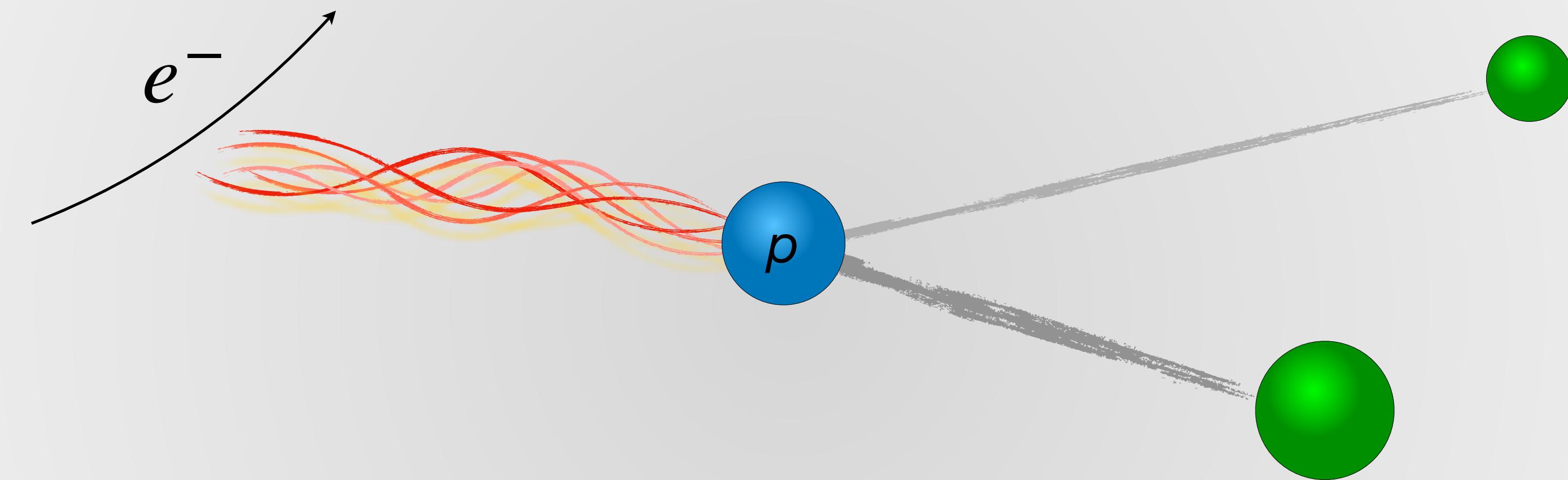




COUPLED-CHANNEL MODEL FOR KY ELECTROPRODUCTION



Maxim Mai

Jülich-Bonn-Washington collaboration:

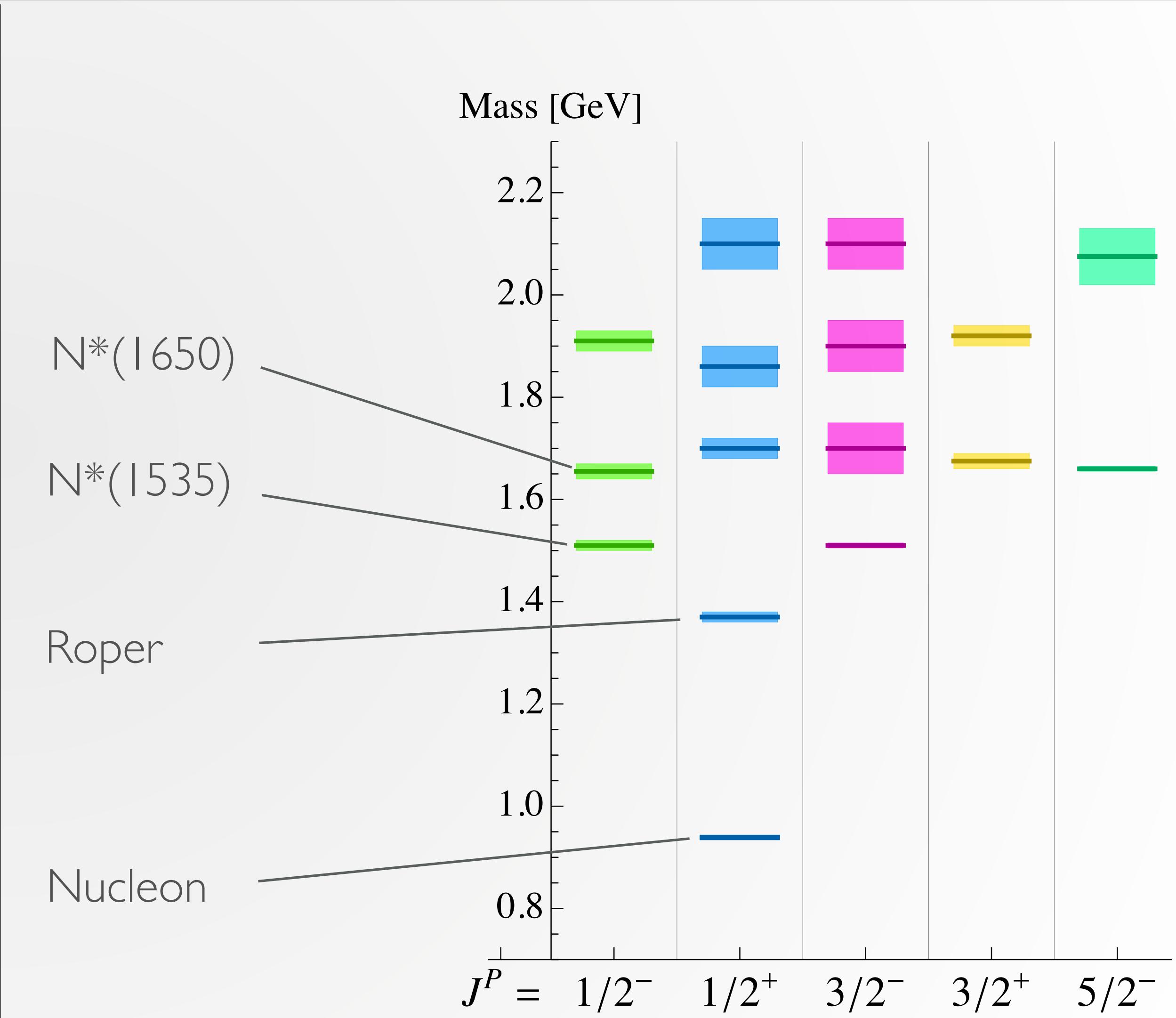
M.Döring, J.Hergenrather, C.Granados, H.Haberzettl, MM, Ulf-G.Meißner, D.Rönchen, I.Strakovsky, R.Workman



HADRON SPECTRUM

Particle Data Group¹:

≈100(50) excited meson(baryon) states (****)



1) Particle Data Goup (Workman et al.)

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



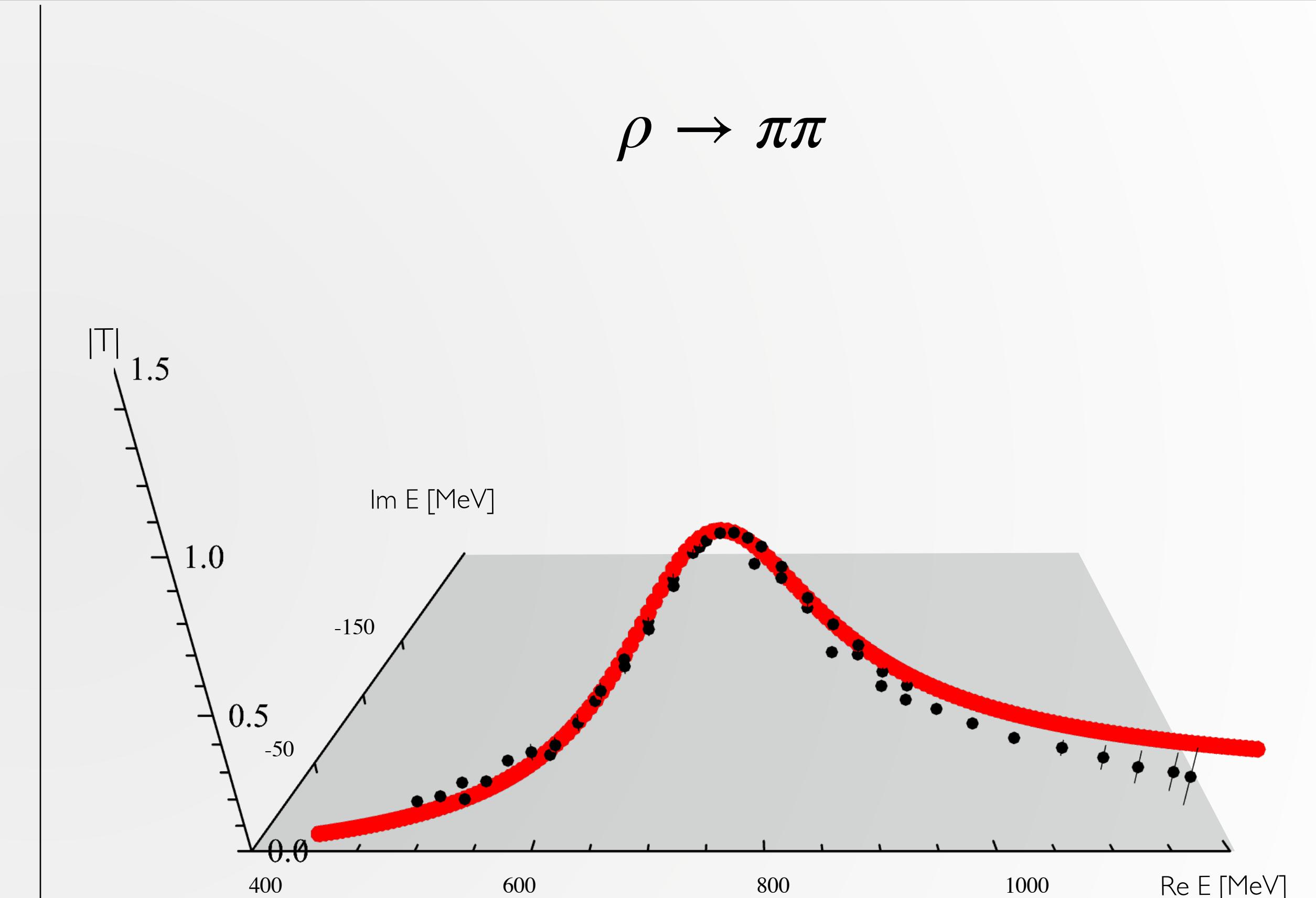
HADRON SPECTRUM

Particle Data Group¹:

≈100(50) excited meson(baryon) states (****)

Reaction-independent (universal) parameters:

- poles on the Riemann Surface
- physical information @ real energies:



1) Particle Data Goup (Workman et al.)

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

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



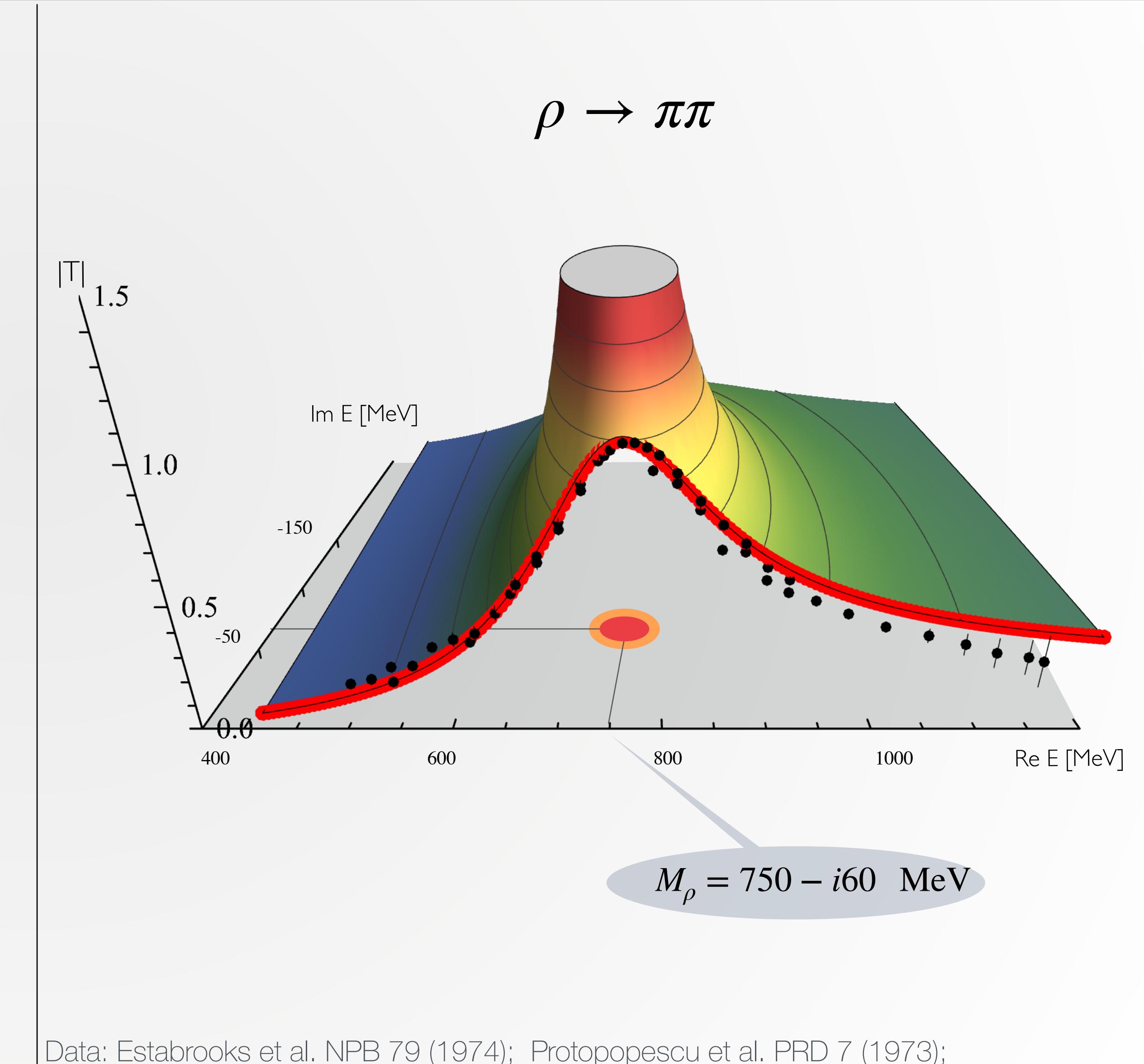
HADRON SPECTRUM

Particle Data Group¹:

≈100(50) excited meson(baryon) states (****)

Reaction-independent (universal) parameters:

- poles on the Riemann Surface
- physical information @ real energies:



1) Particle Data Goup (Workman et al.)

