Coupled-channel dynamics for excited hadrons

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Jefferson Lab

Workshop:

Exploring Hadrons with Electromagnetic Probes: Structure, Excitations, Interactions

JLab, Nov. 2-3, 2017

Supported by

With slides from: Bonn-Gatchina, Burkert, Crede, Mai, ...

National Science Foundation

HPC support by JSC grant *jikp07*

JÜLICH FORSCHUNGSZENTRUM

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

Outline

- Quark and hadron degrees of freedom
- Determination of the baryon spectrum and its properties
  - Highlight: Three-body unitarity
  - Coupled-channels global analysis
  - Statistical aspects
- Transition form factors

Degrees of freedom: Quarks or hadrons?

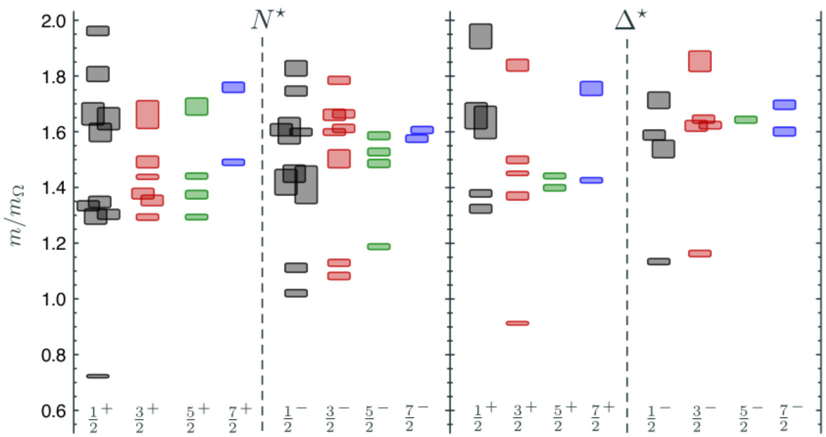
The Missing Resonance Problem

Overview: Int.J.Mod.Phys. E22 (2013) 1330015

- above 1.8 GeV much more states are predicted than observed,

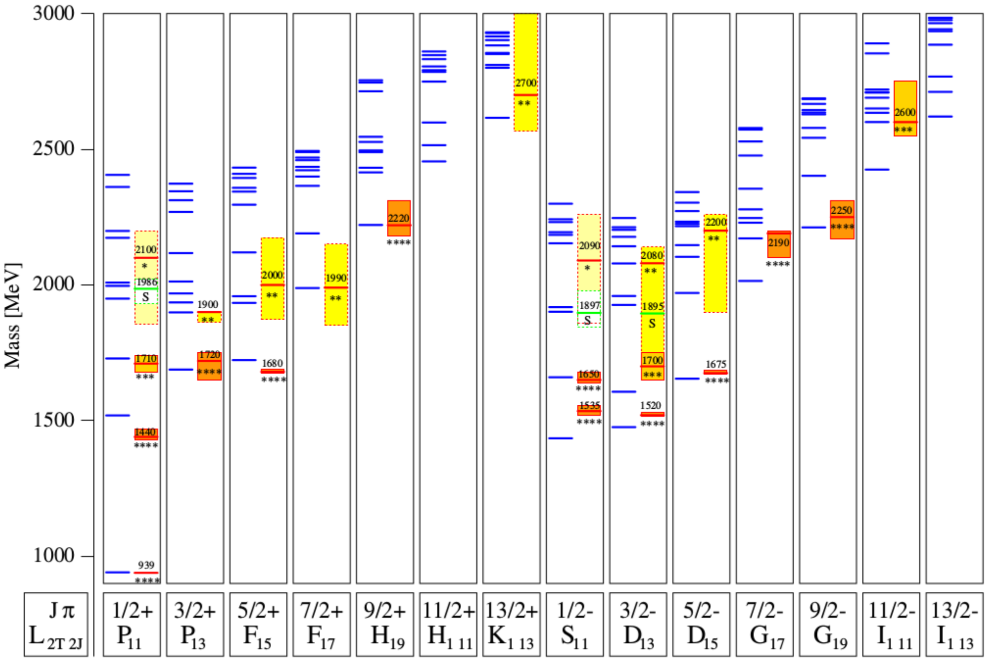
  “Missing resonance problem”

Lattice calculation (single hadron approximation):



[Edwards *et al.*, Phys.Rev. D84 (2011)]

N^* spectrum in a relativistic quark model:

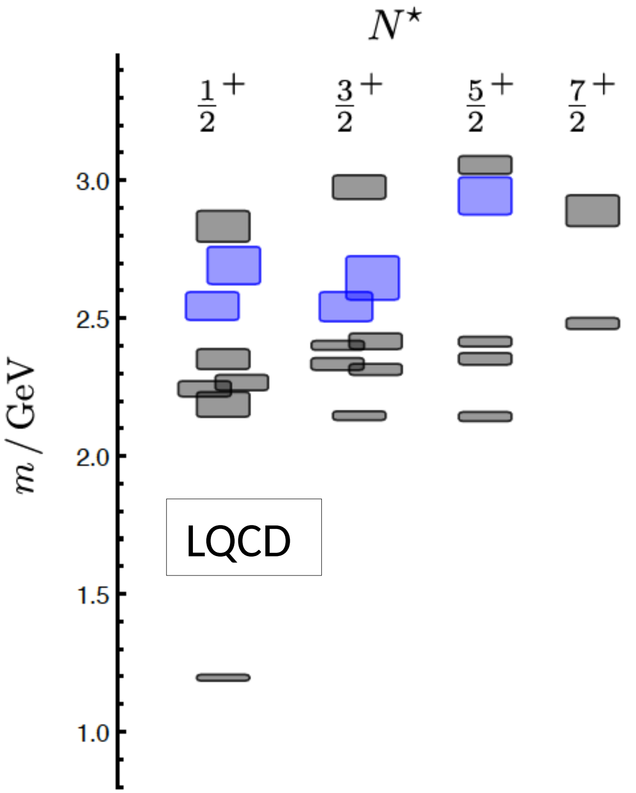


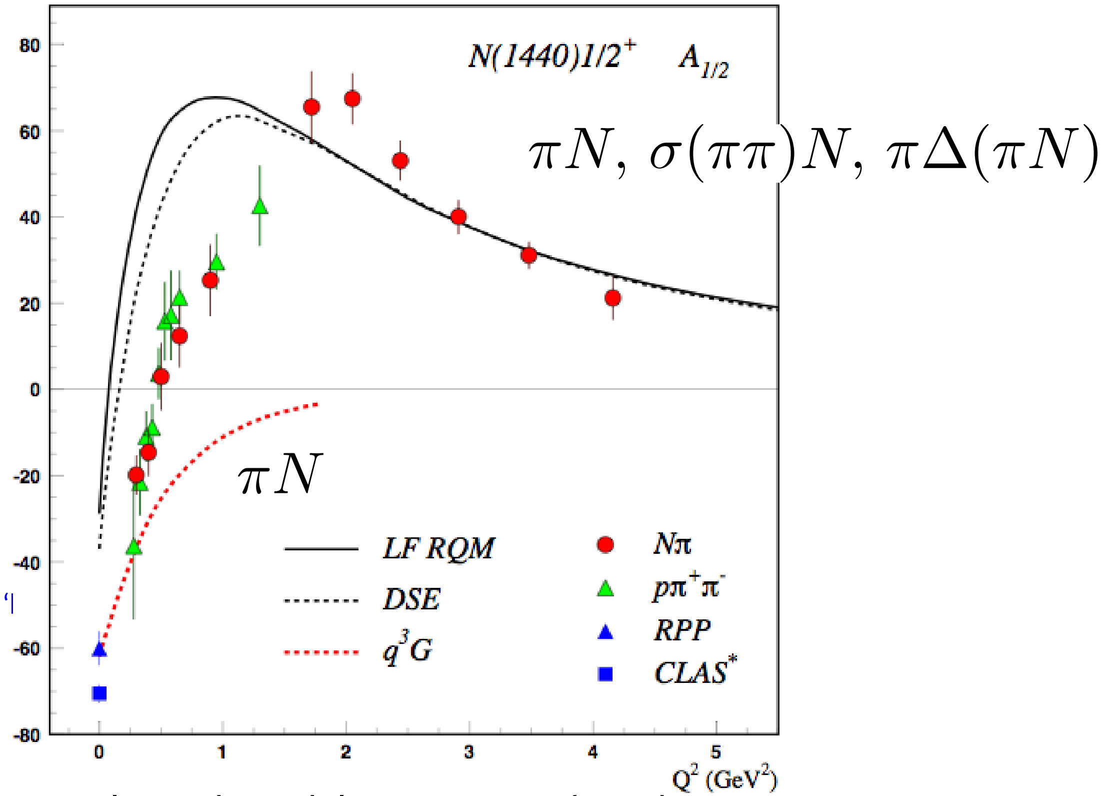
Löring *et al.* EPJ A 10, 395 (2001), experimental spectrum: PDG 2000

- only 15 established N^* states (PDG 2015)
- $\sim$ 48% of the states have **** or *** status (PDG 1982: 58% with **** or ***)

Hybrid Baryons

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





Rel. quark model: Aznauryan (2007)
Dyson-Schwinger: Wilson, Cloet, Chang, C. D. Roberts (2012)

[source: Int. J. Mod. Phys. (2013)]

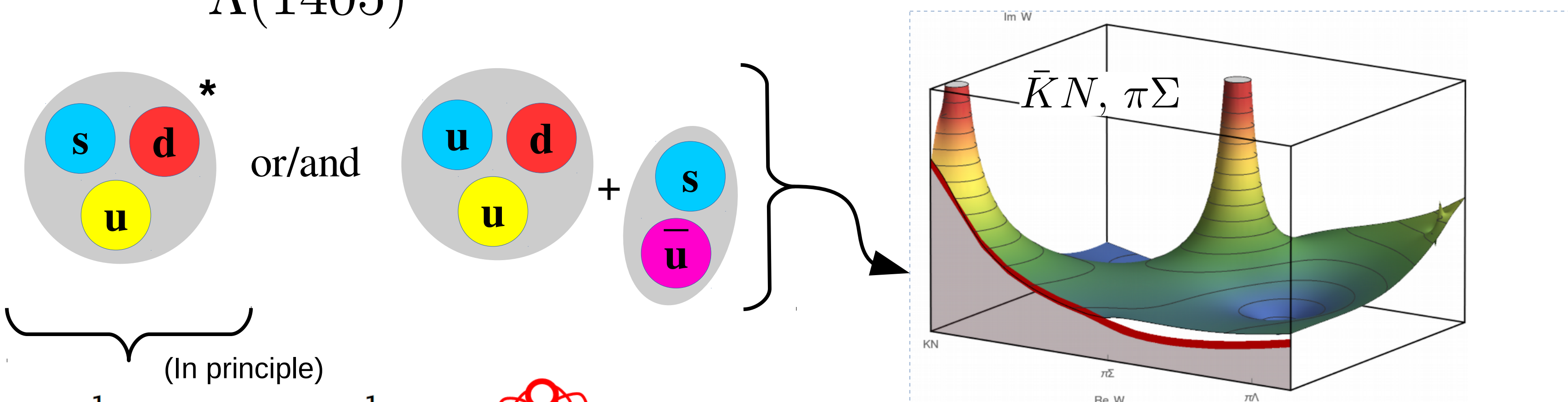
Hybrid states have same J^P values as q^3 baryons. How to identify them? → Measure Q^2 dependence of electro-couplings (CLAS 12)

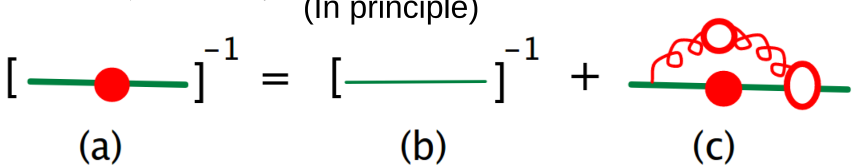
- **QCD** at low energies → *mass generation & confinement*
- Non-perturbative dynamics → rich spectrum of excited states

  Q1: how many are there? (missing resonance problem)

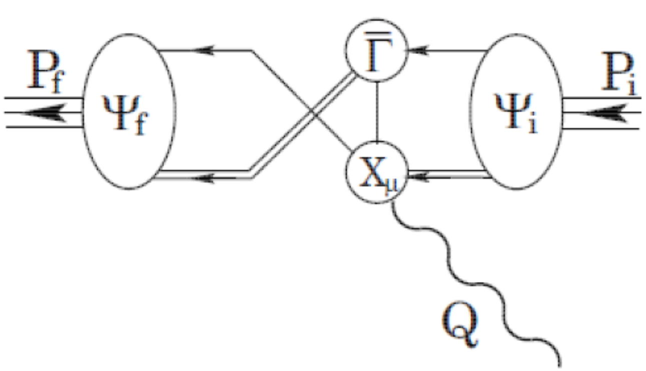
  Q2: what are they? (2-quark/3-quark, hadron molecules, exotics,...)

$\Lambda(1405)$





Oset, Ramos (1998)
Mai, Meißner (2015)
Cieply, M. Mai, Meißner, Smejkal (2016)
On the lattice: M.D., R. Molina (2016)



DSE (Wilson, Cloet, Chang, Roberts)

Impact of data

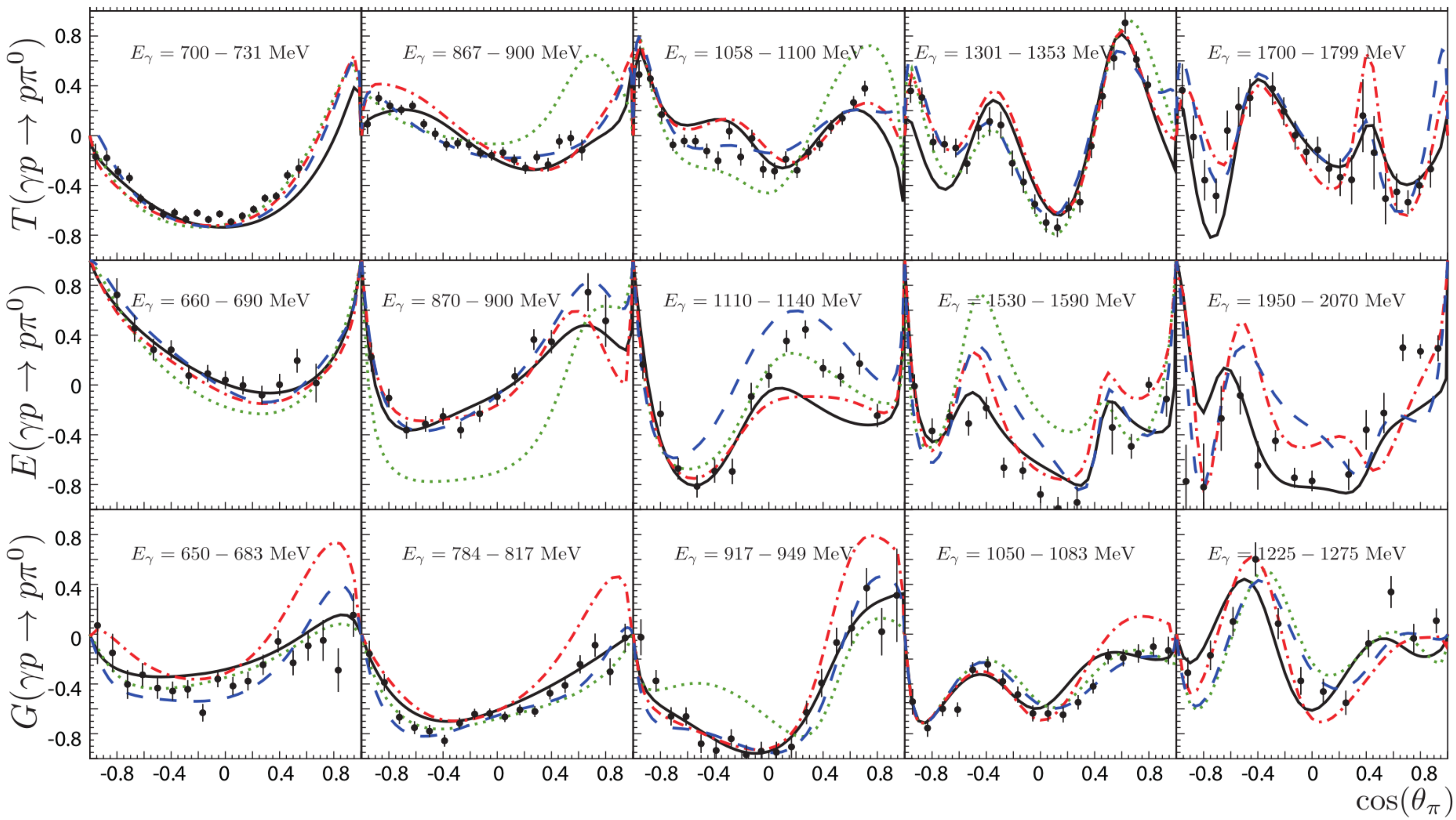
Observable	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
γp→X																
$p\pi^0$	✔	✔	✓		✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓		✔	✓	✓	✓								
$p\eta$	✔	✓	✓		✔	✓	✓	✓								
$p\eta'$	✔	✓	✓		✓	✓	✓	✓								
$K^+\Lambda$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$K^+\Sigma^0$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$p\omega/\phi$	✔	✓	✓		✓	✓	✓	✓	✔ SDME							
$K^{+*}\Lambda$	✔			✔					SDME							
$K^{0*}\Sigma^+$	✔	✓									✓	✓	SDME			
γn→X																
$p\pi^-$	✔	✔			✔	✓	✓									
$p\rho^-$	✓	✓			✓	✓	✓									
$K^-\Sigma^+$	✔	✓			✓	✓	✓									
$K^0\Lambda$	✔	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

[Slide: V. Burkert]

CBELSA/TAPS

Impact of new data

EPJA 52, 284 (2016)

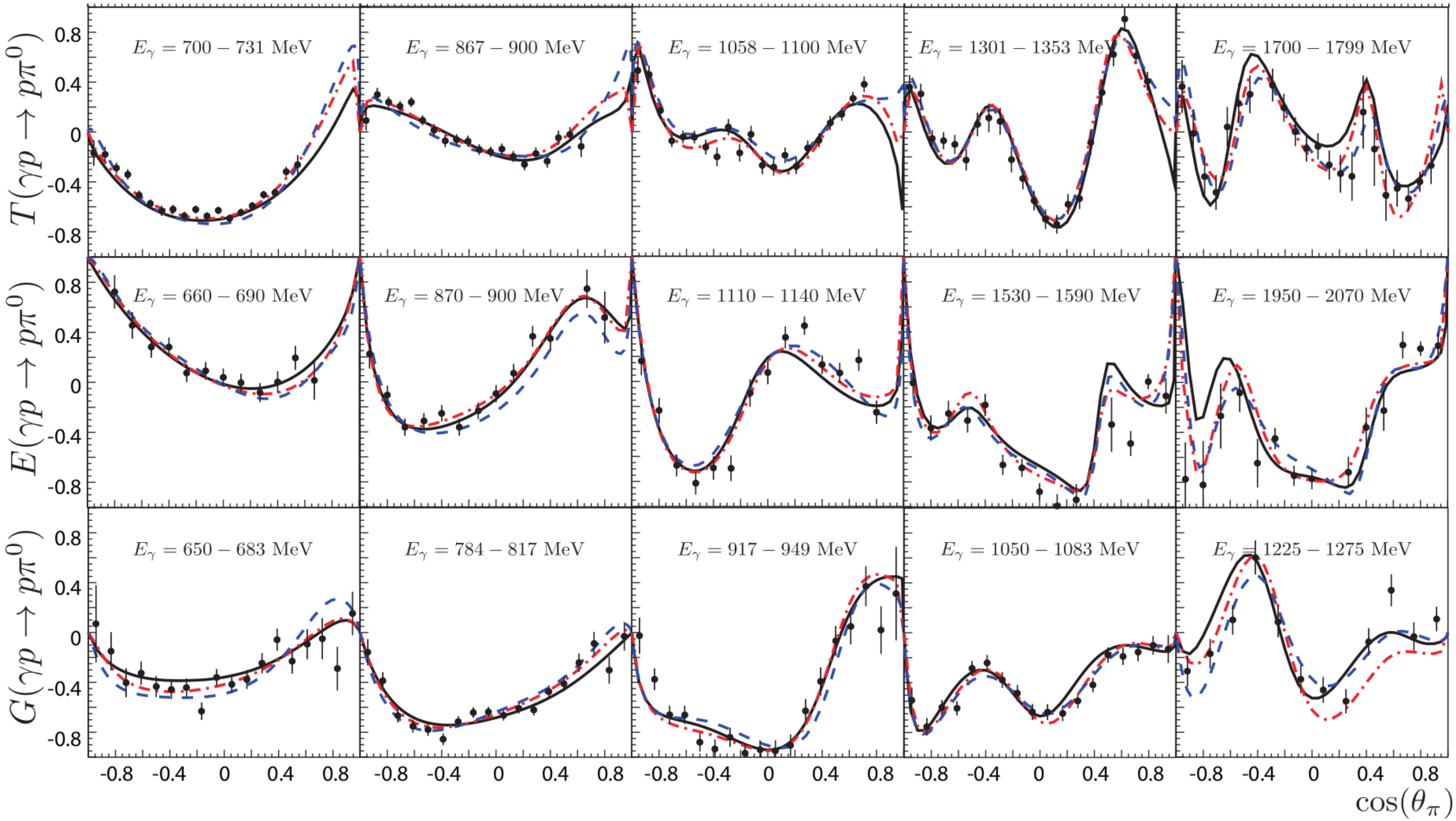


Data: CBELSA/TAPS Collaboration (T: Hartmann et al. PLB 748, 212 (2015) , E: Gottschall et al. PRL 112, 012003 (2014), G: Thiel et al. PRL 109, 102001 (2012), Thiel et al. arXiv:1604.02922)

Predictions: black solid lines: BnGa, red dash-dotted: SAID, blue dashed: JüBo, green dotted: MAID

Impact of new data

EPJA 52, 284 (2016)



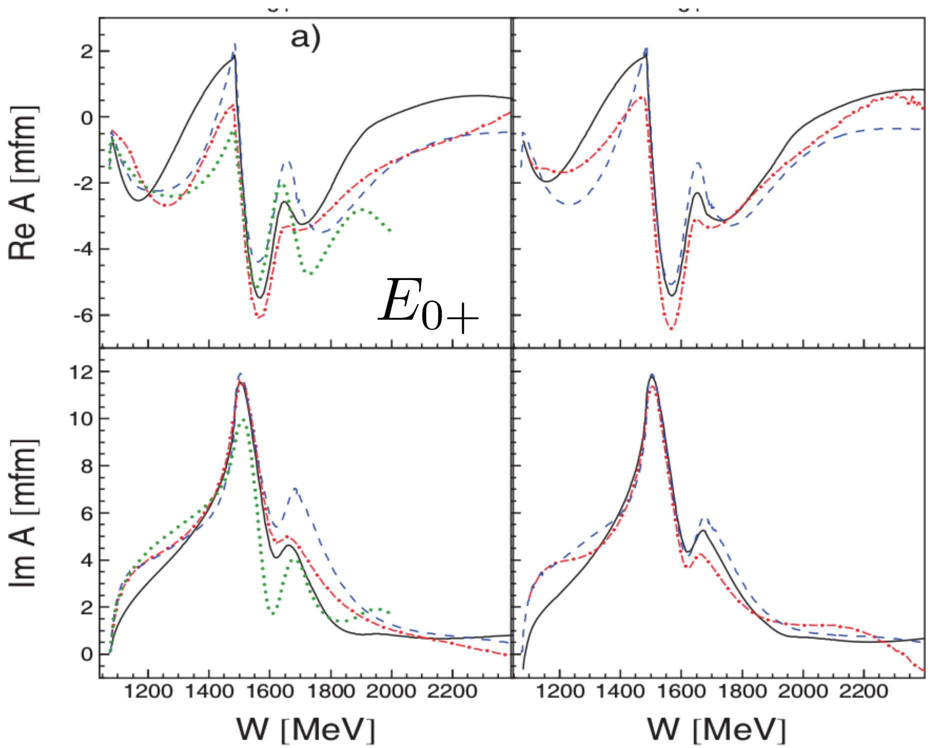
Data: CBELSA/TAPS Collaboration (T: Hartmann et al. PLB 748, 212 (2015) , E: Gottschall et al. PRL 112, 012003 (2014), G: Thiel et al. PRL 109, 102001 (2012), Thiel et al. arXiv:1604.02922)

Fits: black solid lines: BnGa, red dash-dotted: SAID, blue dashed: JüBo

Impact of new data

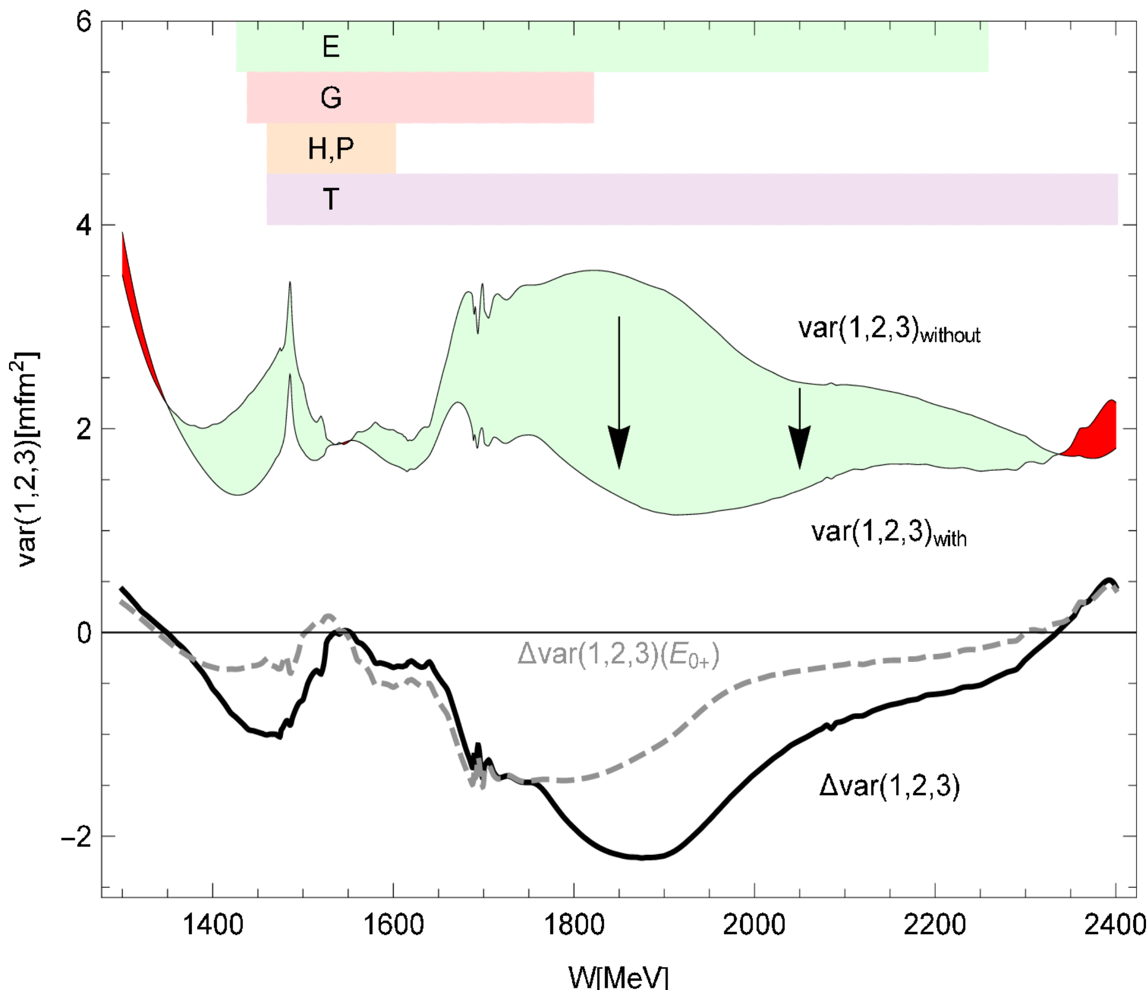
EPJA 52, 284 (2016)

Before After



Julich-Bonn, BnGa, SAID

$$\mathrm{var}(1,2) = \frac{1}{2}\sum_{i=1}^{16}(\mathcal{M}_1(i) - \mathcal{M}_2(i))(\mathcal{M}_1^*(i) - \mathcal{M}_2^*(i)). \quad (31)$$



- Multipole solutions approach each other
- Remaining discrepancies

Three-body unitarity

Excited baryons: Channel space

μ	$J^P =$	$\frac{1}{2}^-$	$\frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{3}{2}^-$	$\frac{5}{2}^-$	$\frac{5}{2}^+$	$\frac{7}{2}^+$	$\frac{7}{2}^-$	$\frac{9}{2}^-$	$\frac{9}{2}^+$
1	πN	S_{11}	P_{11}	P_{13}	D_{13}	D_{15}	F_{15}	F_{17}	G_{17}	G_{19}	H_{19}
2	$\rho N(S=1/2)$	S_{11}	P_{11}	P_{13}	D_{13}	D_{15}	F_{15}	F_{17}	G_{17}	G_{19}	H_{19}
3	$\rho N(S=3/2, \|J-L\|=1/2)$	–	P_{11}	P_{13}	D_{13}	D_{15}	F_{15}	F_{17}	G_{17}	G_{19}	H_{19}
4	$\rho N(S=3/2, \|J-L\|=3/2)$	D_{11}	–	F_{13}	S_{13}	G_{15}	P_{15}	H_{17}	D_{17}	I_{19}	F_{19}
5	ηN	S_{11}	P_{11}	P_{13}	D_{13}	D_{15}	F_{15}	F_{17}	G_{17}	G_{19}	H_{19}
6	$\pi\Delta(\|J-L\|=1/2)$	–	P_{11}	P_{13}	D_{13}	D_{15}	F_{15}	F_{17}	G_{17}	G_{19}	H_{19}
7	$\pi\Delta(\|J-L\|=3/2)$	D_{11}	–	F_{13}	S_{13}	G_{15}	P_{15}	H_{17}	D_{17}	I_{19}	F_{19}
8	σN	P_{11}	S_{11}	D_{13}	P_{13}	F_{15}	D_{15}	G_{17}	F_{17}	H_{19}	G_{19}
9	$K\Lambda$	S_{11}	P_{11}	P_{13}	D_{13}	D_{15}	F_{15}	F_{17}	G_{17}	G_{19}	H_{19}
10	$K\Sigma$	S_{11}	P_{11}	P_{13}	D_{13}	D_{15}	F_{15}	F_{17}	G_{17}	G_{19}	H_{19}

