Single-Pion Electroproduction

Michael Döring, M, Mai, C. Granados, H. Haberzettl, U.-G. Meißner,
D. Rönchen, I. Strakovsky, R. Workman
[Jülich-Bonn-Washington (JBW) collaboration]

arXiv: 2104.07312 [nucl-th], Phys. Rev. C, in print

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Jefferson Lab

Supported by

DOE DE-AC05-06OR23177
& DE-SC0016583

JÜLICH FORSCHUNGSZENTRUM

HPC support by JSC grant *jikp07*

[several slides by
D. Rönchen and M. Mai]

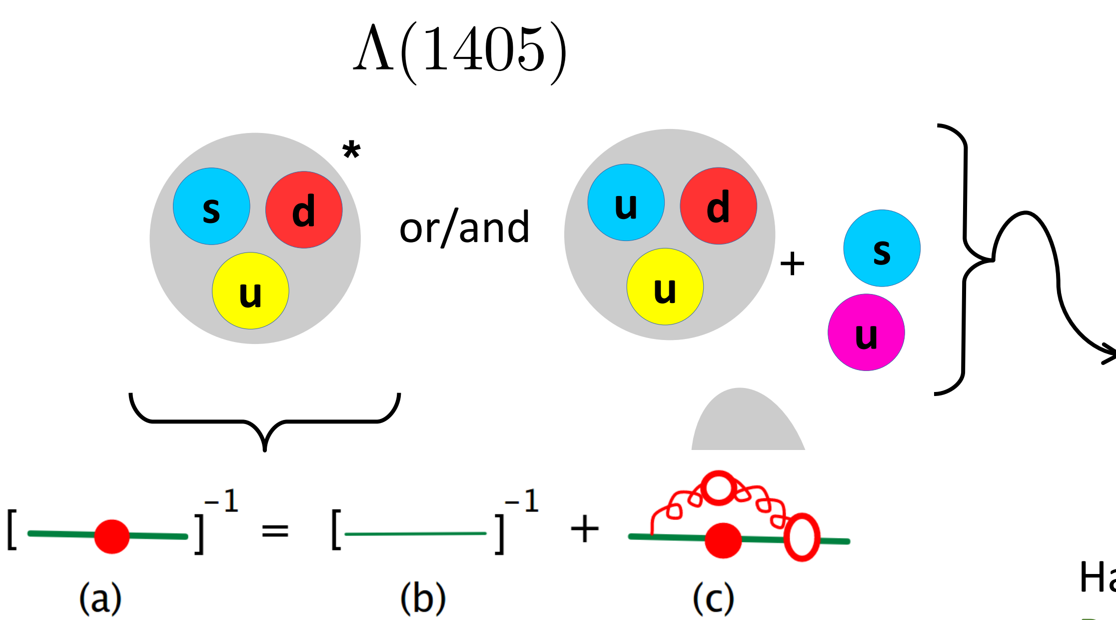
Degrees of freedom: Quarks or hadrons?

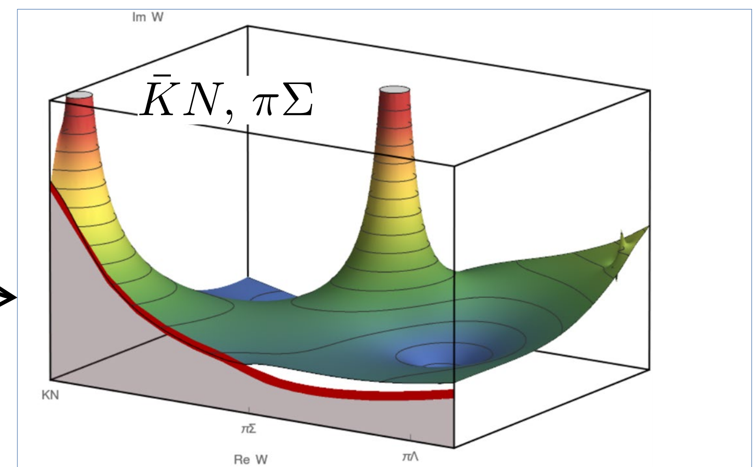
QCD at low energies → *mass generation & confinement*

Non-perturbative dynamics → rich spectrum of excited states

How many are there? → missing resonance problem)

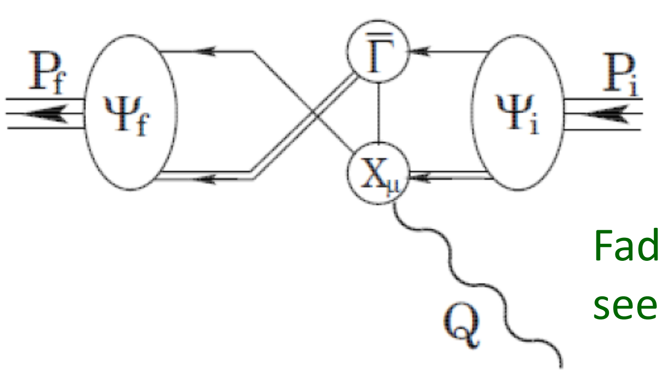
What are they? → 2-quark/3-quark, hadron molecules, …





Hadronic molecule

Review of the (1405), M. Mai, EPJST in print, 2010.00056 [nucl-th]

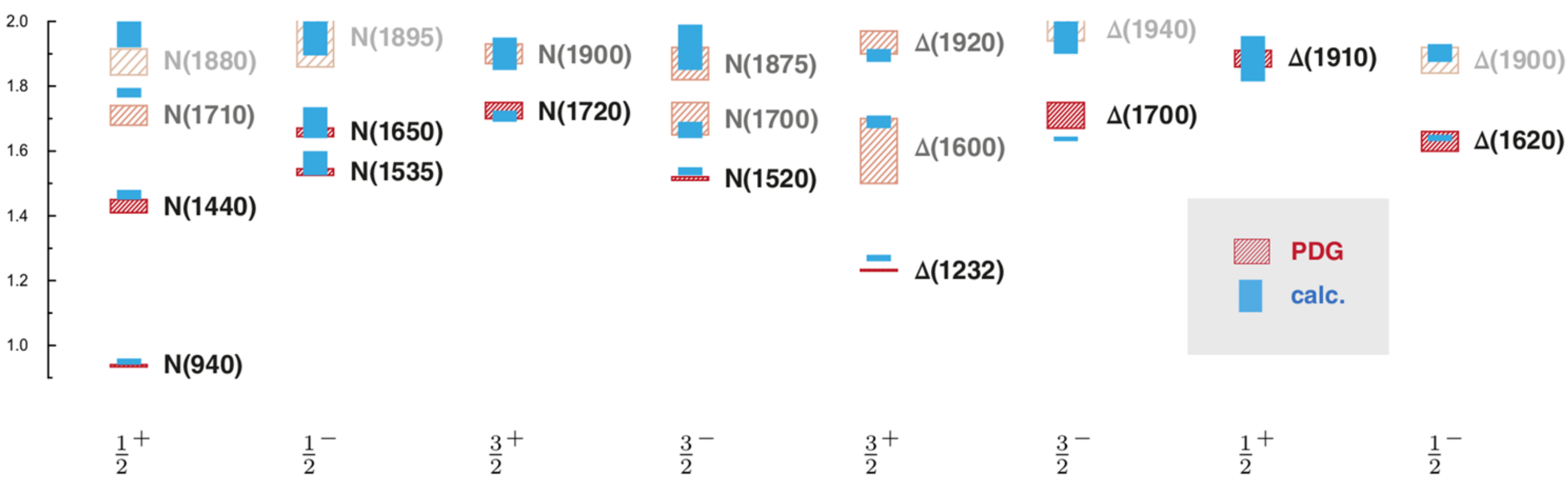


Faddeev Eq. / DSE (Binosi, Cloet, Chang, Roberts; see talk by J. Segovia on this conference)

Results in dynamical quark picture

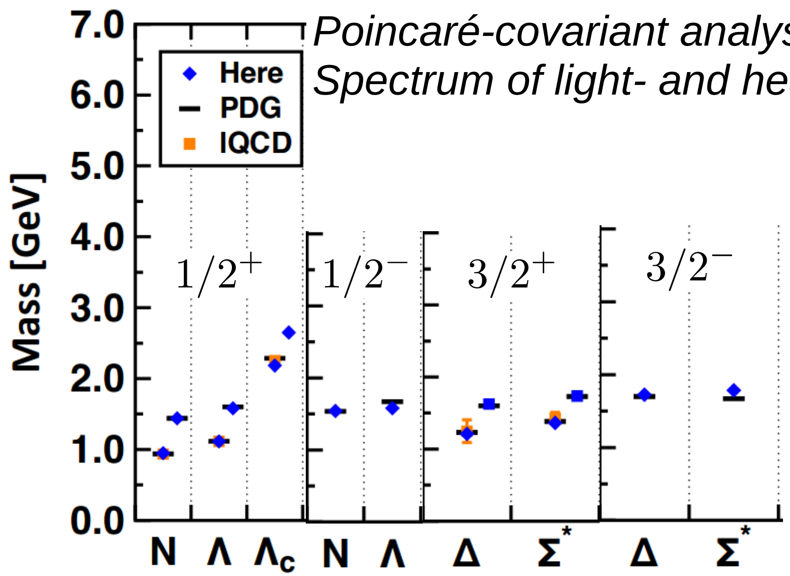
Quark-diquark with reduced pseudoscalar + vector diquarks: GE, Fischer, Sanchis-Alepuz, PRD 94 (2016)

