Theory Overview on Baryon Spectroscopy

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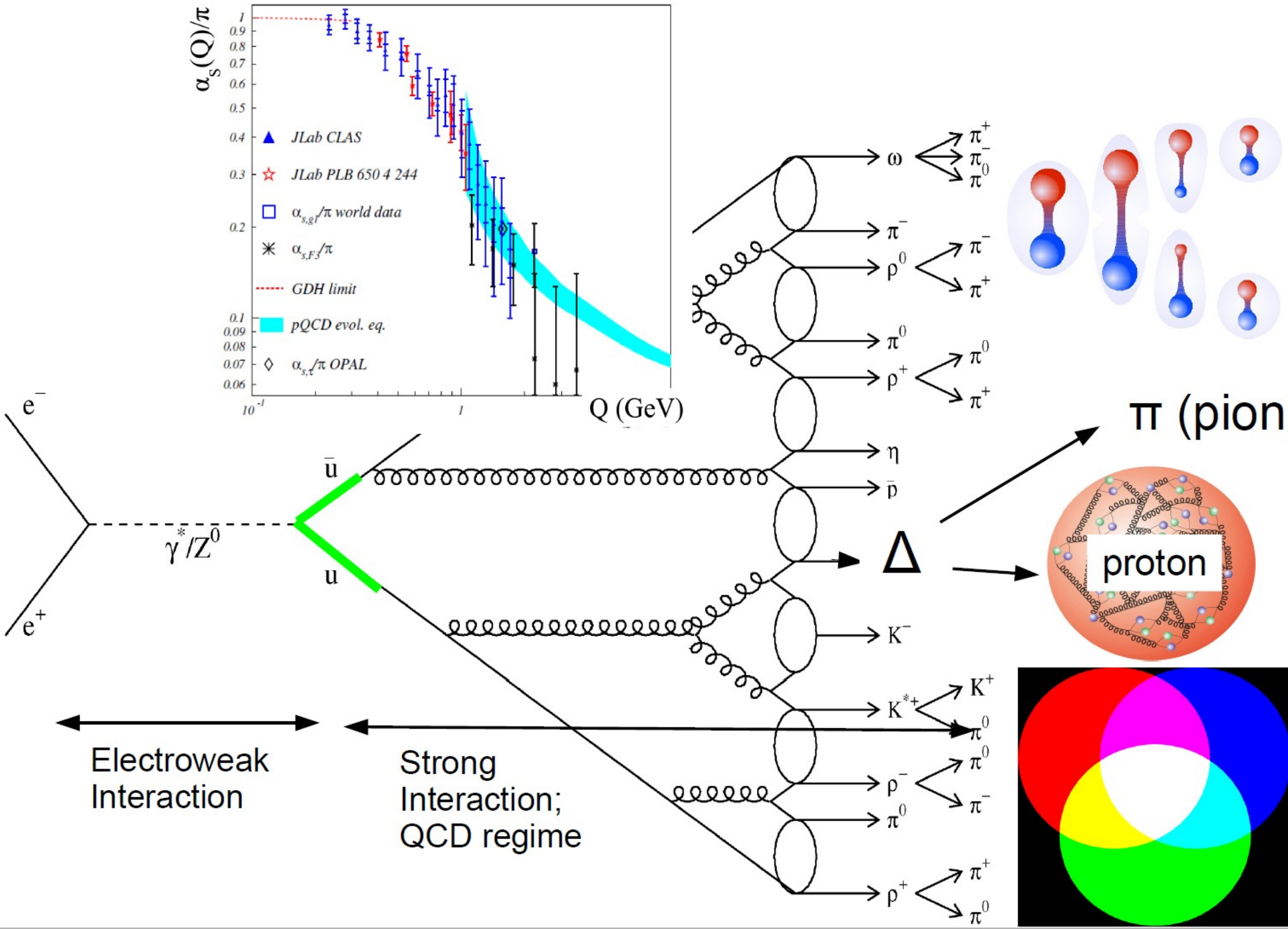
Disclaimers

- Tremendous progress in Baryon Spectroscopy in the last 7 years, experimentally and theoretically → Limit on material.
- Pion electroproduction: Successes in determination of helicity couplings and DSE→ R. Gothe
- Helicity couplings from one- and two-pion electroproduction consistently extracted → V. Mokeev.
- $K\bar{K}$ photoproduction, excited Λ^*, Σ^*→ L. Guo
- Two-pion photoproduction at CLAS [USC, FSU]
- ω photoproduction, event-based resonance analysis

  [M. Williams et al., 2009]

Why study baryons?

The intermediate energy region...



Baryons: The matter we are made of; structure obviously related to color degrees of freedom; flavor pattern in baryon ground states → quark model.

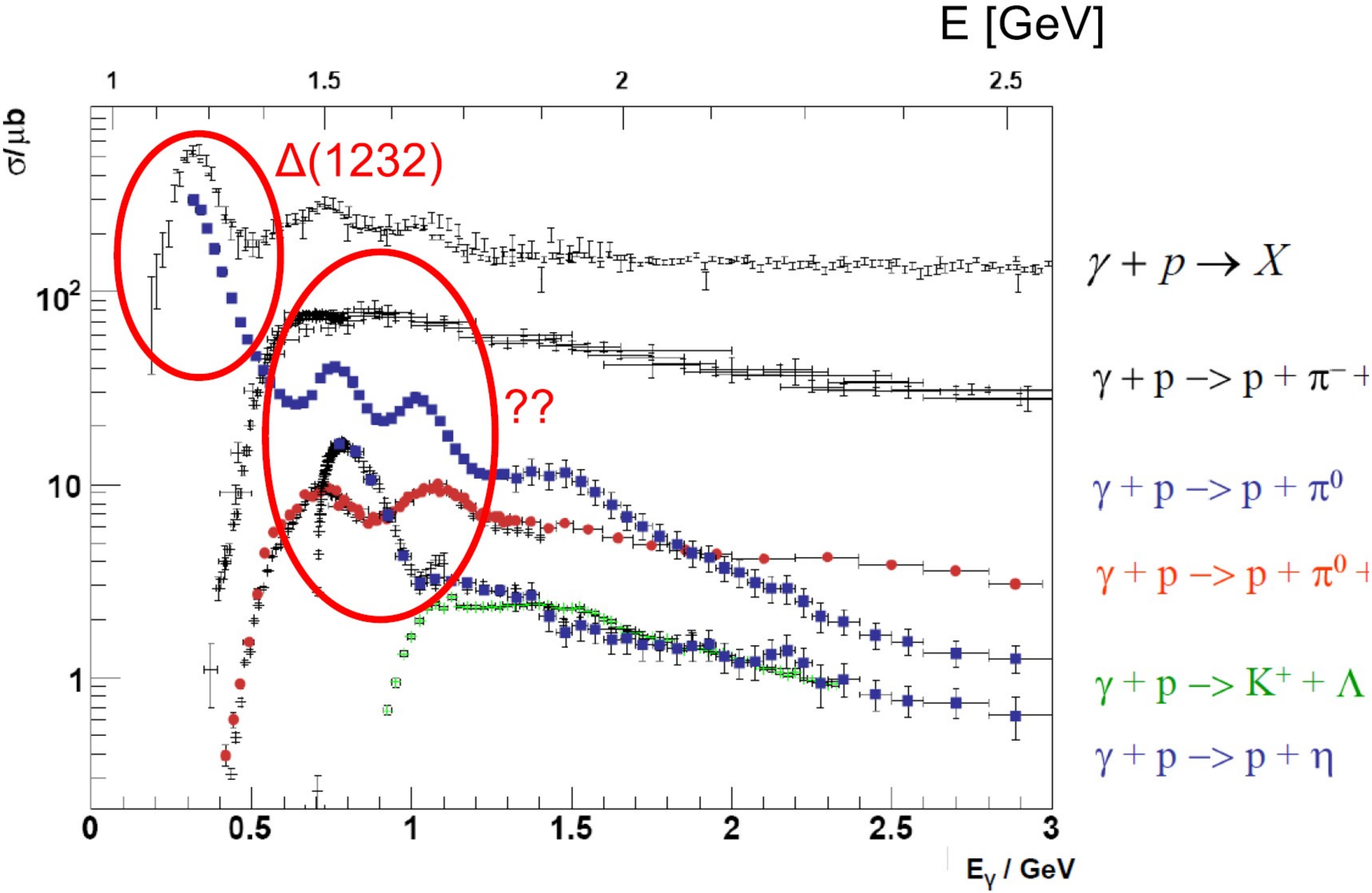
The baryon spectrum: N^* and Δ resonances

- Many resonances predicted in lattice calculations —
  Missing resonance problem from quark model reappears
  [Edwards *et al.*, Phys.Rev. D84 (2011)]:

$m_\pi = 396 MeV$ (!)

- Search for these states in dedicated experimental programs

Photoproduction cross sections



[data: JLab, ELSA, MAMI]

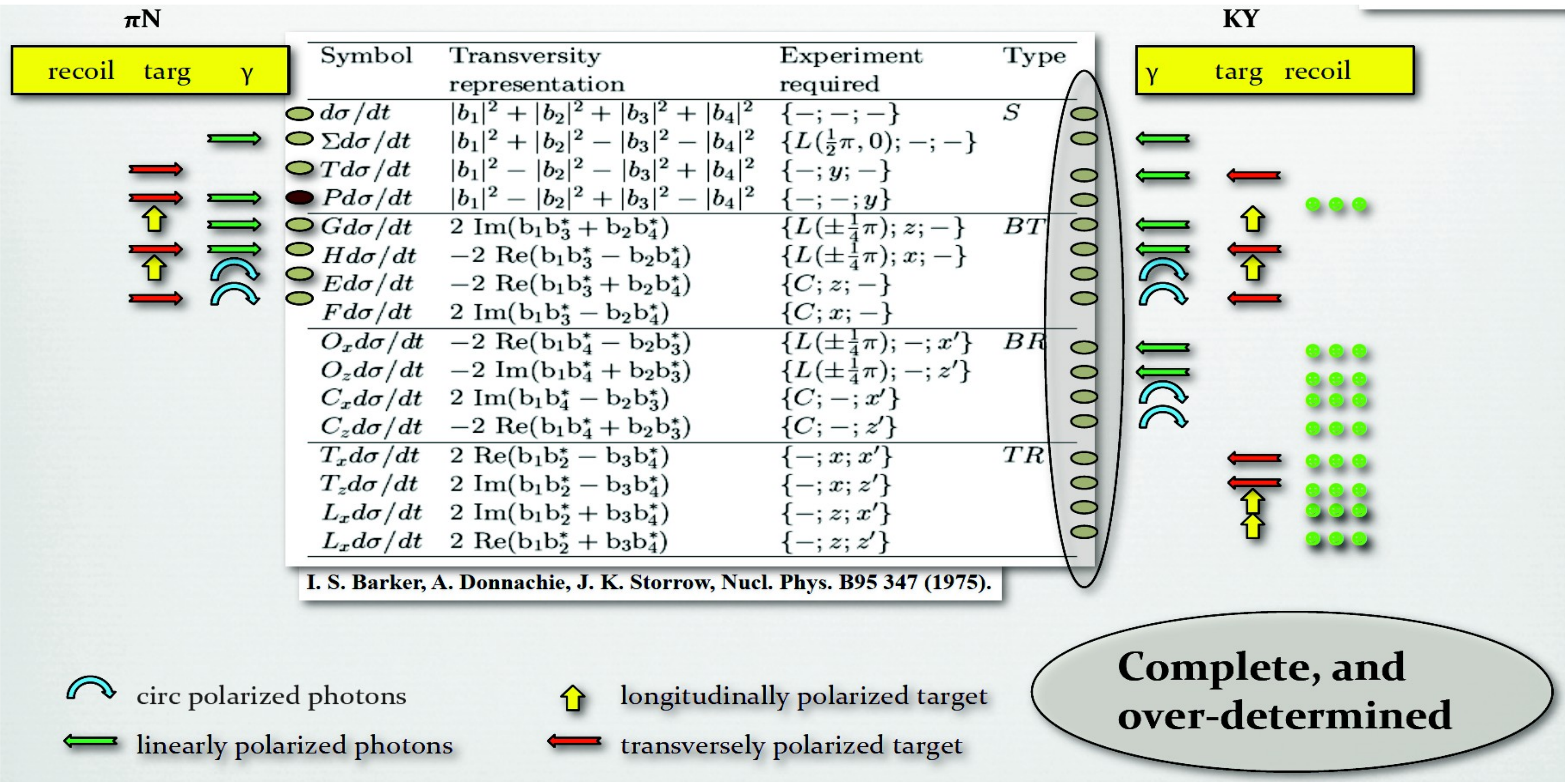
Multipole/PW analysis required

Highlights in Photoproduction
(2007 -)

- CLAS: Complete experiment for $\gamma p \to K^+\Lambda$

  The Λ is self-analyzing (recoil polarization observables)

- Complete experiment: Joint theoretical effort from US and Europe



Symbol	Transversity representation	Experiment required	Type
$d\sigma/dt$	$\lvert b_1\rvert^2+\lvert b_2\rvert^2+\lvert b_3\rvert^2+\lvert b_4\rvert^2$	$\{-;-;-\}$	S
$\Sigma d\sigma/dt$	$\lvert b_1\rvert^2+\lvert b_2\rvert^2-\lvert b_3\rvert^2-\lvert b_4\rvert^2$	$\{L(\frac{1}{2}\pi,0);-;-\}$	
$Td\sigma/dt$	$\lvert b_1\rvert^2-\lvert b_2\rvert^2-\lvert b_3\rvert^2+\lvert b_4\rvert^2$	$\{-;y;-\}$	
$Pd\sigma/dt$	$\lvert b_1\rvert^2-\lvert b_2\rvert^2+\lvert b_3\rvert^2-\lvert b_4\rvert^2$	$\{-;-;y\}$	
$Gd\sigma/dt$	$2\ \mathrm{Im}(b_1b_3^*+b_2b_4^*)$	$\{L(\pm\frac{1}{4}\pi);z;-\}$	BT
$Hd\sigma/dt$	$-2\ \mathrm{Re}(b_1b_3^*-b_2b_4^*)$	$\{L(\pm\frac{1}{4}\pi);x;-\}$	
$Ed\sigma/dt$	$-2\ \mathrm{Re}(b_1b_3^*+b_2b_4^*)$	$\{C;z;-\}$	
$Fd\sigma/dt$	$2\ \mathrm{Im}(b_1b_3^*-b_2b_4^*)$	$\{C;x;-\}$	
$O_xd\sigma/dt$	$-2\ \mathrm{Re}(b_1b_4^*-b_2b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;x'\}$	BR
$O_zd\sigma/dt$	$-2\ \mathrm{Im}(b_1b_4^*+b_2b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;z'\}$	
$C_xd\sigma/dt$	$2\ \mathrm{Im}(b_1b_4^*-b_2b_3^*)$	$\{C;-;x'\}$	
$C_zd\sigma/dt$	$-2\ \mathrm{Re}(b_1b_4^*+b_2b_3^*)$	$\{C;-;z'\}$	
$T_xd\sigma/dt$	$2\ \mathrm{Re}(b_1b_2^*-b_3b_4^*)$	$\{-;x;x'\}$	TR
$T_zd\sigma/dt$	$2\ \mathrm{Im}(b_1b_2^*-b_3b_4^*)$	$\{-;x;z'\}$	
$L_xd\sigma/dt$	$2\ \mathrm{Im}(b_1b_2^*+b_3b_4^*)$	$\{-;z;x'\}$	
$L_xd\sigma/dt$	$2\ \mathrm{Re}(b_1b_2^*+b_3b_4^*)$	$\{-;z;z'\}$	