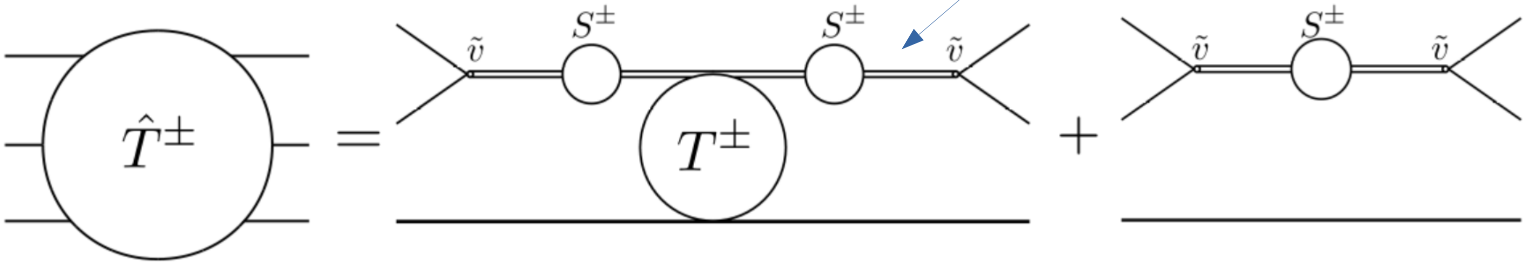
including full 3-body dynamics [Julich-Bonn analysis; ANL-Osaka: similar]

One aspect: Three-Body Unitarity

[**GWU & JPAC** (Mai, Hu, M.D., Pilloni, Szczepaniak)
EPJA (2017), arXiv: 1706.06118 [nucl-th]]

Unitary isobar parametrization

2→ 2 scattering input for isobars ($\pi\pi$)
(not necessarily resonant)

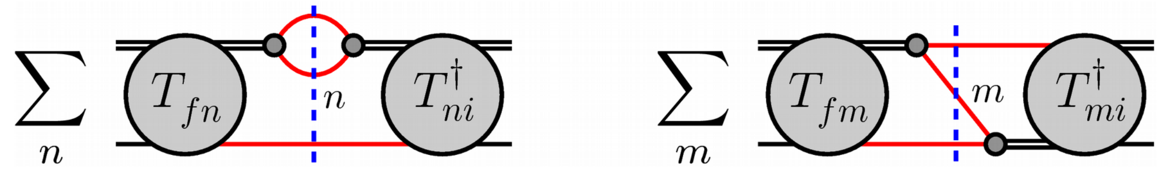


Unitarity

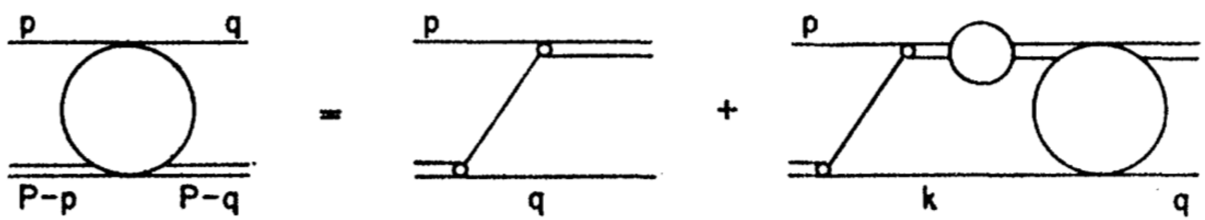
$$\langle q_1, q_2, q_3|(\hat{T}^+ - \hat{T}^-)|p_1, p_2, p_3\rangle = i\int \left(\prod_{\ell=1}^{3} \frac{\mathrm{d}^4 k_\ell}{(2\pi)^4}\,(2\pi)\delta^+(k_\ell^2 - m^2)\right)(2\pi)^4\delta^4\left(P - \sum_{\ell=1}^{3} k_\ell\right) \tag{5}$$

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

unitarity topologies
(oversimplified; 7 in total)



Solution:



- Three-body unitarity induces two-body unitarity of the sub-amplitude

- Solution of 3→3 scattering can be expressed in terms of 2→2 amplitudes:

$$\langle q_1, q_2, q_3 | \hat{T}_c(s) | p_1, p_2, p_3 \rangle = \frac{1}{3!} \sum_{n=1}^{3} \sum_{m=1}^{3} T_{22}(\sigma_{\mathbf{q}_n}) \tilde{T}_{\mathbf{q}_n \mathbf{p}_m}(s) T_{22}(\sigma_{\mathbf{p}_m})$$

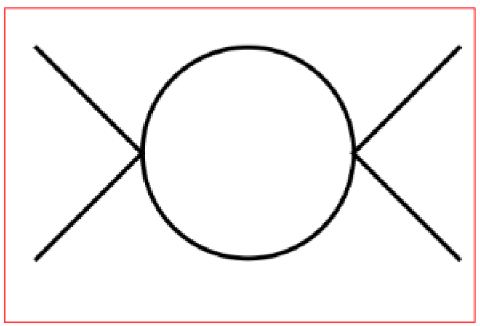
$$\tilde{T}_{\mathbf{q}\mathbf{p}}(s) = \frac{1}{(P-p-q)^2 - m^2} + \int \frac{\mathrm{d}^3 \boldsymbol{\ell}}{(2\pi)^3} \frac{1}{2E_{\boldsymbol{\ell}}} \frac{T_{22}(\sigma_{\boldsymbol{\ell}})}{(P-p-\ell)^2 - m^2} \tilde{T}_{\boldsymbol{\ell}\mathbf{q}}(s)$$

- 3-body equation is of integral type; no K-matrix-type reduction.

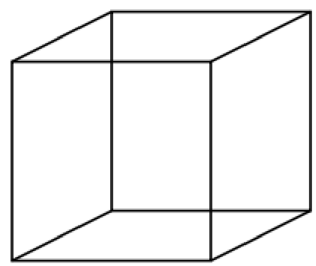
- Three-body unitarity fully dictates the imaginary parts of the amplitude in the physical region.

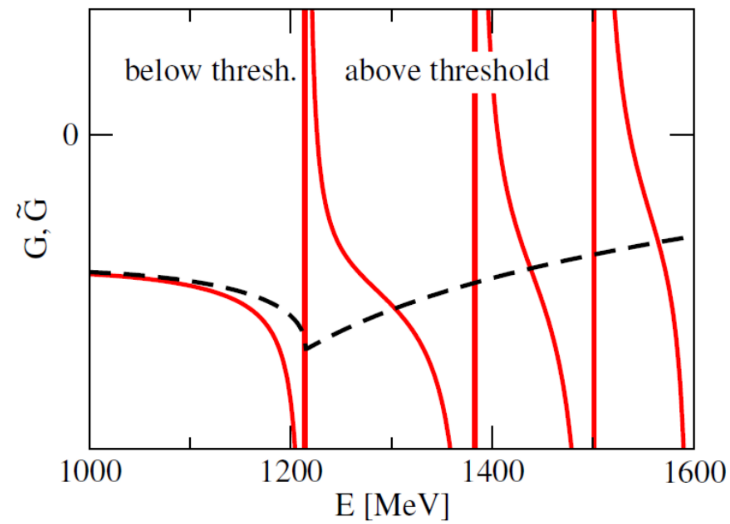
  → dictates the divergences in finite volume.

  → How to relate excited baryons to lattice QCD simulations?

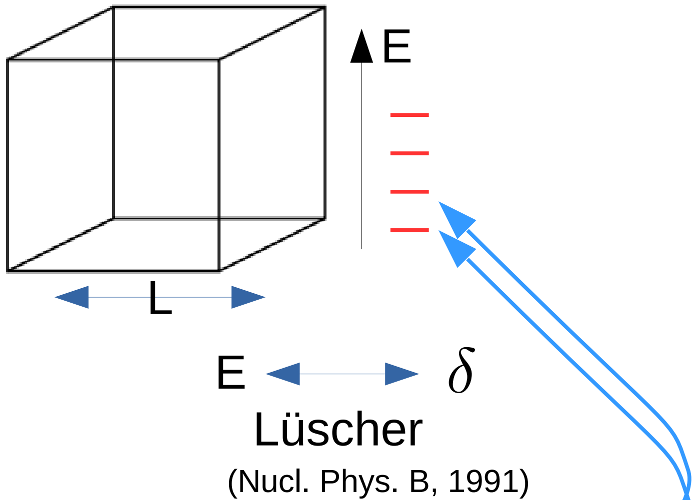


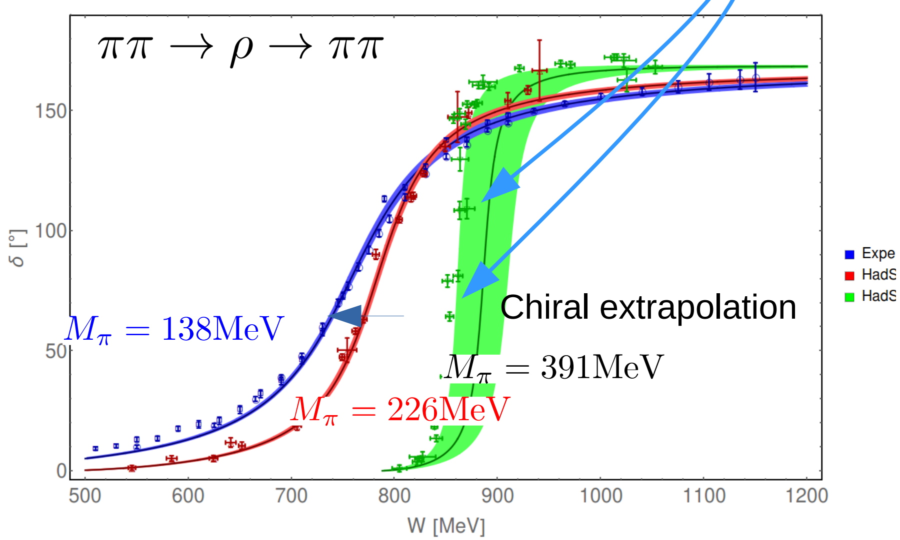
↔

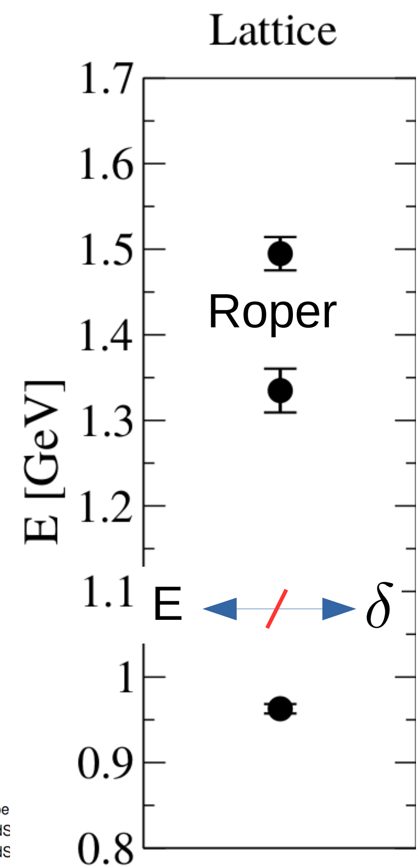




- Roper on lattice from BGR group [Lang et al., Phys.Rev. D95 (2017), 014510]





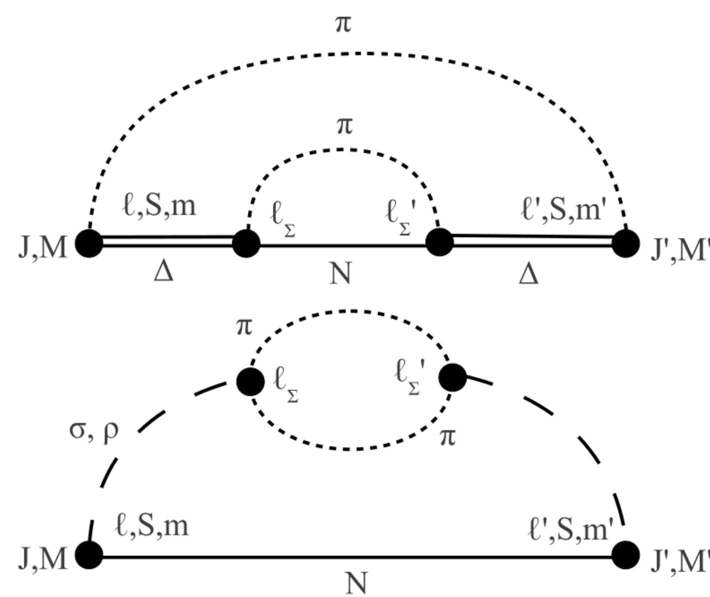


$M_\pi \approx 156\,\text{MeV}$

Channels:

$\pi N, \eta N, \pi\pi N(\sigma N, \pi\Delta, \dots)$

Genuine three-body dynamics



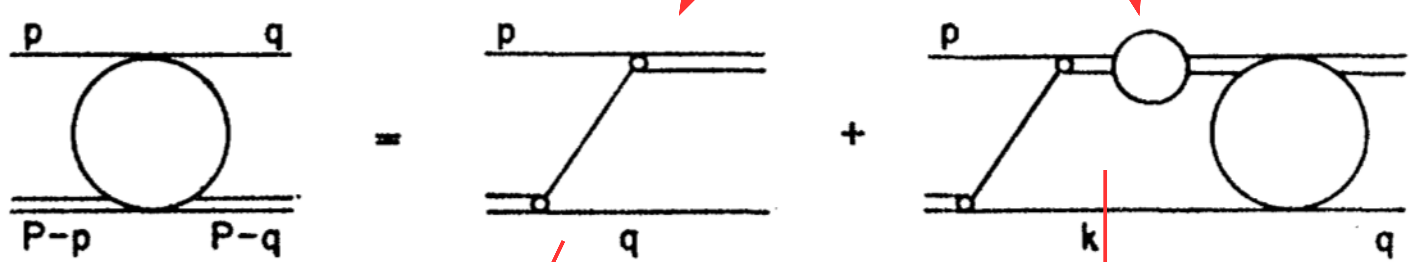
Three-body methods:

- Briceño, Hansen, Sharpe PRD96 (2017)
- Hammer, Pang, Rusetsky, arXiv: 1707.02176,
- ...

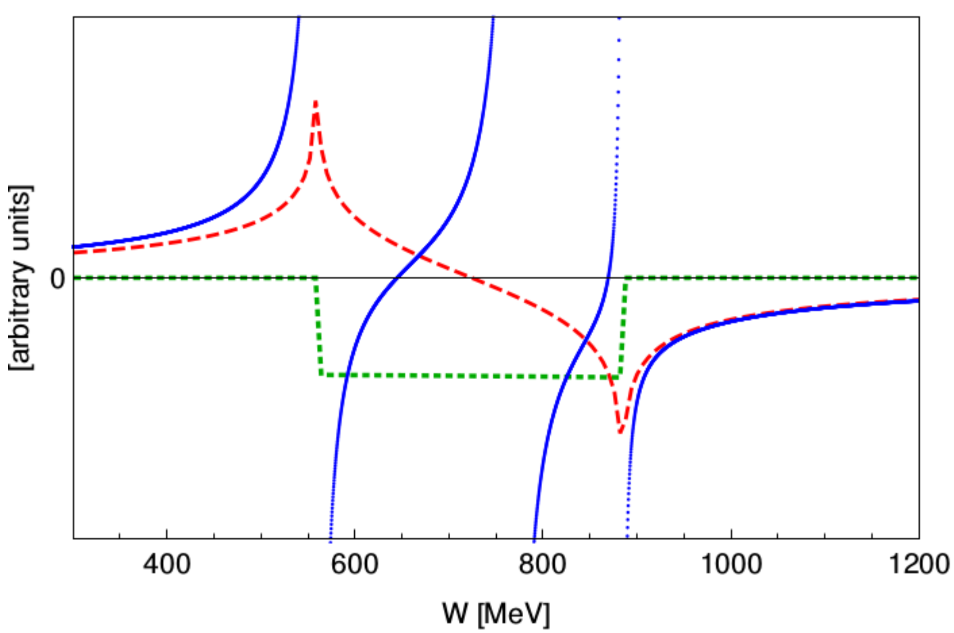
Data: HadronSpectrum (Dudek, PRD 2013,Briceño PRL 2016);
Analysis: M.D., B. Hu, M. Mai, arXiv 1610.10070
See also: Bolton, Briceno, Wilson, Phys.Lett. B757 (2016) 50

M. Mai, M.D., arXiv:1709.08222 [hep-lat]

Power-law finite-volume effects dictated by three-body unitarity

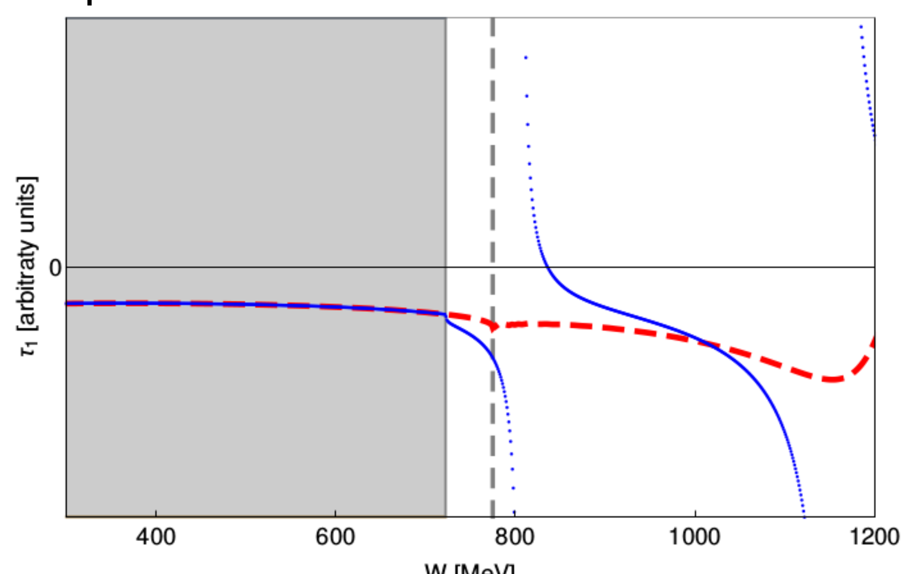


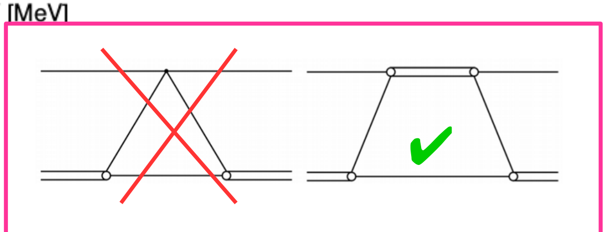
S-wave infinite volume vs. A_1^+ finite volume



$(W = \sqrt{s})$

Tower of boosted $2 \to 2$ amplitudes to implement 3-body quantization condition





Phenomenology

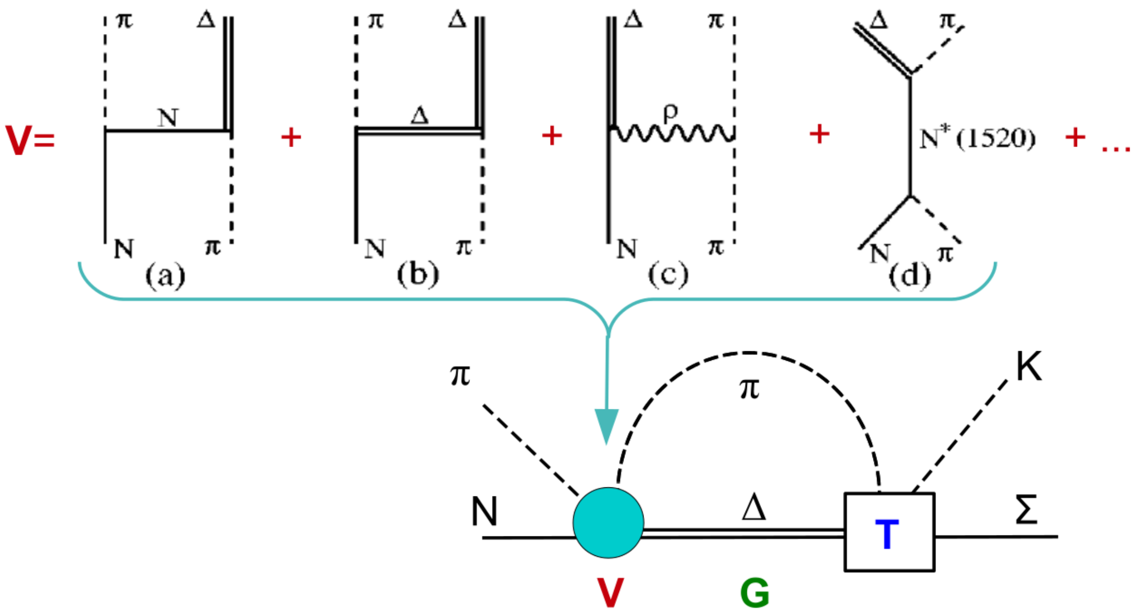
The Julich-Bonn Dynamical Coupled-Channel Approach

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

Jülich-Bonn approach (2)

- **simultaneous** fit of $\gamma p \to \pi^0 p$, $\pi^+ n$, ηp, $K^+\Lambda$ & $\pi N \to \pi N$, ηN, $K\Lambda$, $K\Sigma$
- $\sim$ 40.000 data points, $\sim$ 500 free parameters
  ↳ fit with JURECA supercomputer: parallelization in energy ($\sim$ 300 - 400 processes)

Kaon-photoproduction

Measurement of **recoil polarization** easier due to self-analysing decay of hyperons

→ more recoil and beam-recoil data available

→ possibility of finding new, so far missing states? (**"missing resonances problem"**)

N(1440) PHOTON DECAY AMPLITUDES AT THE POLE

N(1440) → $p\gamma$, helicity-1/2 amplitude $A_{1/2}$

MODULUS ($GeV^{-1/2}$)	PHASE (°)	DOCUMENT ID		TECN	COMMENT
-0.044 ± 0.005	-40 ± 8	SOKHOYAN	15A	DPWA	Multichannel
$-0.054^{+0.004}_{-0.003}$	5^{+2}_{-5}	ROENCHEN	14	DPWA	

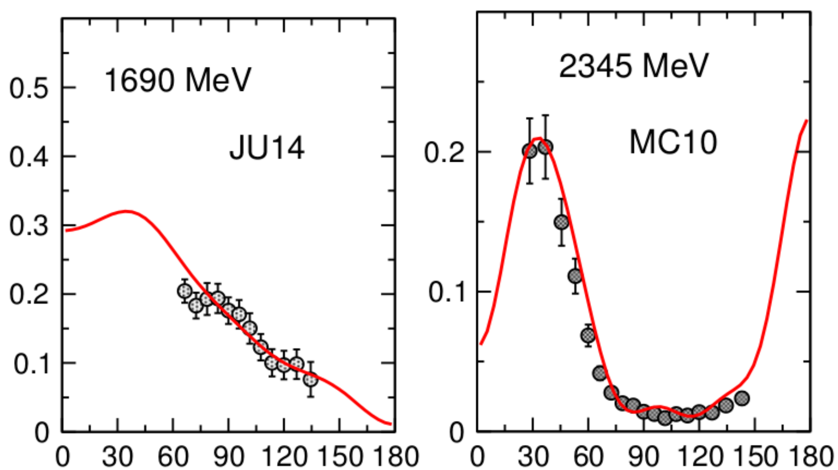
Preliminary: $K^+\Lambda$ photoproduction in the JüBo model

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

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

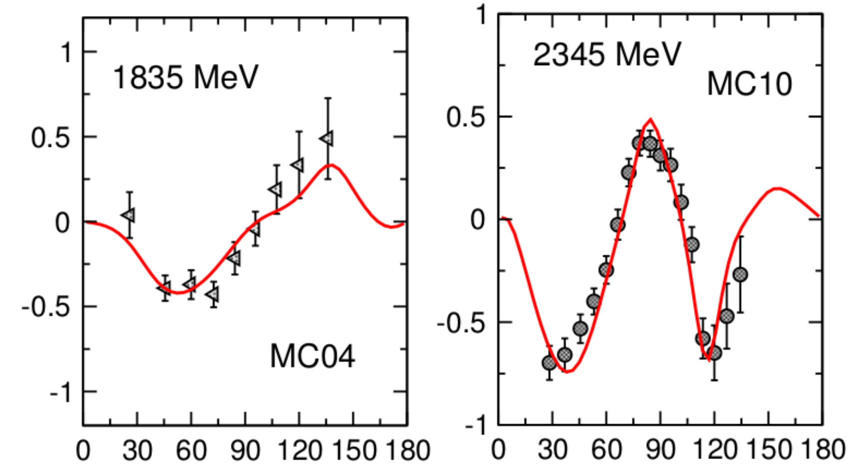
D. Rönchen et al., in progress

- Differential cross section



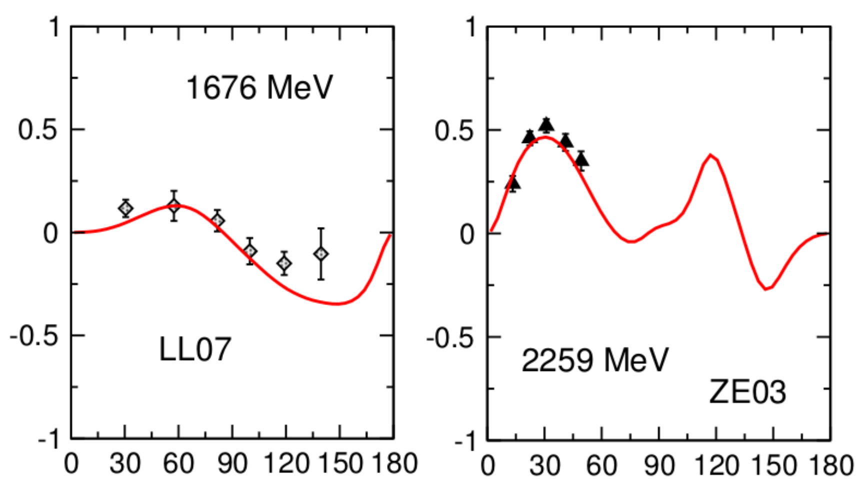
JU14: Jude PLB 735 (2014), MC10: McCracken PRC 81 (2010)

- Recoil polarization



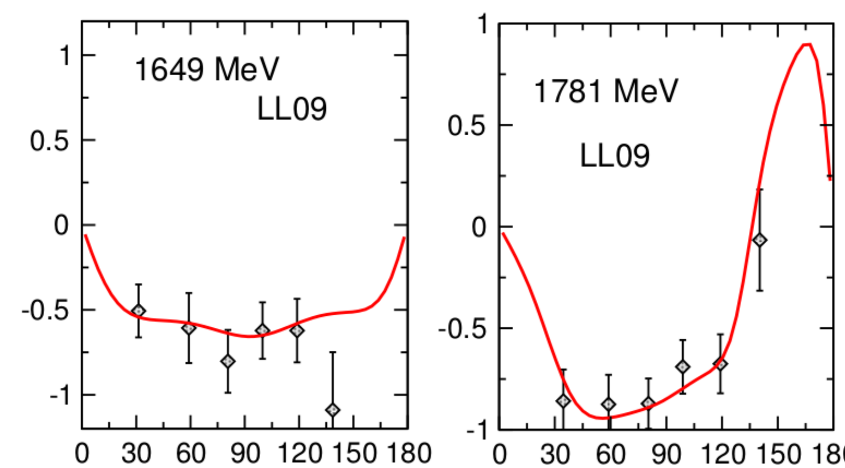
MC04: McNabb PRC 69 (2004), MC10: McCracken PRC 81 (2010)

- Beam asymmetry



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

- Target asymmetry



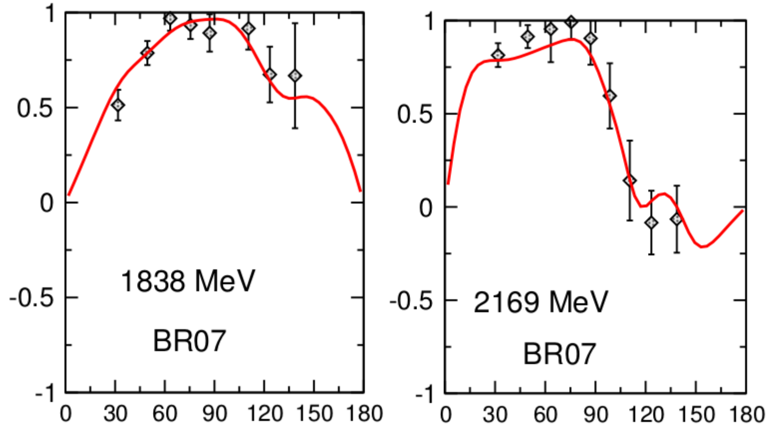
LL09: Lleres EPJA 39 (2009)

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 , $K\Lambda$, $K\Sigma$

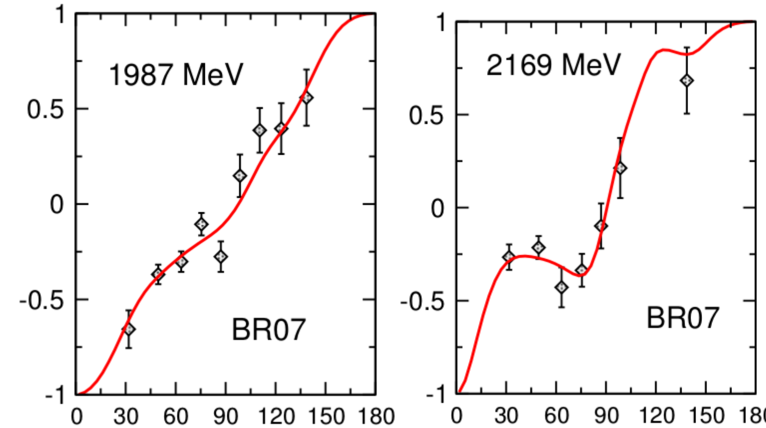
$\gamma p \to K^+\Lambda$:

- C_x



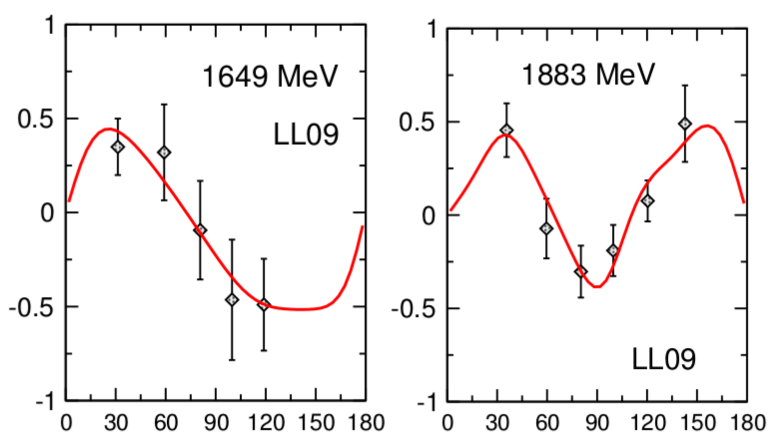
BR07: Bradford PRC 75 (2007)

