News from Bonn-Gatchina PWA

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DATA	BG2011-2015	added in BG2016-2017
$\gamma p \to \pi N$	$\frac{d\sigma}{d\Omega}, \Sigma, T, P, E, G, H, F$	
$\gamma n \to \pi N$	$\frac{d\sigma}{d\Omega}, \Sigma, T, P$	Σ **(CLAS)**
$\gamma n \to \Lambda n, \Sigma^- p$	$\frac{d\sigma}{d\Omega}$	
$\gamma n \to \eta n$	$\frac{d\sigma}{d\Omega}, \Sigma$	$\frac{d\sigma}{d\Omega}$ **(CB-ELSA)** $\frac{d\sigma}{d\Omega}(h=\frac{1}{2})$ **(MAMI)**
$\gamma p \to \eta p$ $\gamma p \to \eta' p$ $\gamma p \to K^+\Lambda$ $\gamma p \to K^+\Sigma^0$ $\gamma p \to K^0\Sigma^+$	$\frac{d\sigma}{d\Omega}, \Sigma$ $\frac{d\sigma}{d\Omega}, \Sigma, P, T, C_x, C_z, O_{x'}, O_{z'}$ $\frac{d\sigma}{d\Omega}, \Sigma, P, C_x, C_z$ $\frac{d\sigma}{d\Omega}, \Sigma, P$	T, P, H, E, F $\frac{d\sigma}{d\Omega}, \Sigma$ Σ, P, T, O_x, O_z **(CLAS)** Σ, P, T, O_x, O_z **(CLAS)**
$\pi^- p \to \eta n$ $\pi^- p \to K^0\Lambda$ $\pi^- p \to K^0\Sigma^0$ $\pi^+ p \to K^+\Sigma^+$	$d\sigma/d\Omega$ $d\sigma/d\Omega, P, \beta$ $d\sigma/d\Omega, P$ $(K^0\Sigma^0)$ $d\sigma/d\Omega$ $(K^+\Sigma^-)$ $d\sigma/d\Omega, P, \beta$	
$\pi^- p \to \pi^0\pi^0 n$ $\pi^- p \to \pi^+\pi^- n$ $\pi^- p \to \pi^-\pi^0 p$	$\frac{d\sigma}{d\Omega}$ **(Crystal Ball)** 	 $d\sigma/d\Omega$ **(HADES)** $d\sigma/d\Omega$ **(HADES)**
$\gamma p \to \pi^0\pi^0 p$ $\gamma p \to \pi^0\eta p$ $\gamma p \to \pi^+\pi^- p$	$d\sigma/d\Omega, \Sigma, E, I_c, I_s$ $d\sigma/d\Omega, \Sigma, I_c, I_s$ 	T, P, H, F, P_x, P_y $d\sigma/d\Omega, I_c, I_s$ **(CLAS)**
$\gamma p \to \omega p$	$d\sigma/d\Omega, \Sigma, \rho^0_{ij}, \rho^1_{ij}, \rho^2_{ij}, E, G$ **(CB-ELSA)**	Σ **(CLAS)** **P,T,F,H (CLAS)**
$\gamma p \to K^*\Lambda$		$d\sigma/d\Omega$, ρ_{ij}

Energy dependent approach

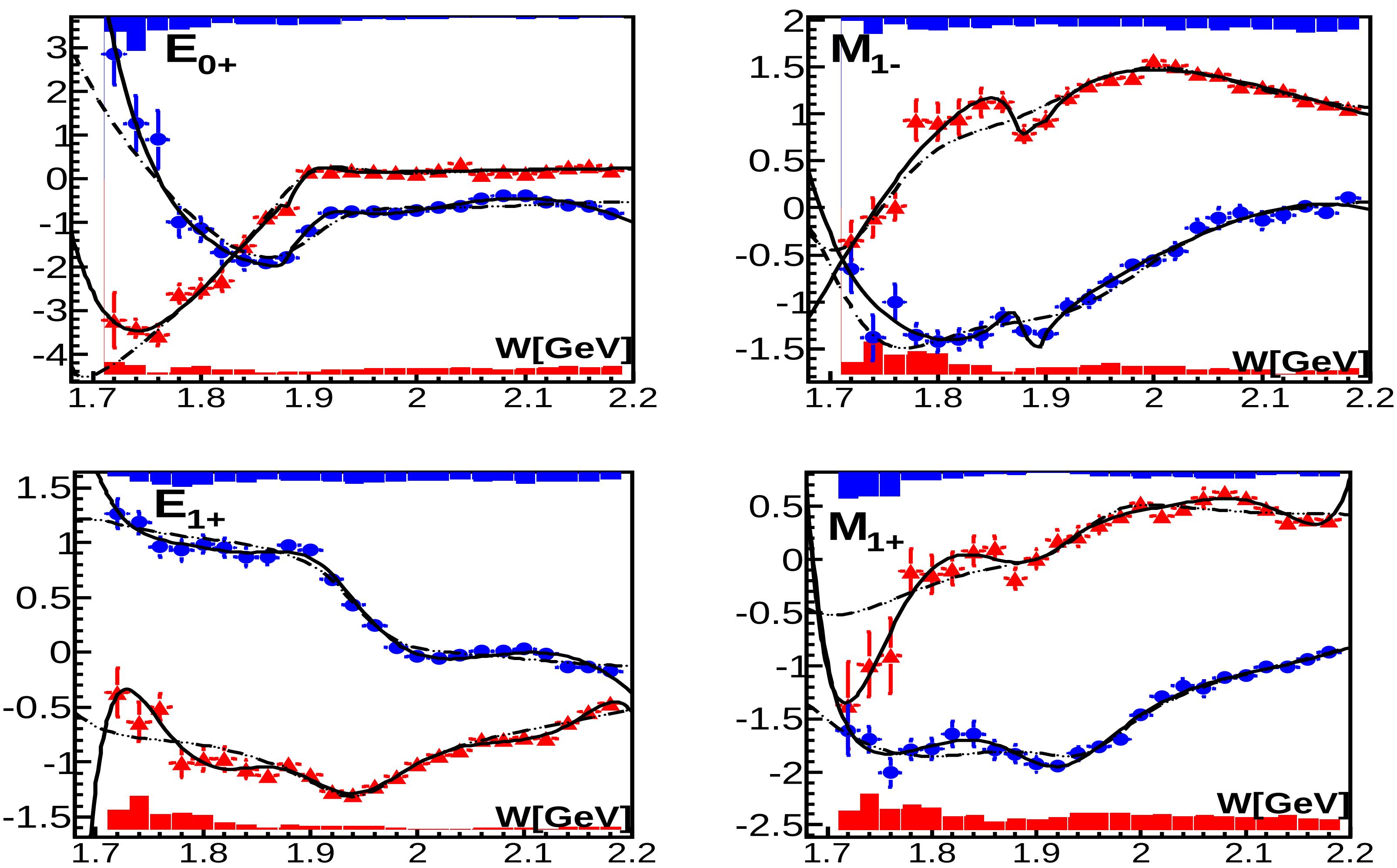
In many cases an unambiguous partial wave decomposition at fixed energies is impossible. Then the energy and angular parts should be analyzed together:

$$A(s,t) \quad = \quad \sum_{\beta\beta' n} A_n^{\beta\beta'}(s) Q^{(\beta)+}_{\mu_1\ldots\mu_n} F^{\mu_1\ldots\mu_n}_{\nu_1\ldots\nu_n} Q^{(\beta')}_{\nu_1\ldots\nu_n}$$

1. **Correlations between angular part and energy part are under control.**
2. **Unitarity and analyticity can be introduced from the beginning.**
3. **Parameters can be fixed from a combined fit of many reactions.**

1 C. Zemach, Phys. Rev. 140, B97 (1965); 140, B109 (1965)
2 S.U.Chung, Phys. Rev. D 57, 431 (1998)
3 A. V. Anisovich, V. V. Anisovich, V. N. Markov, M. A. Matveev and A. V. Sarantsev, J. Phys. G G 28, 15 (2002)
4 B. S. Zou and D. V. Bugg, Eur. Phys. J. A 16, 537 (2003)
5 A. Anisovich, E. Klempt, A. Sarantsev and U. Thoma, Eur. Phys. J. A 24, 111 (2005)
6 A. V. Anisovich and A. V. Sarantsev, Eur. Phys. J. A 30, 427 (2006)
7 A. V. Anisovich, V. V. Anisovich, E. Klempt, V. A. Nikonov and A. V. Sarantsev, Eur. Phys. J. A 34, 129 (2007).

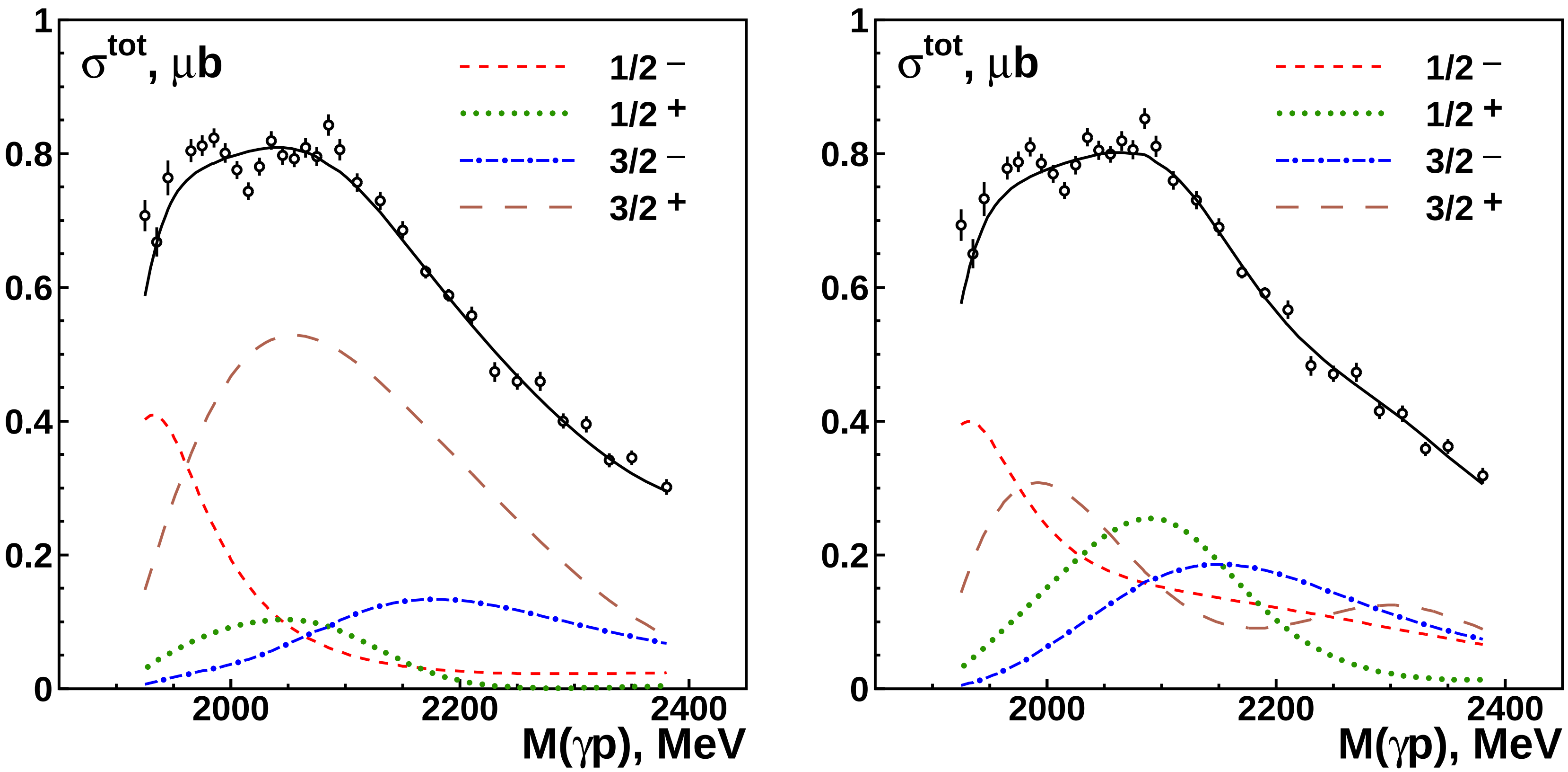
Energy independent analysis of the $\gamma p \to K\Lambda$ reaction (see A. Svarc talk)



The resonance parameters from the Bonn-Gatchina solution and from the analysis of the energy-independent data

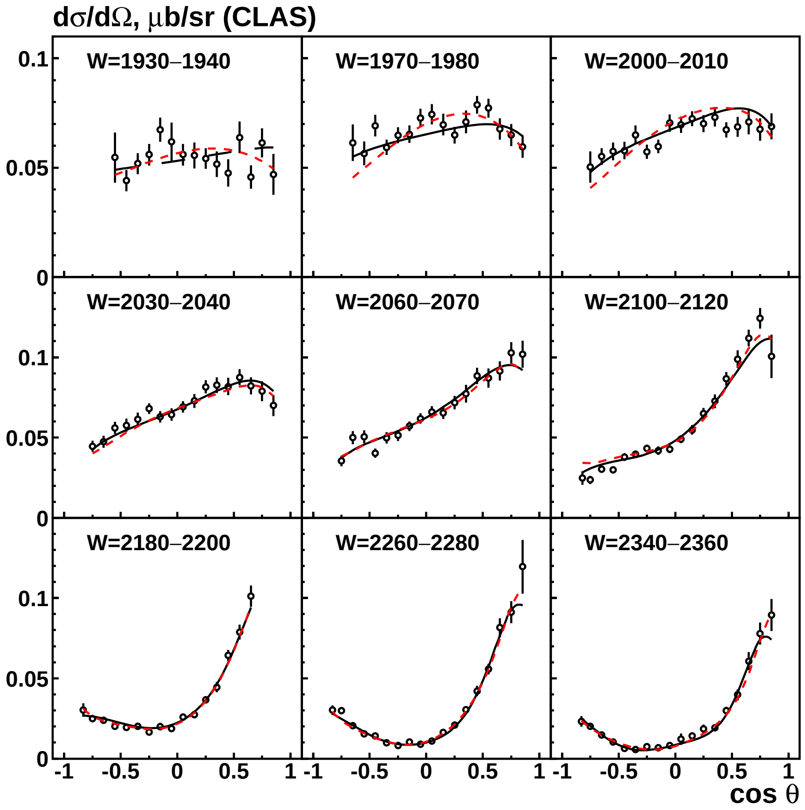
	$J^P = 1/2^-$		$J^P = 1/2^+$		$J^P = 3/2^+$	
	BnGa	**L+P**	**BnGa**	**L+P**	**BnGa**	**L+P**
M_1	1658 ± 10	1660 ± 5	1690 ± 15	1697 ± 23	-	-
Γ_1	102 ± 8	59 ± 16	155 ± 25	84 ± 34	-	-
$\|Res\|$	0.26 ± 0.10	0.10 ± 0.10	0.16 ± 0.05	$0.12^{+0.24}_{-0.12}$	-	-
Θ_1	$(110 \pm 20)^0$	$(95 \pm 33)^0$	$-(160 \pm 25)^0$	$-(119 \pm 83)^0$	-	-
M_2	1895 ± 15	1906 ± 17	1860 ± 40	1875 ± 11	1945 ± 35	1912 ± 30
Γ_2	132 ± 30	100 ± 10	230 ± 50	33 ± 9	135^{+70}_{-30}	166 ± 30
$\|Res\|$	0.09 ± 0.03	0.06 ± 0.02	0.05 ± 0.02	0.30 ± 0.10	0.03 ± 0.02	$-$
Θ_2	$(8 \pm 30)^0$	$(87 \pm 27)^0$	$(27 \pm 30)^0$	$(82 \pm 9)^0$	$(90 \pm 40)^0$	$-$

