

Baryon Resonances in a Dynamical Coupled-Channel Model

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In collaboration with:

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PWA 7, Camogli, September 25, 2013

The excited hadron spectrum: Connection between experiment and QCD

Predictions for resonances (e.g. from lattice calculations, Dyson-Schwinger, quark models)

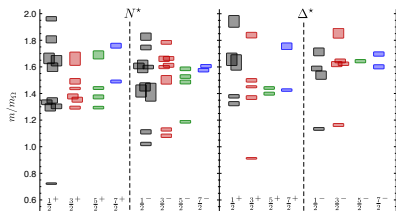
⇔ Intensive **experimental** effort (e.g. at MAMI, ELSA, JLab (CLAS), ...)



Theoretical data analysis required

(e.g. GWU SAID, DMT, Gießen, Bonn-Gatchina, MAID, ANL-Osaka, Zagreb, KSU, ...)

→ here: The **Jülich model**

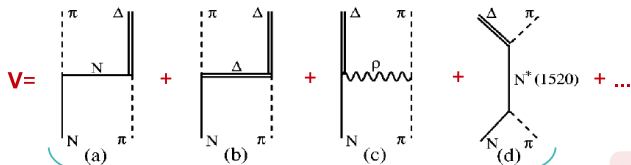


$m_{\pi} = 396 \text{ MeV}$ [Edwards *et al.*, Phys.Rev. D84 (2011)]

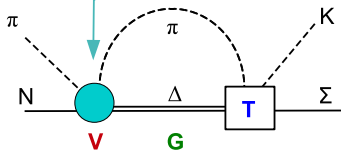
- Combine different reaction in a simultaneous analysis:
Dynamical coupled-channel models

↪ states that couple only weakly to πN
↪ connect with photoproduction

The scattering equation

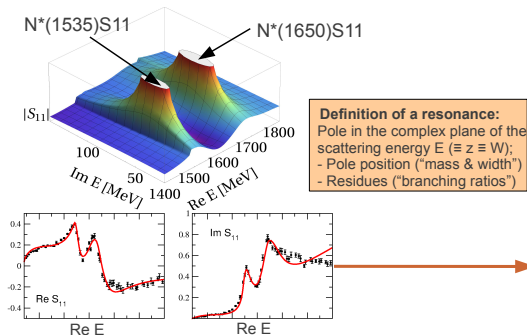


Potentials V constructed from Wess-Zumino \mathcal{L}



$$\langle L'S'k' | T_{\mu\nu}^{IJ} | LSk \rangle = \langle L'S'k' | V_{\mu\nu}^{IJ} | LSk \rangle + \sum_{\gamma, L''S''} \int_0^{\infty} q^2 dq \langle L'S'k' | V_{\mu\gamma}^{IJ} | L''S''q \rangle \frac{1}{Z - E_{\gamma}(q) + i\epsilon} \langle L''S''q | T_{\gamma\nu}^{IJ} | LSk \rangle$$

Basic features of the Jülich model



- **Analyticity** is respected

- real parts of T
- correct structure of branch points and cuts

↔ Resonance parameters in terms of poles and residues

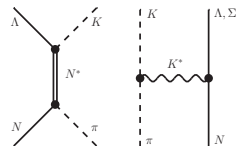
- **Unitarity** is respected → meson exchange from 3-body unitarity

[Schütz, Haidenbauer, Speth, Durso, Phys.Rev. C57 (1998) ; Krehl, Hanhart, Krewald, Speth, Phys.Rev. C62 (2000); Gasparyan, Haidenbauer, Hanhart, Speth, Phys. Rev. C68, (2003)]

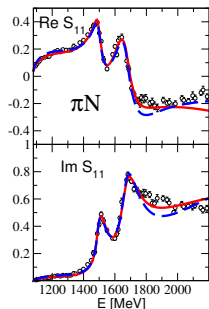
Coupled-channel dynamics in $\pi N \rightarrow \pi N, \eta N, K \Lambda, K \Sigma$ Eur.Phys.J. A49 (2013) 44

Analysis details

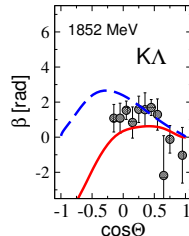
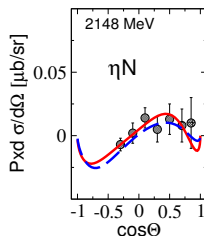
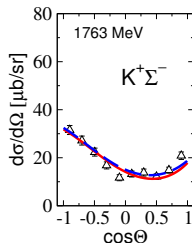
- **Simultaneous fit** to elastic πN PW and $\pi N \rightarrow \eta N, KY$ observables ($d\sigma/d\Omega, P, \beta$)
- 196 free parameters, minimization using MINUIT on the JUROPA supercomputer



Selected results: Fit A and Fit B



Full results



⇒ Resonance parameters (poles + residues)

Photoproduction

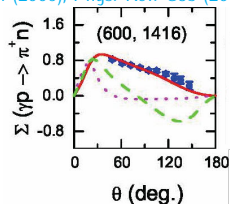
Different approaches

- **Field theoretical** approaches : ANL-Osaka, DMT,
Jülich-Athens-Washington, ...

Example: Gauge invariant formulation by Haberzettl, Huang and Nakayama
[Phys. Rev. C56 \(1997\)](#), [Phys. Rev. C74 \(2006\)](#), [Phys. Rev. C85 \(2012\)](#)

⇒ microscopic reaction dynamics

E.g.: gauge invariance restoring contribution
removed



New approach:

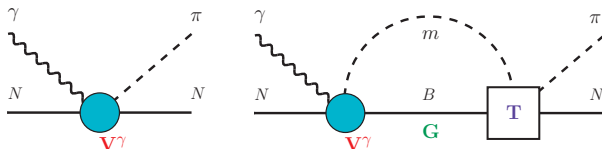
Combine good **analytic** properties of Jülich hadronic T -matrix with a
flexible and **model independent** parameterization of photo excitation

- ⇒ analyze large amounts of data
- ⇒ electromagnetic resonance parameter

Photoproduction in a phenomenological approach

The photoproduction amplitude

$$M_{\mu}^{\gamma} = V_{\mu}^{\gamma} + T_{\mu\kappa} G_{\kappa} V_{\kappa}^{\gamma}$$



$$m = \pi, \eta$$

$$B = N, \Delta$$

$T_{\mu\kappa}$: Jülich hadronic T -matrix

→ Watson's theorem fulfilled by construction

The phenomenological potential

$$V_{\mu}^{\gamma}(E, q) = \text{[Diagram 1]} + \text{[Diagram 2]} = \frac{\tilde{\gamma}_{\mu;i}^a(q)}{m_N} P_{\mu}^{NP}(E) + \sum_i \frac{\gamma_{\mu;i}^a(q) P_i^{PP}(E)}{E - m_i^b}$$

$\tilde{\gamma}_{\mu;i}^a, \gamma_{\mu;i}^a$: hadronic vertices \rightarrow correct threshold behaviour

i : resonance number per multipole

μ : channels $\pi N, \eta N, \pi \Delta$

Method inspired by SAID

but different

\Rightarrow Fit for $\gamma p \rightarrow \pi^0 p, \pi^+ n$

- fit in 2 steps:

1. to GWU/SAID CM12 multipoles \Rightarrow good starting point for observables

2. to data : $d\sigma/d\Omega, \Sigma, T$ and $P \Rightarrow$ final solution

Data base: GWU/SAID up to 2.4 GeV, + 5% syst. error
 $\sim 22\,000$ data points

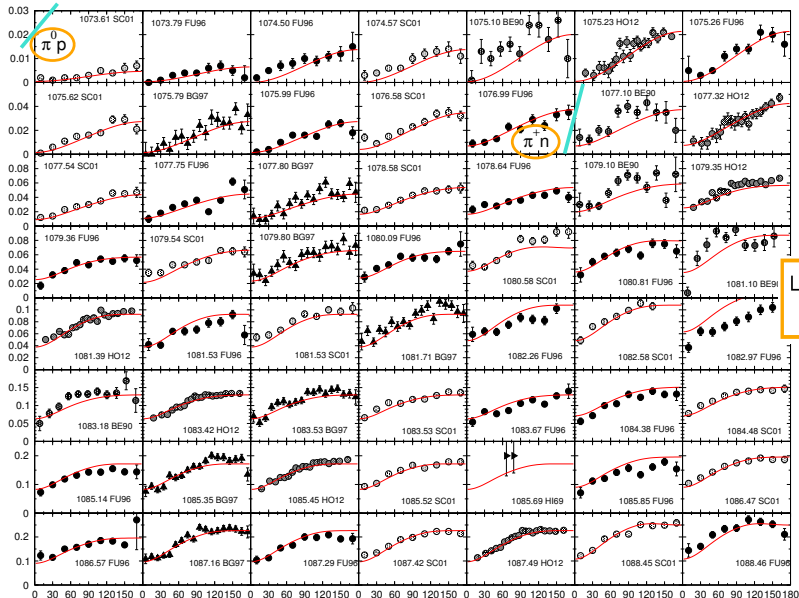
(preliminary) Fit results

$$\gamma p \rightarrow \pi^0 p$$

$$\gamma p \rightarrow \pi^0 p: d\sigma/d\Omega [\mu b]$$

threshold region

(preliminary)

