Baryon Resonances in a Coupled Analysis of Meson and Photon induced Reactions

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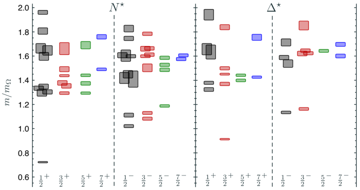
HPC support by Jülich Supercomputing Centre

Introduction: Baryon spectrum in experiment and theory

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

  "Missing resonance problem"

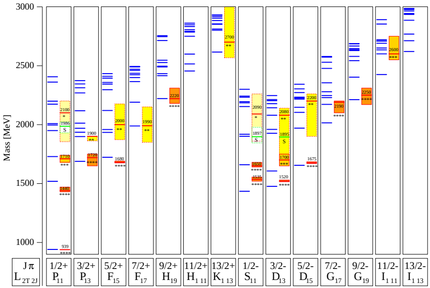
Lattice calculation (single hadron approximation):



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

- only about half of the states have $****$ or $***$ status
- PDG listing: major part of the information from πN elastic (Exception: BnGa multi-channel PWA)

N^* spectrum in a relativistic quark model:



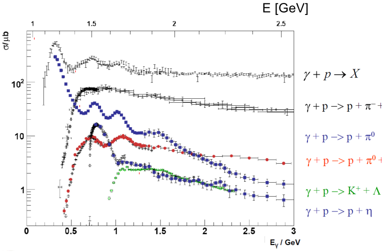
Löring *et al.* EPJ A 10, 395 (2001), experimental spectrum: PDG 2000

$\Rightarrow$ large coupling to inelastic channels?

N^* and Δ^* now

Experimental studies of hadronic reactions: major progress in recent years

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

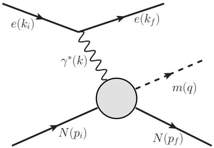


source: ELSA; data: ELSA, JLab, MAMI

- 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



Complete Experiment

- Photoproduction of pseudoscalar mesons: CGLN Phys. Rev. 106, 1345 (1957)

$\vec{q}$: meson
$\vec{k}$ ($\vec{\epsilon}$): photon (polarization)

$$\hat{\mathcal{M}} = iF_1\vec{\sigma}\cdot\vec{\epsilon} + F_2\vec{\sigma}\cdot\hat{q}\vec{\sigma}\cdot(\hat{k}\times\vec{\epsilon}) + iF_3\vec{\sigma}\cdot\hat{k}\hat{q}\cdot\vec{\epsilon} + iF_4\vec{\sigma}\cdot\hat{q}\hat{q}\cdot\vec{\epsilon}$$

F_i: complex functions of θ, W, constructed from multipoles $E_{L\pm}$, $M_{L\pm}$

⇒ 16 polarization observables:

asymmetries composed of **beam**, **target** and/or **recoil** polarization measurements

⇒ **Complete Experiment**: unambiguous determination of the amplitude

8 carefully selected observables Chiang and Tabakin, PRC 55, 2054 (1997)

e.g. $\{\sigma, \Sigma, T, P, E, G, C_x, C_z\}$

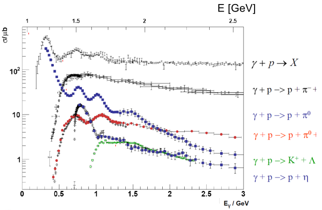
- Electroproduction e.g. Berends, Donnachie, Weaver NPB4,1 (1967)

$$\hat{\mathcal{M}} = iF_1\vec{\sigma}\cdot\vec{\epsilon} + F_2\vec{\sigma}\cdot\hat{q}\vec{\sigma}\cdot(\hat{k}\times\vec{\epsilon}) + iF_3\vec{\sigma}\cdot\hat{k}\hat{q}\cdot\vec{\epsilon} + iF_4\vec{\sigma}\cdot\hat{q}\hat{q}\cdot\vec{\epsilon} + iF_5\vec{\sigma}\hat{k}\hat{k}\cdot\vec{\epsilon} + iF_6\vec{\sigma}\hat{q}\hat{k}\cdot\vec{\epsilon}$$

$F_i = F_i(W,\theta,Q^2)$, multipoles $E_{L\pm}$, $M_{L\pm}$, $L_{L\pm}$ (or $E_{L\pm}$, $M_{L\pm}$, $S_{L\pm}$)

