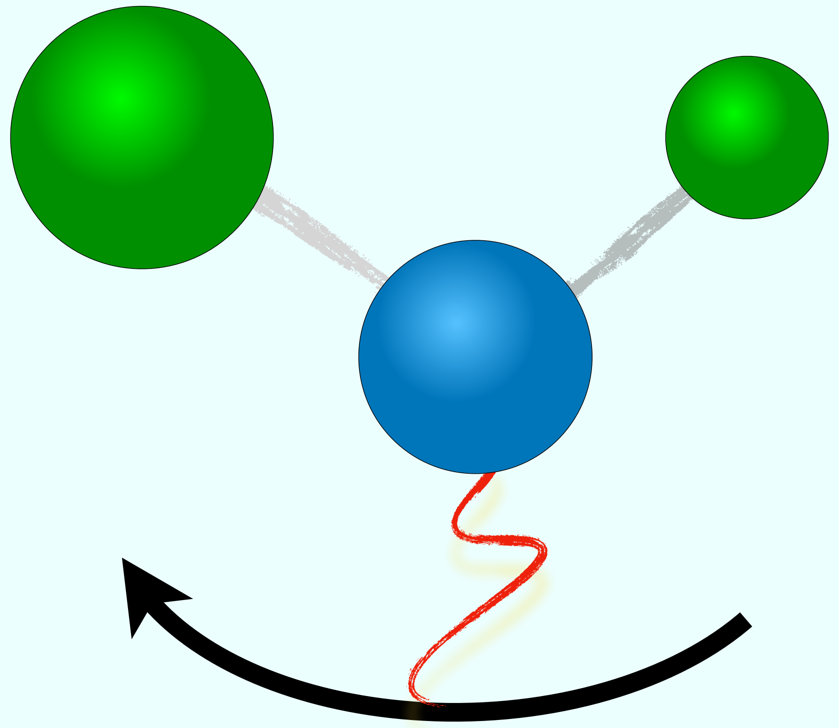
SINGLE MESON ELECTROPRODUCTION



Maxim Mai

[Jülich-Bonn-Washington (JBW) collaboration]

*M. Döring, **J. Hergenrather**, C. Granados, H. Haberzettl, Ulf-G. Meißner, D. Rönchen, I. Strakovsky, R. Workman*

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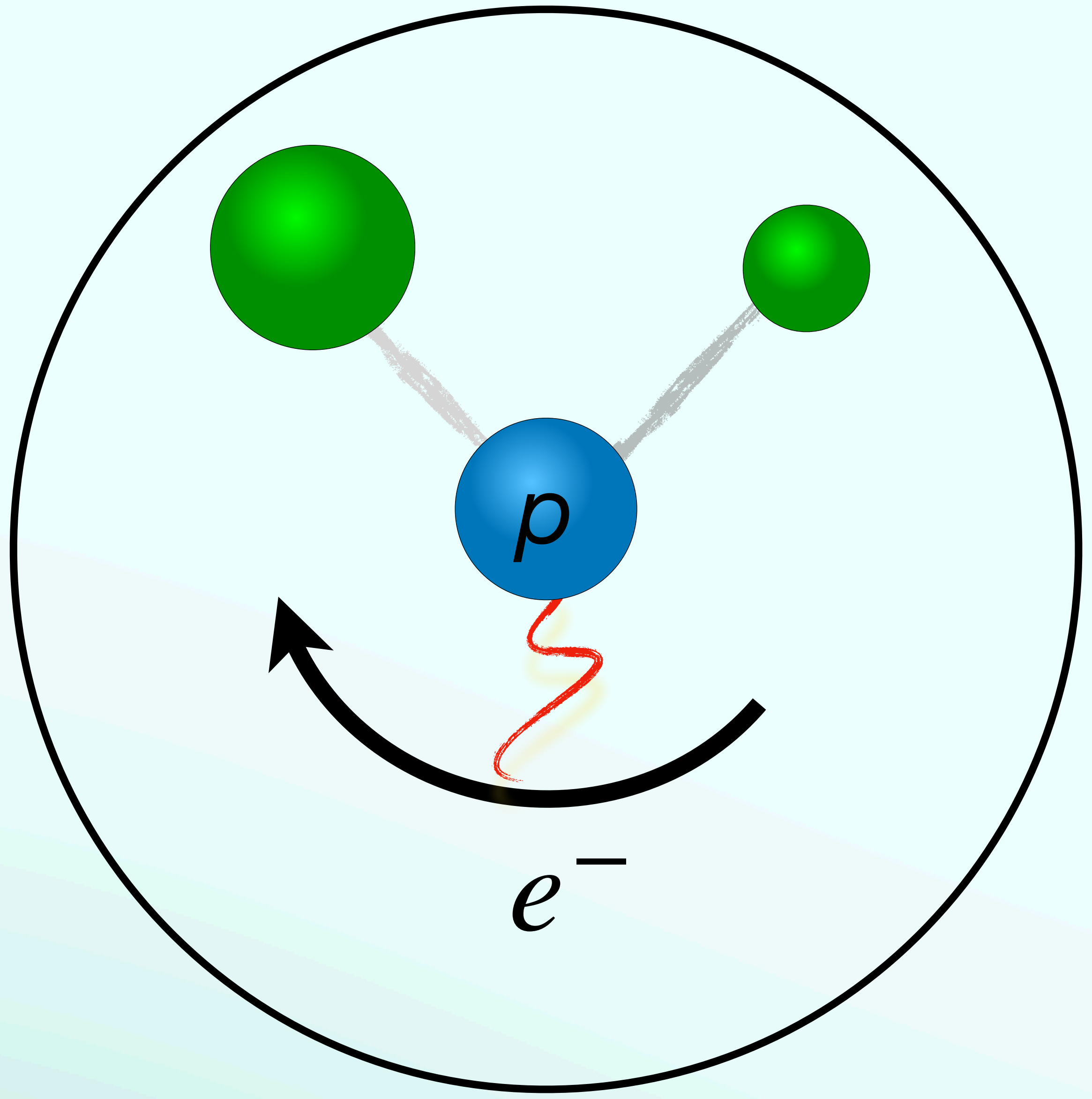
UNIVERSITÄT BONN

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

JÜLICH



INTRODUCTION

NATURE'S LANGUAGE

Quantum mechanics

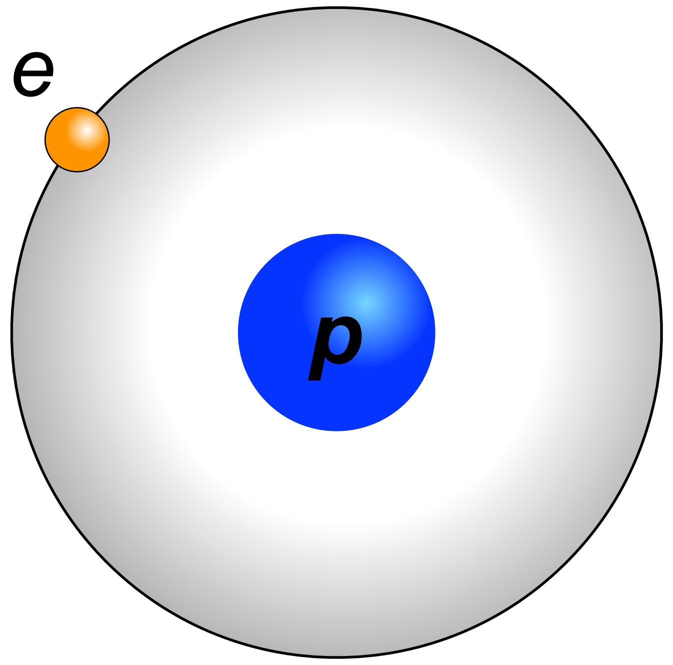
- governs subatomic world
- unconventional language
- various interpretations

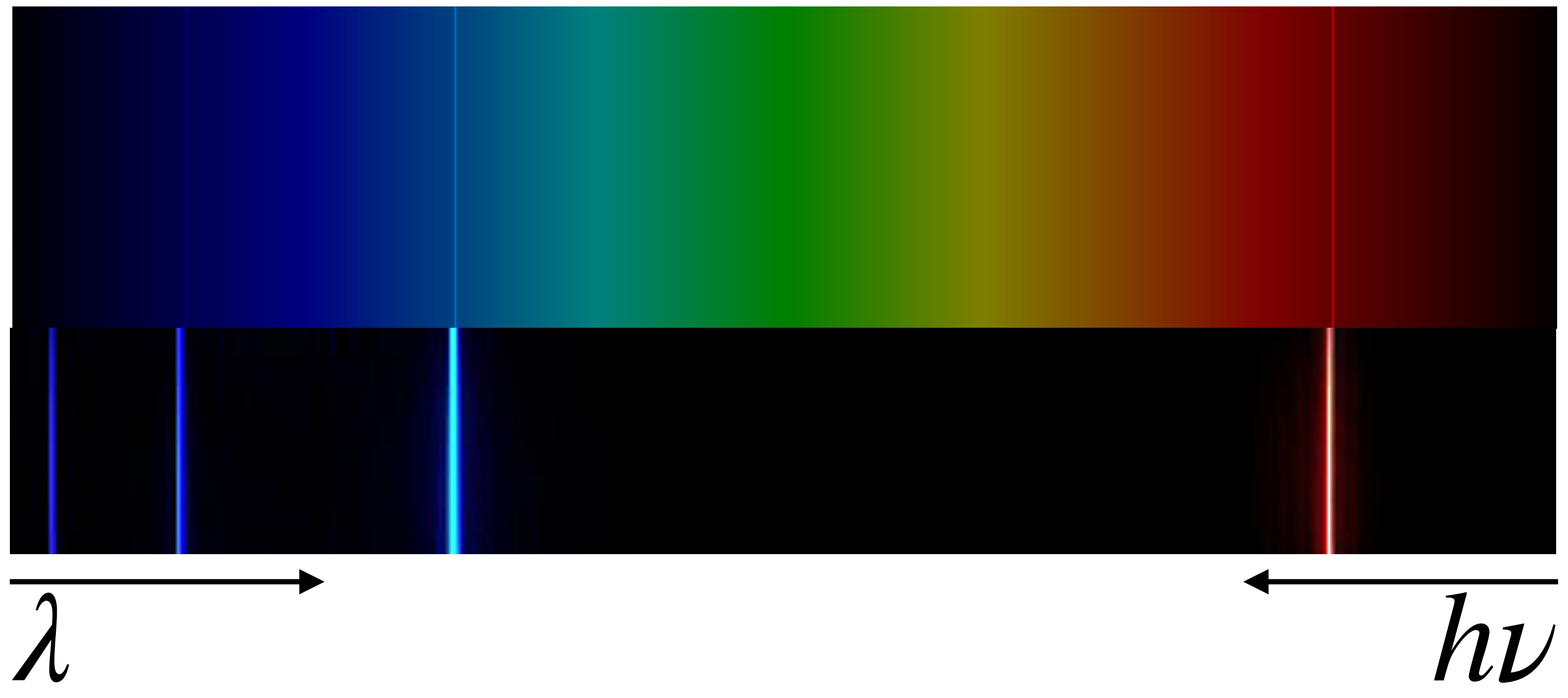
"If you think you understand quantum mechanics then you don't understand quantum mechanics"
R. P. Feynman

NATURE'S LANGUAGE

Breakthrough

- explanation of atomic spectra
- discrete excitation energies
- new paradigm of physics



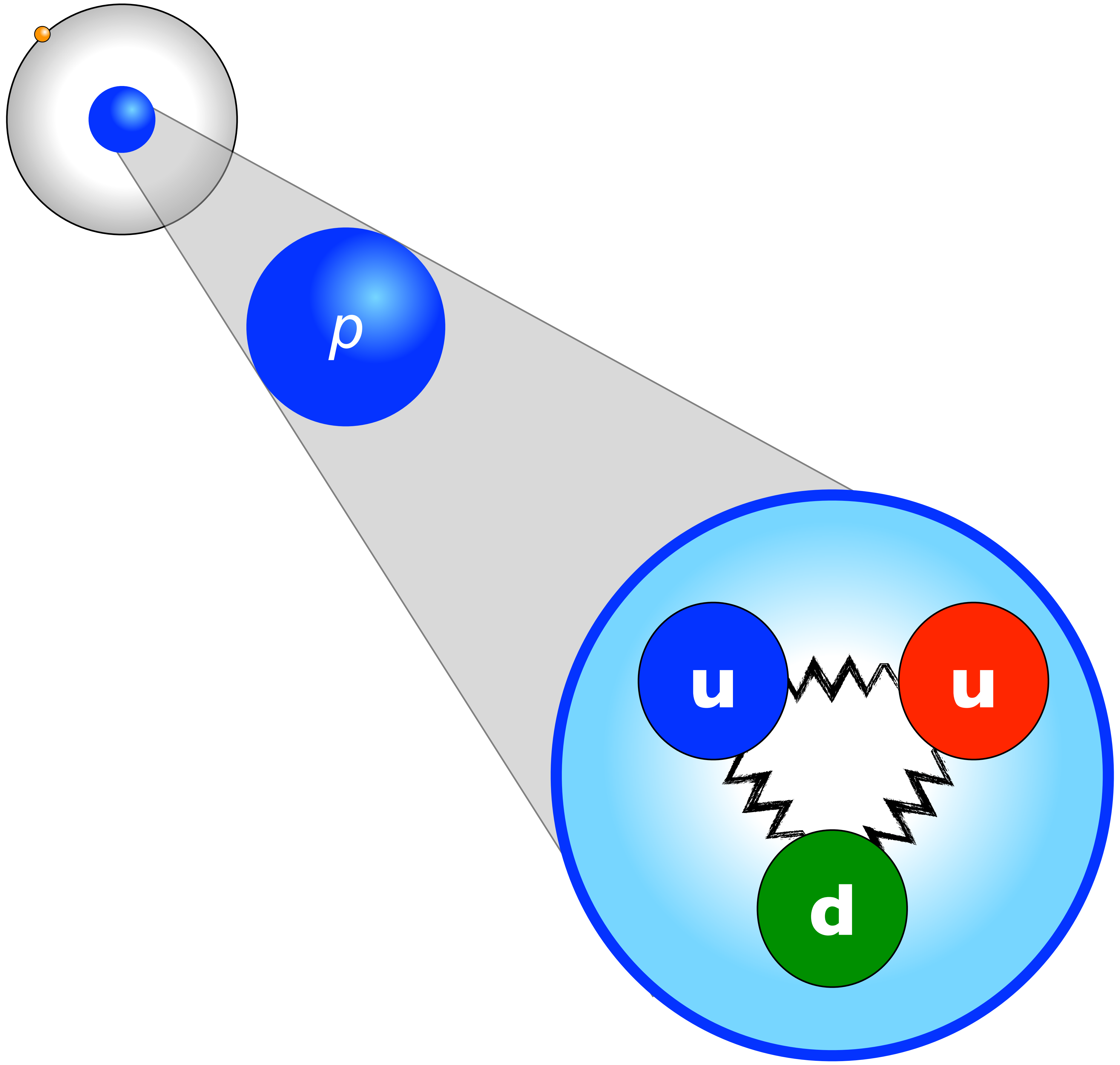


$$\Delta E \sim \frac{1}{n^2} - \frac{1}{m^2}$$

NATURE'S LANGUAGE

Protons/neutrons

- 99% of the mass of visible matter in the universe
- bound and interact via **strong force**
- part of a large class of particles: **hadrons**
- building blocks: **quarks** & **gluons**