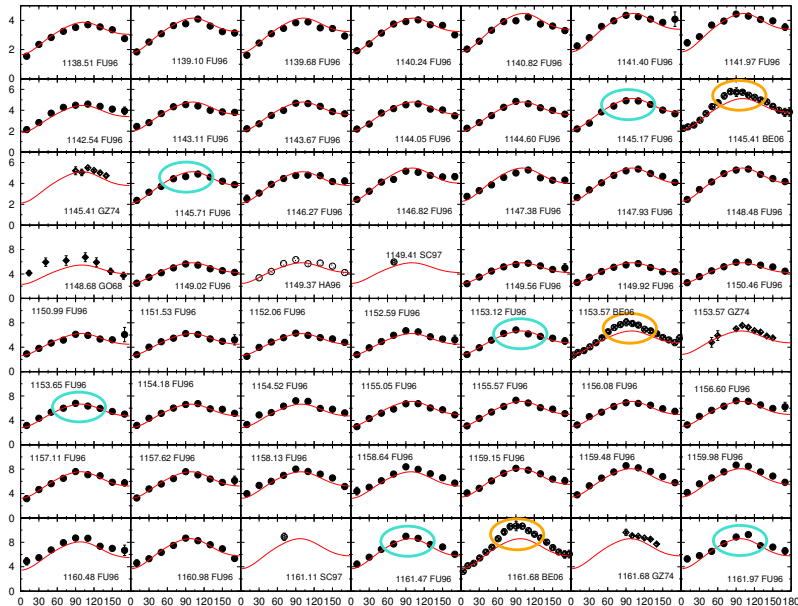


Low energies:
particle basis

$$\gamma p \rightarrow \pi^0 p: d\sigma/d\Omega [\mu b]$$

lower energies

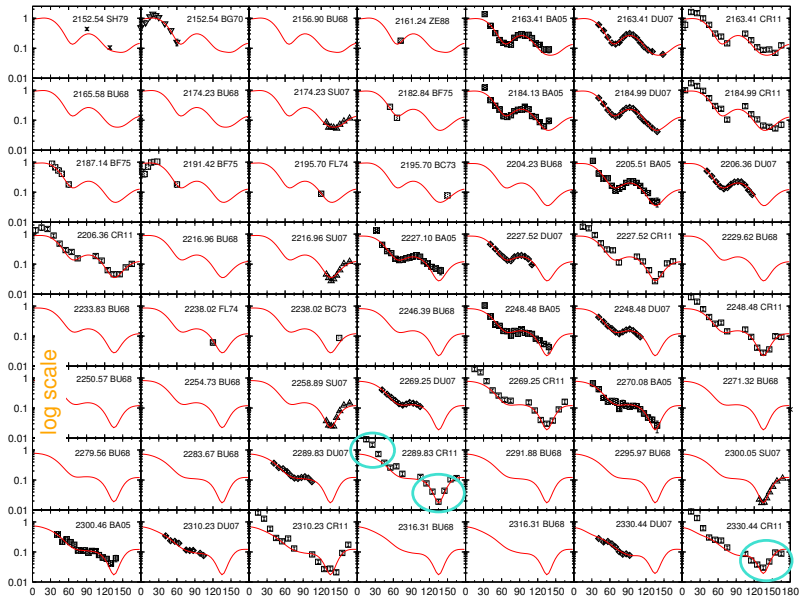
(preliminary)



$$\gamma p \rightarrow \pi^0 p: d\sigma/d\Omega [\mu b]$$

high energies

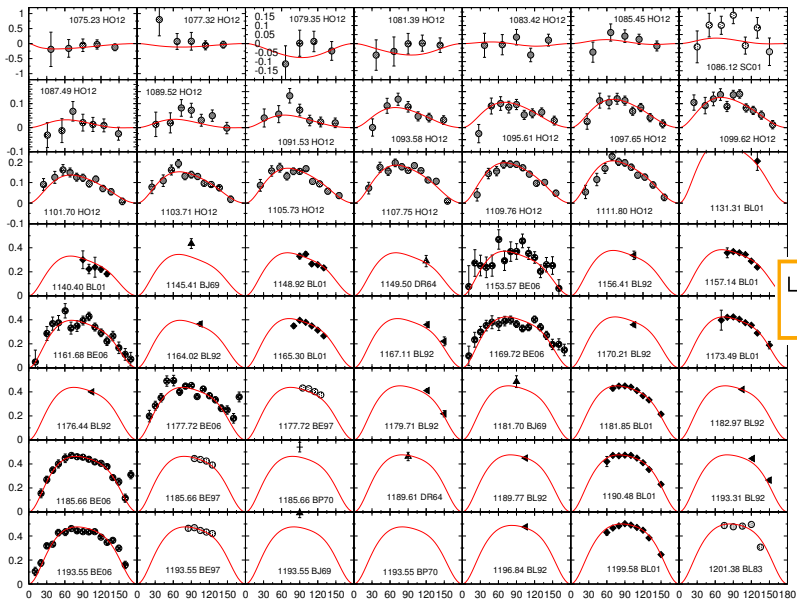
(preliminary)



$$\gamma p \rightarrow \pi^0 p: \Sigma$$

threshold region

(preliminary)

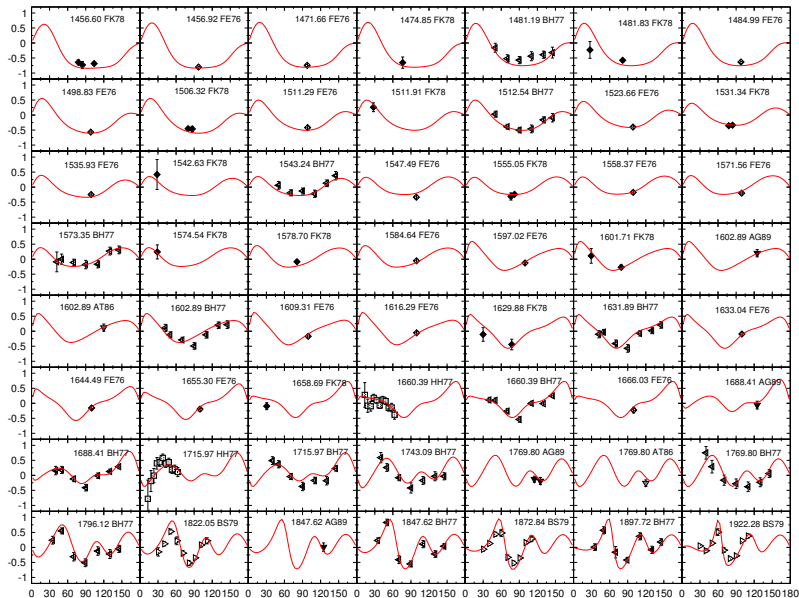


Low energies:
particle basis

$$\gamma p \rightarrow \pi^0 p: T$$

medium energies

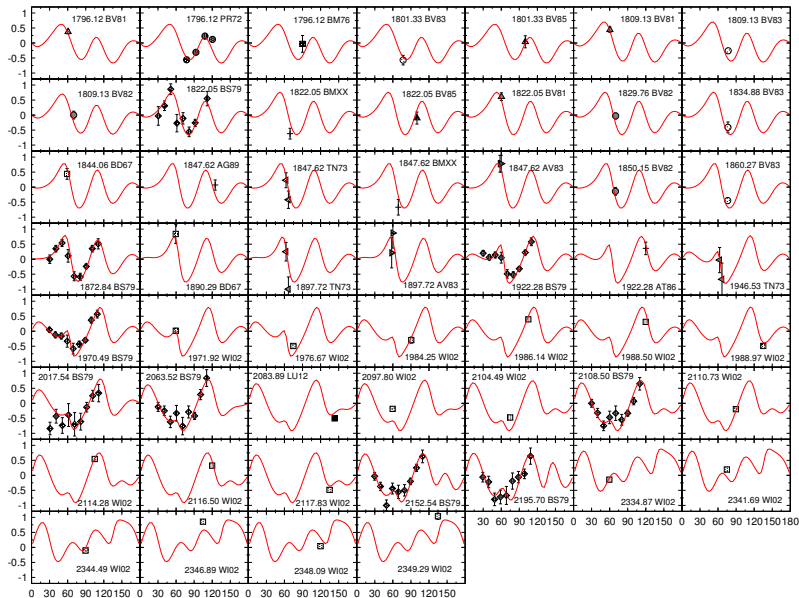
(preliminary)



$\gamma p \rightarrow \pi^0 p: P$

high energies

(preliminary)

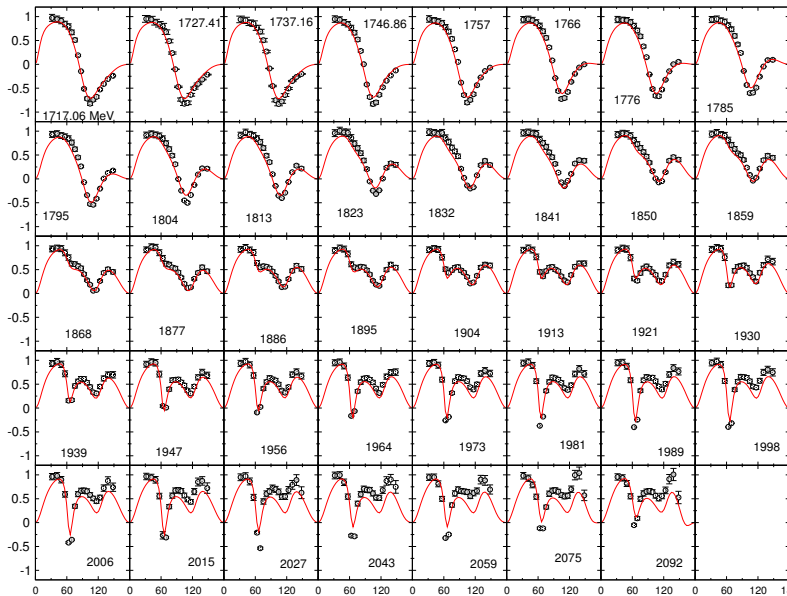


$$\gamma p \rightarrow \pi^0 p: \Sigma$$

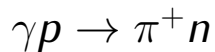
new CLAS data (prediction)

arXiv:1308.4028 [nucl-ex]

