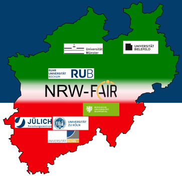
Opportunities with hadron beams for light baryon spectroscopy

November 11, 2024 | Deborah Rönchen | Institute for Advanced Simulation, Forschungszentrum Jülich

with contribution by M. Döring

Supported by DFG, MKW NRW
HPC support by Jülich Supercomputing Centre



⟨NuMeriQS⟩

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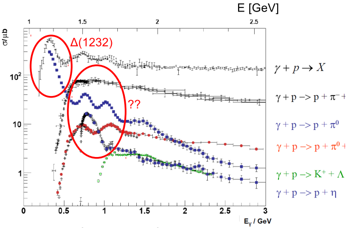
The excited baryon spectrum:

Connect experiment & QCD in the non-perturbative regime

How do quarks get confined in hadrons?

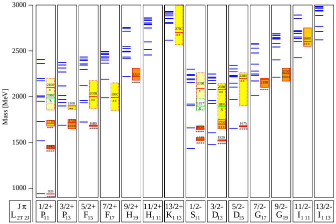
Experimental study of hadronic reactions



source: ELSA; data: ELSA, JLab, MAMI

PWA
↔
poles

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



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

In the past: **elastic or charge exchange πN scattering**

- "missing resonance problem"

In recent years: **photoproduction reactions**

- large data base, high quality polarization observables Prog.Part.Nucl.Phys. 125 (2022), Prog.Part.Nucl.Phys. 111 (2020)

In the future: **electroproduction reactions**

- 10^5 data points for πN, ηN, KY, $\pi\pi N$ Review: e.g. Prog.Part.Nucl.Phys. 67 (2012)

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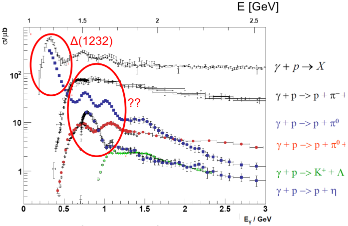
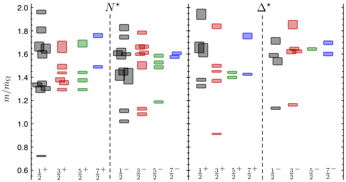


source: ELSA; data: ELSA, JLab, MAMI

PWA

poles

Theoretical predictions of excited hadrons
... or lattice calculations (with some limitations):



$m_\pi = 396$ MeV [Edwards *et al.*, Phys.Rev. D84 (2011)]

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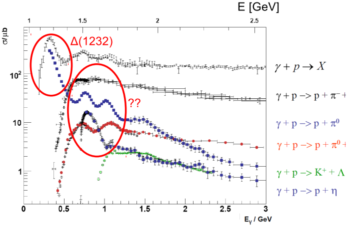


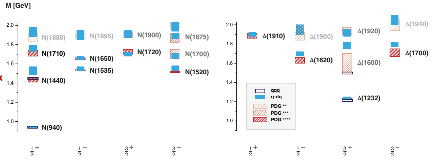
source: ELSA; data: ELSA, JLab, MAMI

PWA

poles

Theoretical predictions of excited hadrons

… or Dyson-Schwinger approaches:



[Eichmann *et al.*, Phys.Rev. D94 (2016), fig. from PoS LC2019 (2019) 003]

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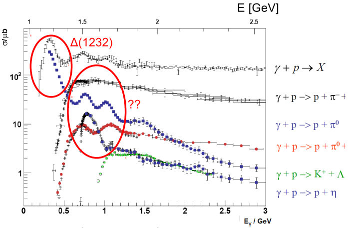
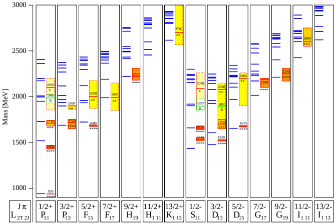


source: ELSA; data: ELSA, JLab, MAMI

PWA ⟷ poles

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



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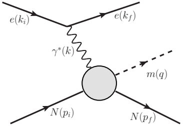
Electroproduction reactions

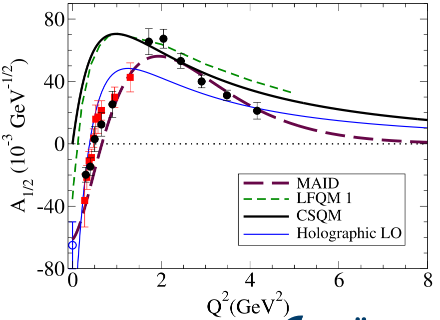
major progress in recent years, e.g., from JLab, MAMI, . . .



- 10^5 data points for πN, ηN, KY, $\pi\pi N$ electroproduction
- access the Q^2 dependence of the amplitude:

  perturbative QCD $\leftrightarrow$ quark confinement

$N(1440)1/2^+$



Baryon Transition Form Factors (TFFs)

Q^2 dependence of residues of helicity amplitudes
$\rightarrow$ conclusions on the nature of resonances

- Zero crossing: important for quark models, DSE (meson cloud contributions or radial excitation of the nucleon?)

