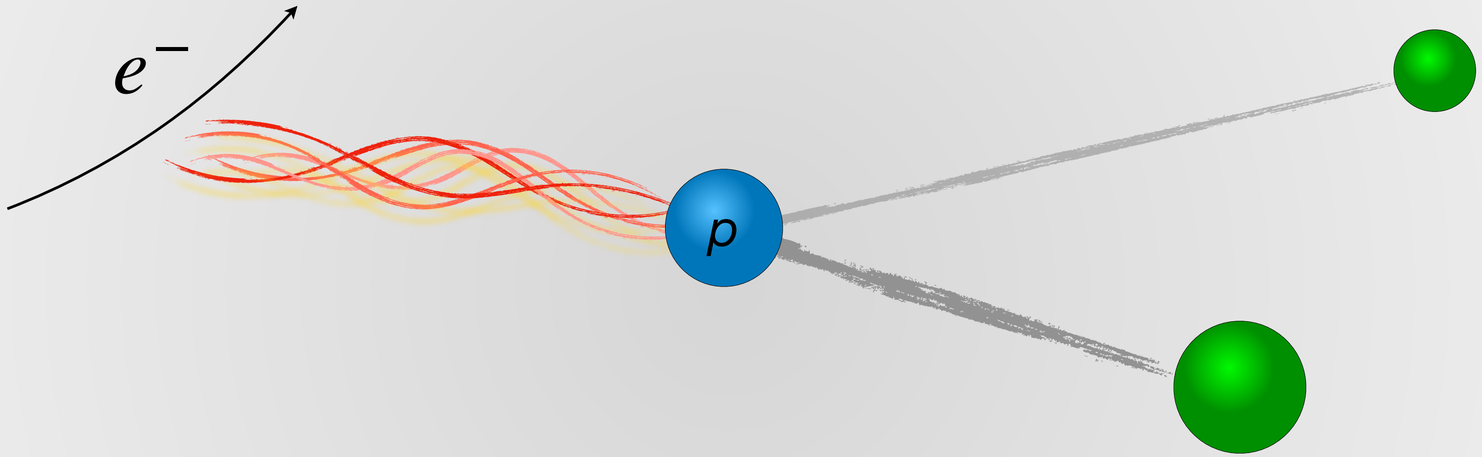
COUPLED-CHANNEL MODEL FOR KY ELECTROPRODUCTION



Maxim Mai

Jülich-Bonn-Washington collaboration:

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

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

DE-SC0016582
DE-SC0016583

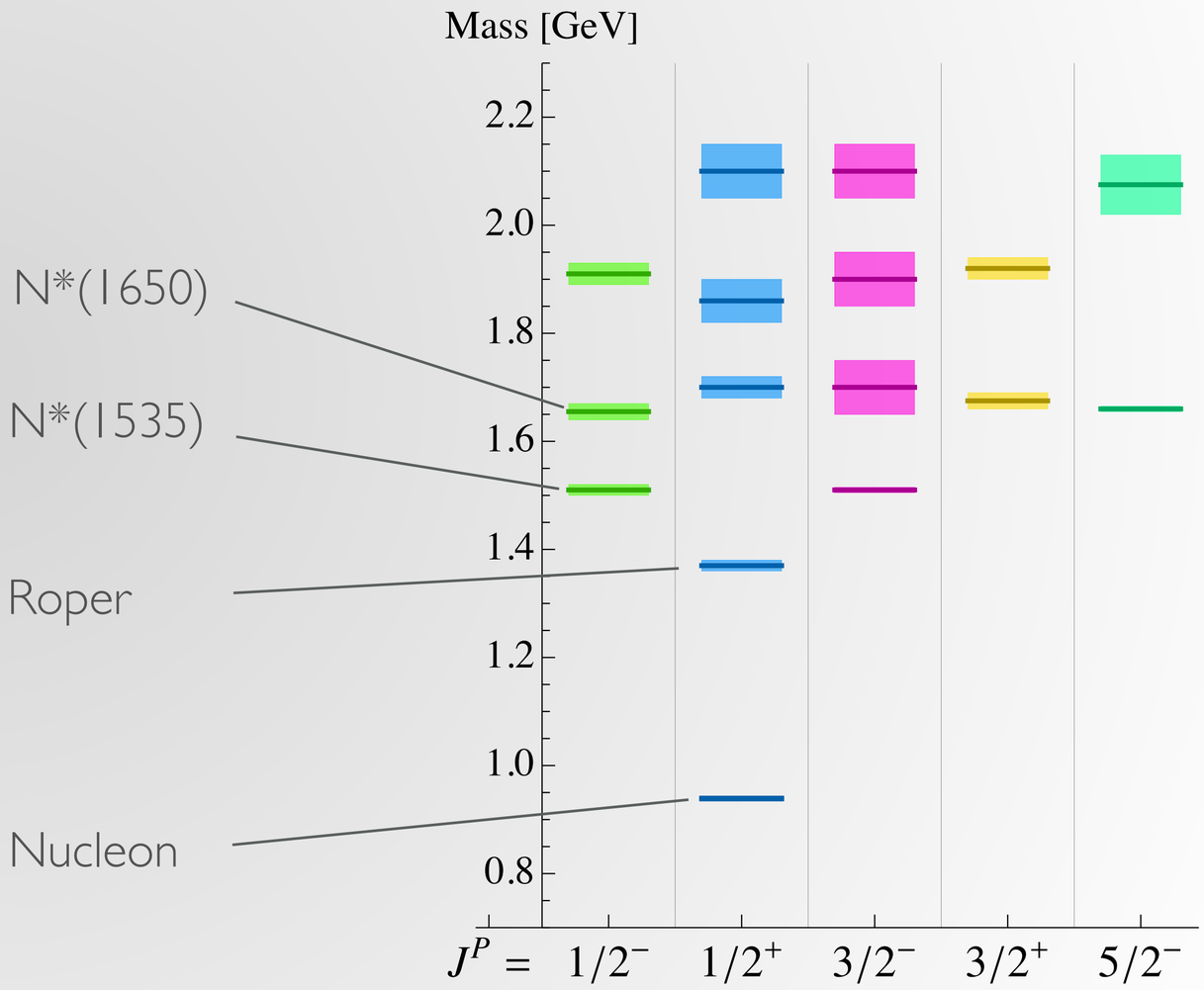
UNIVERSITÄT BONN

JÜLICH

HADRON SPECTRUM

Particle Data Group[1]:

≈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

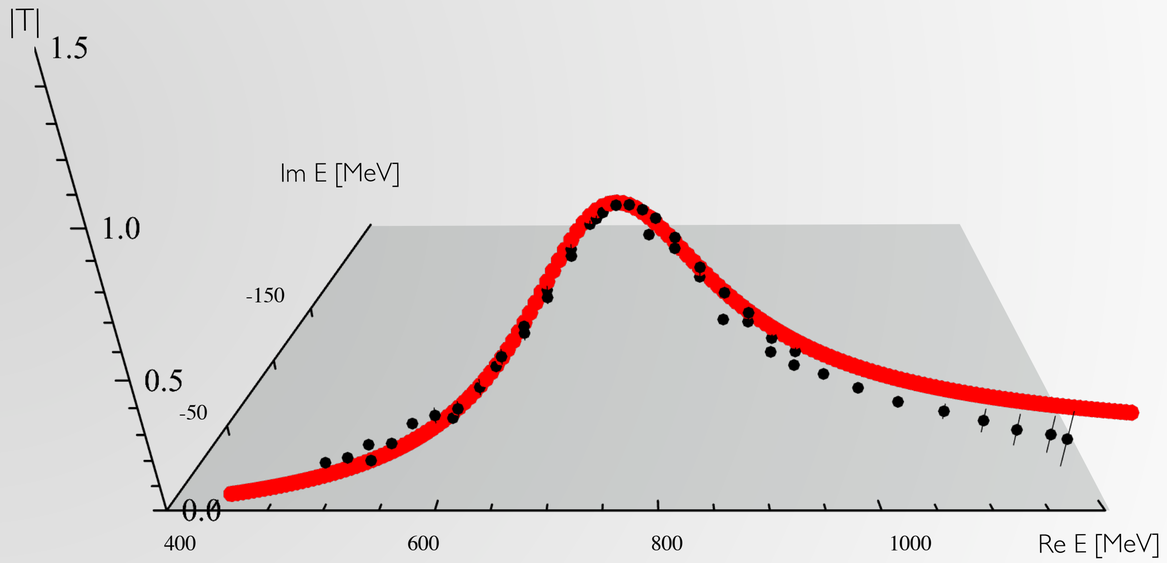
Particle Data Group[1]:

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

Reaction-independent (universal) parameters:

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

$\rho \to \pi\pi$



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

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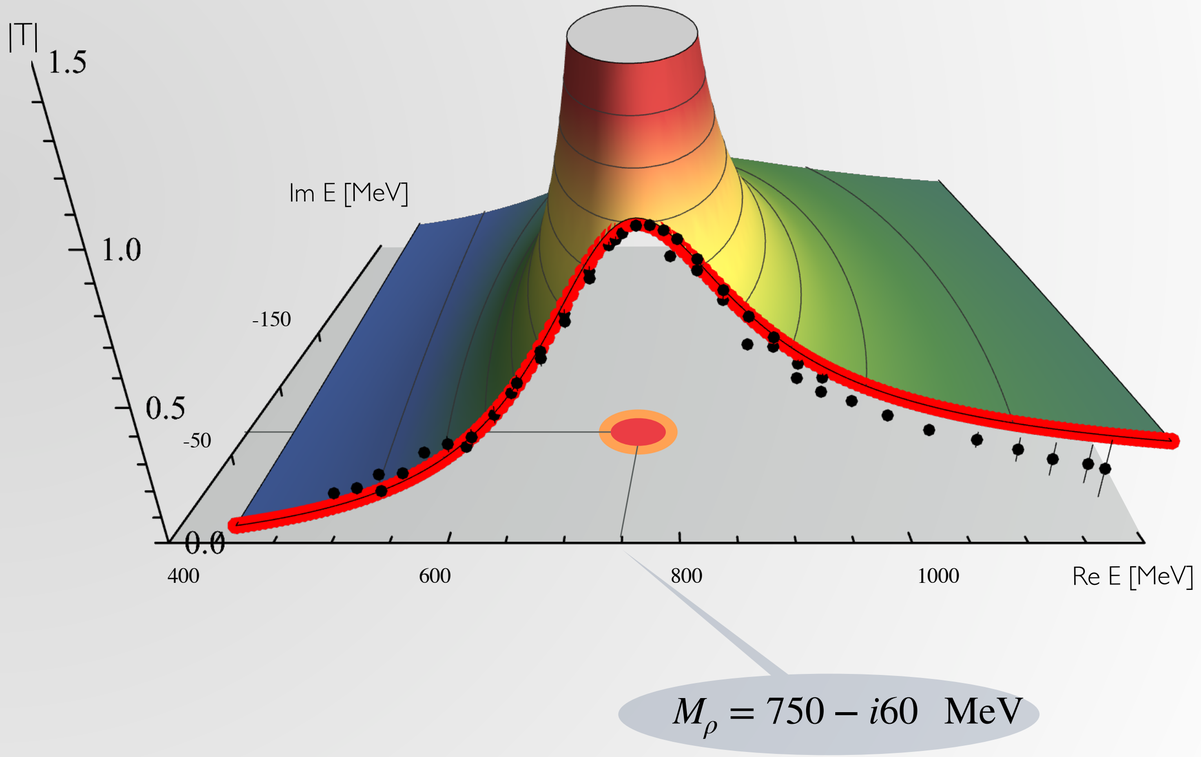

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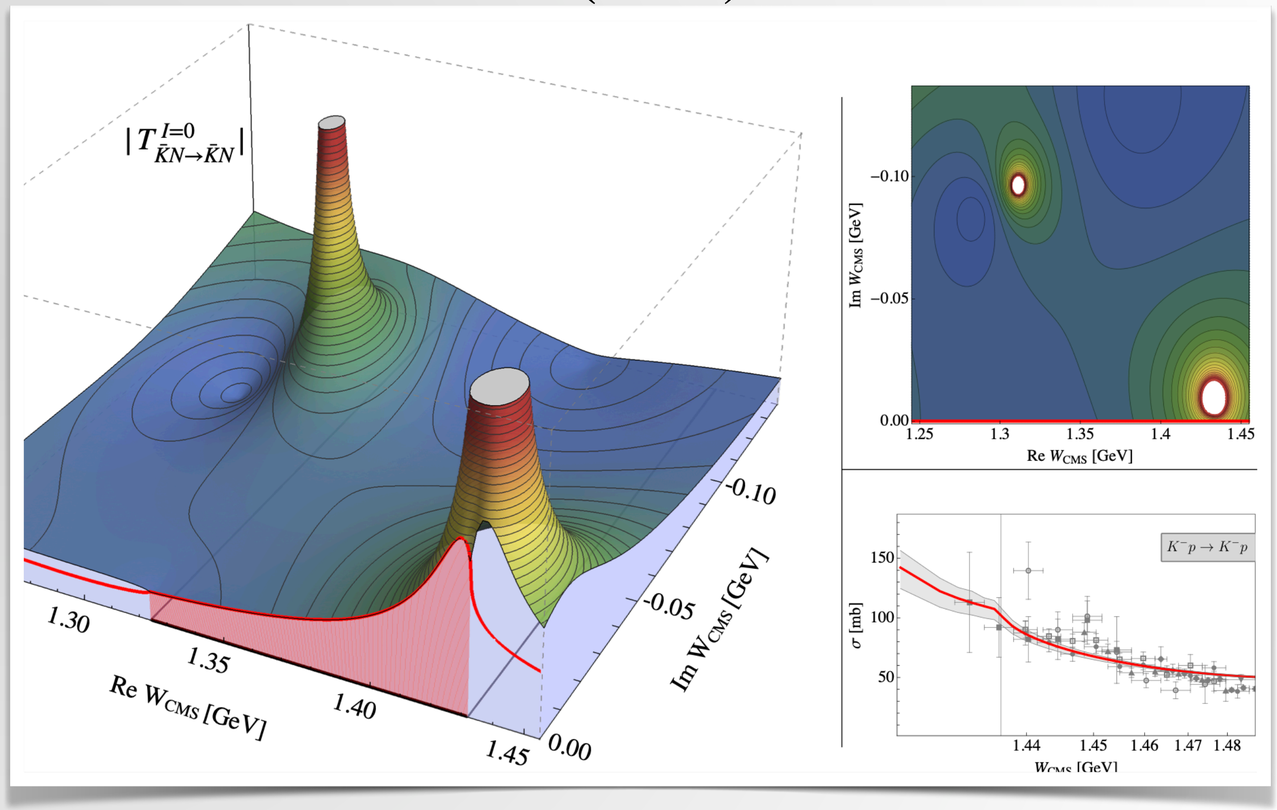
$\Lambda(1405)$



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

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HADRON SPECTRUM

Particle Data Group[1]:

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

Reaction-independent (universal) parameters:

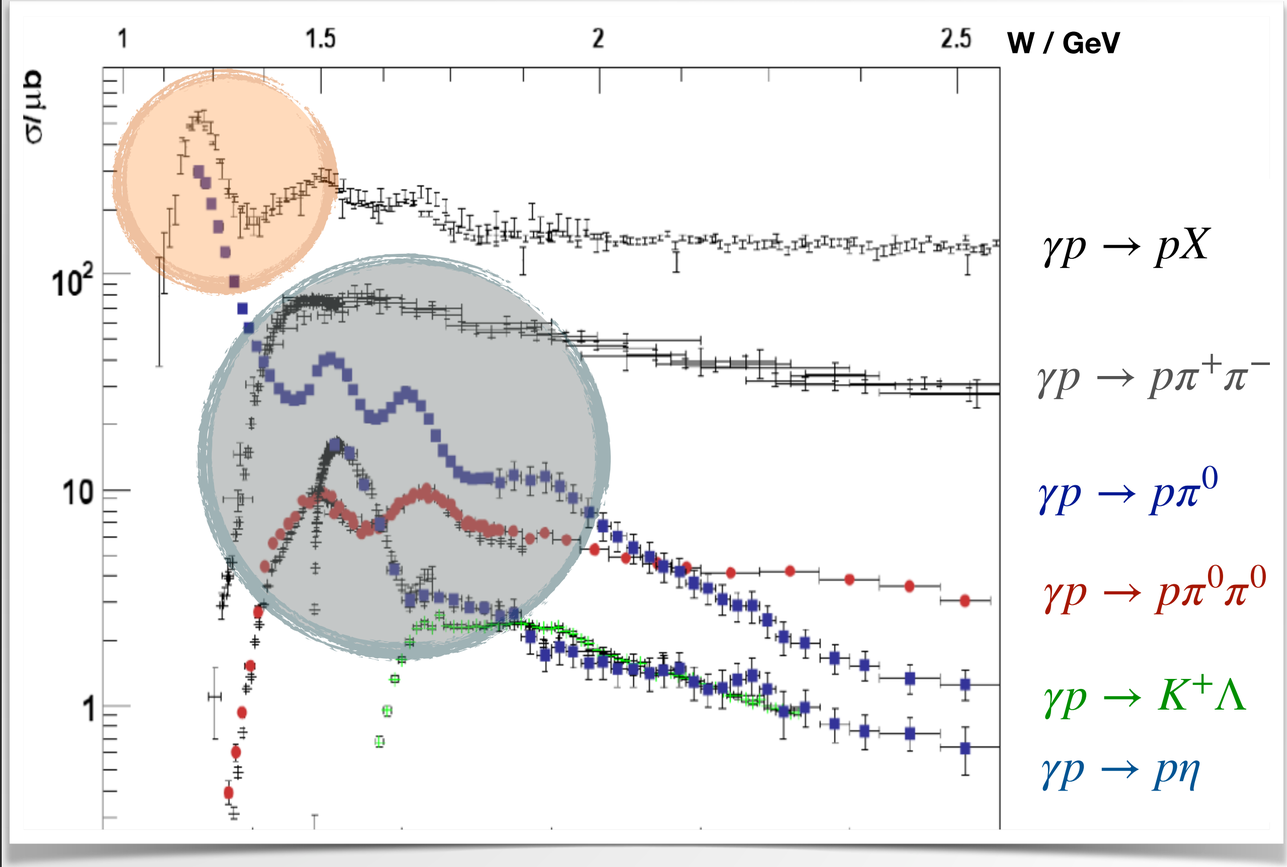
- poles on the Riemann Surface
- physical information @ real energies:
  1. theory: Lattice QCD ➟ new progress[2]
  2. experiment ➟ this talk

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-/electroproduction[1]

- large amount of data (10^5 for $\gamma p \to \pi N$)
- more data to emerge at, e.g., JeffersonLab[2] (Q^2=5-12 GeV^2)