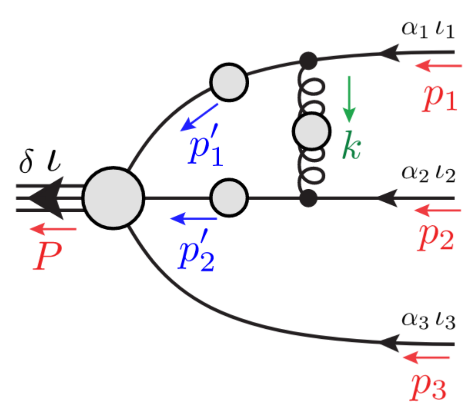
[parts of slide courtesy of G. Eichmann, Few Body 2018]



Poincaré-covariant analysis of heavy-quark baryons, Qin, Roberts, Schmidt, PRD (2018)

Spectrum of light- and heavy-baryons, Qin, Roberts, Schmidt, Few Body Syst. 60 (2019)





Single-meson photoproduction with JuBo

A boundary condition for electroproduction analysis

e.g.: D. Ronchen et al., EPJA (2018), arXiv: 1801.10458

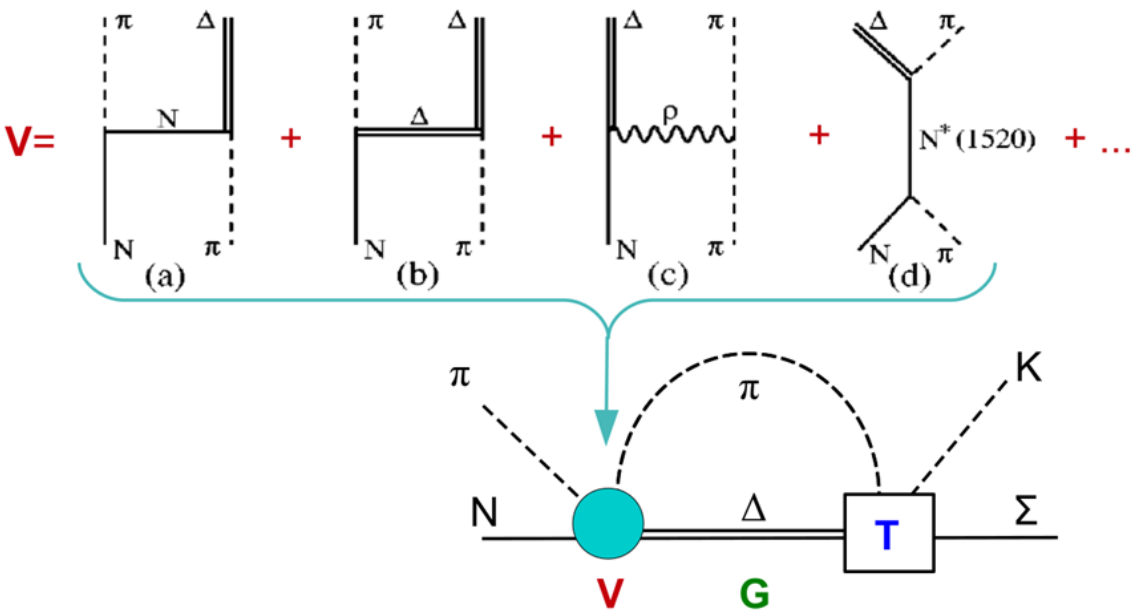
The Julich-Bonn Dynamical Coupled-Channel Approach

e.g. EPJ A 49, 44 (2013)

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

The scattering equation in partial-wave basis

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



- potentials V constructed from effective $\mathcal{L}$
- s-channel diagrams: T^P

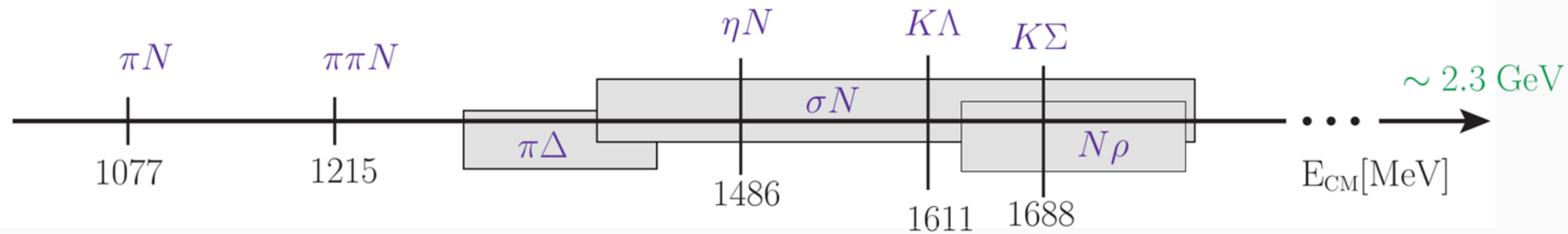
  genuine resonance states
- t- and u-channel: T^{NP}

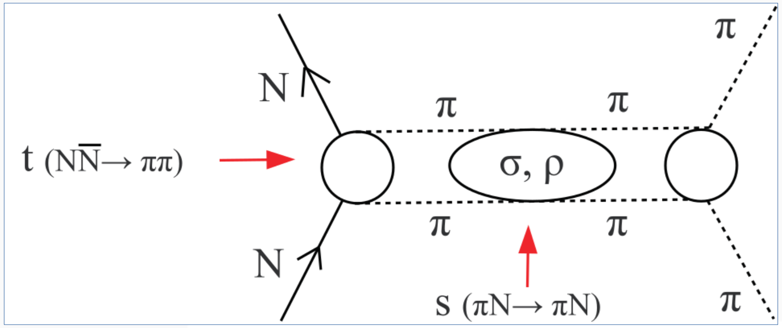
  dynamical generation of poles

  partial waves strongly correlated

JuBo: Channels and Analytic Structure

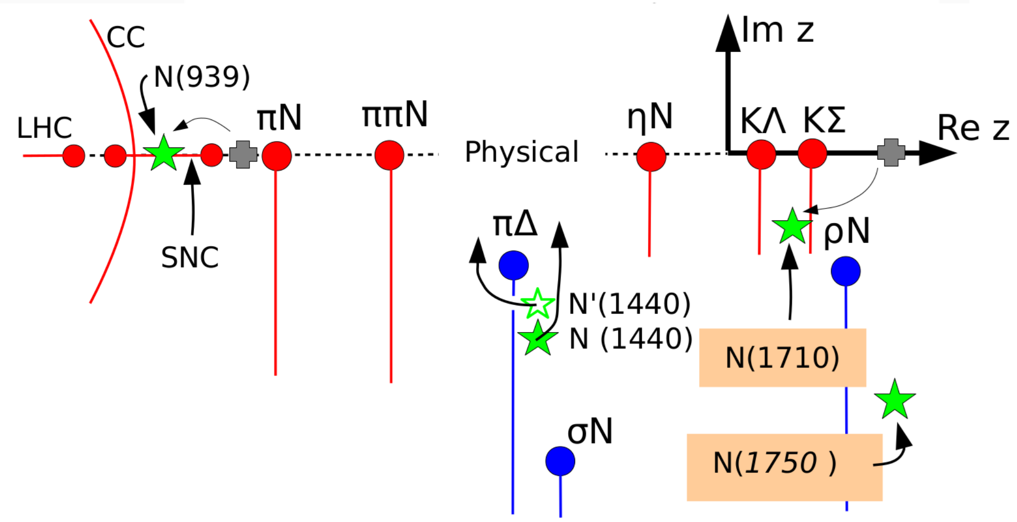
Channels included:





- (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



JuBo: Photoproduction Data base

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

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
$\boldsymbol{\gamma p \to K^+ \Lambda}$	$d\sigma/d\Omega$ (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
$\boldsymbol{\gamma p \to K^+ \Sigma^0}$	$d\sigma/d\Omega$ (4271), P (422), Σ (280), T (127), $C_{x',z'}$ (188), $O_{x,z}$ (254)	5,542
$\boldsymbol{\gamma p \to K^0 \Sigma^+}$	$d\sigma/d\Omega$ (242), P (78)	320
	in total	**57,027**

A new web interface [https://jbw.phys.gwu.edu/]

Pion Electroproduction

A first step towards a coupled-channel photo- and electroproduction analysis

M. Mai et al., 2104.07312 [nucl-th], Phys. Rev. C, in print

Single-meson electroproduction to reveal resonance structure

See talks by **D. Carman and V. Mokeev**

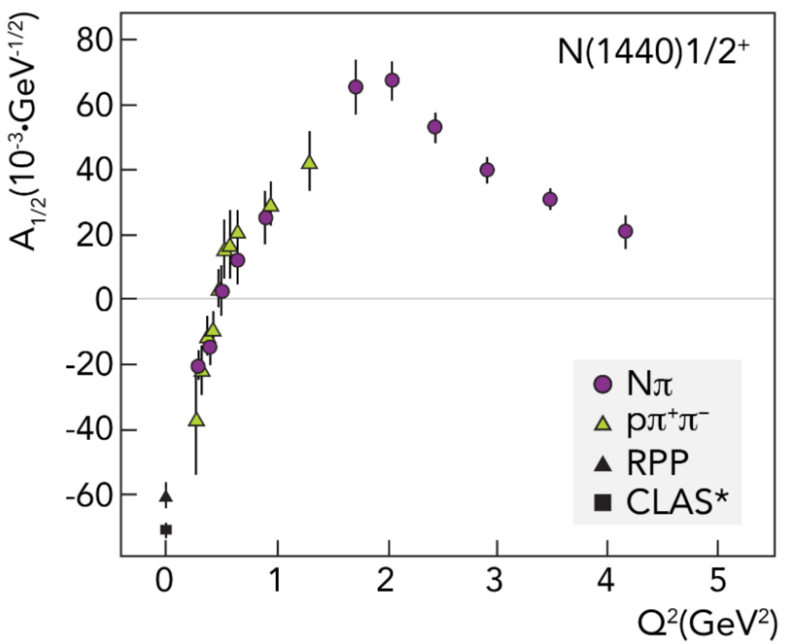
- **ANL-Osaka** PRC **80**, 025207 (2009), Few-Body Syst. 59, 24 (2018),...
- **Aznauryan, Burkert, Mokeev** et al., PRC **80**, 055203 (2009), Int. J. Mod. Phys. E22, 1330015 (2013),..
- **EtaMAID2018**, EPJA 54 (2018), 210
- **MAID2007**, EPJA 34 (2007) 69
- **SAID**, PiN Newsletter 16, 150 (2002)
- **Gent group** Phys. Rev. C 89, 065202 (2014),...