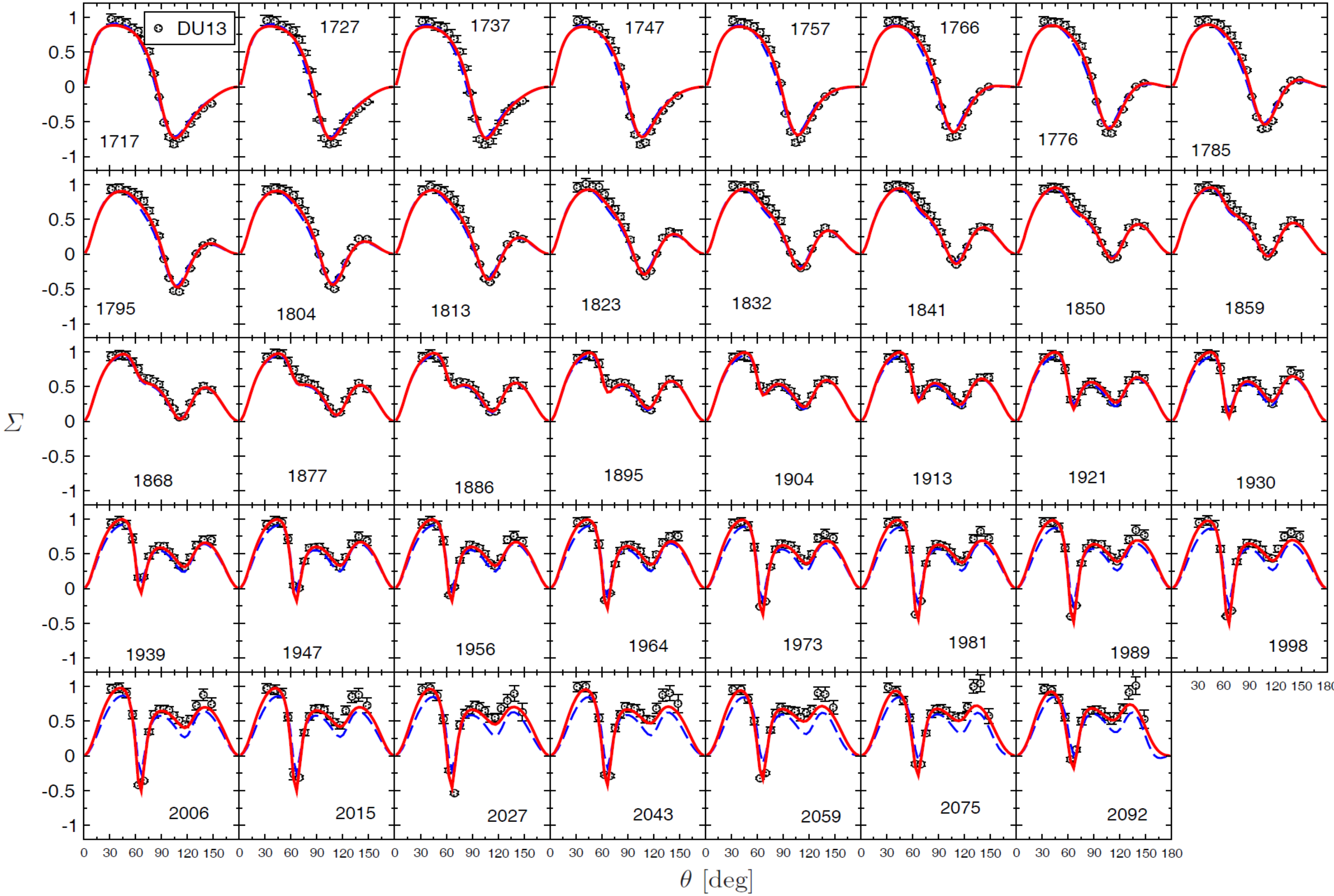
I. S. Barker, A. Donnachie, J. K. Storrow, Nucl. Phys. B95 347 (1975).

transparency: Pasyuk

Selected CLAS results: Beam asymmetry

$\gamma p \rightarrow \pi^0 p$

Dugger et. al, 2013 (including analysis by SAID)



Analysis: Jülich [D. Rönchen, M. D. et al., 2014]

Spectroscopy

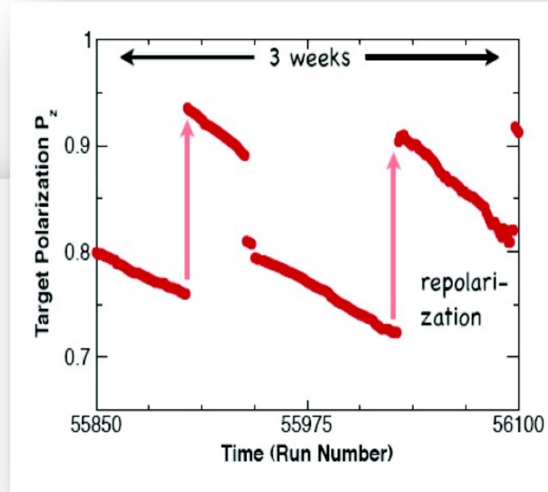
- New resonances mostly from Kaon photoproduction
- by Bonn Gatchina partial wave analysis

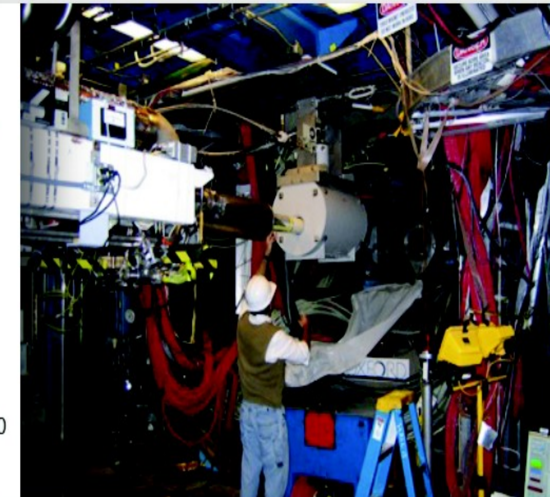
  (PDG accepted)

J^P	Resonance region			
$1/2^+$	$N(1440)$****	$N(1710)$***	$\boldsymbol{N(1880)}$**	$\boldsymbol{N(2100)}$*
$1/2^-$	$N(1535)$****	$N(1650)$****	$\boldsymbol{N(1895)}$**	
$3/2^+$		$N(1720)$****	$N(1900)$***	$\boldsymbol{N(2040)}$*
$3/2^-$	$N(1520)$****	$N(1700)$***	$\boldsymbol{N(1875)}$***	$\boldsymbol{N(2120)}$**
$5/2^+$		$N(1680)$****	$\boldsymbol{N(1860)}$**	$N(2000)$**
$5/2^-$		$N(1675)$****		$\boldsymbol{N(2060)}$**
$3/2^-$		$\Delta(1700)$***	$\Delta(1940)$**	

- Suggest parity doublets –whereas recent LQCD calculations [HadronSpectrum collaboration] see rather $SU(6) \otimes O(3)$ symmetry pattern of the quark model (at unphysical quark masses); diquark QM picture questionable.
- Confirmation through independent PWA needed.

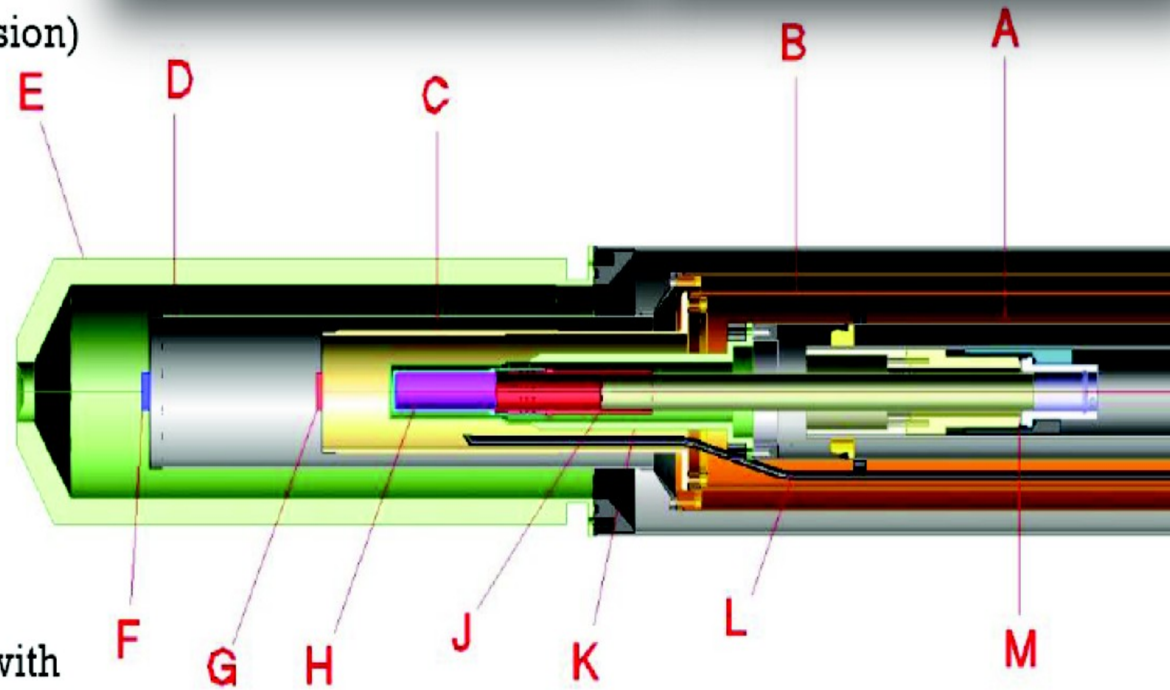
FROST
Frozen Spin Target





The FroST target and its components:

A: Primary heat exchanger
B: 1 K heat shield
C: Holding coil
D: 20 K heat shield
E: Outer vacuum can (Rohacell extension)
F: CH2 target
G: Carbon target
H: Butanol target
J: Target insert
K: Mixing chamber
L: Microwave waveguide
M: Kapton coldseal

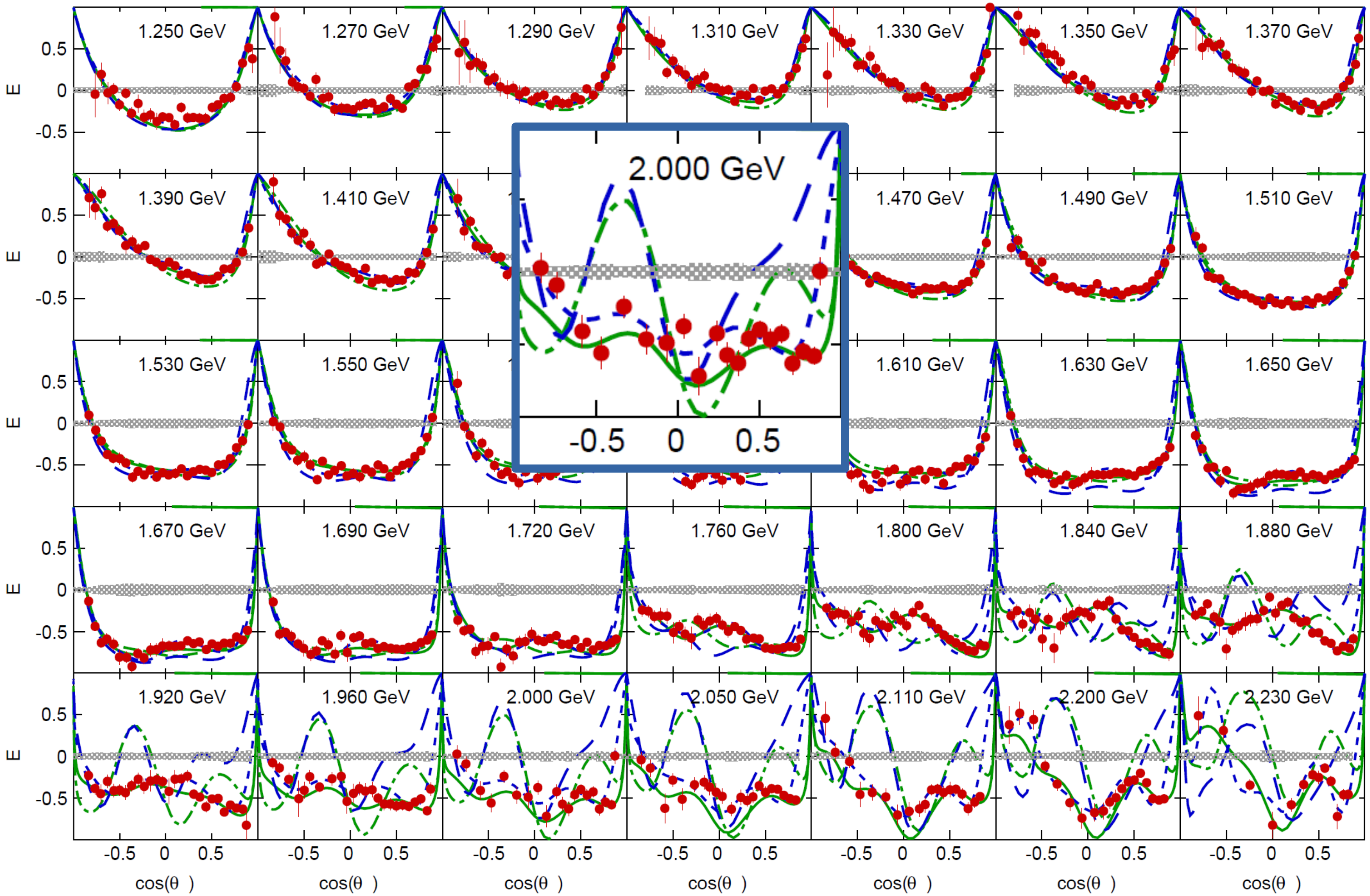


Performance Specs:

Base Temp: 28 mK w/o beam, 30 mK with
Cooling Power: 800 μW @ 50 mK, 10 mW @ 100 mK, and 60 mW @ 300 mK
Polarization: +82%, -90%
1/e Relaxation Time: 2800 hours (+Pol), 1600 hours (-Pol)
Roughly 1% polarization loss per day.

