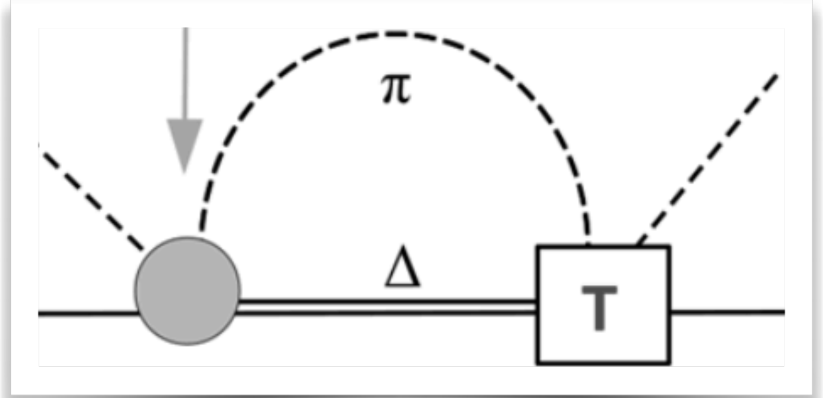
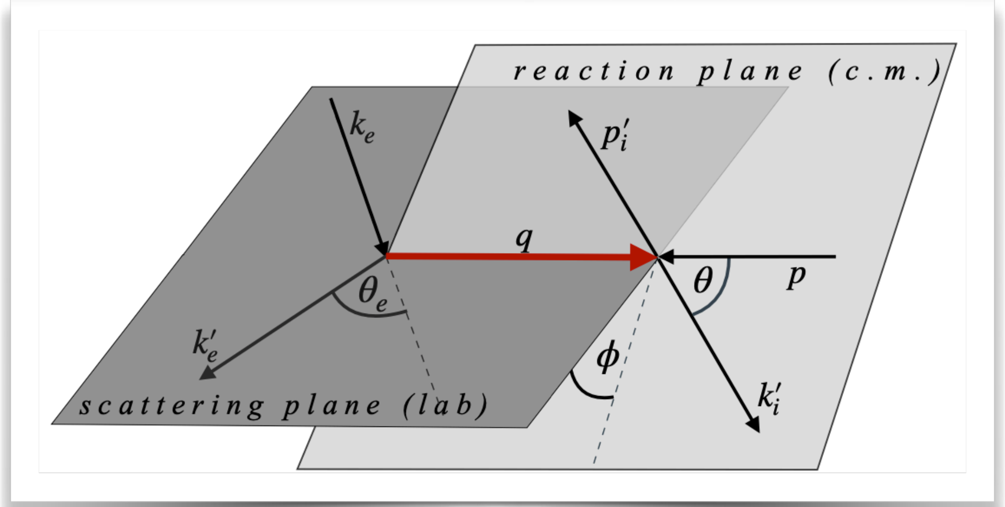
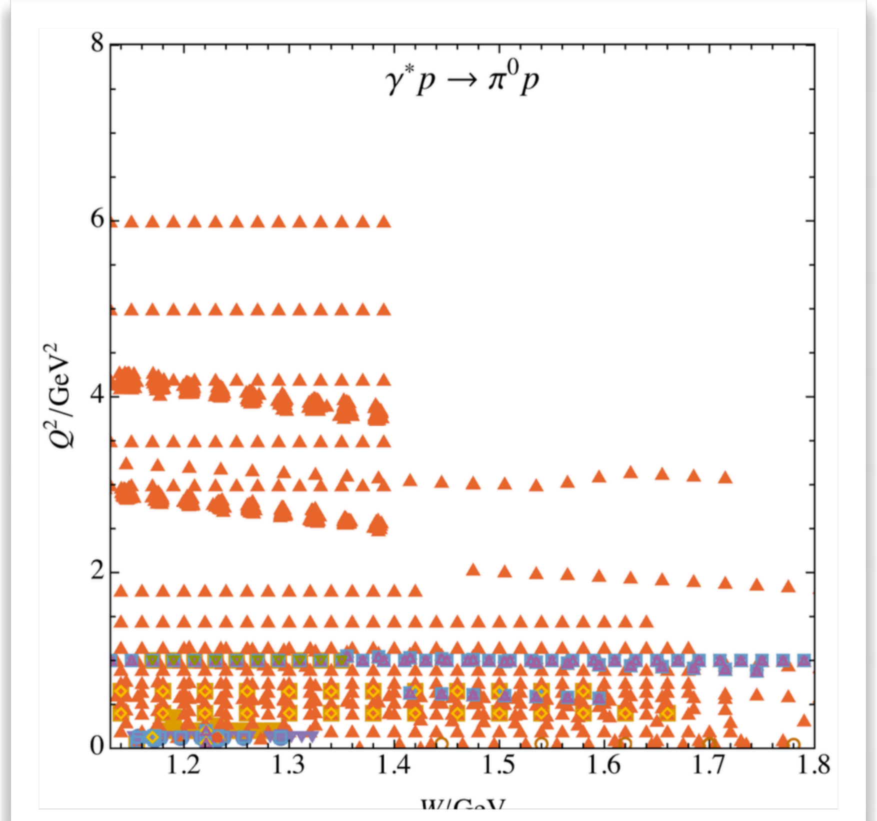
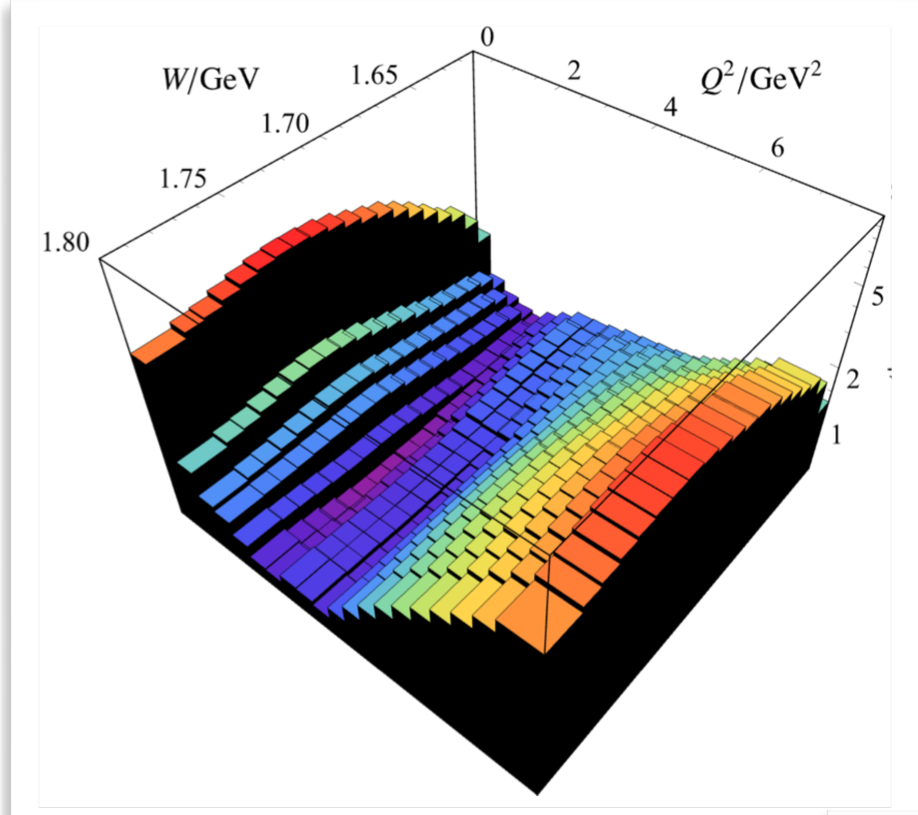
JÜLICH-BONN-WASHINGTON (JBW) COUPLED-CHANNEL APPROACH FOR KY ELECTROPRODUCTION

19.08.2024 — Jefferson Lab, Hadron Structure Group Meeting



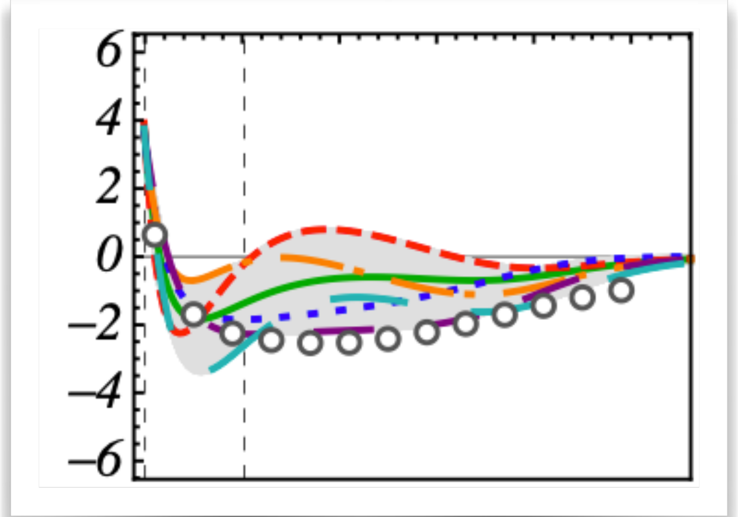


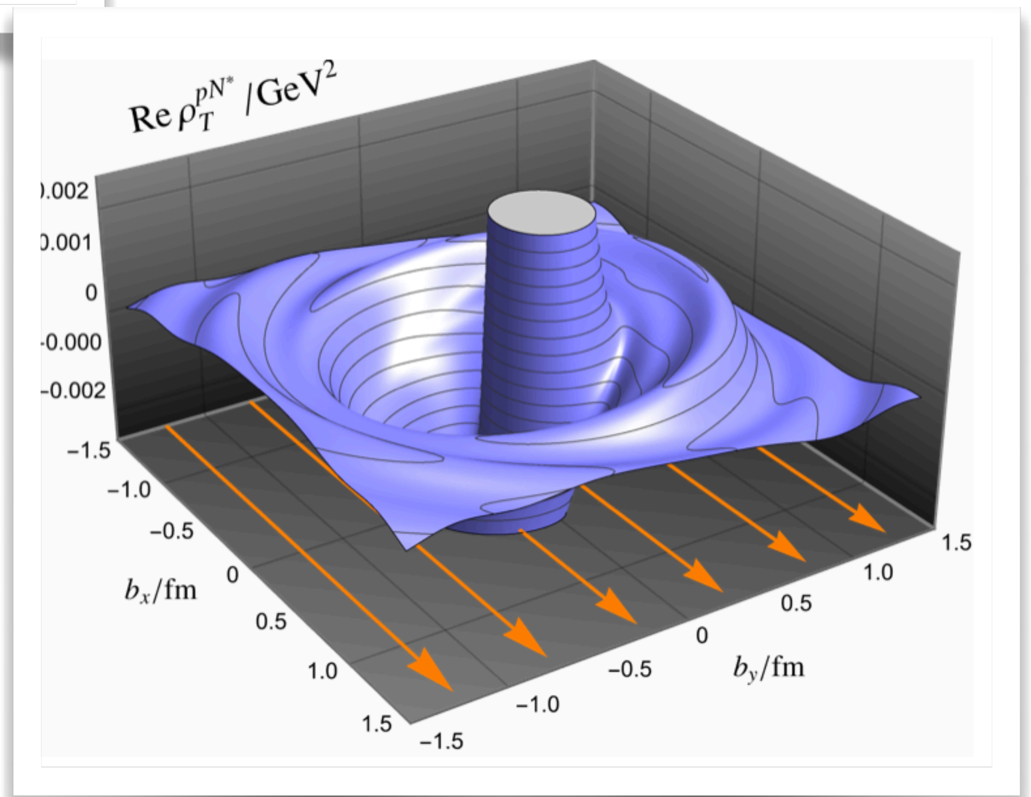




MAXIM MAI

UNIVERSITY OF BERN & THE GEORGE WASHINGTON UNIVERSITY





Heisenberg-Programm
DFG Deutsche Forschungsgemeinschaft

TRR110: NSFC Grant No. 12070131001, DFG Project-ID 196253076

DOE: DE-SC0016582, DE-AC05-06OR23177, DE-FG02-95ER40907

DFG: Heisenberg Programme (project number: 532635001)