Data: Jefferson Laboratory, ELSA, MAMI

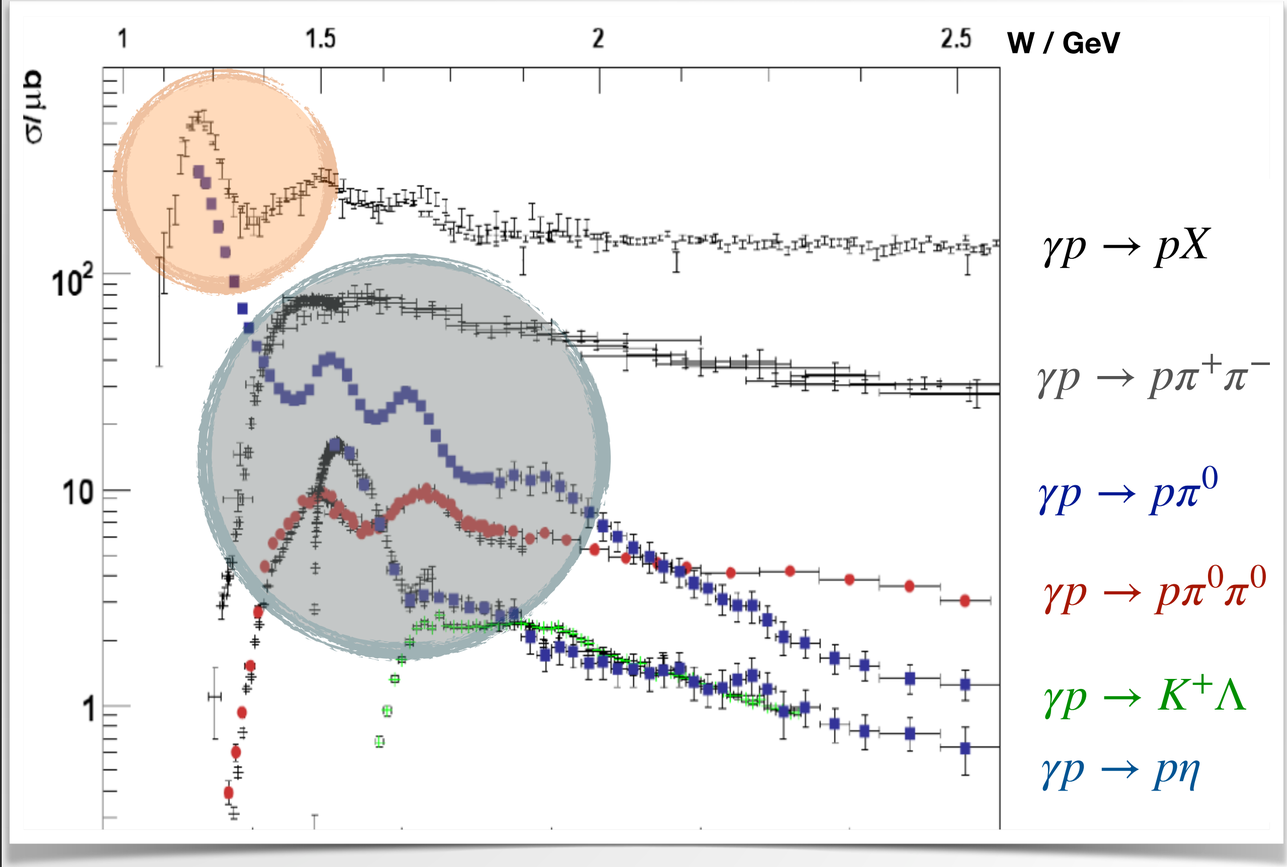
1) **TALKS: Carman; Thoma; Crede; Ganoti; Gothe; Beck; ...**
2) Carman, Joo, Mokeev, Few Body Syst. 61, 29 (2020) ... ; [CLAS] *Phys.Rev.C* 105 (2022) 065201; ...

HADRON SPECTRUM

Key questions:

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

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



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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

THEORY STATUS

- ANL-Osaka[1]
- (eta)(kaon)MAID[2]
- SAID[3]
- ...[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-Osaka[1]
- (eta)(kaon)MAID[2]
- SAID[3]
- ...[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) Review: Burkert, Roberts, Rev.Mod.Phys. 91 (2019)

THEORY STATUS

Jülich-Bonn-Washington approach

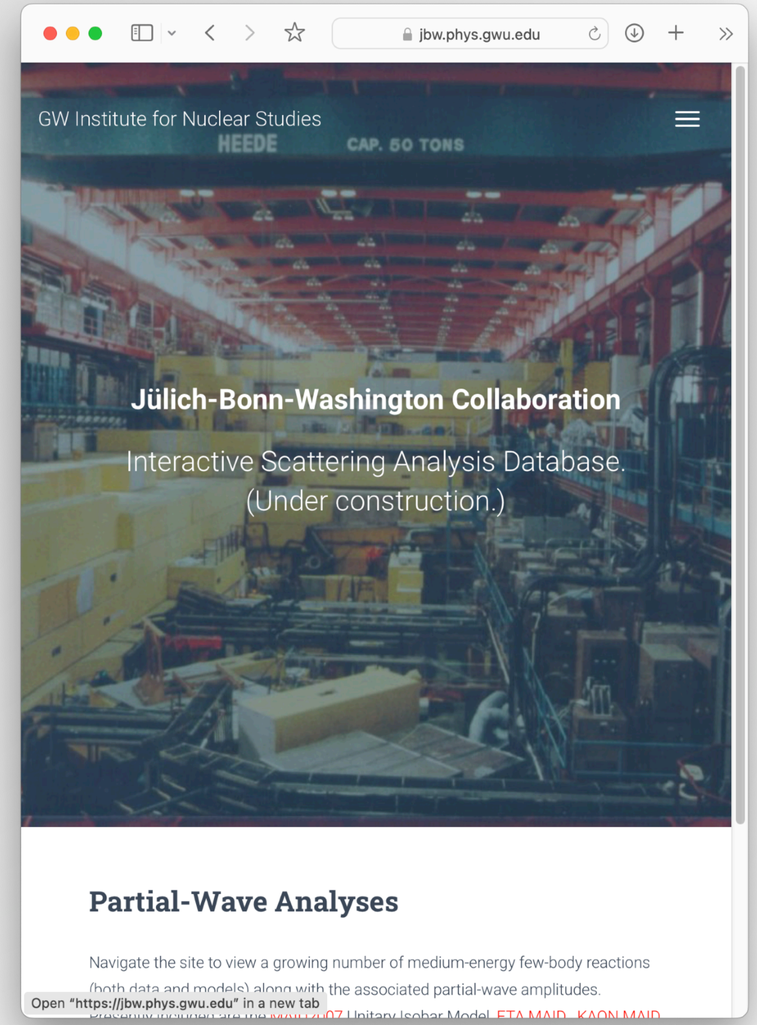
- coupled-channel approach (universality)

  simultaneous description of πN, ηN, $K\Lambda$, $K\Sigma$, ... channels

- threshold constraints, gauge invariance, ...