- C_z



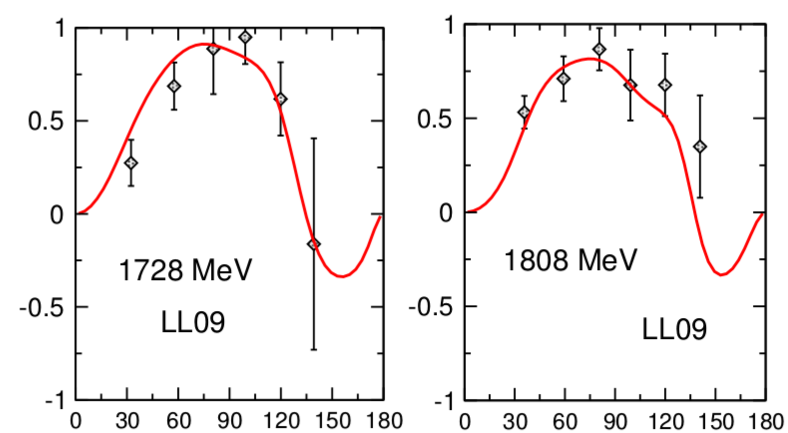
BR07: Bradford PRC 75 (2007)

- O_x



LL09: Lleres EPJA 39 (2009)

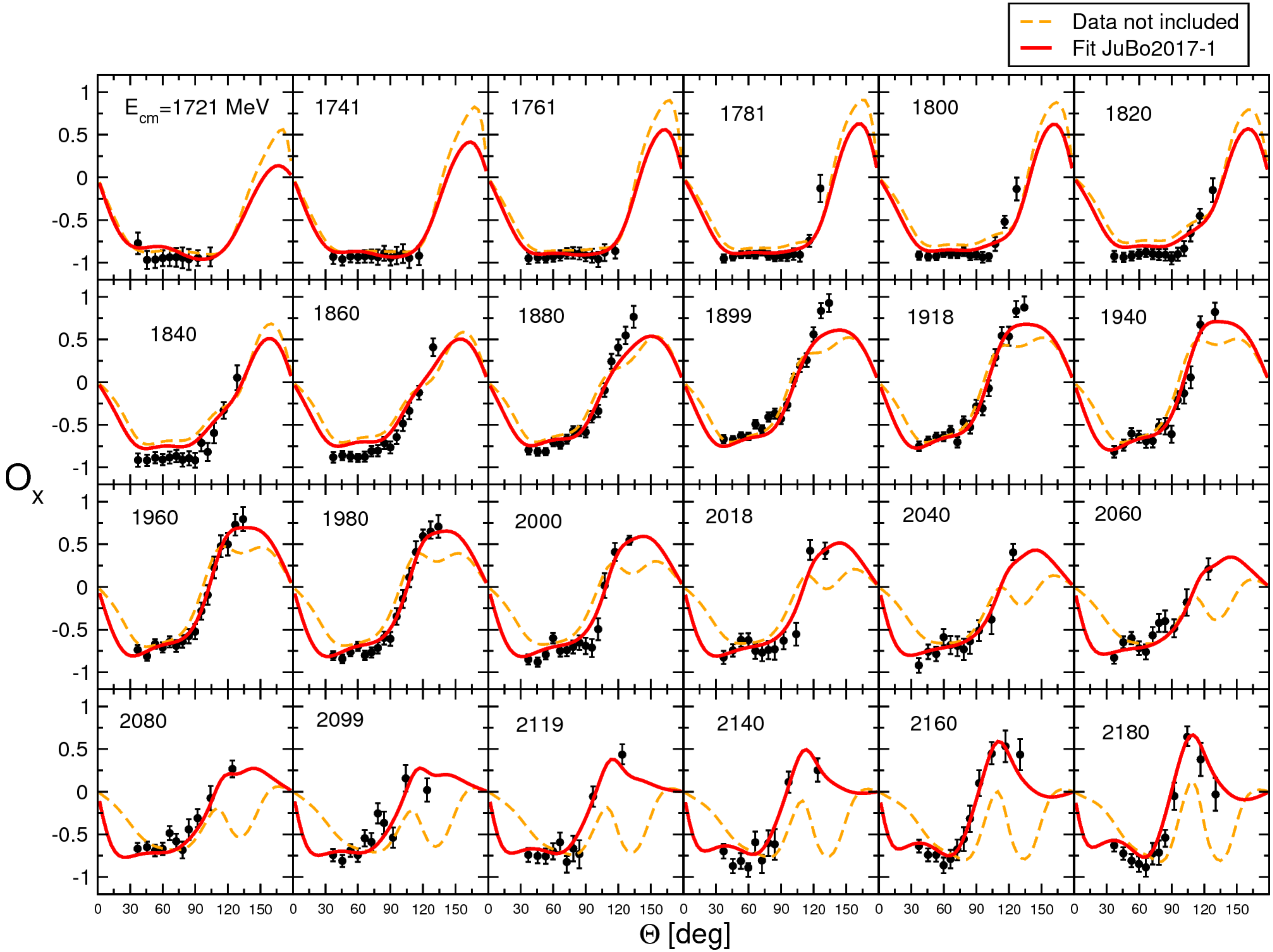
- O_z



LL09: Lleres EPJA 39 (2009)

Introducing a P_{13}*(1900)* resonance improves fit significantly, as well.

Influence of new CLAS data (Paterson *et al.* Phys. Rev. C 93, 065201 (2016))



Resonance content (preliminary)

Previous JüBo analyses of photoproduction:

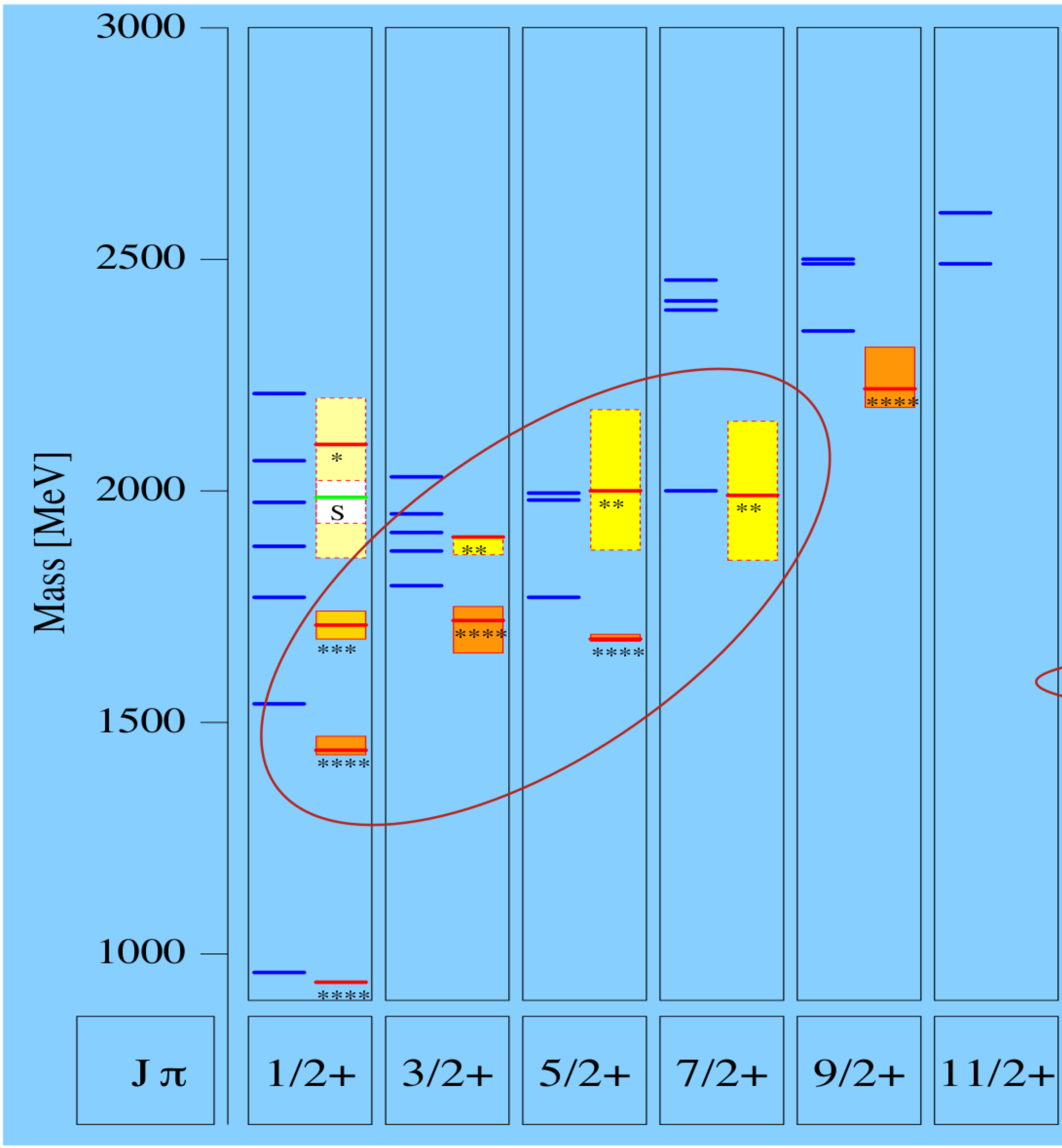
- resonances included in studies of pion-induced reactions sufficient to describe $\gamma p \to \pi N$, ηN
- no additional dynamically generated poles

Inclusion of $\gamma p \to K^+\Lambda$ in JüBo ("JuBo2017-1"): 3 additional states

	z_0 [MeV]	$\frac{\Gamma_{\pi N}}{\Gamma_{tot}}$	$\frac{\Gamma_{\eta N}}{\Gamma_{tot}}$	$\frac{\Gamma_{K\Lambda}}{\Gamma_{tot}}$	$\frac{\Gamma_{K\Sigma}}{\Gamma_{tot}}$	
$N(1900)3/2^+$	$1923 - i\,108.4$	1.5 %	0.78 %	2.99 %	69.5 %	
$N(2060)5/2^-$	$1924 - i\,100.4$	0.35 %	0.15 %	13.47 %	27.02 %	
$\Delta(2190)1/2^+$	$2191 - i\,103.0$	33.12 %			3.78 %	
($N(1730)1/2^-$	$1731 - i\,78.73$	1.86 %	1.30 %	56.43 %	1.11 %	)
($N(1750)1/2^-$	$1750 - i\,158.8$	1.80 %	0.29 %	0.57 %	5.63 %	)

- $N(1900)3/2^+$: s-channel resonances, seen in many other analyses of kaon photoproduction (BnGa), 3 stars in PDG
- $N(2060)5/2^-$: dynamically generated, 2 stars in PDG, seen e.g. by BnGa
- $\Delta(2190)3/2^+$: dyn. gen., no equivalent PDG state
- $N(1730)1/2^-$, $N(1750)1/2^-$: dyn. gen., no equivalent PDG state
  previous JüBo solutions: **one** dyn. $N(1750)1/2^-$ with $z_0 \sim 1745 - i\,155$ MeV

Spectrum of N* resonances



N^*	J^P $(L_{2I,2J})$	2010	2014
$N(1440)$	$1/2^+$ (P_{11})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****
$N(1650)$	$1/2^-$ (S_{11})	****	****
$N(1675)$	$5/2^-$ (D_{15})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****
$N(1685)$			*
$N(1700)$	$3/2^-$ (D_{13})	***	***
$N(1710)$	$1/2^+$ (P_{11})	***	***
$N(1720)$	$3/2^+$ (P_{13})	****	****
$N(1860)$	$5/2^+$		**
$N(1875)$	$3/2^-$		***
$N(1880)$	$1/2^+$		**
$N(1895)$	$1/2^-$		**
$N(1900)$	$3/2^+$ (P_{13})	**	***
$N(1990)$	$7/2^+$ (F_{17})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**
~~$N(2080)$~~	D_{13}	**	
~~$N(2090)$~~	S_{11}	*	
$N(2040)$	$3/2^+$		*
$N(2060)$	$5/2^-$		**
$N(2100)$	$1/2^+$ (P_{11})	*	*
$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^-$ (G_{17})	****	****
~~$N(2200)$~~	D_{15}	**	

- Most new resonances by Bonn-Gatchina group;
- Many from kaon photoproduction

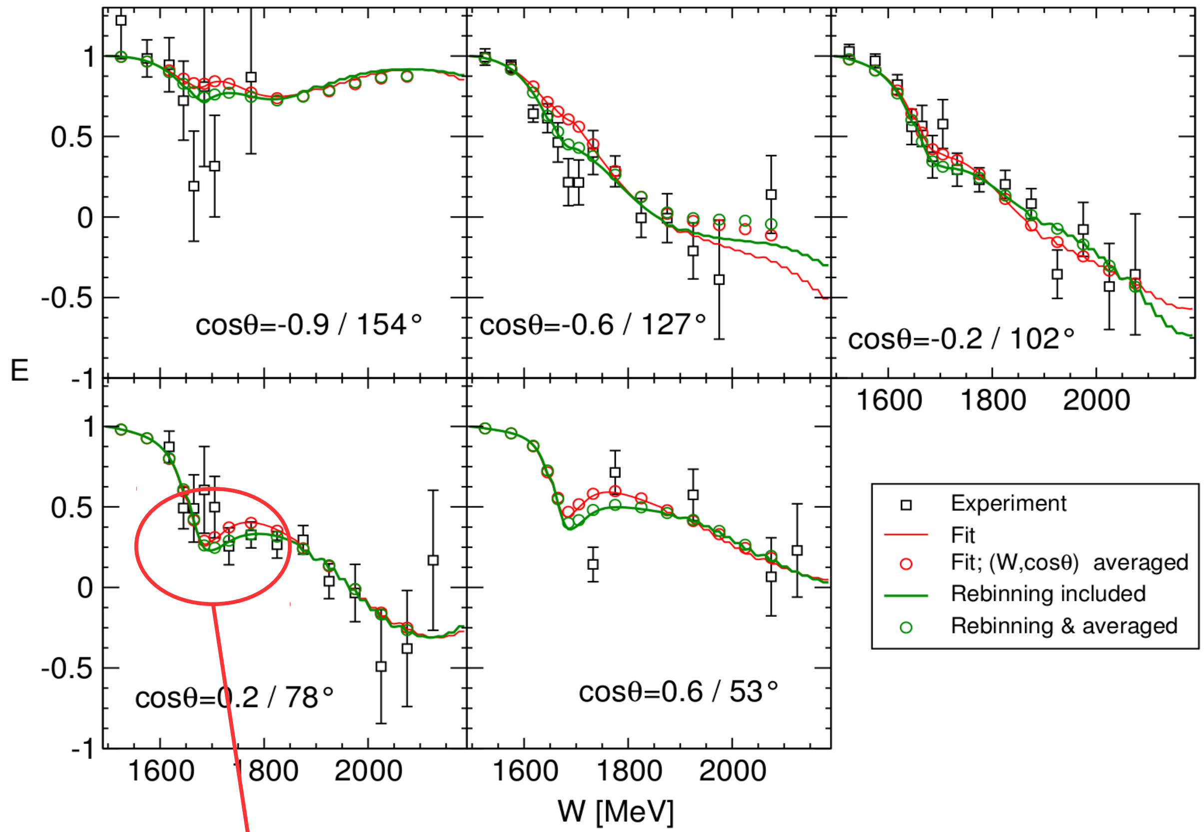
[Slide: V. Crede/Nstar 2017, slight modifications]

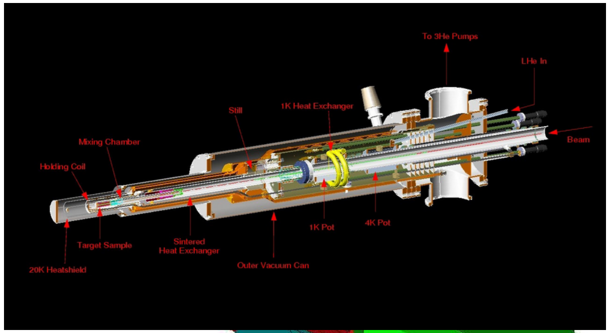
[See also: Crede, Roberts, Rep. Prog. Phys. 76 (2013)]

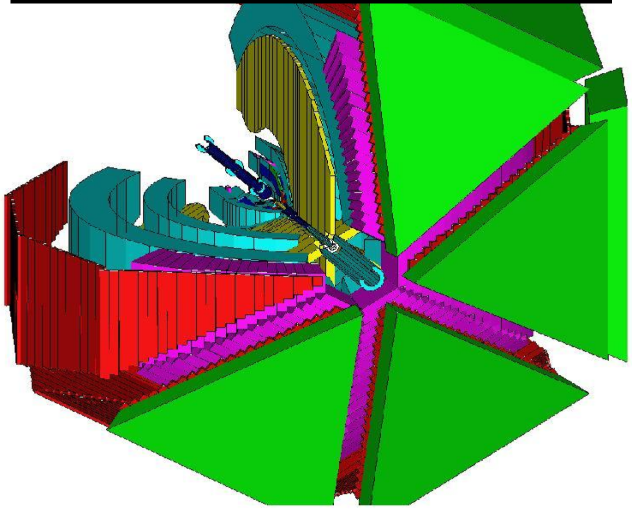
FROST/CLAS

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

- First-ever measurement of observable *E* in η photo-production, enabled through the <u>FROST</u> target





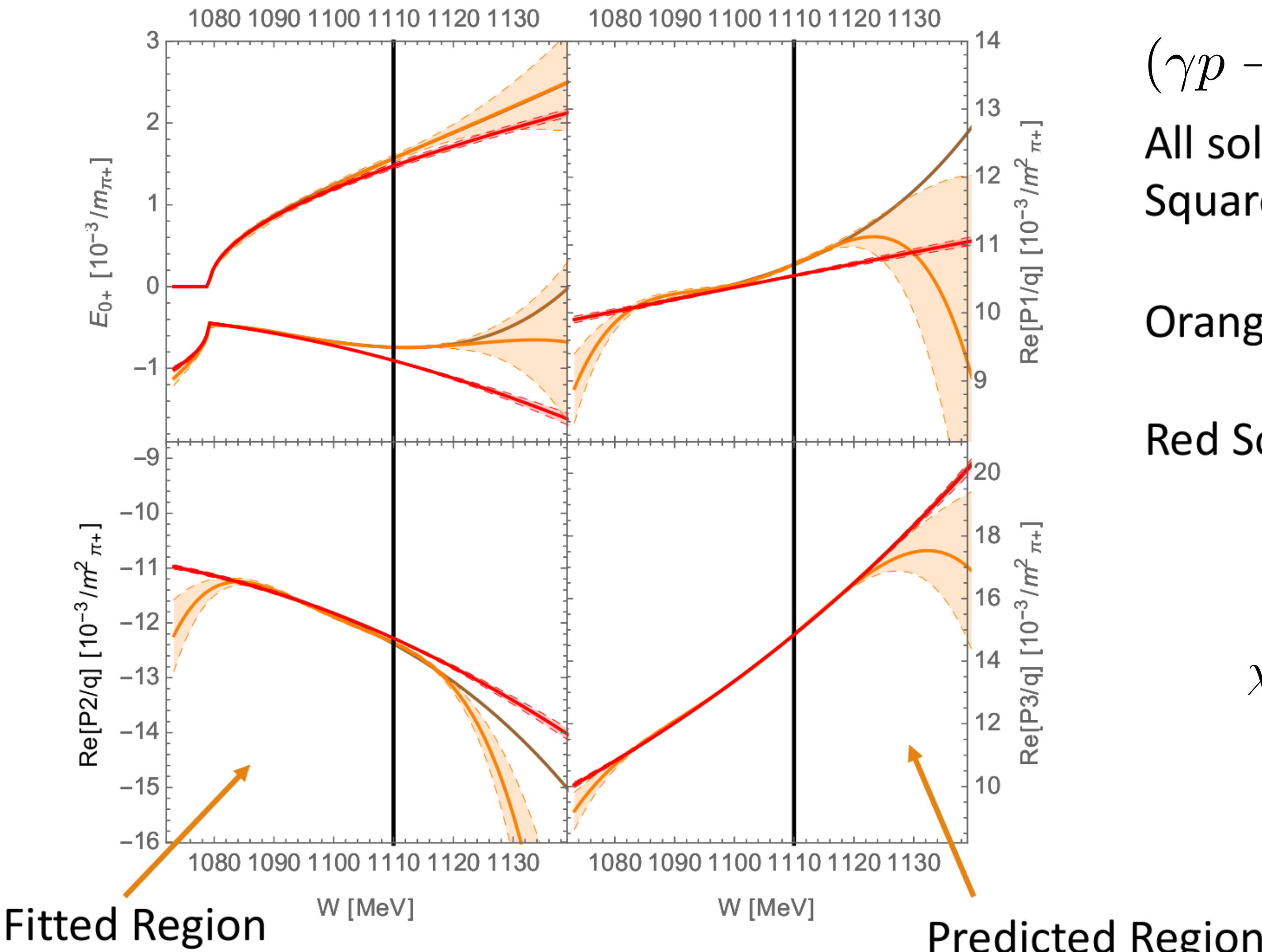


Is this a new narrow baryonic resonance?
→ Conventional explanation in terms of interference effects.

Statistical Aspects

Different models can give satisfactory fits. How do we determine the optimal one?

[J. Landay, M.D., C. Fernandez, B. Hu. R. Molina, PRC 2017]



$(\gamma p \to \pi^0 p)$

All solutions pass Pearson's Chi-Squared test.

Orange Solution- 23 parameters

Red Solution – 13 parameters

LASSO:

$$\chi^2 = \chi^2_{\text{stat.}} + \lambda \sum_i |a_i|$$

Data: MAMI [Hornidge PRL 111 (2013)] [PLB 750 (2015)]

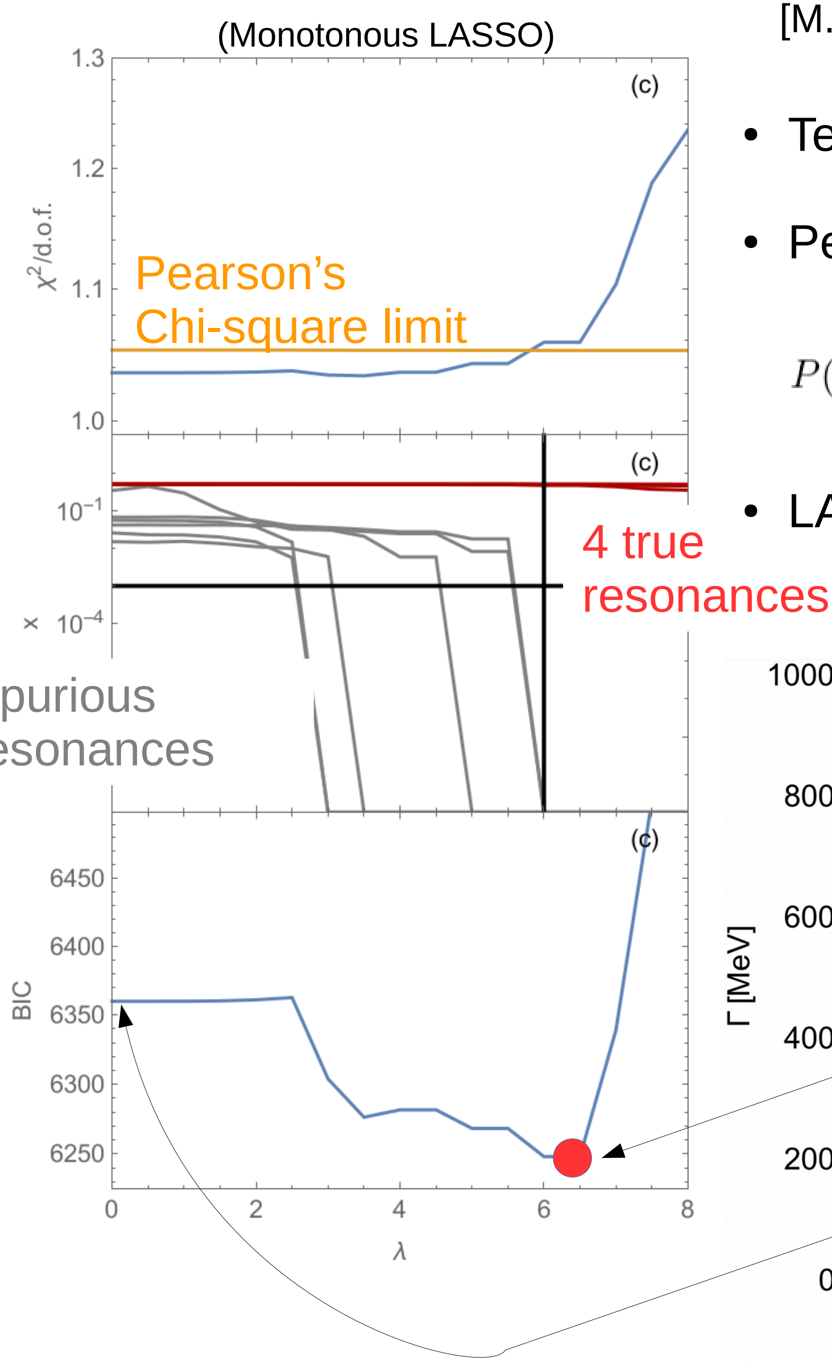
Resonance selection $(K^- p \to K\Xi)$

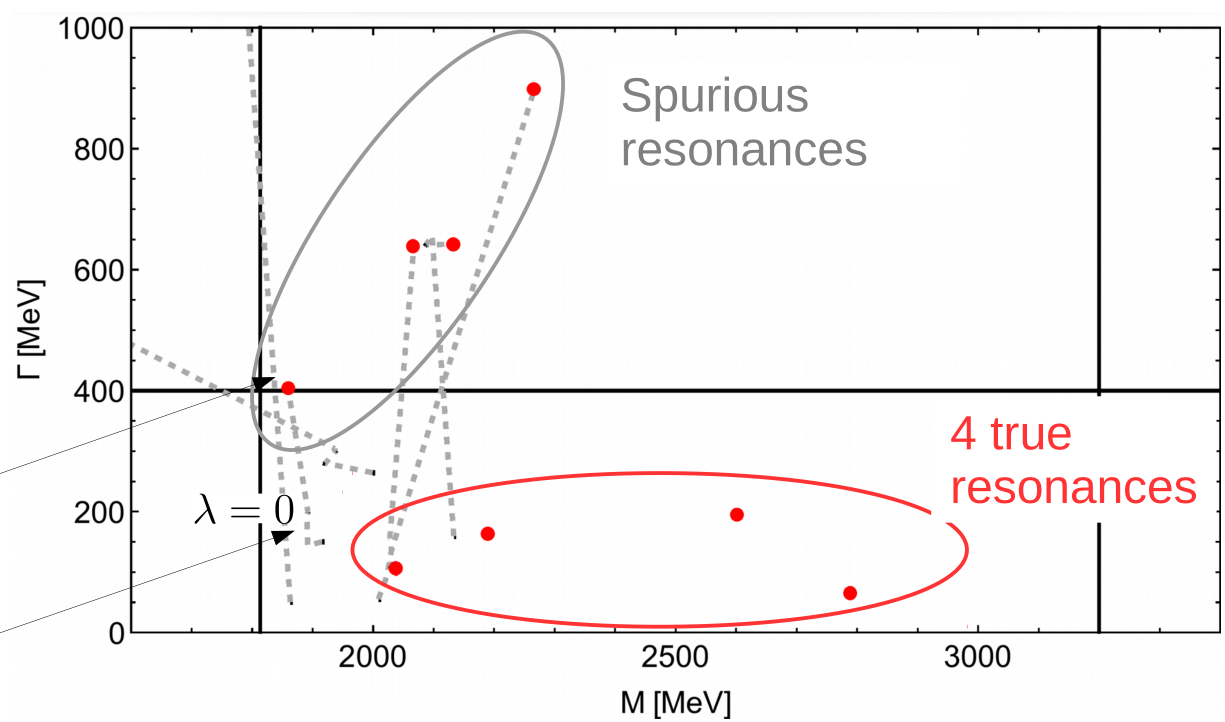
[M.D., J. Landay, H. Haberzettl, M. Mai, K. Nakayama, in progress]

- Ten partial waves; 10 resonances in Ansatz
- Penalty:

$$P(\lambda) = \lambda^5 \sum_{i=0}^{9} \int_{m_K+m_\Xi}^{3200} \frac{\partial^2}{\partial W^2} \left(\left| -x_i\, e^{i\Phi_i} \frac{\Gamma_i}{2(W - M_i + i\frac{\Gamma_i}{2})} \right|^2 \right) dW$$

