

An aerial photograph of a university campus, likely the University of Tennessee, showing various academic buildings, a large white domed structure, and green spaces. The image is overlaid with a blue bokeh effect.

Spectroscopy of light baryons

Andrey Sarantsev

Search for light baryon states

1. Single and double meson production in pion-induced reactions:

The old data on $\pi N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ and HADES data on $\pi^- p \rightarrow \pi\pi N$

2. Single and double meson photoproduction reactions.

$\gamma p \rightarrow \pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N, \pi\eta N, \omega p, K^*\Lambda,$

$\gamma n \rightarrow \pi N, \eta N, K\Lambda, K\Sigma,$

CB-ELSA, CLAS, MAMI, GRAAL, LEPS.

3. The decay of the heavy meson and baryon states $\Psi' \rightarrow \pi^0 p\bar{p}, \eta p\bar{p}$ (BES III),

$\Lambda_b \rightarrow J/\Psi K p, \Lambda_b \rightarrow \gamma K p$ (LHCb).

4. The hyperon production in the kaon-nucleon collision reactions

$K^- p \rightarrow K^- p, K_0 n, \pi\Lambda, \pi\Sigma, \pi\pi\Lambda, \pi\pi\Sigma, K\pi N$

Meson Photoproduction experiments

- ▶ **GRAAL (Grenoble):** Polarized beam. Ideal for the beam asymmetry and double polarization observables for hyperon final states.
 $\gamma p \rightarrow \pi^0 p, \eta p, K\Lambda, K\Sigma, \pi^0 \pi^0 p, \pi^0 \eta p, \omega p, \gamma n \rightarrow \pi^0 n, \eta n.$
- ▶ **CLAS (JLAB):** High statistic, very good detector of charged particles:
 $\gamma p \rightarrow \pi^- n, K\Lambda, K\Sigma, \pi^+ \pi^- p, \omega p.$ As missing mass data $\gamma p \rightarrow \pi^0 p, \eta p.$
Data on deuterium target. Energy is up to $W=2.5$ GeV.
Analysis: EBAC, SAID and recently Bonn-Gatchina.
- ▶ **MAMI (Mainz):** High statistic, very good detector of neutral particles: (Crystal Ball):
 $\gamma p \rightarrow \pi^0 p, K\Lambda, K\Sigma, \pi^0 \pi^0 p, \pi^0 \eta p, \gamma n \rightarrow \eta n, \pi^0 n, \pi^0 \pi^0 n, \pi^0 \eta n.$
Energy is only up to $W=1.85$ GeV. Analysis: MAID and Bonn-Gatchina.
- ▶ **CB-ELSA (Bonn):** Moderate statistic, very good detector of neutral particles: (Crystal Barrel): $\gamma p \rightarrow \pi^0 p, \eta p, \pi^0 \pi^0 p, \pi^0 \eta p, \omega p, \gamma n \rightarrow \eta n, \pi^0 n.$ Energy is up to $W=2.3$ GeV. Analysis: Bonn-Gatchina.
- ▶ **Independent analysis groups:** Jülich (M.Doering), OSAKA (T. Sato), Giessen (V. Shklyar), M. Manley (Kent Uni)

- For the full reconstruction of the amplitude it is necessary to measure **8 observables.**
- Single polarization data are available Σ, T
- Double polarization data are available E, G, H, F, P .
- For the production of the Λ and Σ hyperons all observables can be measured.

Photon		Target			Recoil			Target + Recoil			
	—	—	—	—	x'	y'	z'	x'	x'	z'	z'
	—	x	y	z	—	—	—	x	z	x	z
unpol.	σ_0	0	T	0	0	P	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
lin.pol.	$-\Sigma$	H	$-P$	$-G$	$O_{x'}$	$-T$	$O_{z'}$	$-L_{z'}$	$T_{z'}$	$-L_{x'}$	$-T_{x'}$
circ.pol.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

Bonn-Gatchina partial wave analysis group:
E. Klempt, K. Nikonov, A. Sarantsev, U. Thoma.

<http://pwa.hiskp.uni-bonn.de/>



Bonn-Gatchina Partial Wave Analysis



Address: Nussallee 14-16, D-53115 Bonn Fax: (149) 228 / 73-2505

[Data Base](#)

[Meson Spectroscopy](#)

[Baryon Spectroscopy](#)

[NN-interaction](#)

[Formalism](#)

Analysis of Other Groups

- [SAID](#)
- [MAID](#)
- [Giessen Uni](#)

BG PWA

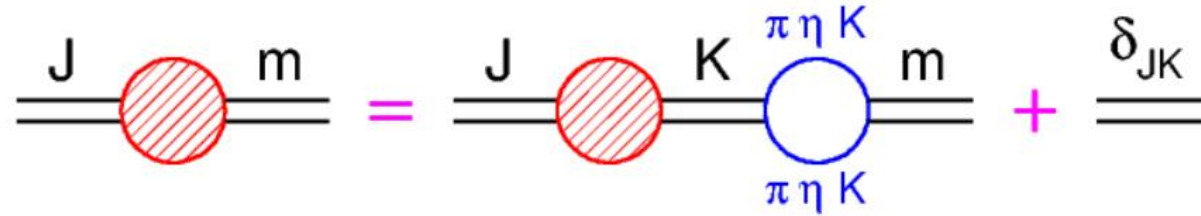
- [Publications](#)
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Useful Links

- [SPIRES](#)
- [PDG Homepage](#)
- [Durham Data Base](#)
- [Bonn Homepage](#)

[CB-ELSA Homepage](#)

N/D based (D-matrix) analysis of the data



$$D_{jm} = D_{jk} \sum_{\alpha} B_{\alpha}^{km}(s) \frac{1}{M_m - s} + \frac{\delta_{jm}}{M_j^2 - s} \quad \hat{D} = \hat{\kappa}(I - \hat{B}\hat{\kappa})^{-1}$$

$$\hat{\kappa} = \text{diag} \left(\frac{1}{M_1^2 - s}, \frac{1}{M_2^2 - s}, \dots, \frac{1}{M_N^2 - s}, R_1, R_2 \dots \right)$$

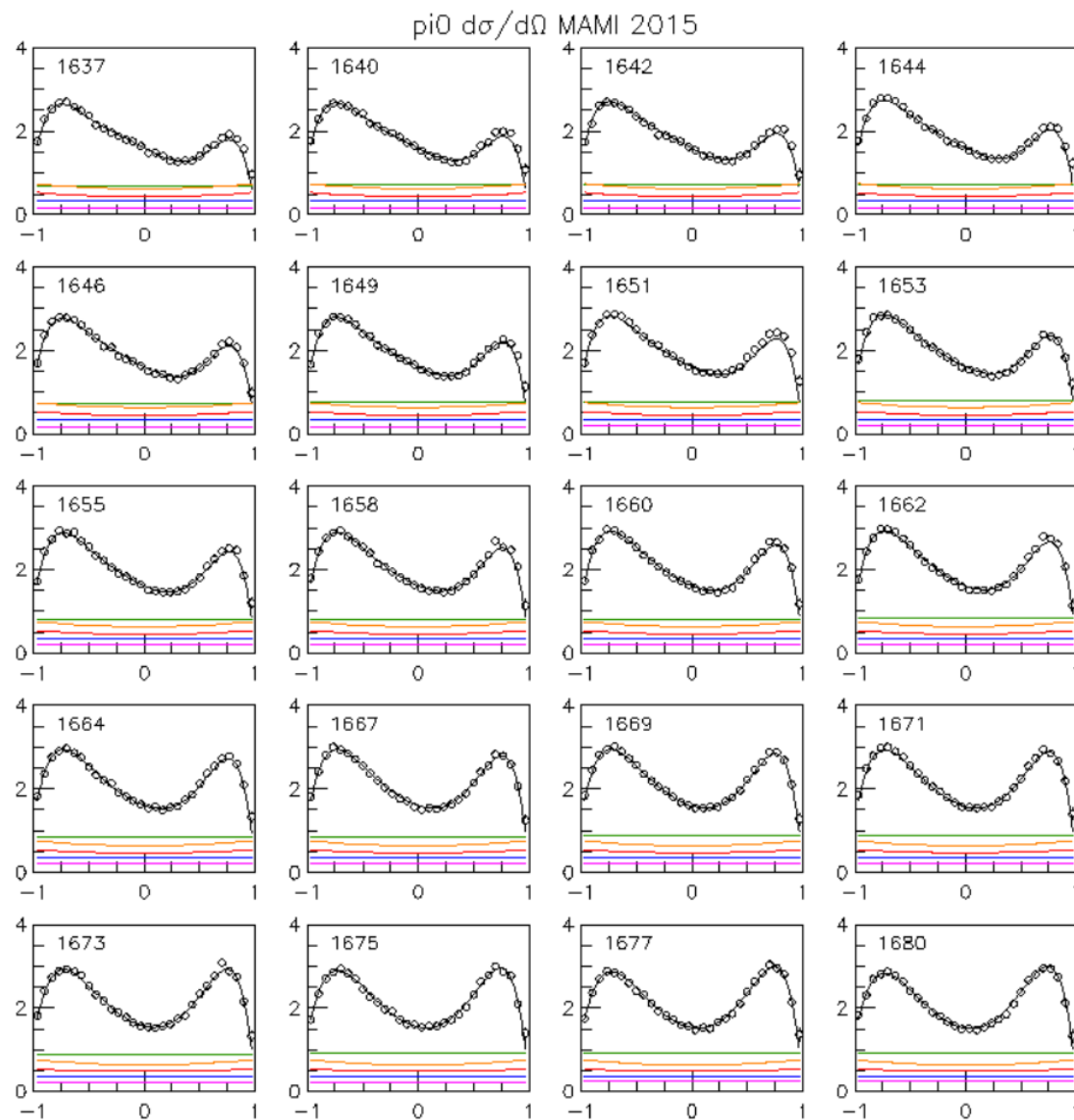
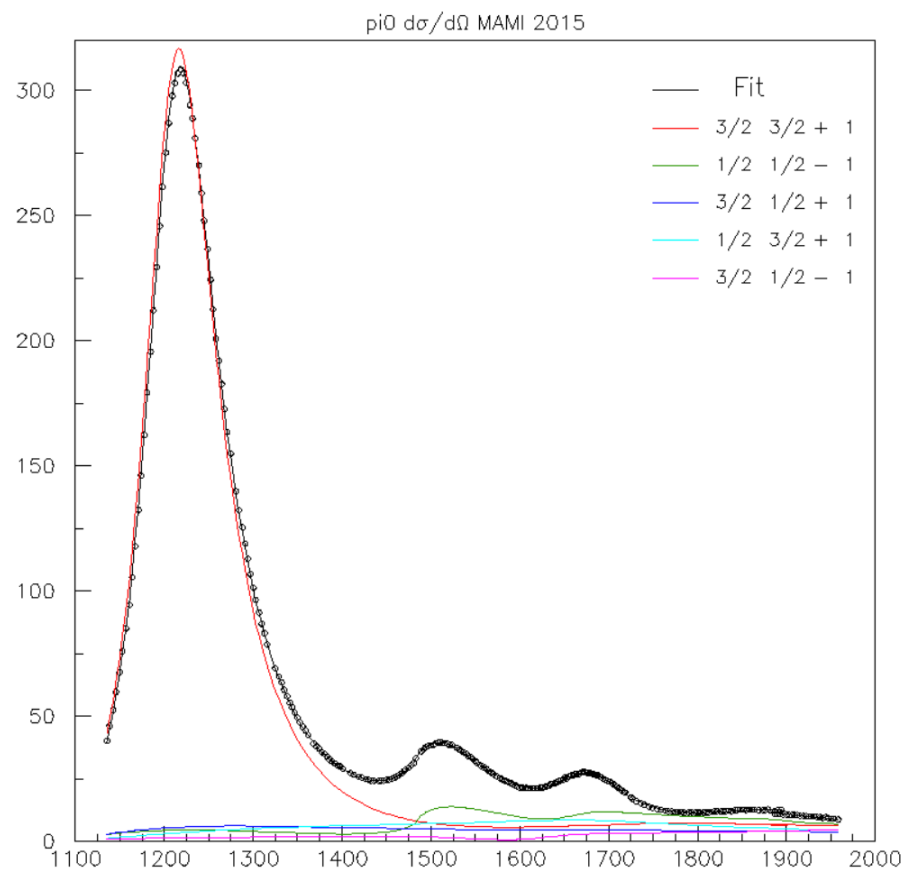
$$\hat{B}_{ij} = \sum_{\alpha} B_{\alpha}^{ij} = \sum_{\alpha} \int \frac{ds'}{\pi} \frac{g_{\alpha}^{(R)i} \rho_{\alpha}(s', m_{1\alpha}, m_{2\alpha}) g_{\alpha}^{(L)j}}{s' - s - i0}$$

Channels included in D-matrix: $\pi N, \eta N, K\Lambda, K\Sigma, \Delta\pi, N\sigma, N\rho(770), N(1520)\pi,$
 $N(1535)\pi, N\omega$, **Black Box**

Data Base of the Bonn-Gatchina analysis

DATA	2011-2022	added in 2024-2026
$\pi N \rightarrow \pi N$ ampl. $\pi^- p \rightarrow \pi \pi N$ $\pi^- p \rightarrow \eta n$ $\pi p \rightarrow K \Lambda, K \Sigma$ $\pi p \rightarrow \omega n$	SAID or Hoehler (energy fixed) $d\sigma/d\Omega$ ($\pi^0 \pi^0 n, \pi^+ \pi^- n, \pi^- \pi^0 p$) $d\sigma/d\Omega$ $d\sigma/d\Omega, P, \beta$ $d\sigma/d\Omega$	
$\gamma p \rightarrow \pi N$ $\gamma p \rightarrow \eta p$ $\gamma p \rightarrow \eta' p$	$d\sigma/d\Omega, \Sigma, T, P, E, G, H$ ($\pi^0 p, \pi^+ n$) $d\sigma/d\Omega, \Sigma, F, T, P, H, G, E$ $d\sigma/d\Omega, \Sigma$	$d\sigma/d\Omega, \Sigma$ (BGOegg)
$\gamma p \rightarrow K \Lambda$ $\gamma p \rightarrow K^0 \Sigma^+$ $\gamma p \rightarrow K^+ \Sigma^0$	$d\sigma/d\Omega, \Sigma, P, T, C_x, C_z, O_{x'}, O_{z'}, T_x, T_z$ $d\sigma/d\Omega, \Sigma, P$ (ELSA) P (CLAS) $d\sigma/d\Omega, \Sigma, P, T, C_x, C_z, O_{x'}, O_{z'}, T_x, T_z$	C_x, C_z (CLAS) $d\sigma/d\Omega, P, E$ (CLAS)
$\gamma p \rightarrow \pi^0 \pi^0 p$ $\gamma p \rightarrow \pi^+ \pi^- p$	$d\sigma/d\Omega, \Sigma, E, I_c, I_s, T, P, H, F$ $d\sigma/d\Omega I_c, I_s$	$I_c, I_s, P_x, P_y, P_{xs}, P_{ys}, P_{xc}, P_{yc}$ $d\sigma/d\Omega I_c, I_s, P_x, P_y$ (CLAS)
$\gamma p \rightarrow \omega p$	$d\sigma/d\Omega, \Sigma, \rho_{ij}^k, E, G$ (CB-ELSA), Σ, P, T, F, H (CLAS)	
$\gamma n \rightarrow \Lambda K, \Sigma^- K$ $\gamma n \rightarrow \pi^- p$ $\gamma n \rightarrow \eta n$ $\gamma n \rightarrow \pi^0 n$	$d\sigma/d\Omega$ (CLAS), E, Σ, G (CLAS) $d\sigma/d\Omega, \Sigma, P, E, \Sigma$ (CLAS) $d\sigma/d\Omega$ (CB-ELSA, MAMI), $\Sigma, d\sigma/d\Omega$ ($h = \frac{1}{2}$) (CB-ELSA) $d\sigma/d\Omega$	P, T, H (CB-ELSA)

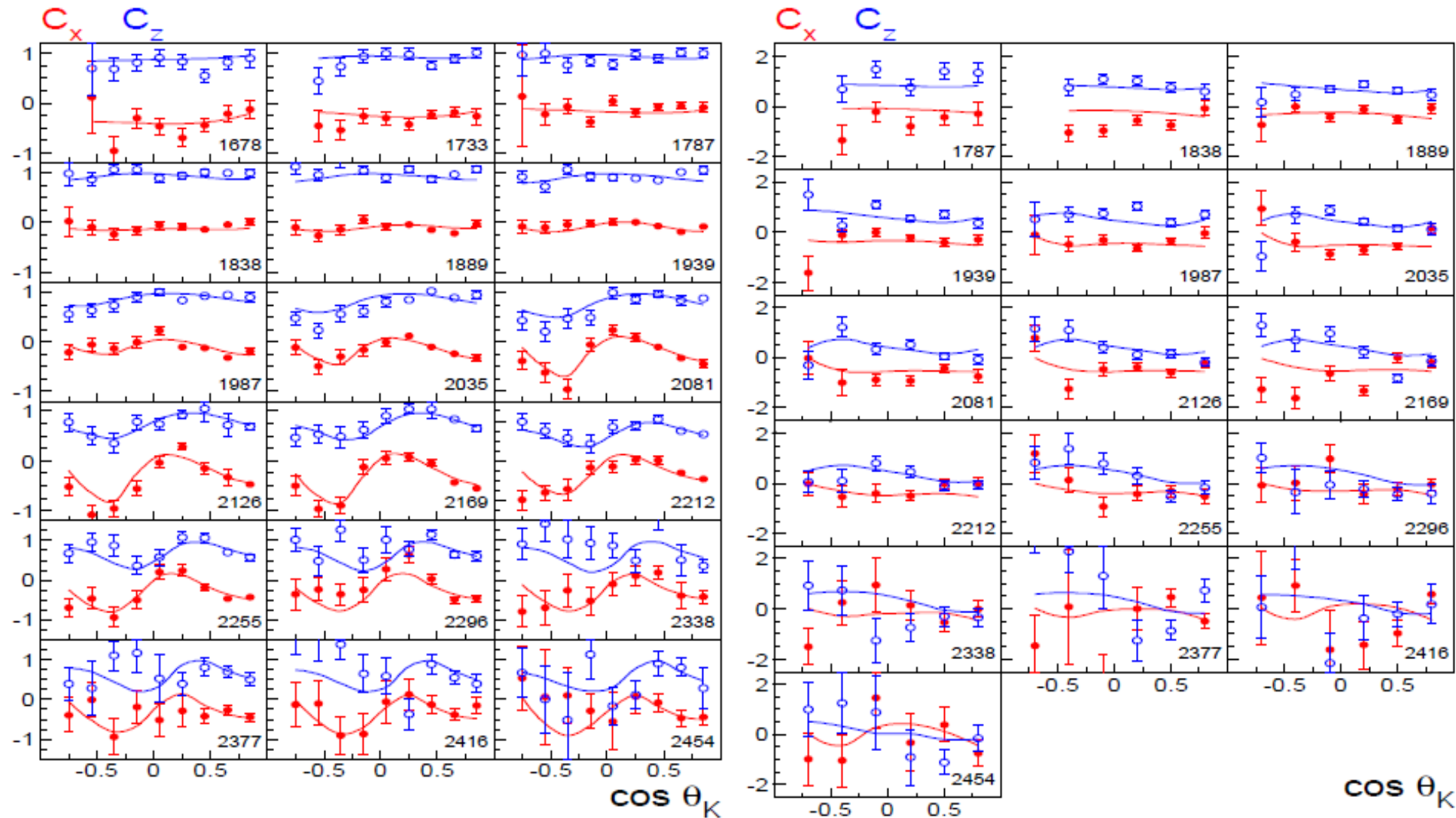
Photo-production of pion $\gamma N \rightarrow \pi^0 N$



For $\gamma p \rightarrow K\Lambda$ and $\gamma p \rightarrow K\Sigma$ we have almost complete photoproduction experiment:

σ (CLAS, SAPHIR), Σ (GRAAL, LEP), P (CLAS), C_x, C_z (CLAS), T, O_x, O_z (GRAAL).