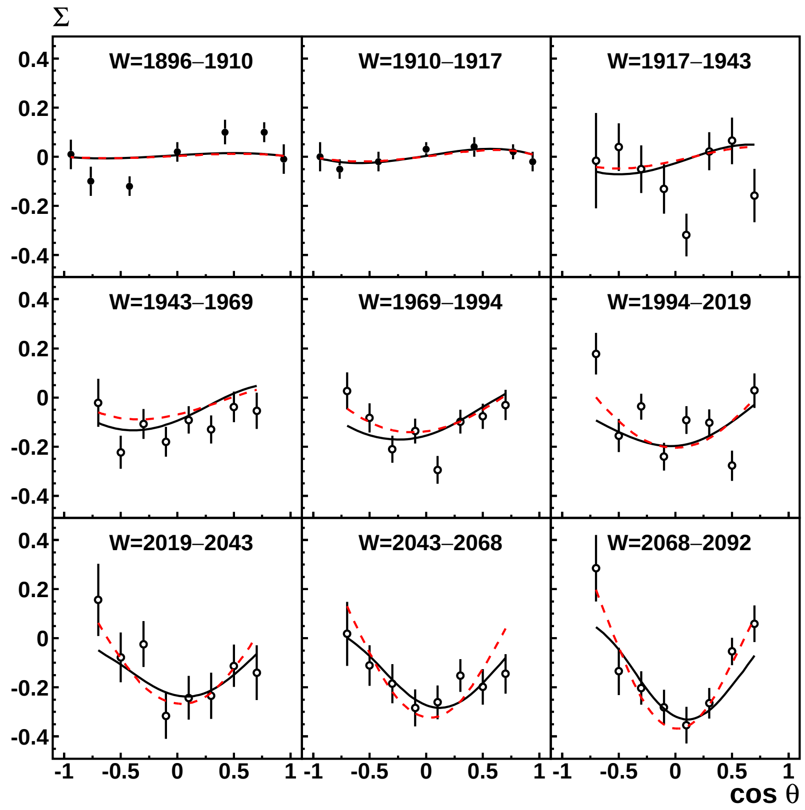
The analysis of the $\gamma p \to \eta' p$ data.



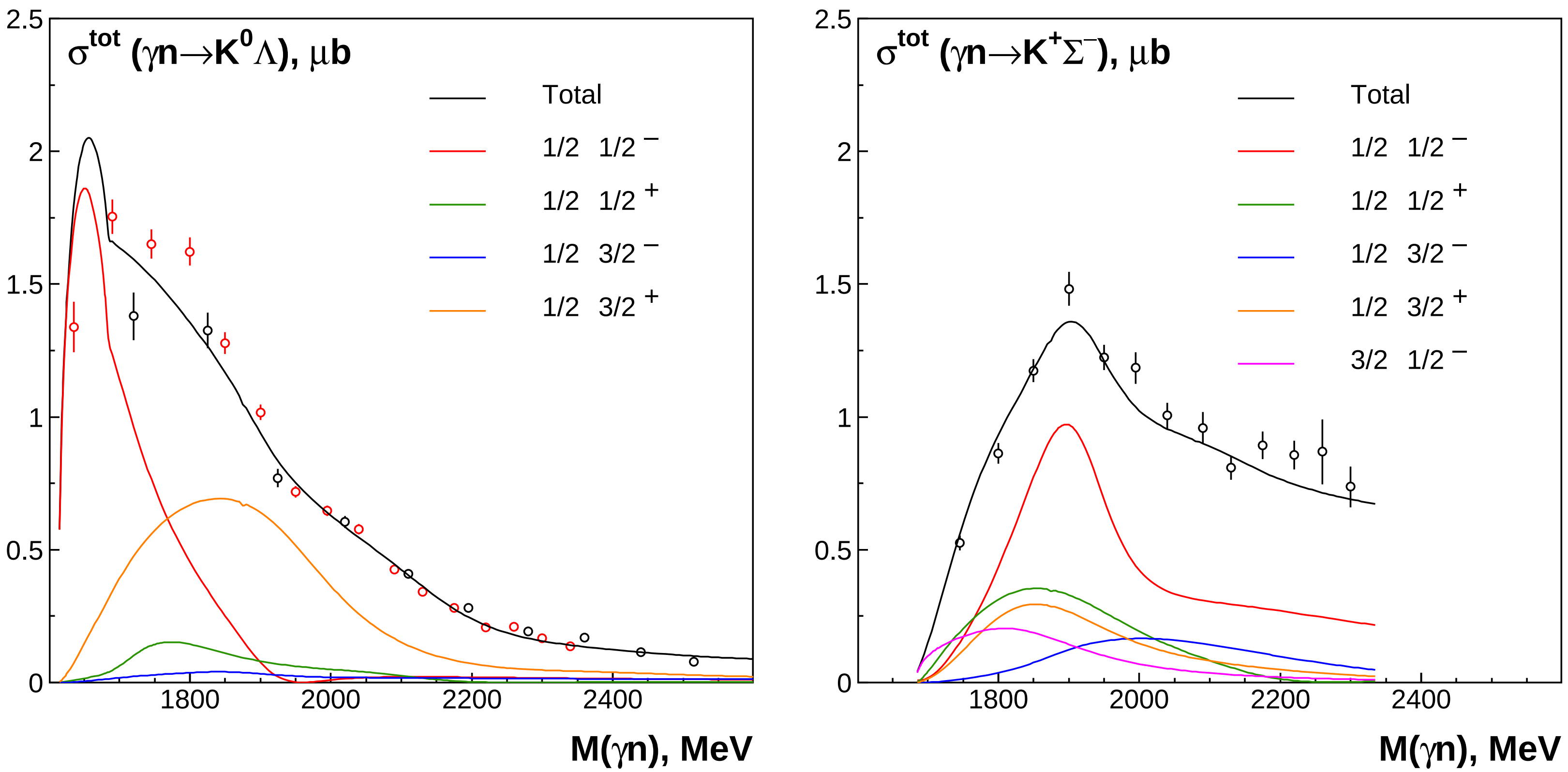
Two solutions, but in both a strong contribution from the $S_{11}(1895)$, $P_{13}(1900)$, $P_{11}(2100)$ and $D_{13}(2120)$ states.

The analysis of the $\gamma p \to \eta' p$ data.





The analysis of the $\gamma n \to K\Lambda$ data and the $\gamma n \to K^+\Sigma^-$ data (Practically no free parameters)



Clear contributions from the $S_{11}(1895)$ and $P_{13}(1900)$ states.

The analysis of the E polarization data from $\gamma n \to \eta n$ (MAMI)

Will be given in the talk of V.Nikonov (this evening)

Photo production of the vector mesons: Density matrices

$$\frac{d\sigma}{d\Omega_\omega\, d\Omega_{dec}} = \frac{d\sigma}{d\Omega_\omega} W(\cos\Theta_{dec}, \Phi_{dec})$$

$$\gamma p \to p\omega(\pi^+\pi^-\pi^0)$$

$$W(\cos\Theta, \Phi) = \frac{3}{4\pi}\left(\frac{1}{2}(1-\rho_{00}) + \frac{1}{2}(3\rho_{00}-1)\cos^2\Theta - \sqrt{2}Re\rho_{10}\sin 2\Theta\cos\Phi - \rho_{1-1}\sin^2\Theta\cos 2\Phi\right).$$

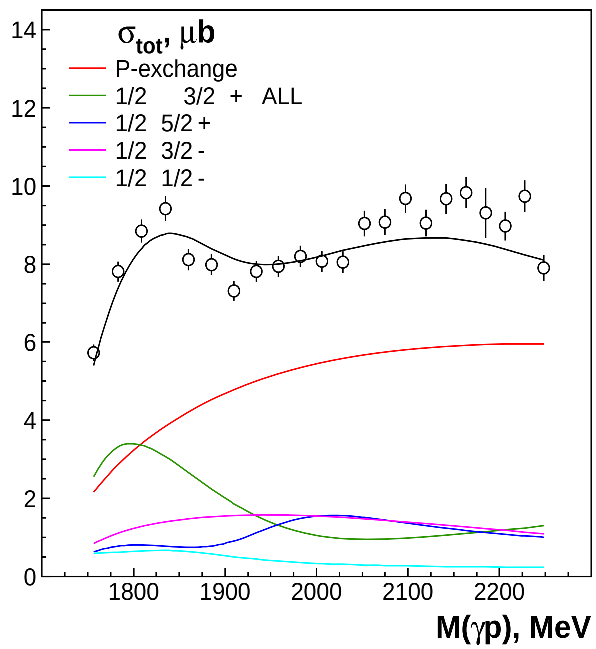
$\cos\Theta, \Phi$ **direction of the vector** $n = \varepsilon_{ijkm} p_j^{\pi^+} p_k^{\pi^-} p_m^{\pi^0}$ **in the** ω **rest frame.**

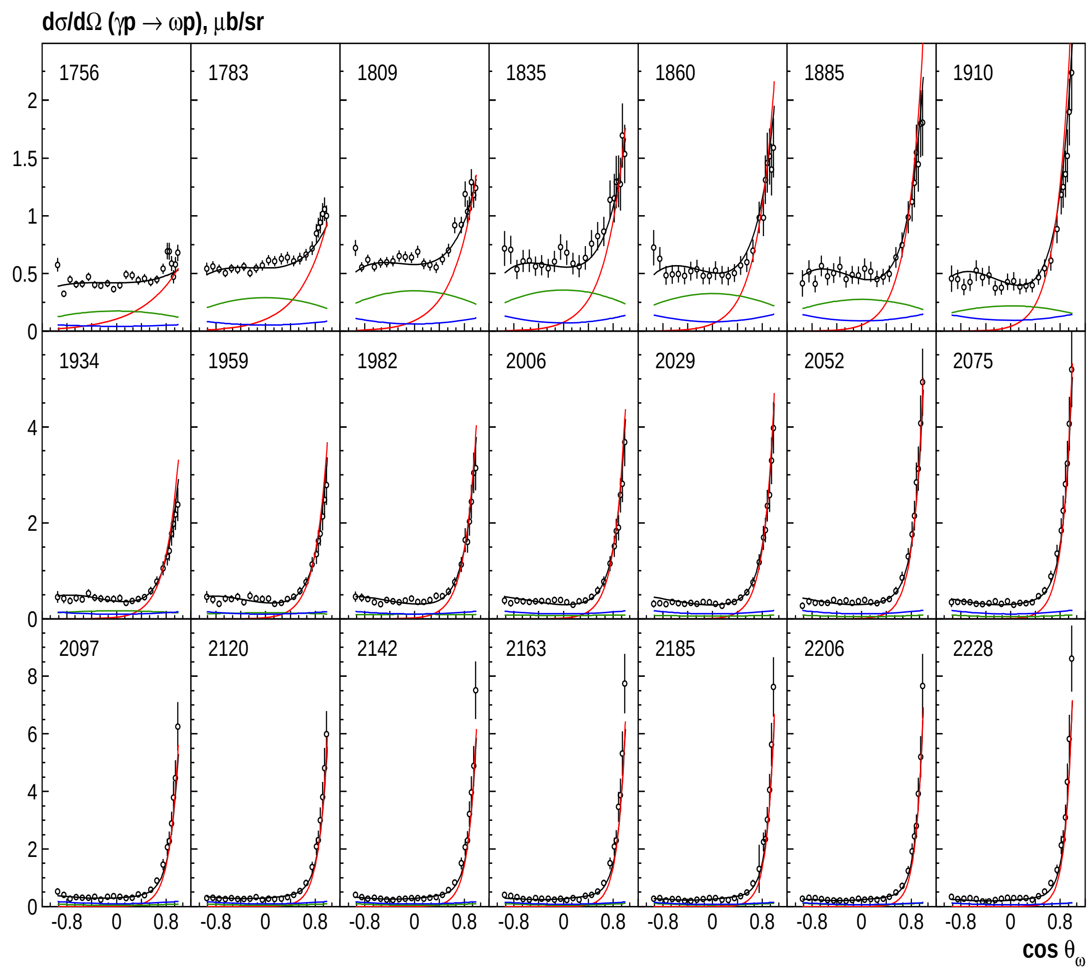
$$\gamma p \to p\omega(\gamma\pi^0)$$

$$W(\cos\Theta, \Phi) = \frac{3}{8\pi}\left(\frac{1}{2}(1+\cos^2\Theta) + \frac{1}{2}(1-3\cos^2\Theta)\rho_{00} + \sqrt{2}Re\rho_{10}\sin(2\Theta)\cos\Phi + \rho_{1-1}\sin^2\Theta\cos 2\Phi\right).$$

$\cos\Theta, \Phi$ **angles of photon from** ω **decay in the** ω **rest frame**

The $\gamma p \to p\omega$ data



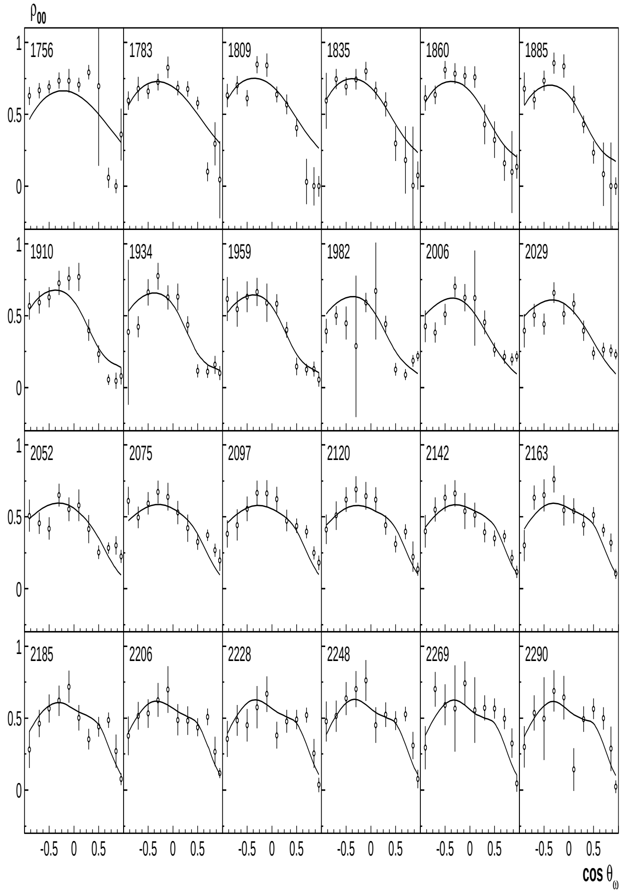


Strong contribution from the $P_{13}(1700)$ and $P_{13}(1900)$ states.