⇒ 36 polarization observables

Different analyses frameworks: a few examples



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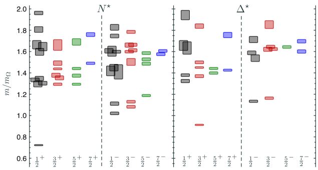

[Edwards *et al.*, Phys.Rev. D84 (2011)]

- GWU/SAID approach: PWA based on Chew-Mandelstam K-matrix parameterization
- unitary isobar models: unitary amplitudes + Breit-Wigner resonances
  MAID, Yerevan/JLab, KSU
- multi-channel K-matrix: BnGa (mostly phenomenological Bgd, N/D approach),
  Gießen (microscopic Bgd)
- dynamical coupled-channel (DCC): 3-dim scattering eq., off-shell intermediate states
  ANL-Osaka (EBAC), Dubna-Mainz-Taipeh, Jülich-Bonn

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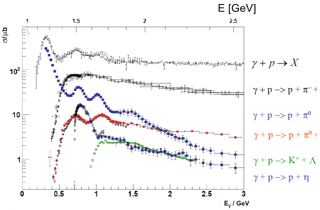
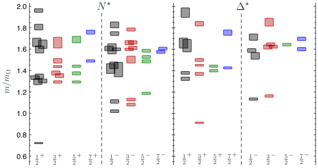


$\Longleftrightarrow$



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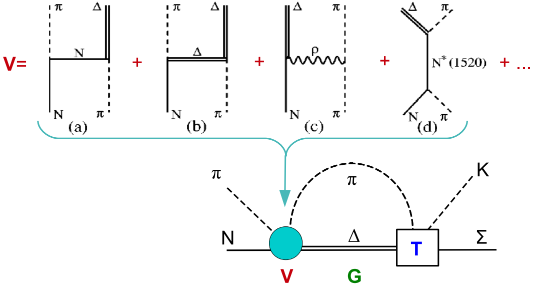
The Jülich-Bonn DCC approach

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

 EPJ A 49, 44 (2013)

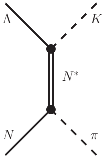
Dynamical coupled-channels (DCC): **simultaneous** analysis of different reactions

The scattering equation in partial-wave basis

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

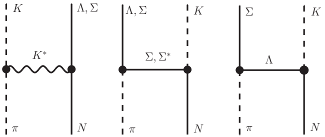
- **free parameters** fitted to data:

s-channel: resonances (T^P)



$m_{bare} + f_{\pi NN^*}$

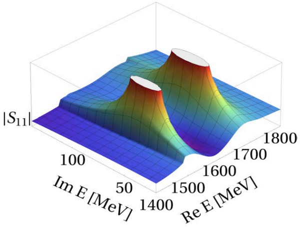
t- and u-channel exchange: "background" (T^{NP})



cut offs Λ in form factors $\left(\frac{\Lambda^2-m^2_{ex}}{\Lambda^2+\vec{q}^2}\right)^n$

(couplings fixed from SU(3))

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

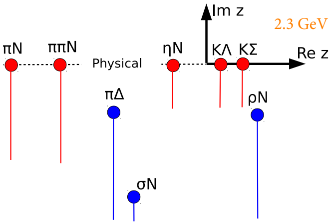


Re(E_0) = "mass", -2Im(E_0) = "width"

- 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

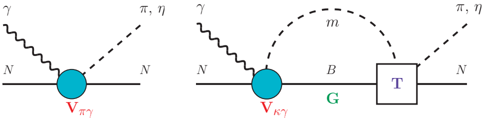
  ↳ branch points move into complex plane



Multipole amplitude

$$M^{IJ}_{\mu\gamma} = V^{IJ}_{\mu\gamma} + \sum_{\kappa} T^{IJ}_{\mu\kappa} G_{\kappa} V^{IJ}_{\kappa\gamma}$$

(partial wave basis)

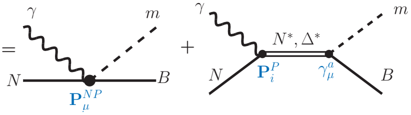


$m = \pi, \eta$, $B = N, \Delta$

$T_{\mu\kappa}$: Jülich hadronic T-matrix → Watson's theorem fulfilled by construction
→ **analyticity of T**: extraction of resonance parameters

Photoproduction potential: approximated by energy-dependent polynomials

$\mathbf{V}_{\mu\gamma}(E,q) =$



$$= \frac{\tilde{\gamma}^a_\mu(q)}{m_N} P^{NP}_\mu(E) + \sum_i \frac{\gamma^a_{\mu;i}(q) P^P_i(E)}{E - m^b_i}$$