The C_x and C_z data can be explained with $P_{13}(1900)$.



New data on C_x and C_z for $\gamma \pi \rightarrow K^+ \Lambda$

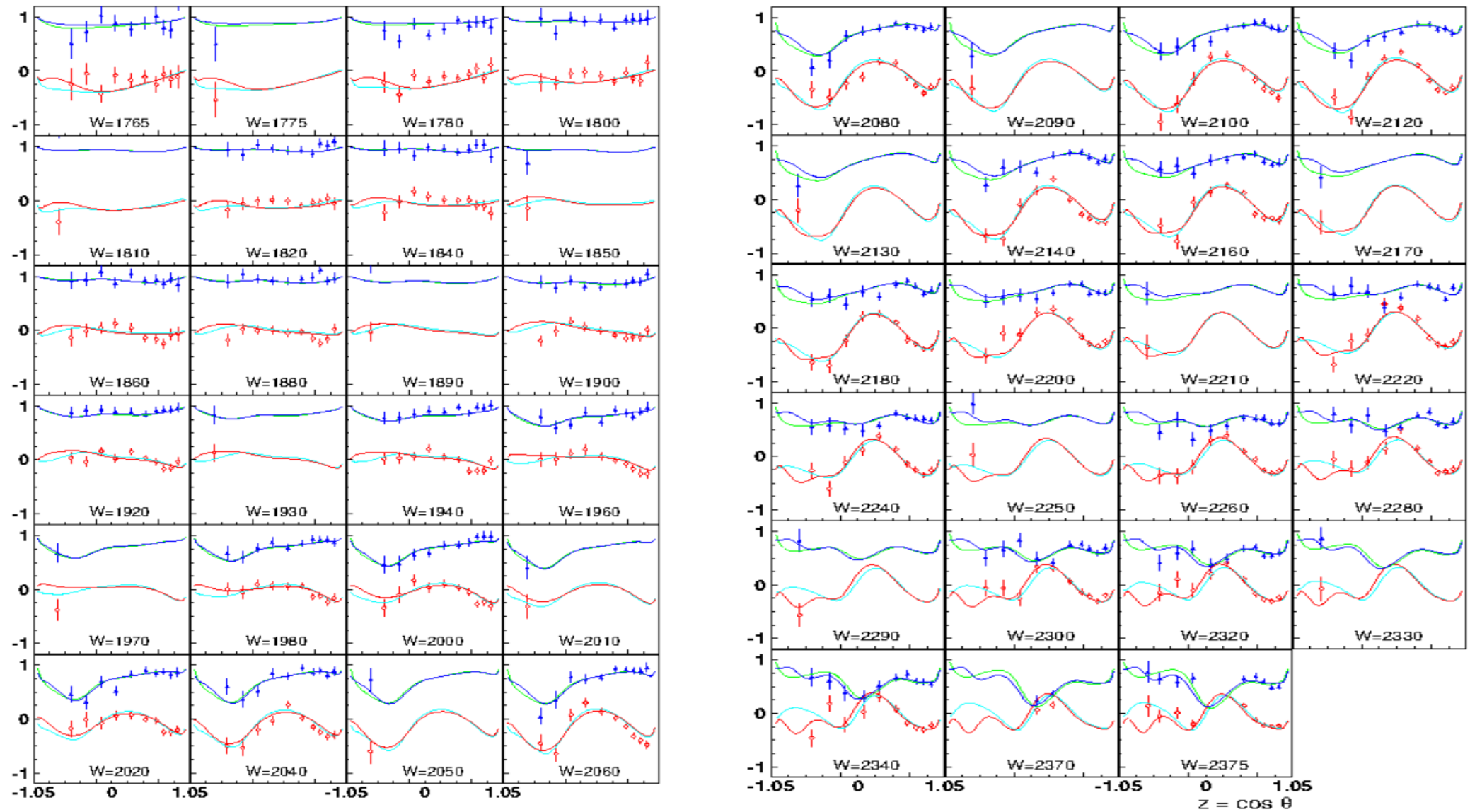
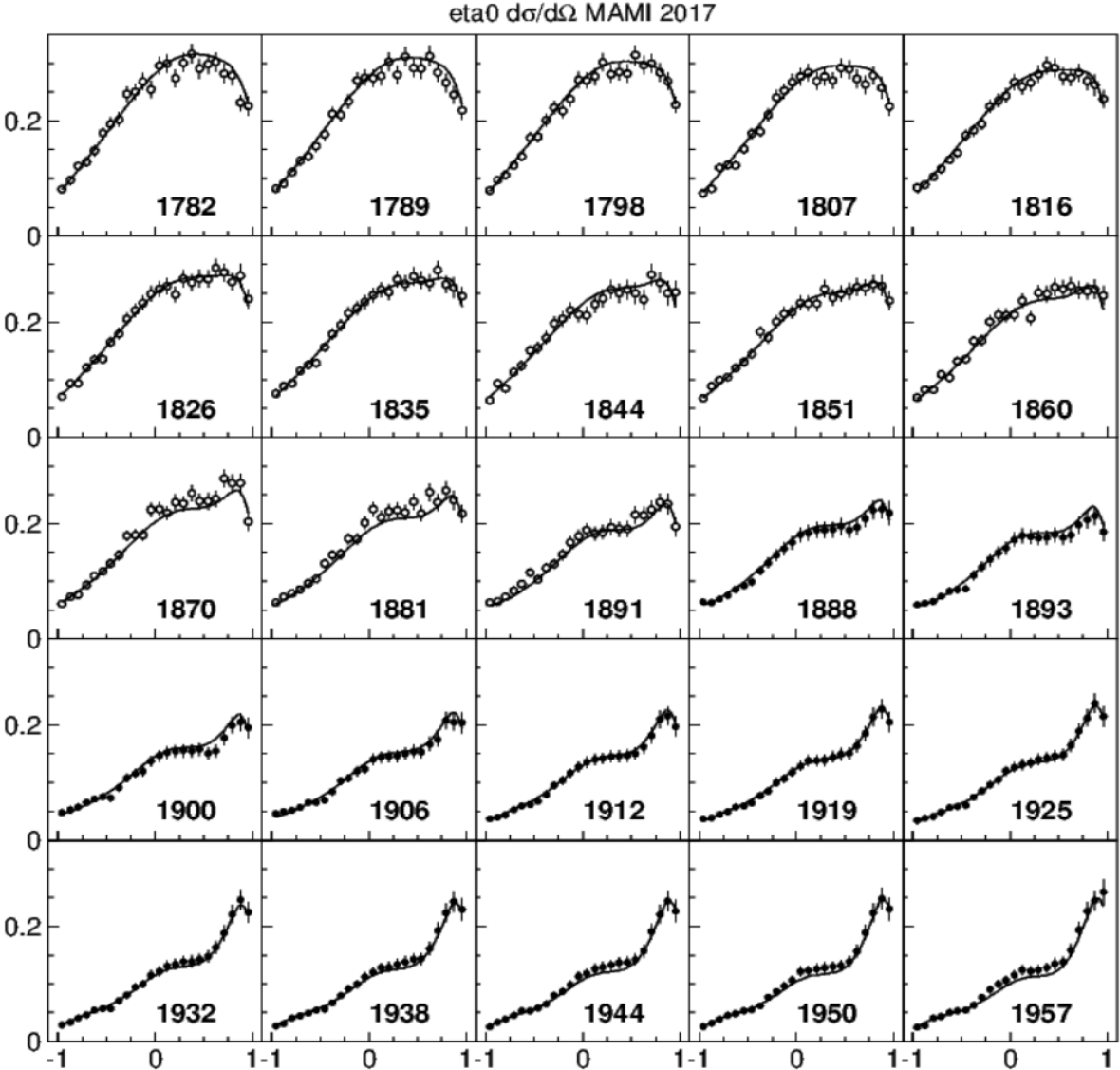
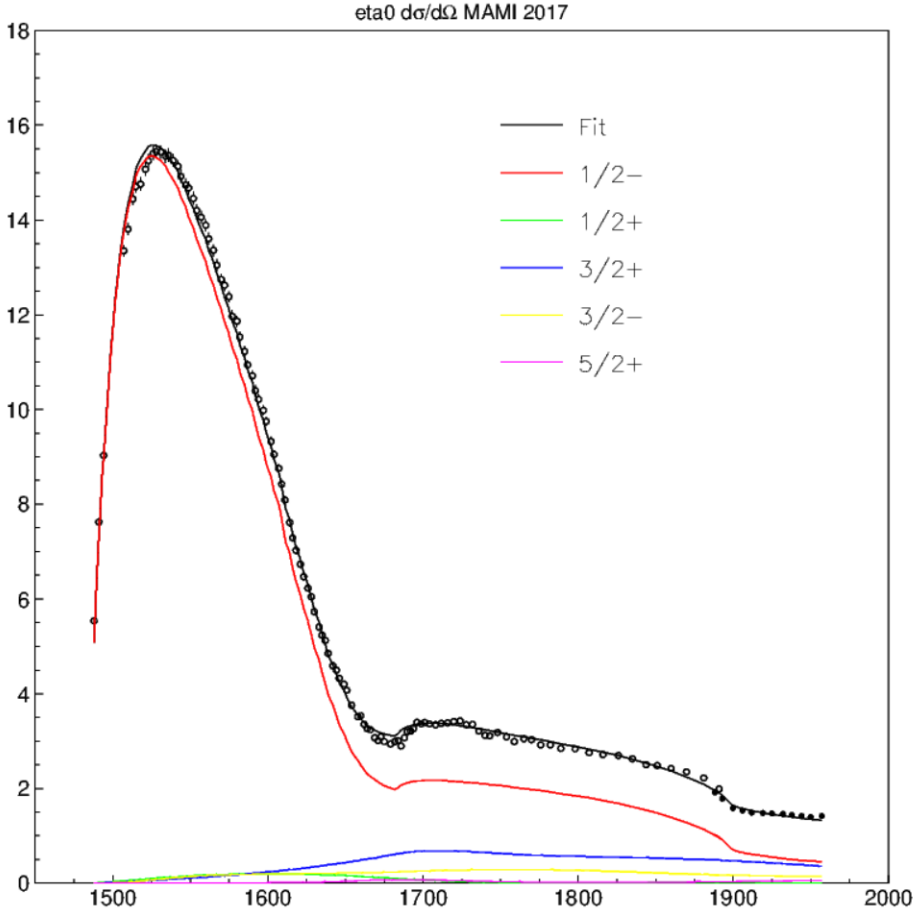
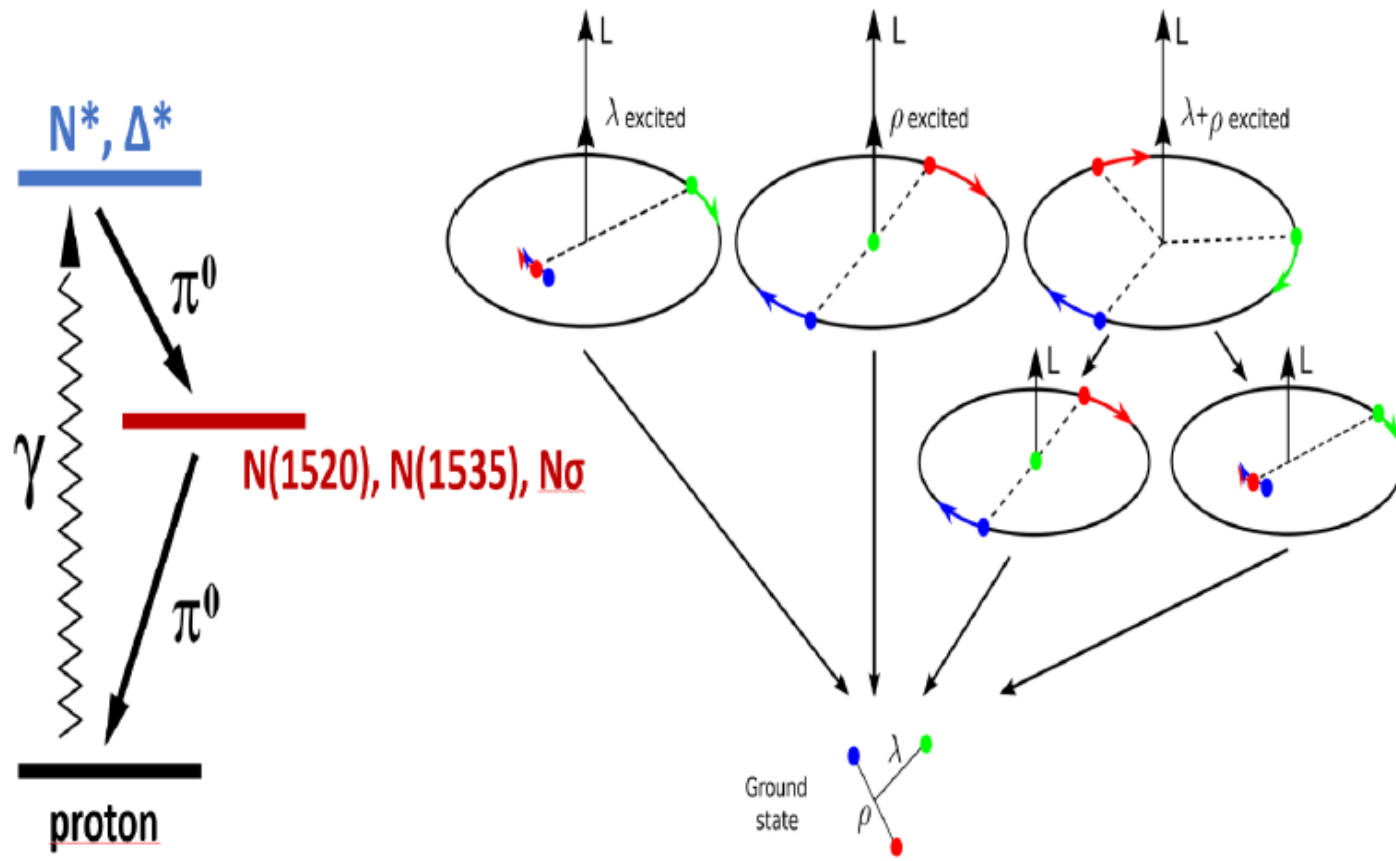


Photo-production of pion $\gamma N \rightarrow \eta N$



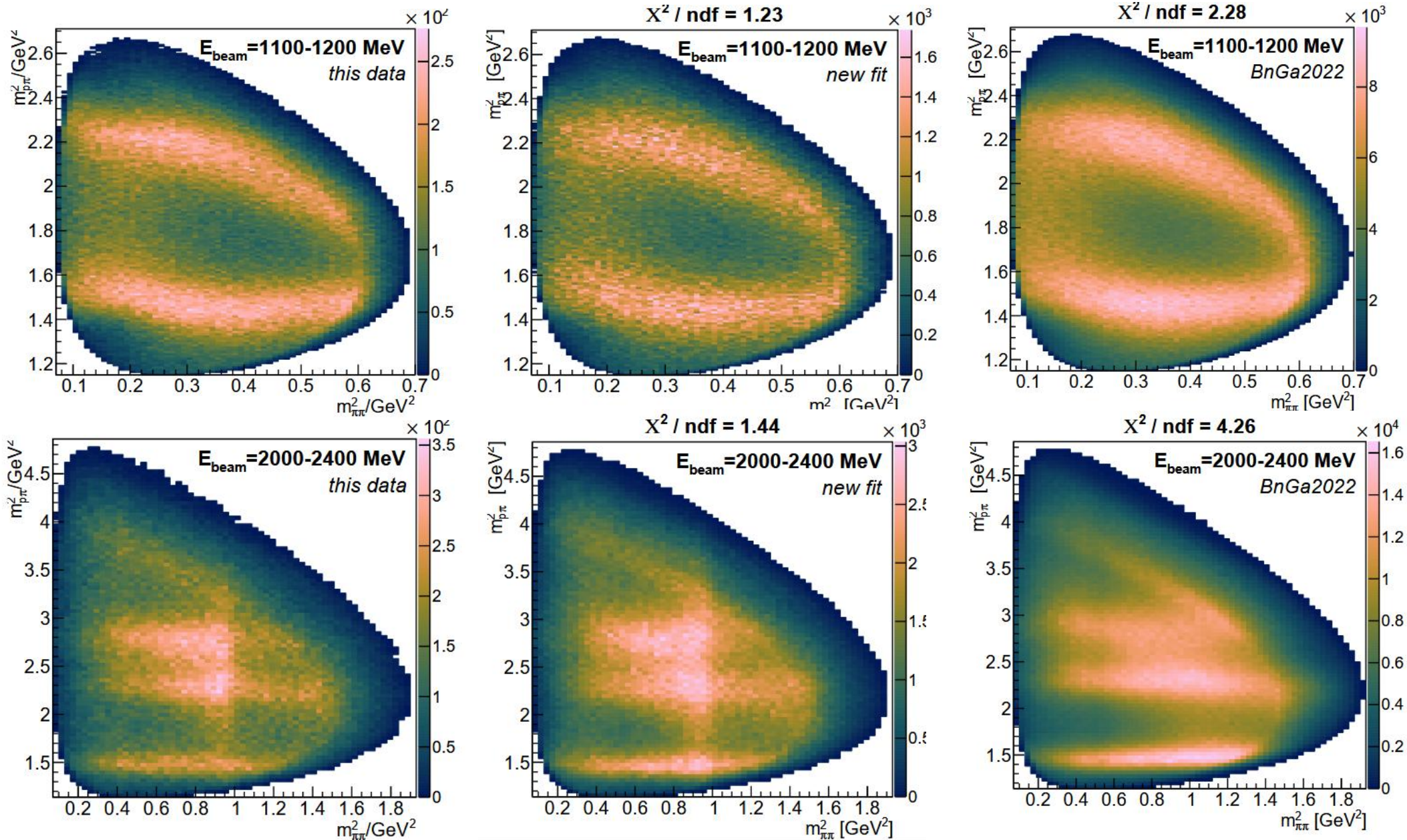
The decay to multi-meson channel can provide important information about nature of the observed states