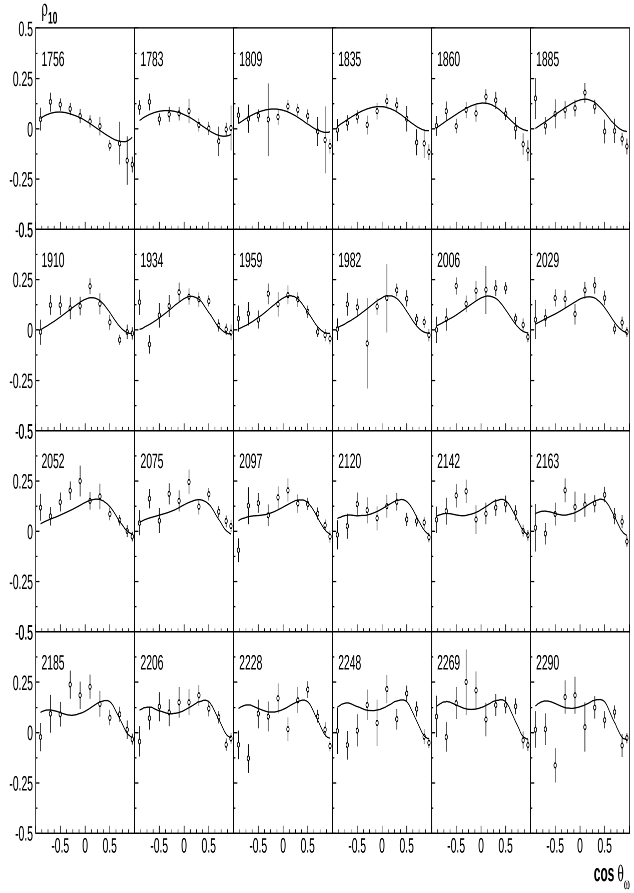
A confirmation of the $F_{15}(2000)$ state.

Fit of the density matrices $\gamma p \to p\omega$ (CB-ELSA) (A.Wilson)

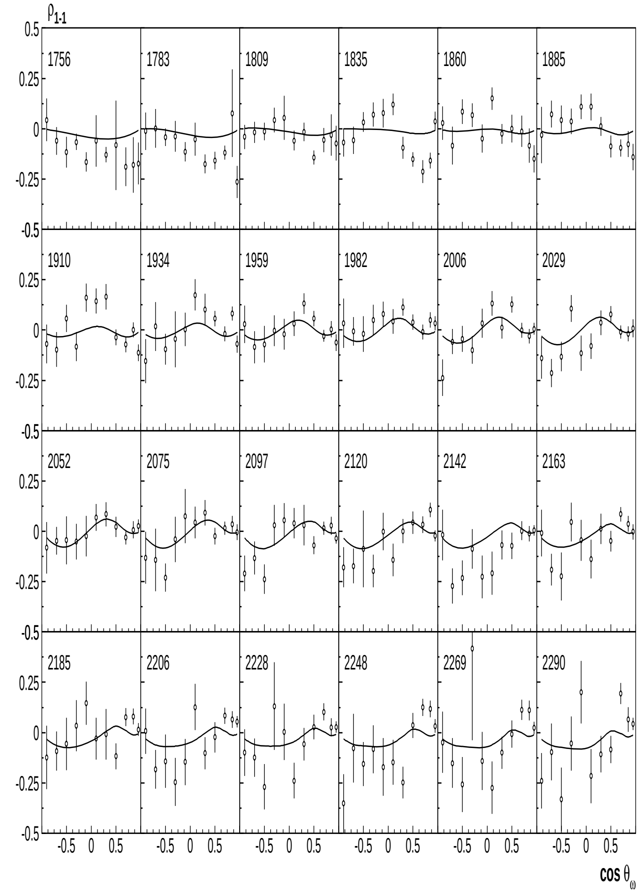
ρ^0_{00}



ρ^0_{10}

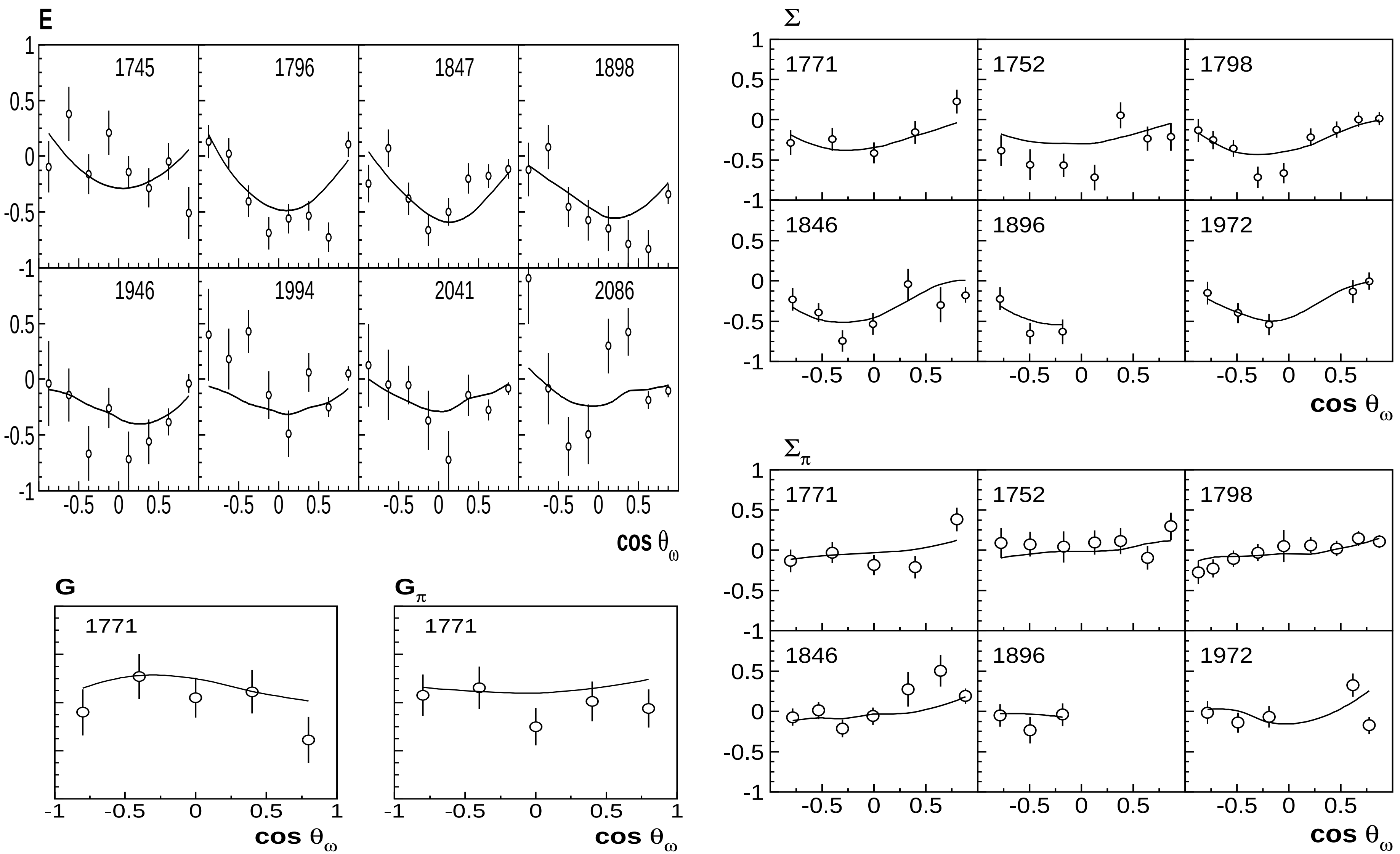


ρ^0_{1-1}

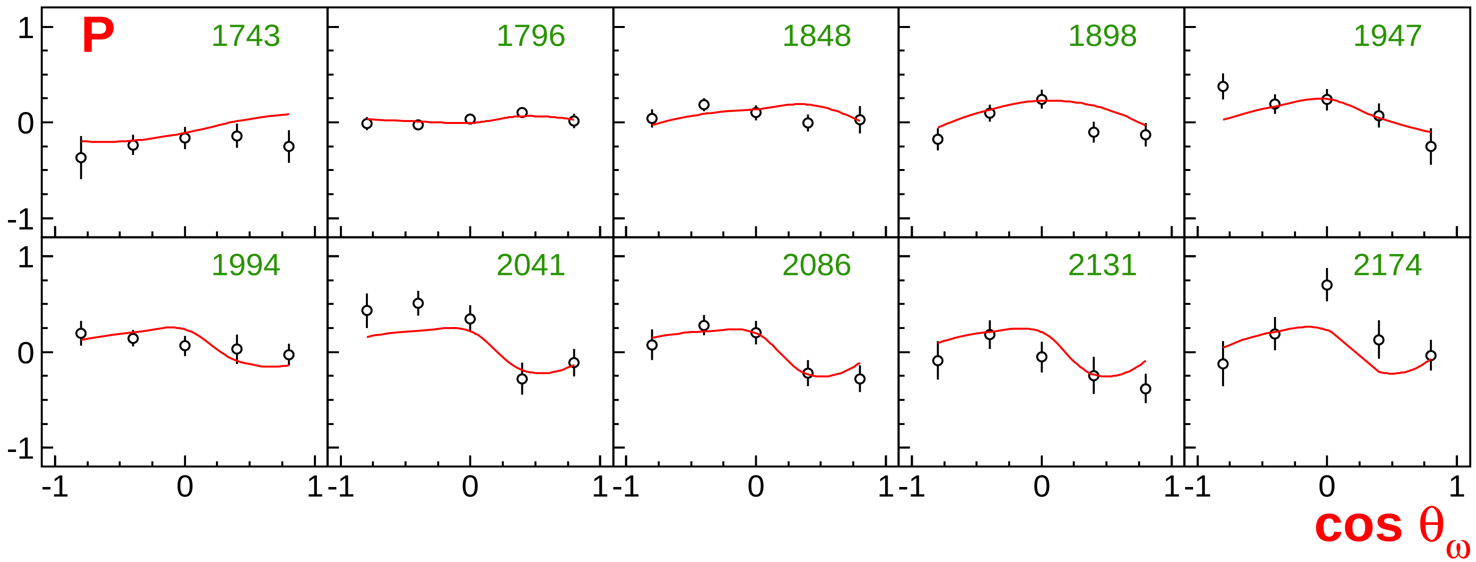


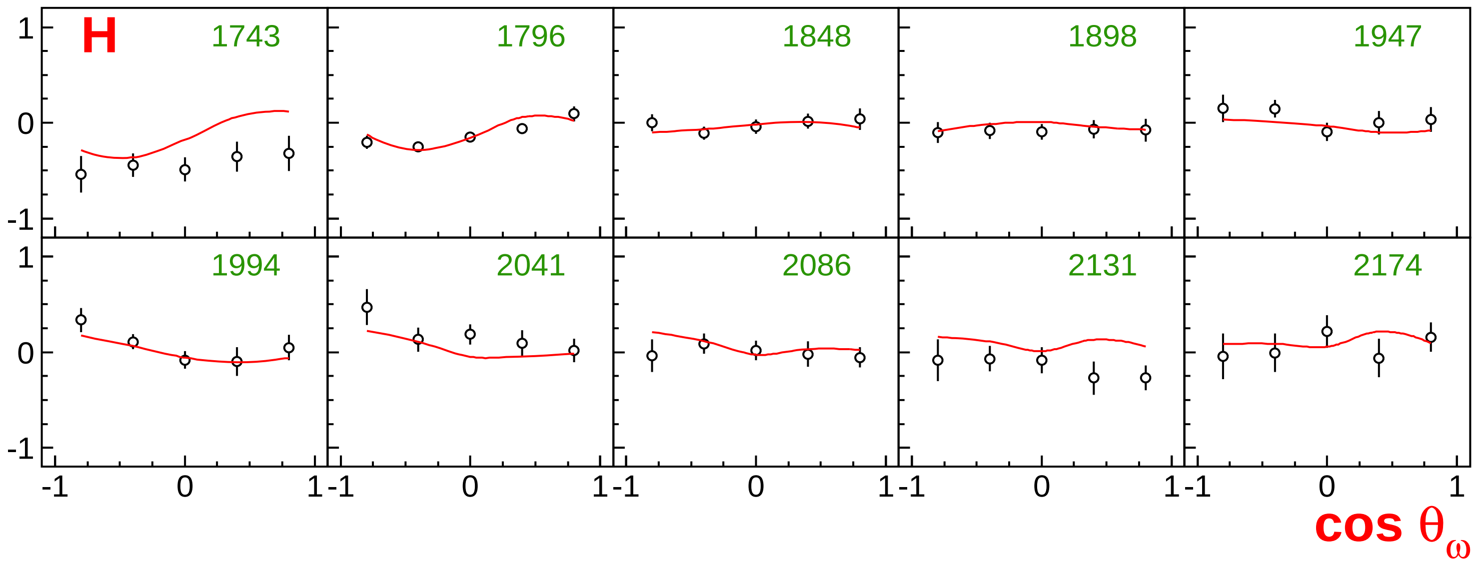
Omega photoproduction

and polarization observables from CB-ELSA H.Eberhard (PhD thesis)



