Coupled-channel meson electroproduction

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Degrees of freedom: Quarks or hadrons

- Resonance review [Mai 2022]

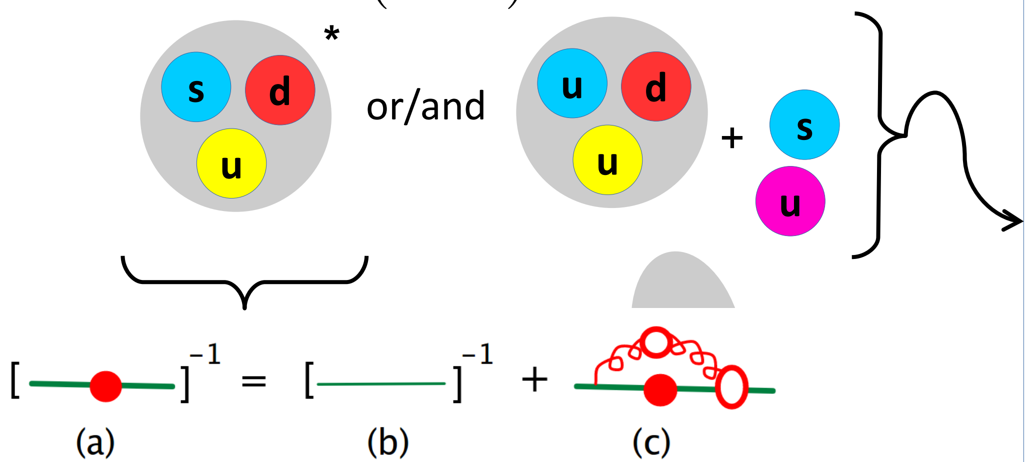
QCD at low energies

Non-perturbative dynamics → rich spectrum of excited states

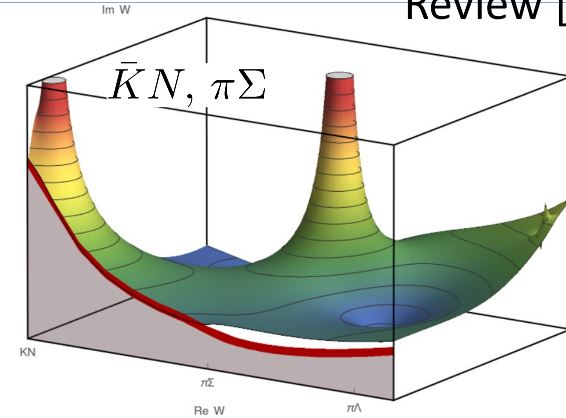
How many states are there? → missing resonance problem (does it exist?)

What are they? → 2-quark/3-quark, hadron molecules, …

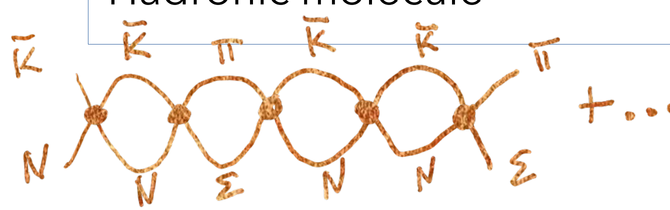
$\Lambda(1405)$

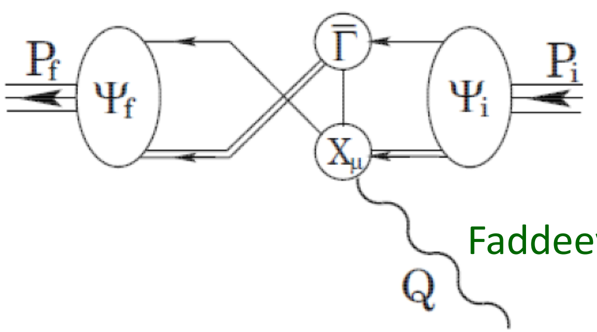


Review [Mai 2021]



Hadronic molecule

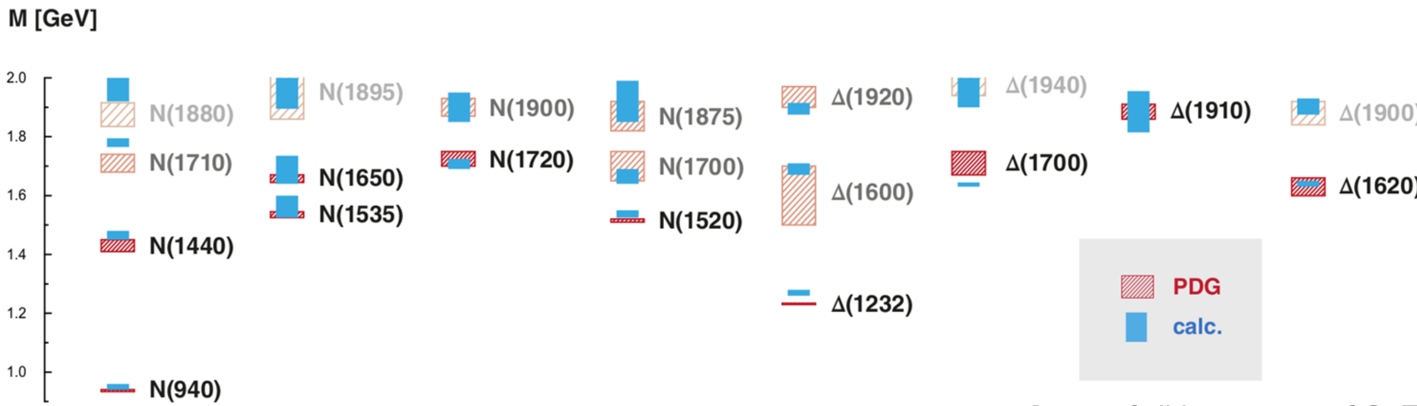




Faddeev Eq. / DSE (Binosi, Cloet, Chang, Eichman, Roberts,…);

Light baryons from diquark dynamics

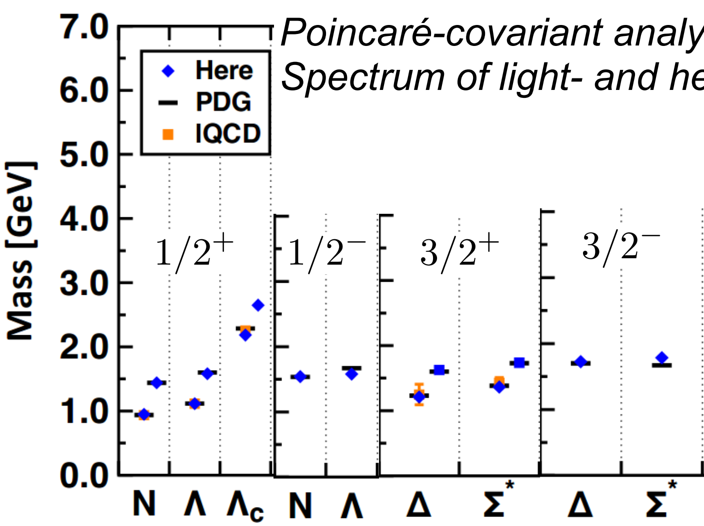
Quark-diquark with reduced pseudoscalar + vector diquarks: [Eichmann (2016)]



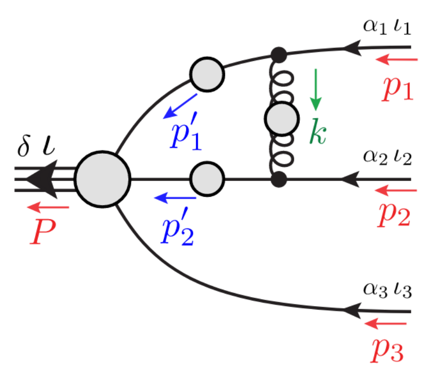
Not much of a missing resonance problem left…

[parts of slide courtesy of G. Eichmann, Few Body 2018]

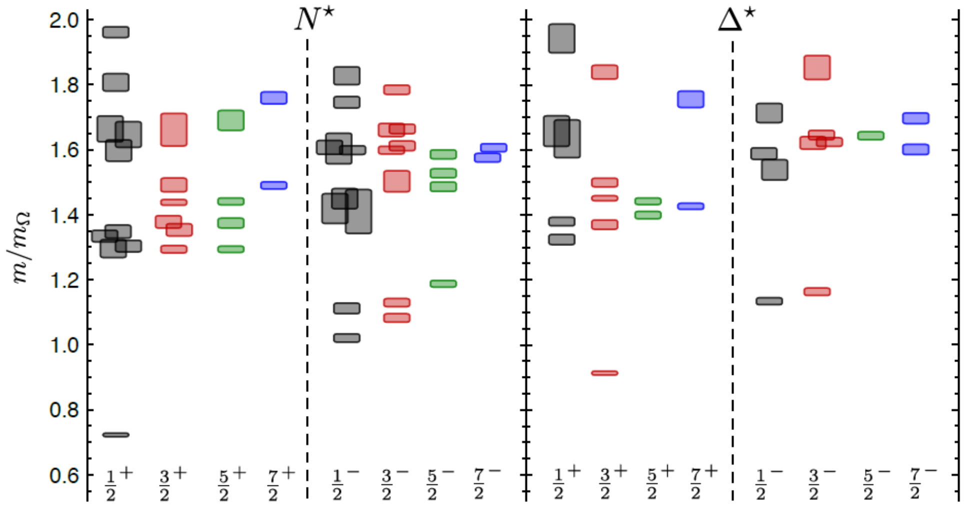
$J^P = \frac{1}{2}^+ \quad \frac{1}{2}^- \quad \frac{3}{2}^+ \quad \frac{3}{2}^- \quad \frac{3}{2}^+ \quad \frac{3}{2}^- \quad \frac{1}{2}^+ \quad \frac{1}{2}^-$