The decay modes in $\pi\pi p$ channels:

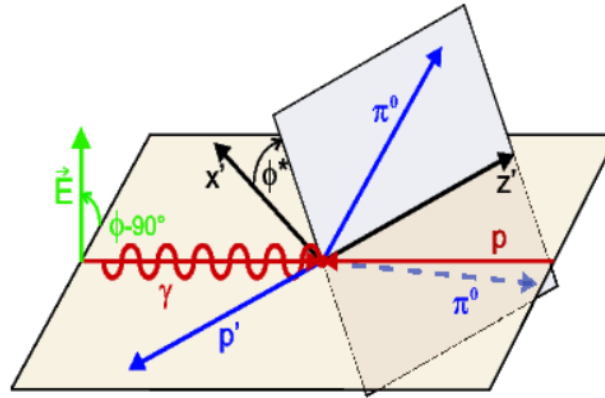
$\Delta(1232)\pi$	$Nf_0(500)$
$N(1440)\pi$	
$N(1520)\pi$	$N\rho(770)$
$N(1535)\pi$	$Nf_0(980)$
$N(1685)\pi$	$Nf_2(1275)$
$N(1710)\pi$	
$N(1720)\pi$	

Analysis of the high statistical data on $\gamma p \rightarrow \pi^0 \pi^0 p$



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

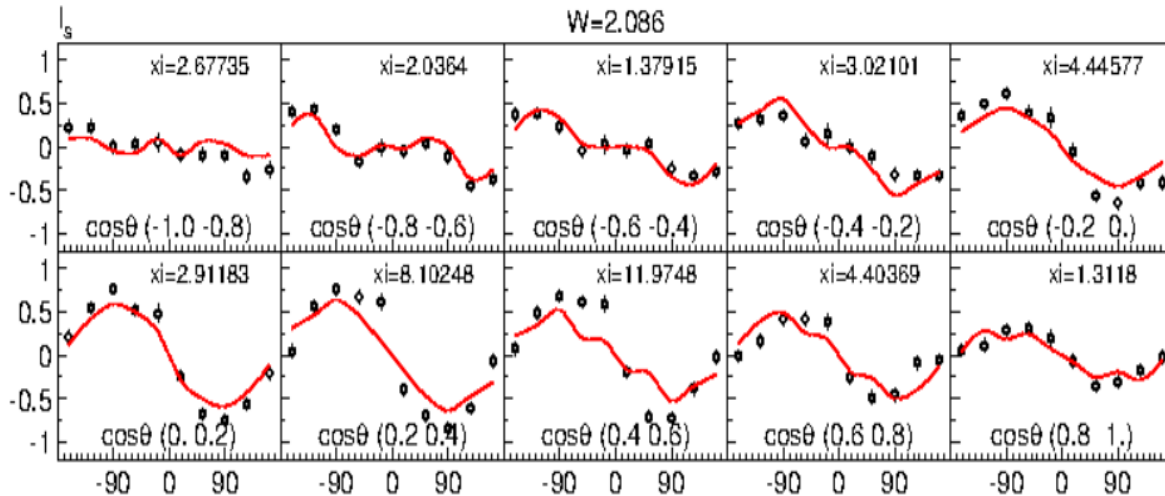
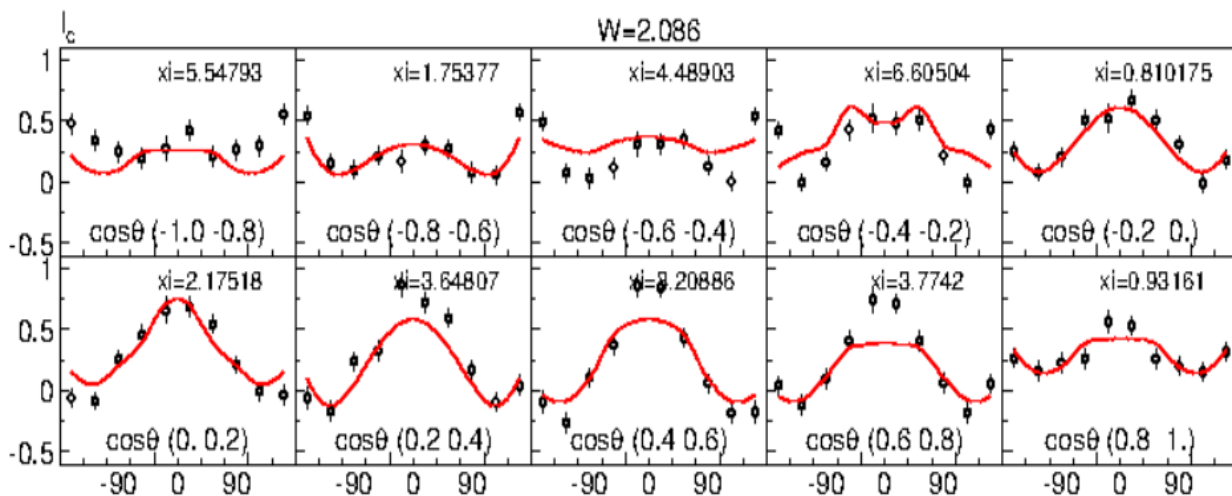
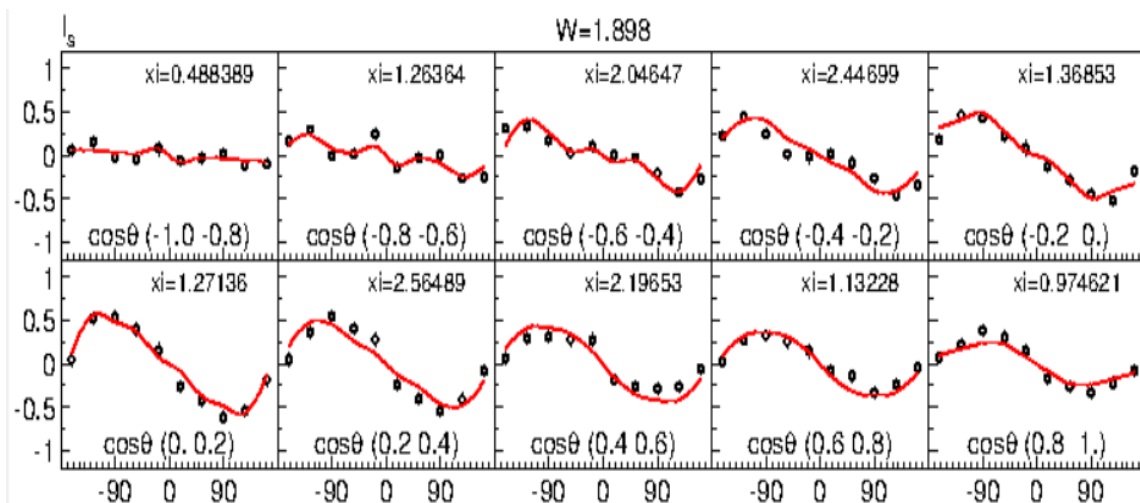
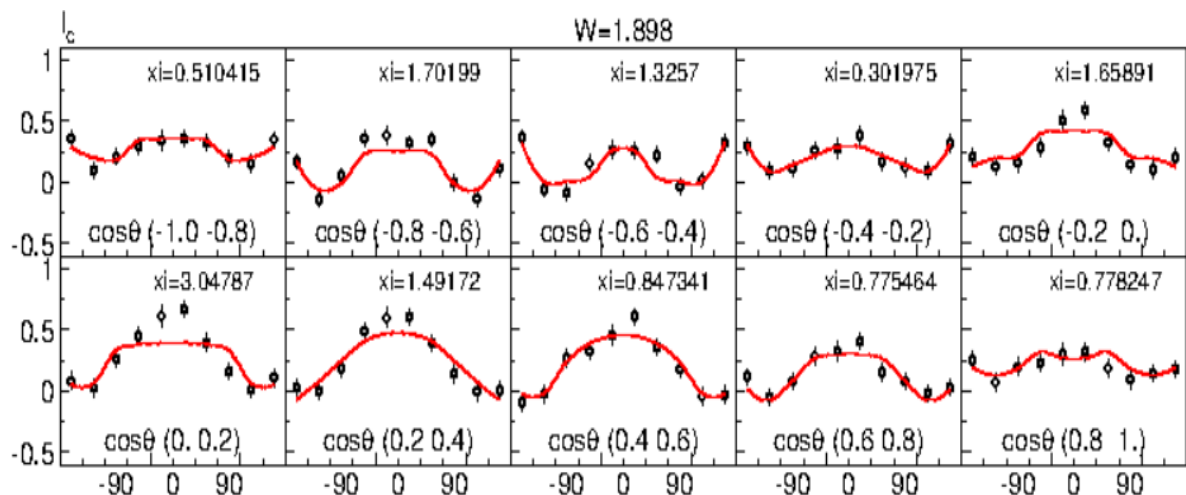
$$\frac{d\sigma}{d\Omega}(\Theta, \varphi) = \frac{d\sigma_0}{d\Omega}(\Theta) [1 - \Sigma(\Theta) \cos(2\varphi) - \Lambda_x H(\Theta) \sin(2\phi) - \Lambda_y P(\Theta) \cos(2\varphi) + \Lambda_y T(\Theta)]$$



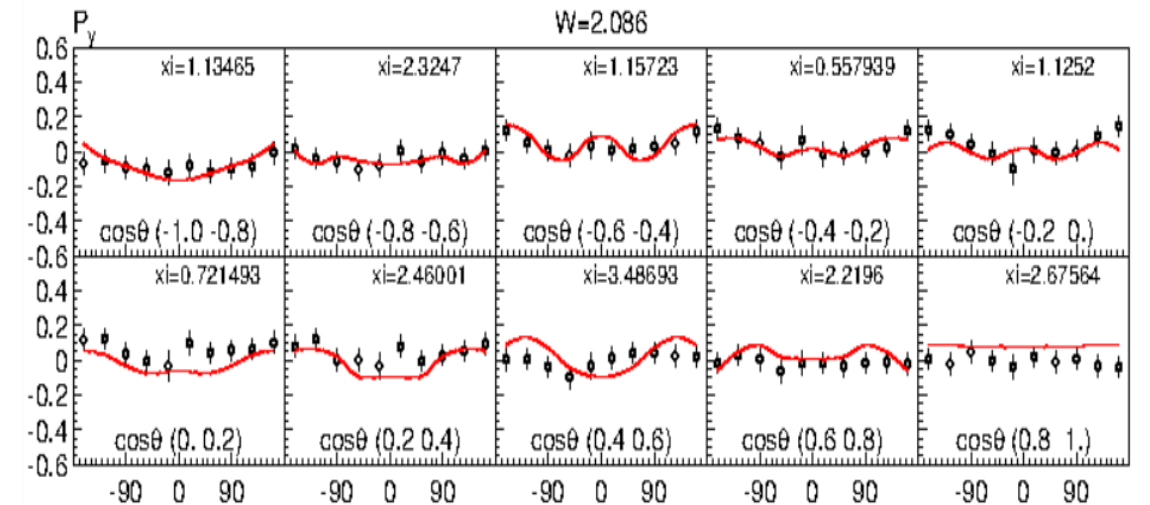
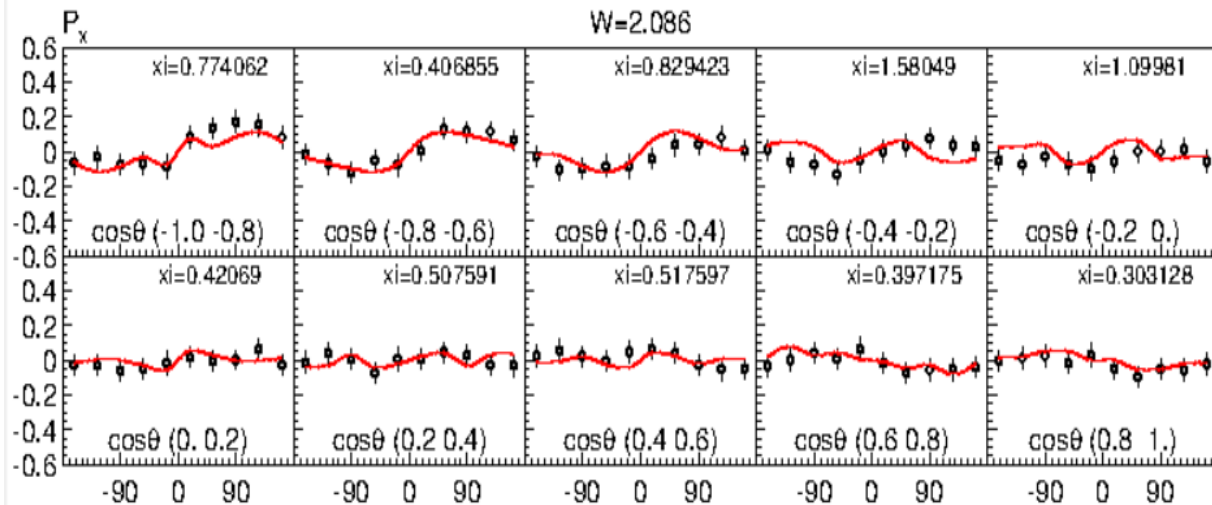
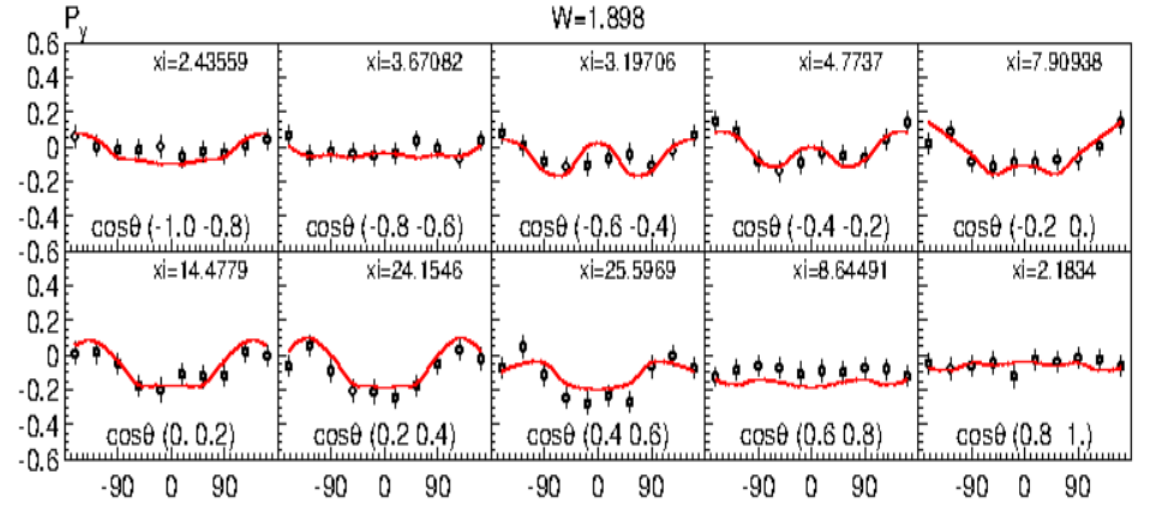
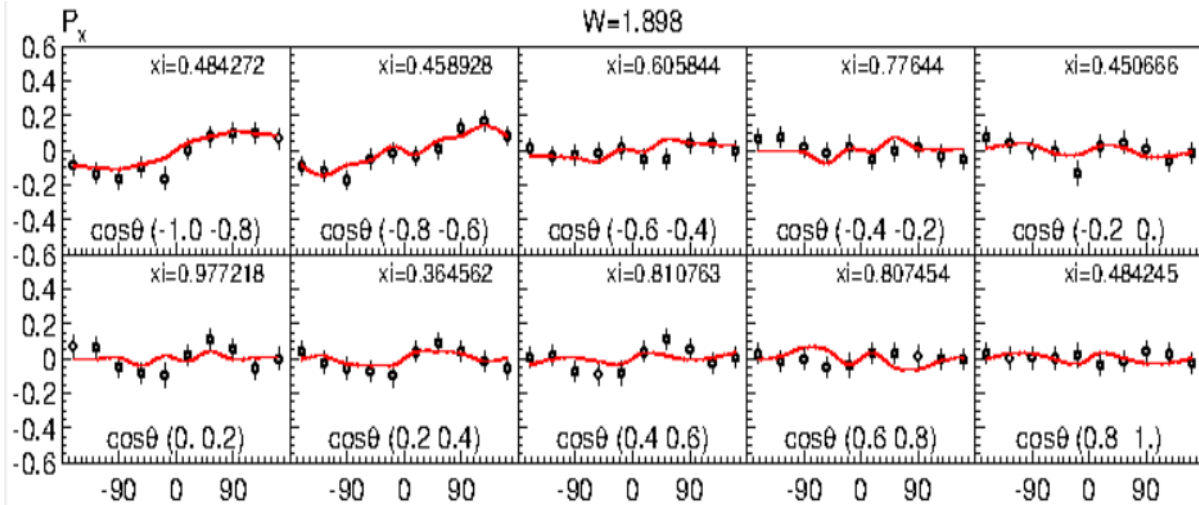
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}(\Theta) \left[1 + \Lambda_x P_x + \Lambda_y P_y + \sin(2\varphi)(I^s + \Lambda_x P_x^s + \Lambda_y P_y^s) + \cos(2\varphi)(I^c + \Lambda_x P_x^c + \Lambda_y P_y^c) \right]$$

22590 ($\chi^2/N=1.3$) fitted bins for polarization observables.