NSF: PHY-2012289

HADRON SPECTRUM

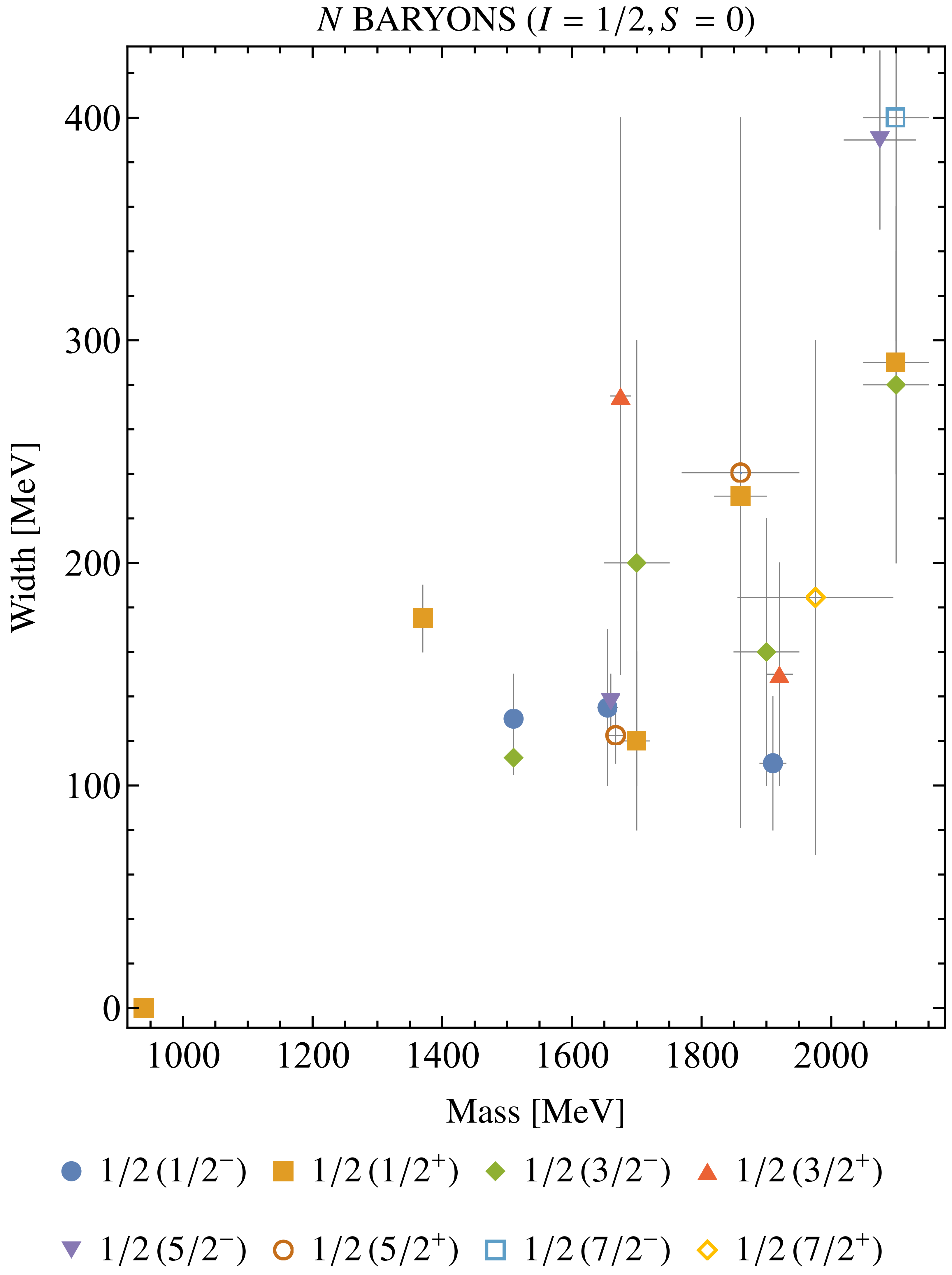
Mostly excited states[1]

≈100 mesons & ≈50 baryons (****)

Theoretical tools

- *Quark models*
- *Functional methods*[1]
- *Effective Field Theories*[3]
- *Lattice QCD*[2,3]
- *Dynamical coupled-channel models*[4]

…



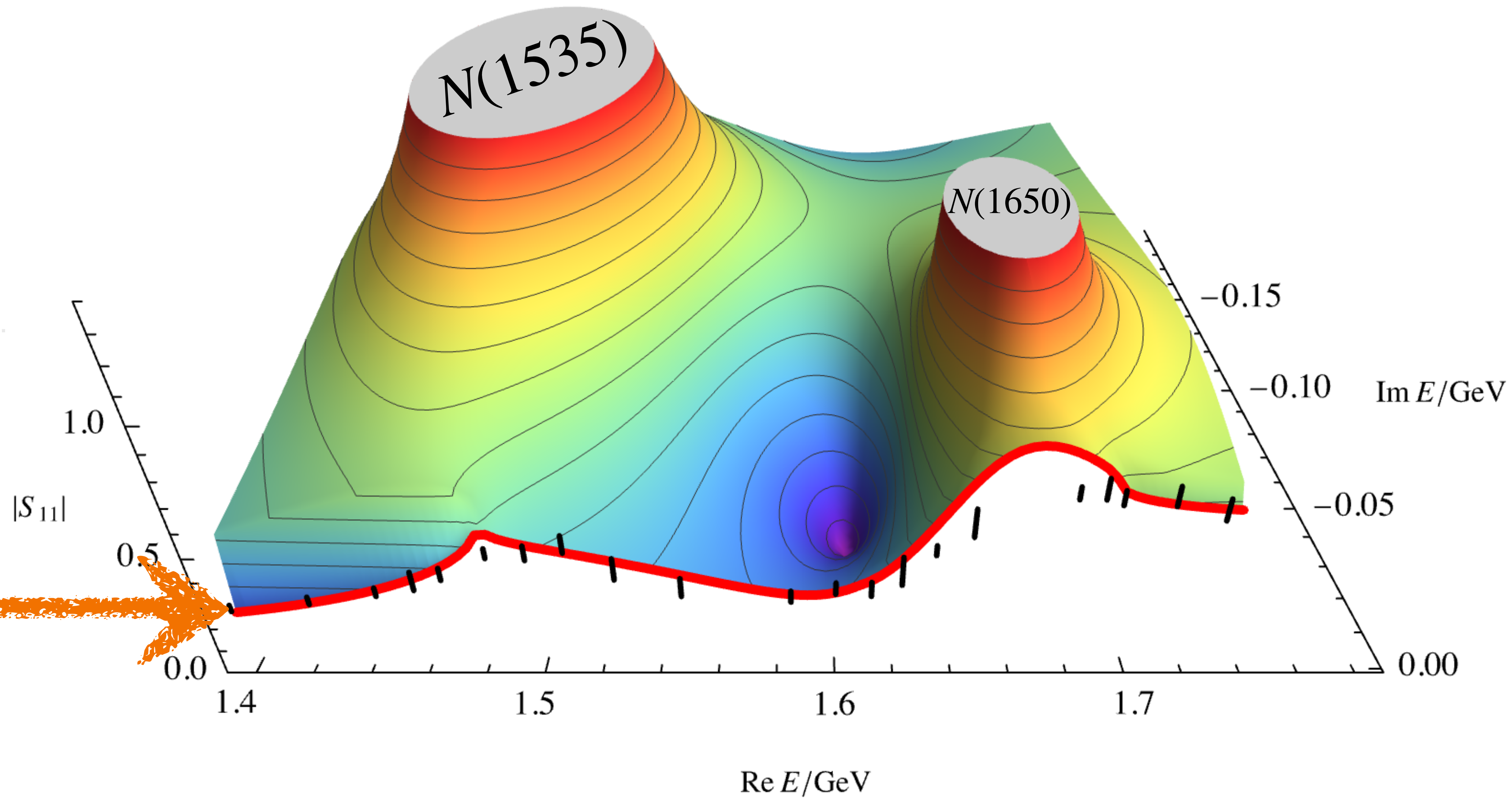
[Fig/Data] Particle Data Group, Workman et al.

[1] Review: Eichmann/Sanchis-Alepuz/Alkofer/Fischer Prog.Part.Nucl.Phys. 91 (2016) 1-100
[2] Review: Briceño/Dudek/Young Rev.Mod.Phys. 90 (2018)
[3] Review: MM/Meißner/Urbach Phys.Rept. 1001 (2023) 1-6
[4] Review: Döring/Haidenbauer/Sato/MM PPNP in progress

RESONANCE PARAMETER

Universal resonance parameter[1]

- S-matrix theory: ***transition amplitude***
  - → Unitarity/Analyticity/Crossing symmetry
  - → Poles on unphysical Riemann Sheets
- Boundary[2] ($E \in \mathbb{R}$):
  - → Experiment
  - → Lattice QCD
  - → CHPT



[Fig/Data] SAID: Phys. Rev. C 74 (2006) 045205
Model: MM et al. Phys.Rev.D 86 (2012) 094033

[1] S. Willenbrock [arXiv:2203.11056 [hep-ph]], … Eden/Olive/….
[2] MM/Meißner/Urbach *Phys.Rept.* 1001 (2023) 1-6

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Tridge (Midland, MI/USA)

[1] S. Willenbrock [arXiv:2203.11056 [hep-ph]], … Eden/Olive/….
[2] MM/Meißner/Urbach *Phys.Rept.* 1001 (2023) 1-6

RESONANCE PARAMETER

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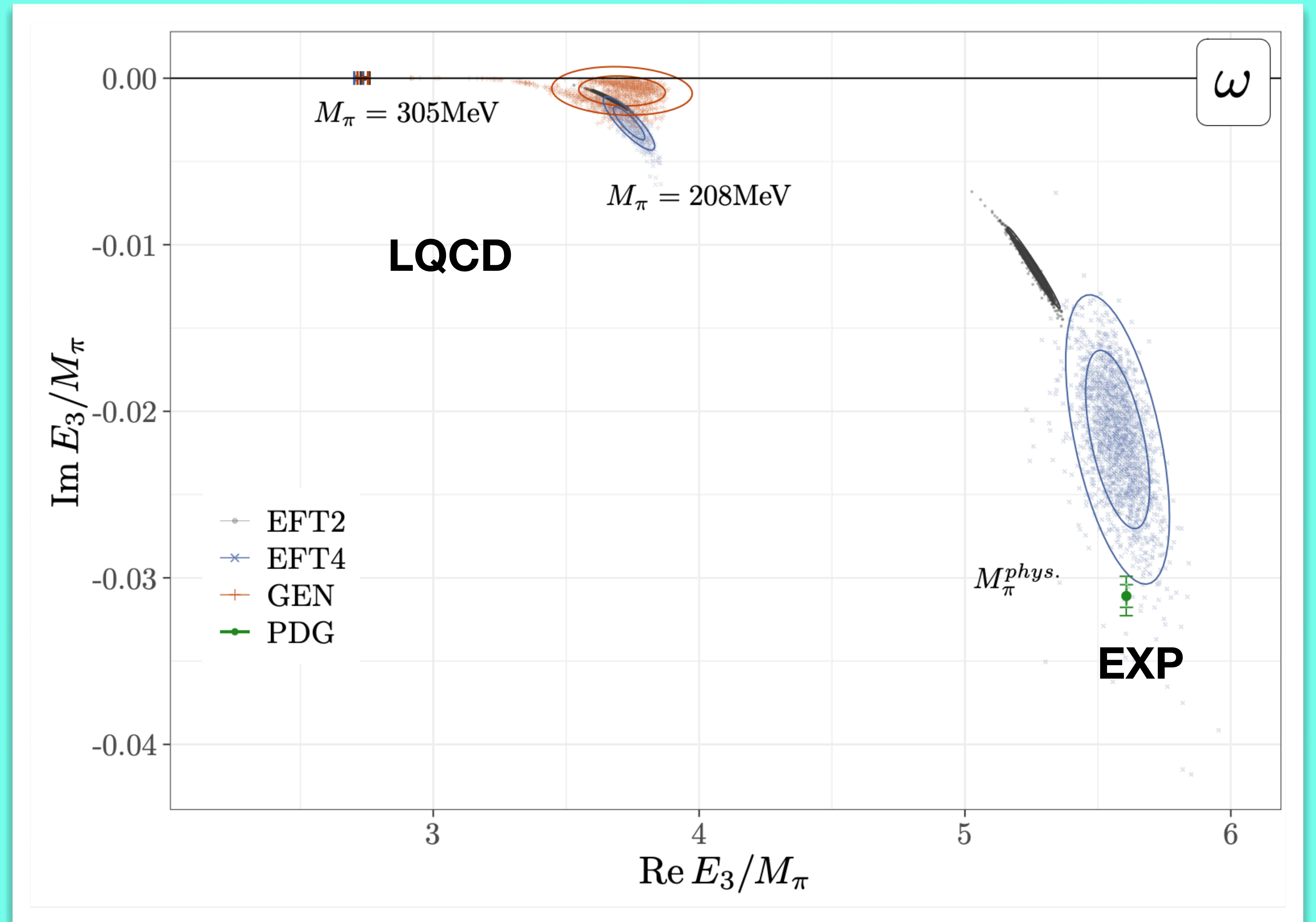
  - → CHPT