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



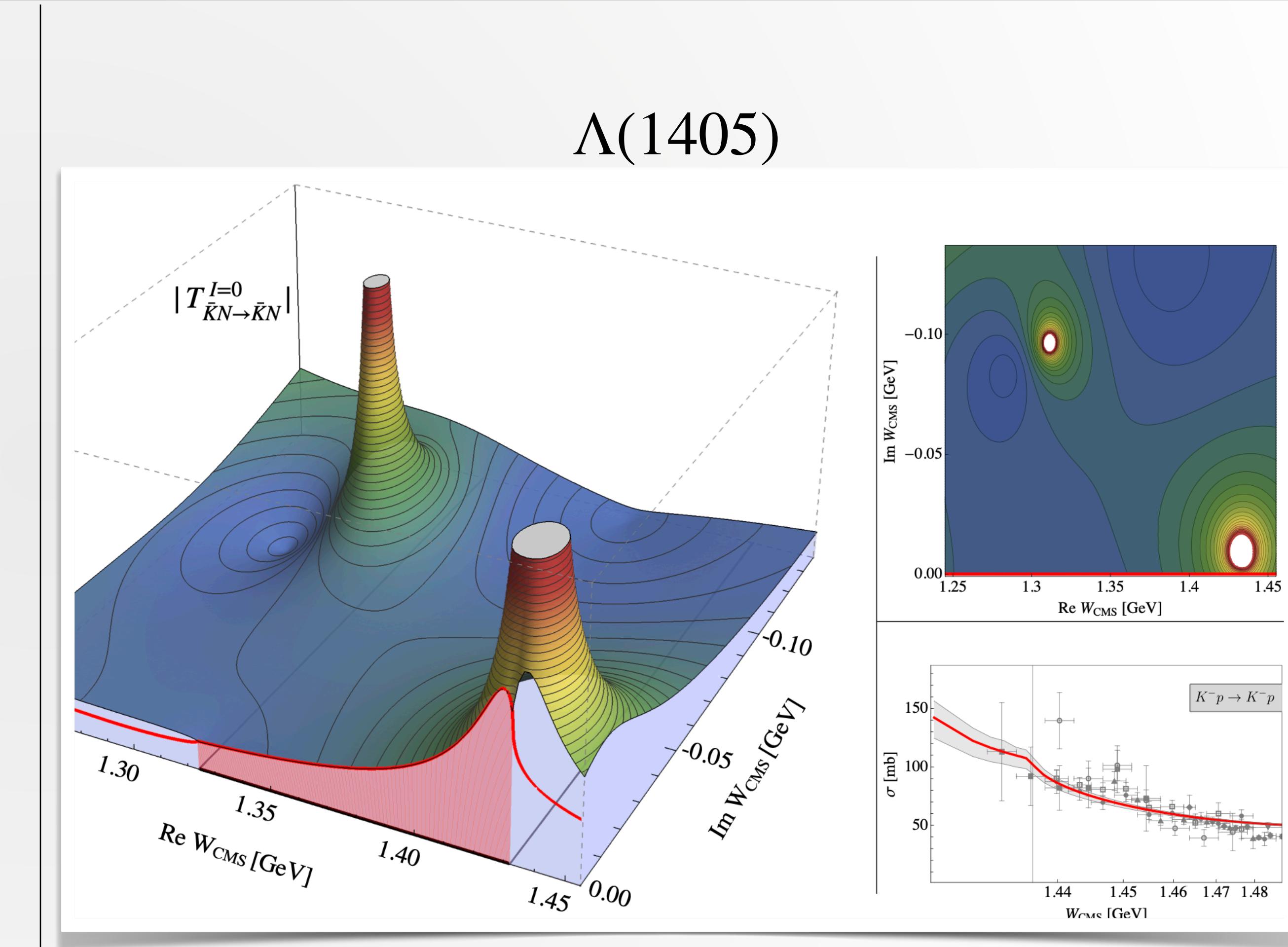
HADRON SPECTRUM

Particle Data Group¹:

$\approx 100(50)$ excited meson(baryon) states (****)

Reaction-independent (universal) parameters:

- poles on the Riemann Surface
- physical information @ real energies:



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

1) Particle Data Goup (Workman et al.)

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



HADRON SPECTRUM

Particle Data Group¹:

≈100(50) excited meson(baryon) states (****)

Reaction-independent (universal) parameters:

- poles on the Riemann Surface
- physical information @ real energies:
 1. theory: Lattice QCD \rightarrow new progress²
 2. experiment \rightarrow this talk

1) Particle Data Goup (Workman et al.)

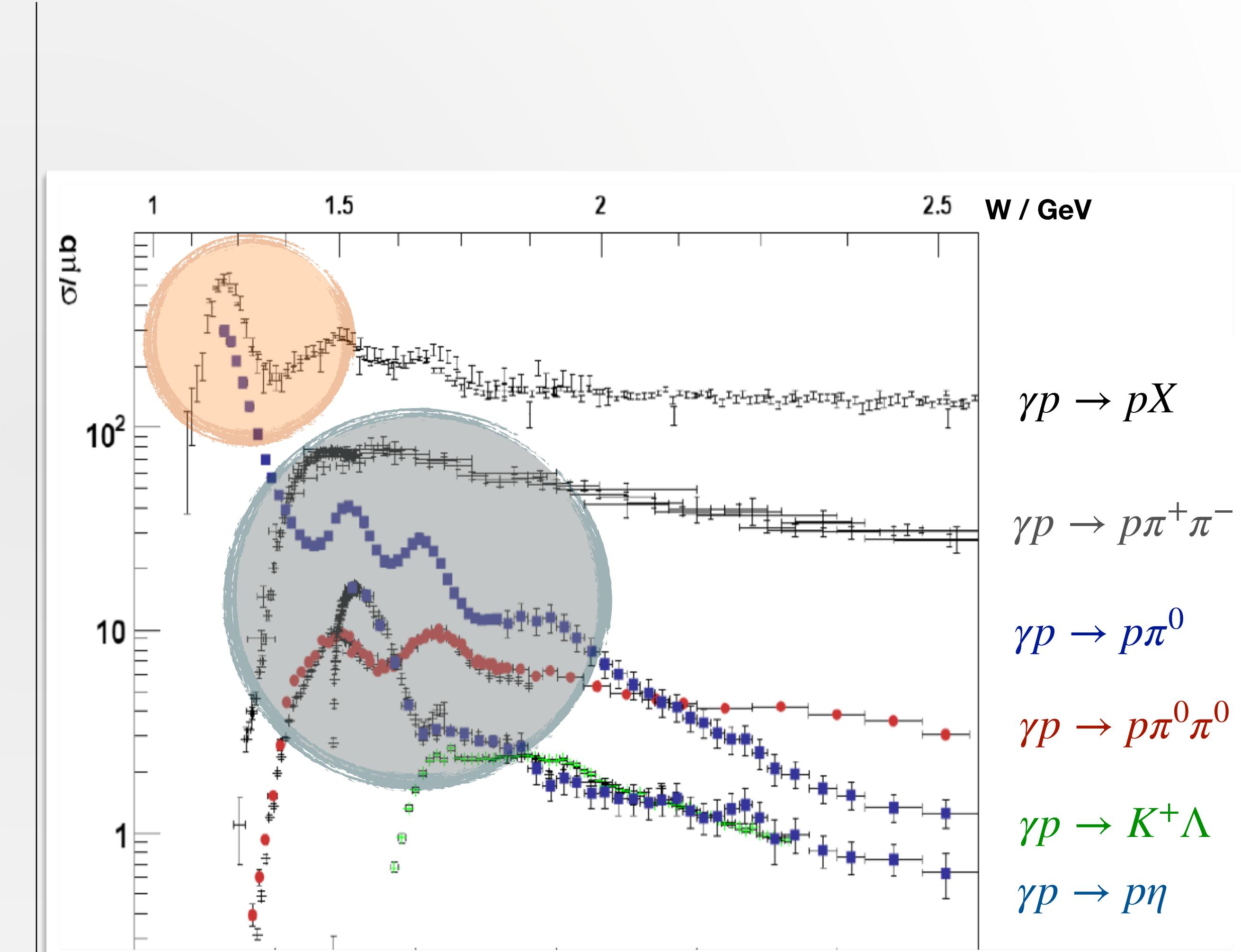
2) Recent review: MM/Meißner/Urbach 2206.01477 (under review in Phys. Rept.)
TALK: M.Hansen (Wednesday)



HADRON SPECTRUM

Meson photo-/electroproduction¹

- large amount of data (10^5 for $\gamma p \rightarrow \pi N$)
- more data to emerge at, e.g., JeffersonLab² ($Q^2=5-12 \text{ GeV}^2$)



1) TALKS: Carman; Thoma; Crede; Ganoti; Gothe; Beck; ...

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

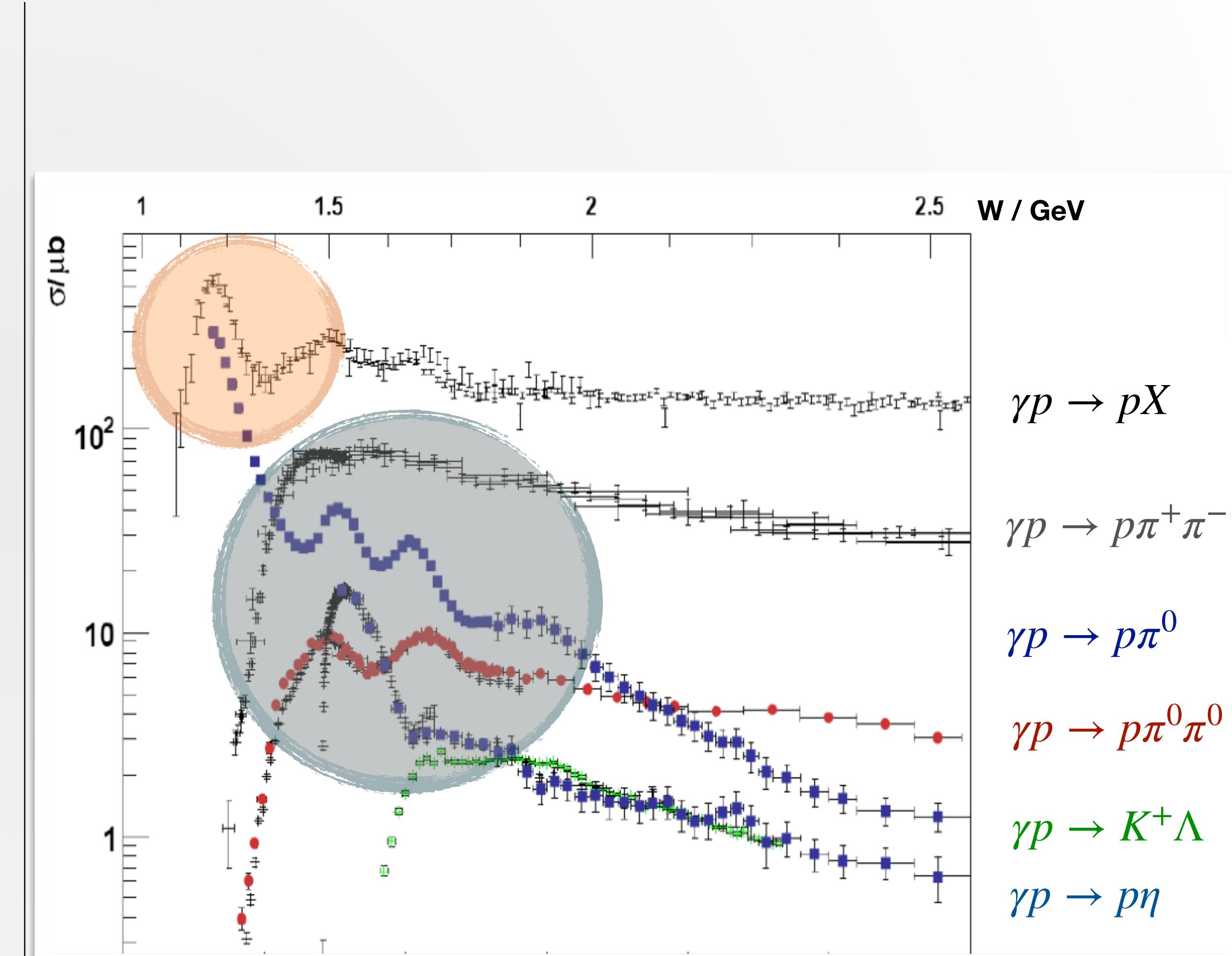


HADRON SPECTRUM

Key questions:

"can we describe the scattering and electroproduction data consistently?"