$I_c, I_s (\Phi^*)$ observables from $\gamma p \rightarrow \pi^+ \pi^- p$ data



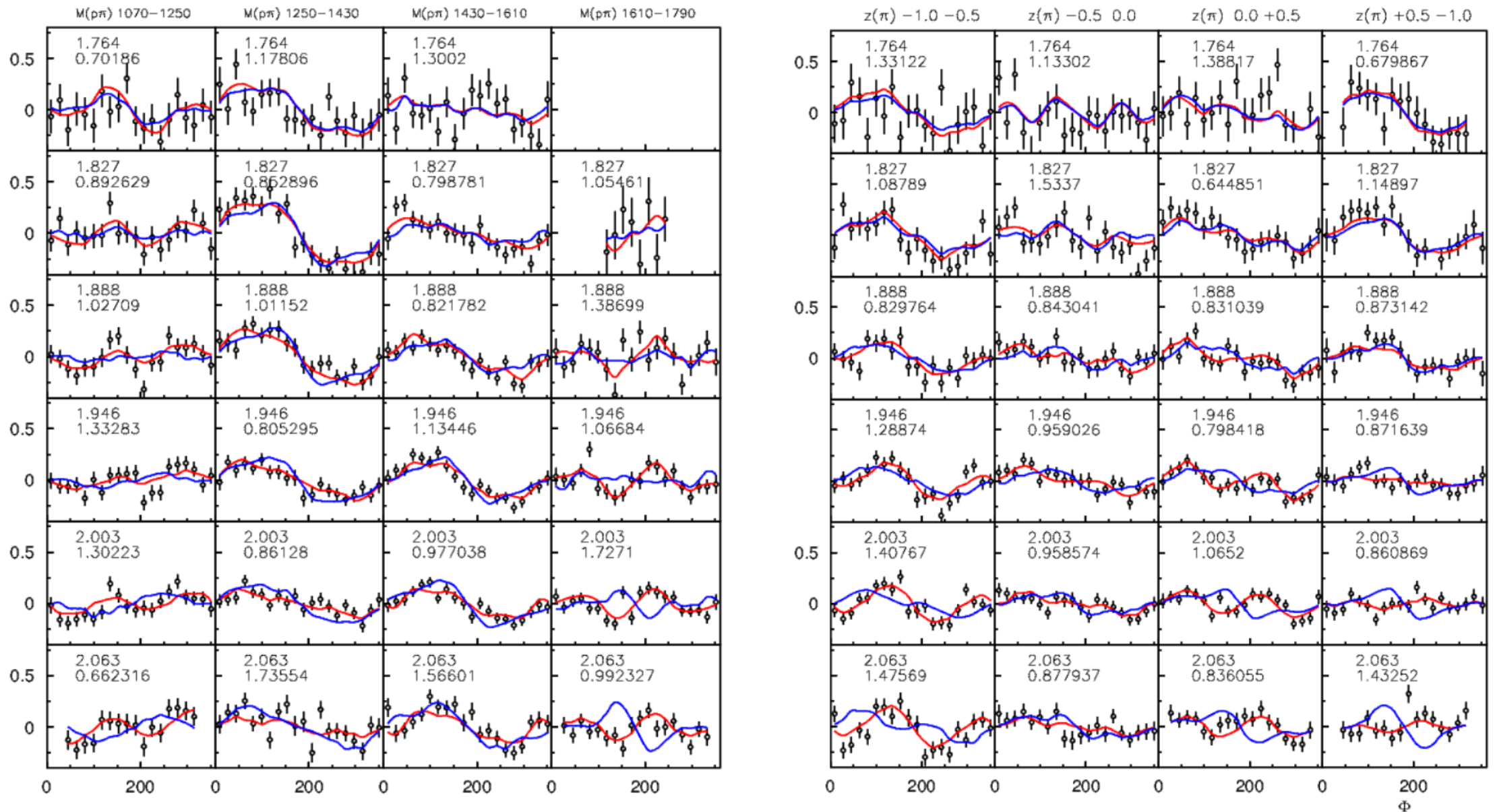
Px, Py (Φ^*)observables from $\gamma p \rightarrow \pi^+ \pi^- p$ data



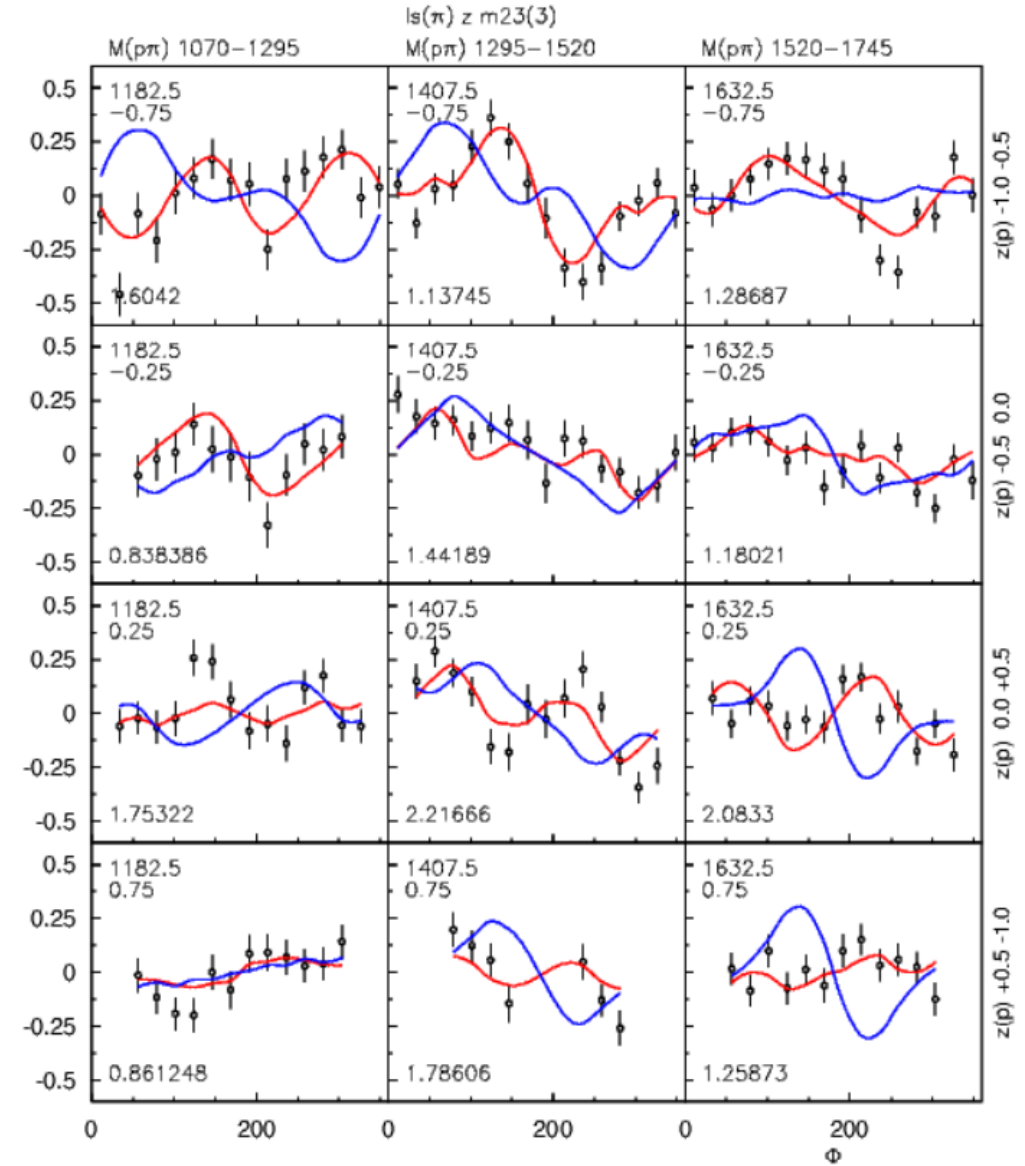
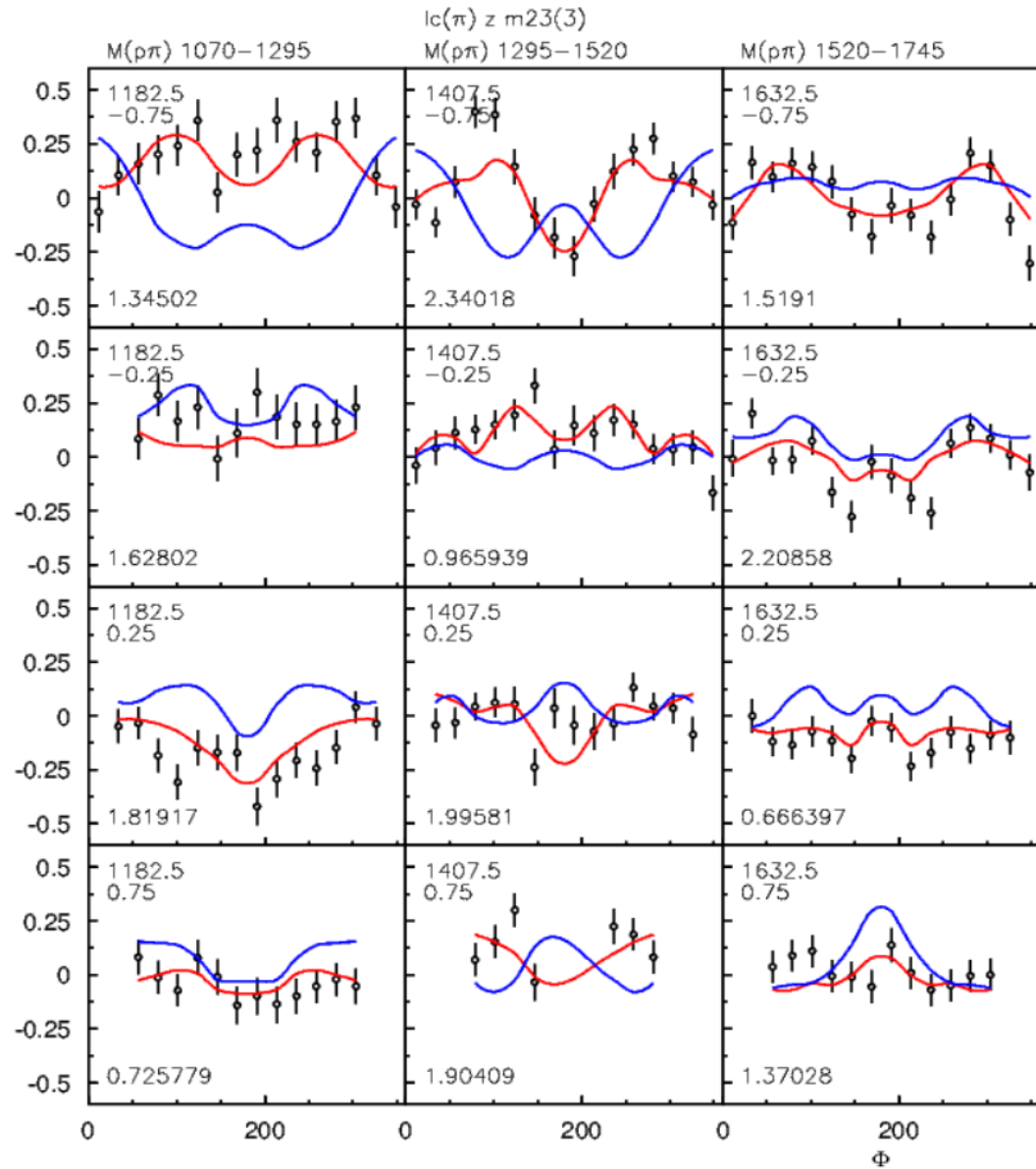
Φ^* dependence of I_S on $\pi\pi$ -mass or $\cos\Theta_\pi$

— BG-2022

— BG-2026



Two-dimension Φ^* dependencies of I_S and I_C



Polarization as key to resolve the baryon spectrum

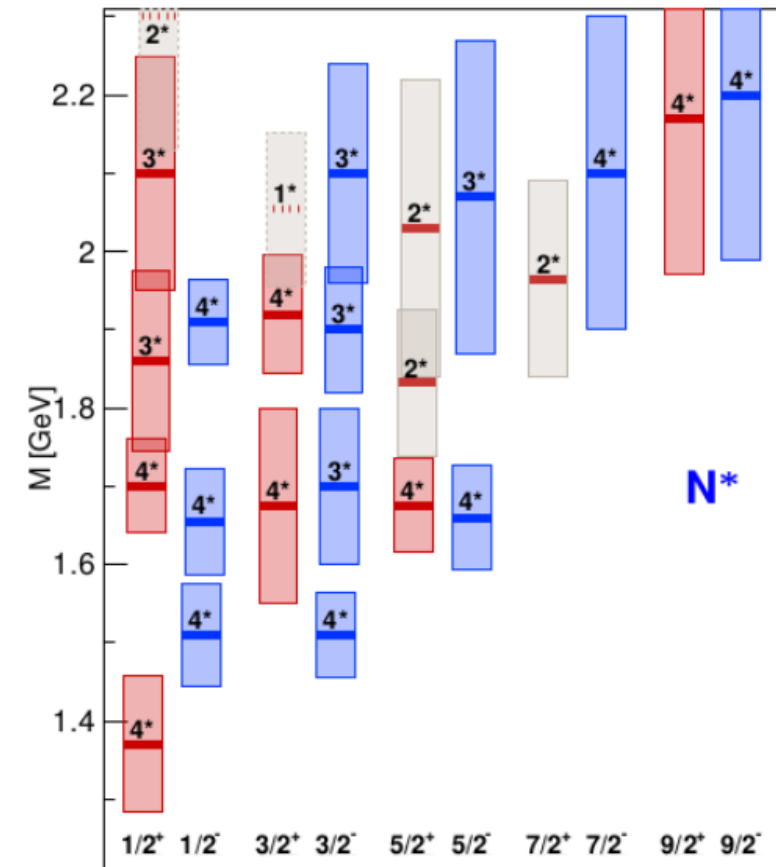
→ huge impact on knowledge of resonances in the second and third resonance region based on data from ELSA + exp. worldwide

	RPP 2010	BnGa- PWA	RPP'25 (2018-25)
N(1710)1/2 ⁺	***	****	****
N(1860)5/2 ⁺		*	**
N(1875)3/2 ⁻		***	***
N(1880)1/2 ⁺		***	***
N(1895)1/2 ⁻		****	****
N(1900)3/2 ⁺	**	****	****
N(2060)5/2 ⁻		***	***
N(2100)1/2 ⁺	*	***	***
N(2120)3/2 ⁻		***	***
Δ(1600)3/2 ⁺	***	***	****
Δ(1900)1/2 ⁻	*	***	***
Δ(1940)3/2 ⁻	*	**	**
Δ(2200)7/2 ⁻	*	***	***

Up to 2.3 GeV:

- **6 new N*- resonances found** (25% of known N*-states)
- **7 N* + 2 Δ* new in the PDG summary tables** (30%)
- Many new resonance properties determined ⇔ RPP

N*-pole positions:



N*, Δ* -parity doublets occur (but not for all states)
 ⇔ Not expected by present lattice calculations or constituent quark models