- constraints from scattering data

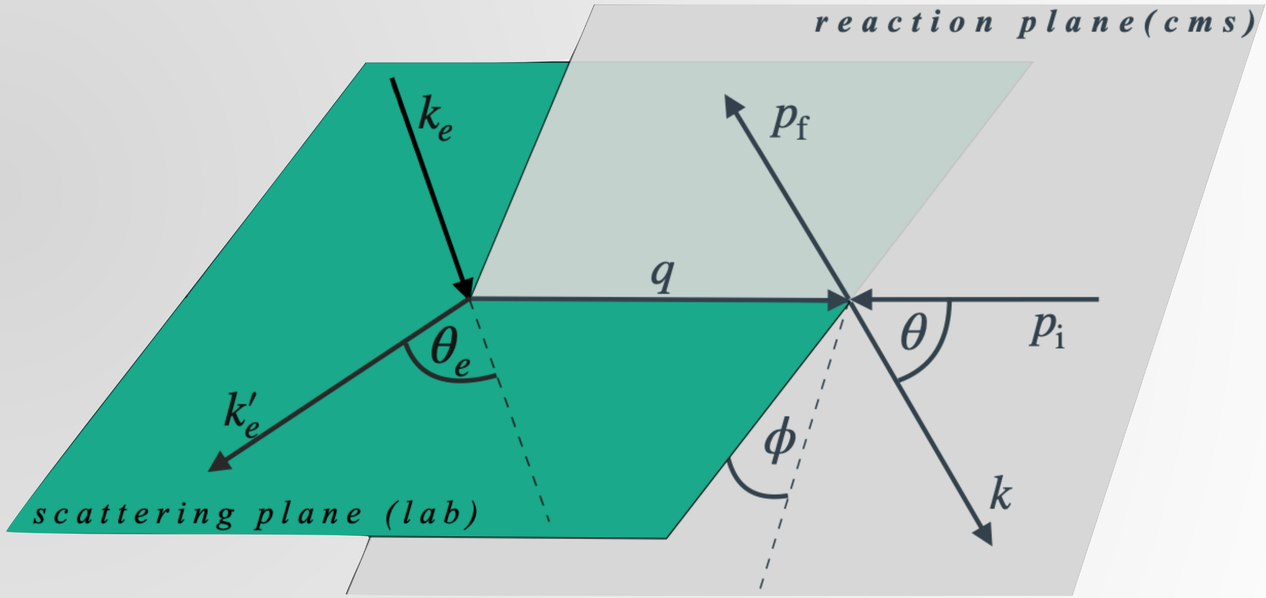
https://jbw.phys.gwu.edu/



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



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

1. total energy: W
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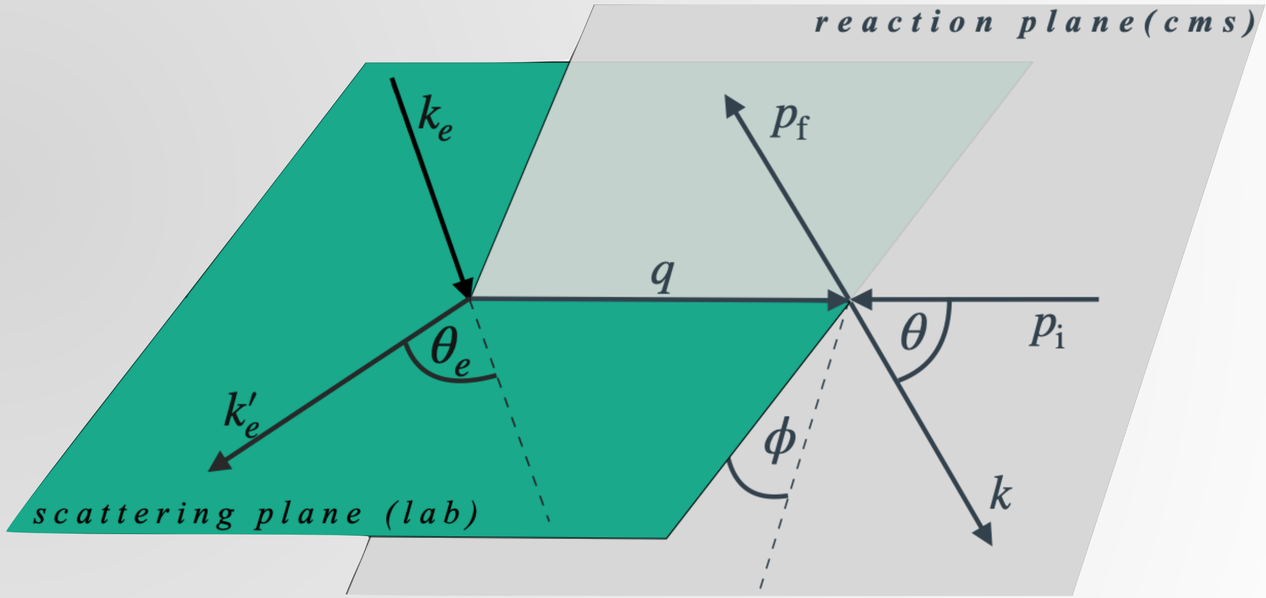
4. production angles: θ,φ

Underlying objects:

➥ Helicity amplitudes: $\{H_i\left(W,Q^2,\theta\right)|\,i=1..8\}$

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



THEORETICAL CONSTRAINTS

I. Gauge invariance

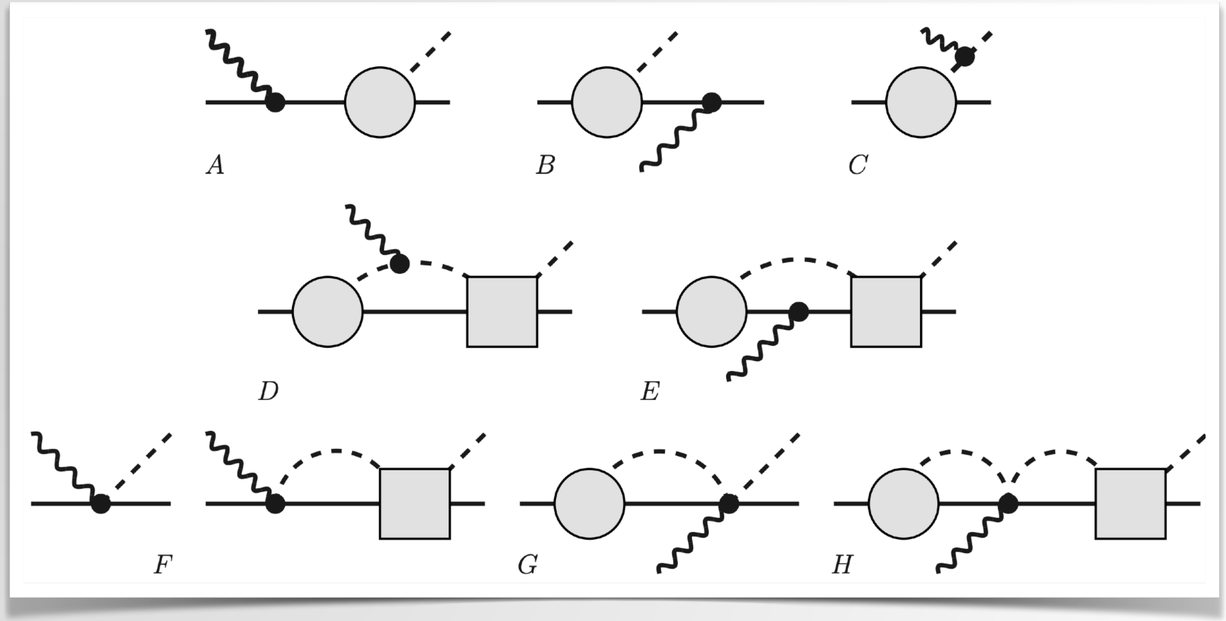
1) Afnan et al.(1995); Kvinikhidze et al.(1999); Haberzettl(19xx-2021); Borasoy et al.(2007); Ruic et al.(2011); MM et al. (2012);
2) Bruns, Cieplý, MM 2206.08767 [nucl-th]

THEORETICAL CONSTRAINTS

I. Gauge invariance

➡ manifest implementation[1] exist even for 2-meson photoproduction[2]

... but usually too costly



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

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THEORETICAL CONSTRAINTS

I. Gauge invariance

➡ manifest implementation[1] exist even for 2-meson photoproduction[2]

... but usually too costly

➡ 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

II. Final-state unitarity

1) Rönchen et al., EPJA 49, 44 (2013) **TALK ON TUESDAY**

THEORETICAL CONSTRAINTS

II. Final-state unitarity

➡ Jülich-Bonn dynamical coupled-channel model[1]

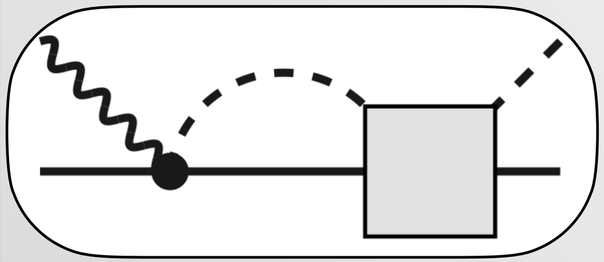

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Fig: MM; D. Rönchen

THEORETICAL CONSTRAINTS

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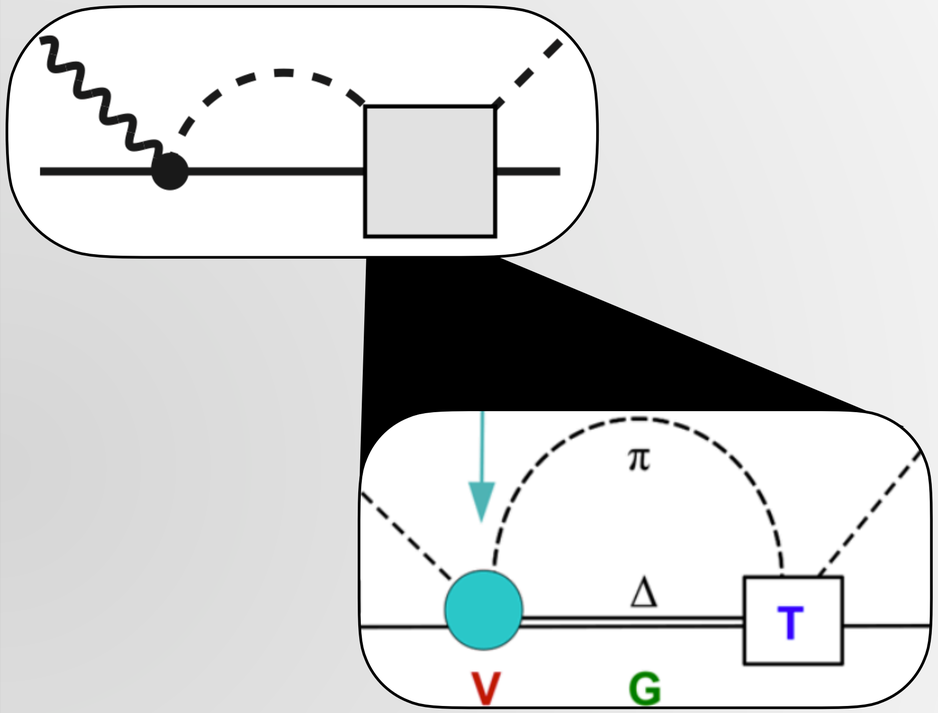

