The light baryon resonance spectrum in a coupled-channel approach

Recent results from the Jülich-Bonn model – NSTAR 2022

October 18, 2022 | Deborah Rönchen | Institute for Advanced Simulation, Forschungszentrum Jülich

In collaboration with: M. Döring, M. Mai, Ulf-G. Meißner, C.-W. Shen, Y.-F. Wang, R. Workman

(Jülich-Bonn and Jülich-Bonn-Washington collaborations)

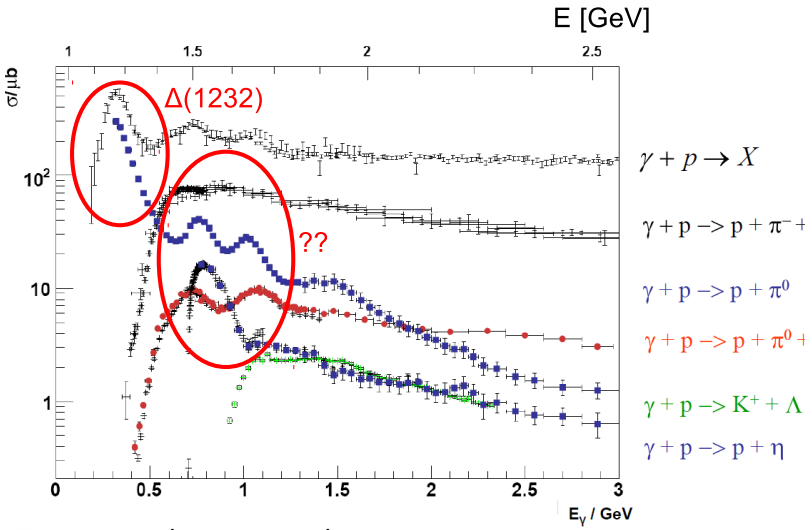
Supported by DFG, NSFC and MKW NRW

HPC support by Jülich Supercomputing Centre

The excited baryon spectrum:

Connection between experiment and QCD in the non-perturbative regime

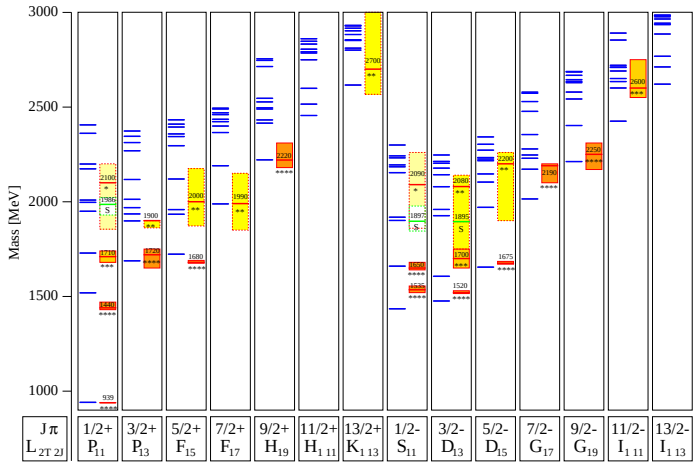
Experimental study of hadronic reactions



source: ELSA; data: ELSA, JLab, MAMI

$\Longleftrightarrow$

Theoretical predictions of excited hadrons
e.g. from relativistic quark models:



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

Major source of information:

In recent years: **photoproduction reactions**

- enlarged data base with high quality (double) polarization observables, towards a complete experiment Reviews: Prog.Part.Nucl.Phys. 125, 103949 (2022), Prog.Part.Nucl.Phys. 111 (2020) 103752

In the future: **electroproduction reactions**

- 10^5 data points for πN, ηN, KY, $\pi\pi N$ already available
- access the Q^2 dependence of the amplitude Reviews: Prog.Part.Nucl.Phys. 67 (2012)

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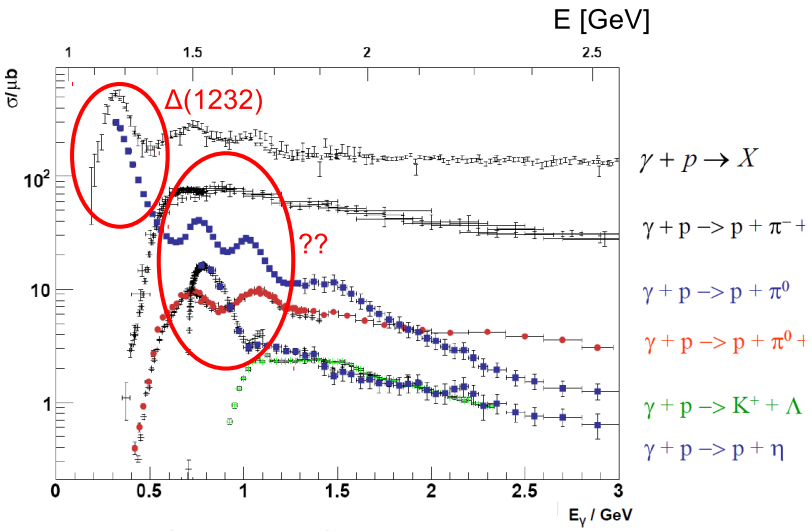

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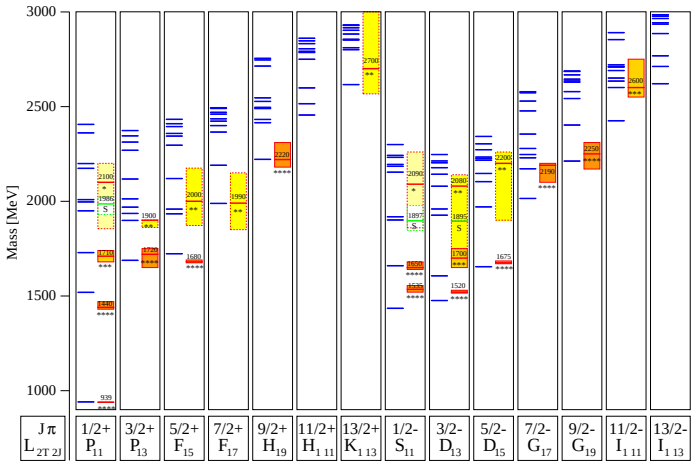