Reviews: e.g. Rev.Mod.Phys. 91 (2019), Prog.Part.Nucl.Phys. 136 (2024)

Figure from Prog.Part.Nucl.Phys. 136 1040… (2024)

Baryon Transition Form Factors

$N(1440)1/2^+$

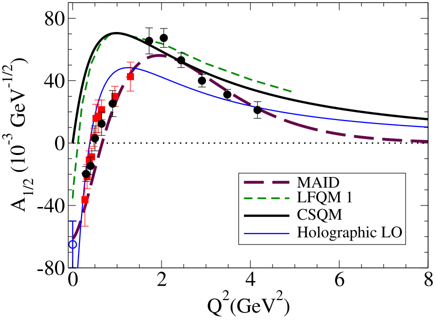


Figure from Prog.Part.Nucl.Phys. 136 104

”points”: NOT experimental data!

- extracted from πN and $\pi\pi N$ electroproduction data (CLAS)
  PRC 80 (2009), PRC 86 (2012), PRC 93 (2016)
- unitary isobar model
- established resonances
- some parameters fixed to PDG BW values

Constraints from pion-induced reactions!

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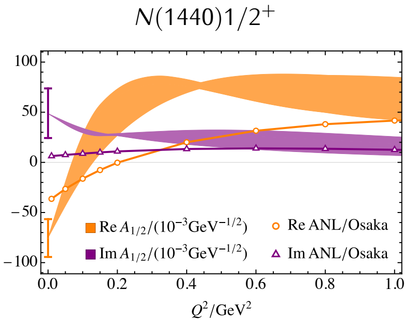
Baryon Transition Form Factors

Y.-F. Wang et al. PRL 133 (2024)

from Jülich-Bonn-Washington model, pole parameters instead of Breit-Wigner resonances



TFFs defined independently of the hadronic final state as (Workman et al. PRC 87 (2013)) :

$$H_h^{l\pm,I}(Q^2) = C_I \sqrt{\frac{p_{\pi N}}{\omega_0}\,\frac{2\pi(2J+1)z_p}{m_N \widetilde{R}_{\pi N}^{l\pm,I}}}\,\widetilde{\mathcal{H}}_h^{l\pm,I}(Q^2)\,,$$

$h = 1/2, 3/2$ helicity, $\mathcal{H}$ ($=\mathcal{A}$ or $\mathcal{S}$) helicity amplitudes, $\widetilde{\mathcal{H}}$, $\widetilde{R}$ residues, z_p pole position

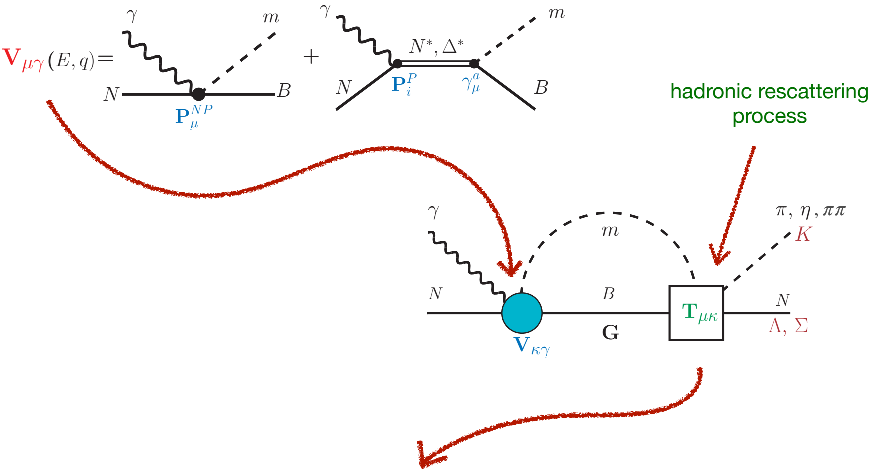
⇒ constraints from photon- & pion-induced reactions!

- Zero crossing at smaller Q^2

$$\mathcal{M}_{\mu\gamma^*}(k,W,Q^2) = R_{\ell'}(\lambda, q/q_\gamma)\left(V_{\mu\gamma^*}(k,W,Q^2) + \sum_\kappa \int_0^\infty dp\, p^2\, T_{\mu\kappa}(k,p,W)\,G_\kappa(p,W)\,V_{\kappa\gamma^*}(p,W,Q^2)\right)$$

- Input from photoproduction: $V_{\mu\gamma}(k,W,Q^2=0)$ — M. Mai *et al.* PRC 103 (2021)
- Input from pion-induced reactions: $T_{\mu\kappa}(k,p,W) \to$ universal pole positions

Photoproduction reactions



Constraints from pion-induced reactions!