Highlights:

- Simultaneous description of pion photo- and electroproduction (MAID)
- Consistent extraction of the Roper form factor from single and double pion electroproduction
- New resonance in electroproduction claimed

Mokeev et al., PLB (2020) 2004.13531 [nucl-ex]

Burkert, Roberts, 1710.02549



Needed: Coupled-channel electroproduction analysis

Take advantage of multi-channel approach
→ analyze simultaneously final states $\pi N,\ \eta N,\ K\Lambda$

~10^6 pion electroproduction data; $\eta N,\ K\Lambda$:

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]

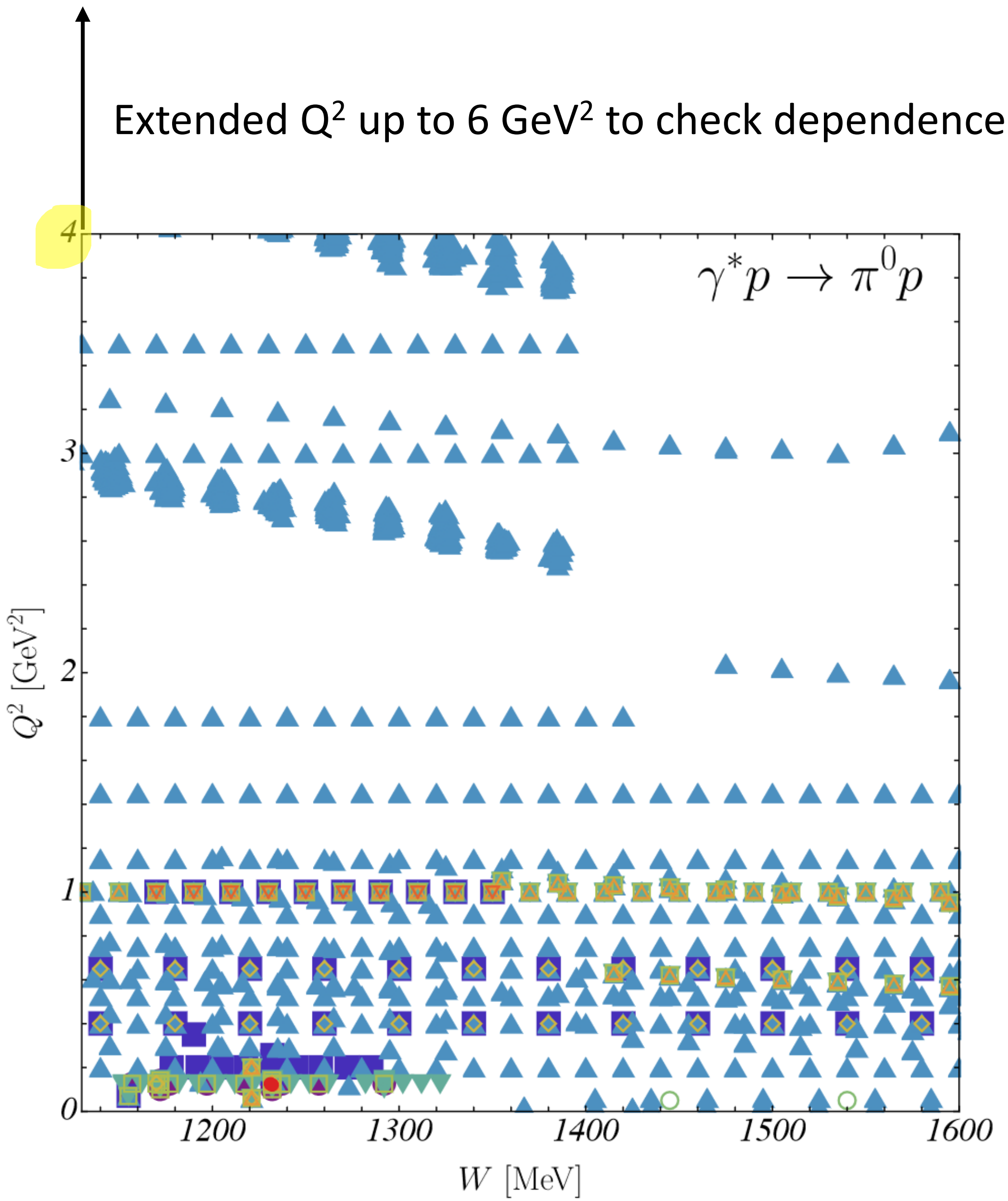
Table 1: Overview of ηp and $K^+\Lambda$ electroproduction data measured at CLAS for different photon virtualities Q^2 and total energy W. Based on material provided by courtesy of D. Carman (JLab) and I. Strakovsky (GW).

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

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

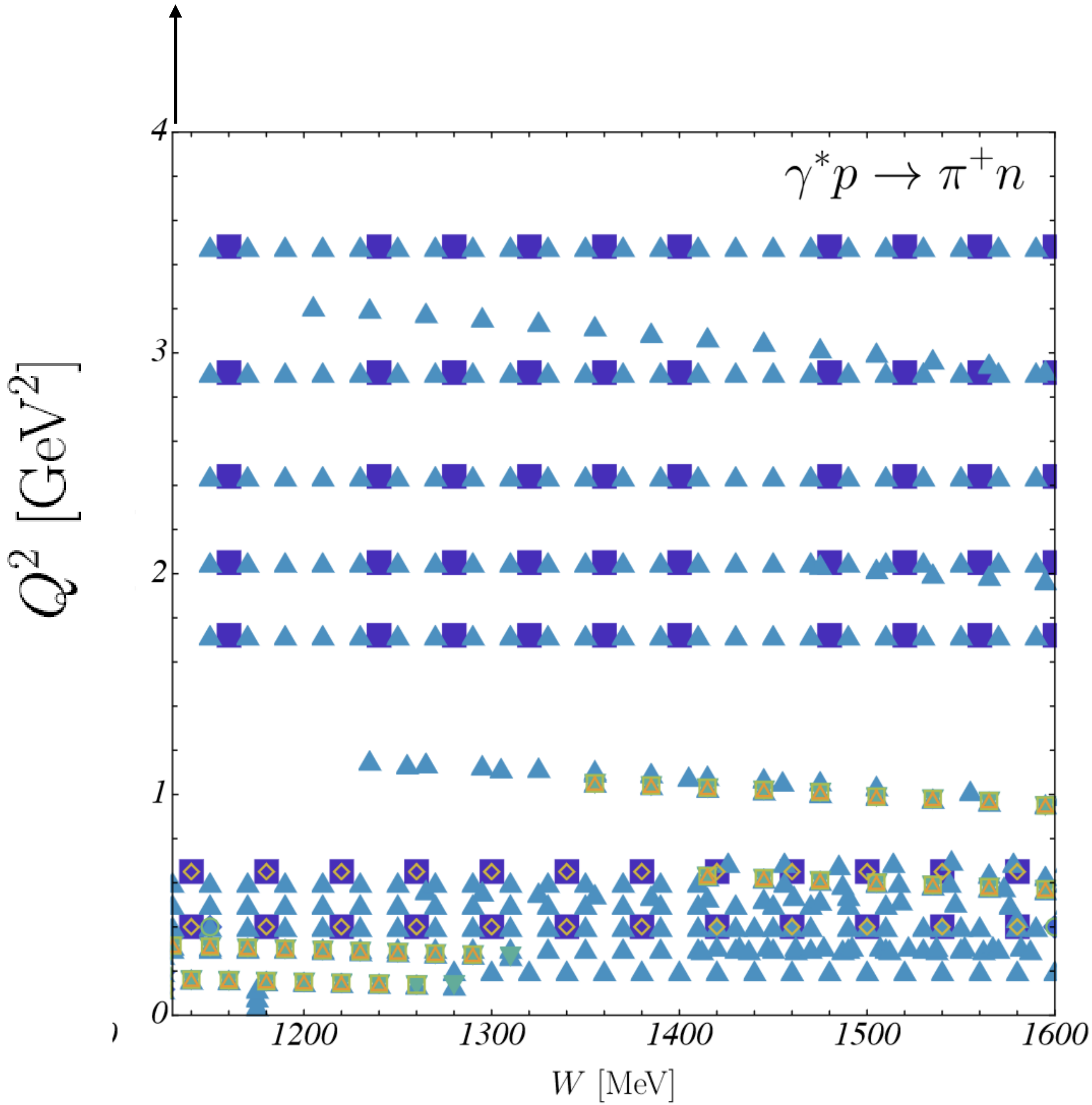
- Approved Jlab experiments to study
  - Higher-lying nucleon resonances
  - Hybrid baryons
  - Transition regime between nonperturbative and perturbative regions