Poincaré-covariant analysis of heavy-quark baryons, [Qin 2018]
Spectrum of light- and heavy-baryons, [Qin 2019]

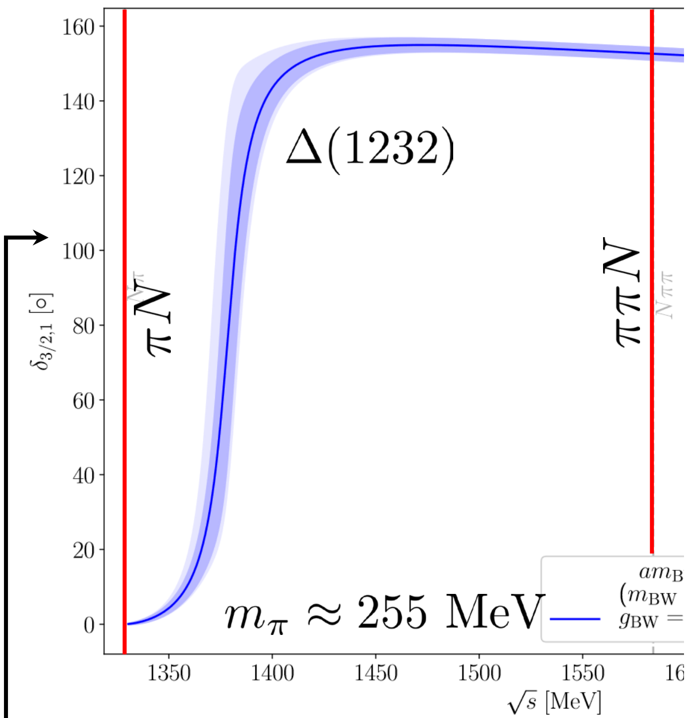


Lattice QCD for excited baryons



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

- Pioneering spectroscopic calculations
- Information on existence, width & properties of resonances requires
    - Meson-baryon interpolating operators
    - Detailed finite-volume analysis



[G. Silvi et. al., arXiv: 2101.00689]

See also: Bulava et al., [2208.03867] → Morningstar talk on Monday

How about $\pi\pi N$?
3B Dynamics?
→ Talk on Thursday

Phenomenology of the baryon spectrum

Review by [Thiel, Afzal, Wunderlich 2022]

Dynamical coupled-channel approaches

- ANL-Osaka (former: EBAC) [Kamano et al.]
- Dubna-Mainz-Taipei model [Tiator]
- Jülich-Bonn(-Washington) [Rönchen]
- …
- Characteristics:
  - Direct fit to data (pion & photon-induced)
  - Simultaneous fit to data of different final states
  - Integral scattering equation as needed for proper treatment of three-body channels ($\pi\pi N$)

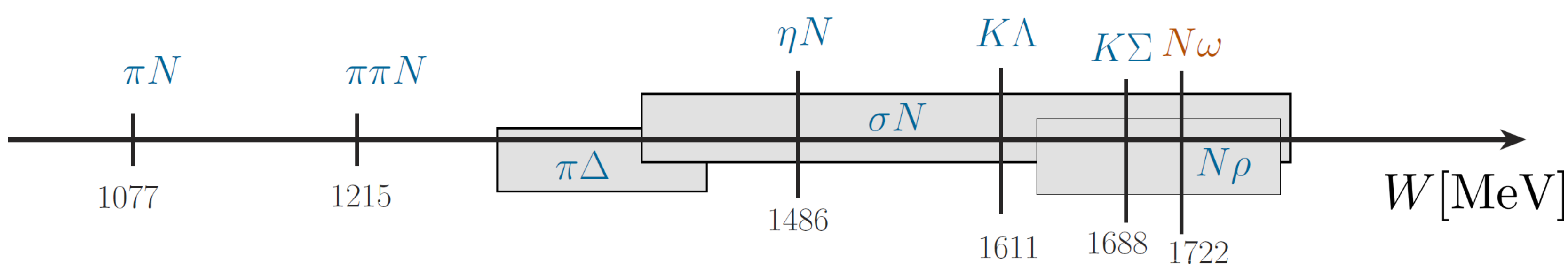
Note: Only a sub-class of analysis efforts; see, e.g., Bonn-Gatchina group K-matrix approach

JBW DCC approach (Jülich-Bonn-Washington)

The scattering equation in partial-wave basis

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

- channels ν, μ, γ:



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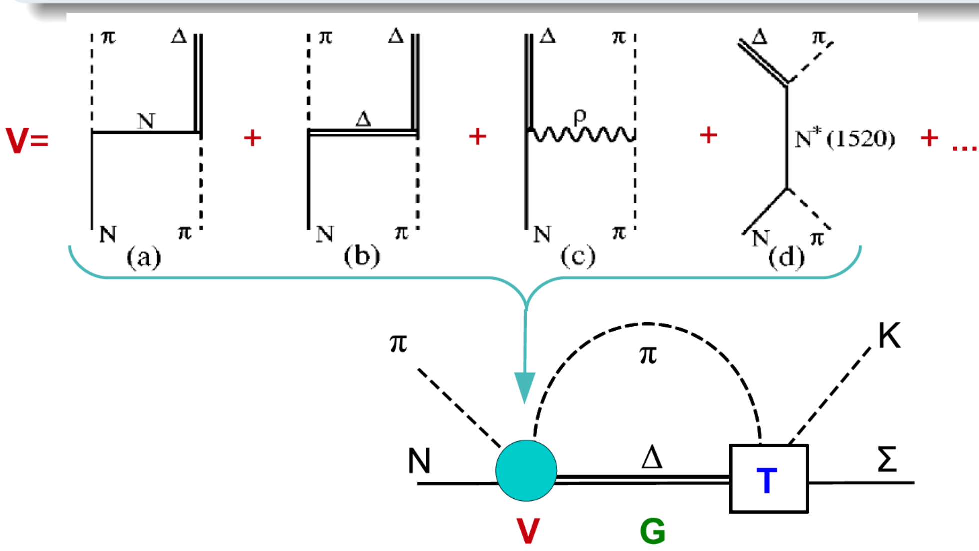
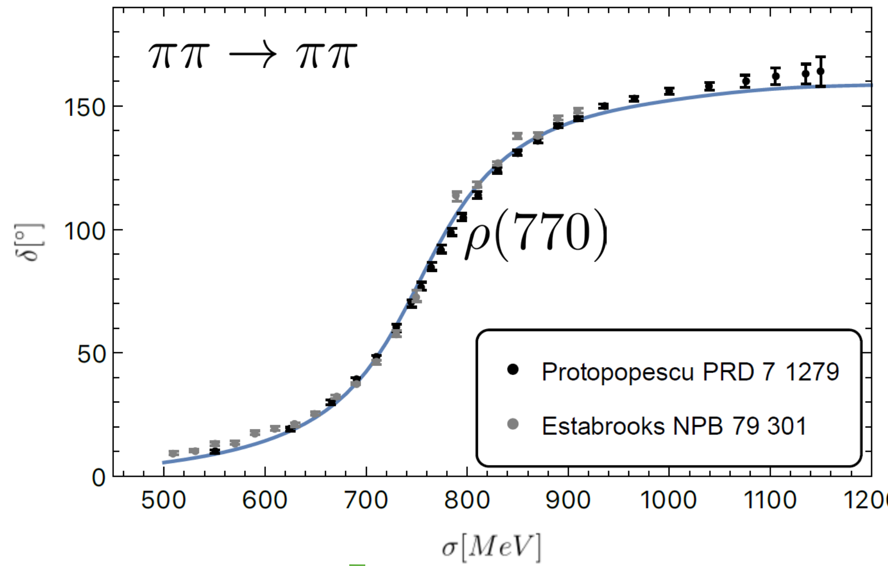
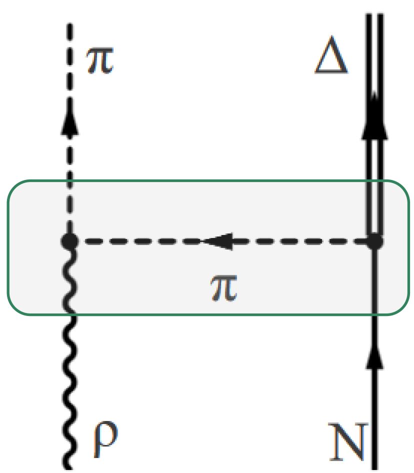


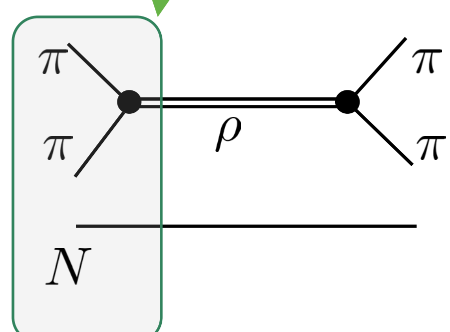
- potentials V constructed from effective $\mathcal{L}$
- s-channel diagrams: T^P
  genuine resonance states
- t- and u-channel: T^{NP}
  dynamical generation of poles
  partial waves strongly correlated
- contact terms

Three-body channels $\sigma N, \pi\Delta, \rho N$

- Resonant sub-channels
- Fit 2→2 amplitude to 2→ 2 scattering data
- Include as sub-channel in 3-body amplitude:
- 3-body unitarity: Requires, e.g.







