Meson production in hadron- and photon-induced reactions

Collaboration: Jülich - Athens/GA - Washington/DC

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F. Huang and K. Nakayama ………………………………….… (UGA-Athens/GA)

H. Haberzettl ………………………………………………. (GWU-Whashington/DC)

Outline of the talk

- Reaction theory in a dynamical coupled-channels approach:

  hadron-induced reactions: $\pi N \to \pi N$, ηN, $K\Lambda$, $K\Sigma$, $\pi\pi N[\sigma N, \rho N, \pi\Delta]$
  some selected results

  photon-induced reactions: $\gamma N \to \pi N$, ηN, $K\Lambda$, $K\Sigma$
  relevance of gauge invariance
  some selected results for pion photoproduction

- Some basic issues:

  experimental
  theoretical

- Outlook.

Baryon spectroscopy: why coupled-channels ?

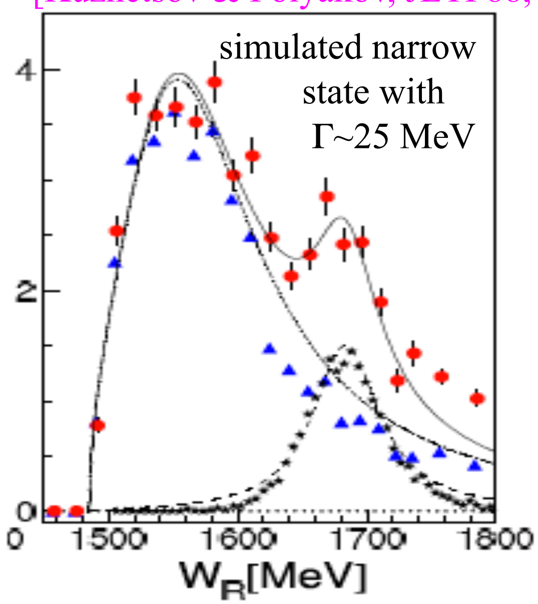
Not every bump is a resonance and not every resonance is a bump !

Moorhouse 1960’

Not every bump is a resonance: *σ_p & σ_n in η photoproduction*

Excess of η in quasi-free γn → ηn

[Kuznetsov & Polyakov, JETP88,'08]



- Excess of η on n found by GRAAL
  [Kuznetsov et al., PLB647,'07]
  confirmed by CBELSA & TAPS
  [Jaegle et al., PRL100,'09]
  and LNS
  [Miyahara et al., PTPS168,'07]

Possible explanations

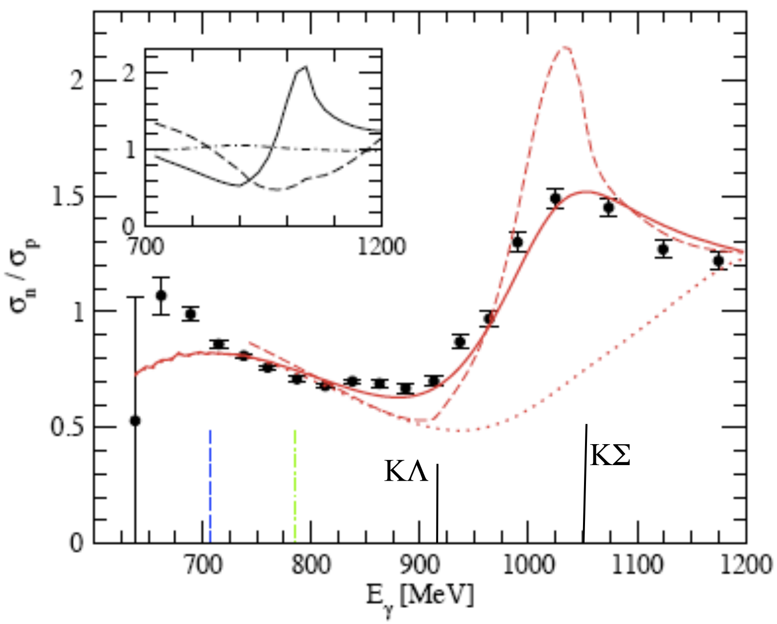
- Non-strange pentaquark (i.e., narrow resonance)
  χQSM prediction
  [Diakonov et al., ZPA359,'97, Polyakov et al., EPJA18, '03,…]

- Many more explanations in terms of conventional resonance(s).

- Coupled-channels effect (KΛ channel openning)

Not every bump is a resonance: *σ_n/σ_p in η photoproduction*

(M. Döring and K.Nakayama, PLB683 '10) *(cont.')*

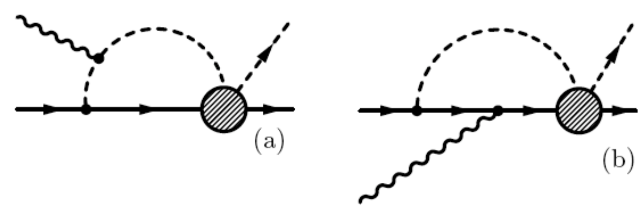


Data: I. Jaegle *et al.*, CBELSA & TAPS

solid : full result (with Fermi motion)
dashed: no Fermi motion
dotted: no $K^+\Lambda$ intermediate state
inset (dash-dotted): only πN intermediate state

UχPT calculation:

intermediate state in the photon loops:
neutron: $\pi^- p$, $\pi^0 n$, ηn, $K^0\Lambda$, $K^+\Sigma^-$, $K^0\Sigma^0$
proton : $\pi^0 p$, $\pi^+ n$, ηp, $K^+\Lambda$, $K^+\Sigma^0$, $K^0\Sigma^+$

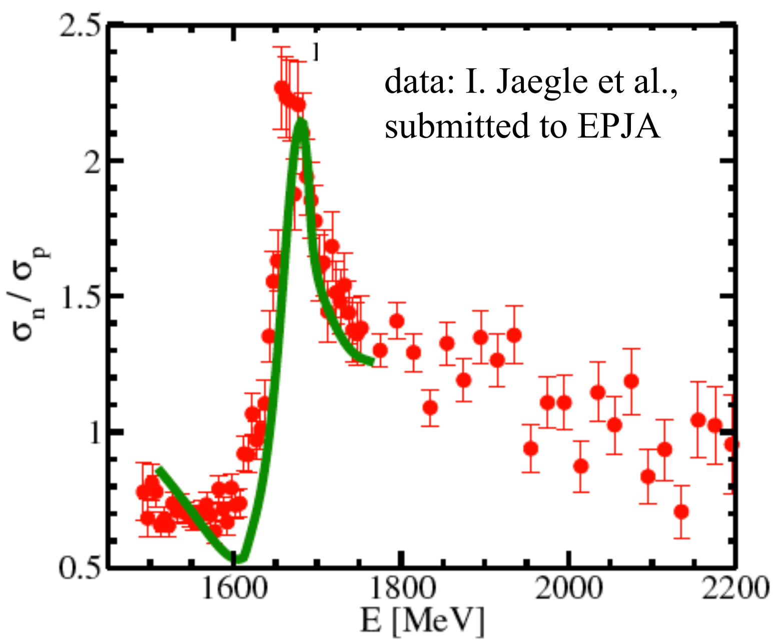


- Peak in σ_n/σ_p :
  direct consequence of the Weinberg-Tomozawa interaction with strong couplings to KΛ and KΣ channels given by the SU(3) structure.
  ($f_K \cong 113$ MeV)
- Simple and quantitative explanation.

Not every bump is a resonance: *σ_n/σ_p in η photoproduction*

(M. Döring and K.Nakayama, PLB683 '10) *(cont.')*

Overlaying published curve with later data.



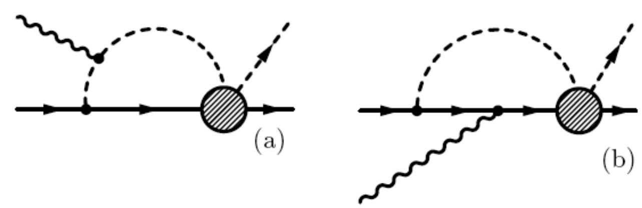
- Neutron in final state reconstructed
  → Elimination of Fermi motion.
- Prediction (at least) as narrow as new CBELSA/TAPS data.

UχPT calculation:

intermediate state in the photon loops:

neutron: π^-p, π^0n, ηn, $K^0\Lambda$, $K^+\Sigma^-$, $K^0\Sigma^0$

proton : π^0p, π^+n, ηp, $K^+\Lambda$, $K^+\Sigma^0$, $K^0\Sigma^+$



- Peak in σ_n/σ_p :
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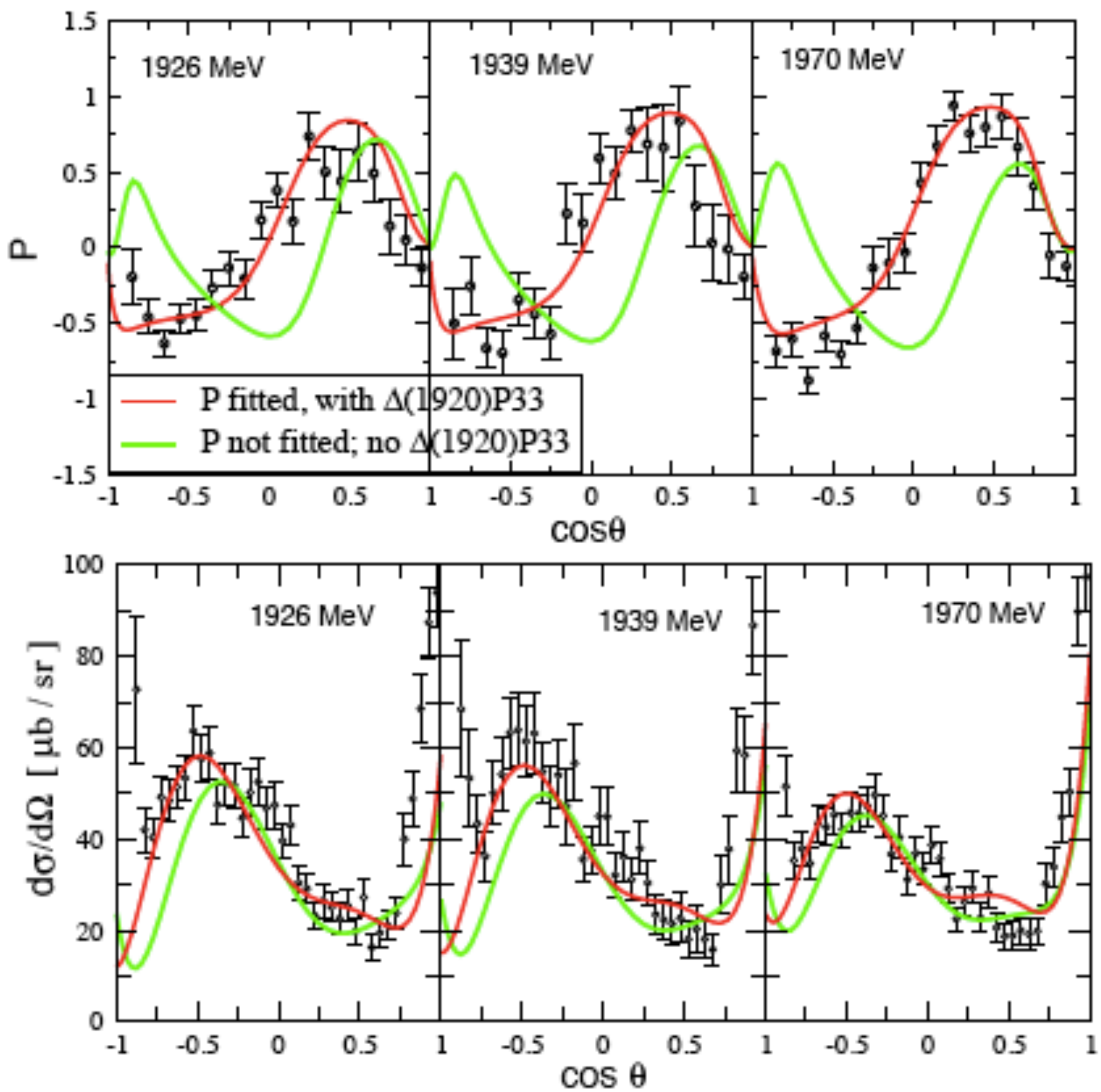
  ($f_K \cong$ 113 MeV)
- Simple and quantitative explanation.

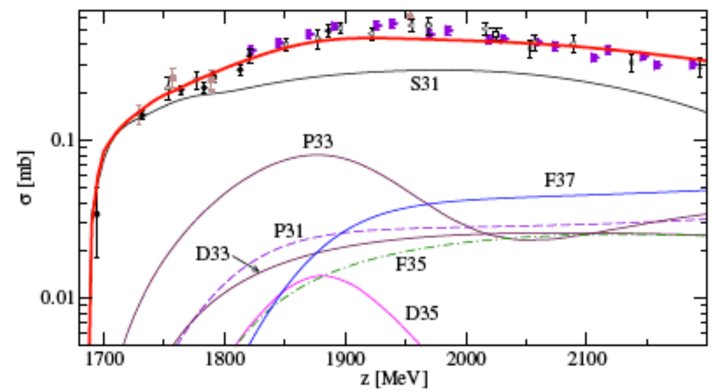
Not every resonance is a bump: *polarization in $\pi^- p \to K^+ \Sigma^+$*

(M. Doring et al., NPA851,'11)

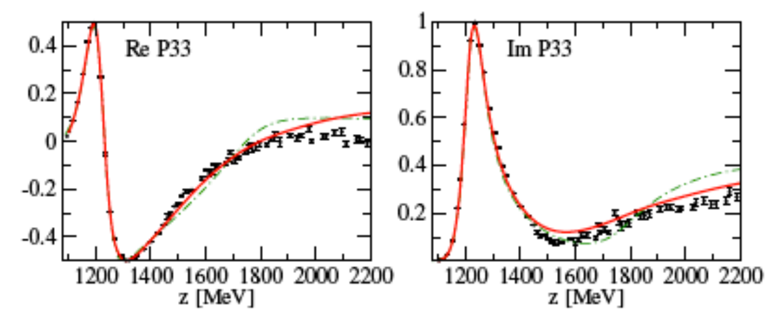
$\pi^+ p \to K^+ \Sigma^+$



Δ(1920) P33:
most important resonance invisible in $\pi N \to \pi N$ but needed in $\pi^+ p \to K^+ \Sigma^+$



$\pi N \to \pi N$



Reaction Theory: *MN→MN reactions*

Jülich hadronic model (TOPT):

C. Schütz et al., PRC49 '94; PRC57 '98
O. Krehl et al., PRC62 '00
A. M. Gasparyan et al., PRC68 '03
M. Döring et al., NPA829 '09; NPA851 '11
D. Rönchen et al., '12, in preparation

$$T = V + VGT$$

Basic features:

- Coupled channels: πN, ηN, KΛ, KΣ, ππN [σN, ρN, πΔ]
- Analyticity
- 2-body unitarity & some requirements for 3-body unitarity
- Chiral Lagrangian of Wess and Zumino [PR163, '67; PR161, '88]
  - Hadron exchange provides the relevant dynamics
  - All partial waves are linked by u- and t-channel processes
  - Reaction channels are linked by SU(3) in the Lagrangian framework
  - Minimum # of explicit resonances needed due to the structured backgroung

Reaction Theory: latest Jülich hadronic model (cont.')