Pion Electroproduction – data base



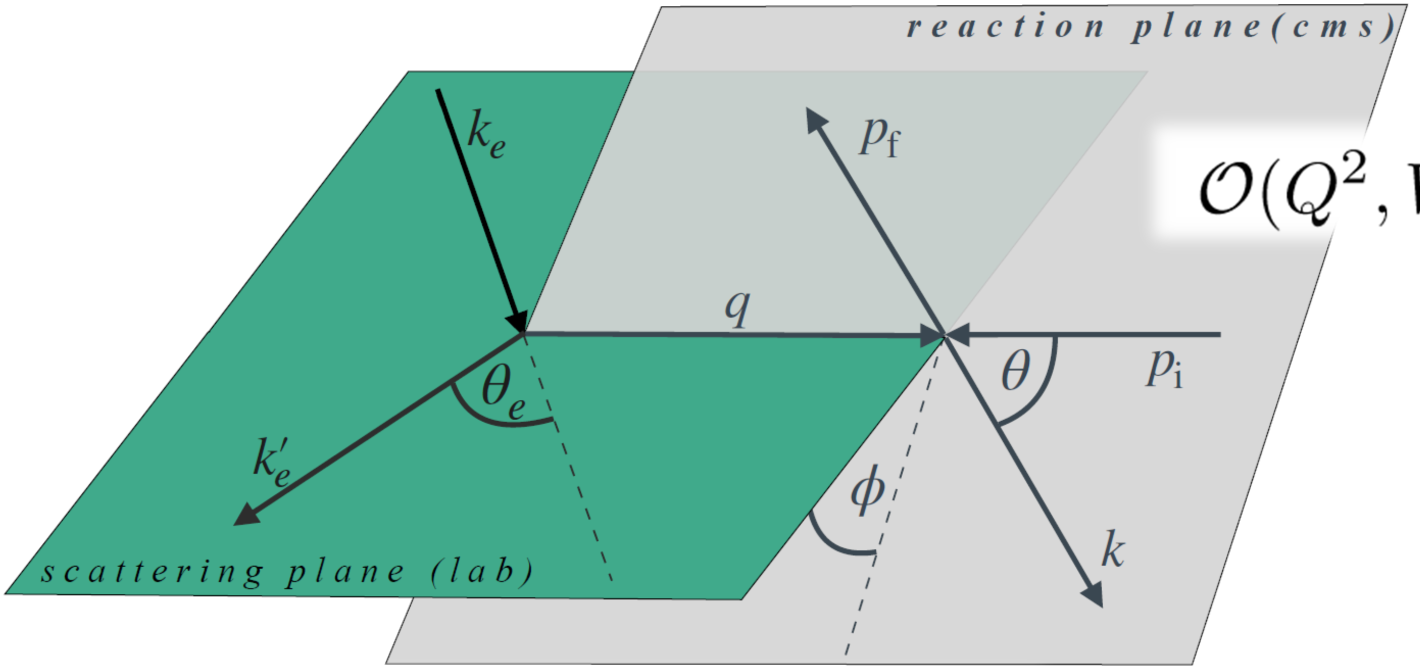
Type	N_{data}
ρ_{LT}	45
$\rho_{LT'}$	2644
σ_L	–
$d\sigma/d\Omega$	39942
$\sigma_T + \epsilon\sigma_L$	318
σ_T	10
σ_{LT}	312
$\sigma_{LT'}$	198
σ_{TT}	266
K_{D1}	1527
P_Y	2

Pion Electroproduction – data base



Type	N_{data}
ρ_{LT}	–
$\rho_{LT'}$	4354
σ_L	2
$d\sigma/d\Omega$	32813
$\sigma_T + \epsilon\sigma_L$	144
σ_T	2
σ_{LT}	106
$\sigma_{LT'}$	192
σ_{TT}	91
K_{D1}	–
P_Y	–

Kinematics



$$\mathcal{O}(Q^2, W, \phi, \theta, \epsilon)$$

$$\frac{d\sigma}{d\Omega_f dE_f d\Omega} = \left(\frac{\alpha}{2\pi^2}\frac{E_f}{E_i}\frac{q_L}{Q^2}\frac{1}{1-\epsilon}\right)\frac{d\sigma^v}{d\Omega},$$

(Un)polarized differential cross section:

$$\frac{d\sigma^v}{d\Omega} = \sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi + \epsilon\sigma_{TT}\cos 2\phi + h\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi$$

$$\epsilon = 1 + 2\frac{q_L^2}{Q^2}\tan^2\frac{\theta_e}{2}$$

Polarized Observables

- CLAS: Structure functions $\sigma_{LT'}$

  K. Joo et al. [CLAS], Phys. Rev. C 68 (2003),

  K. Joo et al. [CLAS], Phys. Rev. C 70 (2004).

- Jlab-Hall A for $K_{1D} = \{K_{1D}^{X} | X = A, B, .., T\}$

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

- Response functions (R) ⇔ Kelly notation (RL, RT, …) ⇐ Helicity amplitudes *H* ⇔ CGNL amplitude. For example:

$$\sigma_T = \frac{k}{q_\gamma} R_T^{00}\,, \quad \sigma_L = \frac{k}{q_\gamma}\frac{Q^2}{\omega^2} R_L^{00}\,, \quad \sigma_{TT} = \frac{k}{q_\gamma} R_{TT}^{00}$$

$$\sigma_{LT} = \frac{k}{q_\gamma}\frac{\sqrt{Q^2}}{\omega} R_{LT}^{00}\,, \quad \sigma_{LT'} = \frac{k}{q_\gamma}\frac{\sqrt{Q^2}}{\omega} R_{LT'}^{00}\,.$$

$$P_Y = -\sqrt{2\epsilon(1+\epsilon)}\frac{\omega}{\sqrt{Q^2}}\frac{R_{LT}^{0Y}}{R_T^{00} + \epsilon\omega^2/Q^2 R_L^{00}}$$

$$\rho_{LT} = \sqrt{2\epsilon(1+\epsilon)}\frac{R_{LT}^{00}}{R_T^{00} + \epsilon(R_L^{00} + R_{TT}^{00})}\,,$$

$$\rho_{LT'} = \sqrt{2\epsilon(1-\epsilon)}\sin\phi\frac{\sigma_{LT'}}{d\sigma^v/d\Omega}\,,$$

Parameterization

- Photoproduction solution as constraint
- Constraints from (Pseudo)-threshold:

$$\left(E^I_{l+}, L^I_{l+}\right) \rightarrow k^l q^l \quad (l \geq 0)$$
$$\left(M^I_{l+}, M^I_{l-}\right) \rightarrow k^l q^l \quad (l \geq 1)$$
$$\left(L^I_{l}\right) \rightarrow kq \quad (l = 1)$$
$$\left(E^I_{l-}, L^I_{l-}\right) \rightarrow k^{l-2} q^l (l \geq 2)$$

$$k = |\mathbf{k}| = \frac{\sqrt{\left((W-M_N)^2 + Q^2\right)\left((W+M_N)^2 + Q^2\right)}}{2W}$$
$$q = |\mathbf{q}| = \frac{\sqrt{\left((W-M_N)^2 - M_m^2\right)\left((W+M_N)^2 - M_m^2\right)}}{2W}$$

- Siegert's theorem at pseudo-threshold:

$$\frac{E_{l_+}}{L_{l_+}} \rightarrow 1, \qquad \frac{E_{l_-}}{L_{l_-}} \rightarrow \frac{-l}{l-1}$$

Amaldi, Fubini, Furlan,
Springer Tracts Mod. Phys. 83, 1 (1979)
Tiator, Few-body Systems 57, 1087 (2016)

- Watson's theorem, multi-channel unitarity

$$M_{\mu\gamma^*}(q, W, Q^2) = V_{\mu\gamma^*}(q, W, Q^2) + \sum_\kappa \int dp\, p^2 T_{\mu\kappa}(q, p, W) G_\kappa(p, W) V_{\nu\gamma^*}(p, W, Q^2)$$

$$V_{\mu\gamma^*}(p, W, Q^2) = \alpha^{NP}_{\mu\gamma^*}(p, W, Q^2) + \sum_i \frac{\gamma^a_{\mu;i}(p)\gamma^c_{\gamma^*;i}(W, Q^2)}{W - m^b_i}$$

Parameterization (2)

- Up to *D*-waves included (photoproduction part includes up to *J=9/2*)
- Energy range up to $W \approx 1.6$ allows to include ηN electro-production without much extra effort, but *KY* electroproduction requires additional work
- Final state interaction given by JuBo/JBW model such that pole positions and hadronic branching ratios (pole residues) are universal as required by reaction dynamics
- Q^2-dependence: Several analytic forms tested; settled for:

$$\tilde{F}(Q^2) = \tilde{F}_D(Q^2)\, e^{-\beta_0 Q^2/m^2}\; P^N(Q^2/m^2)$$

P^N: Polynomial

where

$$\tilde{F}_D(Q^2) = \frac{1}{(1+Q^2/b^2)^2}\,\frac{1+e^{-Q_r^2/Q_w^2}}{1+e^{(Q^2-Q_r^2)/Q_w^2}}$$

- Some multipoles difficult to determine (longitudinal more difficult than E and M; sometime not even Siegert's condition helps because corresponding electric multipole does not exist)
- But: No model-dependent input from (photonic) Feynman diagrams to model longitudinal multipoles

Parameterization Dependence

- Can parametrization dependence be avoided? Not if the data is far from being complete enough to represent even a truncated complete electroproduction experiment

L. Tiator et al. Phys. Rev. C (2017), arXiv: 1702.08375

- Future: Bias-variance tradeoff: Different statistical criteria (Akaike, Bayesian) to find sweet spot between no. of parameters or no. of partial waves and predictivity (model selection)

J. Landay et al., Phys.Rev.C (2017), arXiv: 1610.07547

- Future: Single-Q^2 analysis can decrease parametrization-independence but not remove it (discrete & continuous ambiguities).
- Towards complete data: CLAS/Kelly data provides unique opportunity to confront parametrization with different polarization data at given W and Q^2.