Transparency: E. Pasyuk

The first FROST result: *E* in $\vec{\gamma}\vec{p} \rightarrow \pi^+ n$



Data: CLAS (USC/Strauch et al.); preliminary

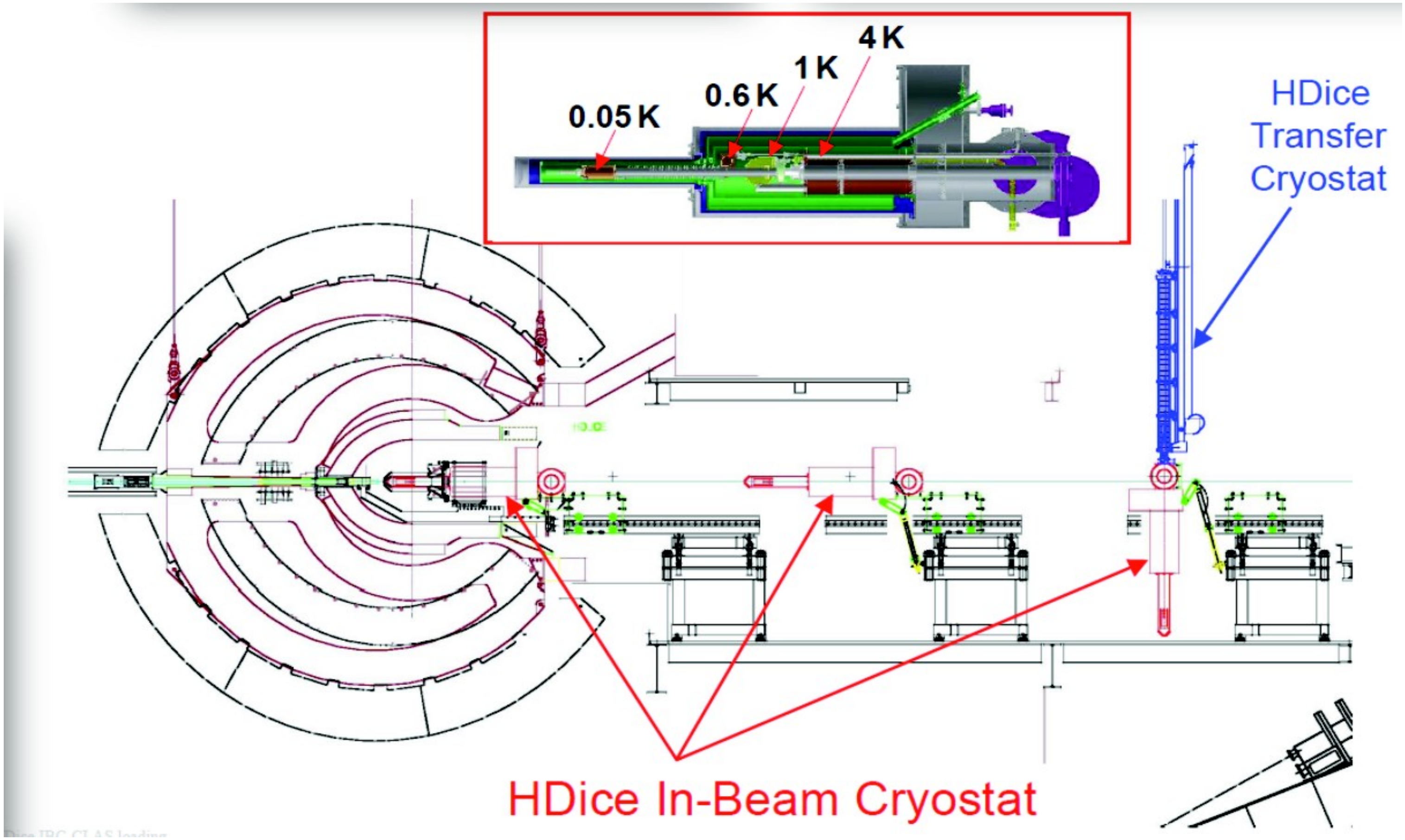
SAID analysis (prediction and re-analysis)

Jülich Athens Washington (prediction and re-analysis)

→ Significant changes of helicity amplitudes $A^{1/2}, A^{3/2}$

HD-ICE: Access to neutron multipoles

Activity at GWU/SAID: Disentangle deuteron effects!



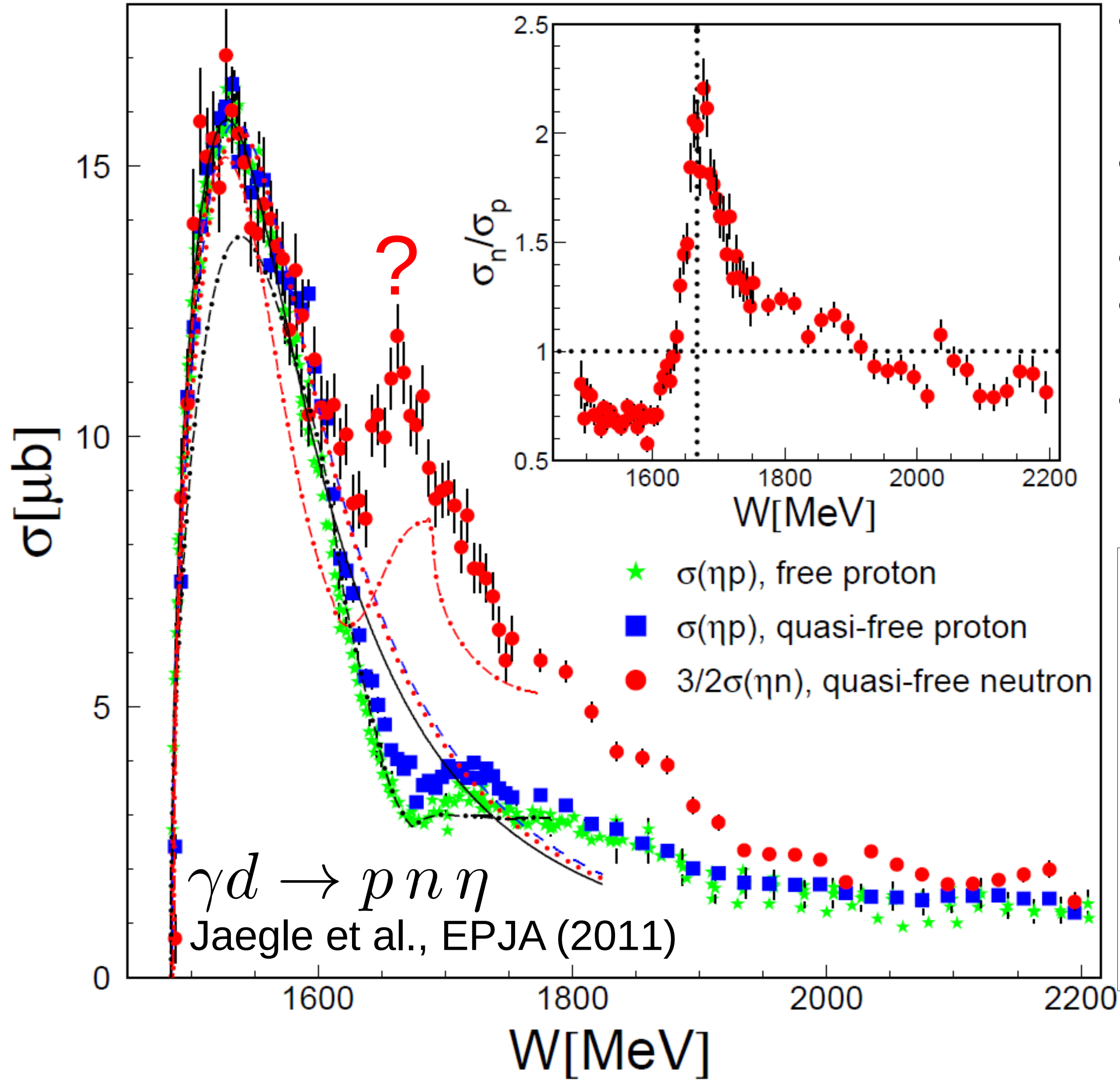
Transparency: E. Pasyuk

Past, Present and Future of Photoproduction Data from CLAS

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
Proton target																
$p\pi^0$	✔ (red)	✔ (green)	✔ (green)	✔ (white)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$n\pi^+$	✔ (red)	✔ (green)	✔ (green)	✔ (white)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$p\eta$	✔ (red)	✔ (green)	✔ (green)	✔ (white)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$p\eta'$	✔ (red)	✔ (green)	✔ (green)	✔ (white)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$K^+\Lambda$	✔ (red)	✔ (green)	✔ (green)	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (red)	✔ (red)
$K^+\Sigma^0$	✔ (red)	✔ (green)	✔ (green)	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (red)	✔ (red)
$K^{0*}\Sigma^+$	✔ (red)	✔ (green)	✔ (green)	✔ (white)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
"Neutron" target																
$p\pi^-$	✔ (red)	✔ (green)	✔ (green)		✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$K^+\Sigma^-$	✔ (red)	✔ (green)	✔ (green)		✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$K^0\Lambda$	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (white)	✔ (white)	✔ (white)	✔ (white)	✔ (white)	✔ (white)	✔ (green)	✔ (green)
$K^0\Sigma^0$	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (white)	✔ (white)	✔ (white)	✔ (white)	✔ (white)	✔ (white)	✔ (green)	✔ (green)

✔ (red) - published ✔ (green) - acquired

Highlights from MAMI (A2)

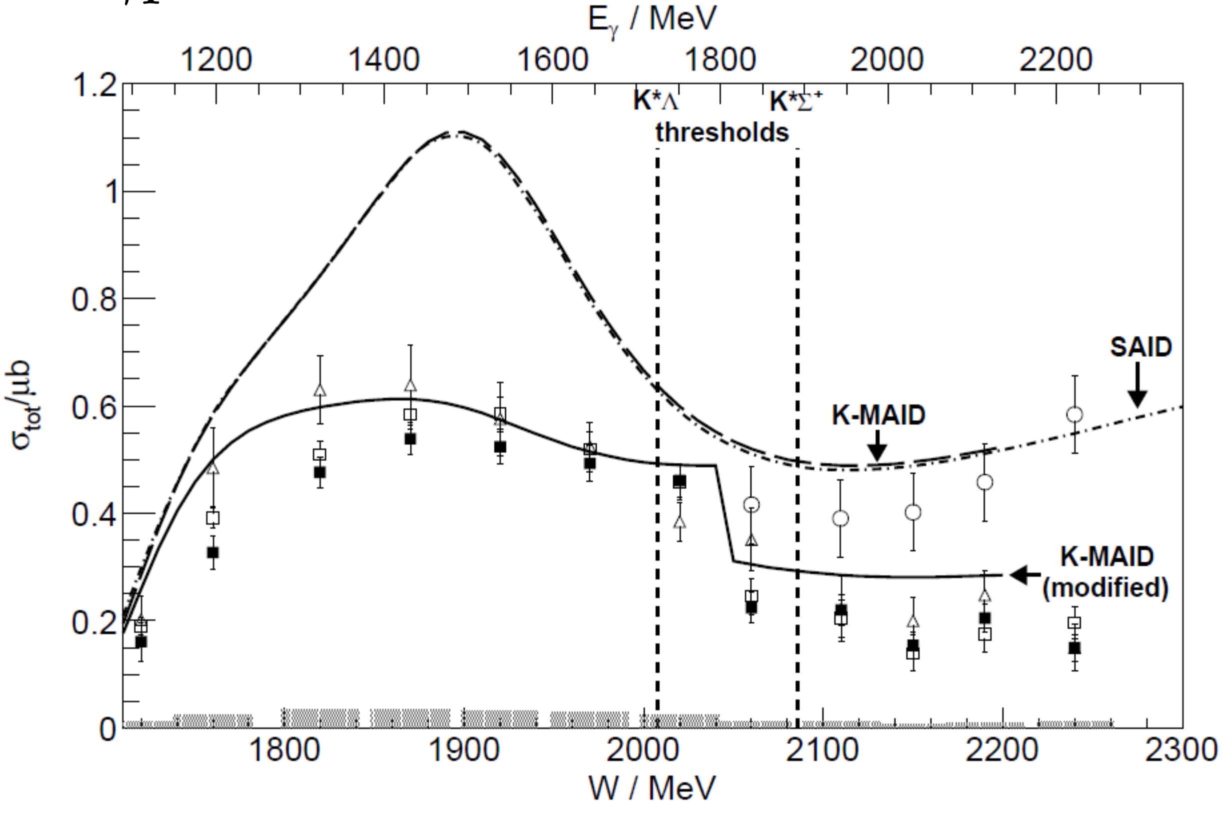


- "*N(1685)*": large couplings to $\gamma n,\ \eta n$
- Pentaquark? [Prediction Polyakov et al.]
- Unusual combination of neutron
- helicity couplings? [BnGa]
- Coupled channel chiral dynamics from $K\Lambda,\ K\Sigma$? [M.D. et al.]

- MAMI: Especially designed for neutral final states.
- Excellent energy resolution & angular coverage
- $\pi^0 p$ final state needed for isospin decomposition in PWA; complementary to CLAS ($\pi^+ n$).
- Strong **involvement** of US physicists (GWU, KSU,...)

Highlights from ELSA

$\gamma p \to K^0 \Sigma^+$



- Sudden drop at W~2.05 GeV
- Dynamic effect
  [Ramos/Oset, PLB 2013]?
- CLAS, MAMI, ELSA: Strong complementary experimental program
- Joint data essential for partial wave analysis
- Still surprises in meson photoproduction.

CBELSA/TAPS [PLB 2012]

Inspiration for Theory

Chiral Unitary Approaches

[Borasoy, Bruns, Meißner, Nißler, EPJA 2007]

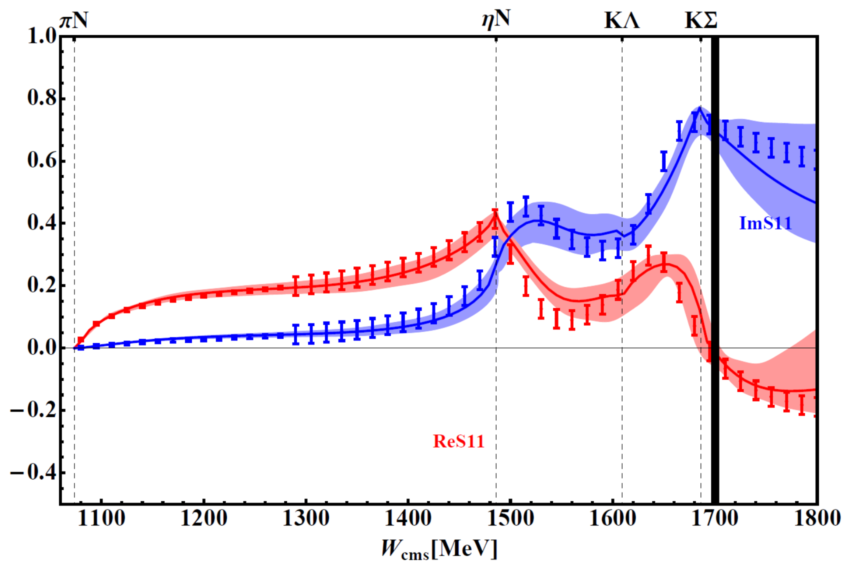
- Full 4-dimensional BSE structure respected
- Off-shell dependence of chiral transitions respected [see also Afnan/Lahiff 2002]
- NLO contact interactions
- Fully gauge invariant coupling of the photon

(to all vertices and propagators, in coupled channels)