(D. Rönchen, M. Döring, F. Huang, ... , in preparation)

Data base :

$\pi N \rightarrow \pi N$: GWU/SAID [Arndt et al., PRC74 '06]

$\sim$ 2500 data points

20 partial-wave amplitudes from S11 to H39

from threshold to W $\sim$ 2.2 GeV

$\pi N \rightarrow \eta N, K^0\Lambda, K^0\Sigma^0, K^+\Sigma^-, K^+\Sigma^+$:

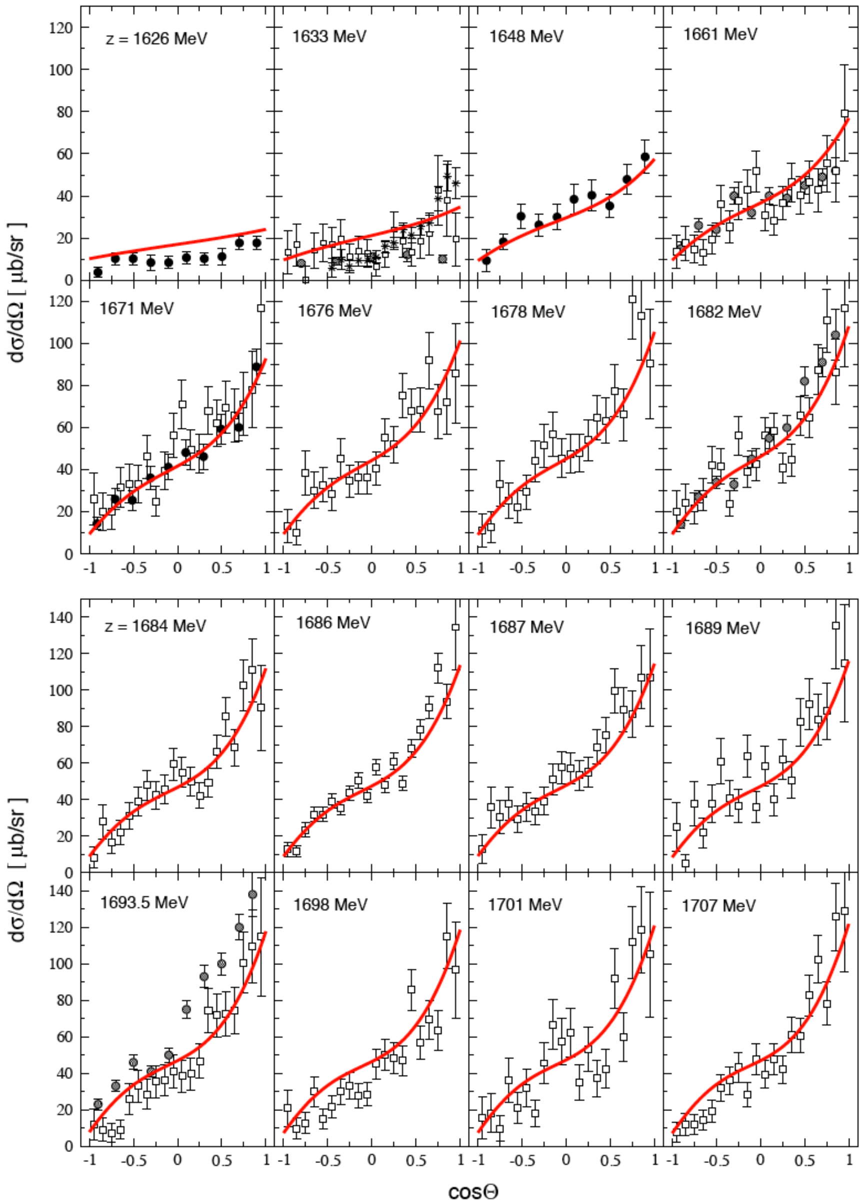
3815 data points

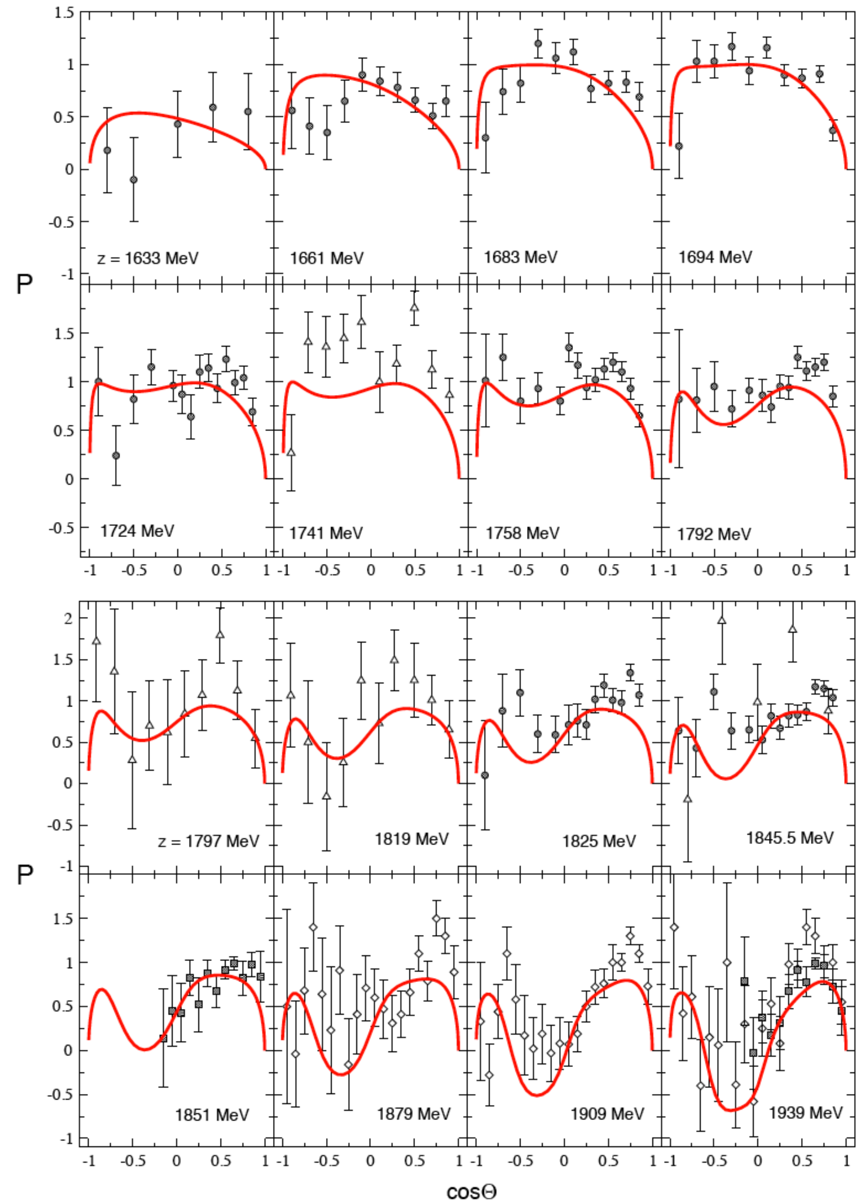
Observables from threshold to W $\sim$ 2.2 GeV

- cross section, $d\sigma/d\Omega$
- polarization, P
- spin rotation parameter, β

Selected results: $\pi^- p \rightarrow K^0 \Lambda$

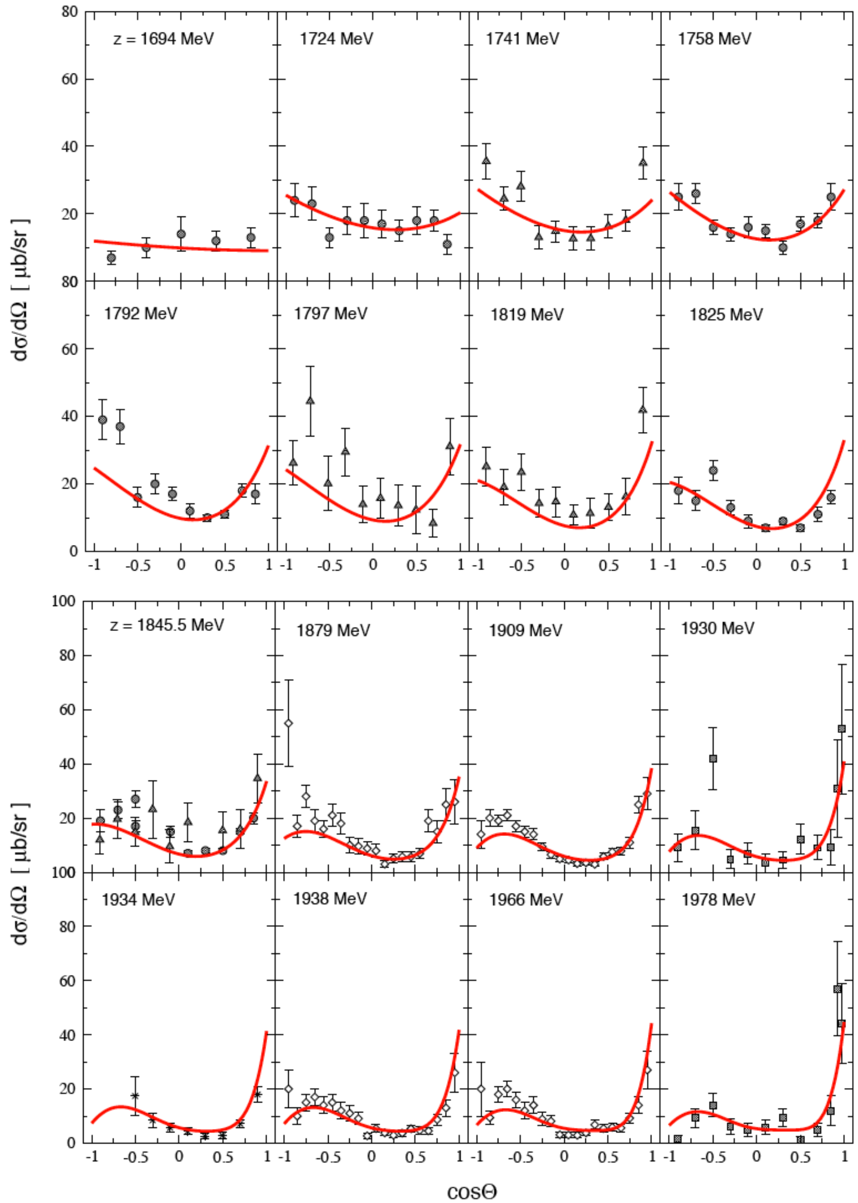
(D. Rönchen, M. Döring, F. Huang, … , in preparation)

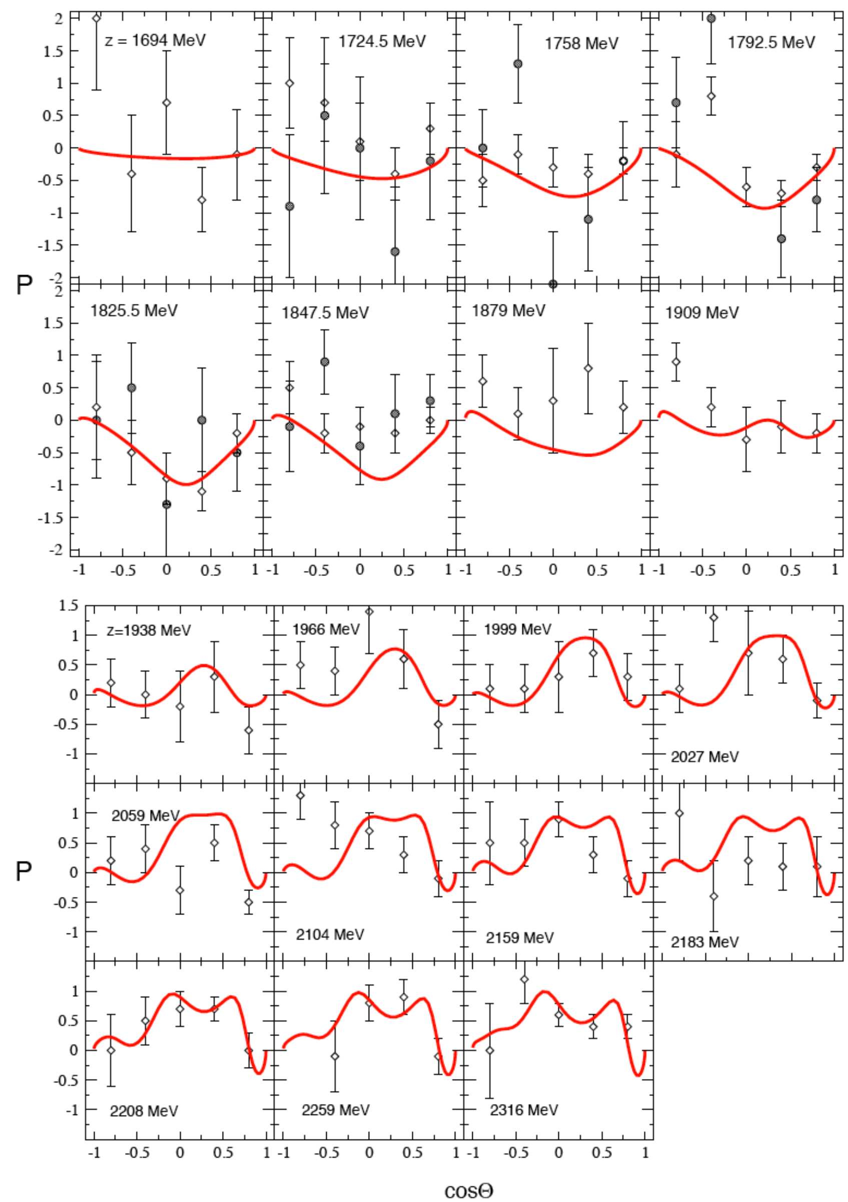




Selected results: $\pi^- p \rightarrow K^0 \Sigma^0$

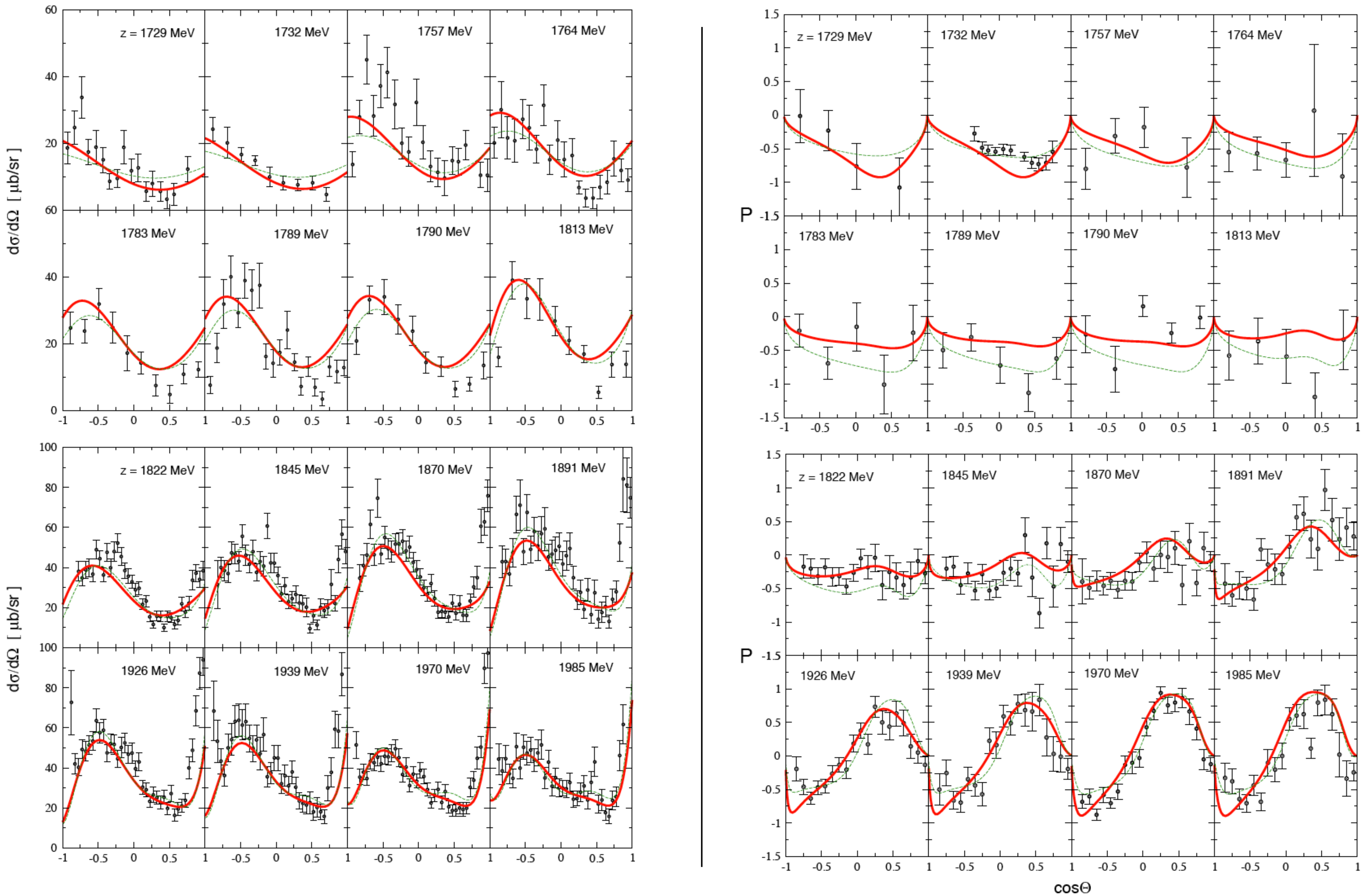
(D. Rönchen, M. Döring, F. Huang, ... , in preparation)





Selected results: $\pi^+ p \rightarrow K^+ \Sigma^+$

(D. Rönchen, M. Döring, F. Huang, … , in preparation)



Selected results: *pole structure of the amplitudes*

(from analytic continuation)

Established 4-star resonances:

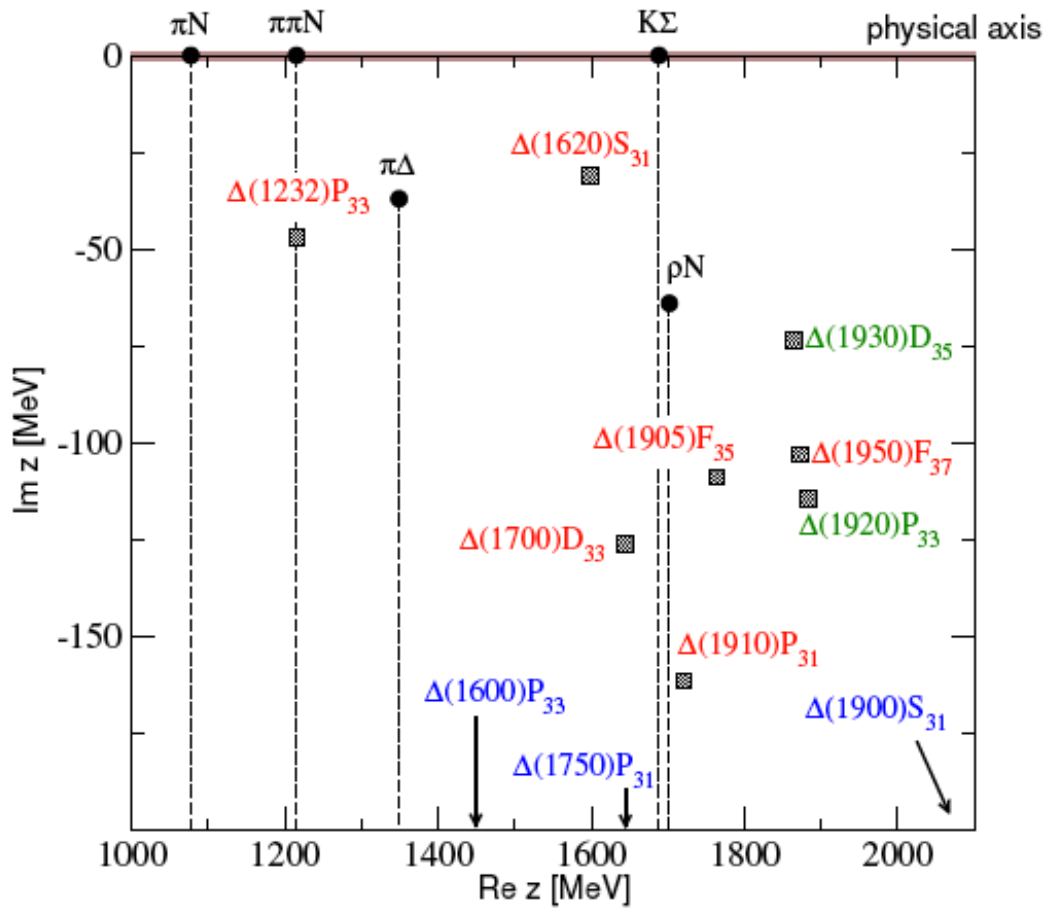
$\Delta(1232)P_{33}$, $\Delta(1700)D_{33}$, $\Delta(1905)F_{35}$, $\Delta(1950)F_{37}$, $\Delta(1620)S_{31}$, $\Delta(1910)P_{31}$

3-star resonances:

$\Delta(1920)P_{33}$, $\Delta(1930)D_{35}$
constraints from $K^+\Sigma^+$ data lead to positions in vicinity of 3-star PDG resonances

Dynamically generated poles:

$\Delta(1600)P_{33}$

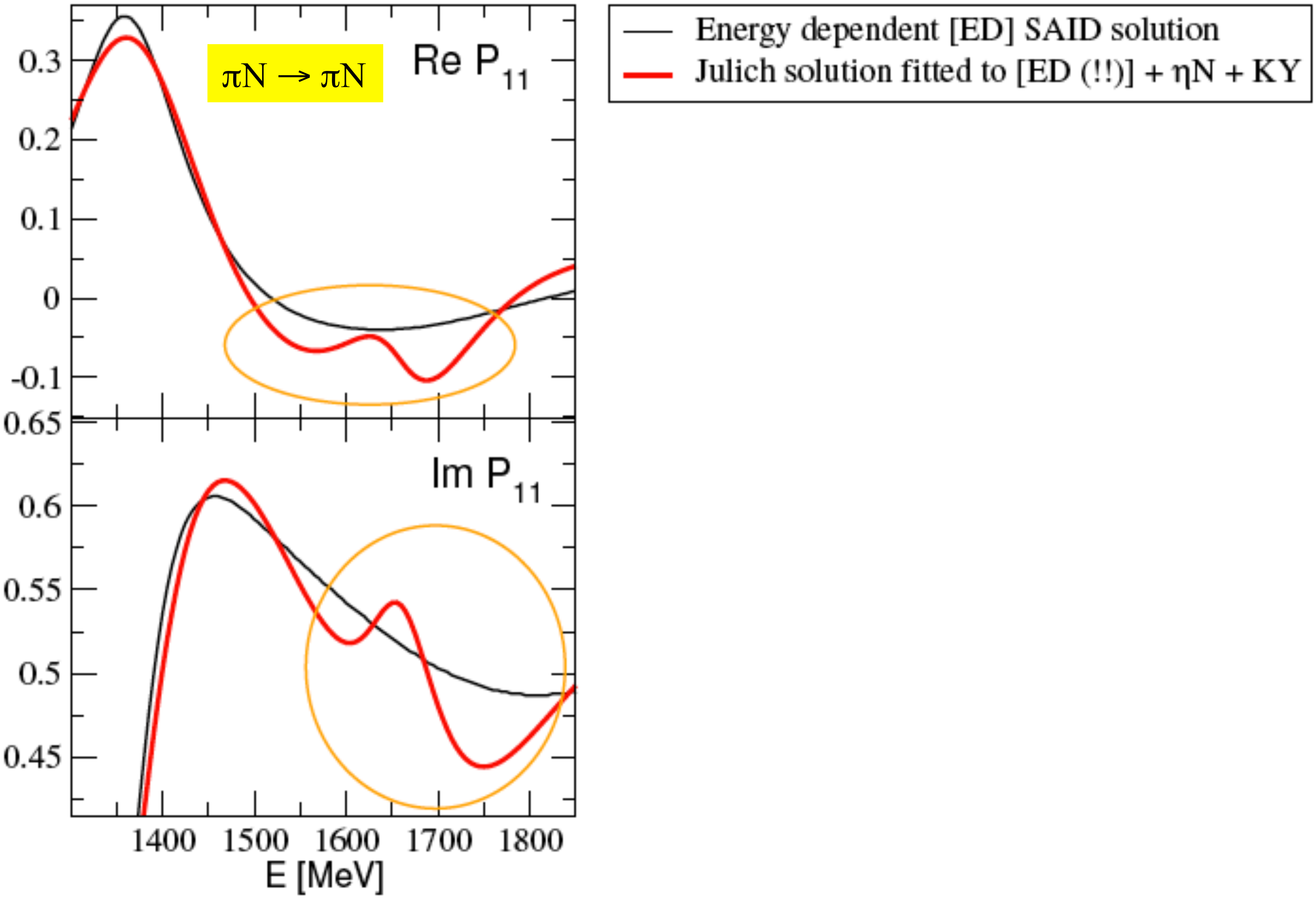


Results in [M.D. *et al.*, Nucl.Phys.A851 (2011)]

newest model results: on the way

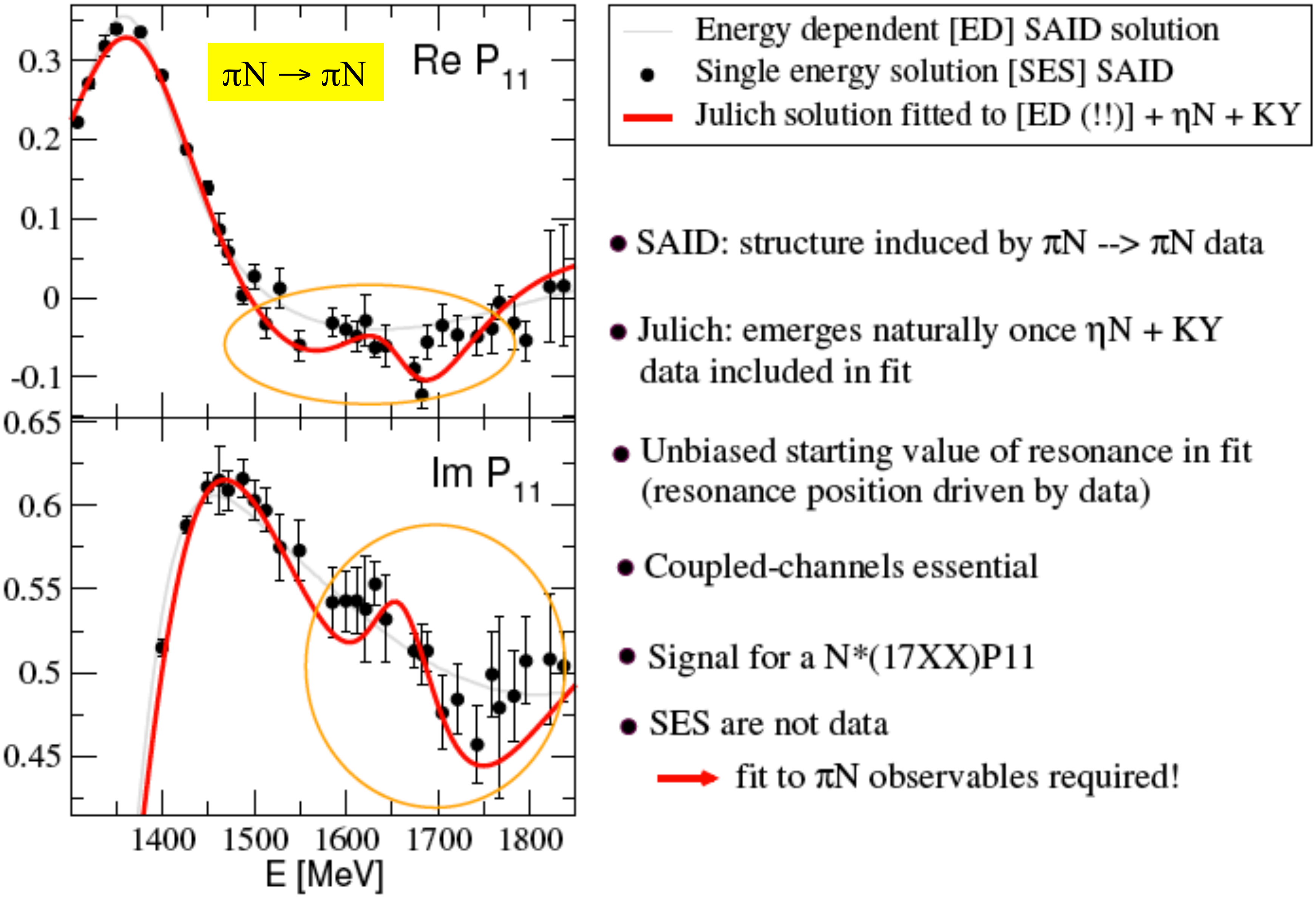
Selected results: importance of the global data analysis

(D. Rönchen, M. Döring, F. Huang, ..., '12, in preparation)



Selected results: importance of the global data analyses

(D. Rönchen, M. Döring, F. Huang, ..., '12, in preparation)



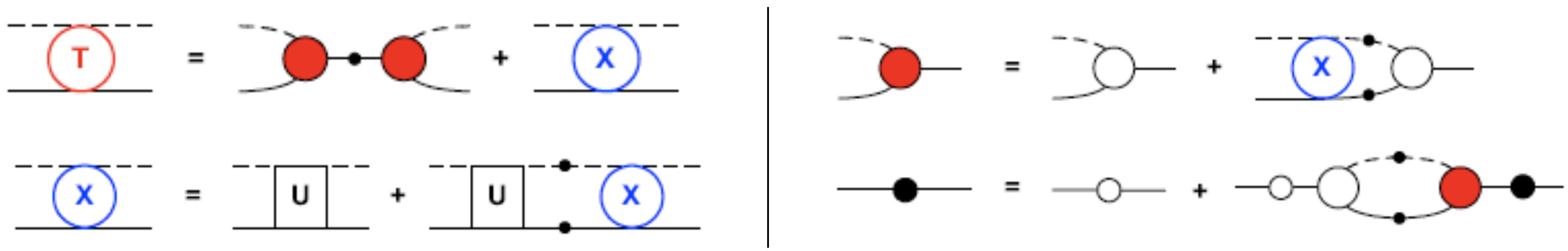
- SAID: structure induced by $\pi N \rightarrow \pi N$ data
- Julich: emerges naturally once ηN + KY data included in fit
- Unbiased starting value of resonance in fit (resonance position driven by data)
- Coupled-channels essential
- Signal for a N*(17XX)P11
- SES are not data

  → fit to πN observables required!

Reaction Theory: $\gamma N \rightarrow MN$ *(field theoretical approach)*

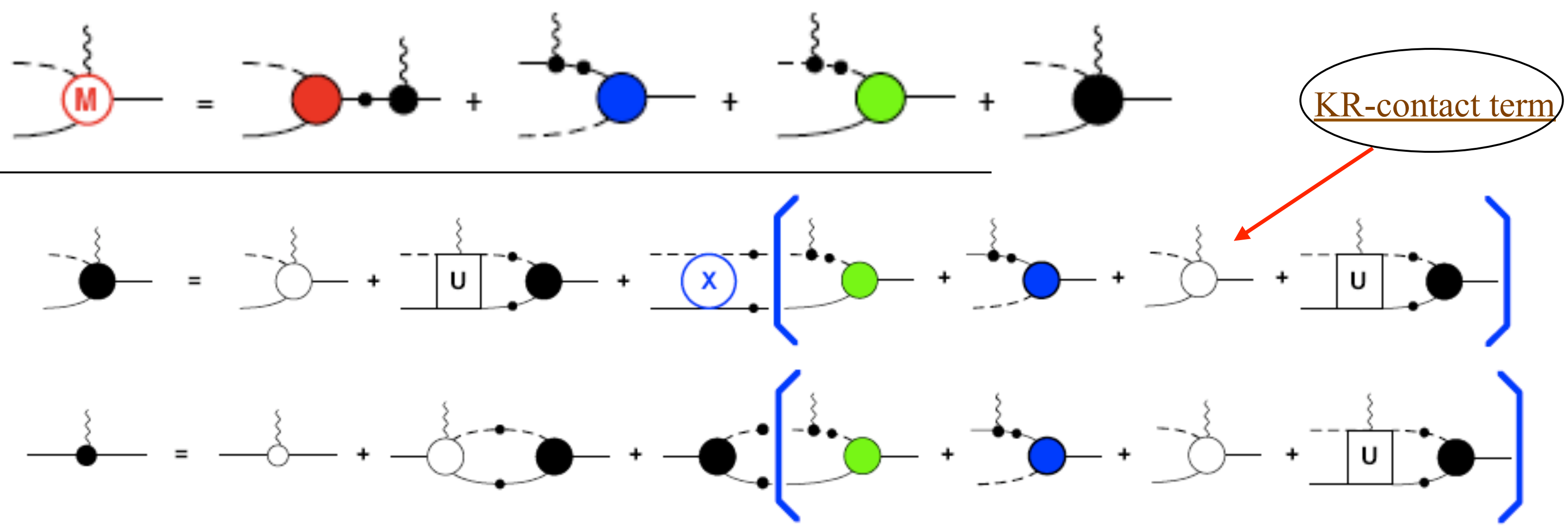
(Haberzettl, PRC56, 2041, '97)

Hadronic Scattering: $\pi N \rightarrow \pi N$



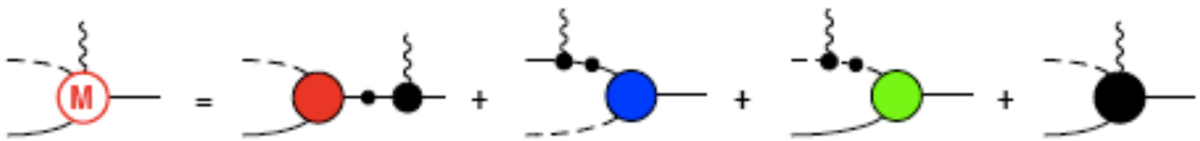
Photoproduction: $\gamma N \rightarrow \pi N$

$$M^{\mu} = M_s^{\mu} + M_u^{\mu} + M_t^{\mu} + M_{\text{int}}^{\mu}$$



Reaction Theory: *gauge invariance*

$$M^{\mu} = M_s^{\mu} + M_u^{\mu} + M_t^{\mu} + M_{\text{int}}^{\mu}$$



$F_s\boldsymbol{\tau}$ $F_u\boldsymbol{\tau}$ $F_t\boldsymbol{\tau}$

current conservation: $k_\mu M^\mu = 0$ (all external legs on-shell)