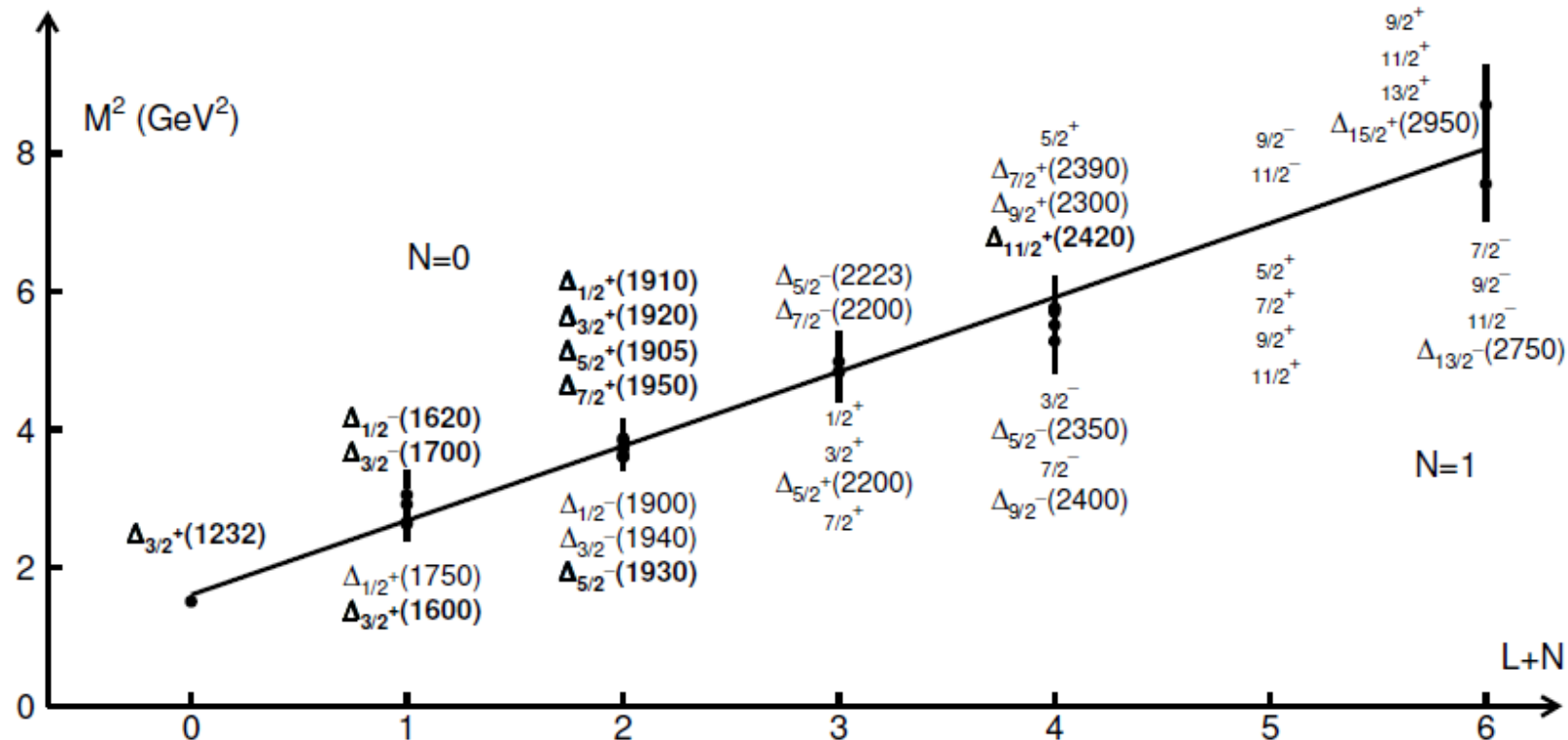
$N(1895)1/2^-$				**
$N(1895)1/2^-$ pole parameters				
M_{pole}	1900 ± 15	Γ_{pole}	330 ± 60	
$A_{\gamma p}^{1/2}$	0.040 ± 0.015	Phase:	$(65 \pm 25)^\circ$	
$A_{\gamma n}^{1/2}$	0.045 ± 0.014	Phase:	$-(90 \pm 25)^\circ$	
$N(1895)1/2^-$ transition residues			phase	
$\pi N \rightarrow \pi N$	27 ± 6 (MeV)		$-(35 \pm 15)^\circ$	
$2(\pi N \rightarrow N\eta)/\Gamma$	$20 \pm 7\%$		$(40 \pm 20)^\circ$	
$2(\pi N \rightarrow N\eta')/\Gamma$	$36 \pm 10\%$		$(70 \pm 30)^\circ$	
$2(\pi N \rightarrow \Lambda K)/\Gamma$	$16 \pm 5\%$		$-(70 \pm 20)^\circ$	
$2(\pi N \rightarrow \Sigma K)/\Gamma$	$22 \pm 8\%$		$(90 \pm 25)^\circ$	
$2(\pi N \rightarrow N\sigma)/\Gamma^{(1)}$	$3 \pm 3\%$		not def.	
$2(\pi N \rightarrow N\rho_{1/2S})/\Gamma$	$6 \pm 3\%$		$-(135 \pm 25)^\circ$	
$2(\pi N \rightarrow N\rho_{3/2D})/\Gamma$	$24 \pm 5\%$		$(140 \pm 30)^\circ$	
$2(\pi N \rightarrow \Delta(1232)\pi)/\Gamma$	$9 \pm 3\%$		$-(80 \pm 30)^\circ$	
$2(\pi N \rightarrow N(1440)\pi)/\Gamma^{(1)}$	$3 \pm 3\%$		not def.	
$N(1895)1/2^-$ Breit-Wigner parameters				
M_{BW}	1907 ± 15	Γ_{BW}	335 ± 60	
$A_{\gamma p BW}^{1/2}$	0.042 ± 0.015	$ A_{\gamma n BW}^{1/2} $	0.045 ± 0.014	
$N(1895)1/2^-$ Branching ratios				
$\text{Br}(N\pi)$	$11 \pm 3\%$	$\text{Br}(\Delta(1232)\pi)$	$7 \pm 3\%$	
$\text{Br}(N(1440)\pi)$	$2 \pm 2\%$	$\text{Br}(N\sigma)$	$2 \pm 2\%$	
$\text{Br}(\Lambda K)$	$9 \pm 3\%$	$\text{Br}(\Sigma K)$	$12 \pm 4\%$	
$\text{Br}(N\eta)$	$10 \pm 3\%$	$\text{Br}(N\eta')$	$8 \pm 3\%$	
$\text{Br}(N\rho_{1/2S})$	$10 \pm 4\%$	$\text{Br}(N\rho_{3/2D})$	$17 \pm 4\%$	
$N(1895)1/2^-$			From Integrals	
$\text{Br}(N\pi)$	$10 \pm 3\%$	$\text{Br}(\Delta(1232)\pi)$	$7 \pm 3\%$	
$\text{Br}(N(1440)\pi)$	$2 \pm 2\%$	$\text{Br}(N\sigma)$	$2 \pm 2\%$	
$\text{Br}(\Lambda K)$	$8 \pm 3\%$	$\text{Br}(\Sigma K)$	$10 \pm 4\%$	
$\text{Br}(N\eta)$	$8 \pm 3\%$	$\text{Br}(N\eta')$	$12 \pm 4\%$	
$\text{Br}(N\rho_{1/2S})$	$10 \pm 4\%$	$\text{Br}(N\rho_{3/2D})$	$21 \pm 6\%$	

$N(1900)3/2^+$				***
$N(1900)3/2^+$ pole parameters				
M_{pole}	1935 ± 15	Γ_{pole}	270 ± 30	
$A_{\gamma p}^{1/2}$	-0.090 ± 0.020	Phase	$-(25 \pm 25)^\circ$	
$A_{\gamma p}^{3/2}$	-0.080 ± 0.015	Phase	$(0 \pm 25)^\circ$	
$A_{\gamma n}^{1/2}$	-0.012 ± 0.006	Phase	$-(20 \pm 20)^\circ$	
$A_{\gamma n}^{3/2}$	0.008 ± 0.006	Phase	$-(5 \pm 20)^\circ$	
$N(1900)3/2^+$ transition residues			phase	
$\pi N \rightarrow \pi N$	3 ± 1 (MeV)		$(30 \pm 20)^\circ$	
$2(\pi N \rightarrow N\eta)/\Gamma$	$1 \pm 1\%$		not def.	
$2(\pi N \rightarrow \Lambda K)/\Gamma$	$4 \pm 2\%$		$-(160 \pm 20)^\circ$	
$2(\pi N \rightarrow \Sigma K)/\Gamma$	$4 \pm 2\%$		$(150 \pm 25)^\circ$	
$2(\pi N \rightarrow N\sigma)/\Gamma$	$6 \pm 2\%$		$(90 \pm 30)^\circ$	
$2(\pi N \rightarrow N\rho_{1/2P})/\Gamma$	$7 \pm 3\%$		$-(70 \pm 30)^\circ$	
$2(\pi N \rightarrow N\rho_{3/2P})/\Gamma$	$12 \pm 4\%$		$-(55 \pm 30)^\circ$	
$2(\pi N \rightarrow N\rho_{3/2F})/\Gamma$	$9 \pm 3\%$		$-(50 \pm 20)^\circ$	
$2(\pi N \rightarrow \Delta(1232)\pi_{L=1})/\Gamma$	$5 \pm 2\%$		$-(175 \pm 20)^\circ$	
$2(\pi N \rightarrow \Delta(1232)\pi_{L=3})/\Gamma$	$3 \pm 2\%$		not def.	
$2(\pi N \rightarrow N(1440)\pi)/\Gamma$	$6 \pm 2\%$		$-(60 \pm 20)^\circ$	
$2(\pi N \rightarrow N(1520)\pi)/\Gamma$	$2 \pm 2\%$		not def.	
$2(\pi N \rightarrow N(1535)\pi)/\Gamma$	$5 \pm 2\%$		not def.	
$N_{3/2^+}(1900)$ Breit-Wigner parameters				
M_{BW}	1938 ± 15	Γ_{BW}	270 ± 30	
$A_{\gamma p BW}^{1/2}$	-0.093 ± 0.020	$A_{\gamma p BW}^{3/2}$	-0.083 ± 0.015	
$A_{\gamma n BW}^{1/2}$	-0.014 ± 0.006	$A_{\gamma n BW}^{3/2}$	0.010 ± 0.006	
$N(1900)3/2^+$ Branching ratios				
$\text{Br}(N\pi)$	$3 \pm 2\%$	$\text{Br}(N\sigma)$	$6 \pm 3\%$	
$\text{Br}(\Delta(1232)\pi_{L=1})$	$5 \pm 2\%$	$\text{Br}(\Delta(1232)\pi_{L=3})$	$4 \pm 2\%$	
$\text{Br}(N(1520)\pi)$	$2 \pm 2\%$	$\text{Br}(N(1440)\pi)$	$6 \pm 3\%$	
$\text{Br}(N(1535)\pi)$	$10 \pm 4\%$	$\text{Br}(N\rho_{3/2F})$	$14 \pm 5\%$	
$\text{Br}(N\rho_{1/2P})$	$8 \pm 3\%$	$\text{Br}(N\rho_{3/2P})$	$24 \pm 8\%$	
$\text{Br}(\Lambda K)$	$6 \pm 3\%$	$\text{Br}(\Sigma K)$	$5 \pm 2\%$	

Analytically solvable model of QCD with constant α_s . The model which contains only one parameter, *size*.

$$M^2 = a \cdot (L + N + 3/2) - b \cdot \alpha_D \text{ [GeV}^2\text{]}$$

$$a = 1.04 \text{ GeV}^2 \text{ and } b = 1.46 \text{ GeV}^2.$$



N(1720)3/2+ in the photo- and electro-production data

V. I. Mokeev, et al. Phys. Lett. B {805} (2020), 135457

Resonance states	Mass, GeV	N^* total width, MeV	Branching fraction for decays to $\pi\Delta$	Branching fraction for decays to ρp
$N(1720)3/2^+$	1.743-1.753	114 ± 6	38-53%	31-46%
$N'(1720)3/2^+$	1.715-1.735	120 ± 6	47-62%	4-10%

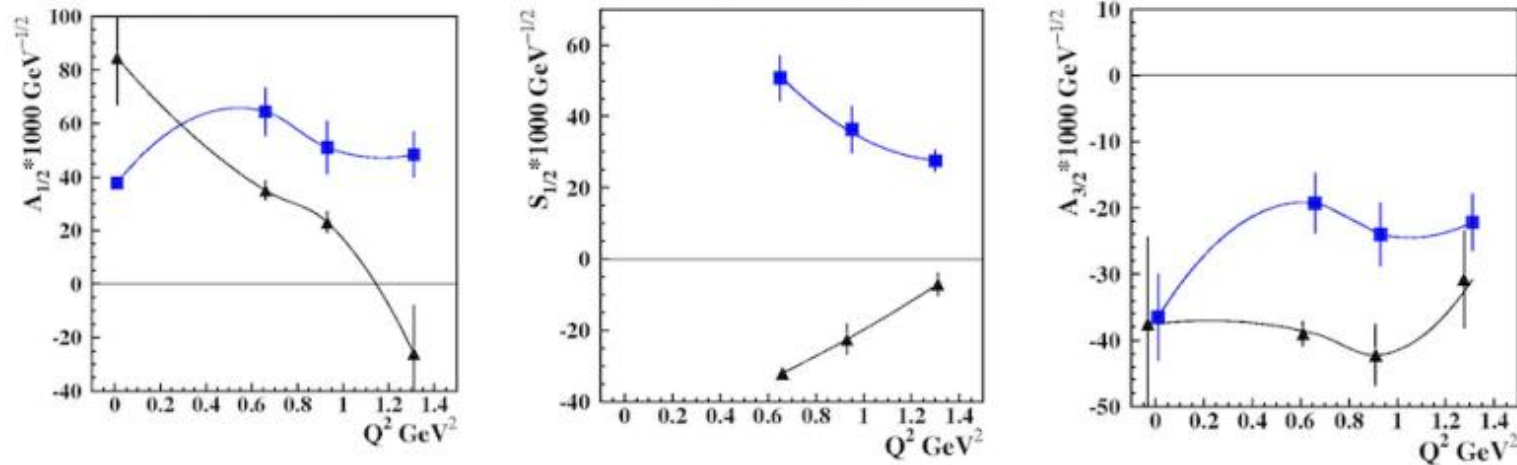
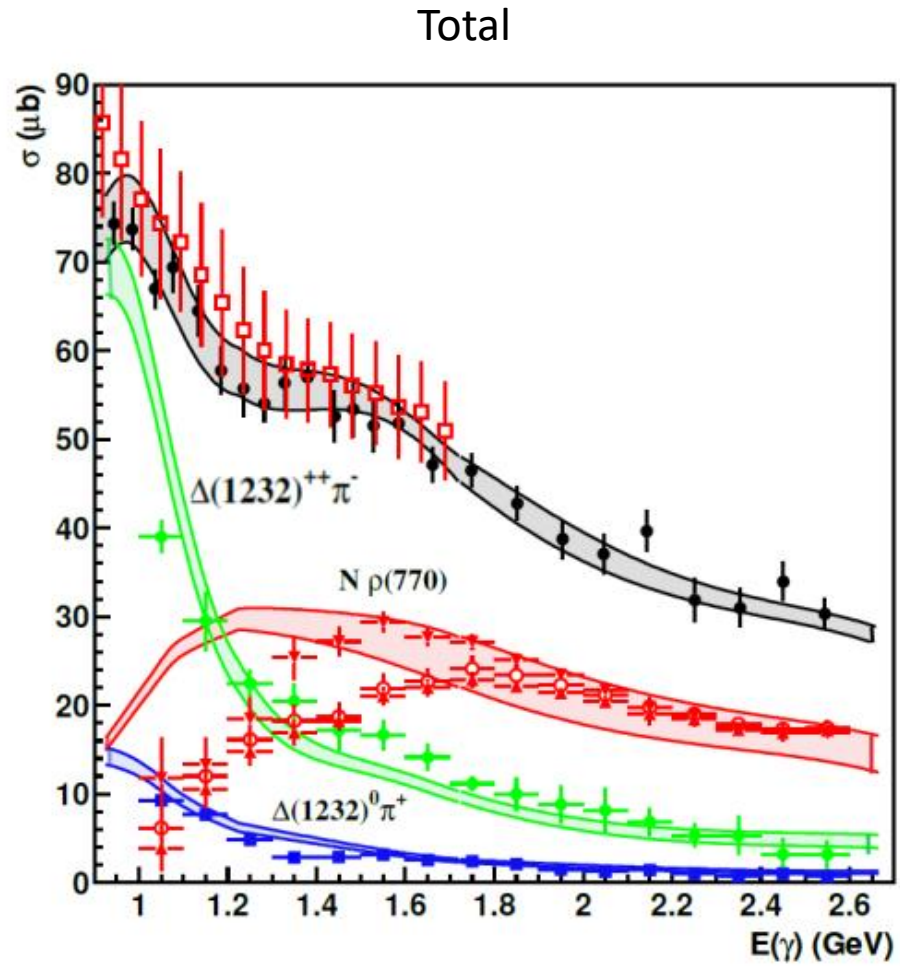
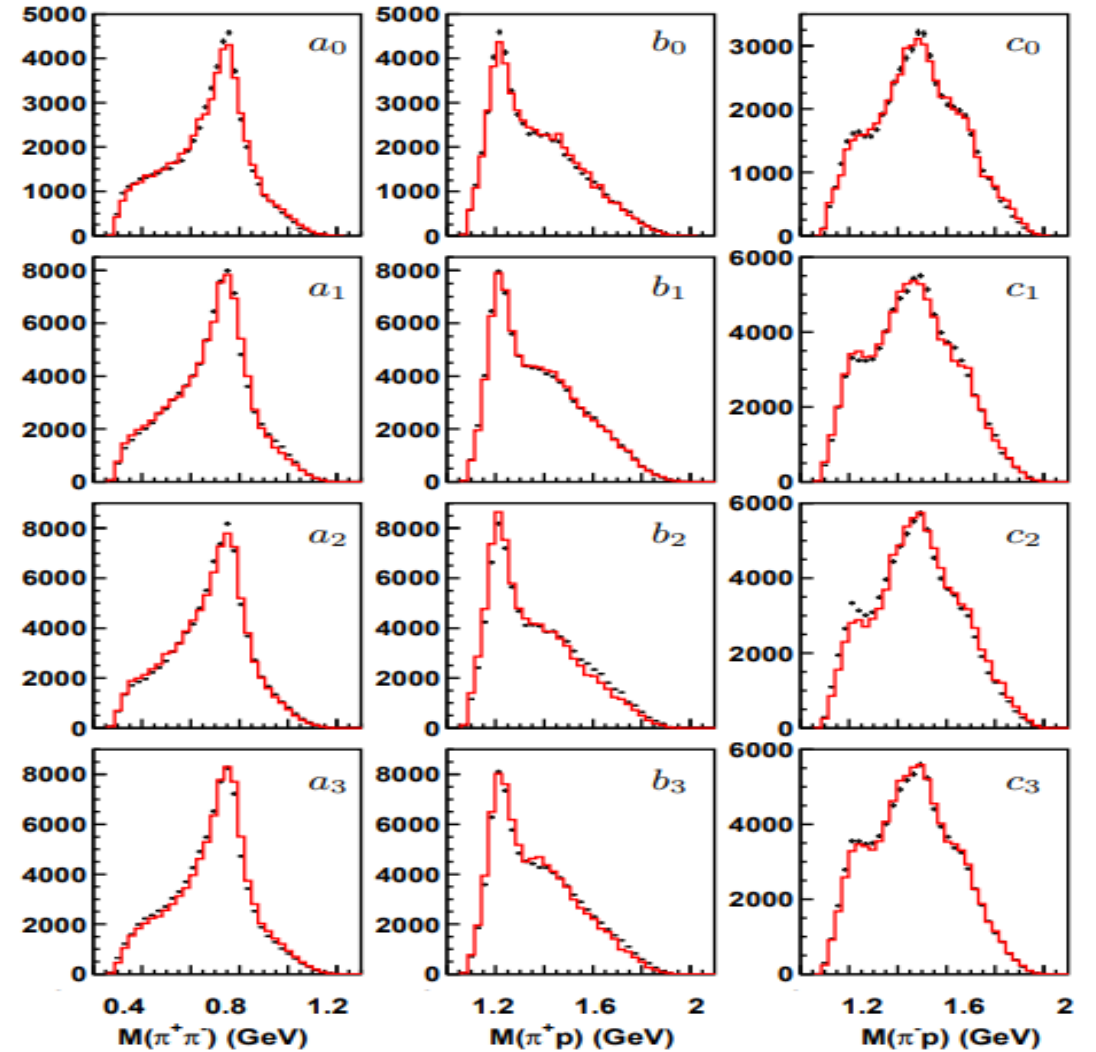


FIGURE 5. The $\gamma_{r,v}pN^*$ photo-/electrocouplings of the conventional $N(1720)3/2^+$ (black) and the new $N'(1720)3/2^+$ (blue) resonances from the $\pi^+\pi^-p$ photo- [18] and electroproduction [25] data fits.

