\,,\check{T}[2]\,,\check{P}[2]\,,\check{F}[1]$
			8(4)3	$I[3]\,,\check{\Sigma}[1]\,,\check{F}[2]\,,\check{H}[2]$
5	$L = 0,1,2\ (E_{0+}, M_{1-}, E_{1+}, E_{2-})$	8(8)	8(8)1	$I[1]\,,\check{\Sigma}[1]\,,\check{T}[1]\,,\check{P}[1]\,,\check{F}[1]\,,\check{G}[1]\,,\check{C}_x[1]\,,\check{O}_x[1]$
			8(4)2	$I[2]\,,\check{\Sigma}[2]\,,\check{T}[2]\,,\check{P}[2]$
			8(3)3	$I[3]\,,\check{\Sigma}[2]\,,\check{T}[3]$
6	$J \leq 3/2\ (E_{0+}, M_{1-}, E_{1+}, M_{1+}, E_{2-}, M_{2-})$	†		TPWA at 1 or 2 angles not possible
			12(5)3	$I[3]\,,\check{\Sigma}[2]\,,\check{T}[3]\,,\check{P}[2]\,,\check{F}[2]$
			12(4)4	$I[4]\,,\check{\Sigma}[2]\,,\check{F}[3]\,,\check{H}[3]$
7	$L = 0,1,2\ (E_{0+}, \ldots, M_{2+})$	†		TPWA at 1 or 2 angles not possible
	full set of 8 S, P, D wave multipoles		16(6)3	$I[3]\,,\check{\Sigma}[3]\,,\check{T}[3]\,,\check{P}[3]\,,\check{F}[3]\,,\check{G}[1]$
			16(5)4	$I[4]\,,\check{\Sigma}[3]\,,\check{T}[3]\,,\check{P}[3]\,,\check{F}[3]$
			16(4)5	$I[5]\,,\check{\Sigma}[3]\,,\check{F}[4]\,,\check{H}[4]$

Four are enough!

Order:
# of different measurements,
# of different observables
# of different angles