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

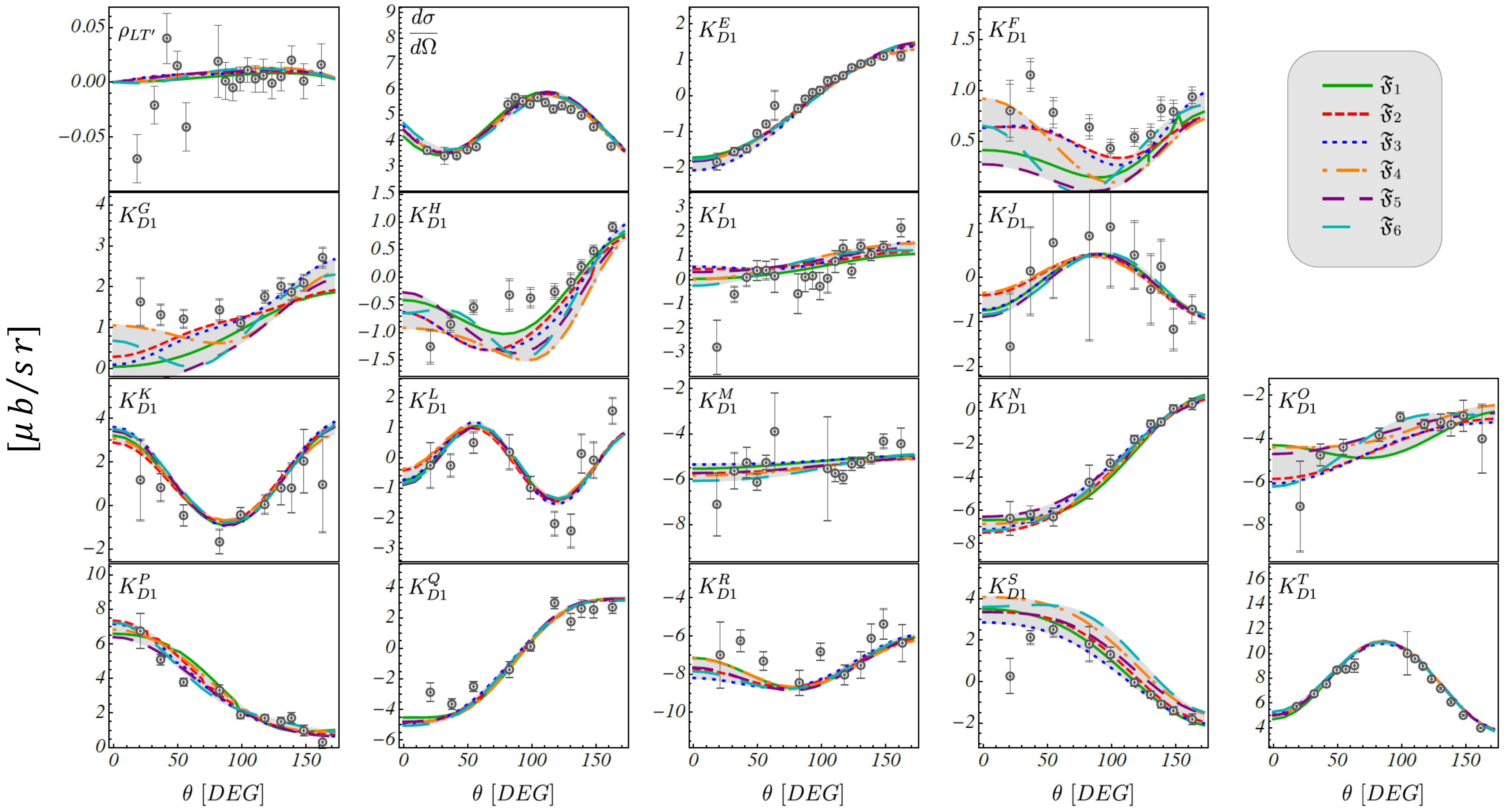
Results (1): Fit Strategies

- Six different fit strategies:
  - Avoid fitting structure function if corresponding cross sections can be fitted (respect data correlations)
  - 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

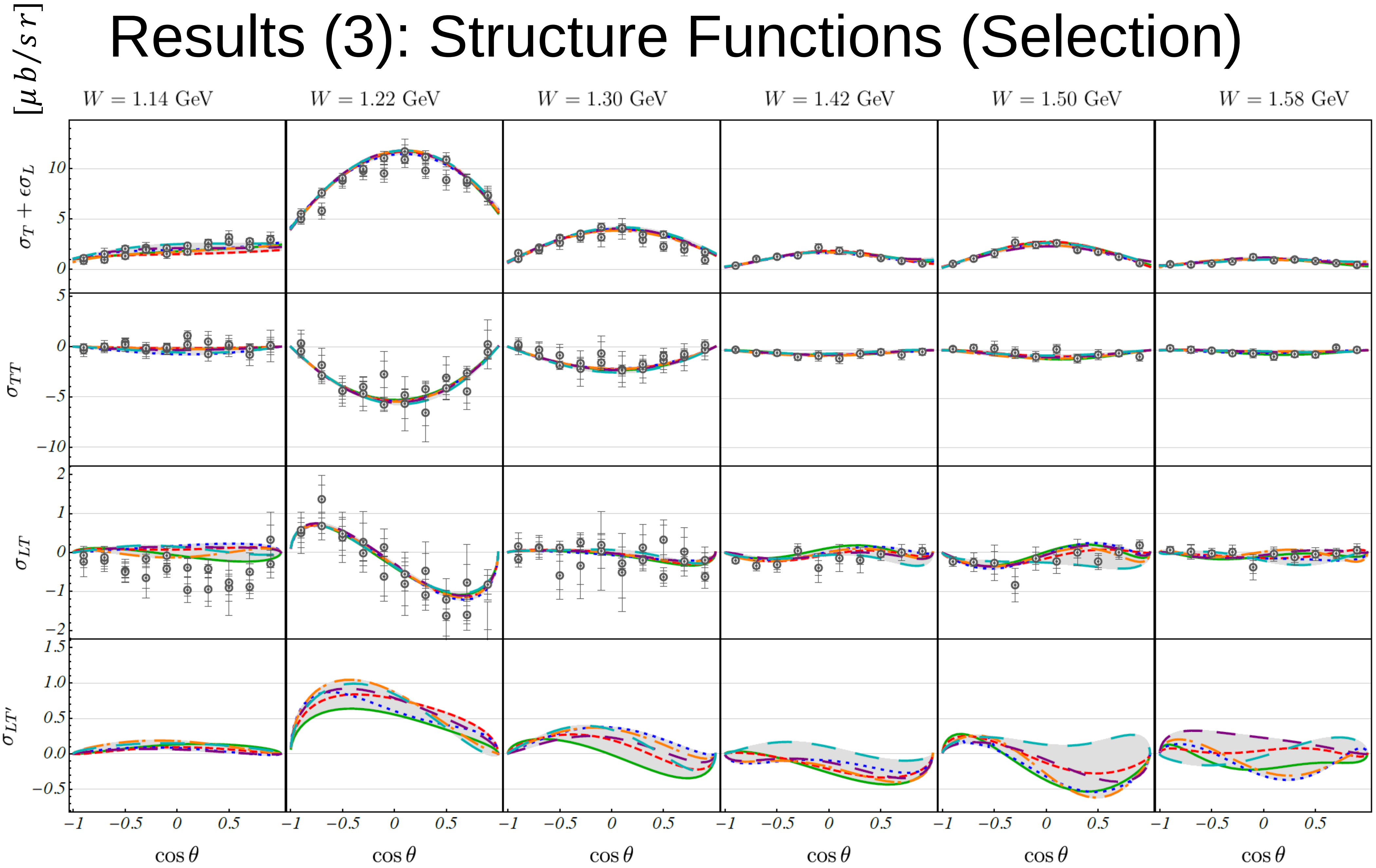
Results (2): Kelly data



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

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

Results (3): Structure Functions (Selection)