"can we extract new universal information about the hadron spectrum?"



1) TALKS: Carman; Thoma; Crede; Ganoti; Gothe; Beck; ...

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

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



THEORY STATUS

- ANL-Osaka¹
- (eta)(kaon)MAID²
- SAID³
- ...⁴

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),...



THEORY STATUS

- ANL-Osaka¹
- (eta)(kaon)MAID²
- SAID³
- ...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 electroproduction⁵

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) Review: Burkert, Roberts, Rev.Mod.Phys. 91 (2019)



THEORY STATUS

Jülich-Bonn-Washington approach

- coupled-channel approach (universality)
simultaneous description of πN , ηN , $K\Lambda$, $K\Sigma$, ... channels
- threshold constraints, gauge invariance, ...
- constraints from scattering data

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

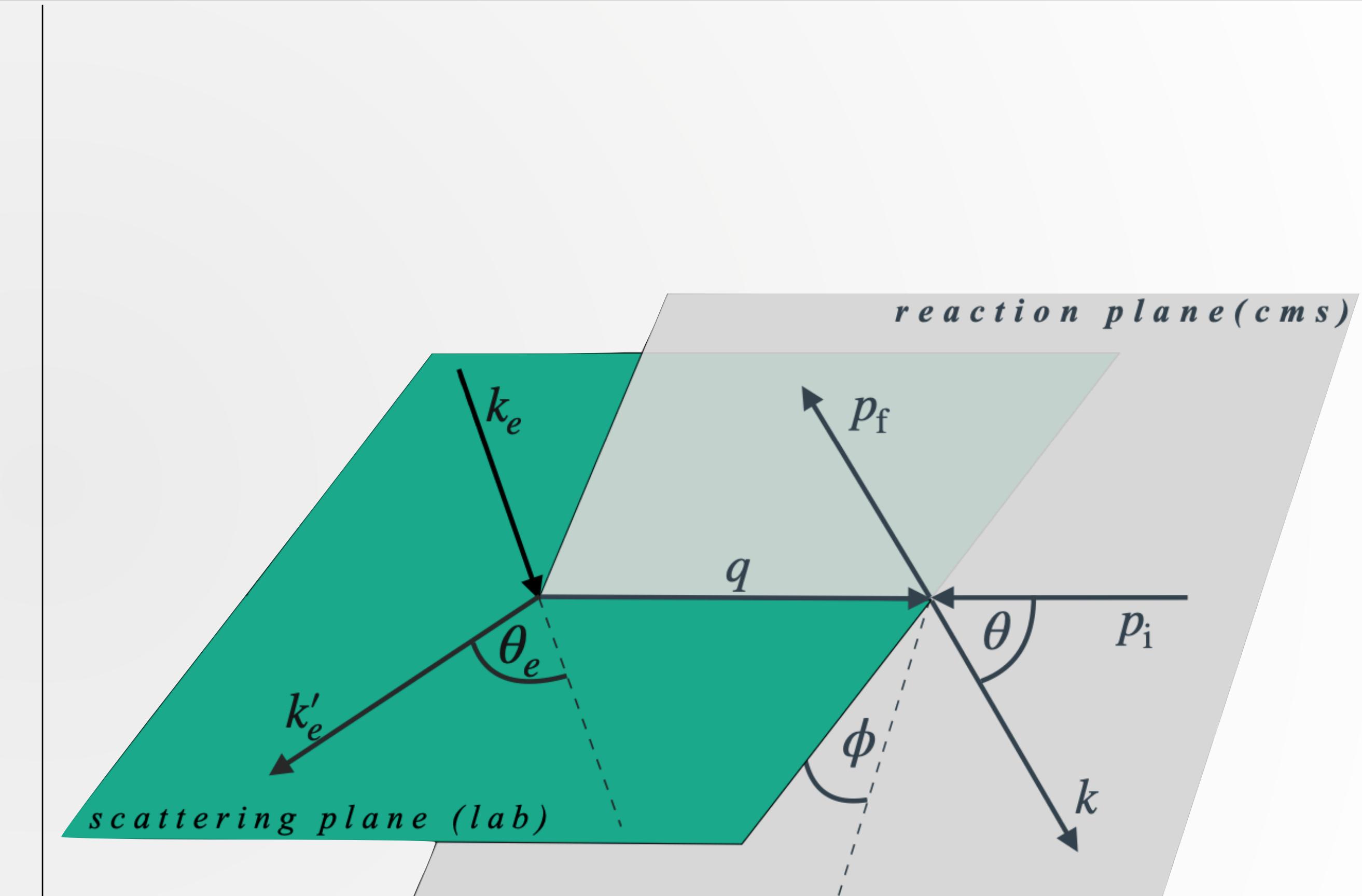
The screenshot shows a web browser window displaying the homepage of the Jülich-Bonn-Washington Collaboration. The URL in the address bar is <https://jbw.phys.gwu.edu/>. The page features a large background image of a particle physics experiment hall with red support structures and equipment. Overlaid on the image are the text "GW Institute for Nuclear Studies", "HEDE CAP. 50 TONS", "Jülich-Bonn-Washington Collaboration", and "Interactive Scattering Analysis Database. (Under construction.)". At the bottom of the page, there is a section titled "Partial-Wave Analyses" with a brief description and a note to "Navigate the site to view a growing number of medium-energy few-body reactions (both data and models) along with the associated partial-wave amplitudes." A small note at the bottom right says "Open 'https://jbw.phys.gwu.edu/' in a new tab".



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





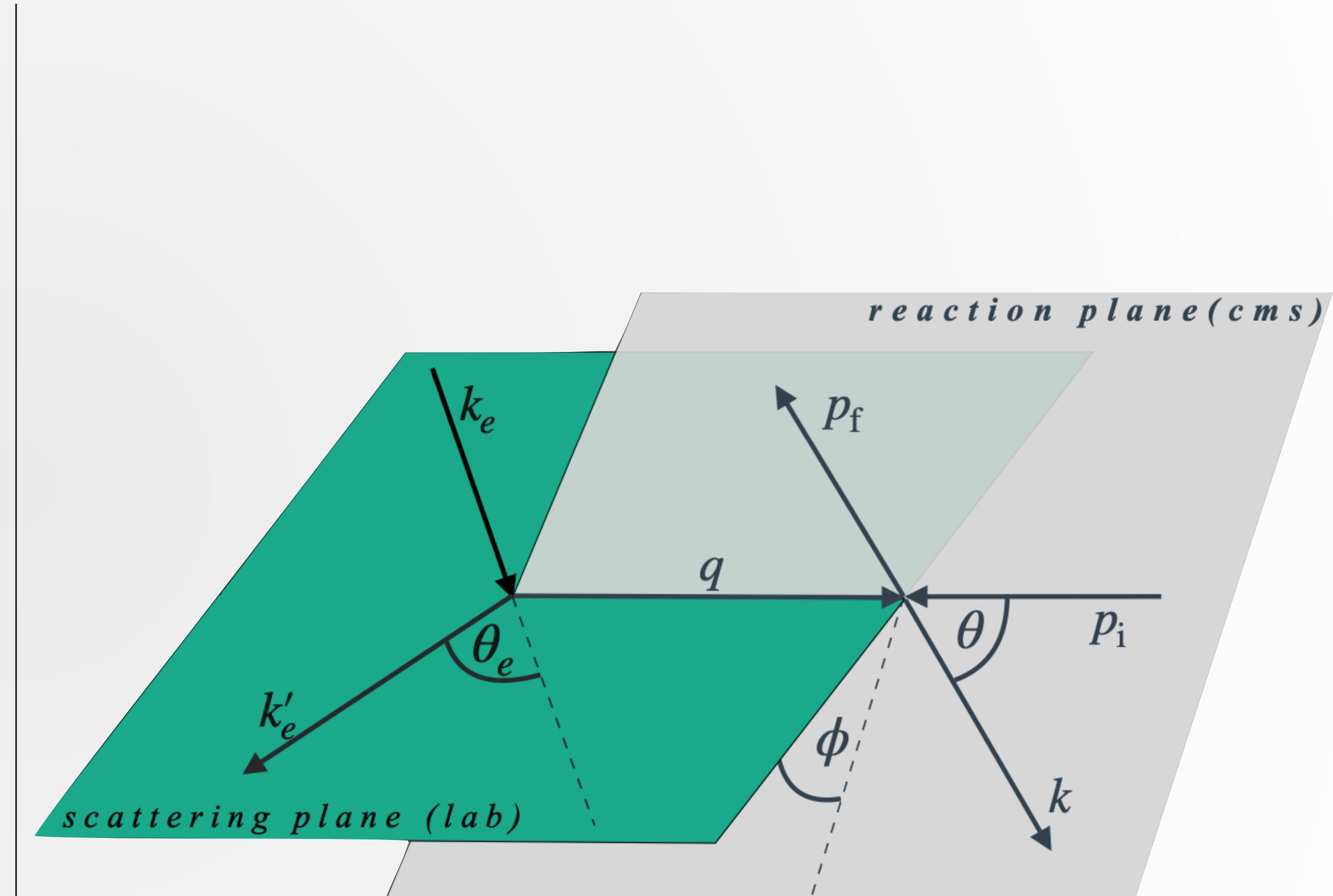
SYMMETRIES OF NATURE

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

Underlying objects:

- Helicity amplitudes: $\{H_i(W, Q^2, \theta) \mid i = 1..8\}$
- Multipoles: $\{E_{\ell\pm}(W, Q^2), L_{\ell\pm}(W, Q^2), M_{\ell\pm}(W, Q^2)\}$





THEORETICAL CONSTRAINTS

I. Gauge invariance

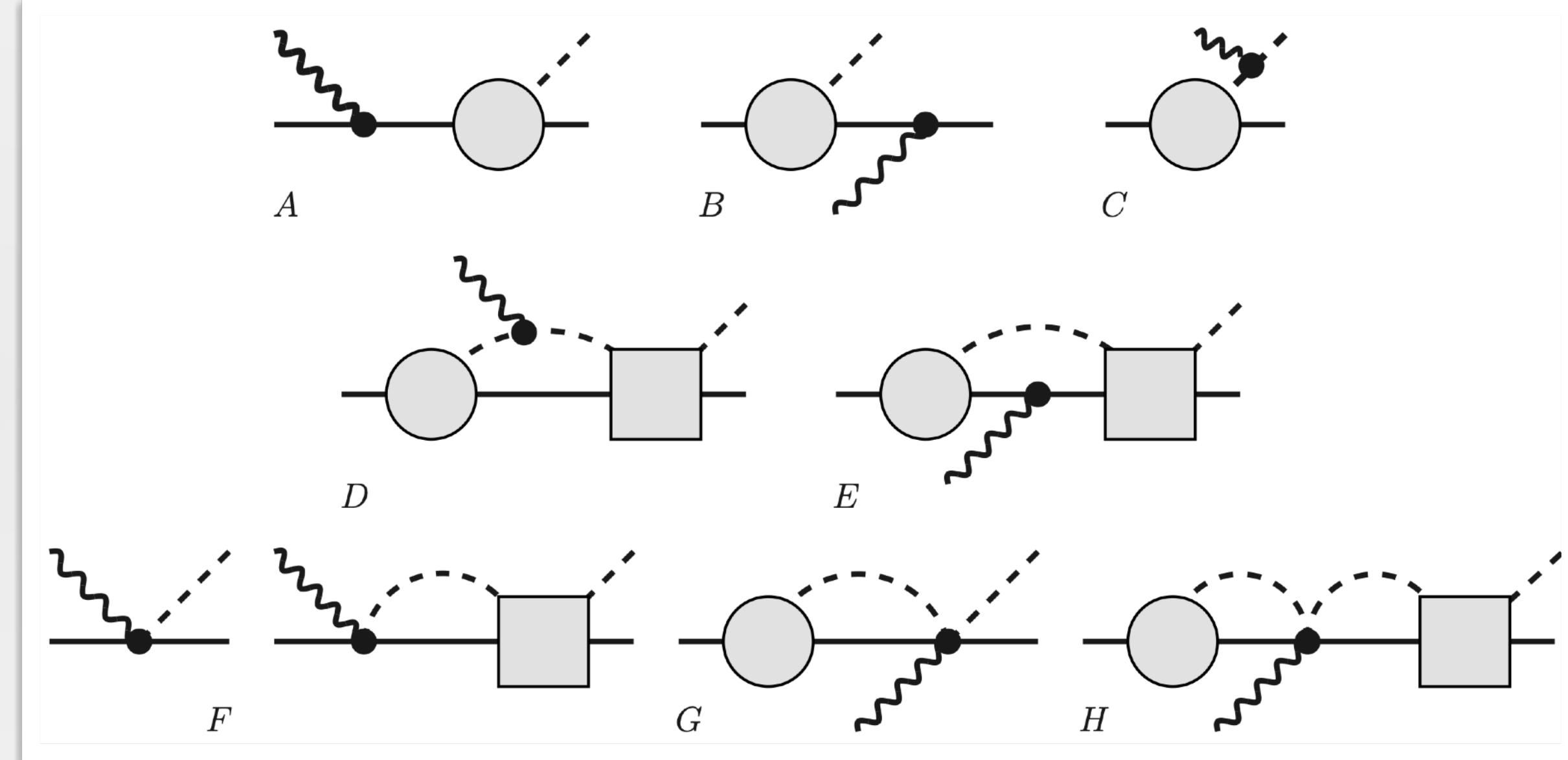
- 1) Afnan et al.(1995); Kvinikhidze et al.(1999); Haberzettl(19xx-2021); Borasoy et al.(2007);
Ruic et al.(2011); MM et al. (2012);
- 2) Bruns, Cieplý, MM 2206.08767 [nucl-th]