Connecting Theory and Phenomenology at the pole

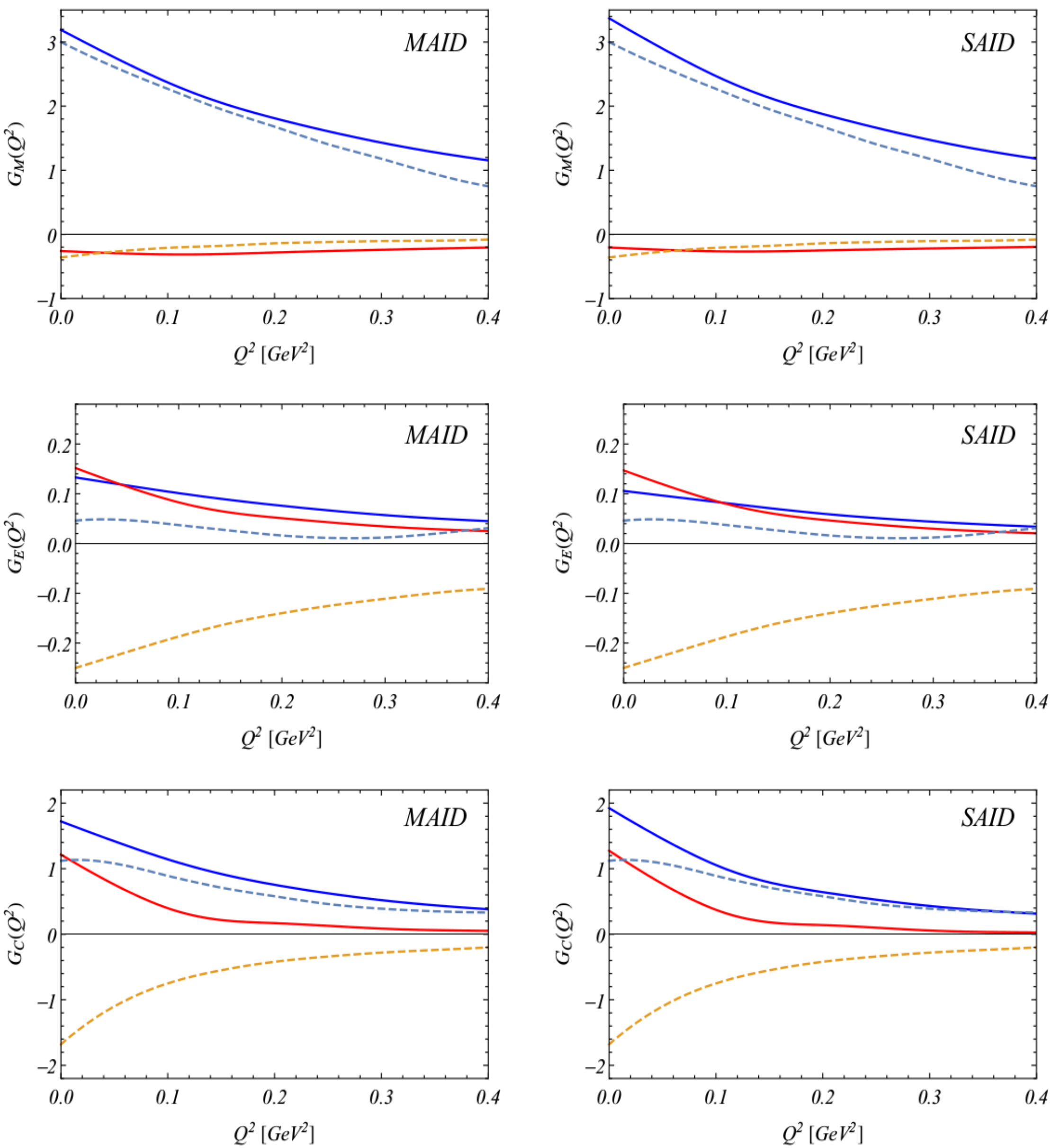


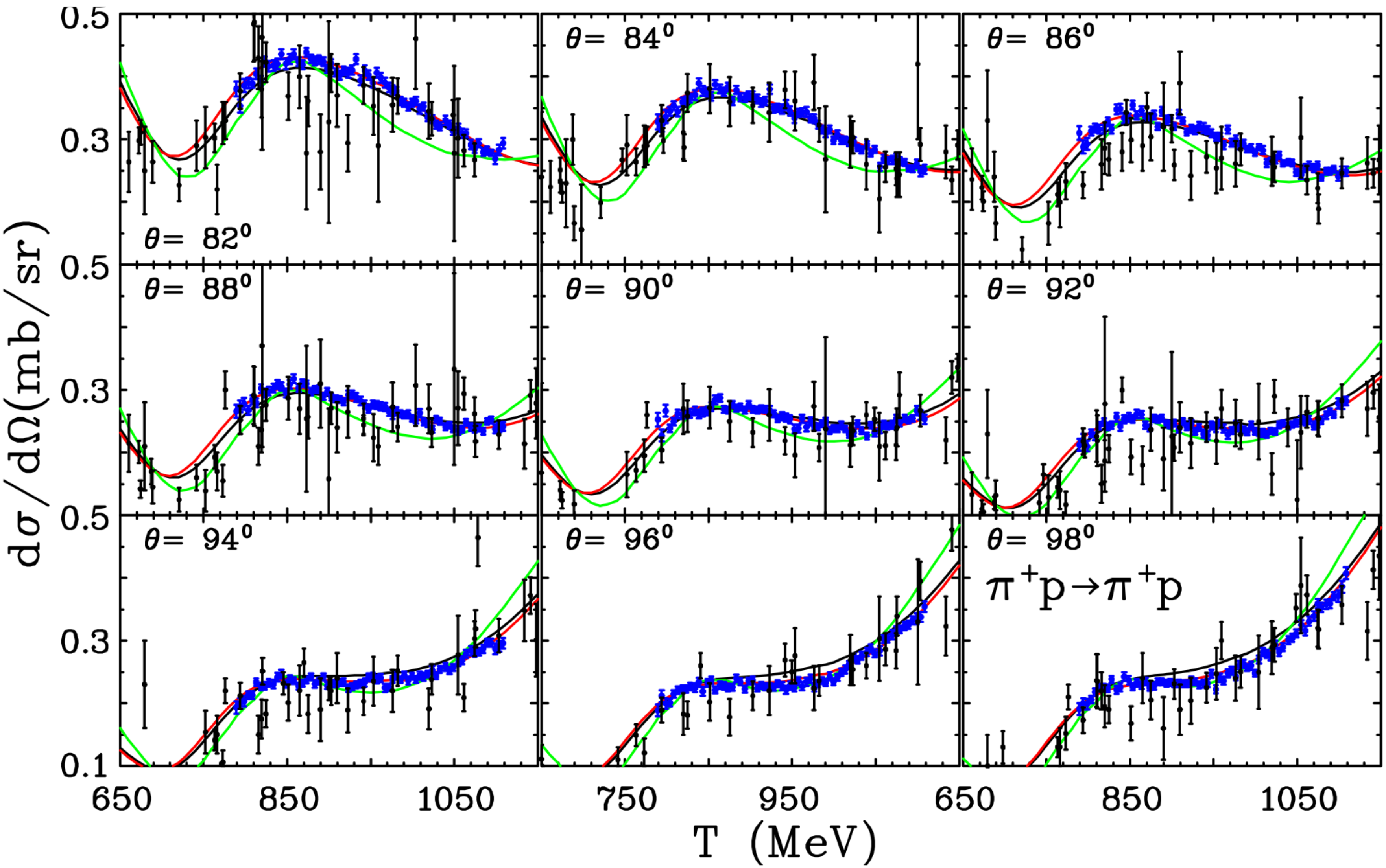
FIG. 4: Magnetic, electric and charge transition form factors compared with the Heavy Baryon chiral effective field theory of Gail and Hemmert [14] at low Q^2. The blue and red lines show real and imaginary parts of the complex pole form factors obtained from MAID and SAID. The dashed lines are the HBChEFT calculations.

T.A. Gail and T.R. Hemmert, Eur. Phys. J. A 28 (2006).

