Status of the Bonn-Gatchina partial-wave analysis

A. Sarantsev

HISKP (Bonn), PNPI (Russia)

Petersburg Nuclear Physics Institute

PWA 2011

23-27 May 2011, GWU, USA

Bonn-Gatchina partial wave analysis group:

A. Anisovich, E. Klempt, V. Nikonov, A. Srantsev, U. Thoma

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

Bonn-Gatchina Partial Wave Analysis

Address: Nussallee 14-16, D-53115 Bonn Fax: (+49) 228 / 73-2505

Data Base | Meson Spectroscopy | Baryon Spectroscopy | NN-interaction | Formalism

Analysis of Other Groups

- SAID
- MAID
- Giessen Uni

BG PWA

- Publications
- Talks
- Contacts

Useful Links

- SPIRES
- PDG Homepage
- Durham Data Base
- Bonn Homepage

CB-ELSA Homepage

Responsible: Dr. V. Nikonov, E-mail: *nikonov@hiskp.uni-bonn.de*
Last changes: January 26th, 2010.

Search for baryon states

1. **Analysis of single meson and double meson photoproduction reactions.**
   $\gamma p \to \pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N, \pi\eta N$**, CB-ELSA, CLAS, GRAAL, LEPS.**
2. **Analysis of single meson and double meson pion-induced reactions.**
   $\pi N \to \pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N$**.**

Search for meson states

1. **Analysis of the** $p\bar{p}$ **annihilation at rest and** $\pi\pi$ **interaction data.**
2. **Analysis of the** $p\bar{p}$ **annihilation in flight into two and tree meson final state.**
3. **Analysis of the** J/Ψ **decays (BES III collaboration).**

Analysis of NN interaction

1. **Analysis of single and double meson production** $NN \to \pi NN$ **and** $\pi\pi NN$
2. **Analysis of hyperon production** $NN \to K\Lambda p$

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:

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

1. **C. Zemach, Phys. Rev. 140, B97 (1965); 140, B109 (1965).**
2. **S.U.Chung, Phys. Rev. D 57, 431 (1998).**
3. **A.V. Anisovich** *et al.* **J. Phys. G 28 15 (2002)**
   V. V. Anisovich, M. A. Matveev, V. A. Nikonov, J. Nyiri and A. V. Sarantsev,
   Hackensack, USA: World Scientific (2008) 580 p

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

πN vertices

$$N^{+}_{\mu_1\ldots\mu_n} = X^{(n)}_{\mu_1\ldots\mu_n} \qquad N^{-}_{\mu_1\ldots\mu_n} = i\gamma_\nu\gamma_5 X^{(n+1)}_{\nu\mu_1\ldots\mu_n} \tag{1}$$

γN vertices

$$Q^{(1+)\mu}_{\alpha_1\ldots\alpha_n} = \gamma_\mu i\gamma_5 X^{(n)}_{\alpha_1\ldots\alpha_n}\ , \qquad Q^{(1-)\mu}_{\alpha_1\ldots\alpha_n} = \gamma_\xi\gamma_\mu O^{(n+1)}_{\xi\alpha_1\ldots\alpha_n}\ ,$$
$$Q^{(2+)\mu}_{\alpha_1\ldots\alpha_n} = \gamma_\nu i\gamma_5 X^{(n+2)}_{\mu\nu\alpha_1\ldots\alpha_n}\ , \qquad Q^{(2-)\mu}_{\alpha_1\ldots\alpha_n} = X^{(n+1)}_{\mu\alpha_1\ldots\alpha_n}\ ,$$
$$Q^{(3+)\mu}_{\alpha_1\ldots\alpha_n} = \gamma_\nu i\gamma_5 X^{(n+1)}_{\nu\alpha_1\ldots\alpha_n} g^{\perp}_{\mu\alpha_n}\ , \qquad Q^{(3-)\mu}_{\alpha_1\ldots\alpha_n} = X^{(n-1)}_{\alpha_2\ldots\alpha_n} g^{\perp}_{\alpha_1\mu}\ .$$

Fermion propagator for $J = N + \frac{1}{2}$

$$F^{\mu_1\ldots\mu_L}_{\nu_1\ldots\nu_L}(p) = (m+\hat{p})O^{\mu_1\ldots\mu_L}_{\alpha_1\ldots\alpha_L}\frac{L+1}{2L+1}\left(g^{\perp}_{\alpha_1\beta_1} - \frac{L}{L+1}\sigma_{\alpha_1\beta_1}\right)\prod_{i=2}^{L} g_{\alpha_i\beta_i} O^{\beta_1\ldots\beta_L}_{\nu_1\ldots\nu_L}$$

$$\sigma_{\alpha_i\alpha_j} = \frac{1}{2}(\gamma_{\alpha_i}\gamma_{\alpha_j} - \gamma_{\alpha_j}\gamma_{\alpha_i})$$

Combined analysis of pion- and photo-production data:

For pion induced reactions:

$$A_{1i} = K_{1j}(I - i\rho K)^{-1}_{ji}$$

and

$$K_{ij} = \sum_{\alpha} \frac{g_i^{\alpha} g_j^{\alpha}}{M_{\alpha}^2 - s} + f_{ij}(s) \qquad f_{ij} = \frac{f_{ij}^{(1)} + f_{ij}^{(2)}\sqrt{s}}{s - s_0^{ij}}\,.$$

where f_{ij} is nonresonant transition part.

For the photoproduction:

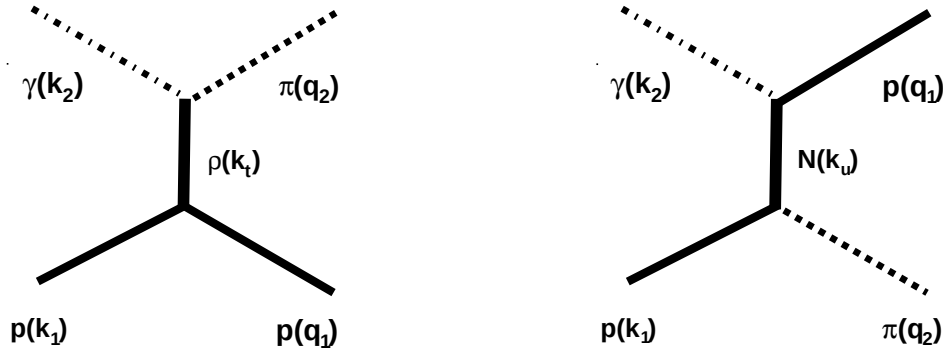
$$A_k = P_j(I - i\rho K)^{-1}_{jk}$$

The vector of the initial interaction has the form:

$$P_j = \sum_{\alpha} \frac{\Lambda^{\alpha} g_j^{\alpha}}{M_{\alpha}^2 - s} + F_j(s)$$

Here F_j is nonresonant production of the final state j.

Reggezied exchanges:



The amplitude for t-channel exchange:

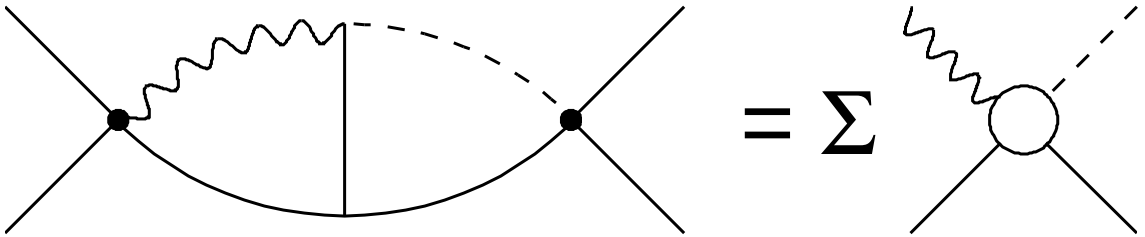
$$A = g_1(t)g_2(t)R(\xi,\nu,t) = g_1(t)g_2(t)\frac{1+\xi exp(-i\pi\alpha(t))}{\sin(\pi\alpha(t))}\left(\frac{\nu}{\nu_0}\right)^{\alpha(t)} \qquad \nu = \frac{1}{2}(s-u).$$

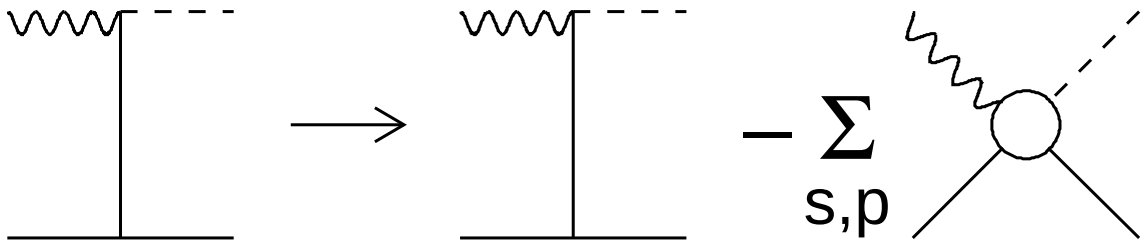
Here $\alpha(t)$ is Reggion trajectory, and ξ is its signature:

$$R(+,\nu,t) = \frac{e^{-i\frac{\pi}{2}\alpha(t)}}{\sin(\frac{\pi}{2}\alpha(t))\Gamma\left(\frac{\alpha(t)}{2}\right)}\left(\frac{\nu}{\nu_0}\right)^{\alpha(t)},$$

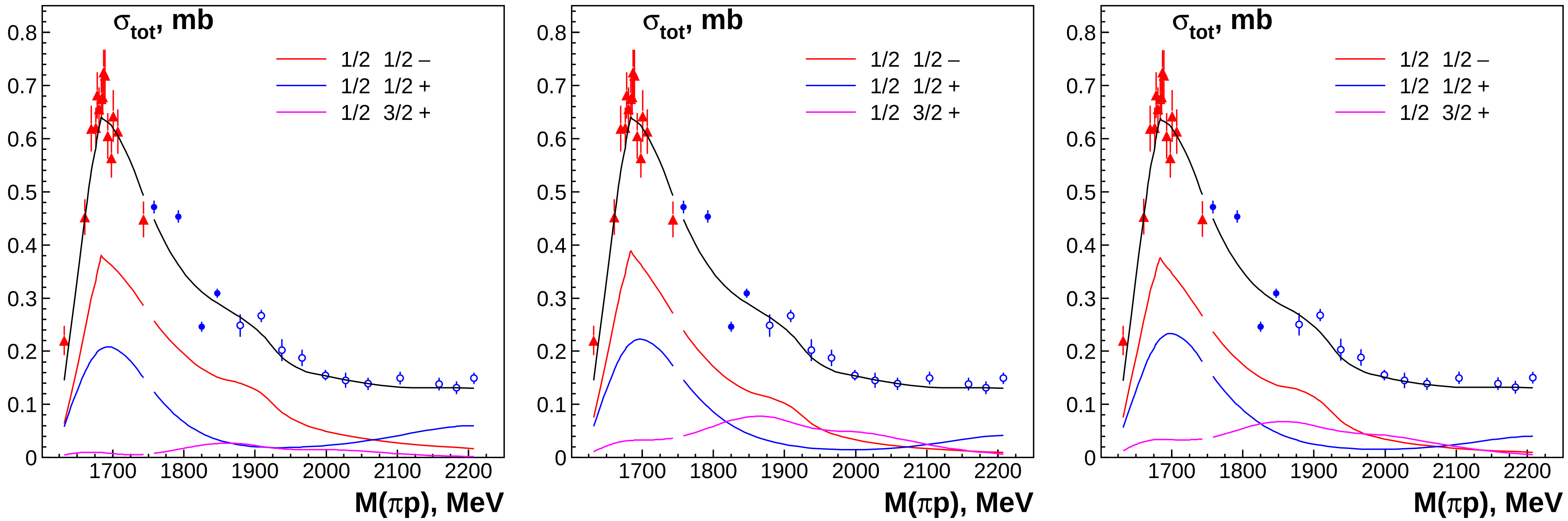
$$R(-,\nu,t) = \frac{ie^{-i\frac{\pi}{2}\alpha(t)}}{\cos(\frac{\pi}{2}\alpha(t))\Gamma\left(\frac{\alpha(t)}{2}+\frac{1}{2}\right)}\left(\frac{\nu}{\nu_0}\right)^{\alpha(t)}.$$

t,u-exchange subtraction procedure



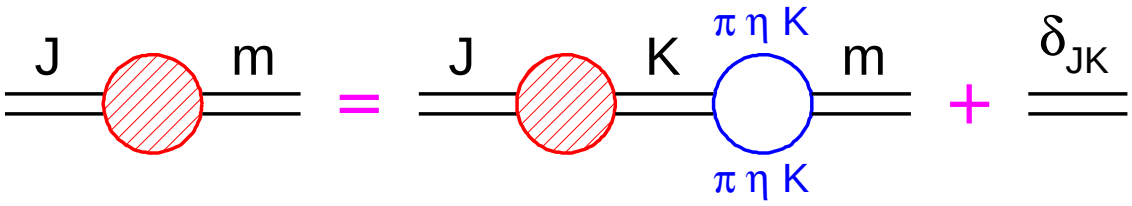


t,u-exchange subtraction procedure



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

In the case of resonance contributions only we have factorization and Bethe-Salpeter equation can be easily solved:



$$D_{jm} = D_{jk}\sum_{\alpha} B_{\alpha}^{km}(s)\frac{1}{M_m - s} + \frac{\delta_{jm}}{M_j^2 - s} \qquad B_{\alpha}^{km}(s) = \int\limits_{4m_{\alpha}^2}^{\infty} \frac{ds'}{\pi}\frac{g_{\alpha}^{(k)}(s')\rho_{\alpha}(s')g_{\alpha}^{(m)}(s')}{s' - s - i0}$$

$$\hat{D} = \hat{\kappa}(I - \hat{B}\hat{\kappa})^{-1} \qquad \kappa_{ij} = \frac{\delta_{ij}}{M_i^2 - s} \qquad B^{ij} = \sum_{\alpha} B_{\alpha}^{km}(s)$$

There is no factorization for non-resonant contributions: for every non-resonant transition to introduce a vertices and propagator (e.g. $R = 1$).

$$B_{\alpha}^{km}(s) = B_{\alpha}^{km}(M_s^2) + (s - M_s^2)\int\limits_{4m_{\alpha}^2}^{\infty} \frac{ds'}{\pi}\frac{g_{\alpha}^{(k)}(s')\rho_{\alpha}(s')g_{\alpha}^{(m)}(s')}{(s' - s - i0)(s' - M_s^2)}$$

Meson spectroscopy. Two body reactions:

Reaction	Experiment	Reaction	Experiment
$\pi^+\pi^- \to \pi^+\pi^-$ **(all waves)**	**CERN-Münich**		
$\pi\pi \to \pi^0\pi^0$ **(S-wave)**	**GAMS**	$\pi\pi \to \pi^0\pi^0$ **(S-wave)**	**E852**
$\pi\pi \to \eta\eta$ **(S-wave)**	**GAMS**	$\pi\pi \to \eta\eta'$ **(S-wave)**	**GAMS**
$\pi\pi \to K\bar{K}$ **(S-wave)**	**BNL**	**S-wave** $\delta(\pi^+\pi^-)$	**Ke4**

Three body reactions from Crystal Barrel: (L-liquid, G-gaseous targets).

Reaction	Target	Reaction	Target	Reaction	Target
$\bar{p}p \to \pi^0\pi^0\pi^0$	**(L)** H_2	$\bar{p}p \to \pi^+\pi^0\pi^-$	**(L)** H_2	$\bar{p}p \to K_S K_S \pi^0$	**(L)** H_2
$\bar{p}p \to \pi^0\eta\eta$	**(L)** H_2	$\bar{p}n \to \pi^0\pi^0\pi^-$	**(L)** D_2	$\bar{p}p \to K^+K^-\pi^0$	**(L)** H_2
$\bar{p}p \to \pi^0\pi^0\eta$	**(L)** H_2	$\bar{p}n \to \pi^-\pi^-\pi^+$	**(L)** D_2	$\bar{p}p \to K_L K^{\pm}\pi^{\mp}$	**(L)** H_2
$\bar{p}p \to \pi^0\pi^0\pi^0$	**(G)** H_2			$\bar{p}n \to K_S K_S \pi^-$	**(L)** D_2
$\bar{p}p \to \pi^0\eta\eta$	**(G)** H_2			$\bar{p}n \to K_S K^-\pi^0$	**(L)** D_2
$\bar{p}p \to \pi^0\pi^0\eta$	**(G)** H_2				

Parameterization of the K-matrix for S-wave:

$$K_{ab}(s) = \left(\sum_{\alpha} \frac{g_a^{(\alpha)} g_b^{(\alpha)}}{M_\alpha^2 - s} + f_{ab} \frac{1\ \textbf{GeV}^2 + s_0}{s + s_0} \right) \frac{s - s_A}{s + s_{A0}} \ ,$$

where K_{ab} is a 5×5 matrix (a, b = $\pi\pi$, $K\bar{K}$, $\eta\eta$, $\eta\eta'$, $4pi + \ldots$)

$$\rho_a(s) = \frac{\sqrt{(s - (m_{1a} + m_{2a})^2)(s - (m_{1a} - m_{2a})^2)}}{s} \quad , \qquad a = \pi,\ K,\ \eta, \eta'$$

The multi-meson phase space factor is defined as

$$\rho_{51} = \rho_0 \int \frac{ds_1}{\pi} \int \frac{ds_2}{\pi} M^2 \Gamma(s_1) \Gamma(s_2) \sqrt{(s + s_1 - s_2)^2 - 4 s s_1} \times$$

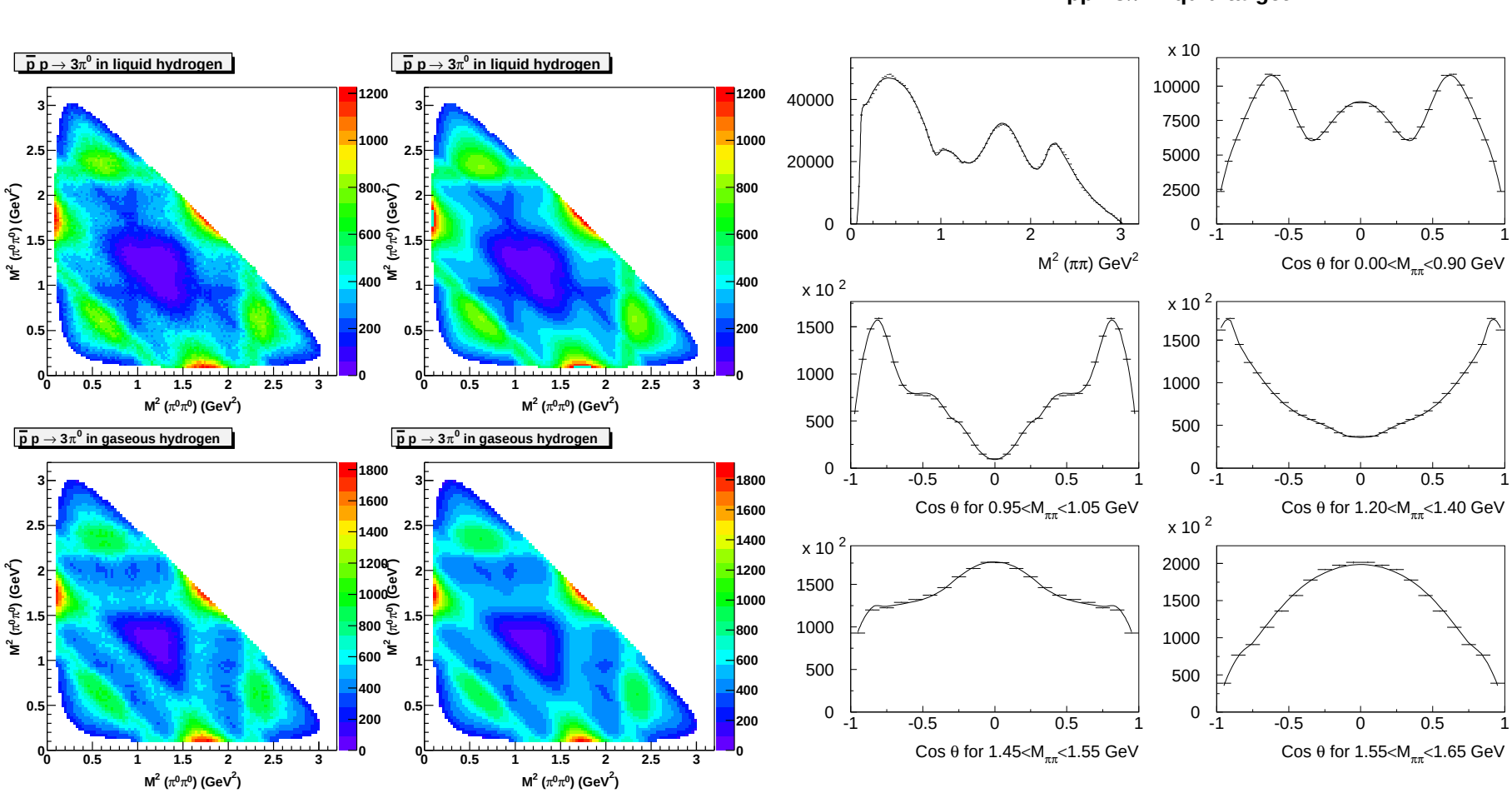
$$\times s^{-1} [(M^2 - s_1)^2 + M^2 \Gamma^2(s_1)]^{-1} [(M^2 - s_2)^2 + M^2 \Gamma^2(s_2)]^{-1},$$

$$B^j_{\alpha\beta}(s) = g_a^{R(\alpha)} \left(b^j + (s - M_j^2) \int_{(m_{1a}+m_{2a})^2}^{\infty} \frac{ds'}{\pi} \frac{\rho_j(s', m_{1a}, m_{2a})}{(s' - s - i0)(s' - M_j^2)} \right) g_b^{L(\beta)} \ ,$$

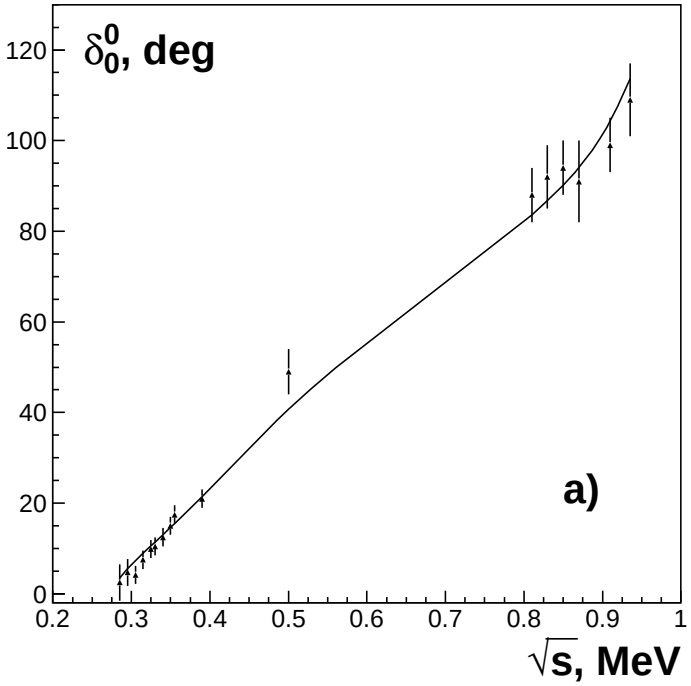
Description of the data with K-matrix and D-matrix approaches

	K-matr.	D-matr.	N		K-matr.	D-matr.	N
$\bar{p}p \to \pi^0\pi^0\pi^0$ **(L)**	**1.32**	**1.37**	**7110**	$\bar{p}p \to \pi^0\pi^0\pi^0$ **(G)**	**1.39**	**1.44**	**4891**
$\bar{p}p \to \pi^0\eta\eta$ **(L)**	**1.33**	**1.34**	**3595**	$\bar{p}p \to \pi^0\eta\eta$ **(G)**	**1.31**	**1.34**	**1182**
$\bar{p}p \to \pi^0\pi^0\eta$ **(L)**	**1.24**	**1.33**	**3475**	$\bar{p}p \to \pi^0\pi^0\eta$ **(G)**	**1.20**	**1.22**	**3631**
$\bar{p}p \to \pi^+\pi^0\pi^-$ **(L)**	**1.54**	**1.46**	**1334**	$\bar{p}p \to K_S K_S \pi^0$ **(L)**	**1.09**	**1.10**	**394**
$\bar{p}n \to \pi^0\pi^0\pi^-$	**1.51**	**1.47**	**825**	$\bar{p}n \to \pi^-\pi^-\pi^+$	**1.61**	**1.54**	**823**
$\bar{p}n \to K^+K^-\pi^0$	**0.98**	**1.00**	**521**	$\bar{p}n \to K_L K^{\pm}\pi^{\mp}$	**0.78**	**0.79**	**737**
$\bar{p}p \to K_S K_S \pi^-$	**1.66**	**1.64**	**396**				
$\pi\pi \to (\pi^0\pi^0)_S$	**1.23**	**1.13**	**68**	$\pi\pi \to (\eta\eta)_S$	**1.02**	**1.05**	**15**
$\pi\pi \to (\eta\eta')_S$	**0.45**	**0.30**	**9**	$\pi\pi \to (K\bar{K})_S$	**1.32**	**1.13**	**35**
$\delta_0^0(\pi^-\pi^+ \to \pi^-\pi^+)$	**1.51**	**1.02**	**17**	K_{e4} **data**			

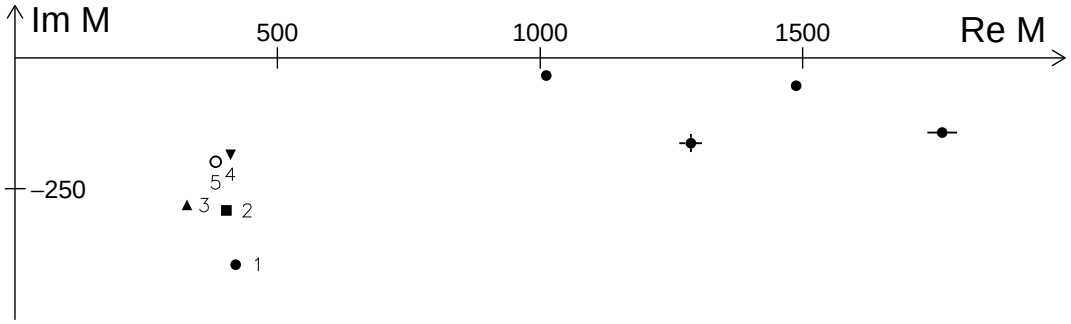
Description of the $\bar{p}p \to 3\pi^0$ data (D-matrix method)



Pole position of the resonances



	K-matrix	D-matrix
σ-meson	420-i 395	407-i 281
$f_0(980)$	1014-i 31	1015-i 36
$f_0(1300)$	1302-i 180	1307-i 137
$f_0(1500)$	1487-i 58	1487-i 60
$f_0(1750)$	1738-i 152	1781-i 140



Masses and couplings of bare states

	K-matrix	D-matrix		K-matrix	D-matrix
M_1	671	685	$g_{4\pi}^{(1)}$	0^*	0^*
M_2	1205	1135	$g_{4\pi}^{(2)}$	0^*	0^*
M_3	1560	1561	$g_{4\pi}^{(3)}$	0.638	0.534
M_4	1210	1290	$g_{4\pi}^{(4)}$	0.997	0.790
M_5	1816	1850	$g_{4\pi}^{(5)}$	-0.901	-0.862
g_1	0.860	0.926	Φ_1	-74	-83
g_2	0.956	0.950	Φ_2	6	-2.6
g_3	0.373	0.290	Φ_3	9	5
g_4	0.447	0.307	Φ_4	38	31
g_5	0.458	0.369	Φ_5	-64	-71
$f_{\pi\pi\to\pi\pi}$	0.337	0.408	$f_{\pi\pi\to K\bar{K}}$	0.212	0.036
$f_{\pi\pi\to 4\pi}$	-0.199	-0.101	$f_{\pi\pi\to\eta\eta}$	0.389	0.438
$f_{\pi\pi\to\eta\eta'}$	0.394	0.518			

Baryon Data Base

Pion induced reactions (χ^2 analysis).