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Fig: MM; D. Rönchen

THEORETICAL CONSTRAINTS

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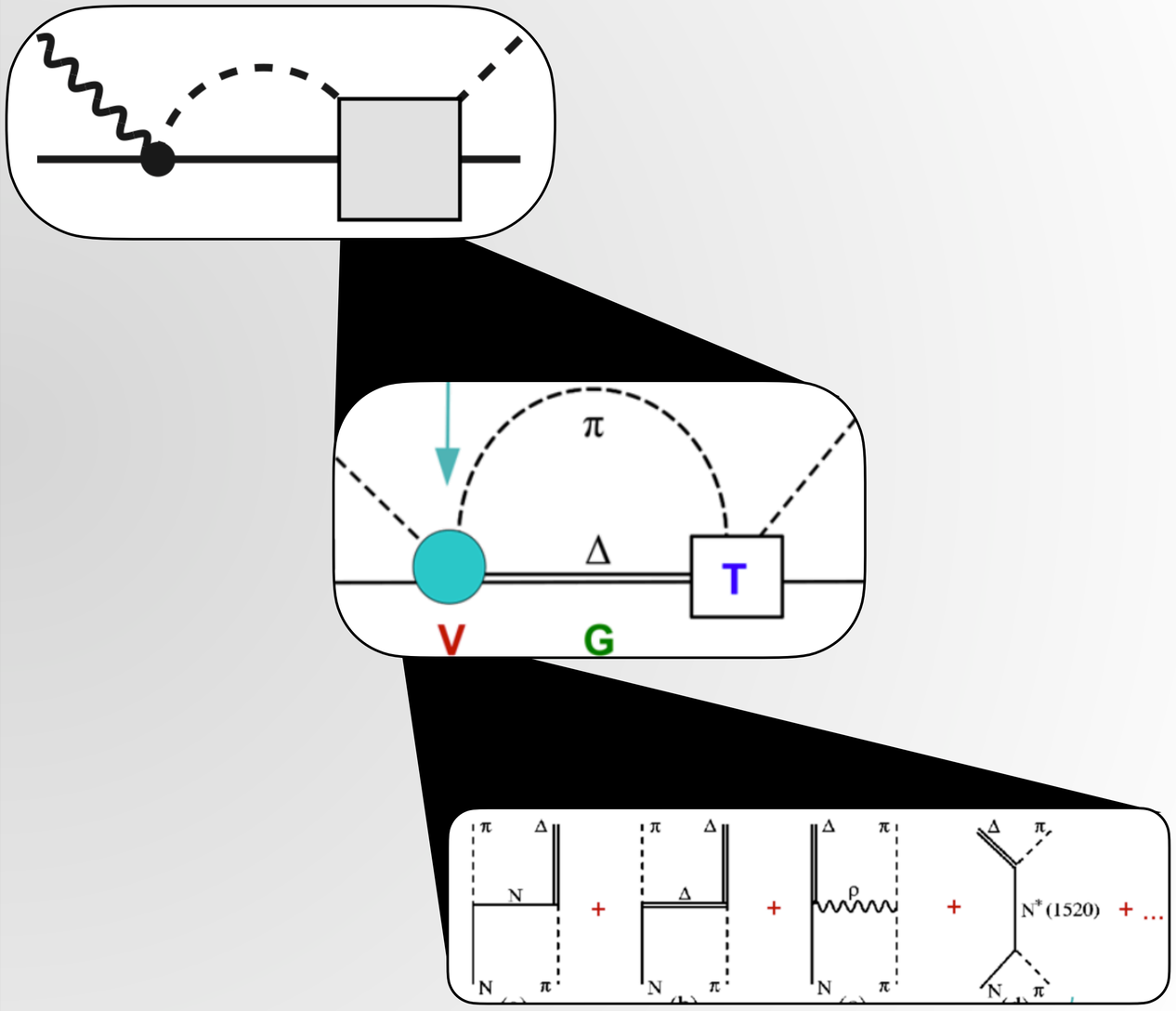

1) Rönchen et al., EPJA 49, 44 (2013) **TALK ON TUESDAY**

Fig: MM; D. Rönchen

THEORETICAL CONSTRAINTS

II. Final-state unitarity

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

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

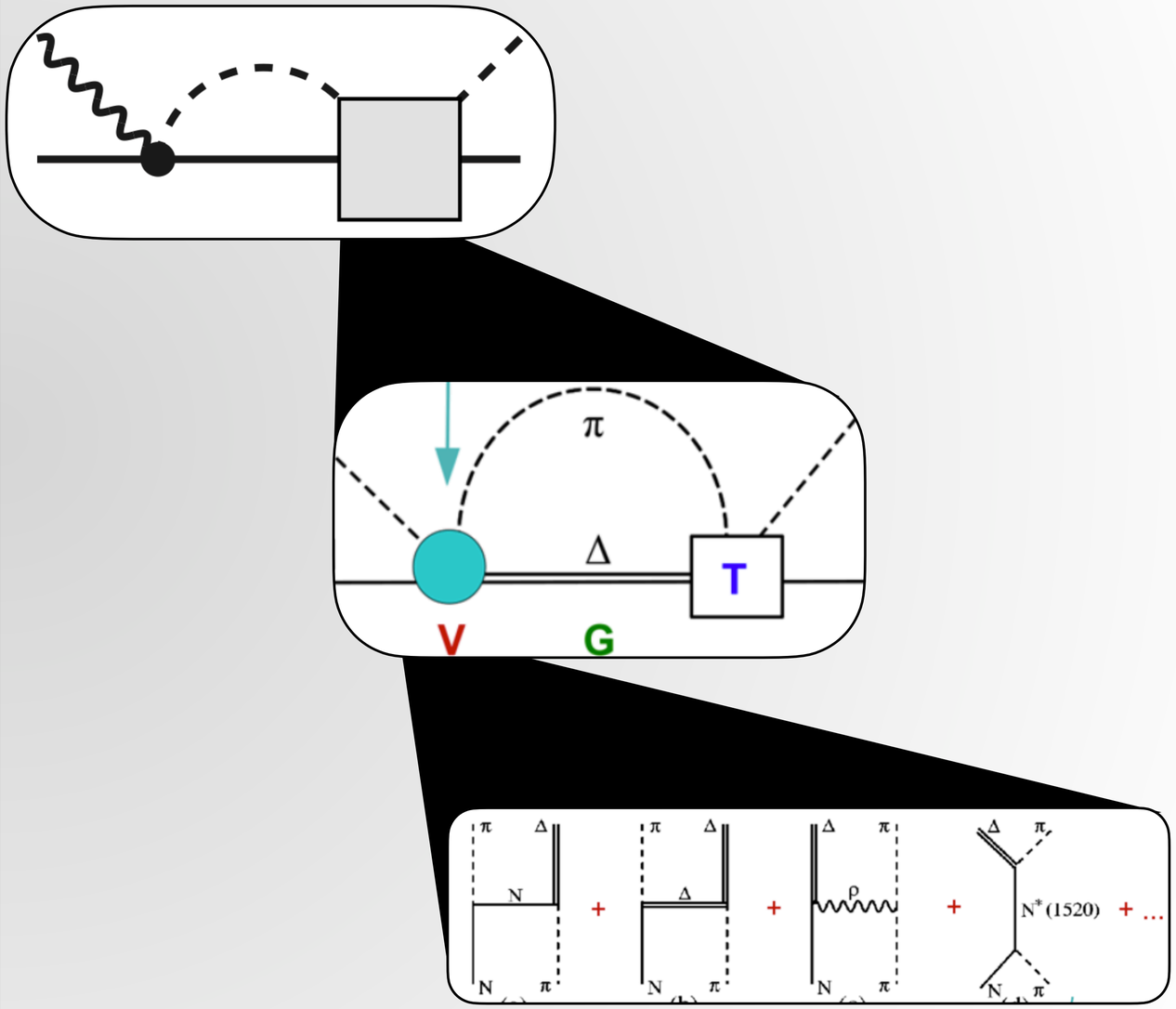

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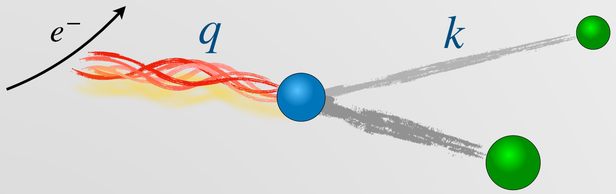
Fig: MM; D. Rönchen

THEORETICAL CONSTRAINTS

III. Pseudo/threshold constraints:

➥ Momentum dependence



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

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

$$\dots$$

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

THEORETICAL CONSTRAINTS

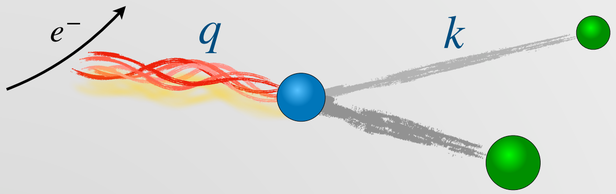
III. Pseudo/threshold constraints:

➥ Momentum dependence

IV. Siegert's theorem[1]

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

good news: fewer parameters needed



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

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$$\dots$$

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

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

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

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

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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

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

Describes

- scattering and photoproduction data — ***TALK Deborah Rönchen***
- parameters (λ, β) from electroproduction data

Parametrization dependence due to incomplete data

- even for a truncated complete electroproduction experiment — Tiator et al.(2017) — **TALKS: Wunderlich, Svarč**
- in future: Bias-variance tradeoff with statistical criteria — Landay et al.(2017) (2019)