current frontier
3-body resonances from EFT/LQCD/Experiment



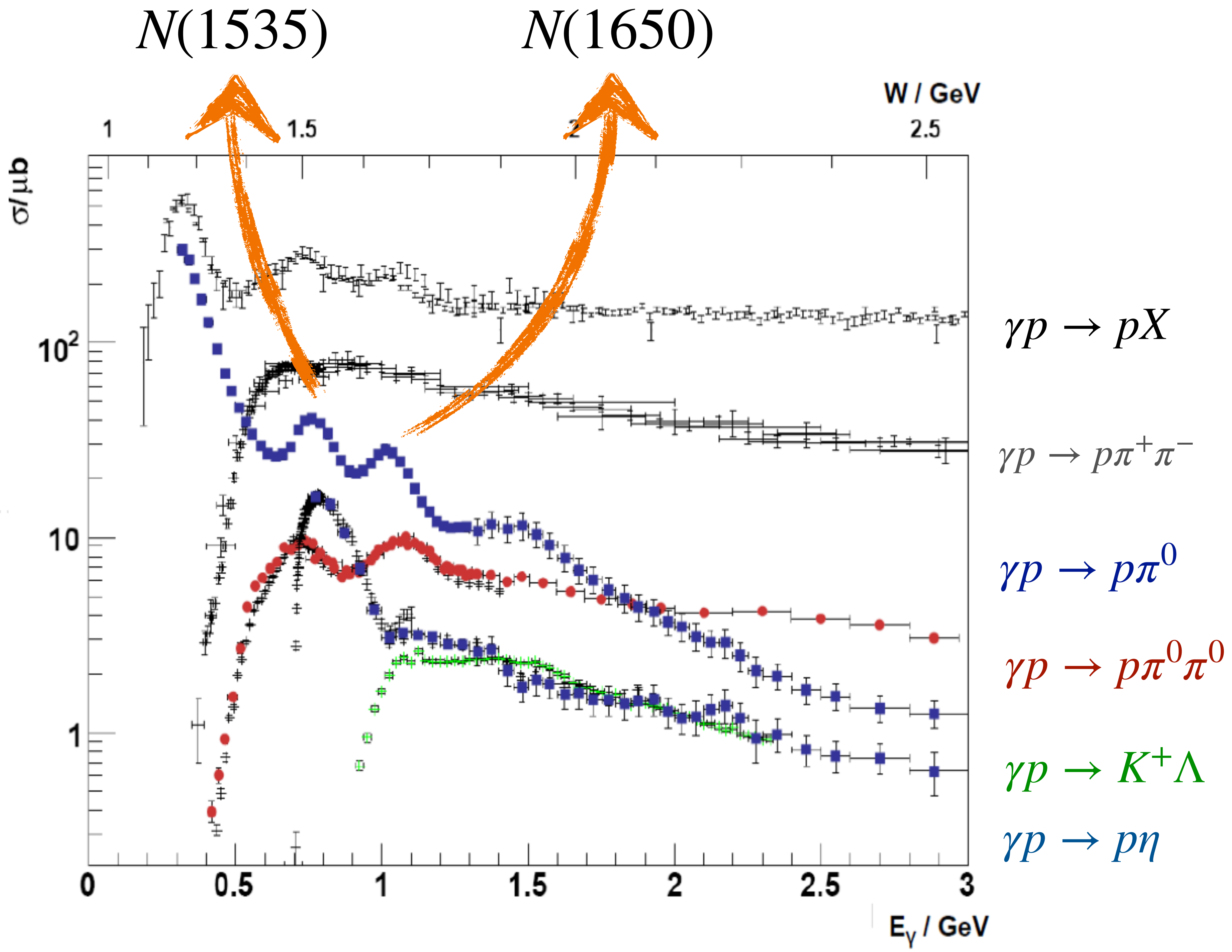
Yan/MM/Garofalo/Meißner/Liu/Liu/Urbach: 2407.16659 [hep-lat]

[1] S. Willenbrock [arXiv:2203.11056 [hep-ph]], … Eden/Olive/….
[2] MM/Meißner/Urbach *Phys.Rept.* 1001 (2023) 1-6

EXPERIMENTAL INPUT

Photon-induced excitation via meson photo-/electroproduction

- large amount of data (10^5 for $\gamma p \to \pi N$)
- many more data to *"emerge"* at JLab[2] ($Q^2 = 5 - 12\,\mathrm{GeV}^2$)
-



[1] Fig/Data Jefferson Laboratory, ELSA, MAMI
[2] CLAS12, GlueX, …

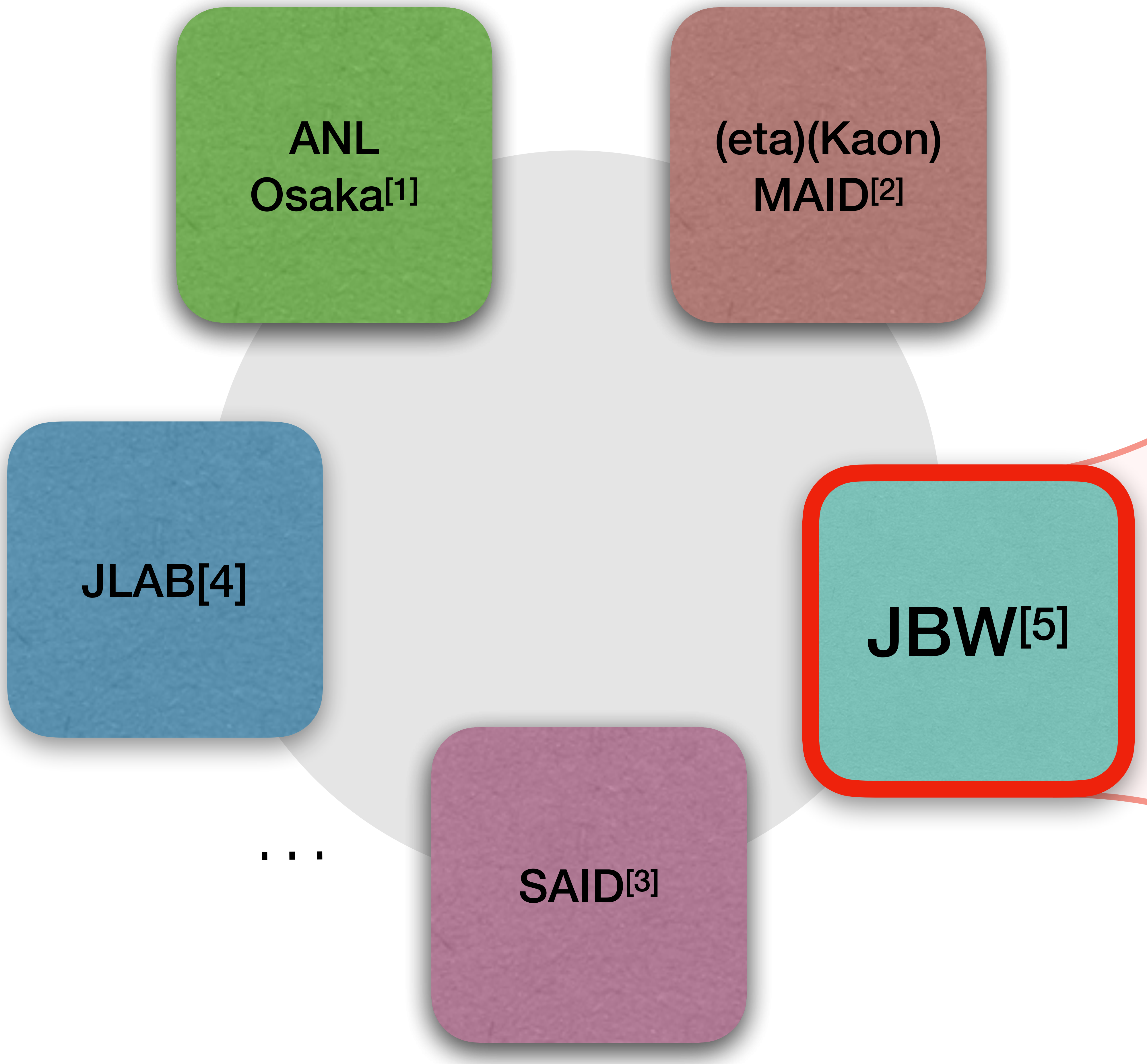
JÜLICH-BONN-WASHINGTON (JBW) COUPLED-CHANNEL APPROACH

Jülich-Bonn-Washington model for pion electroproduction multipoles

Maxim Mai(George Washington U.), Michael Döring(George Washington U. and Jefferson Lab), Carlos Granados(George Washington U.), Helmut Haberzettl(George Washington U.), Ulf-G. Meißner(Bonn U. and Bonn U., HISKP and JCHP, Julich and Tbilisi State U.), Deborah Rönchen(JCHP, Julich and IAS, Julich), Igor Strakovsky(George Washington U.), Ron Workman(George Washington U.)

Published in: Phys.Rev.C 103 (2021) 6, 065204 e-Print: 2104.07312 [nucl-th]

TRANSITION AMPLITUDES



Jülich-Bonn-Washington

- coupled-channel approach (πN, ηN, $K\Lambda$, $K\Sigma$, ...)
- 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] Aznauryan et al., PRC 80(2009), IJMP(2013),... Gent group PRC 89(2014),...

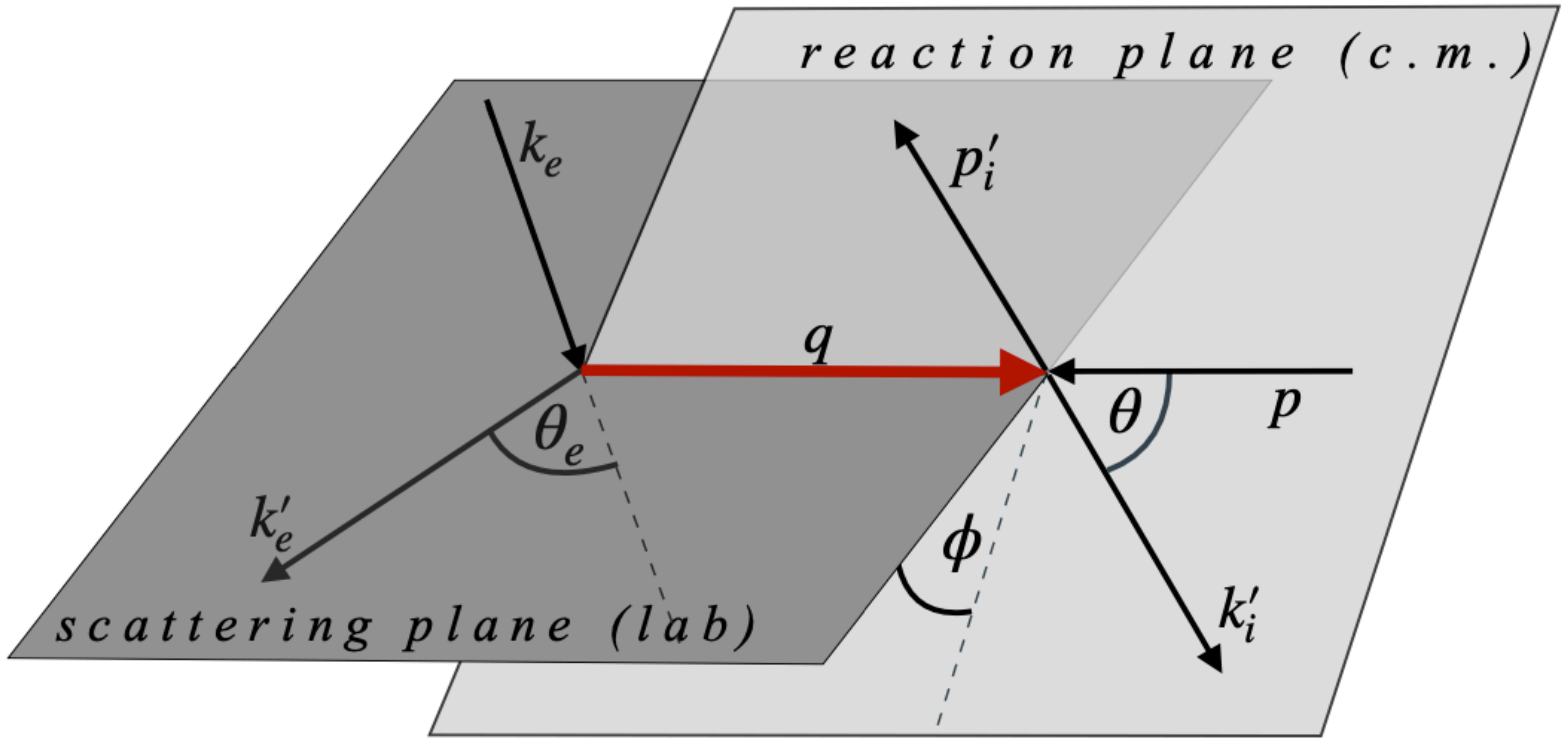
KINEMATICAL VARIABLES

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

1. total energy: W
2. photon virtuality: Q^2
3. transverse photon polarisation:

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

4. production angles: θ, φ



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MULTIPOLES — OBSERVABLES

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

↑

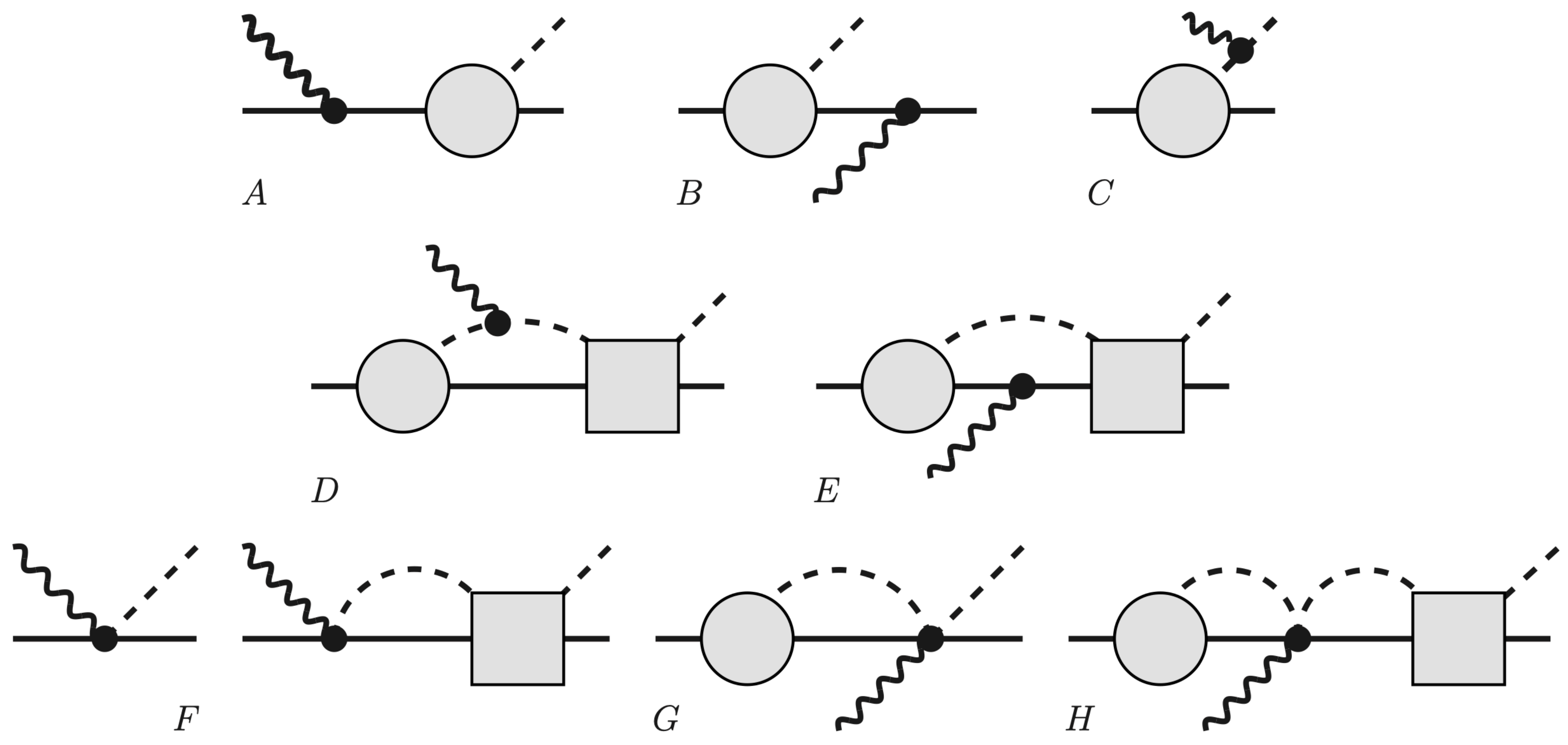
CGLN amplitudes $\mathscr{F}_1\left(W, Q^2, \theta\right) = \sum_{\ell \geq 0} \ell M_{\ell+}(W, Q^2) P'_{\ell+1}(\cos\theta) + \ldots$

↑

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)

THEORETICAL CONSTRAINTS (1)



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

Gauge invariance

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

… but usually too costly

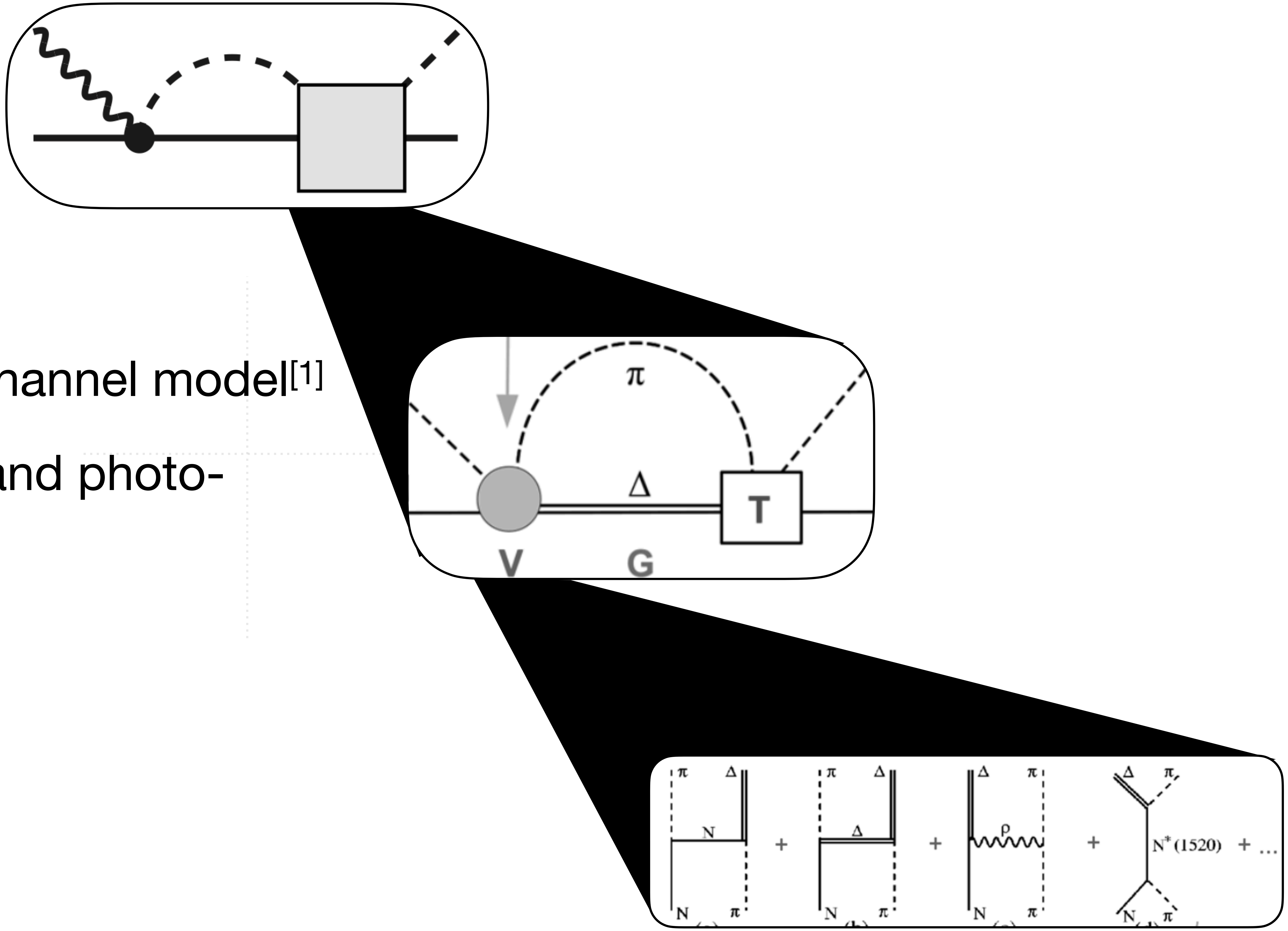
- Here: Ward-Takahashi identity by construction

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

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

[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)



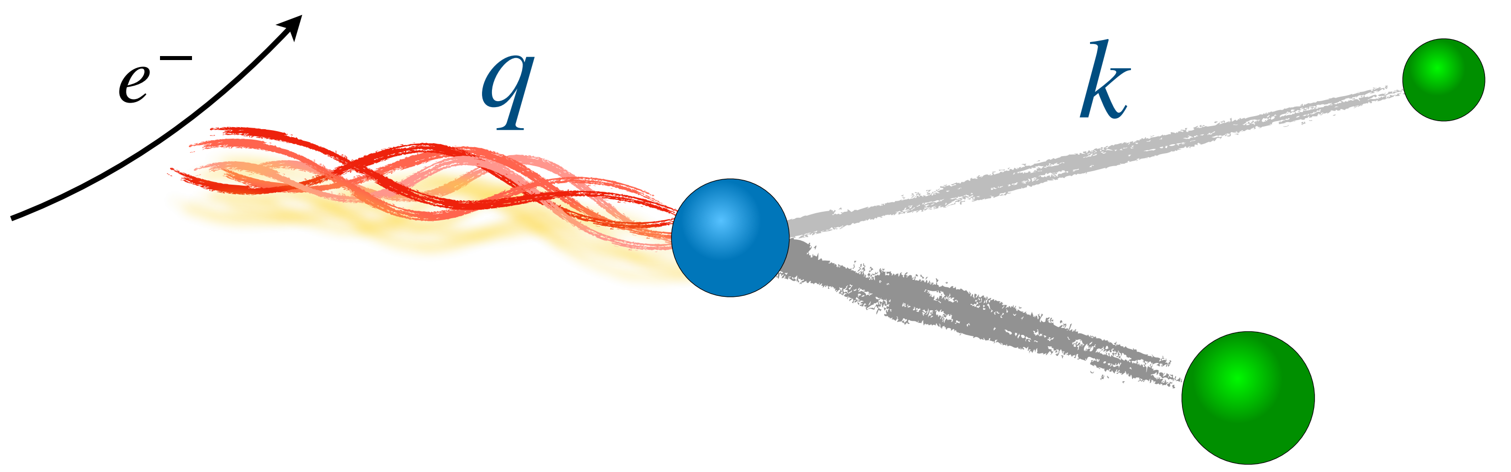
Final-state unitarity

- 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)



Momentum dependence

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

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

$$\dots$$

Siegert's theorem[1]

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

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

➥ good news: fewer parameters needed

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

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

$\boxed{E/L/M}$

$\boxed{\dfrac{B_{\ell'}(\lambda x)}{B_{\ell'}(\lambda)}}$

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

Fulfils/Describes:

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

Parametrisation 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

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Published in: Phys.Rev.C 103 (2021) 6, 065204 e-Print: 2104.07312 [nucl-th]

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

Maxim Mai(George Washington U.), Michael Döring(George Washington U. and Jefferson Lab), Carlos Granados(George Washington U.), Helmut Haberzettl(George Washington U.), Jackson Hergenrather(George Washington U.), Ulf-G. Meißner(Bonn U., HISKP and U. Bonn, Phys. Inst., BCTP and IAS, Julich and JCHP, Julich), Deborah Rönchen(IAS, Julich and JCHP, Julich), Igor Strakovsky(George Washington U.), Ron Workman(George Washington U.)