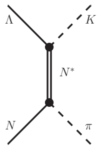
$\tilde{\gamma}^a_\mu$, $\gamma^a_{\mu;i}$: hadronic vertices → correct threshold behaviour, cancellation of singularity at $E = m^b_i$
→ $\gamma^a_{\mu;i}$ affects pion- and photon-induced production of final state mB

i: resonance number per multipole; μ: channels πN, ηN, $\pi\Delta$, KY

Polynomials

Data analysis and fit results

s-channel: resonances (T^P)



m_{bare} + $f_{\pi NN*}$

Fit parameters:

- $\pi N \to \pi N$

  $\pi^- p \to \eta n, \; K^0\Lambda, \; K^0\Sigma^0, \; K^+\Sigma^-$

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

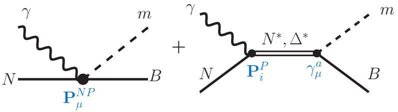
⇒ 128 free parameters

11 N^* resonances × (1 m_{bare}+ couplings to πN, ρN, ηN, $\pi\Delta$, $K\Lambda$, $K\Sigma$))
+ 10 Δ resonances × (1 m_{bare}+ couplings to πN, ρN, $\pi\Delta$, $K\Sigma$)

- $\gamma p \to \pi^0 p$, $\pi^+ n$, ηp, $K^+\Lambda$

  ⇒ ∼ 500 free parameters

  couplings of the polynomials



- ∼ 40.000 data points

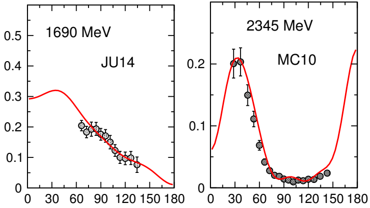
↳ calculations on the JURECA supercomputer: parallelization in energy (∼ 300 - 400 processes)

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

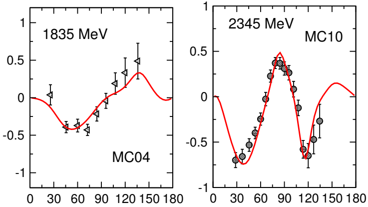
$\gamma p \to K^+\Lambda$:

- Differential cross section



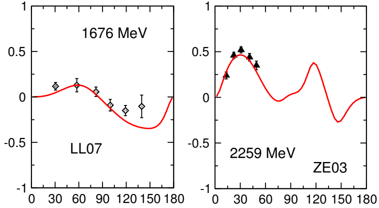
JU14: Jude PLB 735 (2014), MC10: McCracken PRC 81 (2010)

- Recoil polarization



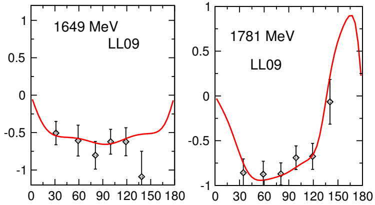
MC04: McNabb PRC 69 (2004), MC10: McCracken PRC 81 (2010)

- Beam asymmetry



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

- Target asymmetry



LL09: Lleres EPJA 39 (2009)

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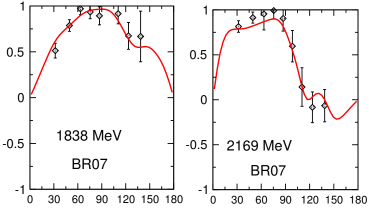
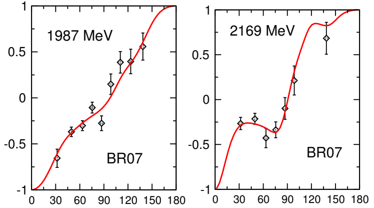
$\gamma p \to K^+\Lambda$:

- C_x



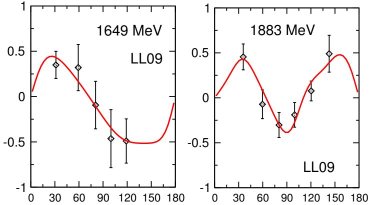
BR07: Bradford PRC 75 (2007)

- C_z



BR07: Bradford PRC 75 (2007)

- O_x



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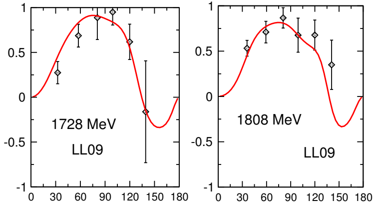