Observable	$N_{\rm data}$	$\frac{\chi^2}{N_{\rm data}}$		Observable	$N_{\rm data}$	$\frac{\chi^2}{N_{\rm data}}$	
$N^*_{1/2-}$ $S_{11}(\pi N\to\pi N)$	112	2.05	SAID (2.10)	$\Delta_{1/2-}$ $S_{31}(\pi N\to\pi N)$	112	2.31	SAID (2.10)
$N^*_{1/2+}$ $P_{11}(\pi N\to\pi N)$	112	2.49	SAID (2.10)	$\Delta_{1/2+}$ $P_{31}(\pi N\to\pi N)$	104	3.81	SAID (2.10)
$N^*_{3/2+}$ $P_{13}(\pi N\to\pi N)$	112	1.33	SAID (2.20)	$\Delta^*_{3/2+}$ $P_{33}(\pi N\to\pi N)$	120	2.79	SAID (2.20)
$N^*_{3/2-}$ $D_{13}(\pi N\to\pi N)$	108	2.55	SAID (2.20)	$\Delta^*_{3/2-}$ $D_{33}(\pi N\to\pi N)$	108	2.47	SAID (2.10)
$N^*_{5/2-}$ $D_{15}(\pi N\to\pi N)$	140	2.37	SAID (2.40)	$N^*_{7/2-}$ $G_{17}(\pi N\to\pi N)$	102	2.54	SAID (2.40)
$N^*_{5/2+}$ $F_{15}(\pi N\to\pi N)$	88	1.72	SAID (2.20)	$\Delta_{5/2+}$ $F_{35}(\pi N\to\pi N)$	62	1.45	SAID (2.10)
$N^*_{7/2+}$ $F_{17}(\pi N\to\pi N)$	82	1.98	SAID (2.50)	$\Delta_{7/2+}$ $F_{37}(\pi N\to\pi N)$	72	2.75	SAID (2.10)
$N^*_{9/2-}$ $G_{19}(\pi N\to\pi N)$	74	2.82	SAID (2.50)	$N^*_{9/2+}$ $H_{19}(\pi N\to\pi N)$	86	2.56	SAID (2.50)
$d\sigma/d\Omega(\pi^- p\to n\eta)$	70	1.58	Richards *et al.*	$d\sigma/d\Omega(\pi^- p\to n\eta)$	84	2.73	CBALL
$d\sigma/d\Omega(\pi^- p\to K\Lambda)$	598	1.67	RAL	$P(\pi^- p\to K\Lambda)$	355	1.67	RAL+ANL
				$\beta(\pi^- p\to K\Lambda)$	72	1.04	RAL
$d\sigma/d\Omega(\pi^+ p\to K^+\Sigma)$	609	1.25	RAL	$P(\pi^+ p\to K^+\Sigma)$	307	1.43	RAL
				$\beta(\pi^+ p\to K^+\Sigma)$	7	2.08	RAL
$d\sigma/d\Omega(\pi^- p\to K^0\Sigma^0)$	259	0.88	RAL	$P(\pi^- p\to K^0\Sigma^0)$	95	1.35	RAL

Baryon Data Base (SAID db: 2008)

π and η photoproduction reactions (χ^2 analysis).

Observable	$N_{\rm data}$	$\frac{\chi^2}{N_{\rm data}}$		Observable	$N_{\rm data}$	$\frac{\chi^2}{N_{\rm data}}$	
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	1106	1.56	CB-ELSA	$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	861	1.58	GRAAL
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	592	1.27	CLAS	$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	1692	2.00	TAPS@MAMI
$\Sigma(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	540	0.71	CB-ELSA	$\Sigma(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	1492	2.48	SAID db
$E(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	140	1.14	A2-GDH				
$\mathrm{P}(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	607	2.98	SAID db	$\mathrm{T}(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	389	3.15	SAID db
$\mathrm{H}(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	71	1.17	SAID db	$\mathrm{G}(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	75	1.70	SAID db
$\mathrm{O_x}(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	7	1.14	SAID db	$\mathrm{O_z}(\gamma\mathrm{p}\to\mathrm{p}\pi^0)$	7	0.27	SAID db
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\mathrm{n}\pi^+)$	484	1.45	CLAS	$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\mathrm{n}\pi^+)$	1583	1.53	SAID db
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\mathrm{n}\pi^+)$	408	0.55	A2-GDH				
$\Sigma(\gamma\mathrm{p}\to\mathrm{n}\pi^+)$	899	2.95	SAID db	$E(\gamma\mathrm{p}\to\mathrm{n}\pi^+$	231	1.52	A2-GDH
$\mathrm{P}(\gamma\mathrm{p}\to\mathrm{n}\pi^+)$	252	2.00	SAID db	$\mathrm{T}(\gamma\mathrm{p}\to\mathrm{n}\pi^+)$	661	2.87	SAID db
$\mathrm{H}(\gamma\mathrm{p}\to\mathrm{p}\pi^+)$	71	4.20	SAID db	$\mathrm{G}(\gamma\mathrm{p}\to\mathrm{p}\pi^+)$	86	5.67	SAID db
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\mathrm{p}\eta)$	680	1.23	CB-ELSA	$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\mathrm{p}\eta)$	100	2.26	TAPS
$\Sigma(\gamma\mathrm{p}\to\mathrm{p}\eta)$	51	1.90	GRAAL 98	$\Sigma(\gamma\mathrm{p}\to\mathrm{p}\eta)$	100	2.43	GRAAL 07
$T(\gamma\mathrm{p}\to\mathrm{p}\eta)$	50	1.39	Phoenics				

Baryon Data Base

Kaon photoproduction (χ^2 analysis).

Observable	$N_{\rm data}$	$\frac{\chi^2}{N_{\rm data}}$		Observable	$N_{\rm data}$	$\frac{\chi^2}{N_{\rm data}}$	
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\Lambda\mathrm{K}^+)$	1320	0.78	CLAS09	$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\Sigma^0\mathrm{K}^+)$	1280	1.98	CLAS
$\mathrm{P}(\gamma\mathrm{p}\to\Lambda\mathrm{K}^+)$	1270	1.75	CLAS09	$\mathrm{P}(\gamma\mathrm{p}\to\Sigma^0\mathrm{K}^+)$	95	1.53	CLAS
$C_x(\gamma\mathrm{p}\to\Lambda\mathrm{K}^+)$	160	1.44	CLAS	$C_x(\gamma\mathrm{p}\to\Sigma^0\mathrm{K}^+)$	94	2.36	CLAS
$C_z(\gamma\mathrm{p}\to\Lambda\mathrm{K}^+)$	160	1.53	CLAS	$C_z(\gamma\mathrm{p}\to\Sigma^0\mathrm{K}^+)$	94	1.62	CLAS
$\Sigma(\gamma\mathrm{p}\to\Lambda\mathrm{K}^+)$	66	3.32	GRAAL	$\Sigma(\gamma\mathrm{p}\to\Sigma^0\mathrm{K}^+)$	42	1.80	GRAAL
$\Sigma(\gamma\mathrm{p}\to\Lambda\mathrm{K}^+)$	45	2.34	LEP	$\Sigma(\gamma\mathrm{p}\to\Sigma^0\mathrm{K}^+)$	45	1.31	LEP
$\mathrm{T}(\gamma\mathrm{p}\to\Lambda\mathrm{K}^+)$	66	1.35	GRAAL 09	$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\Sigma^+\mathrm{K}^0)$	48	3.41	CLAS
$O_x(\gamma\mathrm{p}\to\Lambda\mathrm{K}^+)$	66	1.70	GRAAL 09	$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p}\to\Sigma^+\mathrm{K}^0)$	72	0.67	CB-ELSA 10
$O_z(\gamma\mathrm{p}\to\Lambda\mathrm{K}^+)$	66	1.66	GRAAL 09	$\mathrm{P}(\gamma\mathrm{p}\to\Sigma^+\mathrm{K}^0)$	24	1.17	CB-ELSA 10
$\mathrm{P}(\gamma\mathrm{p}\to\Lambda\mathrm{K}^+)$	84	0.60	GRAAL	$\Sigma(\gamma\mathrm{p}\to\Sigma^+\mathrm{K}^0)$	15	1.39	CB-ELSA 10

Baryon Data Base

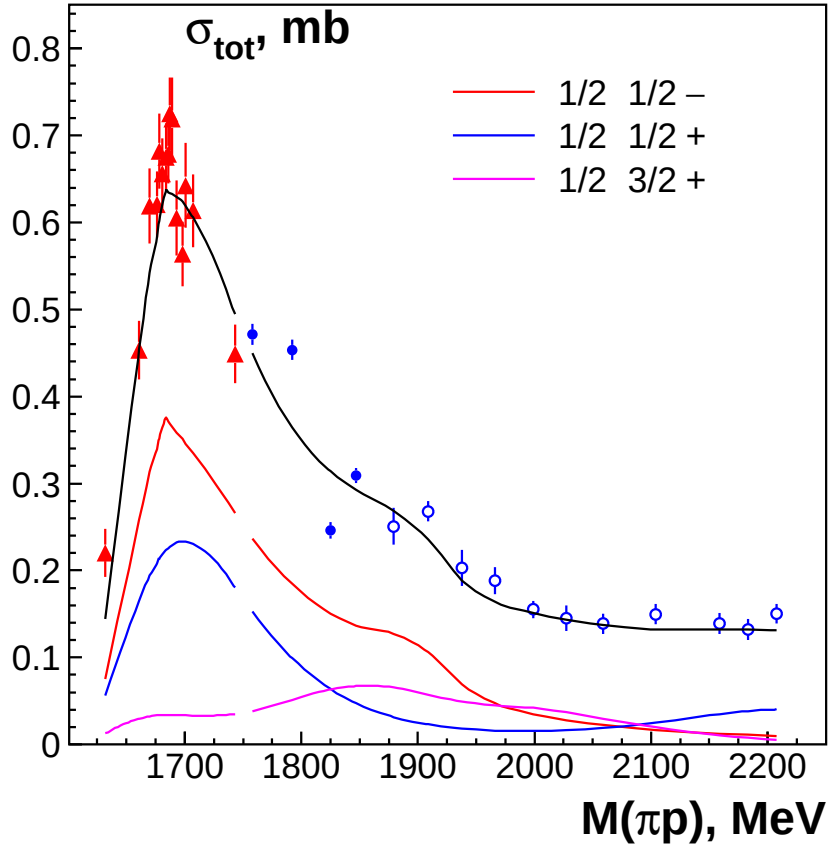
Multi-meson final states (maximum likelihood analysis).

$d\sigma/d\Omega(\pi^- p \to n\pi^0\pi^0)$	**CBALL**				
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p} \to \mathrm{p}\pi^0\pi^0)$	**CB-ELSA (1.4 GeV)**	$\mathrm{E}(\gamma\mathrm{p} \to \mathrm{p}\pi^0\pi^0)$	**16**	**1.91**	**MAMI**
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p} \to \mathrm{p}\pi^0\eta)$	**CB-ELSA (3.2 GeV)**	$\Sigma(\gamma\mathrm{p} \to \mathrm{p}\pi^0\eta)$	**180**	**2.37**	**GRAAL**
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p} \to \mathrm{p}\pi^0\pi^0)$	**CB-ELSA (3.2 GeV)**	$\Sigma(\gamma\mathrm{p} \to \mathrm{p}\pi^0\pi^0)$	**128**	**0.96**	**GRAAL**
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma\mathrm{p} \to \mathrm{p}\pi^0\eta)$	**CB-ELSA (3.2 GeV)**	$\Sigma(\gamma\mathrm{p} \to \mathrm{p}\pi^0\eta)$	**180**	**2.37**	**GRAAL**
$\mathrm{I_c}(\gamma\mathrm{p} \to \mathrm{p}\pi^0\eta)$	**CB-ELSA (3.2 GeV)**	$\mathrm{I_s}(\gamma\mathrm{p} \to \mathrm{p}\pi^0\eta)$	**CB-ELSA (3.2 GeV)**		

The fit of the the $\pi^- p \to K\Lambda$ reaction

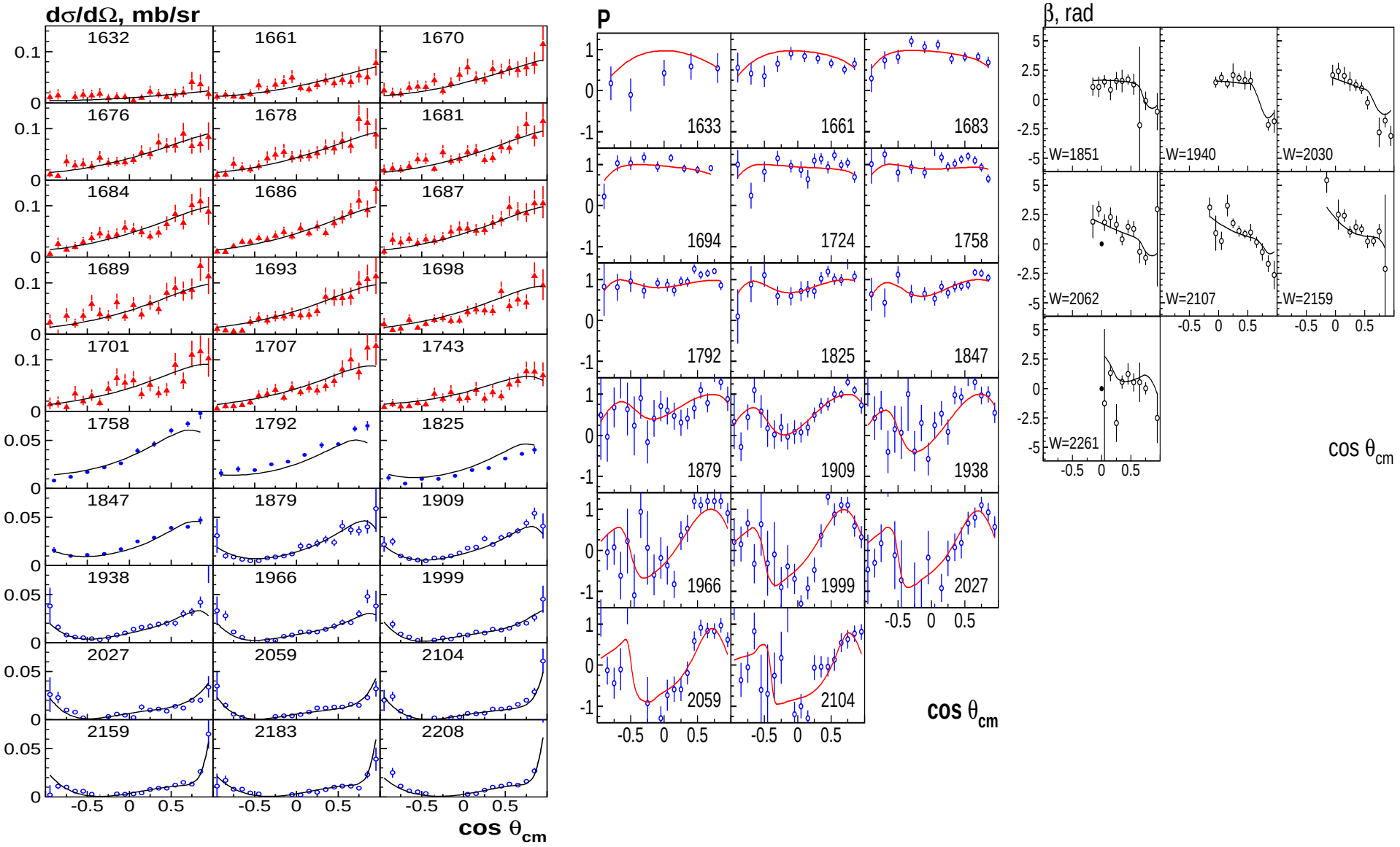
Full experiment for $\pi N \to K\Lambda$: differential cross section, analyzing power, rotation parameter.

A clear evidence for resonances which are hardly seen (or not seen) in the elastic reactions: $N(1710)P_{11}$, $N(1900)P_{13}$,

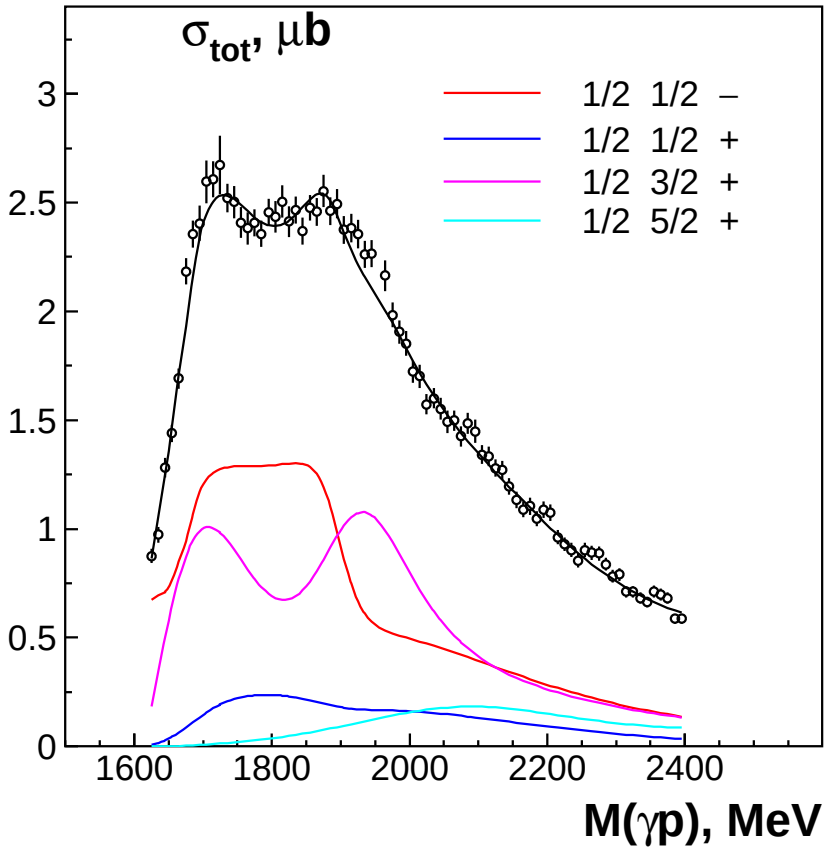


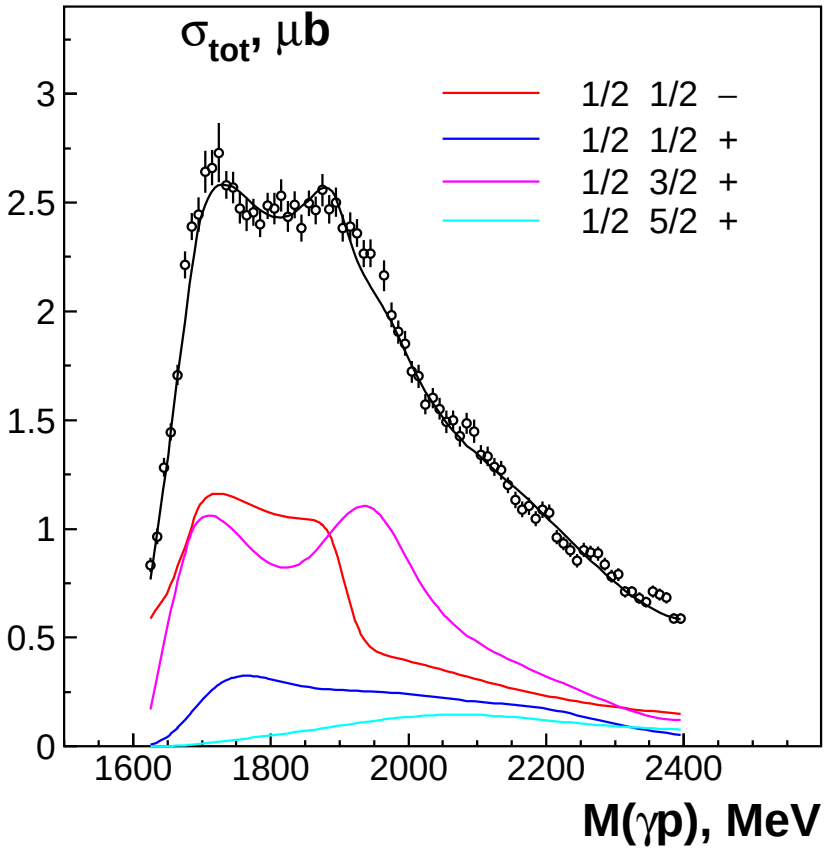
The total cross section for the reaction $\pi^- p \to K^0\Lambda$ and contributions from leading partial waves.

$\pi^- p \to K\Lambda$ $(d\sigma/d\Omega, P, \beta)$



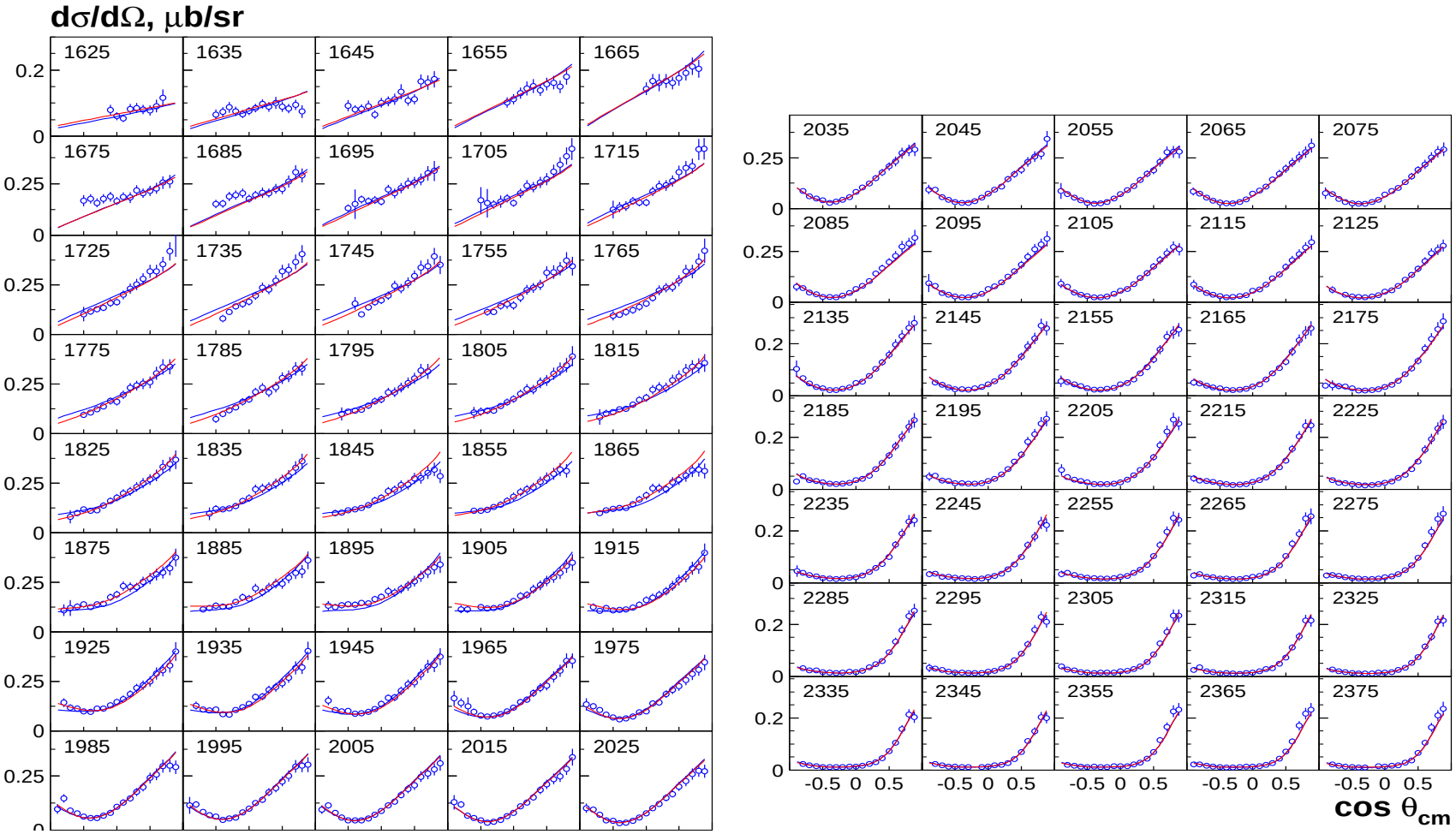
The $\gamma p \to K\Lambda$ reaction (CLAS 2009)