(preliminary)



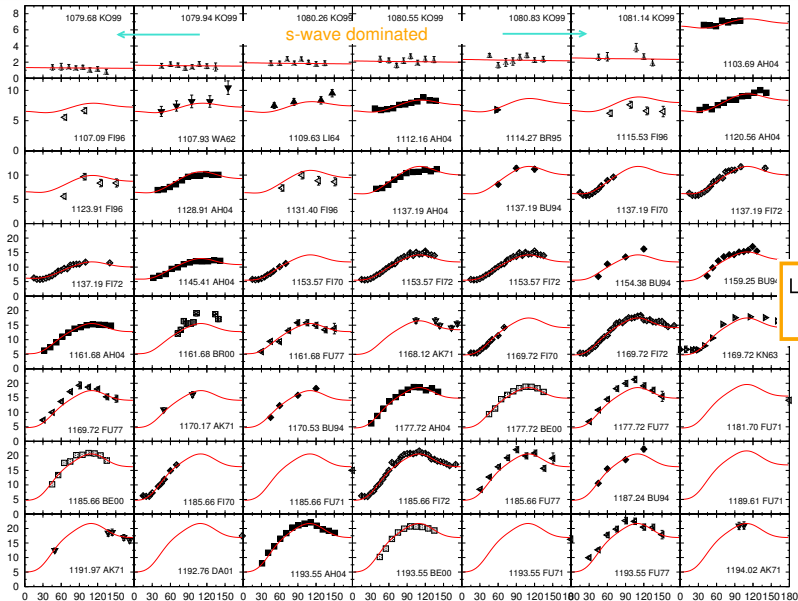
(preliminary) Fit results



$\gamma p \rightarrow \pi^+ n: d\sigma/d\Omega$ [μb]

threshold region

(preliminary)



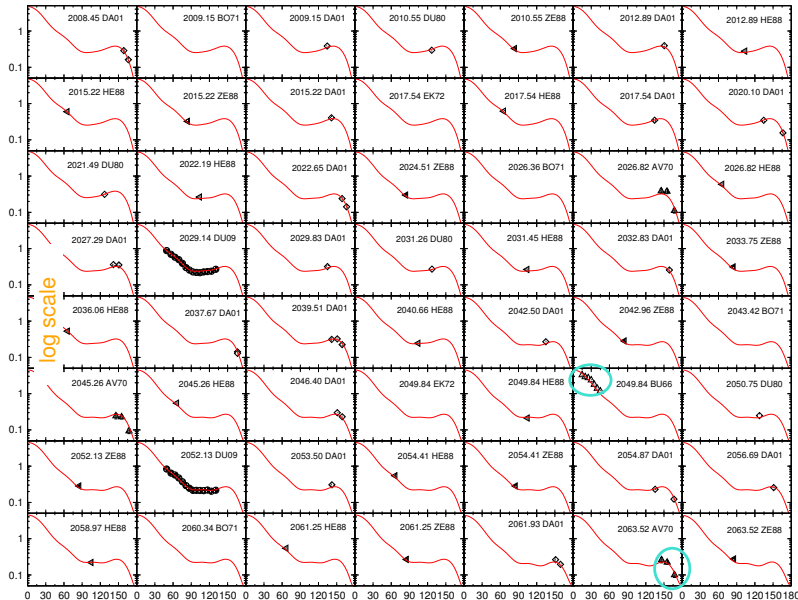
Low energies:
particle basis



$\gamma p \rightarrow \pi^+ n: d\sigma/d\Omega [\mu b]$

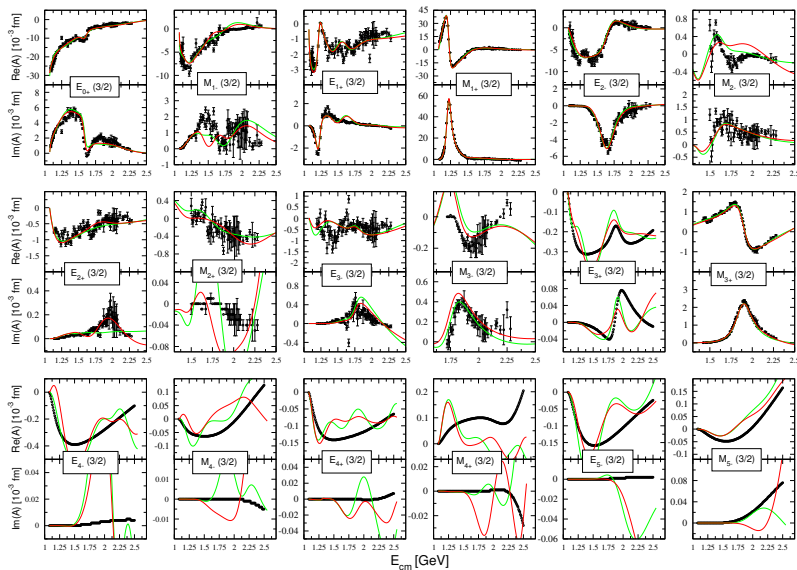
high energies

(preliminary)



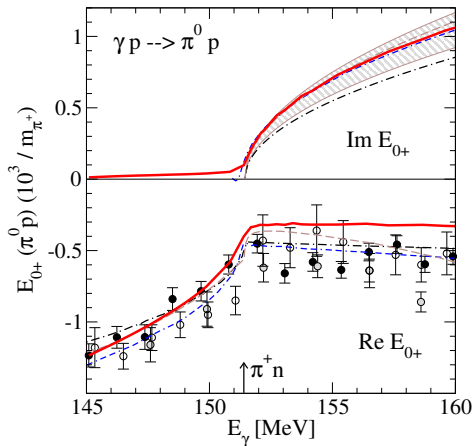
Multipoles: Comparison with GWU/SAID CM12, isospin 3/2

(preliminary)



Multipoles: $E_{0+}(\pi^0 p)$ at threshold

(preliminary)



- PRL 87, 232501 (2001) TAPS/MAMI
- PRC 55, 1016 (1997) [Im: gray band]
- PRC 53, R1052 (1996)
- - - Maid 2007 [EPJA 34,69]
- · - ChPT [ZPhys C70, 483 (1996)]
- - - DR [PLB 399,13]
- Solution Sept. 12

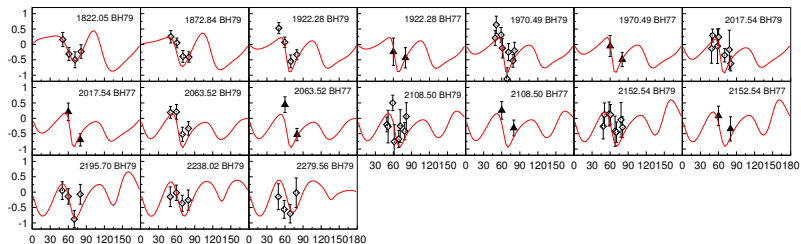
Different pion and nucleon masses
→ cusp effect

See also Hilt, Tiator *et al.* arXiv:1309.3385v1 [nucl-th]

$\gamma p \rightarrow \pi^0 p: H$

prediction

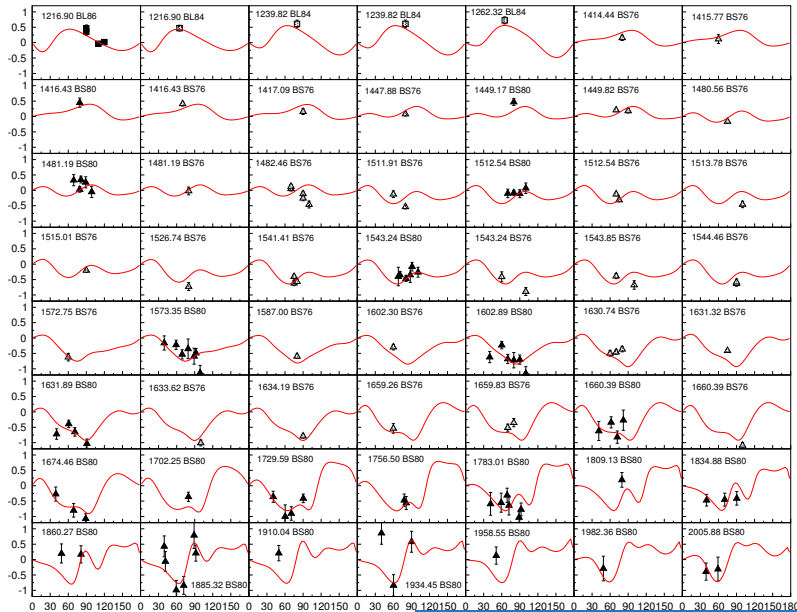
(preliminary)



$\gamma p \rightarrow \pi^+ n: H$

prediction

(preliminary)