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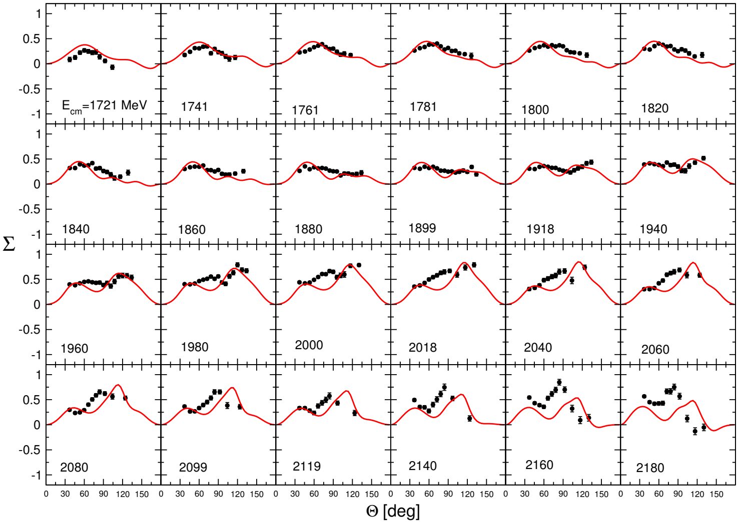
- Prediction for new CLAS data (Paterson *et al.* Phys. Rev. C 93, 065201 (2016)):



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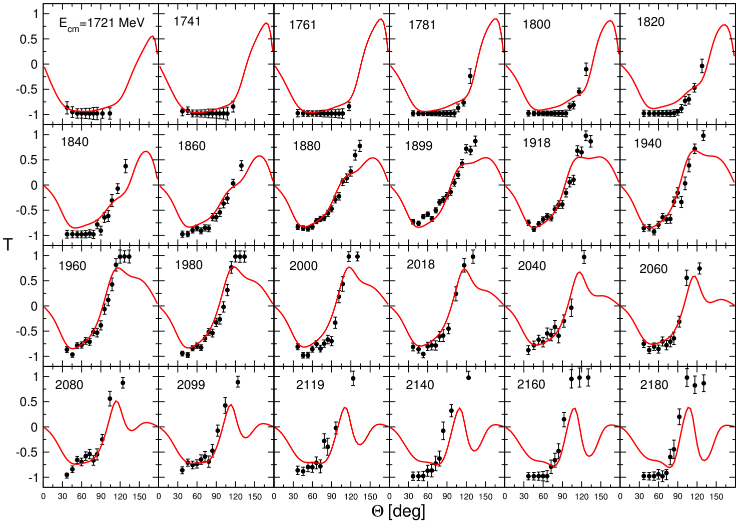

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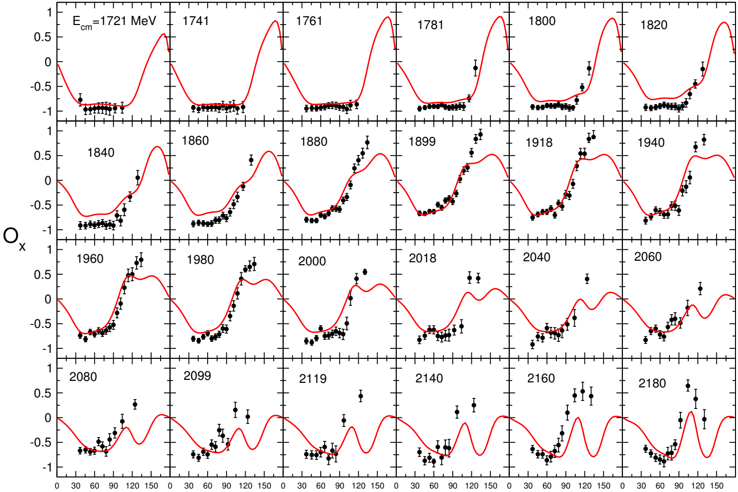