The new polarization data from the Florida State University (CLAS, Priliminary)





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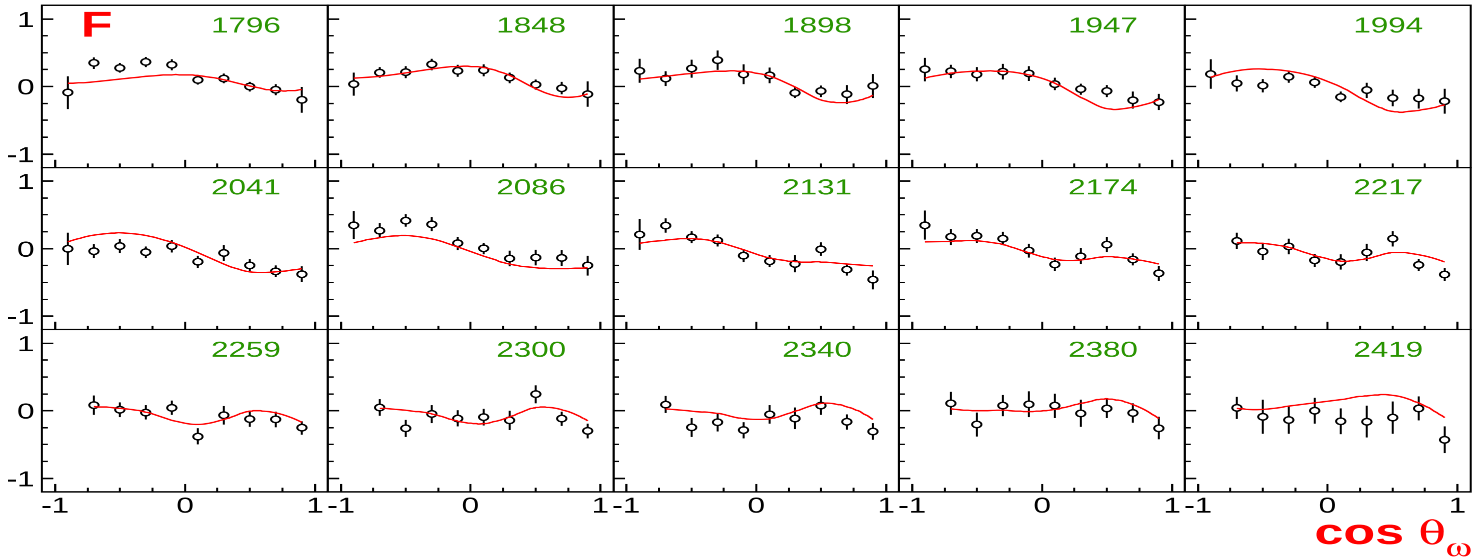
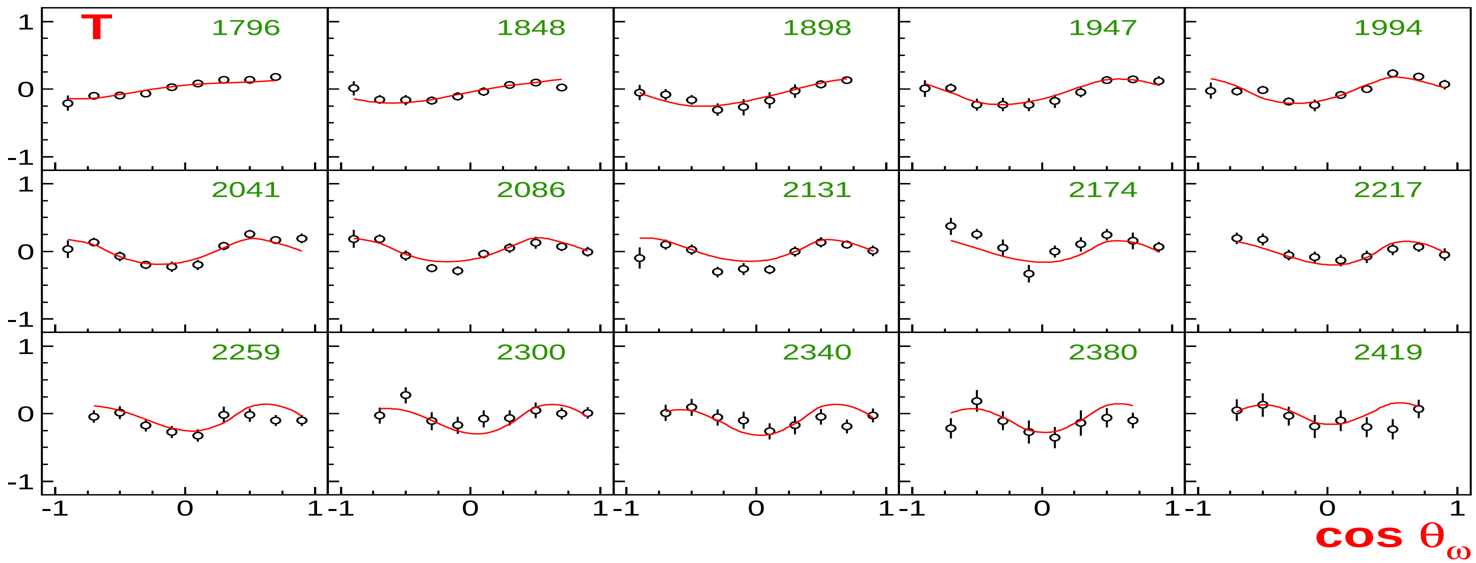
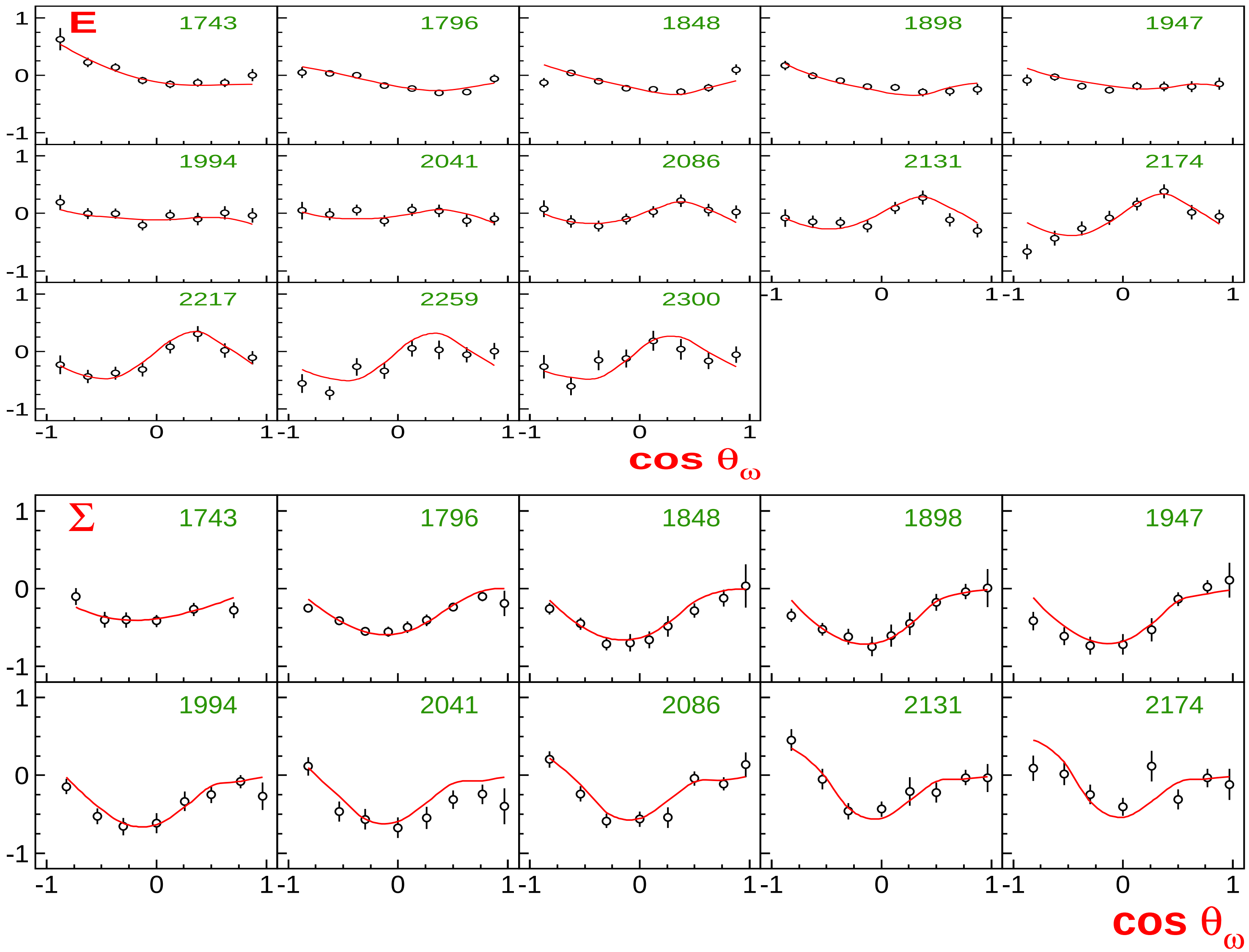
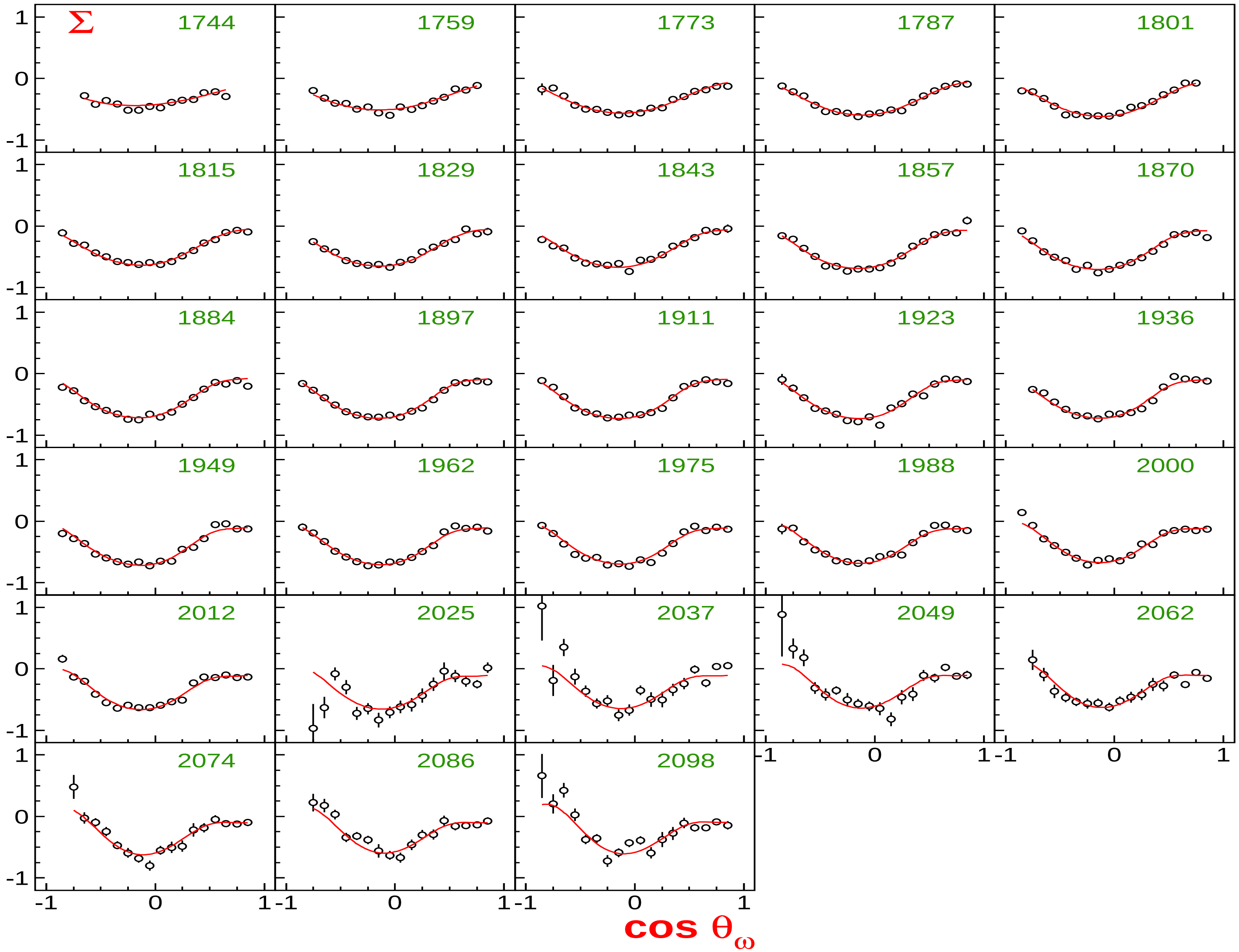




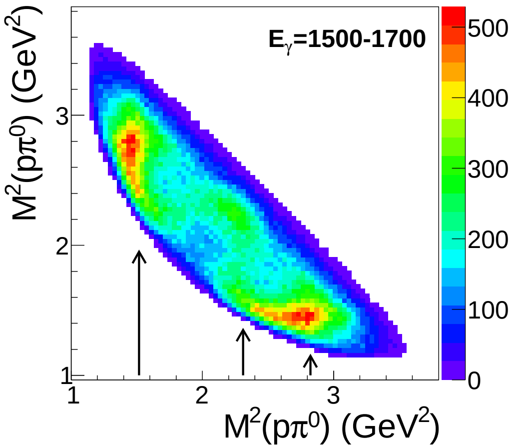
The new polarization data from the Florida State University (CLAS, Priliminary)

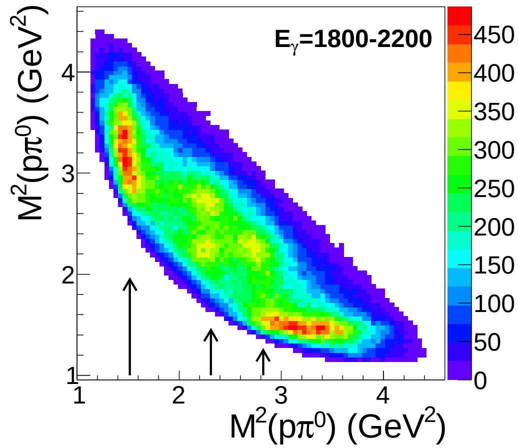


The new beam asymmetry from Arizona State University (CLAS, Priliminary)