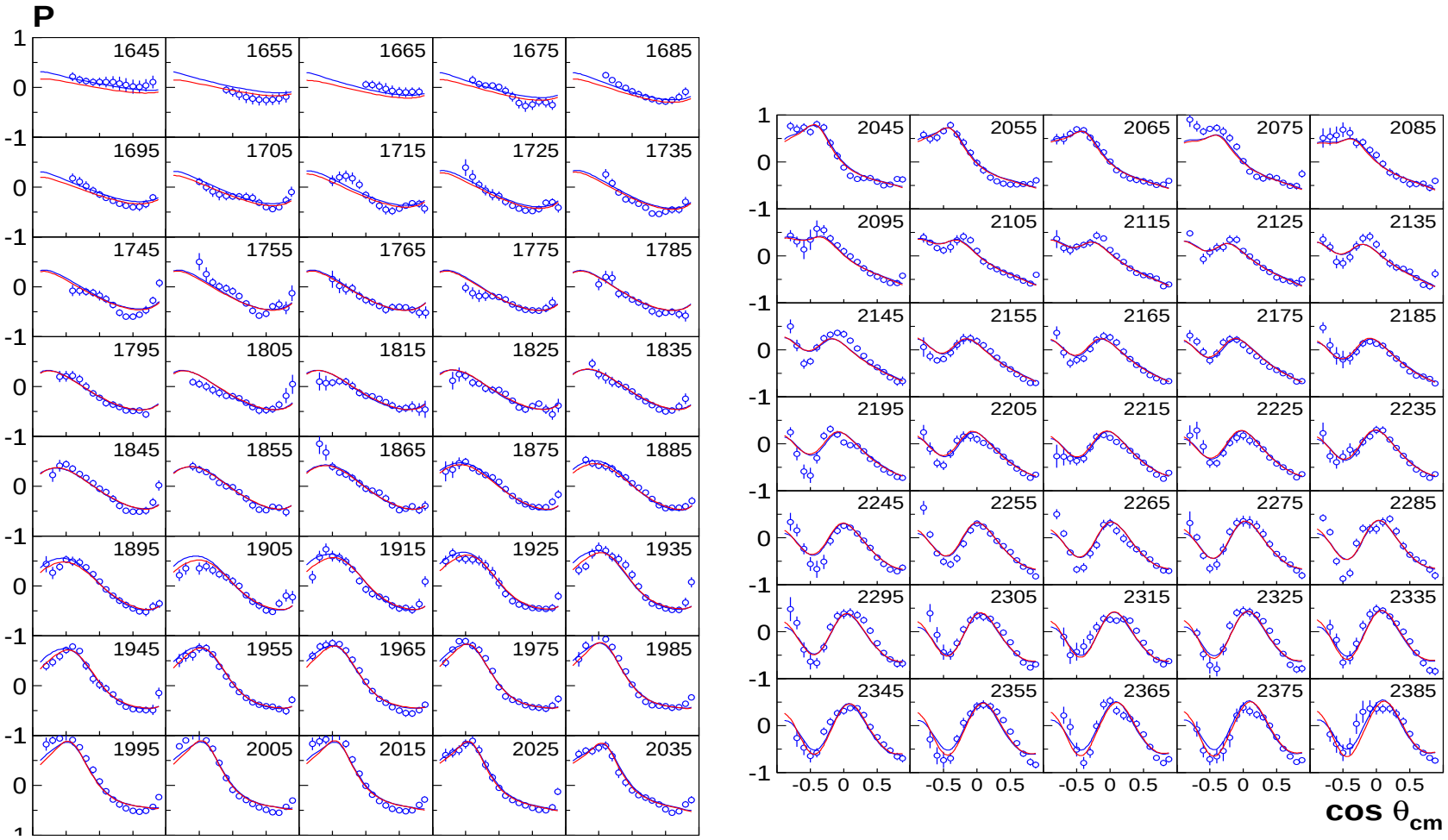
The fit of the $\gamma p \to K\Lambda$ differential cross section

(CLAS 2009)

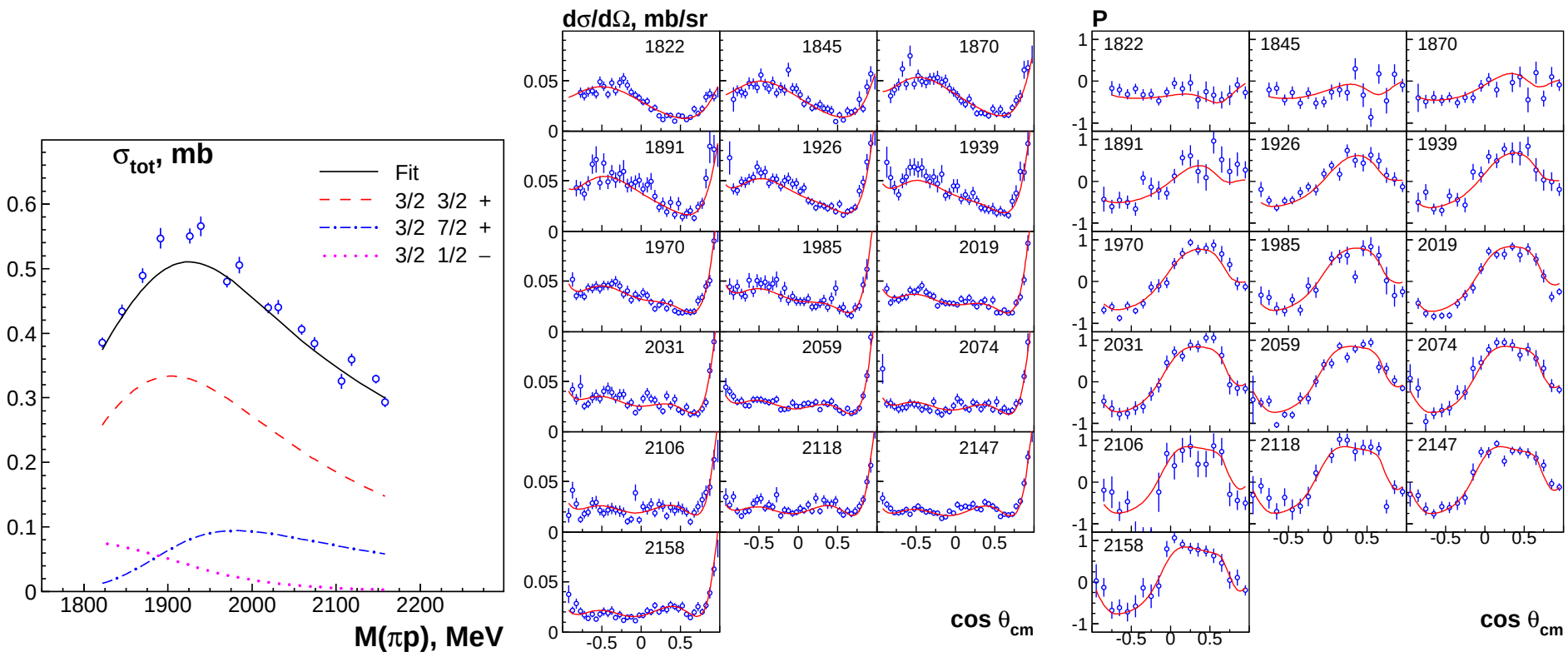


The fit of the $\gamma p \to K\Lambda$ recoil asymmetry

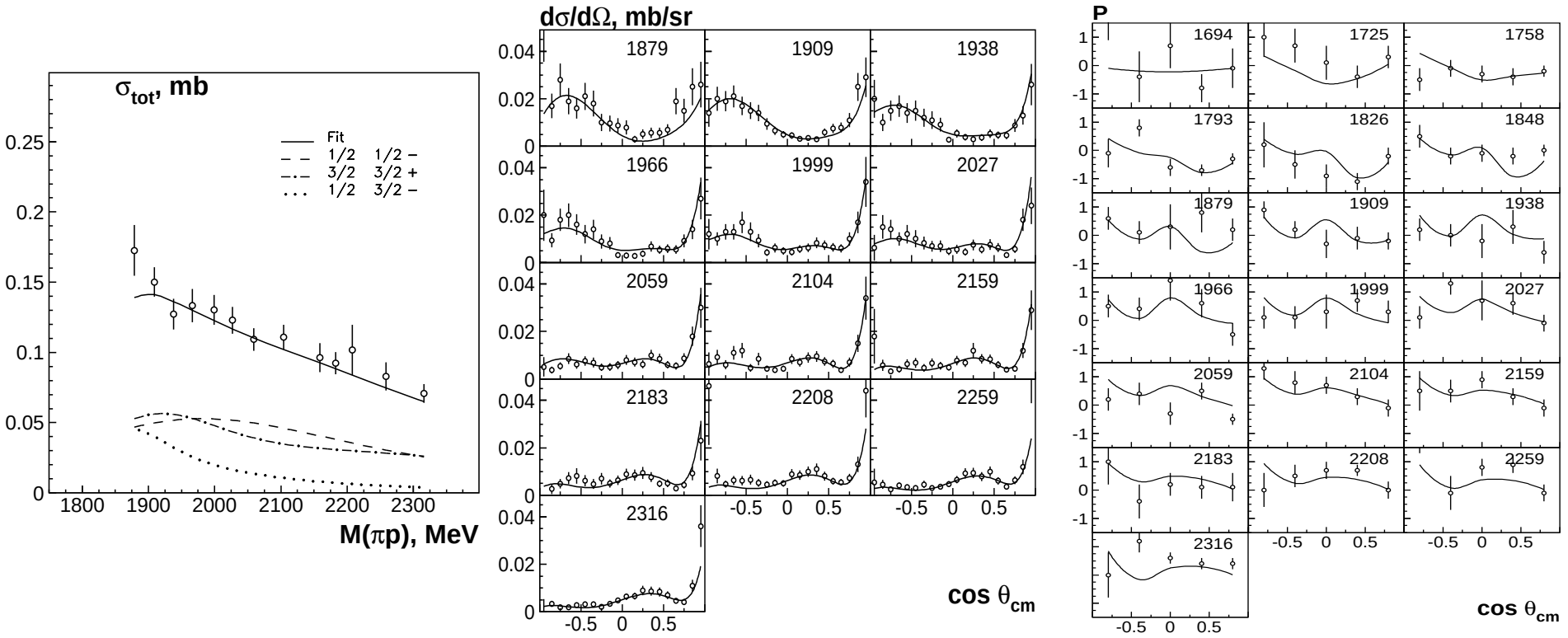
(CLAS 2009)



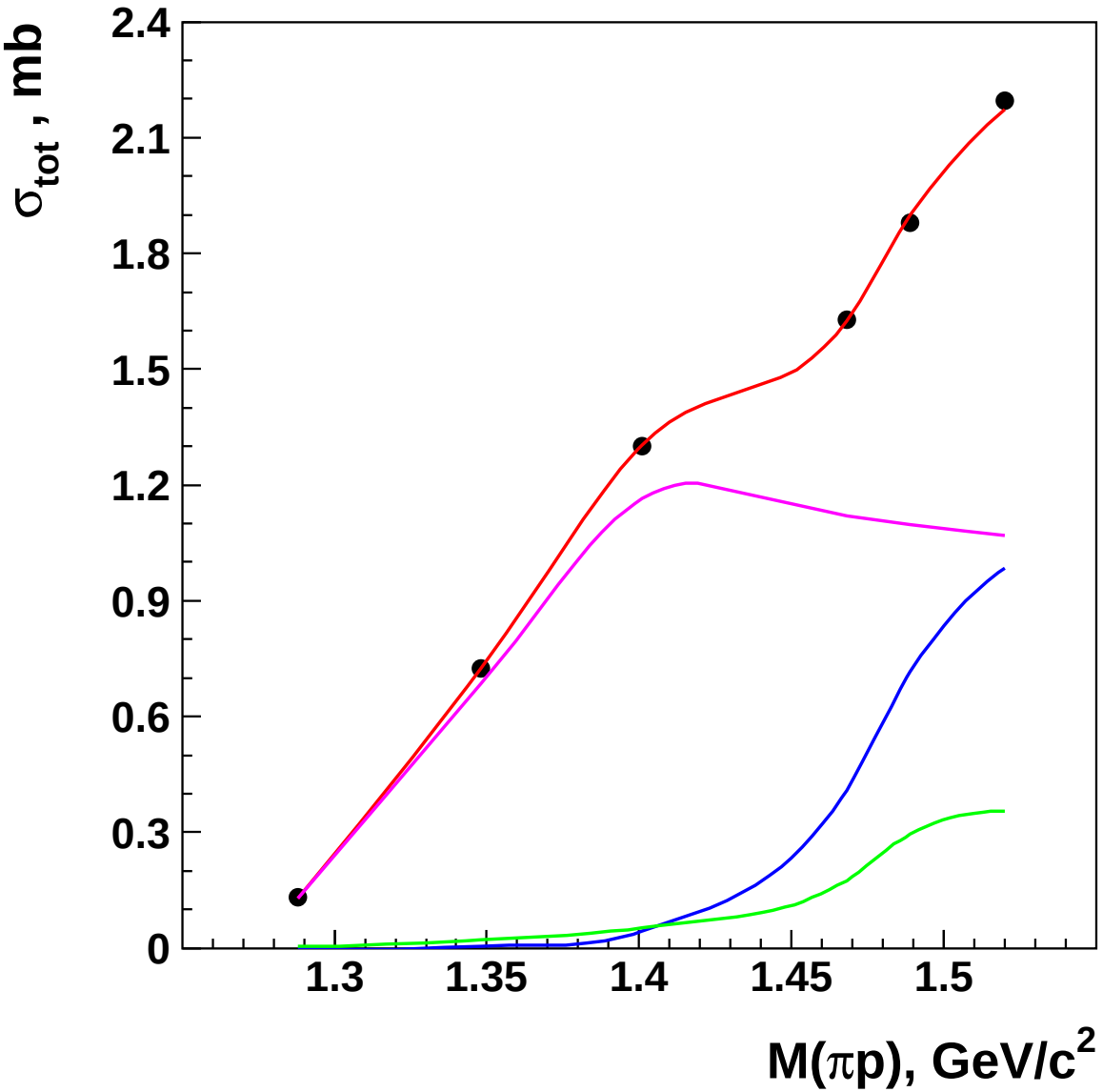
The fit of the the $\pi^+ p \to K^+\Sigma^+$ reaction



The fit of the the $\pi^- p \to K^0 \Sigma^0$ reaction



$\pi^- p \to n\pi^0\pi^0$ (Crystal Ball) total cross section



Fit of the data

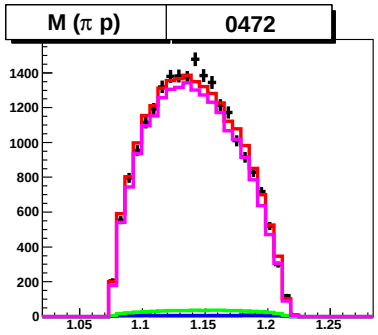
P_{11} **-partial wave**

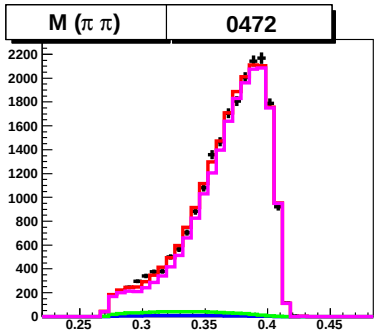
D_{13} **-partial wave**

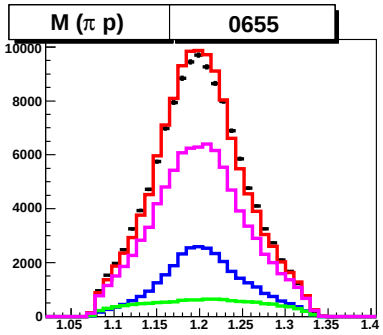
S_{11} **-partial wave**

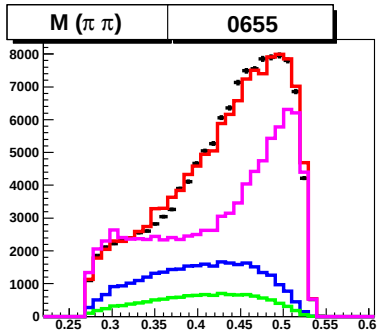
$\pi^- p \to n\pi^0\pi^0$ (Crystal Ball)

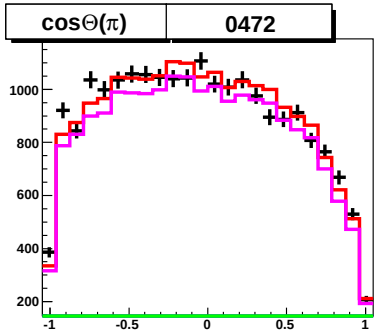
Differential cross sections for 472 and 665 MeV/c data.

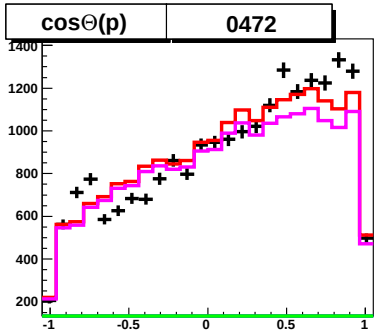


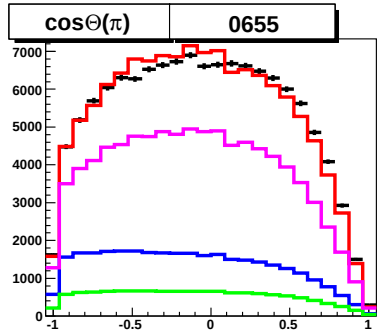


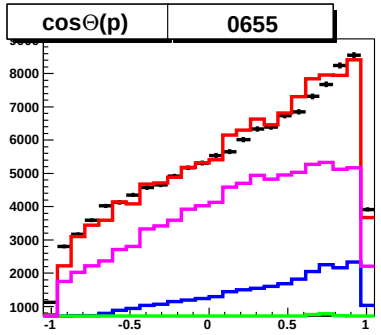


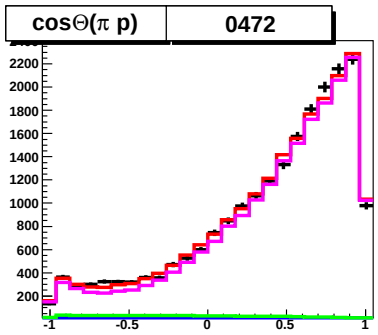


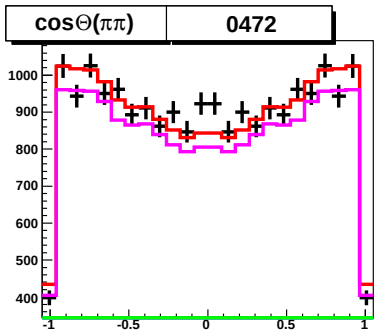


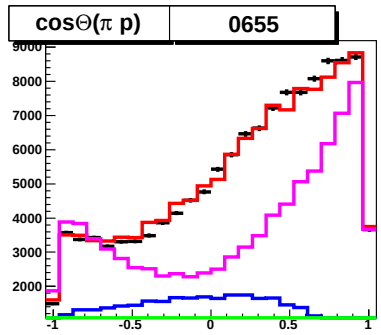


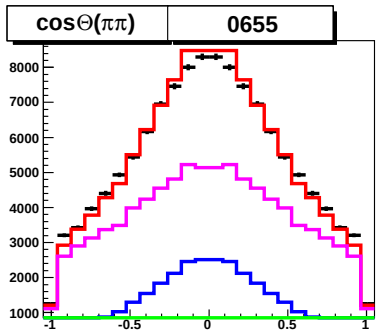






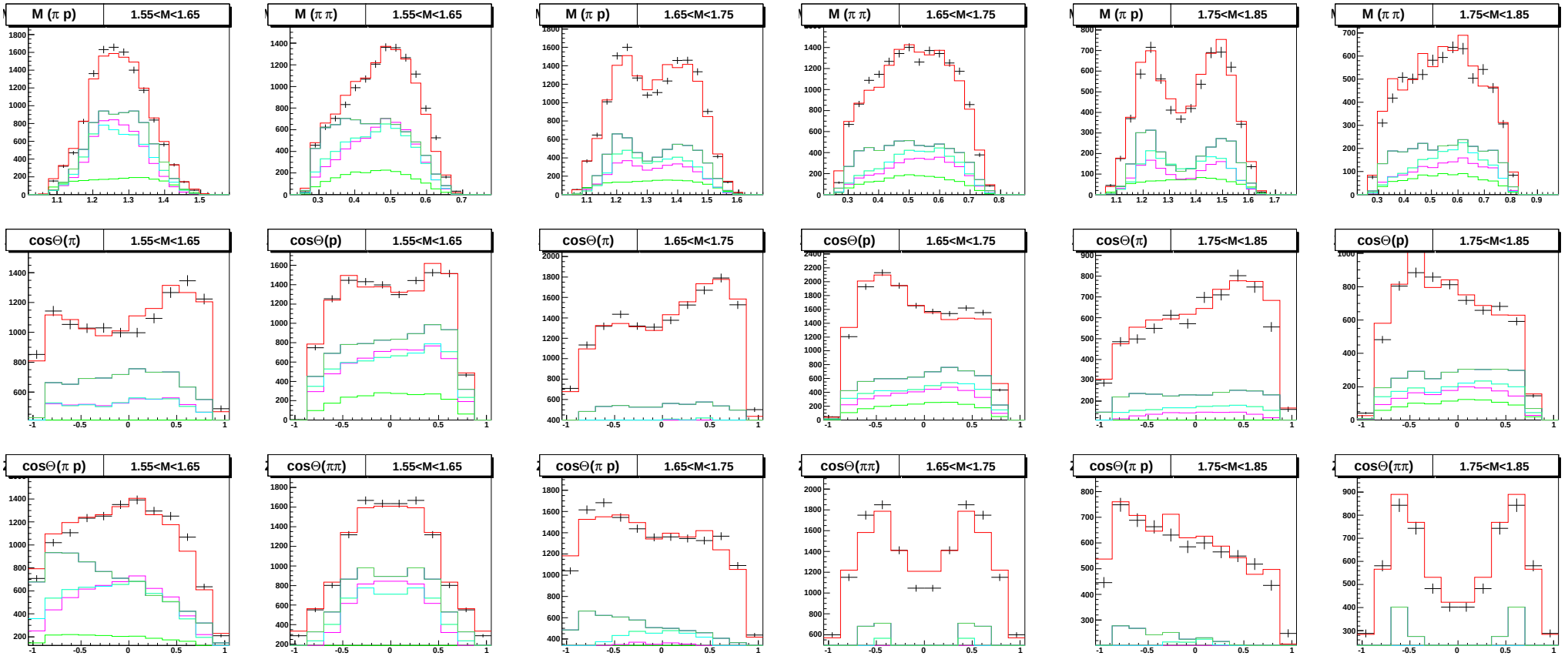






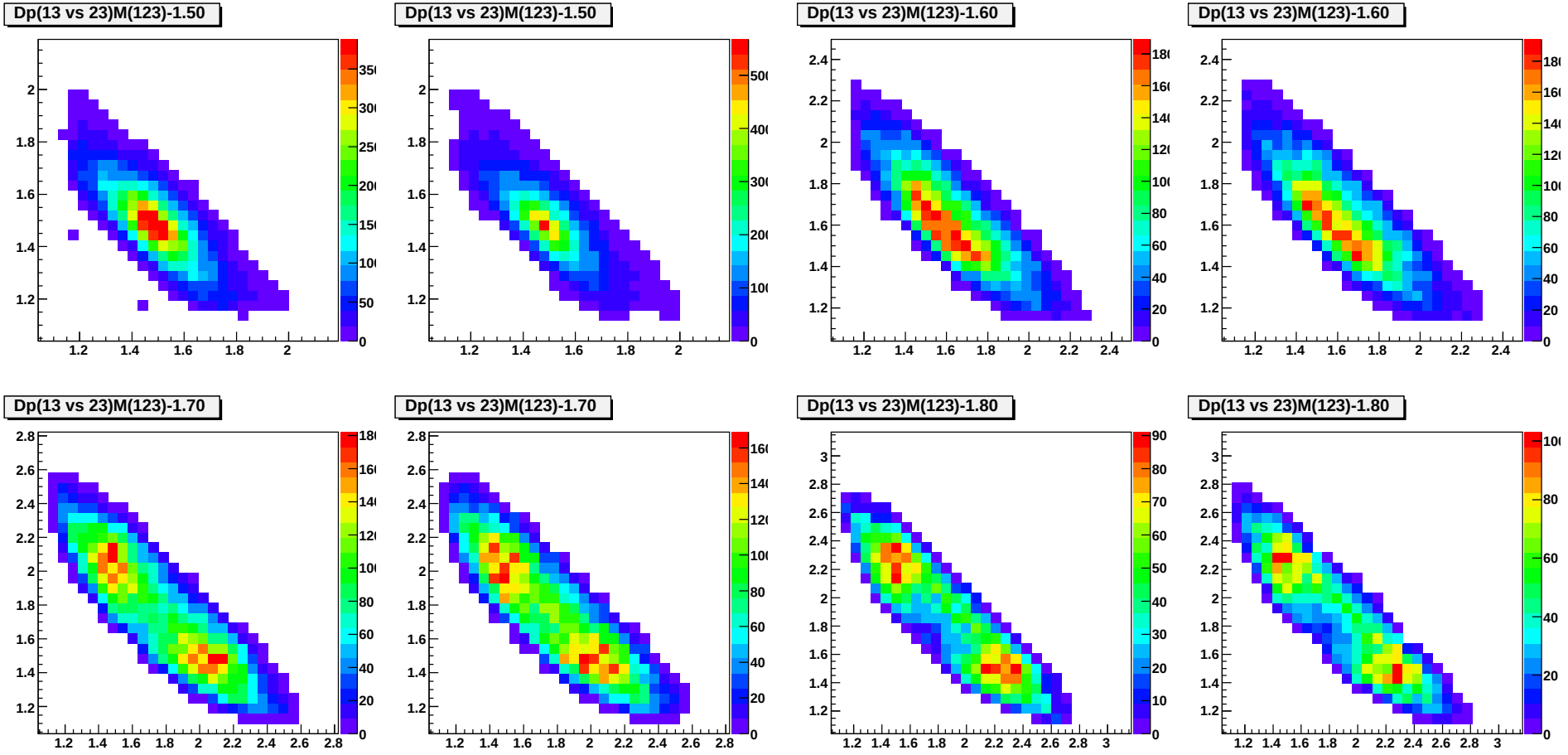
$\gamma p \to p\pi^0\pi^0$ (Crystal Barrel)

Differential cross sections.