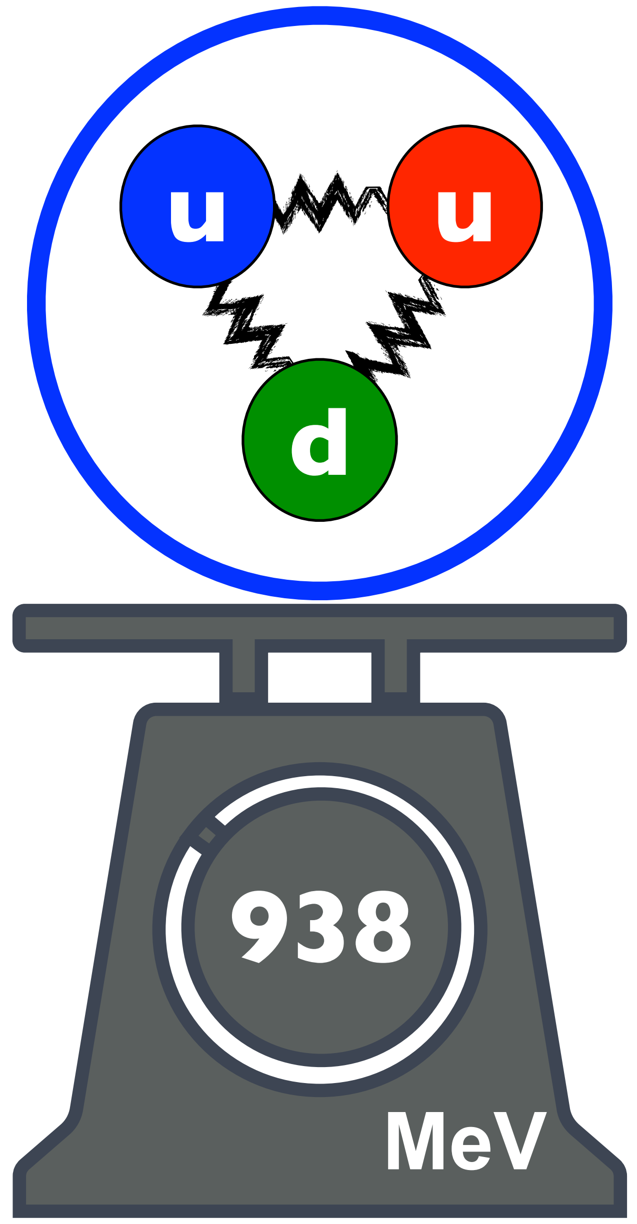


NATURE'S LANGUAGE

Mass puzzle:

- quarks are too light ⇒ constituent quark model?
- Lattice QCD[1]: ~90% of mass is generated by dynamical effects

Higgs mechanism

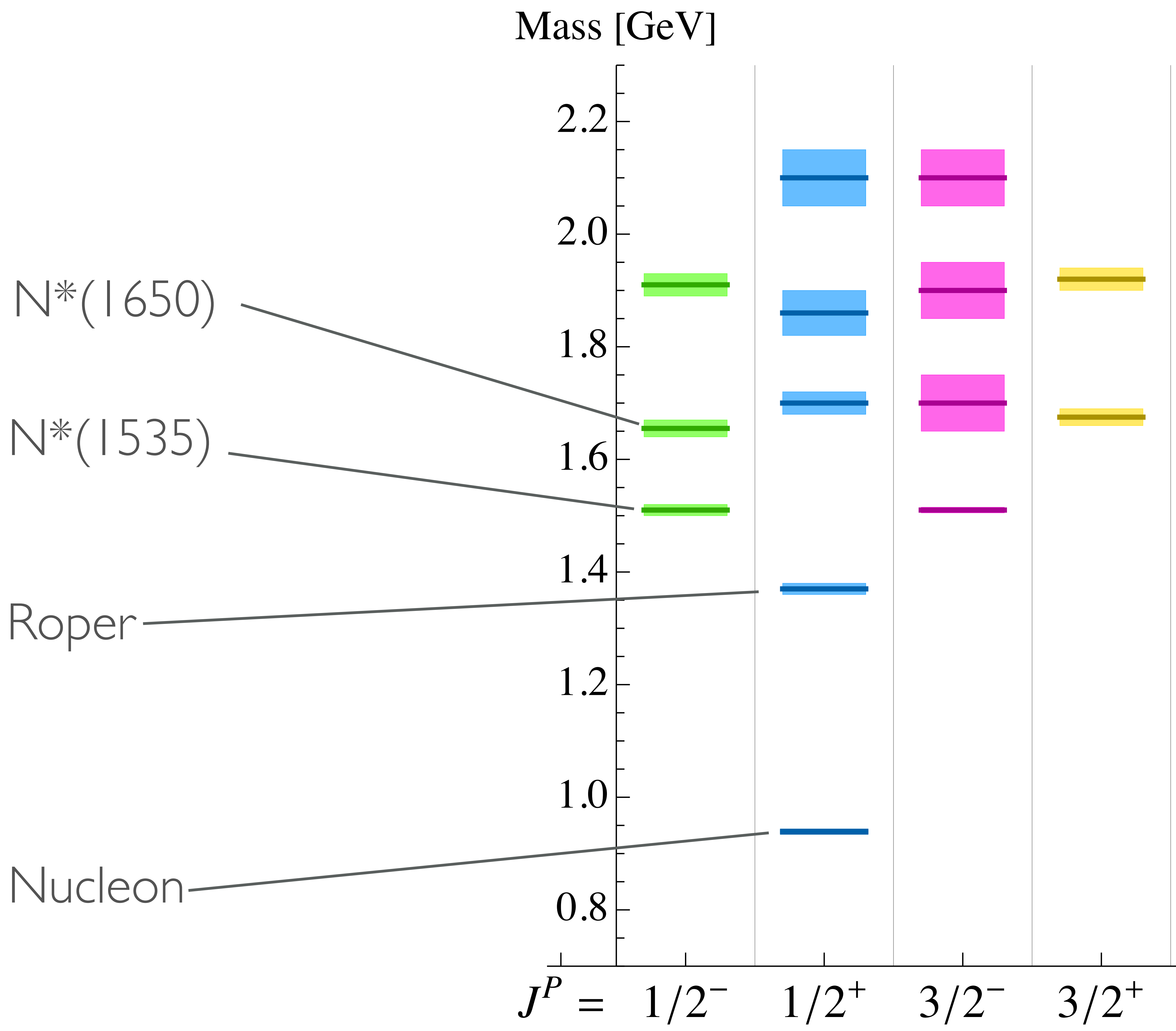


Dynamics of gluons and quarks

1) Durr et al. *Science* 322 (2008)

HADRON SPECTRUM

- PDG: ~100(50) excited meson(baryon) states (****)

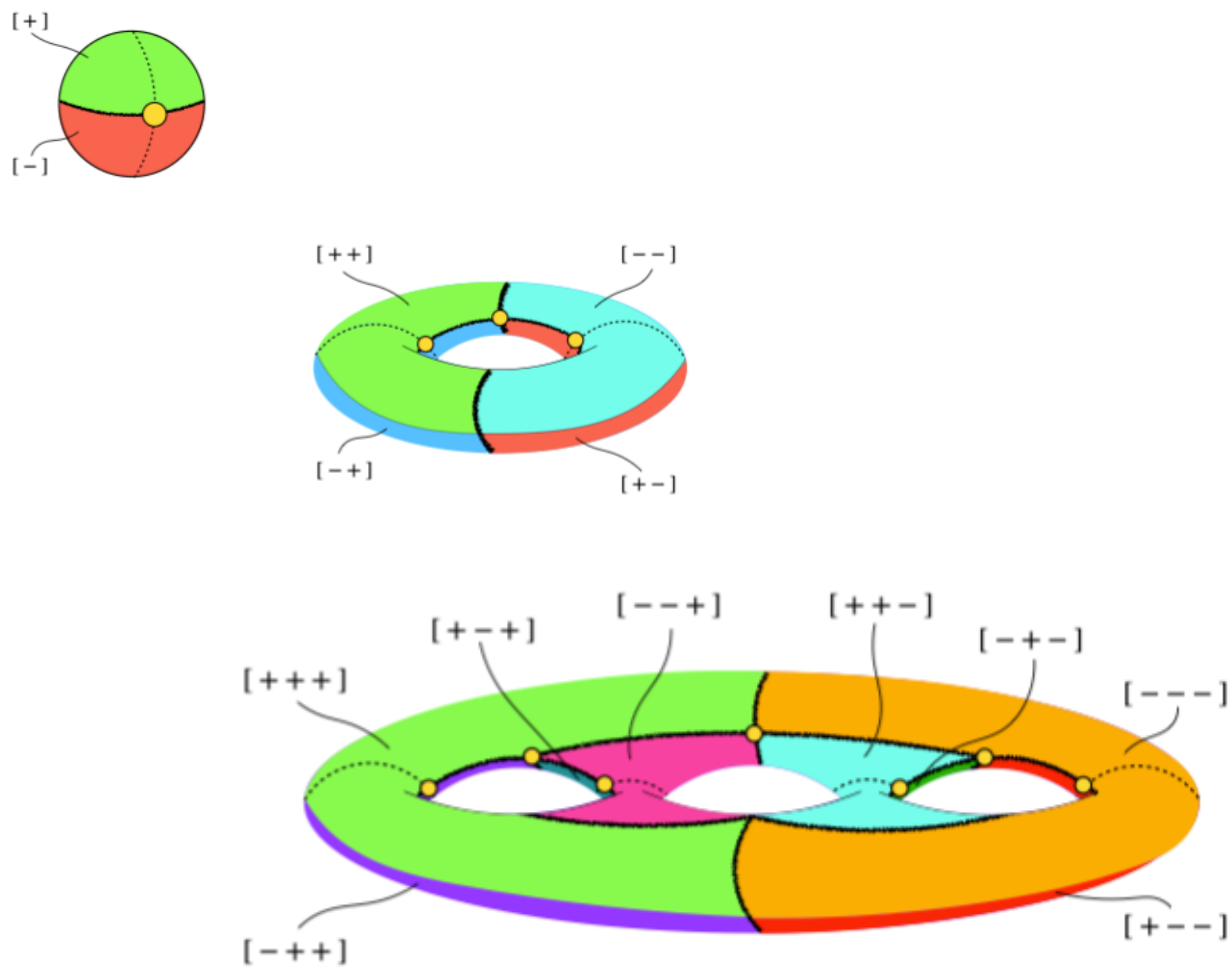


Values.: Particle Data Goup (**Workman** et al.)

HADRON SPECTRUM

- reaction-independent (*universal*) parameters:

  > poles on the Riemann Surface



MM/Meißner/Urbach 2206.01477 under review in Phys. Rept.

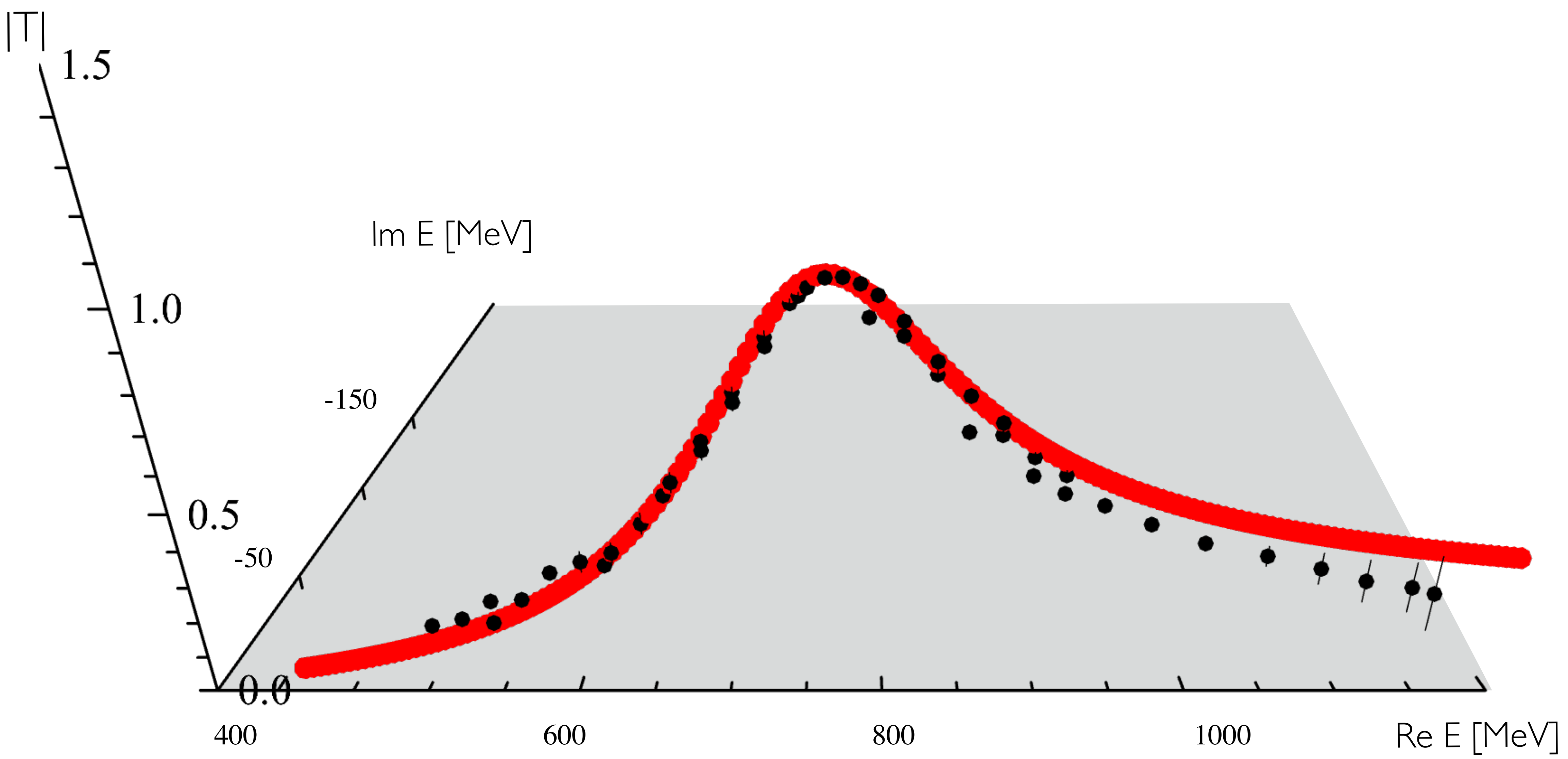
HADRON SPECTRUM

- physical information (**E** $\in \mathbb{R}$)

  > theory -- Lattice QCD (review[1])

  > experiment

$\rho \to \pi\pi$



Data: Estabrooks et al. NPB 79 (1974); Protopopescu et al. PRD 7 (1973);

1) MM/Meißner/Urbach 2206.01477 under review in Phys. Rept.