Role of pion beams in baryon spectroscopy

light, non-strange sector

- Pion-induced reactions

$$\pi N \to \begin{cases} \pi N \\ \eta N,\ K\Lambda,\ K\Sigma \\ \pi\pi N, \pi\eta N, \ldots \end{cases}$$

Data!

- 2 complex amplitudes (g, h)

- Photon-induced reactions

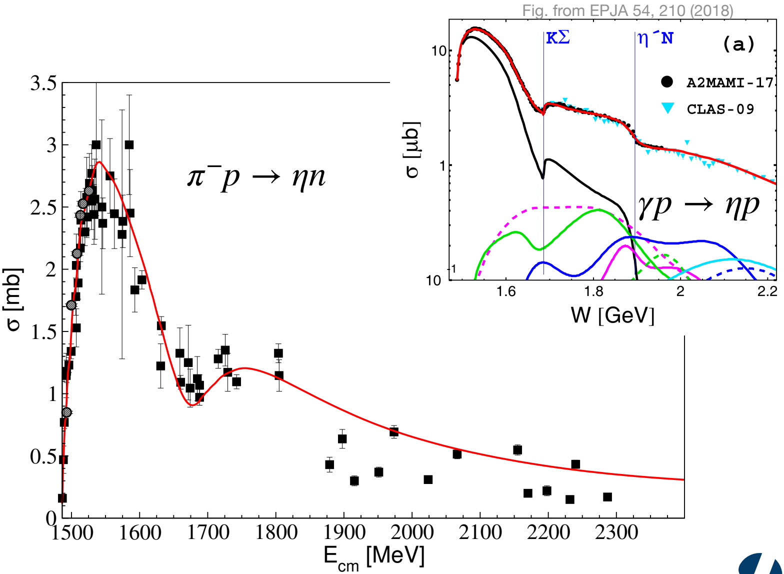
$$\gamma^{(*)} N \to \begin{cases} \pi N \\ \eta N,\ K\Lambda,\ K\Sigma \\ \pi\pi N, \pi\eta N, \ldots \end{cases}$$

$$\begin{cases} \pi N \\ \eta N,\ K\Lambda,\ K\Sigma \\ \pi\pi N, \pi\eta N, \ldots \end{cases} \leftrightarrow \begin{cases} \pi N \\ \eta N,\ K\Lambda,\ K\Sigma \\ \pi\pi N, \pi\eta N, \ldots \end{cases}$$

- hadronic FS interaction as subprocess
- 4 (photo) or 6 (electro) complex amplitudes (CGLN F_i)

γ, γ^*-induced reactions have **more d.o.f**, analysis **depends on π-induced data**.

Pion-induced data: $\pi N \to \eta N$



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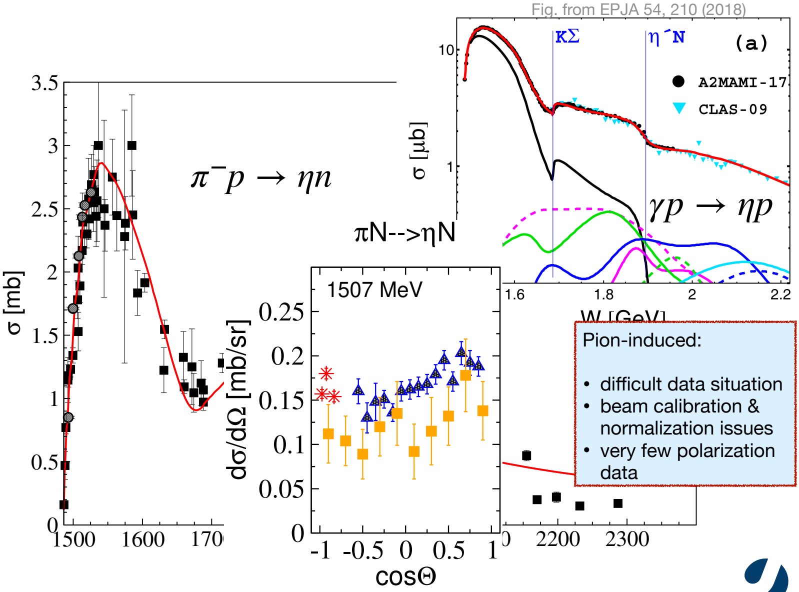
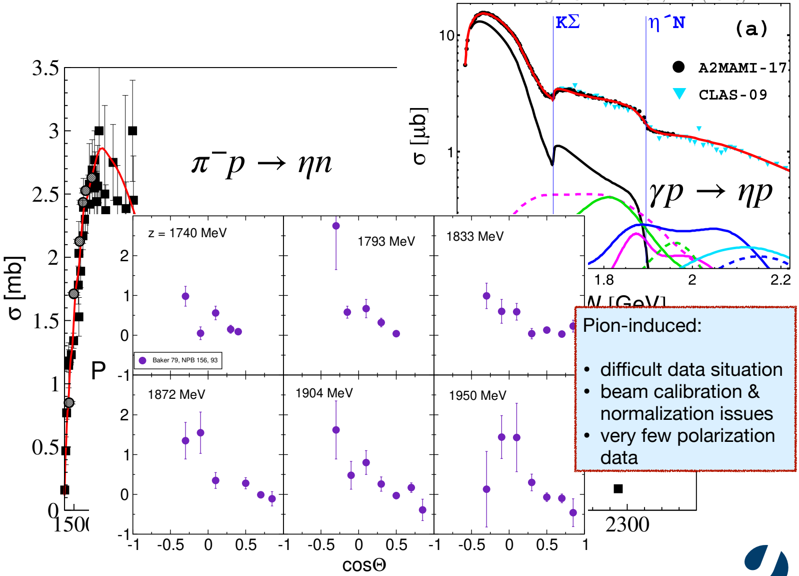