Mai, Bruns, Meißner, Phys. Rev. D, 2012

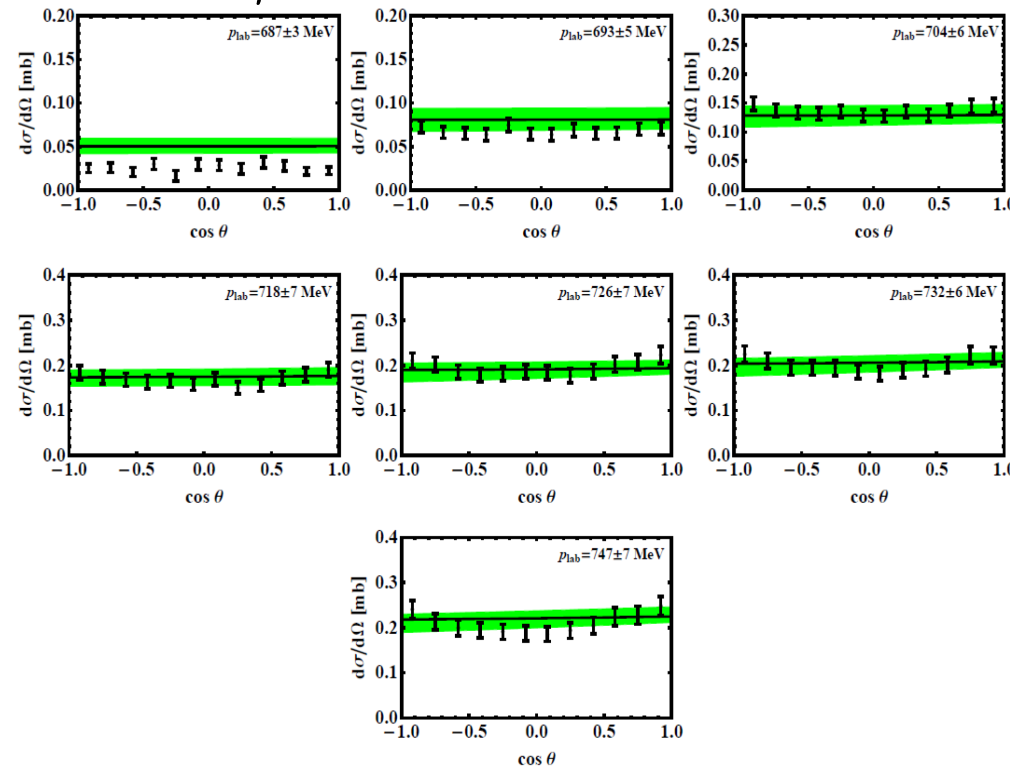
$\pi N \to \pi N$

"Data": SAID/GWU PWA (2006)

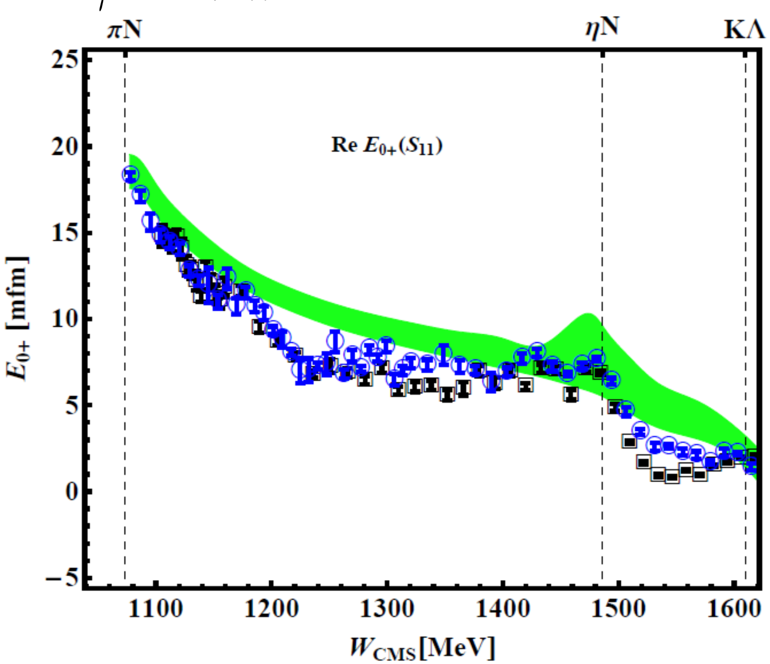


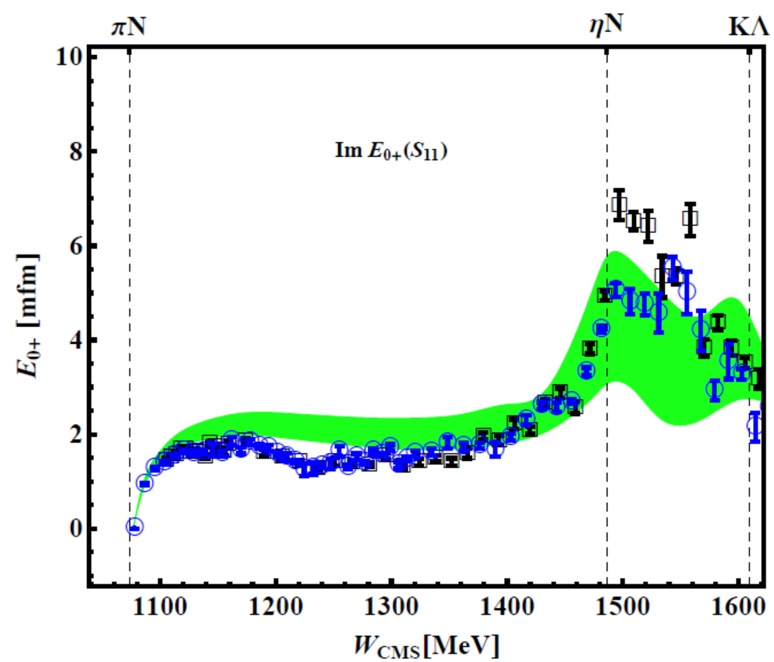
$\pi N \to \eta N$

Data: Prakhov et al. [Crystal Ball] (2005)



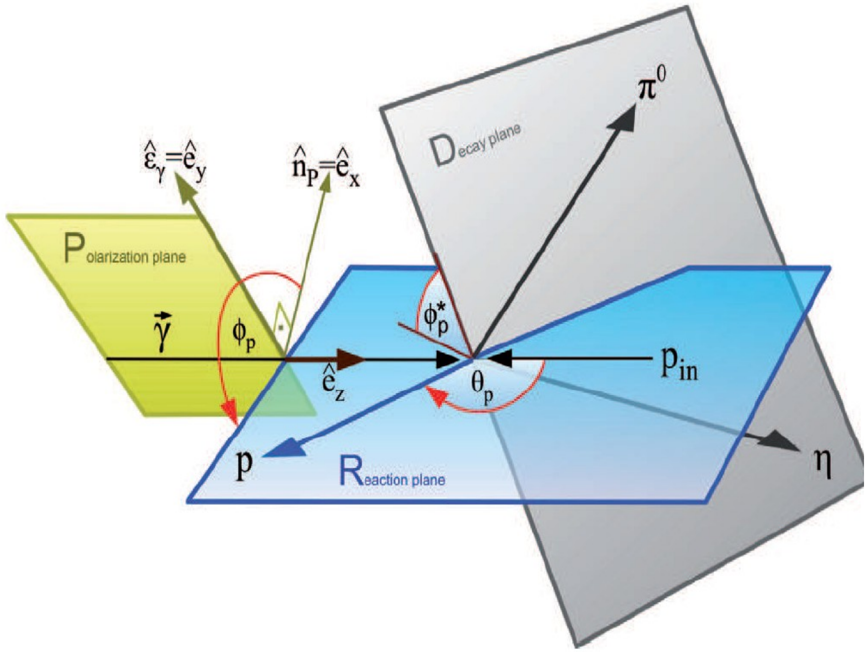
$\gamma N \to \pi N$ **Prediction**





"Data":
SAID, MAID

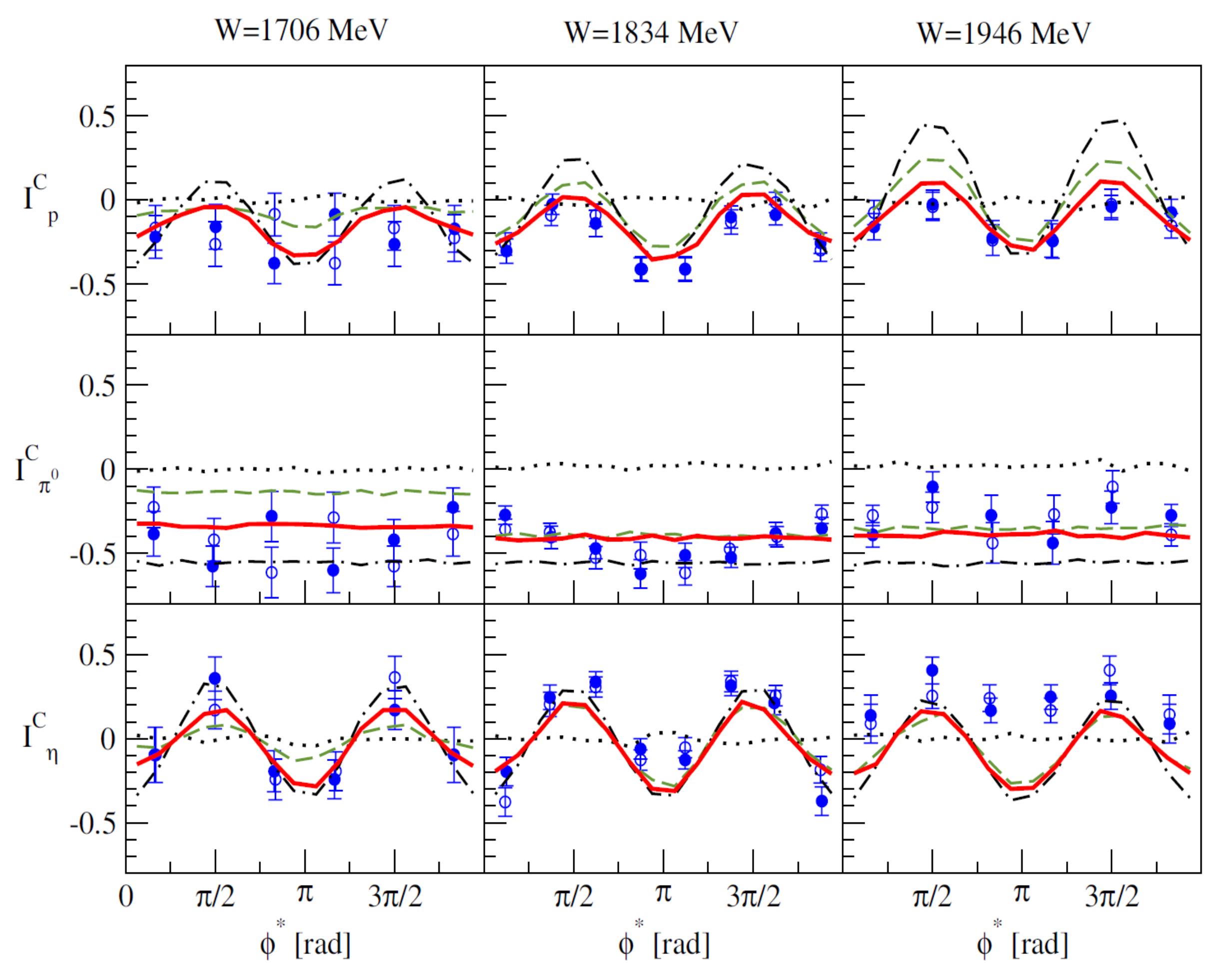
Two-meson Polarization observables $I^S, I^C[\gamma p \to \pi^0 \eta p]$



Chiral Unitary prediction
[M.D., Meißner, Oset, EPJA 46 (2010)]

large $J^P = 3/2^- \to \eta\Delta$

transition from UChiPT.



Data: CBELSA/TAPS [Gutz et al., PLB (2010)]

$1/N_c$ for baryons

[Goity, Calle Cordon, PRD 87 (2013)]

- Large N_c limit: there is a spin-flavor $SU(2\ N_f)$ symmetry
- In baryons, broken by subleading effects in $1/N_c$
- Applications to the baryon spectrum and to partial decay widths and photocouplings
- Predictive power by parameter independent relations at order $1/N_c$: e.g. mass relations.
- Imposes key constraints in BChPT leading to improvement of its convergence.

Baryon Analysis

Baryon Spectroscopy groups

- Unprecedented activity (random order):

➔ **SAID** [GW/INS: Briscoe, Strakovsky, Workman,...]

➔ **MAID** [Kamalov, Tiator,...]

➔ **EBAC** (Excited Baryon Analysis Center)

[Juliá Díaz, Kamano, Nakamura, Matsuyama, Sato, Lee, ...]

➔ **Jülich** (Athens, Washington)

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

➔ **Bonn Gatchina** [Anisovich, Nikonov, Sarantsev, Thoma,...]

Most comprehensive set of analyzed data

➔ **KSU** [Manley,...]

➔ **Giessen** [V. Shklyar]**, Zagreb** [Ceci, Svarc,...]**, …**

JPAC

JLAB
[Aznauryan, Burkert...]

GWU/SAID
[PRC 86 (2012)]

- Pioneers of baryon resonance analysis
- Coupled channel Chew-Mandelstam
- Most model-independent approach

  → Resonance generated by data
- Reference data base for the community
- Only group to fit data of $\pi N \to \pi N$

  → including Coulomb, forward-t dispersion relations
- NN,...
- Neutron target corrections of deuteron effects

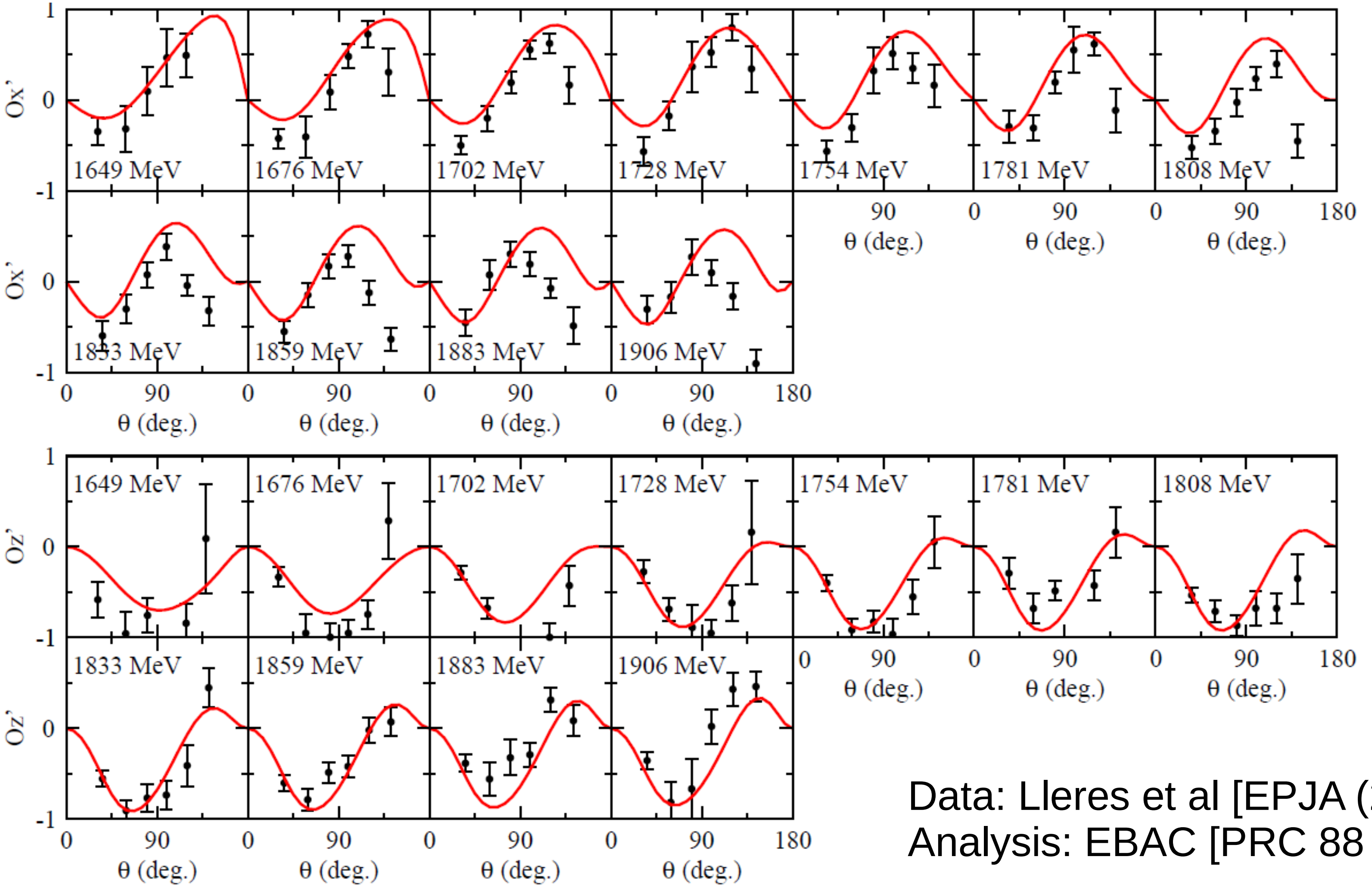
EBAC

[PRC 88 (2013)]