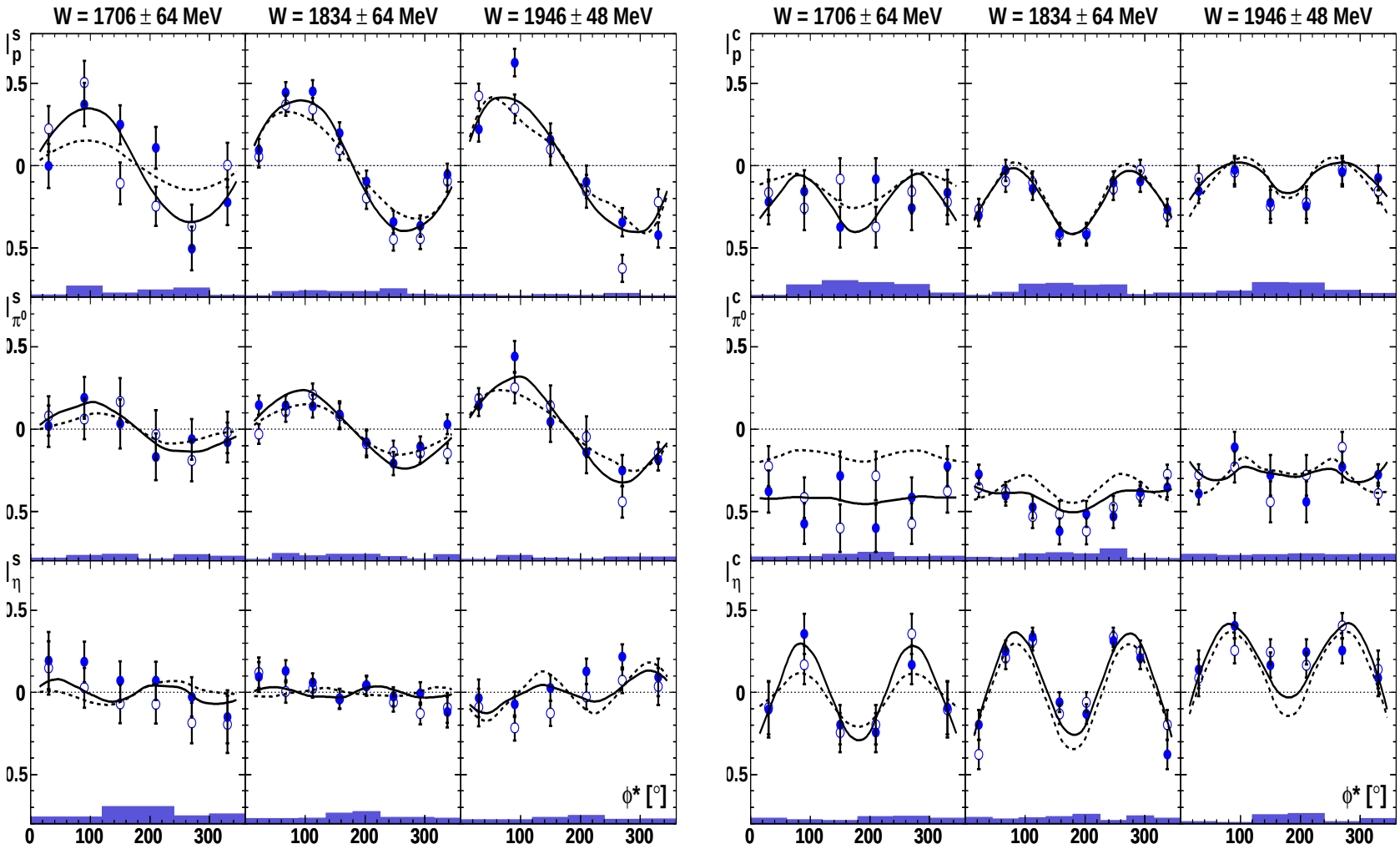


$\gamma p \to p\pi^0\pi^0$ (Crystal Barrel)

Dalitz plots W=1.5, 1.6,1.7,1.8 GeV.



I^c and I^s for $\gamma p \to p\pi^0\eta$ (CB-ELSA)



List of resonances used in the combined analysis of the data. Known states are listed by the PDG names

$N(1535)S_{11}$	$N(1650)S_{11}$	$N(1440)P_{11}$	$N(1710)P_{11}$
$N(1520)D_{13}$	$N(1700)D_{13}$	$N(1720)P_{13}$	$N(1675)D_{15}$
$N(1680)F_{15}$	$\Delta(1620)S_{31}$	$\Delta(1232)P_{33}$	$\Delta(1600)P_{33}$
$N_{1/2-}(1890)$	$N_{3/2-}(1875)$	$N_{3/2-}(2130)$	$N_{1/2+}(1860)$
$N_{3/2+}(1900)$	$N_{5/2-}(2070)$	$N(2000)F_{15}$	$N(1990)F_{17}$
$N(2190)G_{17}$	$\Delta(1900)S_{31}$	$\Delta(1910)P_{31}$	$\Delta(1920)P_{33}$
$\Delta(1905)F_{35}$	$\Delta(1950)F_{37}$	$\Delta(1700)D_{33}$	$\Delta(1940)D_{33}$
$\Delta_{3/2-}(2200)$	$\Delta(1905)F_{35}$	$\Delta(1950)F_{37}$	

Background amplitudes used in the combined analysis of the data.

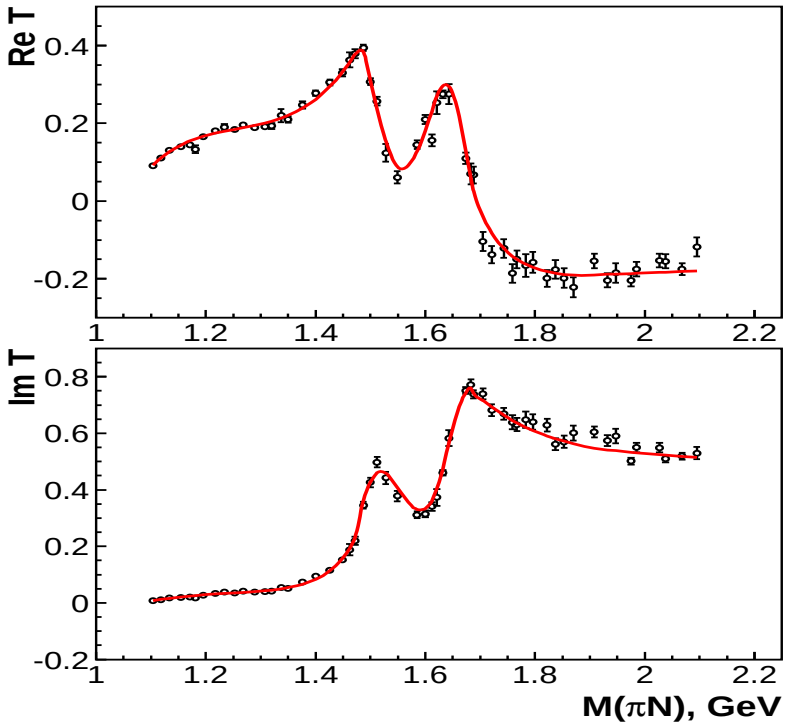
	pion-induced	photo-induced
t-channel exchange		$\pi^{\pm}$, ρ^0/ω, $\rho^{\pm}$
	K^{*0}, $K^{*\pm}$	$K^{\pm}$, K^{*0}, $K^{*\pm}$
u-channel exchange		$N(938)$, Λ, Σ^0, $\Sigma^{\pm}$
Direct production of final-state particles		

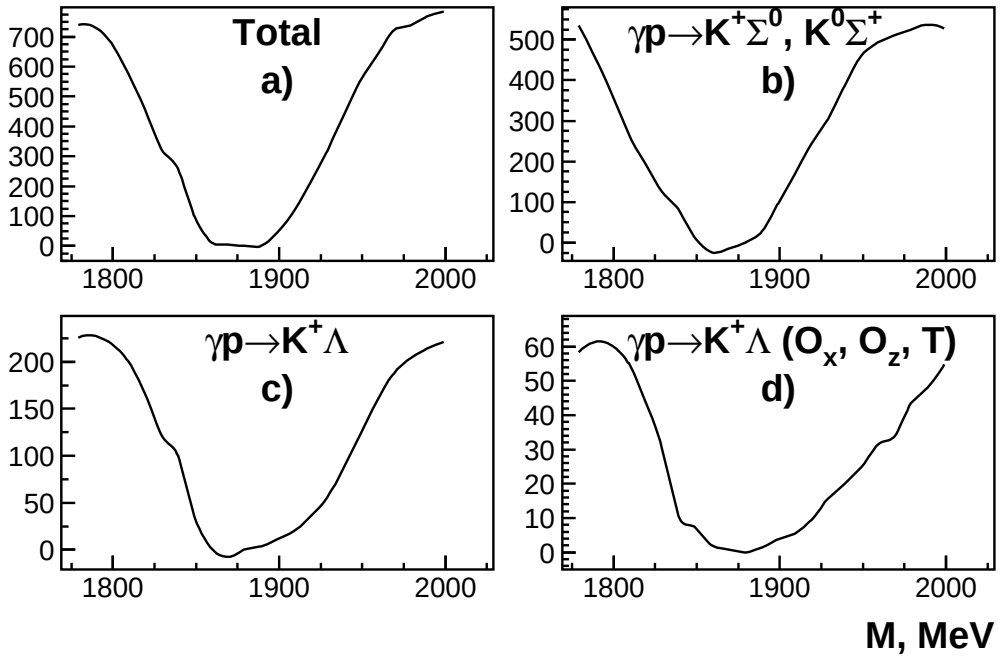
Pole position of baryon states (Re and -2Im) in the mass region 1900-2300 MeV

State		Solution 1	Solution 2	Arndt	Hoehler	Cutcosky
$N(1875)\frac{1}{2}^+$	**Re**	1860 ± 20	1850^{+20}_{-50}		1885 ± 30 **(Manley)**	
$**$	**-2Im**	110^{+30}_{-10}	360 ± 40		113 ± 44 **(Manley)**	
$N(1890)\frac{1}{2}^-$	**Re**	1895 ± 8		–	1880 ± 20	–
$**$	**-2Im**	82 ± 10		–	95 ± 30	–
$N(1880)\frac{3}{2}^-$	**Re**	1860 ± 12		–	–	1880 ± 100
$****$	**-2Im**	185 ± 16		–	–	180 ± 60
$N(2130)\frac{3}{2}^-$	**Re**	2130 ± 45		–	2081 ± 20	2050 ± 70
$***$	**-2Im**	340 ± 45		–	265 ± 40	200 ± 60
$N(1900)\frac{3}{2}^+$	**Re**	1910 ± 40	1920 ± 50	–	–	–
$****$	**-2Im**	270 ± 50	300 ± 60	–	–	–
$N(2000)\frac{5}{2}^+$	**Re**	$1800-1950$		1807	1882 ± 10	–
$*$	**-2Im**	$100-300$		109	95 ± 20	–
$N(2100)\frac{5}{2}^+$	**Re**	2100 ± 25		–	–	–
$**$	**-2Im**	550 ± 40		–	–	–
$N(2070)\frac{5}{2}^-$	**Re**	2060 ± 8		–	–	2100 ± 60
$****$	**-2Im**	370 ± 15		–	–	360 ± 80
$N(1990)\frac{7}{2}^+$	**Re**	1975 ± 15	2090 ± 15	–	~ 1935	1900 ± 30
$**$	**-2Im**	170 ± 50	260 ± 20	–	~ 260	260 ± 60
$N(2190)\frac{7}{2}^-$	**Re**	2160 ± 20		2070	2042	2100 ± 50
$****$	**-2Im**	310 ± 25		520	480	400 ± 160

S_{11}: pole position and Breit-Wigner parameters

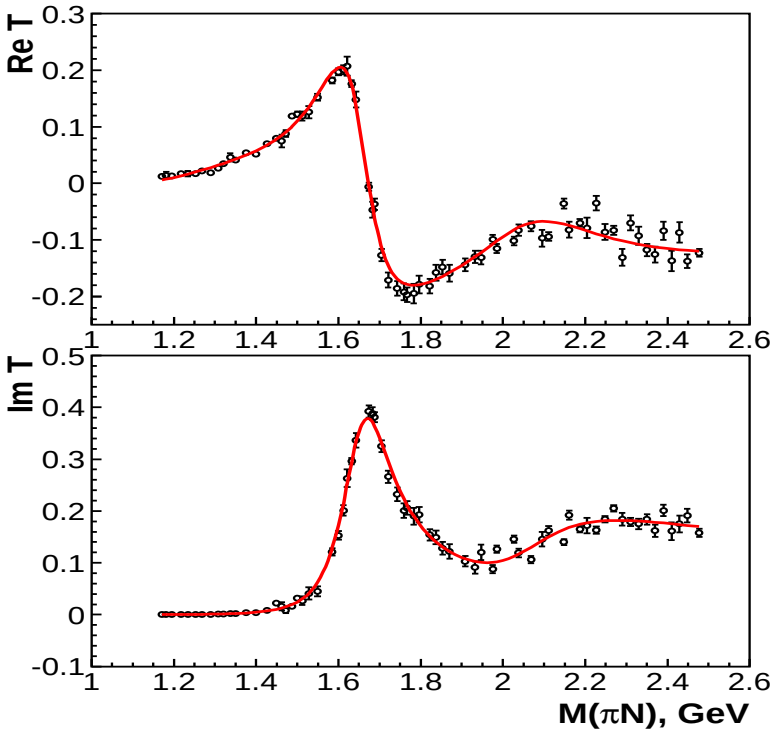
State		Solution 1	Solution 2	Arndt	Hoehler	Cutcosky
$N(1890)\frac{1}{2}^-$	**Re**	1895 ± 8				
$**$	**-2Im**	82 ± 10				
BW	**M**	1900 ± 10			1880 ± 20	
parameters	Γ	77 ± 15			95 ± 30	

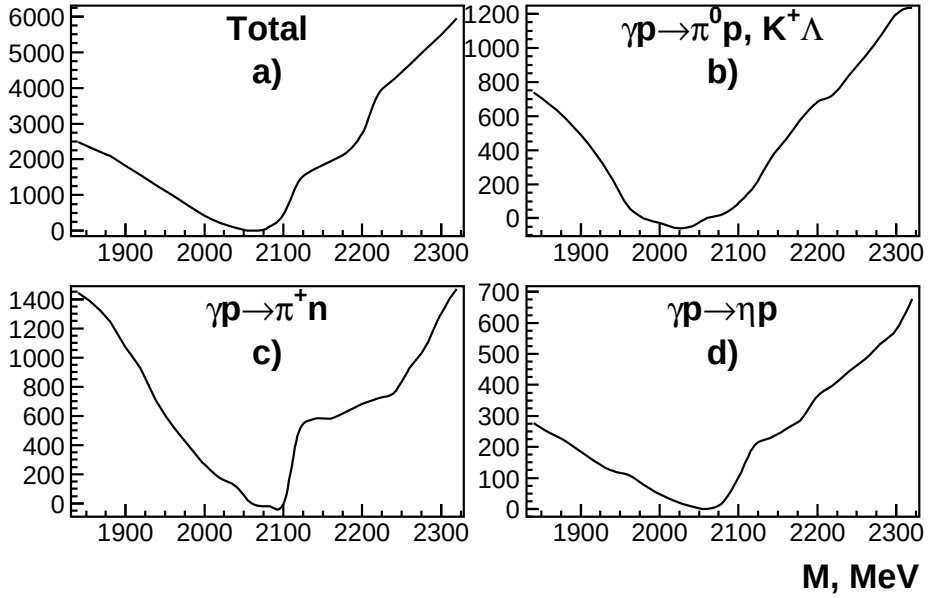




D_{15}: pole position and Breit-Wigner parameters

State		Solution 1	Solution 2	Arndt	Hoehler	Cutcosky
$N(2070)\frac{5}{2}^-$	**Re**	2060 ± 8		–	–	2100 ± 60
$****$	**-2Im**	370 ± 15		–	–	360 ± 80
BW	**M**	2075 ± 12			2228 ± 30	2180 ± 80
parameters	Γ	365 ± 20			310 ± 50	400 ± 100

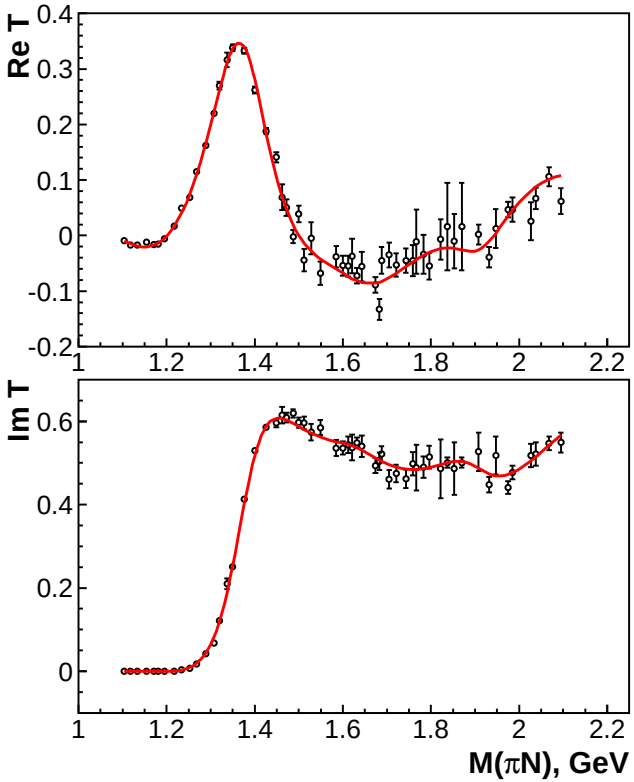




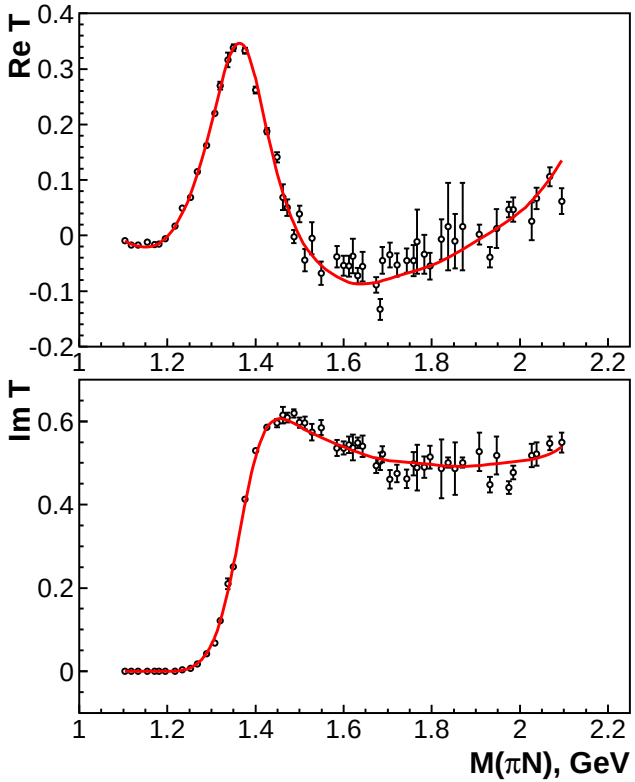
P_{11}: pole position and Breit-Wigner parameters

State		Solution 1	Solution 2	Manley
$N(1875)\frac{1}{2}^+$	**Re**	1860 ± 20	1850^{+20}_{-50}	1885 ± 30
$*$	**-2Im**	110^{+30}_{-10}	360 ± 40	113 ± 44
BW	**M**	1864 ± 10	1863 ± 20	
parameters	Γ	115 ± 20	320 ± 30	

BG2011-01

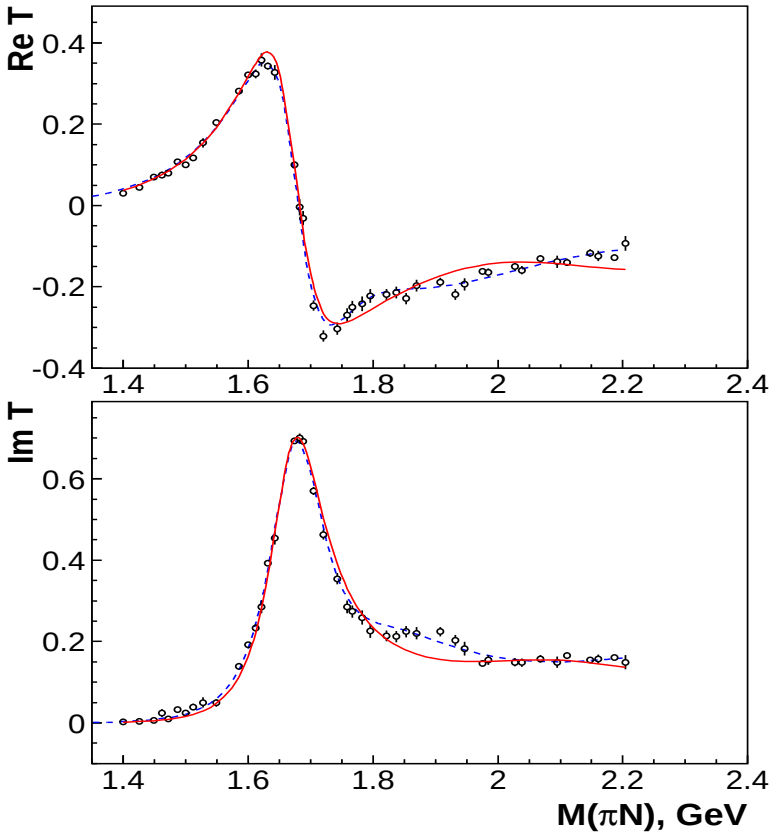


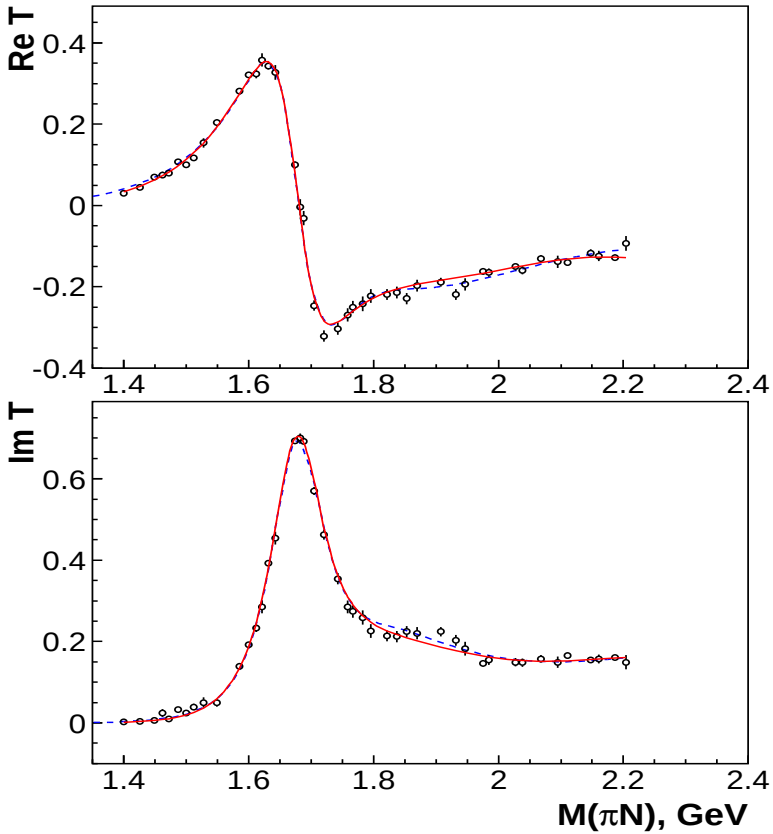
BG2011-02



Pole position of F_{15}: two and three pole solution

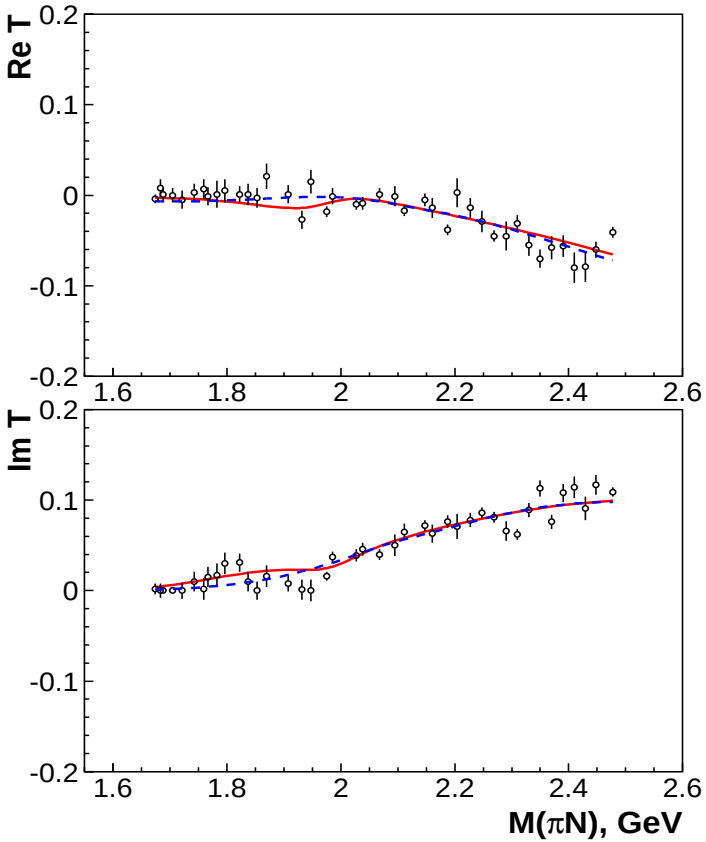
State		Solution 1	Solution 2	Arndt	Hoehler	Cutcosky
$N(2000)\frac{5}{2}^+$	**Re**	$1800-1950$	$1800-1950$	1807	1882 ± 10	–
**	**-2Im**	$100-300$	$100-300$	109	95 ± 20	–
$N(2100)\frac{5}{2}^+$	**Re**	2090^{+20}_{-40}	2110^{+20}_{-80}	–	–	–
	-2Im	560 ± 100	540 ± 100	–	–	–

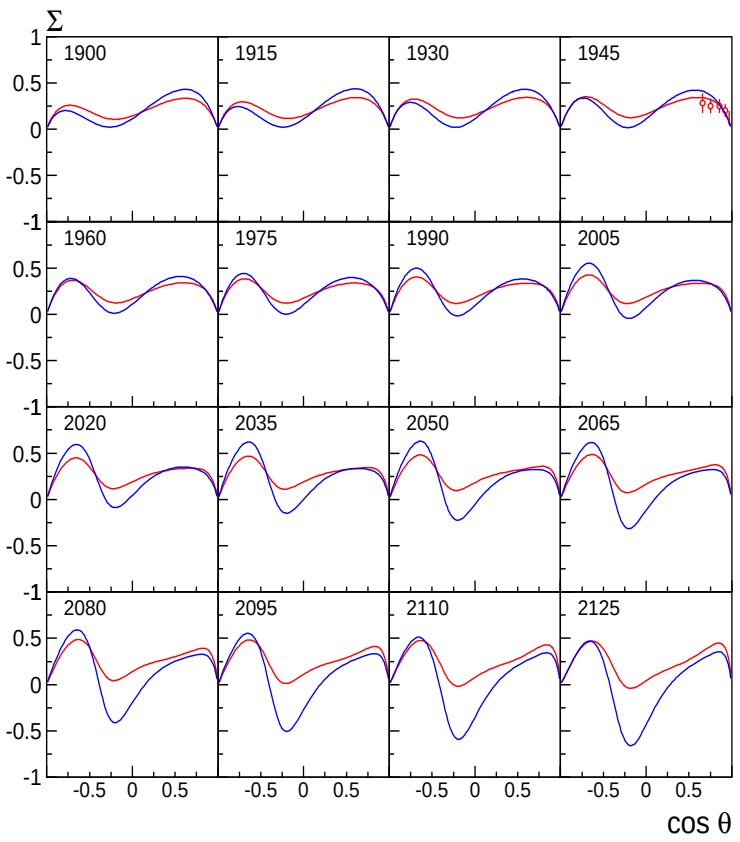




Pole position of F_{17} and helicity couplings (absolute value (10^{-3} GeV$^{\frac{1}{2}}$)/phase (degrees)