JBW: Data base

- $\pi N \to X$: $>$ **7,000** data points ($\pi N \to \pi N$: GW-SAID WI08 (ED solution))
- $\gamma N \to X$:

New: $\pi N \to \omega N$ [2208.03061]
Upcoming data from JParc

Reaction	Observables (# data points)	p./channel
$\gamma p \to \pi^0 p$	$d\sigma/d\Omega$ (18721), 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)	25,542
$\gamma p \to \pi^+ n$	$d\sigma/d\Omega$ (5961), Σ (1456), P (265), T (718), $\Delta\sigma_{31}$ (231),	
	G (86), H (128), E (903)	9,748
$\gamma p \to \eta p$	$d\sigma/d\Omega$ (9112), Σ (403), P (7), T (144), F (144), E (129)	9,939
$\gamma p \to K^+\Lambda$	$d\sigma/d\Omega$ (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
$\gamma p \to K^+\Sigma^0$	$d\sigma/d\Omega$ (4271), P (422), Σ (280), T (127), $C_{x',z'}$ (188), $O_{x,z}$ (254)	5,542
$\gamma p \to K^0\Sigma^+$	$d\sigma/d\Omega$ (242), P (78)	320
	in total	**57,027**

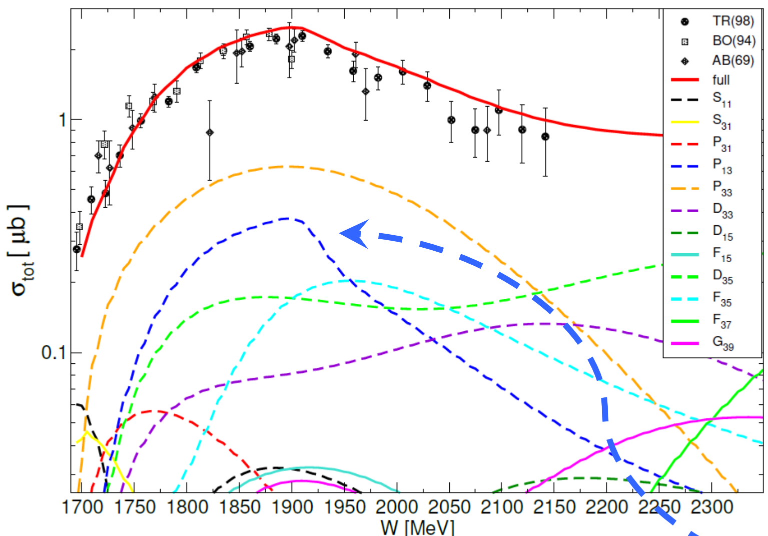
NEW: $N \approx 85{,}000$ data in $\gamma^* N \to \pi N, \eta N, K\Lambda$

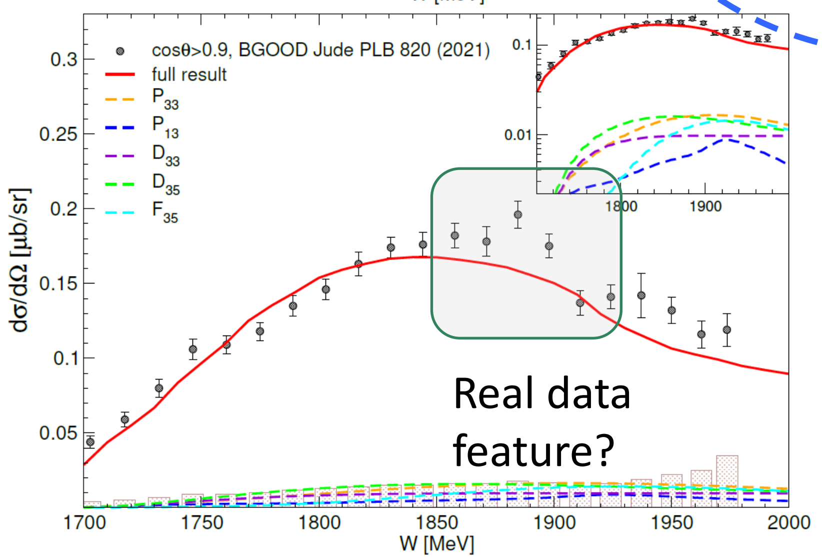
New interface [https://jbw.phys.gwu.edu/]

Resonances in $K\Sigma$ photoproduction

- [D. Roenchen et al. (EPJA 2022)]
- [Webpage all results]

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





Similarly: $K^0\Sigma^+$

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

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

$N(1720)\ 3/2^+$ $****$	Re E_0 [MeV]	-2Im E_0 [MeV]	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Sigma}}{\Gamma_{tot}}$ [%]	$\theta_{\pi N\rightarrow K\Sigma}$ [deg]
2022	1726	185	5.9	82
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 [MeV]	-2Im E_0 [MeV]	$\frac{\Gamma^{1/2}_{\pi N}\Gamma^{1/2}_{K\Sigma}}{\Gamma_{tot}}$ [%]	$\theta_{\pi N\rightarrow K\Sigma}$ [deg]
2022	1905	93	1.3	-40
2017	1923(2)	217(23)	10(7)	$-34(74)$
PDG 2021	1920 ± 20	150 ± 50	4 ± 2	110 ± 30

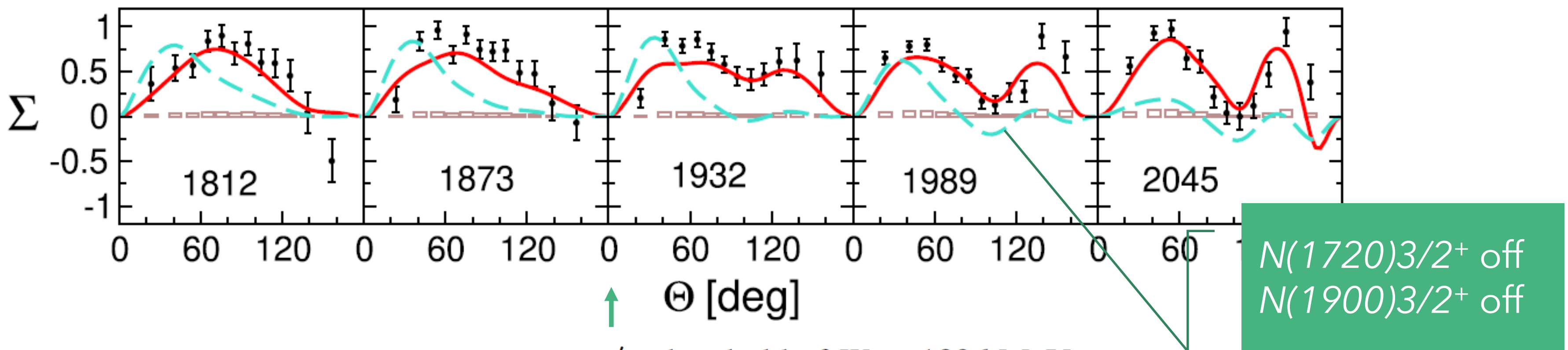
- drop in cross section ("cusp-like structure") due to $N(1900)3/2^+$

$N(1535)$ ½$^-$ $****$	Re E_0 [MeV]	-2Im E_0 [MeV]
2022	1504(0)	74 (1)
2017	1495(2)	112(1)
PDG 2021	1510 ± 10	130 ± 20

New, wide dynamically generated states in $J^P=3/2^-$

2022 Update in other reactions

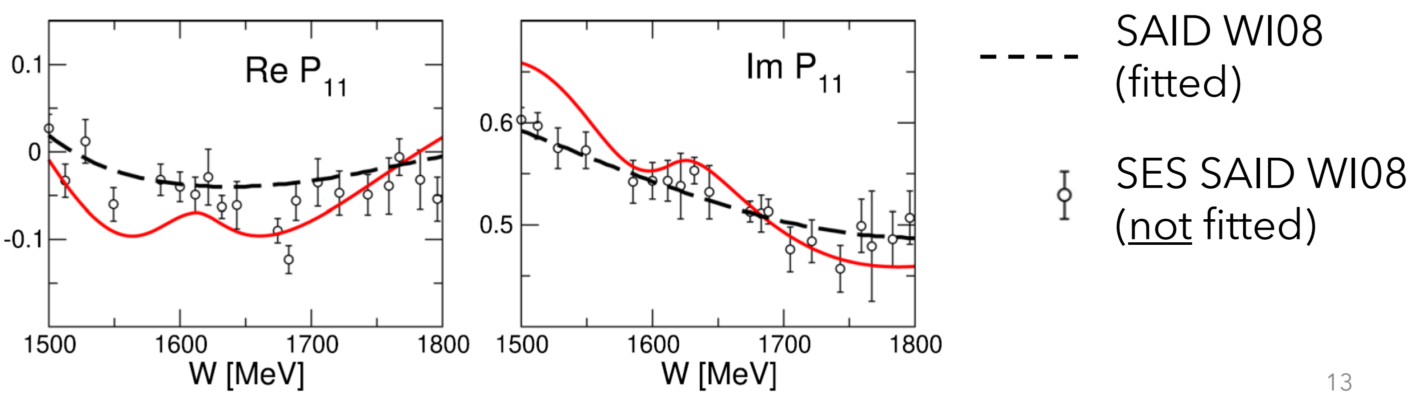
- Beam asymmetry in η photoproduction (different W)