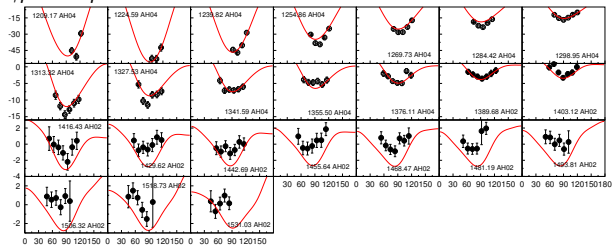


$$-2 \frac{d\sigma}{d\Omega} \cdot E \text{ } [\mu b]$$

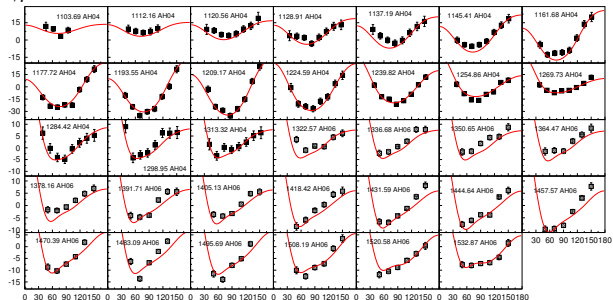
prediction

(preliminary)

$$\gamma p \rightarrow \pi^0 p :$$



$$\gamma p \rightarrow \pi^+ n :$$

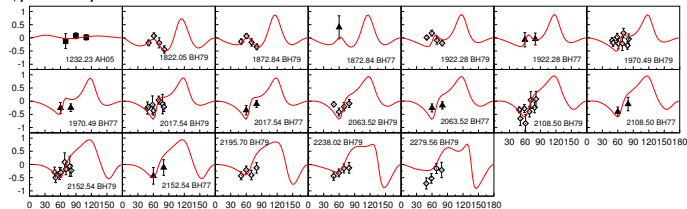


G

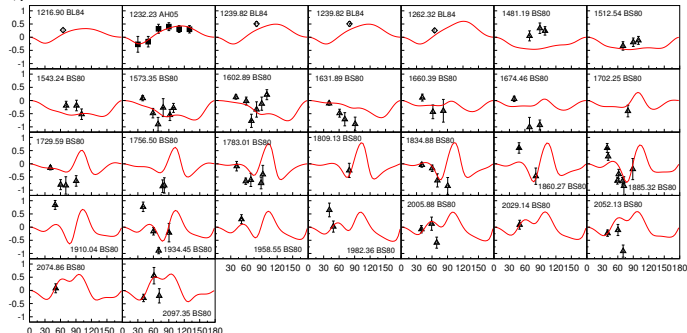
prediction

(preliminary)

$$\gamma p \rightarrow \pi^0 p :$$



$$\gamma p \rightarrow \pi^+ n :$$



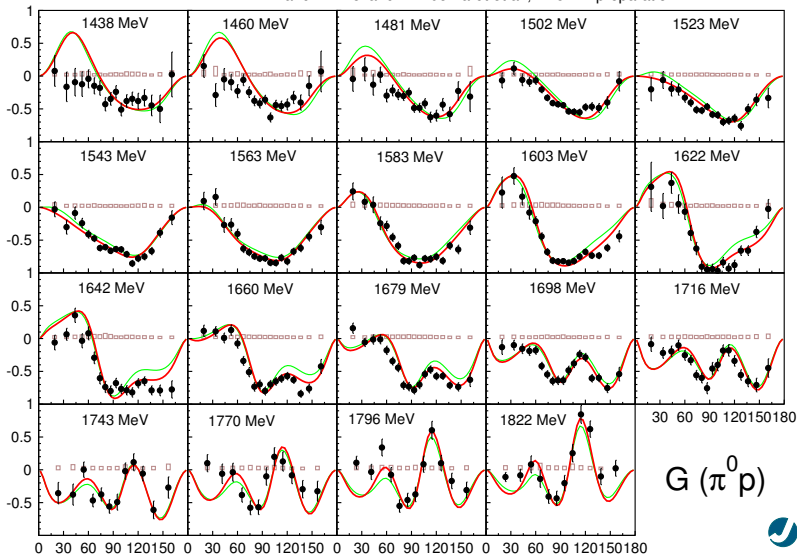
$\gamma p \rightarrow \pi^0 p: G$

new CB-ELSA/TAPS data

prediction (preliminary)

CB-ELSA/TAPS data

A. Thiel et al., PRL 109 (2012) 102001
and A. Thiel and H. Eberhardt et al., EPJA in preparation



Summary and outlook

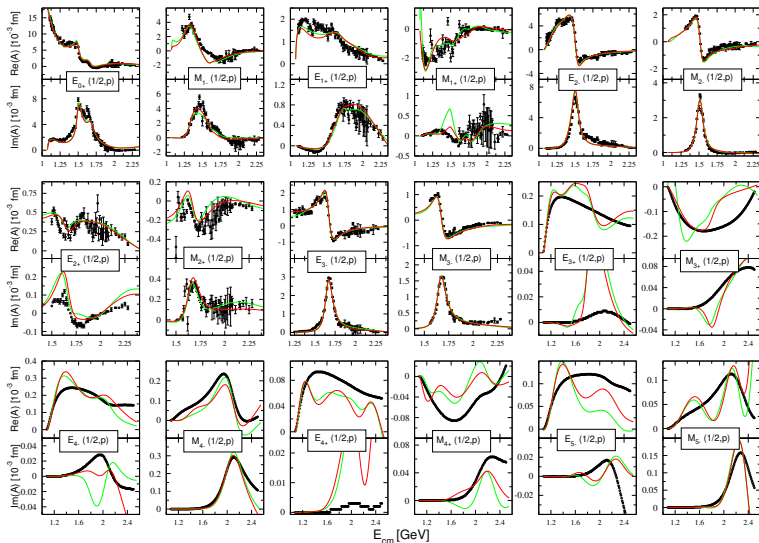
Summary:

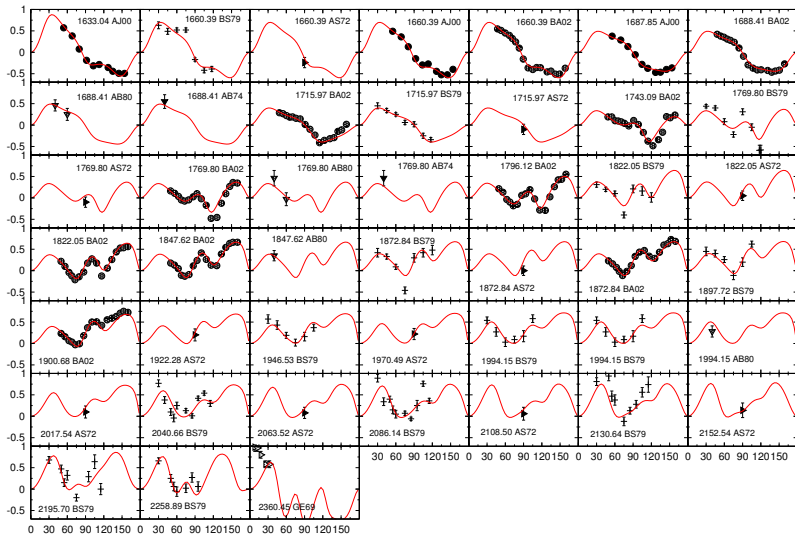
- Good analytic properties of dynamical coupled-channel model + flexible phenomenological approach
 - Data analysis of $d\sigma/d\Omega$, Σ , T , P
($\chi^2/(\#data - \#parms)=1.08$, including 5% syst. err.)
 - Predictions for G , H and E
 - Photo residues determined

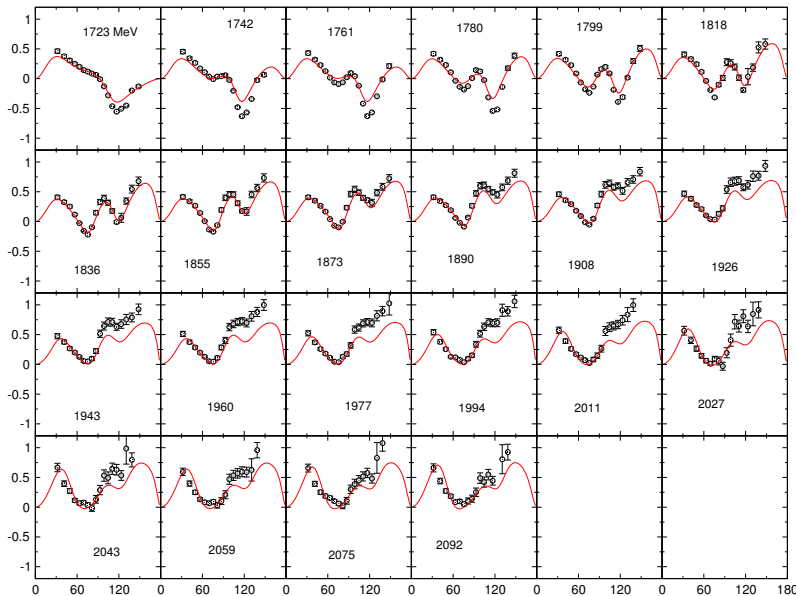
Outlook:

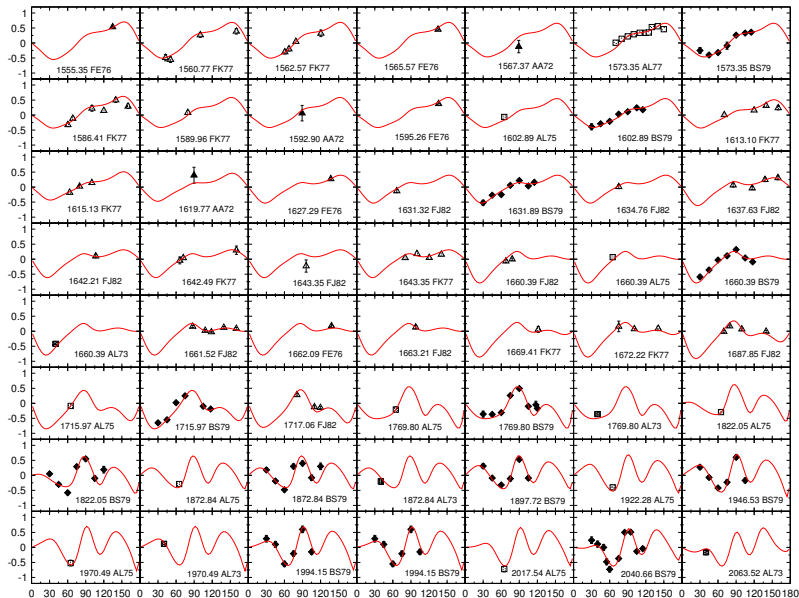
- Systematic test of resonance content
- Improve high energy limit
- Formalism prepared for η and K photoproduction