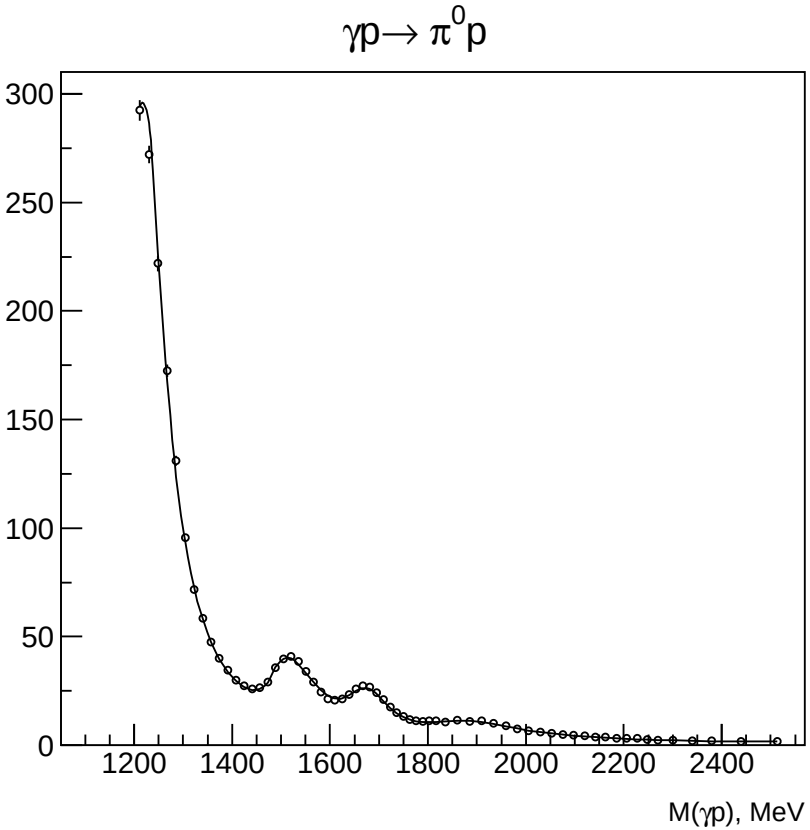
State		Solution 1	$A(\frac{1}{2})/A(\frac{3}{2})$	Solution 2	$A(\frac{1}{2})/A(\frac{3}{2})$
$N(1990)\frac{7}{2}^+$	**Re**	1980 ± 25	$15/14^o$	2100 ± 30	$76/50^o$
$**$	**-2Im**	180 ± 30	$28/3^o$	300 ± 60	$78/45^o$

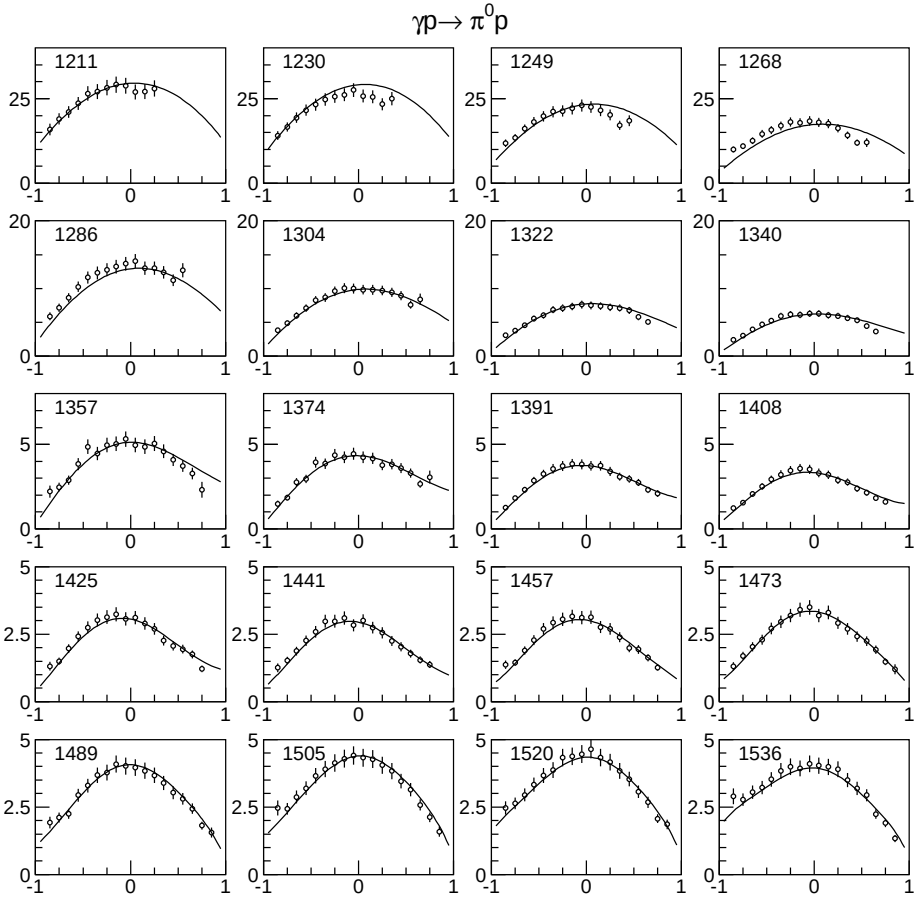


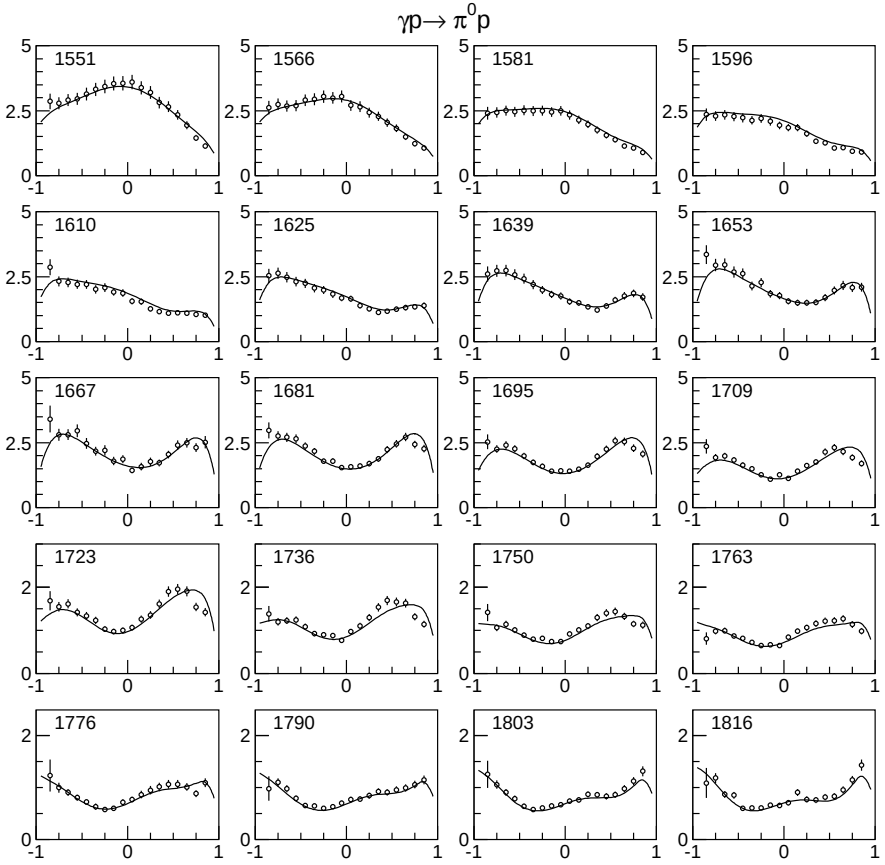


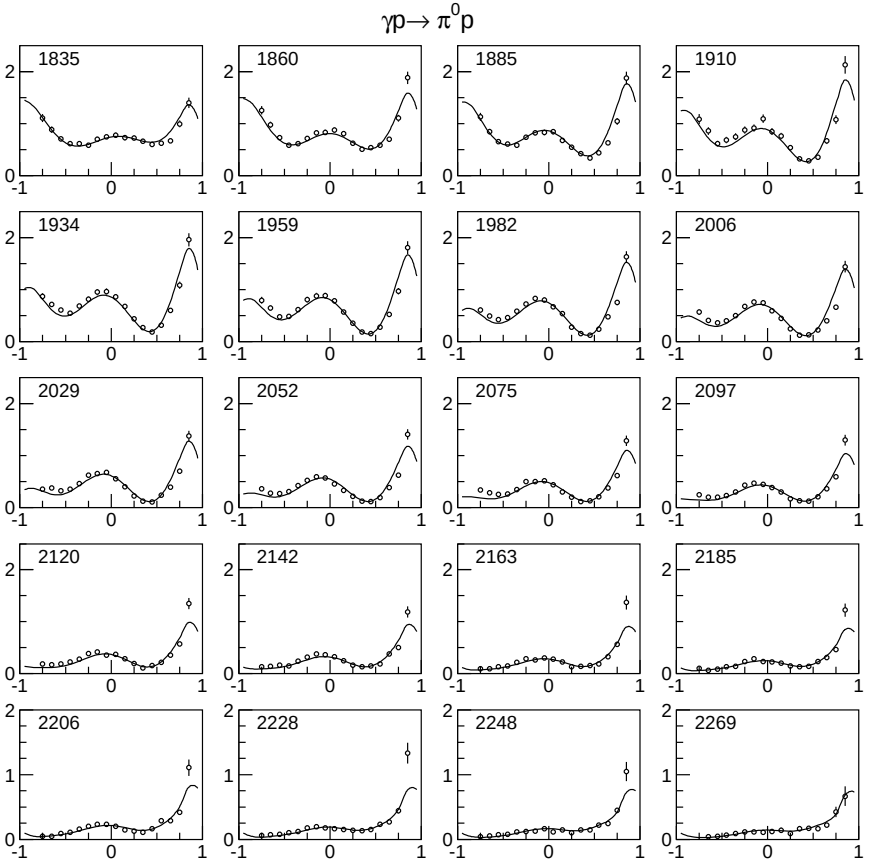
Summary

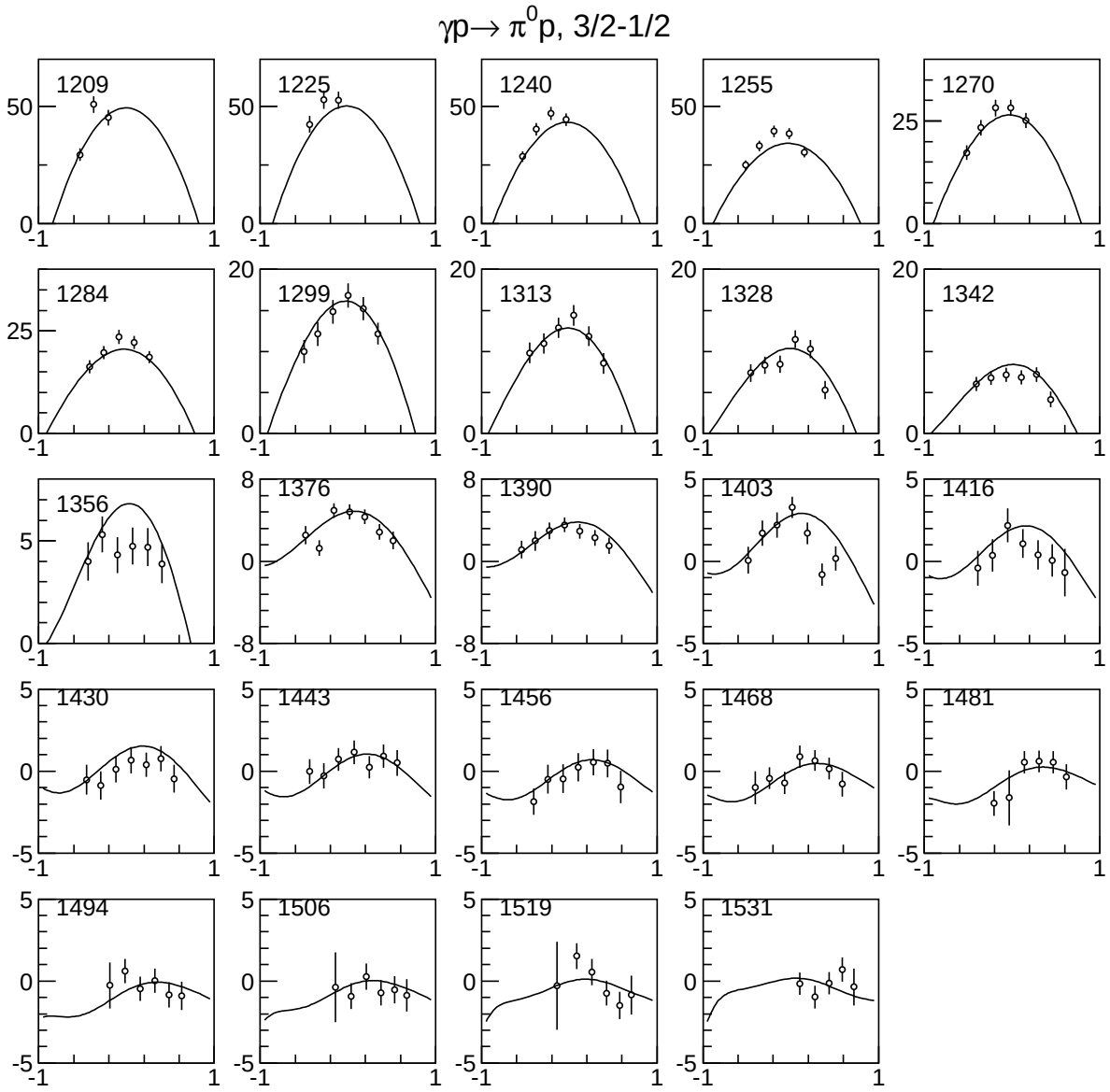
- **The analysis of (almost) all available data for production of baryons in the pion and photo induced reaction is completed.**
- **We have observed a set of new states in the region 1800-2150 MeV, however, this number is much less than that predicted by the classical quark model.**
- **There are two solutions for the $N_{\frac{7}{2}+}$ lowest state which should be distinguished from analysis of beam asymmetry data on photoproduction of hyperon-kaon final states.**
- **The situation for $N(\frac{5}{2}^{+})$ can be resolved with reanalysis of πN elastic data and an analysis of new data on double pion photoproduction (with charged pions).**

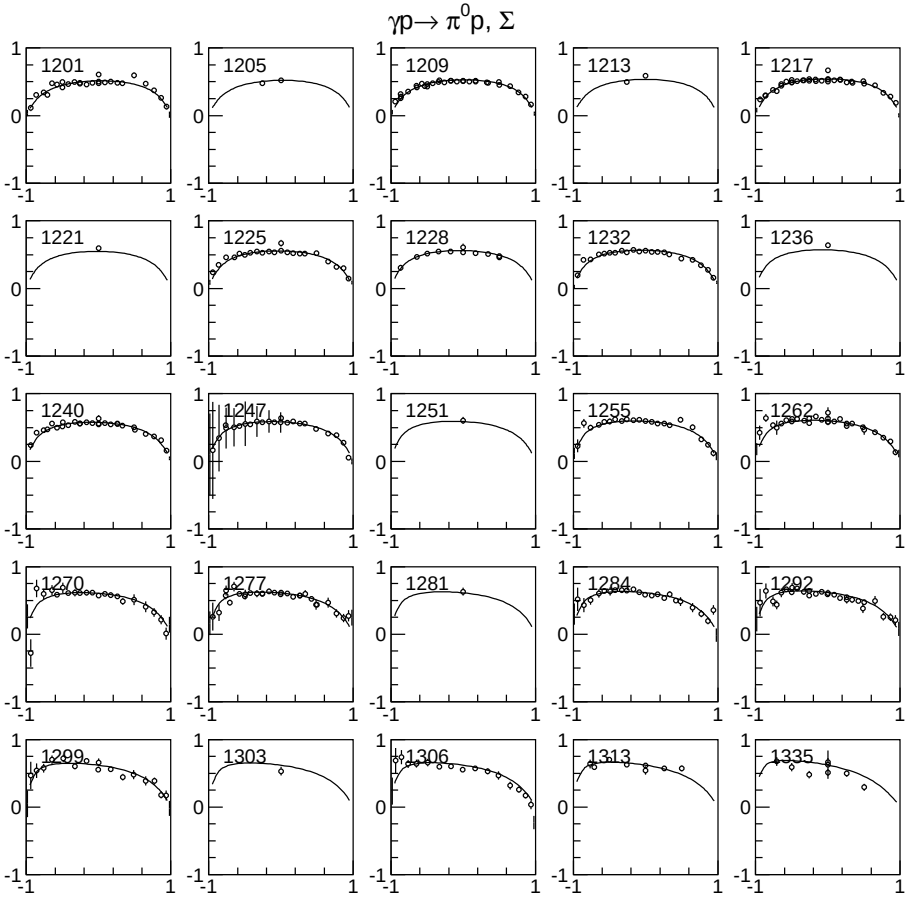

γp→ π0p
300
250
200
150
100
50
0
1200
1400
1600
1800
2000
2200
2400
M(γp), MeV

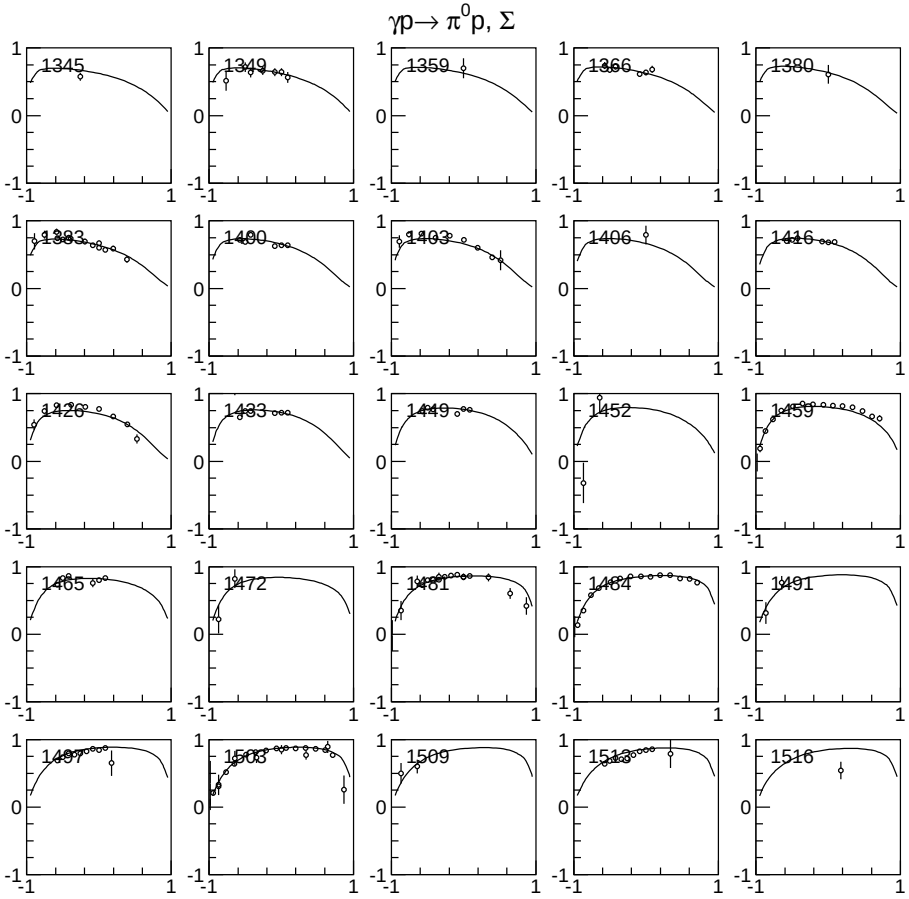

γp→ π0p
1211
1230
1249
1268
1286
1304
1322
1340
1357
1374
1391
1408
1425
1441
1457
1473
1489
1505
1520
1536

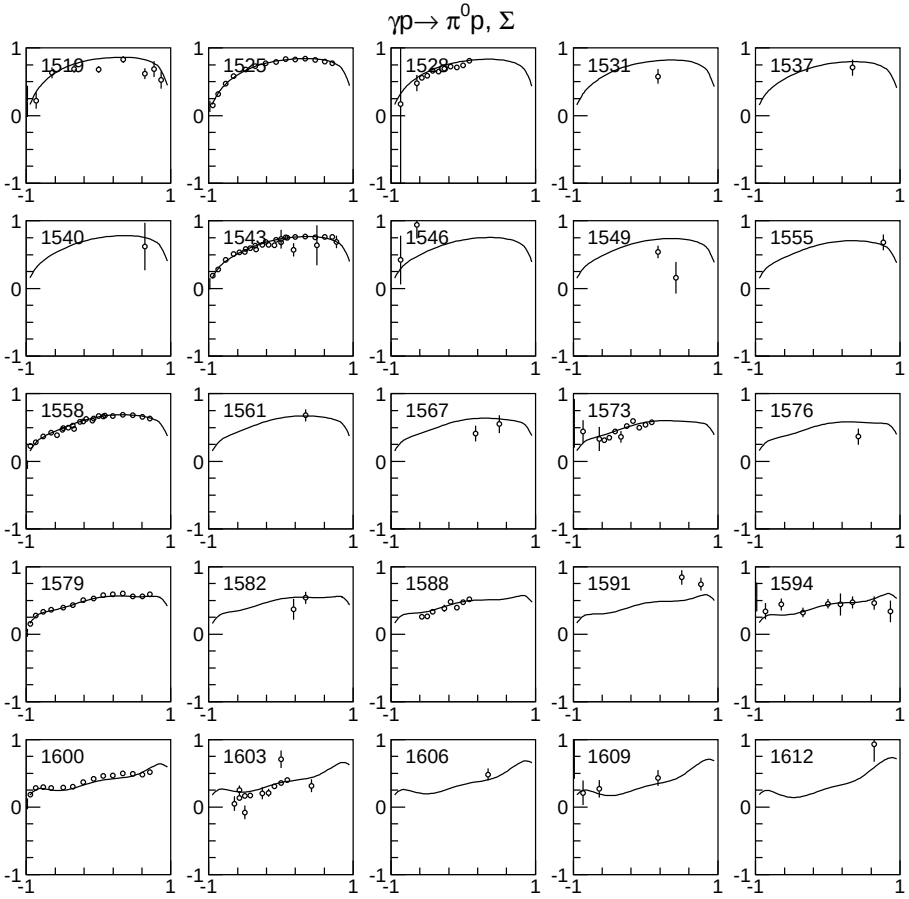

γp→ π0p
1551
1566
1581
1596
1610
1625
1639
1653
1667
1681
1695
1709
1723
1736
1750
1763
1776
1790
1803
1816

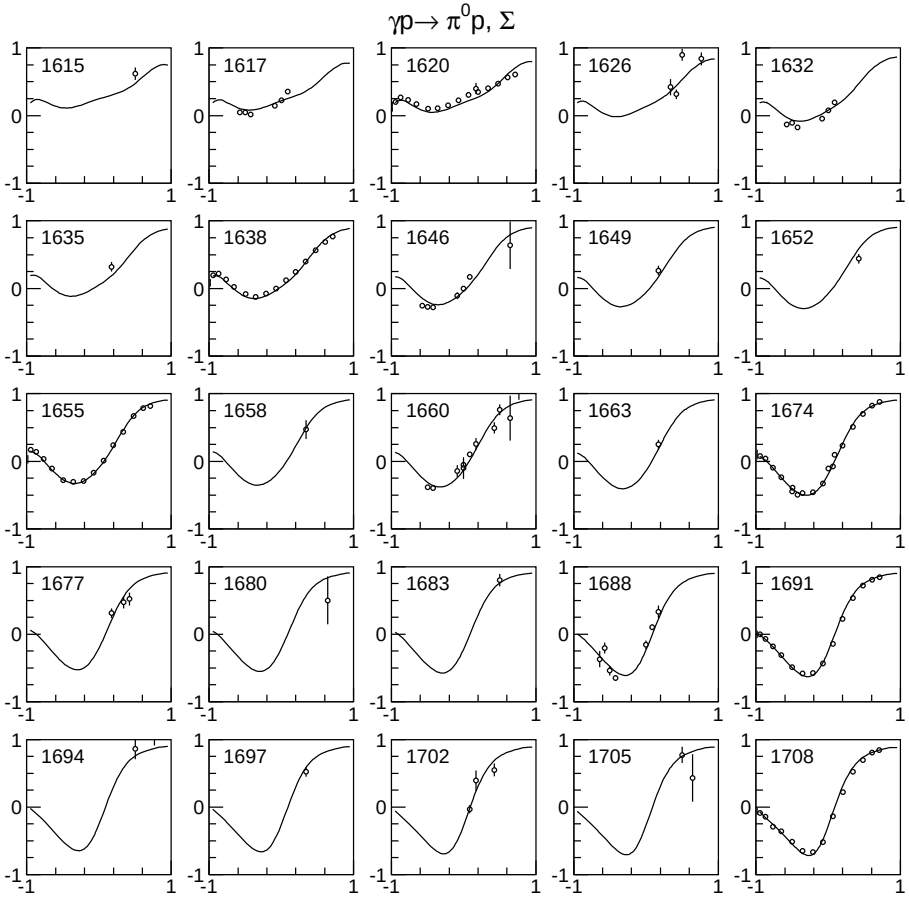

γp→ π0p
1835
1860
1885
1910
1934
1959
1982
2006
2029
2052
2075
2097
2120
2142
2163
2185
2206
2228
2248
2269