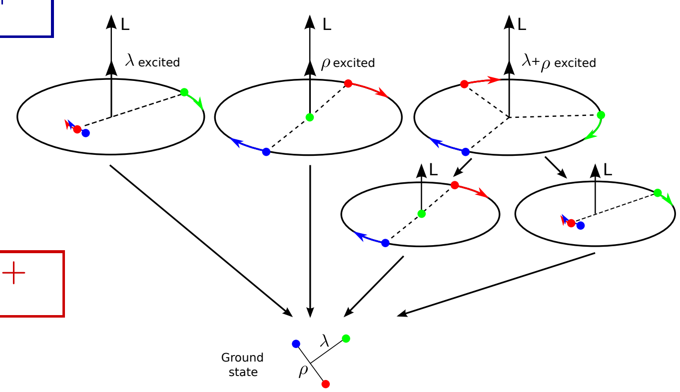
S	space spin isospin
S_1	$\mathcal{S}\mathcal{S}\mathcal{S}$
S_2	$\mathcal{S}(\mathcal{M}_\mathcal{S}\mathcal{M}_\mathcal{S} + \mathcal{M}_\mathcal{A}\mathcal{M}_\mathcal{A})$
S_3	$(\mathcal{M}_\mathcal{S}\mathcal{M}_\mathcal{S} + \mathcal{M}_\mathcal{A}\mathcal{M}_\mathcal{A})\mathcal{S}$
S_4	$(\mathcal{M}_\mathcal{A}\mathcal{M}_\mathcal{A} - \mathcal{M}_\mathcal{S}\mathcal{M}_\mathcal{S})\mathcal{M}_\mathcal{S}$
	$+(\mathcal{M}_\mathcal{S}\mathcal{M}_\mathcal{A} + \mathcal{M}_\mathcal{A}\mathcal{M}_\mathcal{S})\mathcal{M}_\mathcal{A}$
S_5	$(\mathcal{M}_\mathcal{S}\mathcal{S}\mathcal{M}_\mathcal{S} + \mathcal{M}_\mathcal{A}\mathcal{S}\mathcal{M}_\mathcal{A})$
S_6	$\mathcal{A}(\mathcal{M}_\mathcal{A}\mathcal{M}_\mathcal{S} - \mathcal{M}_\mathcal{S}\mathcal{M}_\mathcal{A})$





$\Delta(1910)1/2^+$ $\Delta(1920)3/2^+$ $\Delta(1905)5/2^+$ $\Delta(1950)7/2^+$

$$\mathcal{S} = \frac{1}{\sqrt{2}}\left\{\left[\phi_{0s}(\vec{\rho}) \times \phi_{0d}(\vec{\lambda})\right] + \left[\phi_{0d}(\vec{\rho}) \times \phi_{0s}(\vec{\lambda})\right]\right\}^{(L=2)}$$



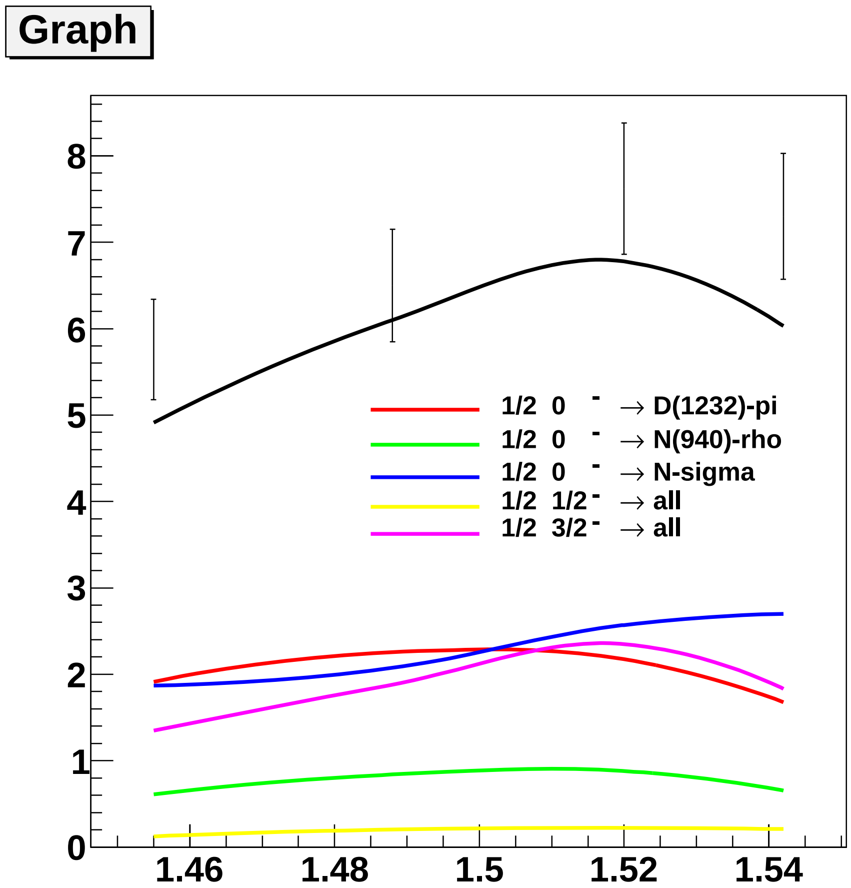
$N(1880)1/2^+$ $N(1900)3/2^+$ $N(2000)5/2^+$ $N(1990)7/2^+$

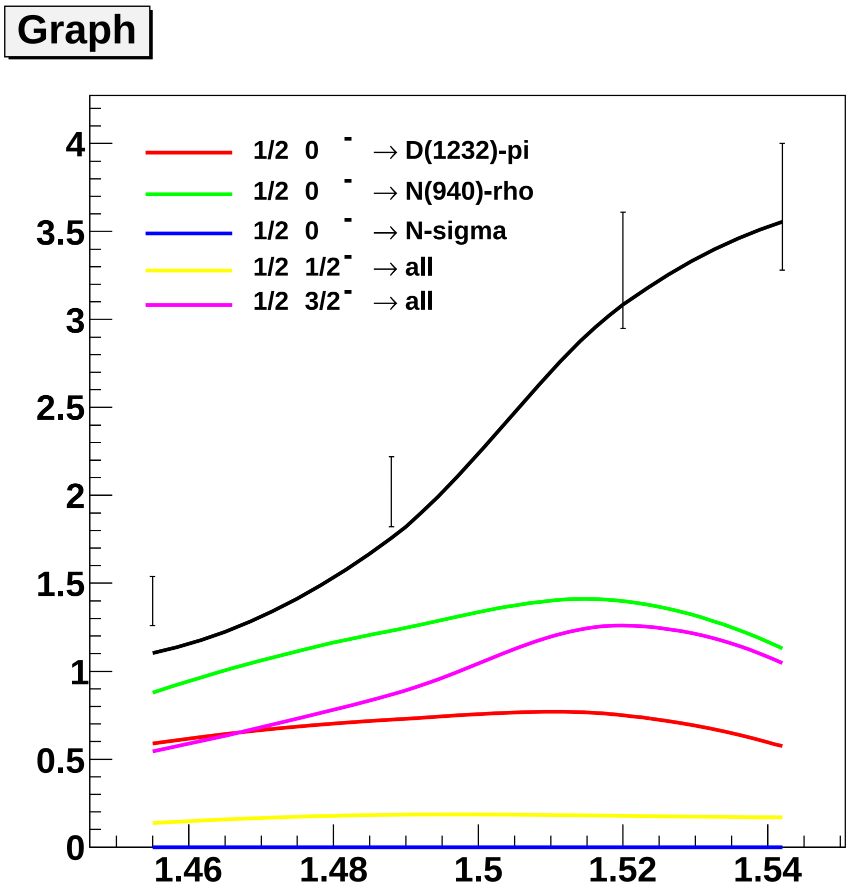
$$\mathcal{M}_\mathcal{S} = \frac{1}{\sqrt{2}}\left\{\left[\phi_{0s}(\vec{\rho}) \times \phi_{0d}(\vec{\lambda})\right] - \left[\phi_{0d}(\vec{\rho}) \times \phi_{0s}(\vec{\lambda})\right]\right\}^{(L=2)}$$

$$\mathcal{M}_\mathcal{A} = \left[\phi_{0p}(\vec{\rho}) \times \phi_{0p}(\vec{\lambda})\right]^{(L=2)} .$$

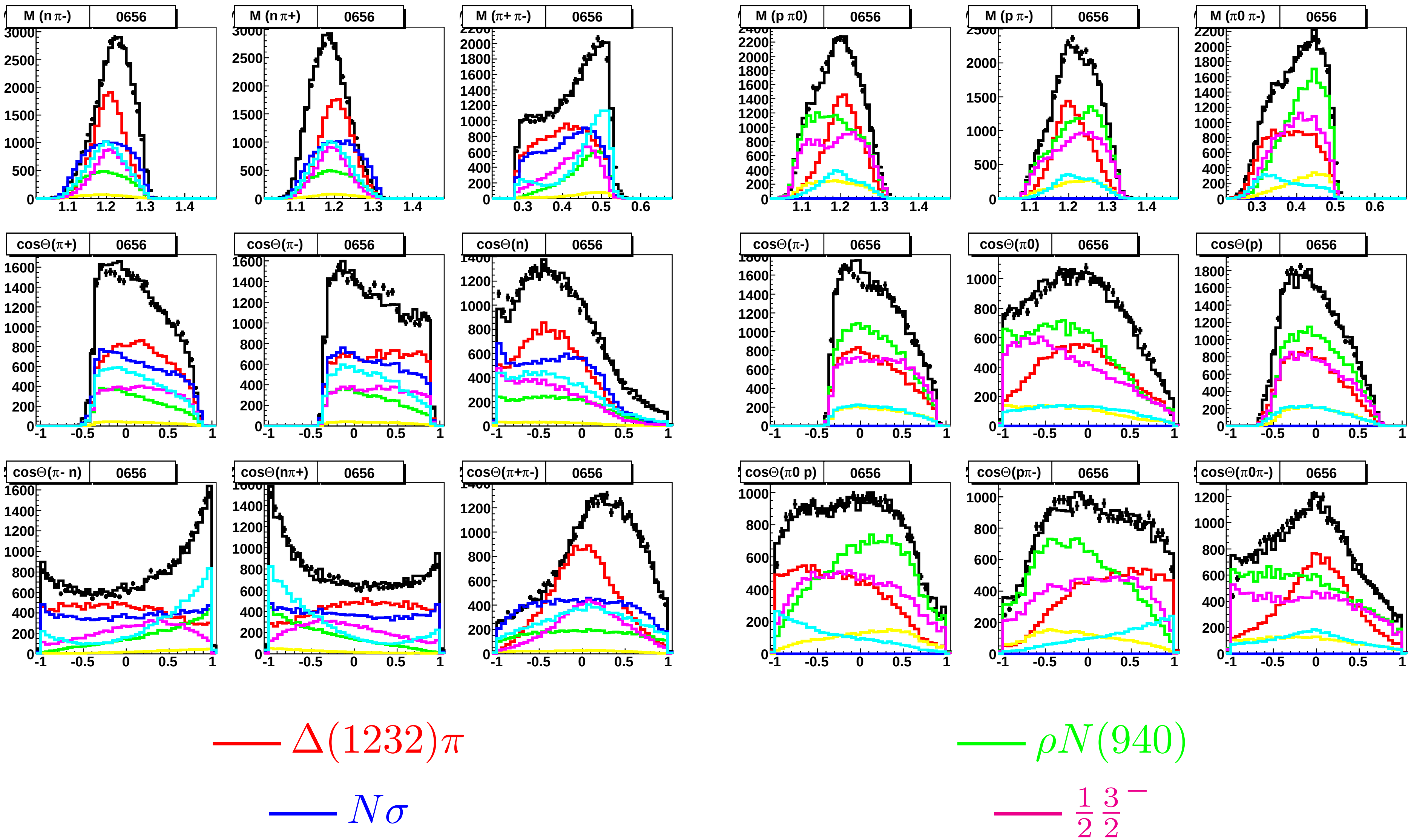
The total cross section from the HADES data

$\pi^- p \to \pi^+ \pi^- n$ and $\pi^- p \to \pi^- \pi^0 p$ data (W.Przigoda)

