Eta-Photoproduction in the Jülich-Bonn model

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SFB-S3 Collaboration meeting: Partial Wave Analysis with Analytical Constraints
Mainz

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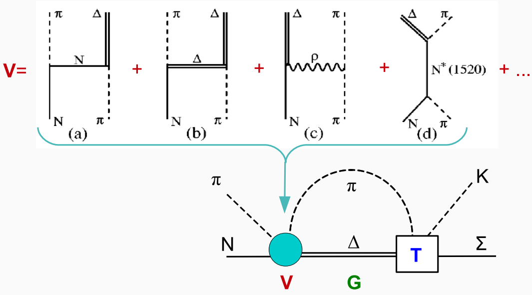
Dynamical coupled-channels (DCC): **simultaneous** analysis of different reactions

The scattering equation in partial-wave basis

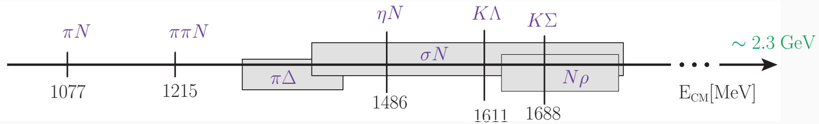
$$\langle L'S'p'|T^{IJ}_{\mu\nu}|LSp\rangle = \langle L'S'p'|V^{IJ}_{\mu\nu}|LSp\rangle + \sum_{\gamma,L''S''}\int_0^\infty dq \quad q^2 \quad \langle L'S'p'|V^{IJ}_{\mu\gamma}|L''S''q\rangle \frac{1}{E-E_\gamma(q)+i\epsilon}\langle L''S''q|T^{IJ}_{\gamma\nu}|LSp\rangle$$



- 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
- contact terms

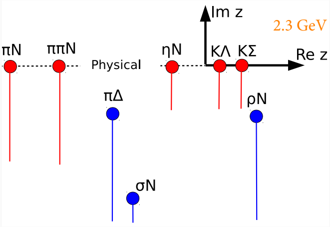
The Jülich-Bonn DCC approach

Channels included:



- (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

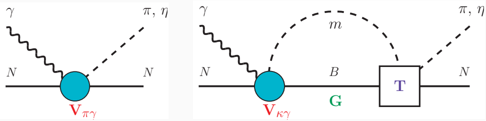


DR, M. Döring *et al.* EPJ A 50, 101 (2015)

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)

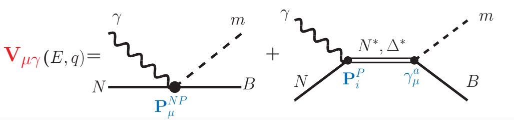


$m = \pi, \eta, K$, $B = N, \Delta, \Lambda$

$T_{\mu\kappa}$: Jülich hadronic T-matrix $\to$ Watson's theorem fulfilled by construction

$\to$ **analyticity of T**: extraction of resonance parameters

Photoproduction potential: approximated by energy-dependent polynomials



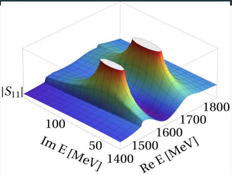
$$= \frac{\tilde{\gamma}^{a}_{\mu}(q)}{m_N} P^{\mathrm{NP}}_{\mu}(E) + \sum_{i} \frac{\gamma^{a}_{\mu;i}(q) P^{\mathrm{P}}_{i}(E)}{E - m^{b}_{i}}$$

$\tilde{\gamma}^{a}_{\mu}$, $\gamma^{a}_{\mu;i}$: hadronic vertices $\to$ correct threshold behaviour, cancellation of singularity at $E = m^{b}_{i}$

$\to$ $\gamma^{a}_{\mu;i}$ affects pion- and photon-induced production of final state mB

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

Polynomials



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

$$\text{Re}(E_0) = \text{“mass”},\ -2\text{Im}(E_0) = \text{“width”}$$

- Scattering amplitude on the 2nd Riemann sheet for two stable particles a and b:

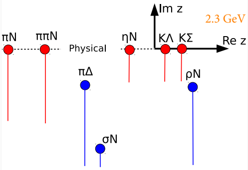
$$T^{(2)}_{\mu\nu}(p'', p', E) - V_{\mu\nu}(p'', p', E) = \delta G + \int dp\, p^2 \frac{V_{\mu\kappa}((p'', p, E) T^{(2)}_{\kappa\nu}(p'', p, E)}{E - E_a(p) - E_b(p) + i\epsilon}$$

with $\delta G = \frac{2\pi i\, p^{>}_{on} E^{on}_a E^{on}_b}{E} V_{\mu\kappa}(p'', p_{on}, E) T^{(2)}(p_{on}, p', E)$

and the two-valued on-shell momentum p_{on} with $p^{>}_{on} = \begin{cases} -p_{on} & \text{if Im} p_{on} < 0 \\ p_{on} & \text{else} \end{cases}$

