COUPLED-CHANNEL ANALYSIS OF PION/ETA/KAON ELECTRO-PRODUCTION AND BARYON RESONANCES

Maxim Mai

JBW (Jülich-Bonn-Washington collaboration)

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CRC 110

International workshop on J-PARC hadron physics 2023

12-15 September 2023

HADRON SPECTROSCOPY

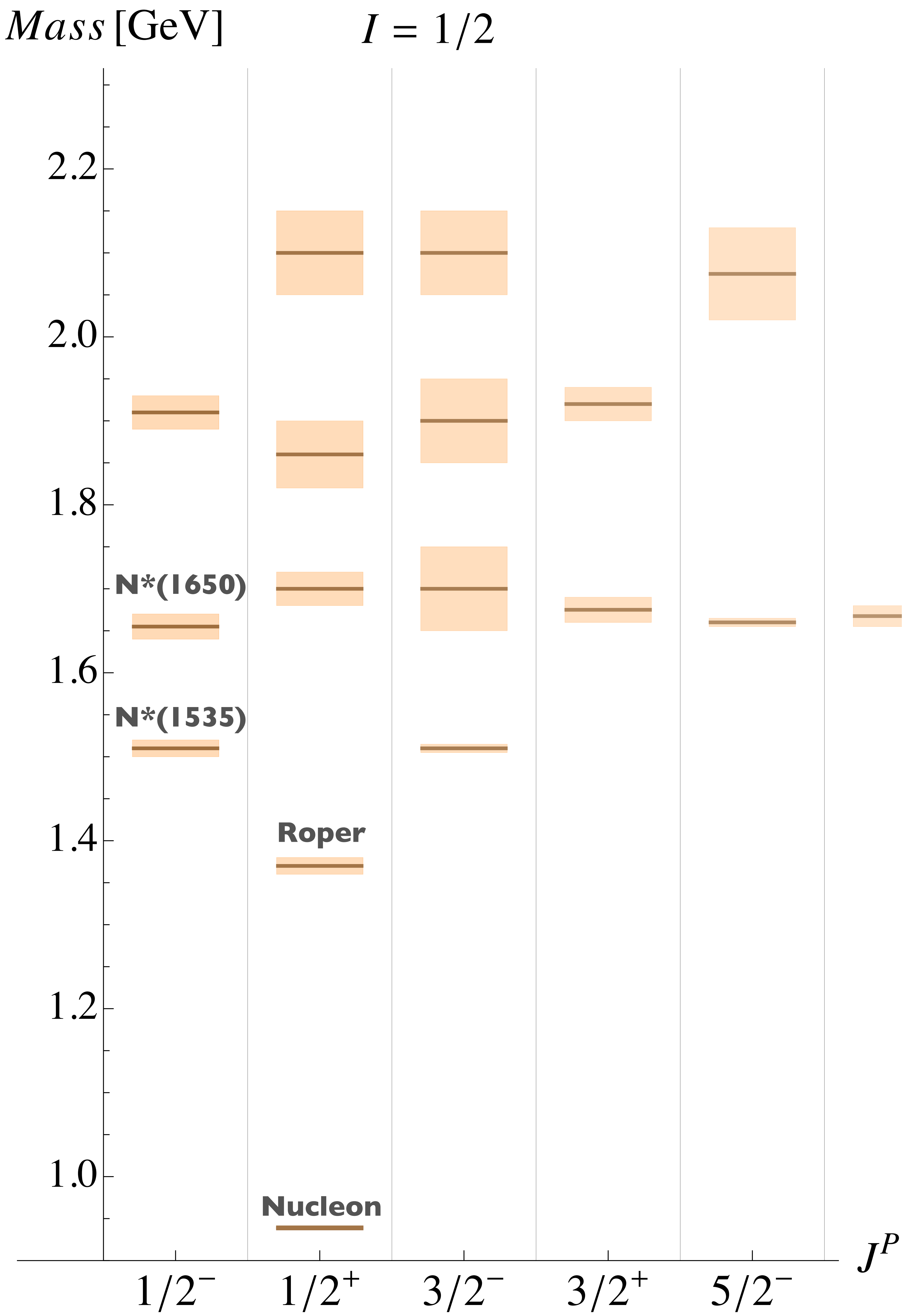
Mostly excited states[1]

≈100 mesons & ≈50 baryons (****)

Key questions

“what is the pattern of these states?“

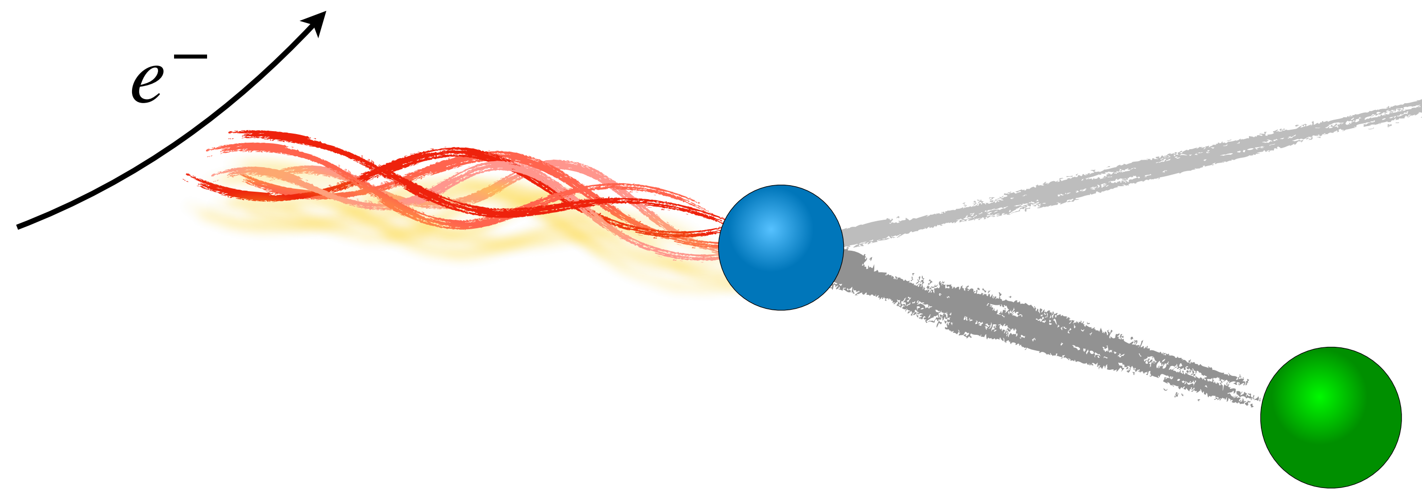
“how they are formed?”



[1] Workman et al. (Particle Data Group) (2022)

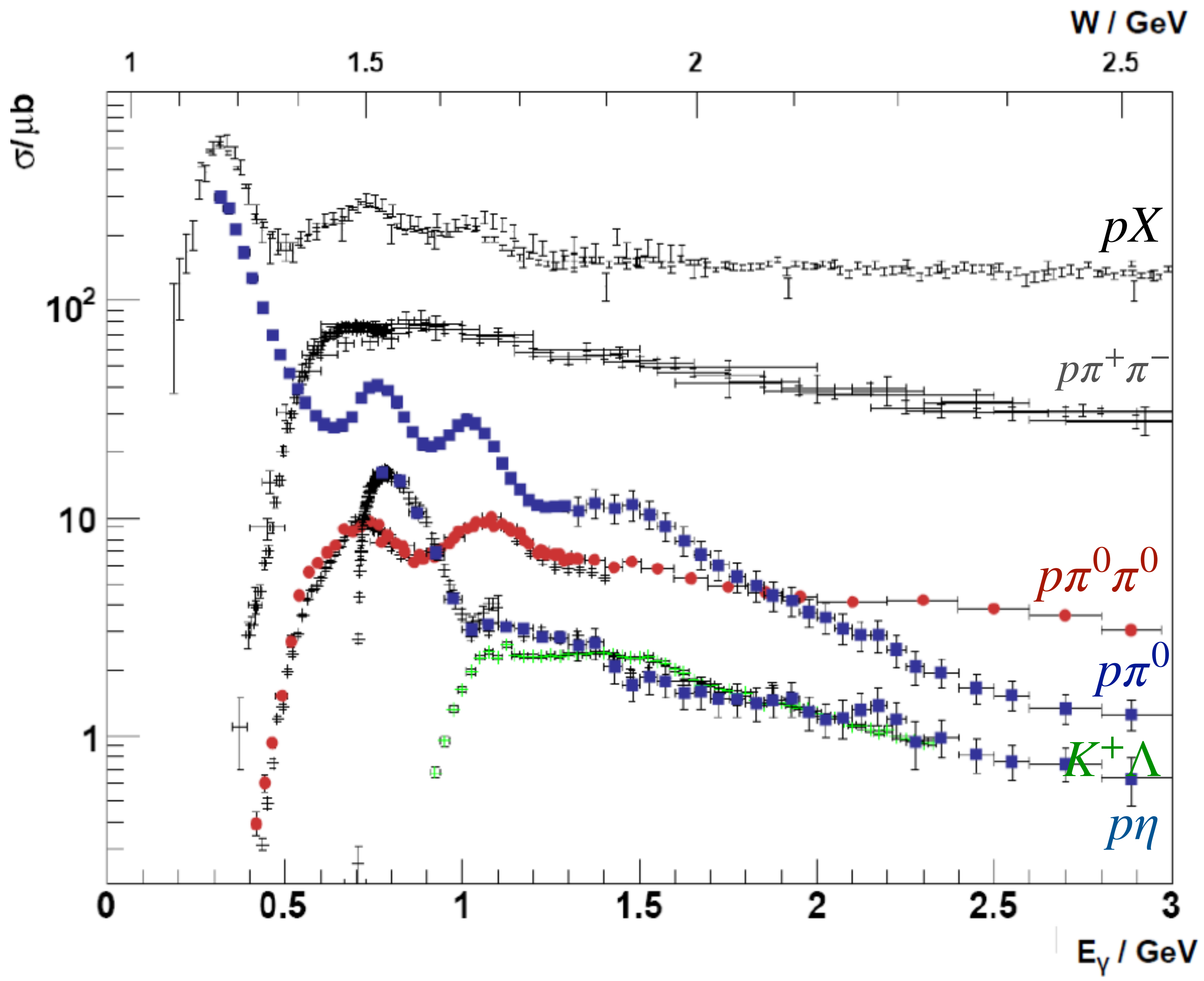
PHOTON-INDUCED EXCITATION

New probe



- 5 independent variables
- Momentum transfer dependence
- State compositeness?[1]