$\eta' p$ threshold of $W = 1896$ MeV

- N(1710)1/2+ returns with large ηN and KΛ branching ratios

$\pi N \to \pi N$



Pion and eta Electroproduction

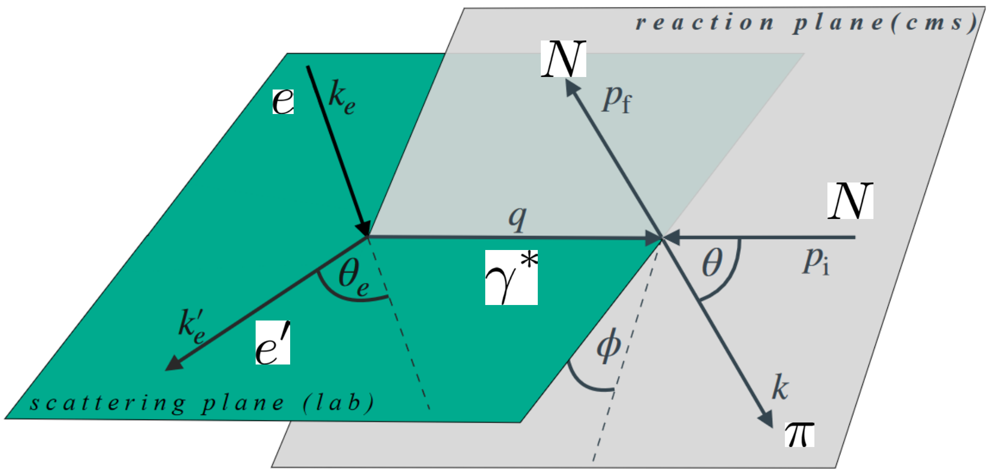
First coupled-channel electroproduction analysis with different final states

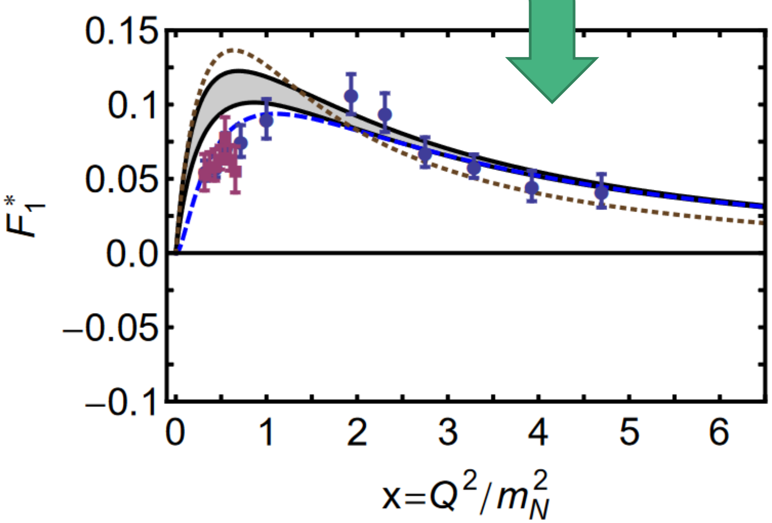
[M. Mai et al., 2104.07312, 2111.04774]

Theory:

- Siegert’s theorem manifestly fulfilled (consequence of gauge invariance)
- Watson theorem fulfilled
- Coupled-channel unitarity fulfilled
- General expansion of electroproduction kernel in Laurent series

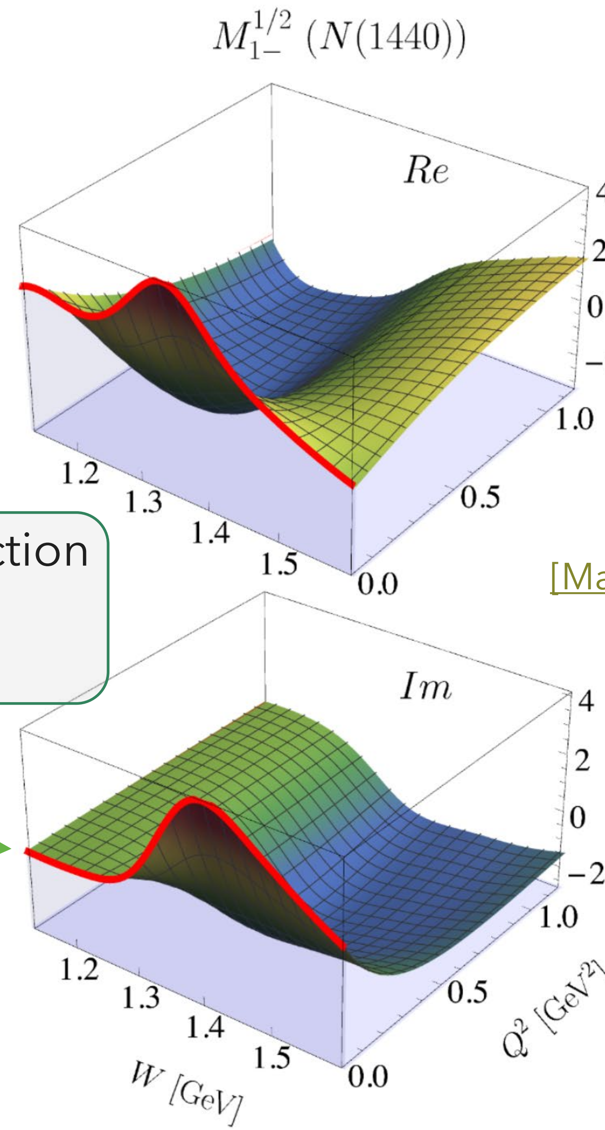
Electroproduction reveals resonance structure





Proton-Roper Transition [Burkert] [Segovia]

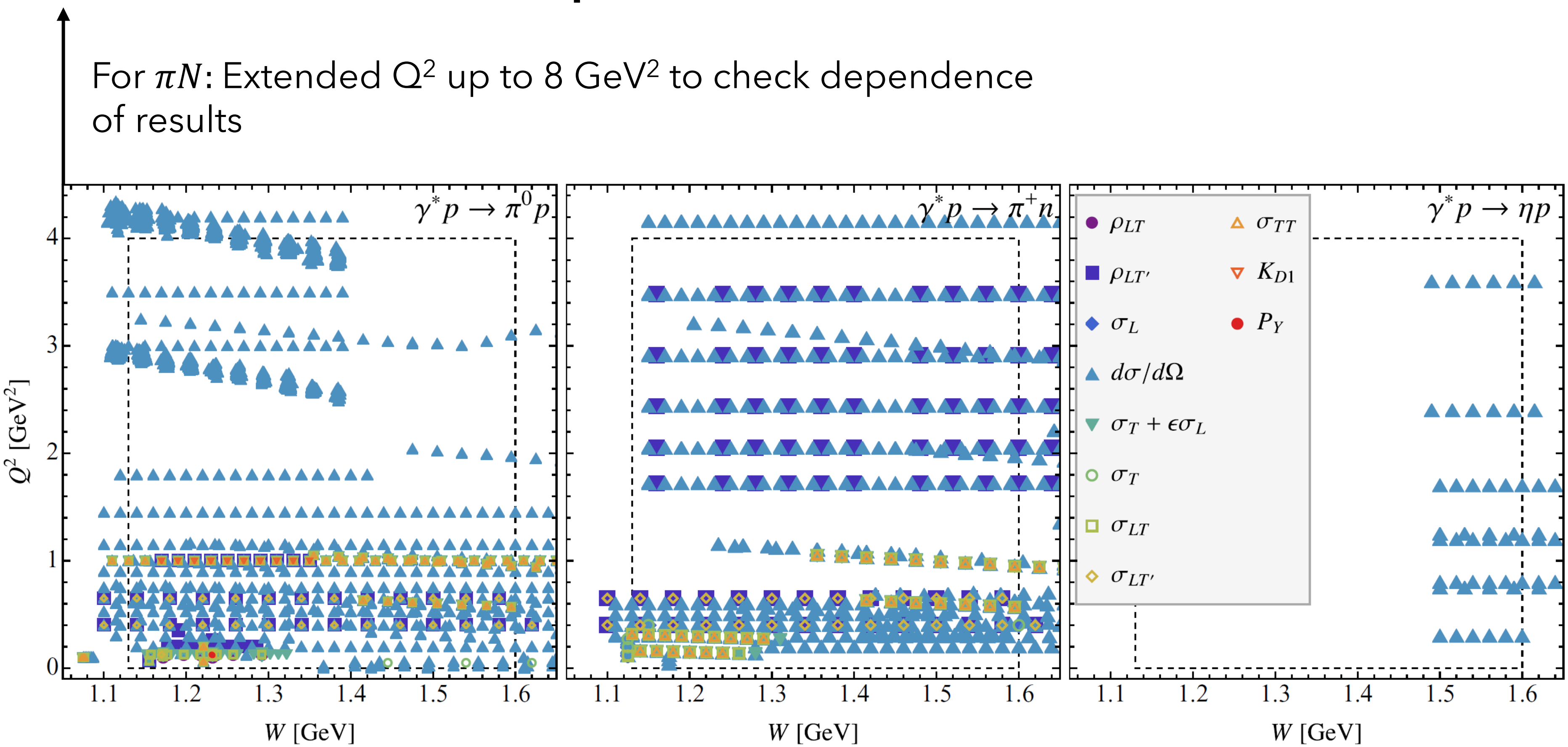
Photoproduction included as boundary



[Mai]

Electroproduction data base

For πN: Extended Q^2 up to 8 GeV^2 to check dependence of results



- Data base grown over decades with recent input mostly by CLAS, MAMI.
- Far from complete: Kinematic gaps & consistency issues. Need to combine information from different (W, Q^2) regions
- Need to combine information from simultaneous analysis of different final states ($\pi N / \eta N / K Y / \pi \pi N, \ldots.$) to extract resonance helicity couplings