(distinguish the two Riemann sheets of p_{on} : $p^{>}_{on}$ real & positive on the real axis above threshold)

- rotate cuts $\Rightarrow$ select part of sheet close to physical axis (“2nd sheet”)



Residues

- Expand $T^{(2)}$ in a Laurent series around pole position E_0:

$$T^{(2)}_{\mu\nu} = \frac{a_{-1,\mu\nu}}{E - E_0} + a_{0,\mu\nu} + \mathcal{O}(E - E_0) \, , \qquad a_{-1} \sim \text{ residue}$$

- residue can be obtained from: $\quad a_n = \frac{1}{2\pi i} \oint_{\Gamma(E)} \frac{T^{(2)}(E)\, dE}{(E-E_0)^{n+1}}$
- or alternatively by: $\quad \frac{\partial}{\partial E}\Big|_{E=E_0} \frac{1}{T^{(2)}(E)} = \frac{1}{a_{-1}}$ $\qquad$ (faster, no integration!)

Quantities quoted in the tables:

- elastic πN residue: $\quad |r_{\pi N}| = \pi |g^2_{\pi N}\, \rho_\mu|, \quad \theta_{\pi N \to \pi N} = \arctan\left[\frac{\text{Im}\,(g^2_{\pi N}\,\rho_{\pi N})}{\text{Re}\,(g^2_{\pi N}\,\rho_{\pi N})}\right]$

  where $a_{-1,\mu\nu} = g_\mu g_\nu$ and $\rho_\mu = \frac{k_\mu E_\mu \omega_\mu}{z}$
- transition branching ratio: $\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{\mu}}{\Gamma_{\text{tot}}} = |(NR)_{\pi N \to \mu\nu}| = \left|\frac{\pi\sqrt{\rho_{\pi N}\rho_\mu}\, g_{\pi N} g_\mu}{\Gamma_{\text{tot}}/2}\right|$

Data analysis and fit results: JüBo2017

Combined analysis of pion- and photon-induced reactions

Data base

DR, M. Döring, U.-G. Meißner EPJ A 54, 110 (2018)

Reaction	Observables (# data points)	p./channel
$\pi N \to \pi N$	PWA GW-SAID WI08 (ED solution)	3,760
$\pi^- p \to \eta n$	$d\sigma/d\Omega$ (676), P (79)	755
$\pi^- p \to K^0 \Lambda$	$d\sigma/d\Omega$ (814), P (472), β (72)	1,358
$\pi^- p \to K^0 \Sigma^0$	$d\sigma/d\Omega$ (470), P (120)	590
$\pi^- p \to K^+ \Sigma^-$	$d\sigma/d\Omega$ (150)	150
$\pi^+ p \to K^+ \Sigma^+$	$d\sigma/d\Omega$ (1124), P (551) , β (7)	1,682
$\gamma p \to \pi^0 p$	$d\sigma/d\Omega$ (10743), Σ (2927), P (768), T (1404), $\Delta\sigma_{31}$ (140),	
	G (393), H (225), E (467), F (397), $C_{x'_L}$ (74), $C_{z'_L}$ (26)	17,564
$\gamma p \to \pi^+ n$	$d\sigma/d\Omega$ (5961), Σ (1456), P (265), T (718), $\Delta\sigma_{31}$ (231),	
	G (86), H (128), E (903)	9,748
$\gamma p \to \eta p$	$d\sigma/d\Omega$ (5680), Σ (403), P (7), T (144), F (144), E (129)	6,507
$\gamma p \to K^+ \Lambda$	$d\sigma/d\Omega$ (2478), P (1612), Σ (459), T (383),	
	$C_{x'}$ (121), $C_{z'}$ (123), $O_{x'}$ (66), $O_{z'}$ (66), O_x (314), O_z (314),	5,936
	in total	**48,050**

$\gamma p \to \eta p$ data base

Differential cross section:

- McNicoll PRC 82, 035208 (2010)
- Bartalini EPJA 33, 169 (2007)
- Nakabayashi PRC 74, 035202 (2006)
- Crede PRL 94, 012004 (2005)
- Dugger PRL 89, 222002 (2002)
- Ahrens EPJA 17, 241 (2003)
- Crede PRC 80, 055202 (2009)
- Williams PRC 80, 045213 (2009)
- Sumihama PRC 80, 052201 (2009)
- + data before 2000