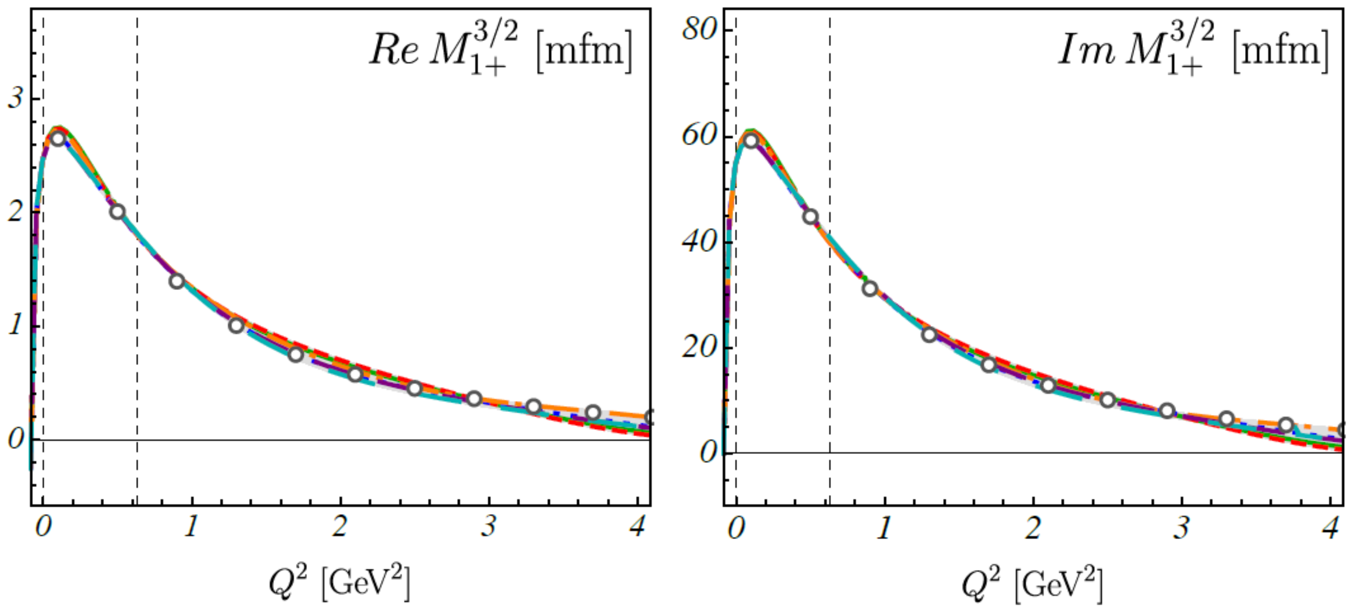


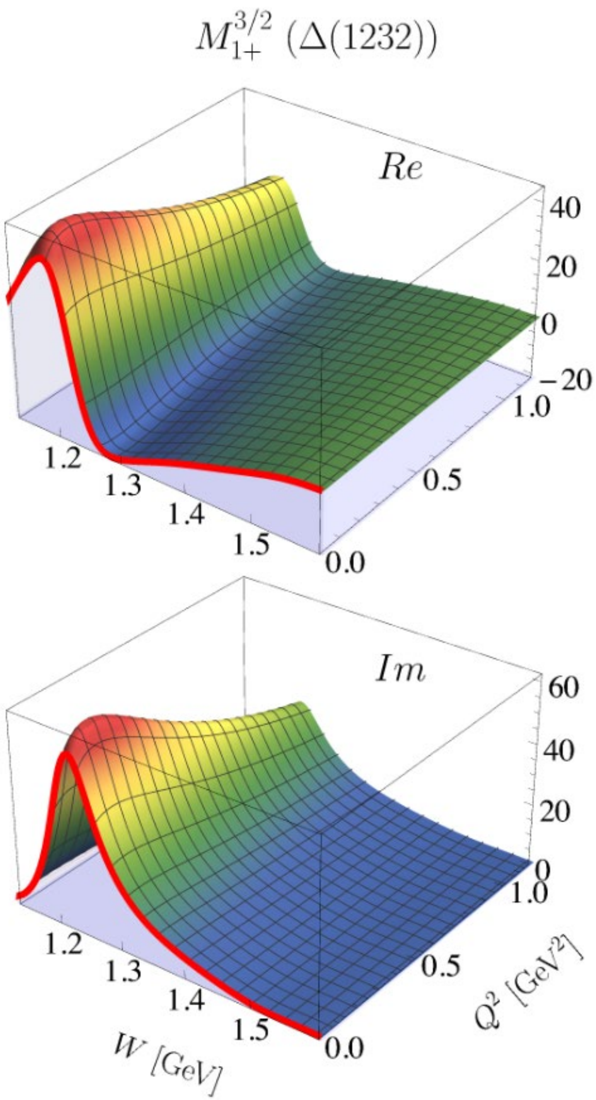
$Q^2 = 0.9$ Gev^2, $\pi^0 p$

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

Results (4): Large Multipoles

Prominent multipoles are well determined, even with significantly different fit strategies (e.g., all parameters initially set to zero, no guidance for fit!)



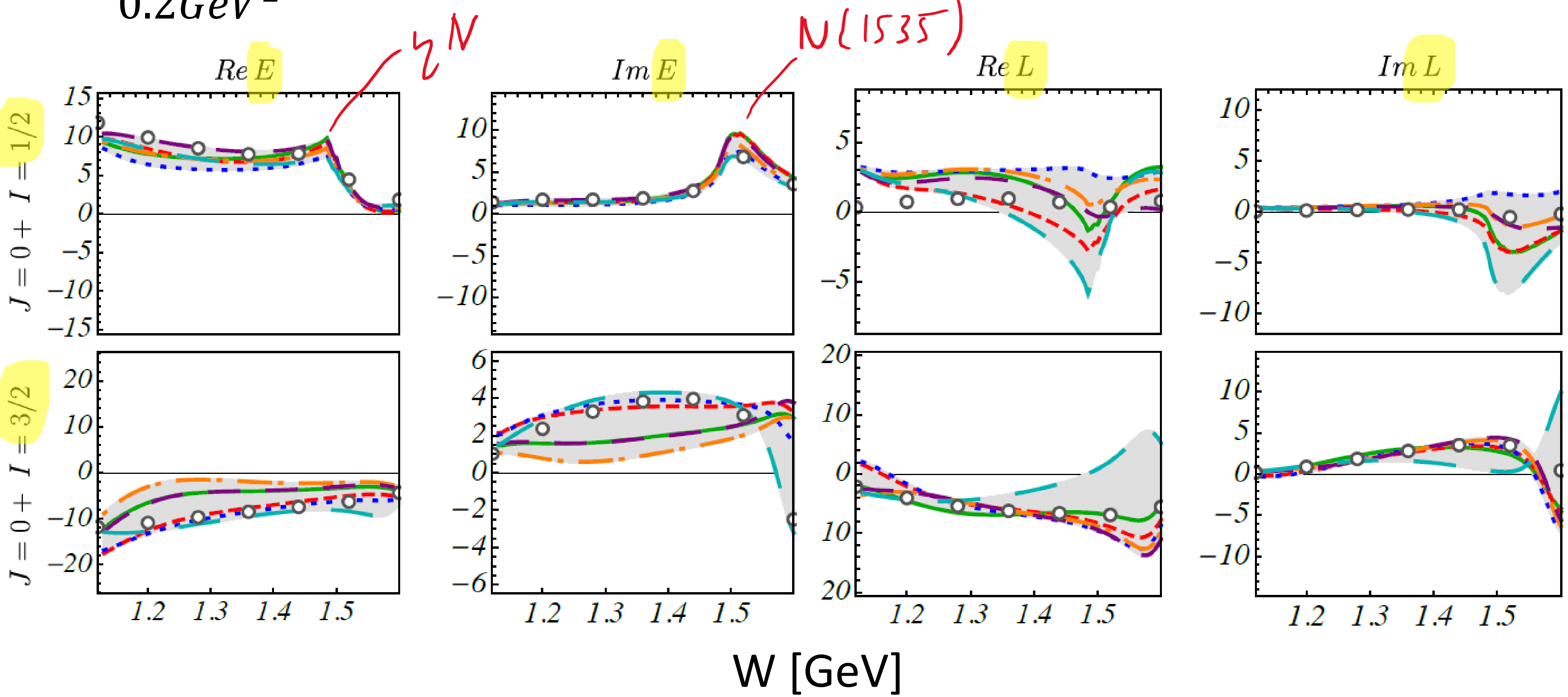


Fit strategies 1-6 together with MAID (open dots) for the magnetic multipole of the $\Delta(1232)$ Drechsel et al., EPJA (2007) 0710.0306 [nucl-th]

(Strategy 1 only)