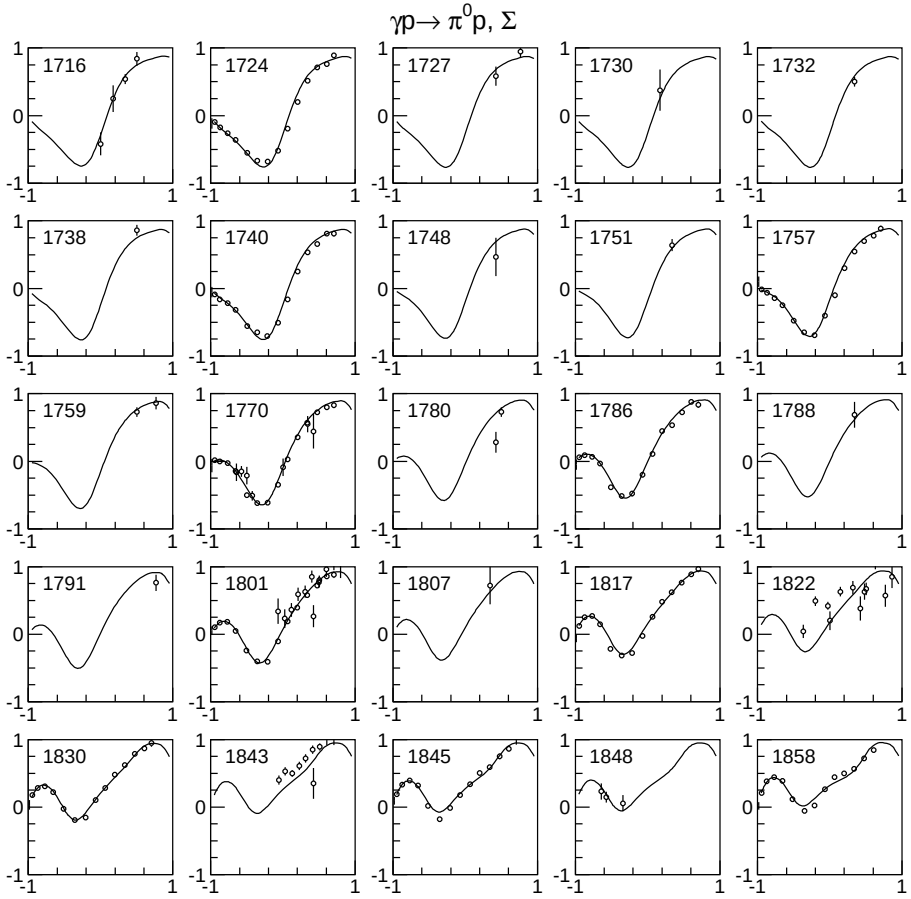

γp→ π0p, 3/2-1/2
1209
1225
1240
1255
1270
1284
1299
1313
1328
1342
1356
1376
1390
1403
1416
1430
1443
1456
1468
1481
1494
1506
1519
1531

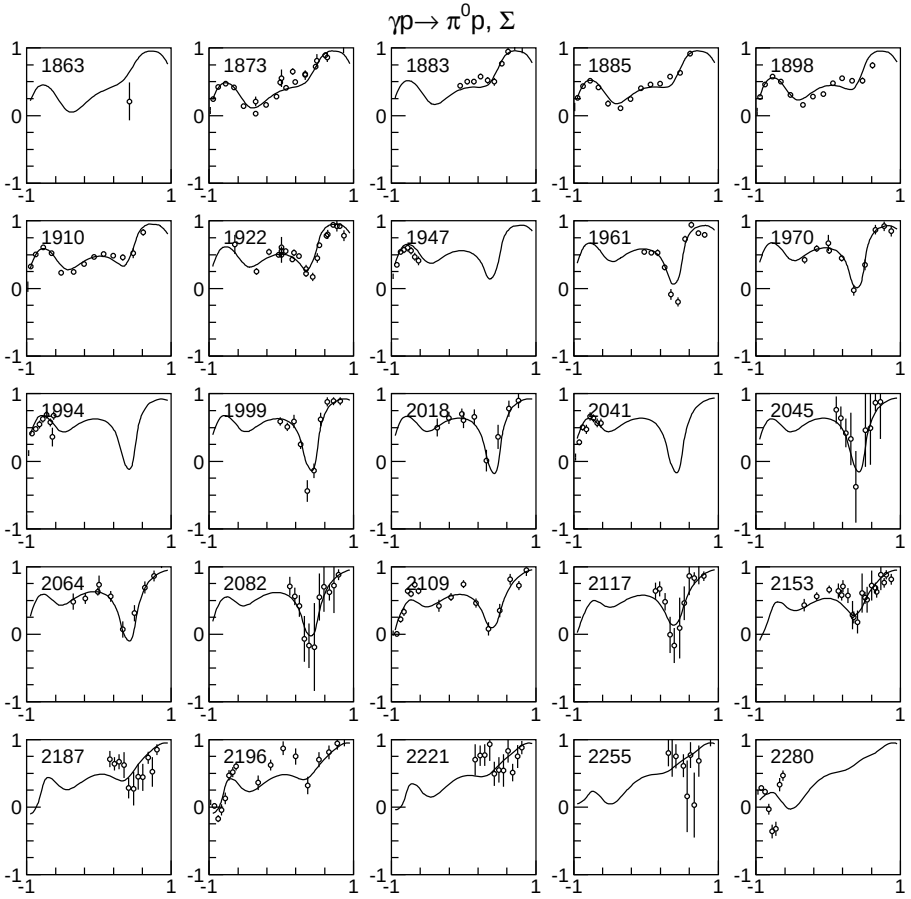

γp→ π0p, Σ
1201
1205
1209
1213
1217
1221
1225
1228
1232
1236
1240
1247
1251
1255
1262
1270
1277
1281
1284
1292
1299
1303
1306
1313
1335

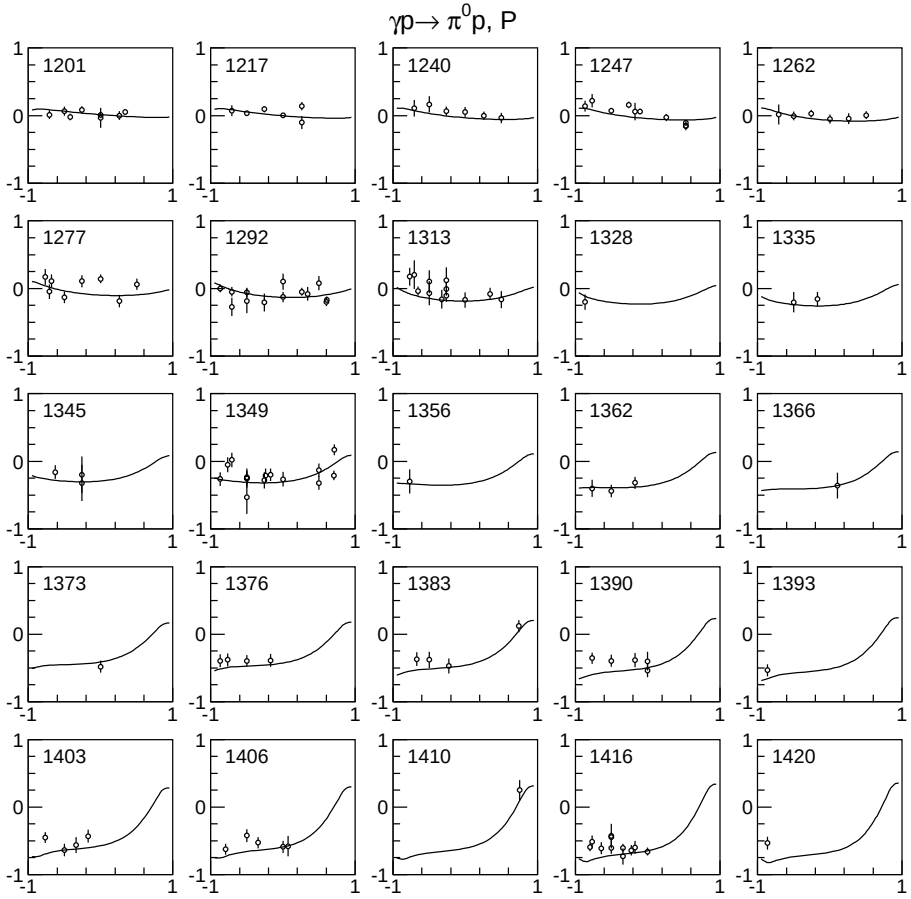

γp→ π0p, Σ
1345
1349
1359
1366
1380
1383
1390
1403
1406
1416
1426
1433
1449
1452
1459
1465
1472
1481
1484
1491
1497
1503
1509
1513
1516

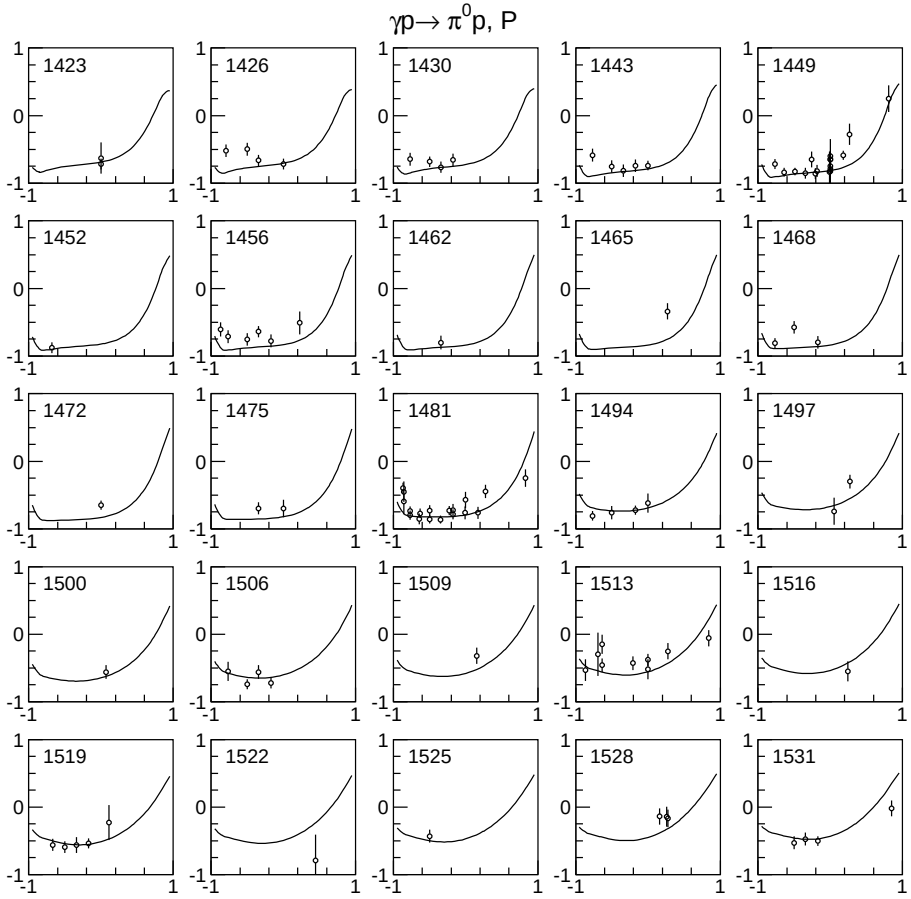

γp→ π0p, Σ
1510
1520
1528
1531
1537
1540
1543
1546
1549
1555
1558
1561
1567
1573
1576
1579
1582
1588
1591
1594
1600
1603
1606
1609
1612

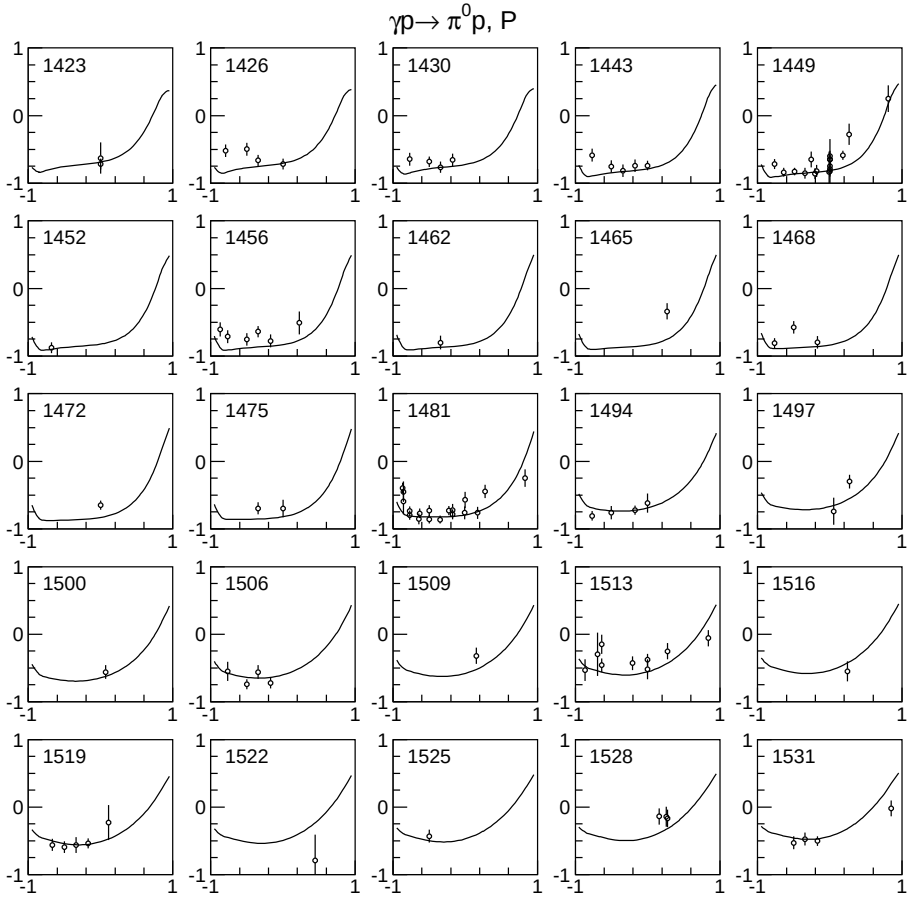

γp→ π0p, Σ
1615
1617
1620
1626
1632
1635
1638
1646
1649
1652
1655
1658
1660
1663
1674
1677
1680
1683
1688
1691
1694
1697
1702
1705
1708

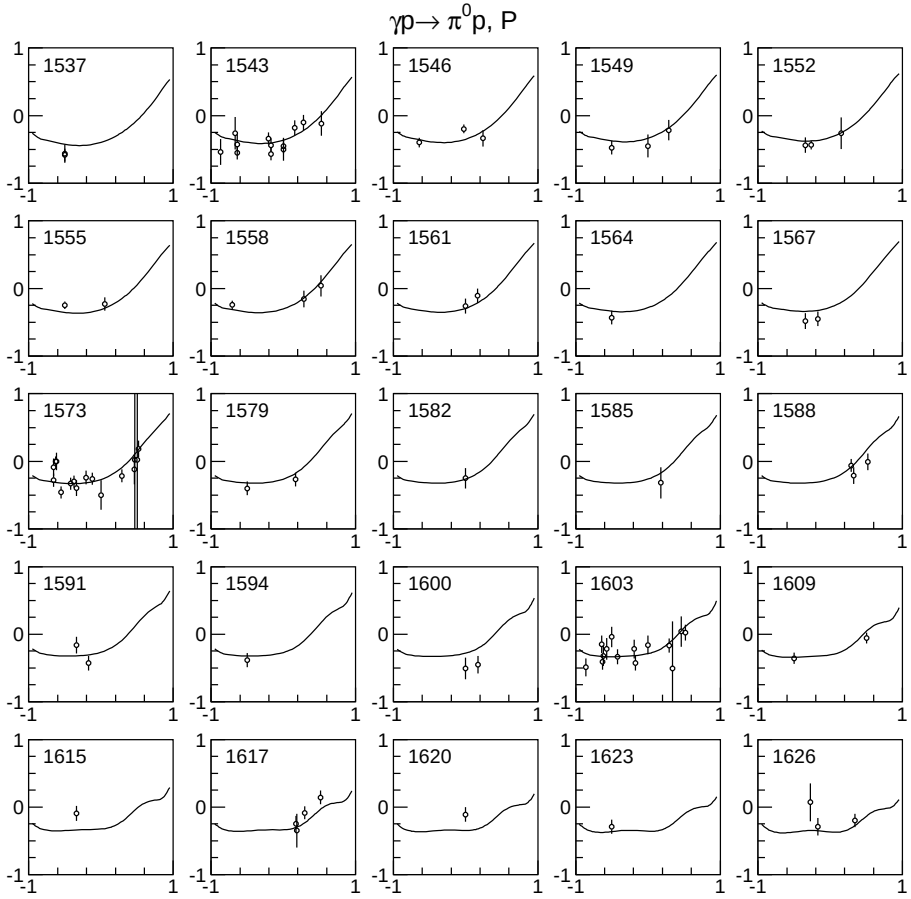

γp→ π0p, Σ
1716
1724
1727
1730
1732
1738
1740
1748
1751
1757
1759
1770
1780
1786
1788
1791
1801
1807
1817
1822
1830
1843
1845
1848
1858

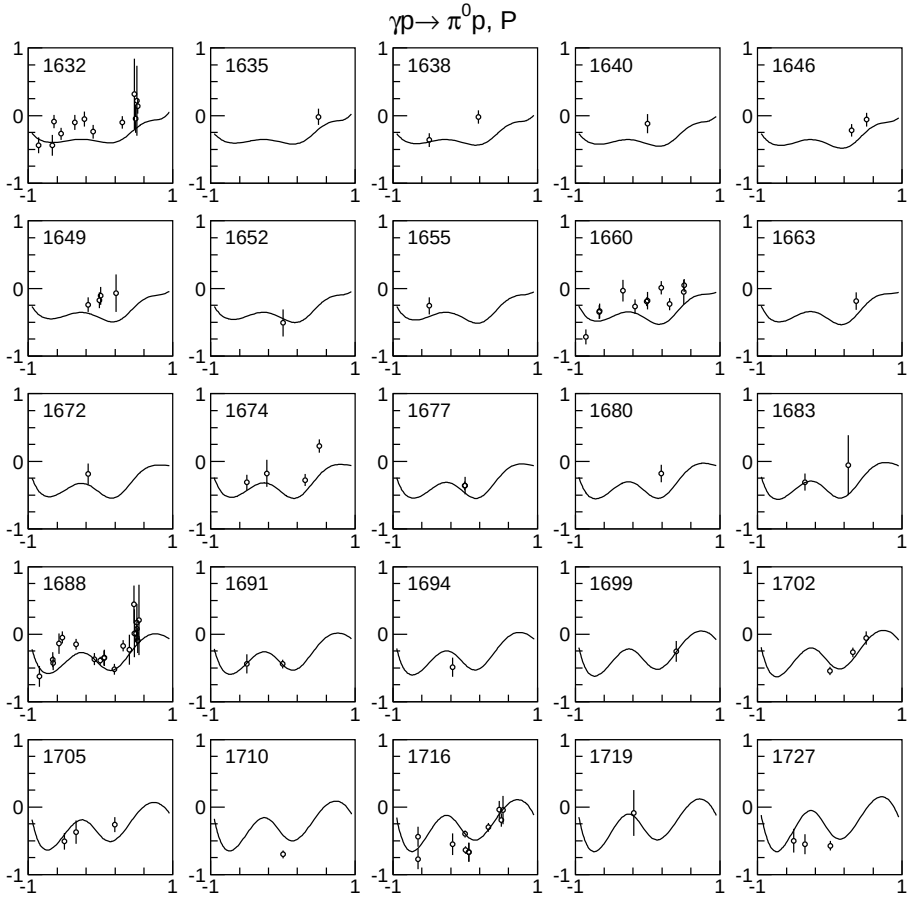

γp→ π0p, Σ
1863
1873
1883
1885
1898
1910
1922
1947
1961
1970
1994
1999
2018
2041
2045
2064
2082
2109
2117
2153
2187
2196
2221
2255
2280

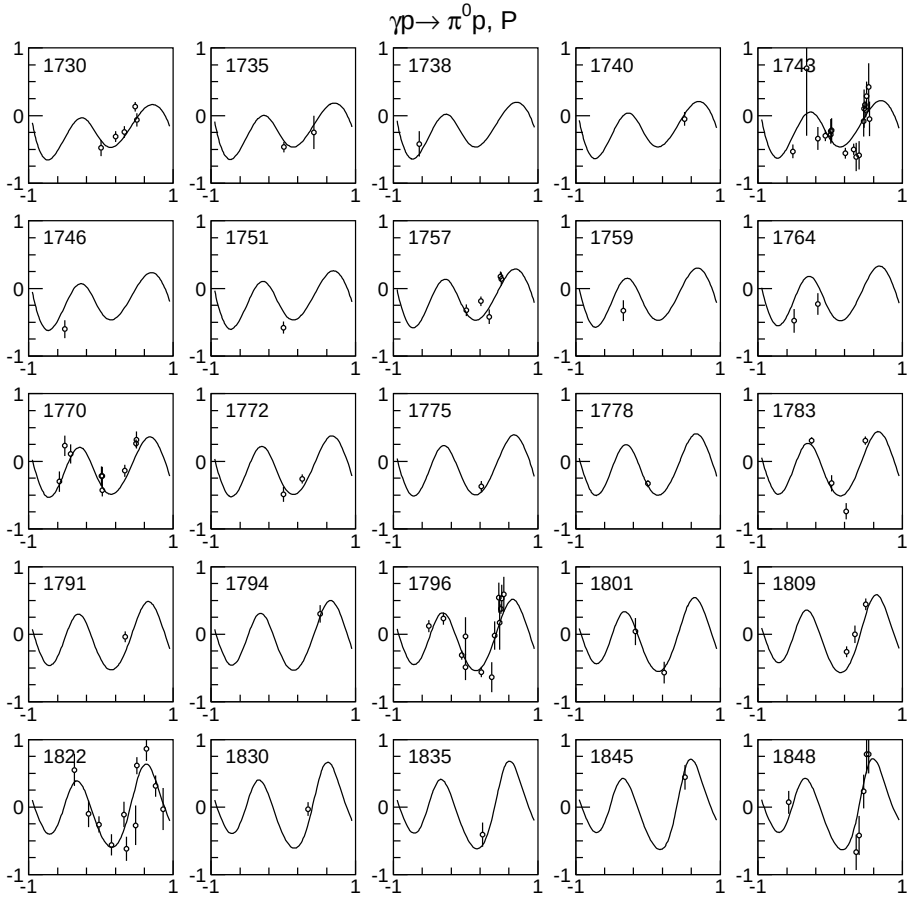

γp→ π0p, P
1201
1217
1240
1247
1262
1277
1292
1313
1328
1335
1345
1349
1356
1362
1366
1373
1376
1383
1390
1393
1403
1406
1410
1416
1420

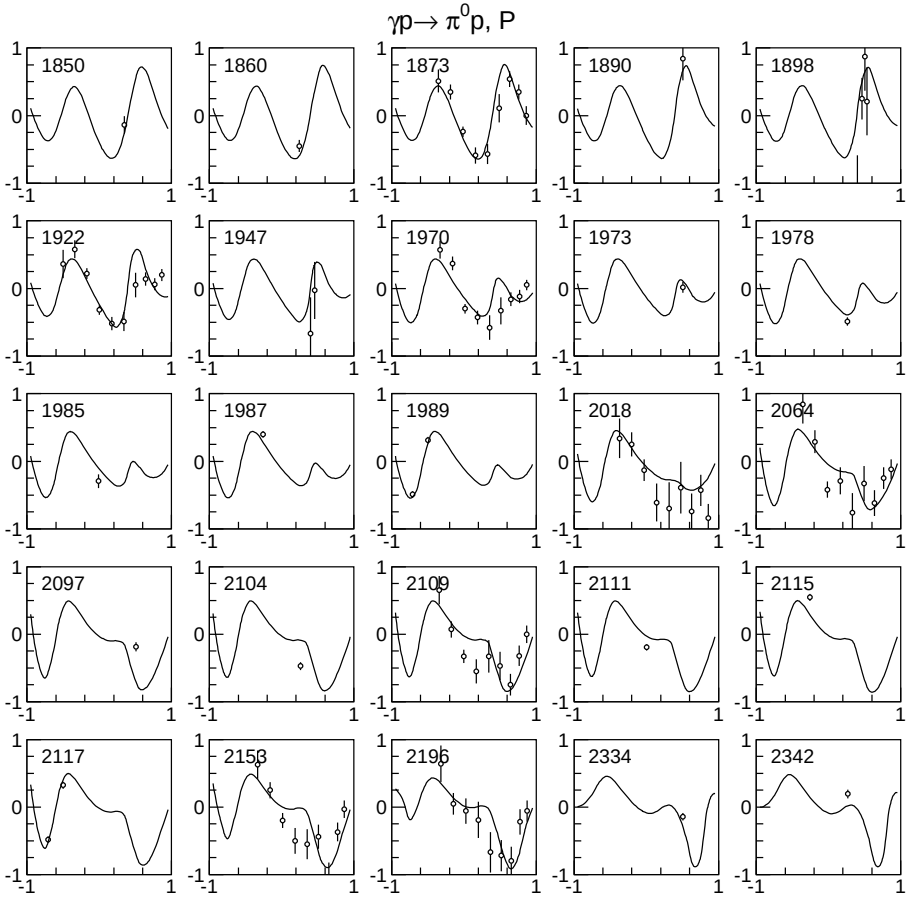

γp→ π0p, P
1423
1426
1430
1443
1449
1452
1456
1462
1465
1468
1472
1475
1481
1494
1497
1500
1506
1509
1513
1516
1519
1522
1525
1528
1531

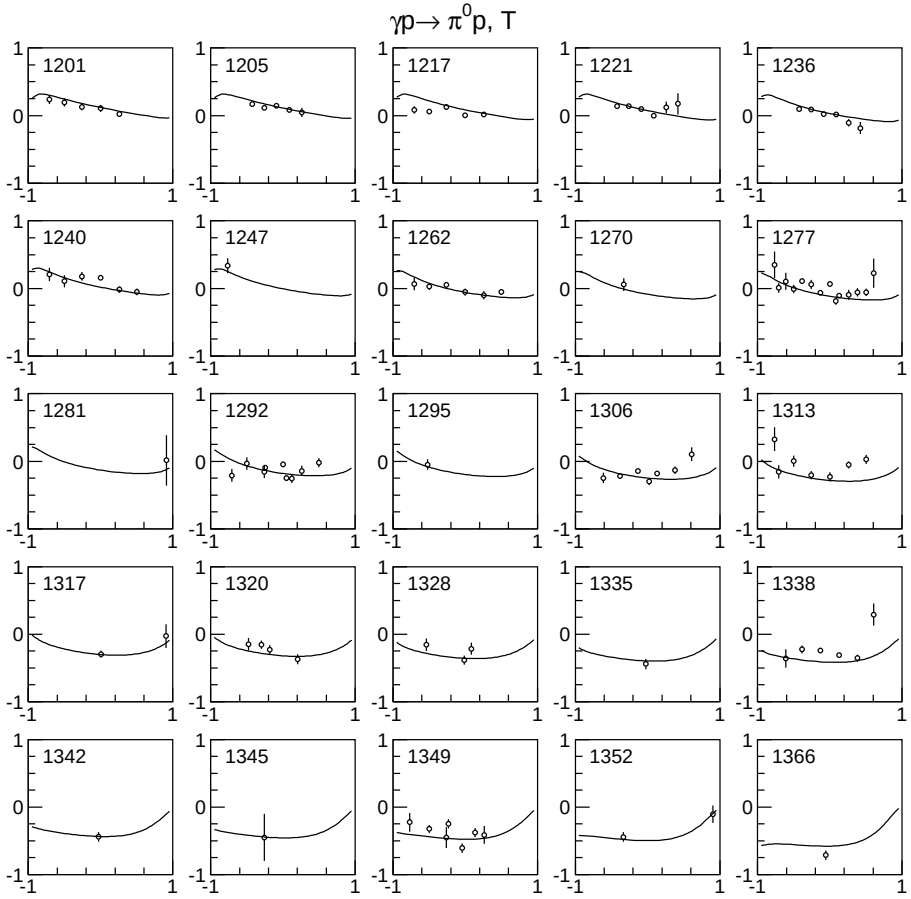

γp→ π0p, P
1423
1426
1430
1443
1449
1452
1456
1462
1465
1468
1472
1475
1481
1494
1497
1500
1506
1509
1513
1516
1519
1522
1525
1528
1531