Theory requires off-shell condition (generalized Ward-Takahashi identity):

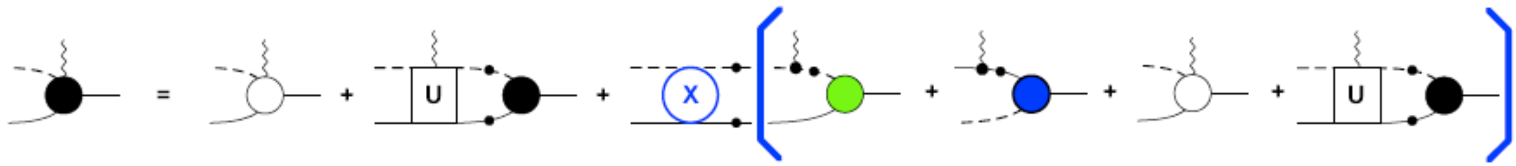
($\boldsymbol{\tau}$ = vertex isospin operator ; Q =charge operator)

$$k_\mu M^\mu = -\,[F_s\boldsymbol{\tau}]S_{p+k}\,Q_i\,S^{-1}_{p} + S^{-1}_{p'}\,Q_f S_{p'-k}\,[F_u\boldsymbol{\tau}] + \Delta^{-1}_{p-p'-k}\,Q_\pi\,\Delta_{p-p'}[F_t\boldsymbol{\tau}]$$

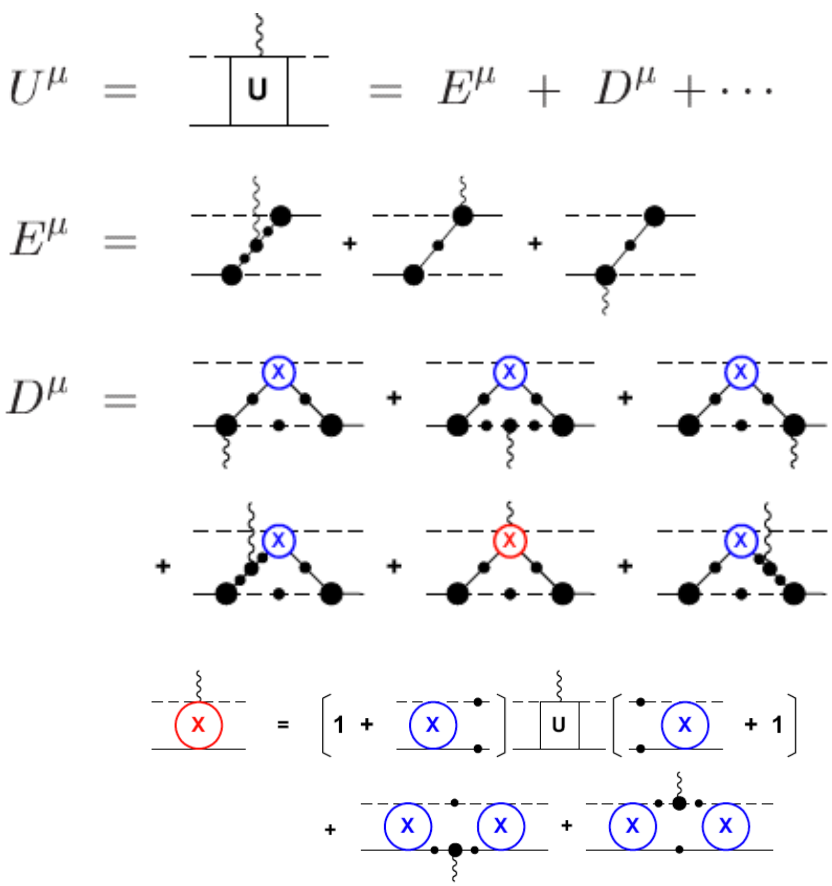
$$k_\mu M^\mu_{int} = -\,[F_s]\,e_i + e_f[F_u] + e_\pi\,[F_t]$$

$$e_i = \boldsymbol{\tau}\,Q_i$$
$$e_f = Q_f\boldsymbol{\tau}$$
$$e_\pi = Q_\pi\boldsymbol{\tau}$$

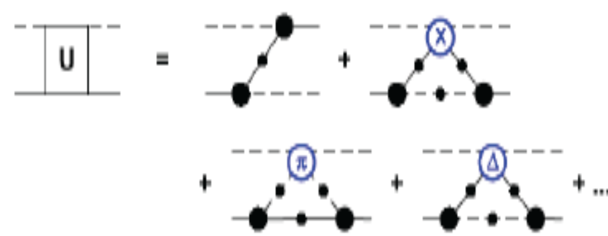
Reaction theory: *interaction current*



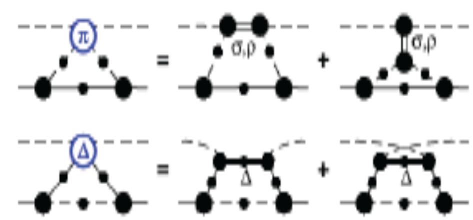
Electromagnetic Couplings to Driving Terms:



Hadronic Driving Terms:

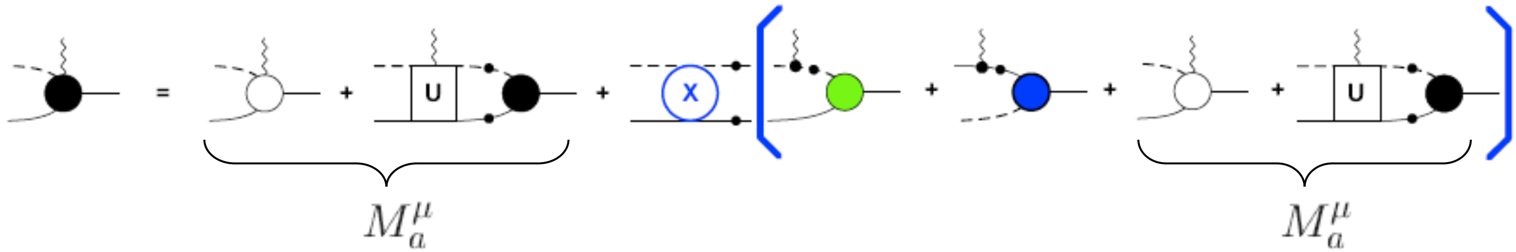


Box graphs:



Reaction Theory: *approx. the interaction current*

Haberzettl, Nakayama, Krewald, PRC74,'06; Haberzettl, Huang, Nakayama, PRC83,'11



$$M^\mu_{\text{int}} = M^\mu_a + XG[M^\mu_t + M^\mu_u + M^\mu_a]$$

generalized contact current

approximated current:

$$M^\mu_{\text{int}} = M^\mu_c + XG\left(M^\mu_u + M^\mu_t + M^\mu_c\right)_T$$

$$k_\mu M^\mu_c = -[F_s]e_i + [F_u]e_f + [F_t]e_\pi$$

full amplitude:

$$M^\mu = M^\mu_s + M^\mu_u + M^\mu_t + M^\mu_c + XG\left(M^\mu_u + M^\mu_t + M^\mu_c\right)_T$$

$$M^\mu_s = |F\tau\rangle S\langle\Gamma^\mu| \qquad \Gamma^\mu = \Gamma^\mu_0 + m^\mu_{KR}G[F\tau] + [F_0\tau]G\left(M^\mu_u + M^\mu_t + M^\mu_c\right)_L$$

$$+[F\tau]G\left(M^\mu_u + M^\mu_t + M^\mu_c\right)_T$$

Reaction Theory: *choosing the contact current M_c^μ*

$$\boxed{k_\mu M_c^\mu = -[F_s]e_i + [F_u]e_f + [F_t]e_\pi}$$

$$M_c^\mu = [F(q)]C^\mu + m_{KR}^\mu f_t \quad \left\{ \begin{array}{l} \text{Genuine contact current} \\ \text{Crossing symmetry} \end{array} \right.$$

[Davidson-Workman, PRC63 '02]

$$C^\mu = -e_\pi \frac{(2q-k)^\mu}{t-q^2}(f_t - \hat{F}) - e_f \frac{(2p'-k)^\mu}{u-p'^2}(f_u - \hat{F}) - e_i \frac{(2p+k)^\mu}{s-p^2}(f_s - \hat{F}),$$

$$\hat{F} = 1 - h(1-\delta_s f_s)(1-\delta_u f_u)(1-\delta_t f_t), \quad h = \text{free parameter}$$

$$\delta_x = \begin{cases} 1\,, & \textit{if x-channel present} \\ 0\,, & \textit{otherwise} \end{cases}$$

Reaction theory: *using the Jülich hadronic model*

Juelich Hadronic Model (TOPT):

$$T(\vec{p}',\vec{p};\sqrt{s}) = V(\vec{p}',\vec{p};\sqrt{s}) + \int d\vec{p}''V(\vec{p}',\vec{p}'';\sqrt{s})\frac{1}{\sqrt{s}-E_{p''}-\omega_{p''}+i\eta}T(\vec{p}'',\vec{p};\sqrt{s})$$

Converting to a covariant 3-D reduction like equation:

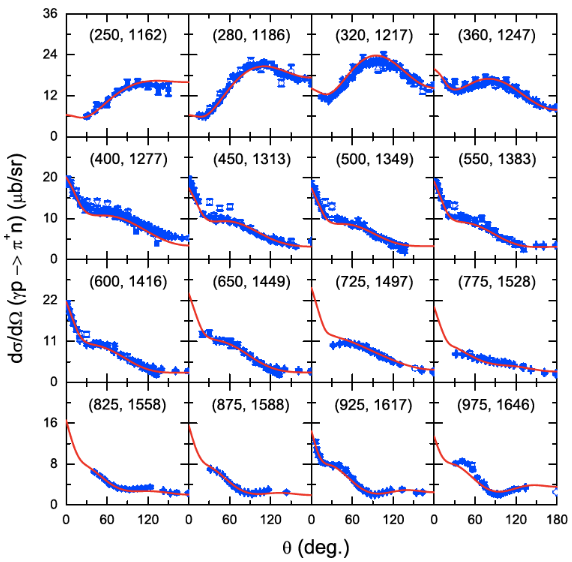
$$\tilde{T}(\vec{p}',\vec{p};\sqrt{s}) = \tilde{V}(\vec{p}',\vec{p};\sqrt{s}) + \int \frac{d\vec{p}''}{(2\pi)^3 2\omega_{p''}}\frac{m}{\varepsilon_{p''}}\tilde{V}(\vec{p}',\vec{p}'';\sqrt{s})\frac{1}{\sqrt{s}-E_{p''}-\omega_{p''}+i\eta}\tilde{T}(\vec{p}'',\vec{p};\sqrt{s})$$

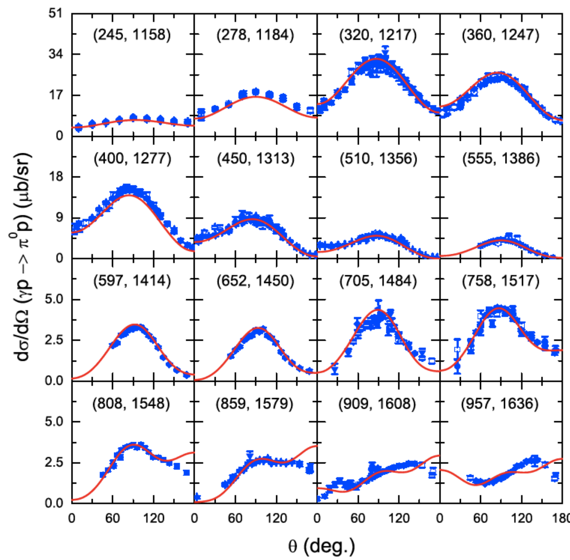
$$\begin{cases} \tilde{V}(\vec{p}',\vec{p};\sqrt{s}) \equiv (2\pi)^3\sqrt{\frac{\varepsilon_{p'}}{m}}\sqrt{2\omega_{p'}}V(\vec{p}',\vec{p};\sqrt{s})\sqrt{\frac{\varepsilon_{p}}{m}}\sqrt{2\omega_{p}} \\ \tilde{T}(\vec{p}',\vec{p};\sqrt{s}) \equiv (2\pi)^3\sqrt{\frac{\varepsilon_{p'}}{m}}\sqrt{2\omega_{p'}}T(\vec{p}',\vec{p};\sqrt{s})\sqrt{\frac{\varepsilon_{p}}{m}}\sqrt{2\omega_{p}} \end{cases}$$

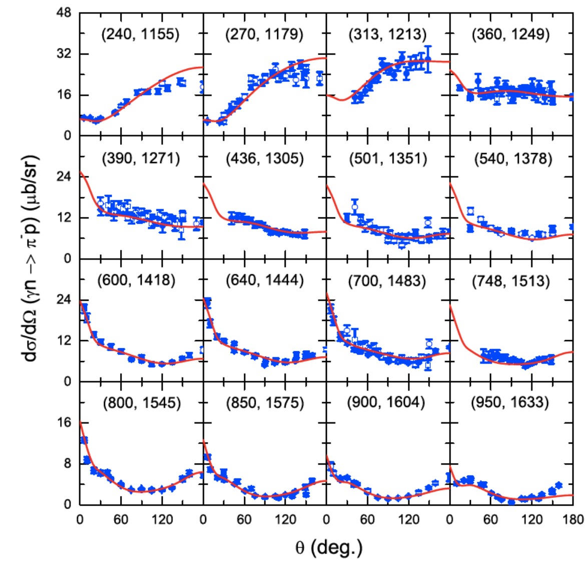
Similarly, make the 3-D reduction of the covariant photoproduction equation.

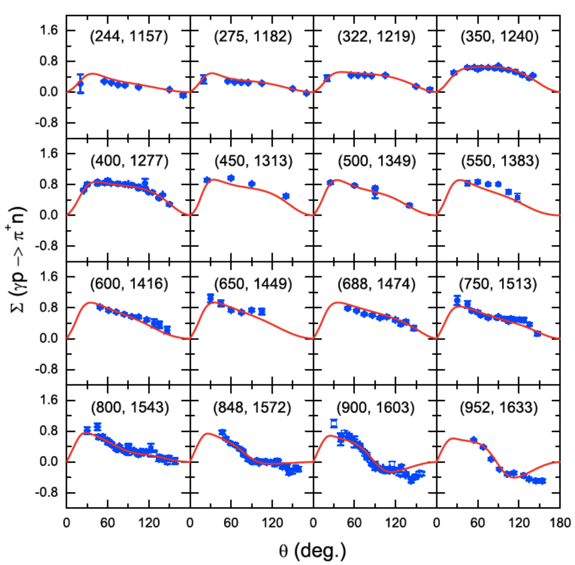
Selected results: *pion photoproduction*

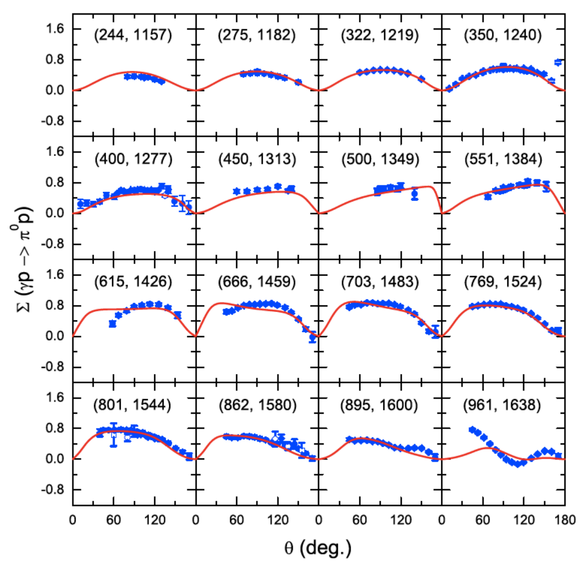
(F. Huang et al., PRC85 '12)