Lattice: Agadjanov, Bernard, Meißner, Rusetsky, Nucl. Phys. B 886 (2014)

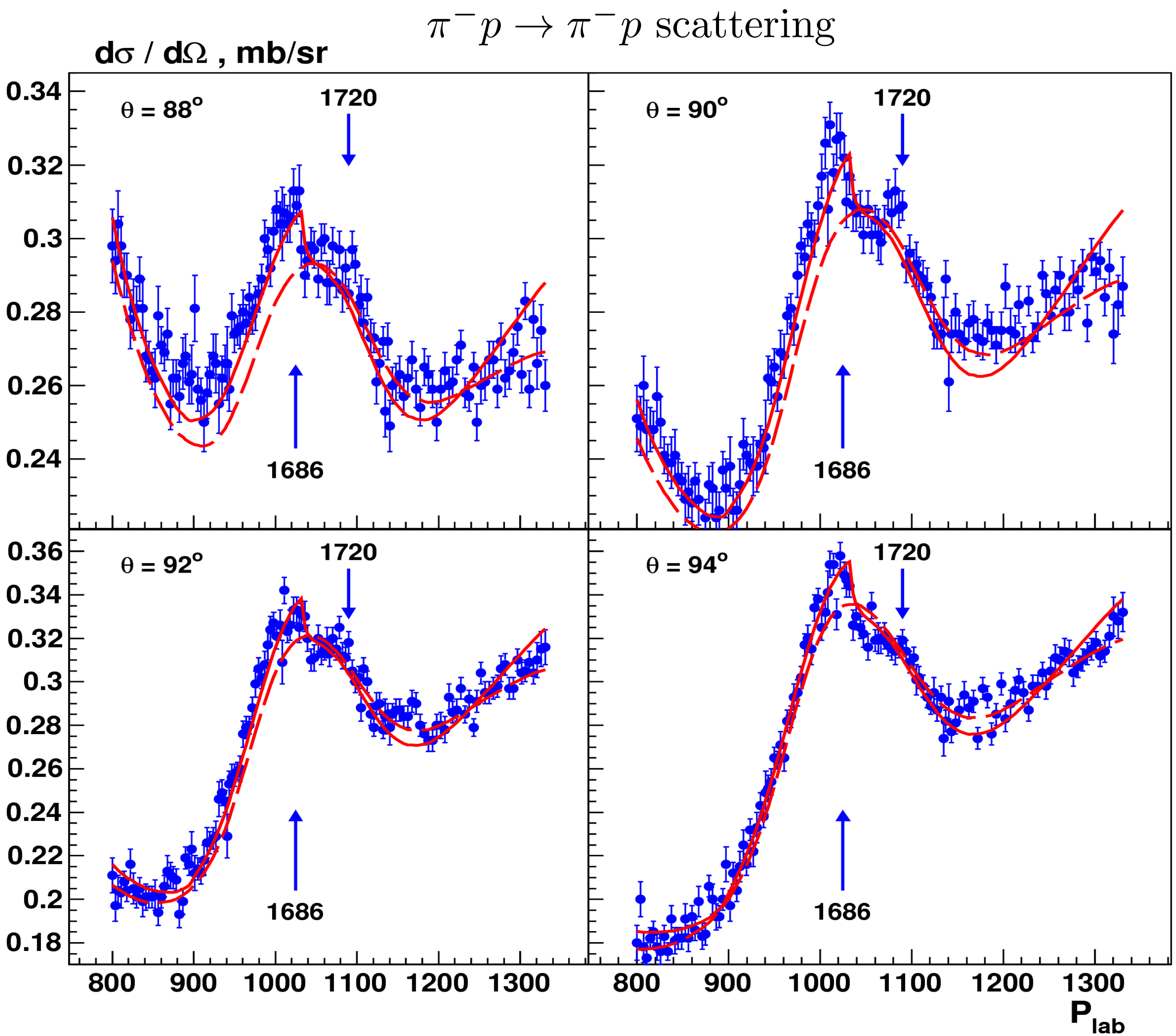
Improvement in Modern Experimental Facilities: $\pi N \to \pi N$

EPECUR & GWU/SAID, Alekseev *et al.*, PRC91, 2015



Black: WI08 prediction; Red: WI14 fit; green: KA84.

New High-precision πN data



Data: EPECUR
Analysis: SAID (dashed)
Gridnev (solid)
ArXiv: 1604.02379

Sharp structures seen in EPECUR data are largely accounted for by channel-coupling ($K\Sigma$) leaving less room for narrow resonance candidates.

In general:

Hadronic data serves as "input" for many PWAs!

Photocouplings at the pole

$$\tilde{A}^h_{pole} = A^h_{pole} e^{i\vartheta^h}$$
$$h = 1/2,\ 3/2$$

$$\tilde{A}^h_{pole} = I_F \sqrt{\frac{q_p}{k_p} \frac{2\pi\,(2J+1)\mathrm{E_0}}{m_N\ \mathrm{r_{\pi N}}}}\ \mathrm{Res}\, A^h_{L\pm}$$

I_F: isospin factor
q_p (k_p): meson (photon) momentum at the pole
$J = L \pm 1/2$ total angular momentum
E_0: pole position
$r_{\pi N}$: elastic πN residue

	$A^{1/2}_{pole}$ [10^{-3} GeV$^{-1/2}$]		$\vartheta^{1/2}$ [deg]		$A^{3/2}_{pole}$ [10^{-3} GeV$^{-1/2}$]		$\vartheta^{3/2}$ [deg]	
fit→	1	2	1	2	1	2	1	2
$N(1710)\ 1/2^+$	15	28^{+9}_{-2}	13	77^{+20}_{-9}				
$\Delta(1232)\ 3/2^+$	-116	-114^{+10}_{-3}	-27	-27^{+4}_{-2}	-231	-229^{+3}_{-4}	-15	$-15^{+0.3}_{-0.4}$