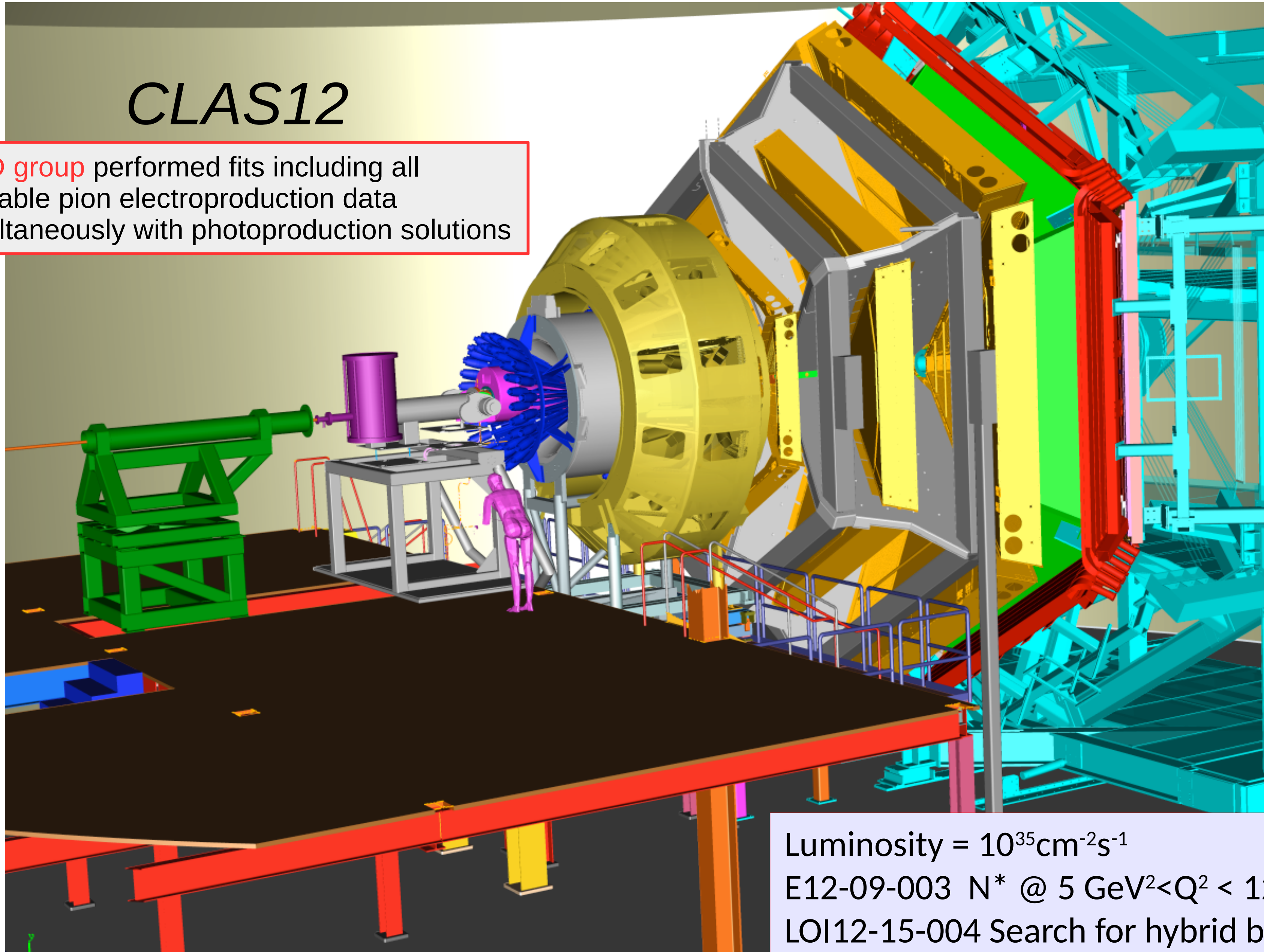
- LASSO picks the 4 correct ones





Form factors

Transition form factors @ CLAS 12



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

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

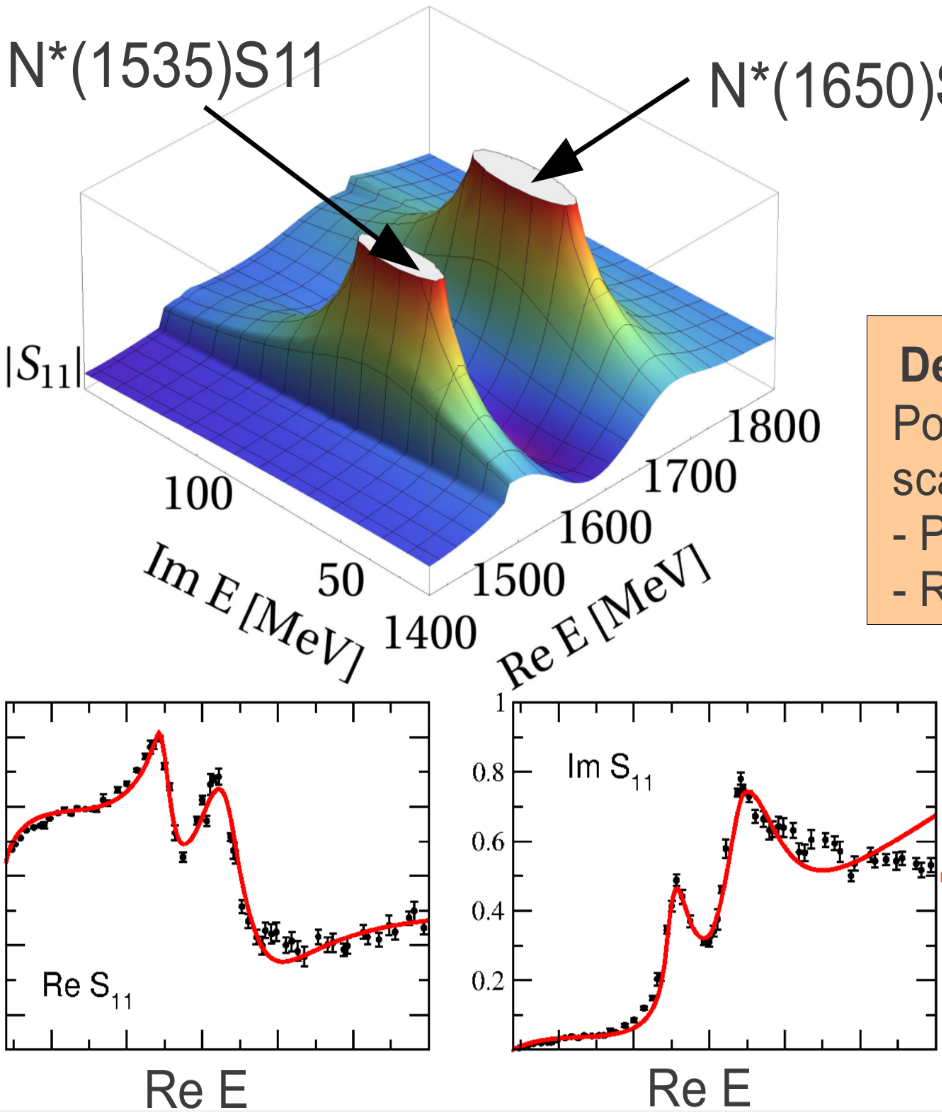
E12-09-003 N* @ 5 $GeV^2 < Q^2 < 12\ GeV^2$

LOI12-15-004 Search for hybrid baryons

E12-06-108A KY Electroproduction with CLAS

Transition Form Factors at the Pole

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



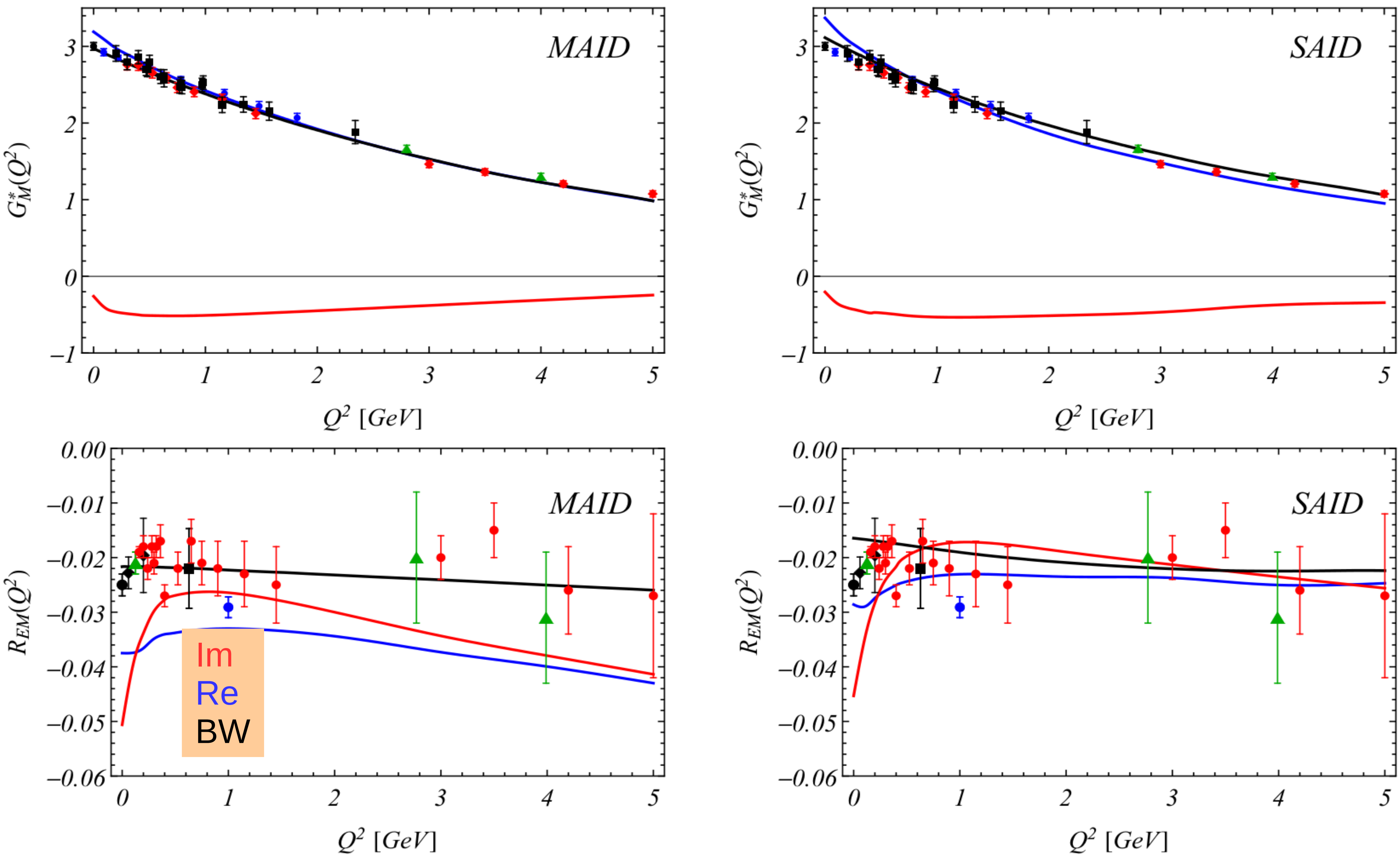
Definition of a resonance:
Pole in the complex plane of the scattering energy E (≡ z ≡ W);
- Pole position ("mass & width")
- Residues ("branching ratios")

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)]

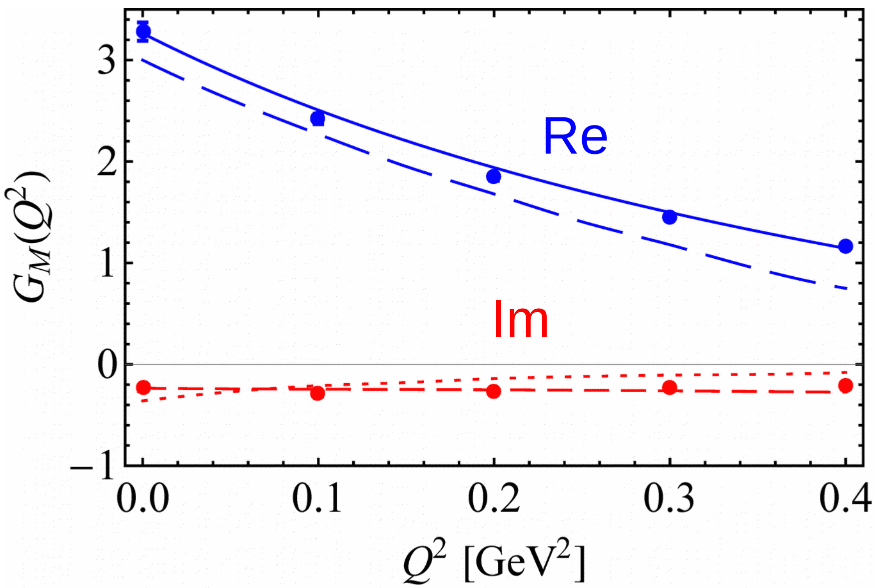
Said/Maid Results for $\Delta(1232)3/2^+$

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



“Data points”: Aznauryan *et al.*

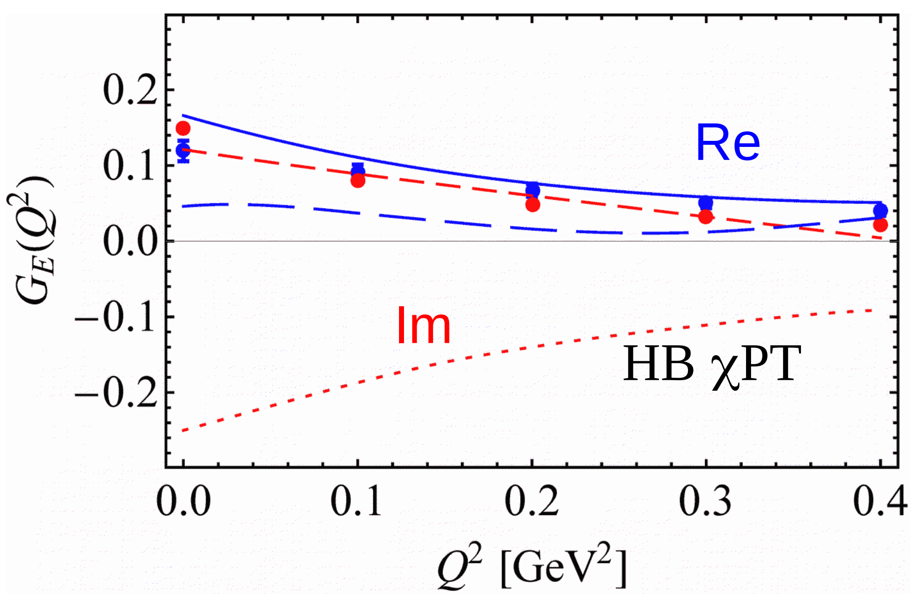
Comparison with ChPT at the pole

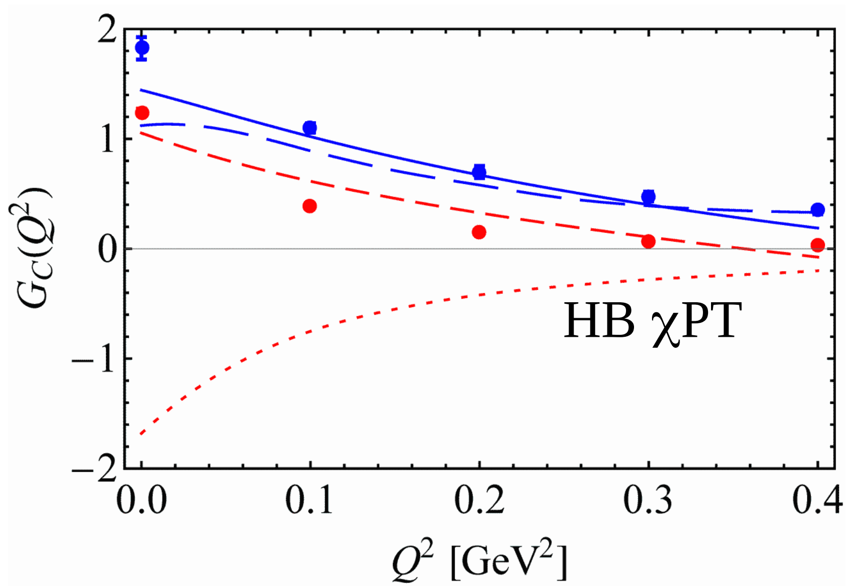


data points: average MAID+SAID (2016)

Baryon χPT (Scherer et al, 2017)

HB χPT (Gail, Hemmert, 2006)



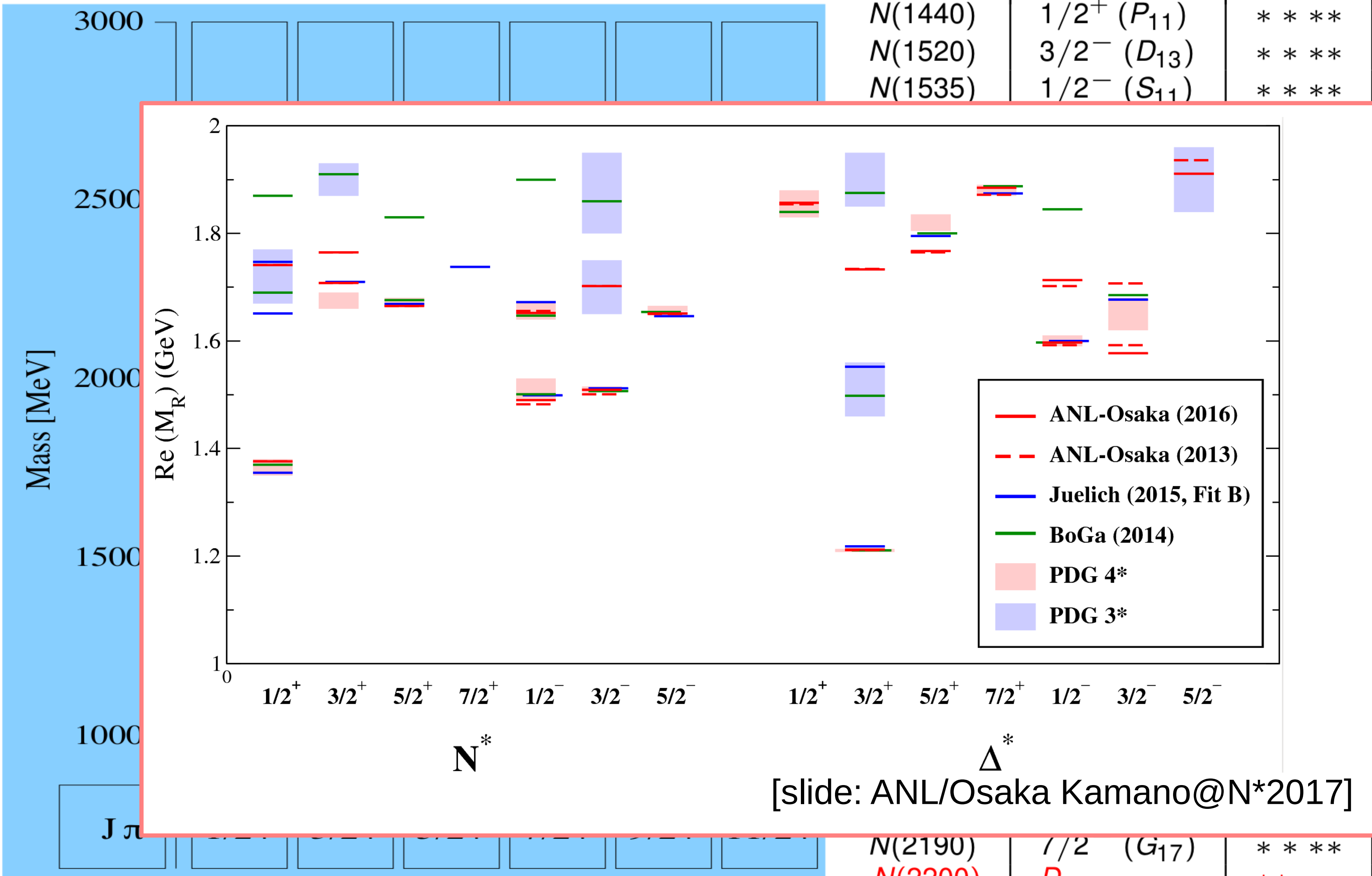


Summary

- Light baryon spectrum below W=1.7 GeV established
- New polarization data brings different analyses closer
  - More focus on statistical aspects desirable
- Matching between meson vs. quark degrees of freedom in baryon models is still a challenge
- Realistic lattice QCD results on excited baryons require 3-body hadron dynamics and probably simulations close to physical quark masses

Spare slides

Spectrum of N* resonances



N^*	J^P $(L_{2I,2J})$	2010	2014
$N(1440)$	$1/2^+$ (P_{11})	* * **	* * **
$N(1520)$	$3/2^-$ (D_{13})	* * **	* * **
$N(1535)$	$1/2^-$ (S_{11})	* * **	* * **
			* * **
			* * **
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			**
$N(2190)$	$7/2^-$ (G_{17})	* * **	* * **
~~$N(2200)$~~	D_{15}	**	

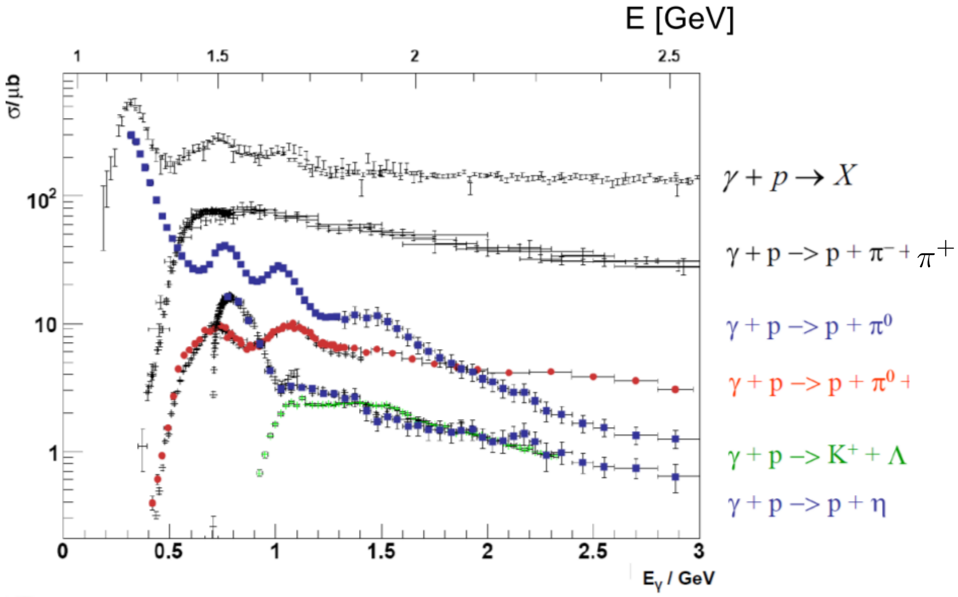
- Most new resonances by Bonn-Gatchina group;
- Many from kaon photoproduction

[Slide: V. Crede/Nstar 2017, slight modifications]

[See also: Crede, Roberts, Rep. Prog. Phys. 76 (2013)]

Experimental studies of hadronic reactions: major progress in recent years

Photoproduction: e.g. from JLab, ELSA, MAMI, GRAAL, SPring-8



source: ELSA; data: ELSA, JLab, MAMI

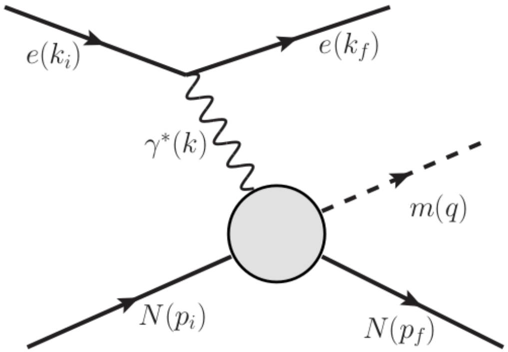
- enlarged data base with high quality for different final states
- (double) polarization observables

  $\rightarrow$ alternative source of information besides $\pi N \rightarrow X$

  $\rightarrow$ towards a complete experiment: unambiguous determination of the amplitude (up to an overall phase)

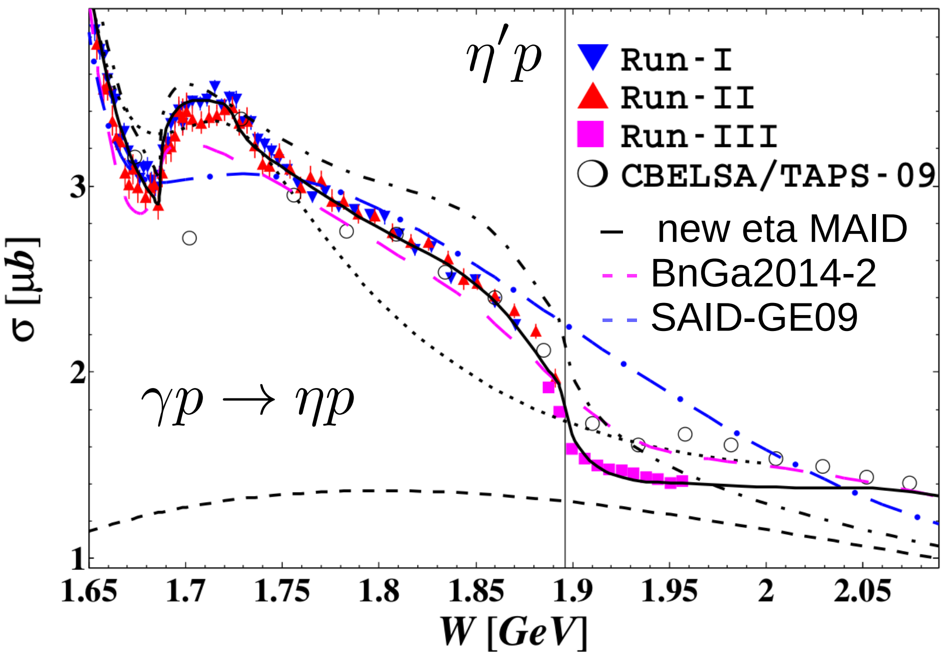
Electroproduction: e.g. from JLab, MAMI, MIT/Bates

- electroproduction of πN, ηN, KY, $\pi\pi N$
- access the Q^2 dependence of the amplitude, information on the internal structure of resonances



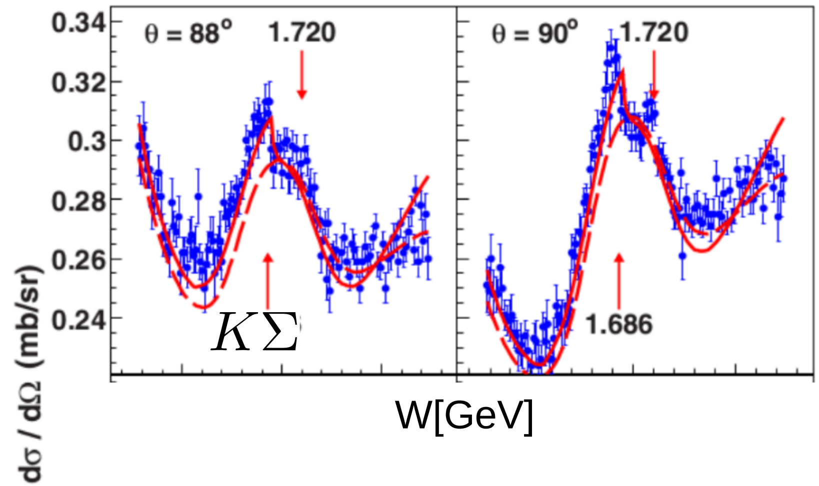
Resonances or not?

A2 MAMI, PRL 118 (2017)

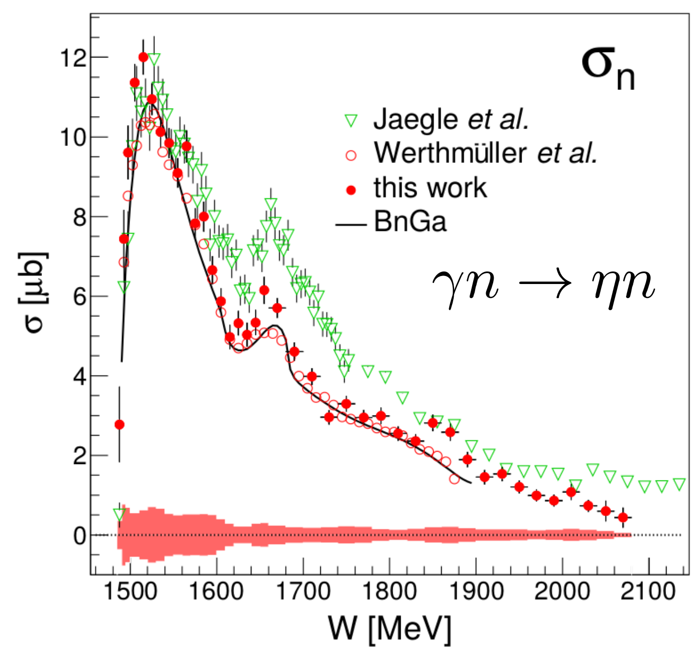


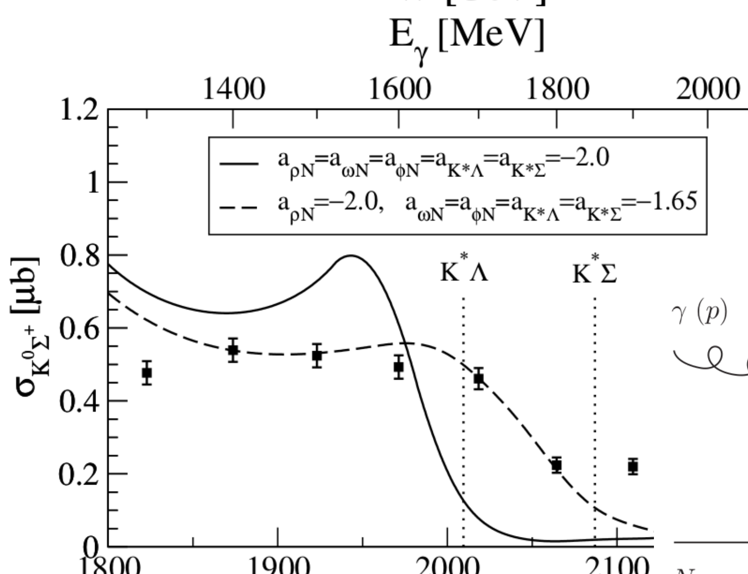
$\pi N \to \pi N$

EPECUR/SAID PRC 93 (2016)

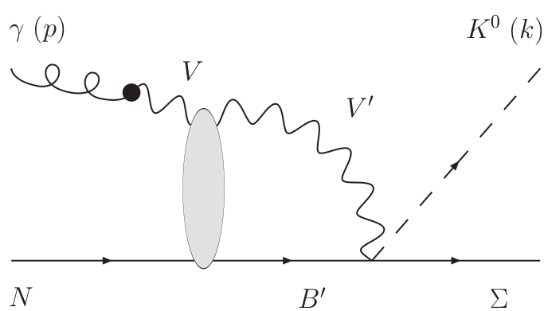


[CBELSA/TAPS EPJA 53 (2017)]





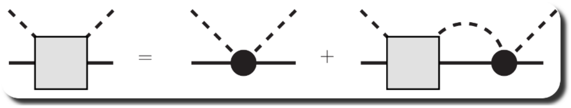
CBELSA/
TAPS
PLB 713 (2012);
Ramos/Oset
PLB 727 (2013)



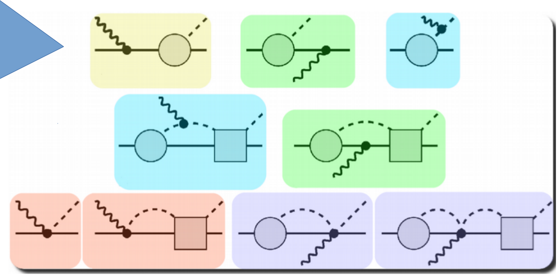
Using ONLY meson-baryon degrees of freedom (no explicit quark dynamics):

Manifestly gauge invariant approach based on full BSE solution

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



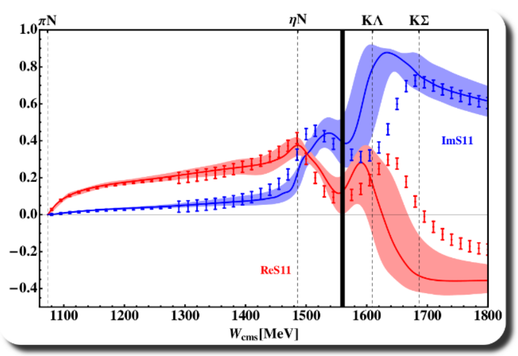
Gauge invariance

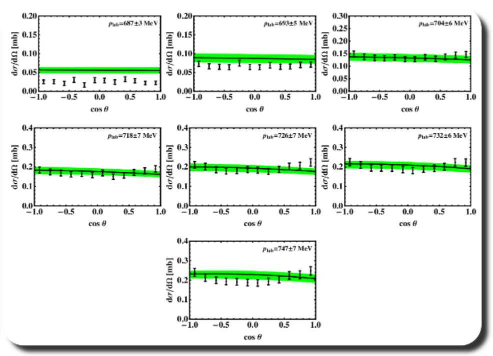


Fit

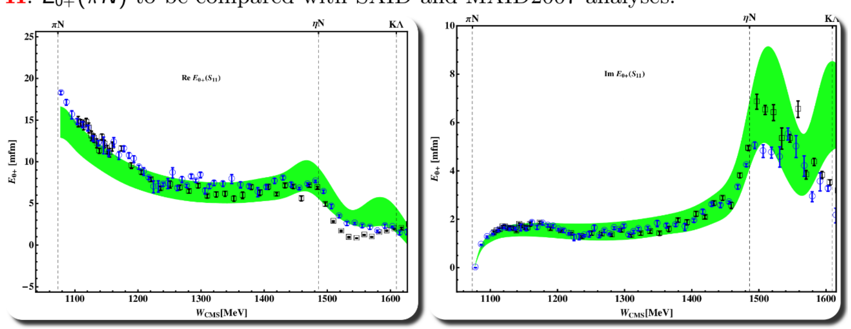
Prediction

- 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)