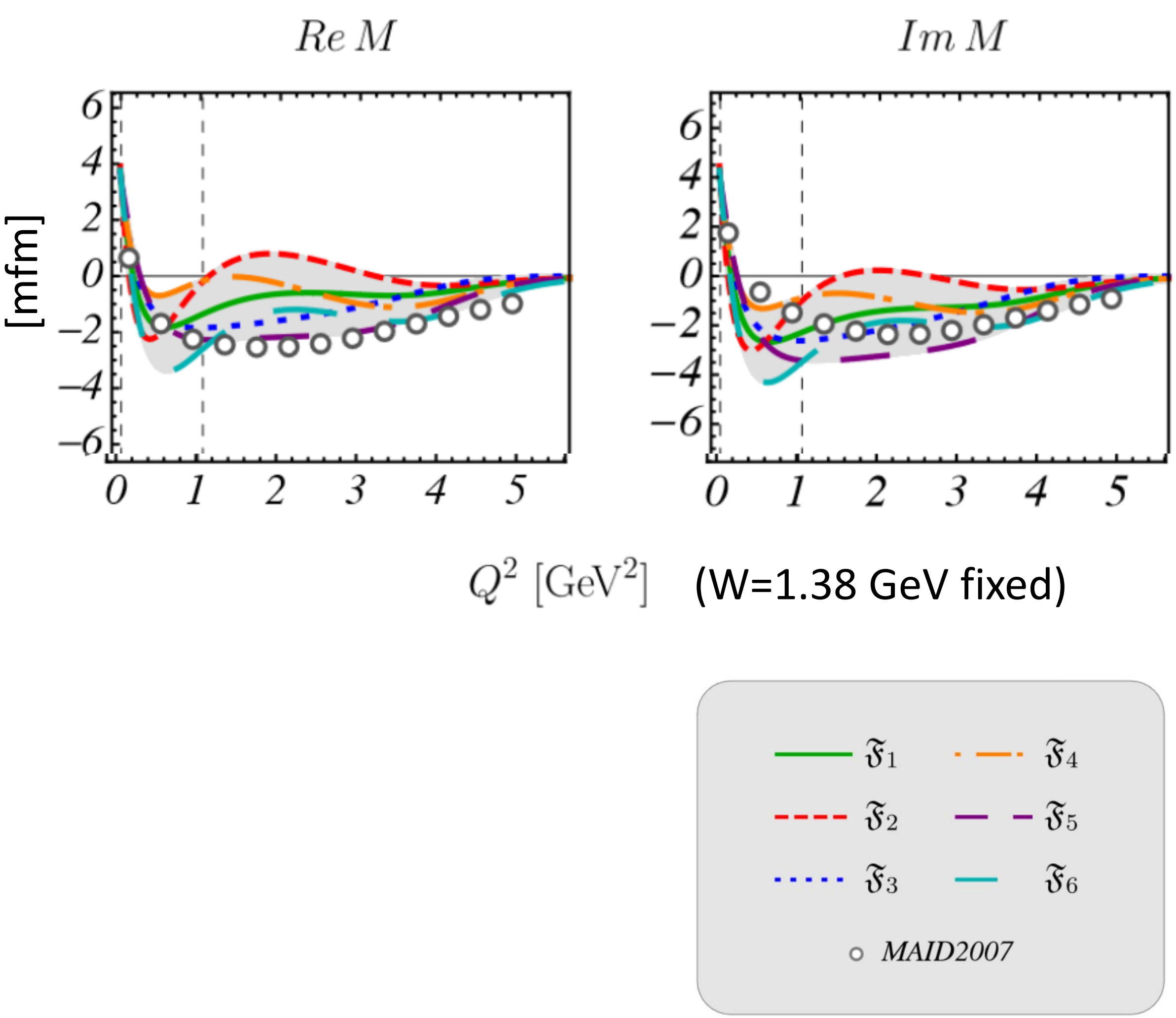
Results (5): Other multipoles

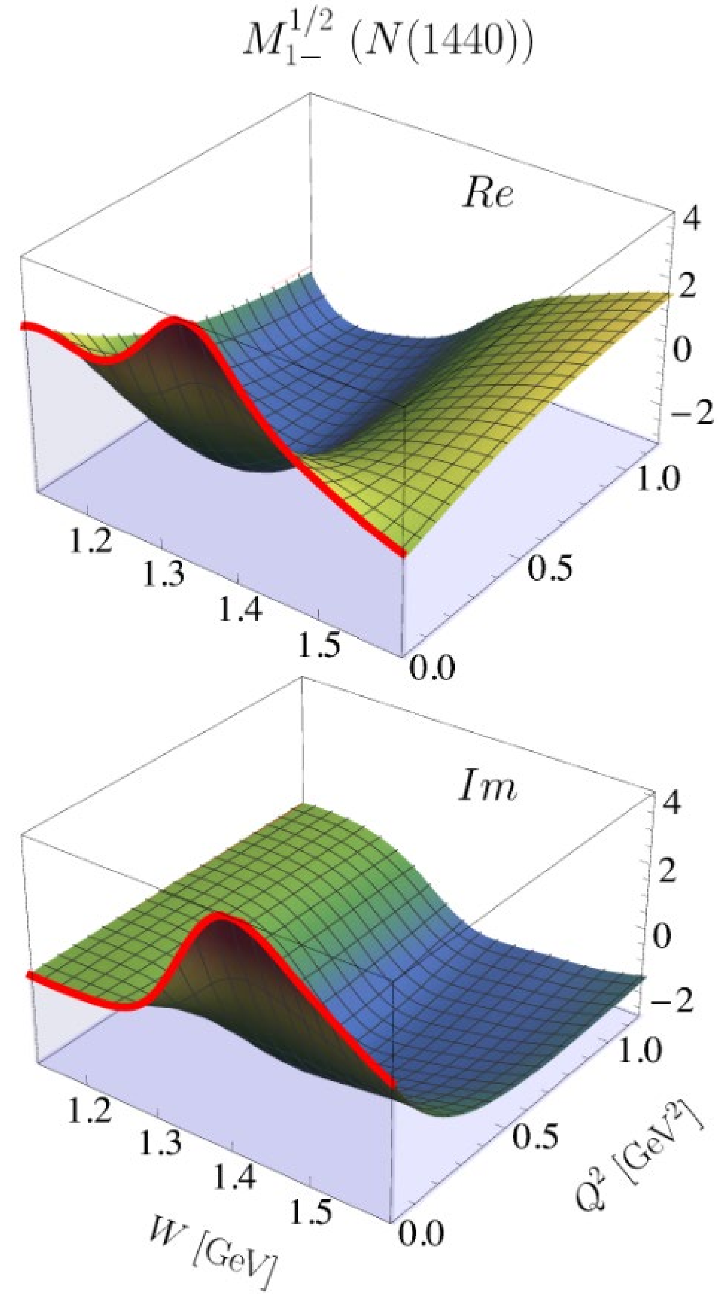
- Less prominent multipoles are sometimes less well determined
- Overall: solutions are still surprisingly close together given vastly different strategies
- Differences from various strategies (different local χ^2minima) much larger than statistical uncertainties; larger than typical MAID uncertainties.
- **Example**: S-wave multipoles [mfm] as function of energy W at fixed $Q^2 = 0.2GeV^2$



Results (6): Roper Multipole

- Non-trivial structure
- Zero transition
- Helicity coupling still to be extracted





(Strategy 1 only)

Summary

- JBW model: Phenomenology of excited baryons through coupled-channels, two- and three-body effects
- Analysis finds/confirms new states in analysis of photo-production data, renewed effort to explore additional reaction channels
- Pion electroproduction analysis performed
  - Exploration of parameter space through different fit strategies reveals different local minima leading to significantly different multipole content.
  - Yet, prominent multipole well determined, albeit with uncertainties larger than in other analyses.

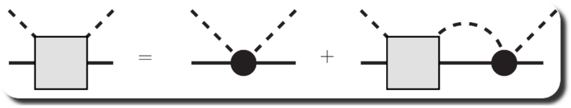
- Extraction of helicity couplings and fixed-Q^2 analysis planned
- Upgrade to η and KY electroproduction straightforward (existing and future JLab data; photoproduction solution exists)
- Statistical upgrade: How to find a minimal resonance spectrum through model selection J. Landay et al., Phys.Rev.D (2019), 1810.00075 [nucl-th]

(spare slides)

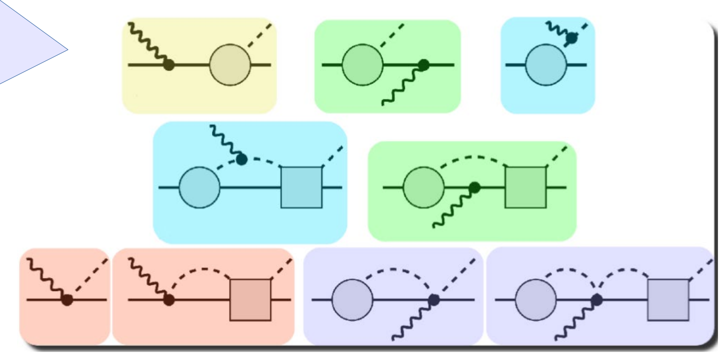
Using ONLY meson-baryon degrees of freedom (no explicit quark dynamics):

Manifestly gauge invariant approach based on full BSE solution

[Ruic, M. Mai, U.-G. Meissner PLB 704 (2011)]

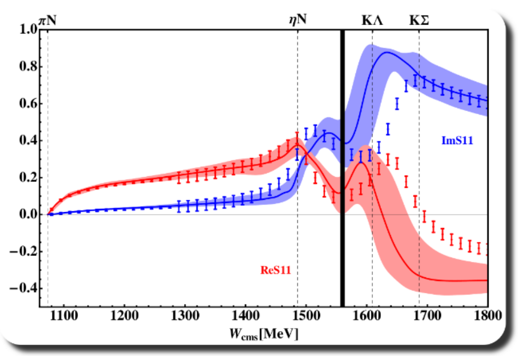


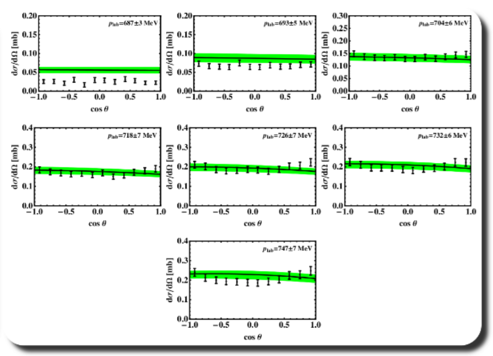
Gauge invariance

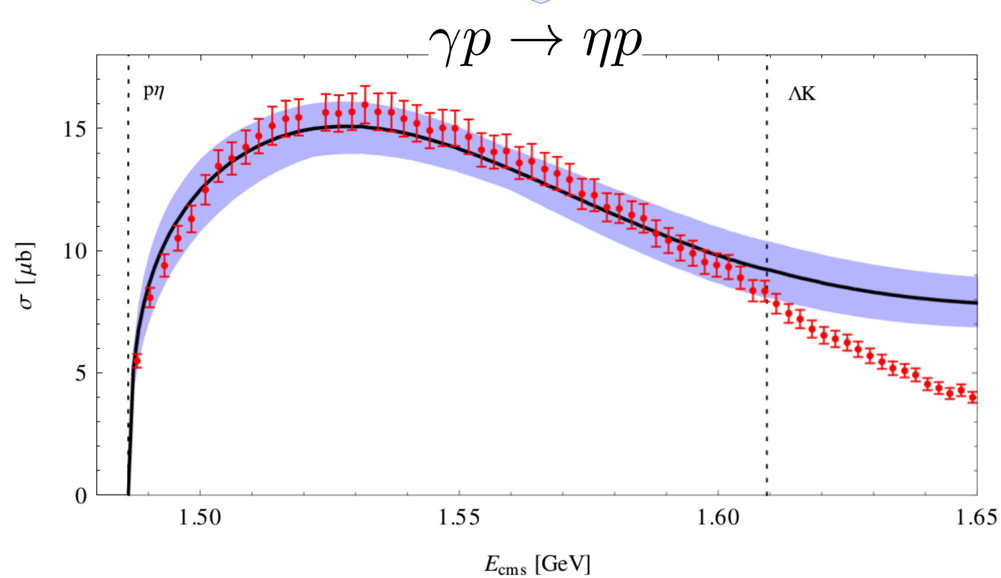


Fit

- Exact unitary meson-baryon scattering amplitude T with parameters, fixed to reproduce:
  - πN-partial wave S_{11} and S_{31} for $\sqrt{s} < 1560$ MeV
    Arndt et al. (2012)
  - $\pi^- p \to \eta n$ differential cross sections
    Prakhov et al. (2005)