Fit details: Weighted vs. unweighted χ^2

- Meson production data bases are heterogeneous:
  - A few polarization measurements with large error bars (small weight in χ^2)
  - Many cross section data with smaller error bars (large weight in χ^2)
  - … but those **few** polarization possess **great** power to discriminate solutions
- Introduce **weighted** vs. **unweighted** χ^2:

$$\chi^2_{\mathrm{wt}} = \sum_{j\in\{\pi^0 p,\pi^+ n,\eta p\}} \frac{N_{\mathrm{all}}}{3N_j} \sum_{i=1}^{N_j} \left(\frac{\mathcal{O}^{\mathrm{exp}}_{ji} - \mathcal{O}_{ji}}{\Delta^{\mathrm{stat}}_{ji} + \Delta^{\mathrm{syst}}_{ji}} \right)^2 .$$

$$\chi^2_{\mathrm{reg}} = \sum_{i=1}^{N_{\mathrm{all}}} \left(\frac{\mathcal{O}^{\mathrm{exp}}_{i} - \mathcal{O}_{i}}{\Delta^{\mathrm{stat}}_{i} + \Delta^{\mathrm{syst}}_{i}} \right)^2$$

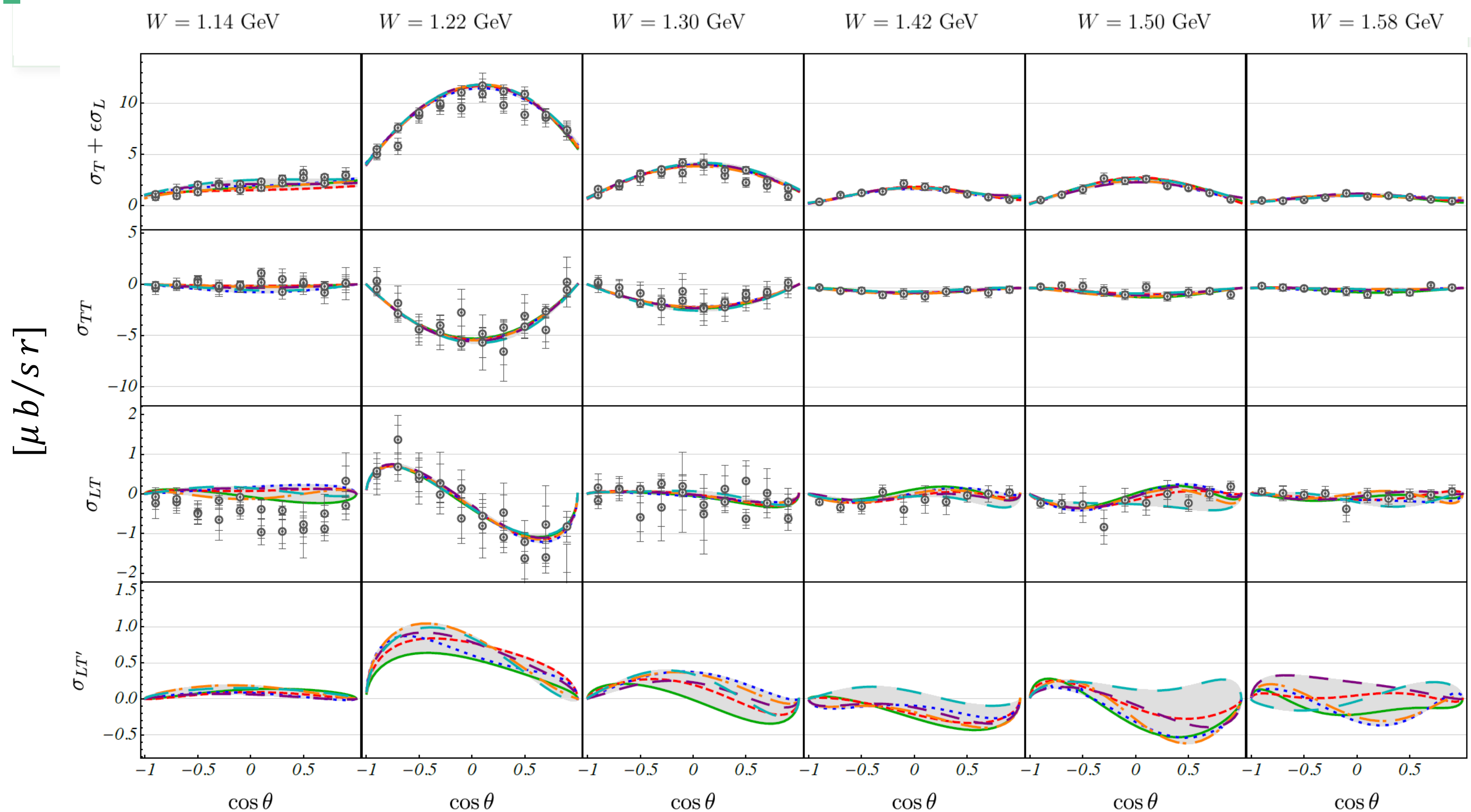
Fit Strategies (πN)

- Different fit strategies for $N \approx 85{,}000$ data in $\gamma^* N \to \pi N, \eta N$:
  - Sequential S → S+P → S+P+D waves;
  - Subsets of data until full data set reached
  - Simultaneous fit all parameters (209) set to zero without any (!) guidance
  - Extend data range from $0 < Q^2 < 4$ Gev² to $0 < Q^2 < 6$ Gev² to check for stability

Fit	σ_L		$d\sigma/d\Omega$		$\sigma_T + \epsilon\sigma_L$		σ_T		σ_{LT}		$\sigma_{LT'}$		σ_{TT}		K_{D1}		P_Y		ρ_{LT}		$\rho_{LT'}$		χ^2_{dof}
	$\pi^0 p$	$\pi^+ n$	$\pi^0 p$	$\pi^+ n$	$\pi^0 p$	$\pi^+ n$	$\pi^0 p$	$\pi^+ n$	$\pi^0 p$	$\pi^+ n$	$\pi^0 p$	$\pi^+ n$	$\pi^0 p$	$\pi^+ n$	$\pi^0 p$	$\pi^+ n$	$\pi^0 p$	$\pi^+ n$	$\pi^0 p$	$\pi^+ n$	$\pi^0 p$	$\pi^+ n$	
$\mathfrak{F}_1$	–	9	65355	53229	870	418	87	88	1212	133	862	762	4400	251	4493	–	234	–	525	–	3300	10294	1.77
$\mathfrak{F}_2$	–	4	69472	55889	1081	619	65	78	1780	150	1225	822	4274	237	4518	–	325	–	590	–	3545	10629	1.69
$\mathfrak{F}_3$	–	8	66981	54979	568	388	84	95	1863	181	1201	437	3934	339	4296	–	686	–	687	–	3556	9377	1.81
$\mathfrak{F}_4$	–	22	63113	52616	562	378	153	107	1270	146	1198	1015	4385	218	5929	–	699	–	604	–	3548	11028	1.78
$\mathfrak{F}_5$	–	20	65724	53340	536	528	125	81	1507	219	1075	756	4134	230	5236	–	692	–	554	–	3580	11254	1.81
$\mathfrak{F}_6$	–	18	71982	58434	1075	501	29	68	1353	135	1600	1810	3935	291	5364	–	421	–	587	–	3932	11475	1.78

χ^2

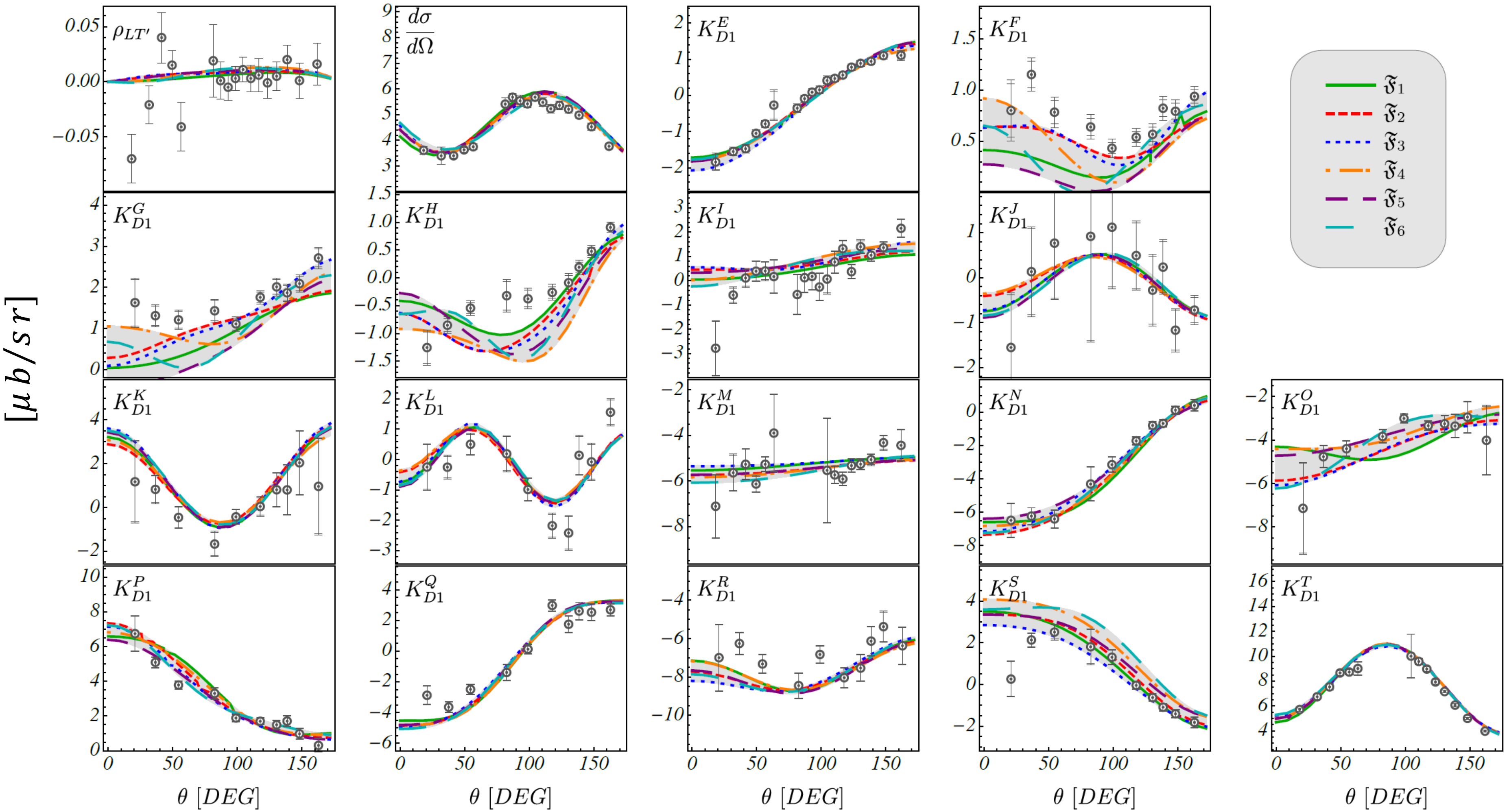
Structure functions $\pi^0 p$ (not fitted)