Pion-induced:

- difficult data situation
- beam calibration & normalization issues
- very few polarization data

Pion-induced data: $\pi N \to \eta N$

Fig. from EPJA 54, 210 (2018)



Pion-induced:

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Polarization observables: Impact on well-established $N(1650)1/2^-$

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

$$\gamma p \to \eta p$$

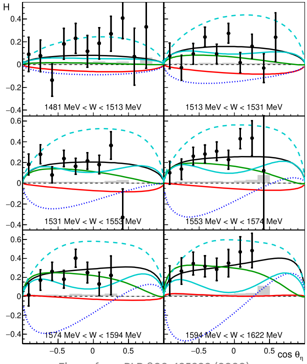

Figure from PLB 803, 135323 (2020)

black lines: BnGa fit

other lines: predictions by various groups

- PDG estimates $\frac{\Gamma_{\eta N}}{\Gamma_{tot}}$ (2010):

$N(1535)1/2^-$: 45-60% vs. $N(1650)1/2^-$: 3-10%

$\to$ new polarization data (CLAS, MAMI, CBELSA) $\gamma N \to \eta N$

- new BnGa fit $\to N(1650)1/2^-$: $\frac{\Gamma_{\eta N}}{\Gamma_{tot}} = 33 \pm 4\%$ (PLB 803 (2020))
- new JüBo fit $\to |\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{\eta N}}{\Gamma_{\text{tot}}}| = 34(12)\%$ vs. $18(3)\%$ (before)

(EPJA 58 (2022)) ($\frac{\Gamma_{\eta N}}{\Gamma_{tot}} = 12\%$ vs. 7%)

Note: photocoupling $A_{1/2}$ also up to changes!

- ηN residue $N(1650)1/2^-$ much larger
- Better pion-induced data to determine resonance parameters! (especially: inelastic residues)

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N^* vs. Δ resonance spectrum: recent advances based on γN data

- 6 new N^*'s

Particle	J^P	overall	Status as seen in $N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***						
$N(1520)$	$3/2^-$	****	****	****	****	**	****					
$N(1535)$	$1/2^-$	****	****	****	***	*	****					
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*				
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*			
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*			
$N(1700)$	$3/2^-$	***	**	***	***	*	*			*		
$N(1710)$	$1/2^+$	****	****	****	*		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**		*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*	**	*	*				*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
$N(2570)$	$5/2^-$	**		**								
$N(2600)$	$11/2^-$	***		***								
$N(2700)$	$13/2^+$	**		**								

Particle	J^P	overall	Status as seen in $N\gamma$	$N\pi$	$\Delta\pi$	ΣK	$N\rho$	$\Delta\eta$
$\Delta(1232)$	$3/2^+$	****	****	****				
$\Delta(1600)$	$3/2^+$	****	****	***	****			
$\Delta(1620)$	$1/2^-$	****	****	****	****			
$\Delta(1700)$	$3/2^-$	****	****	****	****	*	*	
$\Delta(1750)$	$1/2^+$	*	*	*		*		
$\Delta(1900)$	$1/2^-$	***	***	***	*	**	*	
$\Delta(1905)$	$5/2^+$	****	****	****	**	*	*	**
$\Delta(1910)$	$1/2^+$	****	***	****	**	**		*
$\Delta(1920)$	$3/2^+$	***	***	***	***	**		**
$\Delta(1930)$	$5/2^-$	***	*	***	*	*		
$\Delta(1940)$	$3/2^-$	**	*	**	*			*
$\Delta(1950)$	$7/2^+$	****	****	****	**	***		
$\Delta(2000)$	$5/2^+$	**	*	**	*		*	
$\Delta(2150)$	$1/2^-$	*		*				
$\Delta(2200)$	$7/2^-$	***	***	**	***	**		
$\Delta(2300)$	$9/2^+$	**		**				
$\Delta(2350)$	$5/2^-$	*		*				
$\Delta(2390)$	$7/2^+$	*		*				
$\Delta(2400)$	$9/2^-$	**	**	**				
$\Delta(2420)$	$11/2^+$	****	*	****				
$\Delta(2750)$	$13/2^-$	**		**				
$\Delta(2950)$	$15/2^+$	**		**				