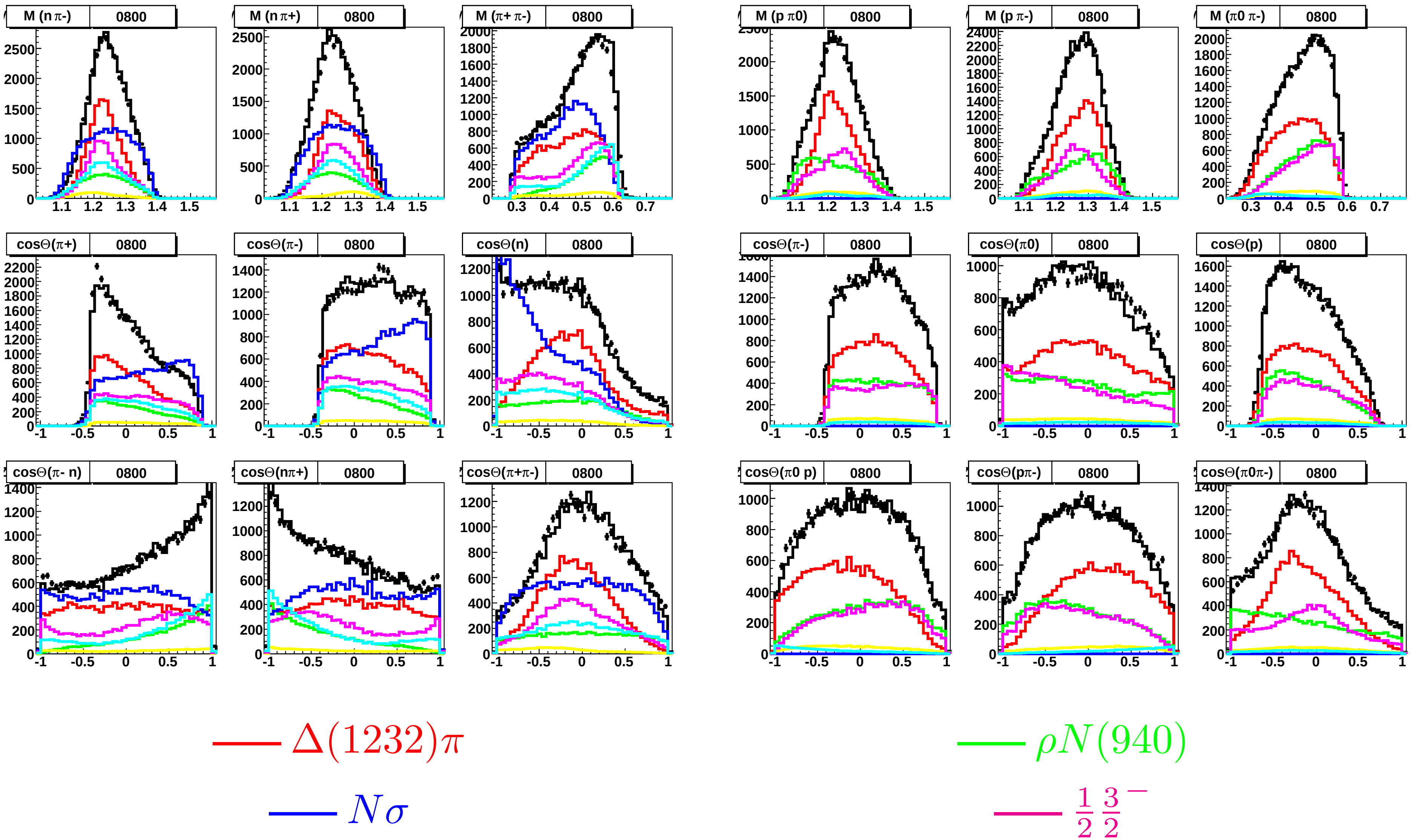




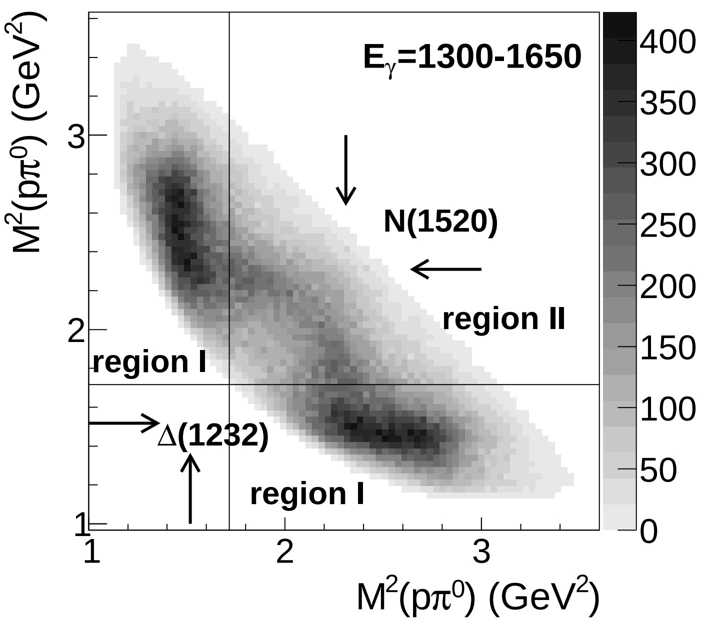
HADES data on $\pi^- p \to \pi^+\pi^- n$ and $\pi^-\pi^0 p$ at P=656 MeV/c

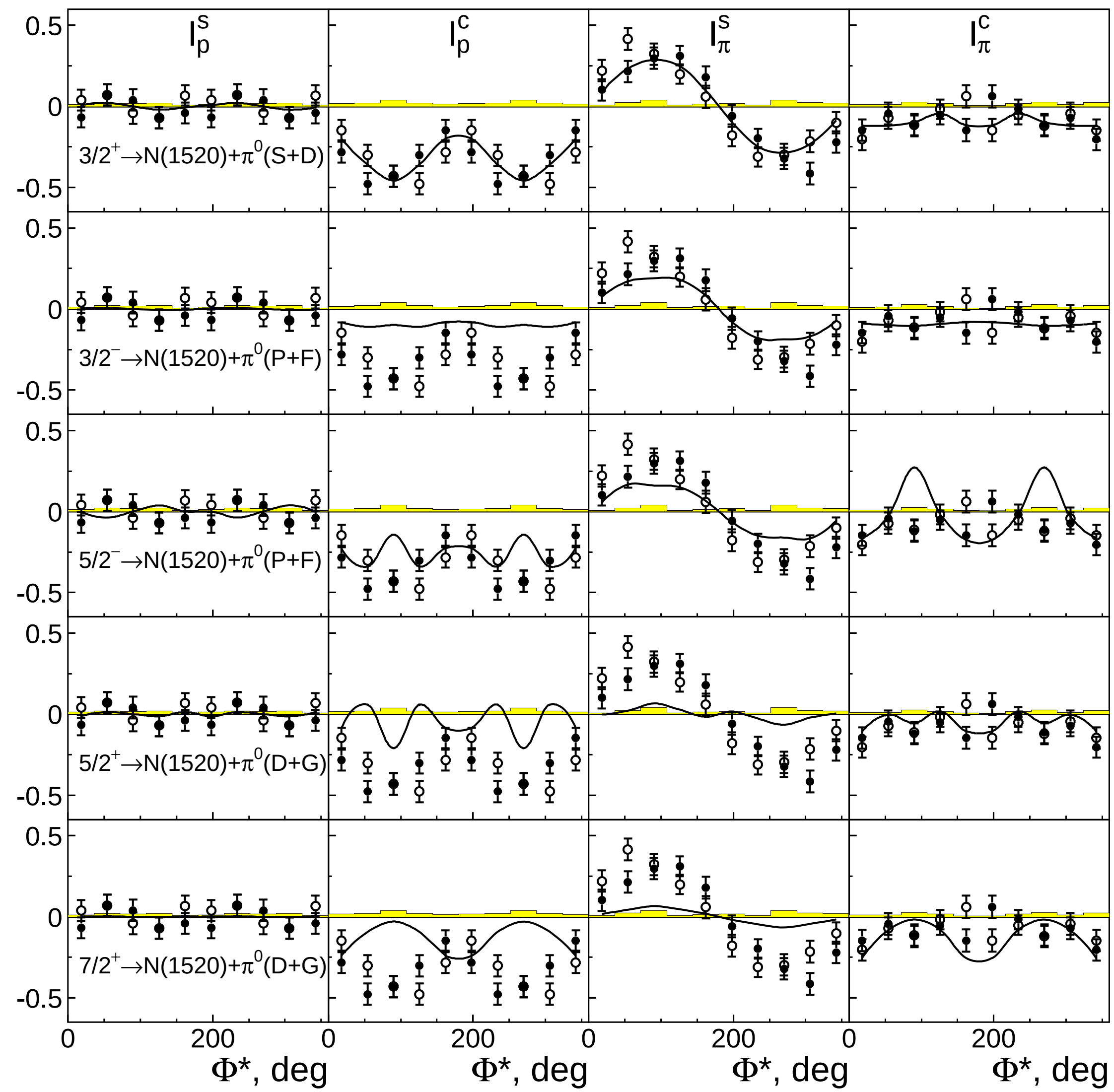


HADES data on $\pi^- p \to \pi^+\pi^- n$ and $\pi^-\pi^0 p$ at P=800 MeV/c



I_c and I_s polarization data are very important for the partial wave analysis

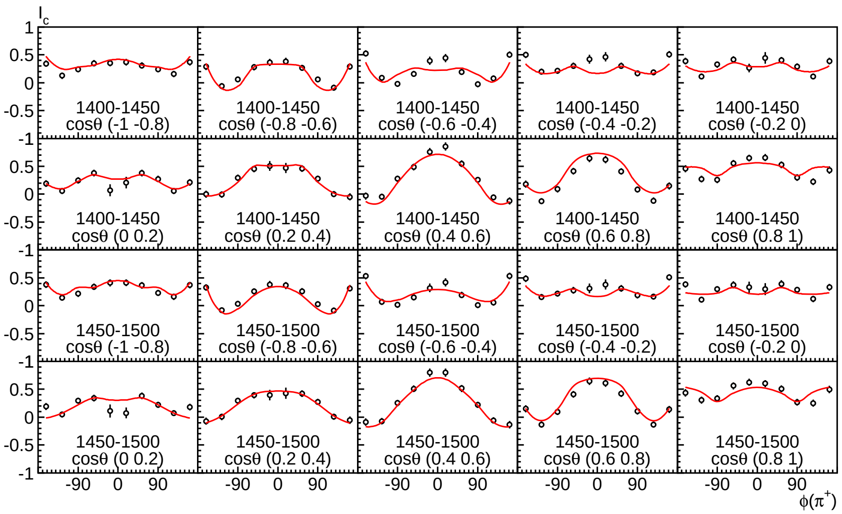




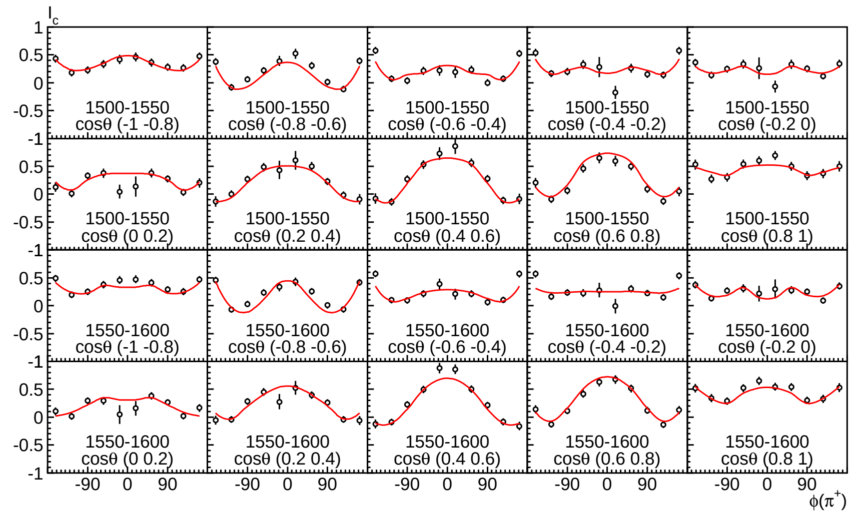
I_c and I_s for $\gamma p \to \pi^+\pi^- p$ from CLAS (Preliminary)

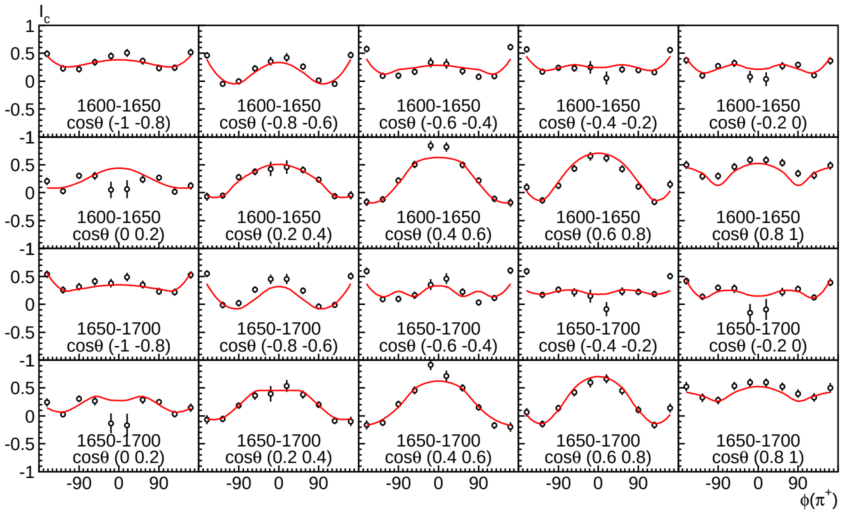
Courtesy of V. Crede, Florida State U

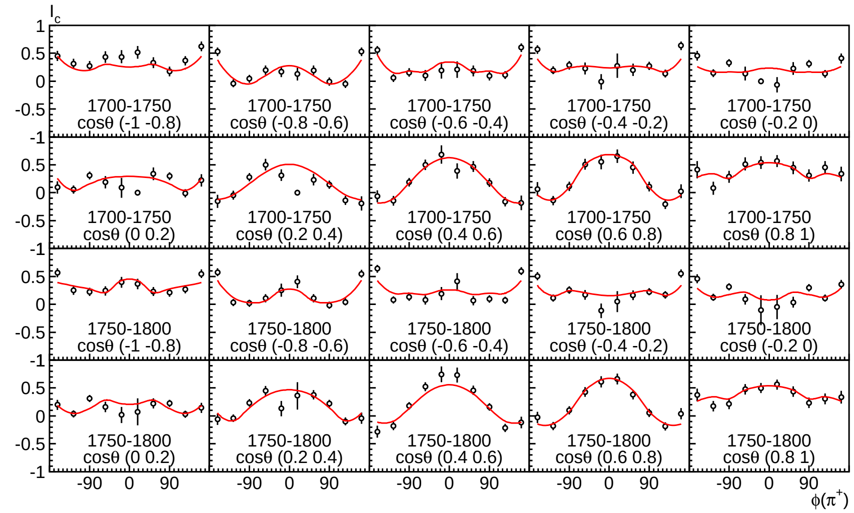
I_c



I_c



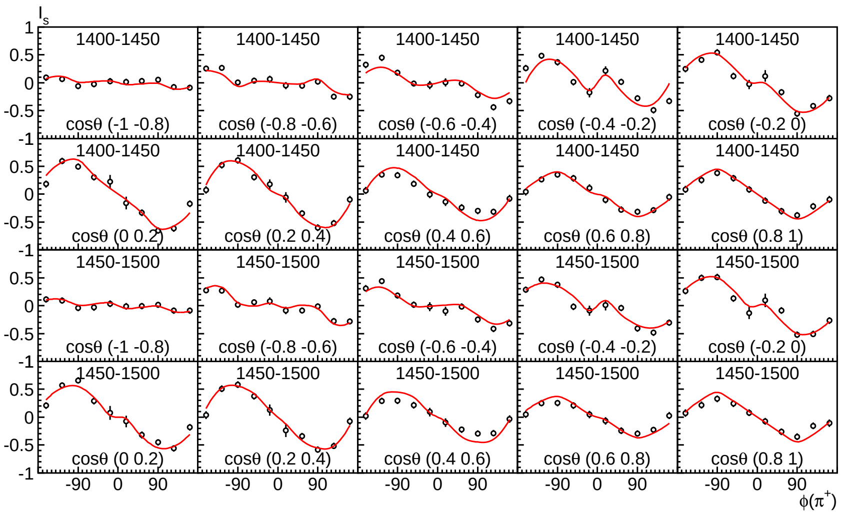




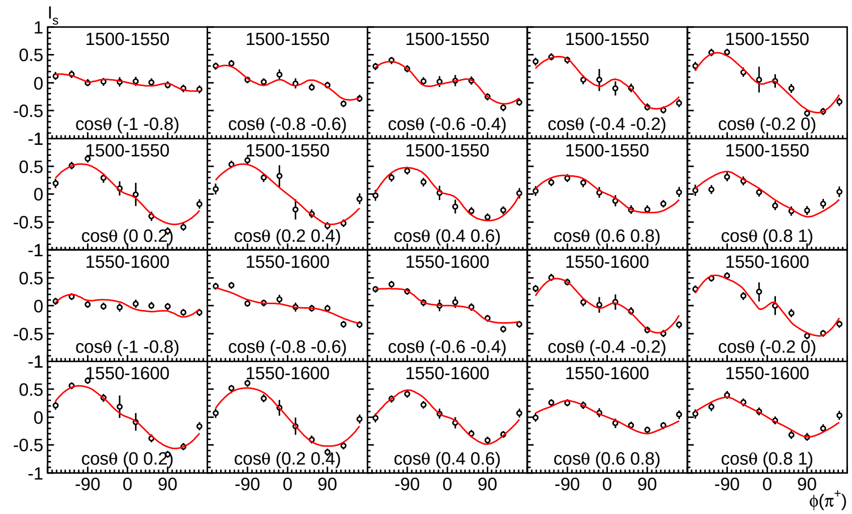
I_c and I_s for $\gamma p \to \pi^+\pi^- p$ from CLAS (Preliminary)