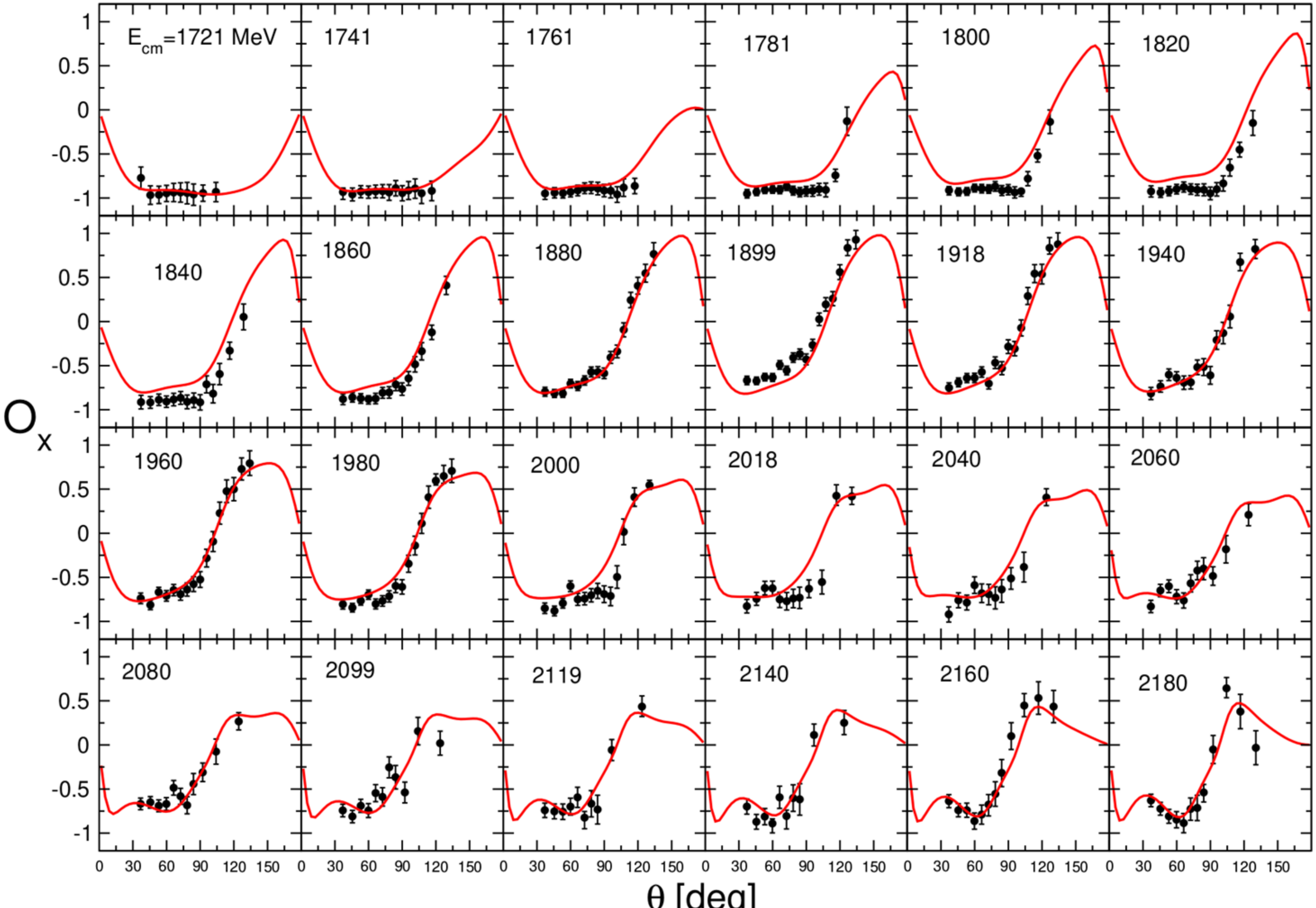


→ Making the “Missing resonance problem” worse ?!

Selected Fit Results (I)

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

http://collaborations.fz-juelich.de/ikp/meson-baryon/main



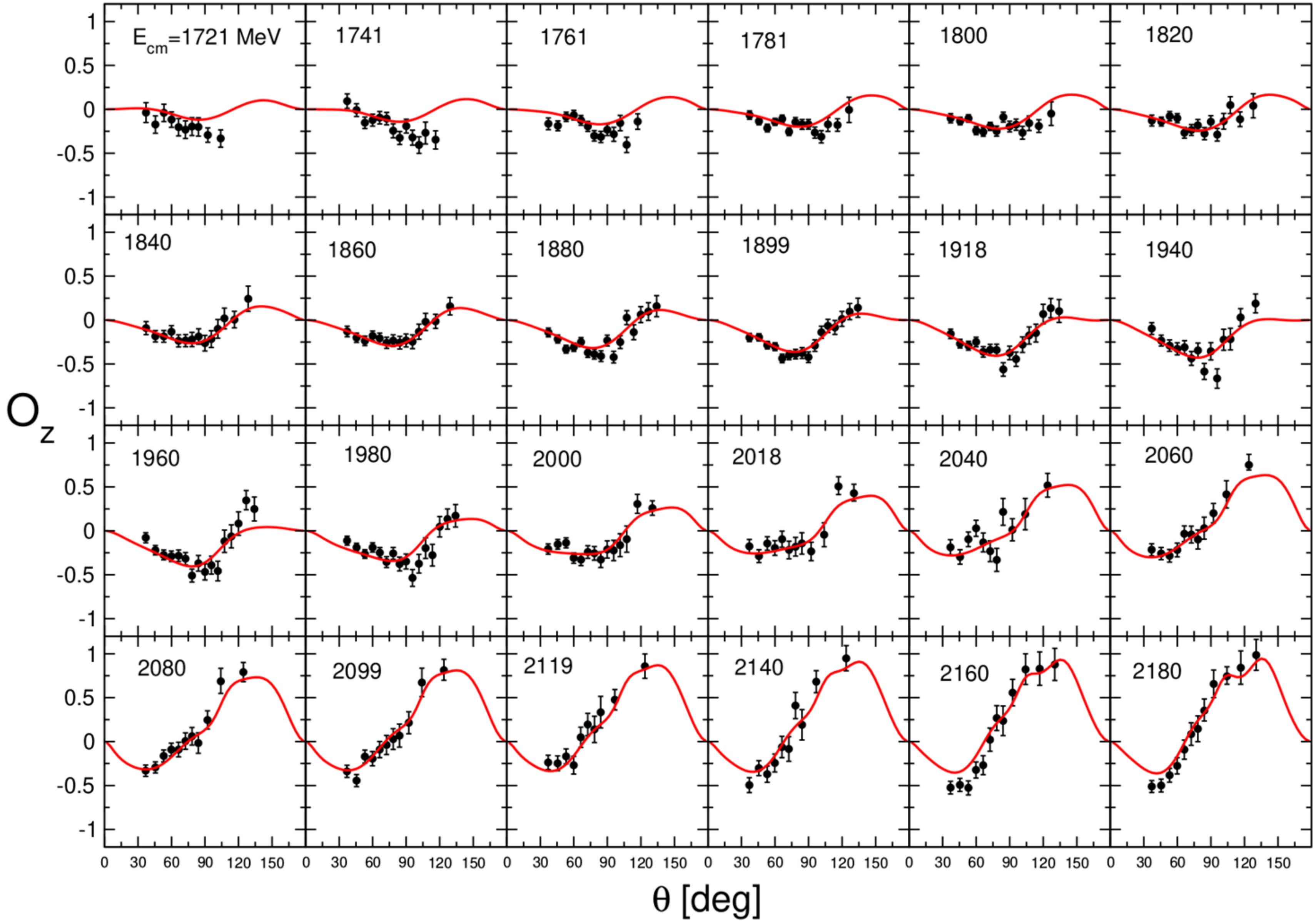
[D. Roenchen, M. D., U.-G. Meißner, EPJ A 54, 110 (2018)]

data: Paterson (CLAS) PRC 93, 065201 (2016), red line: fit JüBo2019

Selected Fit Results (II)

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

http://collaborations.fz-juelich.de/ikp/meson-baryon/main



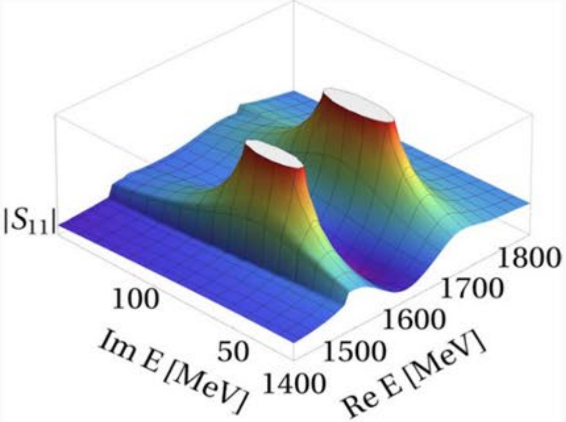
[D. Roenchen, M. D., U.-G. Meißner, EPJ A 54, 110 (2018)]

data: Paterson (CLAS) PRC 93, 065201 (2016), red line: fit JüBo2019

Resonance Couplings

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

[D. Roenchen, M. D., U.-G. Meißner, EPJ A 54, 110 (2018)



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

Inclusion of $\gamma p \to K^+\Lambda$ in JüBo ("JuBo2017-1"): 3 additional states

	z_0 [MeV]	$\frac{\Gamma_{\pi N}}{\Gamma_{tot}}$	$\frac{\Gamma_{\eta N}}{\Gamma_{tot}}$	$\frac{\Gamma_{K\Lambda}}{\Gamma_{tot}}$
$N(1900)3/2^+$	$1923 - i\,108.4$	1.5 %	0.78 %	2.99 %
$N(2060)5/2^-$	$1924 - i\,100.4$	0.35 %	0.15 %	13.47 %
$\Delta(2190)1/2^+$	$2191 - i\,103.0$	33.12 %		

- $N(1900)3/2^+$: s-channel resonances, seen in many other analyses of kaon photoproduction (BnGa), 3 stars in PDG
- $N(2060)5/2^-$: dynamically generated, 2 stars in PDG, seen e.g. by BnGa
- $\Delta(2190\ 1/2^+$: dyn. gen., no equivalent PDG state