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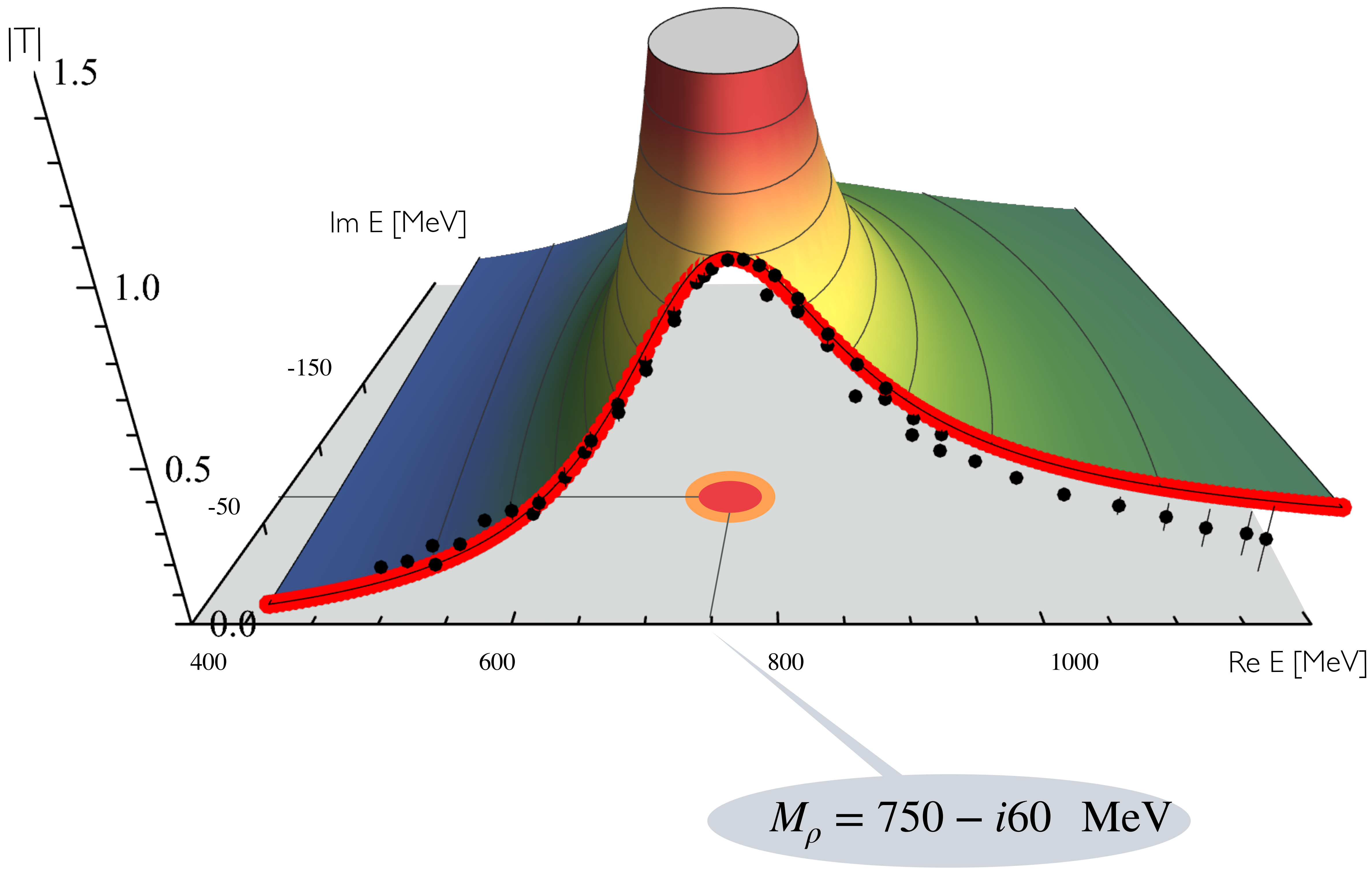

1) MM/Meißner/Urbach 2206.01477 under review in Phys. Rept.

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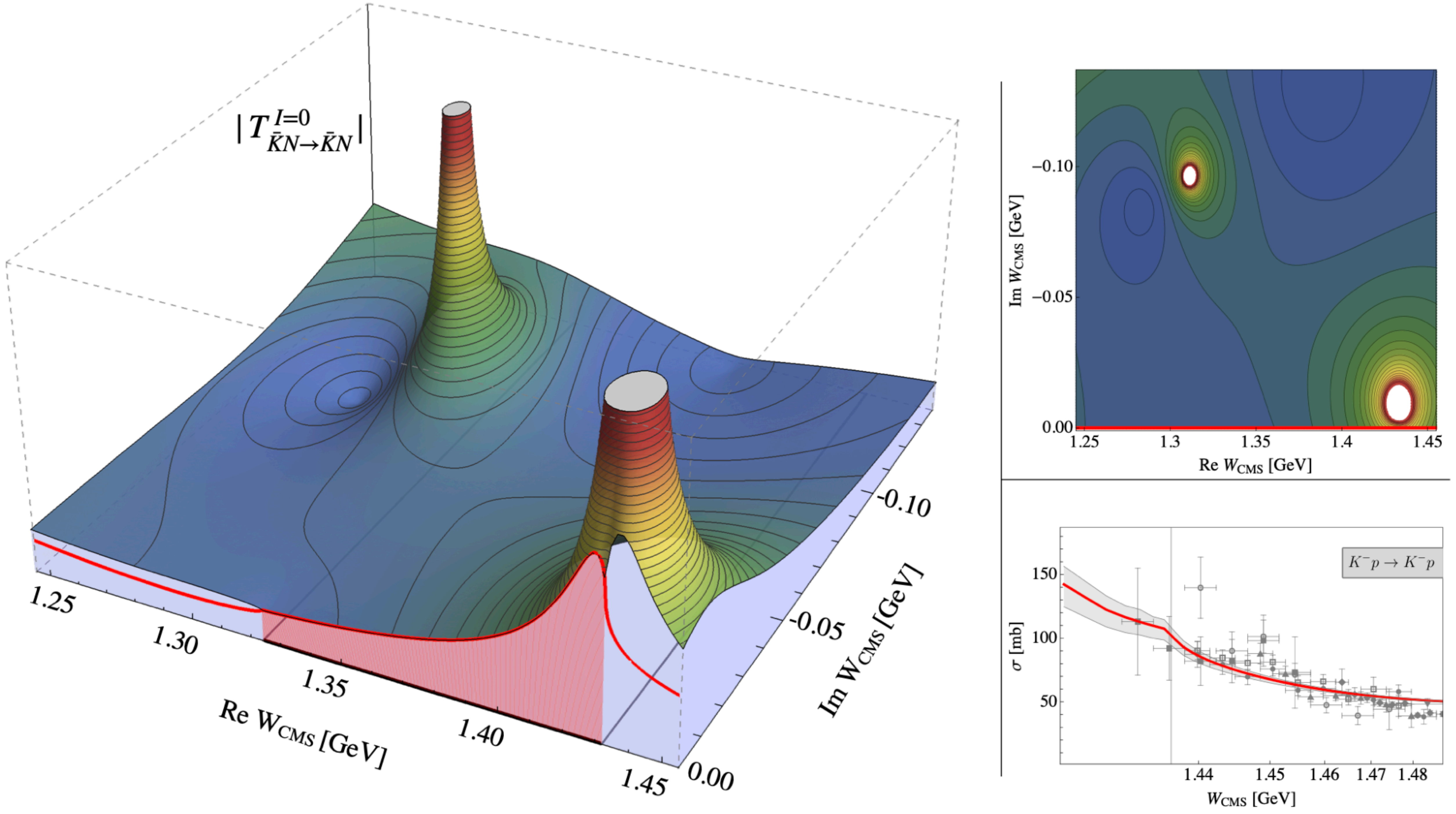
HADRON SPECTRUM

- physical information (**E** $\in \mathbb{R}$)

  > theory -- Lattice QCD (review[1])

  > experiment

$\Lambda(1405)$



MM Eur.Phys.J.ST 230 (2021)

1) MM/Meißner/Urbach 2206.01477 under review in Phys. Rept.

HADRON SPECTRUM

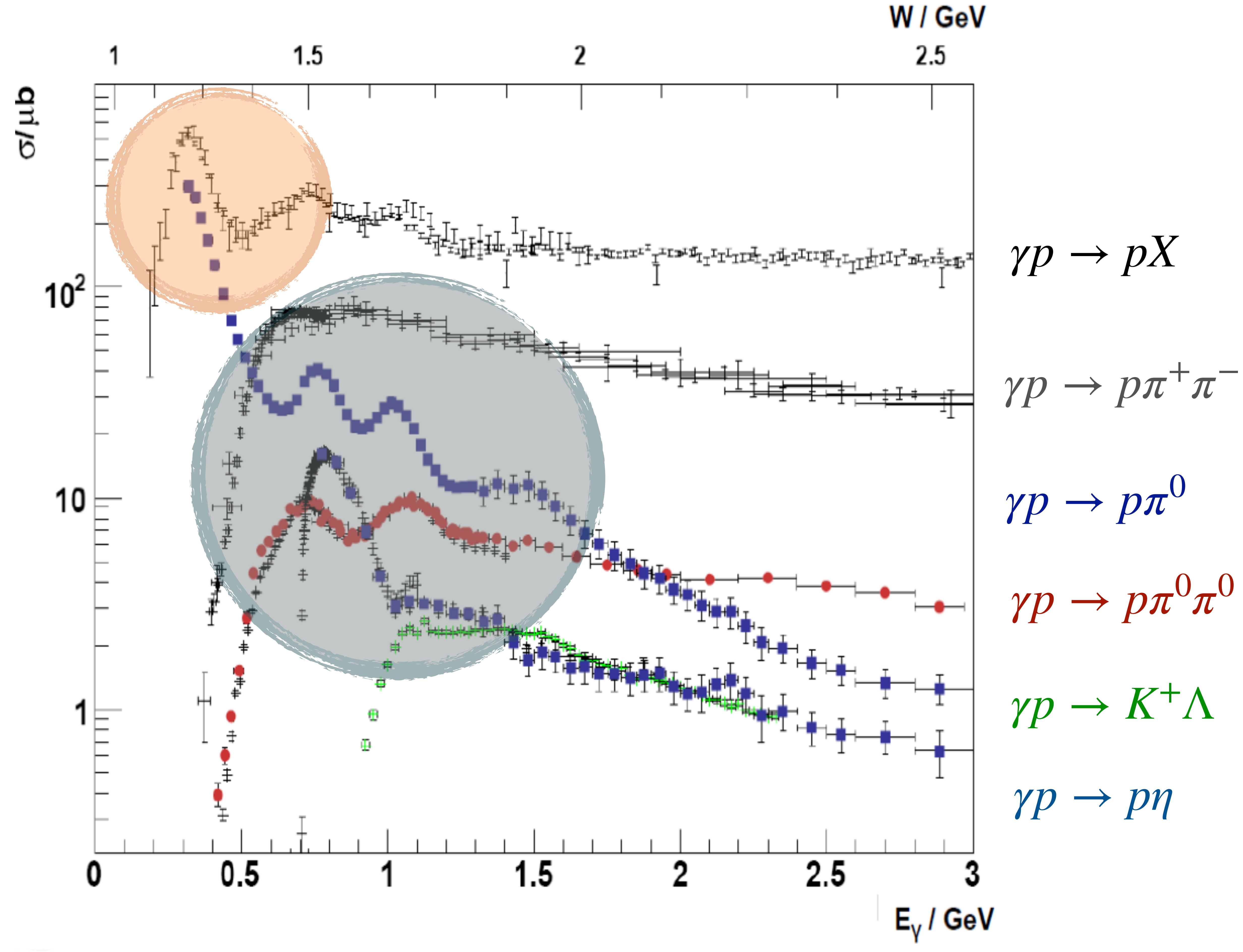
Photon-induced excitation

via **meson photo-/electroproduction**

> large amount of data (10^5 for $\gamma p \to \pi N$)

> bumps are **not** necessarily resonances

> many more data to emerge at JLab[1] (Q^2=5-12 GeV^2)



Data: Jefferson Laboratory, ELSA, MAMI

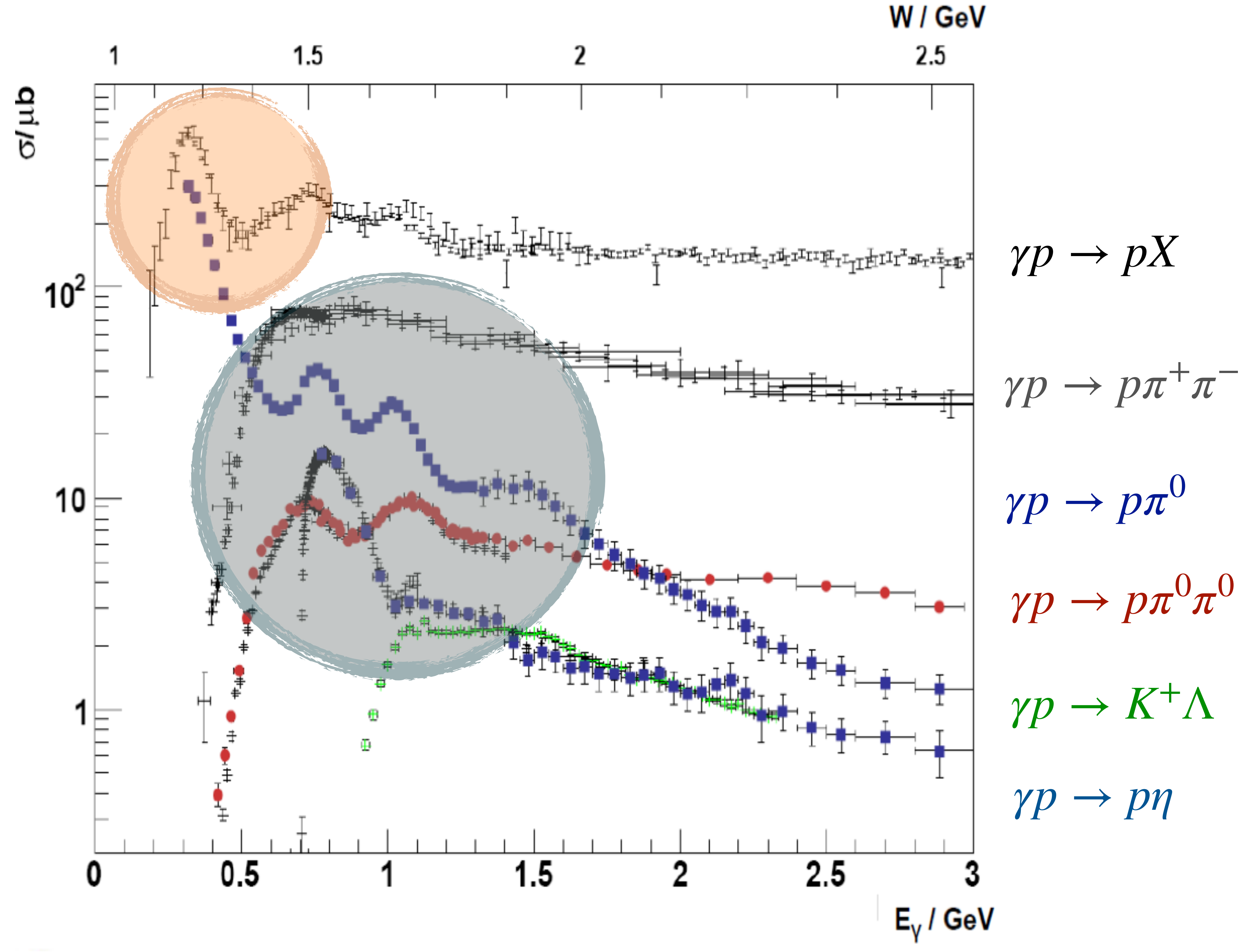
1) Carman, Joo, Mokeev, Few Body Syst. 61, 29 (2020) … ; [CLAS] *Phys.Rev.C* 105 (2022) 065201; …

HADRON SPECTRUM

Key questions:

> can we describe the data consistently with the scattering data?