Not yet included in JüBo2017:
PRL 188, 212001 (2017) (but in next version)

Σ:

- Bartalini EPJA 33, 169 (2007)
- Elsner EPJA 33, 147 (2007)
- Vartapetyan SJNP 32, 804(1980)
- Collins PLB 771, 213 (2017)

P:

- Heusch, PRL 25, 1381 (1970)
- Hongoh, NCL 2, 317 (1971)

T:

- Bock, PRL 81, 534 (1998)
- Akondi PRL 113, 102001 (2014)

E:

- Senderovich PLB 755, 64 (2016)

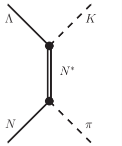
F:

- Akondi PRL 113, 102001 (2014)

Fit parameters:

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

s-channel: resonances (T^P)

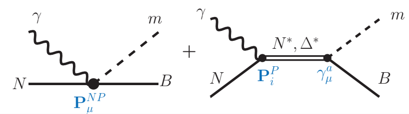


$m_{bare} + f_{mBN*}$

$\Rightarrow$ 134 free parameters
11 N^* resonances $\times$ (1 m_{bare}+ couplings to πN, ρN, ηN, $\pi\Delta$, $K\Lambda$, $K\Sigma$)
+ 10 Δ resonances $\times$ (1 m_{bare}+ couplings to πN, ρN, $\pi\Delta$, $K\Sigma$)

- contact terms: one per partial wave, couplings to πN, ηN, ($\pi\Delta$,) $K\Lambda$, $K\Sigma$
  $\Rightarrow$ 61 free parameters

- $\gamma p \to \pi^0 p$, $\pi^+ n$, ηp, $K^+\Lambda$:
  couplings of the polynomials
  $\Rightarrow$ 566 free parameters



$\Rightarrow$ 761 in total, calculations on the JURECA supercomputer [Jülich Supercomputing Centre, *JURECA: General-purpose supercomputer at Jülich Supercomputing Centre*, Journal of large-scale research facilities, 2, A**62** (2016)]

- t- & u-channel parameters: fixed to values of hadronic DCC analysis (JüBo 2013)

Selceted fit results $\gamma p \to \eta p$

Multipoles $\gamma p \to \eta p$ JüBo2017

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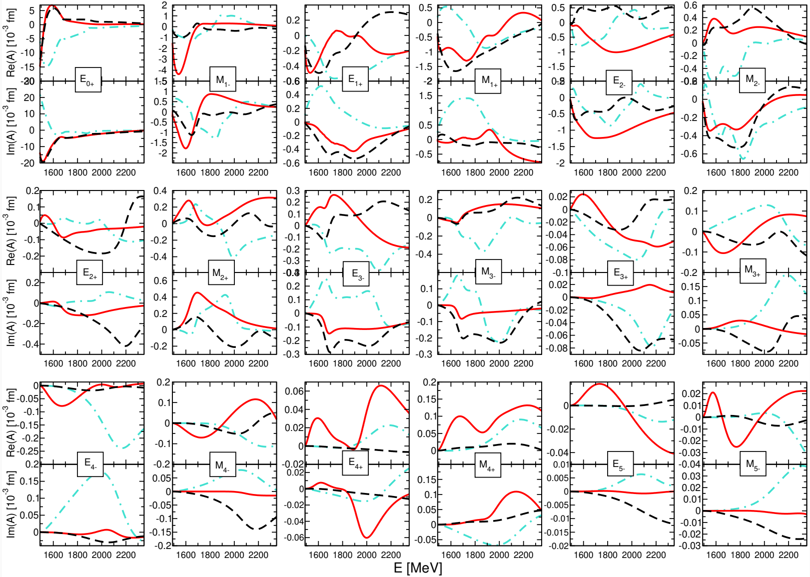
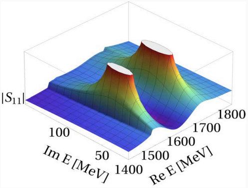


dashed black: BnGa2014-02 dash-dotted blue: EtaMAID2018 solid red: JüBo2017

The resonance spectrum

Resonance spectrum

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



- Re(E_0) = "mass", -2Im(E_0) = "width"
- elastic πN residue $(|r_{\pi N}|, \theta_{\pi N\to\pi N})$, normalized residues for inelastic channels $(\sqrt{\Gamma_{\pi N}\Gamma_\mu}/\Gamma_{\text{tot}}, \theta_{\pi N\to\mu})$
- photocouplings at the pole: $\tilde{A}^h_{pole} = A^h_{pole}\, e^{i\vartheta^h}$, $h = 1/2,\ 3/2$