Experimental accessibility

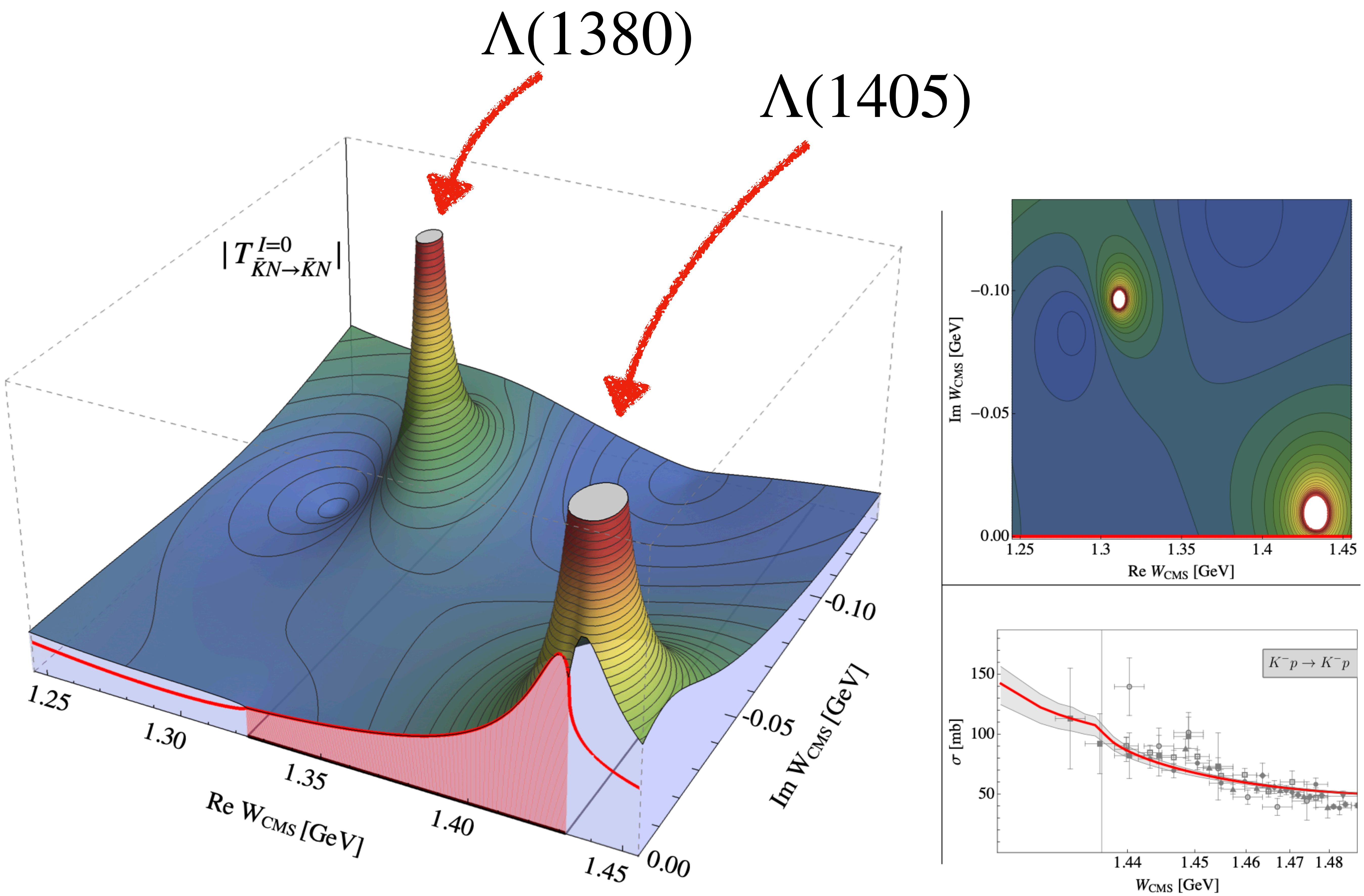


- Large amount of data (*10^5*)
- more data coming up[2] (*Q^2=5-12 GeV^2*)

… *but* ***"Not every bump is a resonance, not every resonance is a bump"*** - *R. G. Moorhouse (1960s)*

[1] e.g., Review: Burkert, Roberts, Rev.Mod.Phys. 91 (2019)
[2] Carman, Joo, Mokeev, Few Body Syst. 61, 29 (2020) ... ; [CLAS] Phys.Rev.C 105 (2022) 065201; ...

UNIVERSAL PARAMETERS



Reaction-independent parameters

pole positions on unphysical Riemann Sheets

KEY QUANTITY — Transition amplitudes

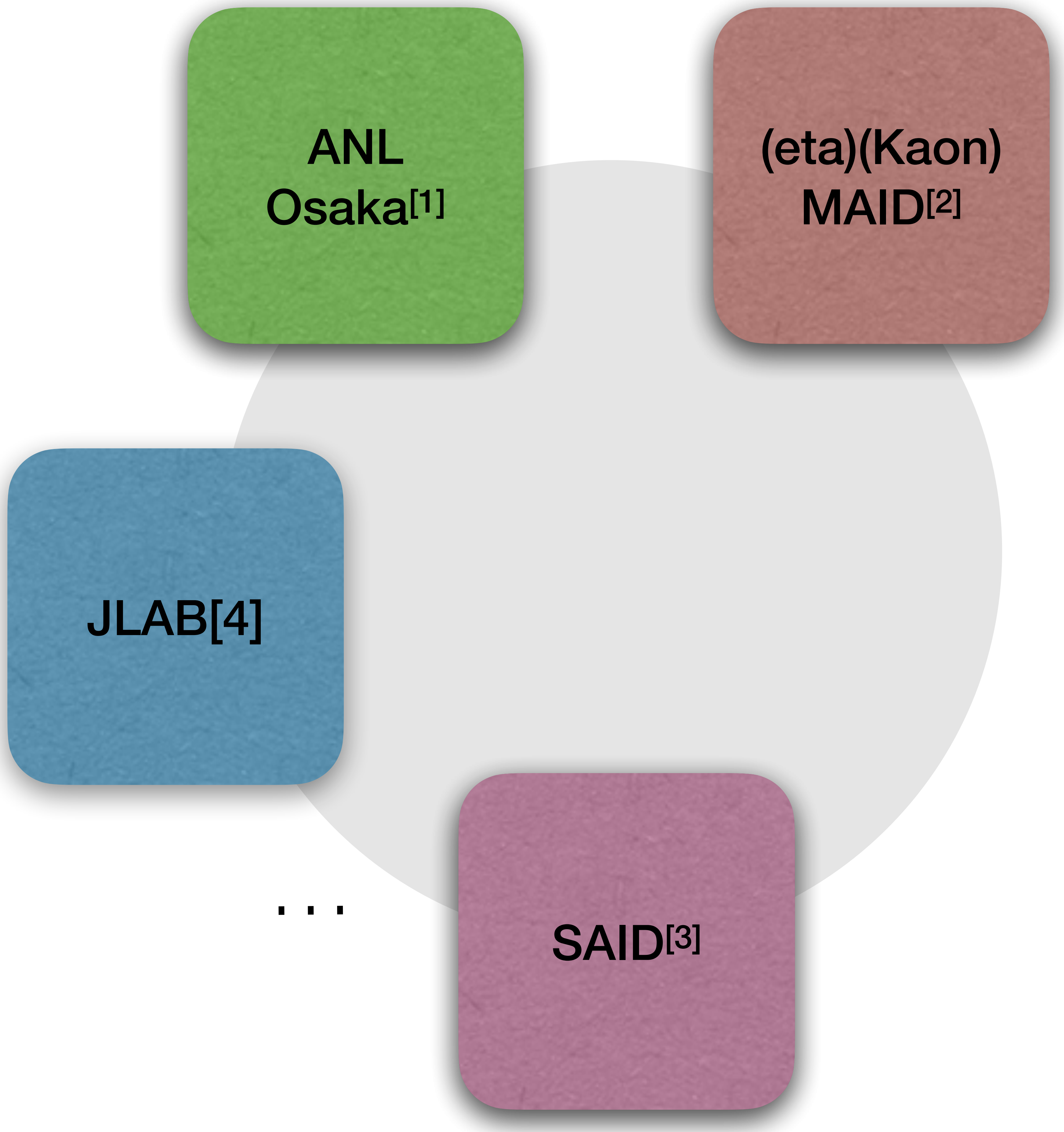
Constrained by Unitarity/Analyticity/Crossing

Constrained by CHPT/LatticeQCD

Constrained by Observations

Review: ``Towards a theory of hadron resonances'' Phys. Rept. 1001 (2023) — MM/Meißner/Urbach
Review: ``Review of the Λ(1405) A curious case of a strangeness resonance'' EPJST (2021) — MM

TRANSITION AMPLITUDES



Some highlights

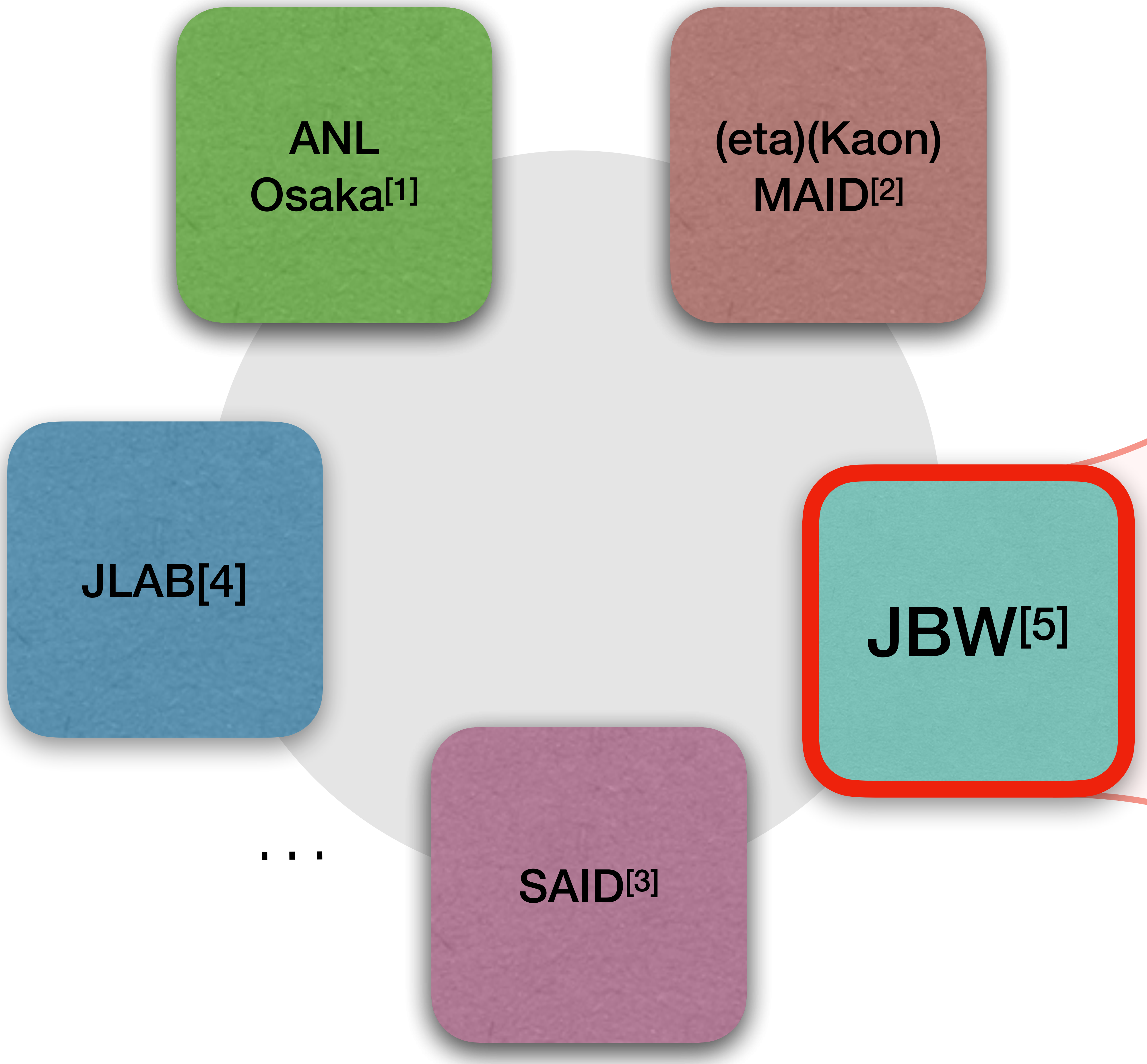
→ simultaneous description of pion photo-/electro-production (MAID)

→ low-energy constraints from CHPT (chiral MAID)

→ . . .

[1] ANL-Osaka PRC 80(2009), Few-Body Syst. 59(2018),... [2] MAID2007, EPJA 34(2007) EtaMAID2018, EPJA 54(2018) [3] SAID, PiN Newsletter 16(2002) [4] Aznauryan et al., PRC 80(2009), IJMP(2013),... Gent group PRC 89(2014),...