RESULTS

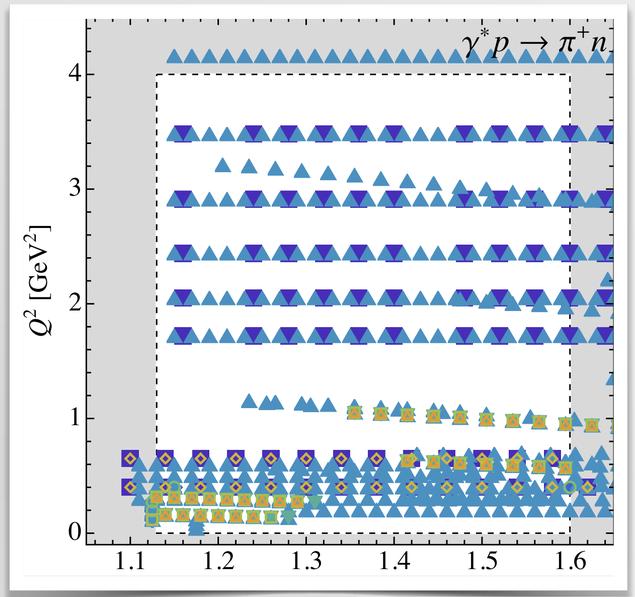
[JBW] MM, M.Döring, C.Granados, H.Haberzettl, J.Hergenrather, Ulf-G. Meißner, D.Rönchen, I.Strakovsky, R.Workman

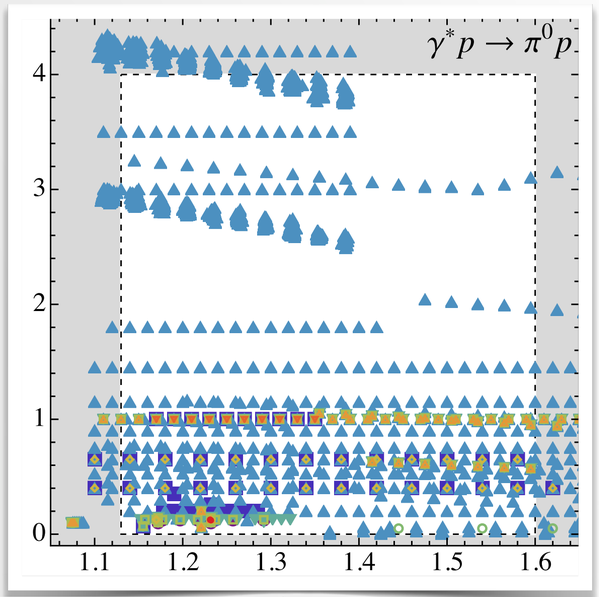
Phys.Rev.C 103 (2021) 6, 065204
Phys.Rev.C 106 (2022) 015201

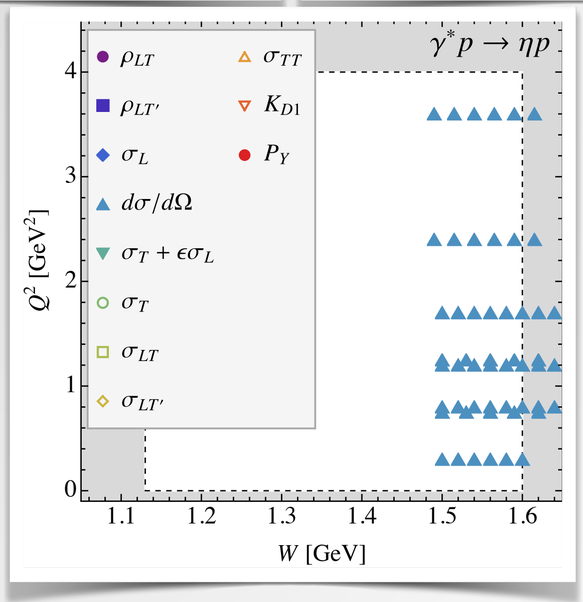
DEGREES OF FREEDOM

Experimental data

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







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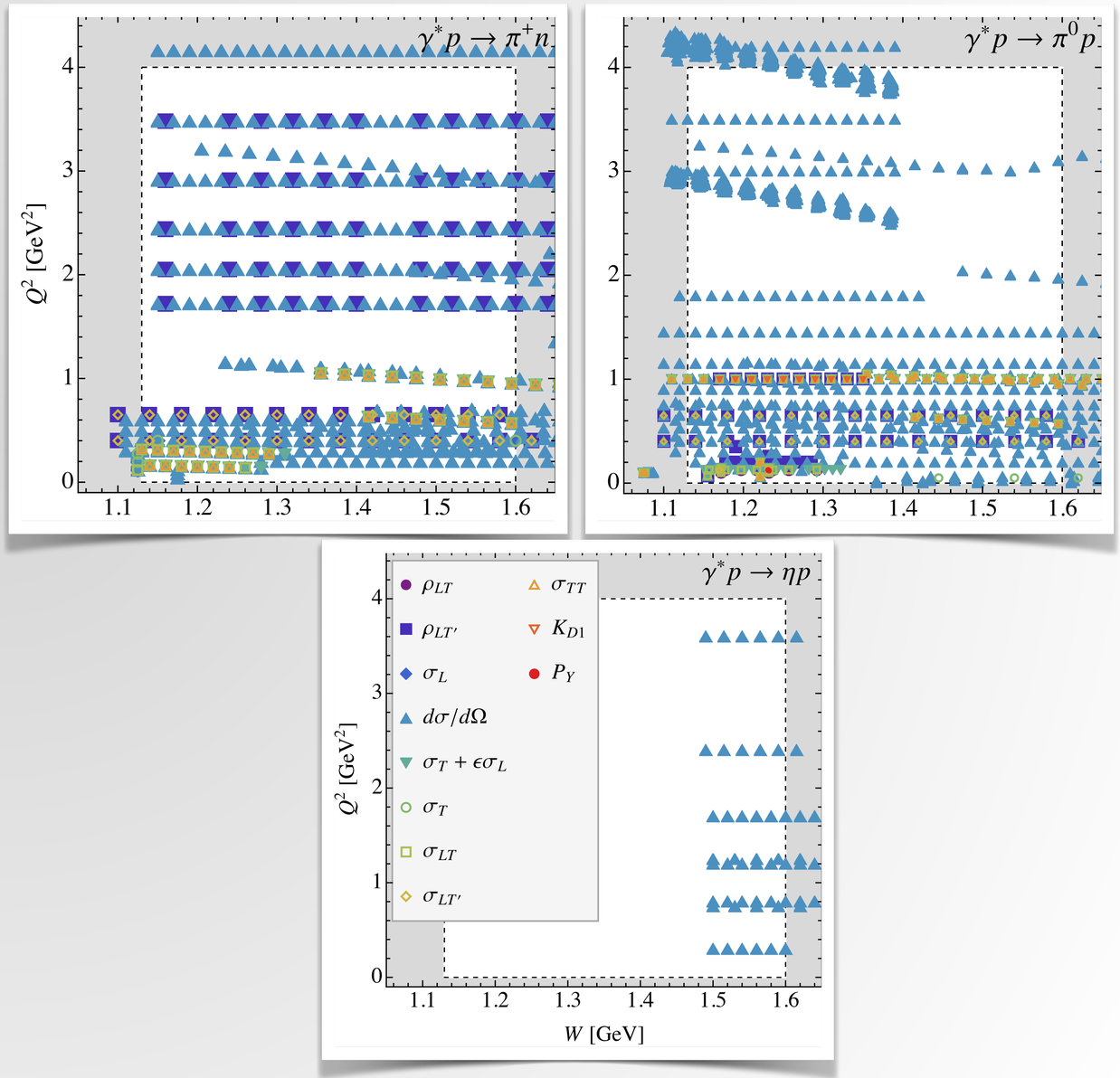
Experimental data

- 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

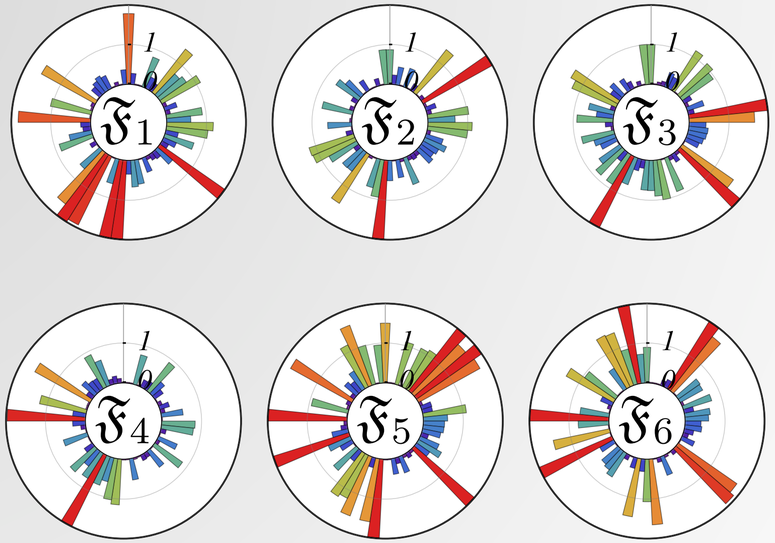


RESULTS

πN data fits[1]:

- 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**

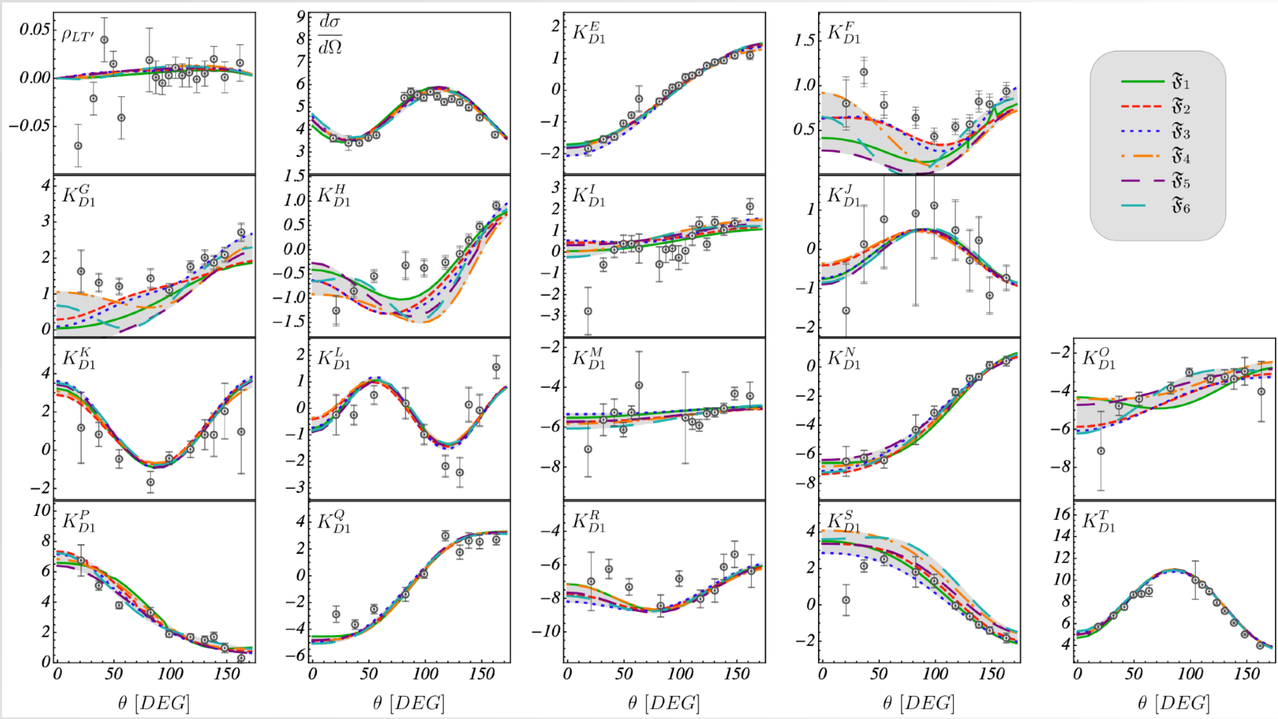


1) [JBW] MM et al. *Phys.Rev.C* 103 (2021) 6; Phys.Rev.C 106 (2022) 015201

RESULTS

πN data fits[1]:

- all strategies converge
- different minima (systematic uncertainties)
- Kelly data[2]

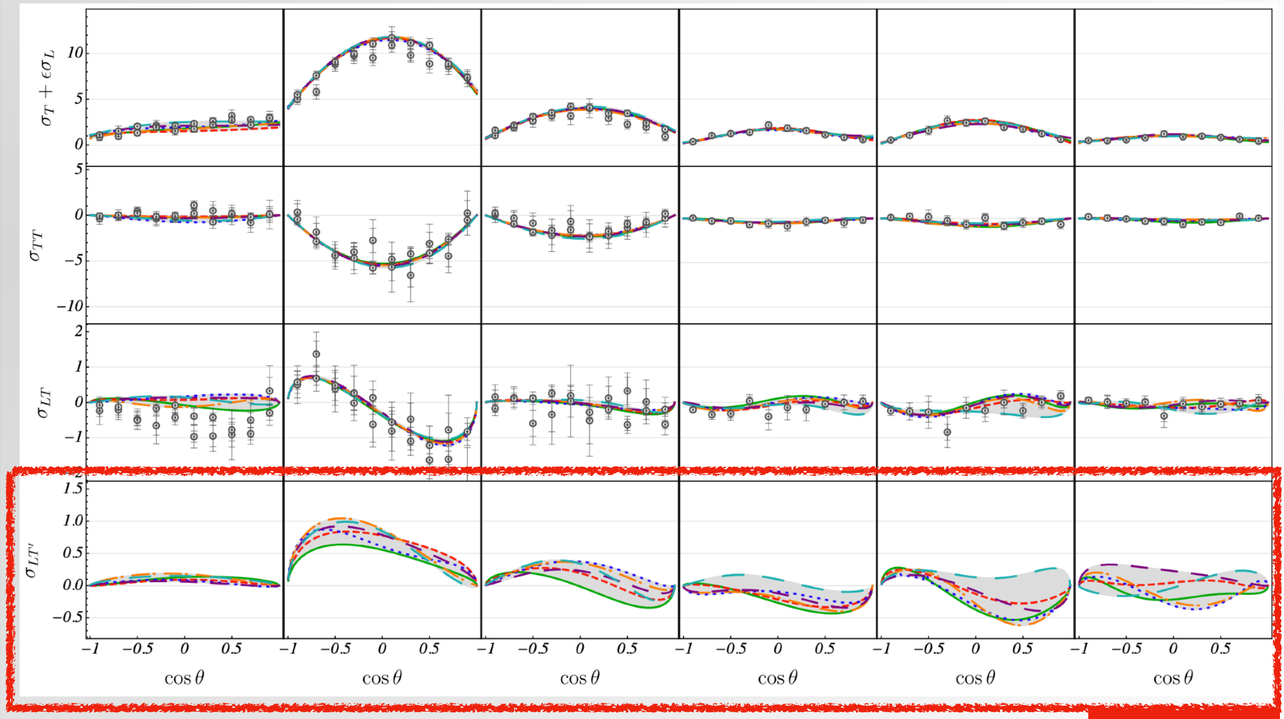


1) [JBW] MM et al. *Phys.Rev.C* 103 (2021) 6; Phys.Rev.C 106 (2022) 015201
2) Jefferson Lab Hall A Collaboration Phys.Rev.Lett. 95 (2005) 102001

RESULTS

πN data fits[1]:

- all strategies converge
- different minima (systematic uncertainties)
- Joo data[2]



PREDICTION

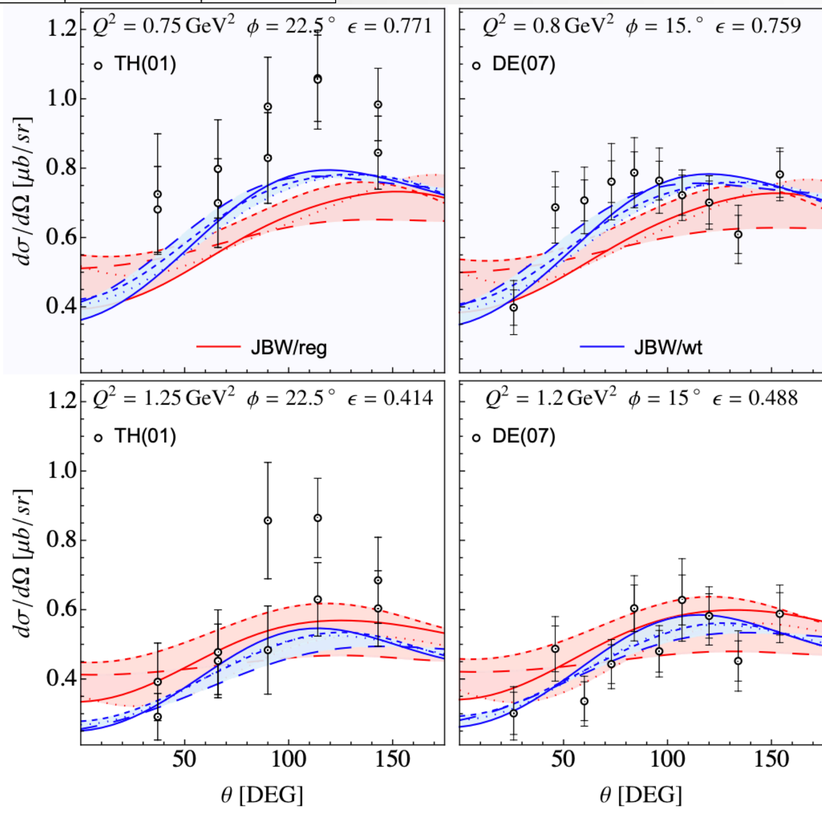
1) [JBW] MM et al. *Phys.Rev.C* 103 (2021) 6; Phys.Rev.C 106 (2022) 015201
2) Joo et al. [CLAS] PRC (2003), PRL (2002)

RESULTS

$\pi N/\eta N$ data fits[1]:

- all strategies converge
- different minima (systematic uncertainties)
- many ambiguities in data[2]