$Q^2 = 0.9$ Gev^2

Data: CLAS, Phys. Rev. C (2003) 0301012 [nucl-ex], Phys. Rev. Lett. (2002) 0110007 [hep-ex]

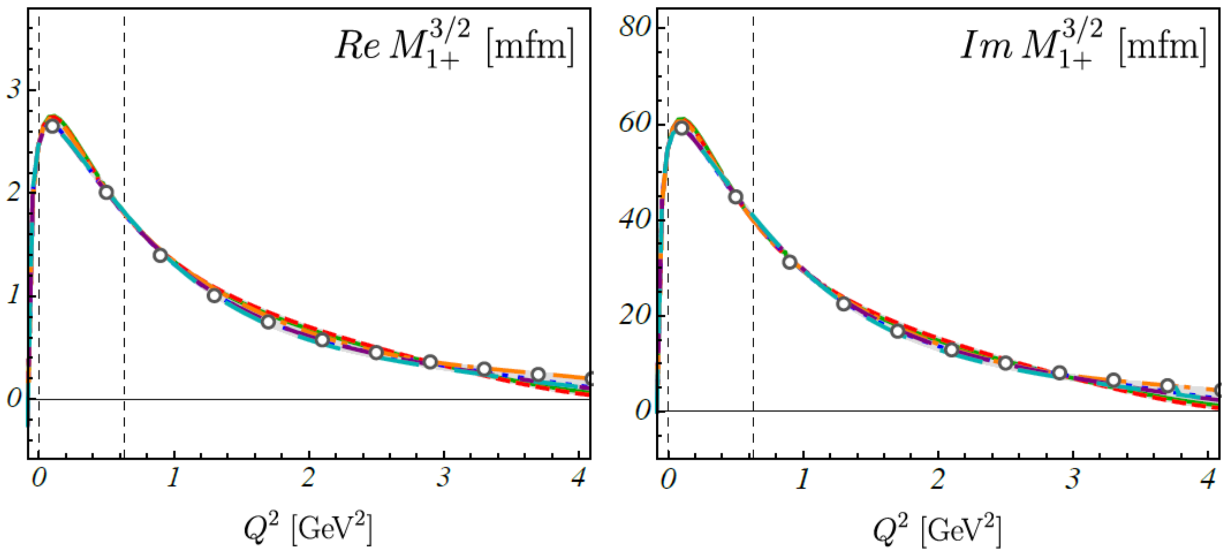
Description of Polarization Observables (πN)

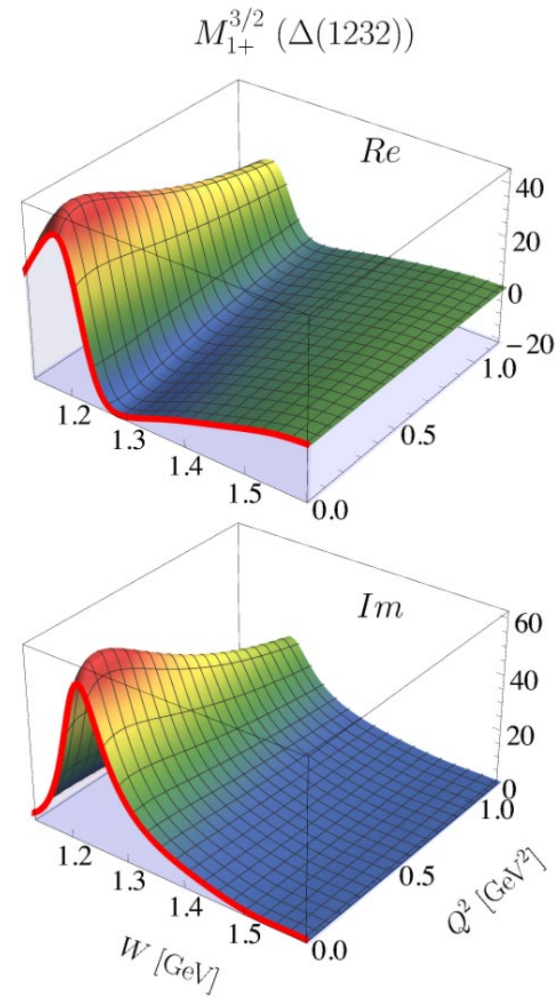


$\pi^0 p$, Q^2=1 GeV^2, W=1.23 GeV, ϕ=15^0

J. J. Kelly, Phys. Rev. Lett. 95 (2005).

Large Multipoles



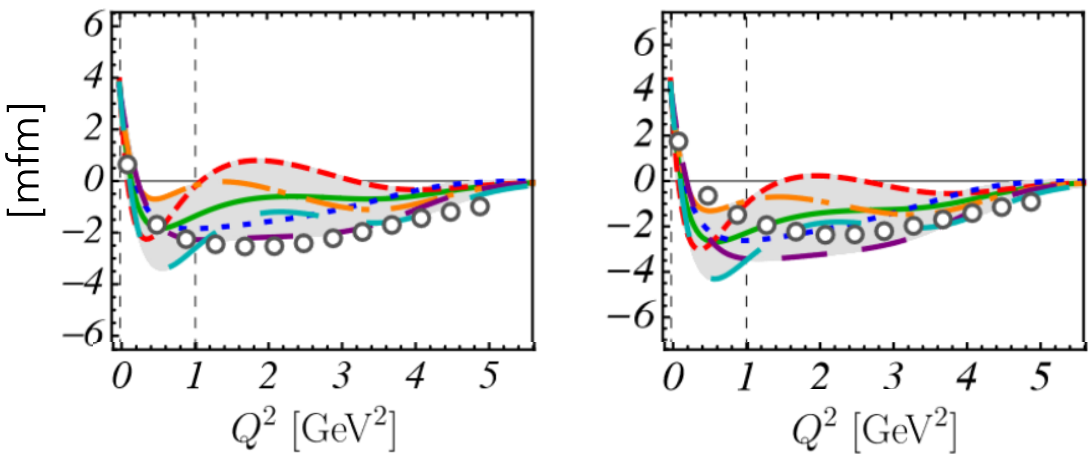


Fit strategies 1-6 together with MAID (open dots) for the magnetic multipole of the $\Delta(1232)$ Drechsel et al., EPJA (2007) 0710.0306 [nucl-th]

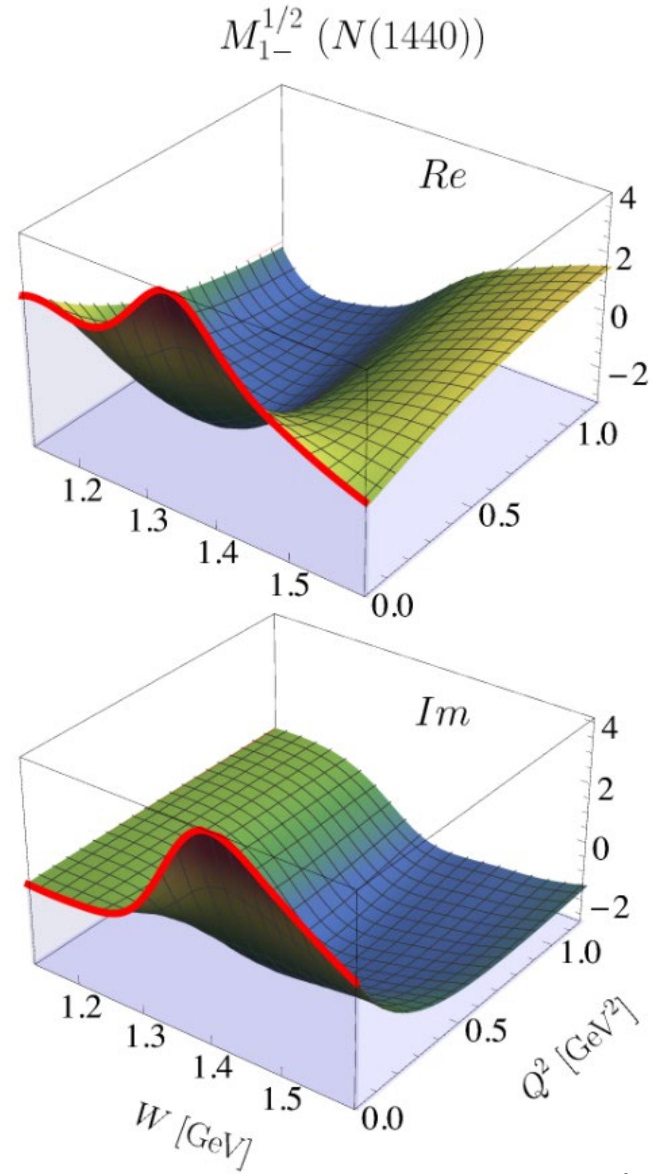
Prominent multipoles are well determined