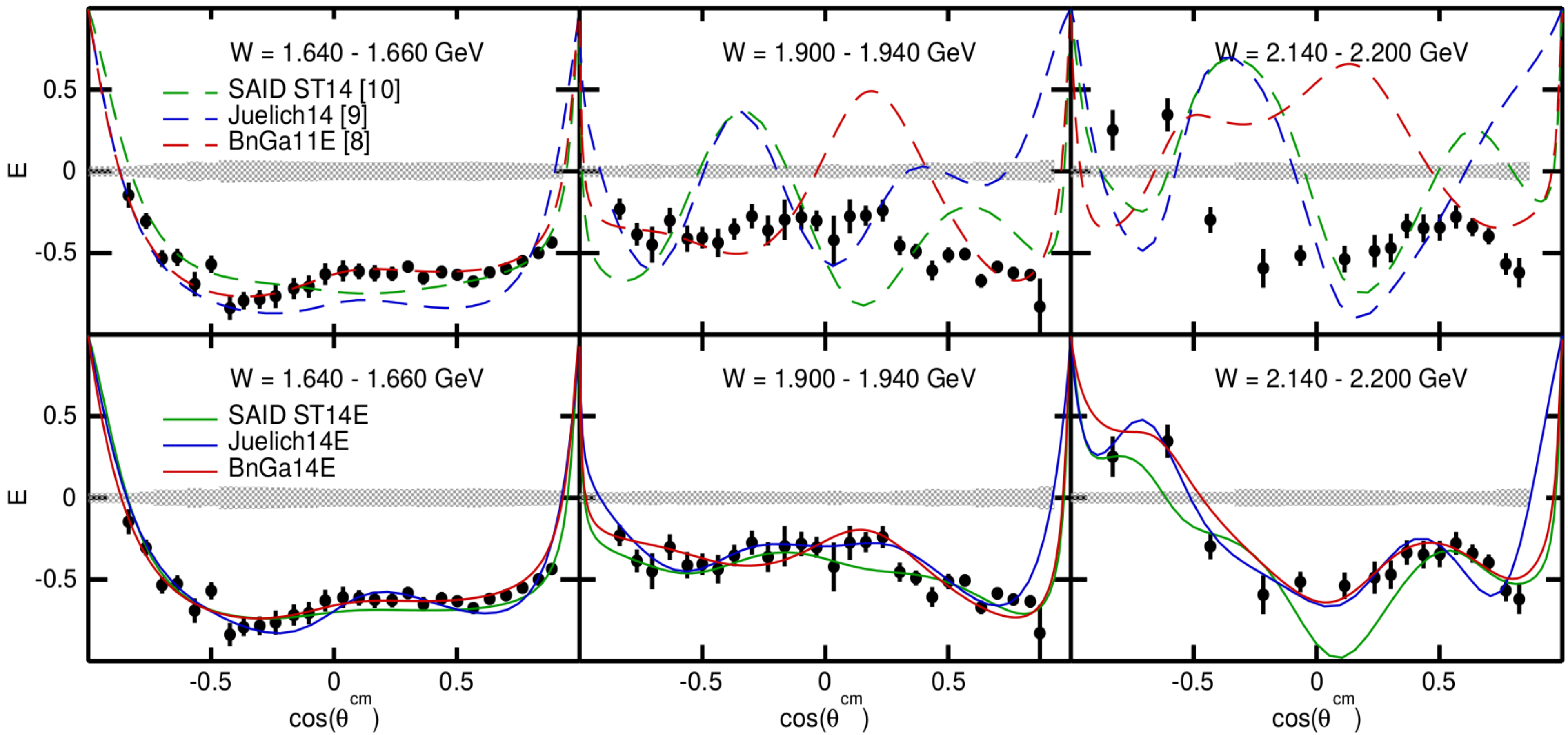
Fit 1: only **single** polarization observables included

Fit 2: also **double** polarization observables included

FROST/CLAS (I)

The E-observable in charged-pion photoproduction

CLAS/BnGa/JuBo/SAID, PLB **750** (2015)