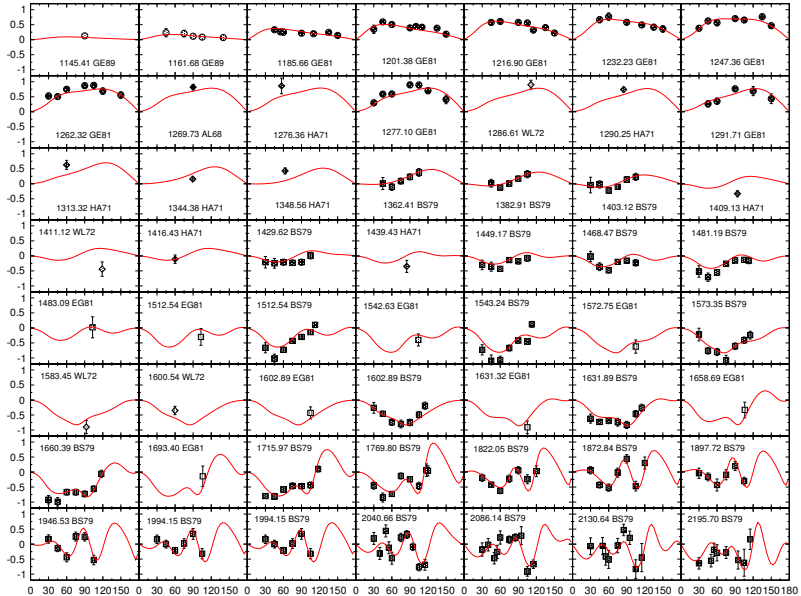
- Full dynamical coupled-channel results for K photoproduction within the *Jülich-Athens-Washington* approach: soon











Polynomials:

$$P_i^P(E) = \sum_{j=1}^n g_{i,j}^P \left(\frac{E - E_0}{m_N} \right)^j e^{-g_{i,n+1}^P (E - E_0)}$$

$$P_\mu^{\text{NP}}(E) = \sum_{j=0}^n g_{\mu,j}^{\text{NP}} \left(\frac{E - E_0}{m_N} \right)^j e^{-g_{\mu,n+1}^{\text{NP}} (E - E_0)}$$

◀ back

- $E_0 = 1077$ MeV
- $g_{i,j}^P, g_{\mu,j}^{\text{NP}}$: fit parameter
- $e^{-g(E-E_0)}$: appropriate high energy behavior
- $n = 3$

Isospin breaking in the πN channel

- Hadronic reactions: data well above threshold \rightarrow **isospin averaged** masses
- Pion-photoproduction: data near threshold \rightarrow include **isospin breaking**
 \hookrightarrow use **exact π^0 (π^+) and p (n) mass**

$E_{cm} < 1140$ MeV:

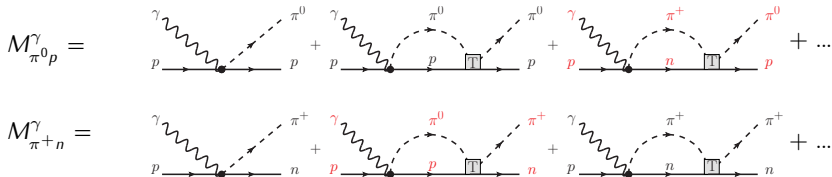
$$M_{\pi^0 p}^\gamma = \text{[diagram 1]} + \text{[diagram 2]} + \text{[diagram 3]} + \dots$$
$$M_{\pi^+ n}^\gamma = \text{[diagram 4]} + \text{[diagram 5]} + \text{[diagram 6]} + \dots$$

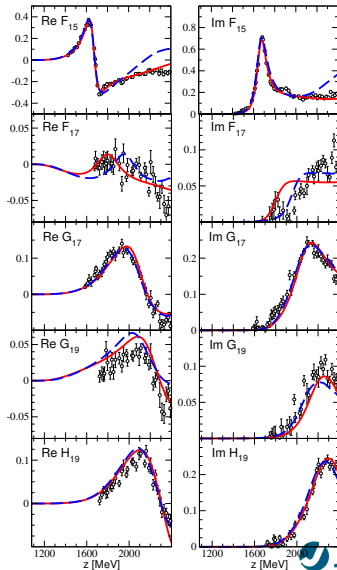
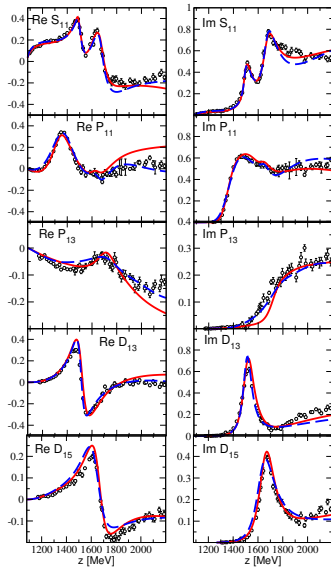
The diagrams illustrate the isospin breaking in pion photoproduction. The first row shows the production of π^0 from a proton (p), and the second row shows the production of π^+ from a neutron (n). Each diagram consists of a wavy line representing a photon (γ) interacting with a nucleon (proton or neutron) via a vertex (black dot). The nucleon then transitions to a resonance state (represented by a box labeled '1'), which subsequently decays into a pion and a nucleon. The diagrams are summed to represent the full amplitude, showing how isospin breaking is introduced through the different nucleon and pion masses.

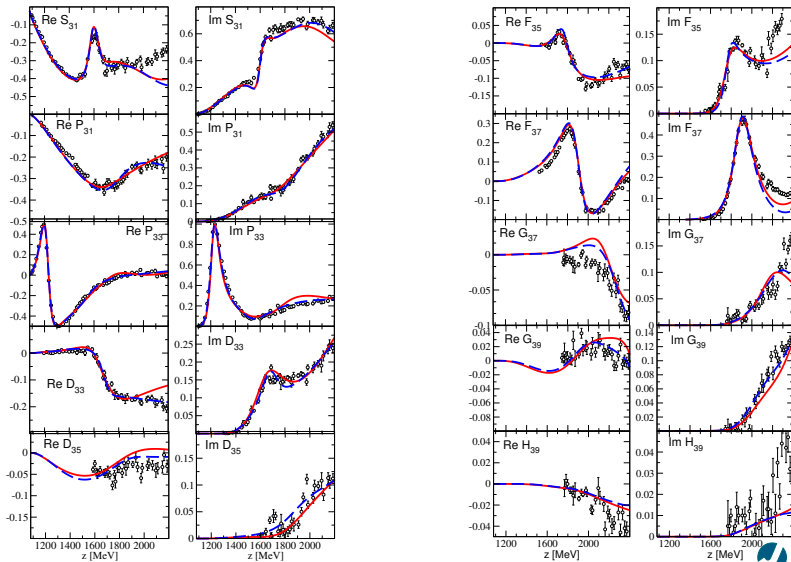
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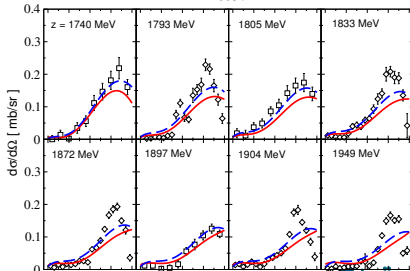
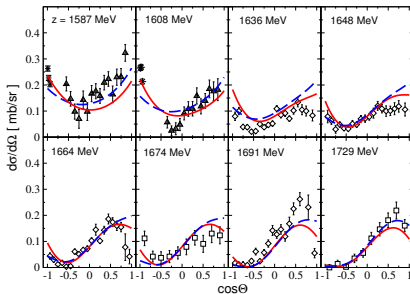
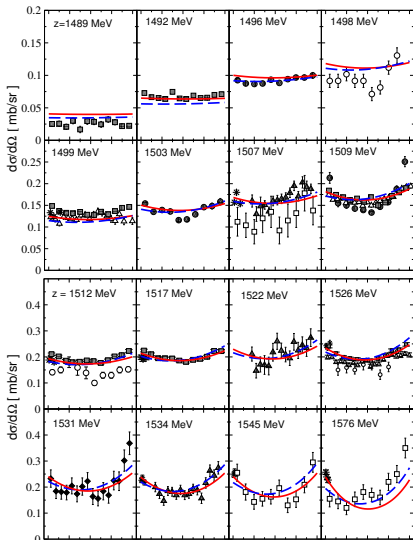
$E_{cm} < 1140$ MeV:



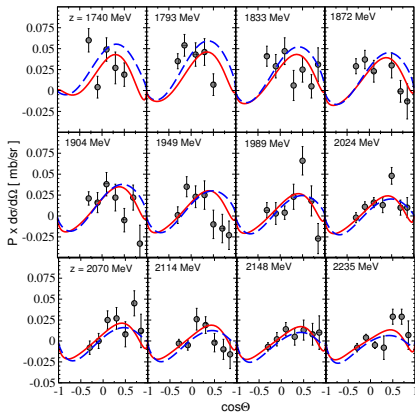
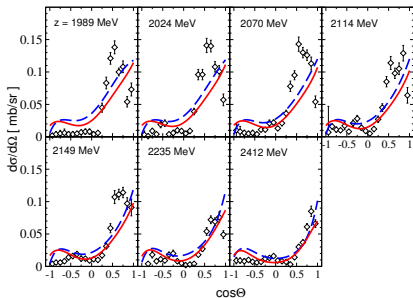