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$\Rightarrow$ Partial wave decomposition:
decompose data with respect to a conserved quantum number:

total angular momentum and parity J^P

$\Rightarrow$ search for resonances/excited states in those partial waves:
poles on the 2nd Riemann sheet
(Breit-Wigner problematic in baryon spectroscopy)

The Jülich-Bonn DCC approach for N^* and Δ^*

pion-induced reactions

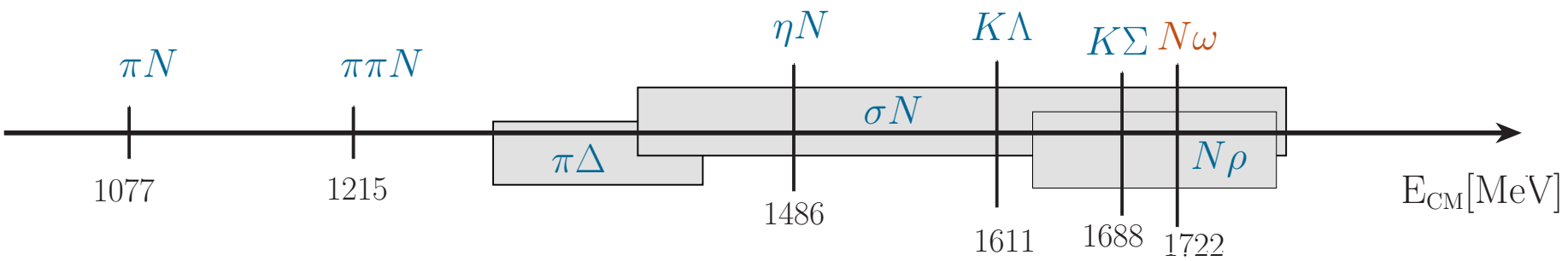
EPJ A 49, 44 (2013)

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

The scattering equation in partial-wave basis

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

- channels ν, μ, γ:



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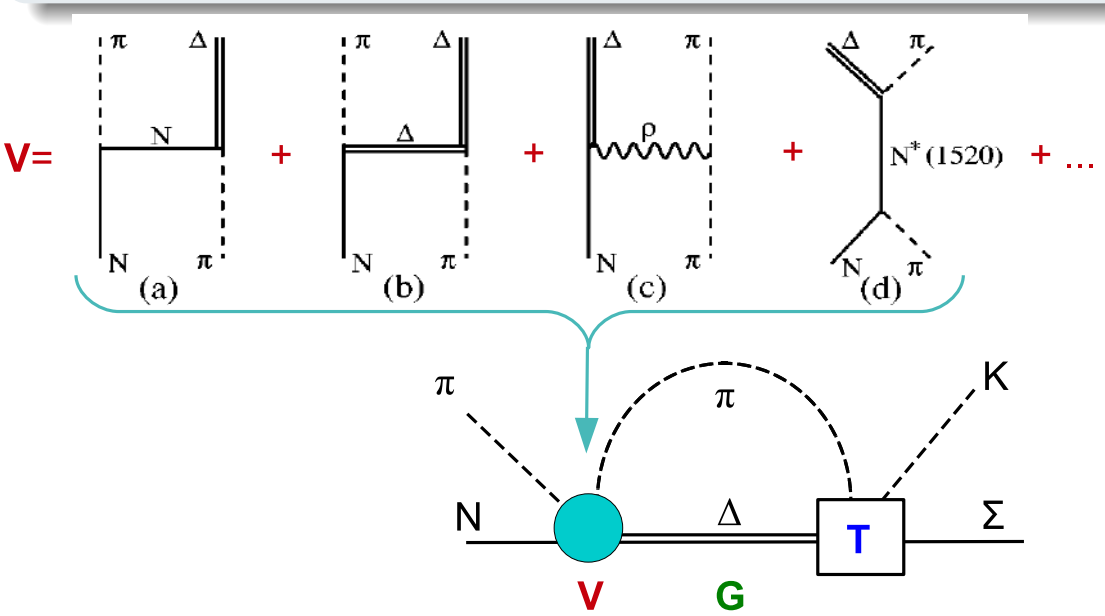

- potentials V constructed from effective $\mathcal{L}$
- s-channel diagrams: T^P
  genuine resonance states
- t- and u-channel: T^{NP}
  dynamical generation of poles
  partial waves strongly correlated
- contact terms

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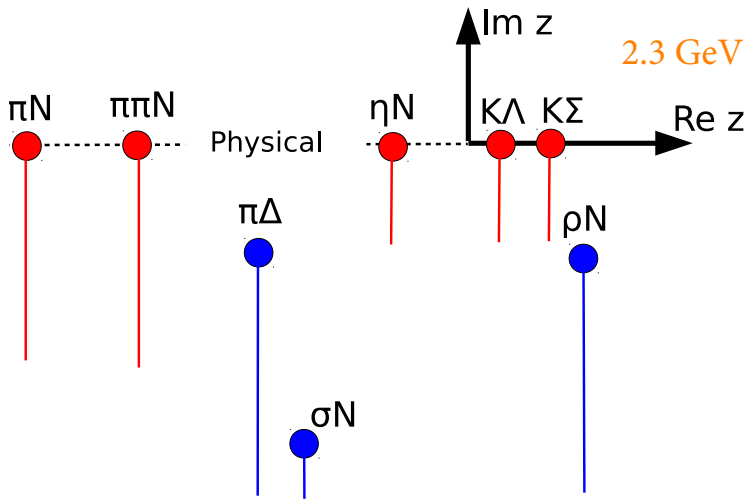
Thresholds of inelastic channels