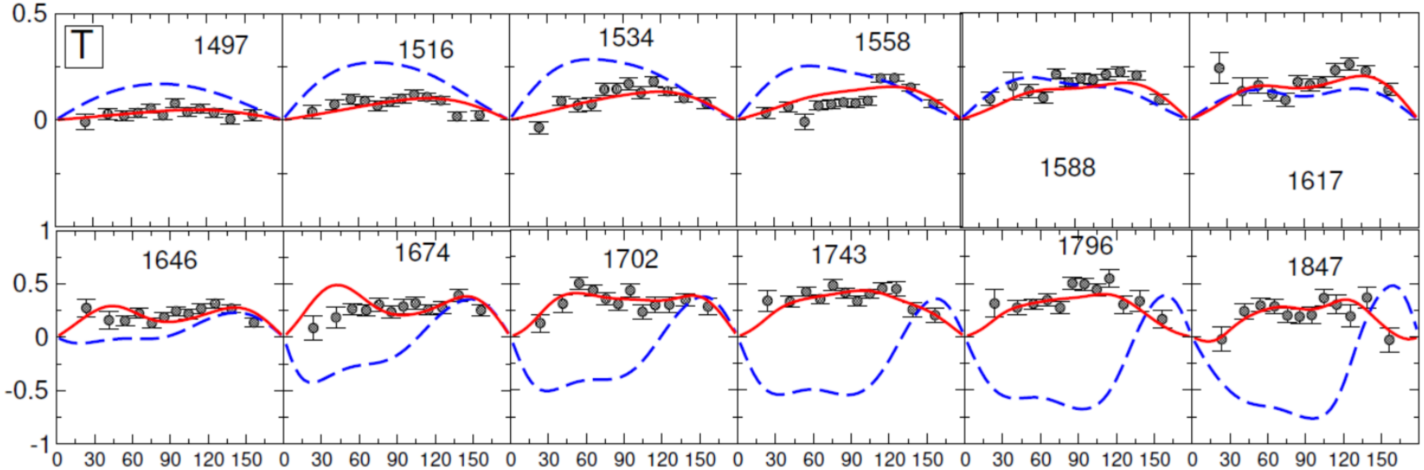


→ Significant impact on resonance parameters/
New resonance (BnGa) [$\Delta(2200)7/2^-$], arXiv: 1503.05774

T and F in $\gamma p \to \eta p$ (MAMI)

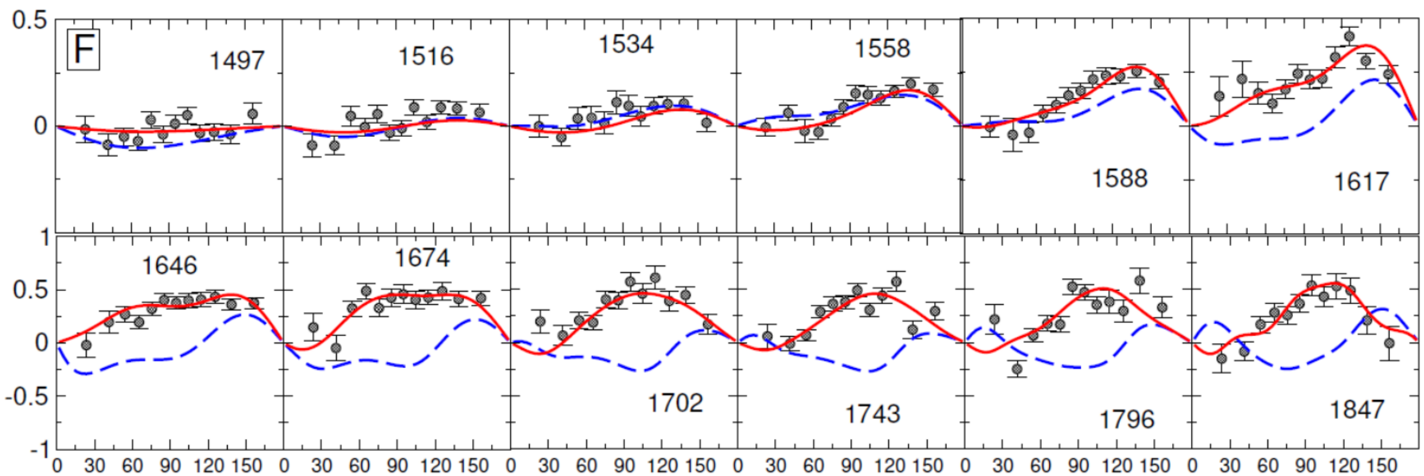
EPJA 51, 6 (2015)

Data: Akondi *et al.* (A2 at MAMI) PRL 113, 102001 (2014)



prediction
fit

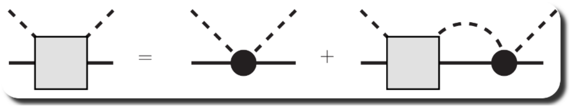
Beam	Target	Recoil
0	$+y$	0
0	$-y$	0



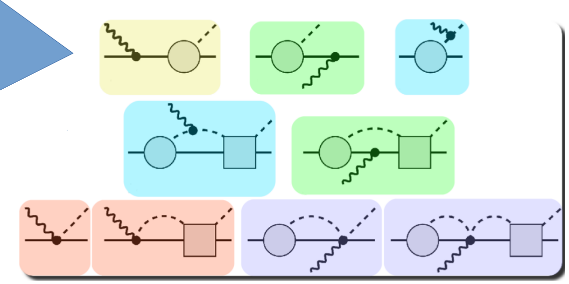
Beam	Target	Recoil
$+1$	$+x$	0
-1	$+x$	0

Manifestly gauge invariant approach based on full BSE solution

[M. Mai, P.C. Bruns, U.-G. Meissner PRD 86 (2012) 094033 [arXiv:1207.4923]