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

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
$A^h_{L\pm}$: helicity multipole

In the present analysis:

- all 4-star N and Δ states up to $J = 9/2$ are seen (exception: $N(1895)1/2^-$)
  + some states rated with less than 4 stars
- one additional s-channel diagram included: $N(1900)3/2^+$
- hints for new dynamically generated poles

Resonance spectrum: selected results $I = 1/2$, $J^P = 1/2^-$

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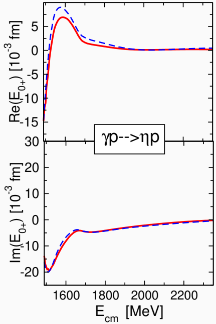
$N(1535)\ 1/2^-$ $\ast\ast\ast\ast$	Re E_0 [MeV]	-2Im E_0 [MeV]	$\lvert r_{\pi N}\rvert$ [MeV]	$\theta_{\pi N\to\pi N}$ [deg]	$\lvert A^{1/2}\rvert$ [10^{-3} GeV$^{-1/2}$]	$\vartheta^{1/2}$ [deg]
2017	1495(2)	112(1)	23(1)	-52(4)	106(3)	-1.6(2.1)
2015-B	1499	104	22	-46	106	5.2
	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{\eta N}}{\Gamma_{tot}}$ [%]	$\theta_{\pi N\to\eta N}$	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Lambda}}{\Gamma_{tot}}$ [%]	$\theta_{\pi N\to K\Lambda}$	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Sigma}}{\Gamma_{tot}}$ [%]	$\theta_{\pi N\to K\Sigma}$
2017	51(1)	105(3)	6.0(1.5)	-44(30)	5.7(1.6)	-86(6)
2015-B	51	112	5.0	32	5.0	-69



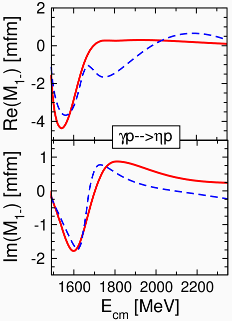
Red lines: JüBo2017, Blue (dashed) lines: JüBo2015-B

- JüBo2015: analysis of eta photoproduction together with pion photoproduction and several pion-induced reactions
- $N(1535)1/2^-$ very stable
- strong ηN coupling

Resonance spectrum: selected results $I = 1/2$, $J^P = 1/2^+$

DR, M. Döring, U.-G. Meißner EPJ A 54, 110 (2018)

$N(1710)\ 1/2^+$ $****$	Re E_0 [MeV]	$-2\text{Im}\ E_0$ [MeV]	$\lvert r_{\pi N}\rvert$ [MeV]	$\theta_{\pi N\to\pi N}$ [deg]	$\lvert A^{1/2}\rvert$ [10^{-3} GeV$^{-1/2}$]	$\vartheta^{1/2}$ [deg]
2017	1731(7)	157(6)	1.5(0.1)	178(9)	-14(2)	-23(188)
2015-B	1651	121	3.2	55	-20	97
	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{\eta N}}{\Gamma_{tot}}$ [%]	$\theta_{\pi N\to\eta N}$	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Lambda}}{\Gamma_{tot}}$ [%]	$\theta_{\pi N\to K\Lambda}$	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Sigma}}{\Gamma_{tot}}$ [%]	$\theta_{\pi N\to K\Sigma}$
2017	1.6(0.4)	$-137(46)$	10(1)	52(5)	1.4(0.1)	$-79(24)$
2015-B	16	-180	12	-32	0.4	-43



Red lines: JüBo2017, Blue (dashed) lines: JüBo2015-B

- $N(1710)1/2^+$ ηN residue much smaller in JüBo2017
- pronounced dip in multipole around 1600 MeV in both solutions
- reason: new dynamically generated pole with strong ηN coupling (needs confirmation!)

New dynamically generated pole with strong ηN coupling

- Hints for a new dynamically generated pole with stronger ηN coupling:
  (inconclusive, needs confirmation!!)