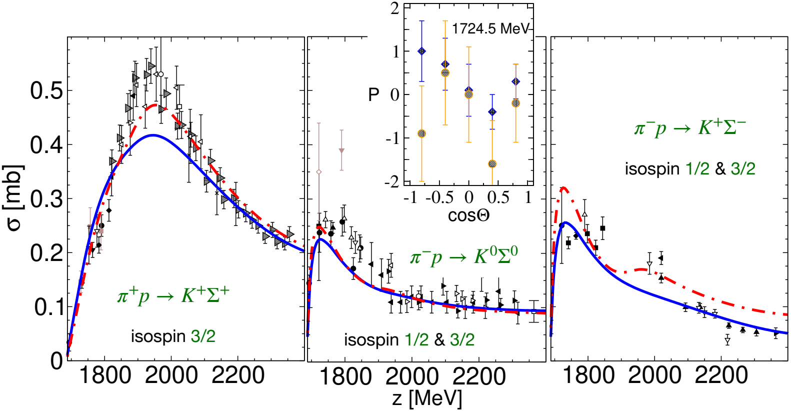
new | upgraded

- no new Δ's, less 4 stars

$\rightarrow$ more & better data $\pi N \rightarrow K\Sigma$?
($I = 1/2$ and $3/2$ contribution)

S. Navas *et al.* (Particle Data Group), Phys. Rev. D110, 030001 (2024)

Pion-induced data base: $K\Sigma$ channels



- relative good data
- consistent P data

- some P data, inconsistent

- only few $d\sigma/d\Omega$
- no P data

Re-fit without $K^+\Sigma^-$ $\to$ much better description of $K^+\Sigma^+$ (red dashed) JüBo EPJA 49 (2013)
$\to$ strong constraints on Δ resonances from $K^+\Sigma^-$

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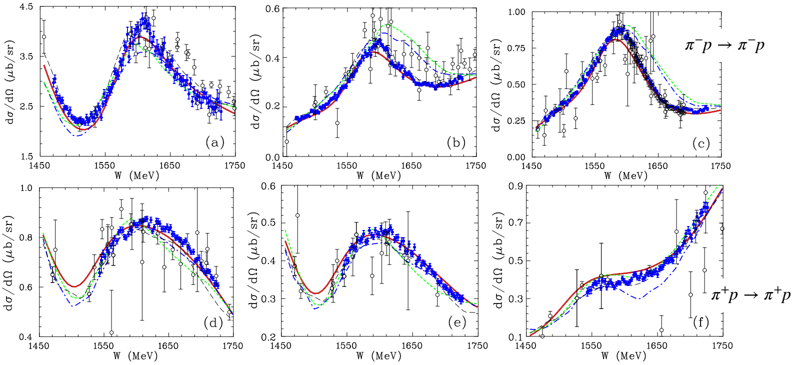
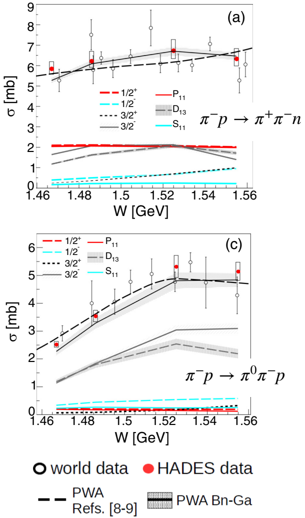
Recent advances for pion-induced data

High-precision data from **EPECUR** Alekseev PRC 91 (2015) (blue points)



Recent advances for pion-induced data

HADES at GSI: $\pi^- p \to \pi^- p$, $\pi^+\pi^- n$, $\pi^0\pi^- p$ HADES PRC 102 (2020)



charged pions → study decay of N^*'s, Δ's to ρN!

(poorly known so far, not in PDG listings)

BnGa fit:

- dominated by $I = 1/2$, $J^P = \frac{1}{2}^\pm, \frac{3}{2}^\pm$ PWs
- $\pi^+\pi^- n$ main contribution: D_{13}, P_{11} & $\pi\Delta$, σN
- $\pi^0\pi^- p$ main contribution: D_{13} & ρN

$\Rightarrow$ branching ratios for $N(1535)\frac{1}{2}^-$, $N(1520)\frac{3}{2}^- \to \rho N$

J-PARC will also measure $\pi N \to \pi N, \pi\pi N, KY$

(Figure from HADES PRC 102 (2020))

Summary

N^* and Δ resonance spectrum: many open questions remain

- large amount of new data from photoproduction $\rightarrow$ some new states, updated parameters
- access Q^2 dependence in electroproduction $\rightarrow$ information on the inner structure

Prerequisite: well-determined resonance parameters!

- pion-induced reactions:
  - data enters photo- & electroproduction analyses
  - direct determination of resonance parameters
  - fewer d.o.f

Need data of high quality & quantity for **all three** reaction types!

Thank you for you attention!

Appendix

The Hyperon Spectrum (Λ^*'s and Σ^*'s)

What happens if we replace a light quark with an s quark?