- 2007 – 2013, now: ANL/Osaka
- Analysis of
  $\pi N,\, \gamma N,\, \gamma^* N \to \pi N,\, \eta N,\, \pi\pi N\, (2007 - 2010),$
  $\pi N,\, \gamma N \to KY\, (2010 - 2014)$
- Dynamical coupled-channel approach
- Field theoretical formalism
- Current conserving photon coupling
- $\bar{K}$N, neutrino-nucleon (JPARC), 2013-
- EBAC collaboration meetings JLAB 2009/2011

EBAC and CLAS data

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



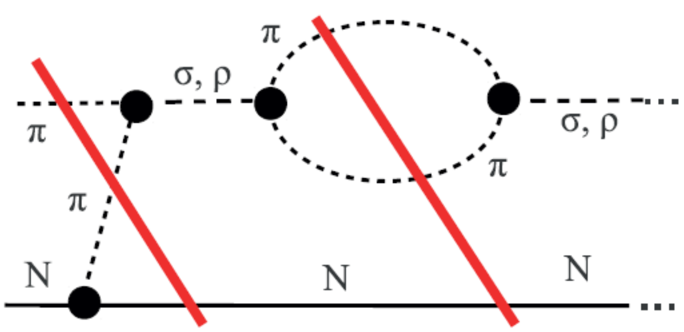
Data: Lleres et al [EPJA (2008)]
Analysis: EBAC [PRC 88 (2013)]

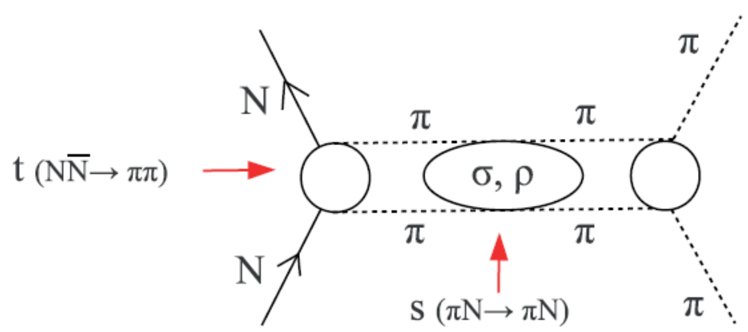
Jülich, Athens, Washington

[EPJA 50(2014)]

- Generalized Ward-Takahashi identity
- Fit of pion (finished) and $\eta N,\ KY$ photoproduction (in progress)
- Special attention to analytic properties
- Three-body unitarity (partial)

* Crossed channels



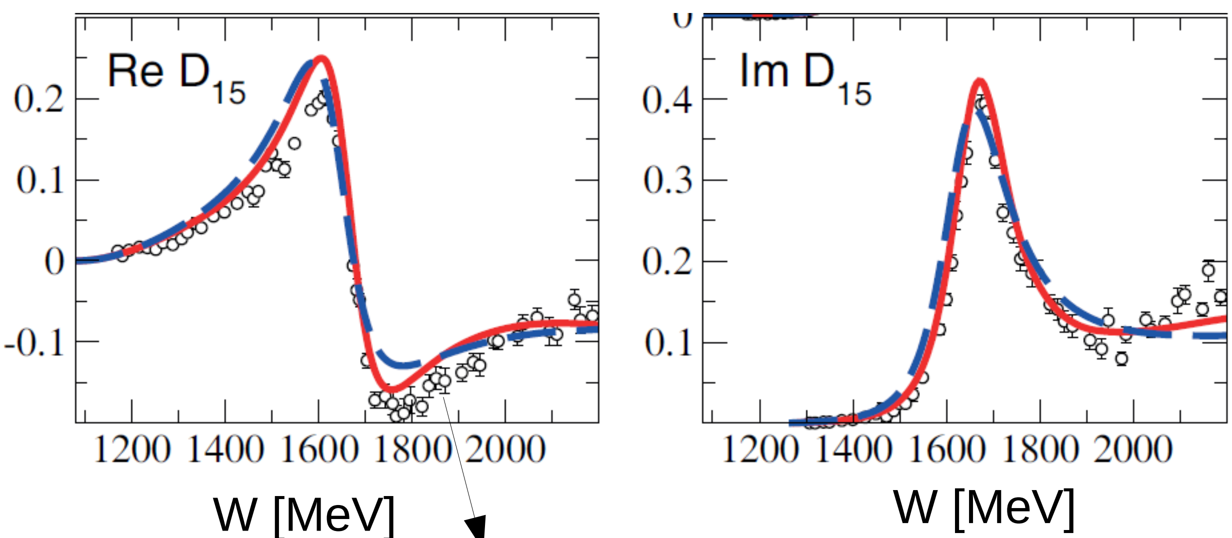


Challenges

* Discrepancies of different analyses (although results converge): What to do?
* Discrepancies in resonance pole properties (“masses” & “widths”) from
  - Different parameterizations
  - Different fit quality
  - Different set of studied reactions

- Error analysis and uncertainties:

  - Many analyses fit GWU/SAID elastic pion-nucleon scattering



Errors of single-energy solutions (SES) cannot be used to define χ^2

→ No statistical error analysis possible in multi-channel (photo)production fits

* Solution: Correlated χ^2 fits.

$$\chi^2 = (x - \bar{x})^T C^{-1} (x - \bar{x}) + \chi^2_{\rm best} + \text{corrections}$$

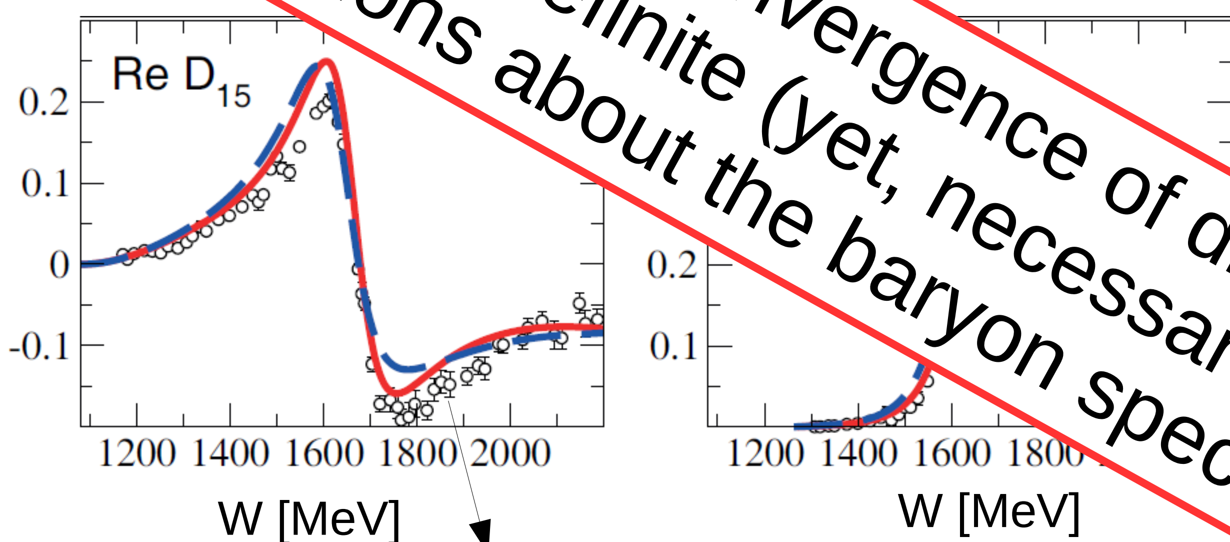
C: Correlations between SAID partial waves; x: PW by other group.

* Discrepancies of different analyses (although results converge): What to do?
* Discrepancies in resonance pole properties (“masses” & “widths”) from
  - Different parameterizations
  - Di… fit quality
  - D… of studied reactions

Work towards convergence of different analyses, to come to definite (yet, necessarily statistical) conclusions about the baryon spectrum

• … uncertainties:

- A… /SAID elastic pion-nucleon scattering



Errors of single-energy solutions (SE… …he χ^2

→ No statistical error analysis possible in multi-channel (photo)pr…

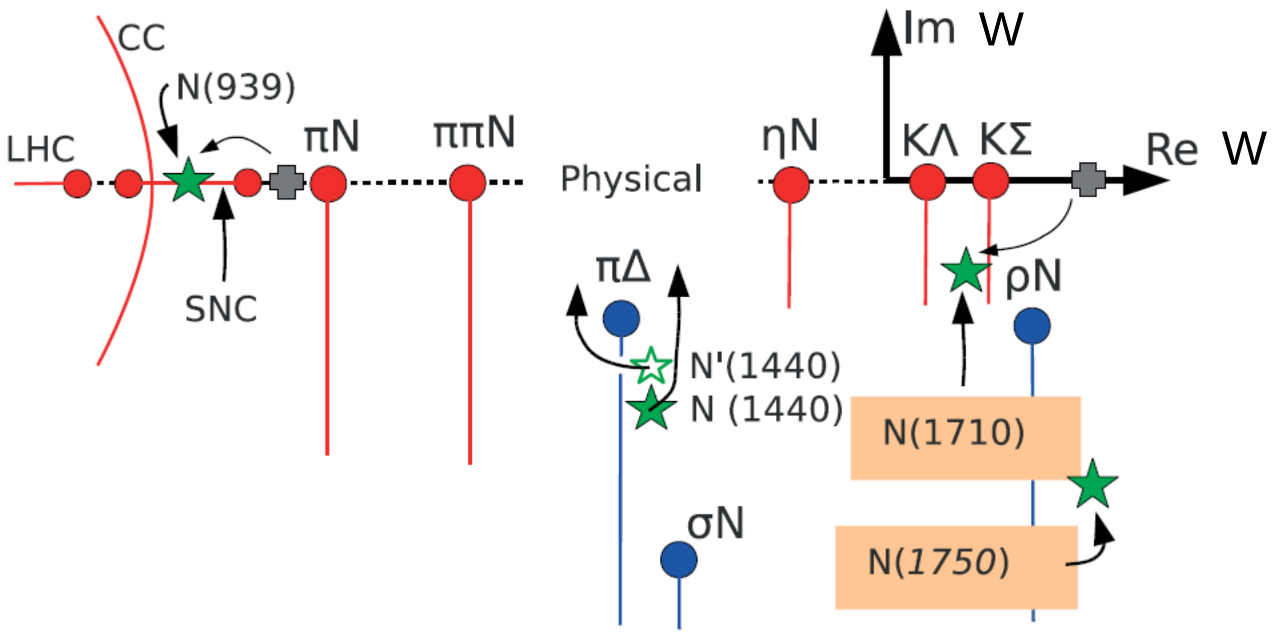
* Solution: SAID provides interface (based on correlation matrices) su… to SES by other groups leads to meaningful χ^2 .

$$\chi^2 = (x - \bar{x})^T C^{-1} (x - \bar{x}) + \chi^2_{\text{best}} + \text{corrections}$$

C: Correlations between partial waves; x: PW by other group.

Conceptual questions

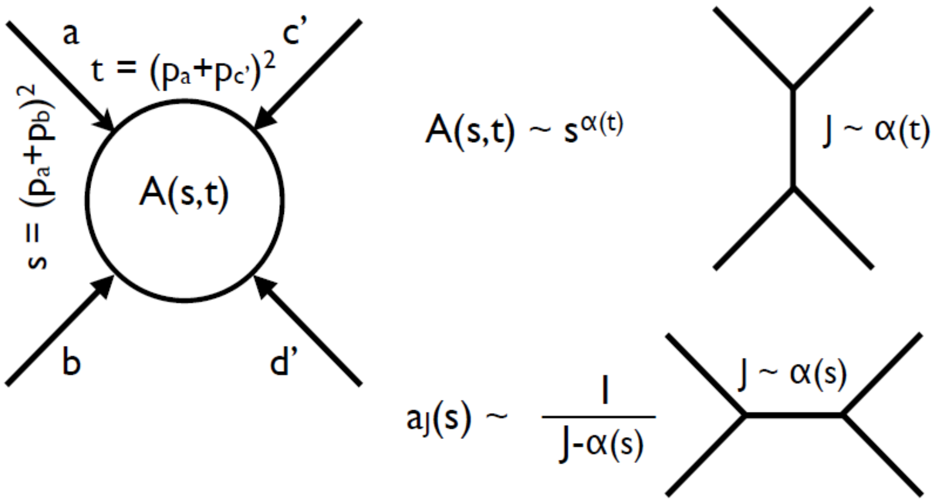
- Analytic structure of the scattering amplitude P11