TRANSITION AMPLITUDES



Jülich-Bonn-Washington

- coupled-channel approach (πN, ηN, $K\boldsymbol{\Lambda}$, $K\boldsymbol{\Sigma}$, ...)
- constraints from scattering data and theory:
  - → gauge invariance
  - → (pseudo)threshold behaviour
  - → Siegert's theorem
  - → Final-state unitarity
- **web-interface: https://jbw.phys.gwu.edu/**

[1] ANL-Osaka PRC 80(2009), Few-Body Syst. 59(2018),... [2] MAID2007, EPJA 34(2007) EtaMAID2018, EPJA 54(2018) [3] SAID, PiN Newsletter 16(2002) [4] Gent group PRC 89(2014),... Aznauryan et al., PRC 80(2009), IJMP(2013),…[5] [JBW] MM et al. Phys.Rev.C 103 (2021) 6 / Phys.Rev.C 106 (2022) 015201

THEORY

Jülich-Bonn-Washington model for pion electroproduction multipoles

Jülich-Bonn-Washington Collaboration • Maxim Mai (George Washington U.) et al.

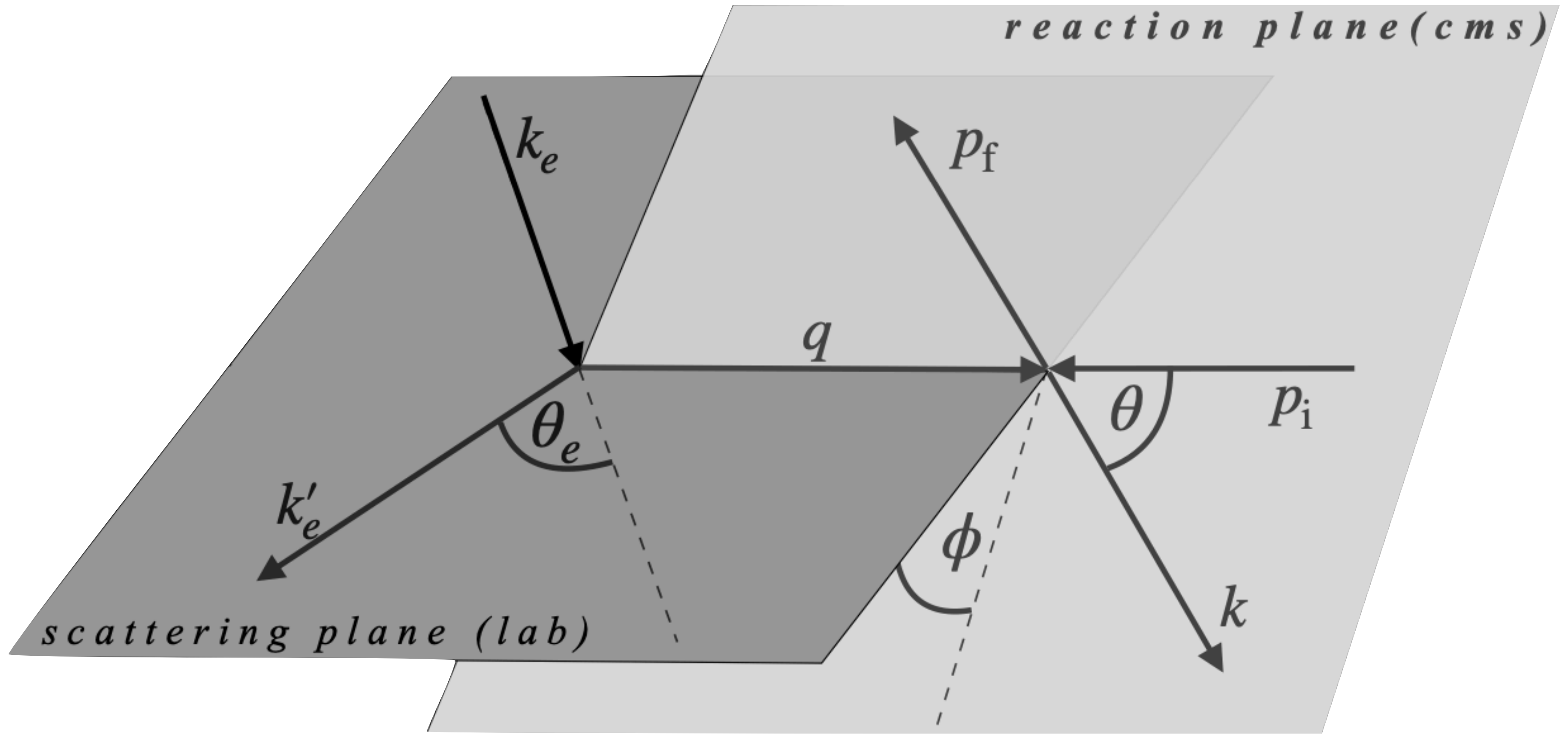
e-Print: 2104.07312 [nucl-th]

Published in: Phys.Rev.C 103 (2021) 6, 065204

SYMMETRIES OF NATURE

Five kinematical variables (3*(2+3)-10=5)

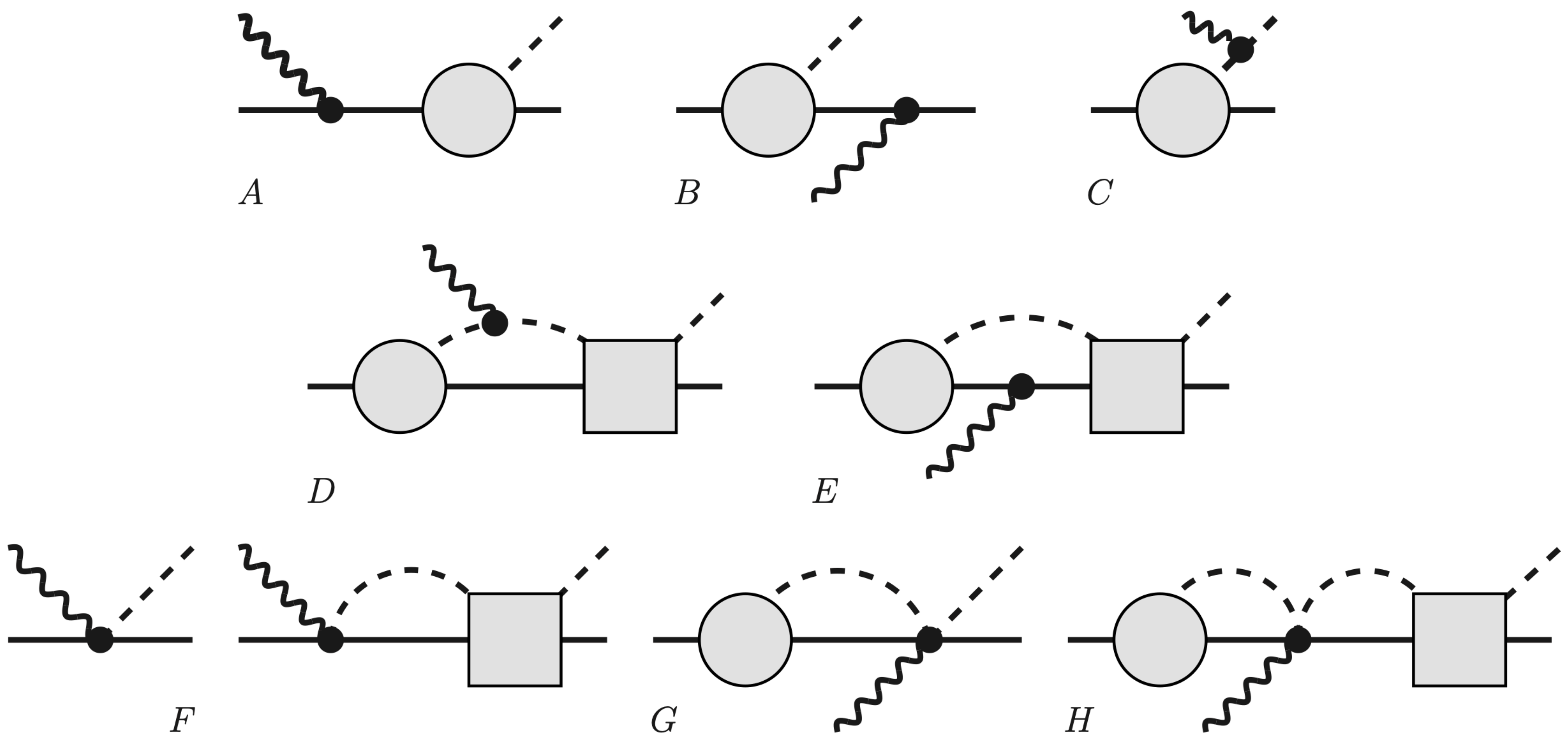
1. total energy: W
2. photon virtuality: Q^2
3. transverse photon polarization: ϵ
4. production angles: θ,φ



Observables		Helicity amplitudes[1]		Multipoles
$\mathcal{O}(W, Q^2, \theta, \varphi, \epsilon)$	⇔	$H(W, Q^2, \theta)$	⇔	$E_{l\pm}(W, Q^2)$, $L_{l\pm}(W, Q^2)$, $M_{l\pm}(W, Q^2)$

[1] P. Dennery, Phys. Rev. 124, 2000 (1961) F. A. Berends, A. Donnachie, and D. L. Weaver, Nucl. Phys. B 4, 1 (1967)

THEORETICAL CONSTRAINTS (I)



MM et al. *Phys.Rev.D* 86 (2012) 094033

I) Gauge invariance

- manifest implementation[1] exist even for 2-meson photo-production[2]

… but usually too costly

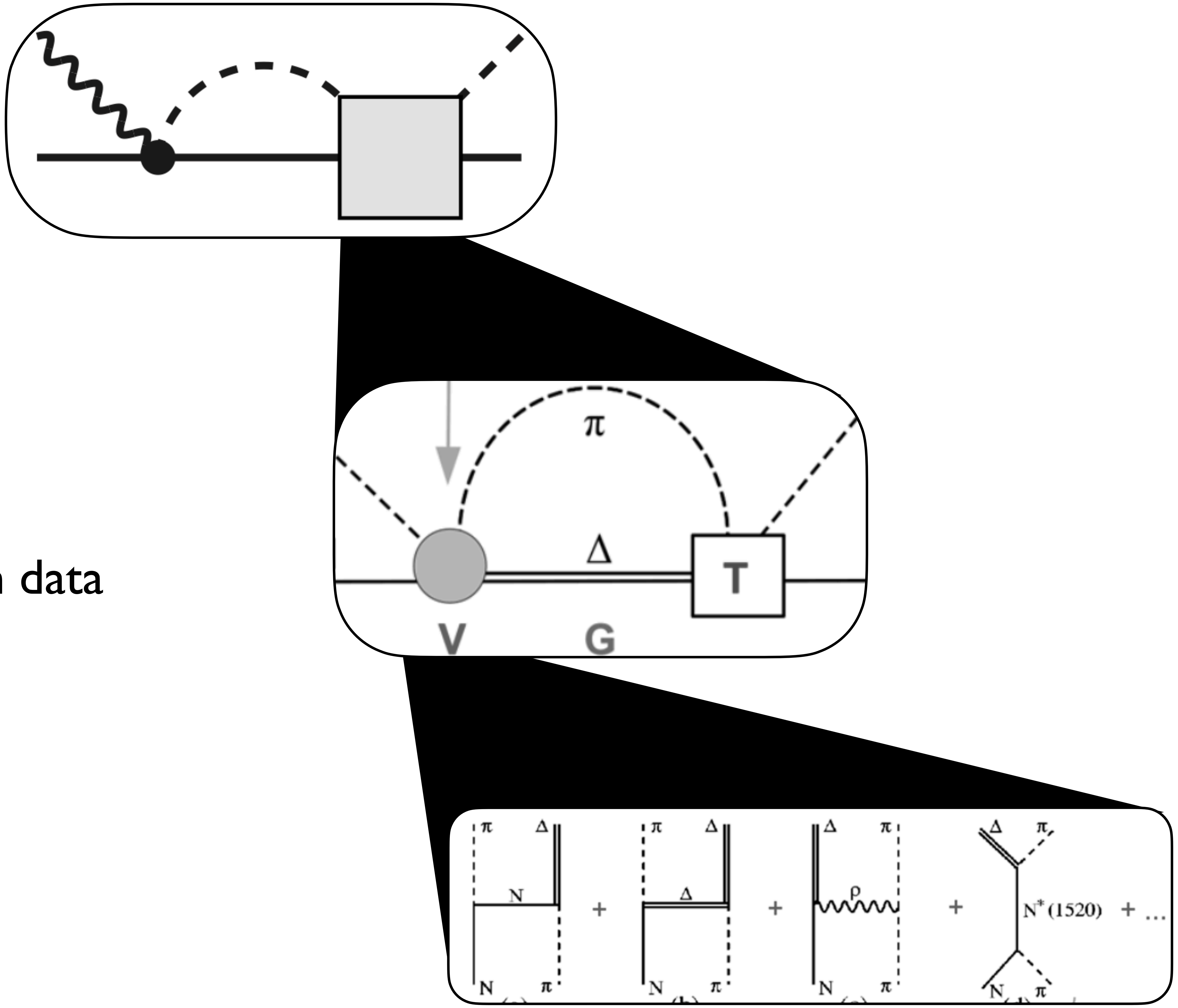
- Here: Ward-Takahashi identity by construction

$$k_\mu T^\mu = 0$$

$$H_7 = \sum_{i=1}^{6} a_i H_i \qquad H_8 = \sum_{i=1}^{6} b_i H_i$$

[1] Afnan et al.(1995); Kvinikhidze et al.(1999); Haberzettl(19xx-2021); Borasoy et al.(2007); Ruic et al.(2011); MM et al. (2012);
[2] Bruns, Cieplý, MM 2206.08767 [nucl-th]