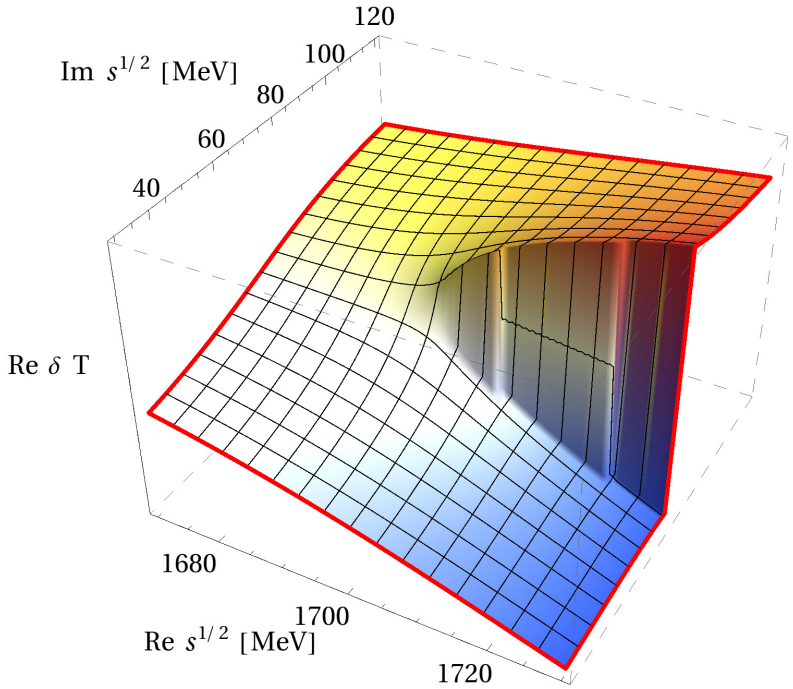
- (2 body) unitarity and analyticity respected (no on-shell factorization, dispersive parts included)
- opening of **inelastic channels** $\Rightarrow$ **branch point** and new **Riemann sheet**

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





Example: ρN branch point at

$$M_N + m_{rho} = 1700 \pm i75 \text{ MeV}$$

Inclusion of branch points important to avoid false resonance signal!

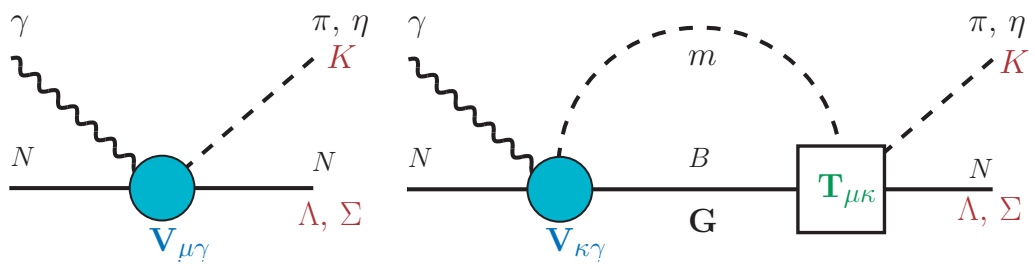
Photoproduction in a semi-phenomenological approach

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)

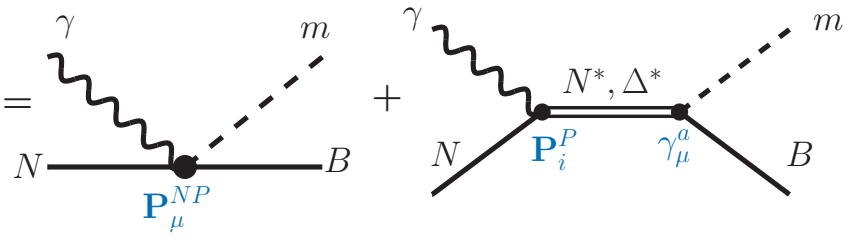


$m = \pi, \eta, K$, $B = N, \Delta, \Lambda$

$T_{\mu\kappa}$: full hadronic T-matrix as in pion-induced reactions

Photoproduction potential: approximated by energy-dependent polynomials (field-theoretical description numerically too expensive)

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



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

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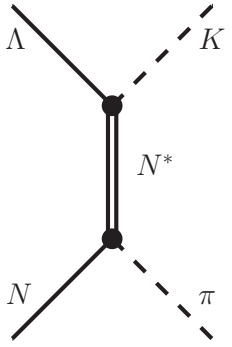
Simultaneous fit of pion- & photon-induced reactions

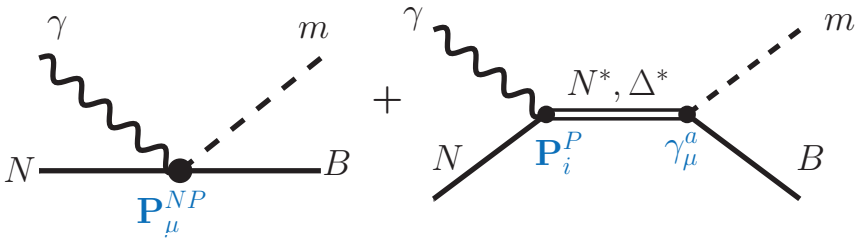
Free parameters

- $\pi N \to \pi N, \eta N, KY$:
  s-channel: resonances (T^P)



m_{bare} + f_{mBN^*}

- $\gamma p \to \pi N, \eta N, KY$: couplings of the polynomials and s-channel parameters



- couplings in contact terms: one per PW, couplings to πN, ηN, ($\pi\Delta$,) $K\Lambda$, $K\Sigma$
- t- & u-channel parameters: cut-offs, mostly fixed to values of previous JüBo studies (couplings fixed from SU(3))

$\Rightarrow$ $>$ 900 fit parameters in total, $\sim$ 72,000 data points

↳ calculations on a supercomputer [JURECA, Jülich Supercomputing Centre, Journal of large-scale research facilities, 2, A**62** (2016)]

- large number of fit parameters, many from polynomials
- can be regarded as advantage: prevents the inclusion of superfluous s-channel states to improve fit