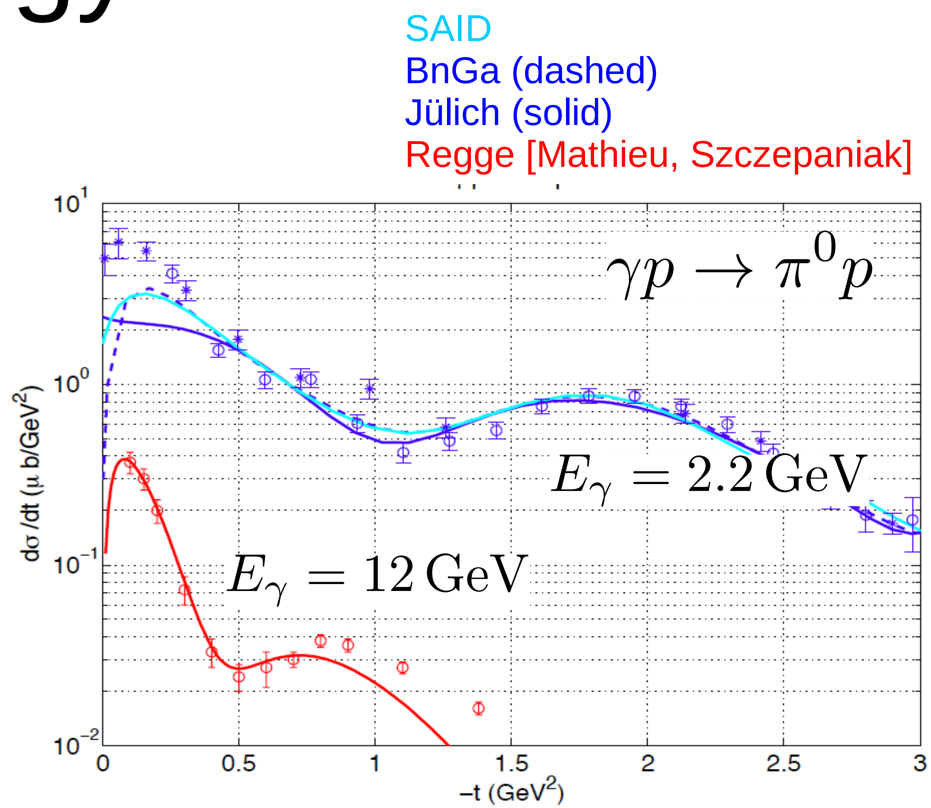


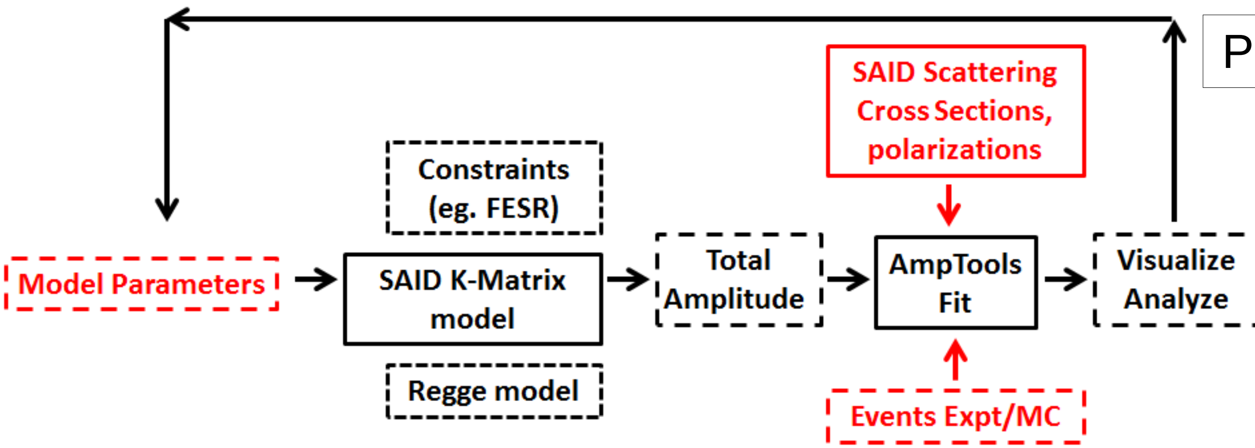
  - Parameterization should explicitly have all branch points
  - Strengths of these structures by Lagrangians (Dynamical Coupled Channels), OR
    polynomials in energy, complex mapping techniques ?
  - Dispersive constraints
  - Finite-energy sum rules (New developments at JPAC)

High-energy limit

- Regge description at high energies
- Challenge of matching





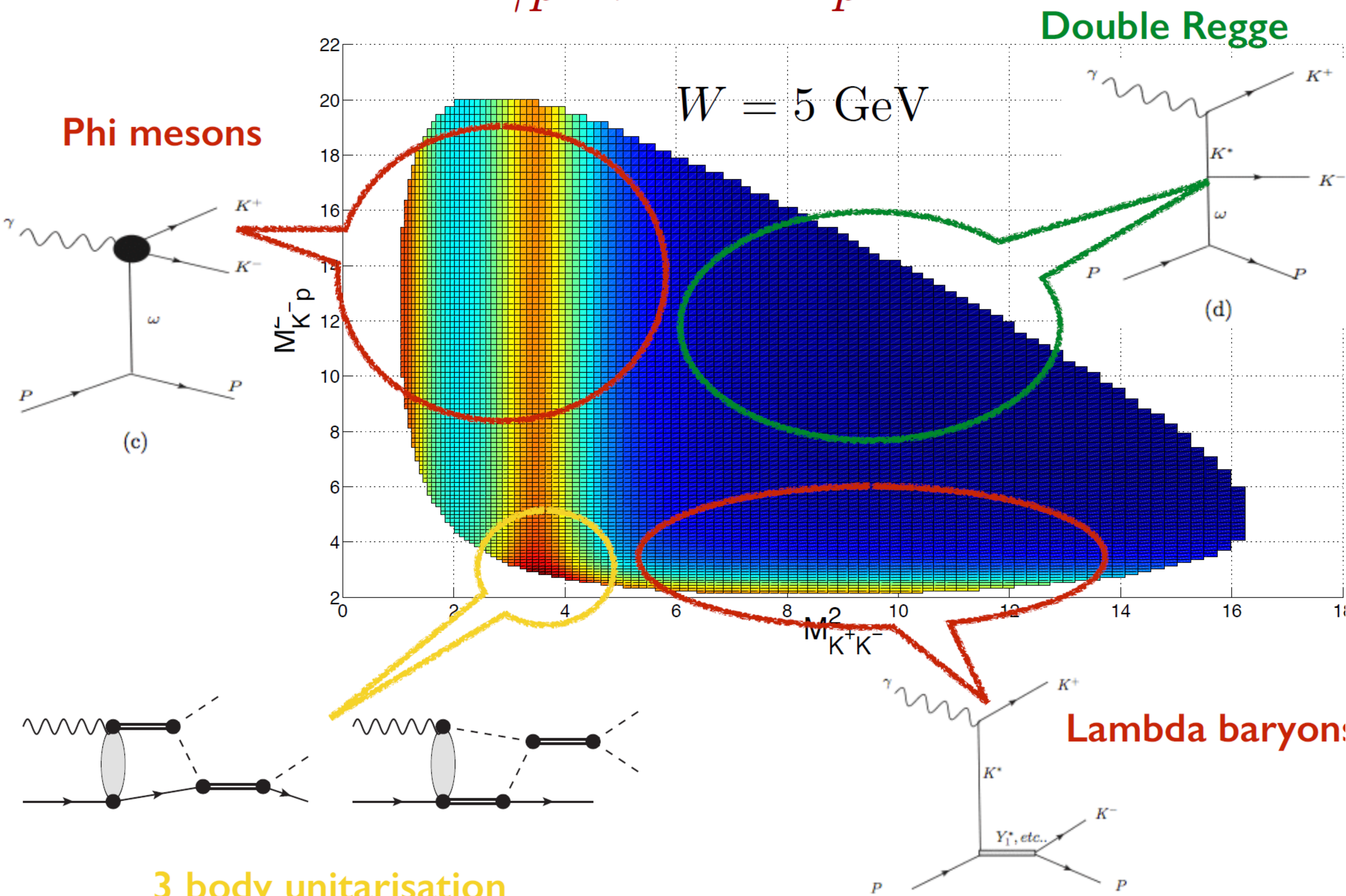


PIF NSF grant [Indiana, Jlab, GWU]

New CLAS data soon (through dileption decay) up to W~3GeV

Transparency: V. Mathieu

$\gamma p \to K^+ K^- p$



$$\gamma p \rightarrow K^+ K^- p$$

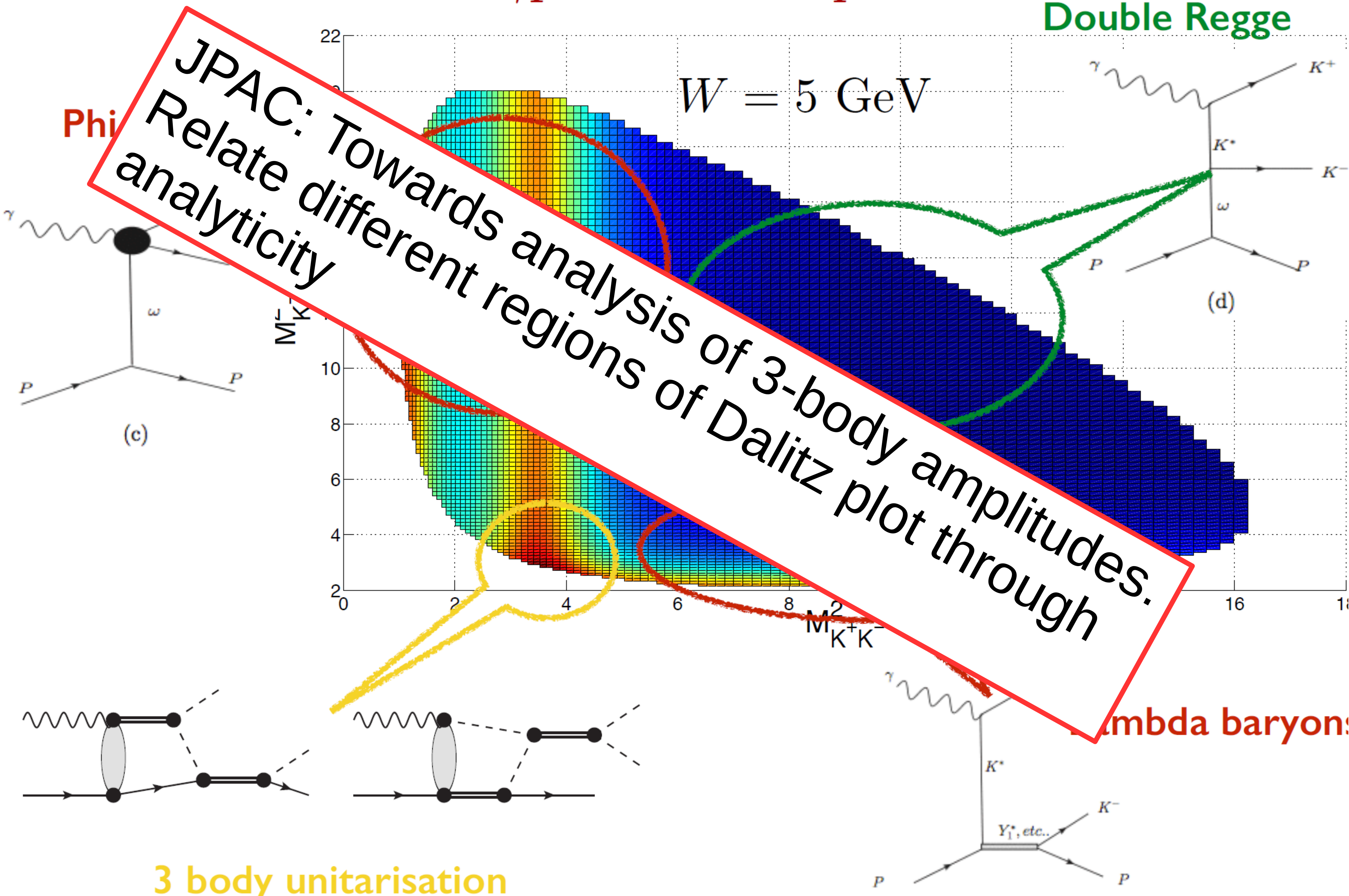
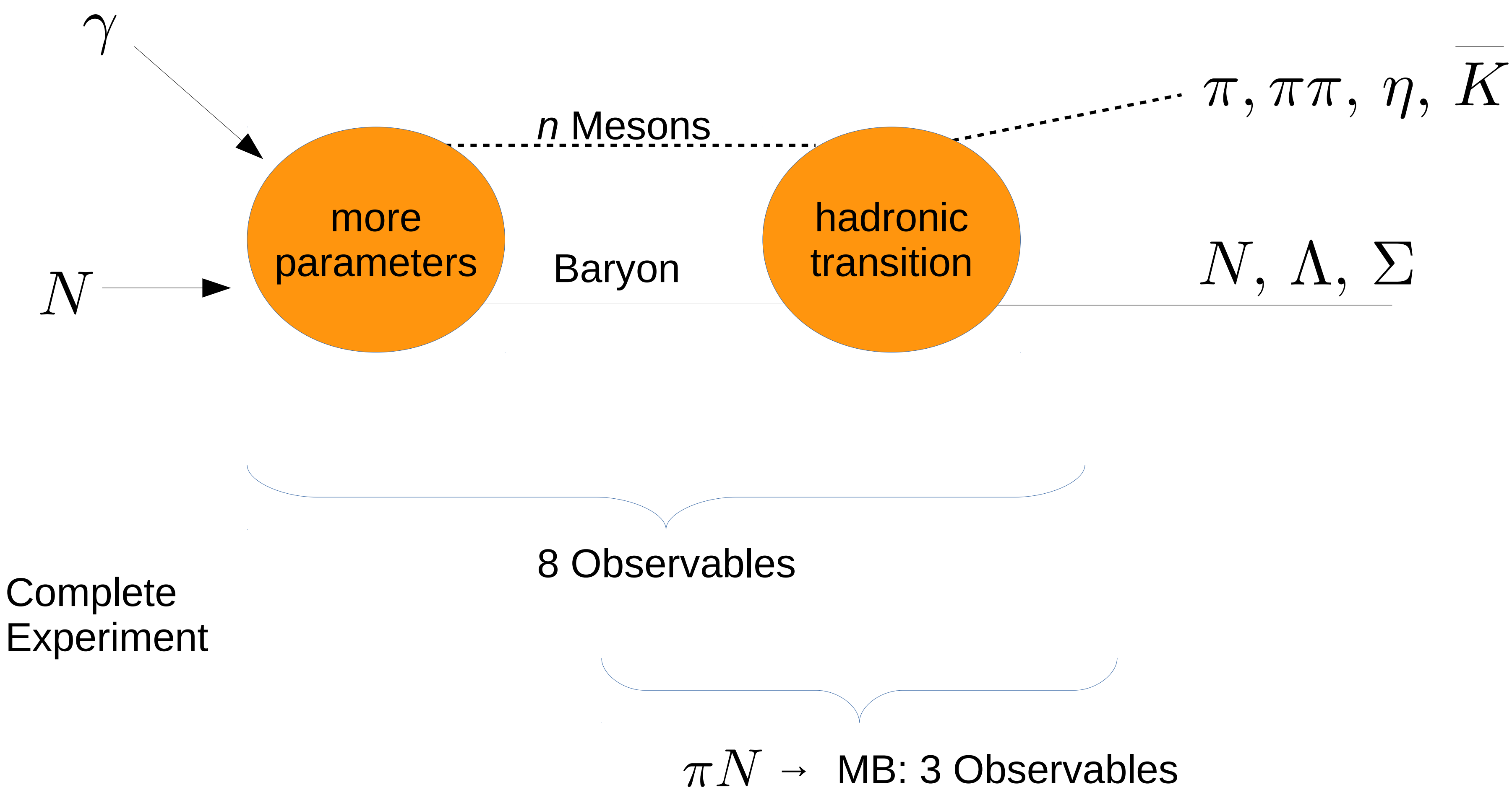


Photo-induced vs. pion-induced meson production

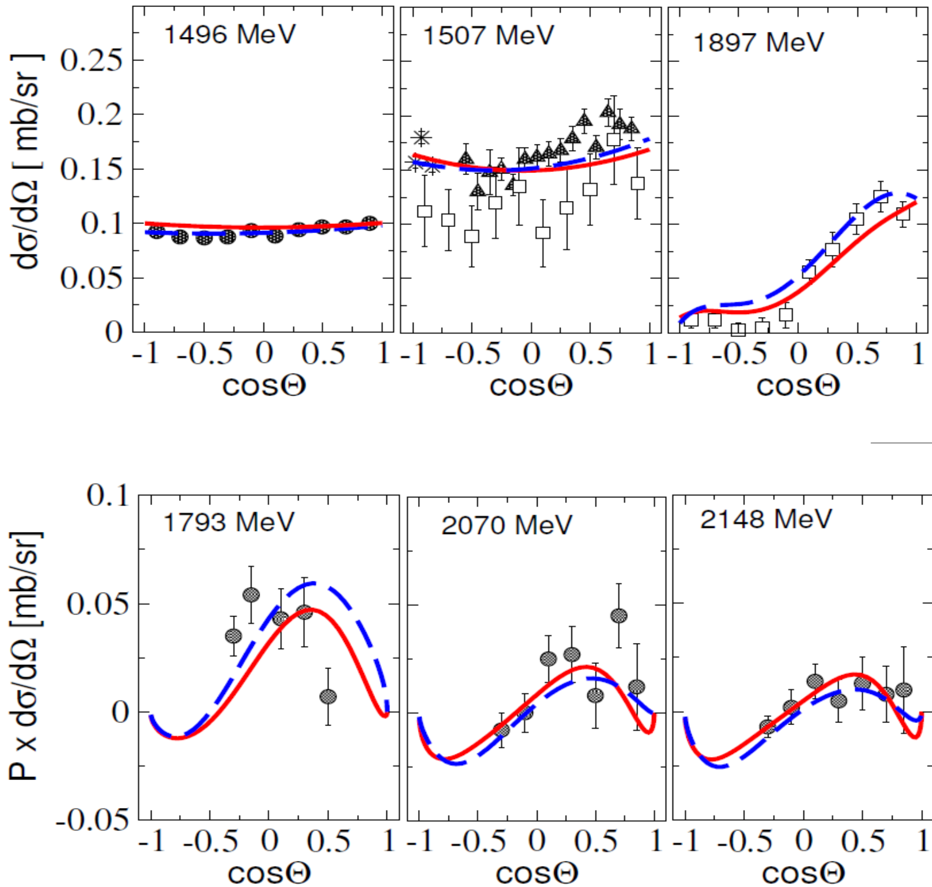


Hadronic transition ALONE fix pole positions and strong branching ratios
→ Principal point of comparison with lattice QCD.