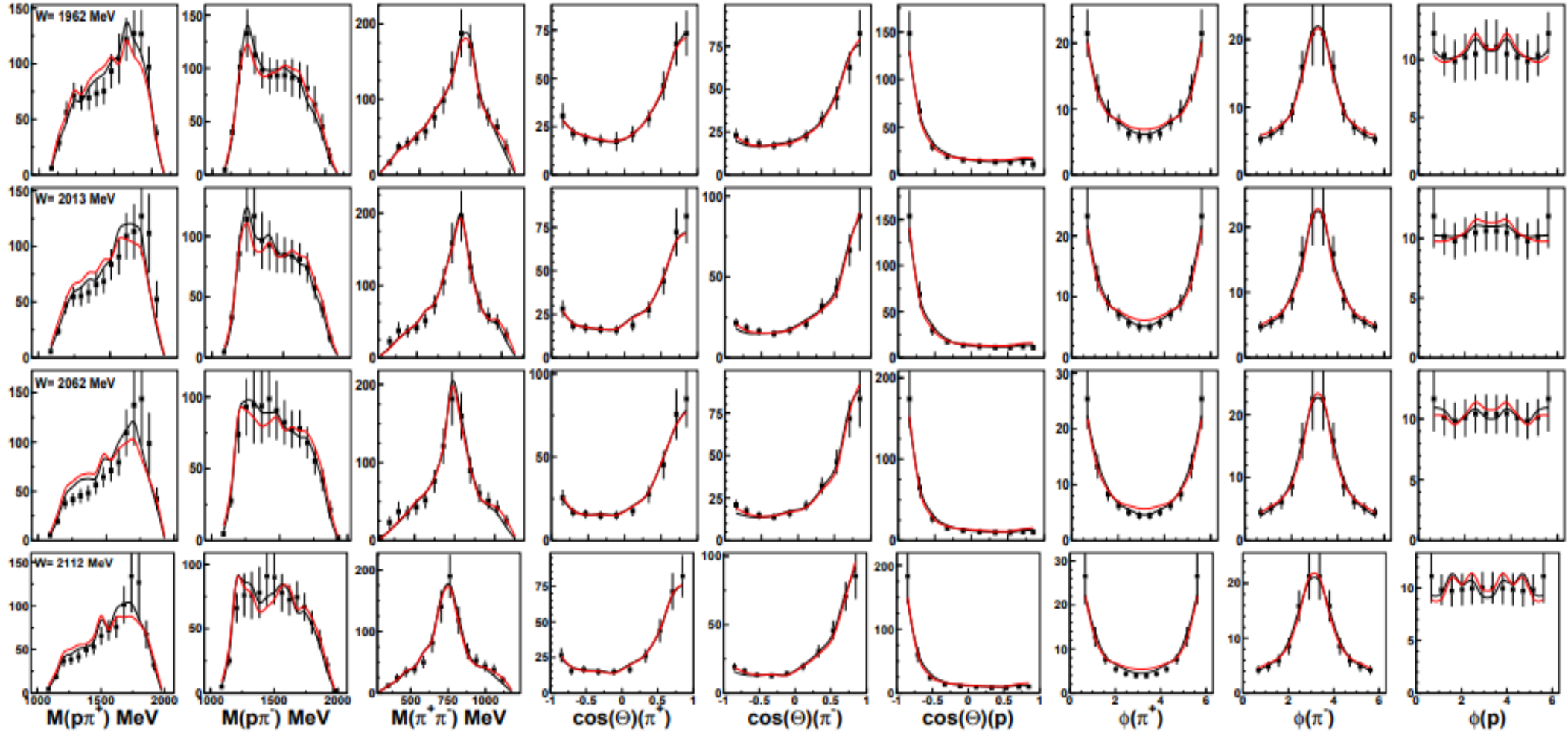
The analysis of the CLAS $\gamma p \rightarrow \pi^+ \pi^- p$ data



4 topologies



The analysis of the CLAS $\gamma p \rightarrow \pi^+ \pi^- p$ data (comparison with CLAS fit)



Structure of the Δ -states ($J^P=1/2^+$) in the mass region around 1800 MeV

$$\Delta(1750) 1/2^+$$

$$I(J^P) = \frac{3}{2}(\frac{1}{2}^+) \text{ Status: } *$$

OMITTED FROM SUMMARY TABLE

$\Delta(1750)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
1748	ARNDT	04	DPWA $\pi N \rightarrow \pi N, \eta N$
1714	VRANA	00	DPWA Multichannel

-2xIMAGINARY PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
524	ARNDT	04	DPWA $\pi N \rightarrow \pi N, \eta N$
68	VRANA	00	DPWA Multichannel

$$\Delta(1910) 1/2^+$$

$$I(J^P) = \frac{3}{2}(\frac{1}{2}^+) \text{ Status: } ***$$

Older and obsolete values are listed and referenced in the 2014 edition, Chinese Physics **C38** 070001 (2014).

$\Delta(1910)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
1800 to 1900 (≈ 1850) OUR ESTIMATE			
1802 \pm 6	ROENCHEN	22	DPWA Multichannel
1840 \pm 40	SOKHOYAN	15A	DPWA Multichannel
1896 \pm 11	¹ SVARC	14	L+P $\pi N \rightarrow \pi N$
1880 \pm 30	CUTKOSKY	80	IPWA $\pi N \rightarrow \pi N$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
1801	HUNT	19	DPWA Multichannel
1799	ROENCHEN	15A	DPWA Multichannel
1840 \pm 40	GUTZ	14	DPWA Multichannel
1850 \pm 40	ANISOVICH	12A	DPWA Multichannel
1771	ARNDT	06	DPWA $\pi N \rightarrow \pi N, \eta N$
1880	VRANA	00	DPWA Multichannel
1874	HOEHLER	93	SPED $\pi N \rightarrow \pi N$

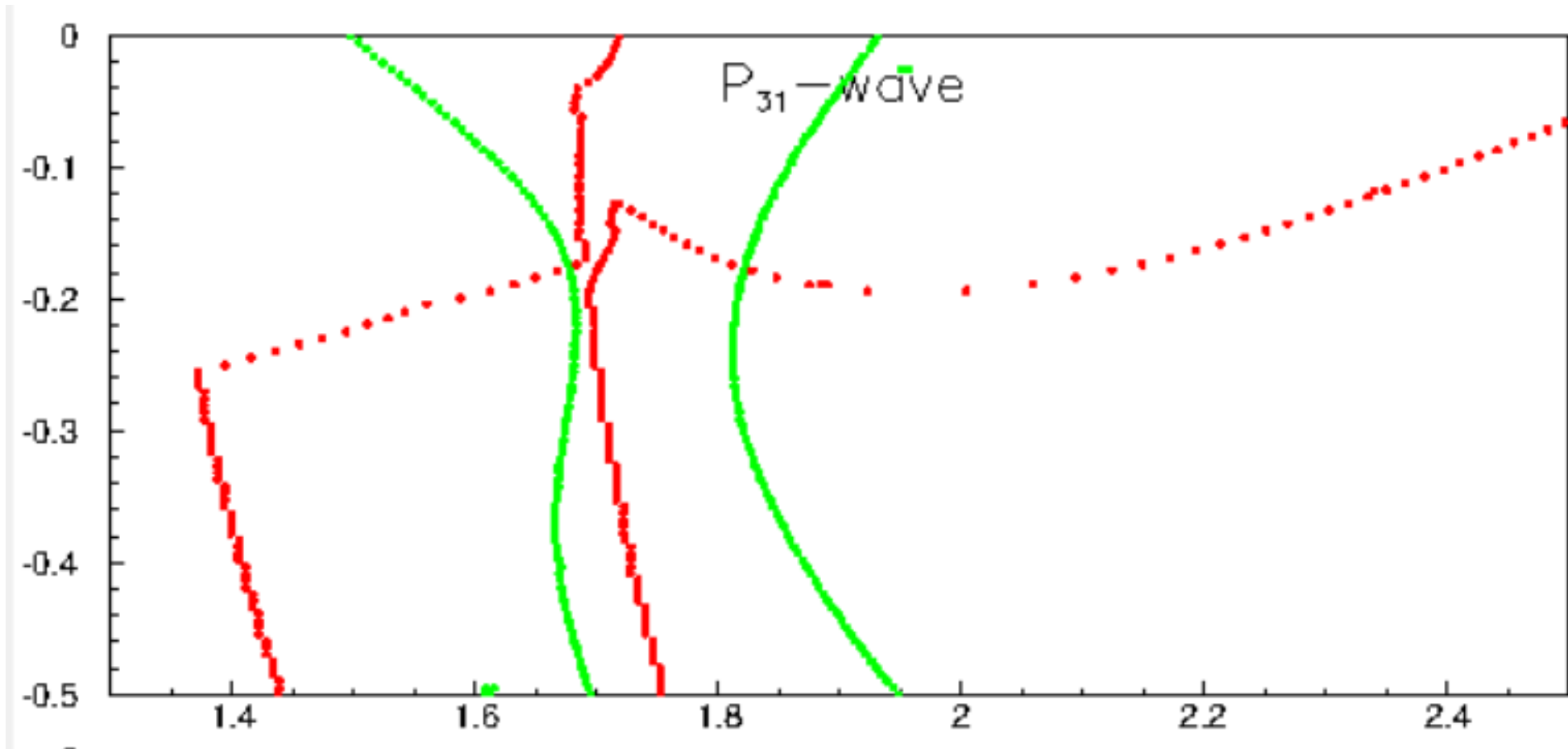
¹Fit to the amplitudes of HOEHLER 79.

-2xIMAGINARY PART

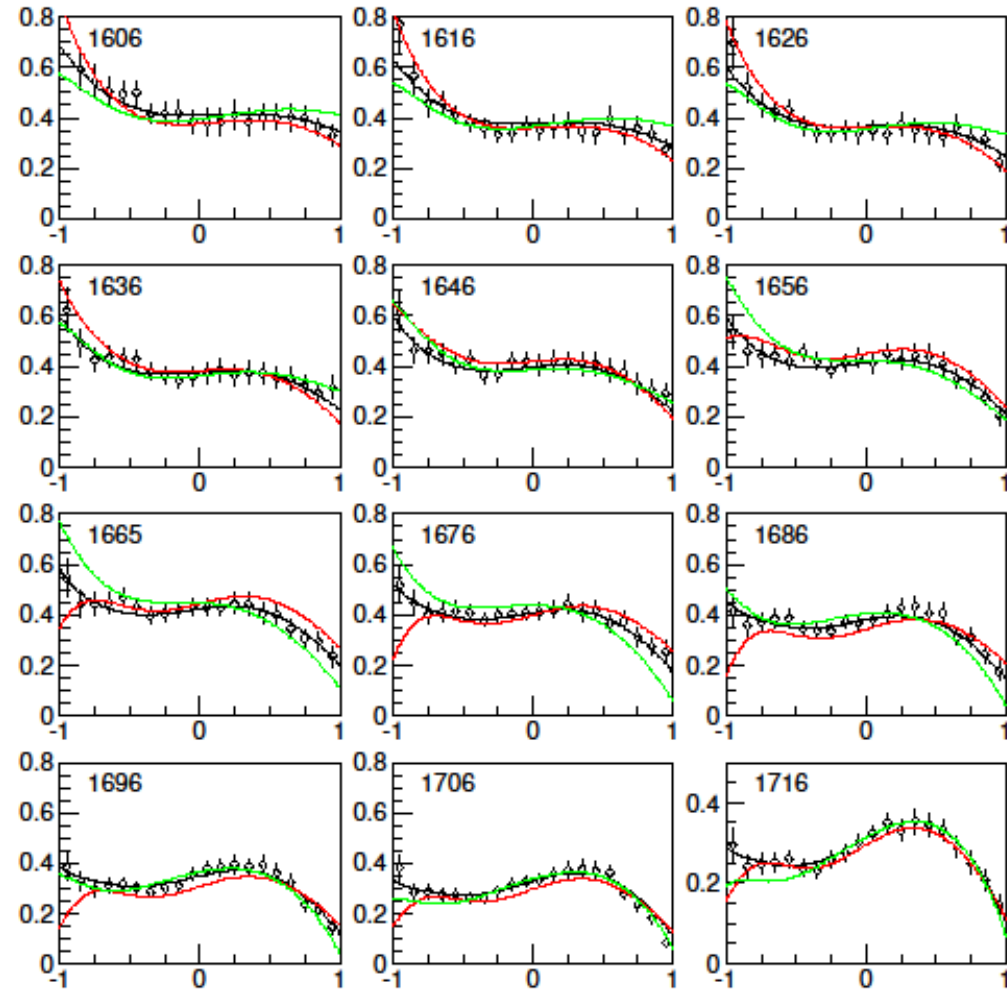
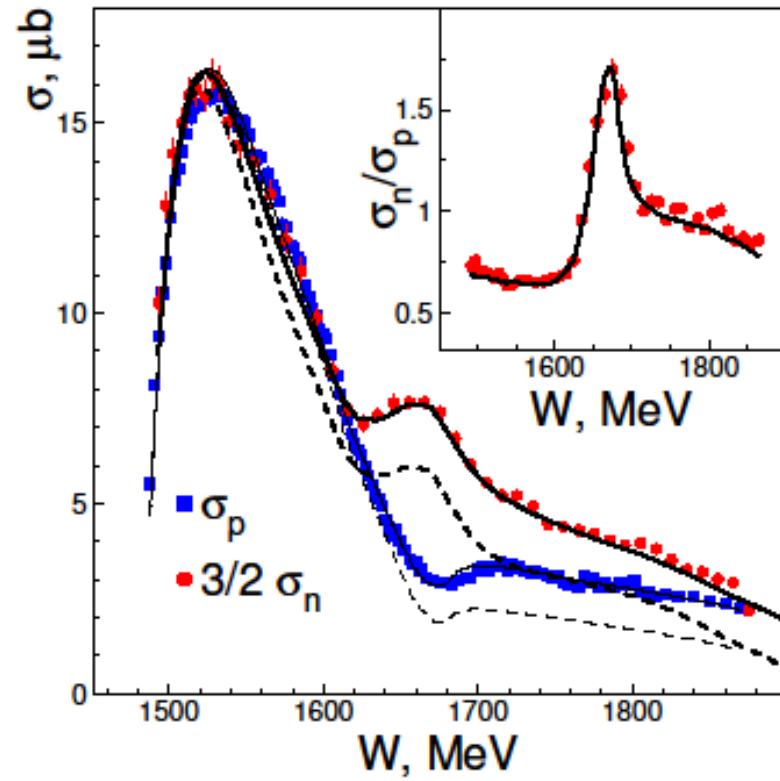
VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
200 to 500 (≈ 350) OUR ESTIMATE			
550 \pm 11	ROENCHEN	22	DPWA Multichannel
370 \pm 60	SOKHOYAN	15A	DPWA Multichannel
302 \pm 22	¹ SVARC	14	L+P $\pi N \rightarrow \pi N$
200 \pm 40	CUTKOSKY	80	IPWA $\pi N \rightarrow \pi N$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
224	HUNT	19	DPWA Multichannel
648	ROENCHEN	15A	DPWA Multichannel
370 \pm 60	GUTZ	14	DPWA Multichannel
350 \pm 45	ANISOVICH	12A	DPWA Multichannel
479	ARNDT	06	DPWA $\pi N \rightarrow \pi N, \eta N$
496	VRANA	00	DPWA Multichannel
283	HOEHLER	93	SPED $\pi N \rightarrow \pi N$

¹Fit to the amplitudes of HOEHLER 79.

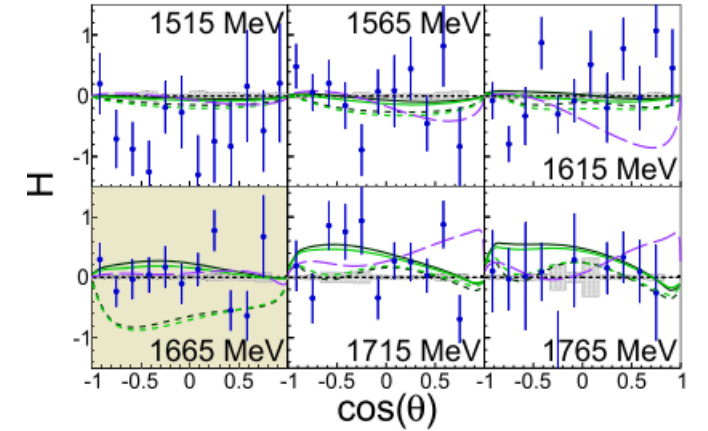
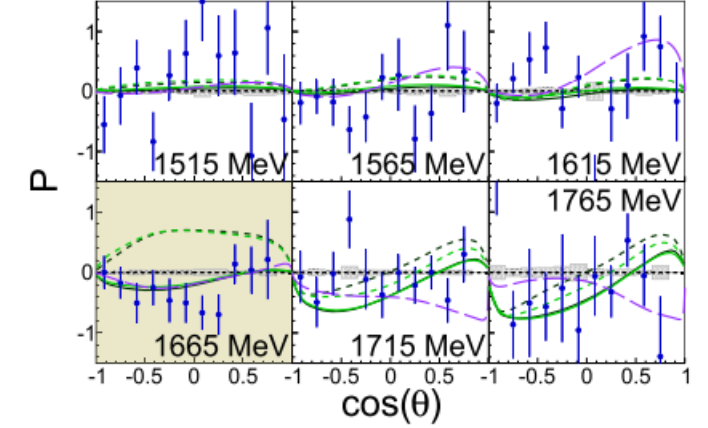
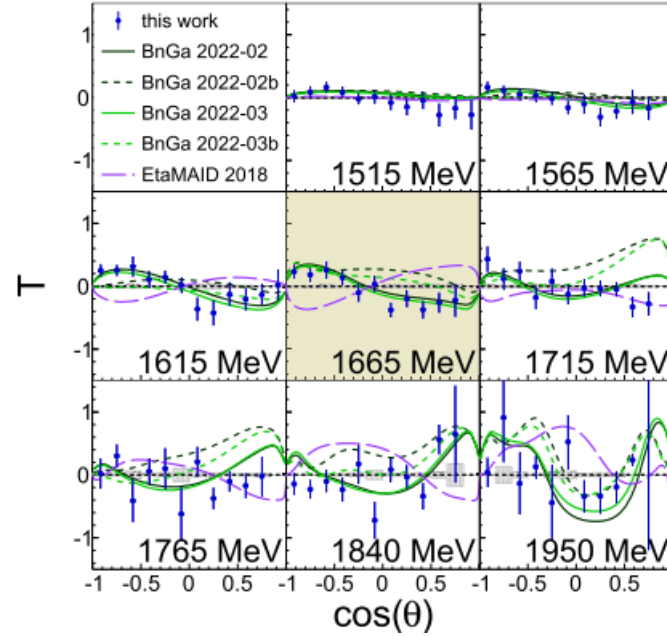
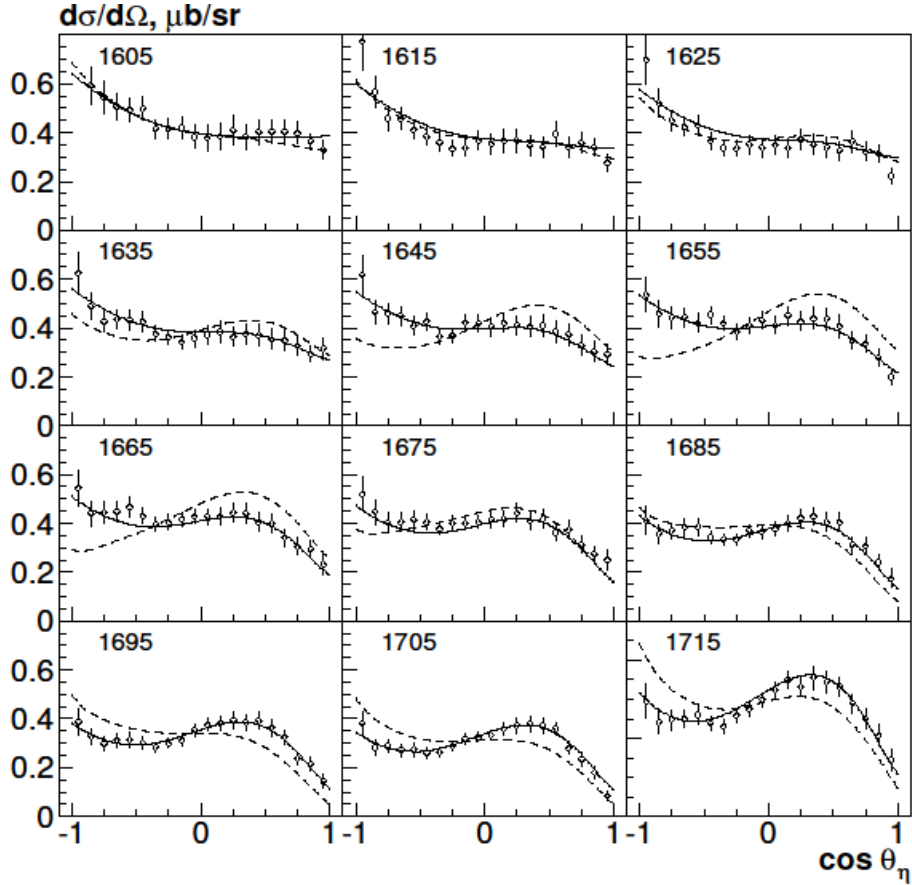
Structure of the P31 partial wave