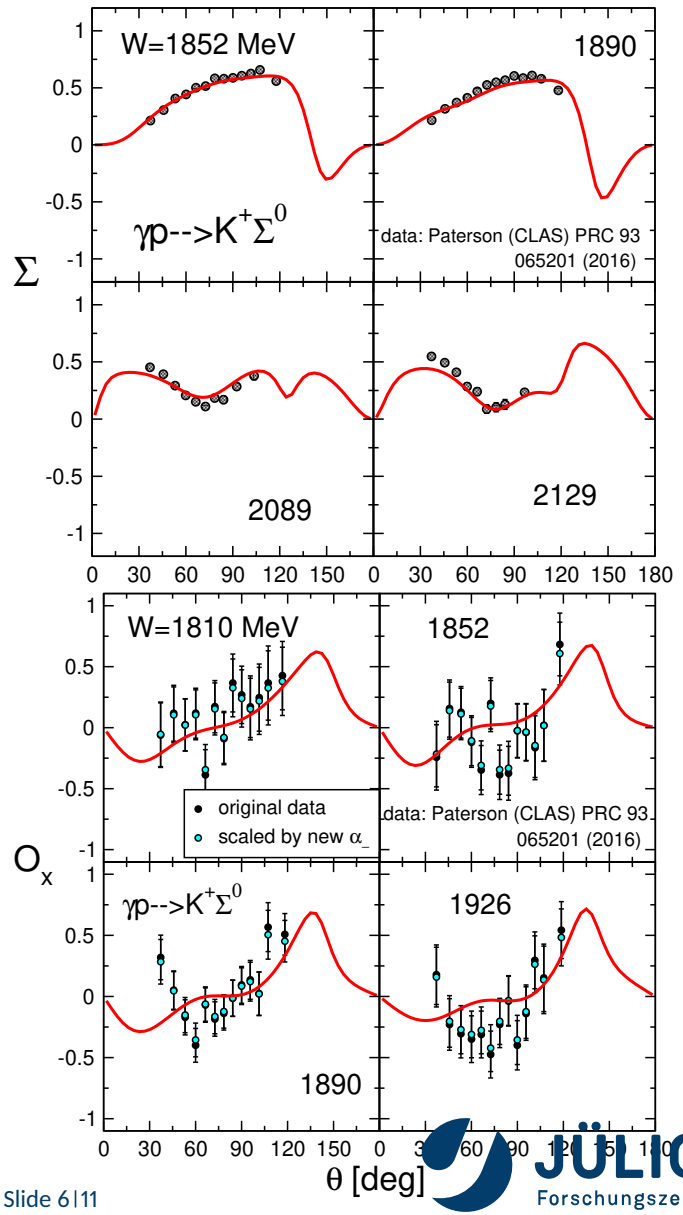
Extension to $K\Sigma$ photoproduction on the proton

JüBo2022 arXiv:2208.00089 [nucl-th], accepted at EPJ A

Unique opportunities in $\gamma p \to K^+\Sigma^0, K^0\Sigma^+$:

- coupling of N^*'s, Δ^*'s to strangeness channels: missing resonances not seen in πN scattering?
- mixed isospin $\to$ more information on Δ states
- self-analyzing decay of Y's: recoil polarization from angular distribution of decay products
  (important for "complete experiment")
- better data quality than in $\pi N \to KY$

Selected fit results



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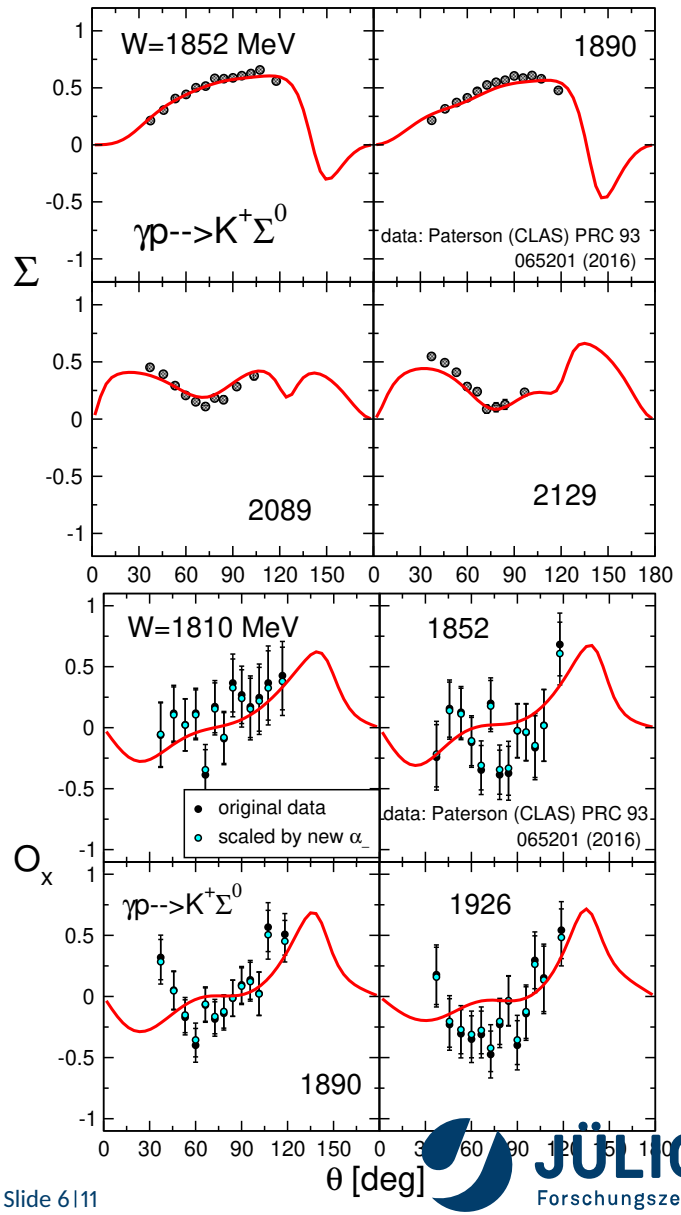
Simultaneous analysis of $\pi N \to \pi N, \eta N, K\Lambda, K\Sigma$ and $\gamma p \to \pi N, \eta N, K\Lambda, K\Sigma$