(Strategy 1 only)

Roper Multipole



(W=1.38 GeV fixed)

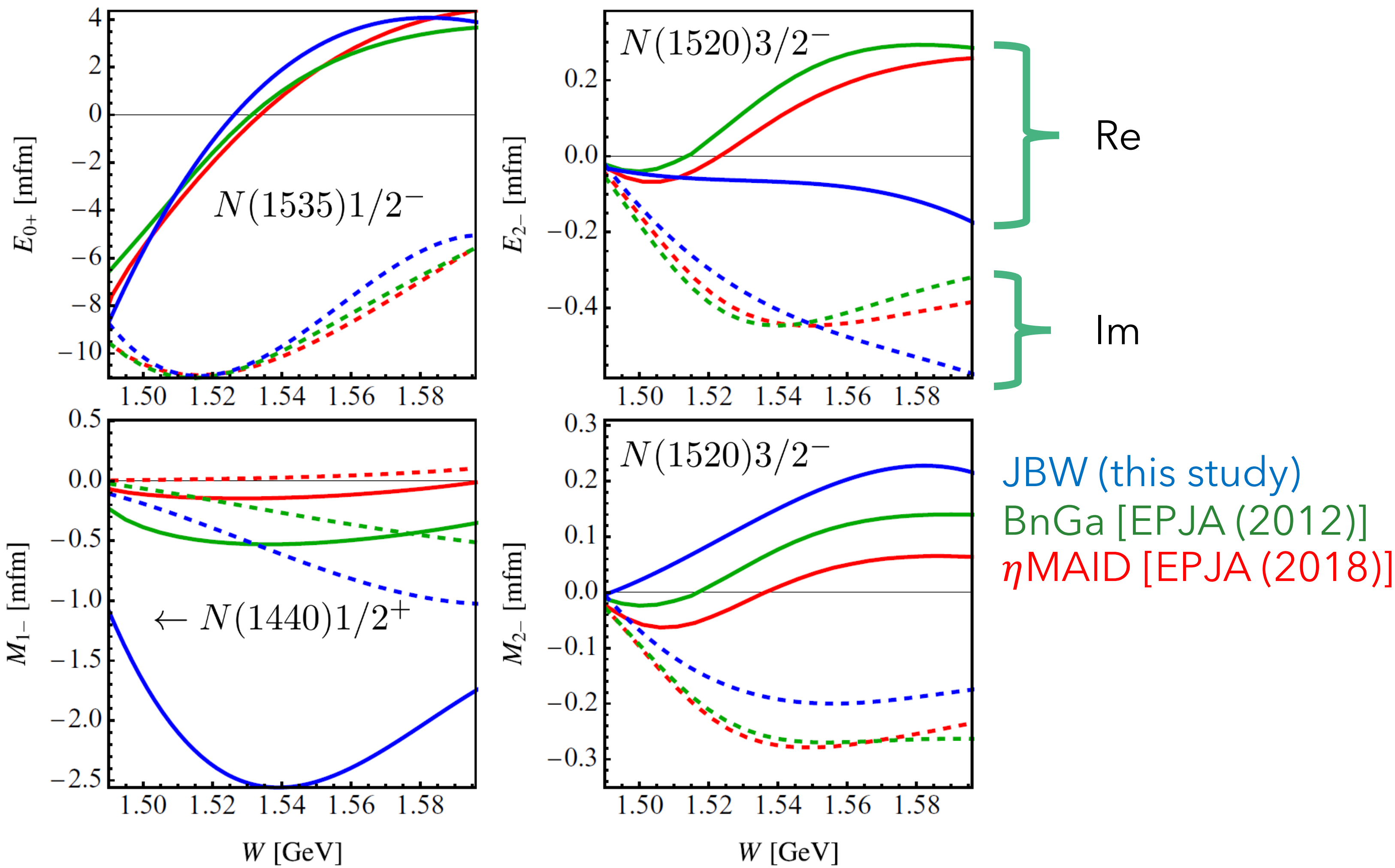


(Strategy 1 only)

- Zero-transition (agrees with MAID)
- Extensive exploration of parameter space reveals ambiguities in PWA and reflects systematic uncertainties
- Resonance parameters to be extracted

η Production at photon point $Q^2 = 0$

[M. Mai et al., PRC (2022)]

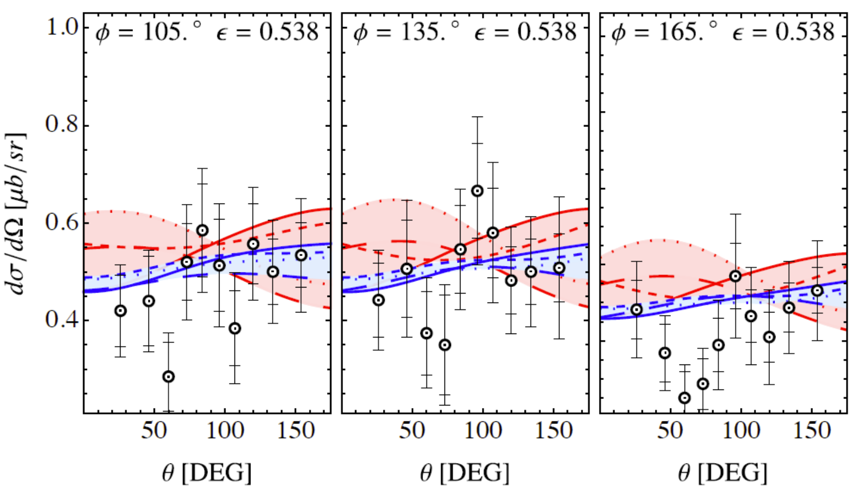


η Electroproduction

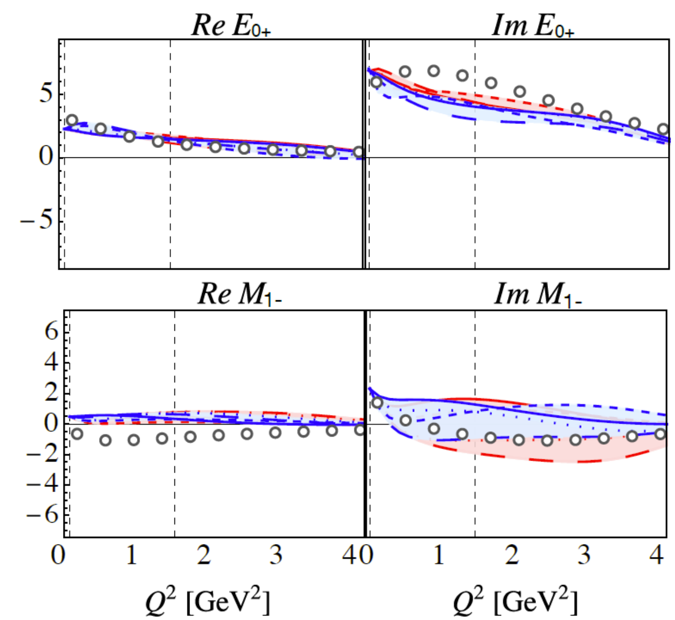
[M. Mai et al., PRC (2022)]

- $N^{\eta p}_{data} = 1,874$ (only $d\sigma/d\Omega$) (84,842 in total)
- kinematic range: $0 < Q^2 < 4$ GeV^2, $1.13 < W < 1.6$ GeV
- 8 different fit strategies: 4 with standard χ^2, 4 with weighted χ^2 to account for the smaller $N^{\eta p}_{data}$
  $\rightarrow$ better data description with weighted fit strategies:

Selected fit results: $\gamma^* p \rightarrow \eta p$ at $W = 1.5$ GeV, $Q^2 = 1.2$ GeV^2. Data: Denizli et al. (CLAS) PRC 76 (2007)