THEORETICAL CONSTRAINTS

I. Gauge invariance

→ manifest implementation¹ exist even for 2-meson photoproduction²
... but usually too costly



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

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

I. Gauge invariance

- manifest implementation¹ exist even for 2-meson photoproduction²
... but usually too costly
- Ward-Takahashi identity by construction

$$k_\mu T^\mu = 0$$
$$H_7 = \sum_{i=1}^6 a_i H_i$$
$$H_8 = \sum_{i=1}^6 b_i H_i$$

```
graph TD; A["k_\mu T^\mu = 0"] --> B["H7 = \sum_{i=1}^6 a_i H_i"]; A --> C["H8 = \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

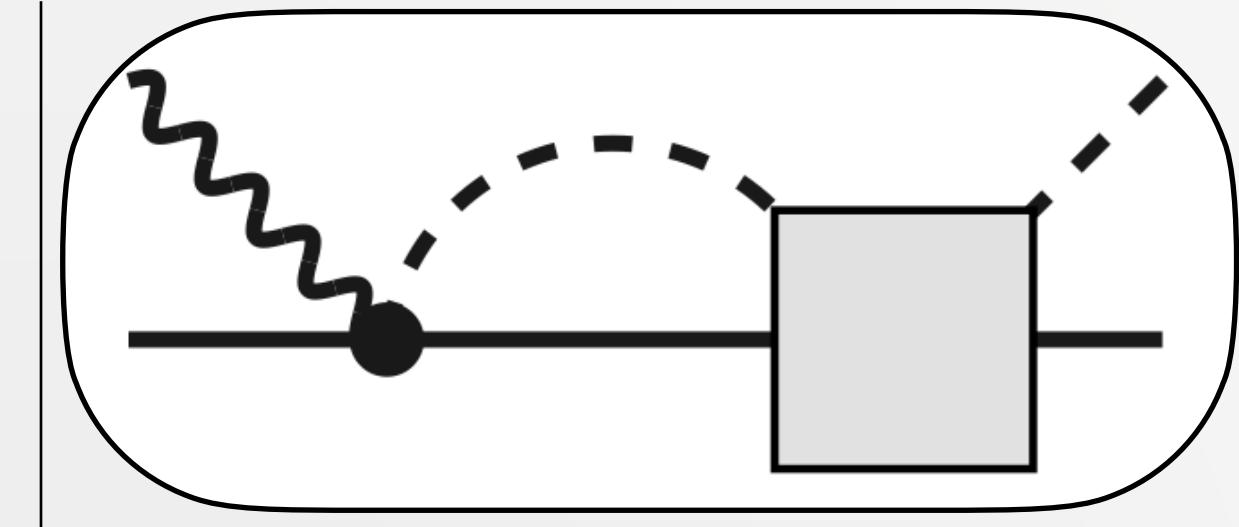
II. Final-state unitarity



THEORETICAL CONSTRAINTS

II. Final-state unitarity

- Jülich-Bonn dynamical coupled-channel model¹

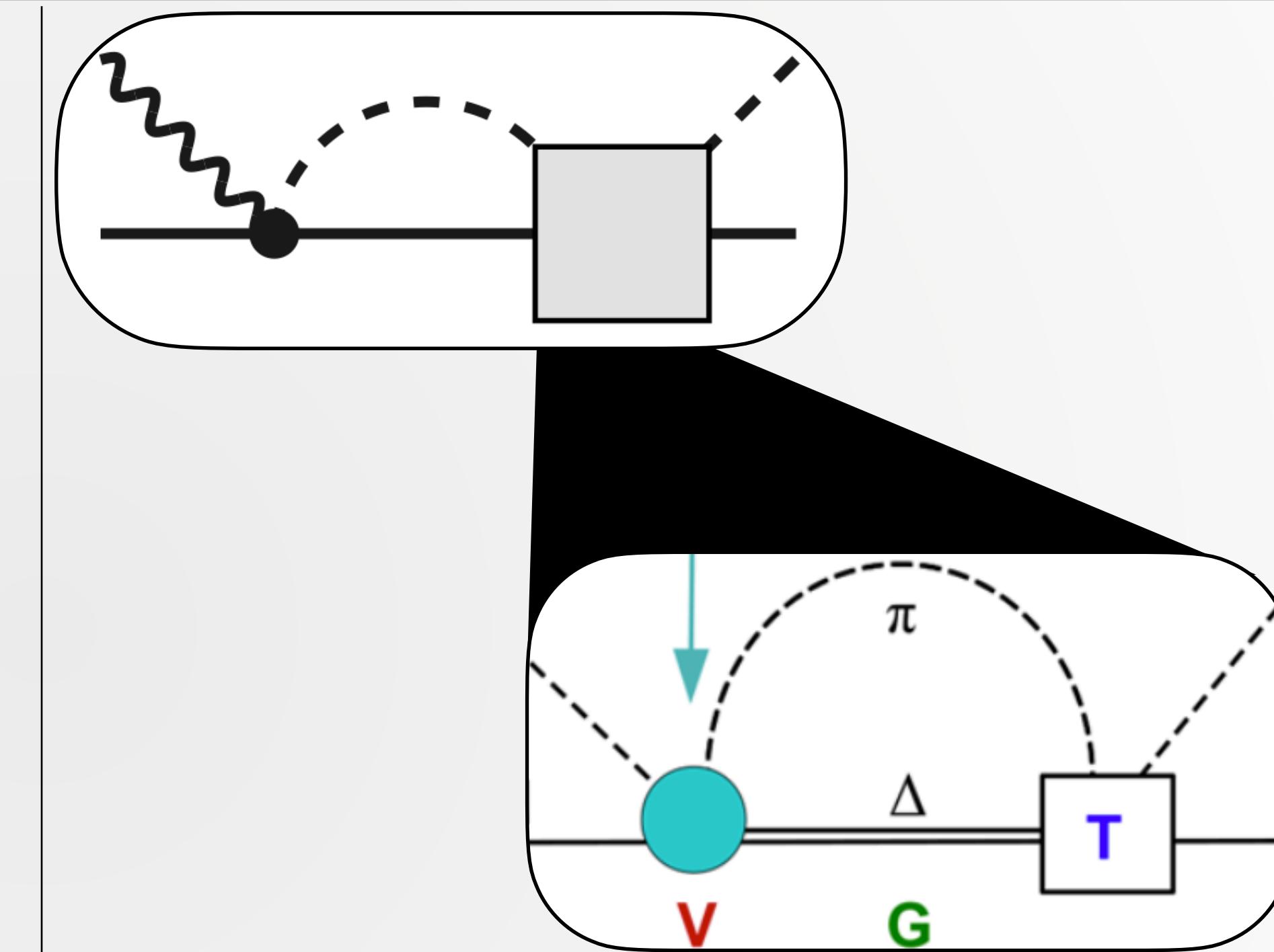




THEORETICAL CONSTRAINTS

II. Final-state unitarity

→ Jülich-Bonn dynamical coupled-channel model¹

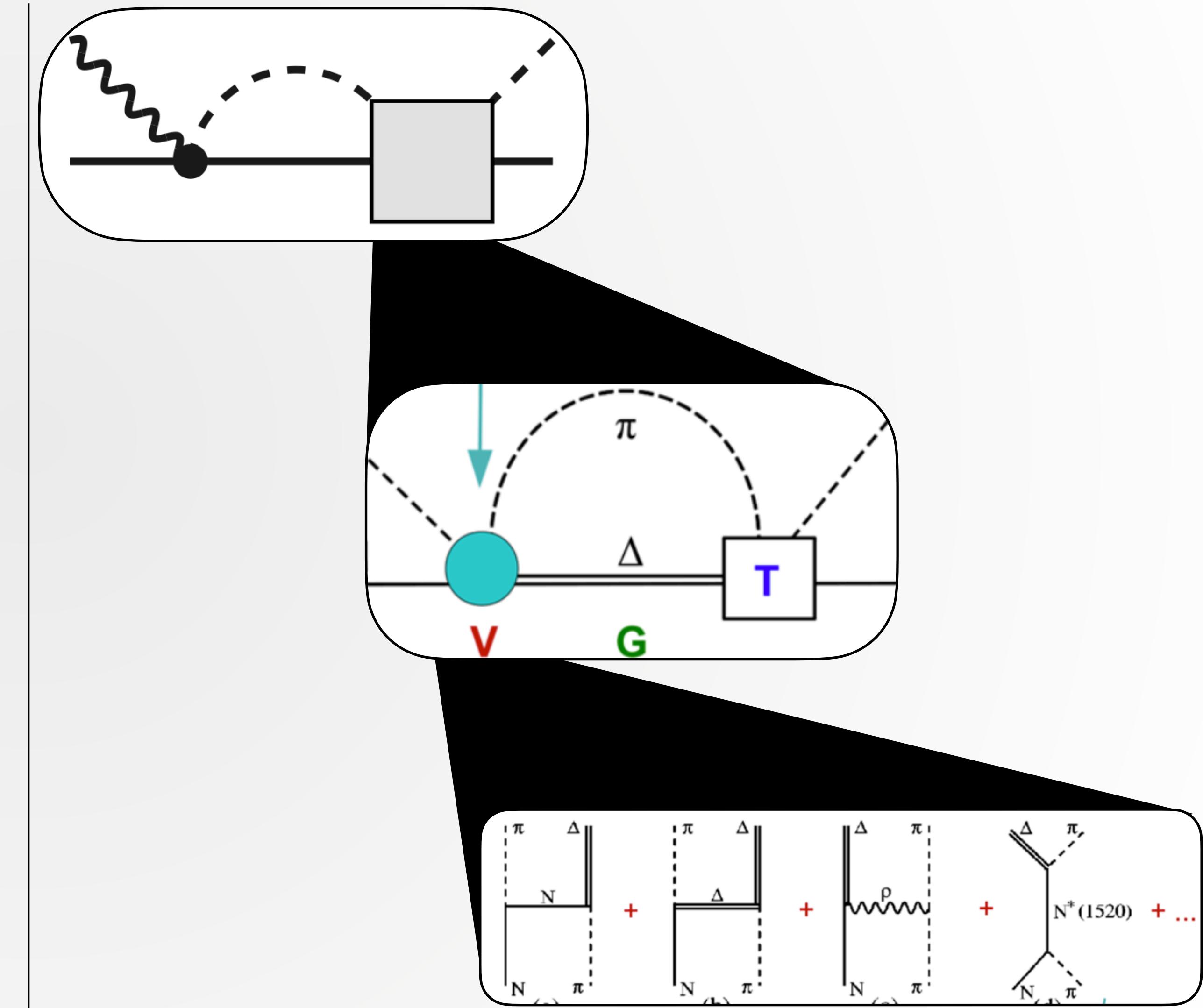




THEORETICAL CONSTRAINTS

II. Final-state unitarity

→ Jülich-Bonn dynamical coupled-channel model¹



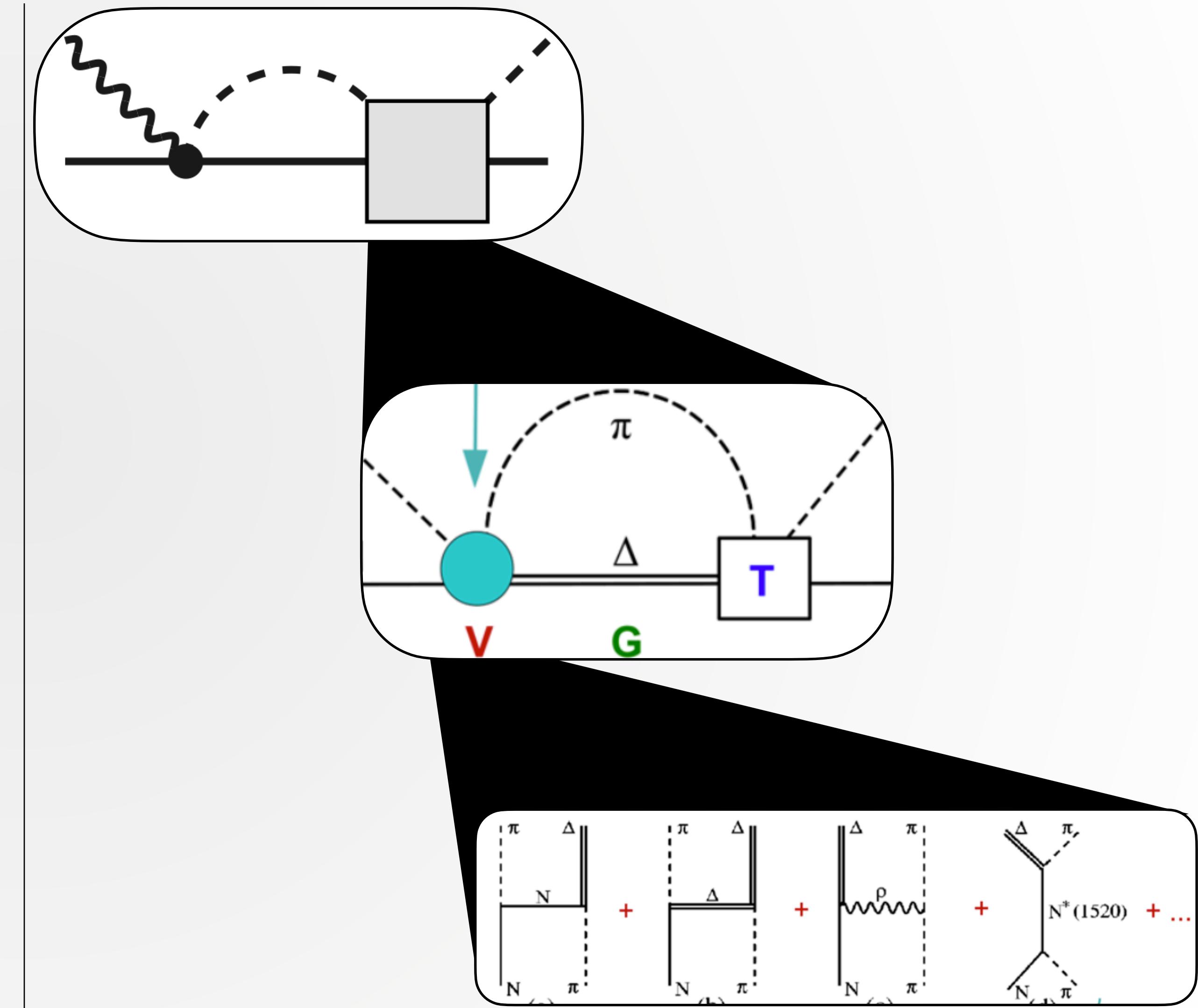


THEORETICAL CONSTRAINTS

II. Final-state unitarity

- Jülich-Bonn dynamical coupled-channel model¹
- Amplitudes fixed from scattering and photoproduction data

$\pi N \rightarrow xX$ and $\gamma N \rightarrow xX$ (~60k data)

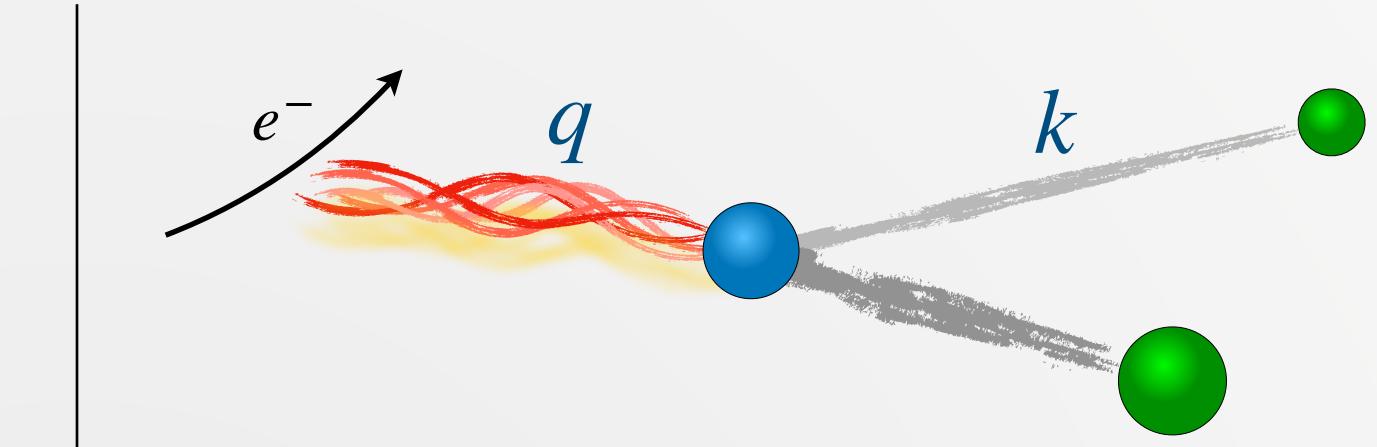




THEORETICAL CONSTRAINTS

III. Pseudo/threshold constraints:

→ Momentum dependence



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

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

...



THEORETICAL CONSTRAINTS

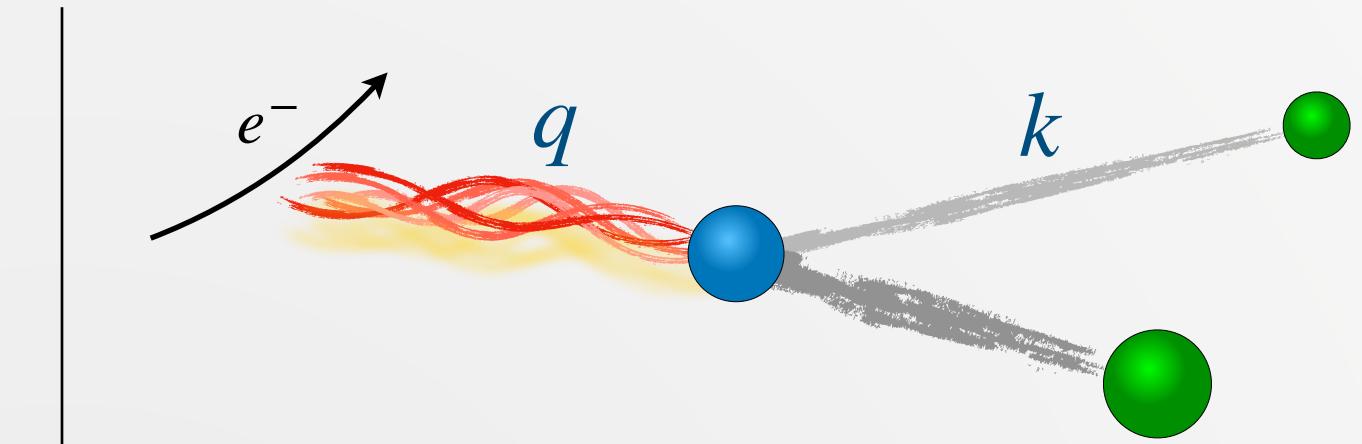
III. Pseudo/threshold constraints:

→ Momentum dependence

IV. Siegert's theorem¹

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