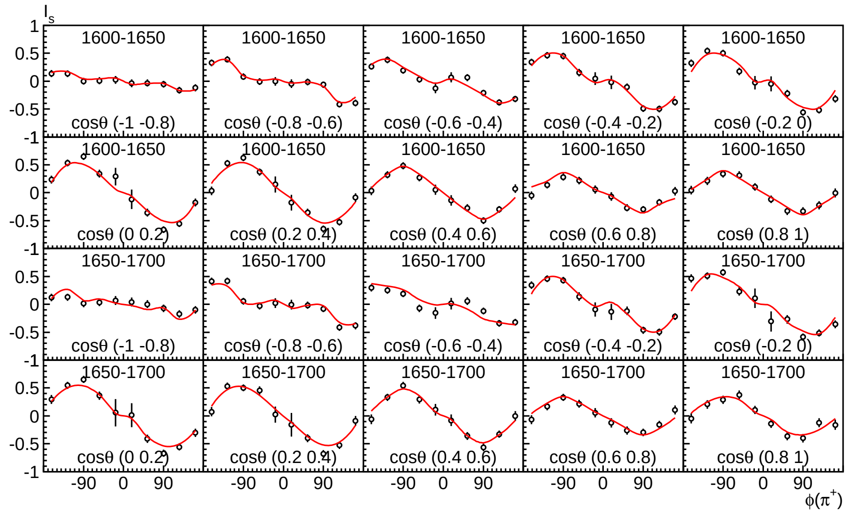
Courtesy of V. Crede, Florida State U

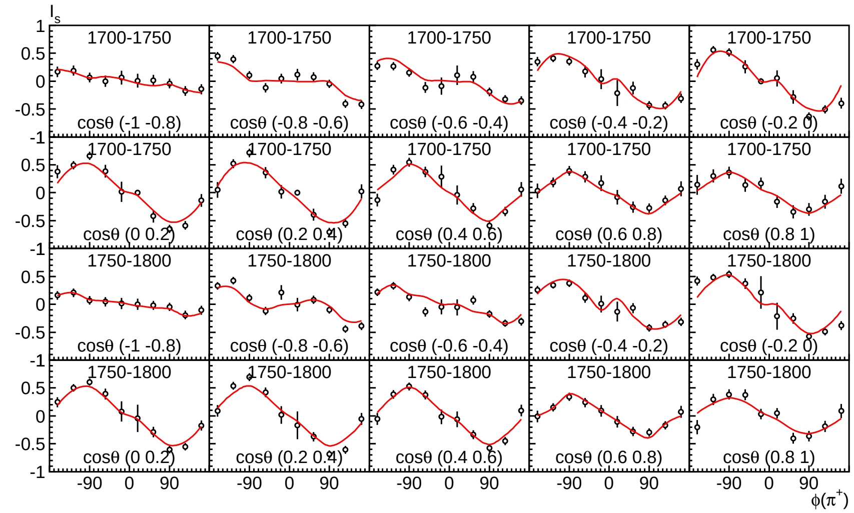
I_s



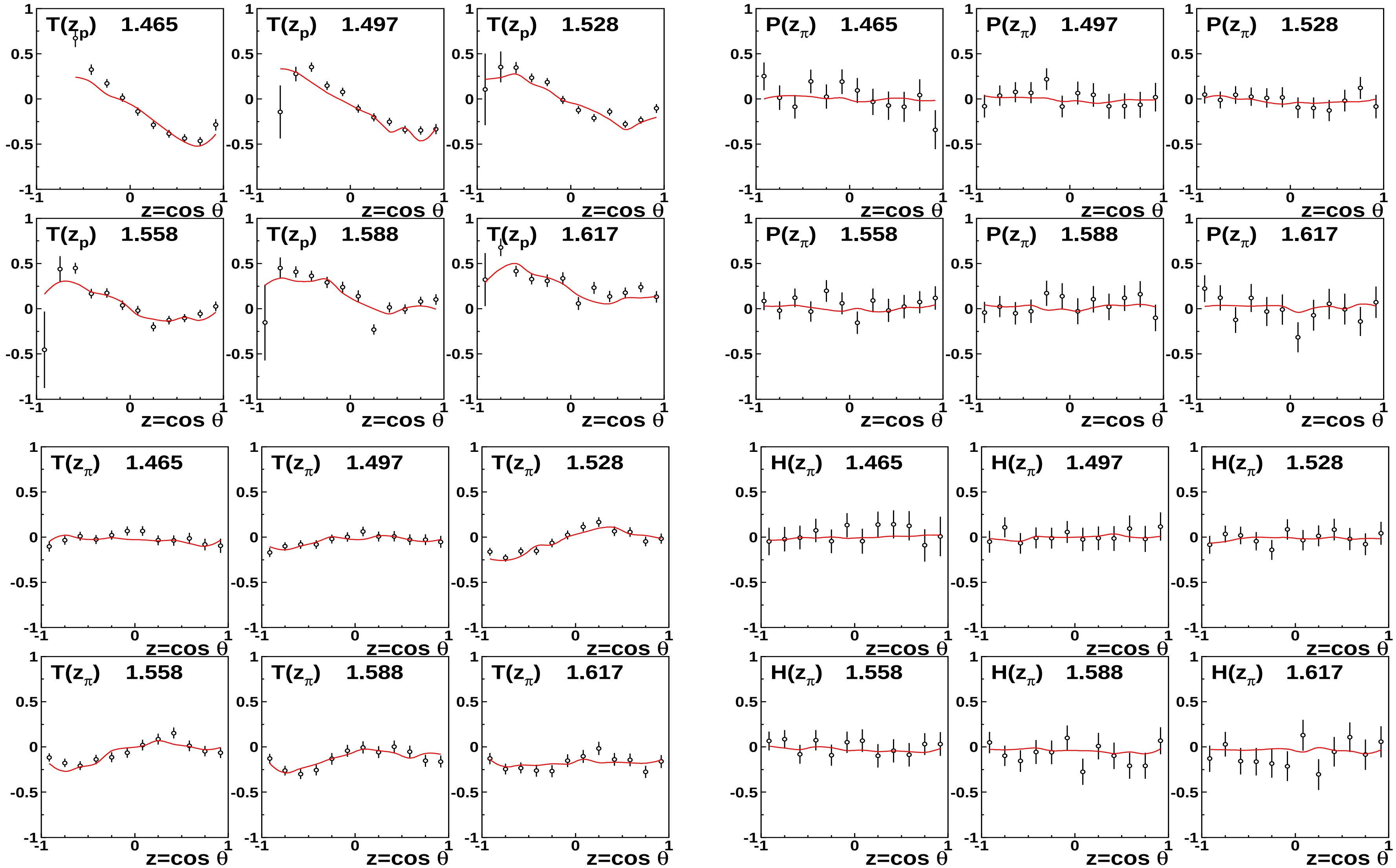
I_s



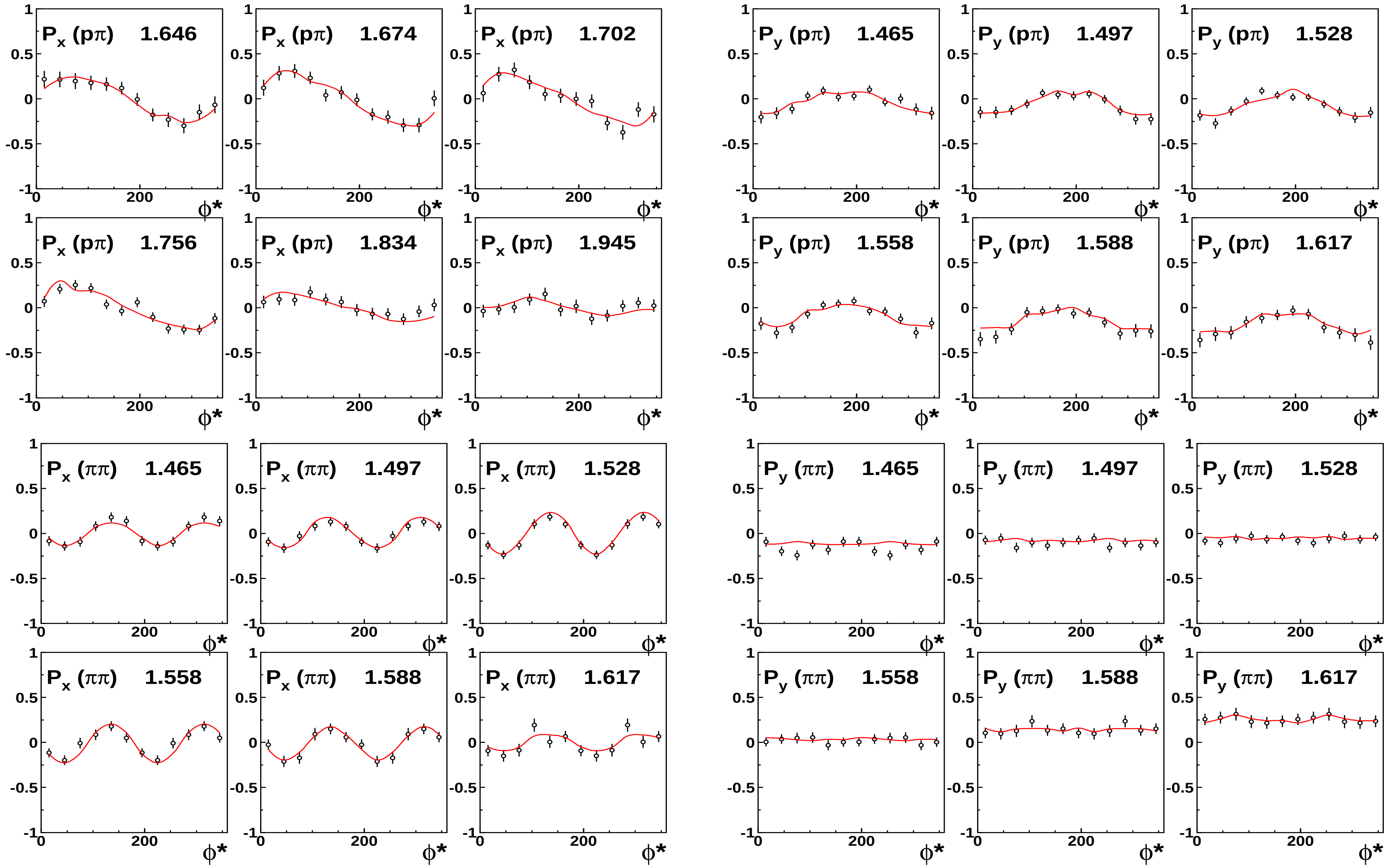




Fit of the H, P, T ($\gamma p \to \pi^0 \pi^0 p$) from CB-ELSA (T. Seifen, Preliminary)



Fit of the P_x, P_y, P_x^S, P_y^s observables ($\gamma p \to \pi^0\pi^0 p$) from CB-ELSA (T. Seifen, Preliminary)



$N\rho(770)$ **branching ratio (Preliminary)**

$N(1440)1/2^+$	$<$**1%**	$N(1520)3/2^-$	**11$\pm$2%**	$N(1535)1/2^-$	**2$\pm$1%**
$N(1650)1/2^-$	**13$\pm$2%**	$N(1675)5/2^-$	$<$**1%**	$N(1685)5/2^+$	**12$\pm$2%**
$N(1710)1/2^+$	**9$\pm$3%**	$N(1720)3/2^+$	**60$\pm$18%**	$N(1880)1/2^+$	**30$\pm$8%**
$N(1895)1/2^-$	**55$\pm$10%**	$N(1875)3/2^-$	**60$\pm$14%**	$N(2060)5/2^-$	**12$\pm$8%**
$N(2120)3/2^-$	**50$\pm$17%**	$N(2000)5/2^+$	**20$\pm$12%**	$N(1900)3/2^+$	**25$\pm$10%**
$\Delta(1600)3/2^+$	**2$\pm$2%**	$\Delta(1620)1/2^-$	**40$\pm$5%**	$\Delta(1940)3/2^+$	**8$\pm$4%**
$\Delta(2200)3/2^+$	**20$\pm$8%**	$\Delta(1700)3/2^-$	**12$\pm$4%**	$\Delta(2100)3/2^-$	**11$\pm$5%**
$\Delta(1750)1/2^+$	**40$\pm$12%**	$\Delta(1900)1/2^-$	**30$\pm$8%**	$\Delta(1905)5/2^+$	**35$\pm$8%**