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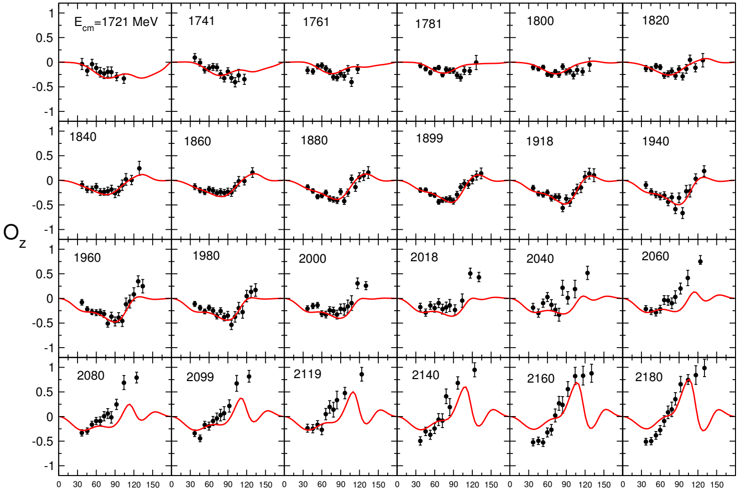


Impact of new polarization data

Impact of new polarization data on $\gamma p \to \pi N$ multipoles

- A joint analysis of the SAID, BnGa and JüBo groups -

EPJ A 52, 284 (2016)

Recent new data on $\gamma p \to \pi N$:

- E, G, H, P, T in $\gamma p \to \pi^0 p$ from ELSA Thiel et al. PRL 109, 102001 (2012); Gottschall et al. PRL 112, 012003 (2014); Hartmann et al. PLB 748, 212 (2015); Thiel et al. arXiv:1604.02922
- Σ in $\gamma p \to \pi^0 p$ and $\gamma p \to \pi^+ n$ from JLab Dugger et al. PRC 88, 065203 (2013) 89, 029901(E) (2014)
- Σ in $\gamma p \to \pi^0 p$ from MAMI Hornidge et al. PRL 111, 062004 (2013)

$\Rightarrow$ included in the SAID, BnGa, JüBo fits

- compare multipoles before and after the inclusion of the new data
- conversion to a common solution?

The SAID, BnGa and JüBo approaches

All three approaches:

- coupled channel effects
- unitarity (2 body)
- amplitudes are analytic functions of the invariant mass

SAID PWA

based on Chew-Mandelstam K-matrix

- K-matrix elements parameterized as energy-dependent polynomials
- resonance poles are dynamically generated (except for the $\Delta(1232)$)
- masses, width and hadronic couplings from fits to pion-induced πN and ηN production

Bonn-Gatchina (BnGa) PWA

Multi-channel PWA based on K-matrix (N/D)

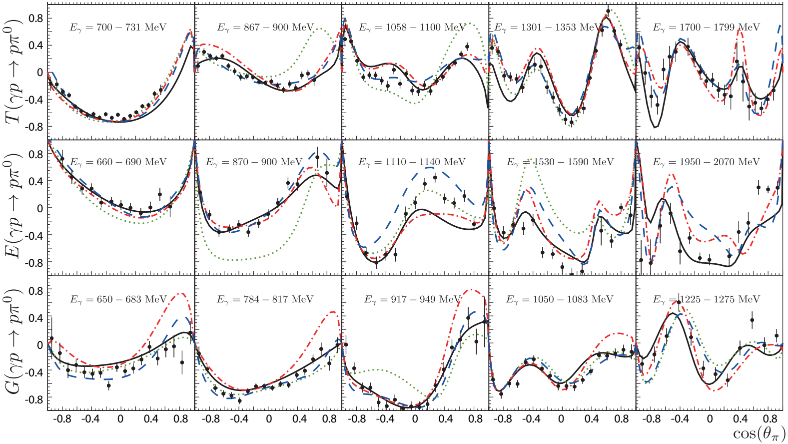
- mostly phenomenological model
- resonances added by hand
- resonance parameters determined from large experimental data base:

  pion-, photon-induced reactions, 3-body final states

Jülich-Bonn (JüBo) DCC model

based on a Lippmann-Schwinger equation formulated in TOPT

- hadronic potential from effective Lagrangians
- photoproduction parameterized by energy-dependent polynomials
- resonances as s-channel states (dynamical generation possible)
- resonance parameters determined from pion- and photon-induced data