THEORETICAL CONSTRAINTS (2)



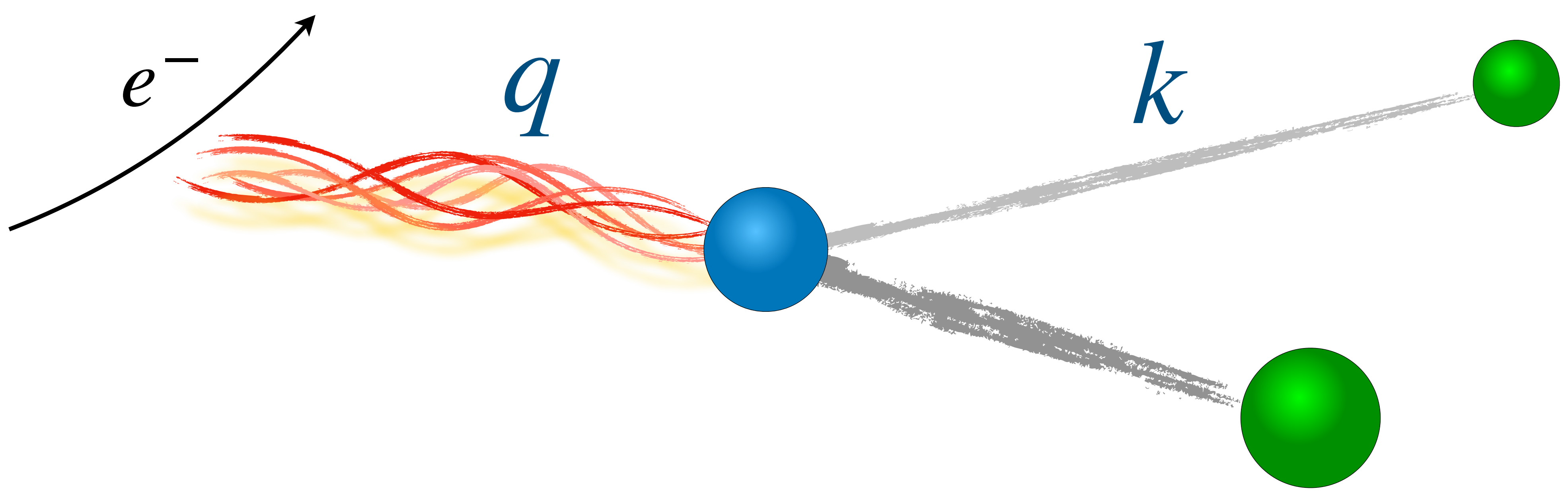
2) Final-state unitarity

- Jülich-Bonn dynamical coupled-channel model[1]
- Amplitudes fixed from scattering and photo-production data

  πN→xX and γN→xX (~60k data)

[1] D. Rönchen, M. Döring, F. Huang, H. Haberzettl, J. Haidenbauer, C. Hanhart, S. Krewald, U.-G. Meißner, and K. Nakayama, Eur. Phys. J. A 50, 101 (2014), [Erratum: Eur.Phys.J.A 51, 63 (2015)], arXiv:1401.0634 [nucl-th].

THEORETICAL CONSTRAINTS (3)



3) Pseudo/threshold constraints:

- Momentum dependence
- Siegert's theorem[1]

➥ in the long-wavelength limit electric and magnetic multipoles are related

➥ good news: fewer parameters needed

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

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

$$\dots$$

$L_{\ell\pm} \sim E_{\ell\pm}$ **for** $q = 0$

[1] A. J. F. Siegert, Phys. Rev. 52, 787 (1937) L. Tiator, Few Body Syst. 57, 1087 (2016).

$$\mathcal{M}_{\mu\gamma^*}(k,W,Q^2) = R_{\ell'}(\lambda, q/q_\gamma)\left(V_{\mu\gamma^*}(k,W,Q^2) + \sum_\kappa \int_0^\infty dp\, p^2\, T^{\text{JUBO}}_{\mu\kappa}(k,p,W) G_\kappa(p,W) V_{\kappa\gamma^*}(p,W,Q^2)\right)$$

$E/L/M$

$$\boxed{V^{\text{JUBO}}_{\mu\gamma}(k,W) \times e^{-\beta^0_\mu Q^2/m_p^2}\left(1 + Q^2/m_p^2\beta^1_\mu + (Q^2/m_p^2)^2\beta^2_\mu\right)}$$

Fulfils/Describes:

- Final state unitarity / Gauge invariance / Siegert's theorem / Threshold behaviour
- scattering and photo-production data
- parameters (λ, β) from electro-production data

Parametrization dependence due to incomplete data

- even for a truncated complete electroproduction experiment[1]
- in future: Bias-variance tradeoff with statistical criteria[2]

[1] L. Tiator, R. L. Workman, Y. Wunderlich, and H. Haberzettl, Phys. Rev. C 96, 025210 (2017), arXiv:1702.08375 [nucl-th].
[2] J. Landay, MM, M. Doring, H. Haberzettl, and K. Nakayama, Phys. Rev. D 99, 016001 (2019) arXiv:1810.00075 [nucl-th].

RESULTS

Jülich-Bonn-Washington model for pion electroproduction multipoles

Jülich-Bonn-Washington Collaboration • Maxim Mai (George Washington U.) et al.

e-Print: 2104.07312 [nucl-th]

Published in: Phys.Rev.C 103 (2021) 6, 065204

Coupled-channels analysis of pion and η electroproduction within the Jülich-Bonn-Washington model

Jülich-Bonn-Washington Collaboration • Maxim Mai (George Washington U.) et al.

e-Print: 2111.04774 [nucl-th]

Published in: Phys.Rev.C 106 (2022) 1, 015201, Phys.Rev.C 106 (2022), 015201

Inclusion of KΛ electroproduction data in a coupled channel analysis

M. Mai (Bonn U. and Bonn U., HISKP and George Washington U.), J. Hergenrather (George Washington U.), M. Döring (George Washington U. and Jefferson Lab), T. Mart (Bandung Inst. Tech.), Ulf-G. Meißner (Bonn U. and Bonn U., HISKP and IAS, Julich and JCHP, Julich and Tbilisi State U.) et al.

e-Print: 2307.10051 [nucl-th]

DEGREES OF FREEDOM

Experimental data

1.13 < W/GeV< 1.8

Q^2 < 8 GeV^2

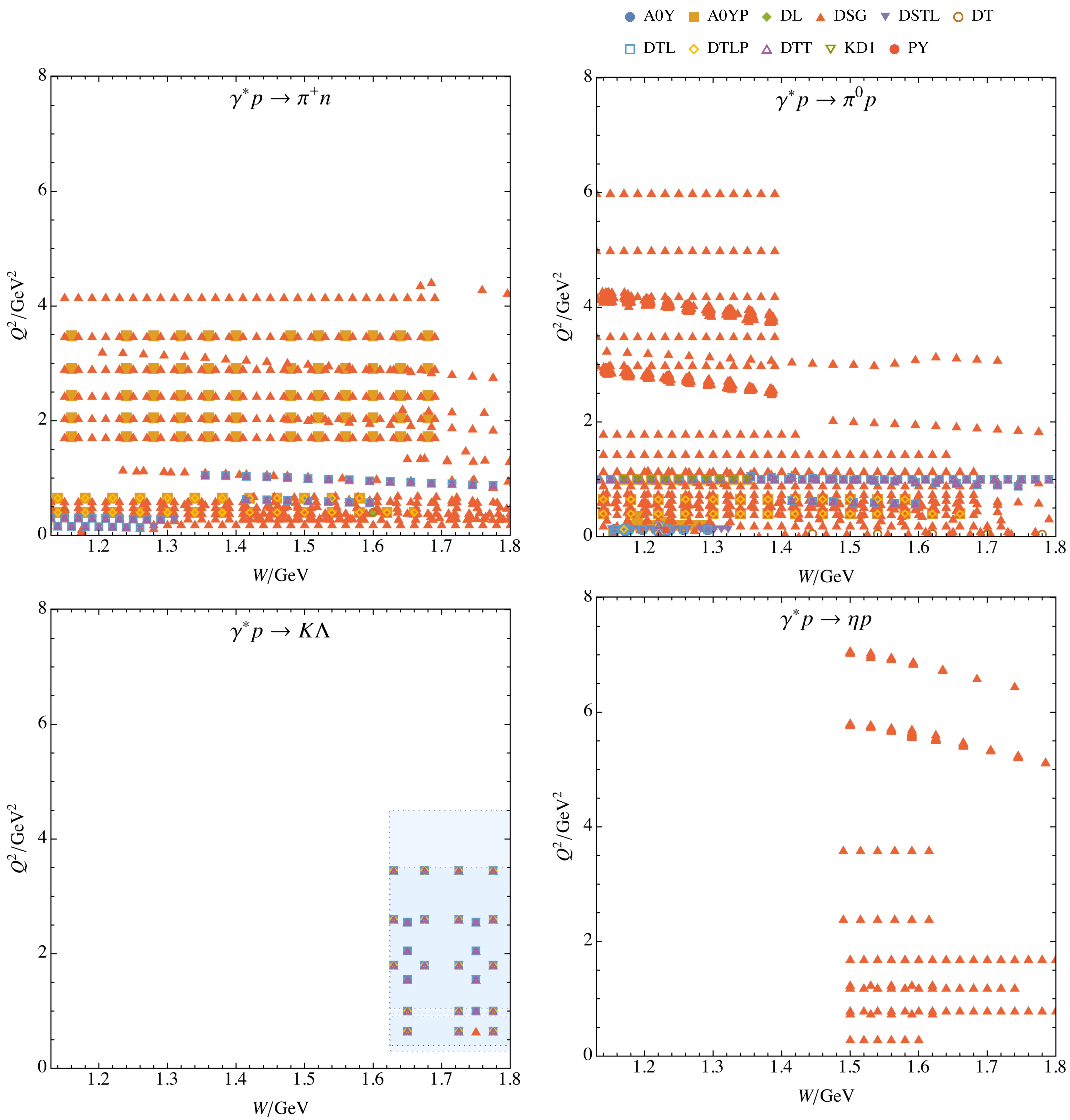
~110k data points

~ 90 observable types

Parametrization

S/P/D/F waves ~500 parameters

DOF~109k   (good ?)