> can we extract universal information about the hadron spectrum?



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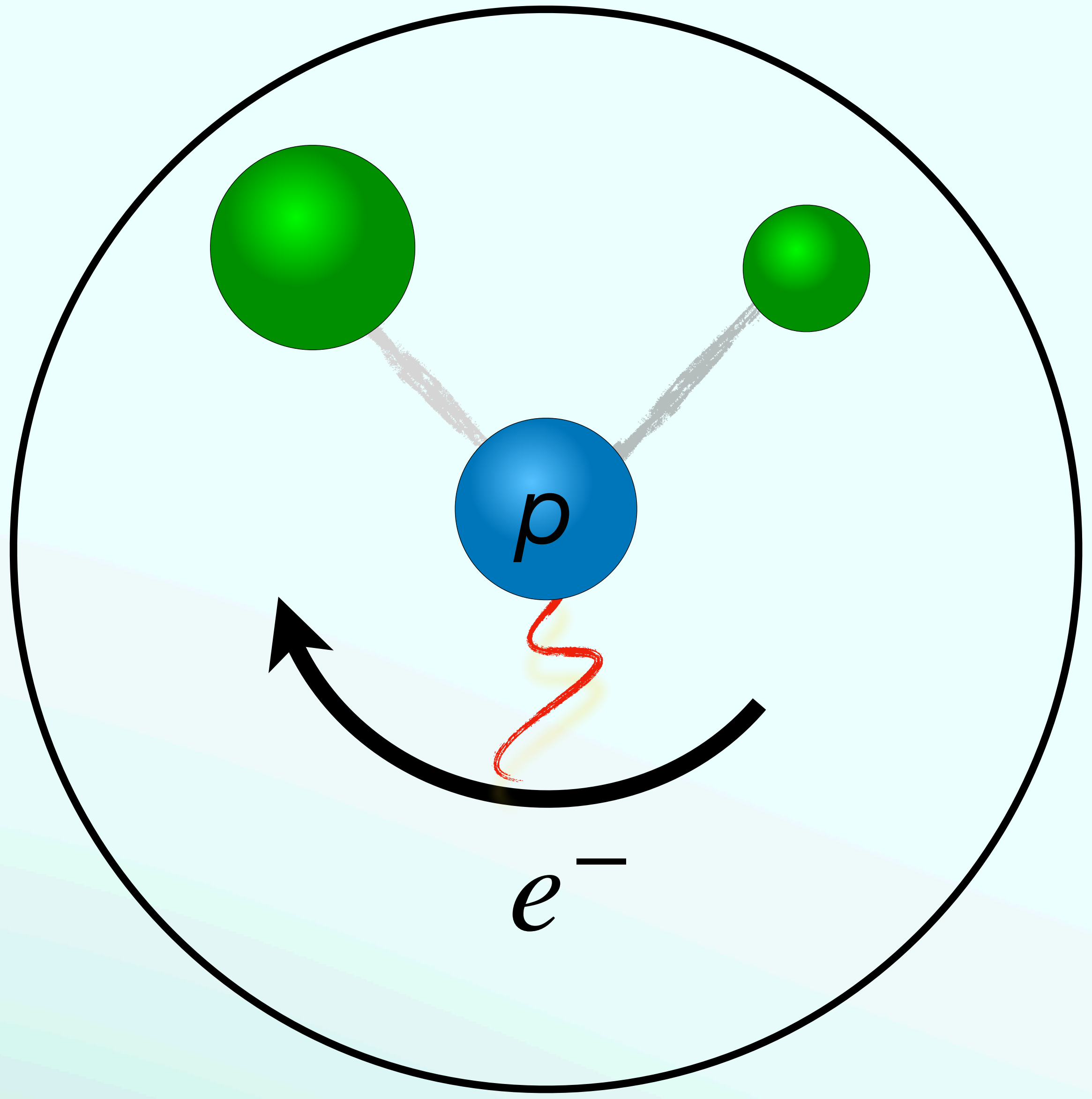


THEORY

[JBW] MM, M.Döring, C.Granados, H.Haberzettl, J.Hergenrather,
U.Meißner, D.Rönchen, I.Strakovsky, R.Workman

Phys.Rev.C 103 (2021) 6, 065204

EXISTING APPROACHES

- ANL-Osaka[1]
- (eta)(kaon)MAID[2]
- SAID[3] [Ron's talk]
- ...[4]

Some highlights

> Simultaneous description of pion photo- and electroproduction (MAID)

> Low-energy constraints from CHPT (chiral MAID)

> Roper form factor from single and double pion electroproduction[5]

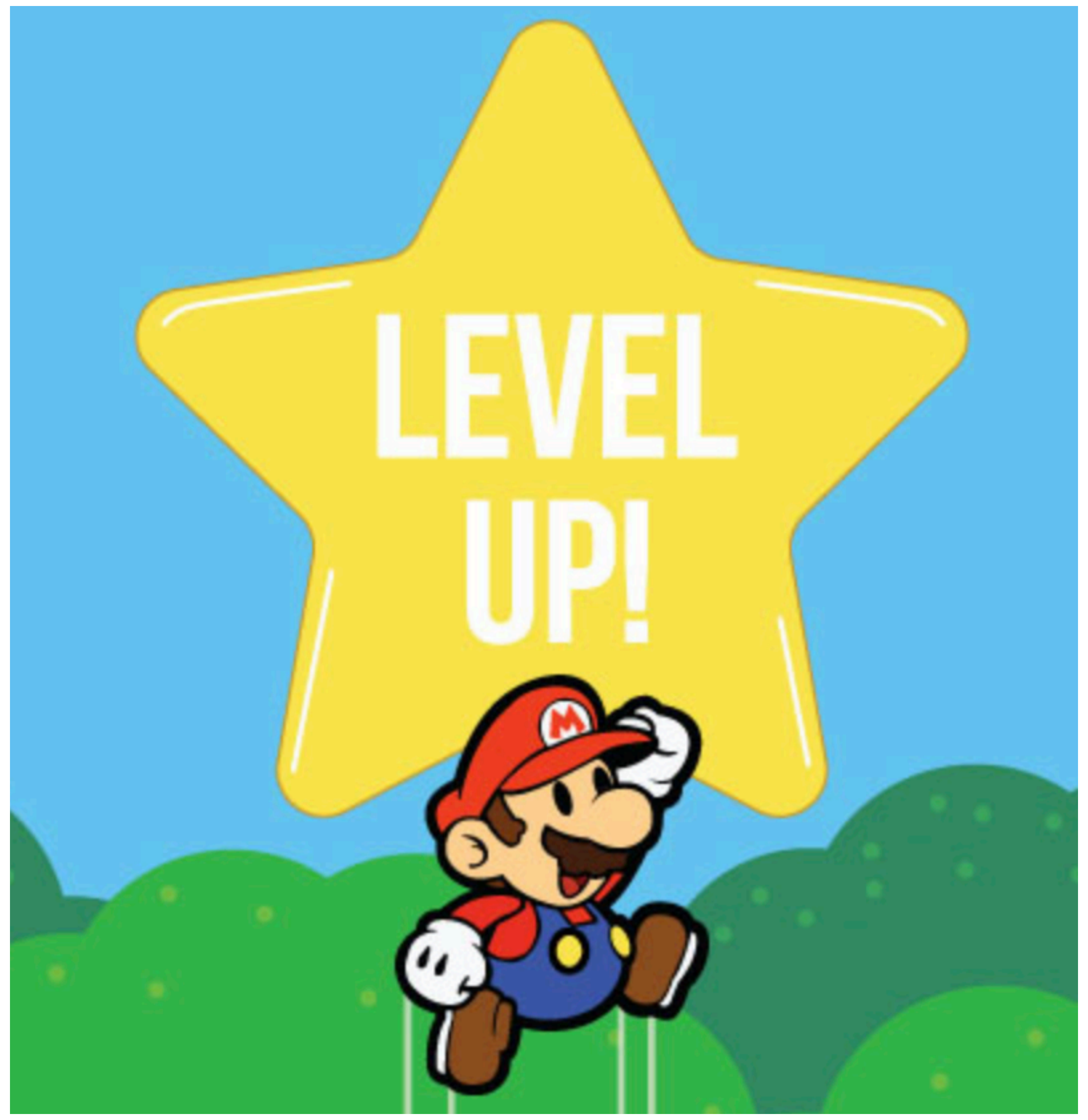
1) ANL-Osaka PRC 80(2009), Few-Body Syst. 59(2018),...
2) MAID2007, EPJA 34(2007) EtaMAID2018, EPJA 54(2018)
3) SAID, PiN Newsletter 16(2002)
4) Gent group PRC 89(2014),... Aznauryan et al., PRC 80(2009), IJMP(2013),...

5) Burkert, Roberts, Rev.Mod.Phys. 91 (2019)

EXISTING APPROACHES

Level up the game

- coupled-channel approach. ***Universality*** ⇔ simultaneous description of πN, ηN, $K\Lambda$ channels
- threshold constraints, gauge invariance, ...
- constraints from scattering data



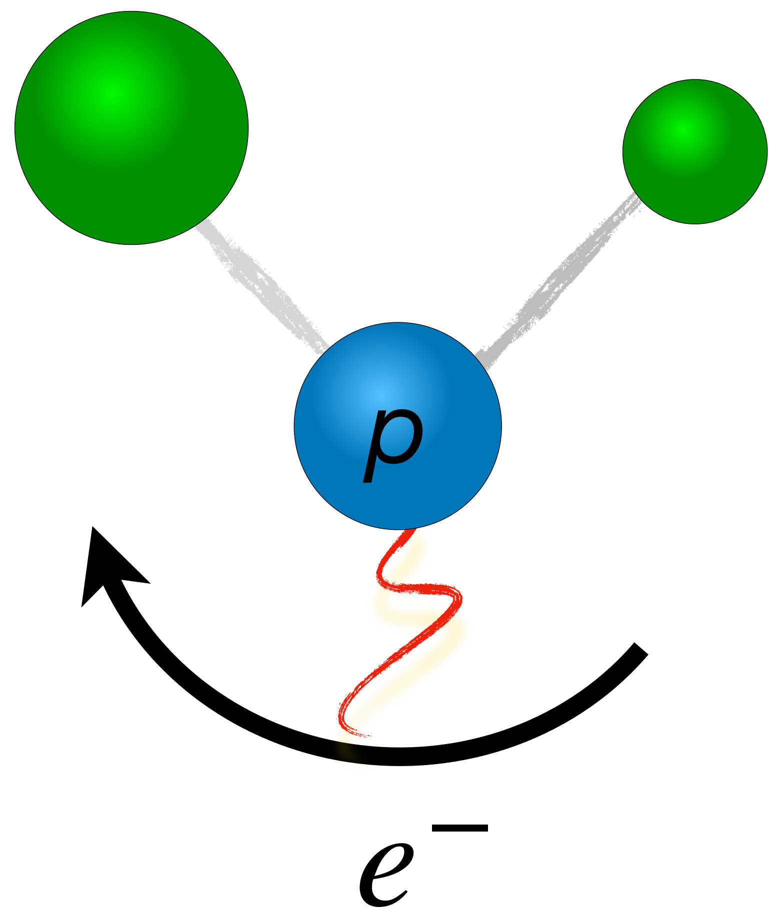
KINEMATICS

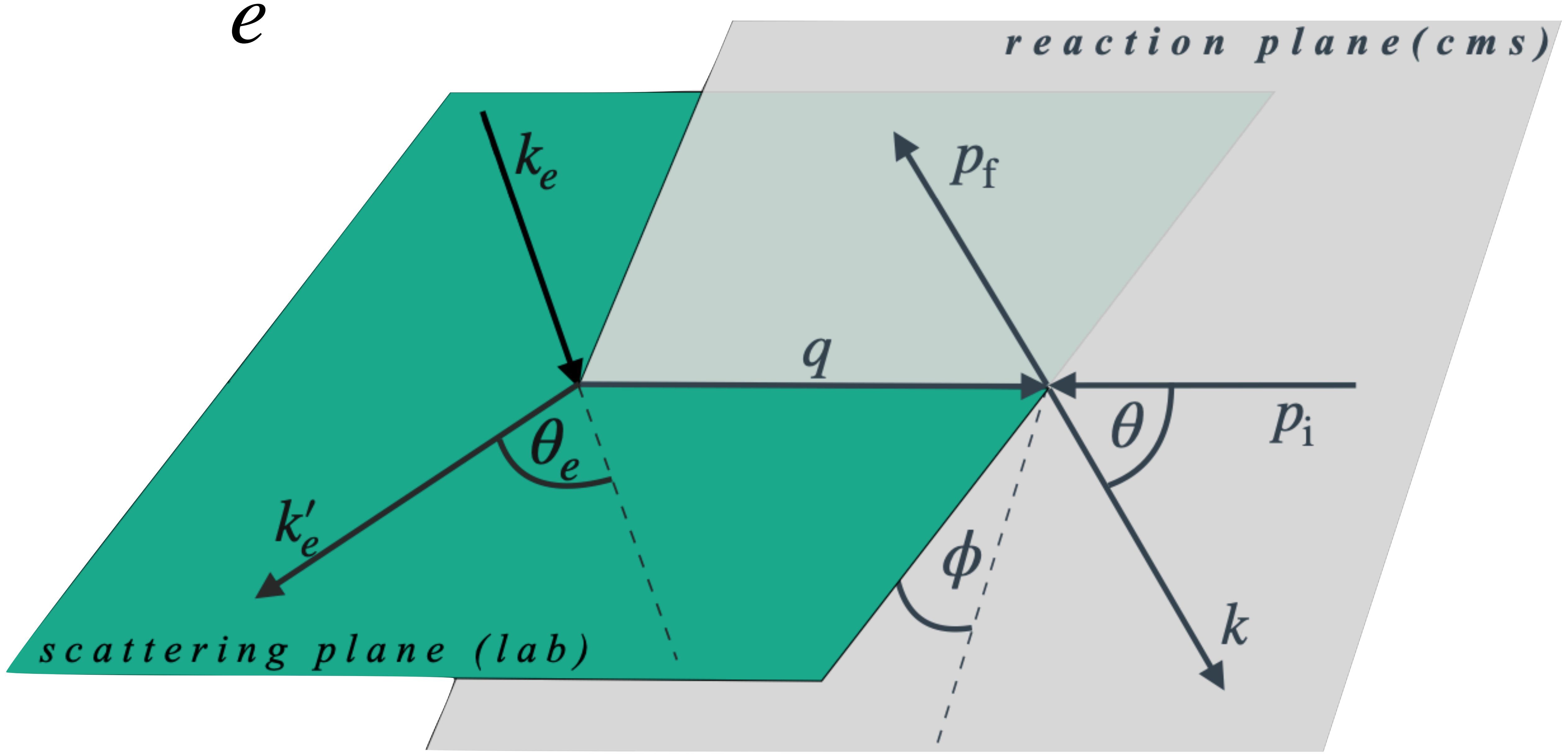
3*(2+3)-10 = five independent variables

- total energy: W
- photon virtuality: Q^2
- transverse photon polarization:

$$\epsilon = 1 + 2q_L^2/Q^2 \tan^2\theta_e/2$$

- production angles: θ,φ

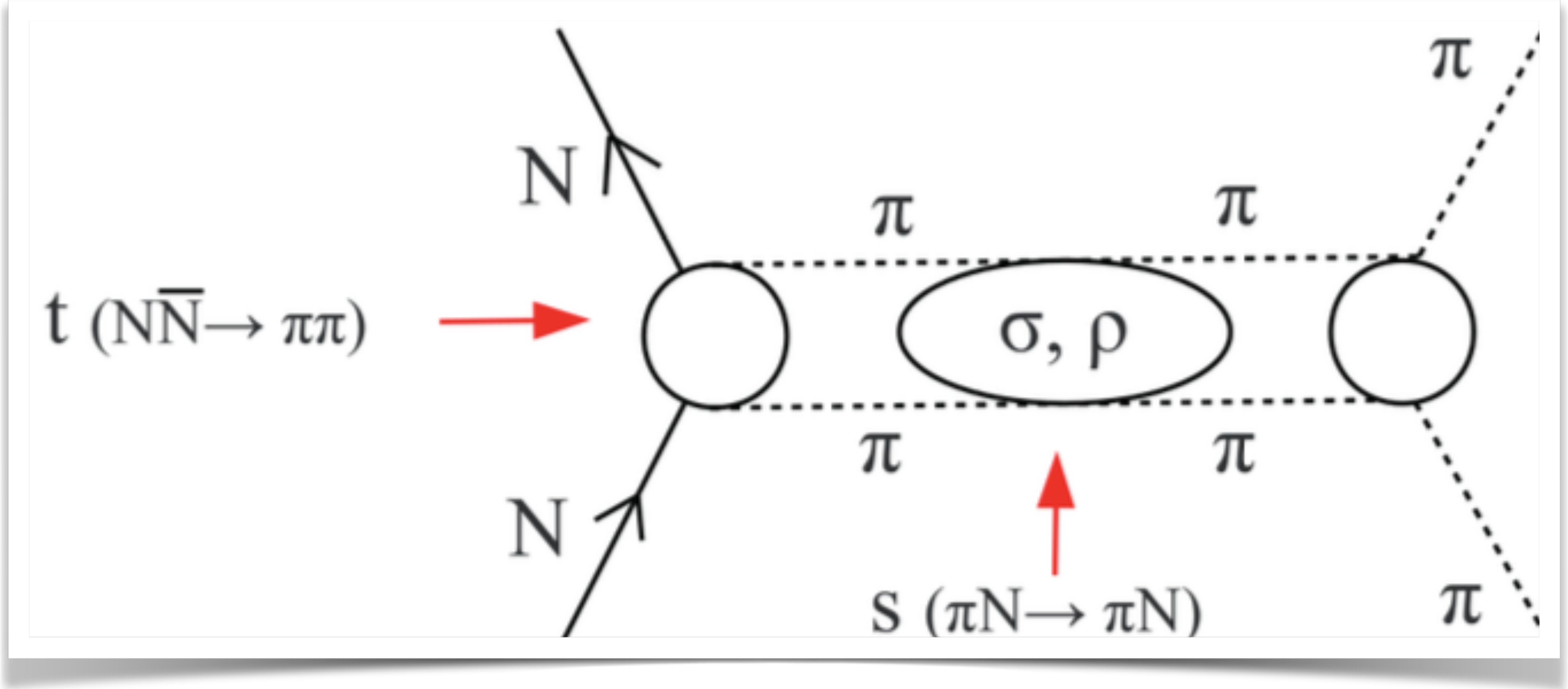




GENERAL PRINCIPLES

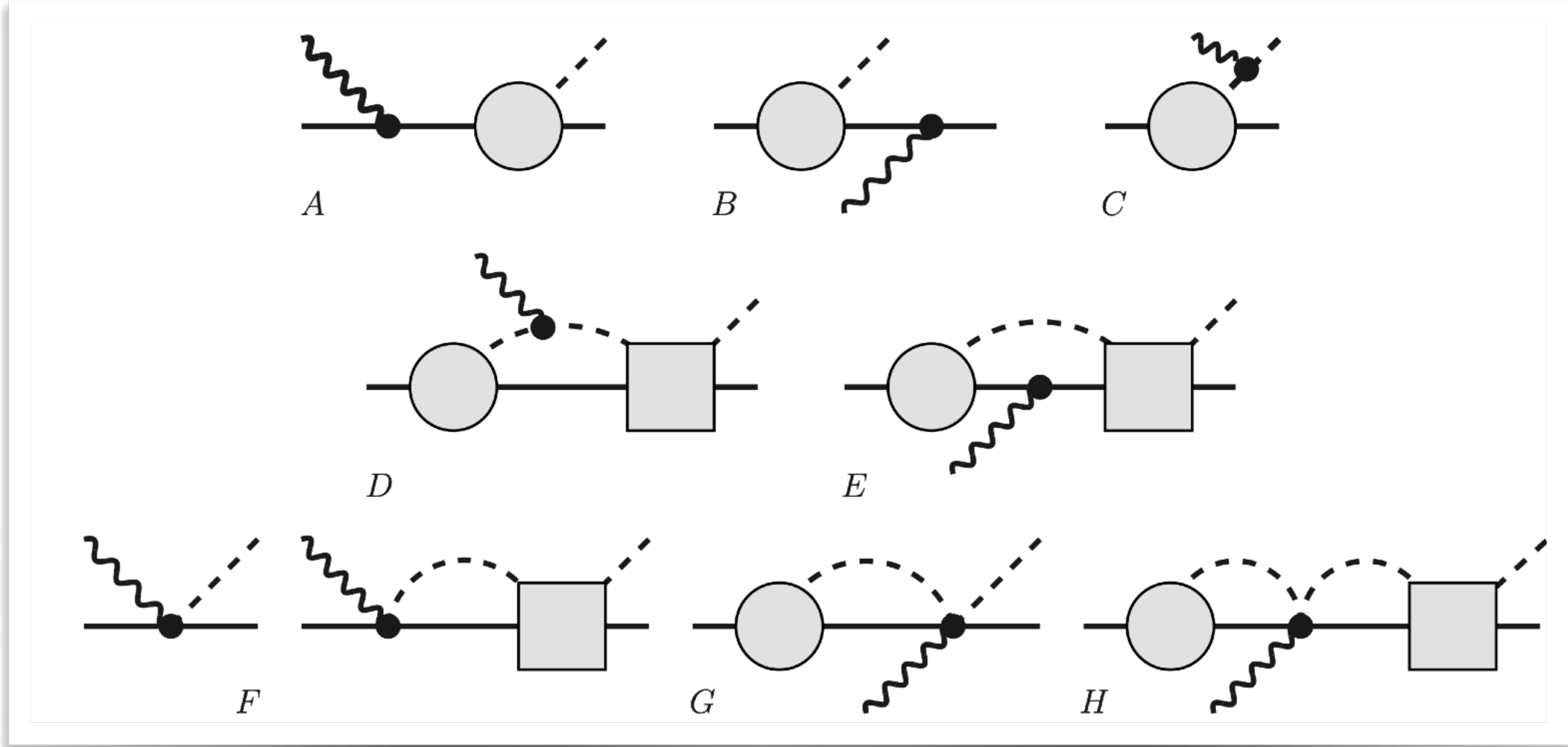
Pion-induced reactions

- Unitarity/Analyticity/Crossing symmetry
- Underlying objects: scattering amplitudes



Photon-induced reactions

- Final state unitarity/Gauge invariance[1]
- Underlying objects: transition matrix element



[1] Afnan et al.(1995) Kvinikhidze et al.(1999) Haberzettl(19xx-2021) Borasoy et al.(2007) Ruic et al.(2011) MM et al.(2012)

MULTIPOLES

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

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)

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

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)

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

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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)

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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)

MULTIPOLES

Gauge invariance

- manifest implementation[1]
- include by design (this work)

Ward-Takahashi identity:

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

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

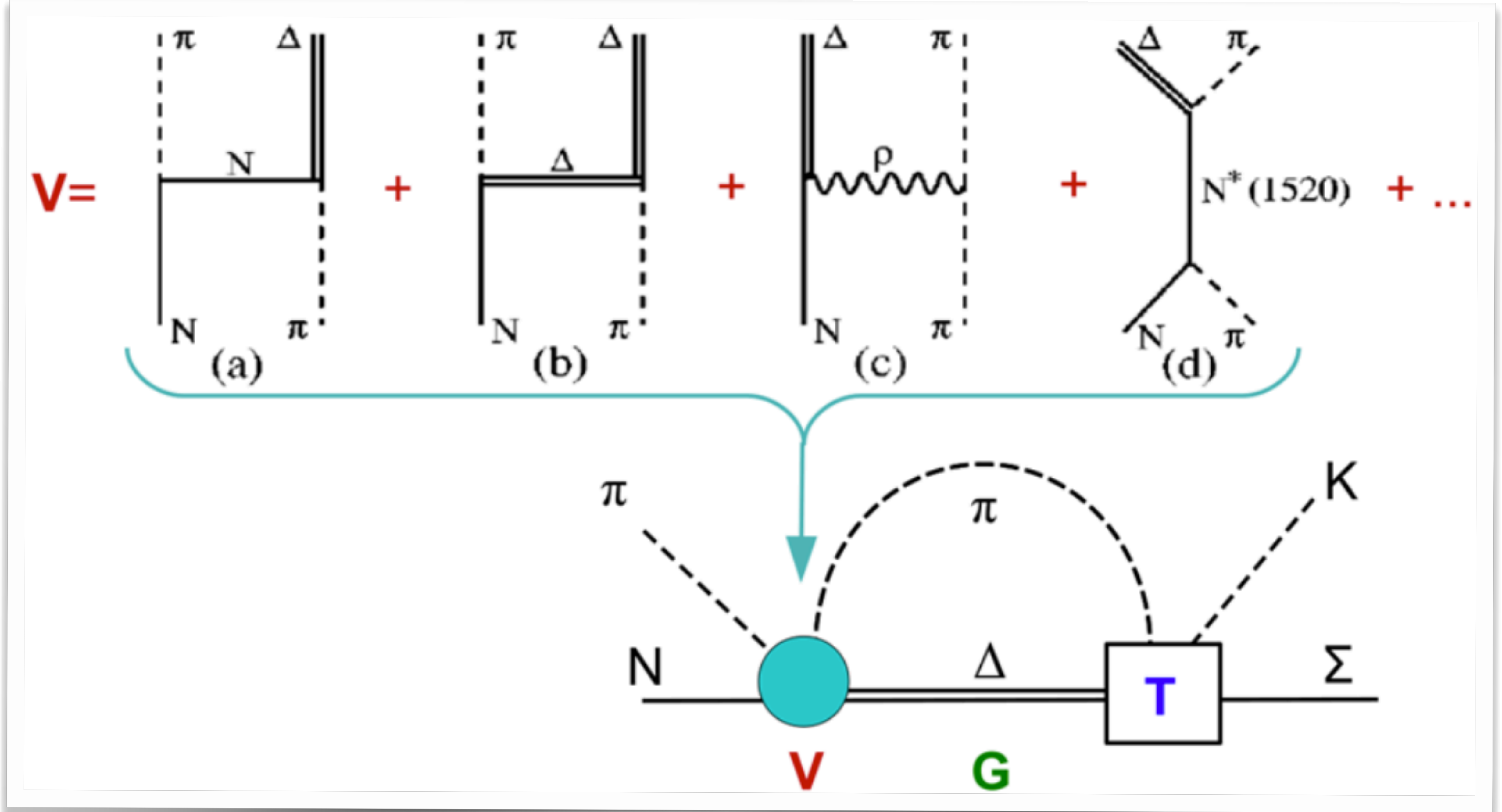
1) Afnan et al.(1995) Kvinikhidze et al.(1999) Haberzettl(19xx-2021) Borasoy et al.(2007) Ruic et al.(2011) MM et al.(2012)

MULTIPOLES

Final-state unitarity and photoproduction limit

- start from Jülich-Bonn coupled-channel model[1]
  - > Potential *V* from an effective Lagrangian
  - > T^P *genuine resonance states* in the s-channel diagrams
  - > T^{NP} *dynamically generated poles:* t/u-channel

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



1) Rönchen et al., EPJA 49, 44 (2013)

Fig: D. Rönchen

MULTIPOLES

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

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

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

1) Siegert(1973) Amaldi et al.(1979) Tiator(2016)
2) Tiator et al.(2017)
3) Landay et al.(2017) (2019)

MULTIPOLES

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Siegerts's theorem[1]
...at pseudo-threshold:

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

1) Siegert(1973) Amaldi et al.(1979) Tiator(2016)
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(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

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

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Siegerts's theorem[1] ...at pseudo-threshold:

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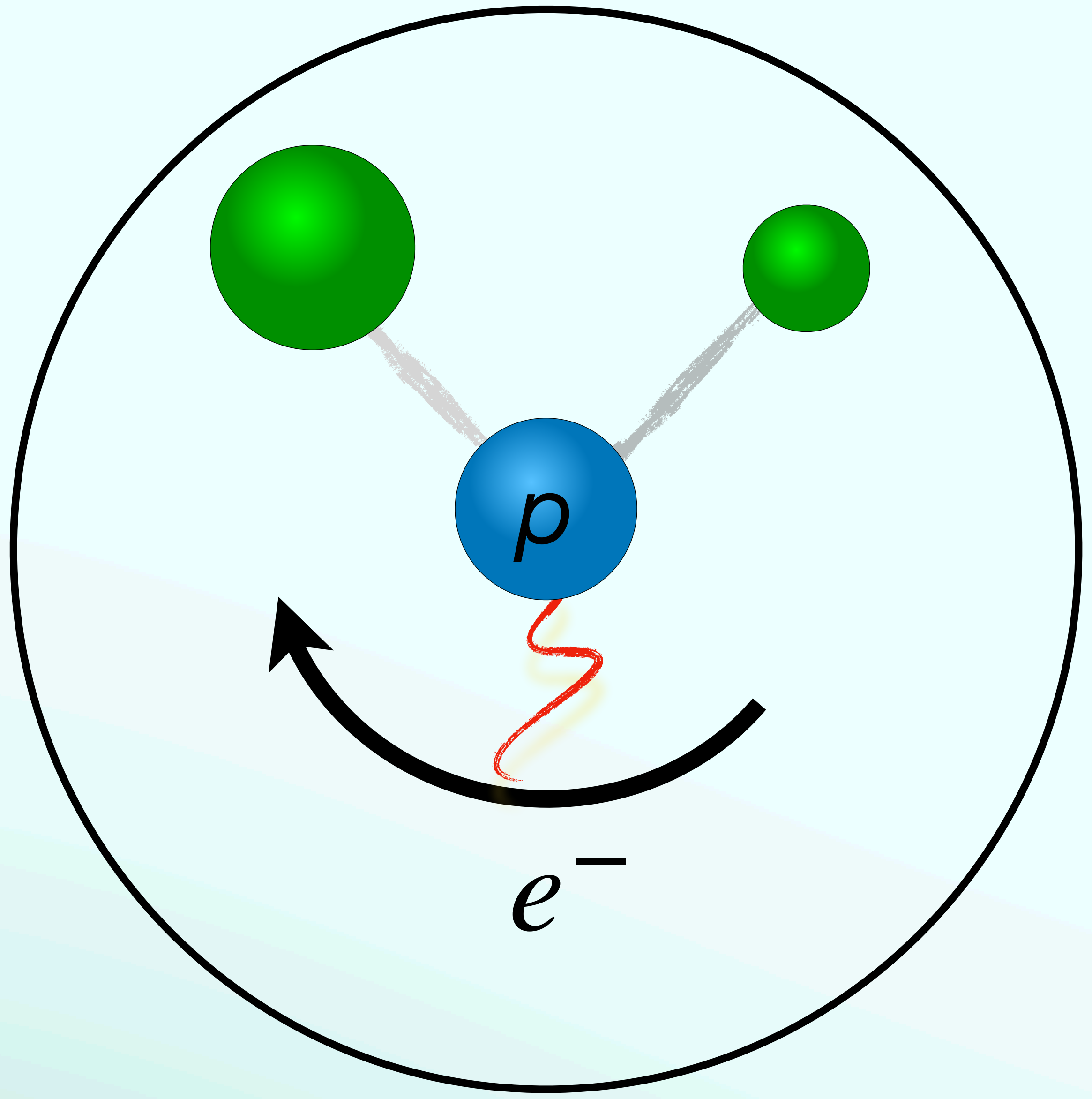
Parametrization dependence due to incomplete data