N(????) $1/2^+$	Re E_0 [MeV]	-2Im E_0 [MeV]	$\lvert r_{\pi N}\rvert$ [MeV]	$\theta_{\pi N\to\pi N}$ [deg]	$\lvert A^{1/2}\rvert$ [10^{-3} GeV$^{-1/2}$]	$\vartheta^{1/2}$ [deg]
2017	1615	260	2.4	-125	25	-77
	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{\eta N}}{\Gamma_{tot}}$ [%]	$\theta_{\pi N\to\eta N}$	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Lambda}}{\Gamma_{tot}}$ [%]	$\theta_{\pi N\to K\Lambda}$	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Sigma}}{\Gamma_{tot}}$ [%]	$\theta_{\pi N\to K\Sigma}$
2017	4.7	-100	0.8	-168	0.5	-2

- new N(????) responsible for dip in ηp multipole
- P_{11} partial wave "pretty crowded":
  - $N(1440)$ (dyn. gen.) at $1353 - i\,107$ MeV
  - $N(1710)$ at $1731 - i\,79$ MeV
  - $N(1750)$ (dyn. gen.) at $1749.79 - i\,159$ MeV
  - new N(????) (dyn. gen.) at $1614 - i\,129$ MeV

Resonance spectrum: selected results $I = 1/2$, $J^P = 3/2^+$

DR, M. Döring, U.-G. Meißner EPJ A 54, 110 (2018)

$N(1900)$ $3/2^+$ $****$	Re E_0 [MeV]	-2Im E_0 [MeV]	$\lvert r_{\pi N}\rvert$ [MeV]	$\theta_{\pi N\to\pi N}$ [deg]		
2017	1923(2)	217(23)	1.6(1.2)	$-61(121)$		
PDG 2018	1920 ± 20	150 ± 50	4 ± 2	-20 ± 30		
	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{\eta N}}{\Gamma_{\text{tot}}}$ [%]	$\theta_{\pi N\to\eta N}$	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Lambda}}{\Gamma_{\text{tot}}}$ [%]	$\theta_{\pi N\to K\Lambda}$	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Sigma}}{\Gamma_{\text{tot}}}$ [%]	$\theta_{\pi N\to K\Sigma}$
2017	1.1(0.7)	$-10(79)$	2.1(1.4)	1.7(86)	10(7)	$-34(74)$
PDG (BnGa)	5 ± 2	70 ± 60	3 ± 2	90 ± 40	4 ± 2	110 ± 30

$N(1720)$ $3/2^+$ $****$	Re E_0 [MeV]	-2Im E_0 [MeV]	$\lvert r_{\pi N}\rvert$ [MeV]	$\theta_{\pi N\to\pi N}$ [deg]		
2017	1689(4)	191(3)	2.3(1.5)	$-57(22)$		
2015-B	1710	219	4.2	-47		
PDG 2018	1675 ± 15	250^{+150}_{-100}	15^{+10}_{-5}	-130 ± 30		
	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{\eta N}}{\Gamma_{\text{tot}}}$ [%]	$\theta_{\pi N\to\eta N}$	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Lambda}}{\Gamma_{\text{tot}}}$ [%]	$\theta_{\pi N\to K\Lambda}$	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Sigma}}{\Gamma_{\text{tot}}}$ [%]	$\theta_{\pi N\to K\Sigma}$
2017	0.3(0.2)	139(35)	1.5(0.9)	$-66(30)$	0.6(0.4)	26(58)
2015-B	0.7	106	1.1	-70	0.2	79
PDG (BnGa)	3 ± 2	—	6 ± 4	-150 ± 45	—	—

Resonance spectrum: selected results $I = 1/2$, $J^P = 3/2^+$

DR, M. Döring, U.-G. Meißner EPJ A 54, 110 (2018)

$N(1900)\ 3/2^+$ $****$	Re E_0 [MeV]	-2Im E_0 [MeV]	$\lvert r_{\pi N}\rvert$ [MeV]	$\theta_{\pi N\to\pi N}$ [deg]		
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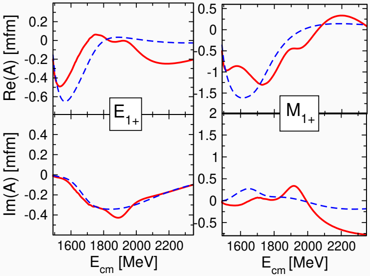
2017	1.1(0.7)	$-10(79)$	2.1(1.4)	1.7(86)	10(7)	$-34(74)$
PDG (BnGa)	5 ± 2	70 ± 60	3 ± 2	90 ± 40	4 ± 2	110 ± 30

E_{1+}, M_{1+} multipoles in $\gamma p \to \eta p$:



Red lines: JüBo2017, Blue (dashed) lines: JüBo2015-B

N(1900) $3/2^+$:

- seen by several other groups
- included ("by hand") to improve fit result for $\gamma p \to K^+\Lambda$ in JüBo2017
- ηN residue not strong, but still visible "bump" around pole position in multipole