DATA DESCRIPTION/FITS

πN[1]

Fit	$\chi^2_{\rm dof}$
$\mathfrak{F}_1$	1.77
$\mathfrak{F}_2$	1.69
$\mathfrak{F}_3$	1.81
$\mathfrak{F}_4$	1.78
$\mathfrak{F}_5$	1.81
$\mathfrak{F}_6$	1.78

$\pi N/\eta N$[2]

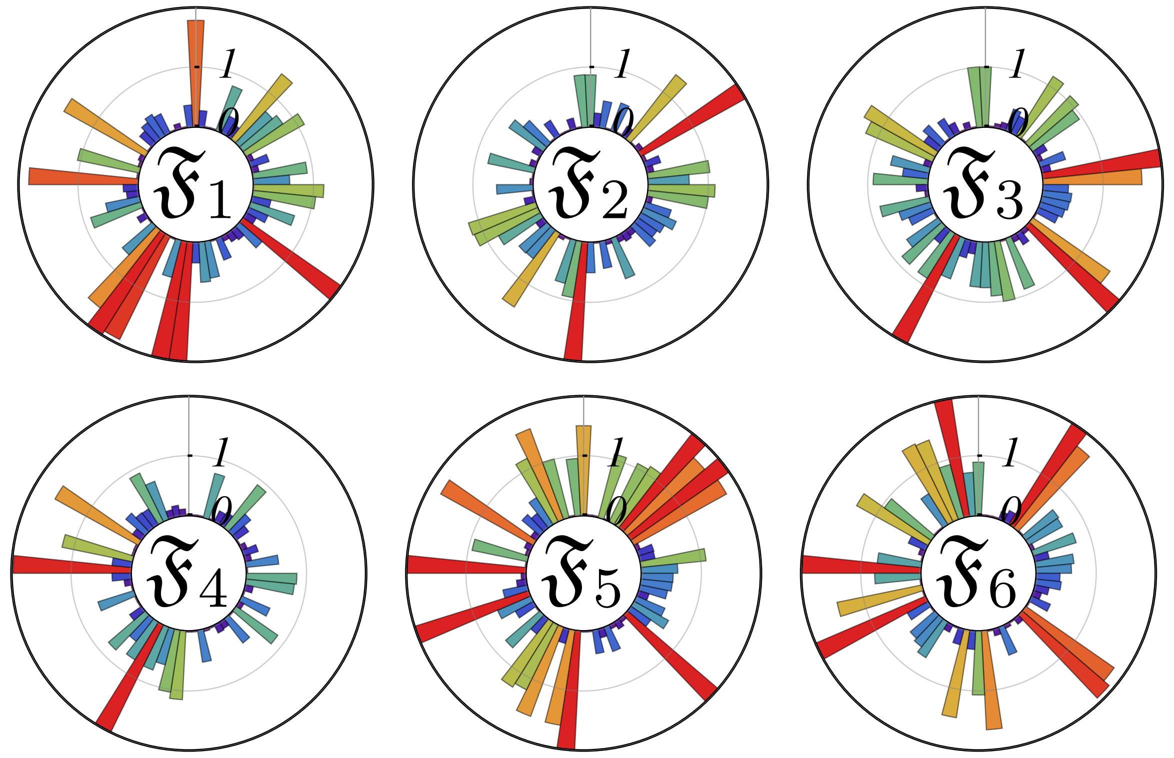
	χ^2/dof
$\mathfrak{F}_1^{\rm reg}$	1.66
$\mathfrak{F}_1^{\rm reg}$	1.73
$\mathfrak{F}_1^{\rm reg}$	1.69
$\mathfrak{F}_1^{\rm reg}$	1.69
$\mathfrak{F}_1^{\rm wt}$	1.54
$\mathfrak{F}_1^{\rm wt}$	1.63
$\mathfrak{F}_1^{\rm wt}$	1.58
$\mathfrak{F}_1^{\rm wt}$	1.58

πN, ηN, $K\Lambda$[3]

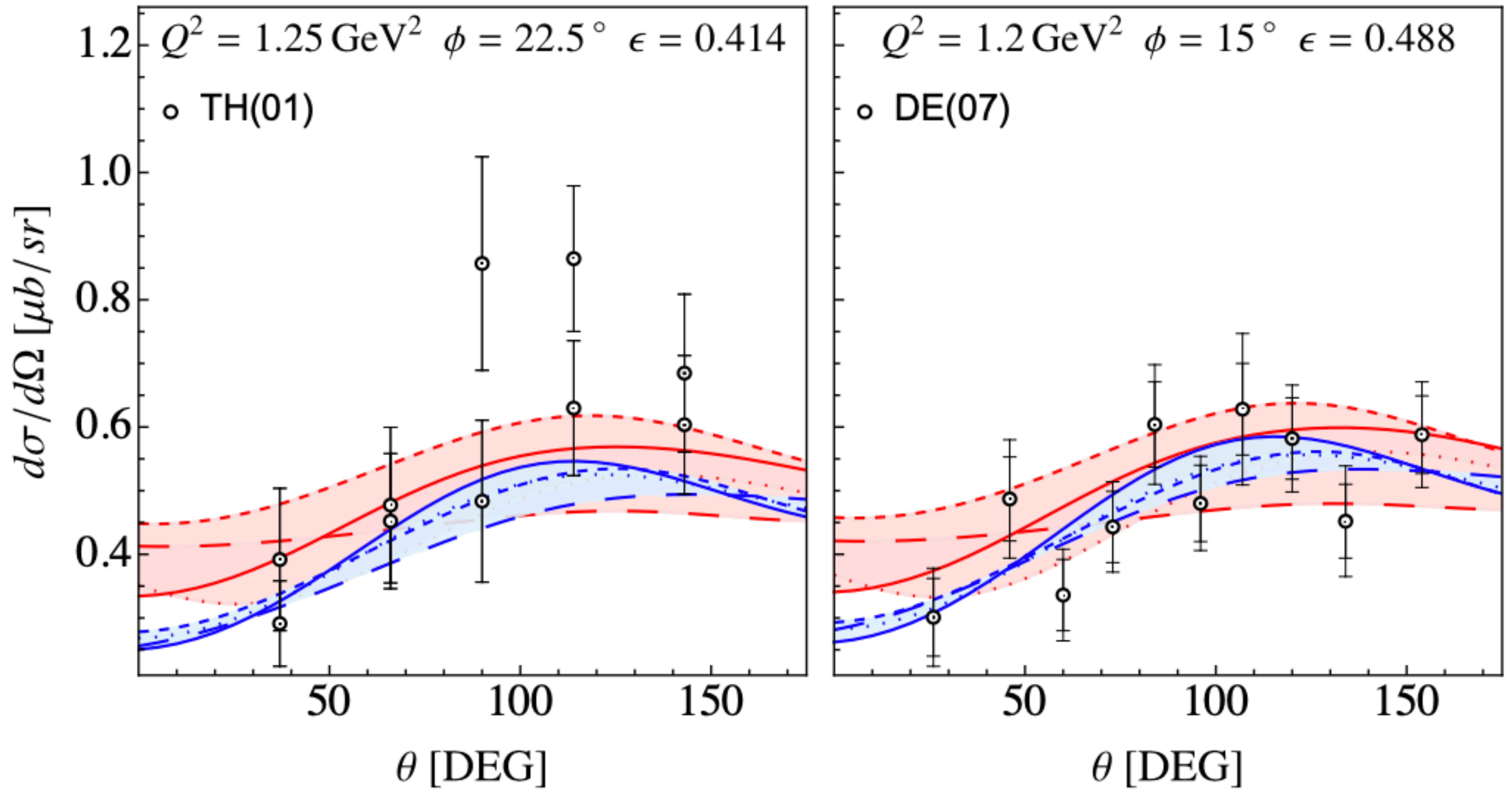
	$\chi^2_{\rm dof}$
FIT$_1$	1.42
FIT$_2$	1.35
	$\chi^2_{\rm wt,dof}$
FIT$_3$	1.12
FIT$_4$	1.06

Uncertainties:

- systematical: due to different fitting strategies studied

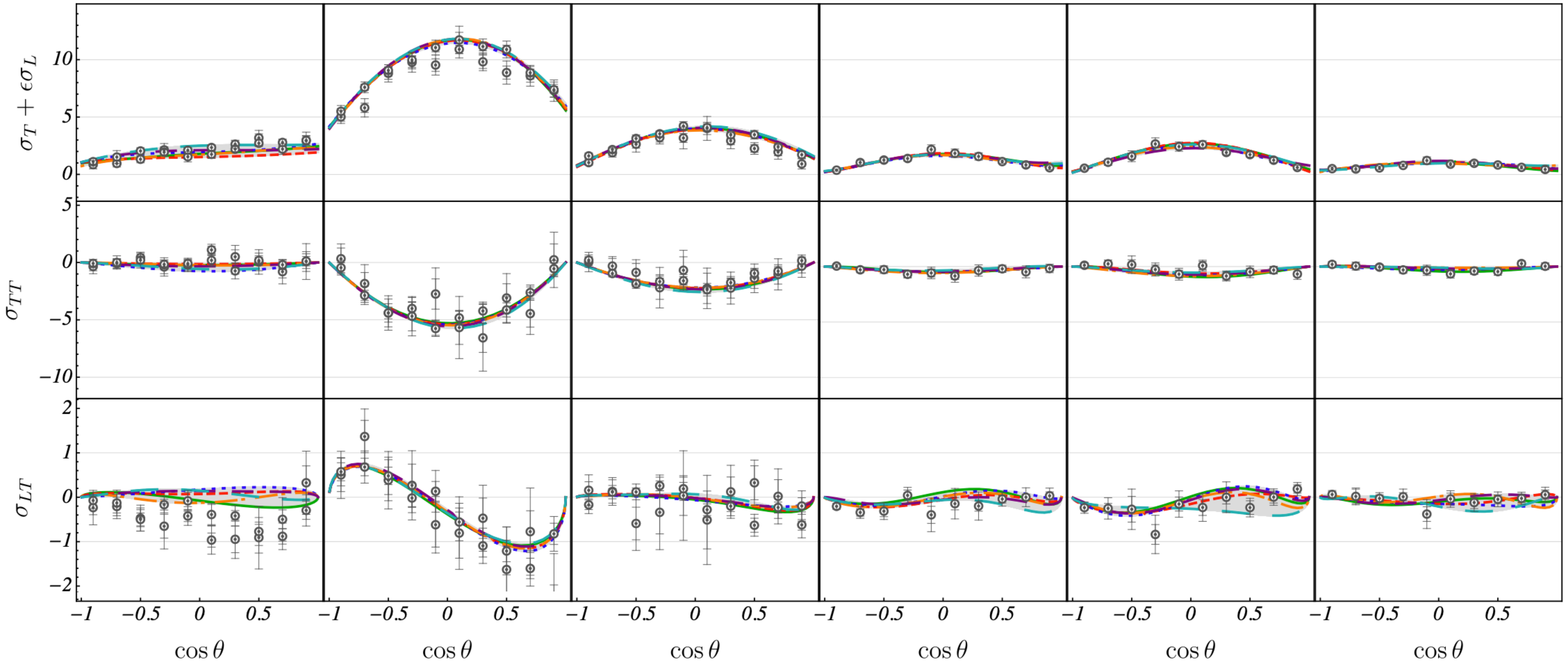


- statistical: not yet — need more data base cleaning, model selection…



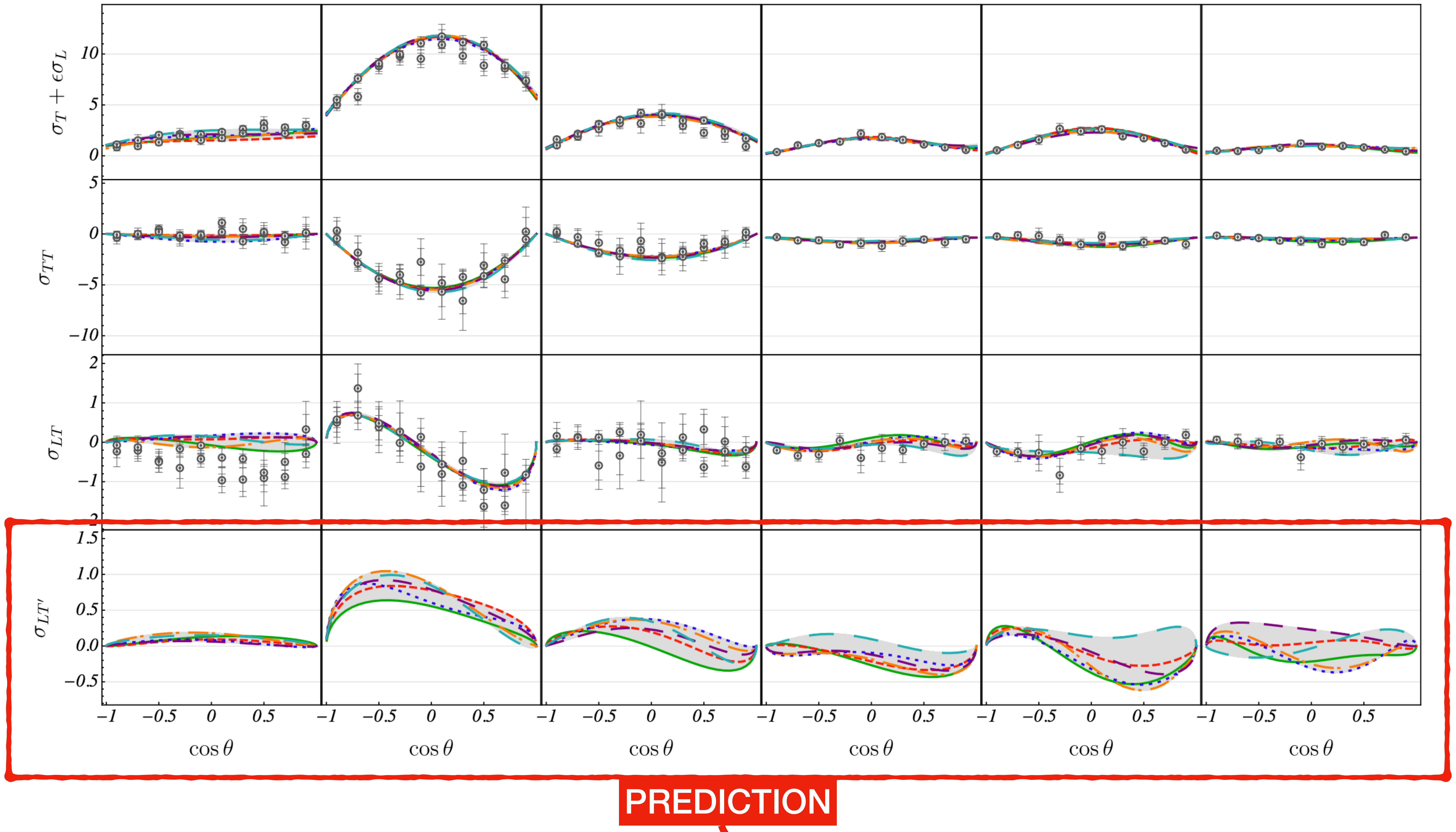
[1] Phys.Rev.C 103 (2021) 6
[2] Phys.Rev.C 106 (2022) 1
[3] 2307.10051 [nucl-th] submitted to EPJA

INTER… VS. EXTRAPOLATOR



[1] MODEL: [JBW] MM et al. *Phys.Rev.C* 103 (2021) 6; Phys.Rev.C 106 (2022) 015201
[2] DATA: Joo et al. [CLAS] PRC (2003), PRL (2002)

INTER… VS. EXTRAPOLATOR



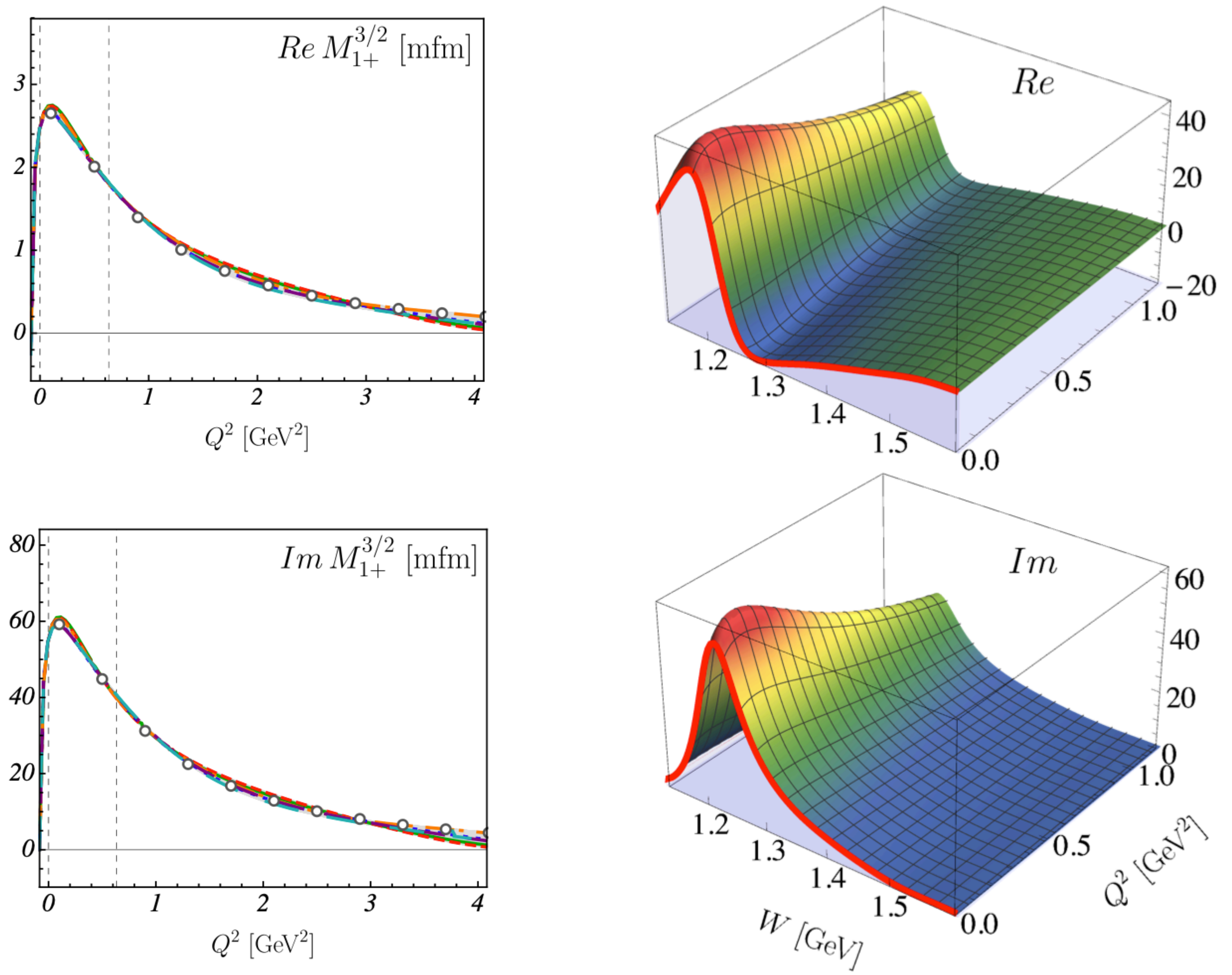
https://jbw.phys.gwu.edu/

[1] MODEL: [JBW] MM et al. *Phys.Rev.C* 103 (2021) 6; Phys.Rev.C 106 (2022) 015201
[2] DATA: Joo et al. [CLAS] PRC (2003), PRL (2002)

PREDICTIONS: VIRTUALITY

Δ(1232) well determined

resonance melts away with higher virtuality



[JBW] MM et al. *Phys.Rev.C* 103 (2021) 6; Phys.Rev.C 106 (2022) 015201

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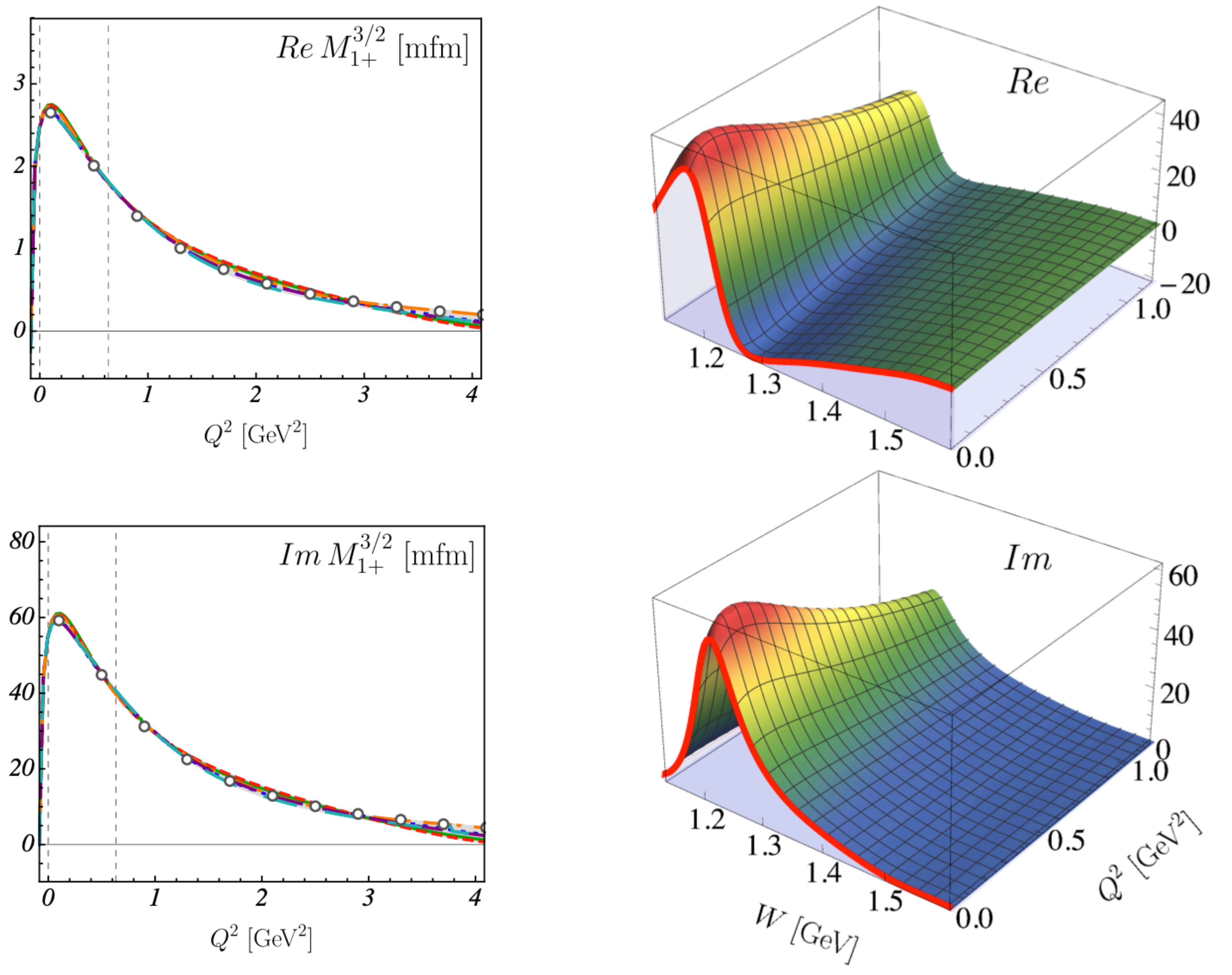
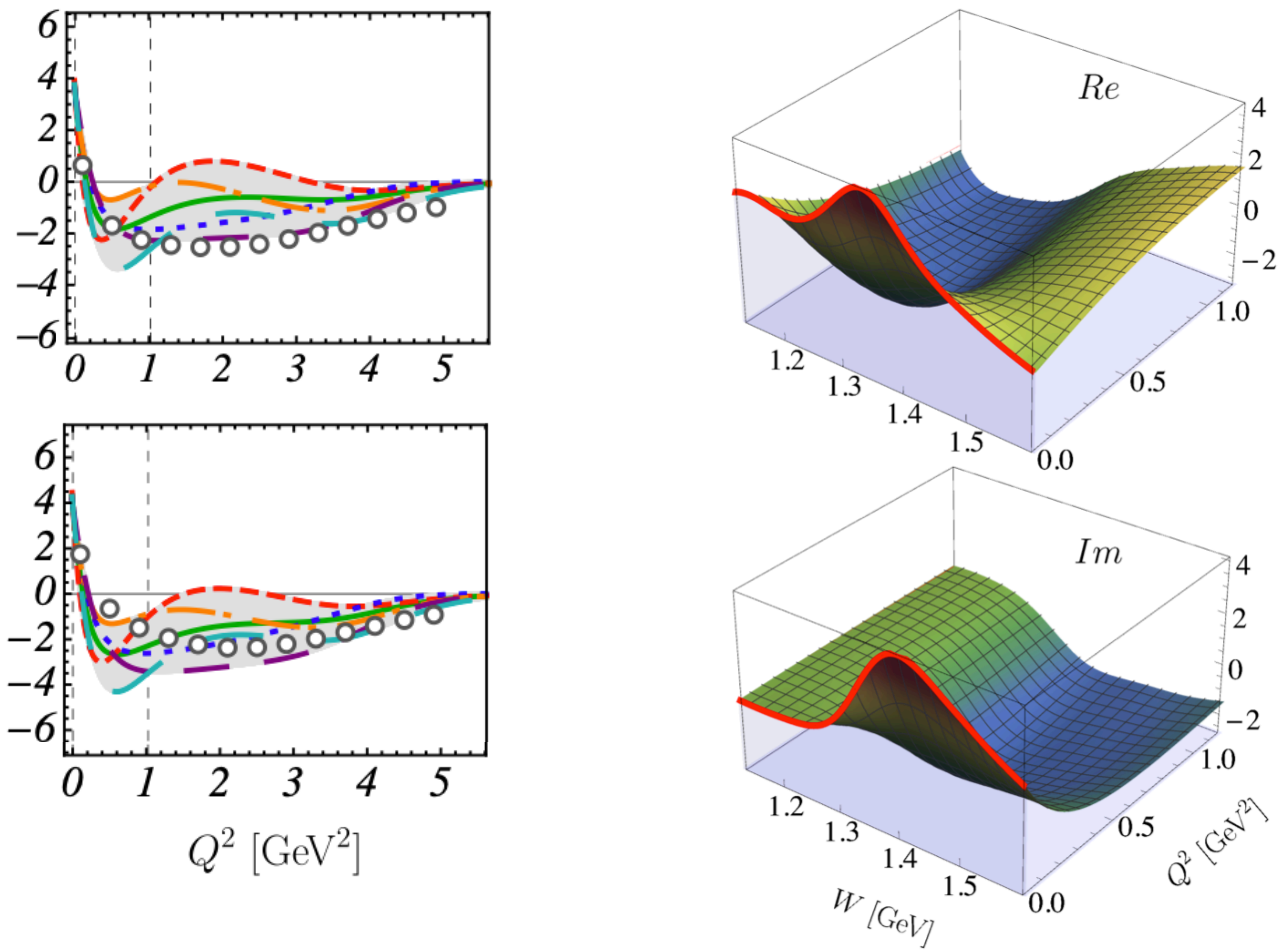