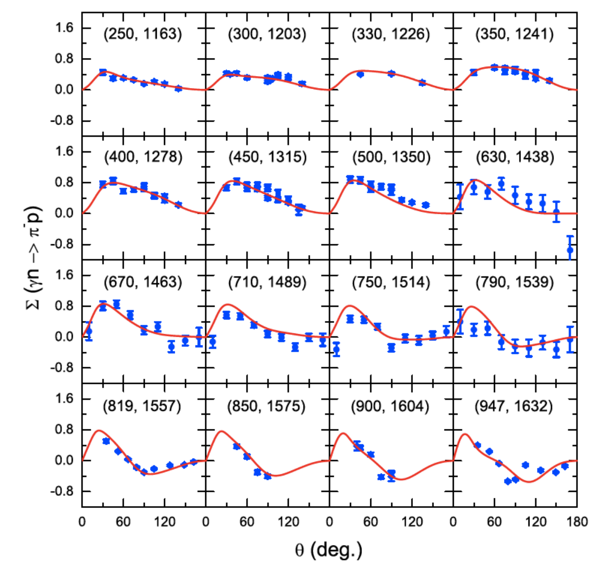












Electromagnetic transition couplings: from residues

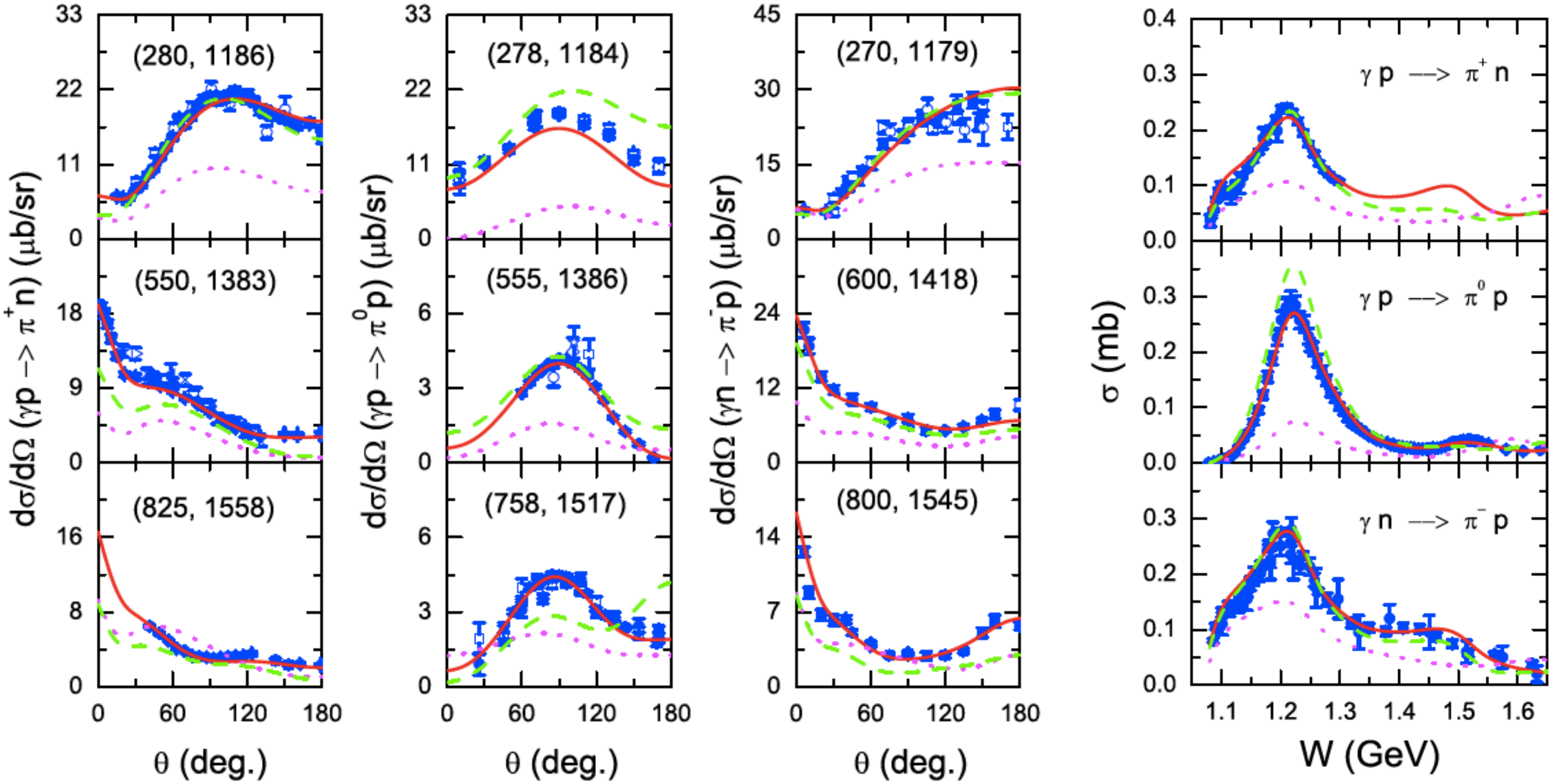
Effective electromagnetic couplings g^γ in helicity basis.
The first and second lines for each isospin 1/2 resonance correspond to the results for proton and neutron, respectively.

	Pole position [MeV]	$g^\gamma_{1/2}$ [MeV$^{1/2}$]	$g^\gamma_{3/2}$ [MeV$^{1/2}$]
$P_{33}(1232)$	$1217 - 45\,\mathrm{i}$	$0.42 - 0.11\,\mathrm{i}$	$4.95 + 1.53\,\mathrm{i}$
$P_{11}(1440)$	$1385 - 72\,\mathrm{i}$	$-0.07 - 0.26\,\mathrm{i}$	
		$-0.92 + 0.08\,\mathrm{i}$	
$D_{13}(1520)$	$1503 - 47\,\mathrm{i}$	$-3.55 + 2.14\,\mathrm{i}$	$2.80 - 1.34\,\mathrm{i}$
		$1.99 - 1.84\,\mathrm{i}$	$-4.00 + 1.68\,\mathrm{i}$
$S_{11}(1535)$	$1520 - 64\,\mathrm{i}$	$-1.52 + 1.87\,\mathrm{i}$	
		$4.05 - 2.01\,\mathrm{i}$	
$S_{31}(1620)$	$1592 - 37\,\mathrm{i}$	$-0.43 - 0.19\,\mathrm{i}$	
$S_{11}(1650)$	$1666 - 70\,\mathrm{i}$	$3.31 + 2.67\,\mathrm{i}$	
		$-1.22 - 2.50\,\mathrm{i}$	
$D_{33}(1700)$	$1638 - 122\,\mathrm{i}$	$0.37 - 8.98\,\mathrm{i}$	$-3.91 + 0.81\,\mathrm{i}$
$P_{13}(1720)$	$1665 - 101\,\mathrm{i}$	$0.11 - 5.41\,\mathrm{i}$	$0.54 + 1.55\,\mathrm{i}$
		$-0.51 + 2.71\,\mathrm{i}$	$0.28 - 3.23\,\mathrm{i}$
$P_{31}(1910)$	$1833 - 110\,\mathrm{i}$	$59.29 - 31.11\,\mathrm{i}$	

preliminary

Relevance of gauge invariance:

(F. Huang et al., PRC85 '12)



Dashed green curves: w/o M_c^μ apart from the Kroll-Ruderman term

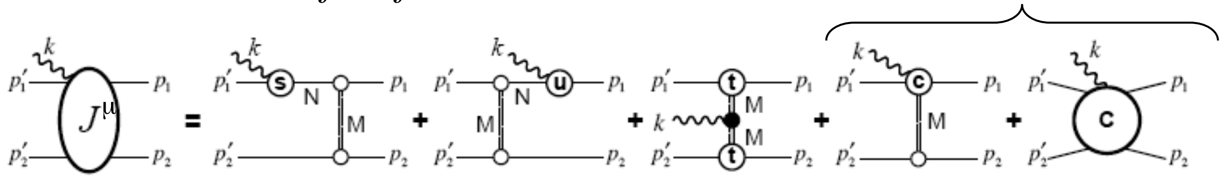
Relevance of gauge invariance: $NN \to \gamma NN$

(Nakayama, Haberzettl, PRC80(R),'10; Haberzettl, Nakayama, PRC85,'12)

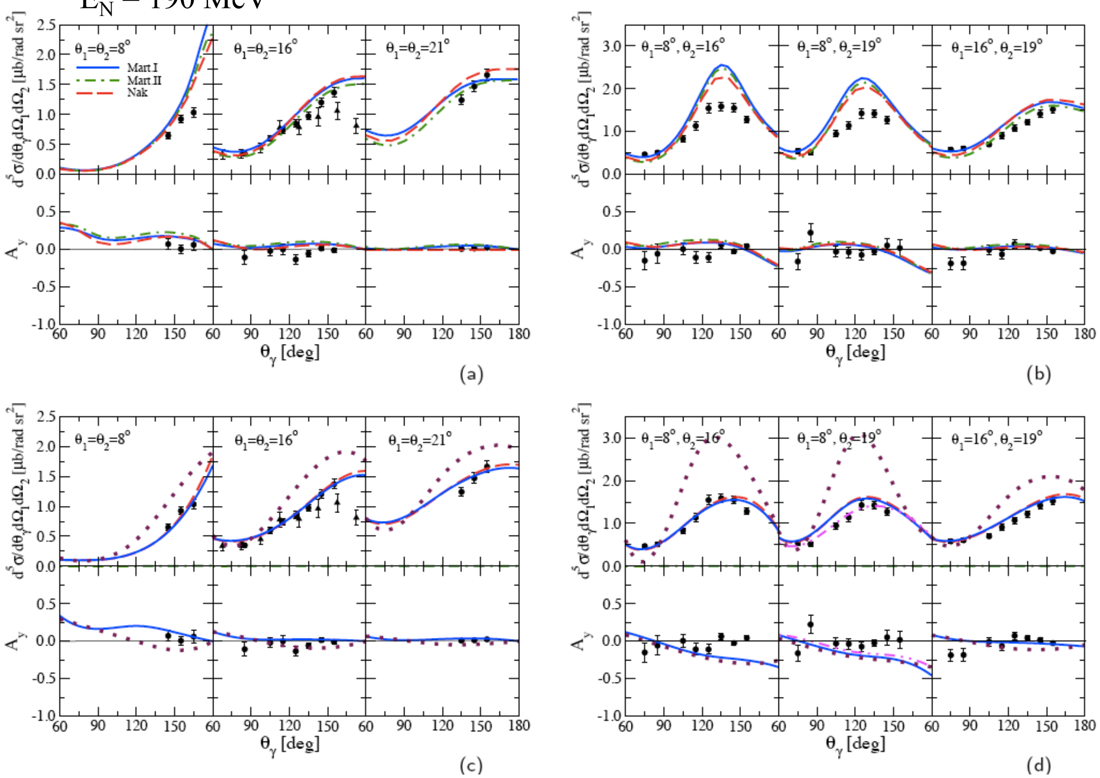
NN → NN scattering: $$T = V + VGT$$

NN → γNN : $$M^{\mu} = (1 + T_f G_f) J^{\mu} (1 + G_i T_i)$$

four- and five-point contact current



E_N = 190 MeV



previously existing calculations (no contact currents) [current conservation, $k_\mu M^\mu=0$]

full gauge-invariant calculation (with contact currents) [interaction current accounted for properly)]

Experimental data issue:

- Scarcity of (2-body) hadronic reactions data
  - → ~3800 data points (~24600 in photoproduction)
  - → existing data suffers from large uncertainties
  - → many of them are incompatible with each other

One of the major limitations for developing more accurate coupled-channels models.

Accurate data from CELSIUS,COSY on NN → NNM (M=π, η, η' ,ω, ϕ) help constrain model parameters. (talk by F. Huang this afternoon, B3)

HADES at GSI: $\pi N \to \omega N$, ρN reactions (W< 2.4 GeV); no spin observables.
J-PARC: $\pi N \to KY$, $\pi\pi N$

EIC at Jlab or BNL ??

Some basic theoretical open issues:

- Low energy behavior → matching with ChPT ?
- Theoretical uncertainties
- Three-body singularities & unitarity
- Connection to QCD and/or QCD-based models

Outlook

Hadron-induced reactions:

done:	$\pi N \to \pi N$ (will fit the data)
done:	$\pi N \to \eta N, K\Lambda, K\Sigma$
next:	$\pi N \to \omega N$
next next:	$\pi N \to \pi\pi N$

Photon-induced reactions:

done:	$\gamma N \to \pi N$ (extension will be carried to ~2 GeV)
in progress:	$\gamma N \to \eta N, K\Lambda, K\Sigma$
next:	$\gamma N \to \omega N$
next:	$\gamma^* N \to \pi N$
next next:	$\gamma N \to \pi\pi N$

2π production: talk by H. Haberzettl this afternoon, C4.

- Different direction: HDCC on the lattice [M. Döring, U. Meiβner, et al., EPJA47'11]

The End

Some basic open issues: connection to QCD & QCD-based models

To learn about the underlying structure of the extracted resonances, they need to be connected to QCD and/or QCD-based models because data do not tell us in general about the underlying structure of these resonances.

Connection through the extracted bare-resonance parameters.

Problem: bare-resonance parameters are highly model-dependent.

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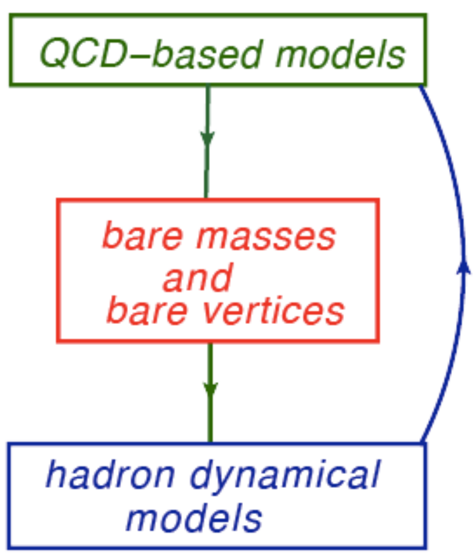
self-consistency:



Collaborations:

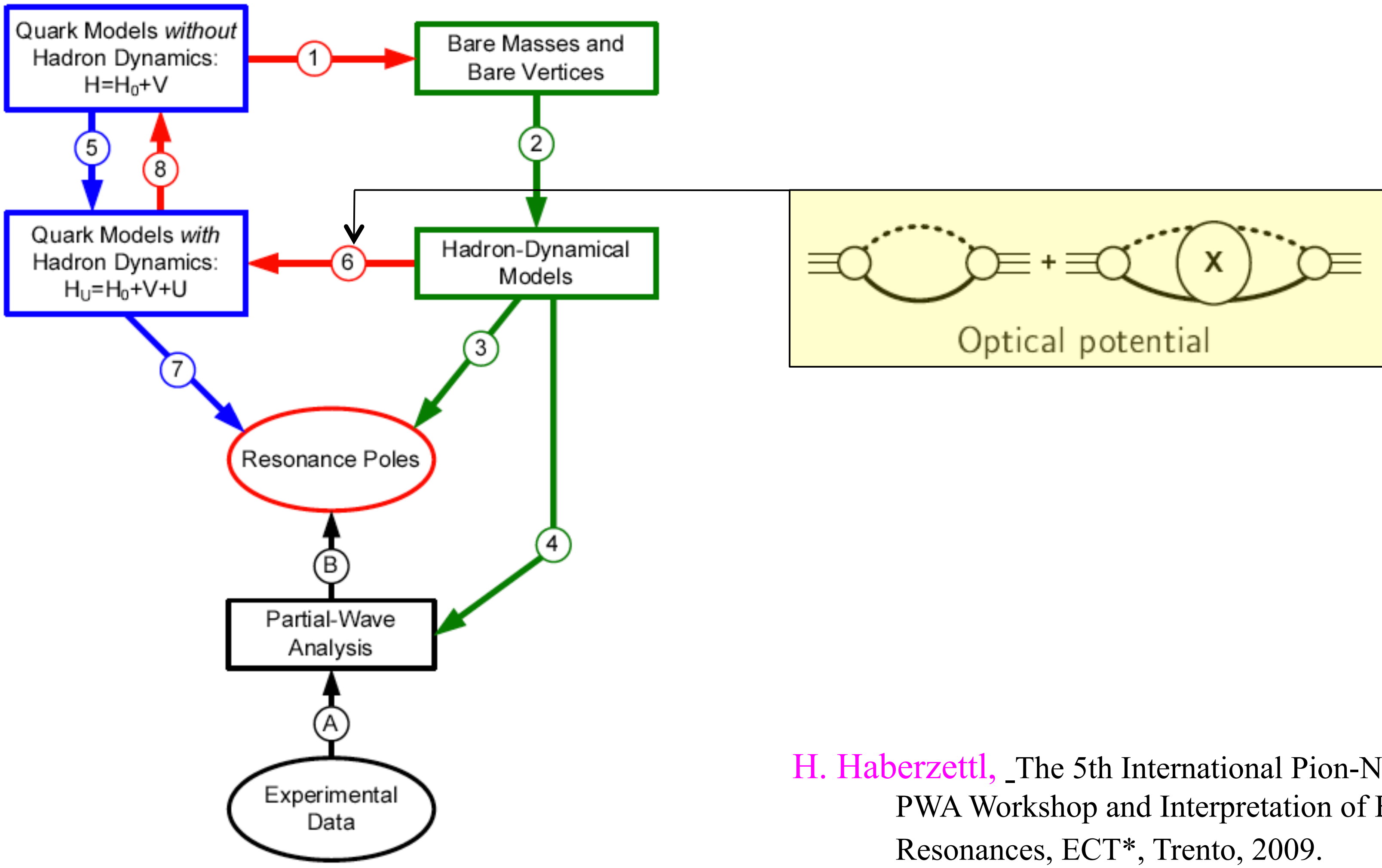
- Constituent quark models: F. Huang (Beijing group)
- Dyson-Schwinger approach: C. Roberts (ANL)

(so far: baryon masses; efforts to calculate the transition couplings in progress)

- Also, should be confronted with the LQCD results (e.g., N-P_{11} form factor [Jlab Lattice group])

Some basic open issues: connection to QCD & QCD-based models

Elementary Resonances — Self-Consistency



H. Haberzettl, The 5th International Pion-Nucleon PWA Workshop and Interpretation of Baryon Resonances, ECT*, Trento, 2009.