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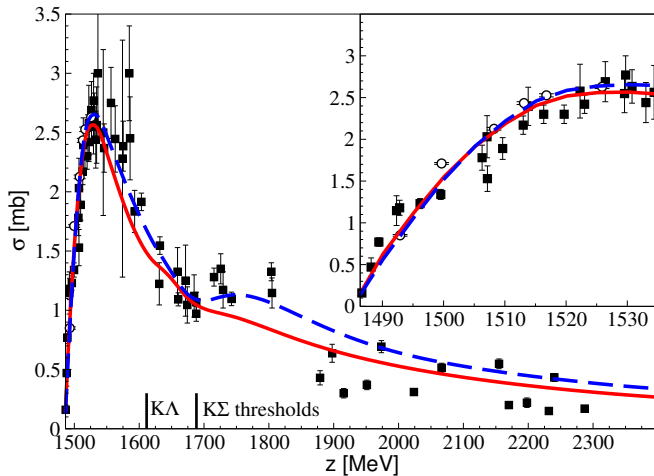
Full results η/N : $d\sigma/d\Omega$



Full results η/N : $d\sigma/d\Omega$ & Polarization

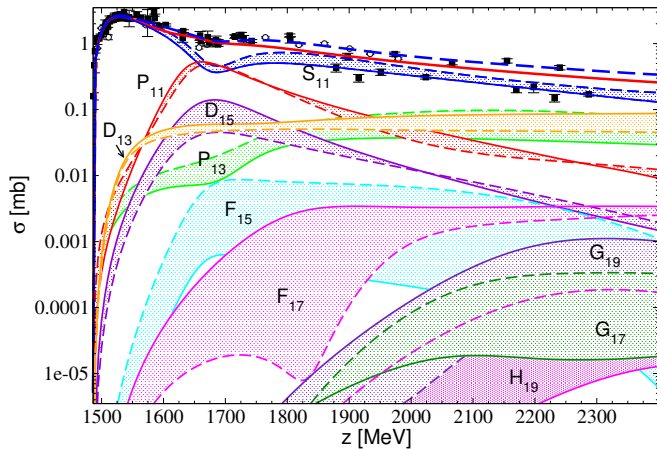


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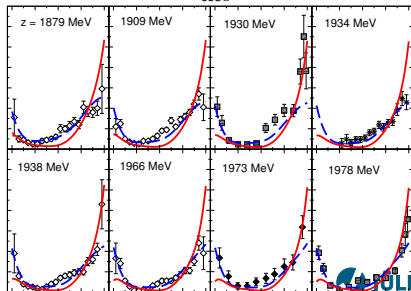
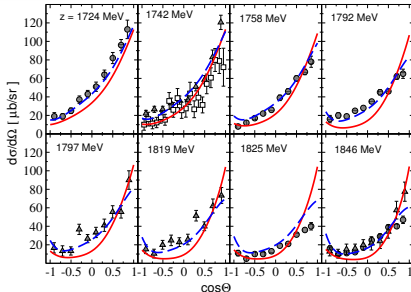
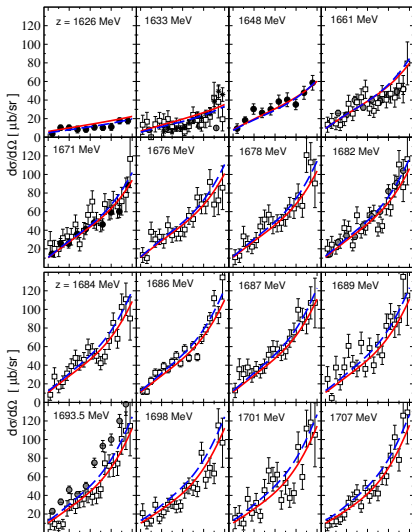
Partial wave content

ηN : Partial wave content



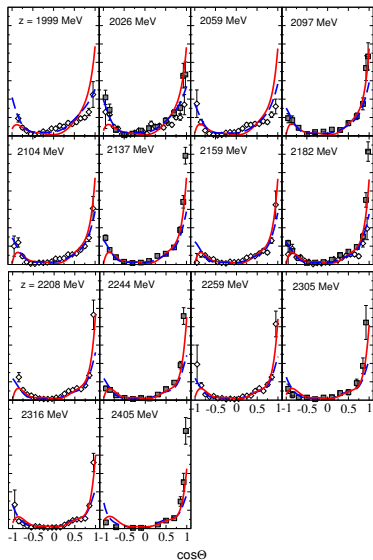
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Full results $K\Lambda$: $d\sigma/d\Omega$



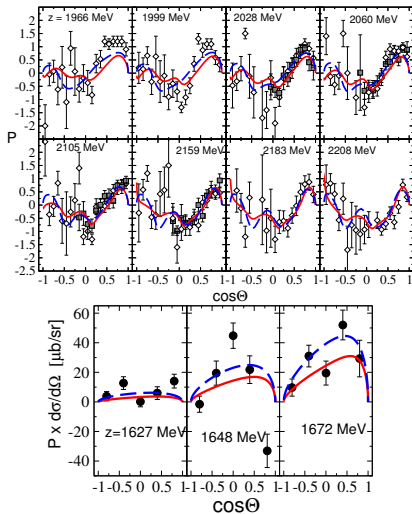
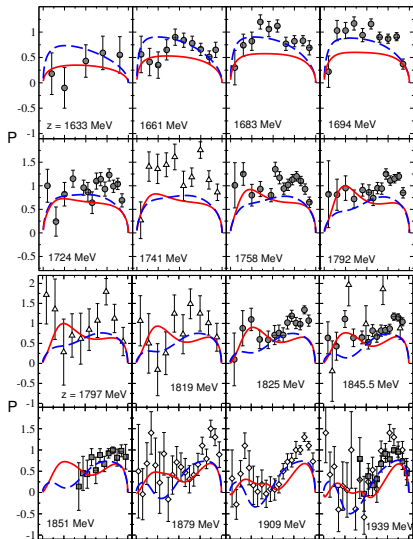
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Full results $K\Lambda$: $d\sigma/d\Omega$



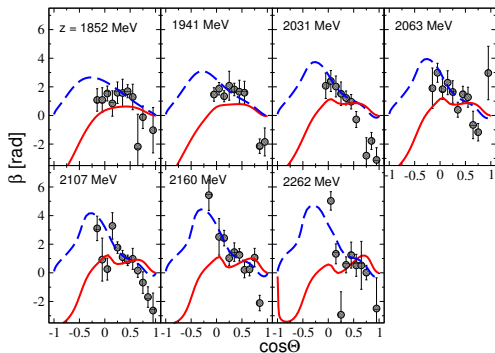
◀ back

Full results $K\Lambda$: Polarization



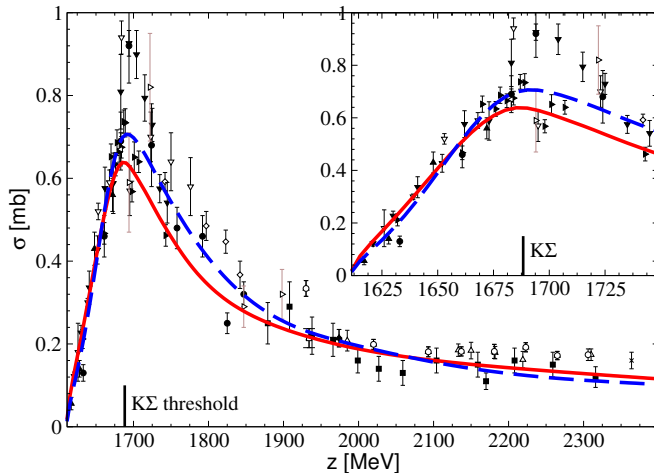
← back

Full results $K\Lambda$: Spinrotation parameter β

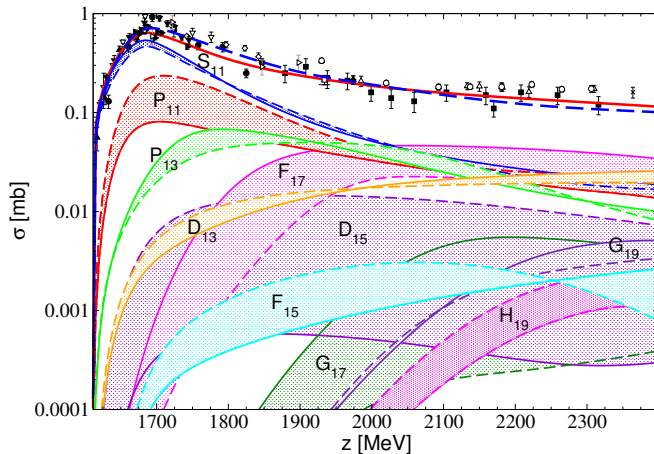


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$$\beta = \arctan \left(\frac{2\text{Im}(h_{fi}^* g_{fi})}{|g_{fi}|^2 - |h_{fi}|^2} \right)$$

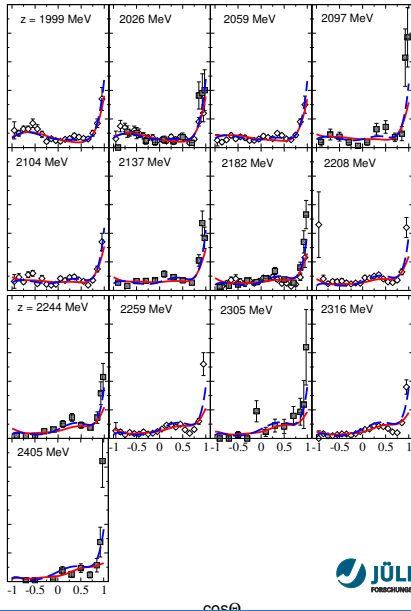
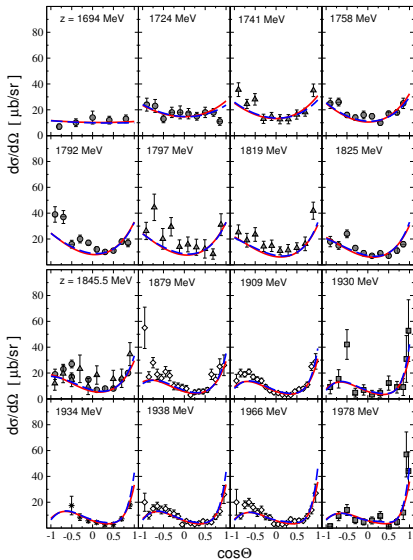
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$K\Lambda$: Partial wave content