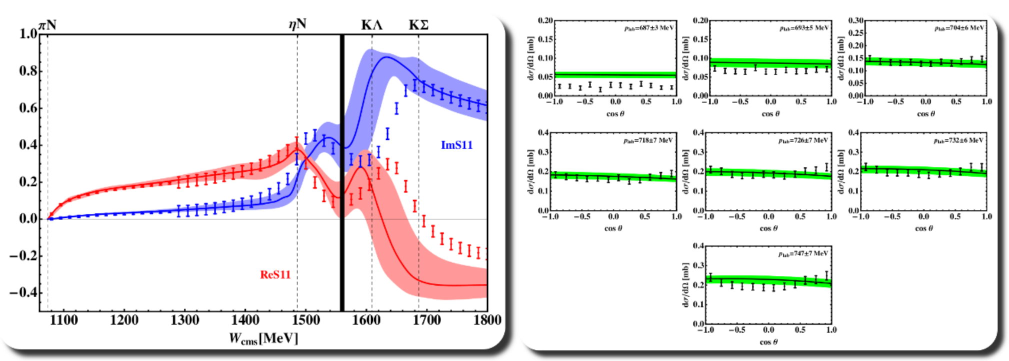
Gauge invariance



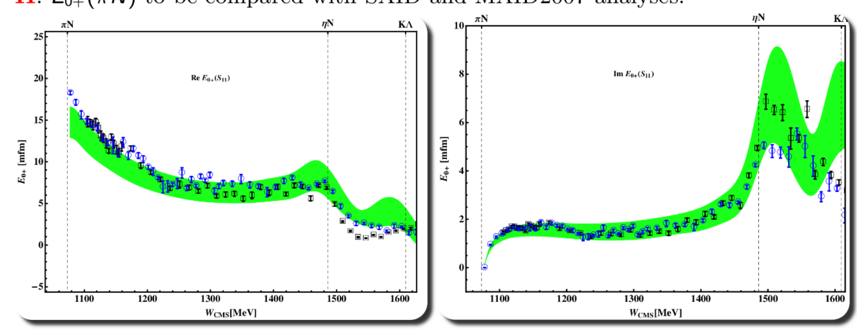
Fit

Prediction

- Exact unitary meson-baryon scattering amplitude T with parameters, fixed to reproduce:
  - πN-partial wave S_{11} and S_{31} for $\sqrt{s} < 1560$ MeV
    Arndt et al. (2012)
  - $\pi^- p \to \eta n$ differential cross sections
    Prakhov et al. (2005)



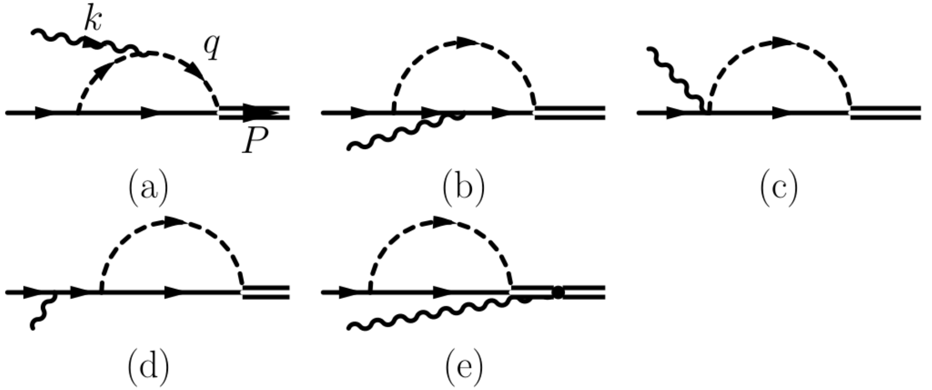
II. $E_{0+}(\pi N)$ to be compared with SAID and MAID2007 analyses:



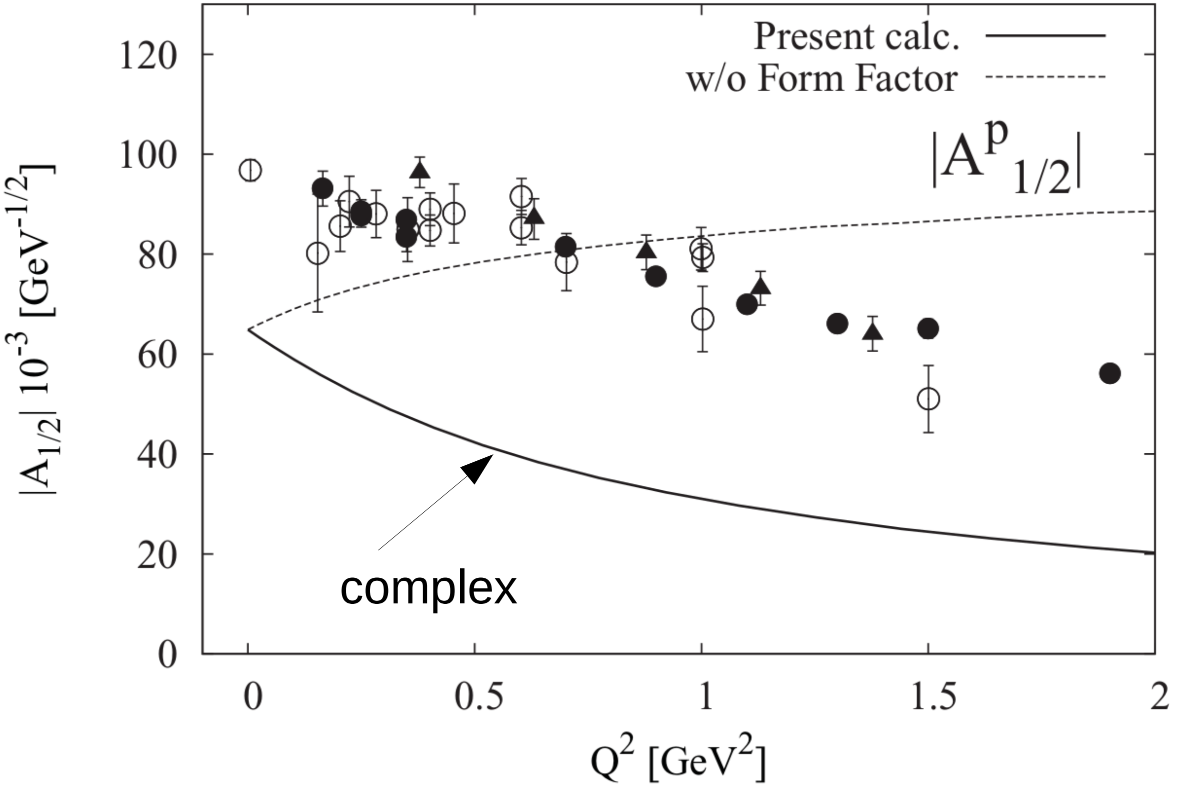
→ There is no explicit s-channel pole term in this approach; there is no other quantity to compare with PWAs, except at the pole.