good news: fewer parameters needed



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

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

...

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

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



$$\mathcal{M}_{\mu\gamma^*}(k, W, Q^2) = R_\ell(\lambda, q/q_\gamma) \left(V_{\mu\gamma^*}(k, W, Q^2) + \sum_{\kappa} \int_0^\infty dp p^2 T_{\mu\kappa}^{\text{JUBO}}(k, p, W) G_\kappa(p, W) V_{\kappa\gamma^*}(p, W, Q^2) \right)$$
$$V_{\mu\gamma^*}(k, W, Q^2) = V_{\mu\gamma}^{\text{JUBO}}(k, W) \times e^{-\beta_\mu^0 Q^2/m_p^2} \left(1 + Q^2/m_p^2 \beta_\mu^1 + (Q^2/m_p^2)^2 \beta_\mu^2 \right)$$



$$\mathcal{M}_{\mu\gamma^*}(k, W, Q^2) = R_\ell(\lambda, q/q_\gamma) \left(V_{\mu\gamma^*}(k, W, Q^2) + \sum_{\kappa} \int_0^\infty dp p^2 T_{\mu\kappa}^{\text{JUBO}}(k, p, W) G_\kappa(p, W) V_{\kappa\gamma^*}(p, W, Q^2) \right)$$
$$V_{\mu\gamma^*}(k, W, Q^2) = V_{\mu\gamma}^{\text{JUBO}}(k, W) \times e^{-\beta_\mu^0 Q^2/m_p^2} \left(1 + Q^2/m_p^2 \beta_\mu^1 + (Q^2/m_p^2)^2 \beta_\mu^2 \right)$$

Fulfils:

- Final state unitarity / Gauge invariance / Siegert's theorem / Threshold behaviour

Describes

- scattering and photoproduction data
- parameters (λ, β) from electroproduction data

TALK Deborah Rönchen



$$\mathcal{M}_{\mu\gamma^*}(k, W, Q^2) = R_\ell(\lambda, q/q_\gamma) \left(V_{\mu\gamma^*}(k, W, Q^2) + \sum_{\kappa} \int_0^\infty dp p^2 T_{\mu\kappa}^{\text{JUBO}}(k, p, W) G_\kappa(p, W) V_{\kappa\gamma^*}(p, W, Q^2) \right)$$
$$V_{\mu\gamma^*}(k, W, Q^2) = V_{\mu\gamma}^{\text{JUBO}}(k, W) \times e^{-\beta_\mu^0 Q^2/m_p^2} \left(1 + Q^2/m_p^2 \beta_\mu^1 + (Q^2/m_p^2)^2 \beta_\mu^2 \right)$$

Fulfils:

- Final state unitarity / Gauge invariance / Siegert's theorem / Threshold behaviour

Describes

- scattering and photoproduction data