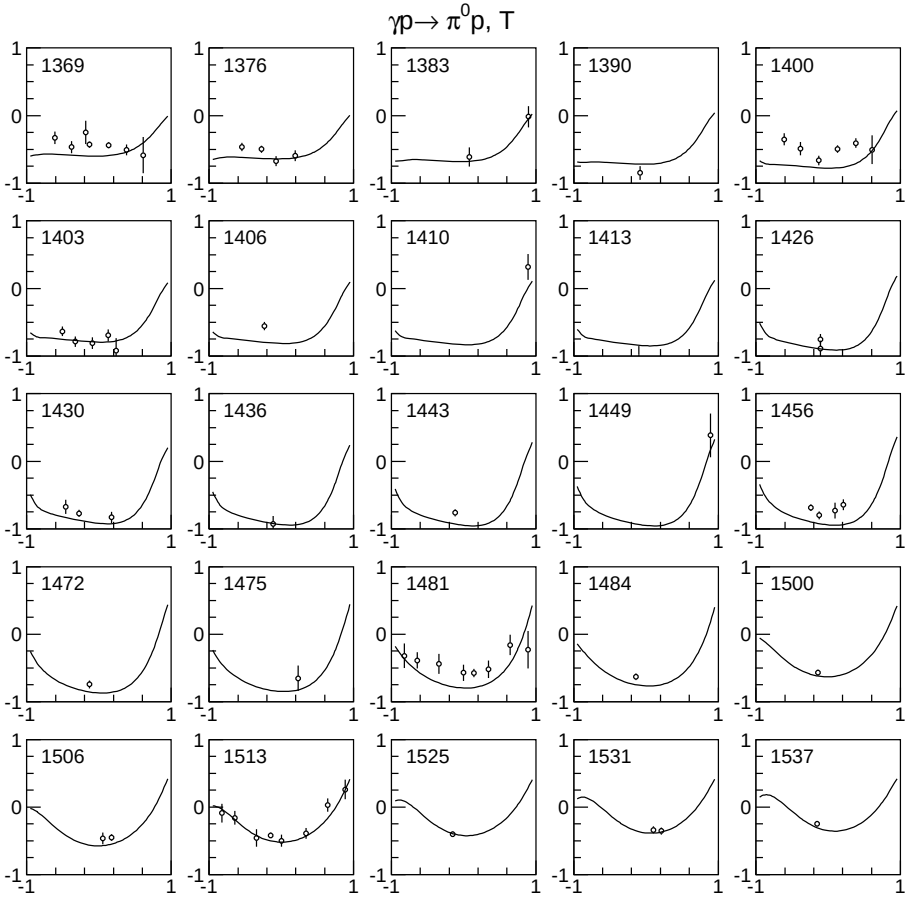

γp→ π0p, P
1537
1543
1546
1549
1552
1555
1558
1561
1564
1567
1573
1579
1582
1585
1588
1591
1594
1600
1603
1609
1615
1617
1620
1623
1626

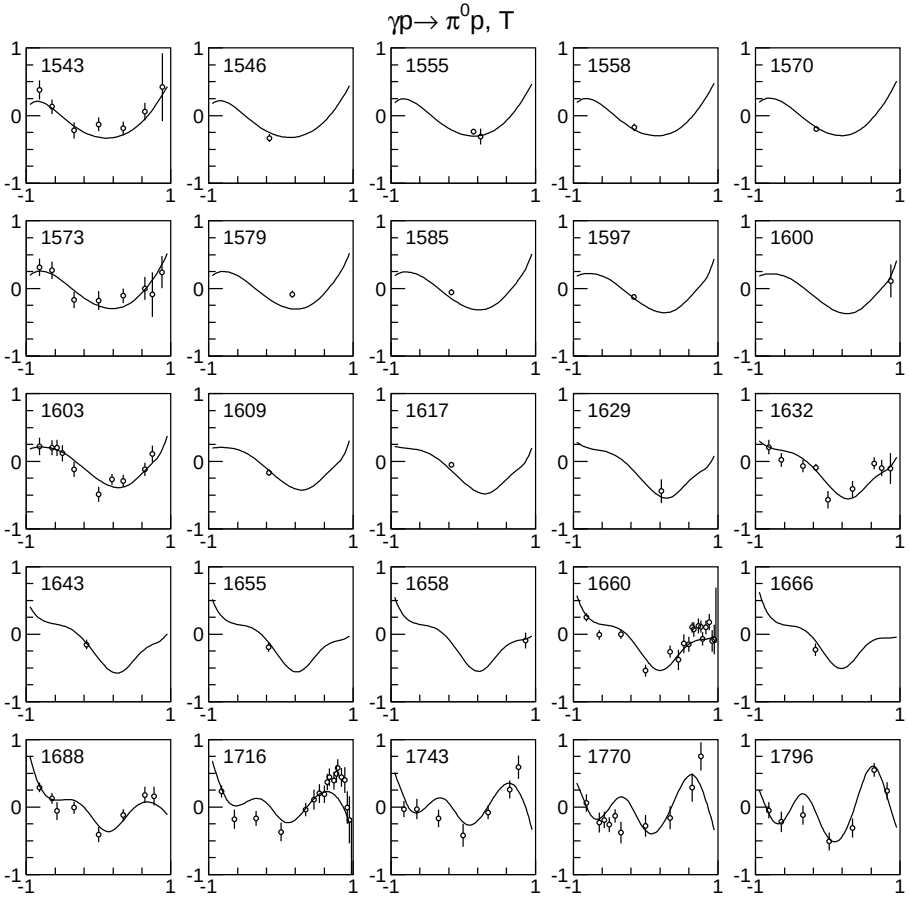

γp→ π0p, P
1632
1635
1638
1640
1646
1649
1652
1655
1660
1663
1672
1674
1677
1680
1683
1688
1691
1694
1699
1702
1705
1710
1716
1719
1727

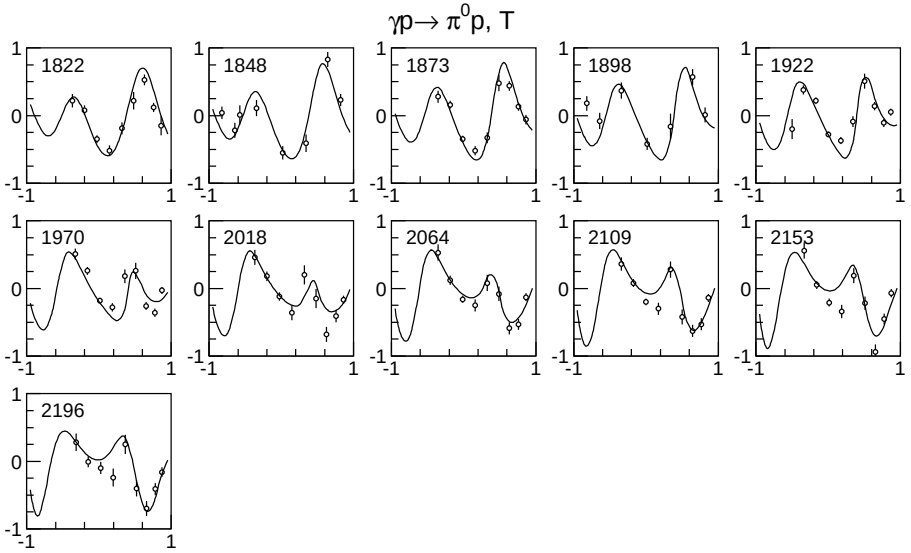

γp→ π0p, P
1730
1735
1738
1740
1743
1746
1751
1757
1759
1764
1770
1772
1775
1778
1783
1791
1794
1796
1801
1809
1822
1830
1835
1845
1848

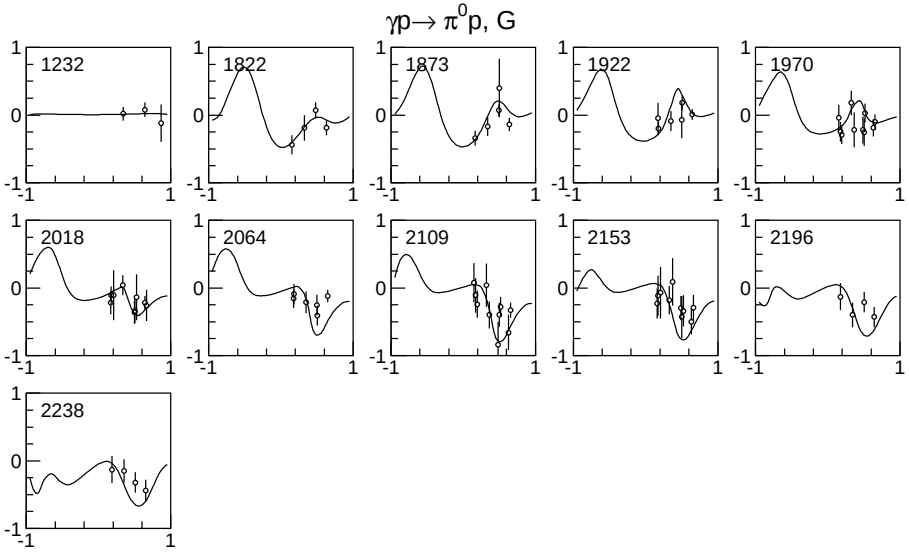

γp→ π0p, P
1850
1860
1873
1890
1898
1922
1947
1970
1973
1978
1985
1987
1989
2018
2064
2097
2104
2109
2111
2115
2117
2153
2196
2334
2342

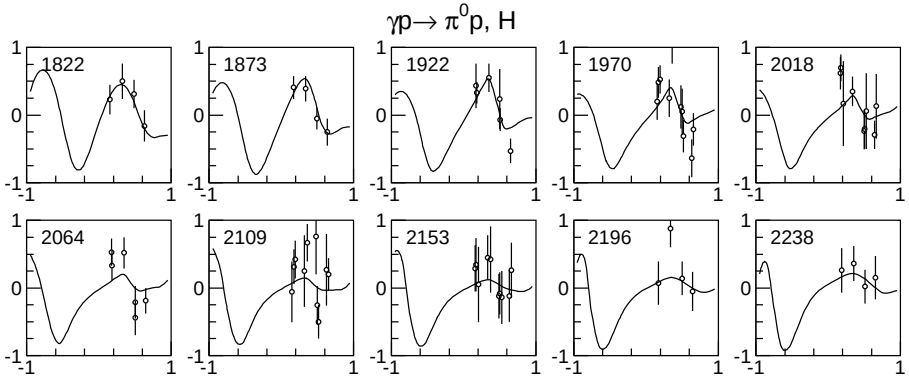

γp→ π0p, T
1201
1205
1217
1221
1236
1240
1247
1262
1270
1277
1281
1292
1295
1306
1313
1317
1320
1328
1335
1338
1342
1345
1349
1352
1366

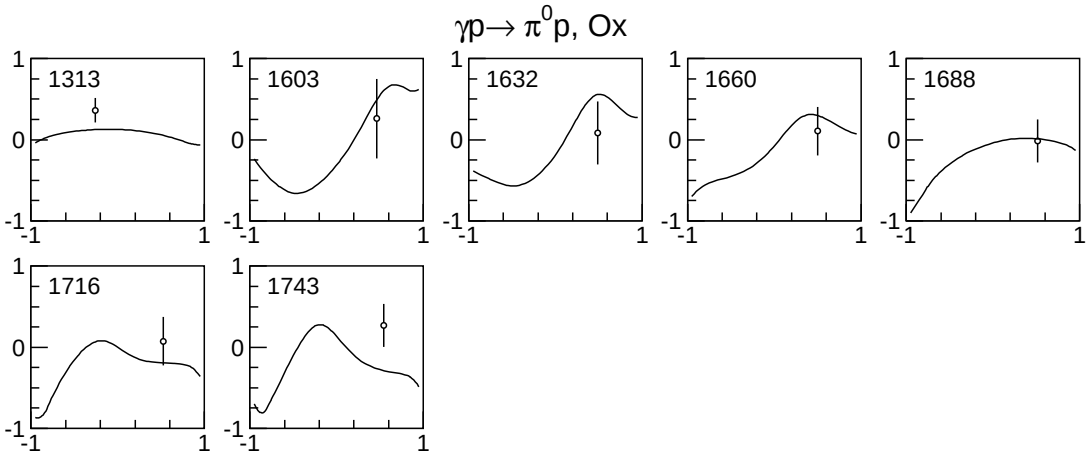

γp→ π0p, T
1369
1376
1383
1390
1400
1403
1406
1410
1413
1426
1430
1436
1443
1449
1456
1472
1475
1481
1484
1500
1506
1513
1525
1531
1537

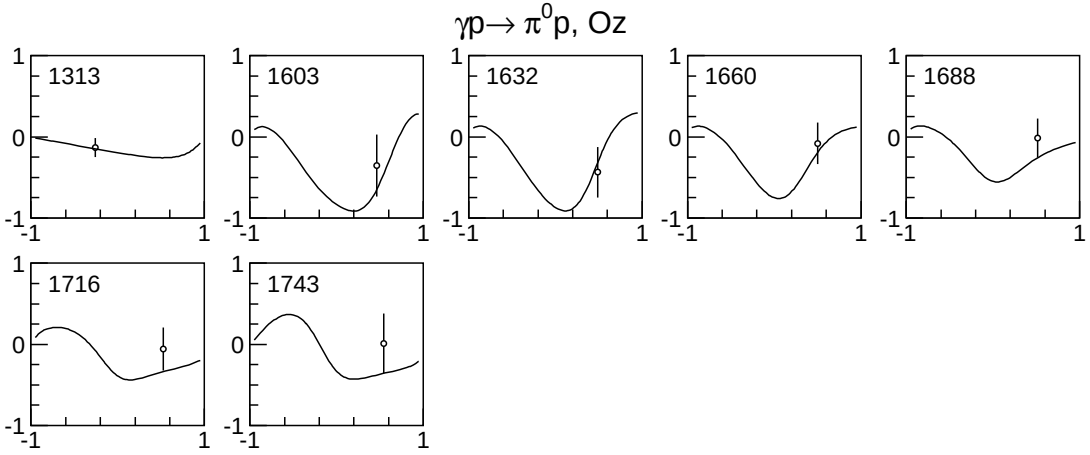

γp→ π0p, T
1543
1546
1555
1558
1570
1573
1579
1585
1597
1600
1603
1609
1617
1629
1632
1643
1655
1658
1660
1666
1688
1716
1743
1770
1796

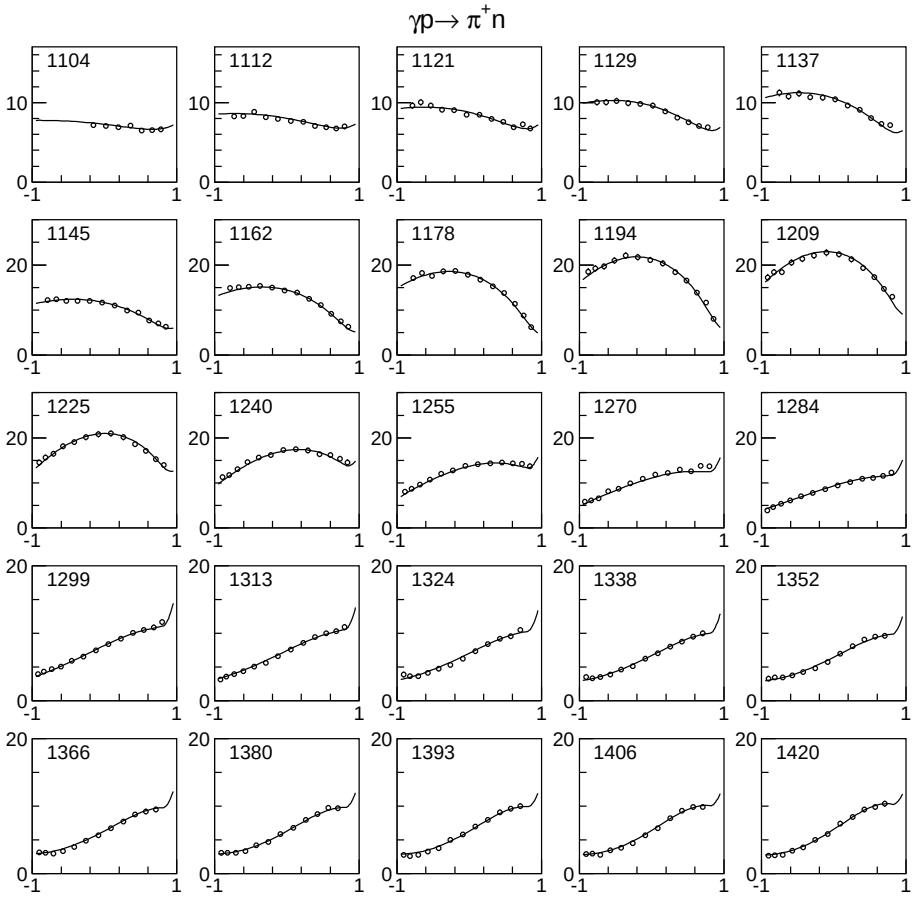

γp→ π0p, T
1822
1848
1873
1898
1922
1970
2018
2064
2109
2153
2196

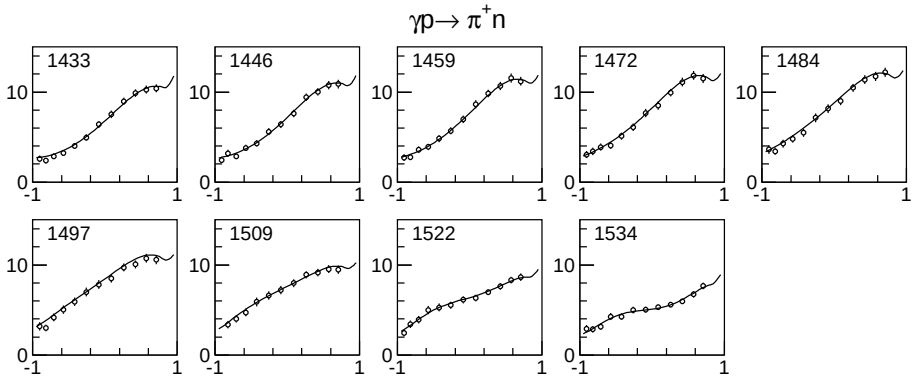

γp→ π0p, G
1232
1822
1873
1922
1970
2018
2064
2109
2153
2196
2238

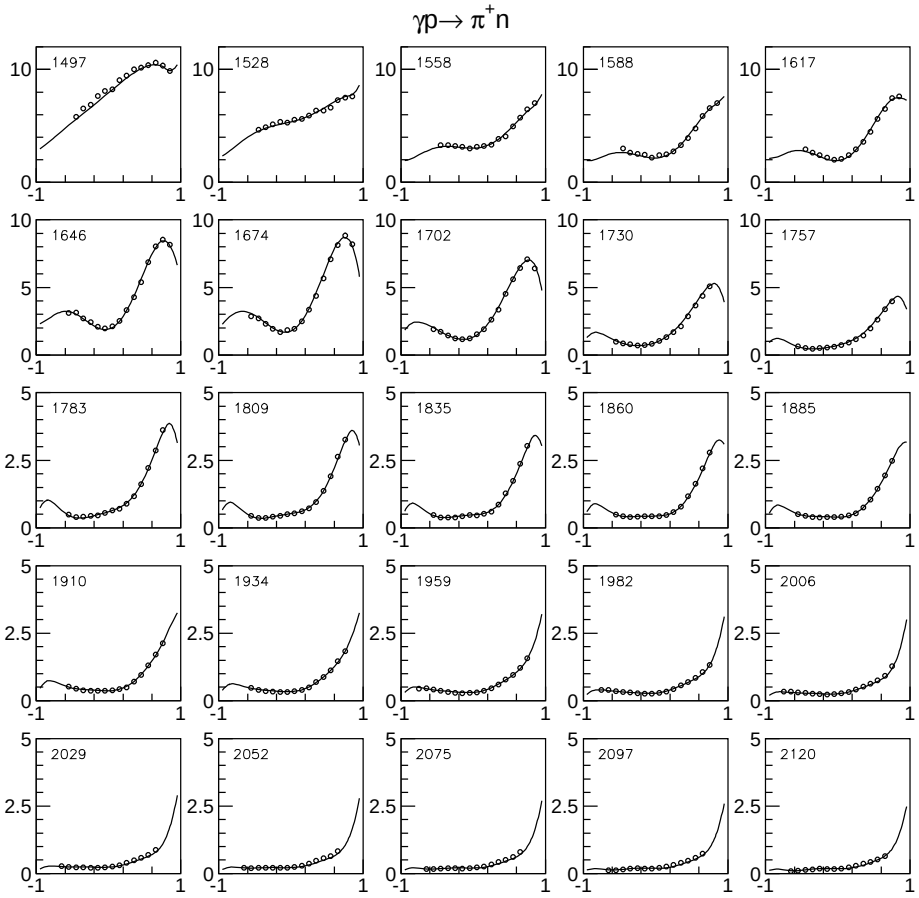

γp→ π0p, H
1822
1873
1922
1970
2018
2064
2109
2153
2196
2238

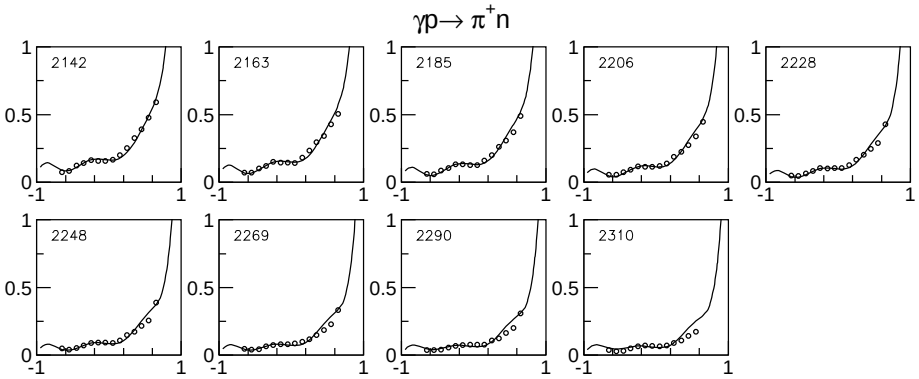

γp→ π0p, Ox
1313
1603
1632
1660
1688
1716
1743

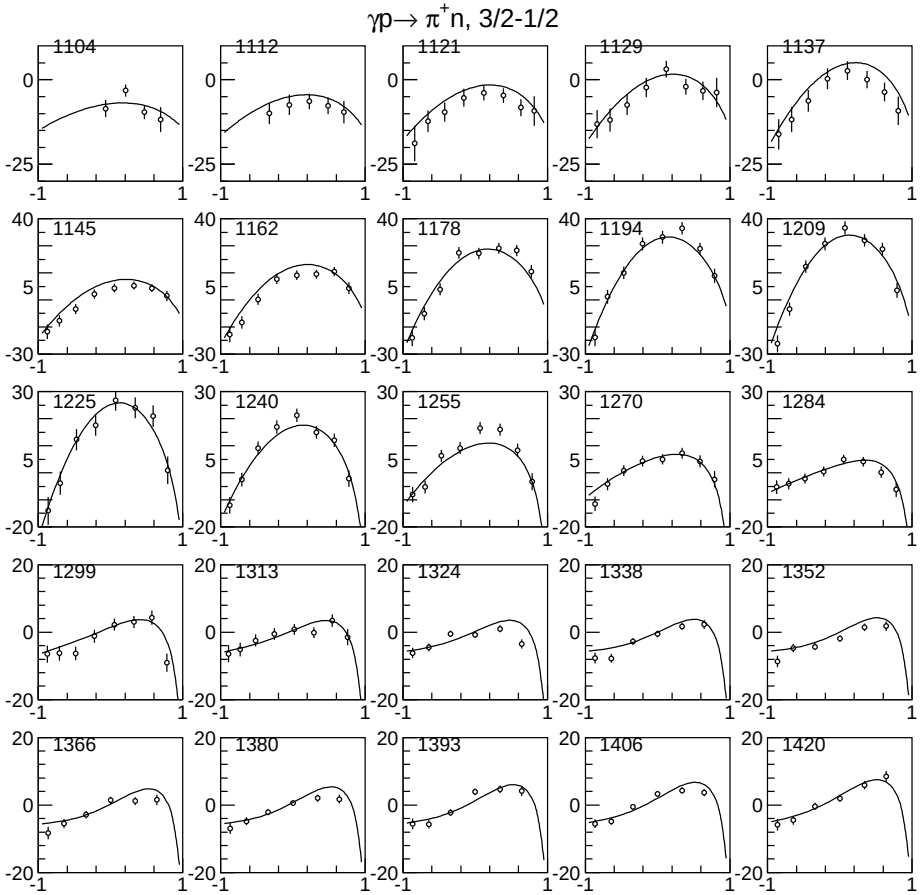

γp→ π0p, Oz
1313
1603
1632
1660
1688
1716
1743

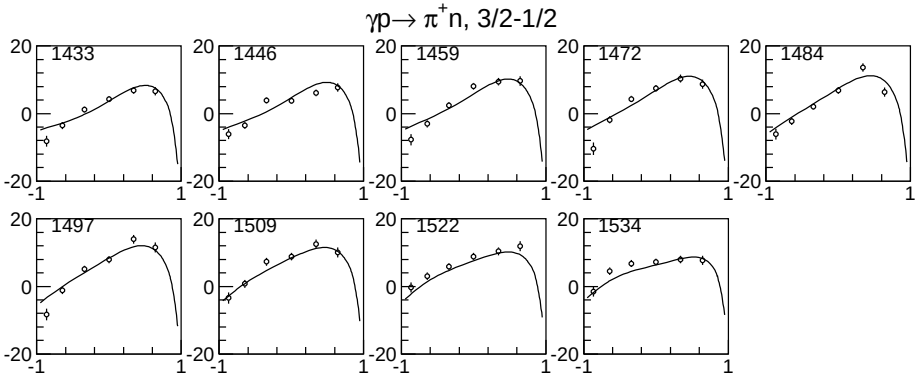

γp→ π+n
1104
1112
1121
1129
1137
1145
1162
1178
1194
1209
1225
1240
1255
1270
1284
1299
1313
1324
1338
1352
1366
1380
1393
1406
1420