Analysis of the reactions with virtual photon in the final state

e^+e^- simulated (full analysis) cocktail

LEGEND

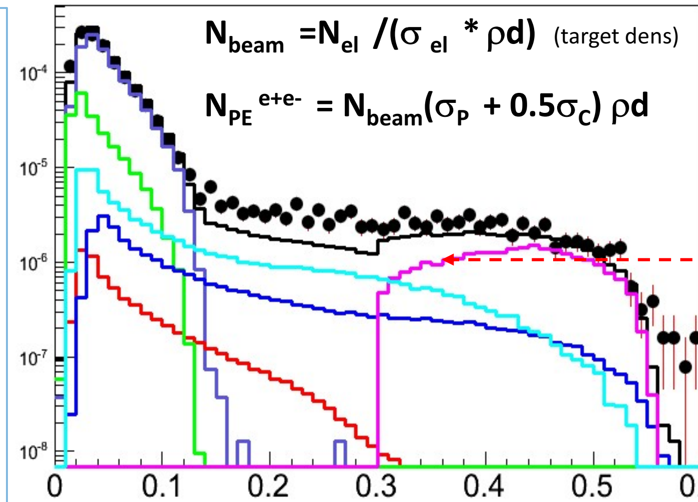
- total
- [9.2 mb] $\pi^0 \to e^+e^-\gamma$
- [7.4 mb] $2{*}\pi^0(\to e^+e^-\gamma)$
- [1.0 mb] $\eta \to e^+e^-\gamma$
- [PWA: $D_{13} \times 2$] $N(1520) \to n\, e^+e^-\ (QED)$
- [8.4 mb] $\Delta(1232) \to n\, e^+e^-\ (QED)$

CS need to be multiplied by BR

Branching Ratios

π^0: 0.012, η: 0.006

$N(1520)$: $4 \cdot 10^{-5}$, $\Delta(1232)$: $4 \cdot 10^{-5}$



- **Large η contribution**
- **ρ(PWA) = 2.3 mb**

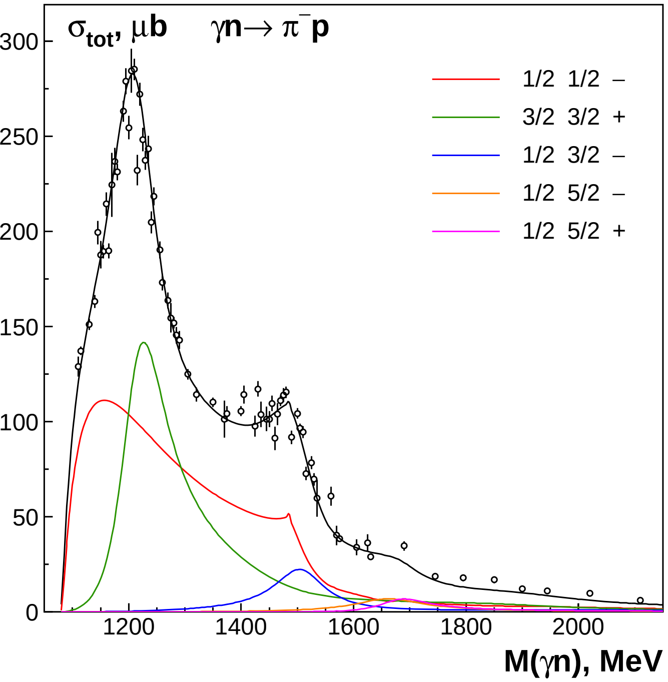
VMD: $\sim 1/M^3 \;\to\; \times 4.6$

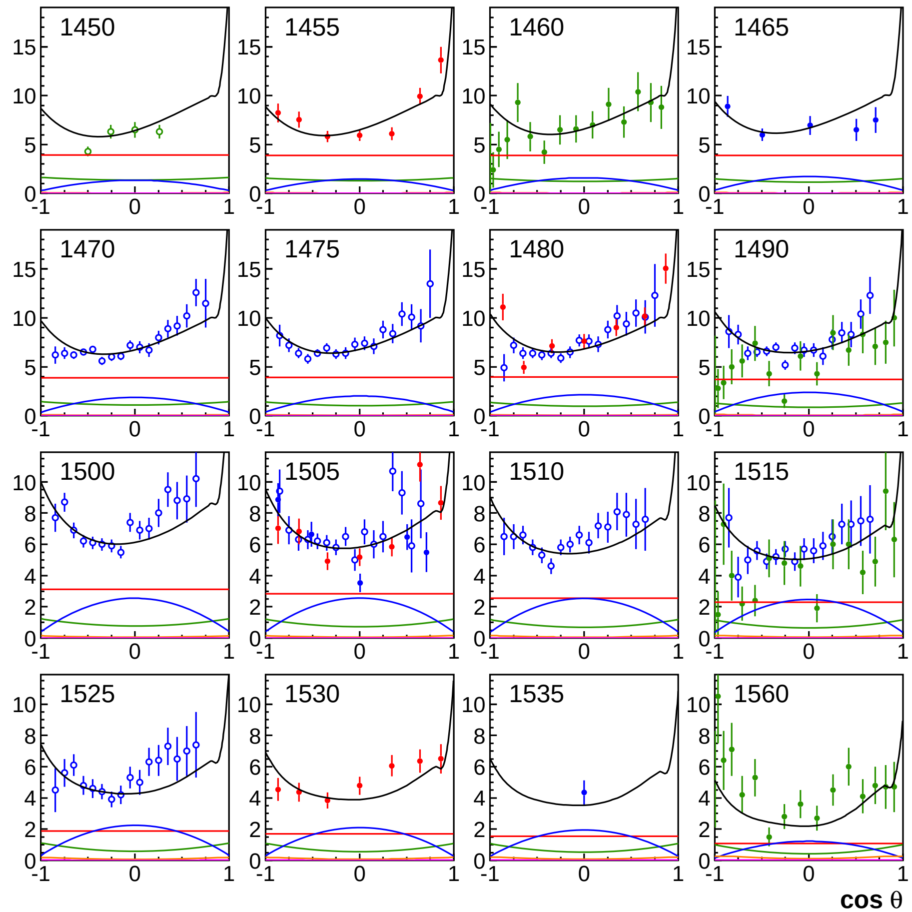
Dilepton cocktail

- **PLUTO event generator + full analysis**

Ingo Fröhlich *et al.*
PoS ACTA2007 (2007) 076

The description of the $\gamma n \to \pi^- p$ reaction (from $\pi^- p \to \gamma n$ reaction)





J.C.Comiso *et al.*, PRD 12, 719 (1975)

G.J.Kim *et al.*, PRD 40, 244 (1989)

A.Shafi *et al.*, PRC 70, 035204 (2004)

M.T.Tran *et al.*, NPA 324, 301 (1979)

The cross section for γ-particle production can be written as:

$$\frac{d\sigma}{dz}(\pi^- p \to \gamma n) = \sum_{ij} H^{ij}_{\mu\nu}(s,z) \sum_{\Lambda} \varepsilon^{*\Lambda}_{\mu} \varepsilon^{\Lambda}{}_{\nu}$$

where $$H^{ij}_{\mu\nu} = \frac{1}{4} \frac{4\pi}{|k_{\pi p}|^2} \rho_i(s) \rho_f(s) J^i_\mu J^{*j}_\nu$$

In the case of real photon with momentum along z-axis

$$\frac{d\sigma}{dz}(\pi^- p \to \gamma n) = \sum_{ij} (H^{ij}_{xx} + H^{ij}_{yy})$$

In the case of the dilepton production:

$$\frac{d\sigma}{dQ^2} = \frac{\alpha}{Q^4} \frac{1}{4\pi} \sum \rho^{(H)}_{\Lambda\Lambda'} \rho^{dec}_{\Lambda\Lambda'} \sqrt{1 - \frac{4m_e^2}{Q^2}} \frac{d\Omega}{4\pi}$$

$$\rho^{(H)}_{\Lambda\Lambda'} = H_{\mu\nu} \varepsilon^{*(\Lambda')}_{\mu} \varepsilon^{(\Lambda)}_{\nu} \qquad \rho^{(dec)}_{\Lambda'\Lambda} = \varepsilon^{(\Lambda')}_{\alpha} Sp\left[(m_e + k_1)\gamma_\alpha (m_e - k_2)\gamma_\beta\right] \varepsilon^{*(\Lambda)}_{\beta}$$

Helicity basis (in c.m.s. of the virtual photon)

$$\varepsilon^{(+1)} = \frac{1}{\sqrt{2}}(0,-1,-i,0) \quad \varepsilon^{(-1)} = \frac{1}{\sqrt{2}}(0,+1,-i,0) \quad \varepsilon^{(\ 0)} = (0,0,0,1)$$

Then for normalized density matrix elements:

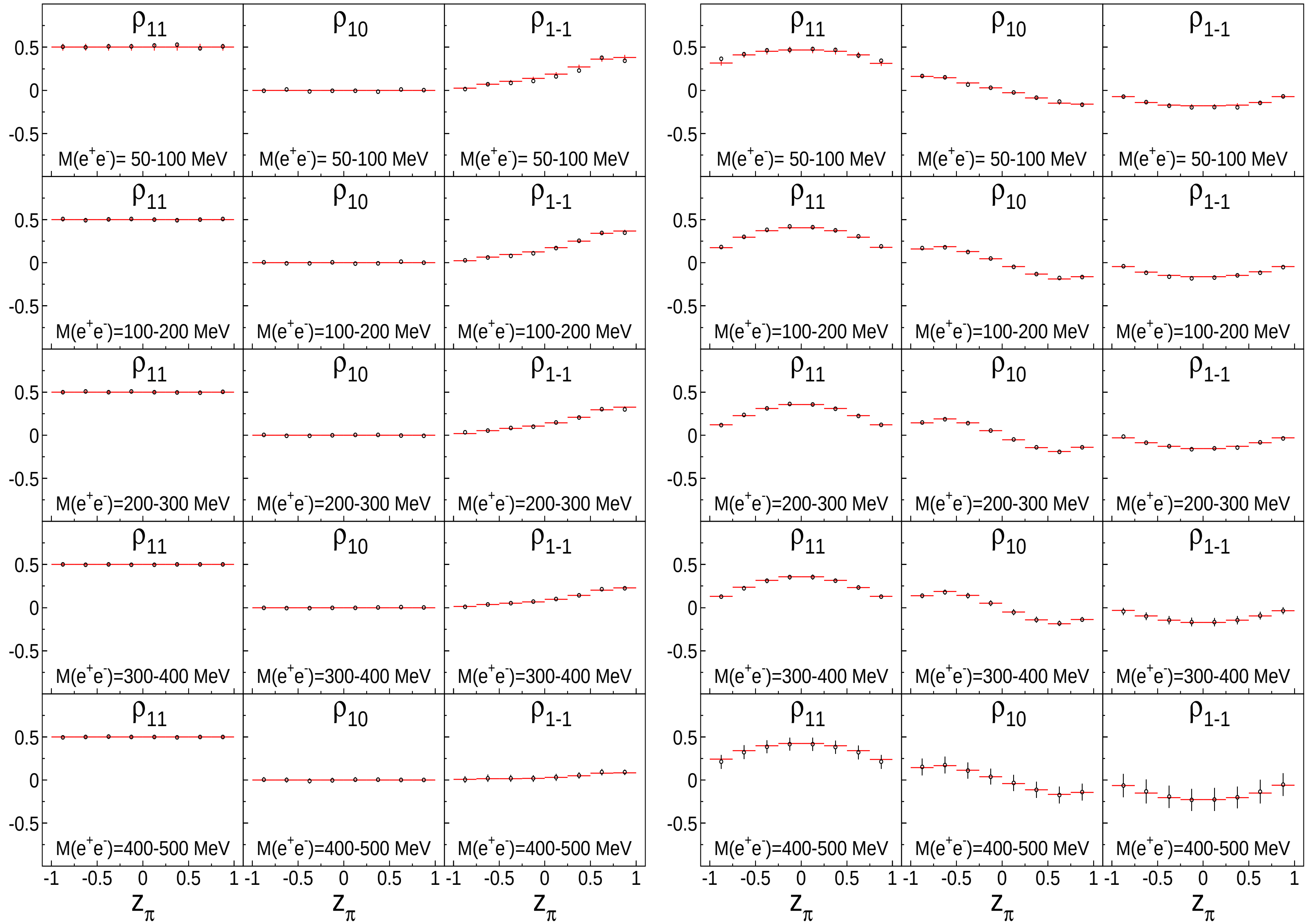
$$\tilde{\rho}_{ij} = \frac{\rho_{ij}}{2\rho_{11} + \rho_{00}}$$

$$\tilde{\rho}^{(H)}_{11} = \frac{1}{2}\frac{H_{xx}+H_{yy}}{H_{xx}+H_{yy}+H_{zz}} \mapsto \frac{1}{2}$$

$$\tilde{\rho}^{(H)}_{10} = \frac{1}{\sqrt{2}}\frac{\mathbf{Re}(-H_{xz}-iH_{yz})}{H_{xx}+H_{yy}+H_{zz}} \mapsto 0$$

$$\tilde{\rho}^{(H)}_{1-1} = \frac{1}{2}\frac{\mathbf{Re}(H_{yy}-H_{yy}-iH_{yx}-iH_{xy})}{H_{xx}+H_{yy}+H_{zz}} \mapsto \frac{1}{2}\Sigma$$

The analysis of the simulated data (photoproduction and the case with a longitudinal couplings)



The high mass states in the analysis of the new data

Resonance	γp	γn	γn	γp	γp	γp	$\pi p, \gamma p$
$\rightarrow$	$K\Lambda$	$K\Lambda$	$K\Sigma$	$K^*\Lambda$	$\eta' p$	ωp	ρN
	E-independent						
$N(1880)1/2^+$	*		**	*			**
$N(1895)1/2^-$	**	*	**	**	**	*	**
$N(1900)3/2^+$	**	**	**	**	**	**	**
$N(2100)1/2^+$				*	**		*
$N(2120)3/2^-$			**		**		**

SUMMARY

- The analysis of the new data confirms the observed earlier states in the mass region 1900-2150 MeV.
- The analysis of reactions with two pions in the final state provides an important information for the classification of the observed states.
- In many partial waves we practically reached the unitarity limit in the energy region below 2 GeV.
- The energy independent analysis of the $\gamma p \to K\Lambda$ is consistent with energy dependent analysis.
- The formalism for the analysis of the electro-production data is developed and encoded. It will help to define baryon form factors in the space-like region.
- The approach for the analysis of the dilepton production reactions is developed, encoded and tested. It will help to define baryon form factors in the time-like region.