Roper less well determined

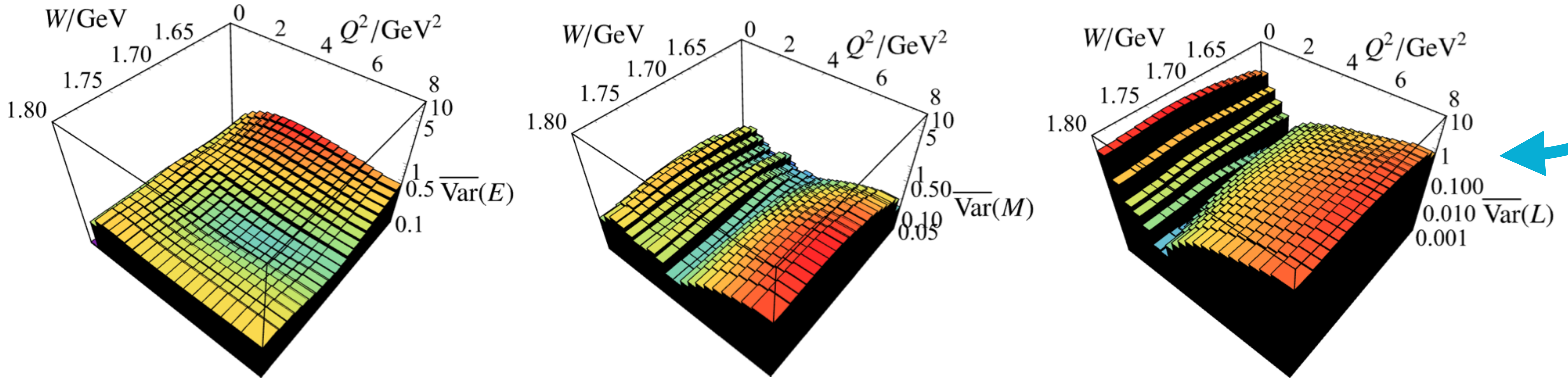
Complex functional behaviour W vs Q^2

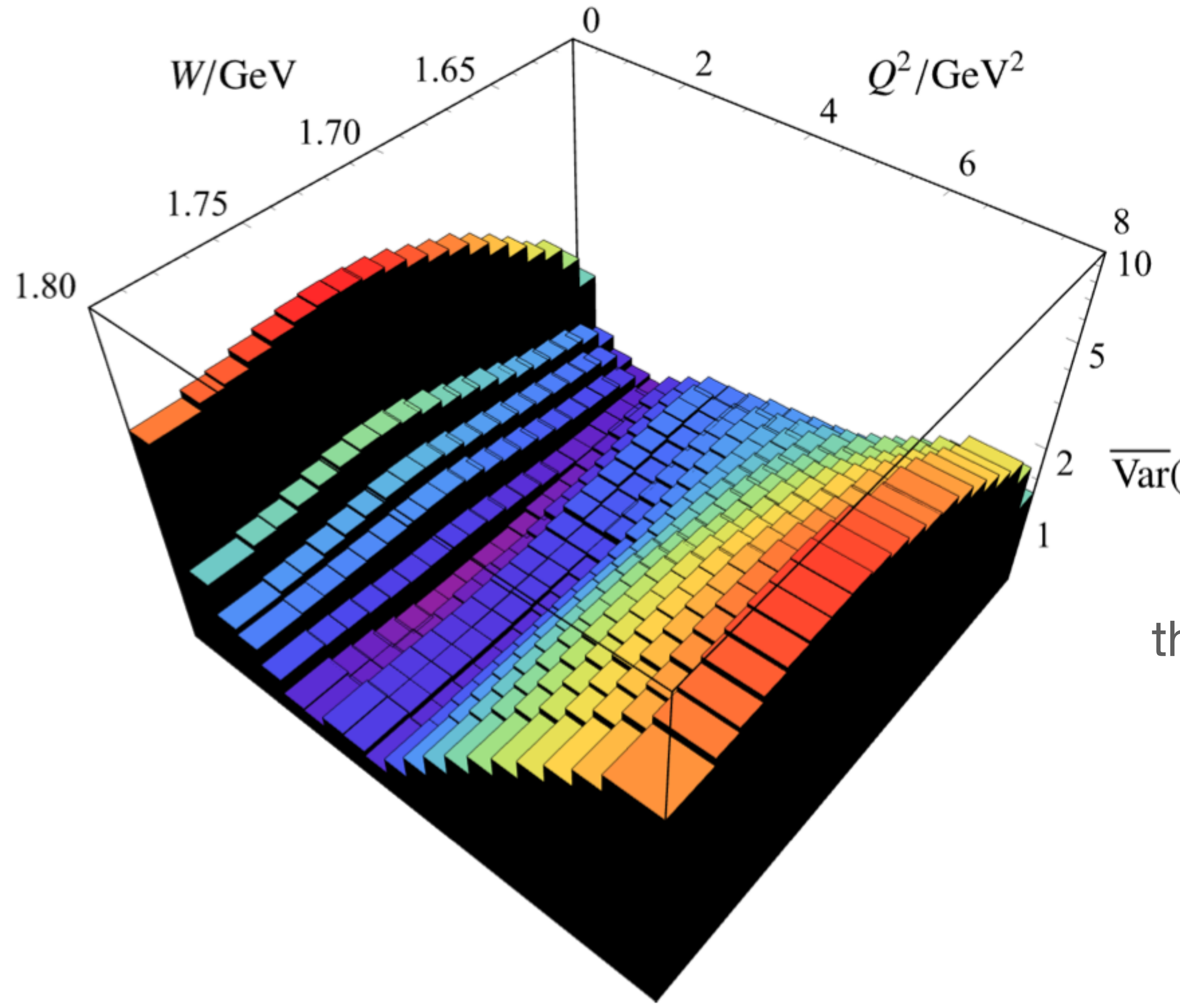


[JBW] MM et al. *Phys.Rev.C* 103 (2021) 6; Phys.Rev.C 106 (2022) 015201

VOLATILITY OF MULTIPOLES (KL)

biggest uncertainty





$$\overline{\mathrm{Var}}(E,M,L) := \sum_{\ell\pm} \frac{\mathrm{Var}\{|\mathrm{X}_{\ell\pm,\mathrm{i}}|\}}{\mathrm{Mean}\{|\mathrm{X}_{\ell\pm,\mathrm{i}}|\}+\varepsilon},$$