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

Fit results

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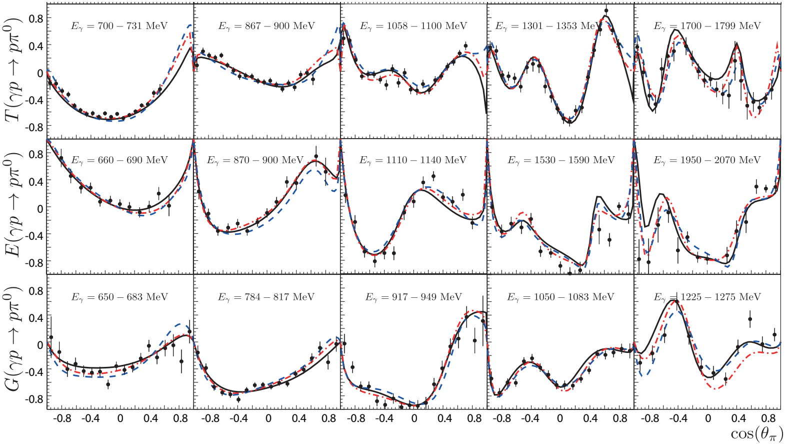

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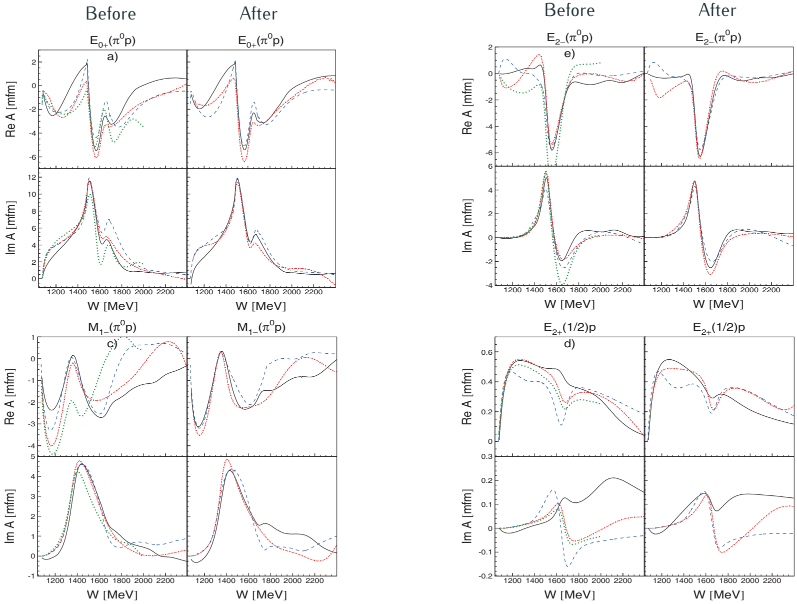
Comparison of multipoles before & after including the new data: Selected examples



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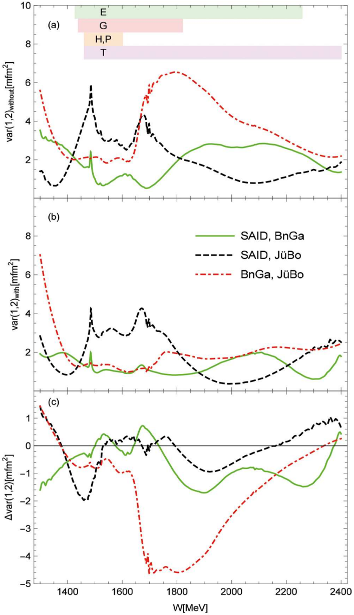
Consistency of the results



- Pairwise variances between two PWAs:

$$\text{var}(1,2) = \frac{1}{2}\sum_{i=1}^{16}\left(\mathcal{M}_1(i) - \mathcal{M}_2(i)\right)\left(\mathcal{M}_1^*(i) - \mathcal{M}_2^*(i)\right)$$

($\mathcal{M}$: $\gamma p \to \pi^0 p$ multipoles up to $L = 4$)

- beyond 1.7 GeV: BnGa, SAID, JüBo multipoles now in closer agreement
- 1.5 to 1.7 GeV:
  - BnGa agrees well with SAID and with JüBo
  - larger discrepancies between SAID and JüBo

Summary

- Progress in experimental and theoretical study of the baryon spectrum
- Jülich-Bonn model:
  - DCC approach that respects analyticity and (2 body) unitarity
  - simultaneous analysis of pion- and photon-induced reactions
  - preliminary results for $K^+\Lambda$ photoproduction
- Impact of new polarization data for pion photoproduction from ELSA, CLAS, MAMI:
  - joint analysis of the BnGa, SAID and JüBo groups
  - comparison of the multipoles before and after the inclusion of the new data

  $\rightarrow$ agreement between the three analyses is improved!

Thank you for your attention!