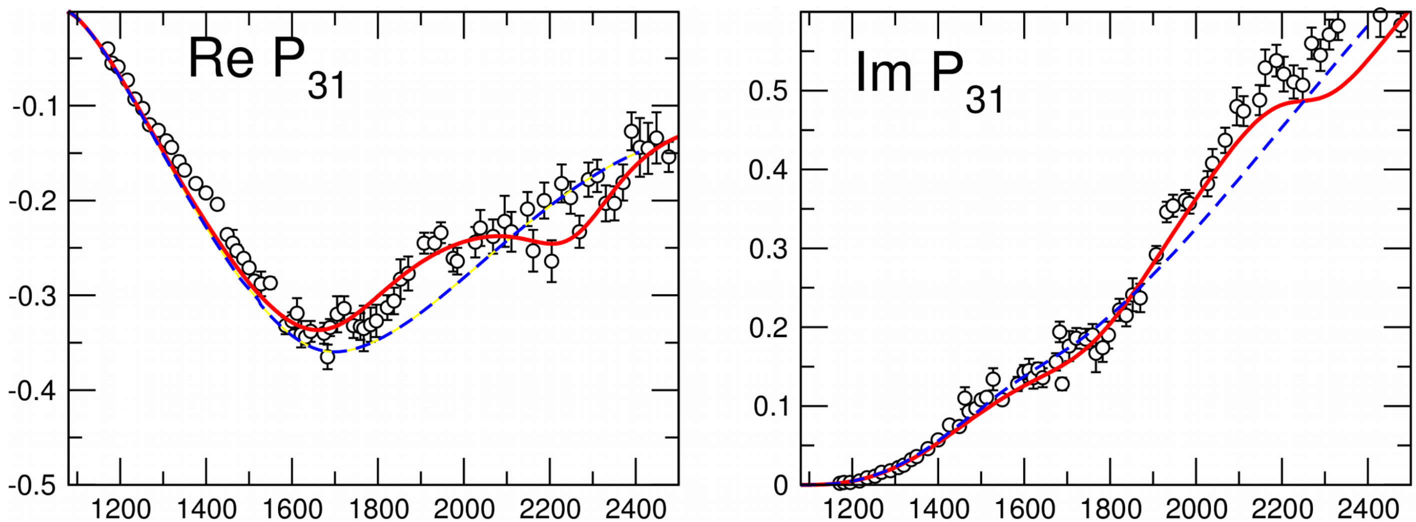
II. $E_{0+}(\pi N)$ to be compared with SAID and MAID2007 analyses:



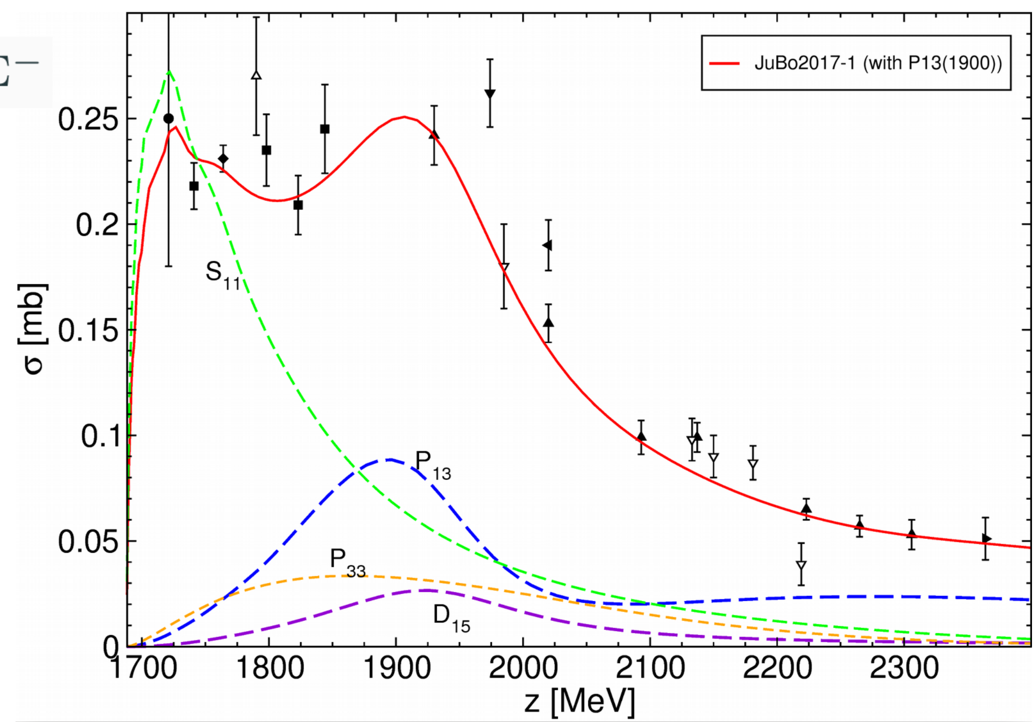
→ Making the "Missing resonance problem" worse ?!

Visible influence of new states

$\Delta(2190)3/2^{+}$ in πN PW



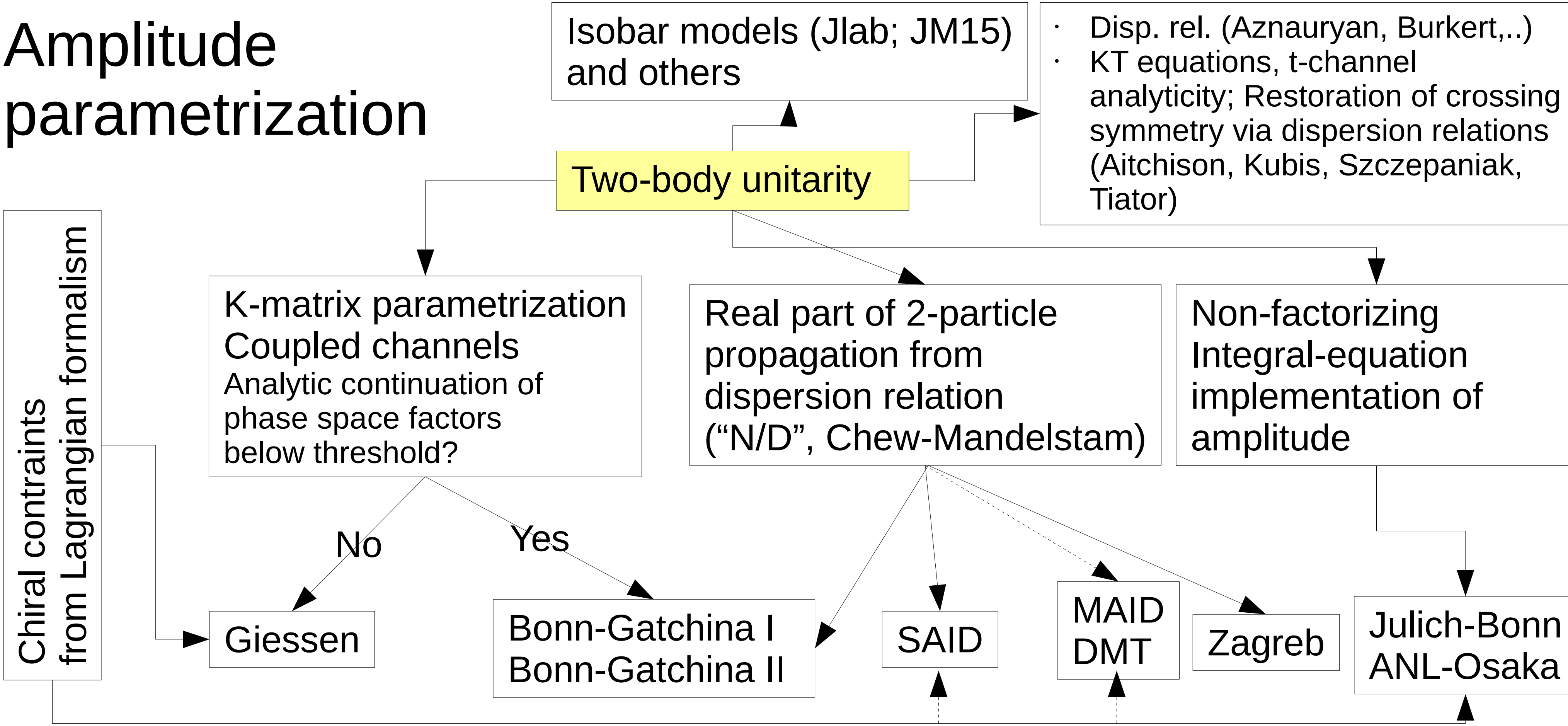
N(1900)$3/2^{+}$, N(2060)$5/2^{-}$ in σ_{tot} in $\pi^{-}p \to K^{+}\Sigma^{-}$

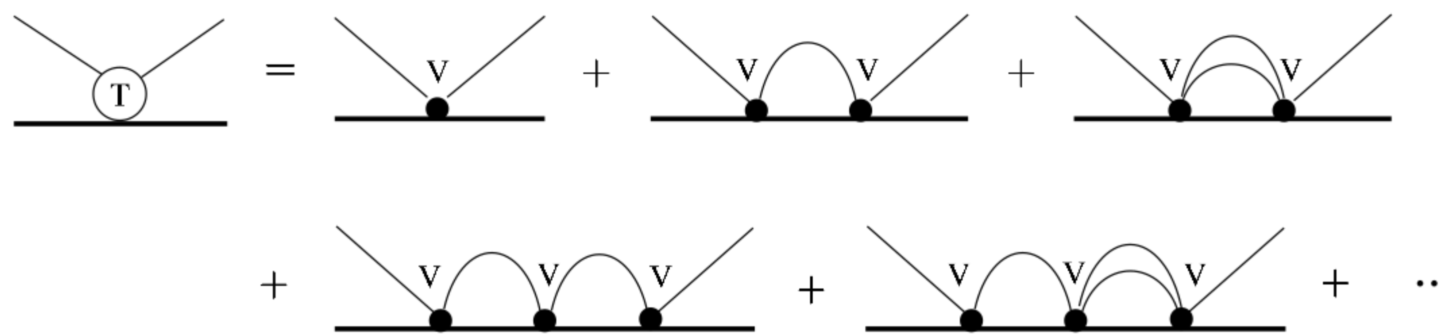


Analyzed reactions (incomplete)

- Bonn-Gatchina: $(\pi N \to \pi N), \to \eta N, K\Lambda, K\Sigma, \pi\pi N, \omega N$
  $\gamma p \to \pi N; \to \eta N, K\Lambda, K\Sigma, \pi\pi N, \omega N, \eta' N$
  $\gamma n \to \pi N$
- Giessen: $(\pi N \to \pi N), \to \eta N, K\Lambda, K\Sigma, (\pi\pi N), \omega N$
  $\gamma p \to \pi N; \to \eta N, K\Lambda, K\Sigma, \omega N$
- SAID: $\pi N \to \pi N; \to \eta N,\ \gamma p \to \pi N,\ \gamma n \to \pi N; \gamma^* p \to \pi N$
- MAID: $(\pi N \to \pi N);\ \gamma p \to \pi N,\ (\to \eta N, \to K\Lambda),\ \gamma n \to \pi N; \gamma^* p \to \pi N$
- ANL-Osaka: $(\pi N \to \pi N), \to \eta N, K\Lambda, K\Sigma, \pi\pi N$
  $\gamma p \to \pi N; \to \eta N, K\Lambda, \pi\pi N; (\gamma^* p \to \pi N)$
  Note refit in [Kamano, Nakamura, Lee, Sato, PRC 94 (2016)]
- Jülich-Bonn: $(\pi N \to \pi N), \to \eta N, K\Lambda, K\Sigma$
  $\gamma p \to \pi N; \to \eta N, K\Lambda$
- JLAB-MSU: $\gamma^* N \to \pi\pi N$

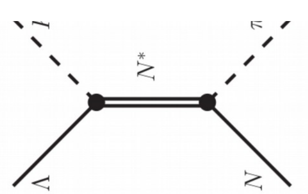
Amplitude parametrization





$$T = V + VGT,$$

Genuine Resonance:

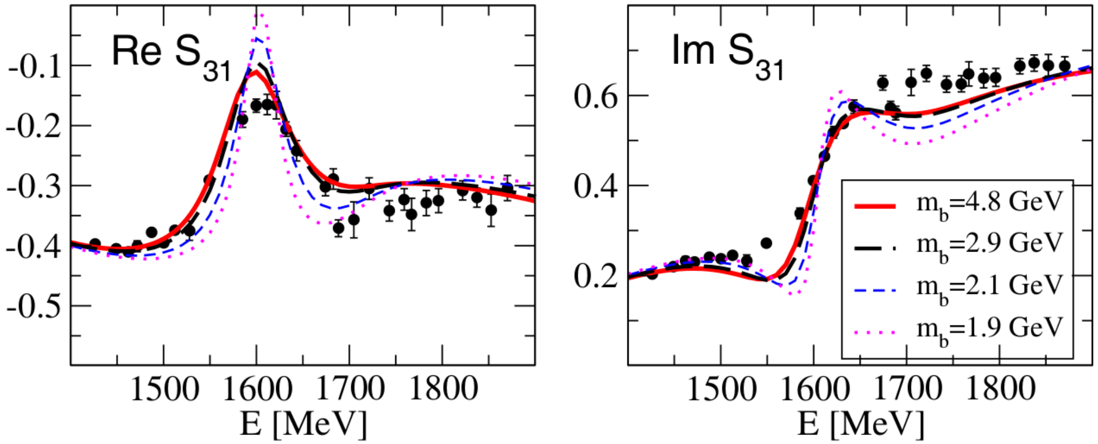


Unitarity loop G:

- Re G → 0: K-matrix
- V point-like: SAID
  Integral equation: Julich-Bonn, ANL-Osaka

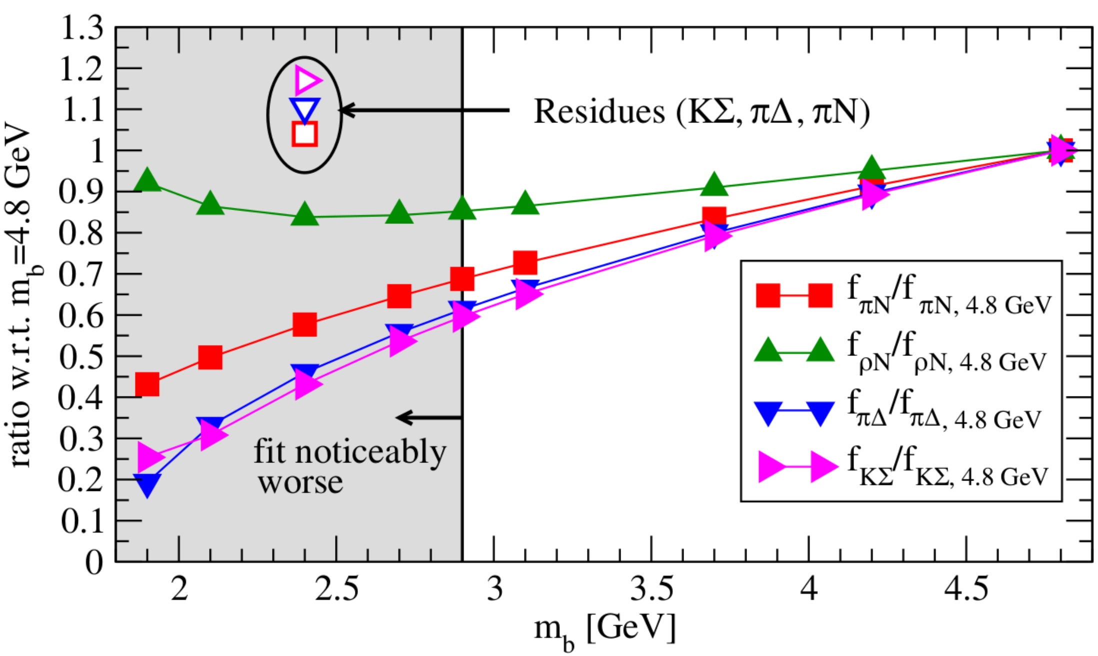
Input parameters and their stability

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

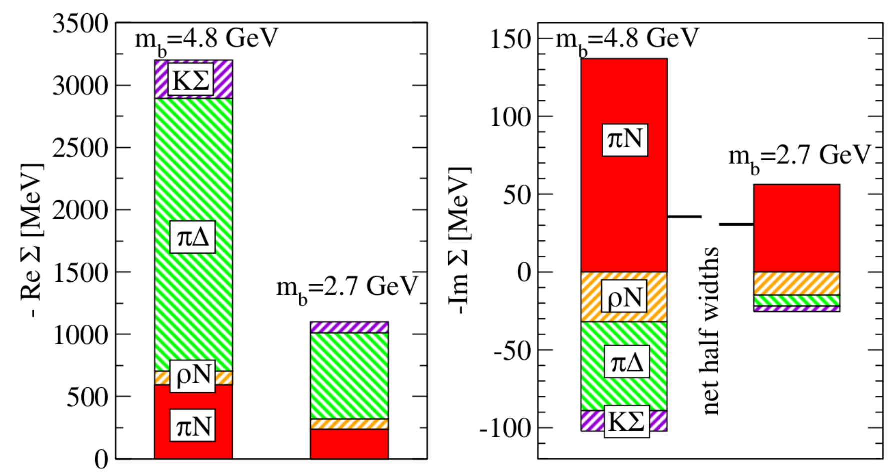


Force bare mass of $\Delta(1600)$
to fixed value; refit full data base

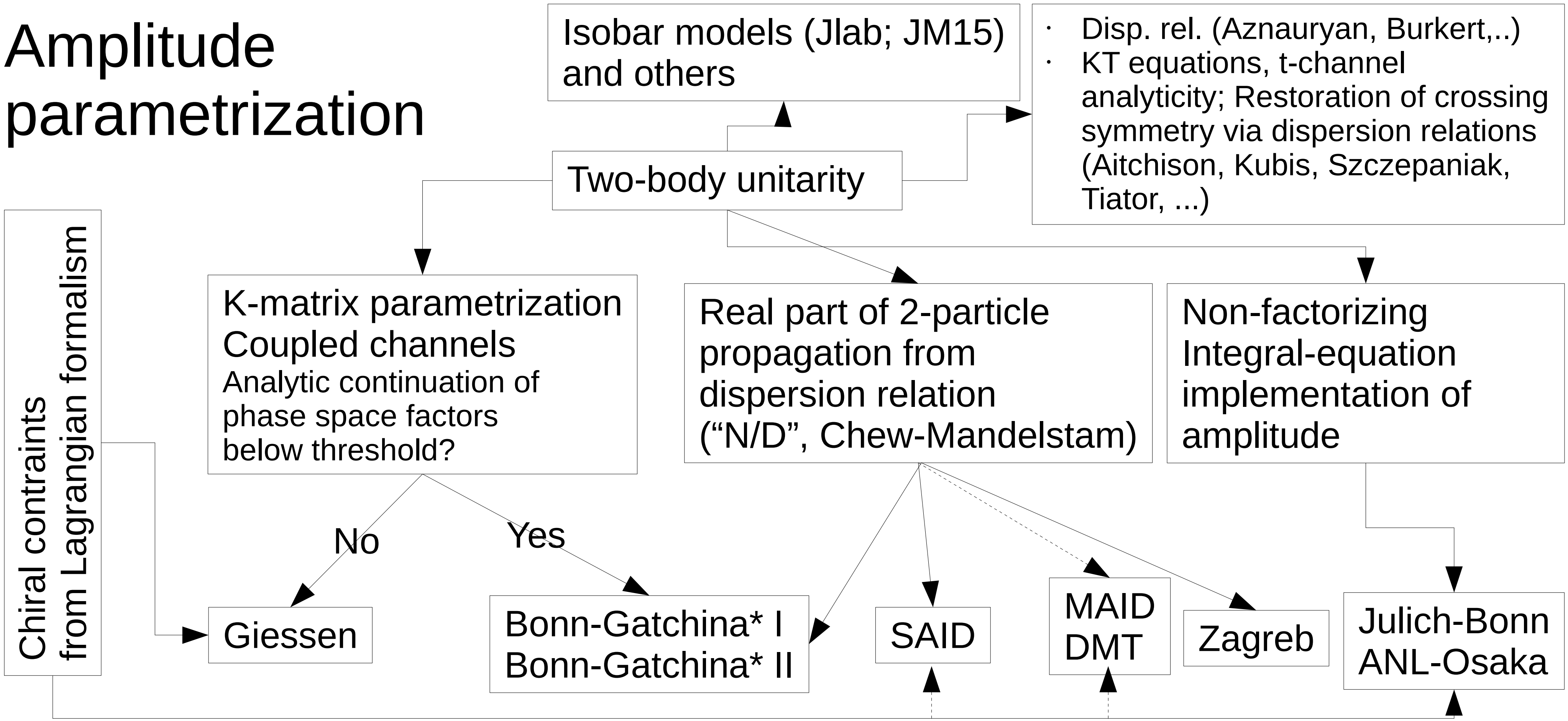
$\pi N \to \pi N, \eta N, K\Lambda, K\Sigma$



Self energy:



Amplitude parametrization



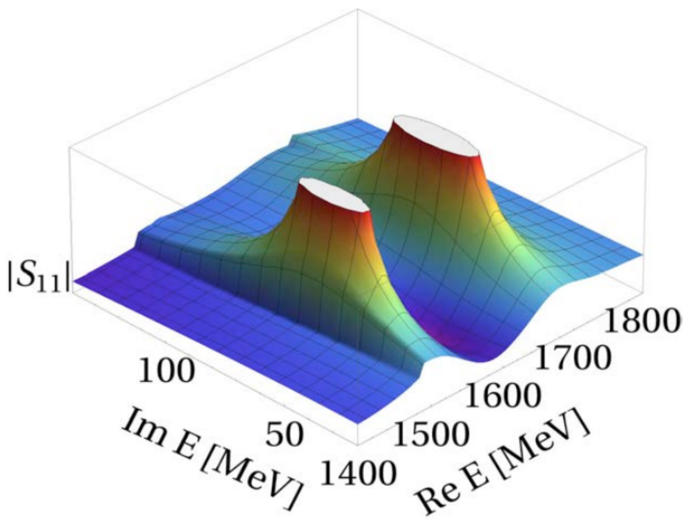
	Giessen	Bonn-Gatchina*	SAID	MAID / DMT	Zagreb	Julich-Bonn / ANL-Osaka
Explicit resonance Terms?	Yes	Yes	No	(Yes)	Yes	Yes/No
Analyticity (math.)	No	Yes	Yes	Yes	Yes	Yes
Analyticity (disp.)	No	No/Yes	Yes			Yes
Effective $\pi\pi N$?	Yes	Yes	Yes	Yes	Yes	Yes
Three-body unitarity?	No	No	No	No	No	Yes

* largest set of analyzed reactions

Analytic structure

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

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

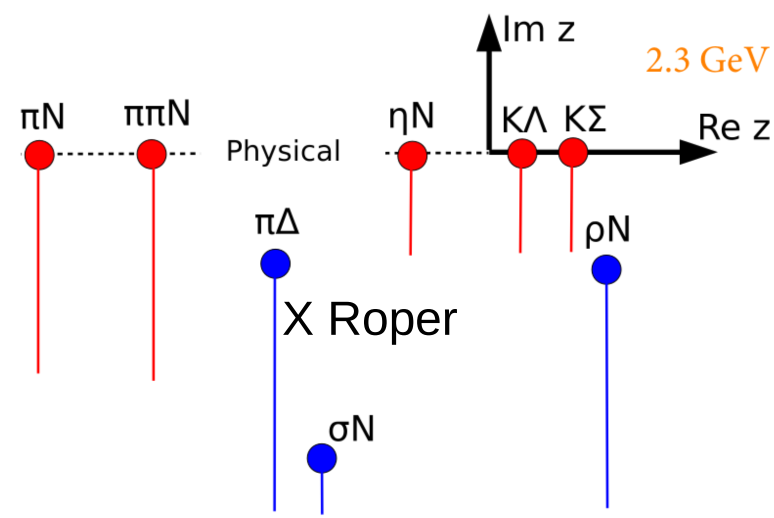


Re(E_0) = "mass", -2Im(E_0) = "width"

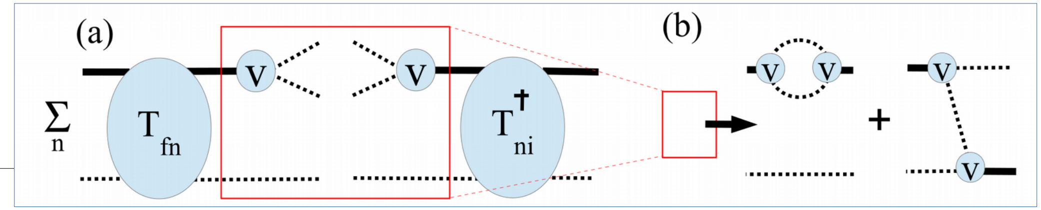
- pole position E_0 is the same in all channels
- residues $\longrightarrow$ branching ratios

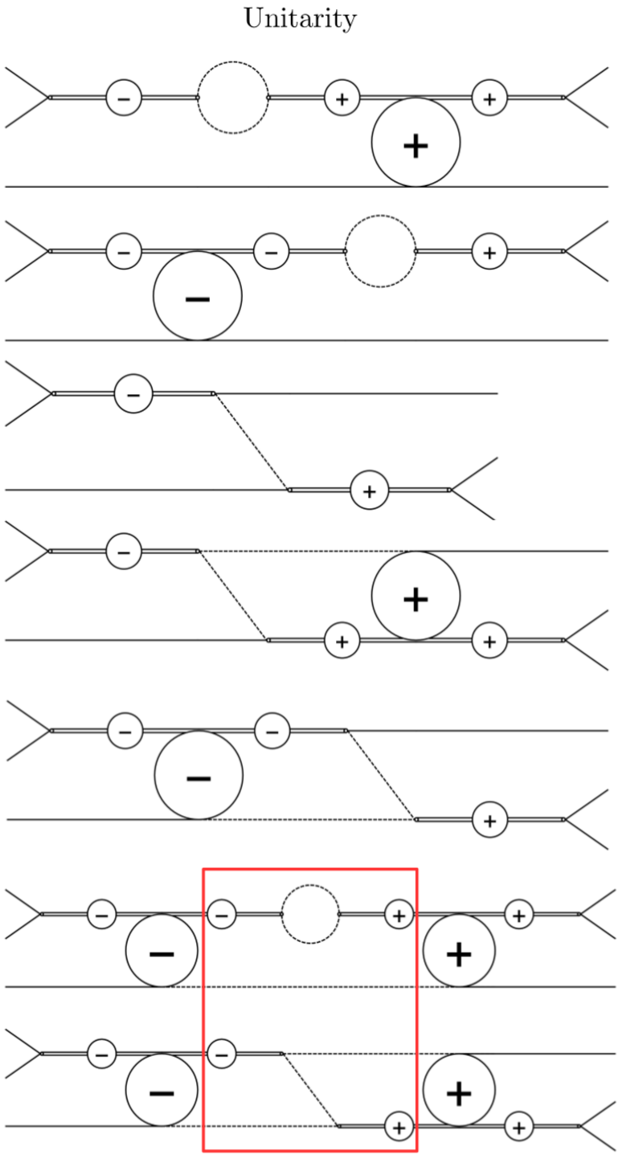
- (2-body) unitarity and analyticity respected
- 3-body $\pi\pi N$ channel:
  - parameterized effectively as $\pi\Delta$, σN, ρN
  - $\pi N/\pi\pi$ subsystems fit the respective phase shifts

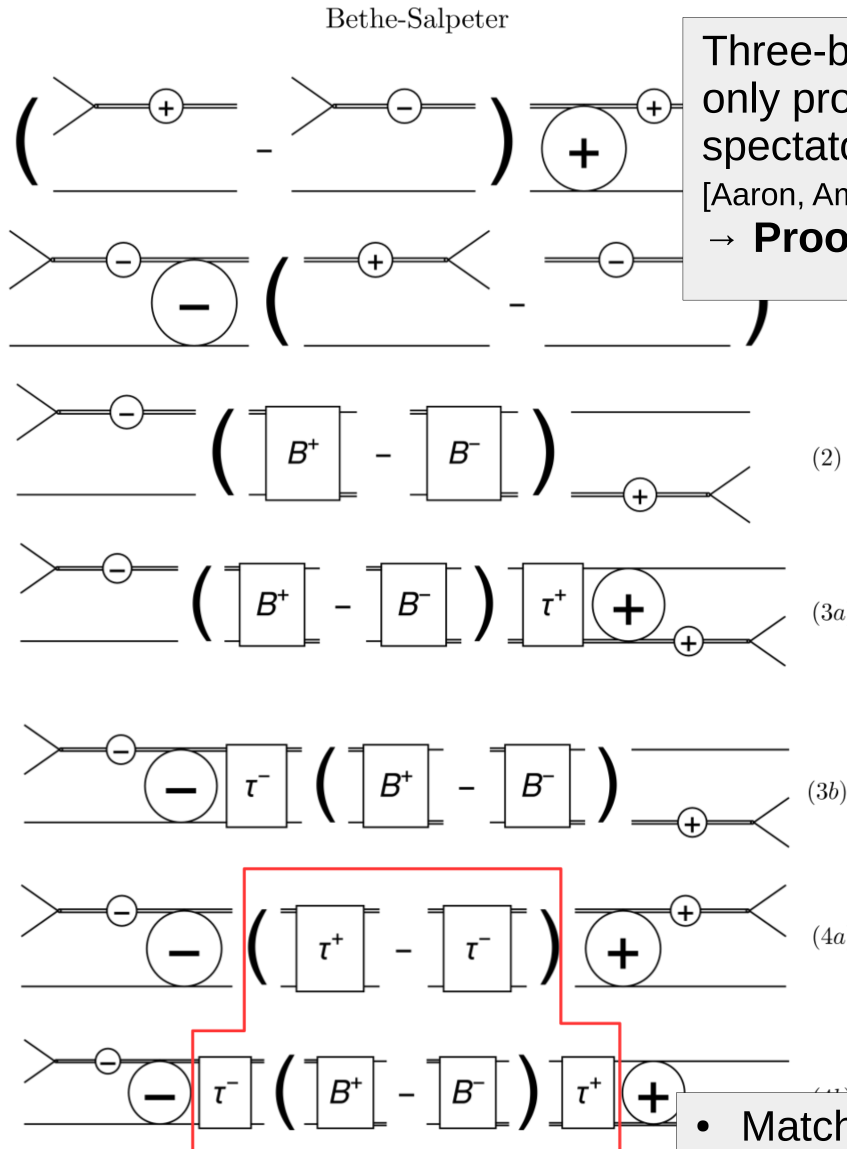
  ↳ branch points move into complex plane



Unitarity above breakup







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

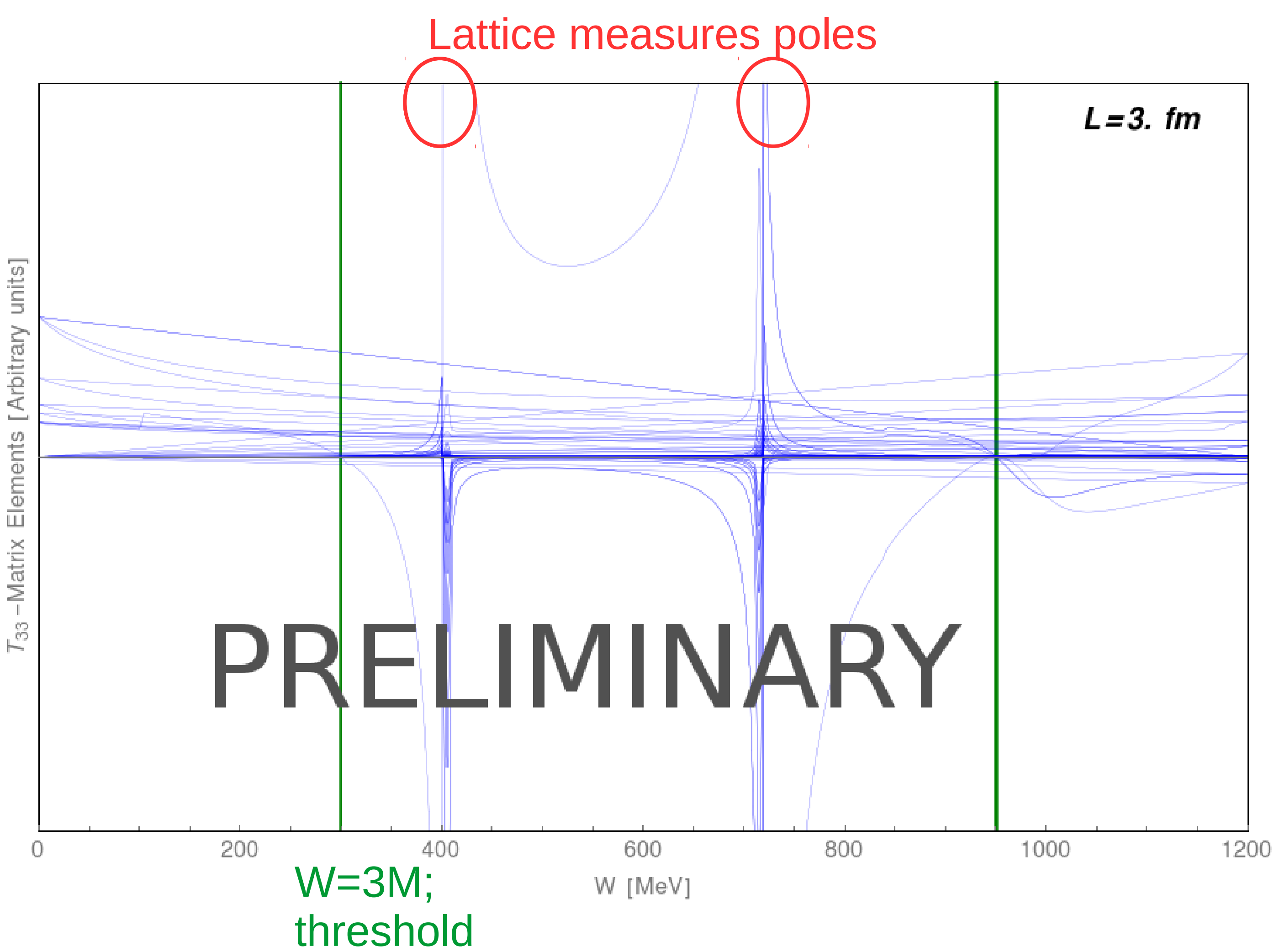
Bound-state particle scattering requires only comparing these.