Reaction Theory: latest Jülich hadronic model (cont.')

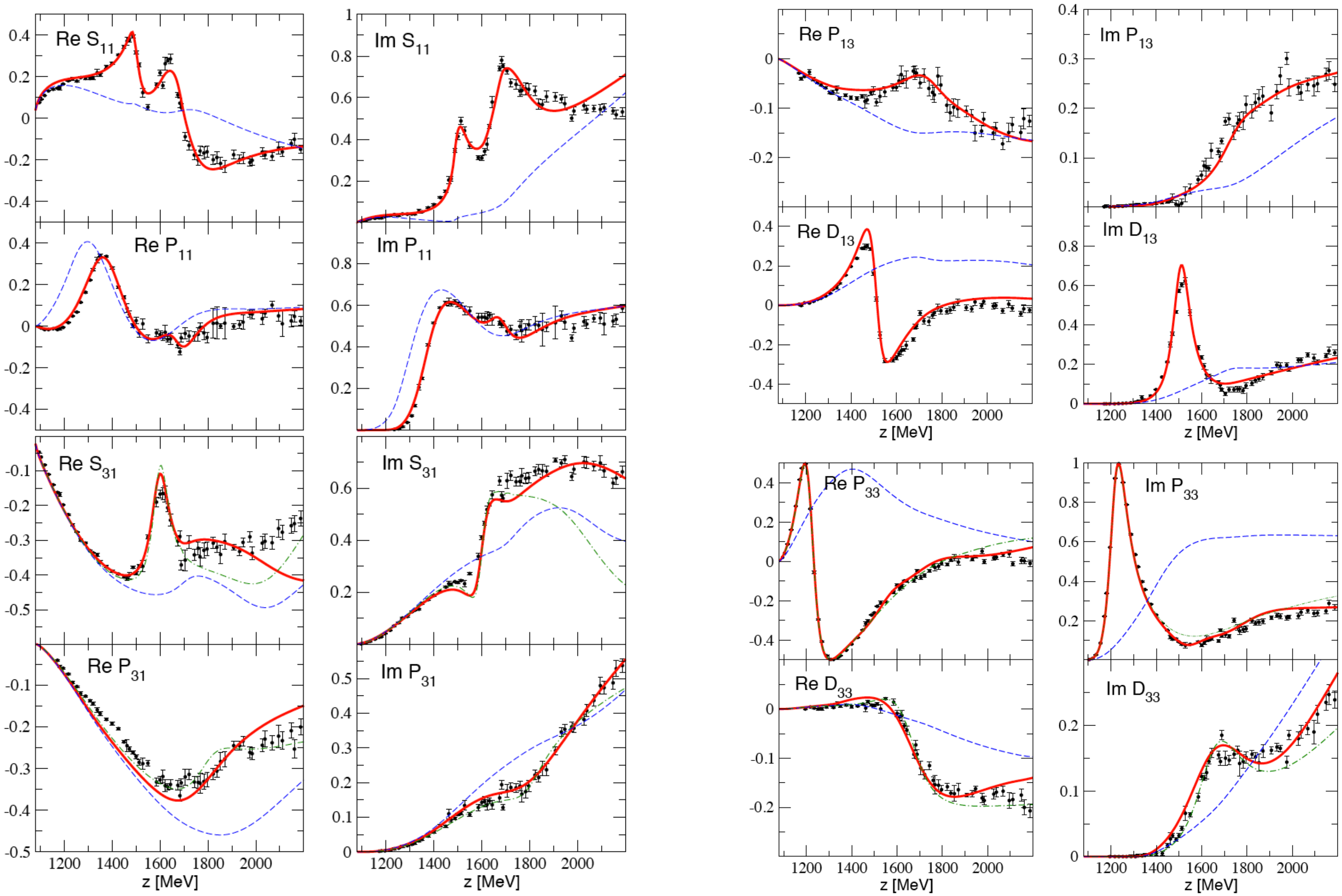
(D. Rönchen, M. Döring, F. Huang, ... , in preparation)

- s-channel states coupling to πN, ηN, $K\Lambda$, $K\Sigma$, $\pi\Delta$, ρN.
- t- and u-channel exchanges:

	πN	ρN	ηN	πΔ	σN	KΛ	KΣ
πN	N,Δ,$(\pi\pi)_\sigma$, $(\pi\pi)_\rho$	N, Δ, Ct., π, ω, a_1	N, a_0	N, Δ, ρ	N, π	Σ, Σ*, K*	Λ, Σ, Σ*, K*
ρN		N, Δ, Ct., ρ	-	N, π	-	-	-
ηN			N, f_0	-	-	K*, Λ	Σ, Σ*, K*
πΔ				N, Δ, ρ	π	-	-
σN					N, σ	-	-
KΛ						Ξ, Ξ*, f_0, ω, ϕ	Ξ, Ξ*, ρ
KΣ							Ξ, Ξ*, f_0, ω, ϕ, ρ

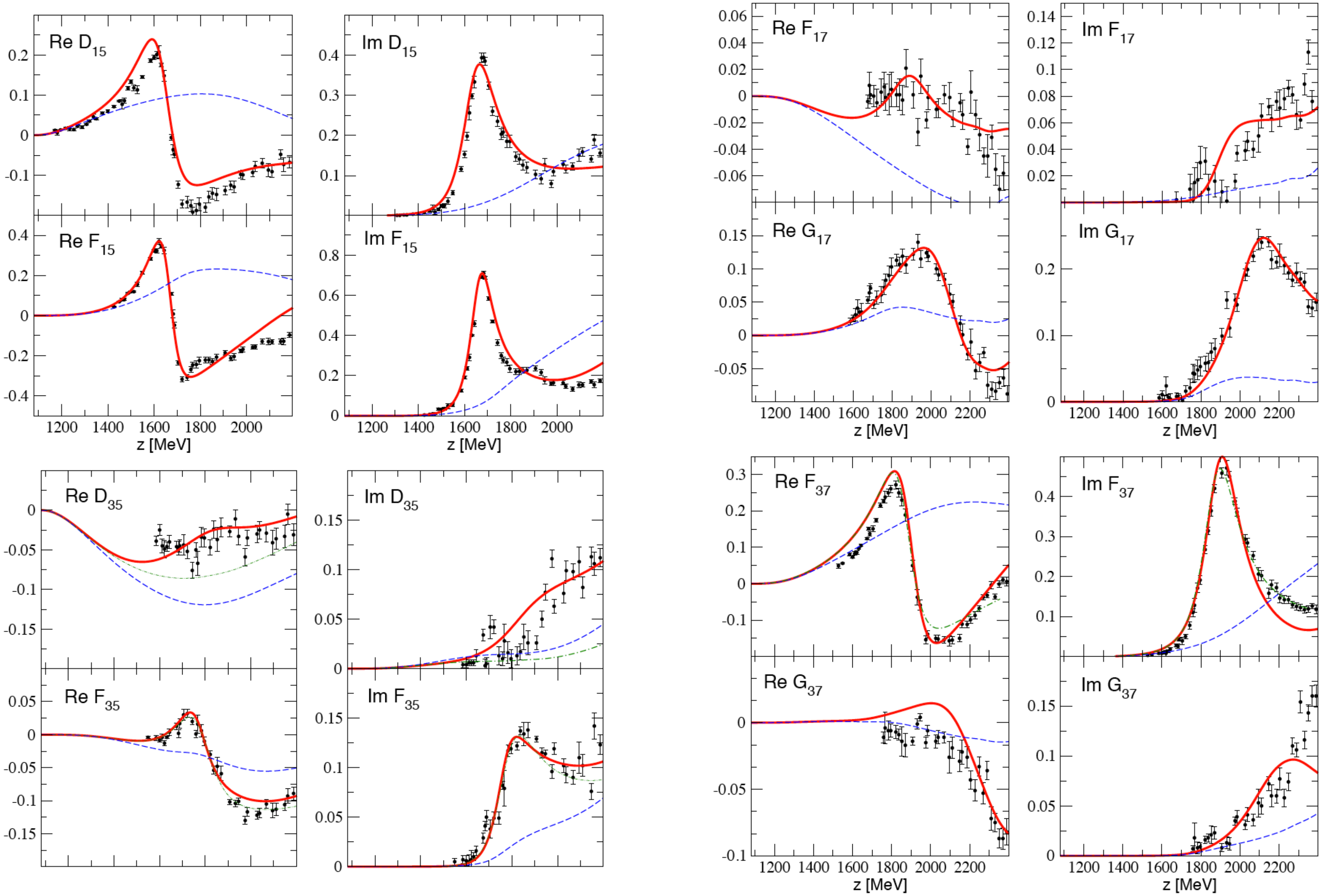
Selected results: $\pi N \rightarrow \pi N$

(D. Rönchen, M. Döring, F. Huang, … , in preparation)



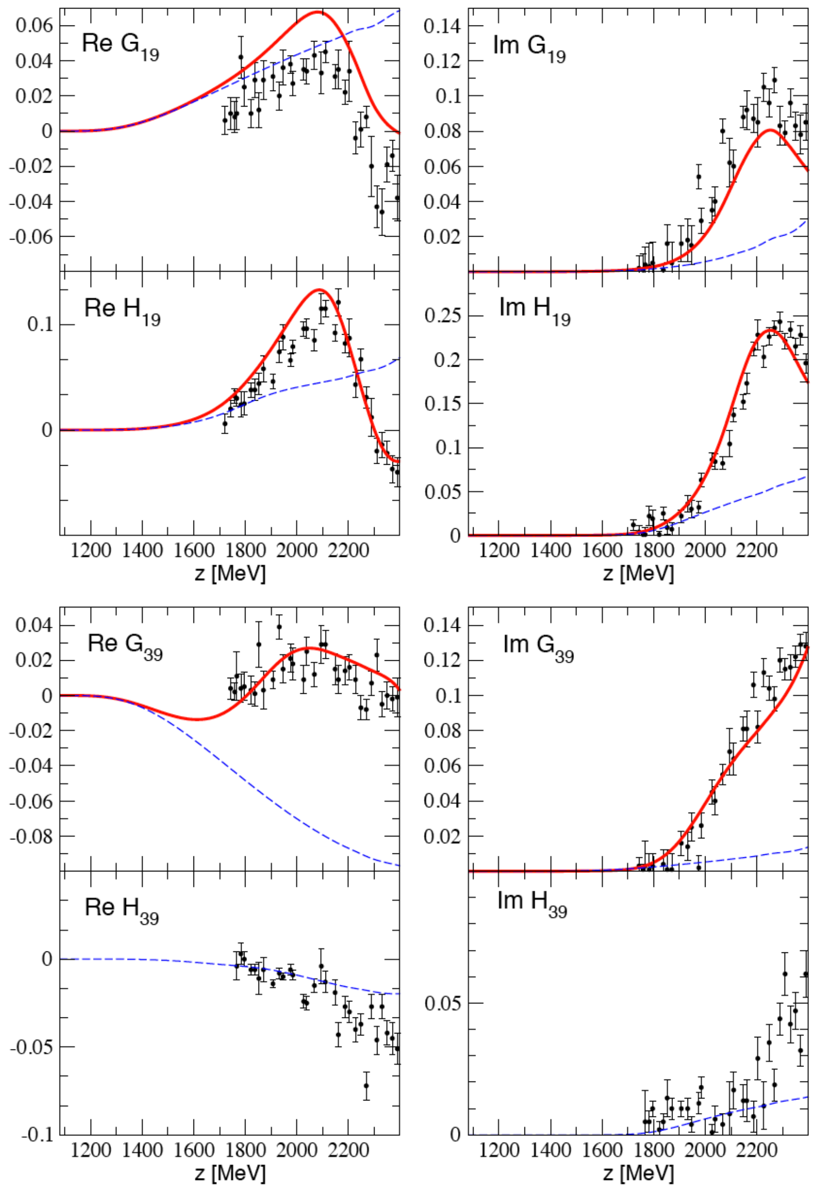
Selected results: $\pi N \rightarrow \pi N$

(D. Rönchen, M. Döring, F. Huang, … , in preparation)



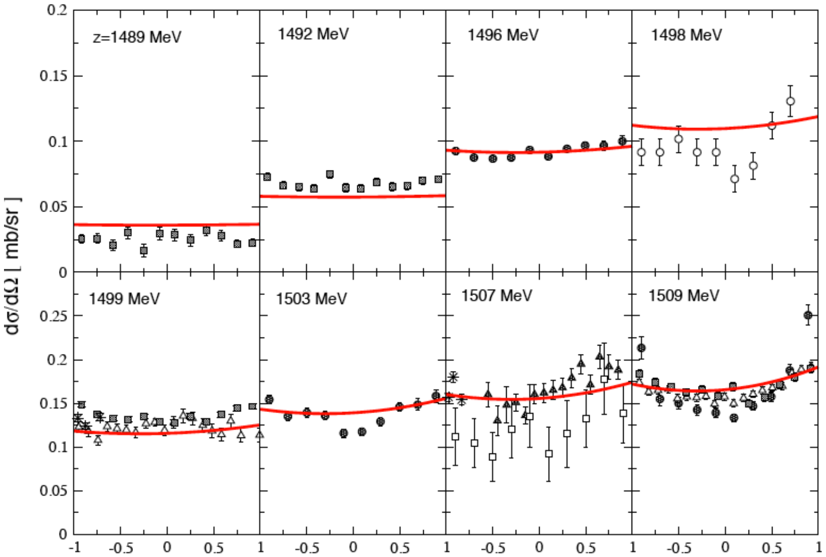
Selected results: $\pi N \rightarrow \pi N$

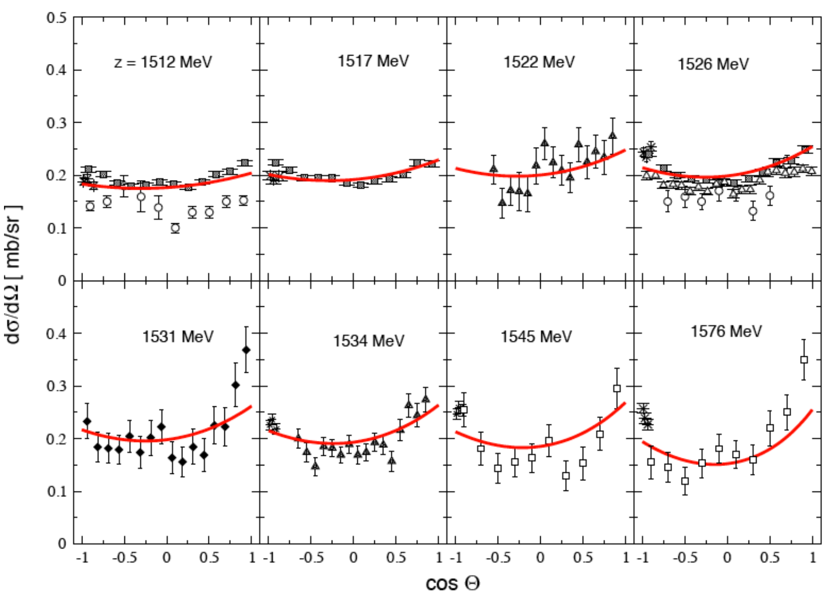
(D. Rönchen, M. Döring, F. Huang, … , in preparation)