- almost 72,000 data points in total, $W_{\text{max}} = 2.4$ GeV
  - $\gamma p \to K^+\Sigma^0$: $d\sigma/d\Omega$, P, Σ, T, $C_{x',z'}$, $O_{x,z}$ = 5,652
  - $\gamma p \to K^0\Sigma^+$: $d\sigma/d\Omega$, P = 448
- polarizations scaled by new Λ decay constant α_- (Ireland PRL 123 (2019), 182301), if applicable
- χ^2 minimization with MINUIT on JURECA [Jülich Supercomputing Centre, JURECA: JLSRF 2, A62 (2016)]

Resonance analysis:

- all 4-star N and Δ states up to $J = 9/2$ are seen (exception: $N(1895)1/2^-$) + some states rated less than 4 stars
- no additional s-channel diagram, but indications for new dyn. gen. poles

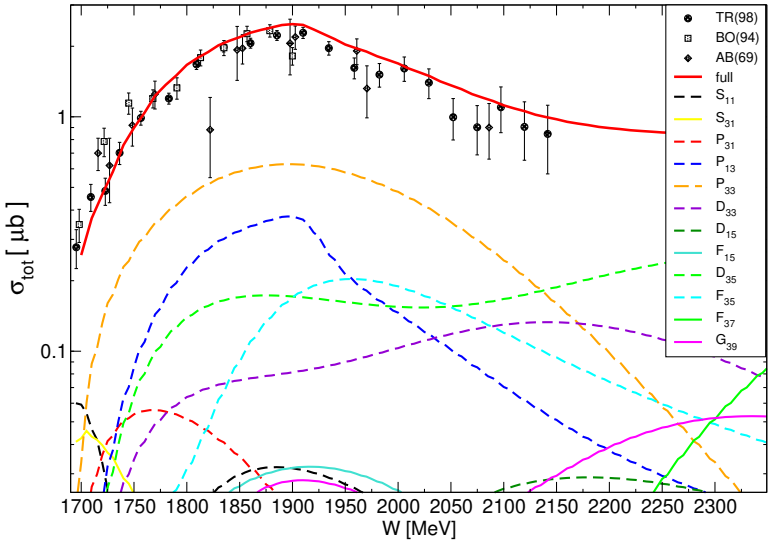
Selected fit results



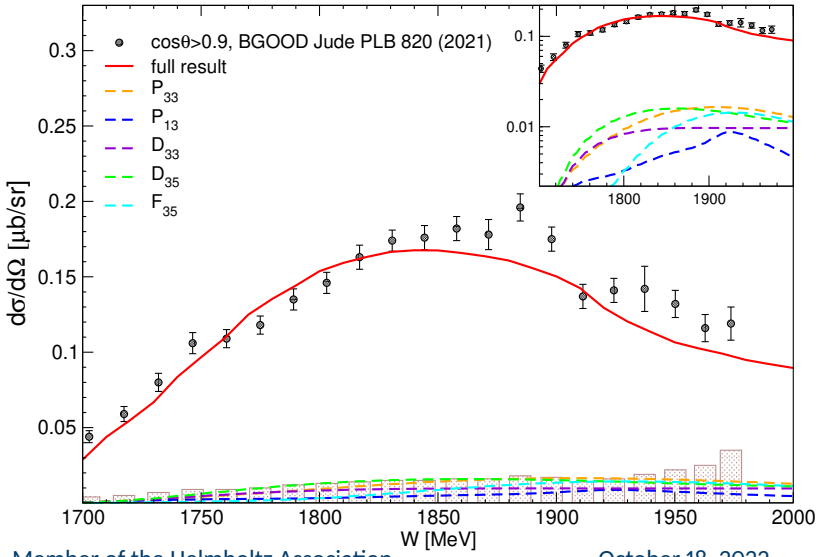
Resonance contributions to $K\Sigma$ photoproduction

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

JüBo2022 arXiv:2208.00089 [nucl-th]



(Data not included in fit)



- dominant partial waves: $I = 3/2$

Exception: P_{13} partial wave ($I = 1/2$):

$N(1720)\ 3/2^+$	Re E_0	$-2\mathrm{Im}\ E_0$	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Sigma}}{\Gamma_{tot}}$	$\theta_{\pi N\to K\Sigma}$
* * **	[MeV]	[MeV]	[%]	[deg]
2022	1726(8)	185(12)	5.9(1)	82(6)
2017	1689(4)	191(3)	0.6(0.4)	26(58)
PDG 2021	1675 ± 15	250^{+150}_{-100}	—	—

$N(1900)\ 3/2^+$	Re E_0	$-2\mathrm{Im}\ E_0$	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Sigma}}{\Gamma_{tot}}$	$\theta_{\pi N\to K\Sigma}$
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2022	1905(3)	93(4)	1.3(0.3)	$-40(18)$
2017	1923(2)	217(23)	10(7)	$-34(74)$
PDG 2021	1920±20	150±50	4±2	110±30

- drop in cross section due to $N(1900)3/2^+$
- "cusp-like structure" only qualitatively explained