Coupled-channels: Any problematic data in MB → MB <u>will</u> cause problems in photoproduction analysis.

Discrepancy in data quality

$\pi^- p \rightarrow \eta N$



input for high-precision
eta photoproduction analyses

PAC-approved proposal to measure
pion-induced reactions at JPARC
(K. Hicks)

Polarization measurement for
complete experiment needed

→ EIC extension?

Whitepaper in progress.

beyond W~1.55 GeV :
unknown systematic errors;
openly conflicting sets

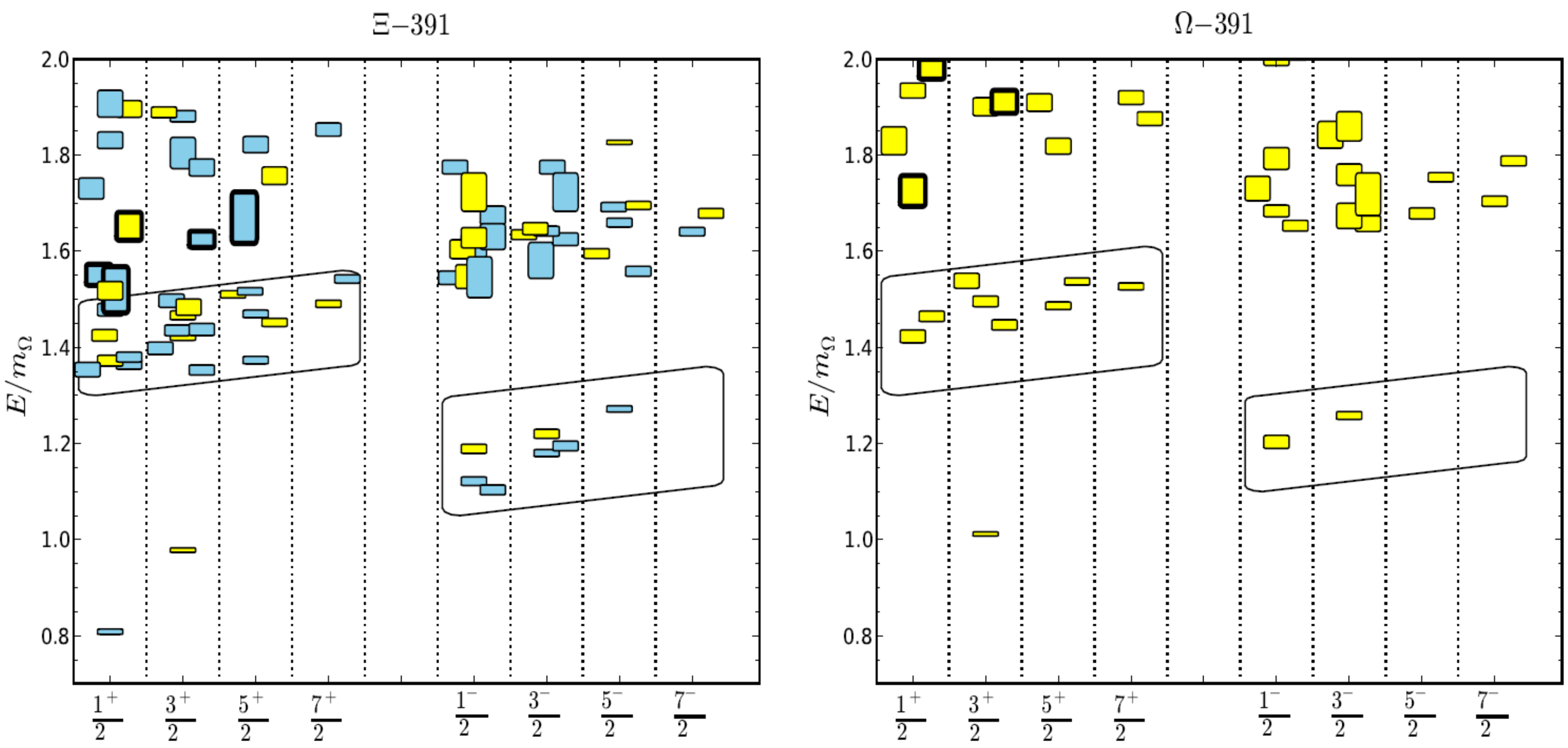
(Very) strange baryons at CLAS12

- S=-2, -3 baryons in exclusive photonuclear reactions
- Search for missing states (and quantum number for known states)
- PAC approved proposal

$$\text{six}\,\Xi(\text{PDG rating} \geq 3***)$$
$$\text{two}\,\Omega(\text{PDG rating} \geq 3***)$$

vs.

Hadron Spectrum Collaboration, PRD87 (2013)



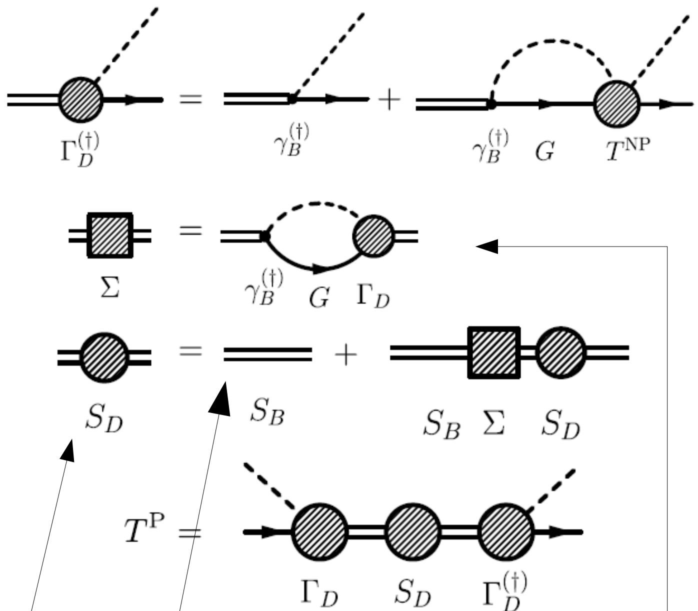
Needs for Baryon Spectroscopy

- Single meson photoproduction: Upcoming analyses of CLAS data critical for spectroscopy. International collaborations (MAMI, JPARC).
- Correct High-energy limit. Dispersive constraints.
- Confirm new baryon resonances found in Kaon photoproduction.
- Experimental improvements of pion-induced data (70's, 80's) through secondary hadron beams.
- The $\pi\pi N$ final state: Hybrid baryons. Conceptual connection to three-body analysis tools needed for GlueX.
- Lattice: Eventually, control $\pi\pi N$ finite-volume effects.

Spare Slides

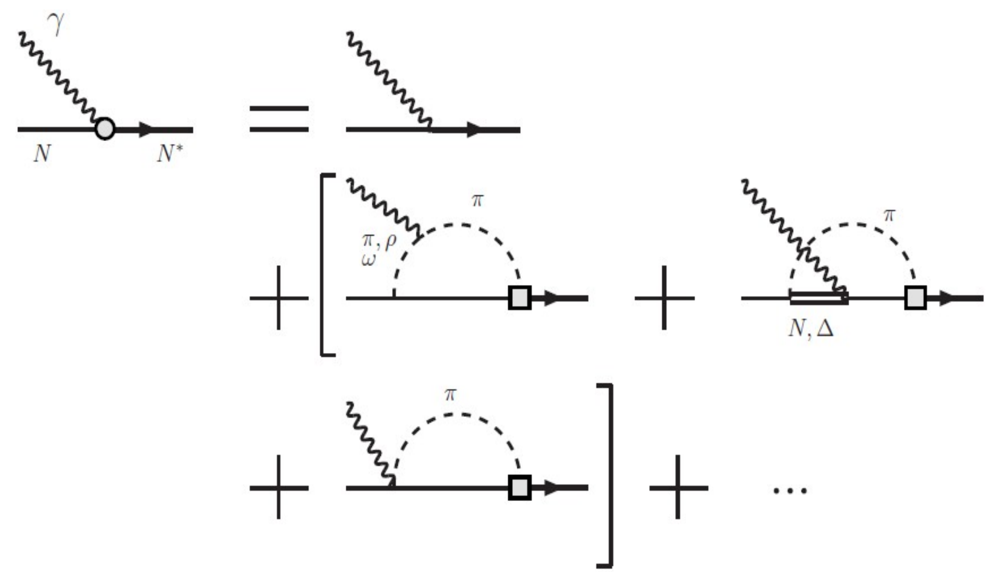
Hadronic part

Photon couplings

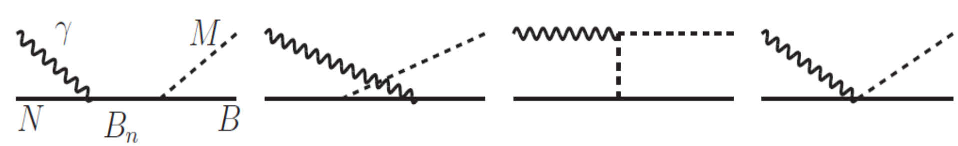


* Bare propagator
* Dressed propagator
* Self energy
* plus non-resonant part (not shown)