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

Finite volume spectrum

M. Mai, M.D., in progress

- Spinless particles; isobar S-wave decay

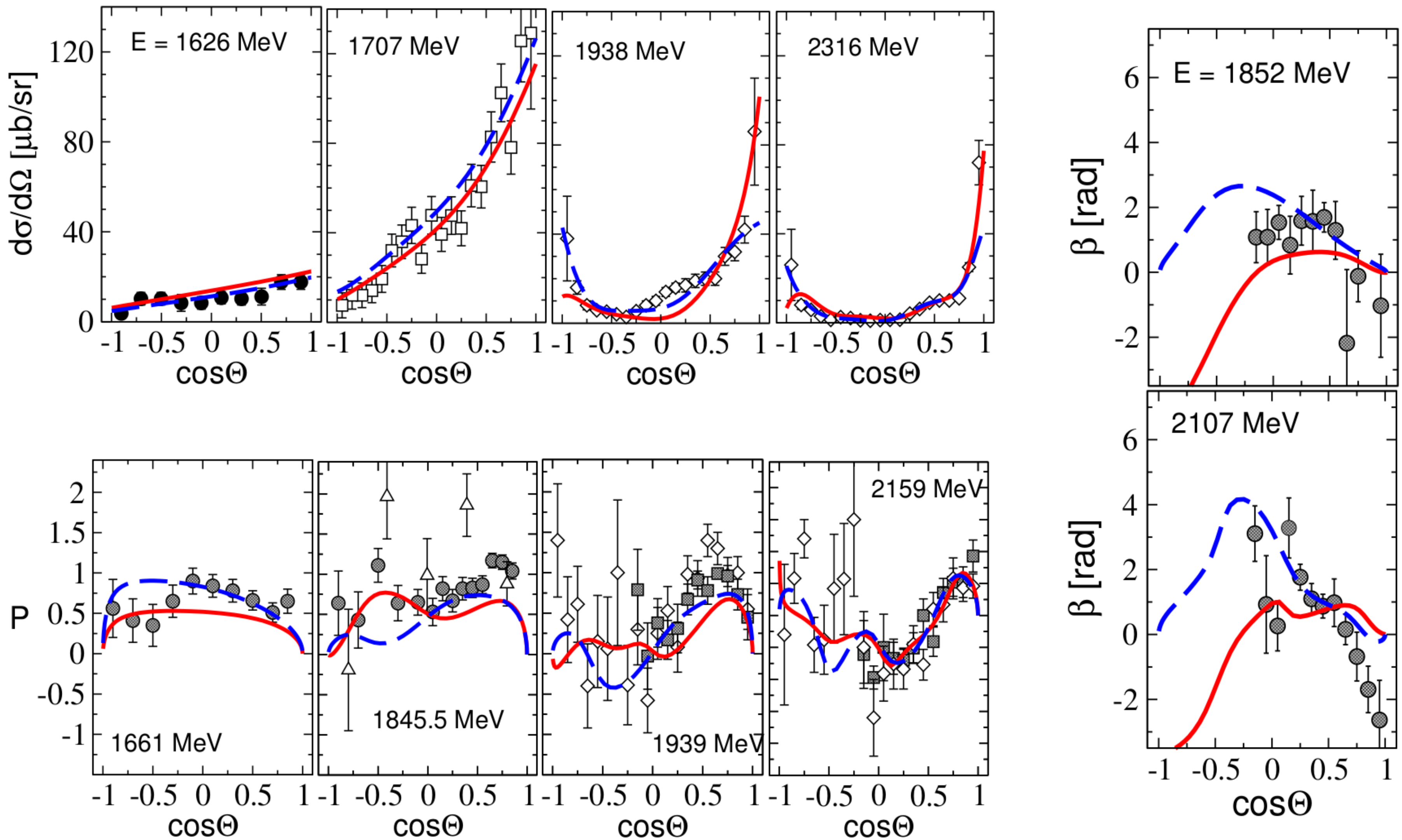


- Isobar-spectator in A_1
- Organization of amplitude in shells |**p**|=n
- Each blue line is a transition from shell i ↔ j (i,j=0,…,8)
- Genuine three-body poles in T(3→3) give the finite-volume eigenvalues
- Green lines are free 3-body energies

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)]

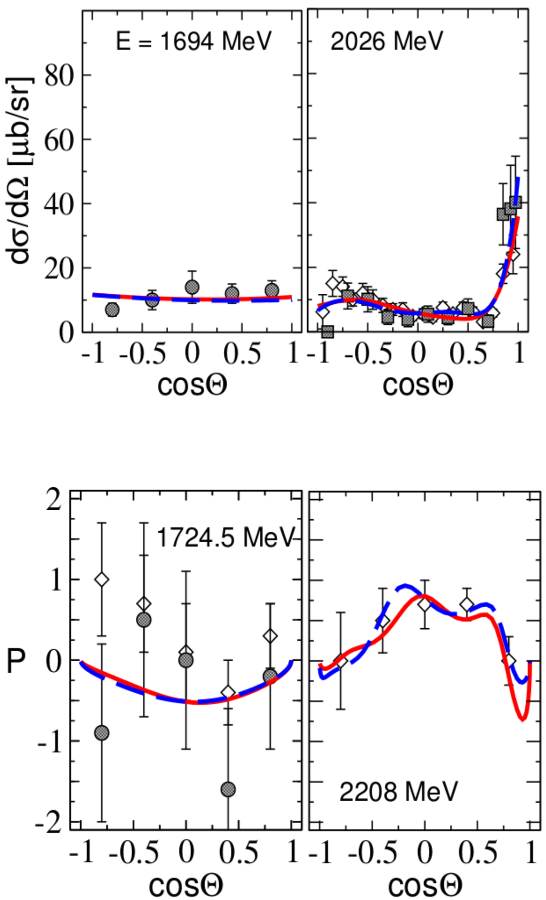
Selected results for $\pi^- p \to K^0 \Lambda$ [almost complete experiment]



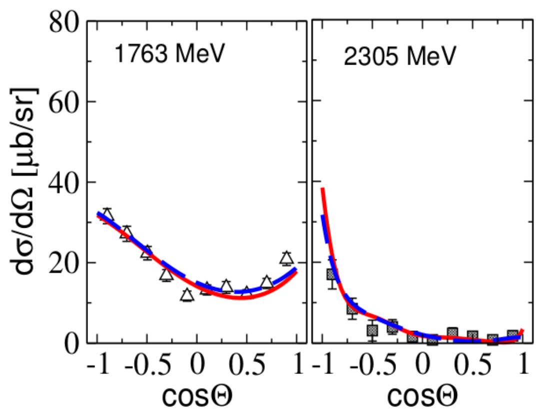
Re-measuring hadron-induced reactions

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

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

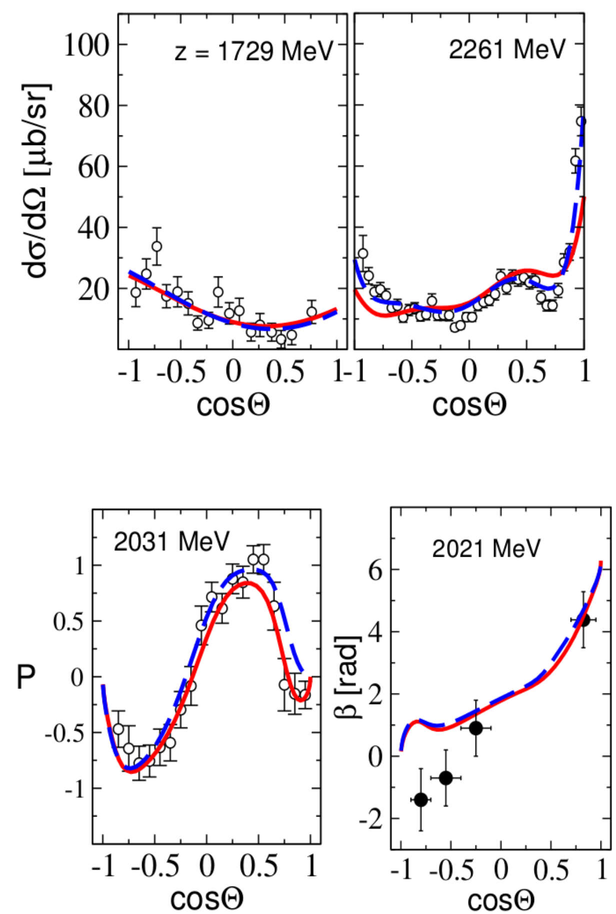


$\pi^- p \to K^+ \Sigma^-$



No polarization data!

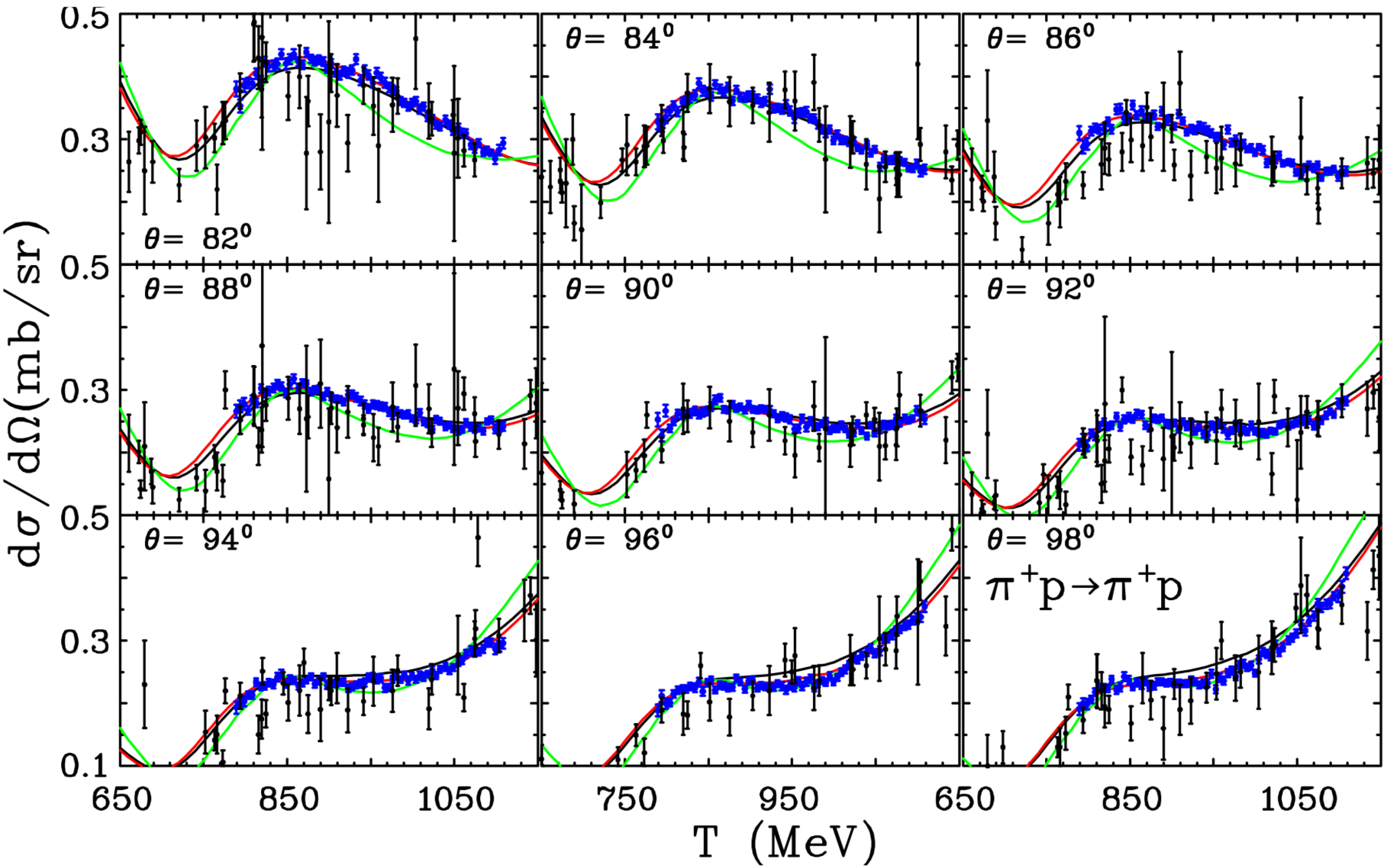
$\pi^+ p \to K^+ \Sigma^+$



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

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.

SAID Analysis of New Data

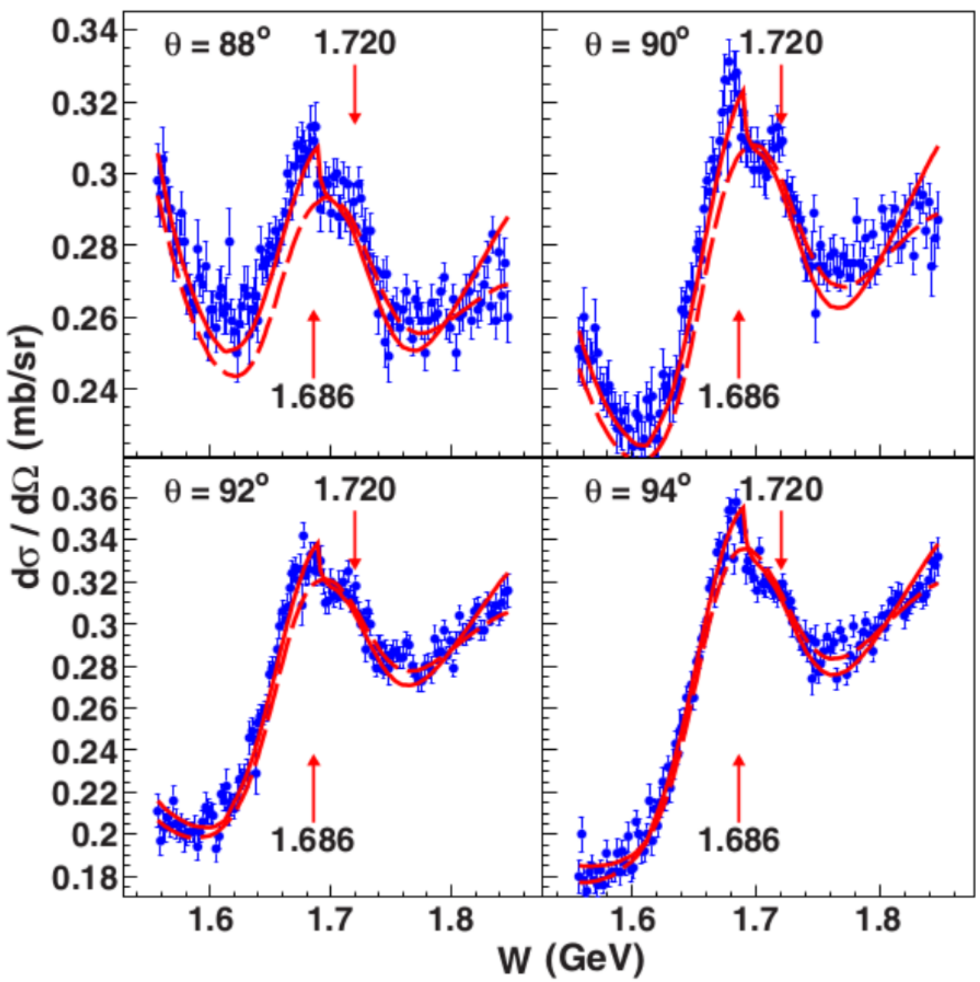


FIG. 2. $\pi^- p$ elastic scattering. Red solid lines correspond to the present calculations. Dashed lines lines are the XP15 solution.

Fit (no KΣ , KΛ channel)

Dashed Line

Fit including KΣ , KΛ channels

Solid Line

Narrow structures largely accounted for by threshold cusp effects.

Phys Rev C93 (2016) 062201

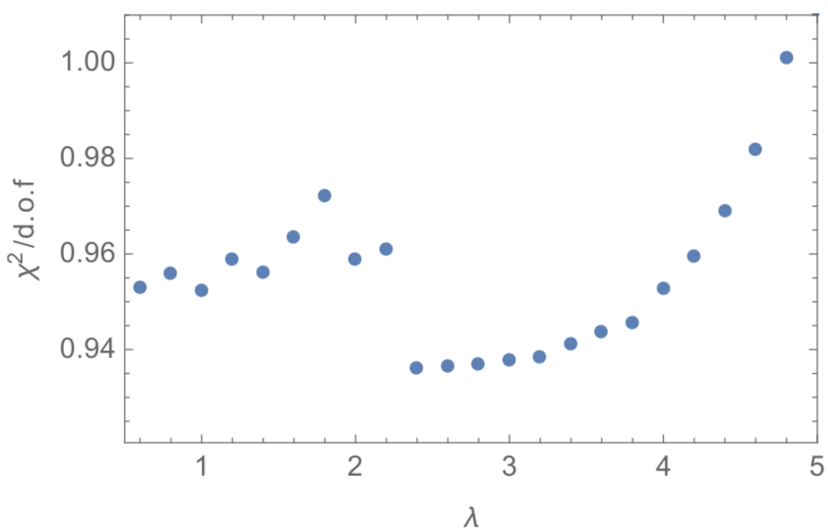
How to decide best value of λ?

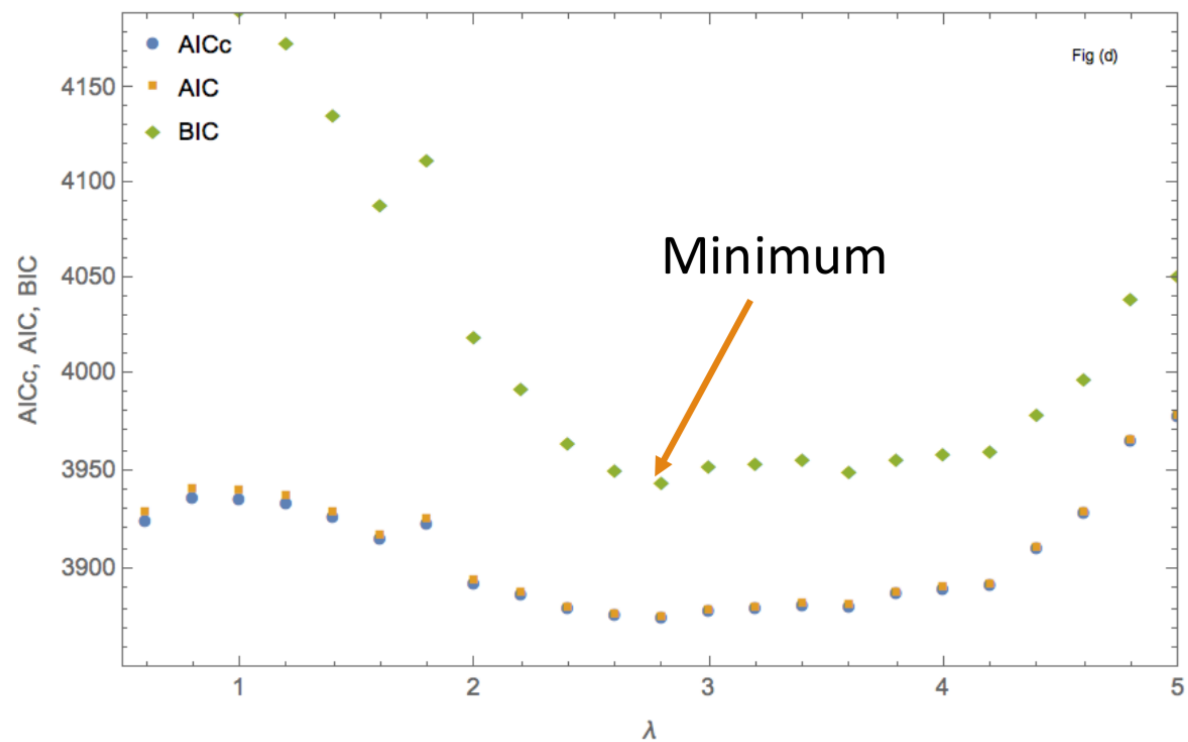
$$AIC = 2k + \chi^2$$

$$AICc = AIC + \frac{2k(k+1)}{(n-k+1)}$$

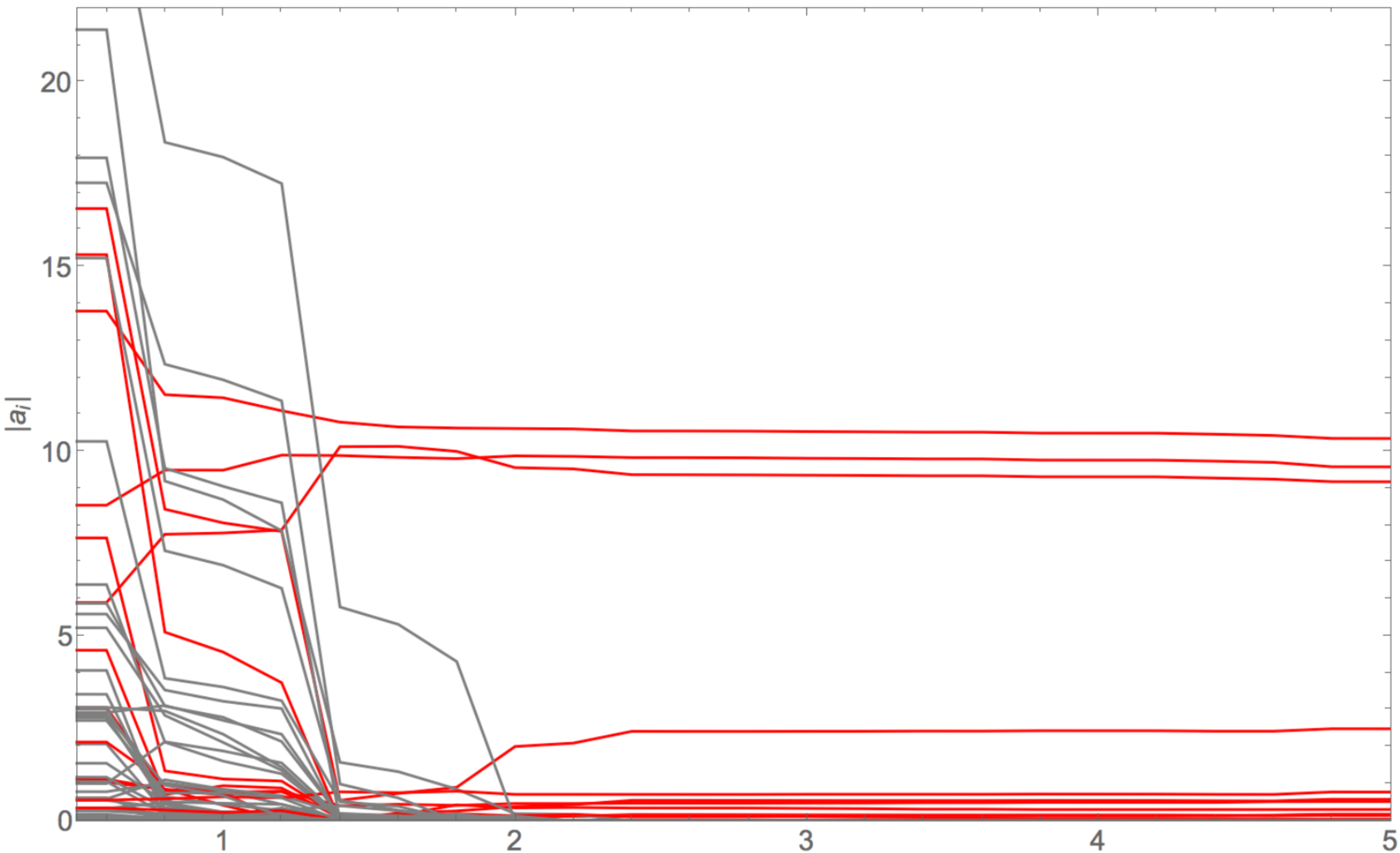
$$BIC = k \log n + \chi^2$$

k : Number of parameters
n : Number of data points





Lasso Example: Fit to data from toy model with known best parameters

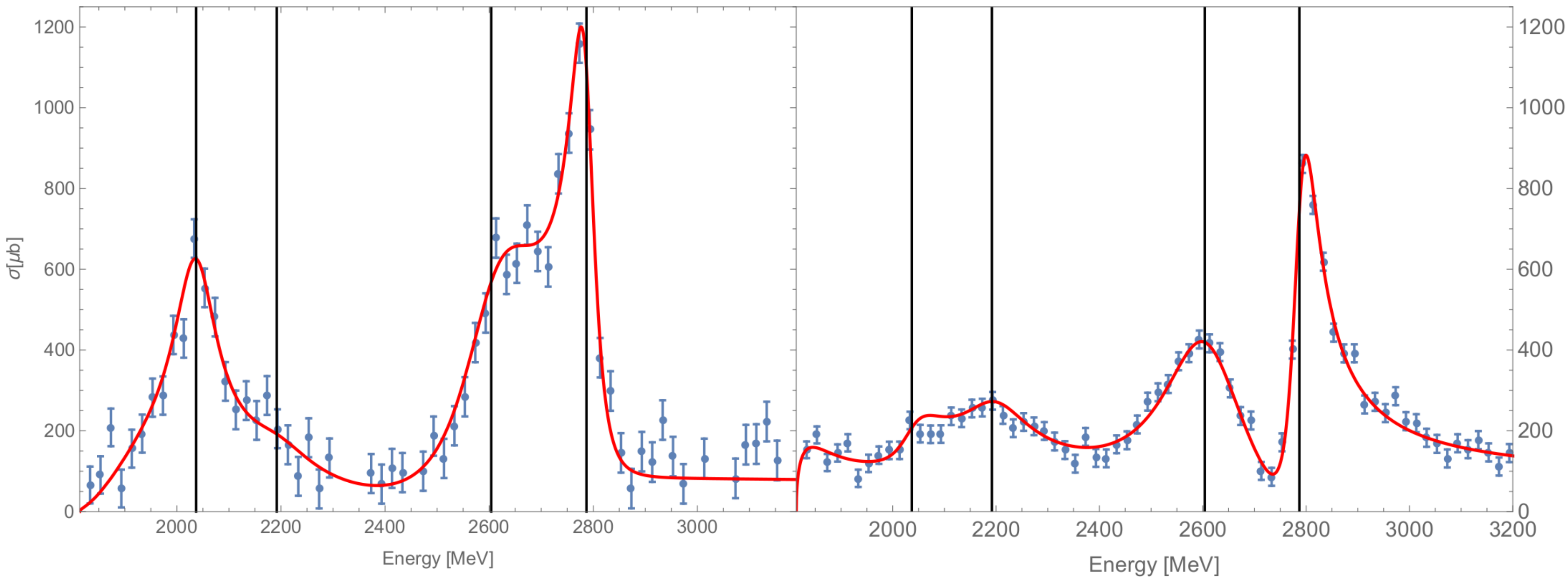


Red- Non-Zero Parameters Gray- Zero-Parameters

Resonance selection

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

Synthetic data with hidden resonances

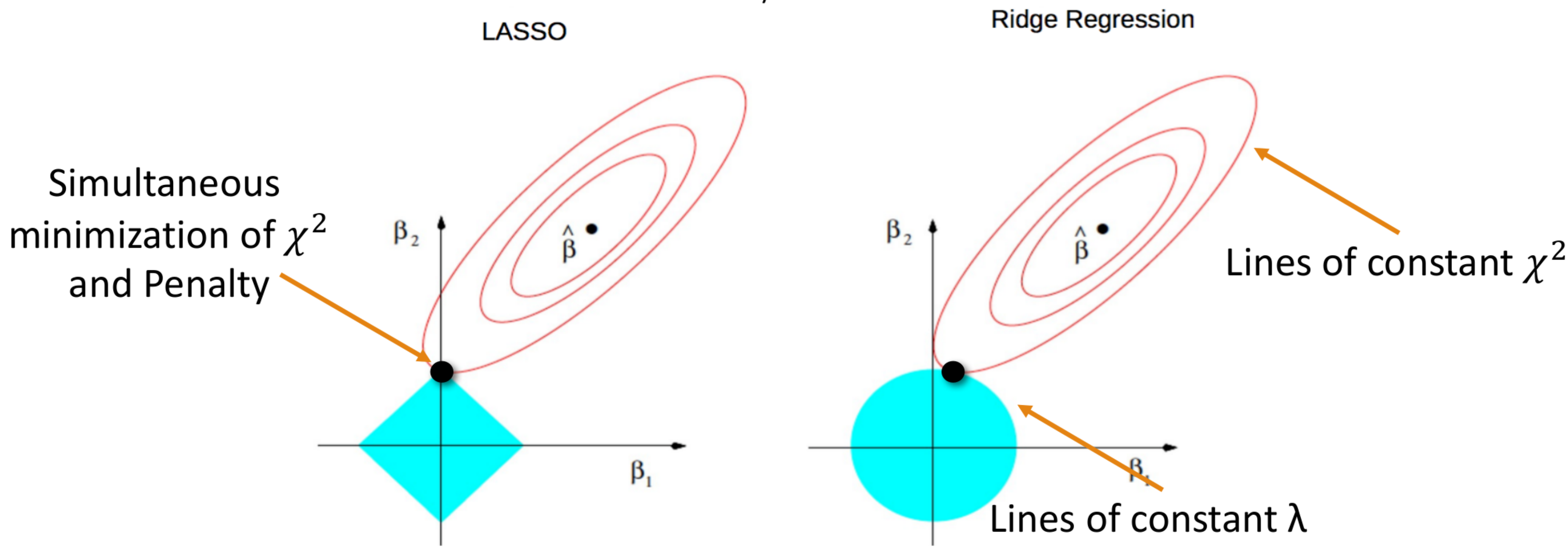


Total cross section + diff cs (not shown) + Polarization P (not shown) assuming Reaction kinematics of $K^- p \to K\Xi$