- parameters (λ, β) from electroproduction data

TALK Deborah Rönchen

Parametrization dependence due to incomplete data

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

Tiator et al.(2017)

TALKS: Wunderlich, Svarč

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

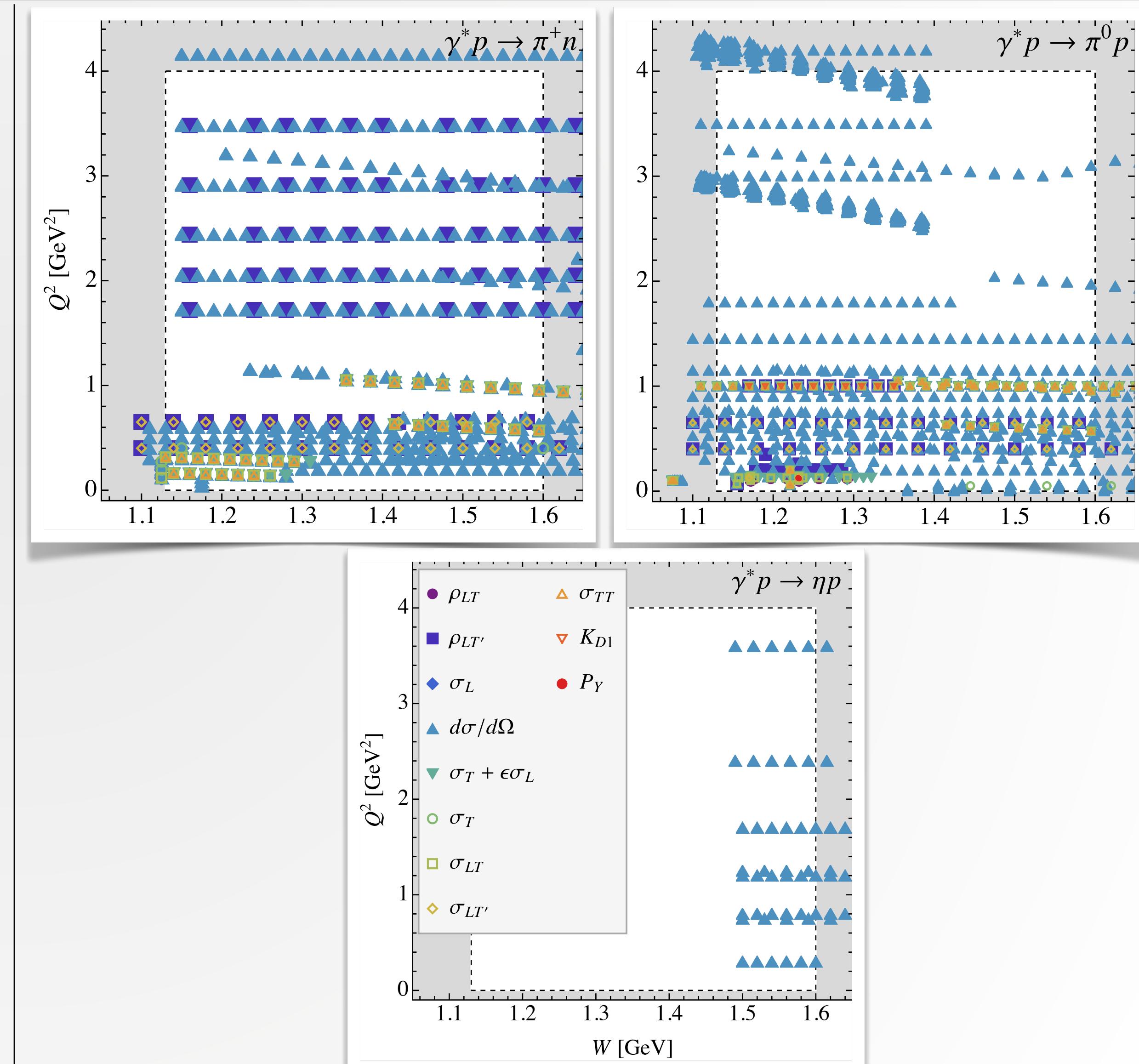
Phys.Rev.C 103 (2021) 6, 065204
Phys.Rev.C 106 (2022) 015201

DEGREES OF FREEDOM



Experimental data

- $1.13 < W/\text{GeV} < 1.6$, $Q^2 < 4 \text{ GeV}^2$
- $45k(\pi^0 p) + 37k(\pi^+ n) + 2k(\eta p) = 84k$ data
- 11 observable types



DEGREES OF FREEDOM

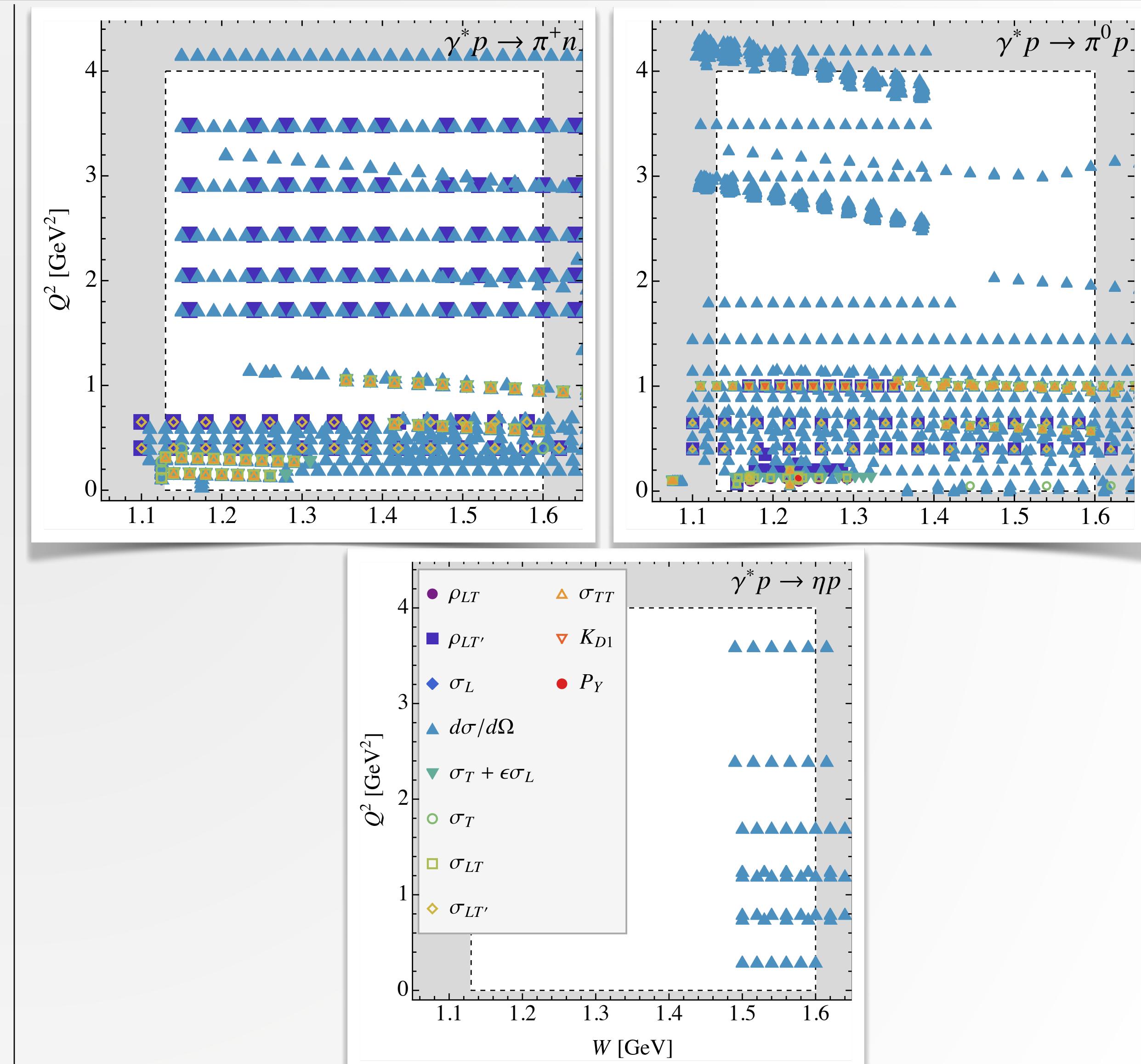


Experimental data

- $1.13 < W/\text{GeV} < 1.6$, $Q^2 < 4 \text{ GeV}^2$
- $45k(\pi^0 p) + 37k(\pi^+ n) + 2k(\eta p) = 84k$ data
- 11 observable types

Parameters (S/P/D waves)

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



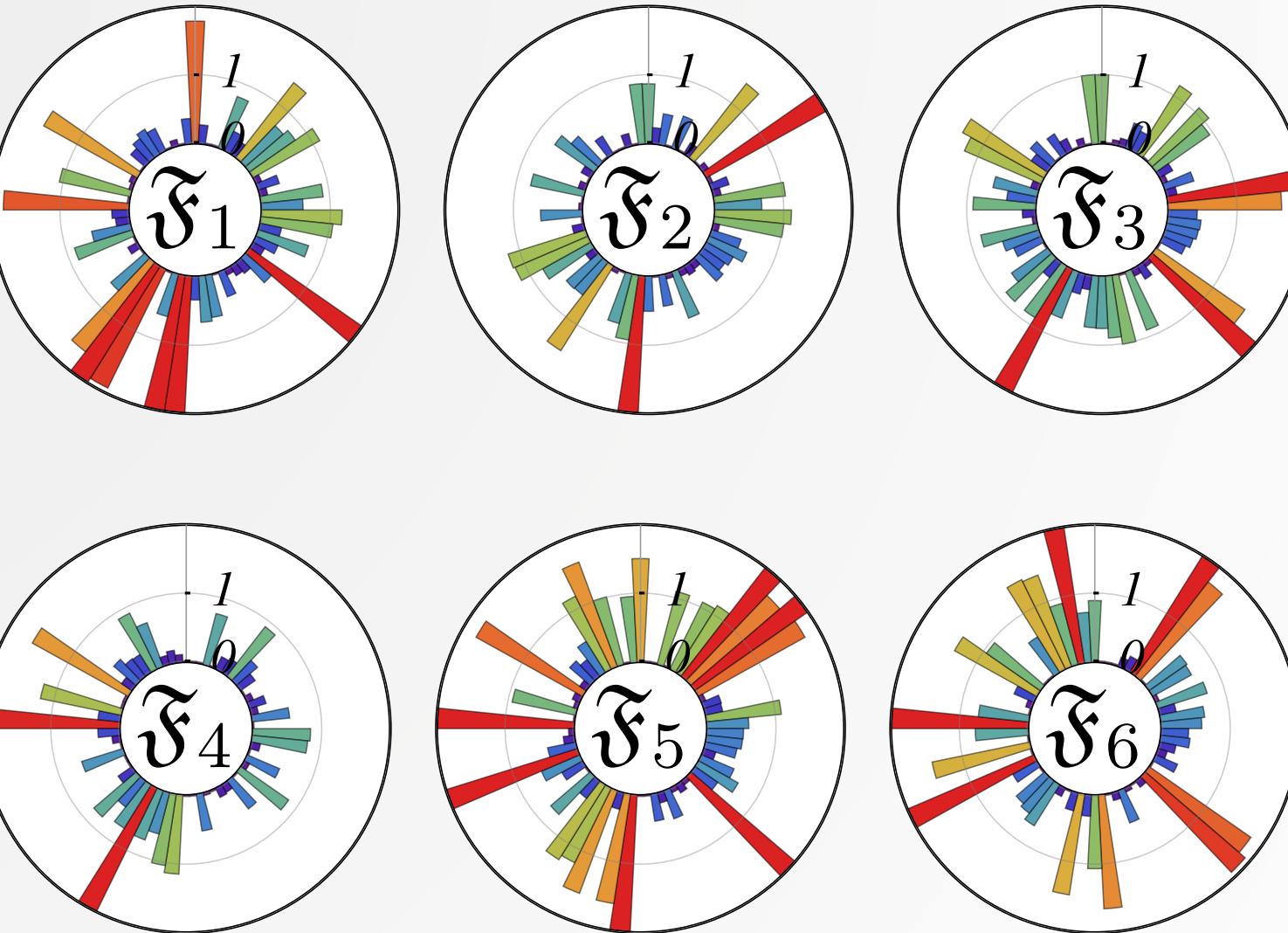


RESULTS

πN data fits¹:

- all strategies converge
- different minima (systematic uncertainties)

Fit	σ_L $\pi^0 p \pi^+ n$	$d\sigma/d\Omega$ $\pi^0 p \pi^+ n$	$\sigma_T + \epsilon\sigma_L$ $\pi^0 p \pi^+ n$	σ_T $\pi^0 p \pi^+ n$	σ_{LT} $\pi^0 p \pi^+ n$	$\sigma_{LT'}$ $\pi^0 p \pi^+ n$	σ_{TT} $\pi^0 p \pi^+ n$	K_{D1} $\pi^0 p \pi^+ n$	P_Y $\pi^0 p \pi^+ n$	ρ_{LT} $\pi^0 p \pi^+ n$	$\rho_{LT'}$ $\pi^0 p \pi^+ n$	χ^2_{dof}
\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

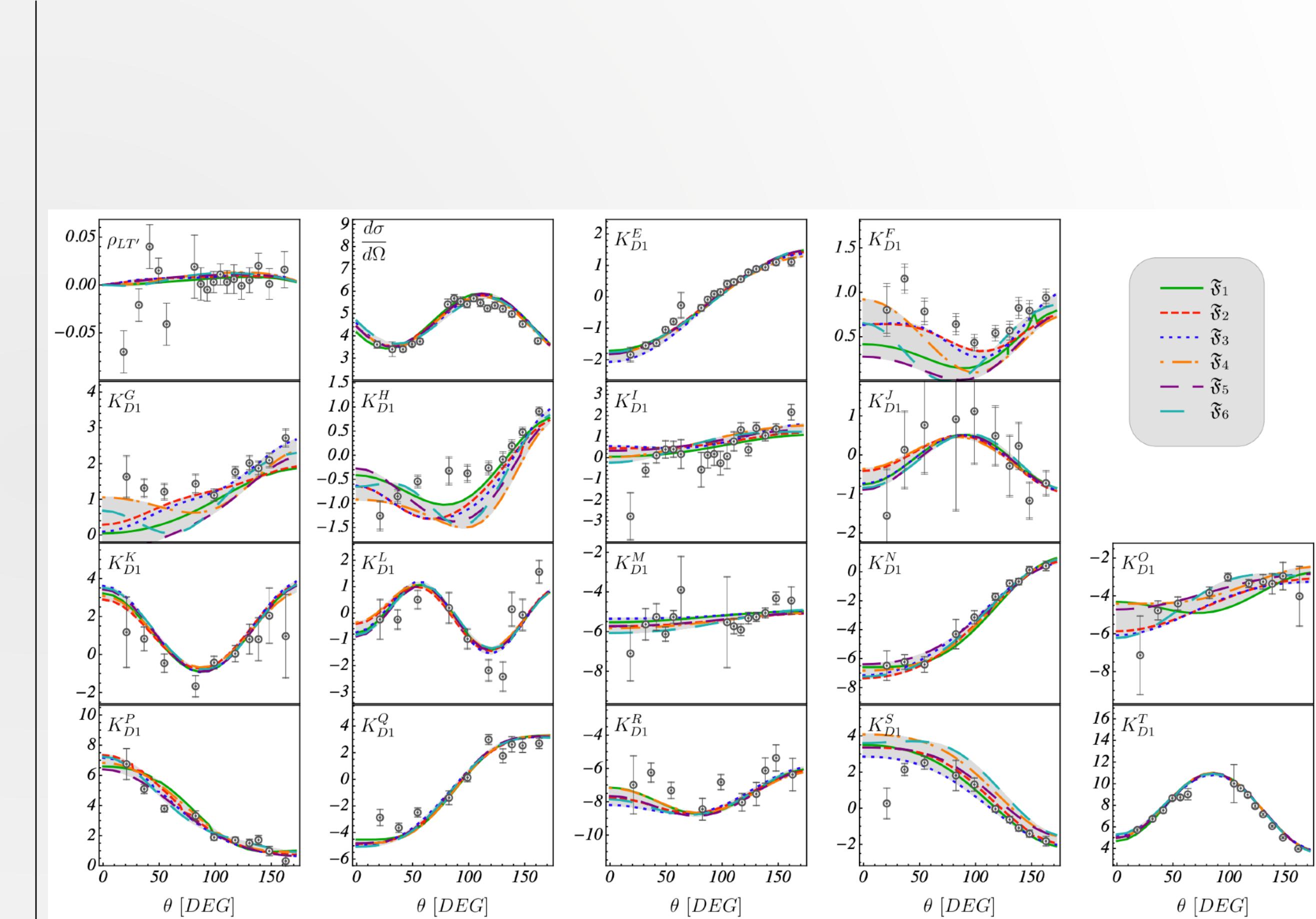




RESULTS

πN data fits¹:

- all strategies converge
- different minima (systematic uncertainties)
- Kelly data²



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

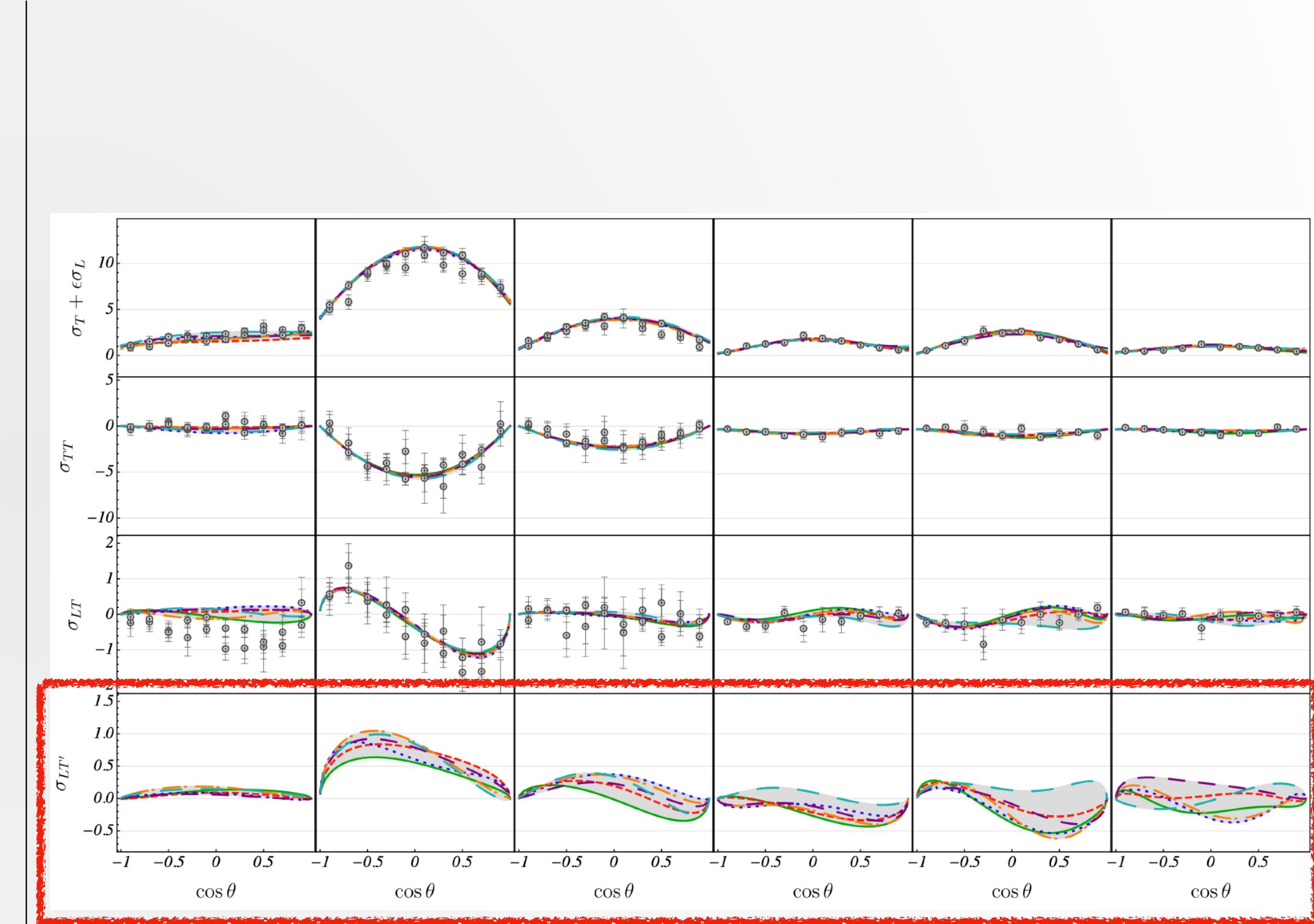
2) Jefferson Lab Hall A Collaboration *Phys.Rev.Lett.* 95 (2005) 102001



RESULTS

πN data fits¹:

- all strategies converge
- different minima (systematic uncertainties)
- Joo data²