* Dressed resonance photon vertex

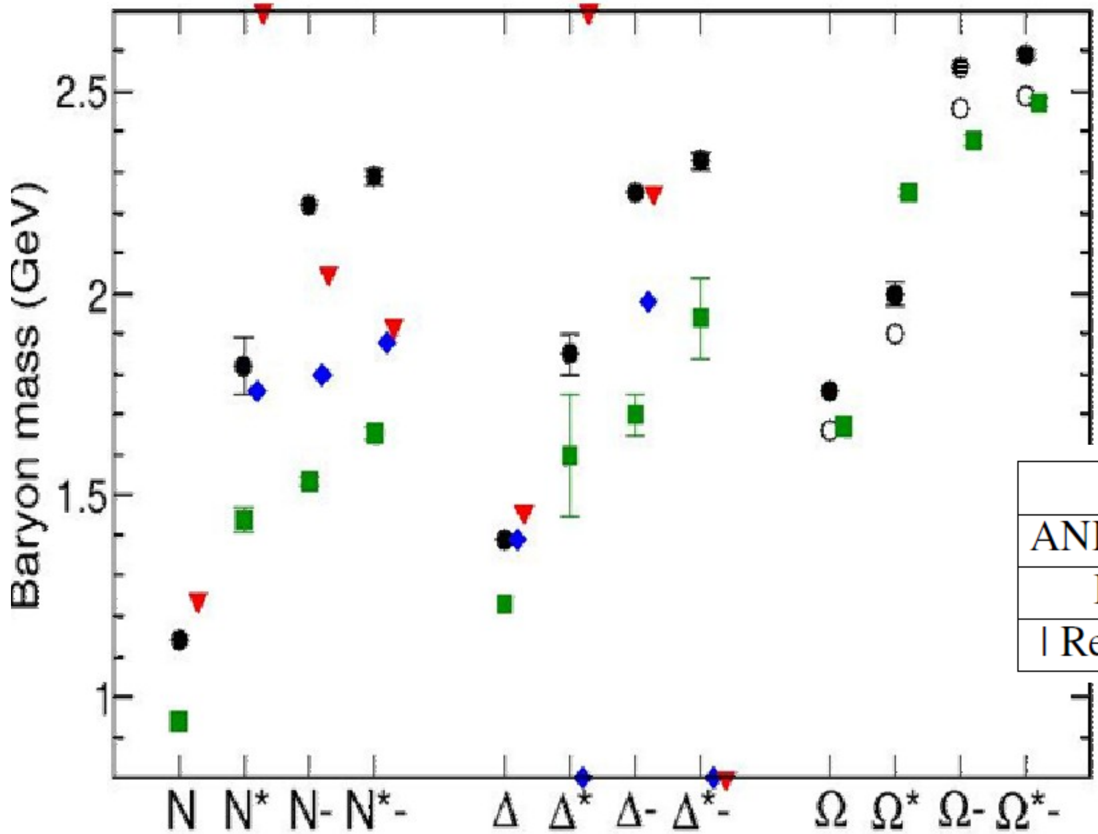


* Non-resonant photon excitation



Picture: EBAC

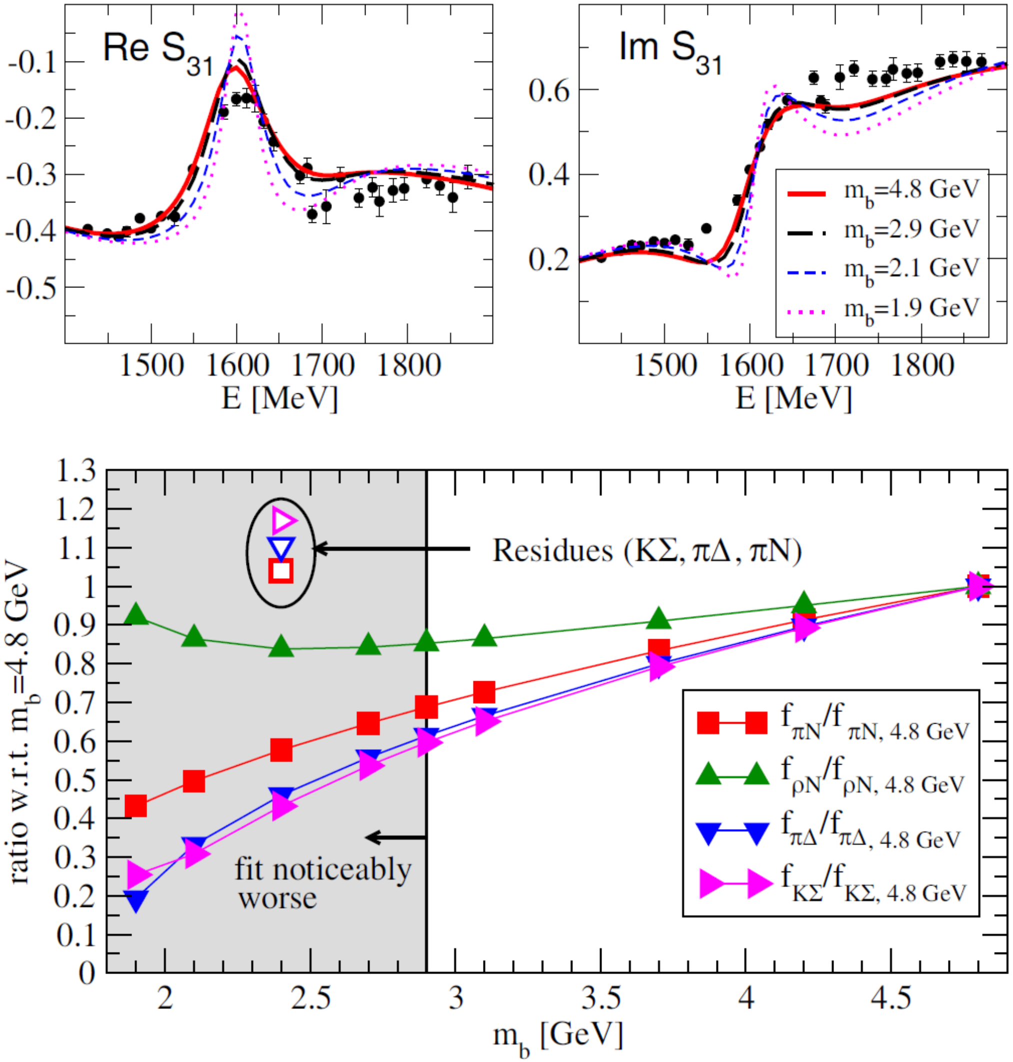
Masses and DSE



Experiment [PDG]
DSE [Few Body syst. 51 (2011)]
EBAC [PRL 104 (2010)]
Jülich [PRC68 (2003)]

	P_{11}	S_{11}	S_{11}	P_{33}	P_{33}	D_{33}
ANL-Osaka	1.83	2.04	2.61	1.28	2.16	2.17
DSE	1.83	2.30	2.35	1.39	1.84	2.33
| Rel. Err. |	0	11.3%	11.1%	7.9%	17.4%	8.6%

Correlations

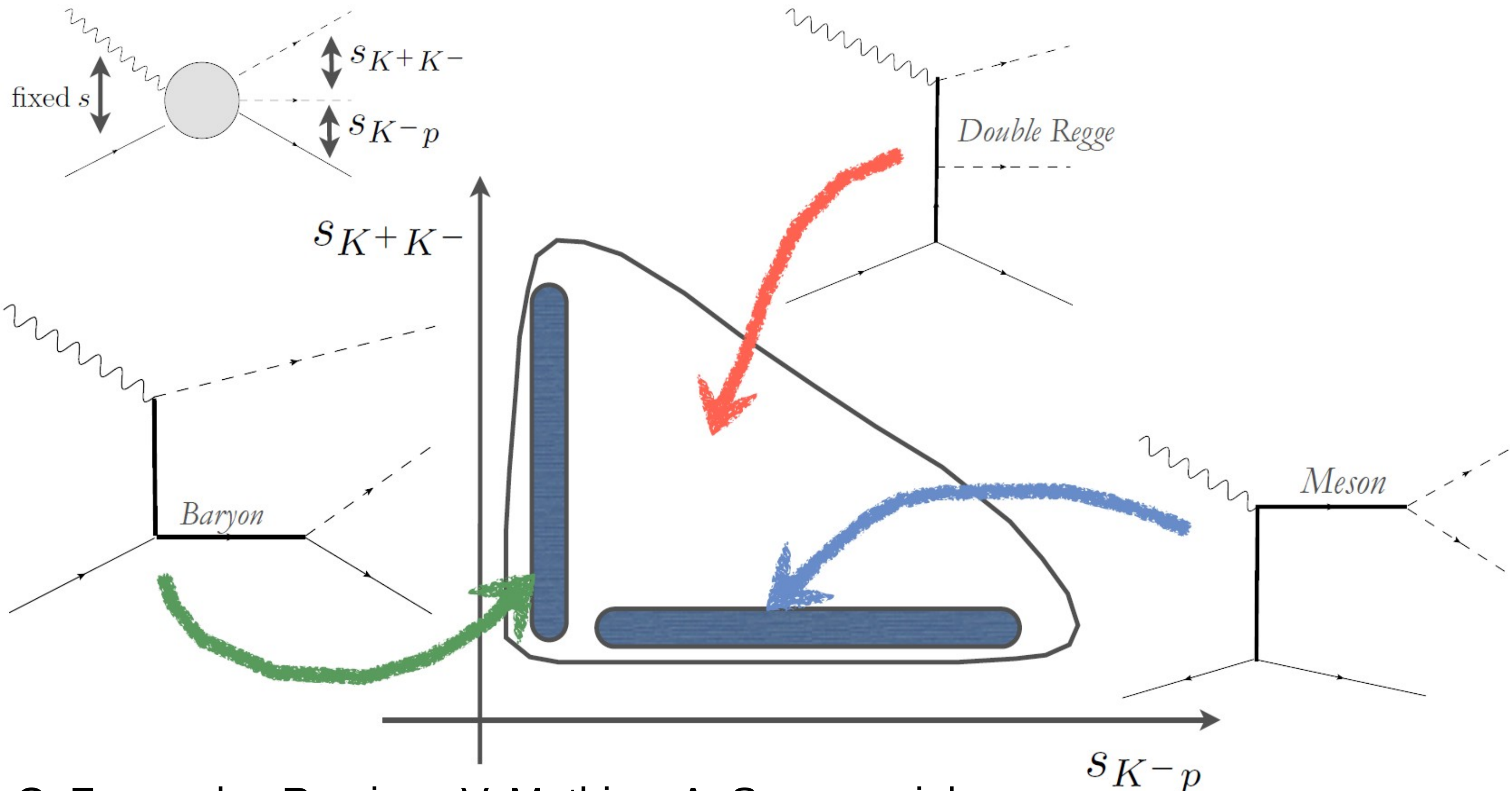


Vary bare masses, refit bare couplings
[D. Rönchen, M.D. et al., EPJA 2013]

- Correlations between bare masses & couplings
- Residues (physical) and pole positions stable
- Conceptual work remains to be done to connect Fock spaces with quark degrees of freedom to meson-baryon degrees of freedom.
- **Challenge** for the future.

JPAC: Analyticity for 3 particles

- Template reaction for GlueX: $\gamma p \to K^+ K^- p$
- Every region of the Dalitz plot has its most effective parameterization
- Imposing analyticity (dispersion relations) to connect



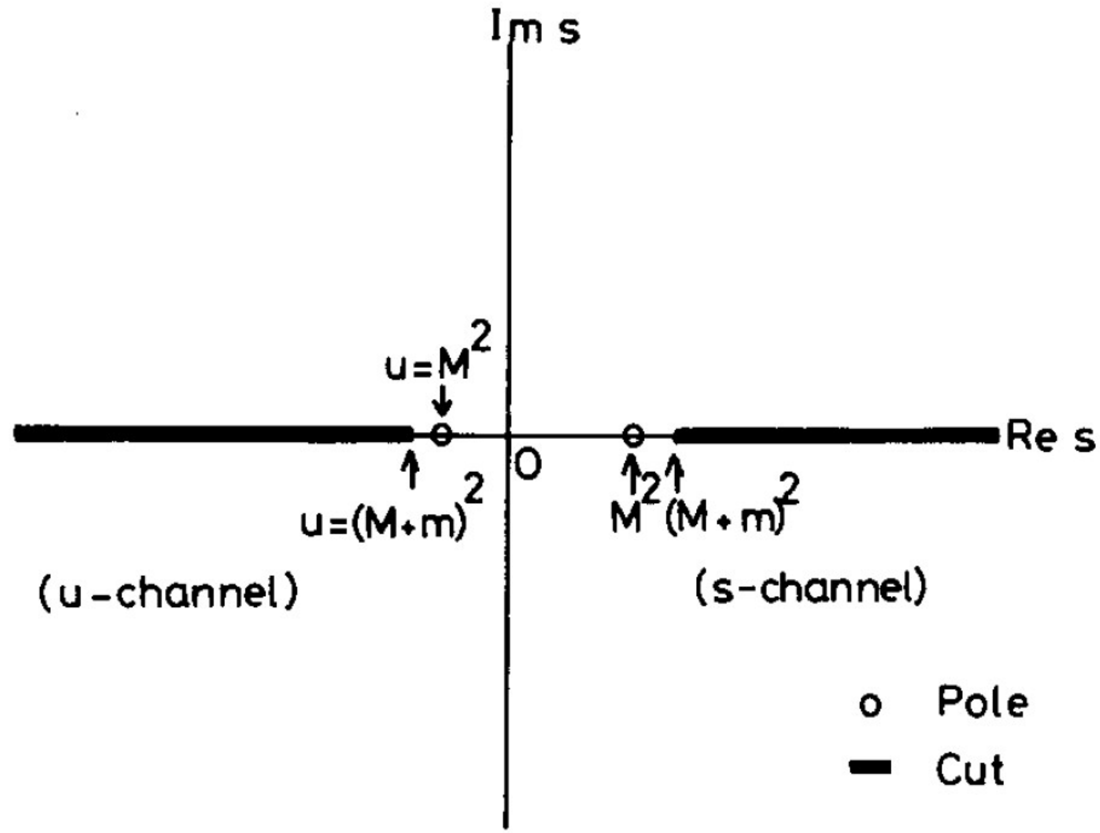
C. Fernandez Ramirez, V. Mathieu, A. Szczepaniak,...

→ Implement modified KSU analysis [Manley 2013].

Invariant amplitudes A and their structure

Dispersion relations generate correct analytic structure

(see also: Analysis of electro-couplings at CLAS with dispersion relations by Burkert/Aznauryan et al.)



$$\mathrm{Re}\,A_{i,\mathrm{ch}}(s,t) = R_{i,\mathrm{ch}}(s,t) + \frac{1}{\pi}$$

$$\times P\int_{(m+M)^2}^{\infty} \mathrm{d}s' \left\{ \frac{\mathrm{Im}\,A_{i,\mathrm{ch}}(s',t)}{(s'-s)} + \xi_i \frac{\mathrm{Im}\,A_{i,\overline{\mathrm{ch}}}(s',t)}{(s'-u)} \right\},$$

$$(\xi_1 = \xi_2 = \xi_4 = +1,\ \xi_3 = -1),$$

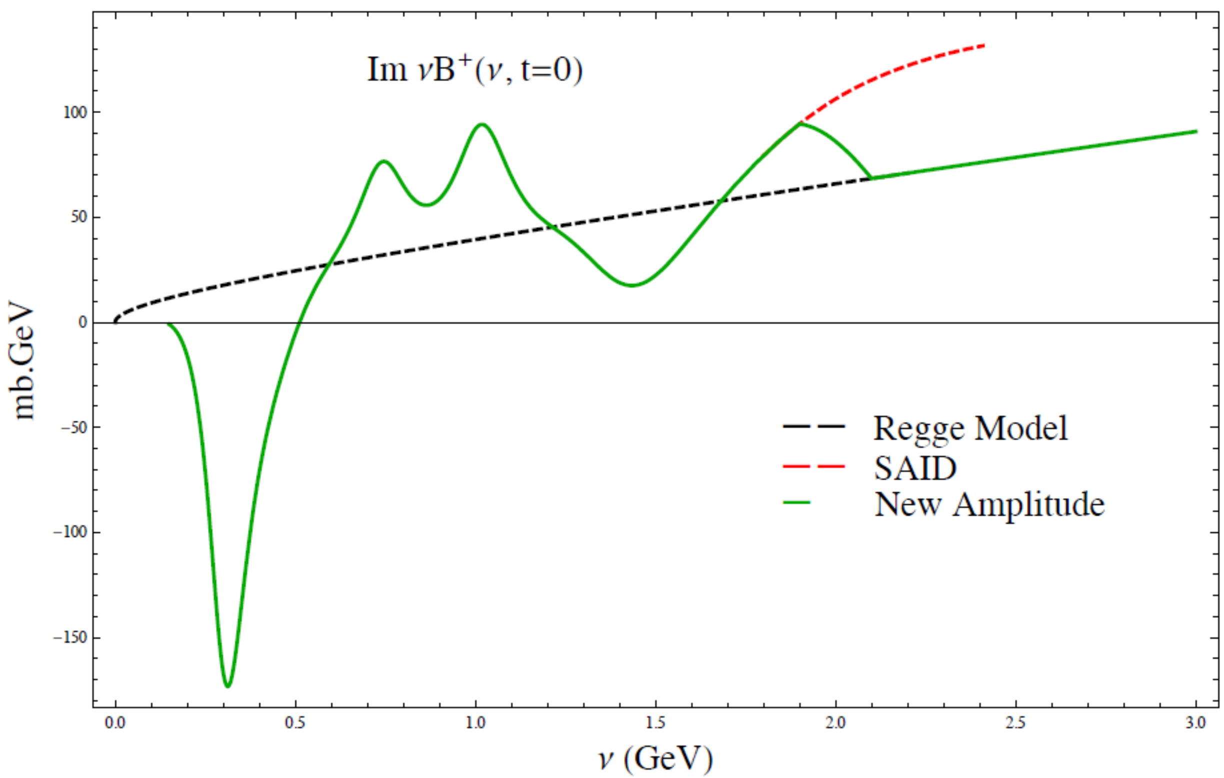
Arai, Fujii (1980)

Connecting kinematic regimes through dispersion relations

[Mathieu et al.]

$\pi^- p \to \pi^0 n$

$$\text{Re } \nu B^{(+)}(\nu,t) = \frac{g_r^2}{2m}\frac{2\nu^2}{\nu_m^2-\nu^2} + \frac{2\nu^2}{\pi}\text{P}\int_{\nu_0}^{\infty}\frac{\text{Im } B^{(+)}(\nu',t)}{\nu'^2-\nu^2}d\nu'$$



Finite Energy Sum rules

$$\int_0^{\Lambda} \text{Im } \nu B(\nu,t)d\nu = \beta_R \frac{\Lambda^{\alpha}}{\alpha+1}$$

For fixed t

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CLAS collaboration

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Viktor Mokeev (JLab)
HASPECT (Italy)

Formalisms

Regge Theory
Dispersive Relations
Dual Models
Isobar Models
...

Projects

$J/\psi \to 3\pi$

$\eta \to 3\pi$

$\omega \to 3\pi$

$\omega \to \pi\gamma^*(e^+e^-)$

$\pi N \to \pi N$

$\pi N \to \eta N$

$KN \to KN$

$\gamma N \to \pi N$

$\gamma p \to K^+K^-p$

$\gamma p \to \pi^0\eta p$

$\pi^-p \to \pi^-\eta p$