LASSO is capable of setting coefficients exactly to zero

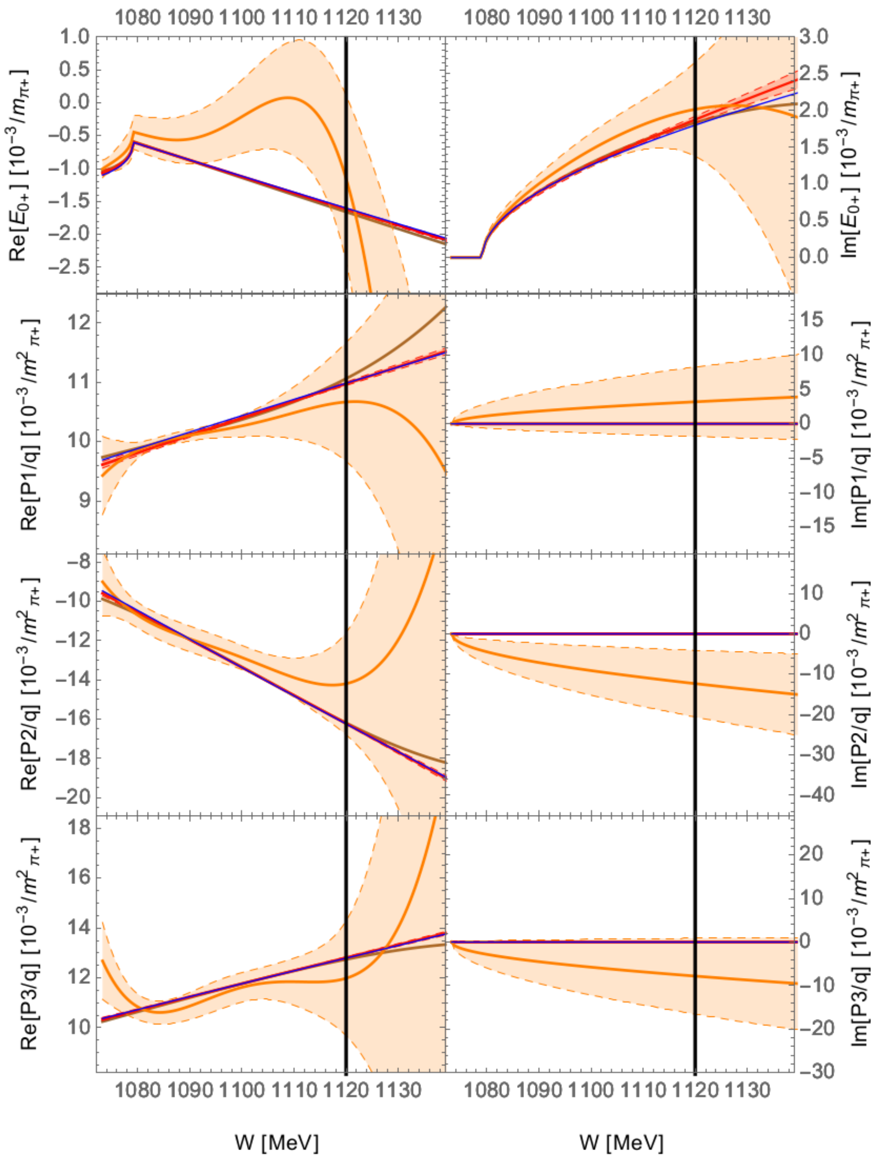
$$\underbrace{\sum_{i=1}^{n} \frac{(y_i - f(x_i, \beta_j))^2}{\sigma_i^2}}_{\text{Normal } X^2} + \lambda \underbrace{\sum_{j=1}^{m} |\beta_j|}_{\text{Penalty Term}}$$

$\hat{\beta}_i$: Best parameters without penalty
$\beta_i = 0$: Best parameters only penalty



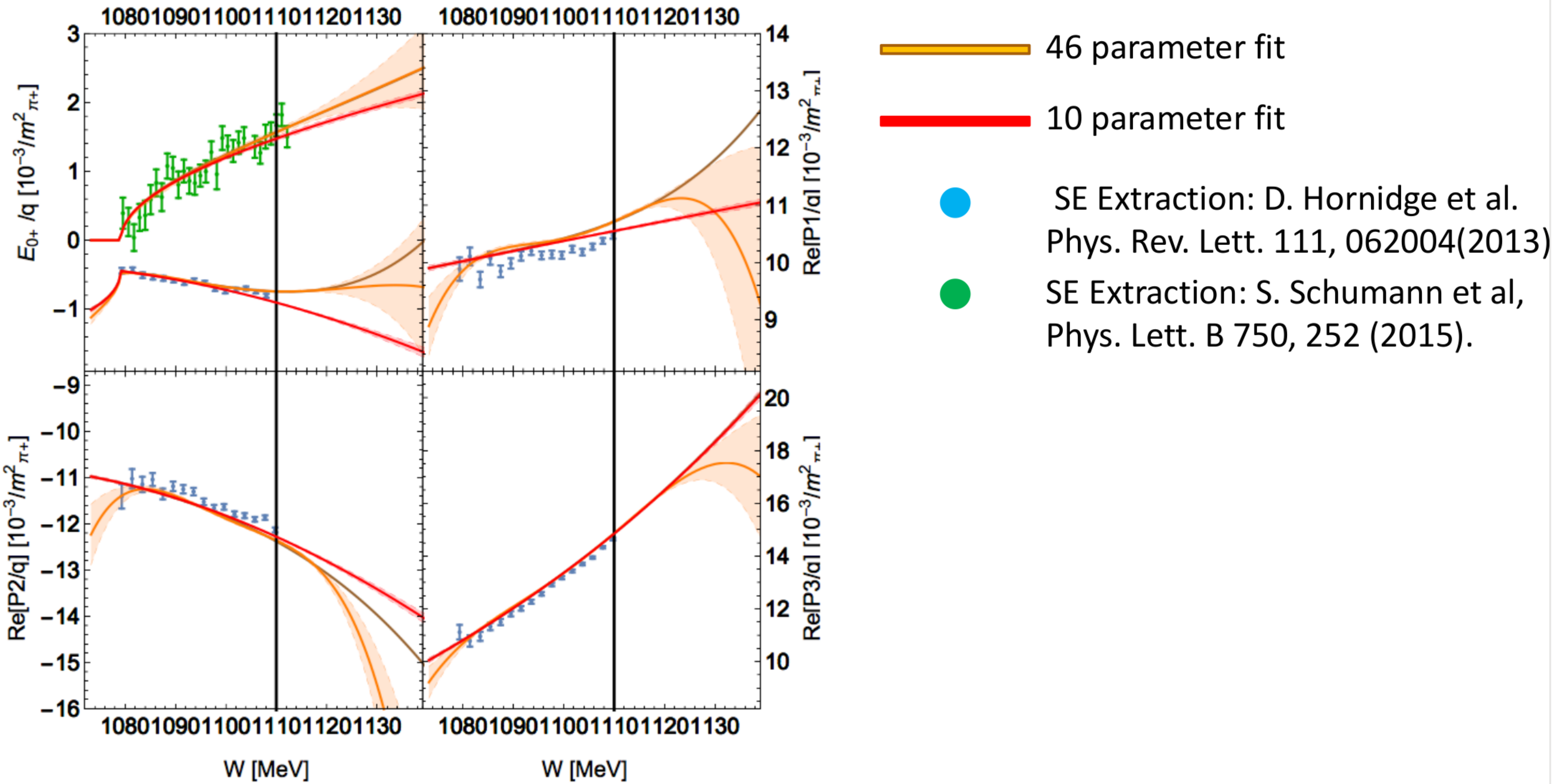
(Least Absolute Shrinkage and Selection Operator LASSO)

Toy Model Results



- Generate data from a toy model using a 9 parameter model (2 real S-waves, 1 imaginary S-wave, and 2 real $P_{1,2,3}$ –waves shown in blue
- LASSO (red) eliminates 36 parameters from a 46 parameter fit (orange) and reconstructs the true solution (blue) quite accurately
- LASSO sets all imaginary parts of P-waves and D- waves correctly to 0
- LASSO solution predicts true solution quite accurately beyond the fitted W_{max} =1120 MeV

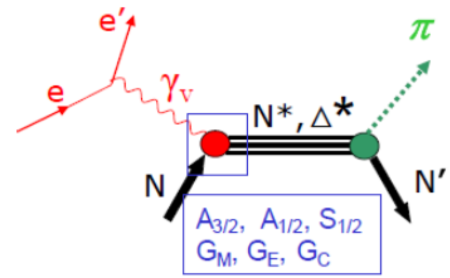
Model selection with real data



→ Selection of relevant partial waves in fit of scarce lattice QCD data

Electroproduction - SAID

- Energy dependent SM08 and associated SES & SQS
- W = 1080 – 2000 MeV $\quad Q^2$ = 0 – 6 GeV^2
- PWs = 60 [multipoles] $\quad$ [J < 6]
- Prms = 171
- Constraint: πN + Pion Photo PWAs [no theoretical input]



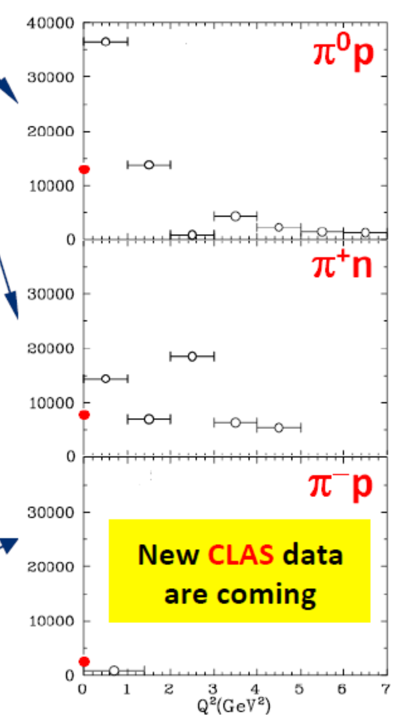
- 0.85 World Electro Prod from JLab CLAS

- PWA Problems:
  - Additional [S] Multipoles
  - Q^2 dependence

- Database Problems:
  - Most of data are unPolarized measurements
  - There are no π^0n data and very few π^-p [no Pol measurements] That does not allow to determine n-couplings at $Q^2 > 0$

Reaction	Data	χ^2
$\gamma^*p \to \pi^0 p$	55,766	81,284
$\gamma^*p \to \pi^+ n$	51,312	80,004
Redundant	14,772	17,375
Total	121,850	178,663
$\gamma N \to \pi N$	25,358	53,458
All Photo*	147,208	232,121
$\pi N \to \pi N$	31,479	57,157
All πN	178,687	289,278
$\gamma^*n \to \pi^- p$	801	
$\gamma^*n \to \pi^0 n$	No Data	

Q^2-Data



Details 3→ 3 formalism

$$\langle q_1,q_2,q_3|\hat{T}(s)|p_1,p_2,p_3\rangle = \langle q_1,q_2,q_3|\hat{T}_c(s)|p_1,p_2,p_3\rangle + \langle q_1,q_2,q_3|\hat{T}_d(s)|p_1,p_2,p_3\rangle \tag{1}$$

$$= \frac{1}{3!}\sum_{n=1}^{3}\sum_{m=1}^{3} v(q_{\bar{n}},q_{\bar{\bar{n}}})\hat{T}(q_n,p_m;s)v(p_{\bar{m}},p_{\bar{\bar{m}}})$$

$$:= \frac{1}{3!}\sum_{n=1}^{3}\sum_{m=1}^{3} v(q_{\bar{n}},q_{\bar{\bar{n}}})\left(\tau(\sigma(q_n))\,T(q_n,p_m;s)\,\tau(\sigma(p_m)) - 2E(q_n)\tau(\sigma(q_n))(2\pi)^3\delta^3(\mathbf{q}_n-\mathbf{p}_m)\right)v(p_{\bar{m}},p_{\bar{\bar{m}}})$$

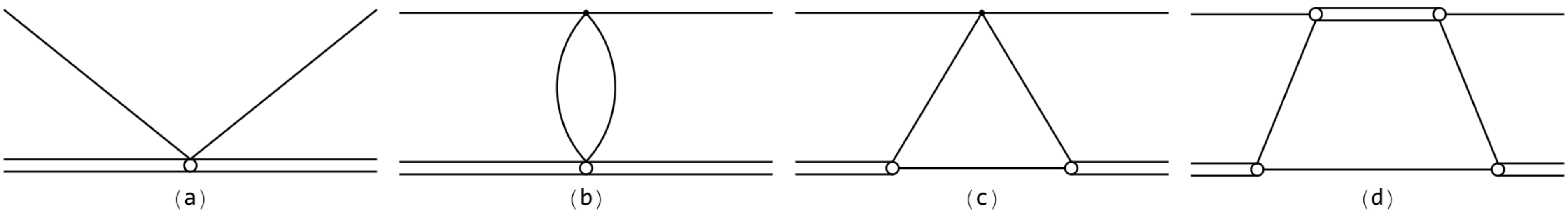
$$T(q,p;s) = B(q,p;s) - \int\frac{\mathrm{d}^3\boldsymbol{l}}{(2\pi)^3}B(q,l;s)\frac{1}{2E(l)D(\sigma(l))}T(l,p;s)\,,$$

$$\frac{1}{\tau(\sigma(l))} = \sigma(l) - M_0^2 - \int\frac{d^3\boldsymbol{k}}{(2\pi)^3}\frac{\lambda^2(f(4\boldsymbol{k}^2))^2}{2E(k)(\sigma(l)-4E(k)^2+i\epsilon)}\,,$$

$$B(q,p;s) = -\frac{\lambda^2 f((P-q-2p)^2)f((P-2q-p)^2)}{2E(q+p)\,(W-E(q)-E(p)-E(q+p)+i\epsilon)}$$

Which role do other “diagrams” play?

- Preferable to think in on-shell amplitudes (2 → 2 and 3 → 3), not in “diagrams”; if one still insists:



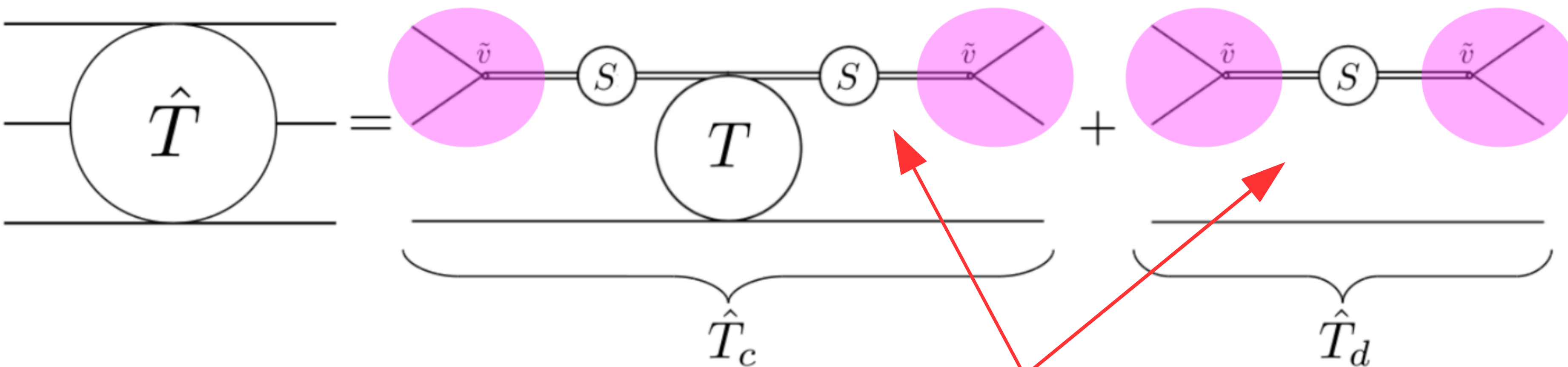
Genuine 3-body force

Non-local but real interaction

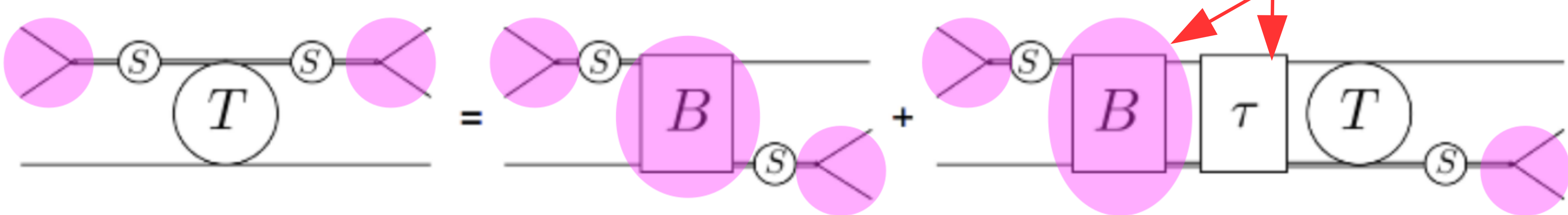
Part of isobar Insertion (d)

Cancellation mechanism of 2-body poles

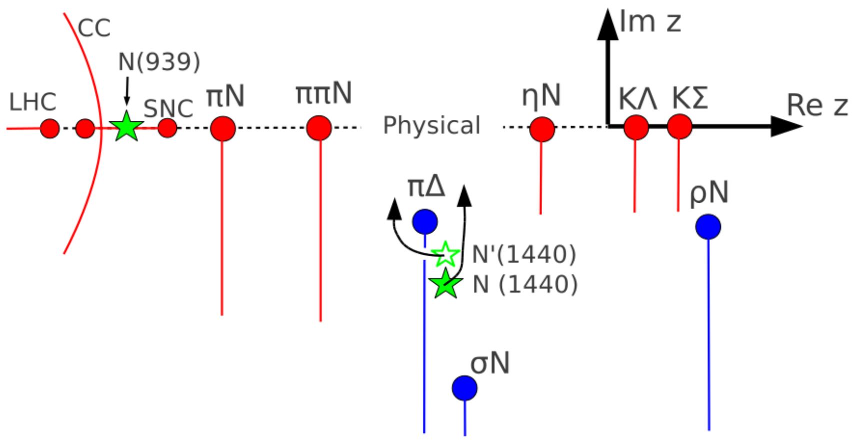
2→2 boosted eigenvalues
In principle present



Subtle but complete cancellations involving disconnected topology

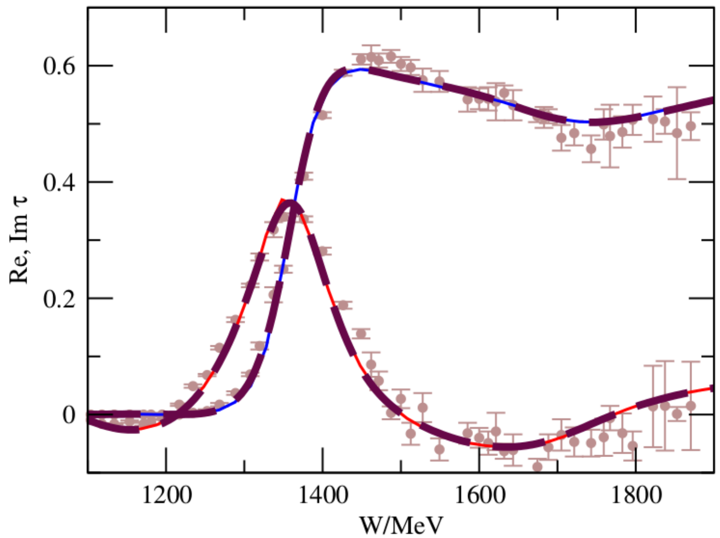


Relevance of three-body dynamics



- 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]

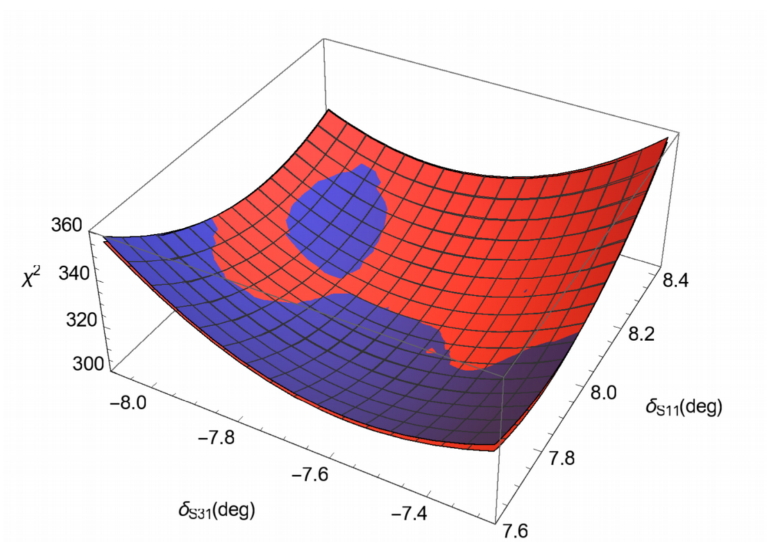
- CMB fit to JM has pole at $1698 - 130\,i$ MeV, simulates missing branch point.

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

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.

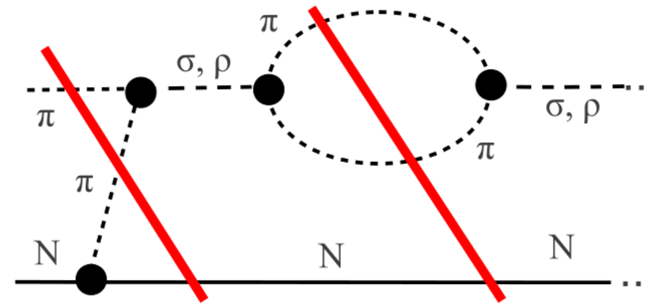
$$\chi^2(\mathbf{A}) = \chi^2(\hat{\mathbf{A}}) + (\mathbf{A} - \hat{\mathbf{A}})^T \hat{\Sigma}^{-1} (\mathbf{A} - \hat{\mathbf{A}}) + \mathcal{O}(\mathbf{A} - \hat{\mathbf{A}})^3$$

Covariance matrices etc. can be downloaded on the SAID and JPAC web pages.

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

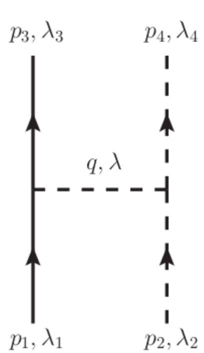
Unitarity: $SS^\dagger = 1 \Leftrightarrow -i(T - T^\dagger) = T\,T^\dagger$

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

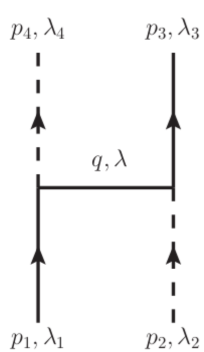


Other cuts

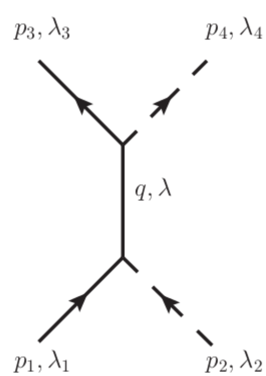
- to approximate left-hand cut → Baryon u-channel exchange
- σ, ρ exchanges from crossing plus analytic continuation.



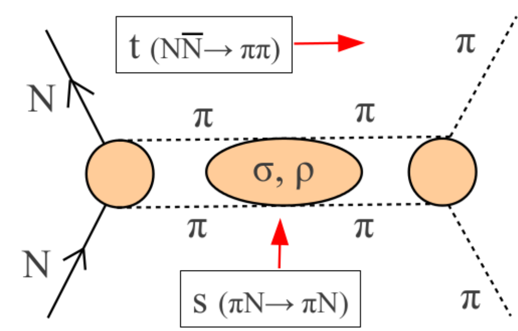
$\vec{q} = \vec{p}_1 - \vec{p}_3$



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



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



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

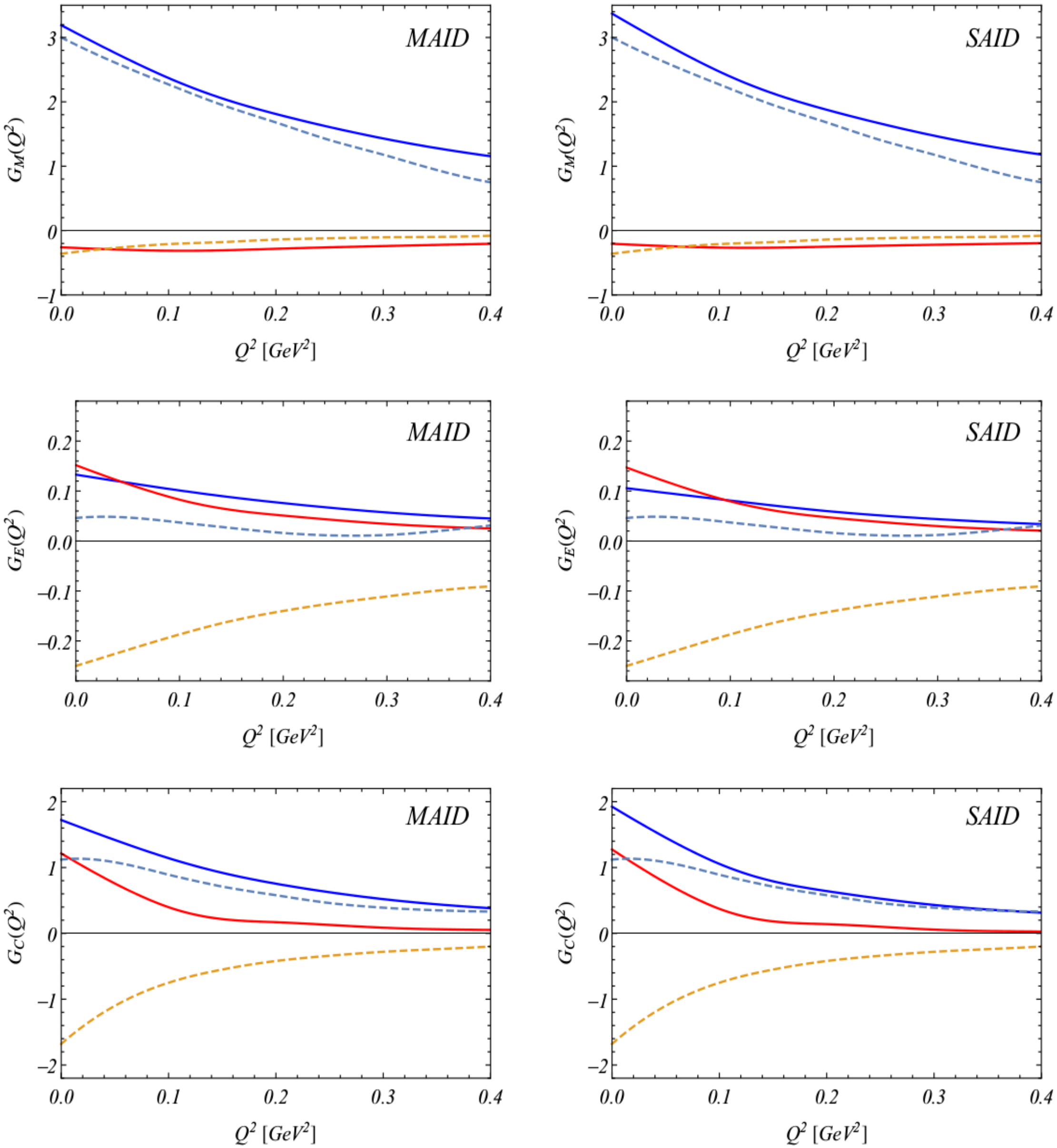


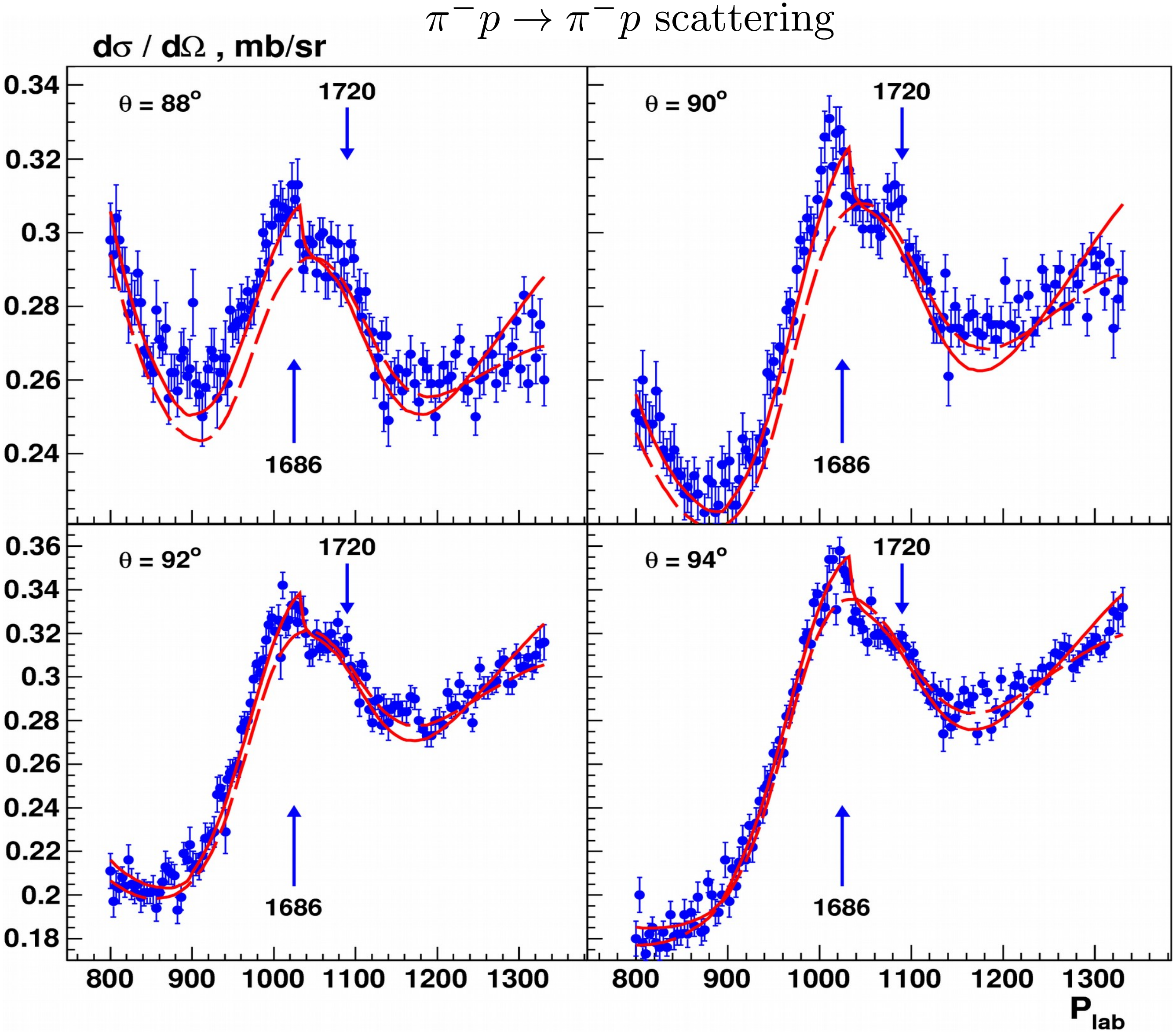
FIG. 4: Magnetic, electric and charge transition form factors compared with the Heavy Baryon chiral effective field theory of Gail and Hemmert [14] at low Q^2. The blue and red lines show real and imaginary parts of the complex pole form factors obtained from MAID and SAID. The dashed lines are the HBChEFT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