> even for a truncated complete electroproduction experiment[2]

> in future: Bias-variance tradeoff with statistical criteria[3]

1) Siegert(1973) Amaldi et al.(1979) Tiator(2016)
2) Tiator et al.(2017)
3) Landay et al.(2017) (2019)



RESULTS

[JBW] MM, M.Döring, C.Granados, H.Haberzettl, J.Hergenrather, Ulf-G. Meißner, D.Rönchen, I.Strakovsky, R.Workman

Phys.Rev.C 103 (2021) 6, 065204
Phys.Rev.C 106 (2022) 015201

INTERACTIVE WEB INTERFACE: https://jbw.phys.gwu.edu

DEGREES OF FREEDOM

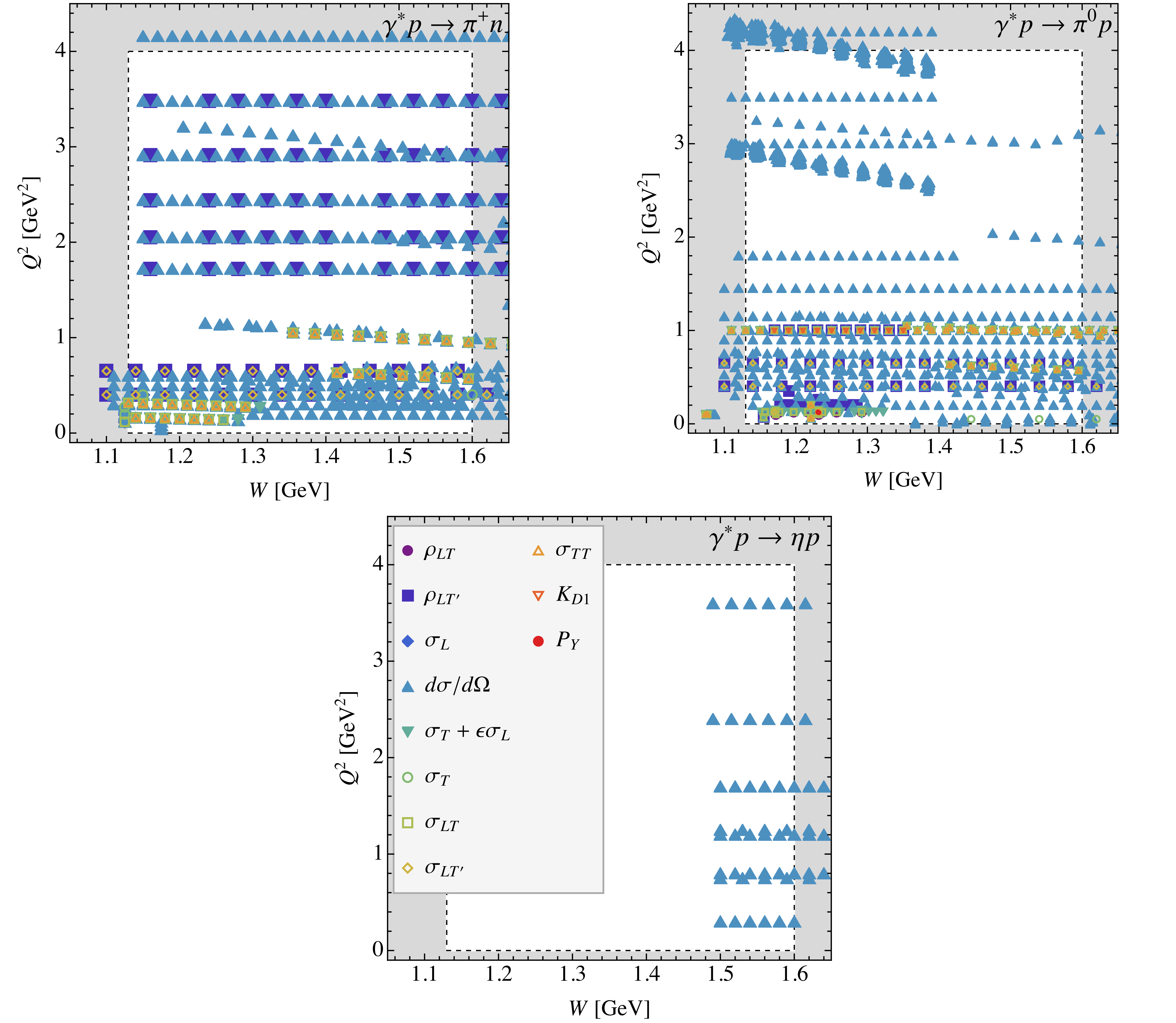
Data (1.13 < W/GeV< 1.6, Q^2<4 GeV^2)

45k($\pi^0 p$) + 37k($\pi^+ n$) + 2k(ηp) = 84k data

11 observable types

Parameters (S/P/D waves)

26 multipoles * (10..13 pars) = 257 pars

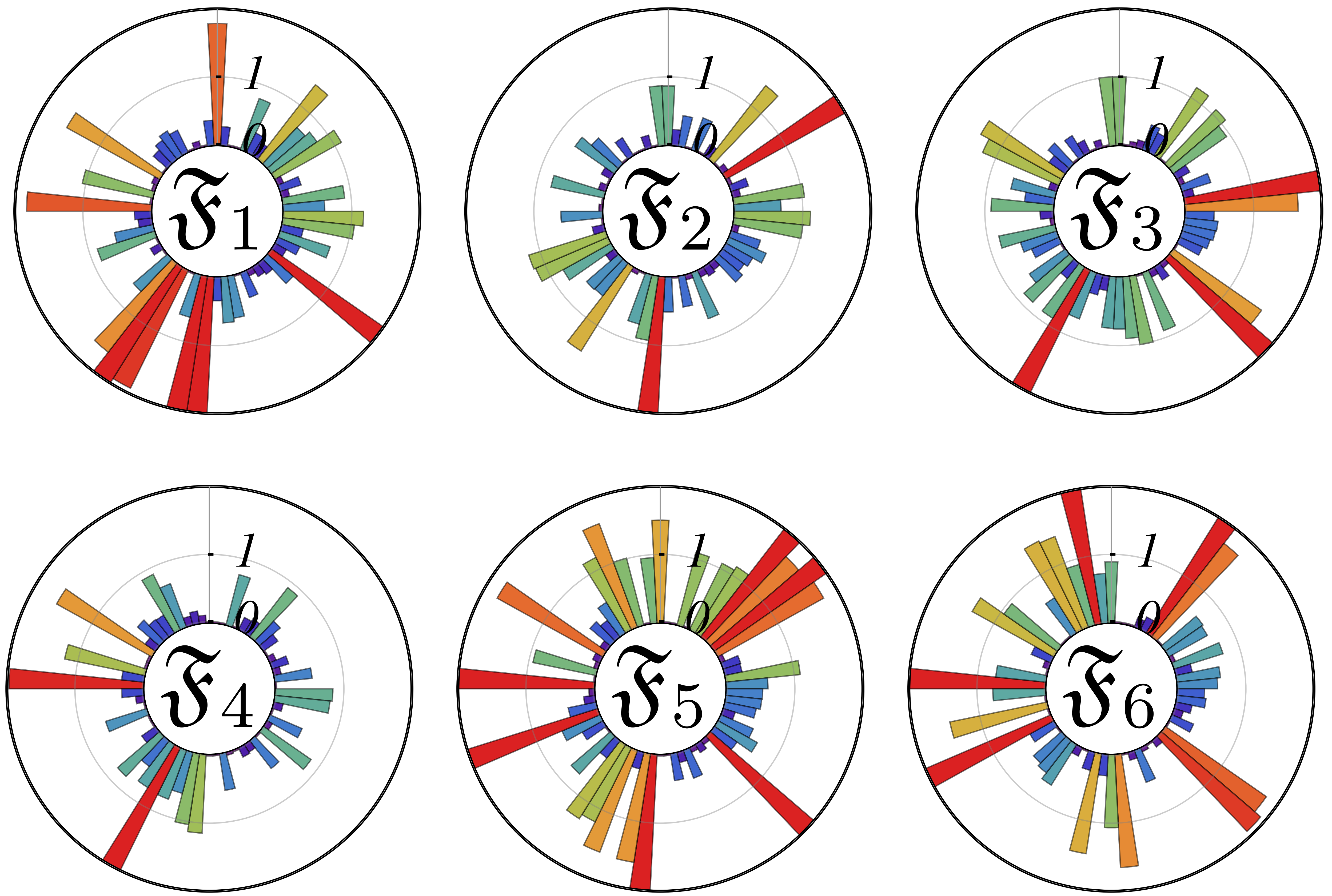


DEGREES OF FREEDOM

Systematic uncertainties:

- many local minima:

  > different fit strategies (sequential, all-in fits)



DEGREES OF FREEDOM

Systematic uncertainties:

- piN data is dominant:

  > weighted or unweighted fits

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

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

RESULTS

πN data fits:

> all strategies converge

> different minima (systematic uncertainties)

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}		$\rho_{LT'}$		$\chi^2_{\rm dof}$
	π^0p	π^+n	π^0p	π^+n	π^0p	π^+n	π^0p	π^+n	π^0p	π^+n	π^0p	π^+n	π^0p	π^+n	π^0p	π^+n	π^0p	π^+n	π^0p	π^+n	π^0p	π^+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**

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

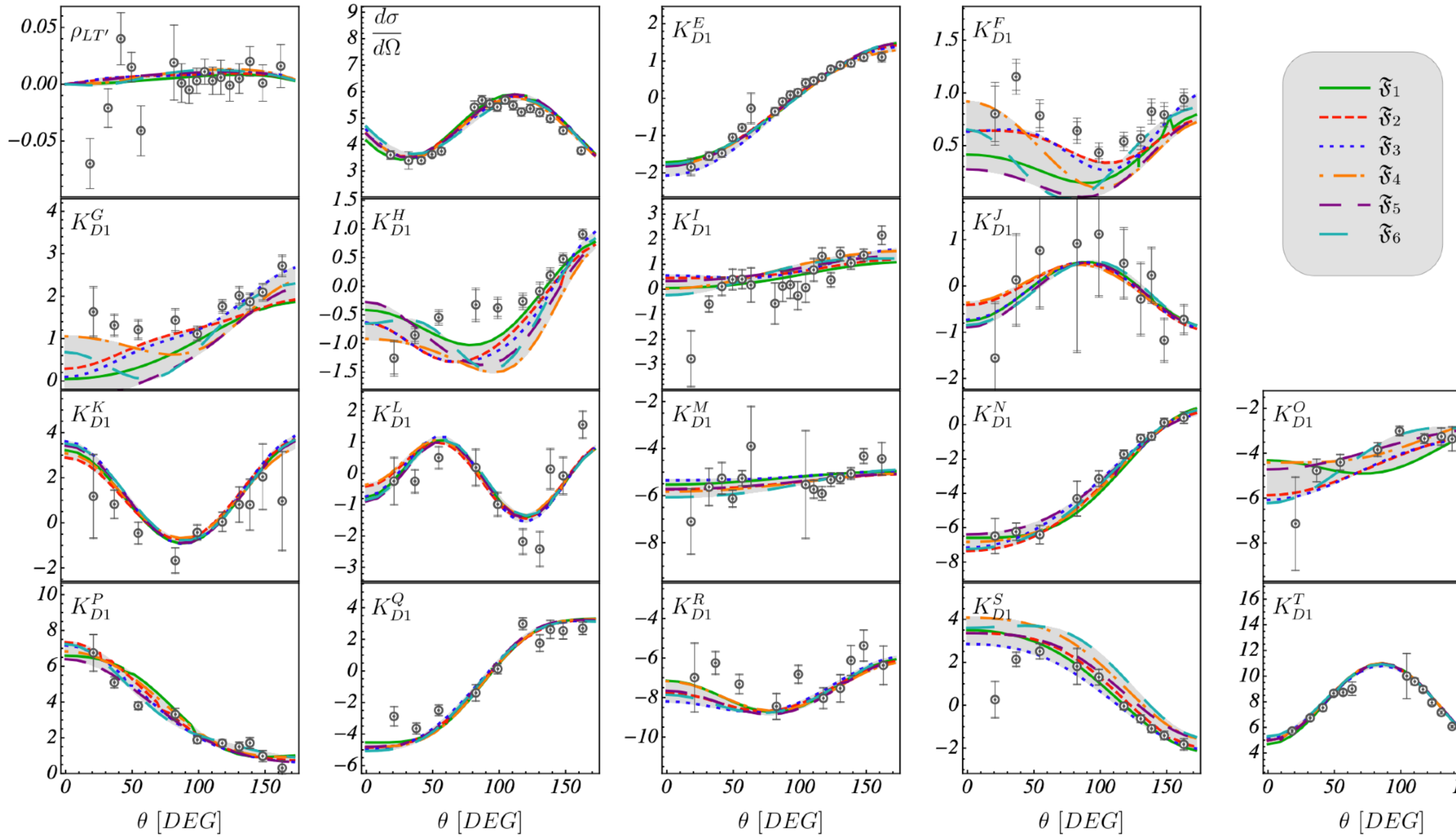
Data: Kelly et al.(2005)

RESULTS

πN data fits:

> all strategies converge

> different minima (systematic uncertainties)



Data: Kelly et al.(2005)