the bigger the value the less we know the multipole

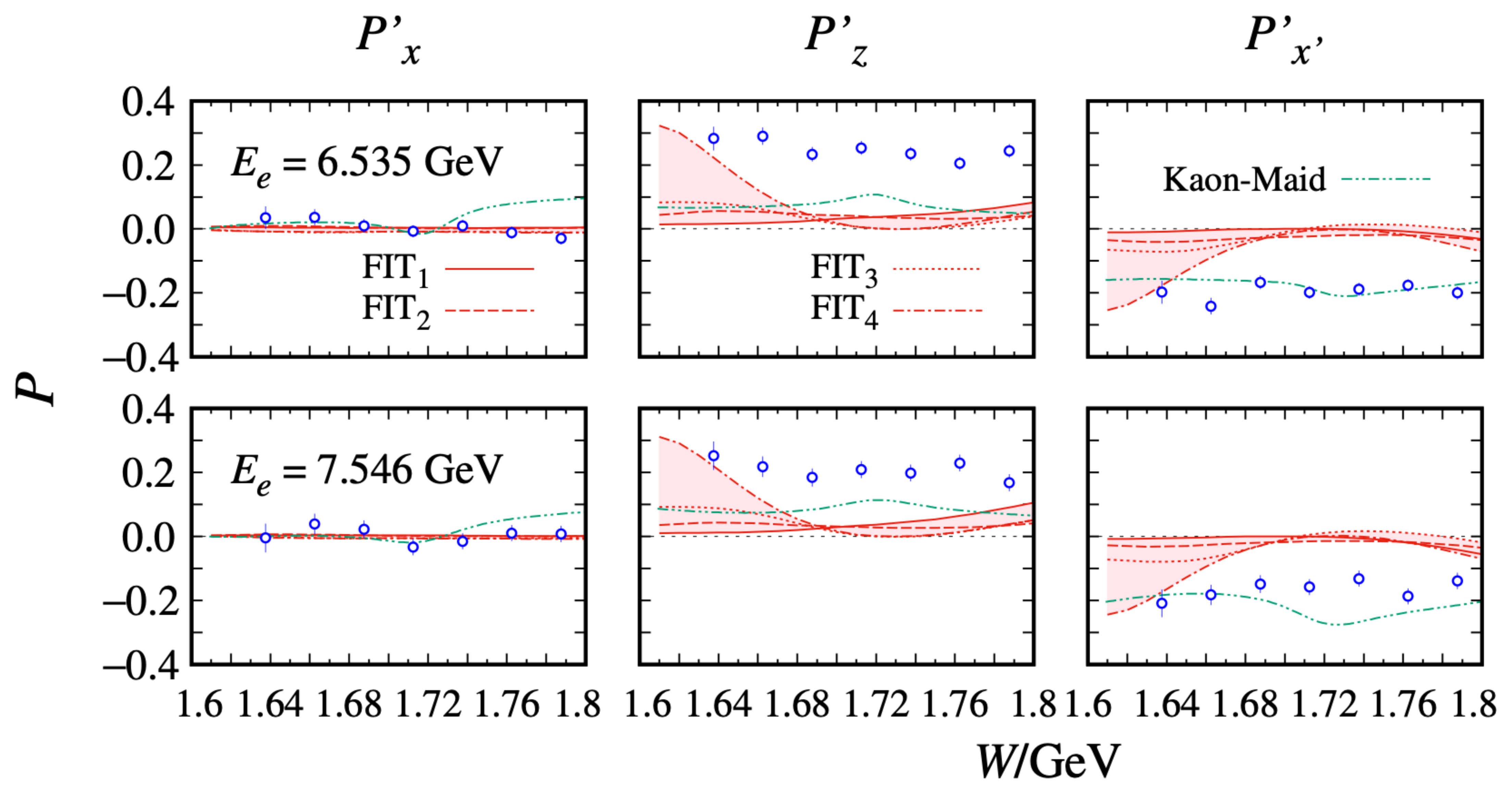
NEW L-SENSITIVE DATA

Beam-recoil transferred polarisation[1]

- so far only for integrated kinematics[2]
- compare to our prediction (no fit)

➥ large drop-off in Q^2 due to L-multipoles

➥ fits to new data[2] will be instrumental



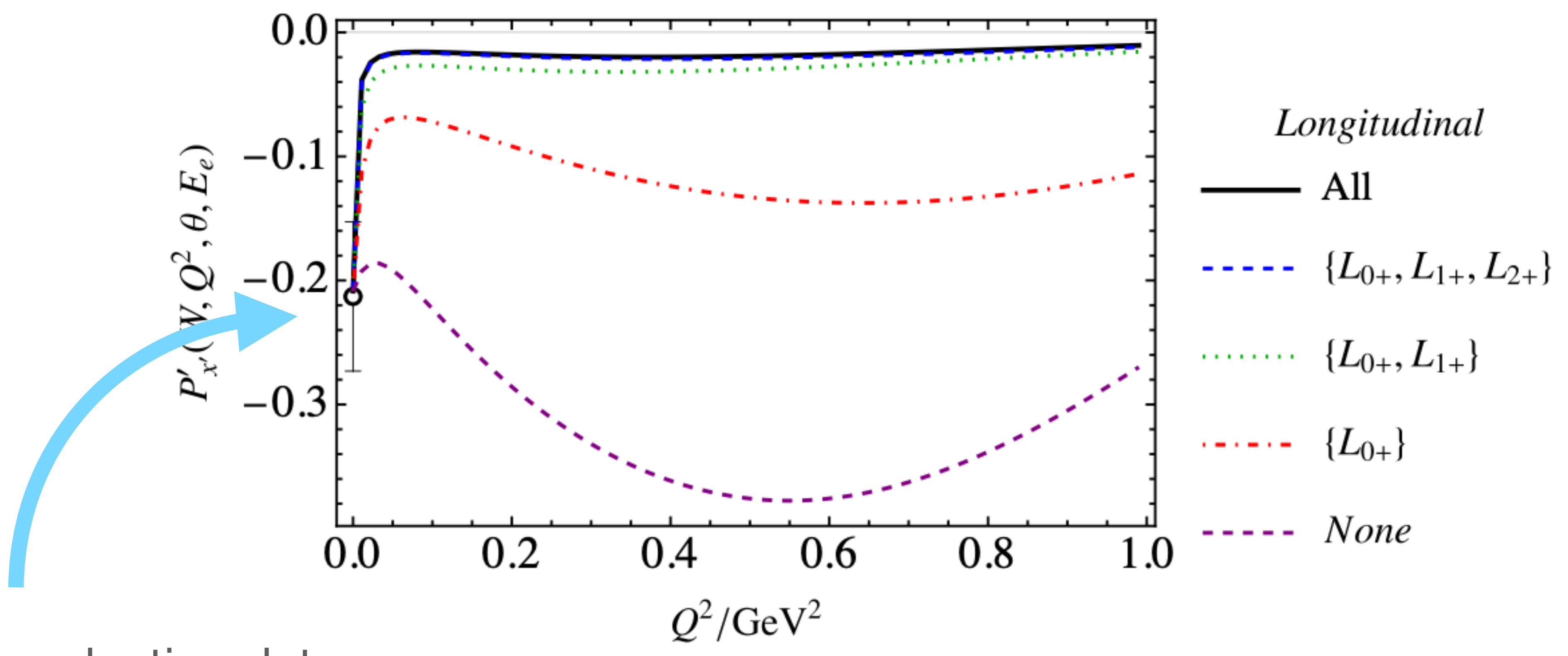


Photo-production datum
form the fitted data base

[1] Carman et al. Phys. Rev. C 105, 065201 (2022), arXiv:2202.03398 [nucl-ex]
[2] running analysis at JLAB — unintegrated data

SUMMARY

Jülich-Bonn-Washington bucket list

- ☑ new model developed (constraints from symmetries and scattering/photoproduction data)
- ☑ fits to $\pi N/\eta N/K\Lambda$ data finished
- ☑ WEB INTERFACE: https://jbw.phys.gwu.edu

- ☐ Helicity couplings [soon]
- ☐ statistical/parameter importance (LASSO, Machine Learning, …) [soon]
- ☐ energy-dependent analysis [soon-ish]
- ☐ simultaneous fit to scattering and photo-production data [not soon]

…

DEGREES OF FREEDOM

piN data is dominant:

> weighted or unweighted fits

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

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

HADRON SPECTROSCOPY

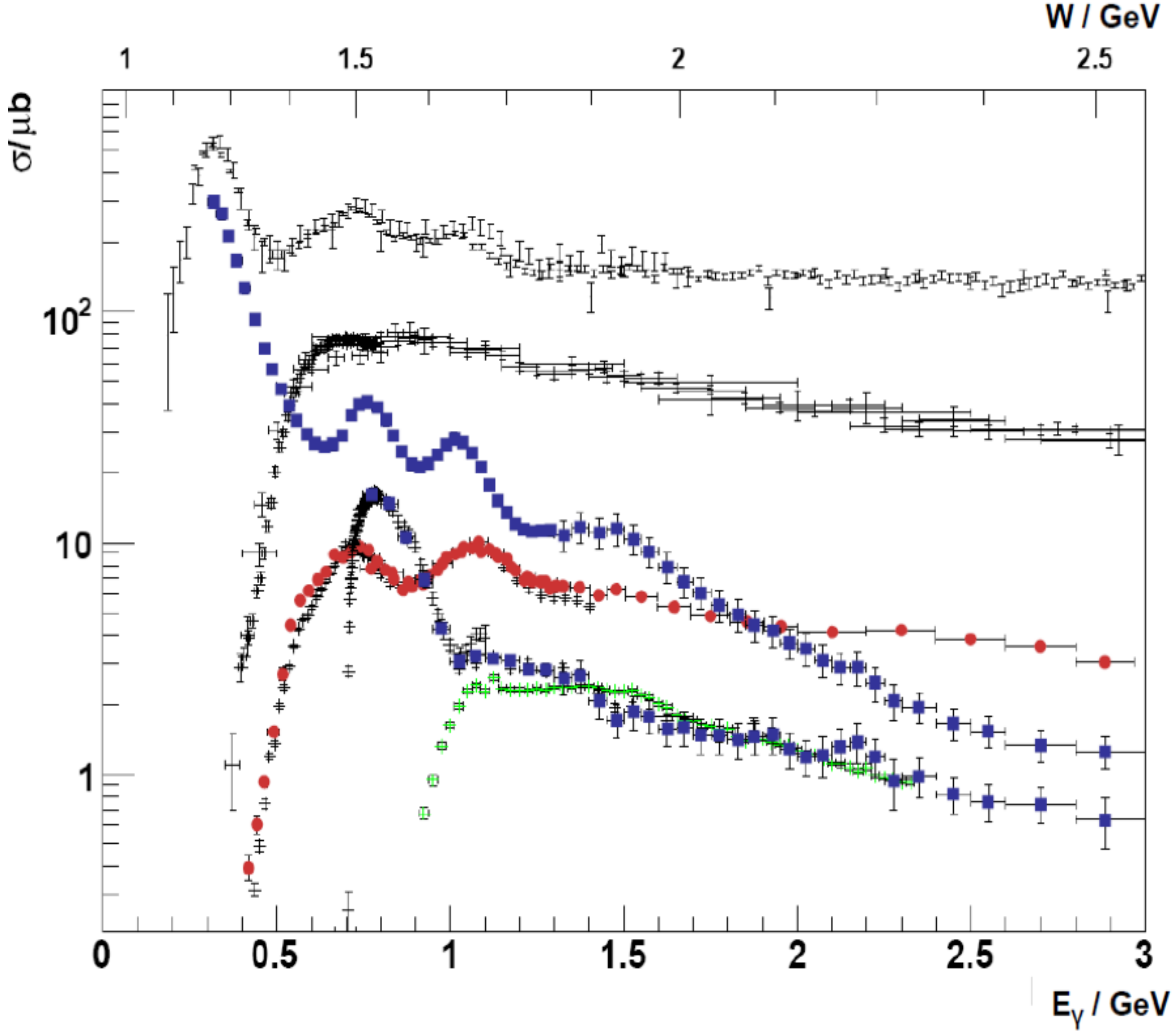
Physical input

many experimental data

many ongoing experiments

Resonance parameter

"Not every bump is a resonance, not every resonance is a bump" - R. G. Moorhouse (1960s)



$\gamma p \to pX$

$\gamma p \to p\pi^+\pi^-$

$\gamma p \to p\pi^0$

$\gamma p \to p\pi^0\pi^0$

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

$\gamma p \to p\eta$

Data: Jefferson Laboratory, ELSA, MAMI

MULTIPOLES

Observable (e.g. cross section) $\frac{d\sigma^v}{d\Omega}\left(W,Q^2,\epsilon,\theta,\phi\right)=\sigma_T+\epsilon\sigma_L+\sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi+\ldots$

Structure functions $\sigma_T\left(W,Q^2,\theta\right)=k/q_\gamma\left(|H_1|^2+|H_2|^2+|H_3|^2+|H_4|^2\right)/2\,,\ldots$

Helicity amplitudes $H_1\left(W,Q^2,\theta\right)=\sin\theta\cos\theta/2(-\mathscr{F}_3-\mathscr{F}_4)/\sqrt{2}\,,\ldots$

CGLN amplitudes $\mathscr{F}_1\left(W,Q^2,\theta\right)=\sum_{\ell>0}\ell M_{\ell+}(W,Q^2)P'_{\ell+1}(\cos\theta)+\ \ldots$

Multipoles $\{E_{\ell\pm}(W,Q^2),L_{\ell\pm}(W,Q^2),M_{\ell\pm}(W,Q^2)\}$

Chew et al. *Phys.Rev.* 106 (1957); Dennery *Phys.Rev.* 124 (1961); Berends et al. Nucl.Phys.B 4 (1967); ... (for explicit formulas) MM et al. Phys.Rev.C 103 (2021)

DEGREES OF FREEDOM

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

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 ($Q^2 = 5 - 12\ Gev^2$)

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