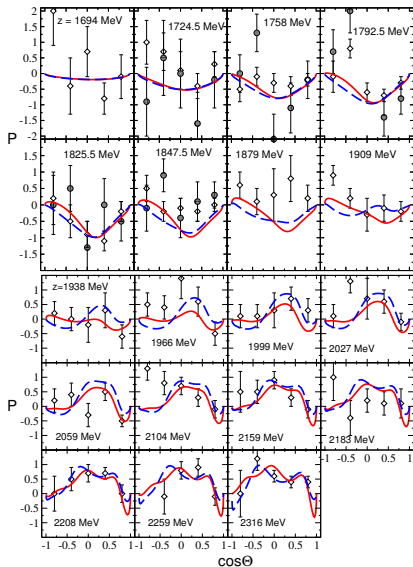


◀ back

Full results $K^0\Sigma^0$: $d\sigma/d\Omega$

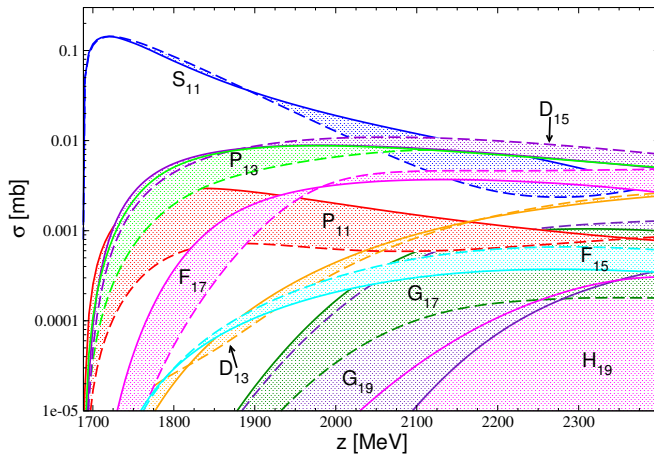


Full results $K^0\Sigma^0$: Polarization



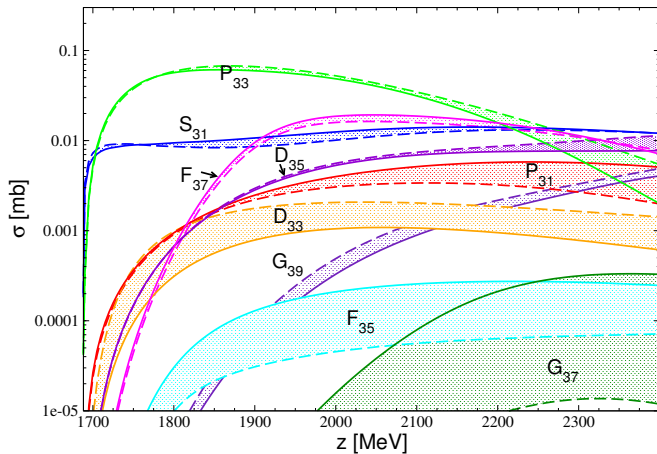
← back

$K^0\Sigma^0$: Partial wave content $l=1/2$



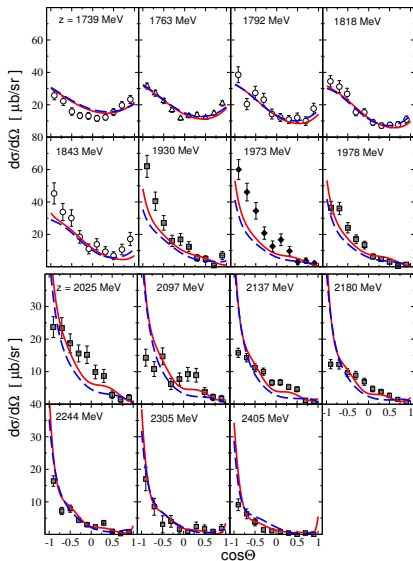
← back

$K^0\Sigma^0$: Partial wave content $l=3/2$



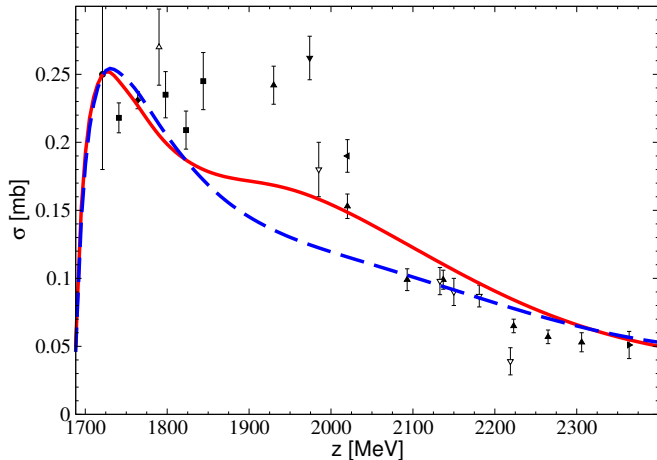
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Full results $K^+\Sigma^-$: $d\sigma/d\Omega$

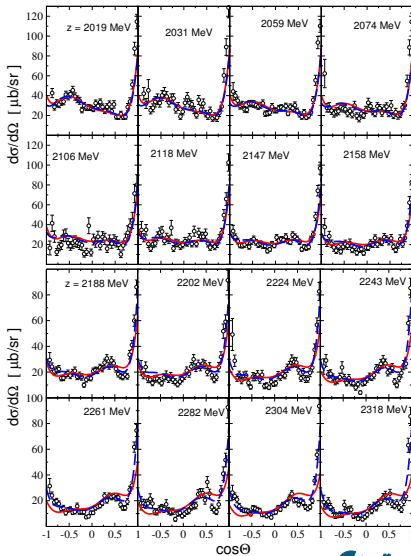
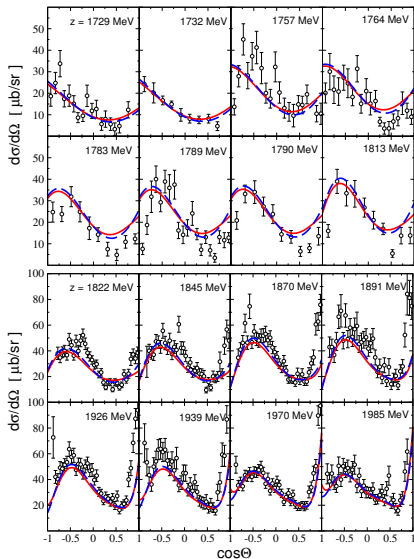


no Polarization data !

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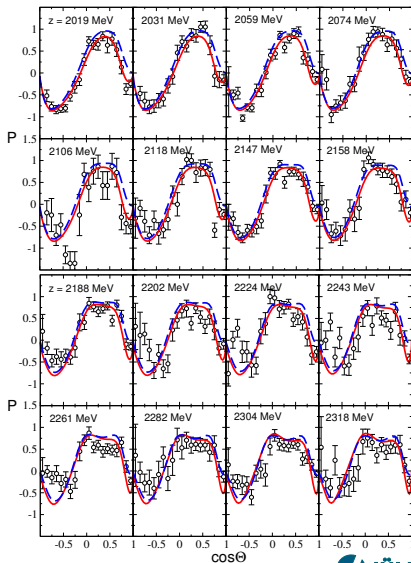
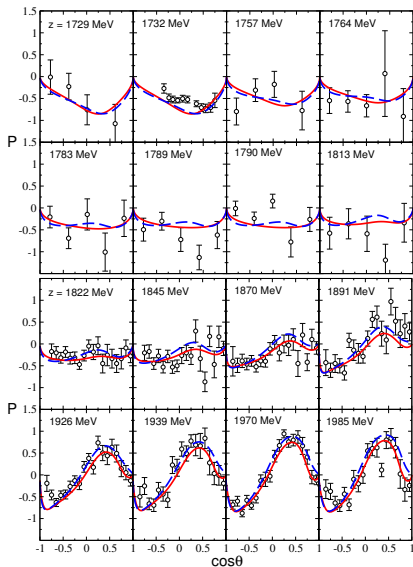
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Full results $K^+\Sigma^+$: $d\sigma/d\Omega$