- Very little new experimental data in the last decades for the complete resonance region

$\rightarrow$ spectrum much less known than N^* or Δ

but equally important to understand QCD at low energies!

- 4 groups world-wide re-analyzed old $K^- p$ data over the complete resonance region
  - KSU, JPAC, ANL/Osaka, BnGa
  - JüBo: DCC analysis of $\bar{K}N$ reactions in progress

Particle	J^P	Overall status	Status as seen in — $N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$
$\Sigma(1193)$	$1/2^+$	****			
$\Sigma(1385)$	$3/2^+$	****		****	****
$\Sigma(1580)$	$3/2^-$	*	*	*	*
$\Sigma(1620)$	$1/2^-$	*	*	*	*
$\Sigma(1660)$	$1/2^+$	***	***	***	***
$\Sigma(1670)$	$3/2^-$	****	****	****	****
$\Sigma(1750)$	$1/2^-$	***	***	**	***
$\Sigma(1775)$	$5/2^-$	****	****	****	**
$\Sigma(1780)$	$3/2^+$	*	*	*	*
$\Sigma(1880)$	$1/2^+$	**	**	*	
$\Sigma(1900)$	$1/2^-$	**	**	*	**
$\Sigma(1910)$	$3/2^-$	***	*	*	**
$\Sigma(1915)$	$5/2^+$	****	***	***	***
$\Sigma(1940)$	$3/2^+$	*	*		*
$\Sigma(2010)$	$3/2^-$	*	*	*	
$\Sigma(2030)$	$7/2^+$	****	****	****	**
$\Sigma(2070)$	$5/2^+$	*	*		*
$\Sigma(2080)$	$3/2^+$	*		*	
$\Sigma(2100)$	$7/2^-$	*	*	*	*
$\Sigma(2110)$	$1/2^-$	*	*	*	*
$\Sigma(2230)$	$3/2^+$	*	*	*	*
$\Sigma(2250)$		**	**	*	*
$\Sigma(2455)$		*	*		
$\Sigma(2620)$		*	*		
$\Sigma(3000)$		*	*	*	
$\Sigma(3170)$		*			

R. L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

Status updated | Quantum numbers updated | New

Prospects for new data:

- K_L facility at JLab: Strange Hadron Spectroscopy with a secondary K_L Beam at GlueX 2008.08215
- planned new experiment at ELSA in Bonn: $\gamma p \rightarrow K^+\Lambda^* \rightarrow K^+\Sigma^0\pi^0$, $\gamma p \rightarrow K^+\Sigma^* \rightarrow K^+\Lambda\pi^0$
- PANDA at FAIR: $\bar{p}p \rightarrow \bar{Y}Y^*$: besides Ξ^* and Ω^* also Λ^* and Σ^* spectrum accessible 0903.3905

How to determine TFFs?

Example: Jülich-Bonn-Washington (JBW) parametrization

M. Mai *et al.* PRC 103 (2021)

$\widetilde{\mathcal{H}} = Res\mathcal{A}$ or Res$\mathcal{S}$ (“Helicity amplitudes”, calculated from “multipole amplitude” $\mathcal{M}$)

$$\mathcal{M}_{\mu\gamma^*}(k, W, Q^2) = R_{\ell'}(\lambda, q/q_\gamma)\left(V_{\mu\gamma^*}(k, W, Q^2) + \sum_\kappa \int_0^\infty dp\, p^2\, T_{\mu\kappa}(k, p, W) G_\kappa(p, W) V_{\kappa\gamma^*}(p, W, Q^2)\right)$$

(Pseudo)-threshold behavior with meson/photon momenta

$$lim_{k\to 0} E_{\ell+} = k^\ell$$
$$lim_{q\to 0} L_{\ell+} = q^\ell$$
$$\dots$$

For $Q^2=0$ (real photons) identical to Jülich-Bonn photoproduction amplitude

$$V_{\mu\gamma^*}(k, W, Q^2) = V^{\rm JUBO}_{\mu\gamma}(k, W) \cdot \tilde{F}_D(Q^2) \cdot e^{-\beta^0_\mu Q^2/m_p^2}\left(1 + Q^2/m_p^2 \beta^1_\mu + (Q^2/m_p^2)^2 \beta^2_\mu\right)$$

Siegerts's theorem Siegert(1973) Amaldi et al.(1979) Tiator(2016)

$$V^{L_{\ell\pm}} = (\text{const.}) \cdot V^{E_{\ell\pm}}$$

...at pseudo-threshold

- simultaneous fit to πN, ηN, $K\Lambda$ electroproduction off proton ($W < 1.8$ GeV, $Q^2 < 8$ GeV^2)
- Input from photoproduction: $V_{\mu\gamma}(k, W, Q^2 = 0)$
- Input from pion-induced reactions: $T_{\mu\kappa}(k, p, W)$, $G_\kappa(p, W)$
  $\to$ universal pole positions and residues (fixed in this study)

The light baryon spectrum:

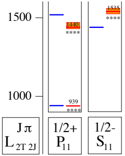
Many open questions

- Missing resonances?
- Different analyses often not agree on parameters or even existence of a state

E.g., the Roper resonance $N(1440)1/2^+$: discussed since $>$ 50 years

(Review: e.g. Burket & Roberts Rev.Mod.Phys. 91 (2019))

- q^3 quark models: first $1/2^-$ state lower than first $1/2^+$ state
- lattice QCD: e.g. Lang 2017 Phys. Rev. D 95, 014510



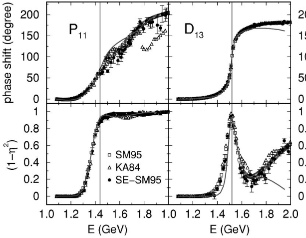


Fig. from PRC 62 025207 (2000)

- not a standard Breit-Wigner shape
- influence by meson-baryon background interaction?
- effects from nearby thresholds?

$\rightarrow$ not a simple radial excitation of the nucleon?

$\rightarrow$ information from photo- and electroproduction! (Q^2 dependence of helicity amplitudes)

(Review: Ramalho & Pena Prog.Part.Nucl.Phys. 136 (2024))

Jülich-Bonn-Washington (JBW) parametrization

M. Mai *et al.* PRC 103 (2021), PRC 106 (2022), EPJ A 59 (2023)

$$\mathcal{M}_{\mu\gamma^*}(k,W,Q^2) = R_{\ell'}(\lambda, q/q_\gamma)\left(V_{\mu\gamma^*}(k,W,Q^2) + \sum_\kappa \int_0^\infty dp\, p^2\, T_{\mu\kappa}(k,p,W) G_\kappa(p,W) V_{\kappa\gamma^*}(p,W,Q^2)\right)$$

(Pseudo)-threshold behavior with meson/photon momenta

$$lim_{k\to 0} E_{\ell+} = k^\ell$$
$$lim_{q\to 0} L_{\ell+} = q^\ell$$
$$\dots$$

For $Q^2=0$ (real photons) identical to Jülich-Bonn photoproduction amplitude

$$V_{\mu\gamma^*}(k,W,Q^2) = V^{\rm JUBO}_{\mu\gamma}(k,W)\cdot \tilde{F}_D(Q^2)\cdot e^{-\beta^0_\mu Q^2/m_p^2}\left(1 + Q^2/m_p^2\beta^1_\mu + (Q^2/m_p^2)^2\beta^2_\mu\right)$$

←

Siegerts's theorem Siegert(1973) Amaldi et al.(1979) Tiator(2016)

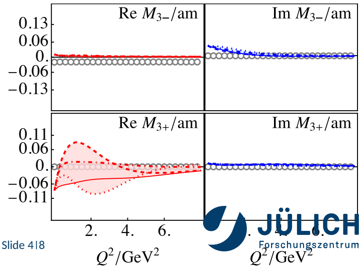
$$V^{L_{\ell\pm}} = ({\rm const.})\cdot V^{E_{\ell\pm}}$$

...at pseudo-threshold

- simultaneous fit to πN, ηN, $K\Lambda$ electroproduction off proton $(W < 1.8\text{ GeV}, Q^2 < 8\text{ GeV}^2)$
- 533 fit parameters, 110.281 data points
- Input from JüBo: $V_{\mu\gamma}(k,W,Q^2=0)$, $T_{\mu\kappa}(k,p,W)$, $G_\kappa(p,W)$

  → universal pole positions and residues (fixed in this study)
- long-term goal: fit pion-, photo- and electron-induced reactions simultaneously

$\gamma^* p \to K\Lambda$ at $W = 1.7$ GeV

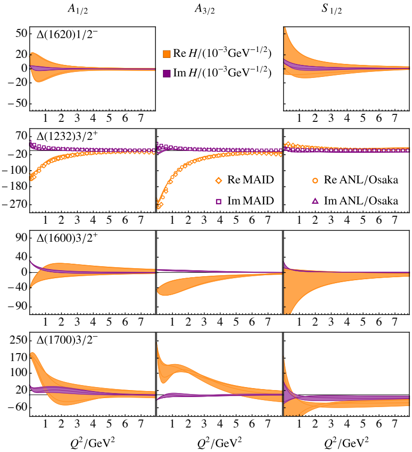


Baryon Transition Form Factors

Y.-F. Wang et al. PRL 133 (2024)

based on most recent JBW, pole parameters from JüBo2017

Δ states:



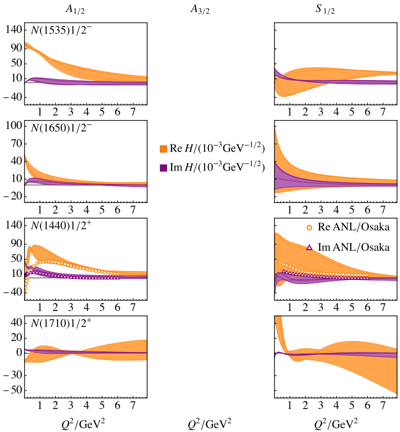
[ANL/OSAKA: Kamano Few Body Syst. 59, 24 (2018), MAID: Tiator et al. PRC94 (2016)]