Resonance contributions to $K\Sigma$ photoproduction

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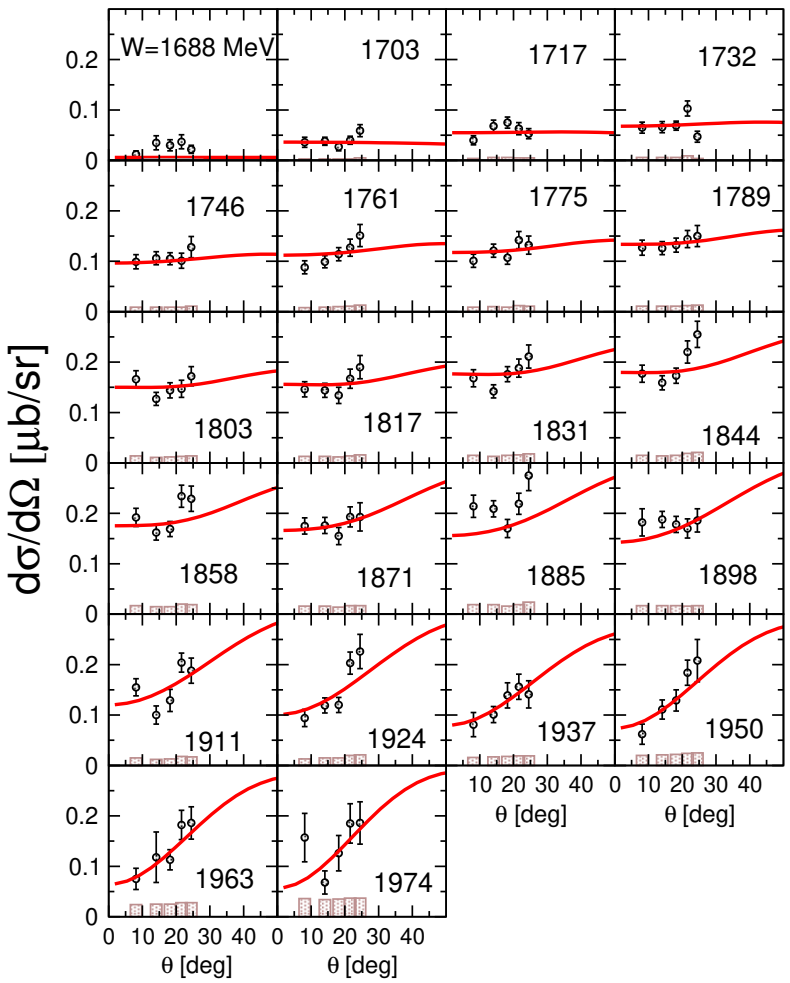
$\gamma p \to K^+\Sigma^0$



Data: Jude et al. (BGOOD) PLB 820 (2021)

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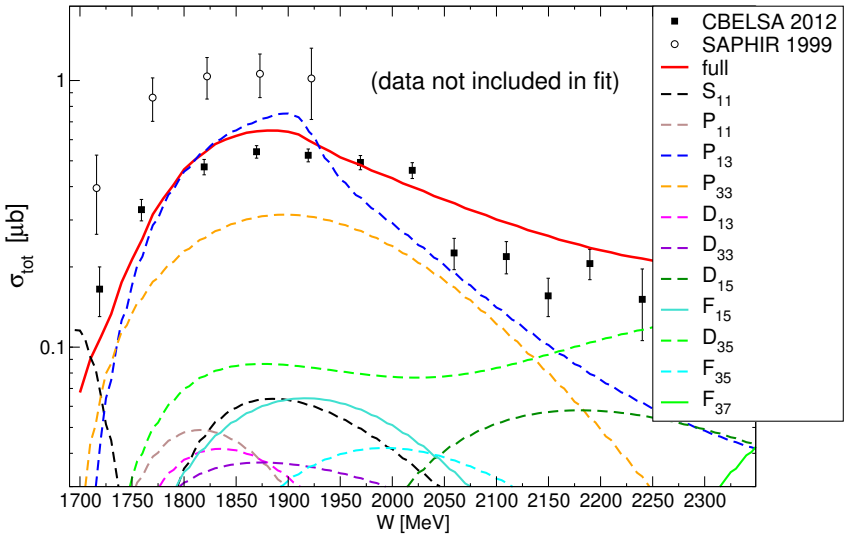
Selected results $\gamma p \to K^0\Sigma^+$

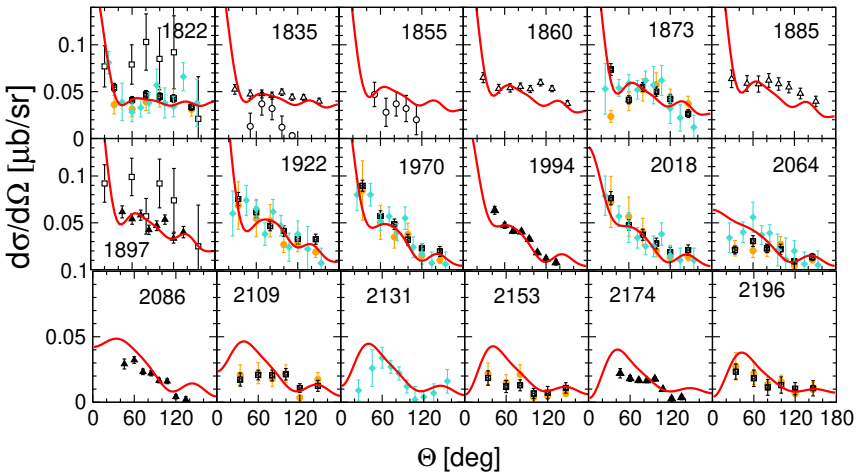
JüBo2022 arXiv:2208.00089 [nucl-th]



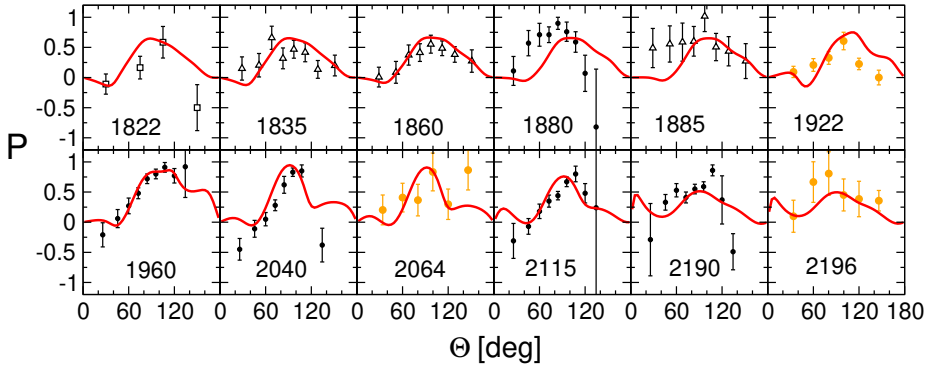
- much less data than for $K^+\Sigma^0$ (448 vs 5,652 data points)
- in parts inconsistent data