Older, more incomplete Chiral unitary prediction

[Jido, M.D., Oset, PRC77 (2008)]



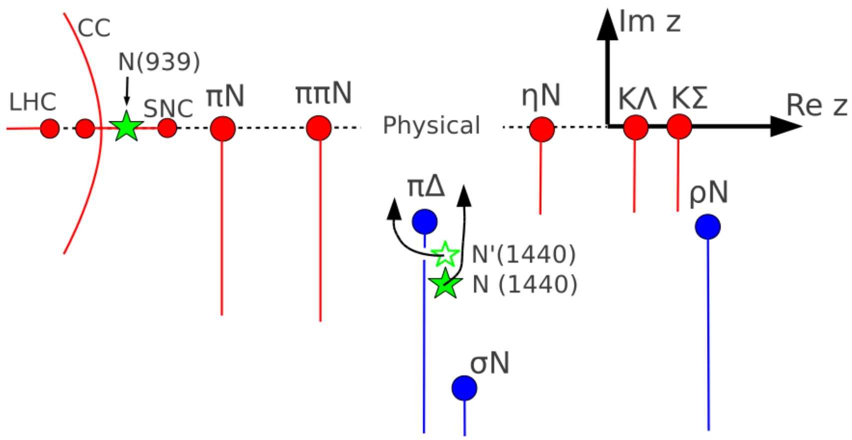
$\pi N,\ \eta N,\ K\Lambda,\ K\Sigma$ channels



Discrepancy: Genuine problem
or due to different definitions?

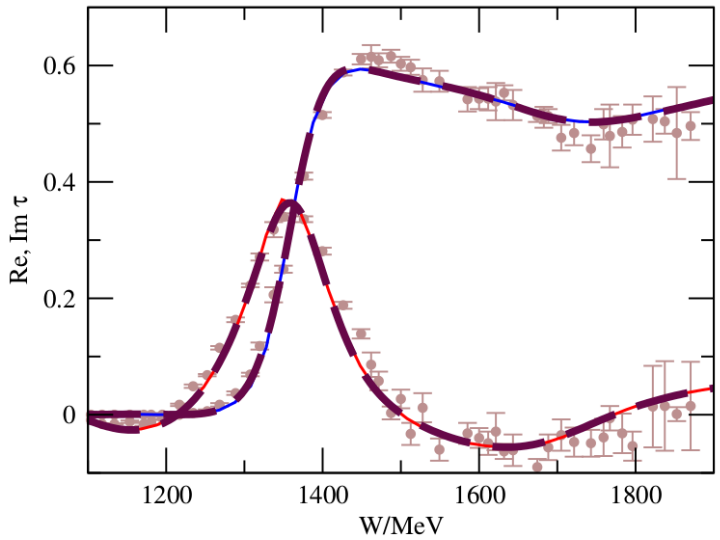
This workshop: remarkable progress
On complex helicity couplings
by ANL-Osaka group.

Relevance of three-body dynamics



- Roper pole + $\pi\Delta$ branch point $\rightarrow$ non-standard resonance shape.
- See results by GWU/SAID data analysis center.

- Where is the 3∗ N(1710)? [S. Ceci, M.D. et al, PRC84, 2011]