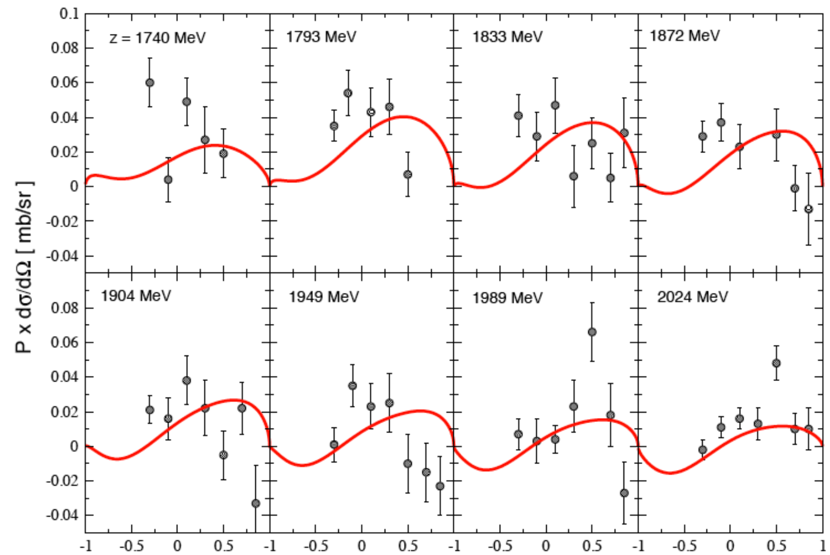


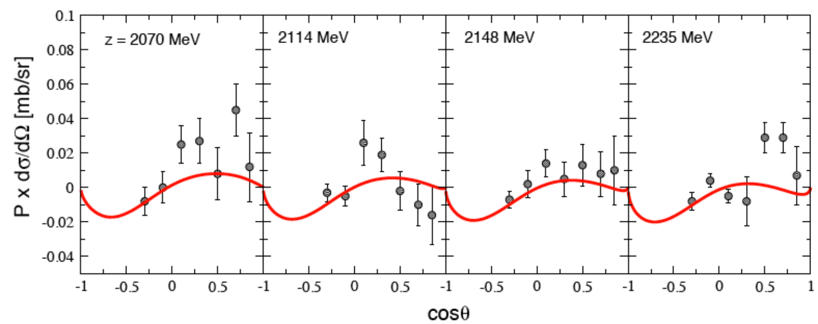
Selected results: $\pi N \rightarrow \eta N$

(D. Rönchen, M. Döring, F. Huang, … , in preparation)



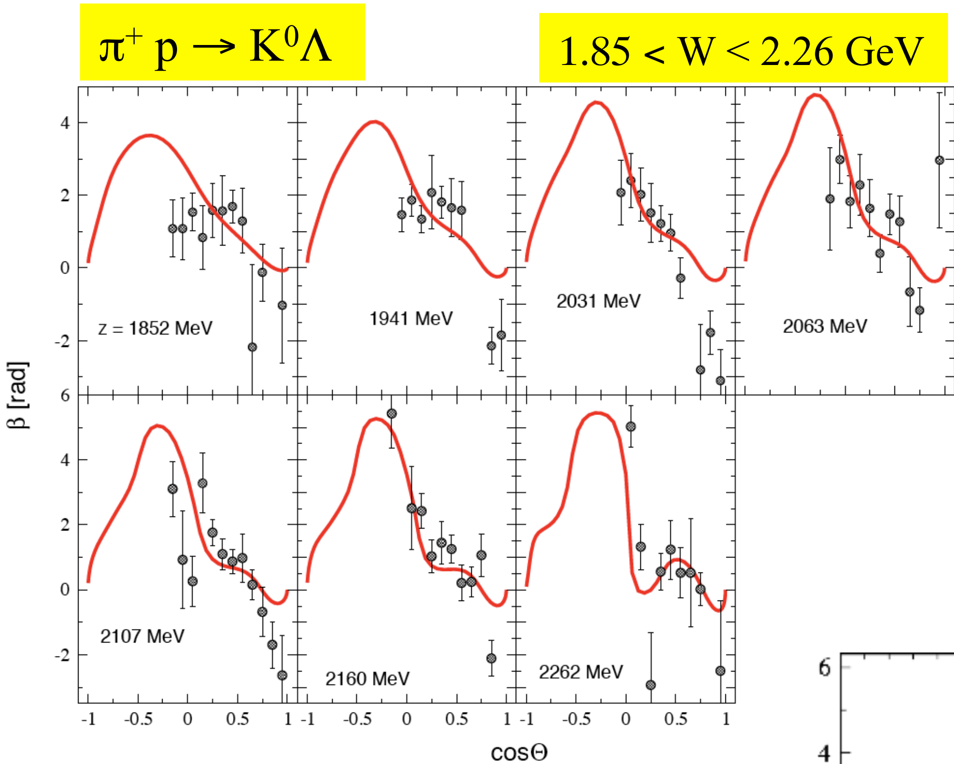


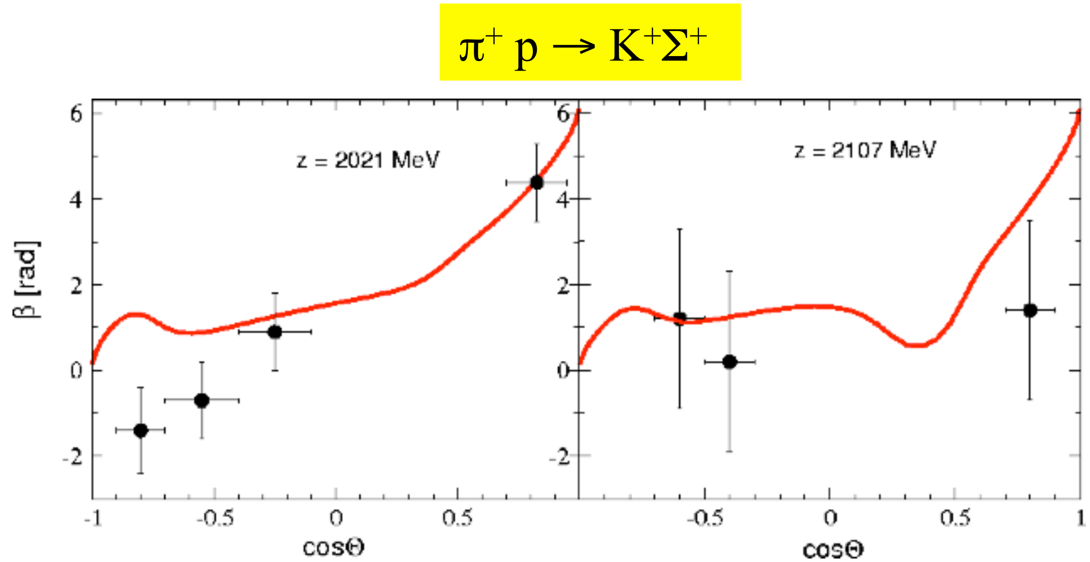




Selected results: $\pi^- p \rightarrow K^0\Lambda,\ K^+\Sigma^+$, *spin rotation param.* β

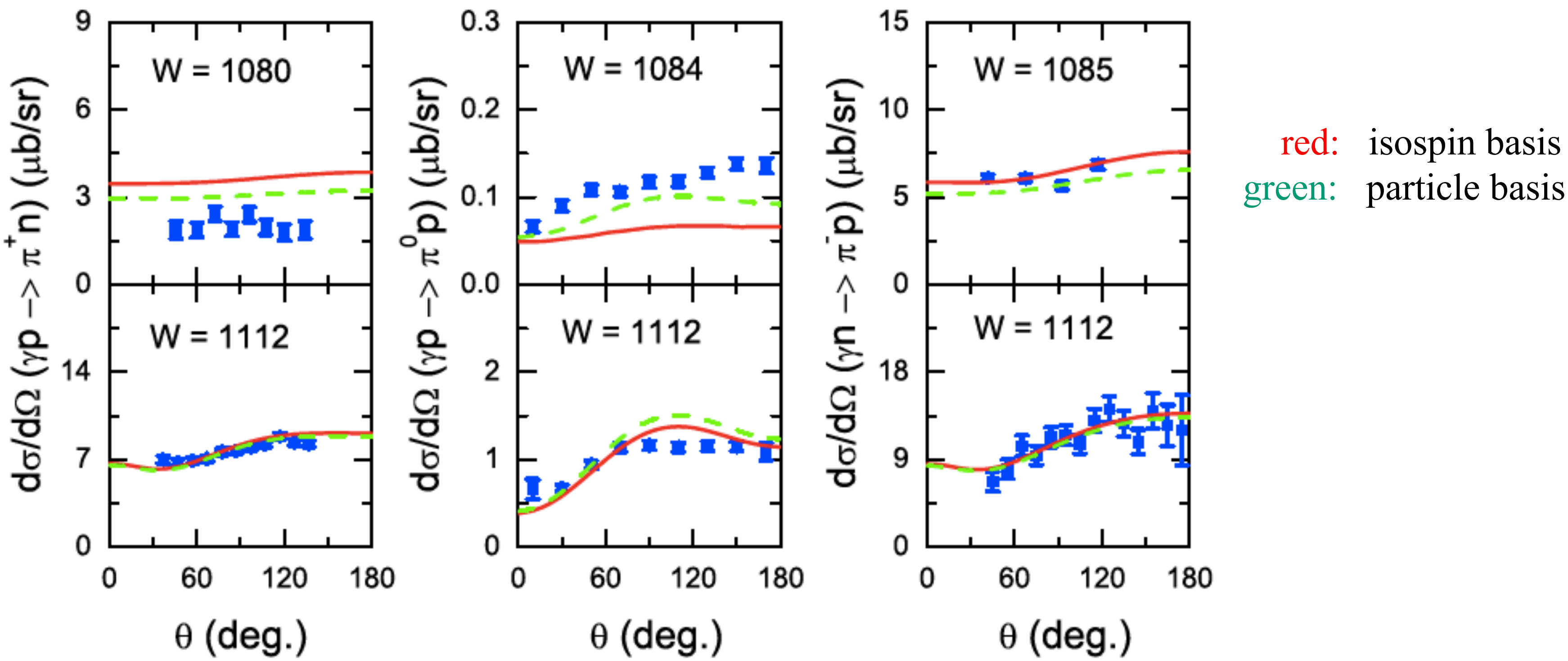
(D. Rönchen, M. Döring, F. Huang, ... , in preparation)





Some basic open issues: low energy behavior

(F. Huang et al., PRC85 ’12)



Chiral constraints?

- The model uses the phenomenological chiral Lagrangian of Wess-Zumino [PR163, ’67] supplemented by additional Lagrangian couplings of Δ, ω, η, σ, and a_0.
- But, phenomenological form factors usually destroy chiral symmetry

MDT [PLB522, ’01] describes quite well the near-threshold pion photo- & electro-production data

Some basic open issues: theoretical uncertainties

Statistical uncertanties: arising from the uncertainties in the data used to fix the model parameters are relatively straightforward to quantify in principle.

In our model at present, not possible due to the absence of a quantitative statistical error analysis of the πN scattering. Needs to fit the data. [Döring et al., NPA851, '11].

Systematic uncertanties: are difficulty to quantify due to the absence of a precise ordering scheme for refining the approximation inherent in all phenomenological effective Lagrangian based approaches. They arise, e.g., from the:

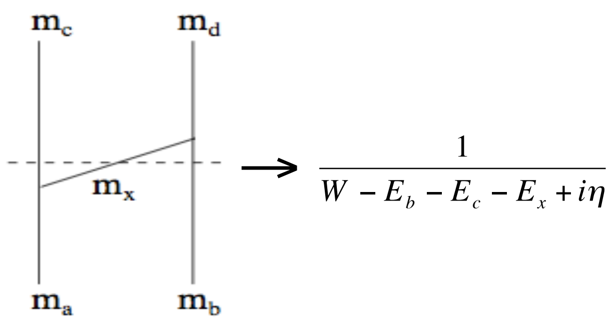
- violation of unitarity, analyticity, gauge invariance
- truncation of meson-nucleon channel space
- number of baryon resonances considered

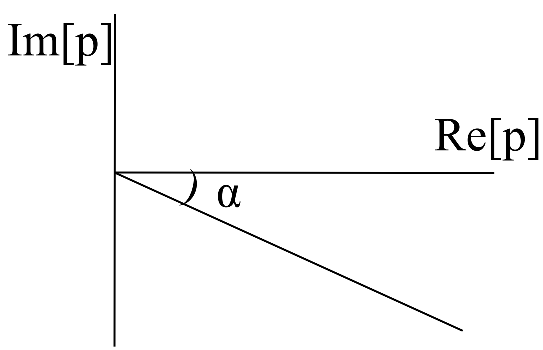
So far in our model: missing the ωN channel, in addition to the $K\Lambda$ and $K\Sigma$ channels and higher-spin resonances in photo-induced channels.

Comparison with other models (EBAC, DMT, …): better understanding the systematic uncertainties.

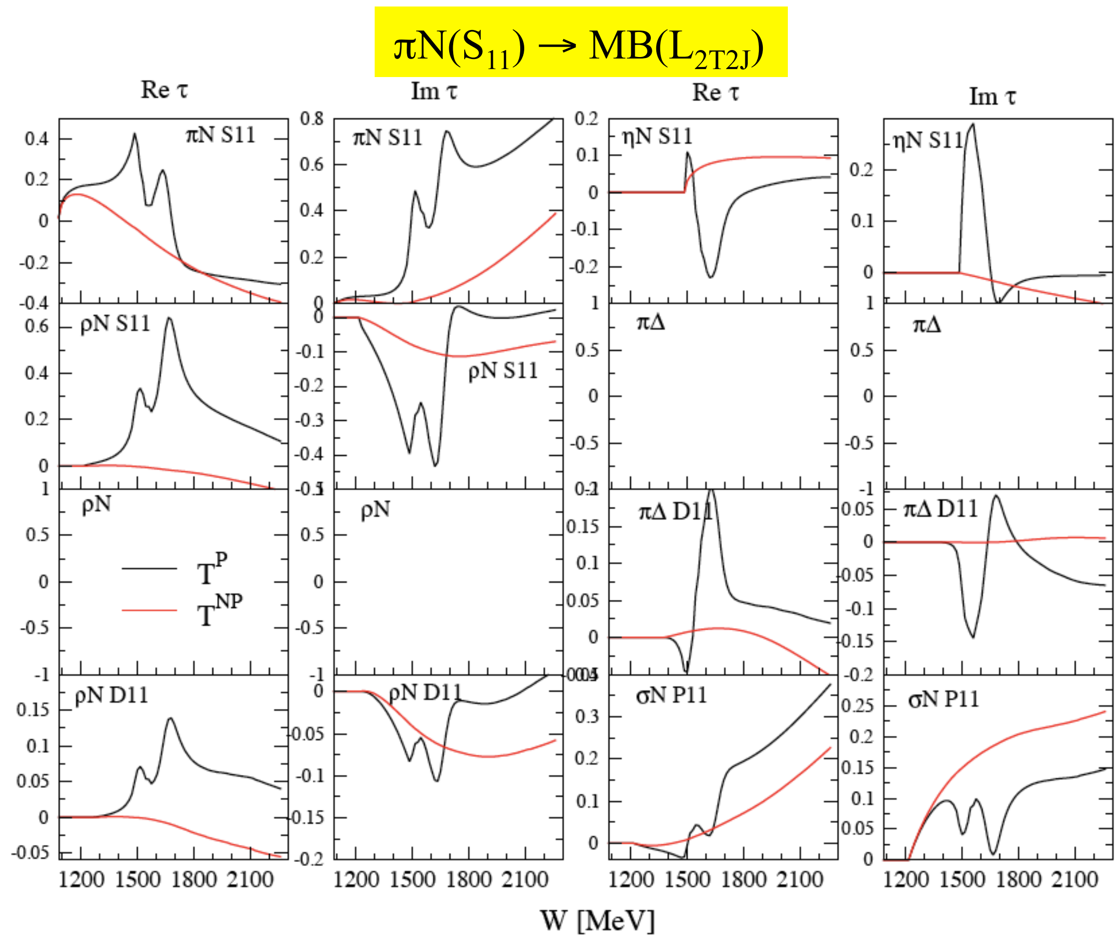
Some basic open issues: three-body singularities & unitarity

Three-body singularities: arise from V in the kinematics (off-shell p) → (on-shell, i.e., real p). E.g., t-channel πN(off-shell) → σN, ρN(on-shell). It can be dealt by an integration over the rotated axis (off-shell complex momenta) & extrapolation to on-shell real momenta. (Döring et al.)





rotated integration axis



Some basic open issues: three-body singularities & unitarity

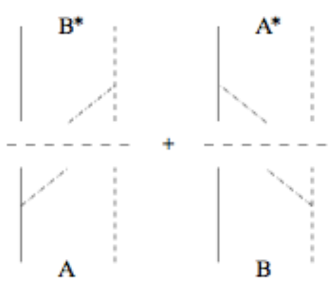
Three-body singularities: arise from V in the kinematics (off-shell p) → (on-shell, i.e., real p). E.g., t-channel πN(off-shell) → σN, ρN(on-shell). It can be overcome by an integration over the rotated axis (off-shell complex momenta) & extrapolation to on-shell real momenta. (Döring et al.)