  $\to$ difficult to achieve a good fit result
- cusp in σ_{tot} at $\sim$ 2 GeV not reproduced (data not included in fit)

Selected fit results:



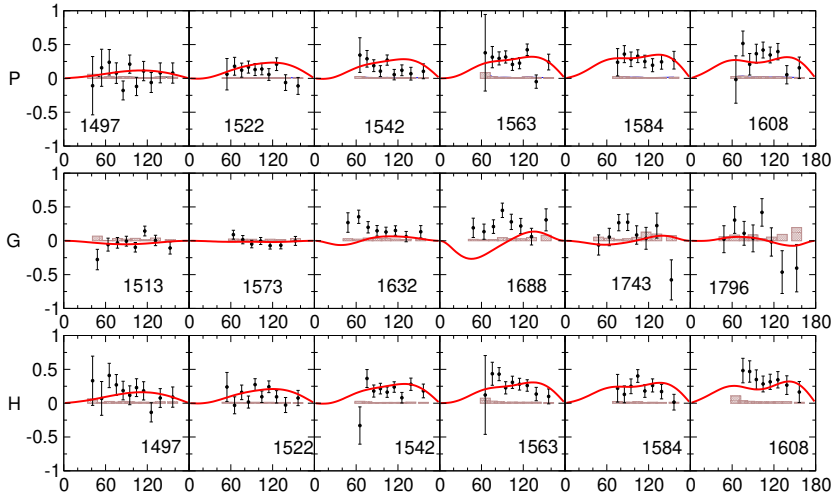
Data: open squares: SPAHIR 1999, cyan: SAPHIR 2005, orange: CBELSA/TAPS 2007, black squares: CBELSA/TAPS 2011, open circles: A2 2018, open triangles: A2 2013, black triangles: Hall B 2003, black circles: CLAS 2013



New data for $\gamma p \to \eta p$ from CBELSA/TAPS

included in JüBo2022 arXiv:2208.00089 [nucl-th]

- T, P, H, G, E Müller PLB 803, 135323 (2020): very first data on H, G (and P) in this channel



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2022	1504(0)	74 (1)	50(3)	118(3)
2017	1495(2)	112(1)	51(1)	105(3)
PDG 2022	1510 ± 10	130 ± 20	43 ± 3	-76 ± 5

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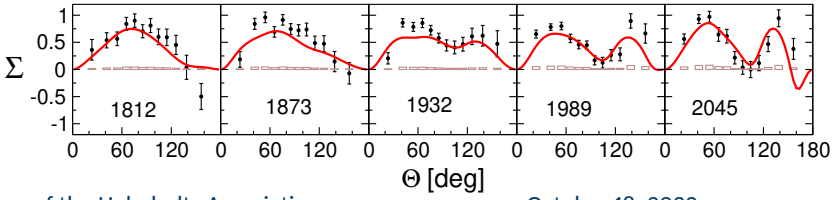
$\to \eta N$ residue $N(1650)1/2^-$ much larger (similarly observed by BnGa)

- Σ Afzal PRL 125, 152002 (2020): Backward peak in data

$\to$ Observation of $\eta' N$ cusp + importance of $N(1895)1/2^-$ (BnGa)



JüBo2022:

- no $\eta' N$ channel (or cusp), to be included in the future
- no $N(1895)1/2^-$ (not needed)
- backward peak from $N(1720)$ & $N(1900)3/2^+$

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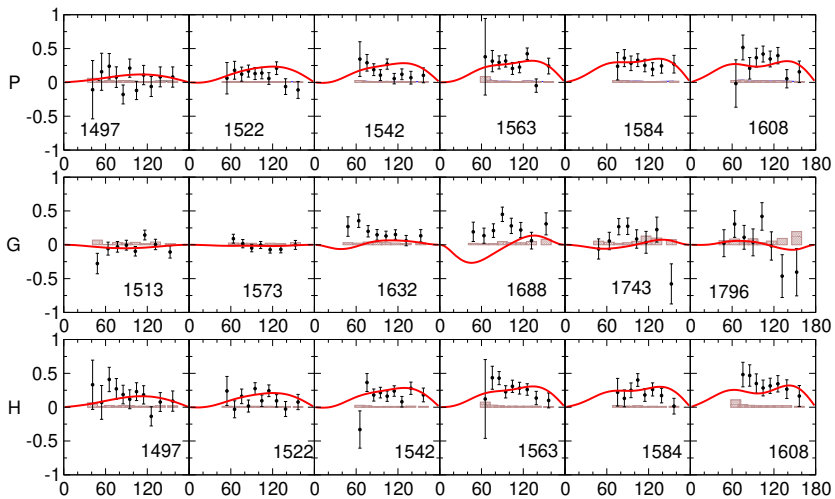

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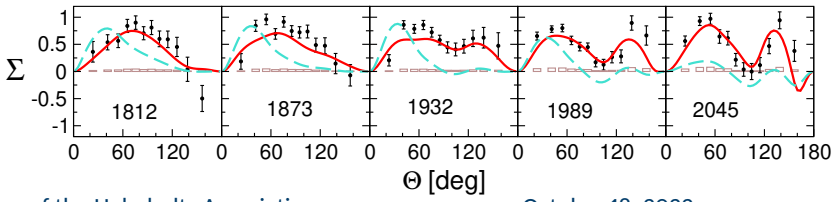