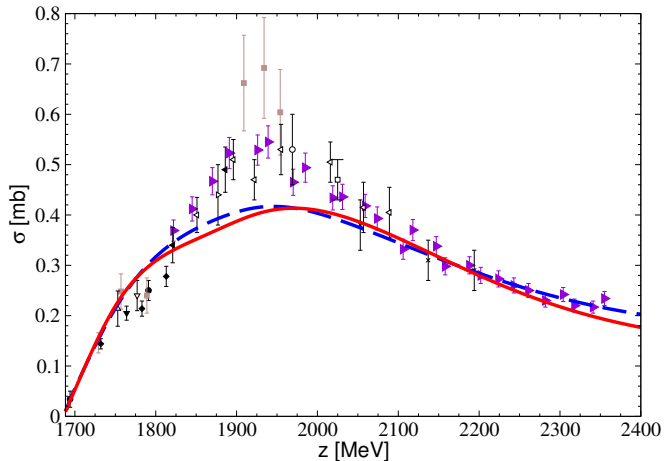


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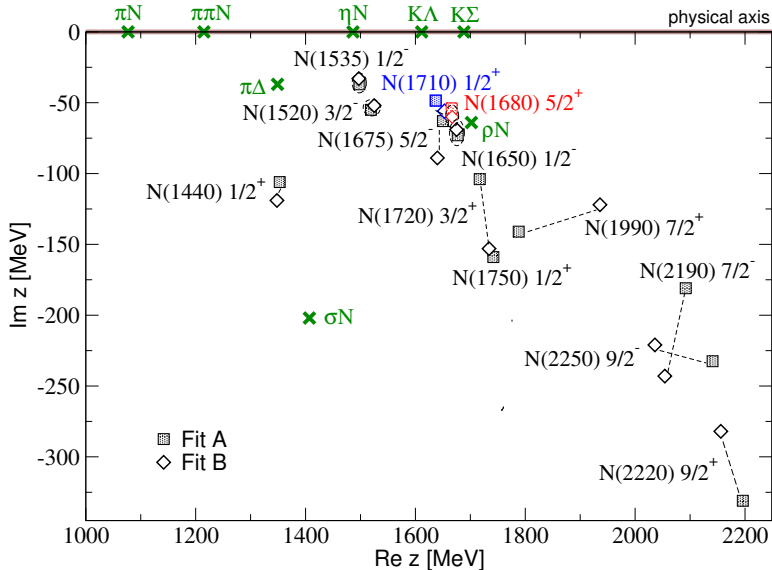
Full results $K^+\Sigma^+$: Polarization



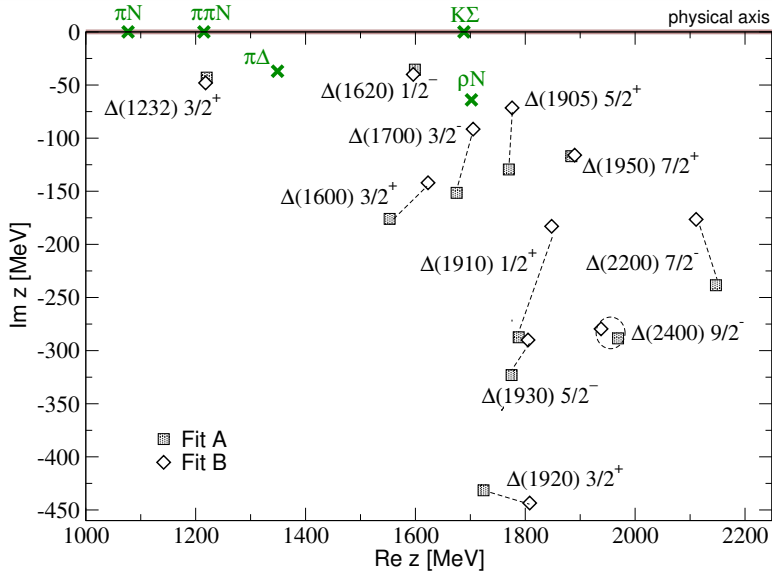
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Resonance content: $l=1/2$



Resonance content: $I=3/2$



Resonance content: $I = 1/2$

fit→	Re z_0		$-2\text{Im } z_0$		$ r_{\pi N} $		$\theta_{\pi N \rightarrow \pi N}$		$\Gamma_{\pi N}/\Gamma_{\text{tot}}$	
	[MeV]		[MeV]		[MeV]		[deg]		[%]	
	A	B	A	B	A	B	A	B	A	B
$N(1535) 1/2^-$	1498	1497	74	66	17	13	-37	-43	40	44
$N(1650) 1/2^-$	1677	1675	146	131	45	27	-43	-38	61	41
$N(1440) 1/2^+_{(a)}$	1353	1348	212	238	59	62	-103	-111	56	52
$N(1710) 1/2^+$	1637	1653	97	112	4	8	-30	34	8.2	14
$N(1750) 1/2^+_{(*,a)}$	1742	(nf)	318	-	8	-	161	-	5.1	-
$N(1720) 3/2^+$	1717	1734	208	306	7	18	-76	-23	6.6	11.6
$N(1520) 3/2^-$	1519	1525	110	104	42	36	-16	10	79	69
$N(1675) 5/2^-$	1650	1640	126	178	24	34	-19	-32	39	38
$N(1680) 5/2^+$	1666	1667	108	120	36	41	-24	-24	67	68
$N(1990) 7/2^+$	1788	1936	282	244	4	4	-84	-87	3.2	3.6
$N(2190) 7/2^-$	2092	2054	363	486	42	44	-31	-57	23	18
$N(2250) 9/2^-$	2141	2036	465	442	17	13	-67	-62	7.5	5.7
$N(2220) 9/2^+$	2196	2156	662	565	87	46	-67	-72	26	16

Resonance content: $I = 1/2$ Branching ratios

	$\frac{\Gamma_{\pi N}^{1/2} \Gamma_{\eta N}^{1/2}}{\Gamma_{\text{tot}}}$				$\frac{\Gamma_{\pi N}^{1/2} \Gamma_{K\Lambda}^{1/2}}{\Gamma_{\text{tot}}}$				$\frac{\Gamma_{\pi N}^{1/2} \Gamma_{K\Sigma}^{1/2}}{\Gamma_{\text{tot}}}$			
	[%]		[deg]		[%]		[deg]		[%]		[deg]	
	A	B	A	B	A	B	A	B	A	B	A	B
$N(1535) 1/2^-$	51	48	120	115	7.7	8.3	68	77	15	34	-74	-83
$N(1650) 1/2^-$	15	12	57	46	25	18	-46	-43	26	15	-63	-59
$N(1440) 1/2^+_{(a)}$	2	5	-40	-26	2	11	156	152	1	2	67	189
$N(1710) 1/2^+$	24	23	130	164	9.4	17	-83	-41	3.9	0.1	-136	-112
$N(1750) 1/2^+_{(*,a)}$	0.5	-	-140	-	0.8	-	-170	-	2.2	-	4	-
$N(1720) 3/2^+$	1.2	3.1	98	117	3.1	2.9	-89	-63	1.7	2.2	64	90
$N(1520) 3/2^-$	3.5	3.0	87	113	5.8	6.3	158	177	0.8	3.6	163	164
$N(1675) 5/2^-$	6.0	3.6	-40	-66	0.3	1.7	-93	-122	3.3	3.7	-168	179
$N(1680) 5/2^+$	0.4	1.5	-47	-54	0.2	0.3	-99	72	0.1	0.1	141	141
$N(1990) 7/2^+$	0.4	0.5	-99	90	1.7	1.5	-123	-99	0.8	1.2	28	70
$N(2190) 7/2^-$	0.1	0.4	-28	99	1.9	0.3	-51	-75	1.3	0.5	-63	-105
$N(2250) 9/2^-$	0.6	0.1	-92	-96	1.1	0.7	-103	-106	0.3	0.7	-114	62
$N(2220) 9/2^+$	0.1	0.3	63	74	0.9	0.8	53	59	0.8	0.1	-138	52

Resonance content: $I = 3/2$

fit→	Re z_0		-2Im z_0		$ r_{\pi N} $		$\theta_{\pi N \rightarrow \pi N}$	
	[MeV]		[MeV]		[MeV]		[deg]	
	A	B	A	B	A	B	A	B
$\Delta(1620) 1/2^-$	1599	1596	71	80	17	18	-107	-107
$\Delta(1910) 1/2^+$	1788	1848	575	376	56	20	-140	-143
$\Delta(1232) 3/2^+$	1220	1218	86	96	44	50	-35	-38
$\Delta(1600) 3/2^+_{(a)}$	1553	1623	352	284	20	27	-158	-124
[$\Delta(1920) 3/2^+$	1724	1808	863	887	36	19	163	-70]
$\Delta(1700) 3/2^-$	1675	1705	303	185	24	14	-9	-4
$\Delta(1930) 5/2^-$	1775	1805	646	580	18	14	-159	3
$\Delta(1905) 5/2^+$	1770	1776	259	143	17	9	-59	-40
$\Delta(1950) 7/2^+$	1884	1890	234	232	58	58	-25	-19
$\Delta(2200) 7/2^-$	2147	2111	477	353	17	20	-52	7
$\Delta(2400) 9/2^-$	1969	1938	577	559	25	19	-80	-112

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Resonance content: $I = 3/2$ Branching ratios

fit→	$\Gamma_{\pi N}/\Gamma_{\text{tot}}$		$\frac{\Gamma_{\pi N}^{1/2}\Gamma_{K\Sigma}^{1/2}}{\Gamma_{\text{tot}}}$		$\theta_{\pi N \rightarrow K\Sigma}$	
	[%]		[%]		[deg]	
	A	B	A	B	A	B
$\Delta(1620) 1/2^-$	48	45	22	24	-107	-107
$\Delta(1910) 1/2^+$	20	10	4.7	1.9	-144	-115
$\Delta(1232) 3/2^+$	100	100				
$\Delta(1600) 3/2^+_{(a)}$	11	19	11	13	-7	41
$[\Delta(1920) 3/2^+]$	8.3	4.3	16	14	-20	50
$\Delta(1700) 3/2^-$	16	16	1.5	1.6	-150	-121
$\Delta(1930) 5/2^-$	5.6	4.8	3.1	1.7	-3	135
$\Delta(1905) 5/2^+$	13	12	0.5	0.1	-142	-99
$\Delta(1950) 7/2^+$	50	50	4.0	3.8	-78	-71
$\Delta(2200) 7/2^-$	7.2	11	0.6	0.1	-98	-33
$\Delta(2400) 9/2^-$	8.7	5.7	1.3	0.8	40	6

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