Published in: *Phys.Rev.C* 106 (2022) 1, 015201, *Phys.Rev.C* 106 (2022) 015201 • e-Print: 2111.04774 [nucl-th]

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.), D. Rönchen(IAS, Julich and JCHP, Julich), R. Workman(George Washington U.)

Published in: *Eur.Phys.J.A* 59 (2023) 12, 286 • e-Print: 2307.10051 [nucl-th]

Global data-driven determination of baryon transition form factors

Yu-Fei Wang(IAS, Julich and Beijing, GUCAS), Michael Döring(George Washington U. and Jefferson Lab), Jackson Hergenrather(George Washington U.), Maxim Mai(George Washington U. and Bonn U. and Bonn U., HISKP), Terry Mart(Bandung Inst. Tech.), Ulf-G. Meißner(IAS, Julich and Bonn U. and Bonn U., HISKP and Tbilisi State U.), Deborah Rönchen(IAS, Julich), Ronald Workman(George Washington U.)

In print at PRL e-Print: 2404.17444 [nucl-th]

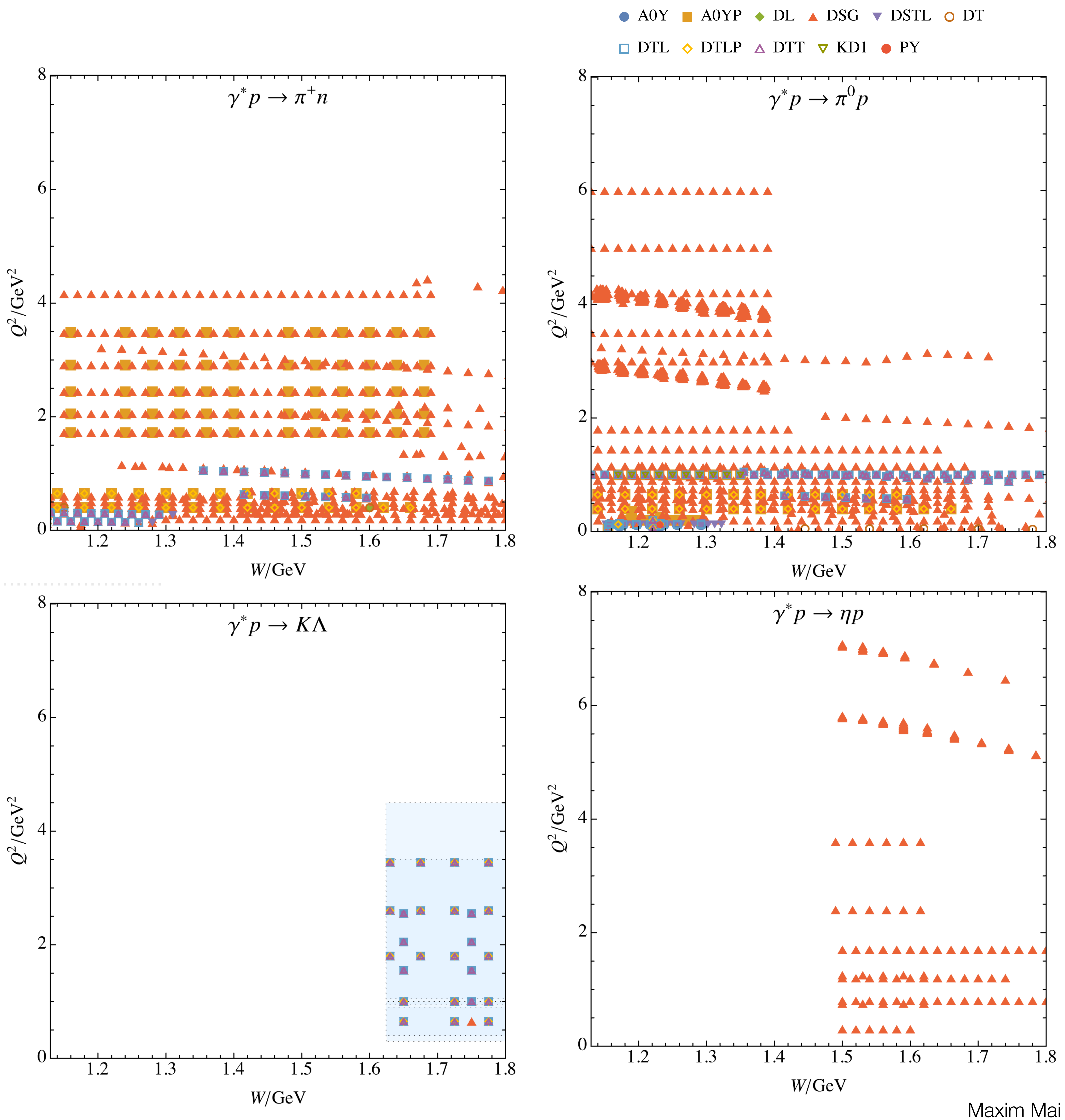
DEGREES OF FREEDOM

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 ?)



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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]

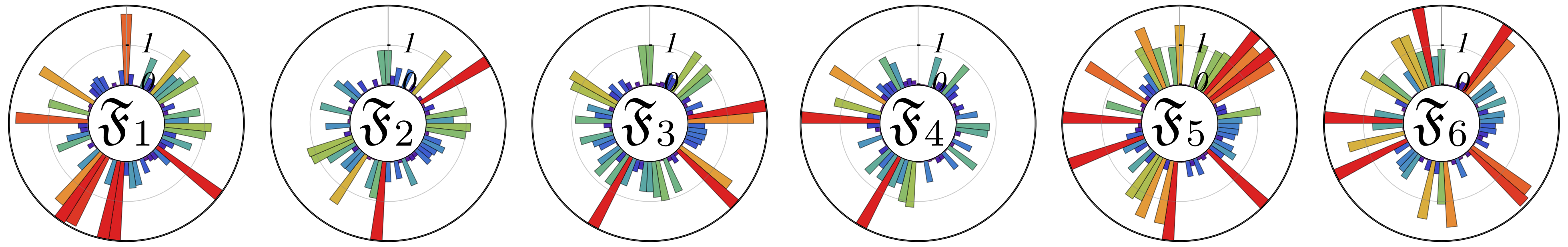
	χ^2/dof
$\mathfrak{F}_1^{\rm reg}$	1.66
$\mathfrak{F}_1^{\rm reg}$	1.73
$\mathfrak{F}_1^{\rm reg}$	1.69
$\mathfrak{F}_1^{\rm reg}$	1.69
$\mathfrak{F}_1^{\rm wt}$	1.54
$\mathfrak{F}_1^{\rm wt}$	1.63
$\mathfrak{F}_1^{\rm wt}$	1.58
$\mathfrak{F}_1^{\rm wt}$	1.58

$\pi N, \eta N, K\Lambda$[3]

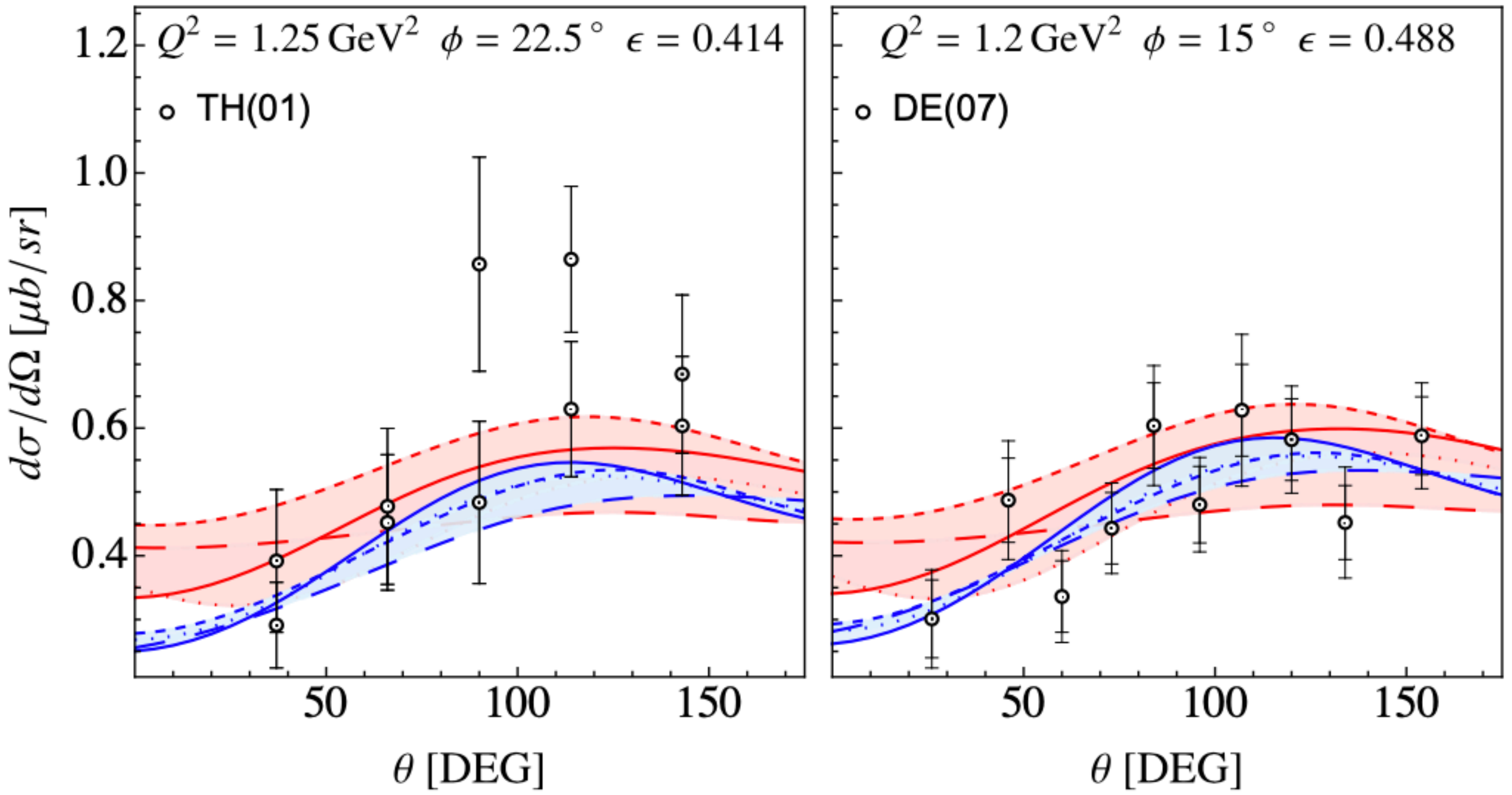
	$\chi^2_{\rm dof}$
FIT$_1$	1.42
FIT$_2$	1.35
	$\chi^2_{\rm wt,dof}$
FIT$_3$	1.12
FIT$_4$	1.06

Uncertainties:

- systematical: due to different fitting strategies studied

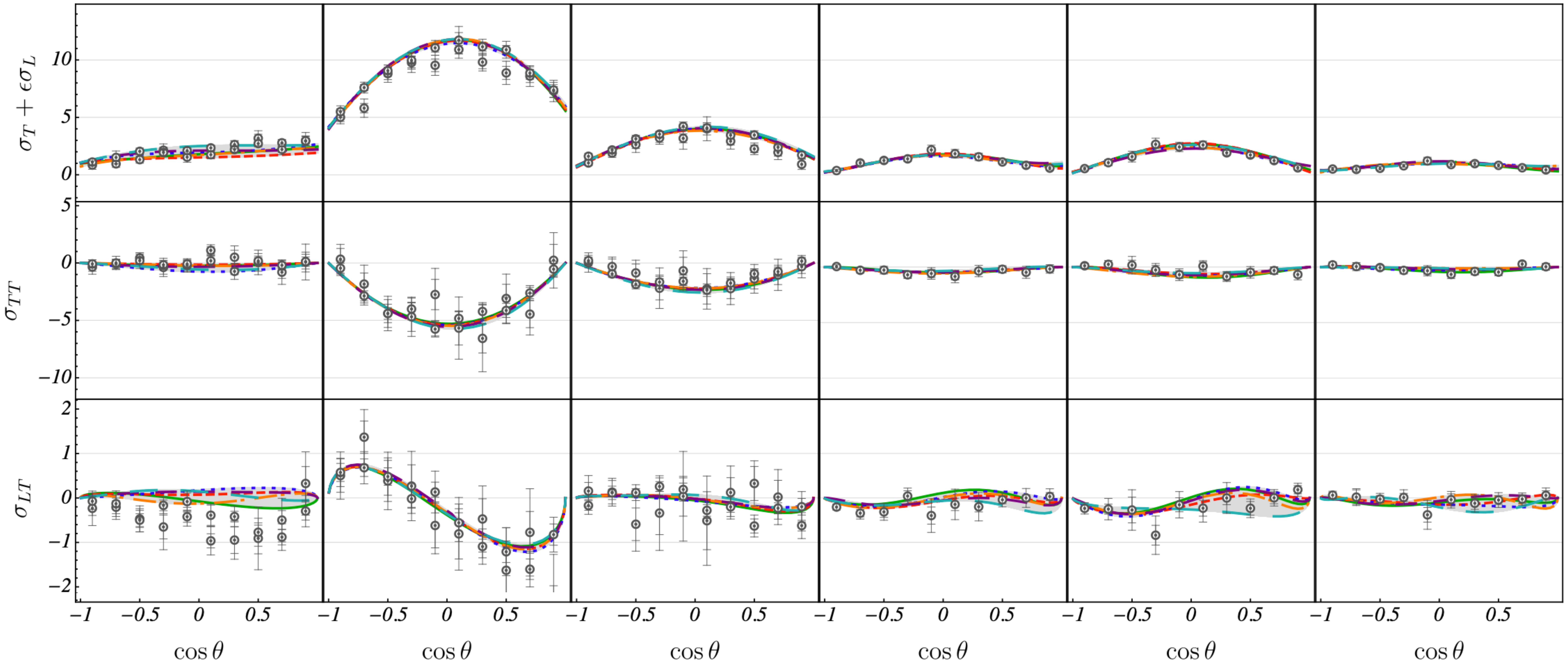


- statistical: not yet — need more data base cleaning, model selection…



[1] Phys.Rev.C 103 (2021) 6
[2] Phys.Rev.C 106 (2022) 1
[3] Eur.Phys.J.A 59 (2023) 12

INTERPOLATOR OR 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)

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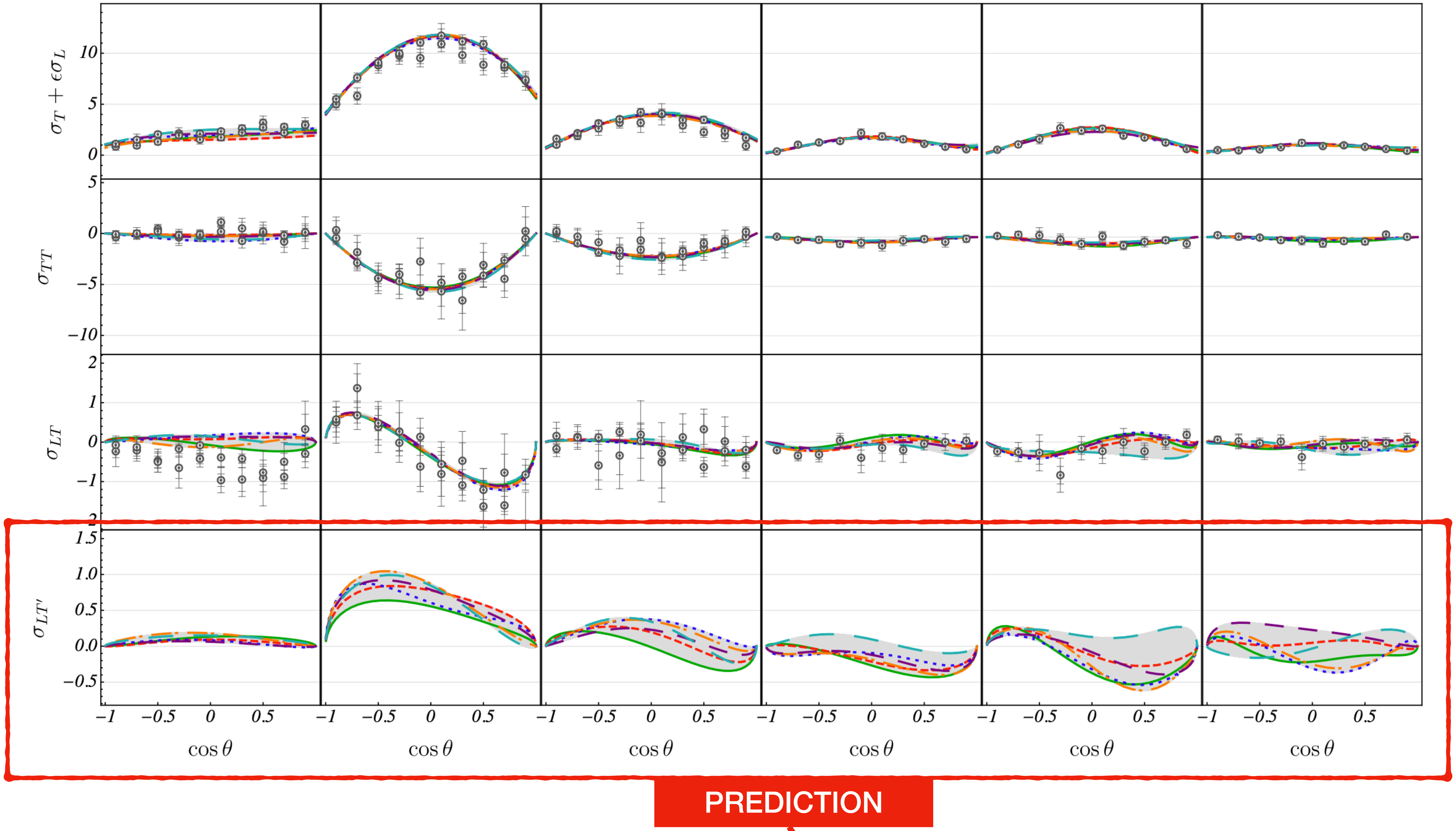

https://jbw.phys.gwu.edu/

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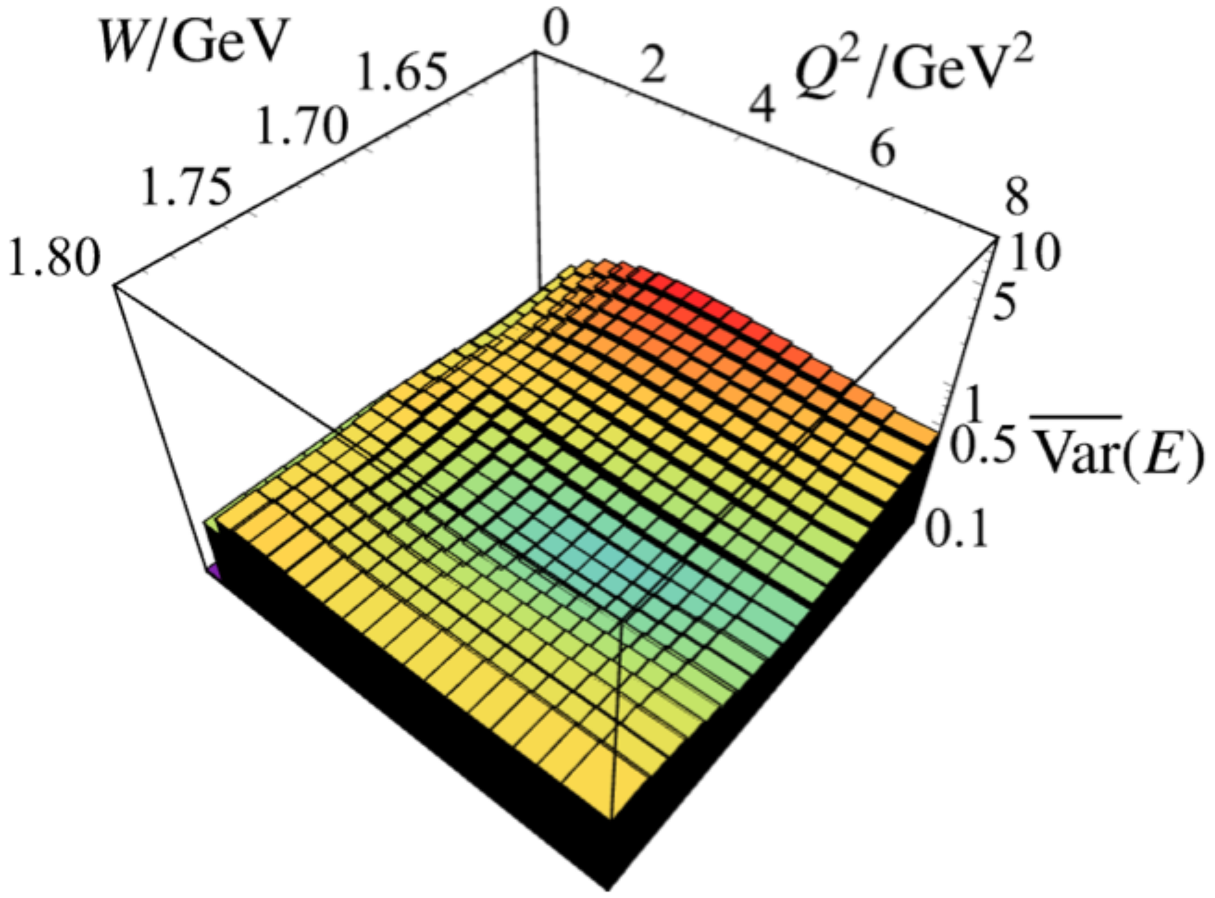
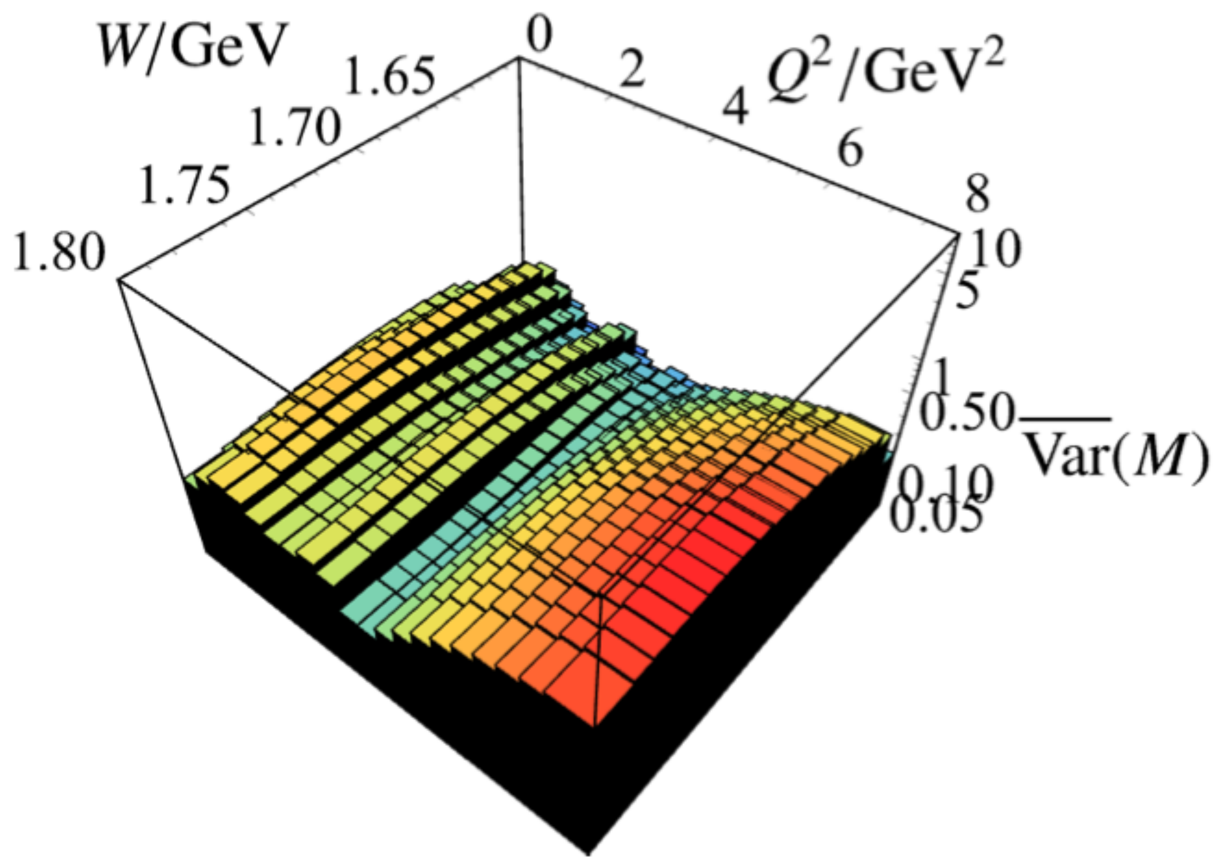
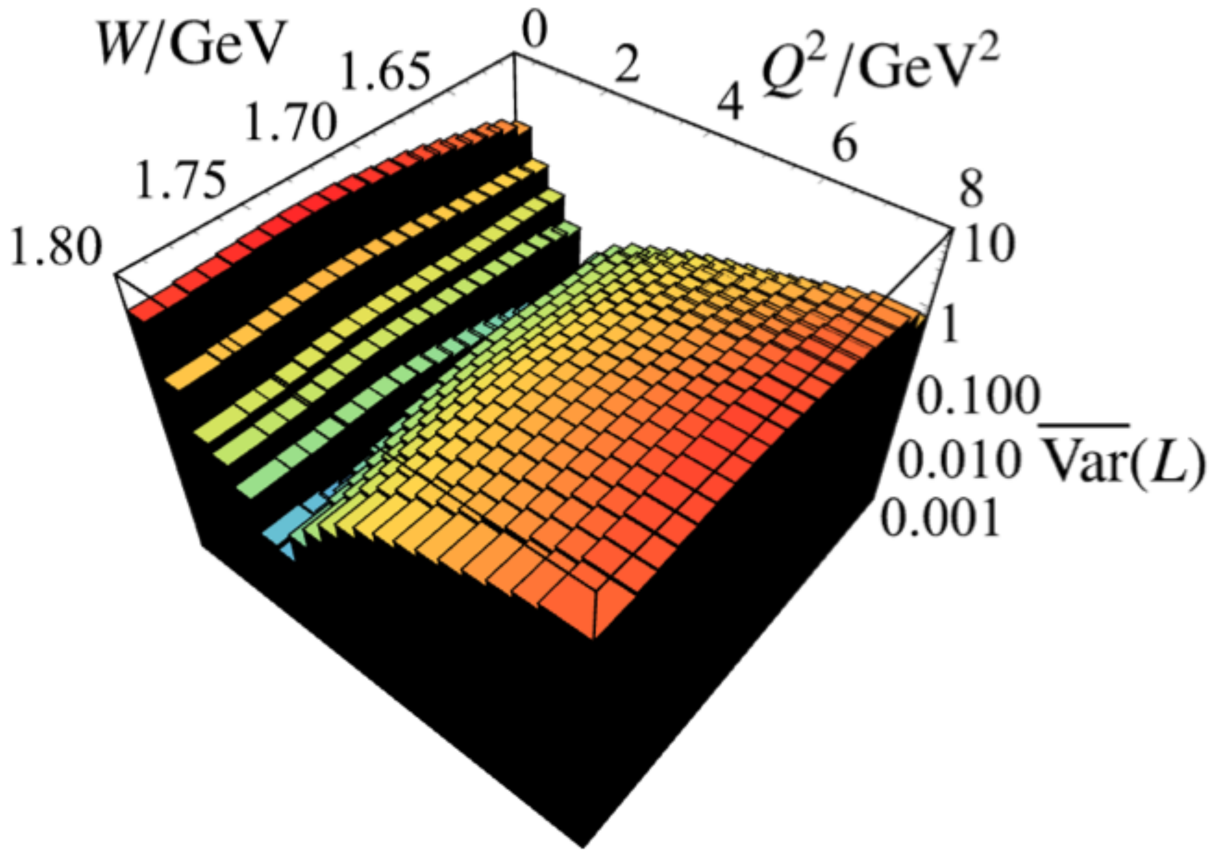
[1] MODEL: [JBW] MM et al. *Phys.Rev.C* 103 (2021) 6; Phys.Rev.C 106 (2022) 015201
[2] DATA: Joo et al. [CLAS] PRC (2003), PRL (2002)