Search for the pentaquark state in $\gamma n \rightarrow \eta n$ reaction



Fit of new polarization observables from the $\gamma n \rightarrow \eta n$ reaction (CB-ELSA/TAPS)



$$\hat{T} \equiv \mathbf{T} \mathcal{I} = 3 \sin \theta (\mathbf{E}_0^+ - x[(2\mathbf{M}_1^+ + \mathbf{M}_1^-) - 3(\mathbf{E}_1^+ + \mathbf{M}_1^+)]) \otimes (\mathbf{E}_1^+ - \mathbf{M}_1^+).$$

$$\hat{P} \equiv \mathbf{P} \mathcal{I} = \sin \theta (-\mathbf{E}_0^+ + 3x\mathbf{M}_1^-) \otimes (3\mathbf{E}_1^+ + 2\mathbf{M}_1^- + \mathbf{M}_1^+),$$

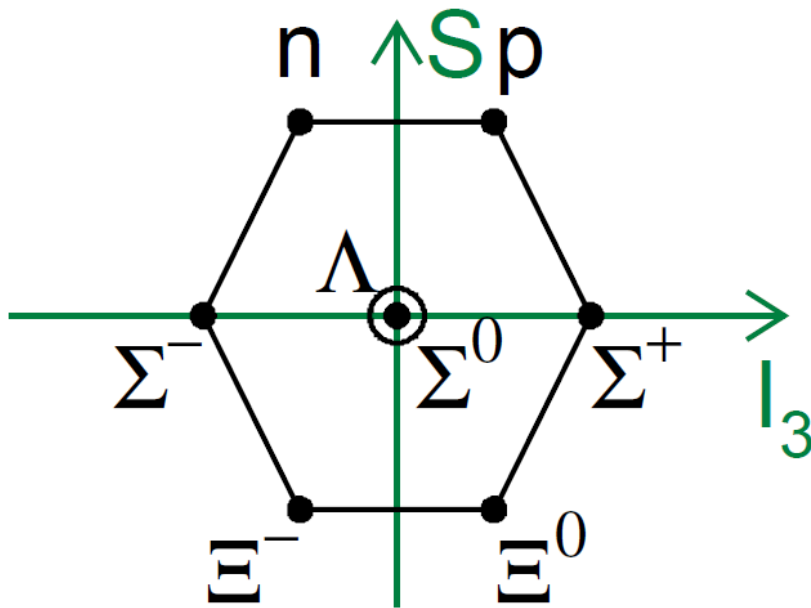
$$\hat{H} \equiv \mathbf{H} \mathcal{I} = \sin \theta (-\mathbf{E}_0^+ + 3x\mathbf{M}_1^-) \otimes (3\mathbf{E}_1^+ + 2\mathbf{M}_1^- + \mathbf{M}_1^+)(-1)$$

Conclusion

- 1) Photoproduction experiments lead to discovery of 6 new baryon states.
- 2) The one star nucleon three one star Δ -states were confirmed.
- 3) Many properties of the states were determined with a good accuracy. For the decay into two-meson final states many properties were defined for the first time.
- 4) The latest high precision data confirmed the states observed before but not led to a discovery of new states.
- 5) The new polarization data helped to define the branching ratios to different final states and phases of the coupling constants.
- 6) It is possible that we have a double pole structure in the mass region 1650-1800 MeV in the P31 partial wave. But this should be carefully investigated.
- 7) The analysis of the electroproduction data from CLAS predicts two states N(1720) and N'(1720) with similar masses and widths but different branching ratios to $N\rho(775)$ and $\Delta\pi$. Possibly it can be checked in pion-induced experiments.

$$3 \otimes 3 \otimes 3 = 10_S \oplus 8_M \oplus 8_M \oplus 1_A$$

Octet



Decuplet

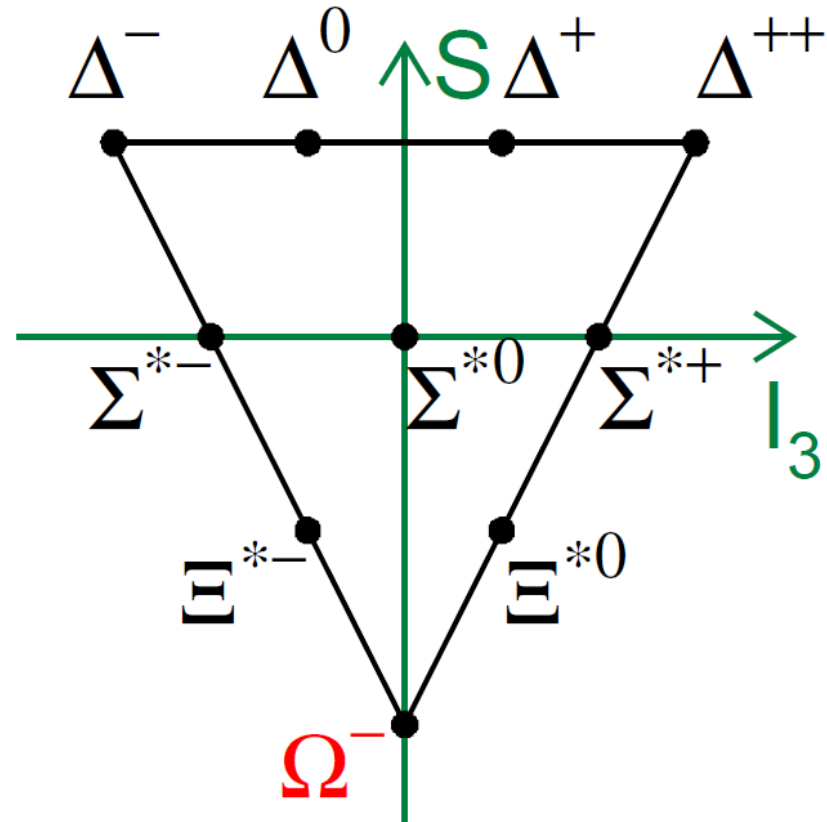


Table 1. List of reactions used in the partial-wave analysis. Δ denotes the $\Delta(1232)3/2^+$, Λ^* the $\Lambda(1520)3/2^-$, Σ^* the $\Sigma(1385)3/2^+$.

$K^- p \rightarrow K^- p$	$K^- p \rightarrow \bar{K}^0 n$	$K^- p \rightarrow \pi^0 \Lambda$
$K^- p \rightarrow \omega \Lambda$	$K^- p \rightarrow \eta \Lambda$	$K^- p \rightarrow \pi^0 \Sigma^0, \eta \Sigma^0$
$K^- p \rightarrow \pi^\mp \Sigma^\pm$	$K^- p \rightarrow K^{+/-0} \Xi^{-/0}$	$K^- p \rightarrow K^{-/0} \Delta^{+/-0}$
$K^- p \rightarrow \pi^\pm \Sigma^{*\mp}$	$K^- p \rightarrow \pi^0 \Lambda^*$	$K^- p \rightarrow K^{*-} p$
$K^- p \rightarrow K^{*0} n$	$K^- p \rightarrow \pi^0 \pi^0 \Lambda$	$K^- p \rightarrow \pi^0 \pi^0 \Sigma$

Similar reactions (existing data) were fitted by different groups including the Bonn-Gatchina PWA

Example for the fit quality

(and data consistency – many different data sets)

Sarantsev et al. EPJ A55 180 (2019)

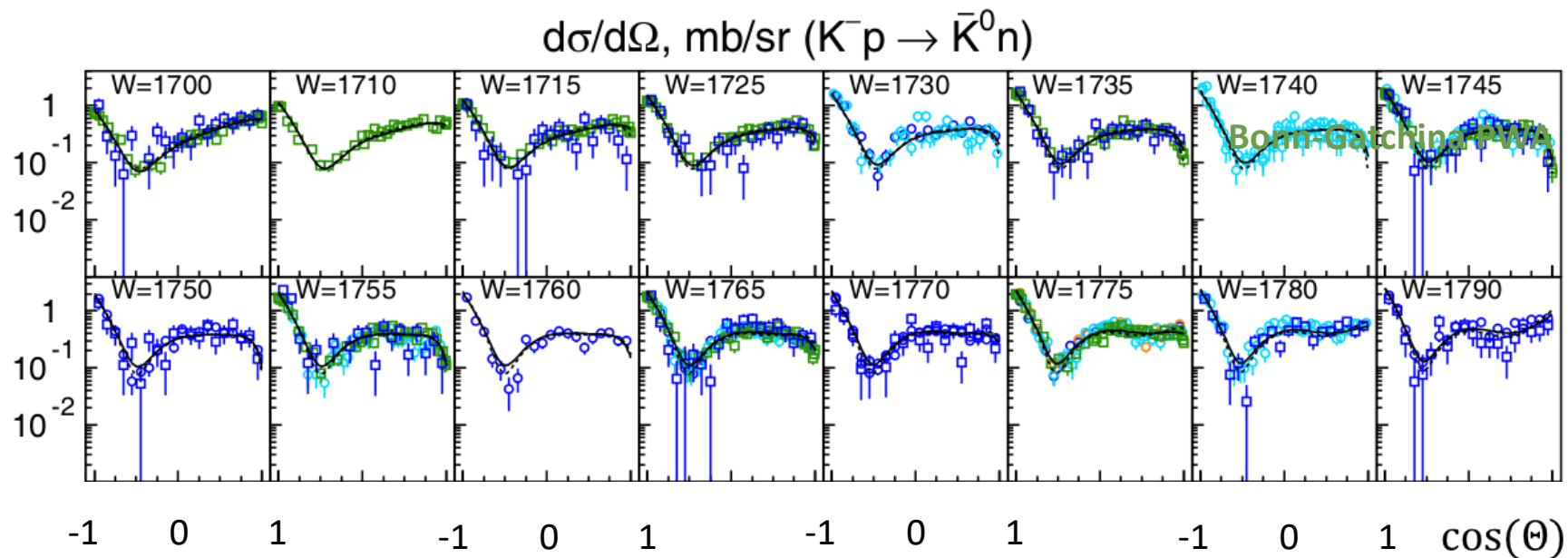


Table 2: Σ -Hyperons used in the first fit of the data.

		J^P	Status	Mass	Width
$N(1440)$	$\Sigma(1660)$	$1/2^+$	***	1630 – 1690	40 – 200
$\Delta(1230)$	$\Sigma(1385)$	$3/2^+$	****	1382.80 ± 0.35	36.0 ± 0.7
$N(1680), \Delta(1905)$	$\Sigma(1915)$	$5/2^+$	****	1900 – 1935	80 – 160
$N(1990), \Delta(1950)$	$\Sigma(2030)$	$7/2^+$	****	2025 – 2040	150 – 200
$N(1520)$	$\Sigma(1670)$	$3/2^-$	****	1665 – 1685	40 – 80
$N(1535), \Delta(1620), N(1650)$	$\Sigma(1750)$	$1/2^-$	***	1730 – 1800	60 – 160
$N(1675)$	$\Sigma(1775)$	$5/2^-$	****	1770 – 1780	105 – 135
$N(1700), \Delta(1700)$	$\Sigma(1940)$	$3/2^-$	***	1900 – 1950	150 – 300

Many Σ states are missing.

TABLE I. The pole position in the partial wave amplitudes for two ANL-Osaka solutions and for the Bonn-Gatchina solutions.

Resonance	M_R (MeV)			PDG 2014
	ANL-Osaka Model A	ANL-Osaka Model B	Bonn- Gatchina	
$\Lambda(????)1/2^-$		$(1512_{-1}^{+1}, 370_{-4}^{+2})$		—
$\Lambda(1670)1/2^-$	$(1669_{-8}^{+3}, 18_{-2}^{+18})$	$(1667_{-2}^{+1}, 24_{-2}^{+6})$	$(1676 \pm 2, 33 \pm 4)$	****
$\Lambda(1800)1/2^-$			$(1809 \pm 9, 205 \pm 16)$	***
$\Lambda(1600)1/2^+$	$(1544_{-3}^{+3}, 112_{-2}^{+12})$	$(1548_{-6}^{+5}, 164_{-14}^{+14})$	$(1562 \pm 8, 232 \pm 15)$	****
$\Lambda(1810)1/2^+$		$(1841_{-4}^{+3}, 62_{-4}^{+6})$	$(1773 \pm 7, 38 \pm 14)$	***
$\Lambda(2100)1/2^+$	$(2097_{-1}^{+40}, 166_{-12}^{+64})$			—
$\Lambda(1670)3/2^+$		$(1671_{-8}^{+2}, 10_{-4}^{+22})$		—
$\Lambda(1890)3/2^+$	$(1859_{-7}^{+5}, 112_{-4}^{+20})$		$(1872 \pm 5, 101 \pm 10)$	****
$\Lambda(2070)3/2^+$			$(2044 \pm 20, 360 \pm 45)$	—
$\Lambda(1520)3/2^-$	$(1517_{-4}^{+4}, 16_{-8}^{+10})$	$(1517_{-3}^{+4}, 16_{-12}^{+12})$	$(1517.5 \pm 0.4, 15.3 \pm 0.9)$	****
$\Lambda(1690)3/2^-$	$(1697_{-6}^{+6}, 66_{-14}^{+14})$	$(1697_{-5}^{+6}, 74_{-14}^{+14})$	$(1683 \pm 3, 72 \pm 5)$	****
$\Lambda(1830)5/2^-$	$(1766_{-34}^{+37}, 212_{-62}^{+94})$	$(1924_{-24}^{+52}, 90_{-34}^{+114})$	$(1819.5 \pm 3, 62 \pm 5)$	****
$\Lambda(2080)5/2^-$	$(1899_{-37}^{+35}, 80_{-34}^{+100})$		$(2070 \pm 15, 172 \pm 28)$	
$\Lambda(1820)5/2^+$	$(1824_{-1}^{+2}, 78_{-2}^{+2})$	$(1821_{-1}^{+1}, 64_{-2}^{+2})$	$(1813 \pm 3, 78 \pm 7)$	****
$\Lambda(2110)5/2^+$			$(2048 \pm 10, 255 \pm 20)$	***
$\Lambda(2085)7/2^+$	$(1757, 73)$	$(2041_{-82}^{+80}, 238_{-34}^{+114})$		*
$\Lambda(2100)7/2^-$	-	-	$(2040 \pm 14, 215 \pm 29)$	****