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

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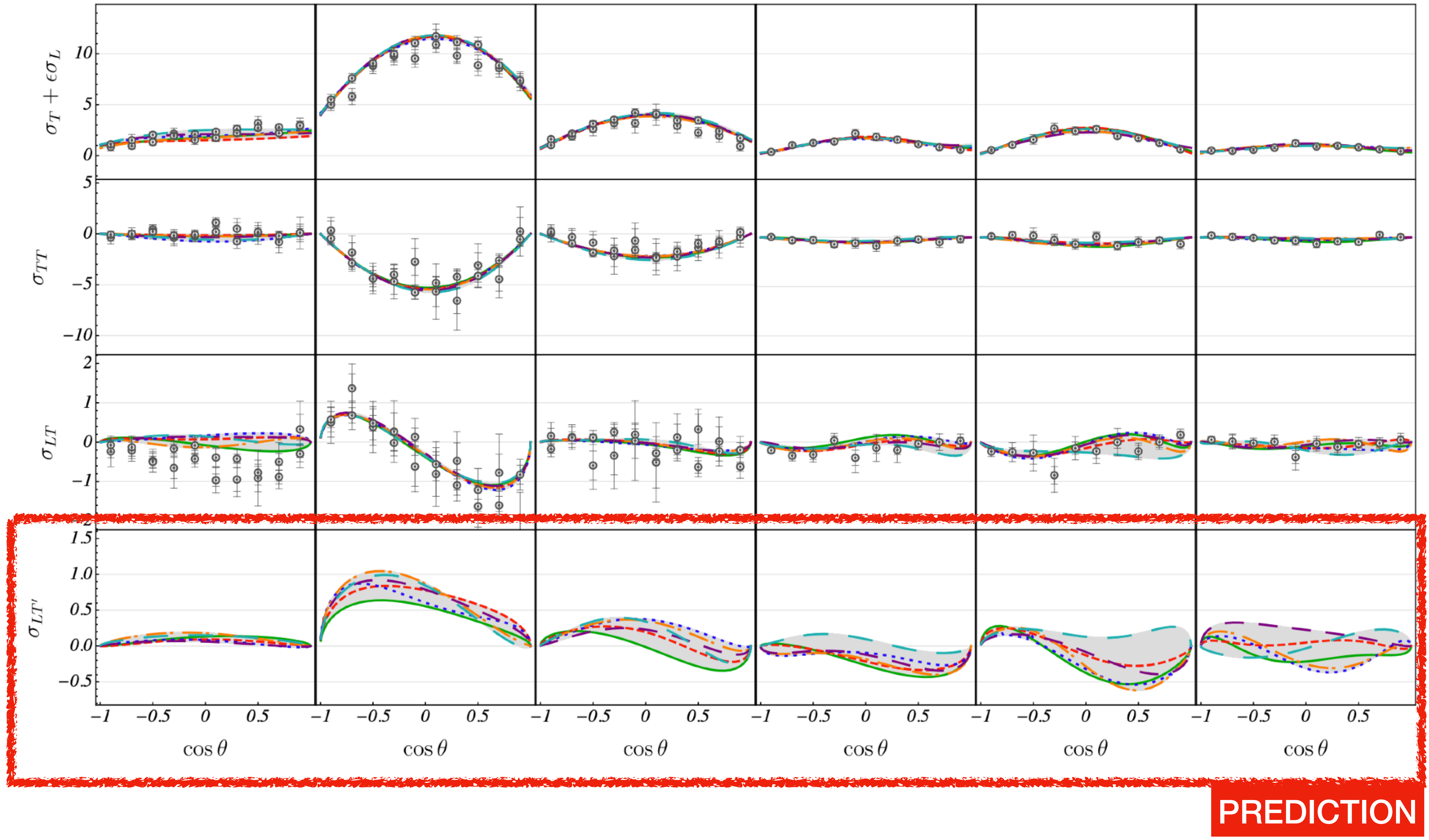


Data: Joo et al. [CLAS] PRC (2003), PRL (2002)

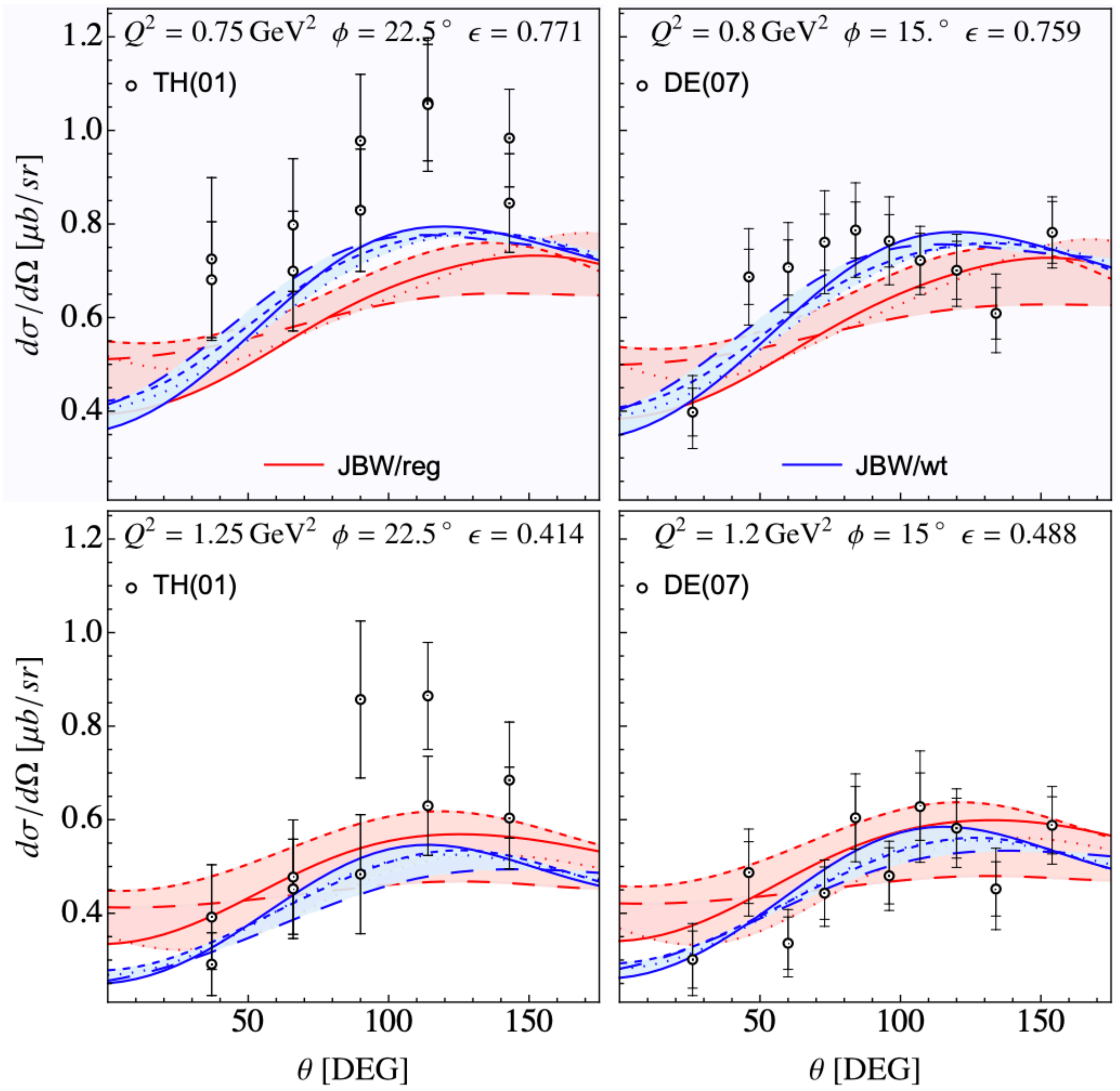
RESULTS

	χ^2/dof	$\chi^2_{\pi^0 p/\mathrm{data}}$	$\chi^2_{\pi^+ n/\mathrm{data}}$	$\chi^2_{\eta p/\mathrm{data}}$
$\mathfrak{F}_1^{\mathrm{reg}}$	1.66	1.68	1.61	1.77
$\mathfrak{F}_2^{\mathrm{reg}}$	1.73	1.71	1.71	2.29
$\mathfrak{F}_3^{\mathrm{reg}}$	1.69	1.69	1.66	1.89
$\mathfrak{F}_4^{\mathrm{reg}}$	1.69	1.7	1.64	2.05
$\mathfrak{F}_1^{\mathrm{wt}}$	1.54	1.74	1.63	1.25
$\mathfrak{F}_2^{\mathrm{wt}}$	1.63	1.82	1.79	1.27

η*N* data fits:

> all strategies converge

> different minima (systematic uncertainties)



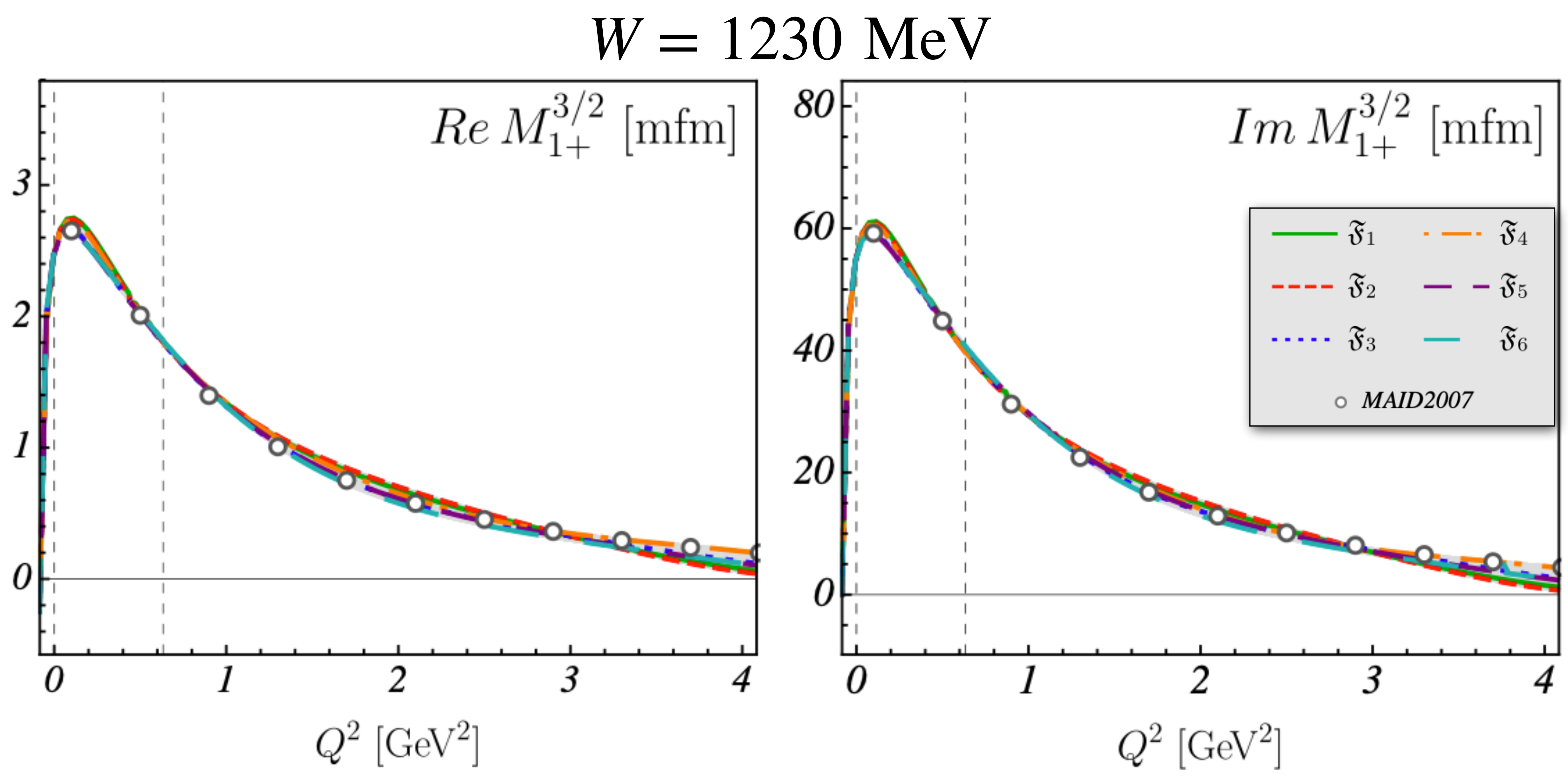
Data: H. Denizli et al. (CLAS) PRC 76, 015204 (2007); Thompson et al. (CLAS), PRL86, 1702–1706 (2001)

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

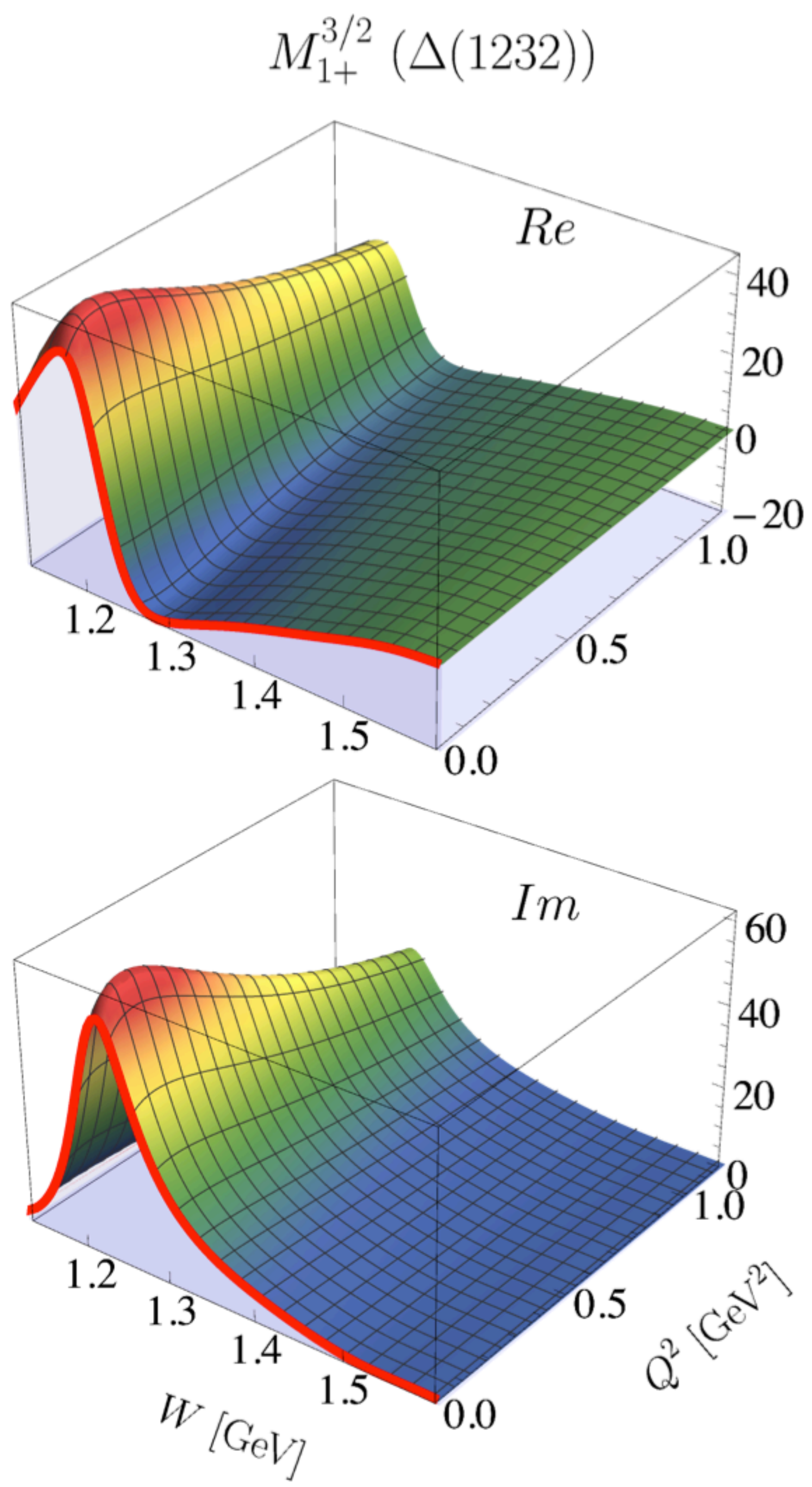
MULTIPOLES

Delta:

- Large multipoles well determined small systematic uncertainties



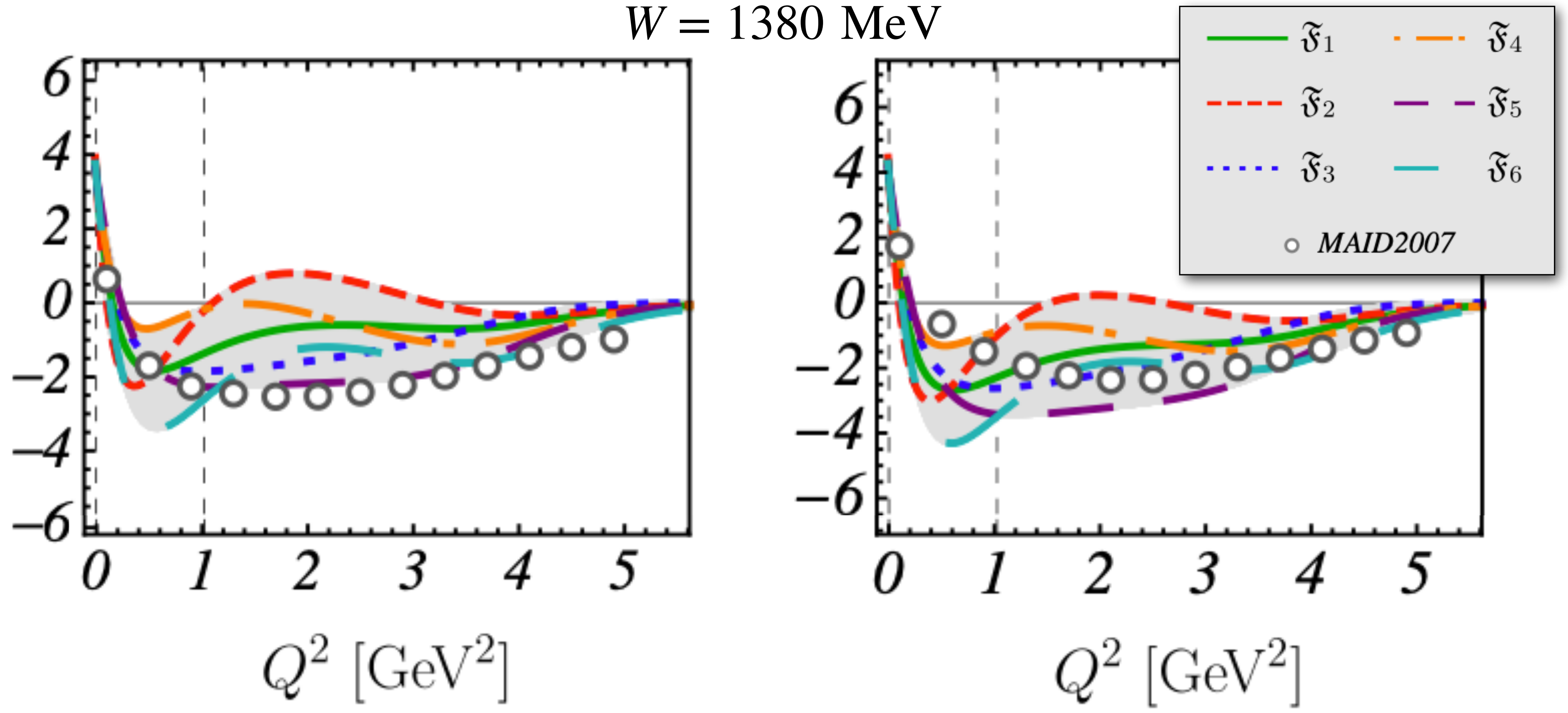
[JBW] MM et al. *Phys.Rev.C* 103 (2021) 6; Phys.Rev.C 106 (2022) 015201

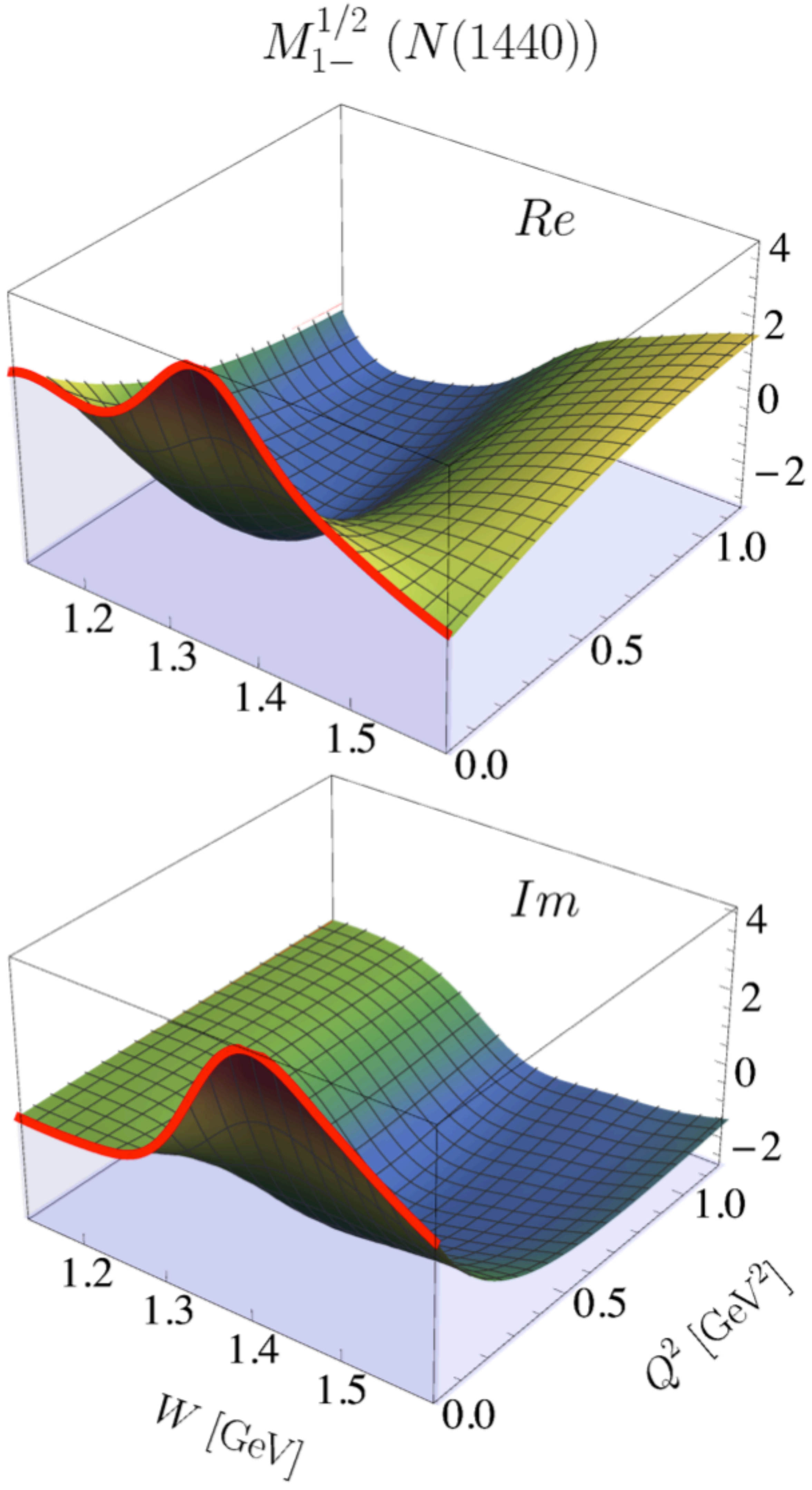


MULTIPOLES

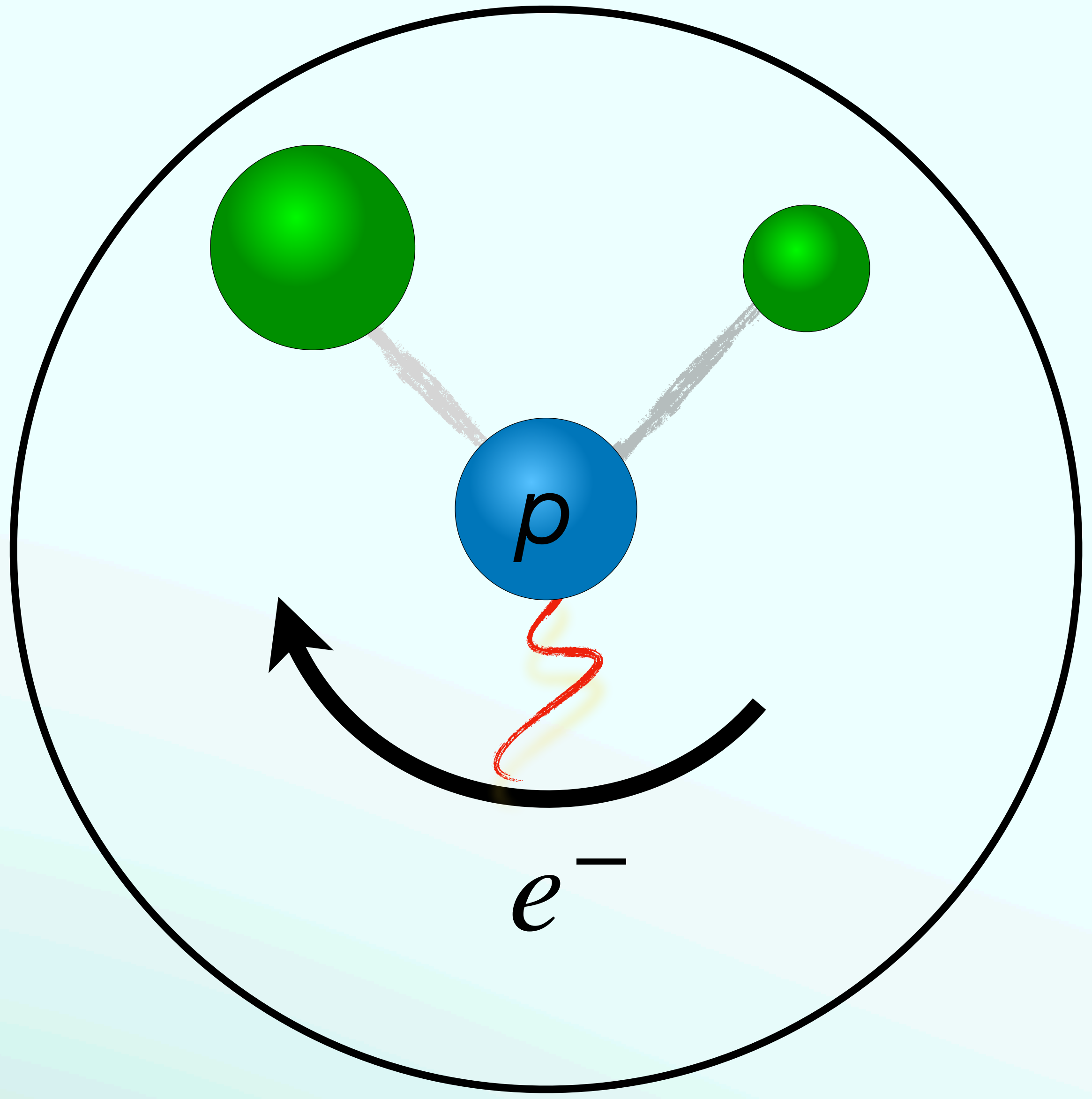
Roper:

- Non-trivial Q^2 behavior
- Zero transition





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



SUMMARY

SUMMARY

Jülich-Bonn-Washington model

➡ new model developed

➡ constraints from scattering, photoproduction data and fundamental principles

➡ fits to piN/etaN data finished

➡ WEB INTERFACE:

https://jbw.phys.gwu.edu

OUTLOOK

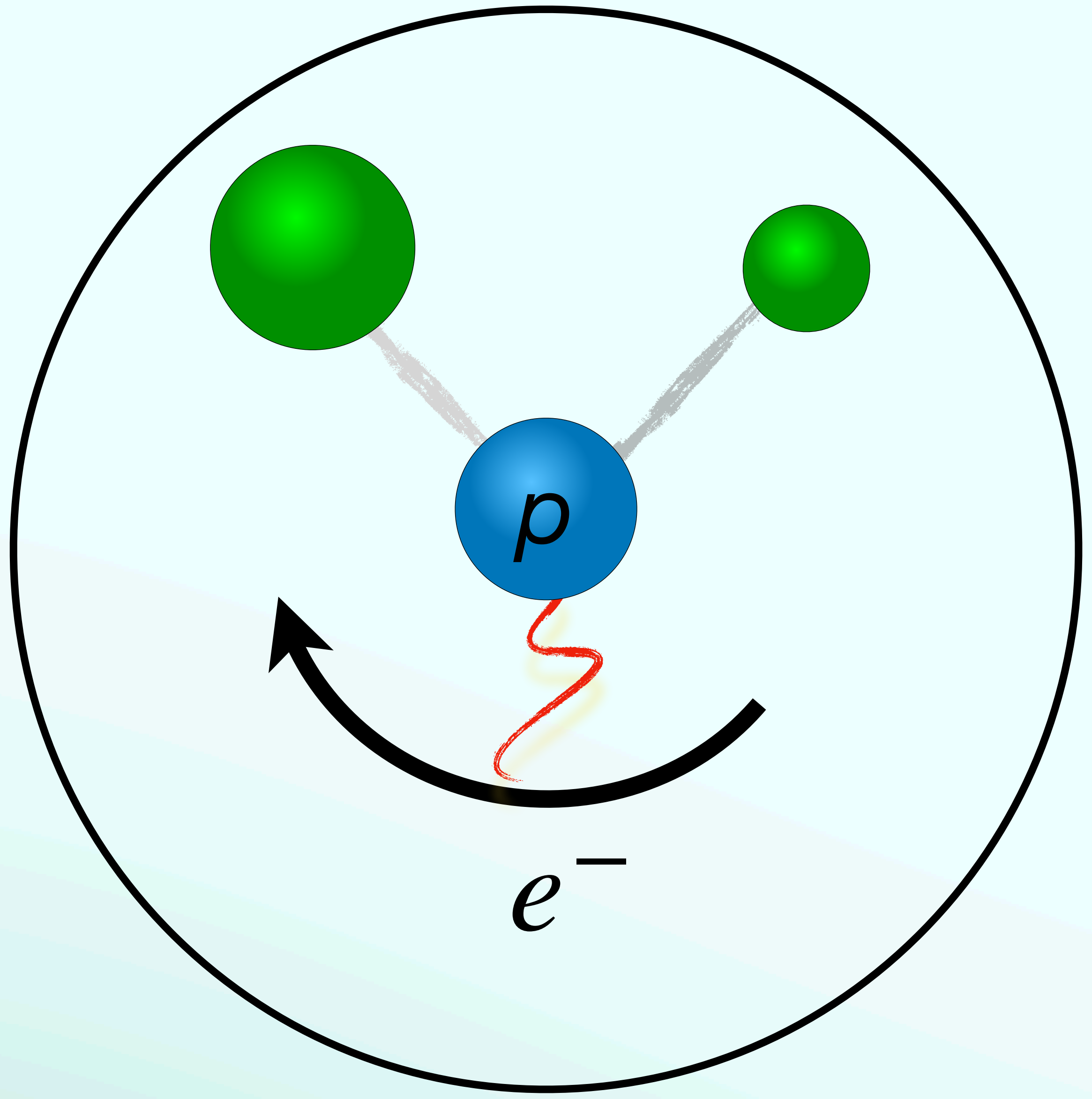
[this year] $\pi N/\eta N/K\Lambda$ fits (nearly world data)

[this decade] simultaneous fit to scattering and photoproduction data

[this decade] statistical studies of parameter importance (LASSO, Machine Learning, ...)

Landay et al., Phys.Rev.D (2019), 1810.00075 [nucl-th]

[this decade] energy independent analysis(?)



THANKS