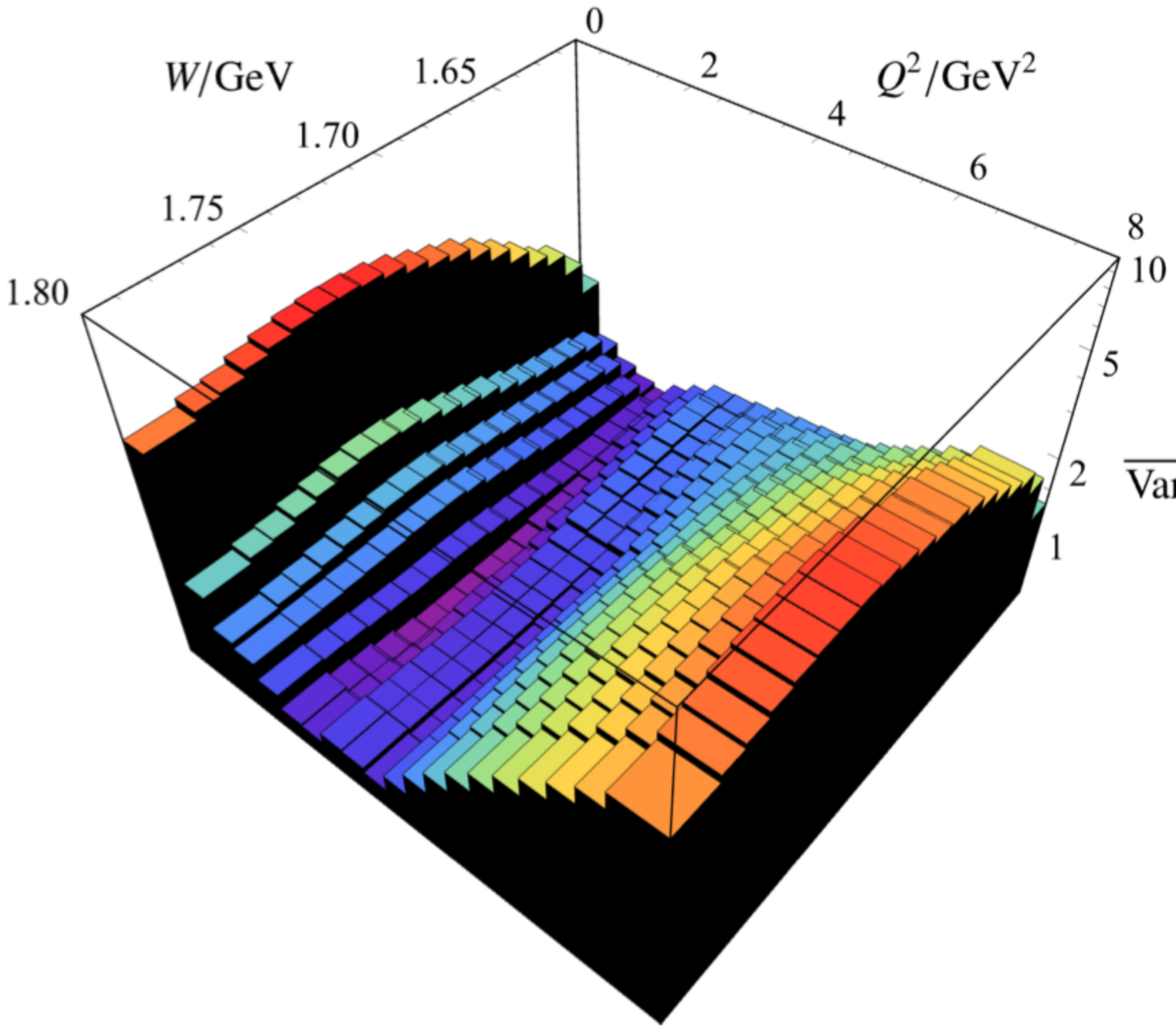
VOLATILITY OF MULTIPOLES (KL)







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

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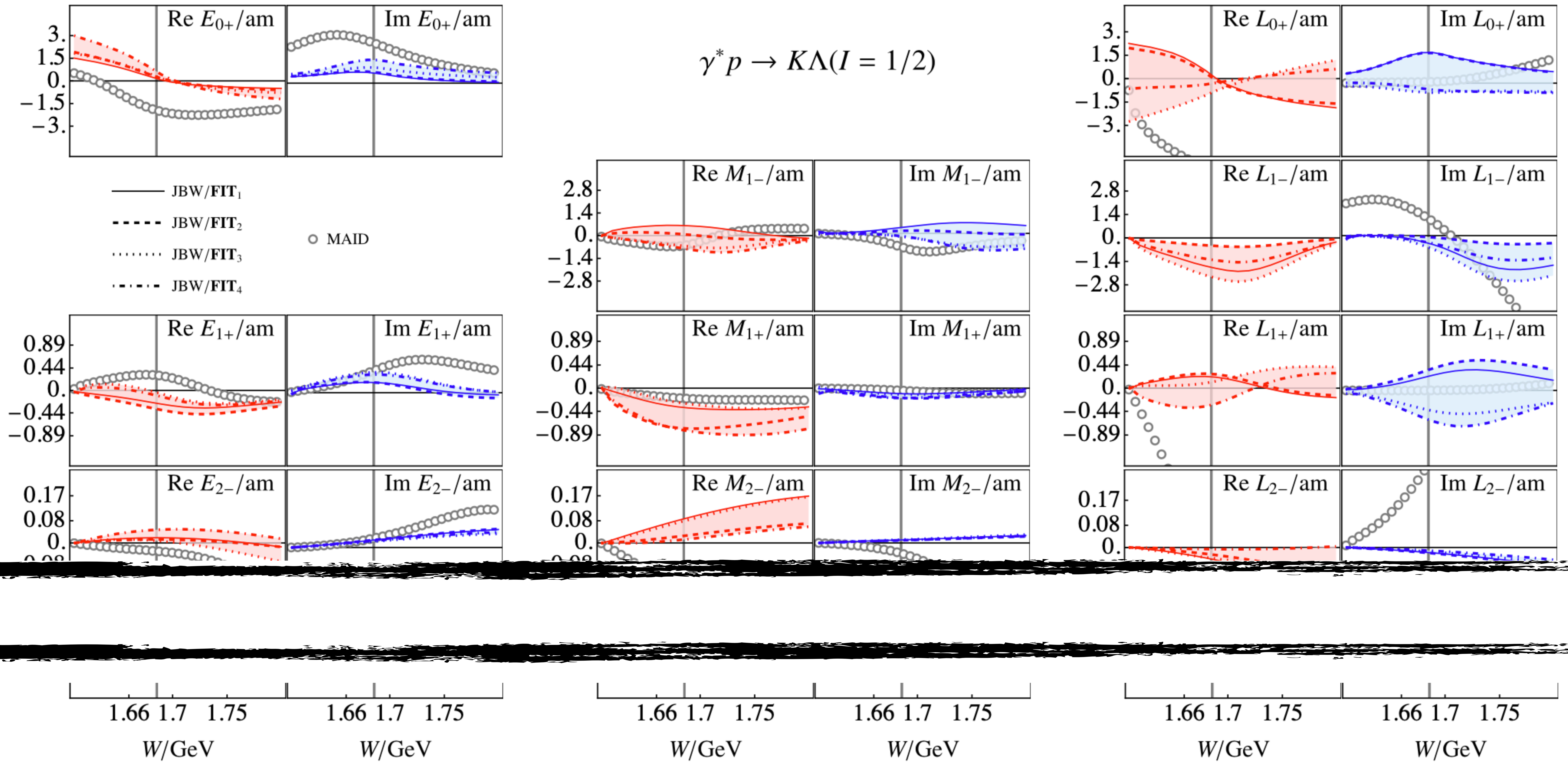
MULTIPOLES (KL)