	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



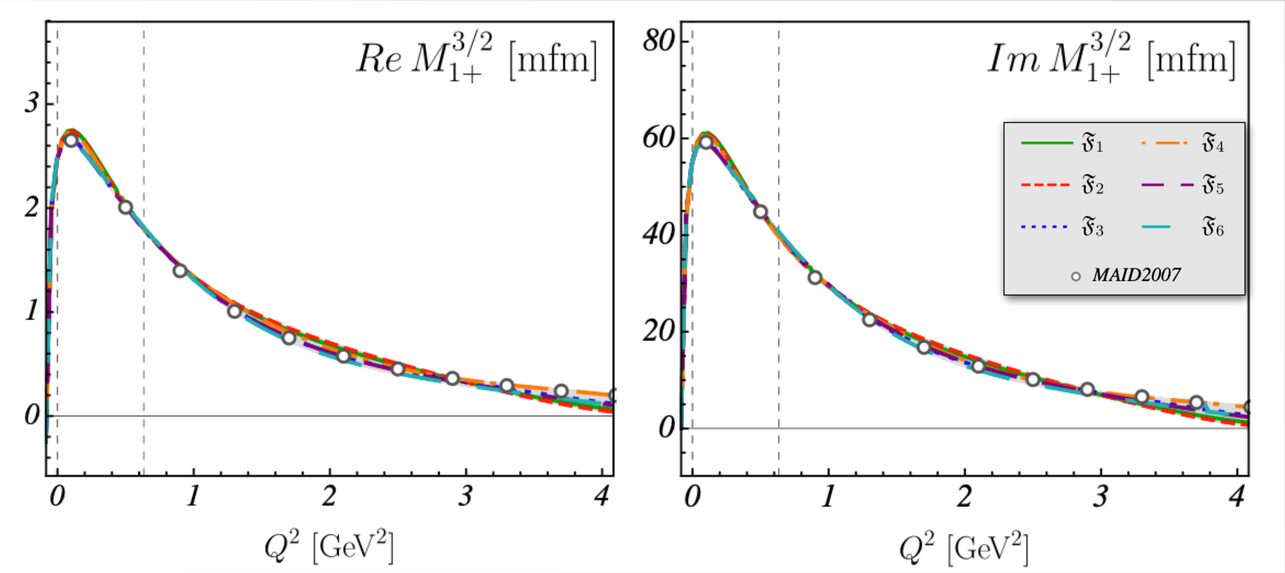
1) [JBW] MM et al. *Phys.Rev.C* 103 (2021) 6; Phys.Rev.C 106 (2022) 015201
2) H. Denizli et al. (CLAS) PRC 76, 015204 (2007); Thompson et al. (CLAS), PRL86, 1702–1706 (2001); ...

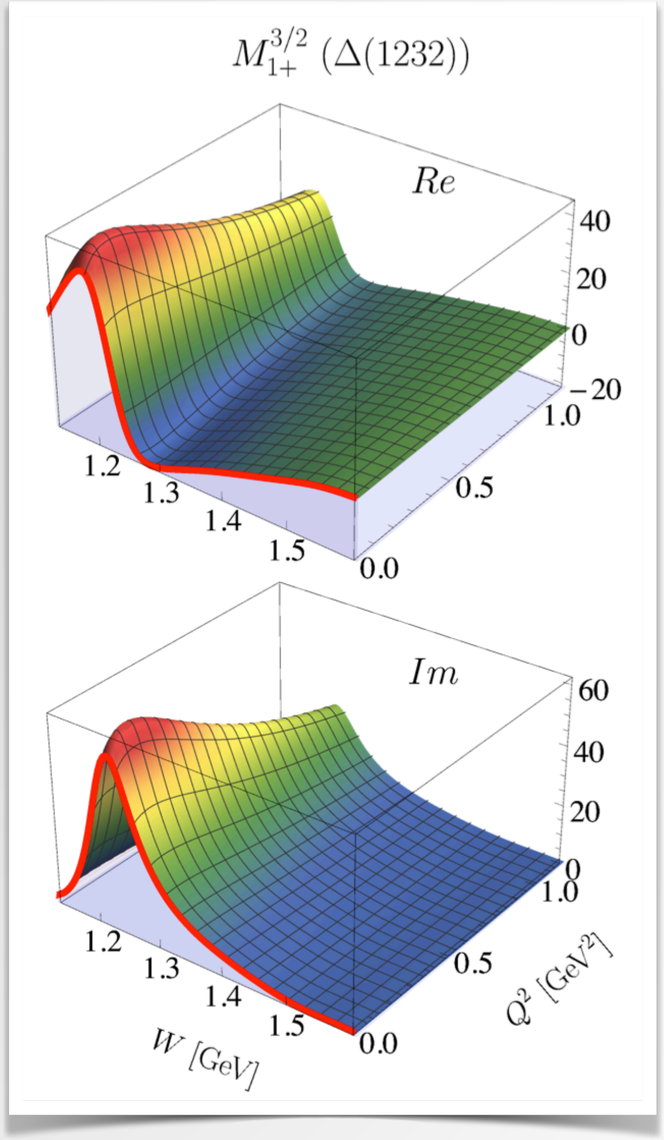
MULTIPOLES

Delta:

- Large multipoles well determined

$$W = 1230 \text{ MeV}$$





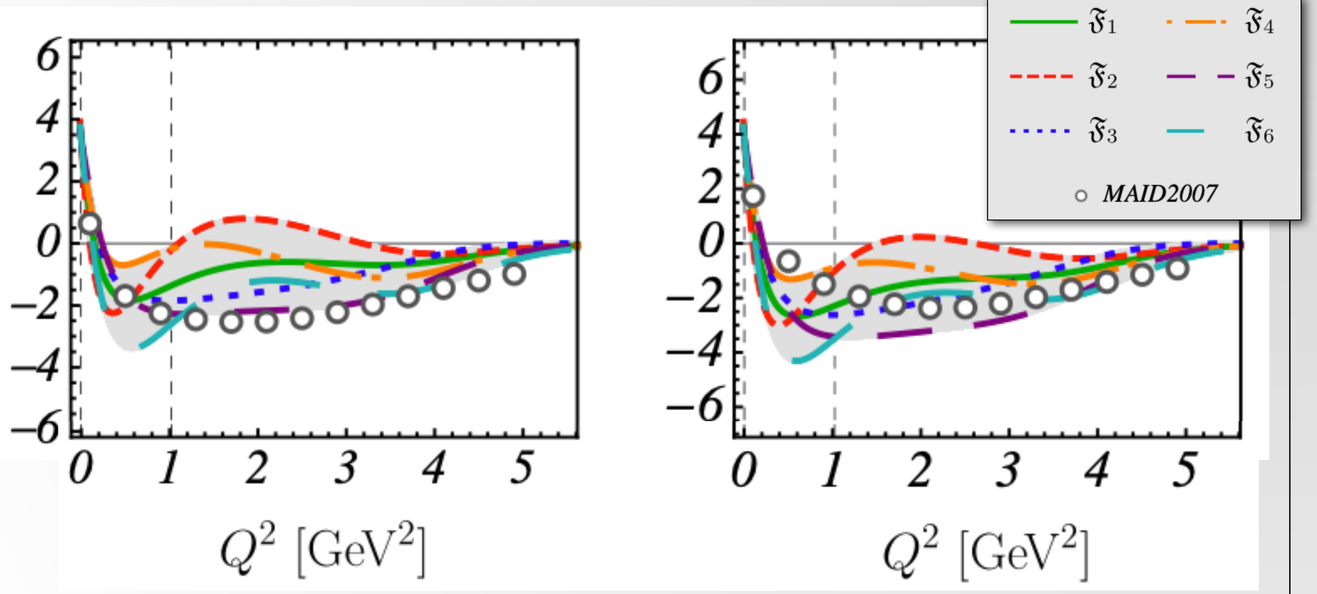
[JBW] MM et al. *Phys.Rev.C* 103 (2021) 6; Phys.Rev.C 106 (2022) 015201

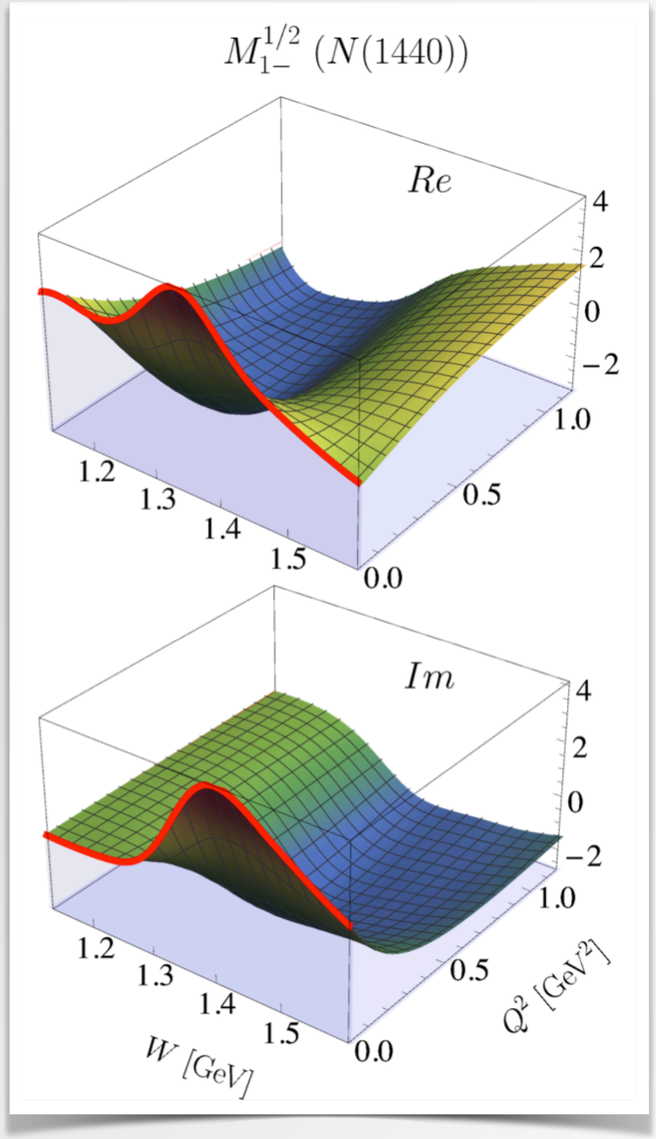
MULTIPOLES

Roper:

- Non-trivial Q^2 behavior
- Zero transition

$W = 1380$ MeV





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

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

- πN/ηN/KΛ fits (nearly world data)
- Helicity couplings

- simultaneous fit to scattering and photoproduction data
- statistical studies of parameter importance[1] (LASSO, Machine Learning, ...)
- energy dependent analysis(?)

...

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

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