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

2) Joo et al. [CLAS] *PRC* (2003), *PRL* (2002)

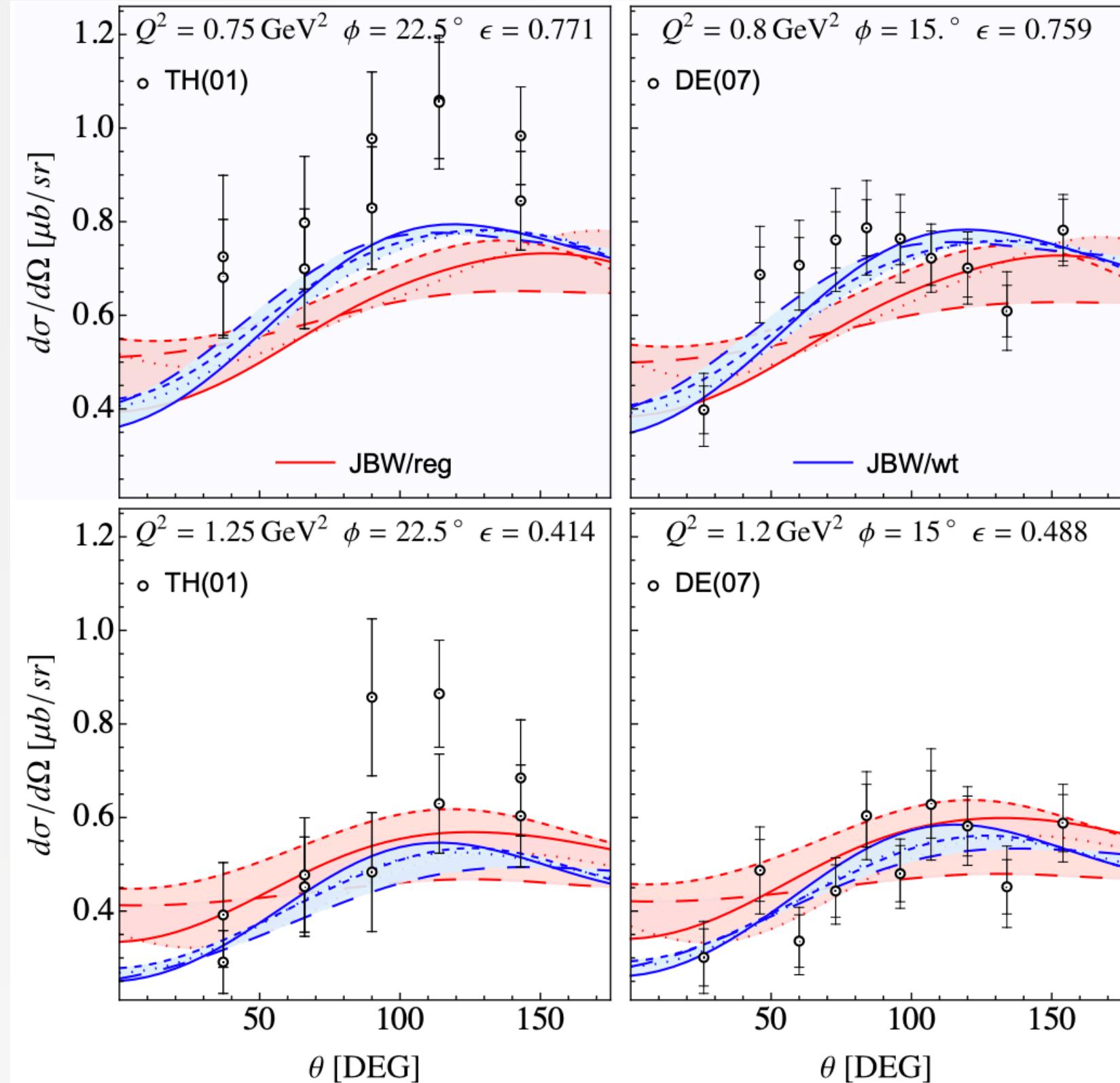


RESULTS

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

$\pi N/\eta N$ data fits¹:

- all strategies converge
- different minima (systematic uncertainties)
- many ambiguities in data²



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

2) H. Denizli et al. (CLAS) *PRC* 76, 015204 (2007); Thompson et al. (CLAS), *PRL* 86, 1702–1706 (2001); ...

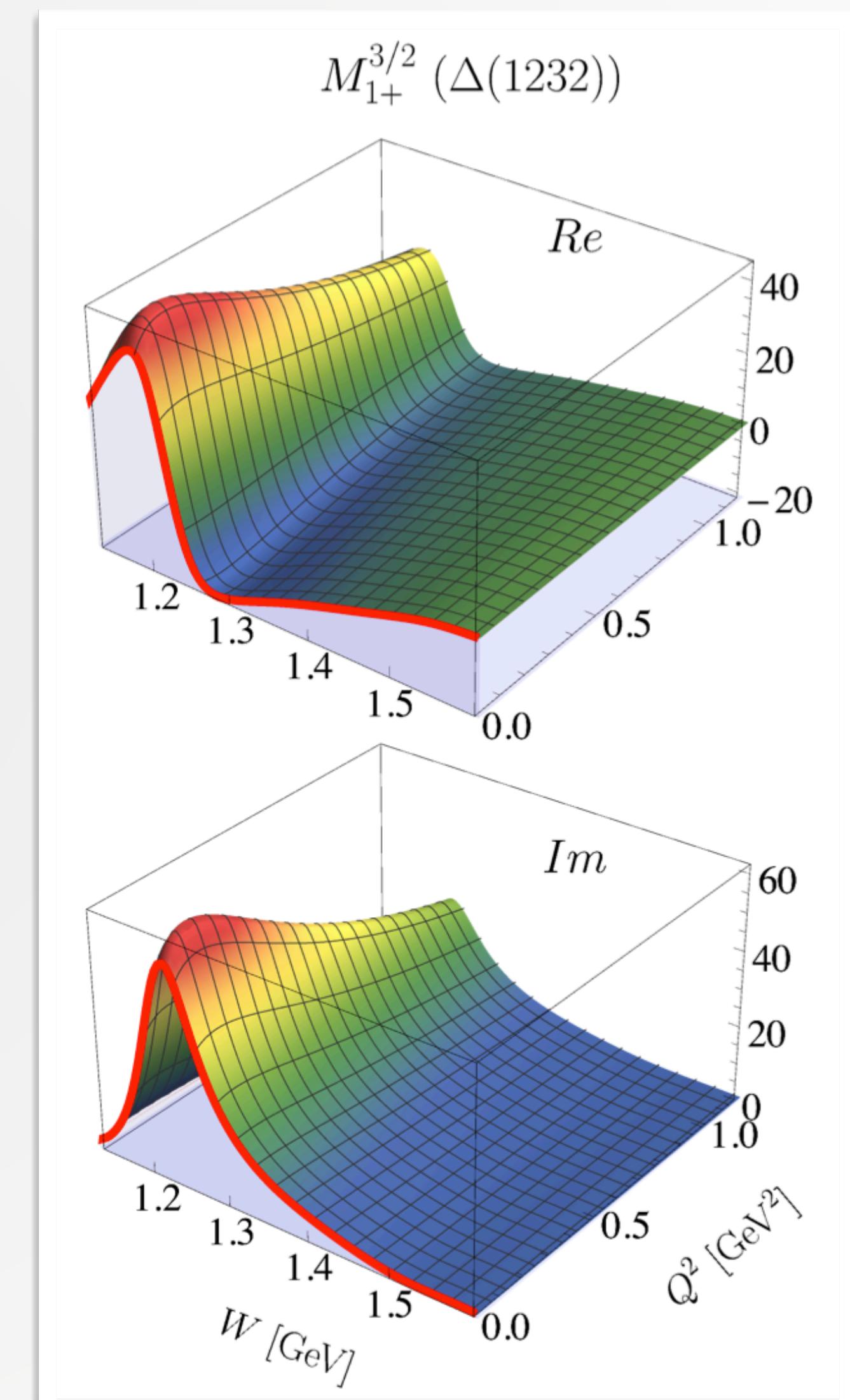
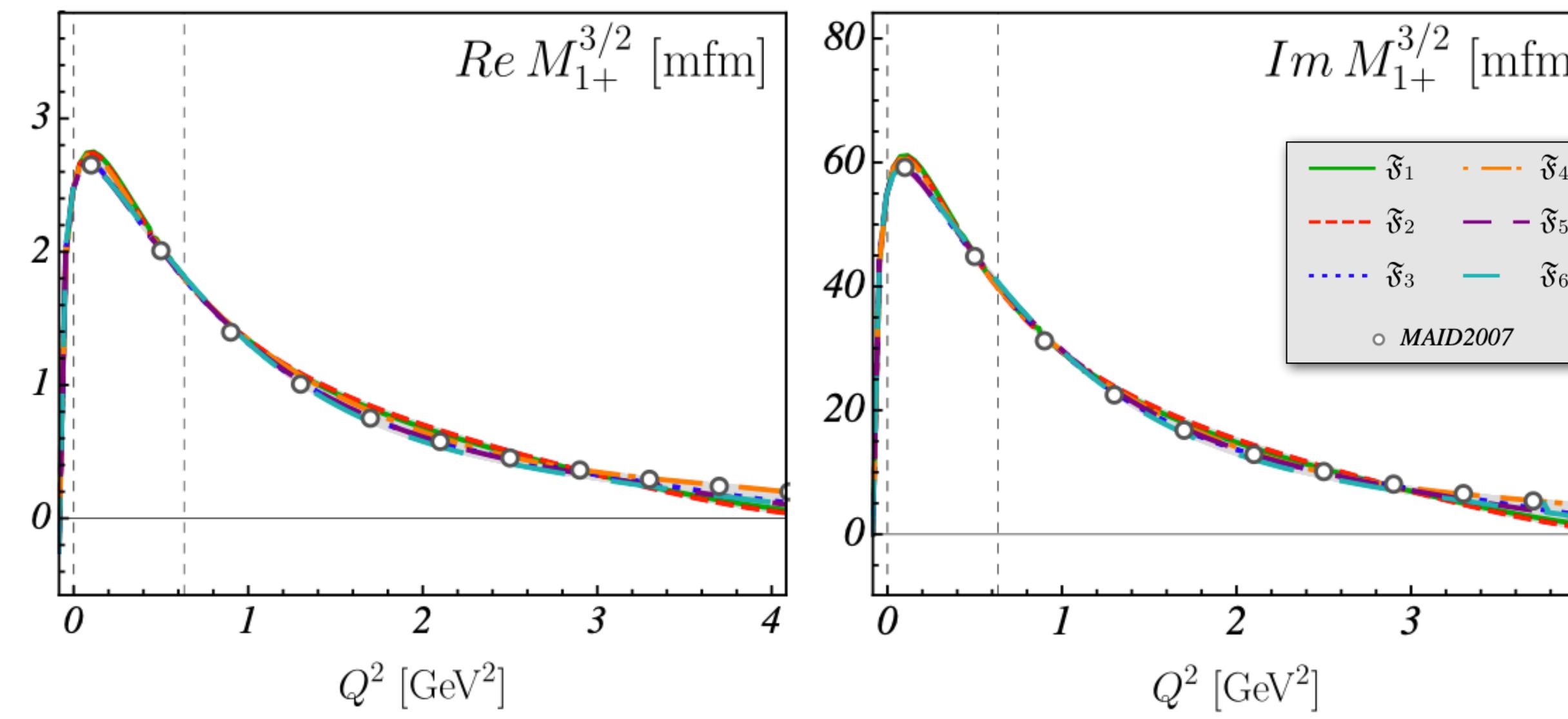


MULTIPOLES

Delta:

- Large multipoles well determined

$W = 1230 \text{ MeV}$

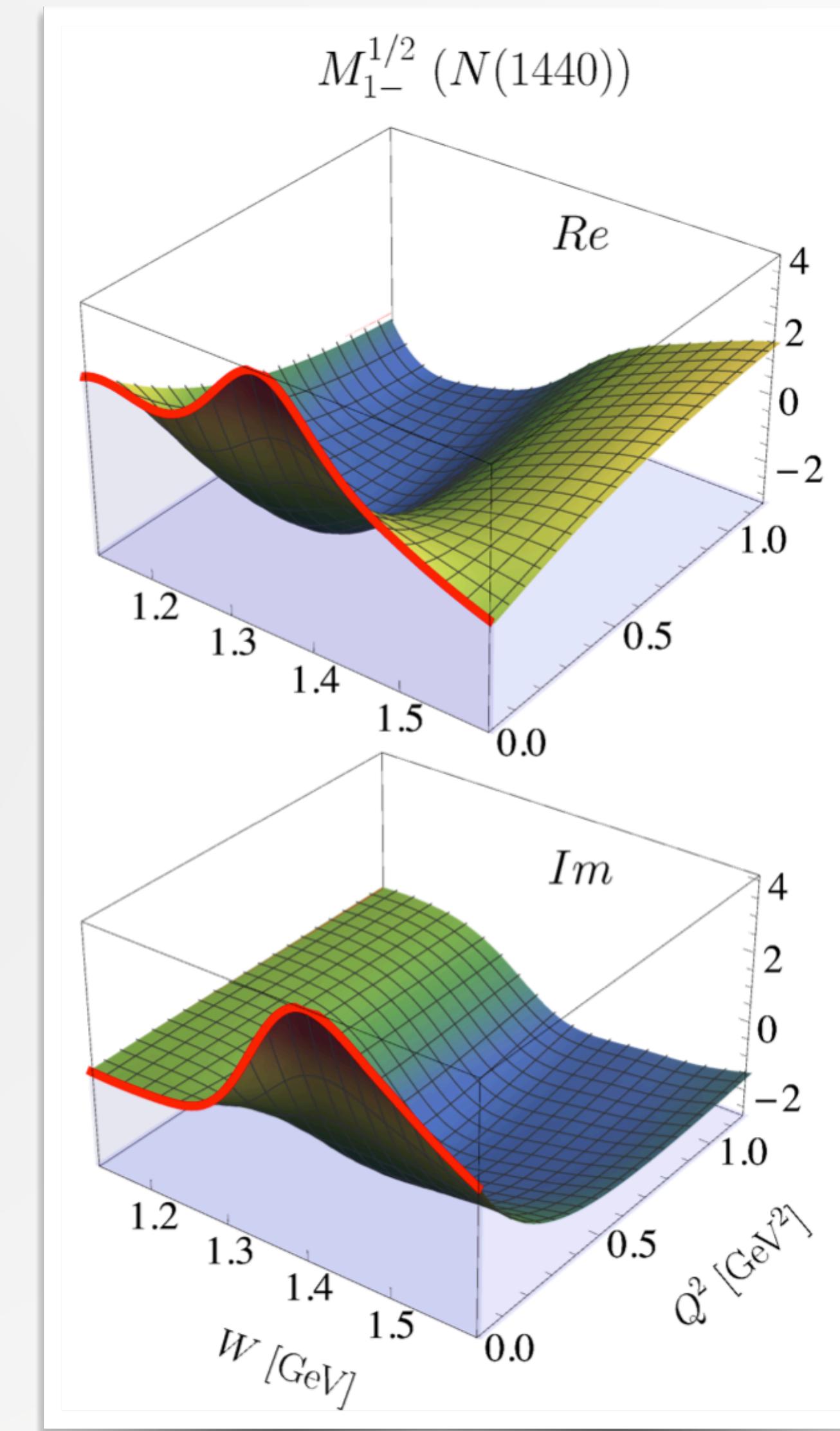
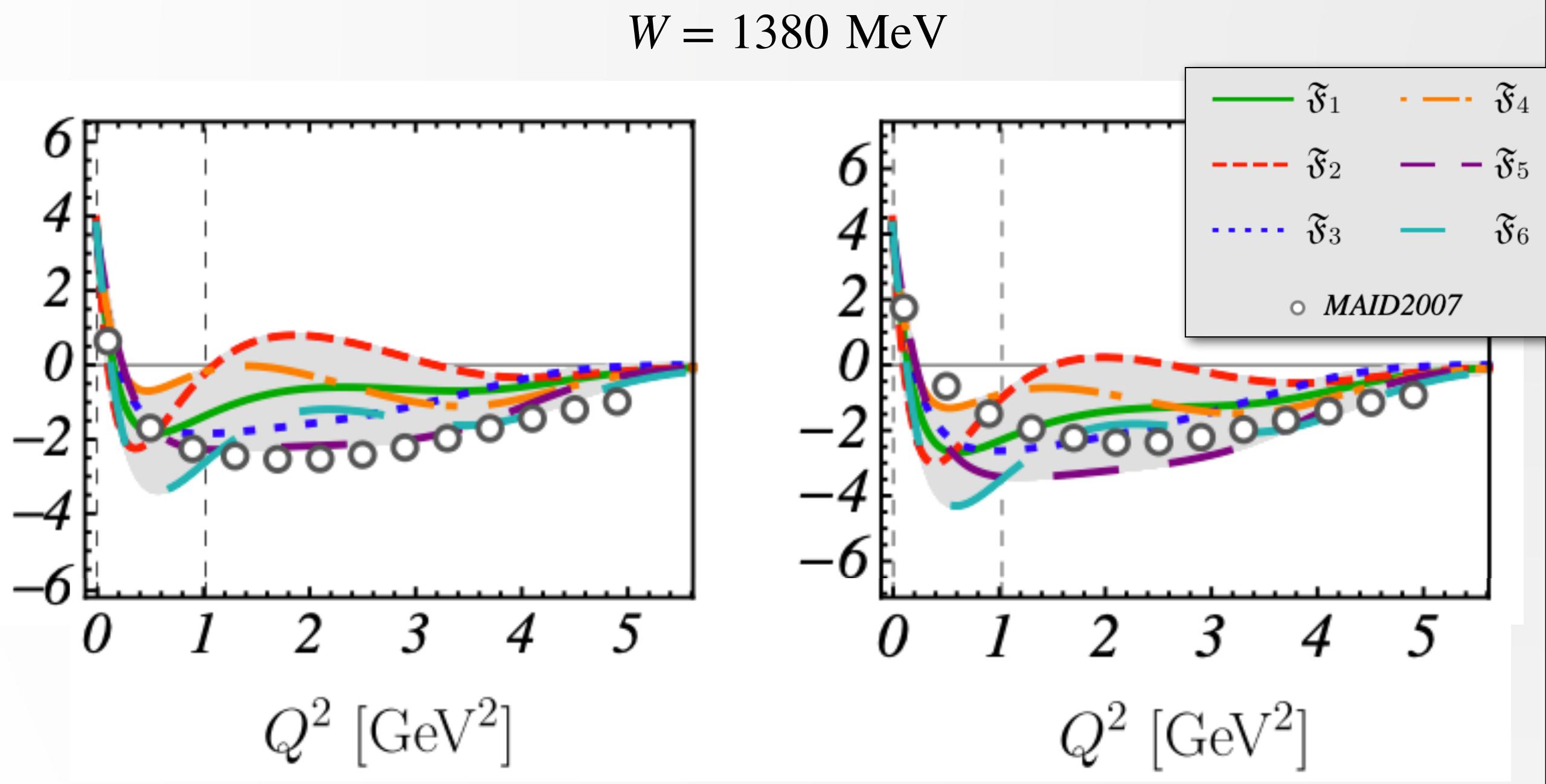




MULTIPOLES

Roper:

- Non-trivial Q^2 behavior
- Zero transition



SUMMARY

Jülich-Bonn-Washington

- new model developed (constraints from symmetries and scattering/photoproduction data)
- fits to $\pi N/\eta N$ data finished
- WEB INTERFACE: <https://jbw.phys.gwu.edu>
- $\pi N/\eta N/K\Lambda$ fits (nearly world data)
- Helicity couplings
- simultaneous fit to scattering and photoproduction data
- statistical studies of parameter importance¹ (LASSO, Machine Learning, ...)
- energy dependent analysis(?)



...

Jülich-Bonn-Washington

- new model developed (constraints from symmetries and scattering/photoproduction data)
 - fits to $\pi N/\eta N$ data finished
 - WEB INTERFACE: <https://jbw.phys.gwu.edu>
 - $\pi N/\eta N/K\Lambda$ fits (nearly world data) → SOON!!!
 - Helicity couplings → SOON!!!
 - simultaneous fit to scattering and photoproduction data
 - statistical studies of parameter importance¹ (LASSO, Machine Learning, ...)
 - energy dependent analysis (?)
- ...





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

(Pseudo)-threshold behavior