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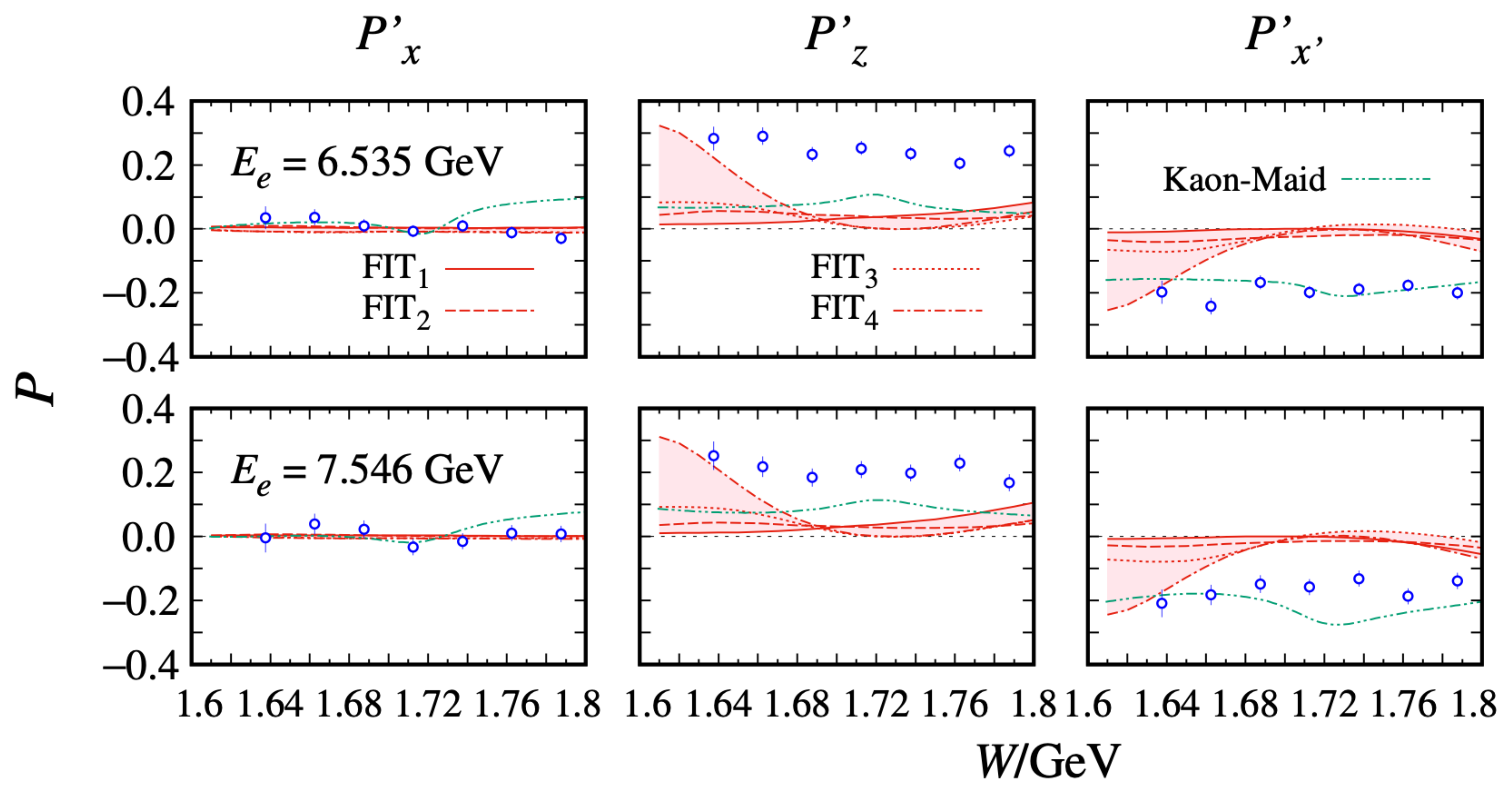
NEW L-SENSITIVE DATA

Beam-recoil transferred polarisation[1]

- compare to our prediction (no fit) for integrated kinematics

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

➥ fits to new data[2] will be instrumental



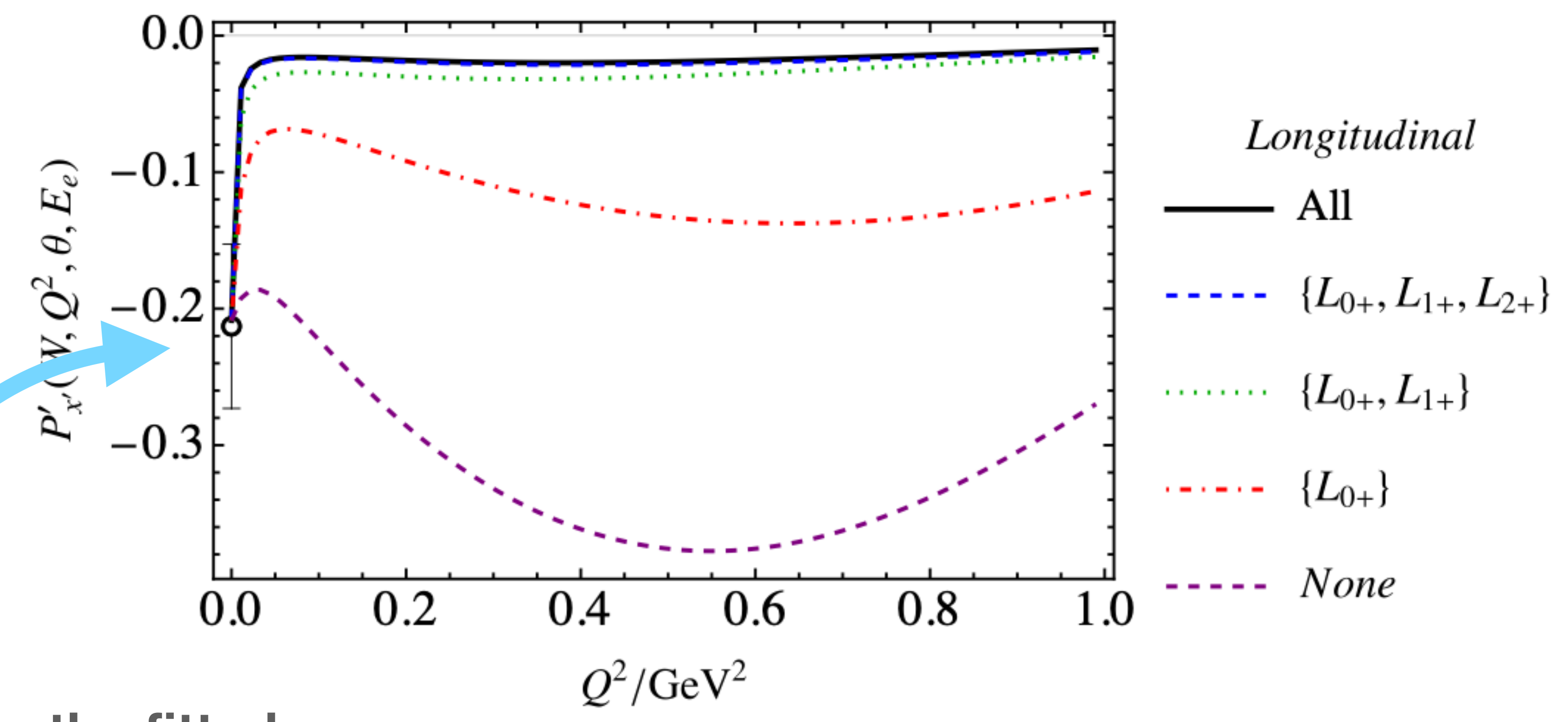


Photo-production datum form the fitted data base

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

TRANSITION FORM FACTORS

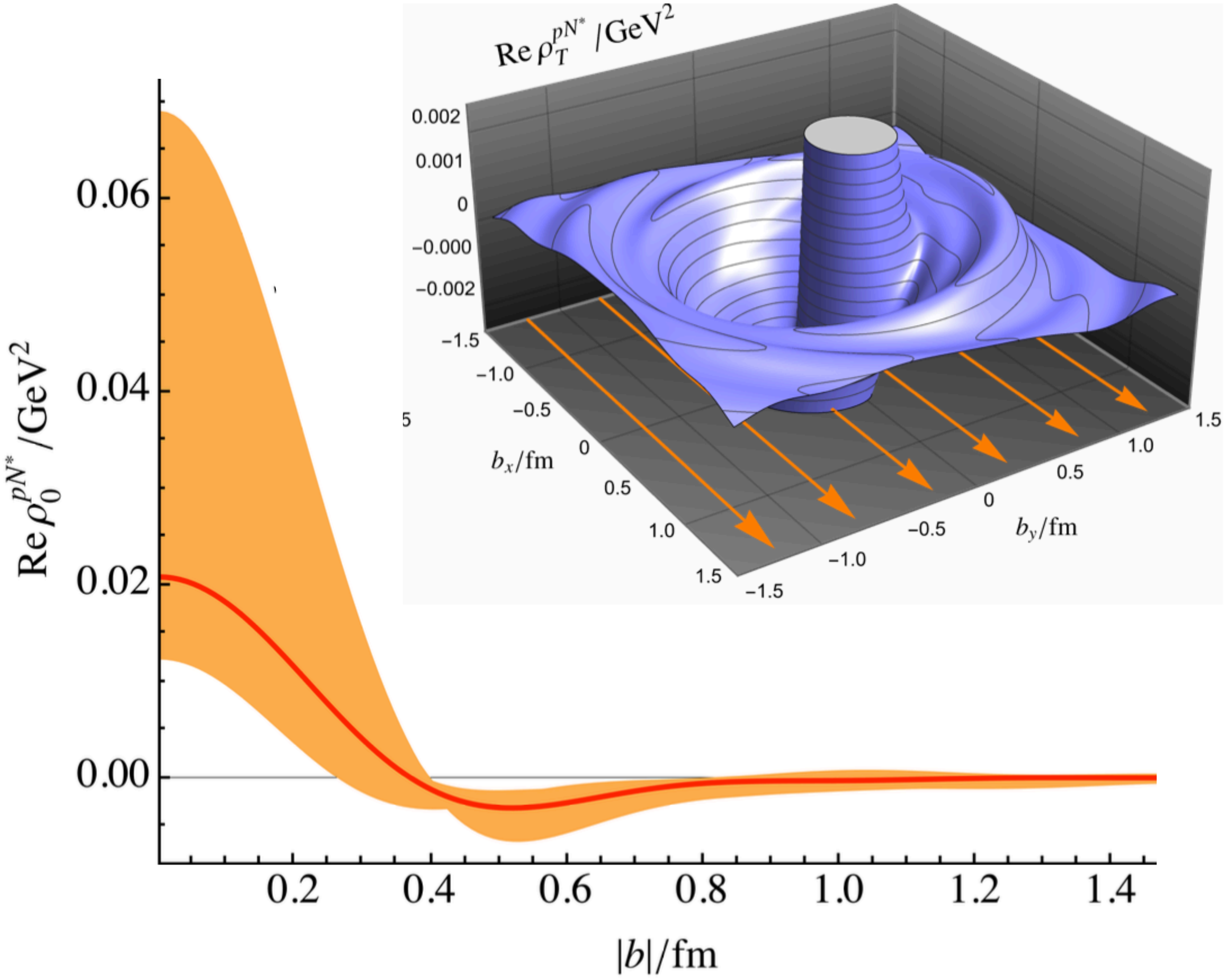
Hadron structure probe[1]

- transition between excited and ground state baryons[2]

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

- 12 N/Δ states are determined
- Charge distribution in light front RF[3]

$$\rho_0^{NN^*}(\vec{b}) = \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(bQ) F_1^{NN^*}(Q^2),$$



[JBW] Wang et al. in print at PRL e-Print: 2404.17444

[1] Aznauryan and V. D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012), arXiv:1109.1720 [hep-ph]; G. Ramalho and M. T. Peña, Prog. Part. Nucl. Phys. 136, 104097 (2024), arXiv:2306.13900 [hep-ph].
[2] Workman, L. Tiator, and A. Sarantsev, Phys. Rev. C 87, 068201 (2013), arXiv:1304.4029 [nucl-th].
[3] Tiator et al. CPC(HEP & NP), 2009, 33(X)

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

☐ statistical/parameter importance (LASSO, Machine Learning, …) [soon]

☐ energy-dependent analysis [soon-ish]

☐ simultaneous fit to scattering and photo-production data [not so soon]

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