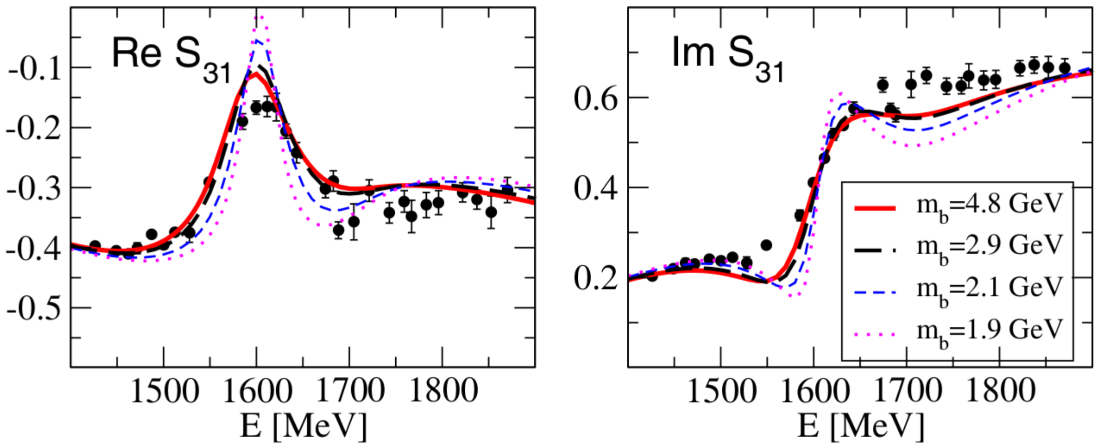
Fit of a model without ρN branch point (CMB type) [solid lines] to the Jülich amplitude [dashed lines]

- CMB fit to JM has pole at $1698 - 130\,i$ MeV, simulates missing branch point.

- Inclusion of full analytic structure important to avoid false pole signals in baryon spectroscopy.

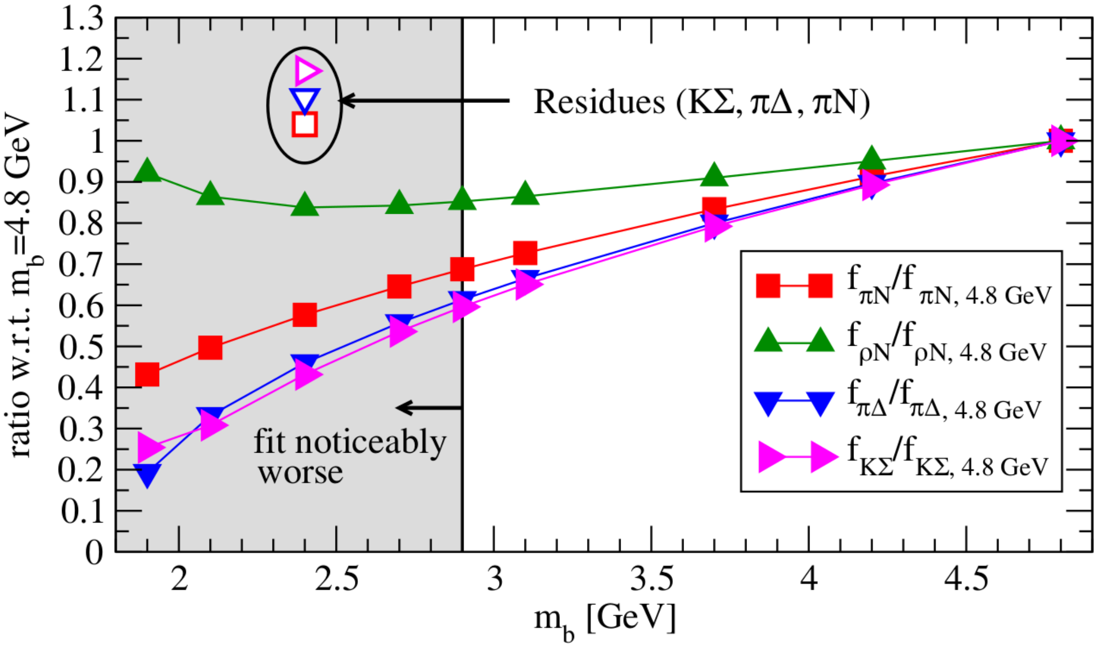
Input parameters and their stability

Eur. Phys. J. A (2013) 49: 44

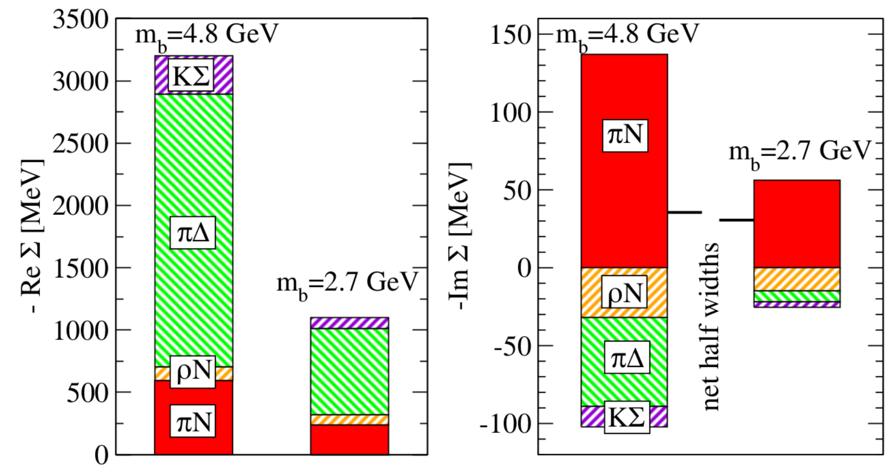


Force bare mass of $\Delta(1600)$ to fixed value; refit full data base

$$\pi N \to \pi N,\ \eta N,\ K\Lambda,\ K\Sigma$$



Self energy:



Field-theoretical approach; TOPT unitarized; implemented on supercomputers.
Example:

$\gamma N \ (\pi N) \rightarrow K\Sigma$