with meson/photon momenta

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

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

...

Final-state unitarity & Jülich-Bonn photoproduction amplitude

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

Siegert's theorem

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

Parametrization dependence due to incomplete data

- even for a truncated complete electroproduction experiment

Tiator et al.(2017)

- in future: Bias-variance tradeoff with statistical criteria

Landay et al.(2017) (2019)



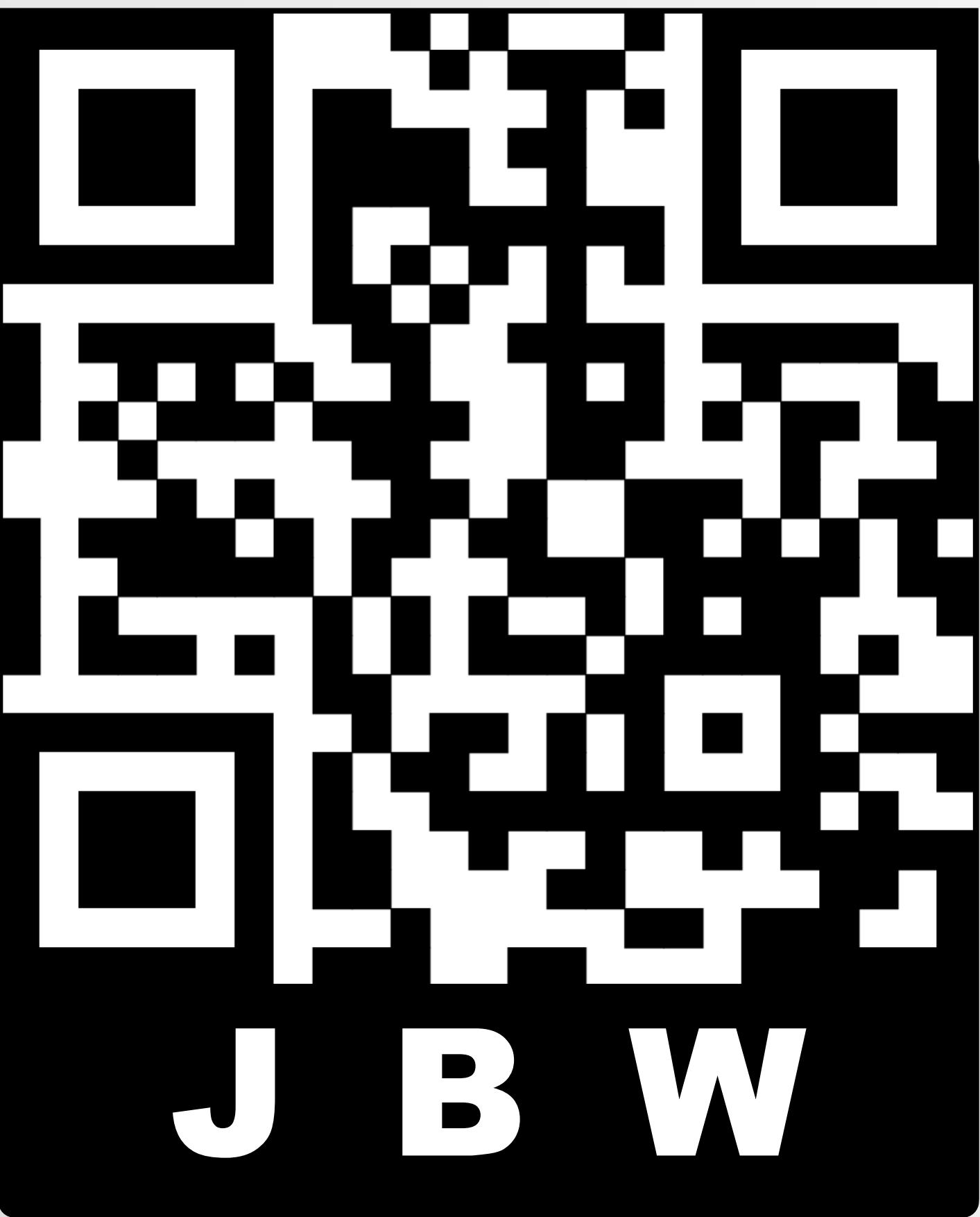
DEGREES OF FREEDOM

piN data is dominant:

> weighted or unweighted fits

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

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





MULTIPOLES

Observable (e.g. cross section)

$$\frac{d\sigma^\nu}{d\Omega}(W, Q^2, \epsilon, \theta, \phi) = \sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi + \dots$$

Structure functions

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

Helicity amplitudes

$$H_1(W, Q^2, \theta) = \sin\theta\cos\theta/2(-\mathcal{F}_3 - \mathcal{F}_4)/\sqrt{2}, \dots$$

CGLN amplitudes

$$\mathcal{F}_1(W, Q^2, \theta) = \sum_{\ell>0} \ell M_{\ell+}(W, Q^2) P'_{\ell+1}(\cos\theta) + \dots$$

Multipoles

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

Outlook for electroproduction analysis

Reaction	Observable	Q^2 [GeV]	W [GeV]	Ref.
$ep \rightarrow e' p' \eta$	$\sigma_U, \sigma_{LT}, \sigma_{TT}$	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]
$ep \rightarrow e' K^+ \Lambda$	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 $K^+ \Lambda$ electro-production 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 ($Q^2 = 5 - 12 \text{ Gev}^2$)
 - 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