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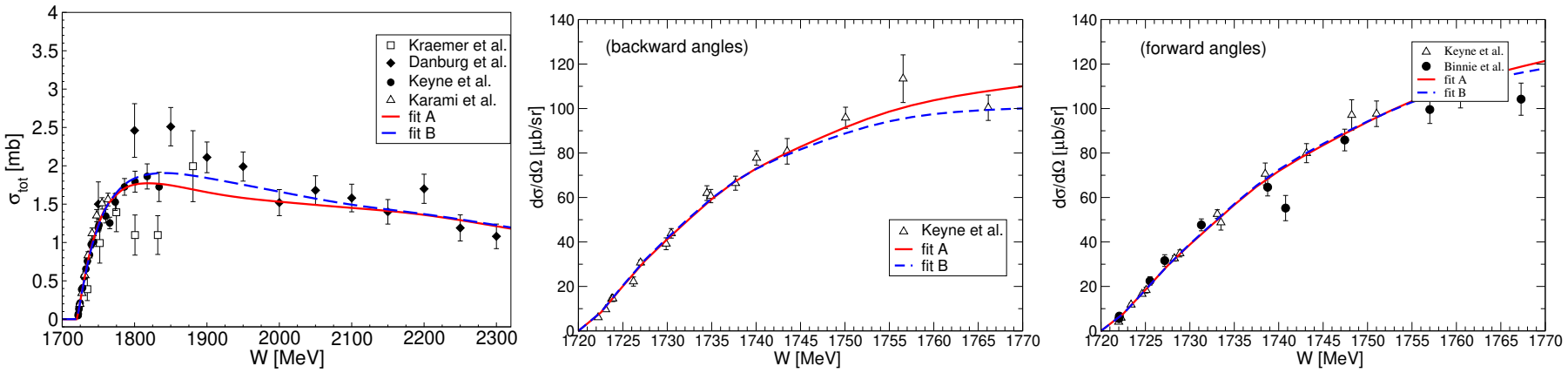
- no $N(1895)1/2^-$ (not needed)
- backward peak from $N(1720)$ & $N(1900)3/2^+$ (turquoise lines: both states off)

Inclusion of the ωN channnel: $\pi N \to \omega N$ channel

Wang *et al.* 2208.03061 [nucl-th]

- Preparation of the study of $\gamma N \to \omega N$ (abundant high quality data)
- importance of ω in nuclear matter [H. Shen et al. 1998 NPA]
- Scattering length $a_{\omega N} \to$ whether or not there are in-medium bound states

Selected fit results: Total cross section, backward/forward differential cross section



Data: Kraemer et al. 1964 PR, Danburg et al. 1970 PRD, Binnie et al. 1973 PRD, Keyne et al. 1976 PRD, Karami et al. 1979 NPB

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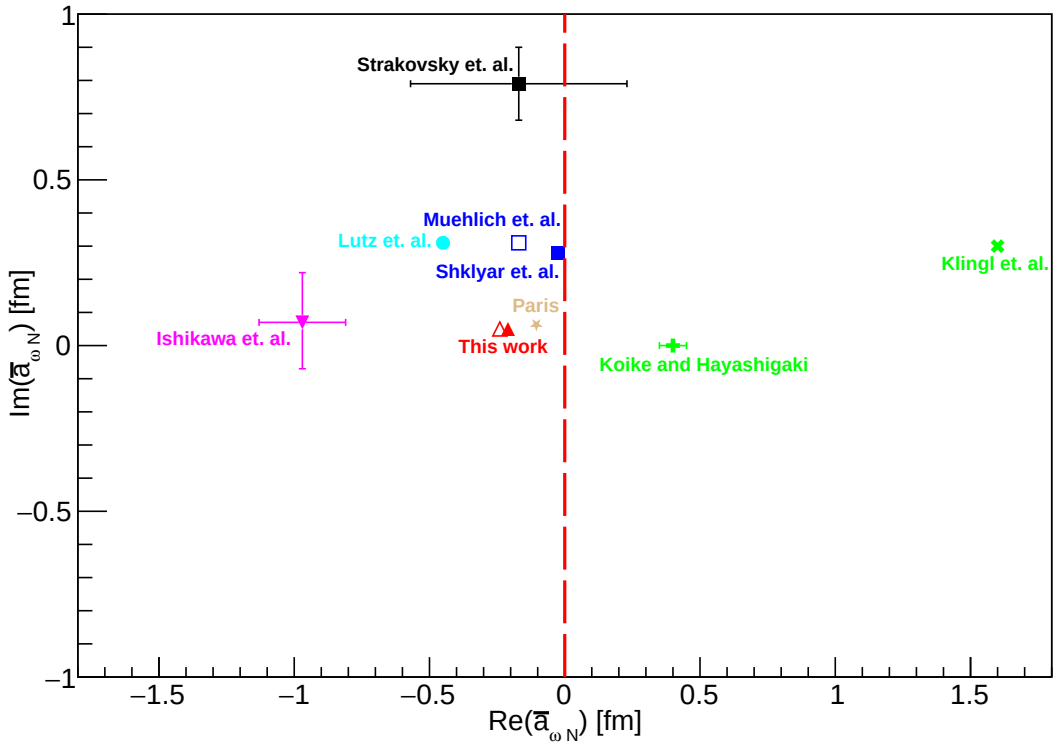
Scattering length:

- Re$\bar{a} > 0 \to$ in-medium bound states
- Result of fit A(B)
  $\bar{a} = -0.24(-0.21) + 0.05i(0.05i)$



Summary

Jülich-Bonn dynamical coupled-channel analysis:

- Extraction of the N^* and Δ^* spectrum in a simultaneous analysis of pion- and photon-induced reactions:

  - $\pi N \to \pi N$, ηN, $K\Lambda$ and $K\Sigma$
  lagrangian based description, unitarity & analyticity respected

  - $\gamma N \to \pi N$, ηN, $K\Lambda$ and $K\Sigma$ in a semi-phenomenological approach
  hadronic final state interaction: JüBo DCC analysis

  $\to$ analysis of almost 72,000 data points

- $\pi N \to \omega N$ channel included, prerequisite for ω photoproduction
- Electroproduction: *Jülich-Bonn-Washington* approach Mai *et al.* PRC 103 (2021), PRC 106 (2022)

  - JüBo photoproduction amplitude as input at Q^2=0

  - New interactive web interface: **https://jbw.phys.gwu.edu** (multipoles, observables, data)

$\to$ Talk by Maxim Mai on Wednesday

Thank you for your attention!