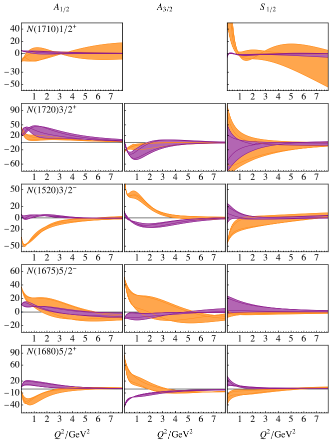
Baryon Transition Form Factors

Y.-F. Wang et al. PRL 133 (2024)

based on most recent JBW, pole parameters from JüBo2017

N^* states:





[ANL/OSAKA: Kamano Few Body Syst. 59, 24 (2018), MAID: Tiator et al. PRC94 (2016)]

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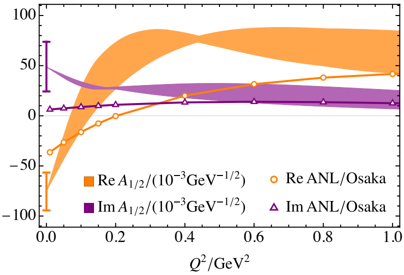
Baryon Transition Form Factors

Y.-F. Wang et al. PRL 133 (2024)

based on most recent JBW, pole parameters from JüBo2017

The Roper resonance $N(1440)1/2^+$:

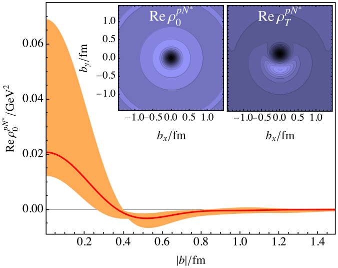


- Zero crossing in Re$A_{1/2}$ at smaller Q^2 than in Breit-Wigner determinations or in ANL/OSAKA
  [Kamano, Few Body Syst. 59, 24 (2018)]
- important for quark models, DSE: meson cloud contributions or radial excitation of the nucleon?

Transverse charge density ρ of $p \to N(1440)$ transition:

following Tiator et al. Chin. Phys. C 33 (2009)

- study flavor decomposition, u and d quark distribution



Orange band: JBW, red line: MAID 2007.
Insets: light/dark shades represent negative/positive values
b: transverse position in xy-plane

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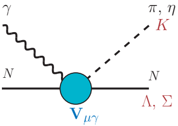
Photoproduction in a semi-phenomenological approach

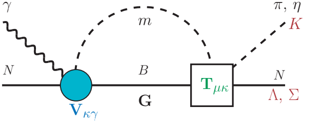
EPJ A 50, 101 (2015)

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)



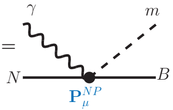


$$m = \pi, \eta, K\ ,\ B = N, \Delta, \Lambda$$

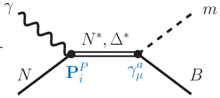
$T_{\mu\kappa}$: full hadronic T-matrix as in pion-induced reactions

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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JüBo2024: Data base

Christian Schneider

Reaction	Observables (# data points)	p./channel
$\pi N \to \pi N$	PWA GW-SAID WI08 (ED solution)	8,396
$\pi^- p \to \eta n$	$d\sigma/d\Omega$ (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
$\gamma p \to \pi^0 p$	$d\sigma/d\Omega$ (18721), Σ (3287), P (768), T (1404), $\Delta\sigma_{31}$ (140),	
	G (393+198), H (225), E (1227+495), F (397), $C_{x'_L}$ (74), $C_{z'_L}$ (26)	26,662
$\gamma p \to \pi^+ n$	$d\sigma/d\Omega$ (5670), Σ (1456), P (265), T (718), $\Delta\sigma_{31}$ (231),	
	G (86+217), H (128), E (903)	9,457
$\gamma p \to \eta p$	$d\sigma/d\Omega$ (9112+320), Σ (535+80), P (63), T (291), F (144),	
	E (306), G (47), H (56)	10,554
$\gamma p \to K^+ \Lambda$	$d\sigma/d\Omega$ (2563), P (1663), Σ (459), T (383),	
	$C_{x'}$ (121), $C_{z'}$ (123), $O_{x'}$ (66), $O_{z'}$ (66), O_x (314), O_z (314),	6,072
$\gamma p \to K^+ \Sigma^0$	$d\sigma/d\Omega$ (4381), P (402), Σ (280)	
	T (127) , $C_{x'}$ (94), $C_{z'}$ (94), O_x (127), O_z (127)	5,632
$\gamma p \to K^0 \Sigma^+$	$d\sigma/d\Omega$ (281), P (167)	448
	in total	73,066

Update $K^0\Sigma^+$: Σ, T, P, O_x, O_z with CLAS Collaboration, 2404.19404 [nucl-ex]