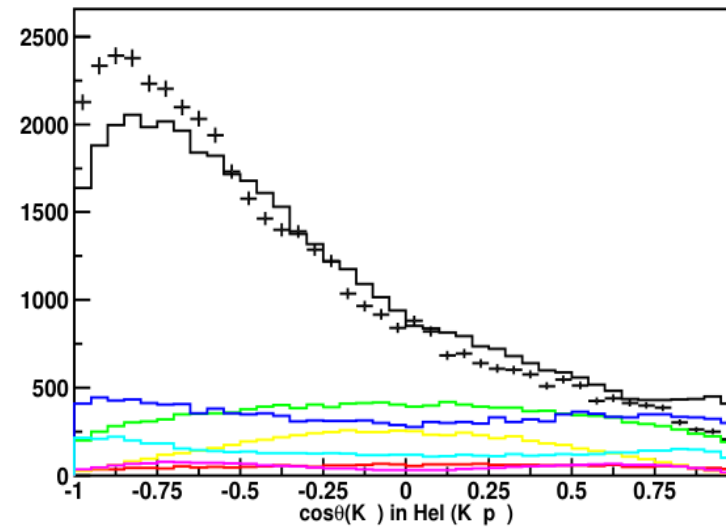
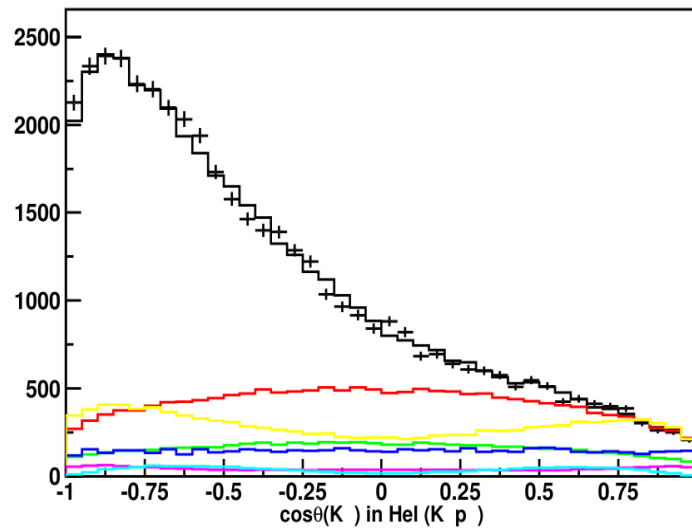
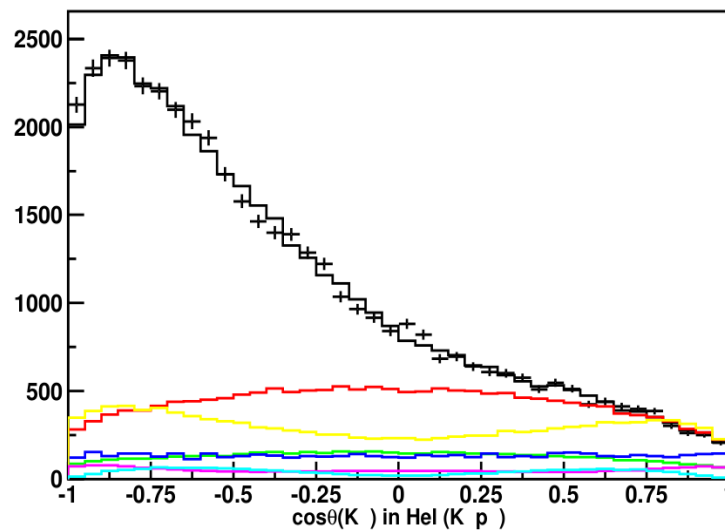
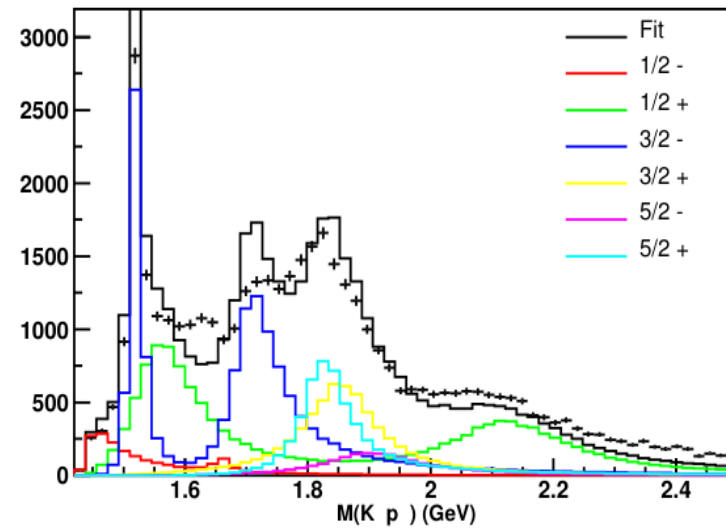
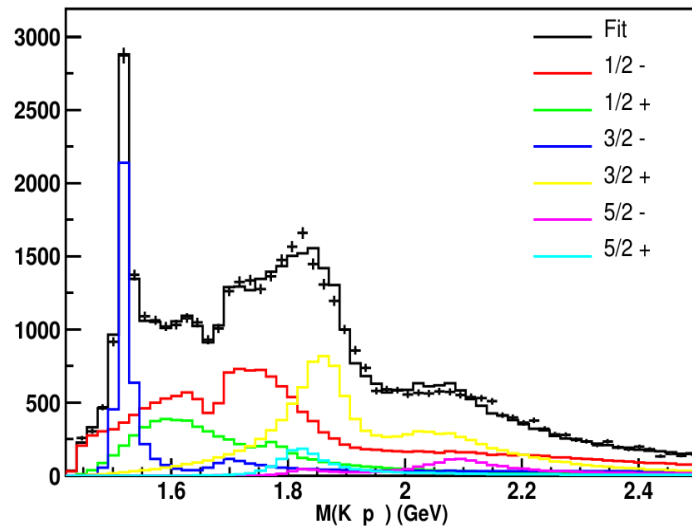
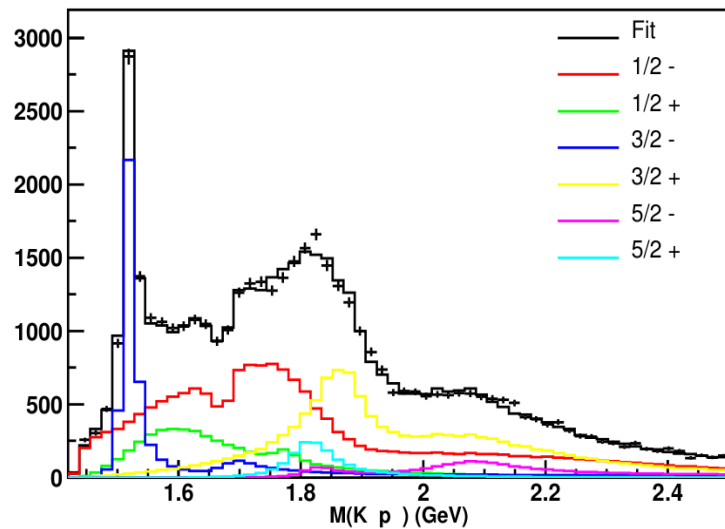
ANL-Osaka: Kamano et al. Phys.Rev. C92 025205 (2015)

Simplified fit with Breit-Wigner amplitudes corresponding to BG and ANL-Osaka poles

K-matrix BG $-\log L = -26029$

BW-BG $-\log L = -25730$

ANL-Osaka $-\log L = -22432$



Klong experiment (JLAB)

Let us consider the decay of the isospin 0 and isospin 1 states into $K^- p$ and $K^0 n$

$$|A(K^- p)|^2 = \left(A_1 \frac{1}{\sqrt{2}} + A_0 \frac{1}{\sqrt{2}} \right)^2 = \frac{1}{2} (|A_1|^2 + |A_0|^2 + 2\text{Re}(A_1 A_0^*))$$

$$|A(K^0 n)|^2 = \left(A_1 \frac{1}{\sqrt{2}} - A_0 \frac{1}{\sqrt{2}} \right)^2 = \frac{1}{2} (|A_1|^2 + |A_0|^2 - 2\text{Re}(A_1 A_0^*))$$

$$A_{KN} = \omega^* [G(s, t) + H(s, t)i(\vec{\sigma}\vec{n})] \omega' \quad \vec{n}_j = \varepsilon_{\mu\nu j} \frac{q_\mu k_\nu}{|\vec{k}||\vec{q}|}.$$

Differential cross section in c.m.s. of the reaction

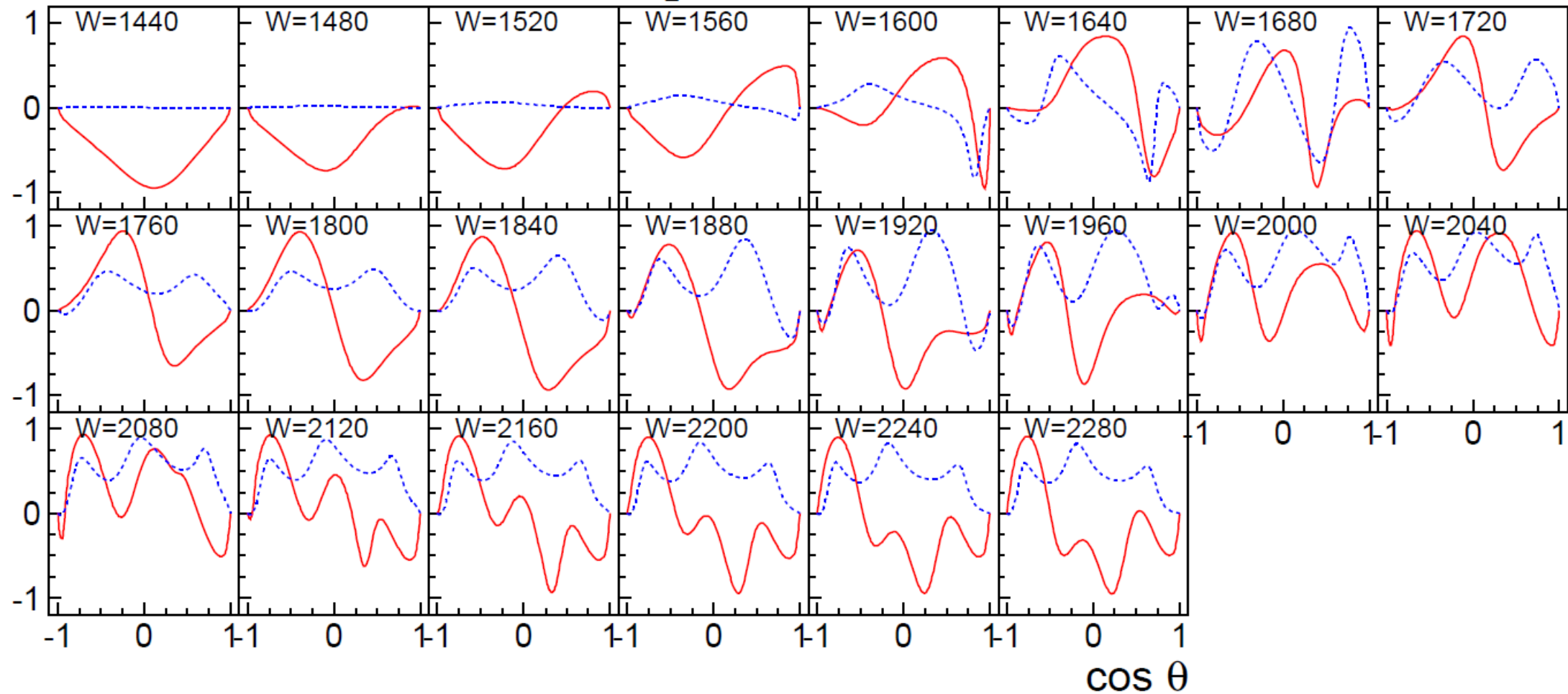
$$|A|^2 = \frac{1}{2} \text{Tr} [A_{\pi N}^* A_{\pi N}] = |G(s, t)|^2 + |H(s, t)|^2(1 - z^2)$$

the recoil asymmetry:

$$P = \frac{\text{Tr} [A_{\pi N}^* \sigma_2 A_{\pi N}]}{2|A|^2 \cos \phi} = \sin \Theta \frac{2\text{Im} (H^*(s, t)G(s, t))}{|A|^2}.$$

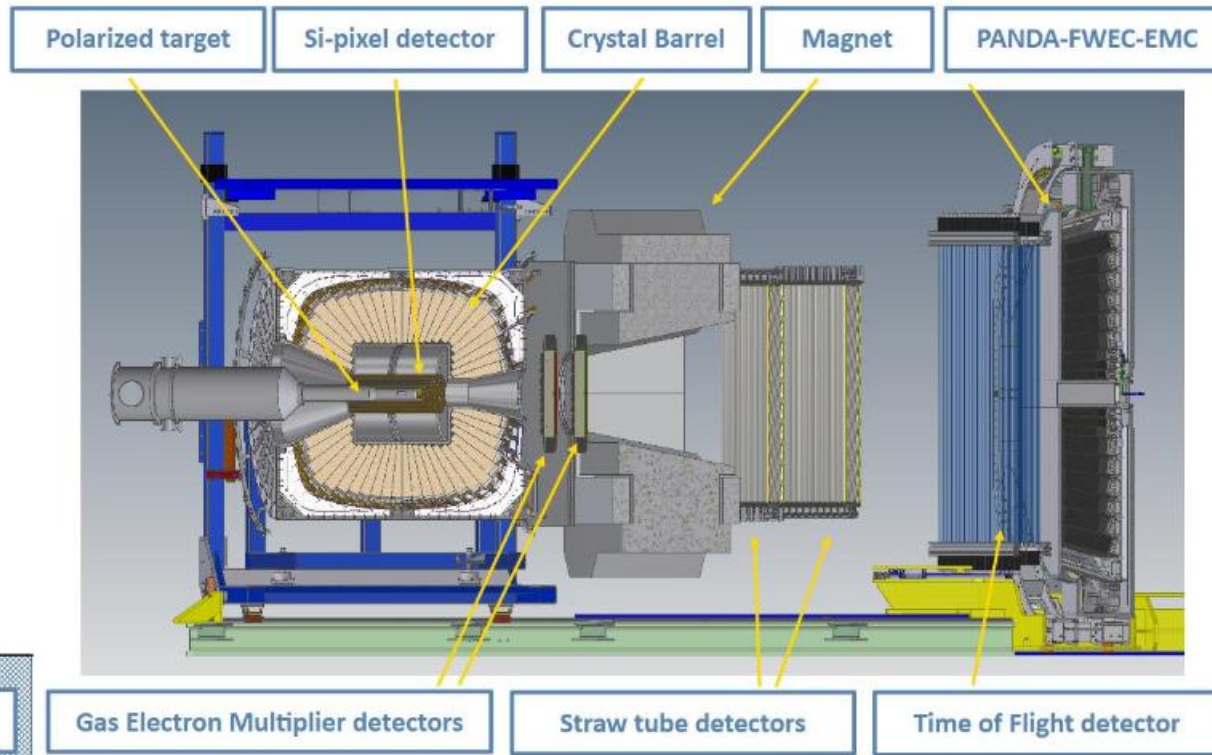
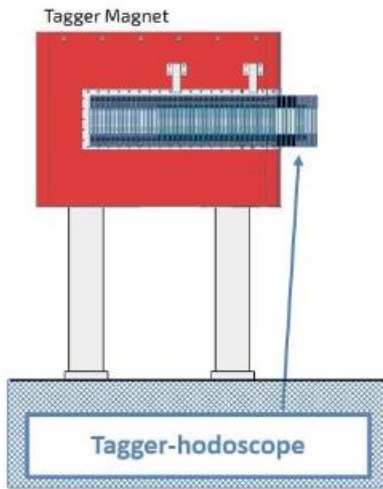
Prediction for the recoil asymmetry $K_L p \rightarrow K^0 p(K^+ n)$

$P(K_L p \rightarrow K^0 p(K^+ n))$

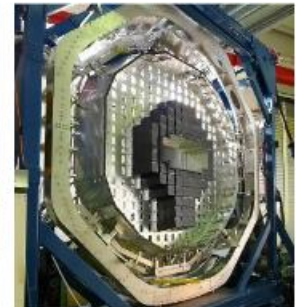


Physics at ELSA - the future

A new experiment as integral part of the new Cluster of Excellence „Color meets Flavor“:



Arrival of the PANDA-FWEC in Bonn



at the FTD

- Over almost the entire 4π -solid angle:
 - High resolution photon measurements
 - Precise charged particle detection
- Polarized beam and polarized target

→ unique possibilities!

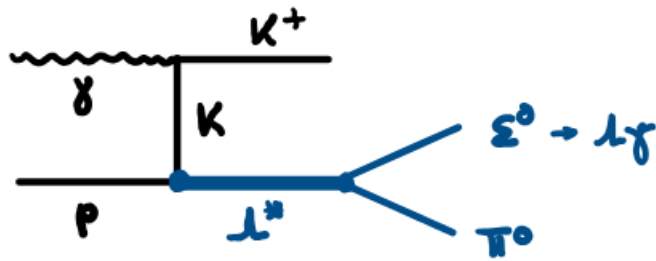
@ELSA: Advantage of polarization experiments

Several PWA groups have re-analysed the existing data (KN-scatt.) on strange baryon resonances

Almost the same data included in the fit, but quite different solutions

Use a PWA-solution toy model

↔ calculation based on t-channel K-exchange only



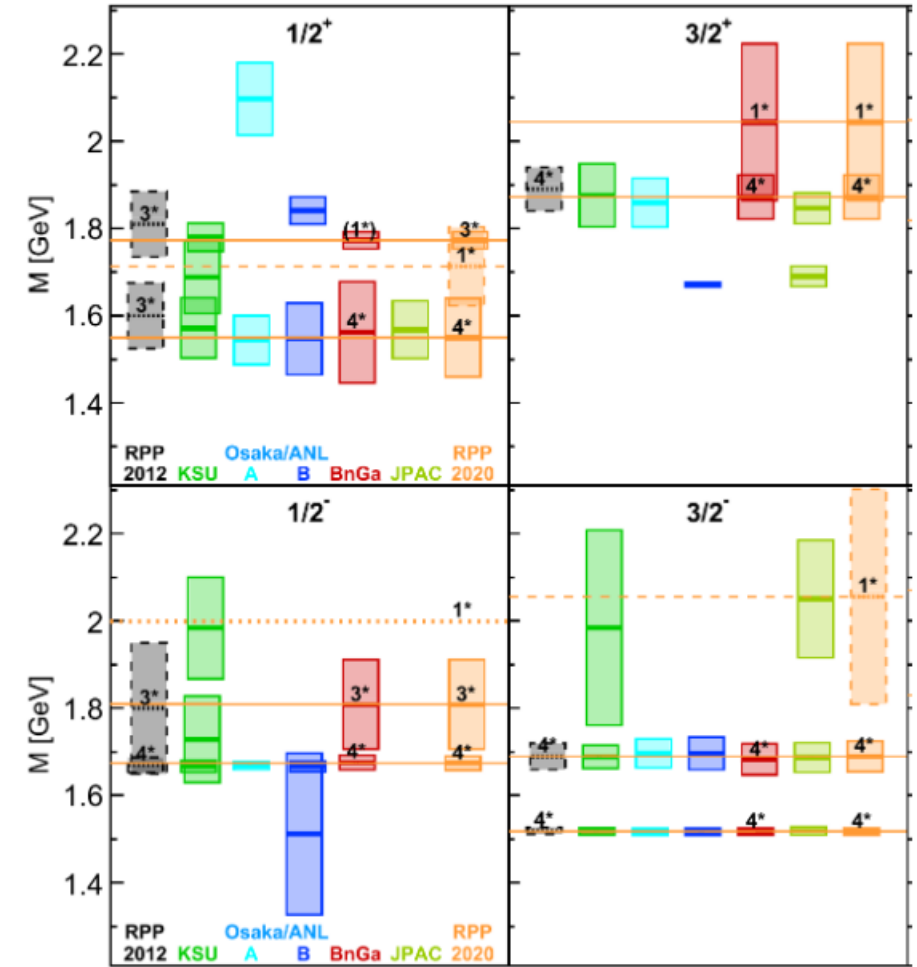
Resonances based on
ANL/Osaka- and BnGa-PWA

Use resonance properties and $pK\Lambda^*$ couplings from BnGa

↔ Predict solution

↔ Fit to BnGa-“data“ with ANL/Osaka pole positions

(only $J=1/2, 3/2, P=+/-$ shown)



↑ ↑ ↑