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

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

New High-precision πN data

$\pi^- p \to \pi^- p$ scattering



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

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

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

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

	$A^{1/2}_{pole}$ $[10^{-3}\ \mathrm{GeV}^{-1/2}]$		$\vartheta^{1/2}$ [deg]		$A^{3/2}_{pole}$ $[10^{-3}\ \mathrm{GeV}^{-1/2}]$		$\vartheta^{3/2}$ [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	$-15^{+0.3}_{-0.4}$

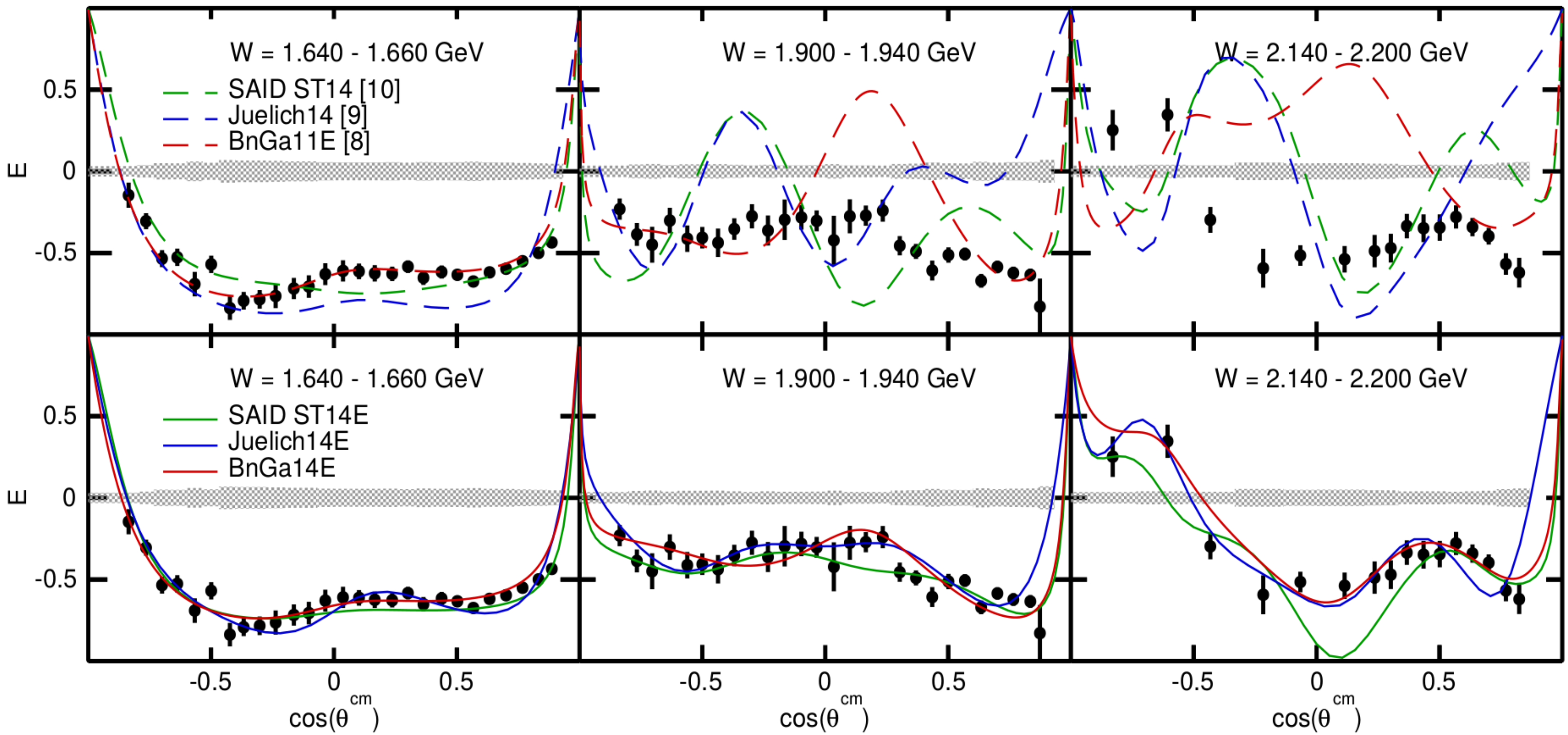
Fit 1: only **single** polarization observables included

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

FROST/CLAS (I)

The E-observable in charged-pion photoproduction

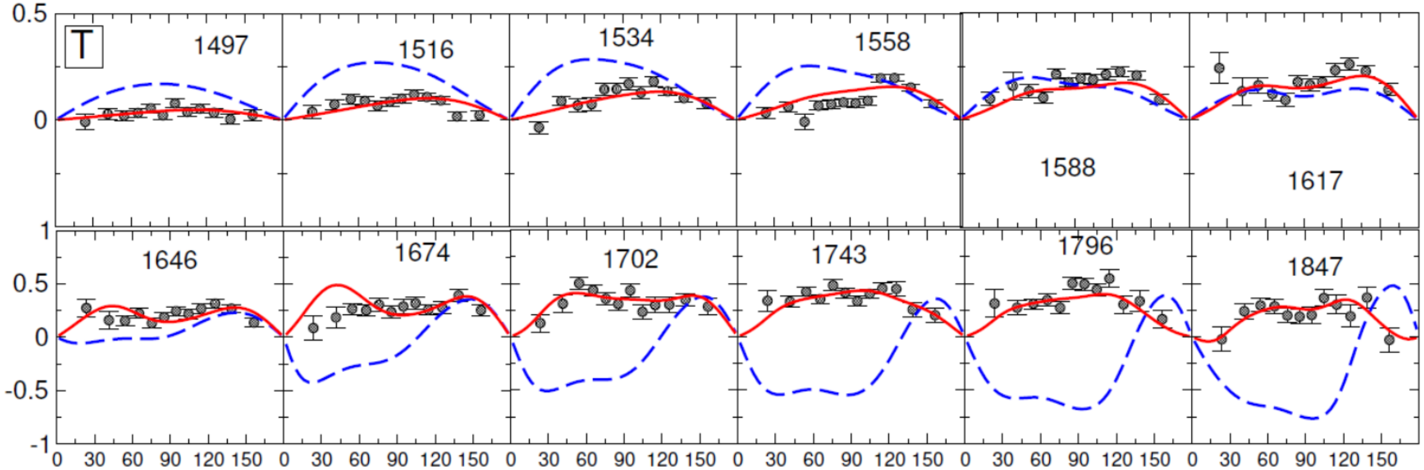
CLAS/BnGa/JuBo/SAID, PLB **750** (2015)



→ 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)

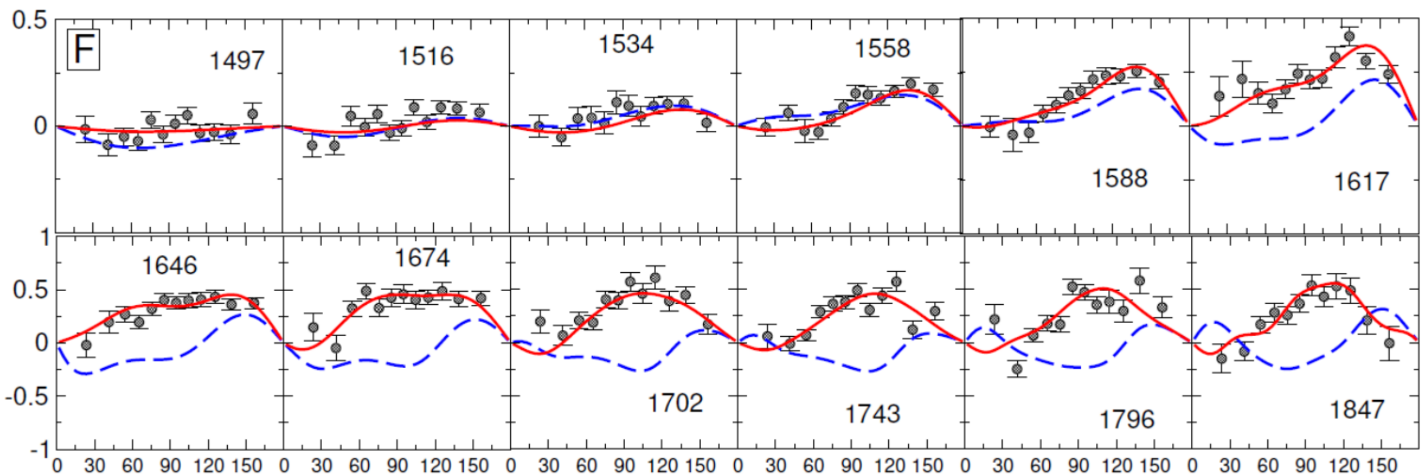
Data: Akondi *et al.* (A2 at MAMI) PRL 113, 102001 (2014)



prediction

fit

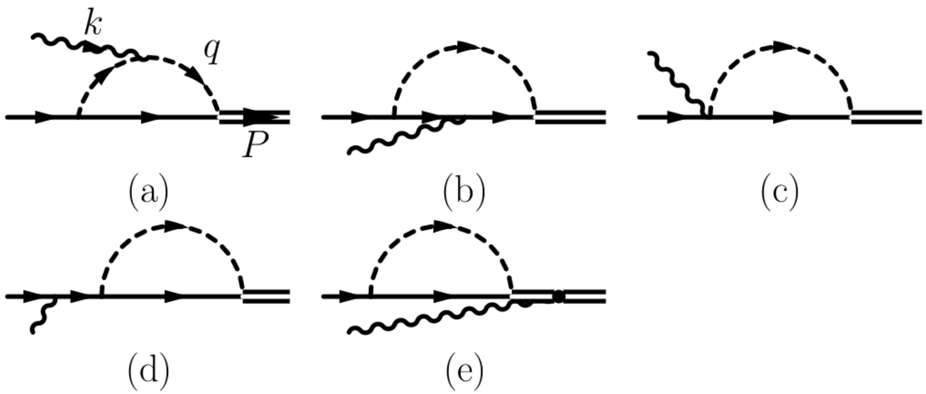
Beam	Target	Recoil
0	$+y$	0
0	$-y$	0



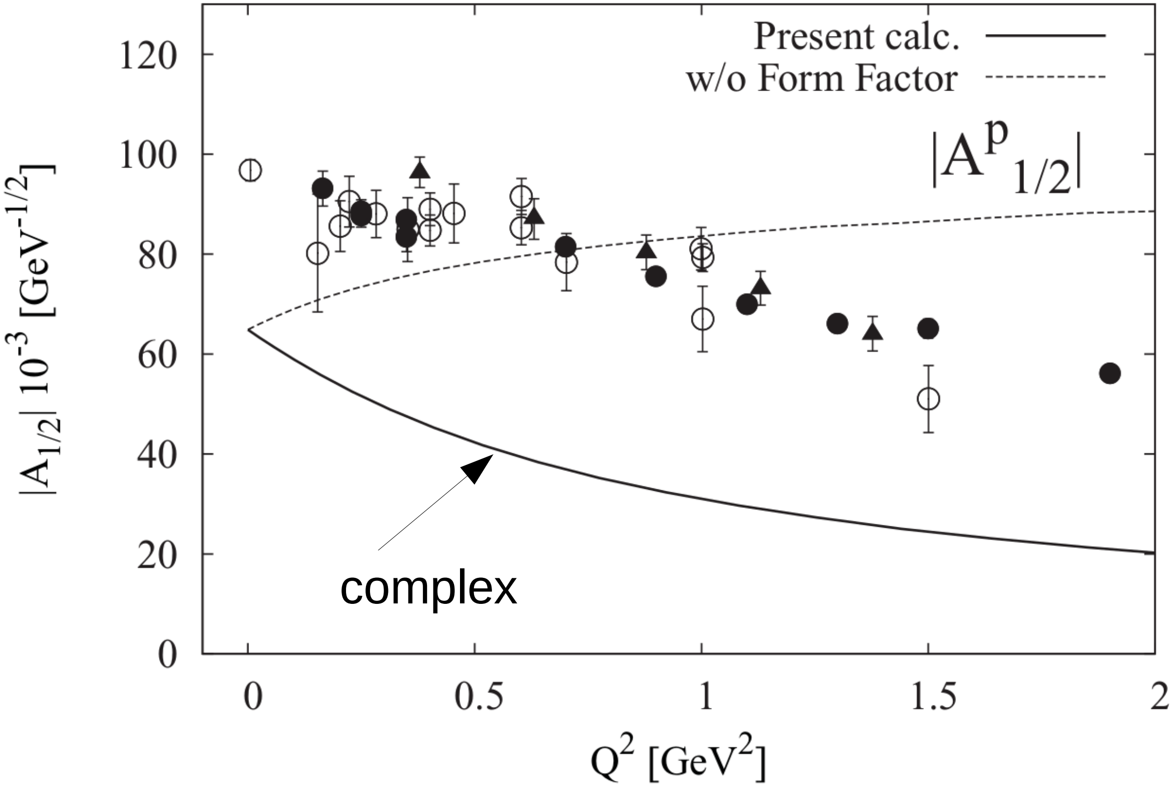
Beam	Target	Recoil
$+1$	$+x$	0
-1	$+x$	0

Older, more incomplete Chiral unitary prediction

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



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

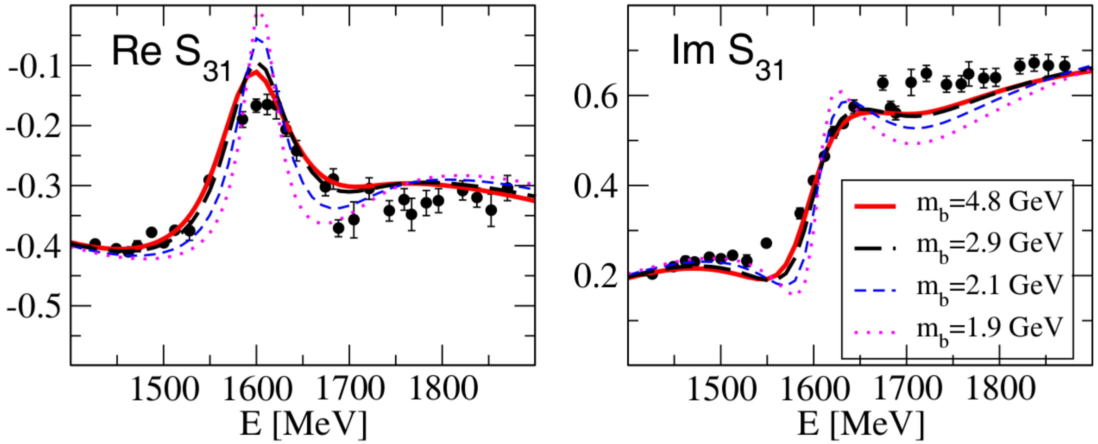


Discrepancy: Genuine problem or due to different definitions?

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

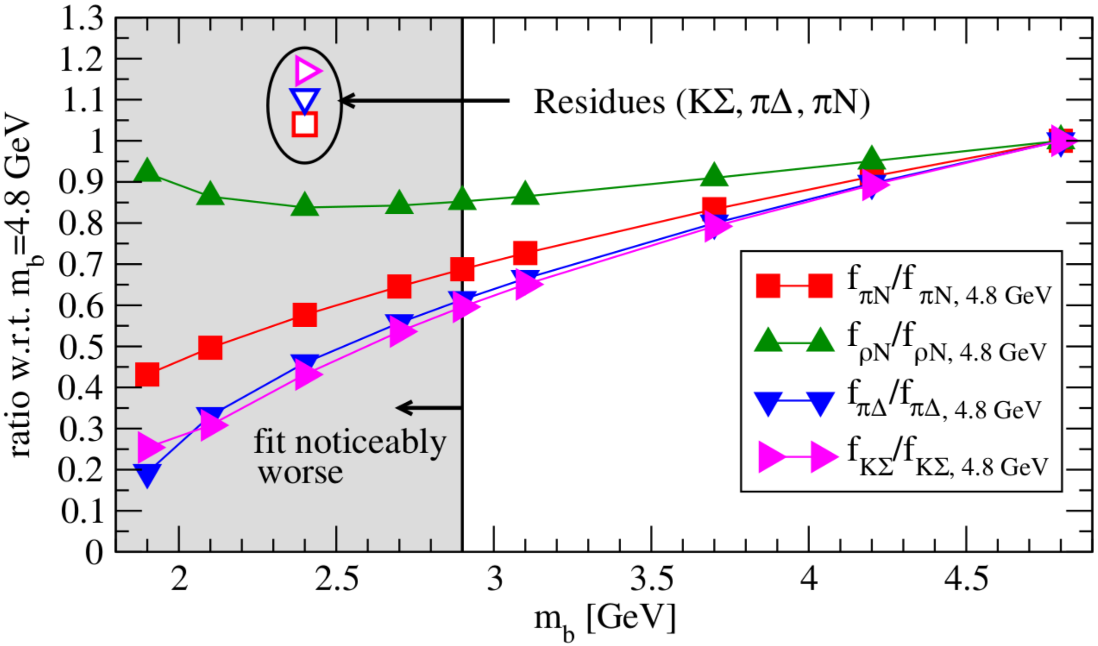
Input parameters and their stability

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

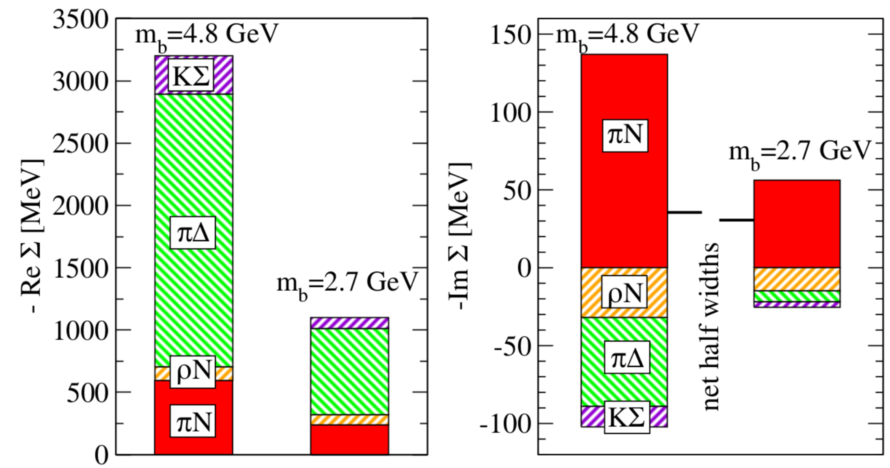


Force bare mass of $\Delta(1600)$
to fixed value; refit full data base

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

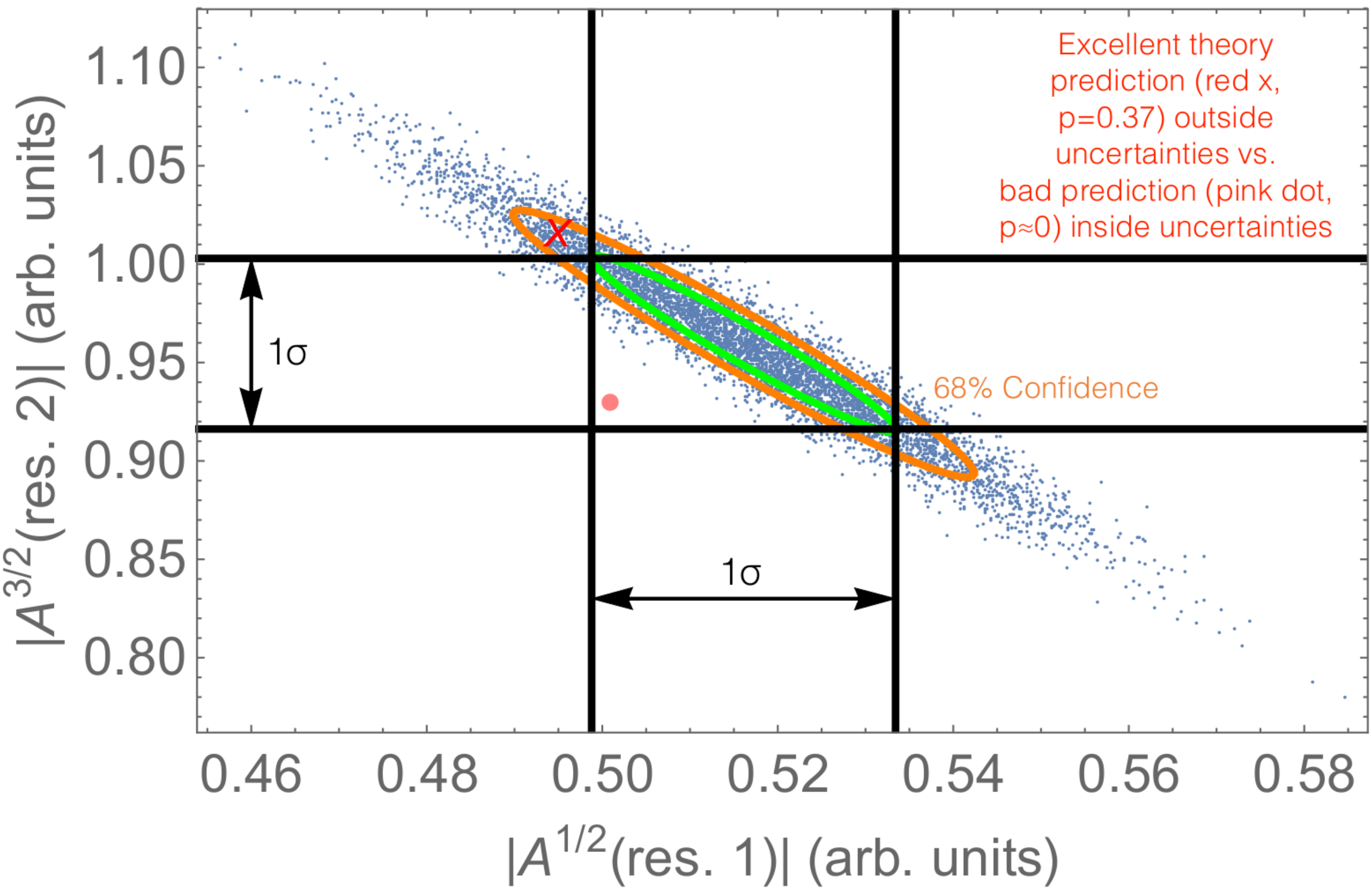


Self energy:



How to quantify the impact of new measurements?

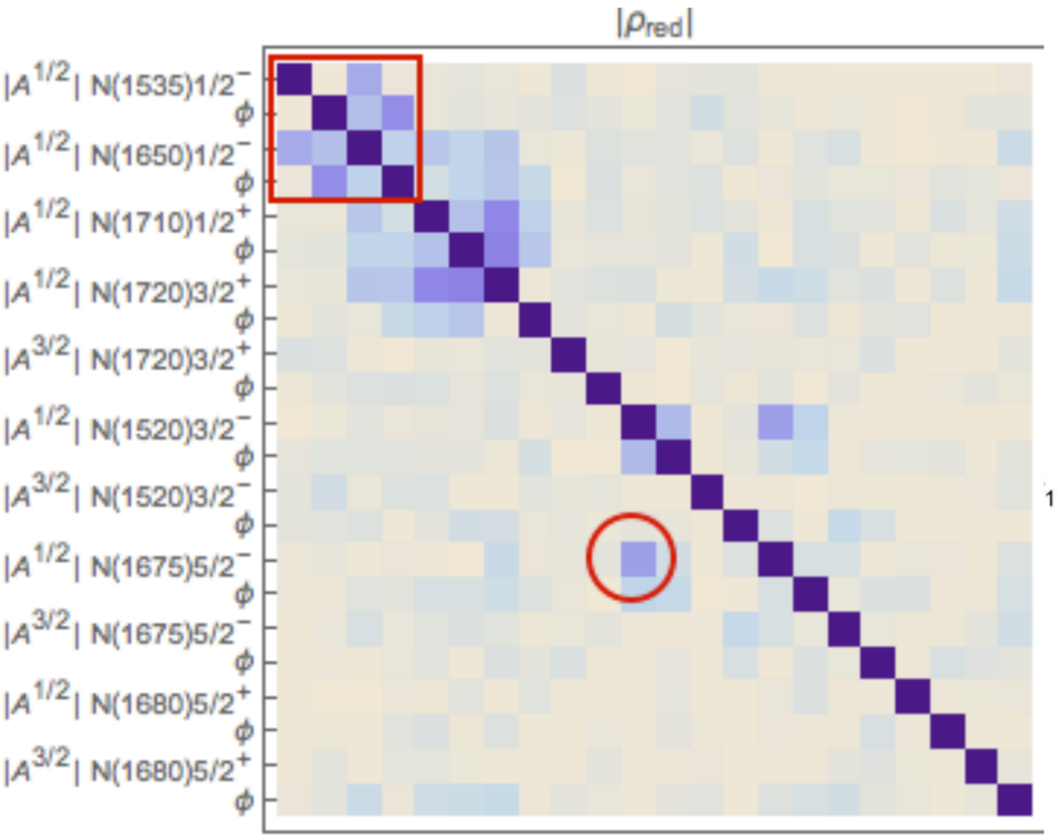
Consider correlations of helicity couplings extracted from experiment

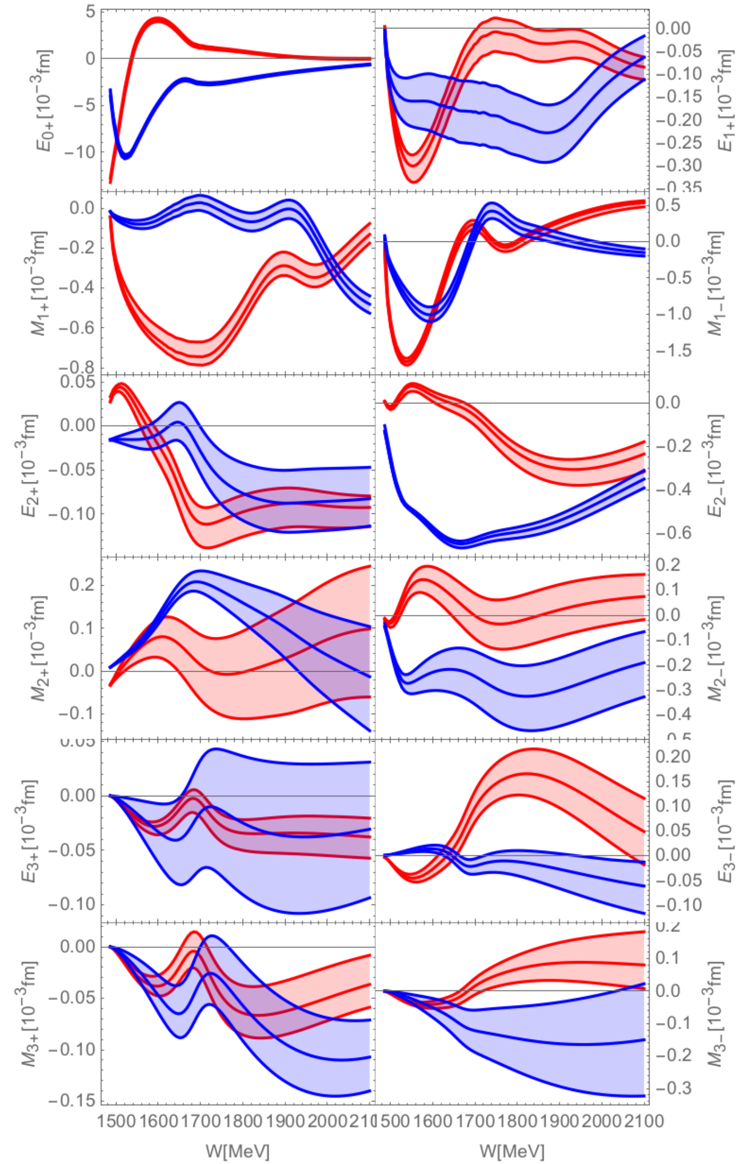


Results from analysis of world data of η photoproduction

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

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





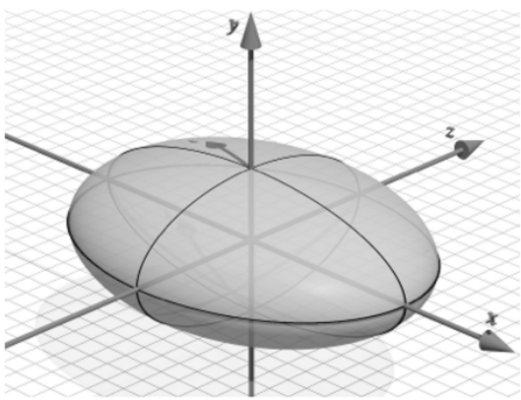
Bulk properties of uncertainties from different data sets

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

The Jülich approach – Principles from scattering theory

[M.D., Haberzettl, Hanhart, Huang, Krewald, Meißner, Nakayama, Rönchen]

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

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