Three-body unitarity: arise whenever W> ππN threshold

$$i(T_{ii} - T_{ii}^{+}) < \sum_{j} (2\pi)\delta(E_i - E_j) T_{ij} T_{ji}^{+} \quad \text{(if Im[V] < 0)}$$

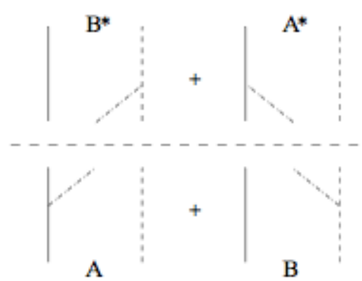
no problem if no 3-particle production

unitarity cuts for t-channel diagrams



a)

A x B* + B x A*
(sign not well defined)



b)

(A+B) x (A+B)*
(sign well defined)

unitarity restoring additional diagrams

A. Gasparyan, PhD thesis ('02)

See also 2- & 3-body unitarity in the isobar approx., [Aaron, Amado, Young, PR174, '68]

more rigorous three-body unitarity constraints (if possible at all): still missing

Overview of the data for pion-induced reactions < 3 GeV

Reaction	Observables	Energy range	ND
$\pi^- p \to \eta n$	σ	1486 ~ 2280	230
	$d\sigma/d\Omega$	1486 ~ 2410	154
	P	1740 ~ 2230	115
$\pi^- p \to \omega n$	σ	1720 ~ 2300	34
	$d\sigma/d\Omega$	1730 ~ 2000	110
	$\rho_{\lambda\lambda'}$	1800 ~ 2300	90
$\pi N \to \eta' N$	σ	1930 ~ 2450	16
$\pi N \to \rho N$	σ	1630 ~ 3000	28
$\pi N \to \phi N$	σ	1960 ~ 2350	12

total: 789

$\pi^- p \to \pi^+ \pi^- n$	σ	1228 ~ 2646	31
	$d^2\sigma/d\Omega_{++}dT_{++}$	1242 ~ 1301	40
	W	1301 ~ 1168	324
	$d\sigma/dm_{\pi\pi}^2$	1256 ~ 1315	33
	$d\sigma/dt$	1256 ~ 1315	41
$\pi^- p \to \pi^0 \pi^- p$	σ	1228 ~ 2646	17
$\pi^- p \to \pi^0 \pi^0 n$	σ	1236 ~ 1266	39
	$d\sigma/d\Omega$	1269 ~ 1525	280
$\pi^+ p \to \pi^+ \pi^+ n$	σ	1221 ~ 2574	26
	$d\sigma/dm_{\pi\pi}^2$	1256 ~ 1315	37
	$d\sigma/dt$	1256 ~ 1315	42
$\pi^+ p \to \pi^+ \pi^0 p$	σ	1228 ~ 2867	19

total: 957

Reaction	Observables	Energy range	ND
$\pi^+ n \to K^+ \Lambda$	$d\sigma/d\Omega$	2143	5
	P	2143	1
$\pi^- p \to K^0 \Lambda$	σ	1631 ~ 2948	62
	$d\sigma/d\Omega$	1631 ~ 2900	854
	P	1930 ~ 2900	724
	β	1852 ~ 2262	72
$\pi^+ p \to K^+ \Sigma^+$	σ	1729 ~ 2355	34
	$d\sigma/d\Omega$	1821 ~ 2979	1041
	P	1731 ~ 2355	644
	β	2020 ~ 2106	7
$\pi^+ n \to K^0 \Sigma^+$	P	2022 ~ 2323	12
$\pi^- p \to K^0 \Sigma^0$	σ	1985 ~ 2948	31
	$d\sigma/d\Omega$	1694 ~ 2900	512
	P	1693 ~ 2883	124
$\pi^- p \to K^+ \Sigma^-$	σ	1740 ~ 2948	16
	$d\sigma/d\Omega$	1740 ~ 2900	193
	P	2733	10

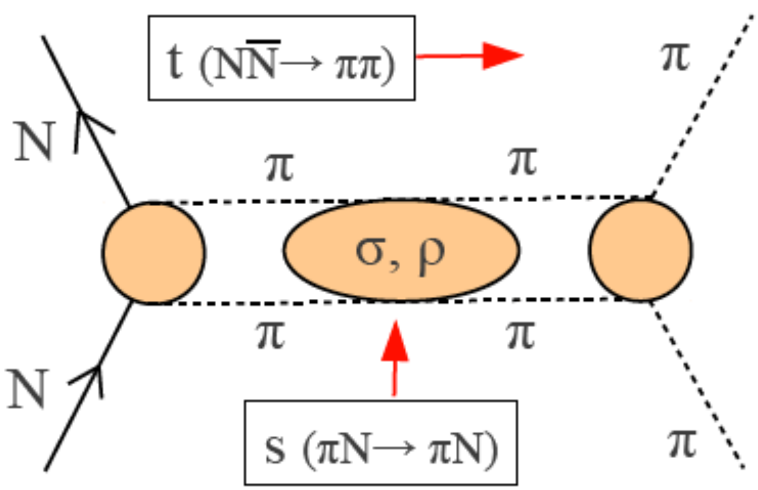
total: 4342

$\pi N \to \pi N$ (SAID PWA):

S11,S31,P11,P31, …, H19,H39 (SES) [ND ~2500]

Reaction Theory: hadronic model (cont.')

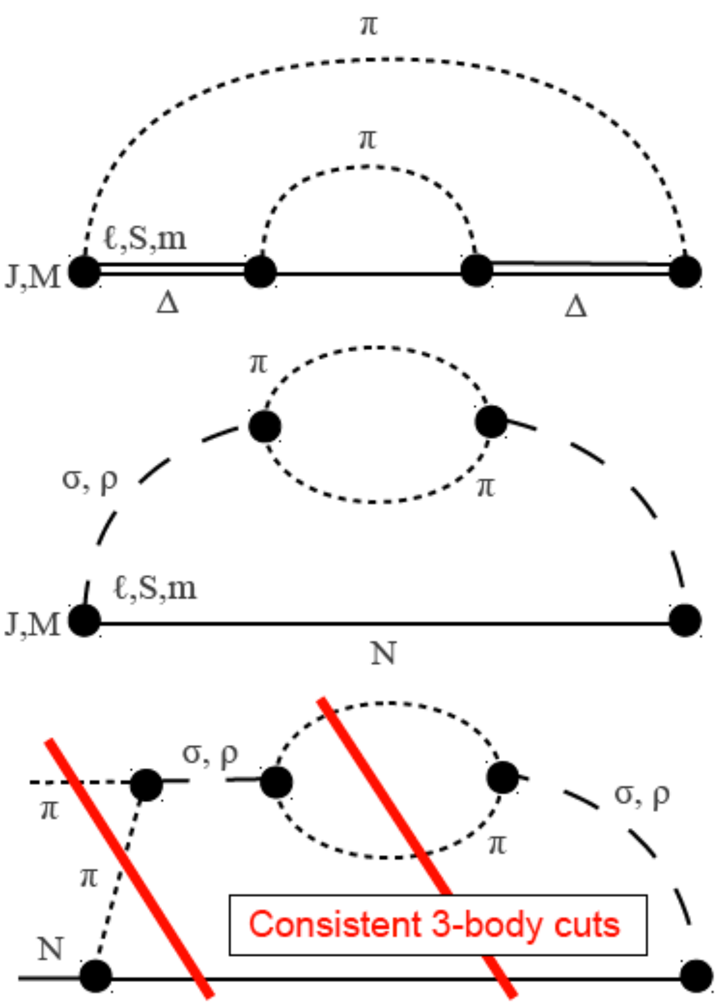
Crossing symmetry (at the potential level):



- πN t-channel interaction from $\bar{N}N \to \pi\pi$ (analytically continued) data, for $\sigma(600)$ and $\rho(770)$ quantum numbers.
- Use of crossing symmetry and dispersion techniques [Schütz *et al.* PRC 49 (1994) 2671].

Reaction Theory: hadronic model (cont.')

ππN states: σN, ρN, πΔ



- $\pi\pi/\pi N$ subsystems fit the respective phase shifts.
- Towards a consistent inclusion of 3-body cuts.
- Will allow for *a-priori* 3-body unitarity per construction

[Aaron, Almado, Young, PR 174 (1968) 2022].

Reaction Theory: *approx. the interaction current*

(cont.')

interaction current:

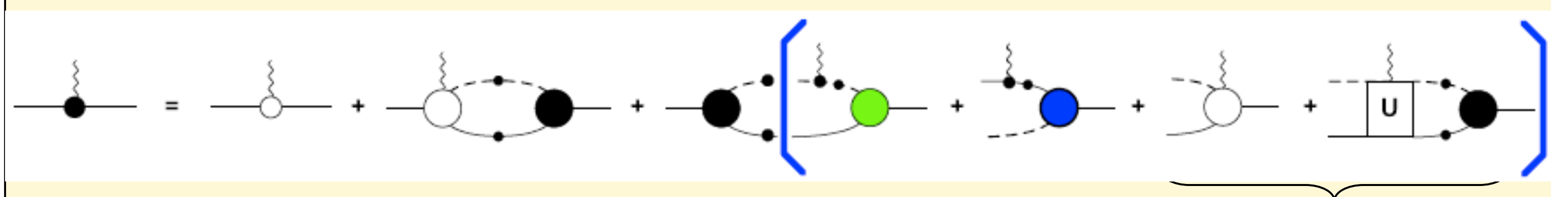
$$M^{\mu}_{\text{int}} = M^{\mu}_{a} + XG[M^{\mu}_{t} + M^{\mu}_{u} + M^{\mu}_{a}]$$

$$= M^{\mu}_{c} + T_{X}{}^{\mu} + XG\underbrace{\left[M^{\mu}_{uT} + M^{\mu}_{tT} + T_{X}{}^{\mu}\right]}_{\text{pure transverse}}$$

M^{μ}_{uT} = transverse part of M^{μ}_{u}

M^{μ}_{tT} = transverse part of M^{μ}_{t}

dressed NNγ vertex:



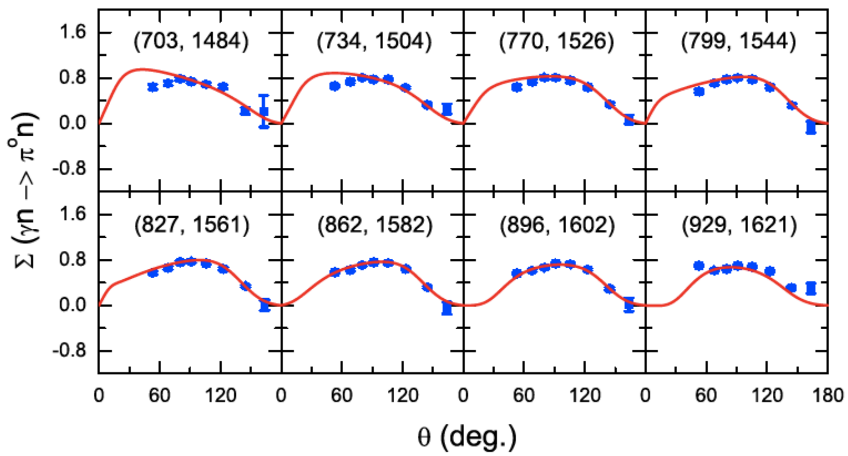
M^{μ}_{a}

$$\Gamma^{\mu} = \Gamma^{\mu}_{0} + m_{KR}G[F\tau] + [F_{0}\tau]G\left(M^{\mu}_{c} + M^{\mu}_{uL} + M^{\mu}_{tL}\right)$$

$$+[F\tau]G\left[M^{\mu}_{uT} + M^{\mu}_{tT} + T_{X}{}^{\mu}\right]$$

Some results for pion photoproduction: (cont.')

(F. Huang et al., PRC85 '12)



Analytic continuation into the complex E-plane: resonances

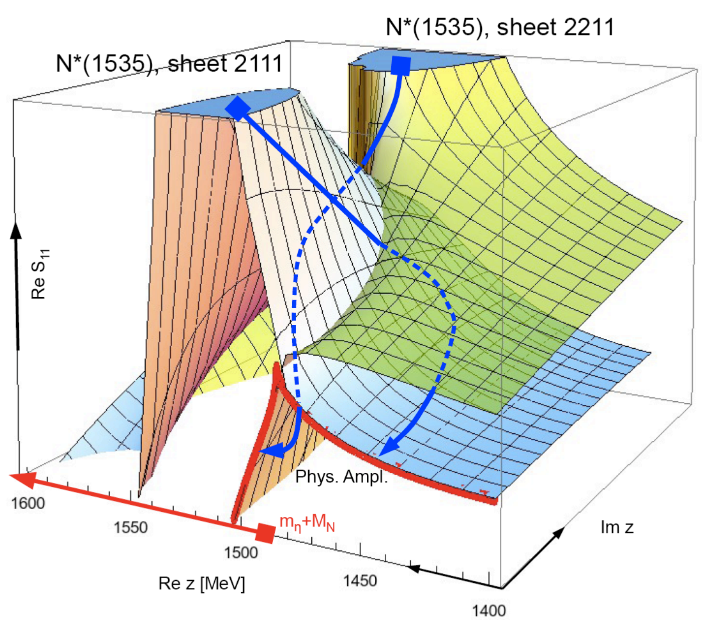
Resonances: poles of the reaction amplitude in the complex E-plane (second Riemann sheet).

They are reached by an analytic continuation of the reaction amplitude into the complex E-plane. Analyticity is essential.

Insights into the development/formation of the resonances and how they affect the physical amplitude:

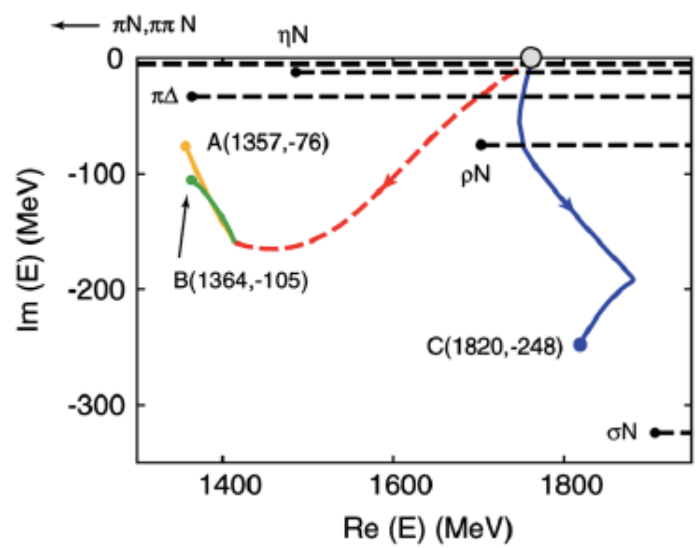
Jülich, M.Döring et al., NPA829,'09
EBAC, N. Suzuki et al., PRL104,'10

η phtoproduction amplitude



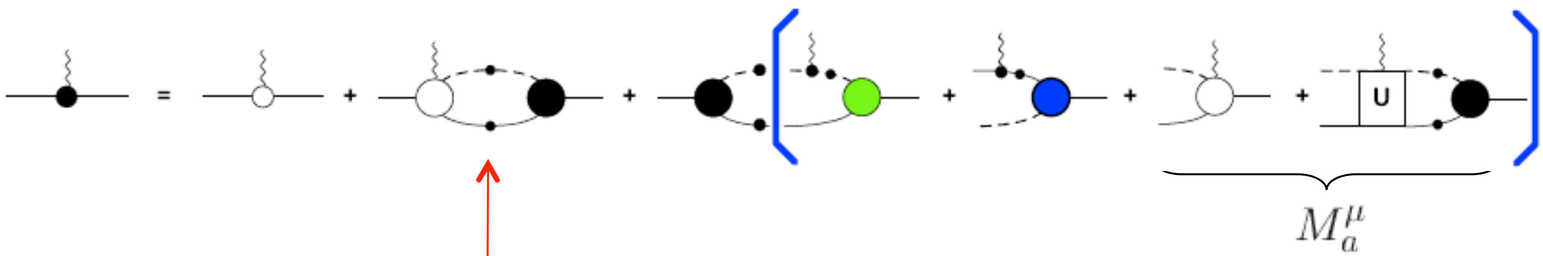
Döring & Nakayama, EPJA43, '10

Evolution of the P_{11} resonance



Electroproduction: *to be tacked next*

Dressed NRγ vertex:



unique to the present approach

$$\Gamma^\mu = \Gamma_0^\mu + m_{KR} G[F\tau] + [F_0\tau]G\left(M_c^\mu + M_{uL}^\mu + M_{tL}^\mu\right)$$
$$+[F\tau]G\left[M_{uT}^\mu + M_{tT}^\mu + T_X{}^\mu\right]$$