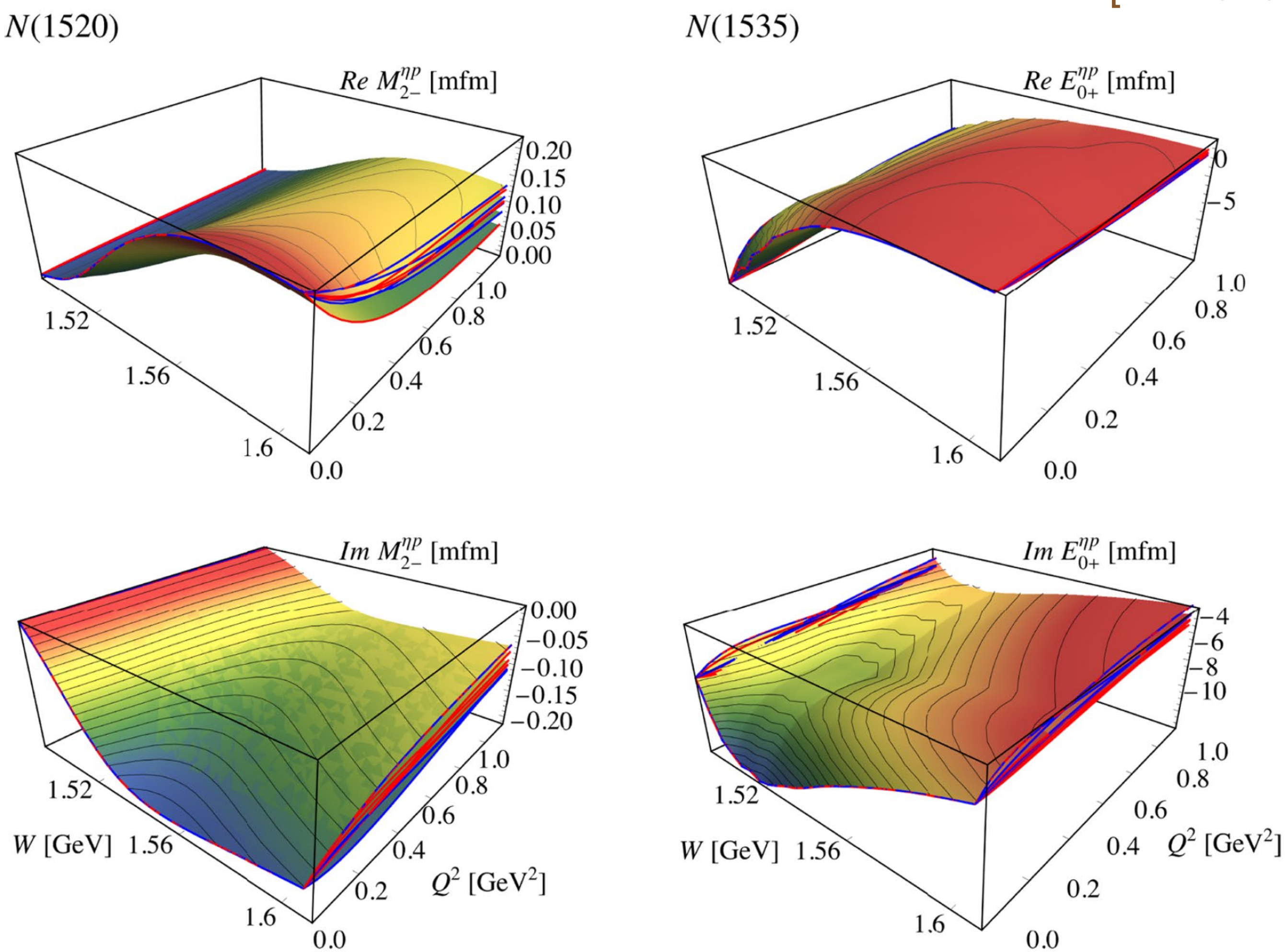
Selected multipoles at $W = 1535$ MeV



Dots: eta-MAID, arXiv:0110034

η Multipoles: Resonances disappear at high Q^2

[M. Mai et al., PRC (2022)]



Extraction of resonance helicity couplings at the pole is under way

Outlook for electroproduction analysis

Reaction	Observable	Q^2 [GeV]	W [GeV]	Ref.
$ep \to e'p'\eta$	$\sigma_U,\ \sigma_{LT},\ \sigma_{TT}$	$1.6 - 4.6$	$2.0 - 3.0$	[132]
	$\sigma_U,\ \sigma_{LT},\ \sigma_{TT}$	$0.13 - 3.3$	$1.5 - 2.3$	[137]
	$d\sigma/d\Omega$	$0.25 - 1.5$	$1.5 - 1.86$	[138]
$ep \to e'K^+\Lambda$	P_N^0	$0.8 - 3.2$	$1.6 - 2.7$	[139]
	$\sigma_U,\ \sigma_{LT},\ \sigma_{TT},\ \sigma_{LT'}$	$1.4 - 3.9$	$1.6 - 2.6$	[140]
	$P'_x,\ P'_z$	$0.7 - 5.4$	$1.6 - 2.6$	[141]
	$\sigma_T,\ \sigma_L,\ \sigma_{LT},\ \sigma_{TT}$	$0.5 - 2.8$	$1.6 - 2.4$	[142]
	$P'_x,\ P'_z$	$0.3 - 1.5$	$1.6 - 2.15$	[143]

Table 1: Overview of ηp and $K^+\Lambda$ electroproduction data measured at CLAS for different photon virtualities Q^2 and total energy W. Based on material provided by courtesy of D. Carman (JLab) and I. Strakovsky (GW).

- Many of these (and similar) data await analysis.
- Many more data to emerge at Jlab ($Q^2 = 5 - 12\ \mathrm{Gev}^2$)

e.g.: Carman, Joo, Mokeev, Few Body Syst. 61, 29 (2020)

- Approved Jlab experiments to study
  - Higher-lying nucleon resonances
  - Hybrid baryons
  - High-Q^2 transition between nonperturbative and perturbative QCD regimes

Summary

- Juelich-Bonn-Washington/JBW model: Phenomenology of excited baryons through coupled-channels, two- and three-body dynamics; data from Jlab, ELSA, MAMI, …
- Renewed effort to explore additional reaction channels in the last year:
  - $\gamma p \to K\Sigma$
  - $\pi N \to \omega N$
  - $\gamma^* p \to \pi N, \eta N$ (Electroproduction)
- Extensive exploration of parameter space leads to *significant* variance of some multipoles. Consequence of ambiguities, incomplete kinematic coverage.
- Many "faint" resonance signals confirmed, others not
- Many hyperon polarization data changed (α_- decay parameter of Λ changed)

  [D.G. Ireland et al., PRL, 1904.07616]

- How to find a minimal resonance spectrum? Model selection.

  [J. Landay et al., PRD, 1810.00075]

- Data aspects: How to get solid statistical statements out of a heterogeneous data base dominated by systematic errors? [New experiments: Klong, Epecur,..]

(spare slides)

S-, t- and u-channel exchanges

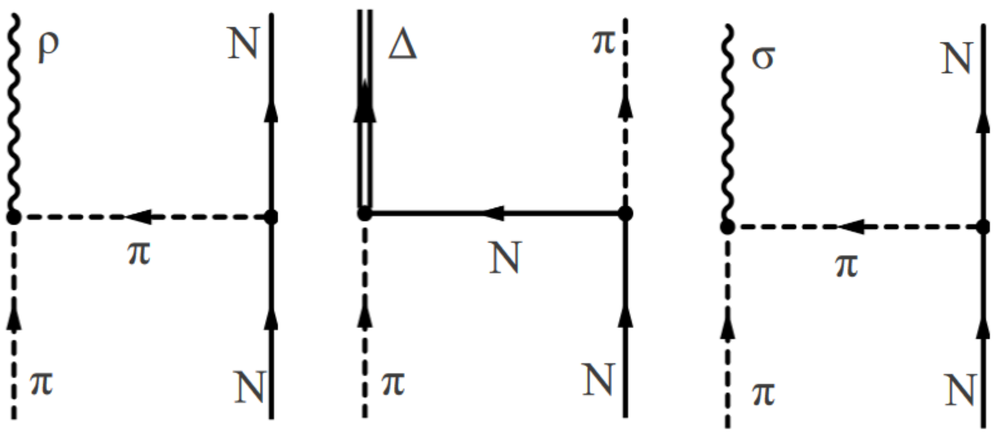
- 21 *s*-channel states (resonances) coupling to πN, ηN, $K\Lambda$, $K\Sigma$, $\pi\Delta$, ρN.
- *t*- and *u*-channel exchanges ("*background*"):

	πN	ρN	ηN	$\pi\Delta$	σN	KΛ	KΣ
πN	N,Δ,$(\pi\pi)_\sigma$, $(\pi\pi)_\rho$	N, Δ, Ct., π, ω, a_1	N, a_0	N, Δ, ρ	N, π	Σ, Σ^*, K*	Λ, Σ, Σ^*, K*
ρN		N, Δ, Ct., ρ	-	N, π	-	-	-
ηN			N, f_0	-	-	K*, Λ	Σ, Σ^*, K*
$\pi\Delta$				N, Δ, ρ	π	-	-
σN					N, σ	-	-
KΛ						Ξ, Ξ^*, f_0, ω, ϕ	Ξ, Ξ^*, ρ
KΣ							Ξ, Ξ^*, f_0, ω, ϕ, ρ

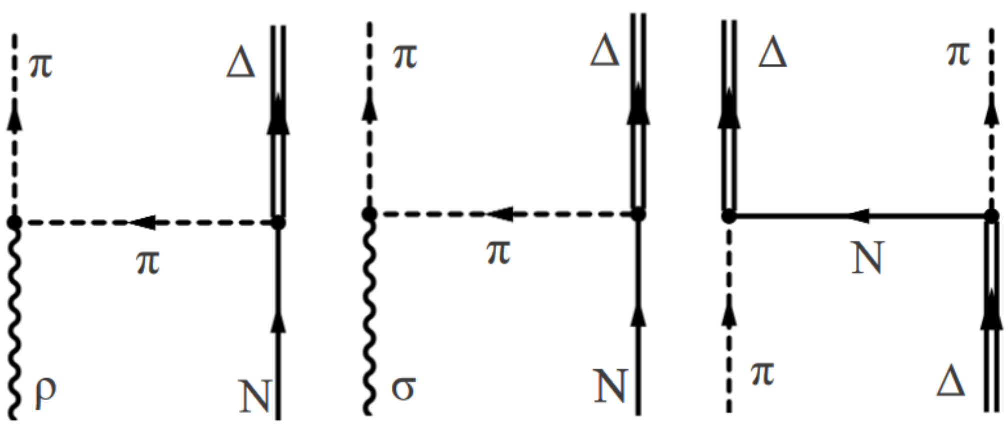
Is there a system behind this?

2→ 3 and 3→3 body unitarity

- Unitarity requires certain transition amplitudes



2→3



3→3