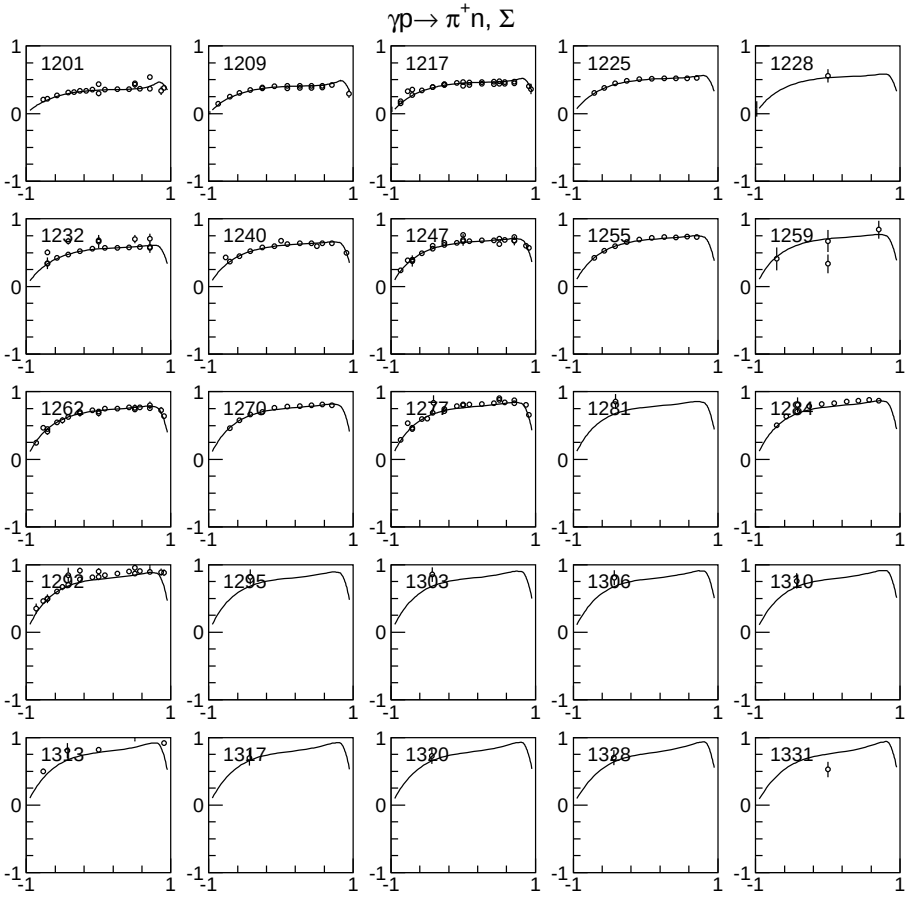

γp→ π+n
1433
1446
1459
1472
1484
1497
1509
1522
1534

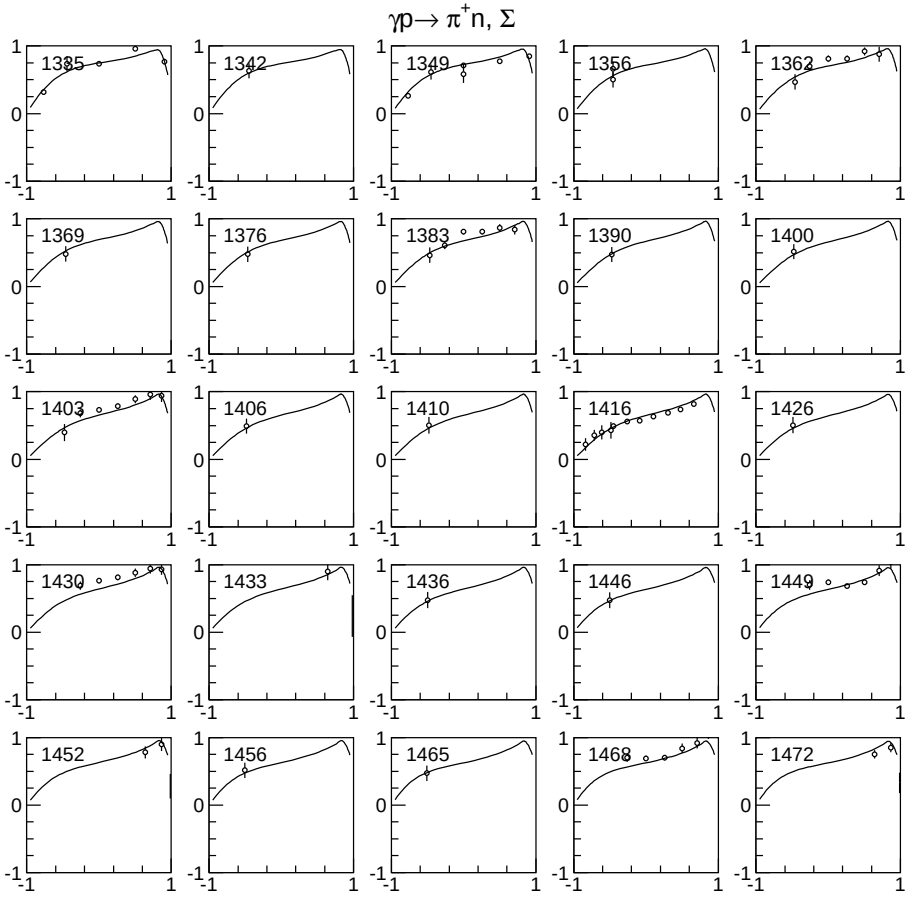

γp→ π+n
1497
1528
1558
1588
1617
1646
1674
1702
1730
1757
1783
1809
1835
1860
1885
1910
1934
1959
1982
2006
2029
2052
2075
2097
2120

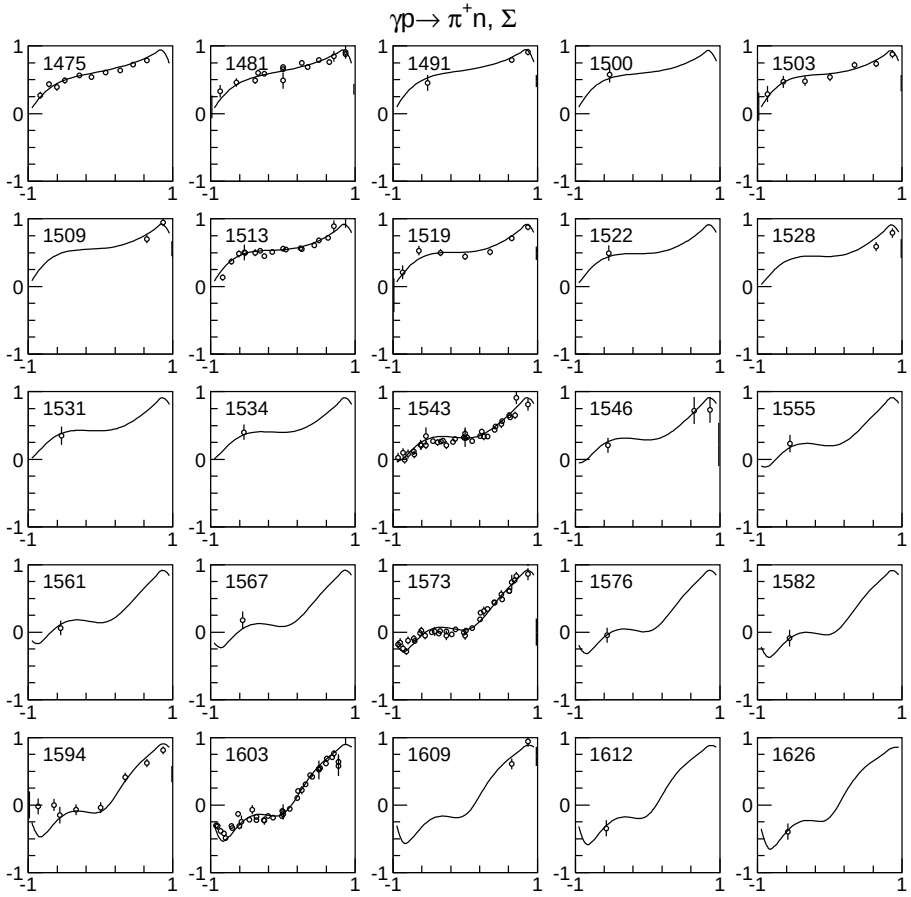

γp→ π+n
2142
2163
2185
2206
2228
2248
2269
2290
2310

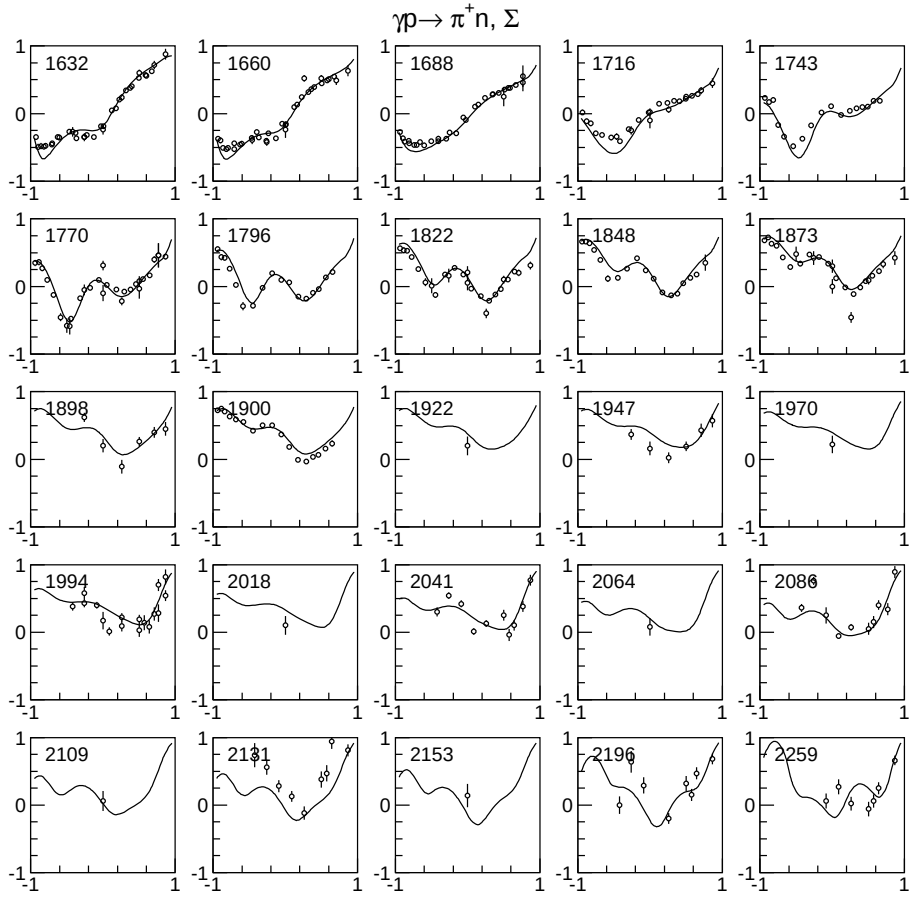

γp→ π+n, 3/2-1/2
1104
1112
1121
1129
1137
1145
1162
1178
1194
1209
1225
1240
1255
1270
1284
1299
1313
1324
1338
1352
1366
1380
1393
1406
1420

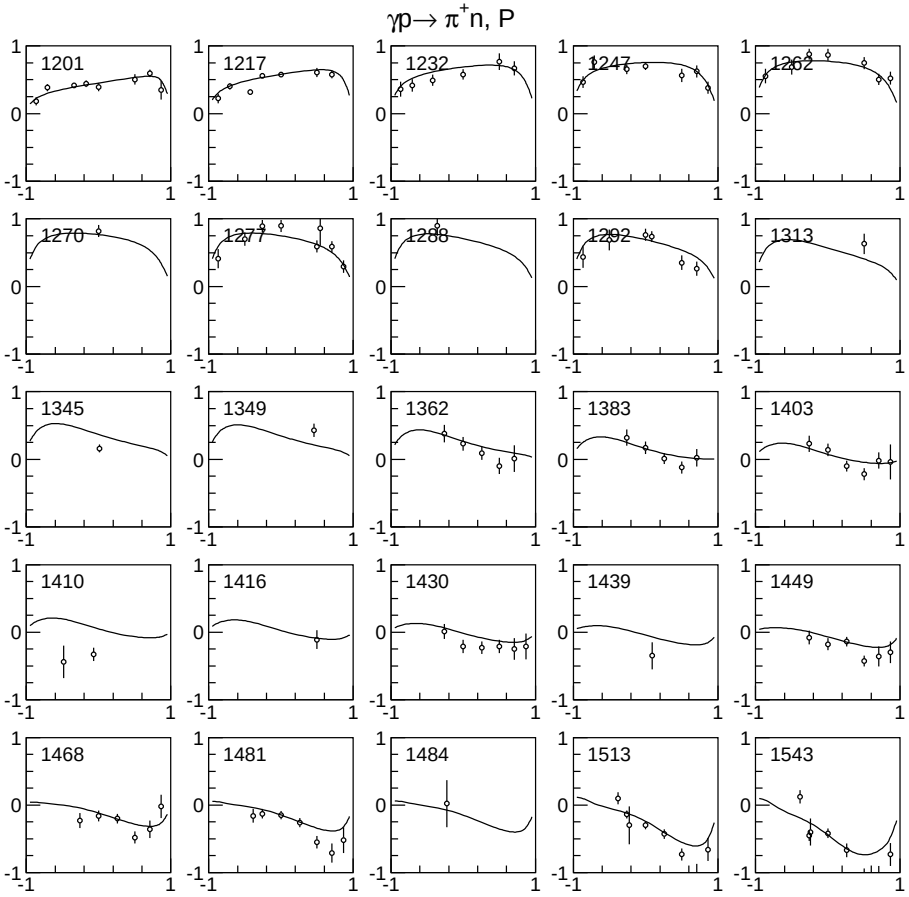

γp→ π+n, 3/2-1/2
1433
1446
1459
1472
1484
1497
1509
1522
1534

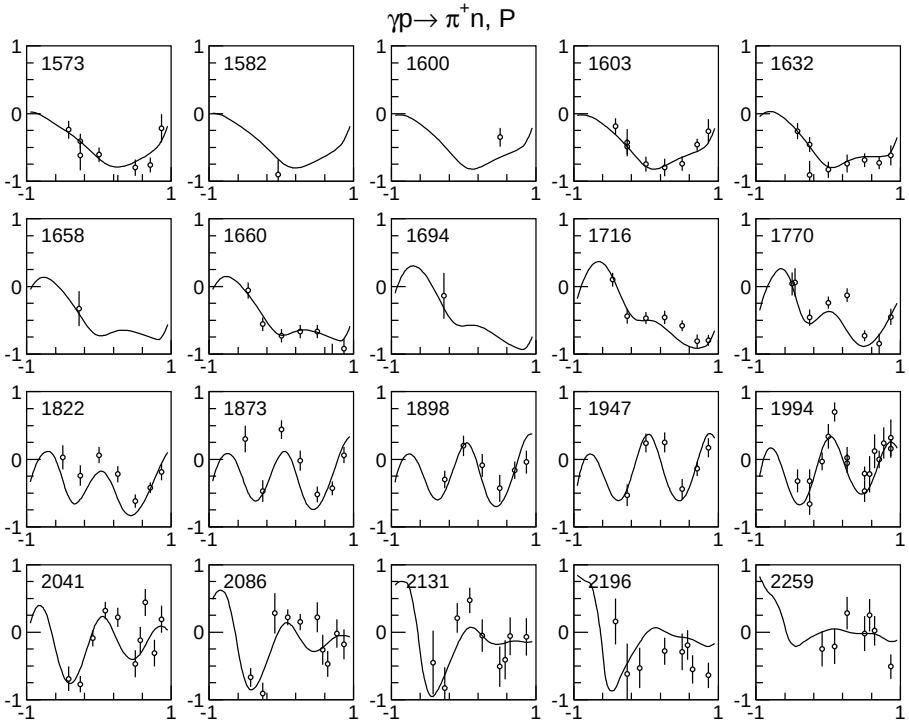

γp→ π+n, Σ
1201
1209
1217
1225
1228
1232
1240
1247
1255
1259
1262
1270
1277
1281
1284
1292
1295
1303
1306
1310
1313
1317
1320
1328
1331

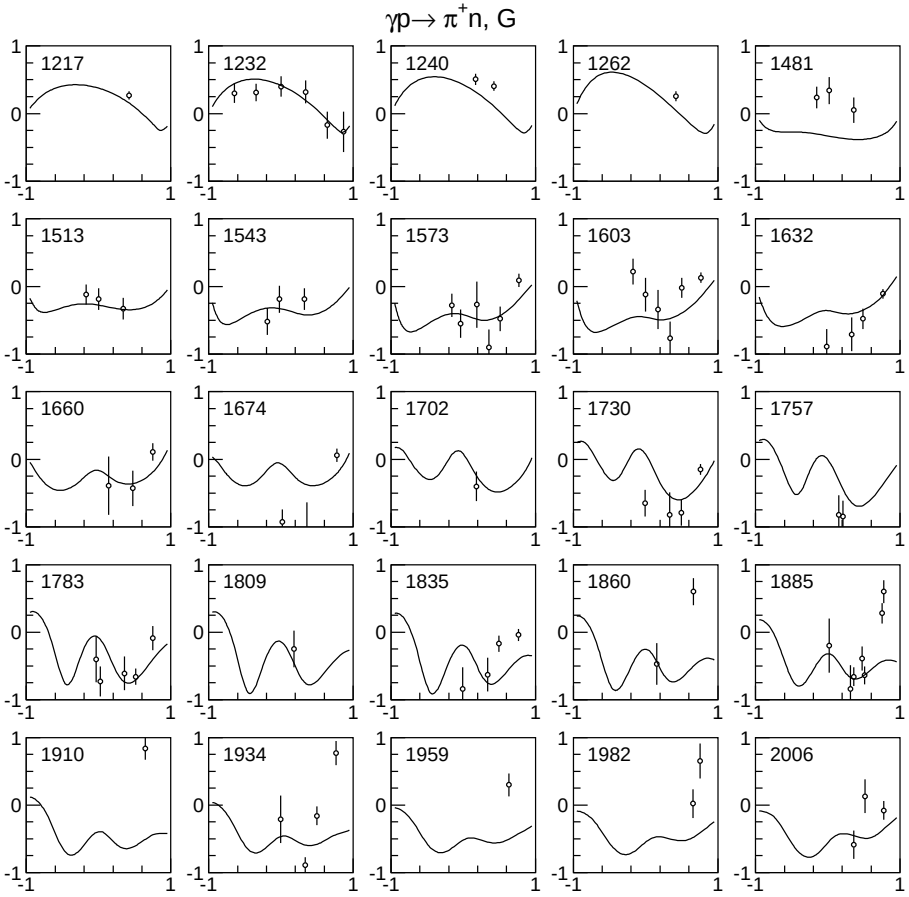

γp→ π+n, Σ
1335
1342
1349
1356
1362
1369
1376
1383
1390
1400
1403
1406
1410
1416
1426
1430
1433
1436
1446
1449
1452
1456
1465
1468
1472

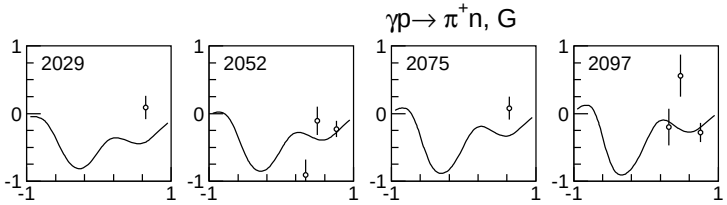

γp→ π+n, Σ
1475
1481
1491
1500
1503
1509
1513
1519
1522
1528
1531
1534
1543
1546
1555
1561
1567
1573
1576
1582
1594
1603
1609
1612
1626

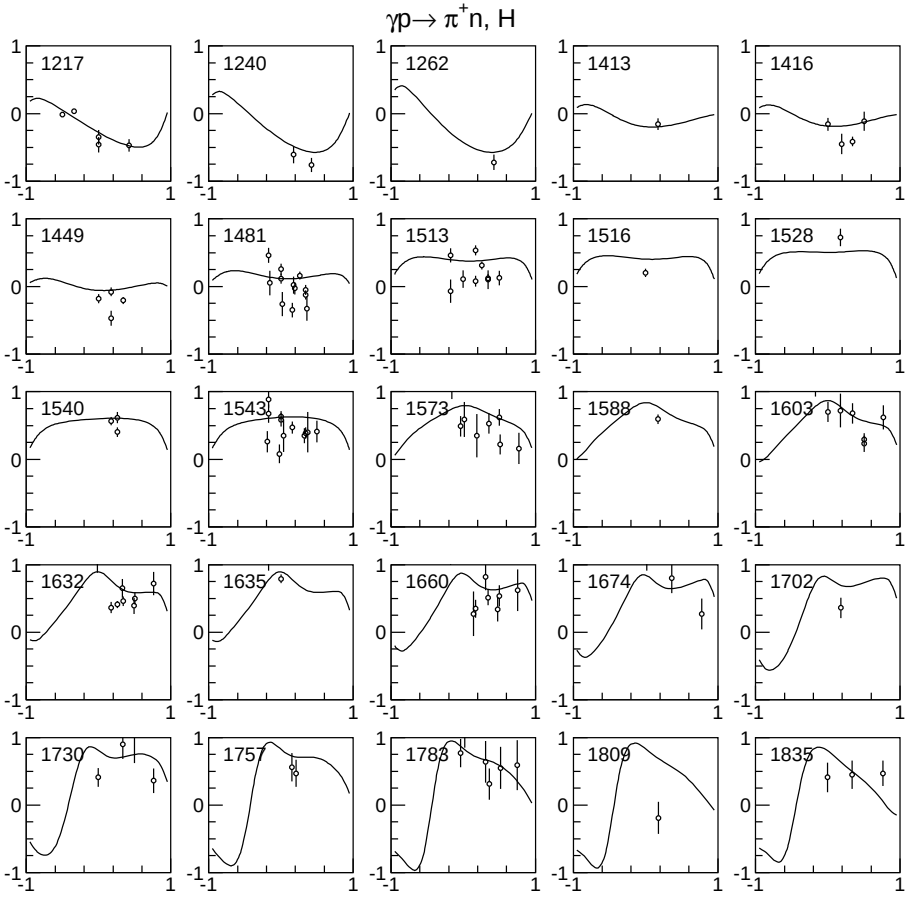

γp→ π+n, Σ
1632
1660
1688
1716
1743
1770
1796
1822
1848
1873
1898
1900
1922
1947
1970
1994
2018
2041
2064
2086
2109
2131
2153
2196
2259

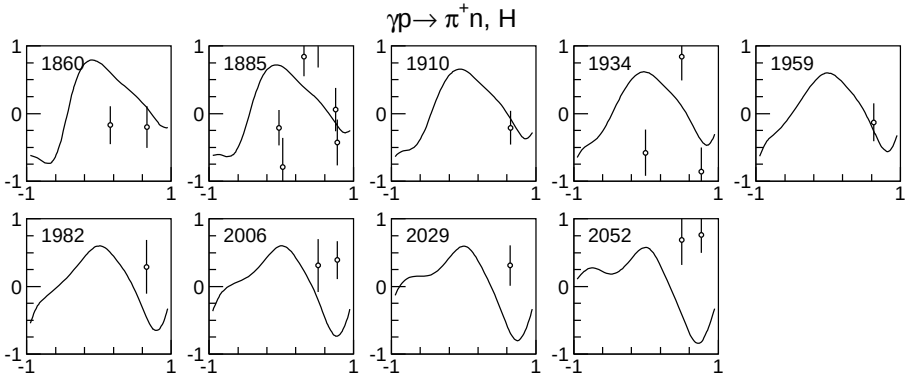

γp→ π+n, P
1201
1217
1232
1247
1262
1270
1277
1288
1292
1313
1345
1349
1362
1383
1403
1410
1416
1430
1439
1449
1468
1481
1484
1513
1543

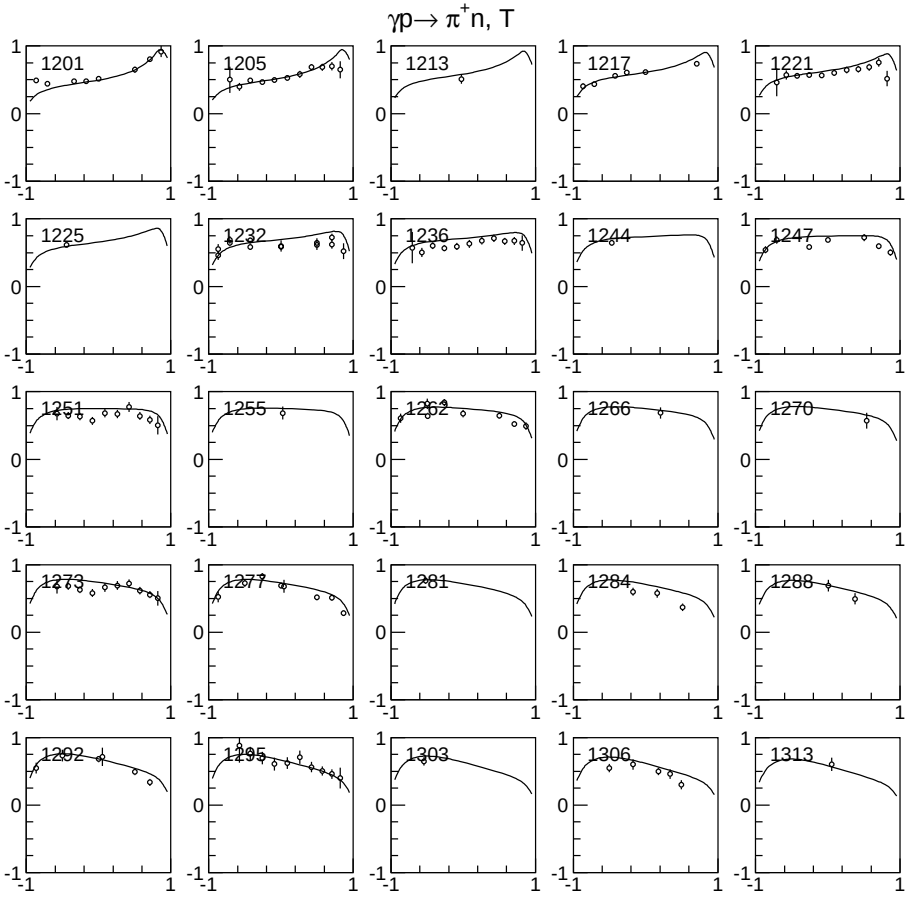

γp→ π+n, P
1573
1582
1600
1603
1632
1658
1660
1694
1716
1770
1822
1873
1898
1947
1994
2041
2086
2131
2196
2259

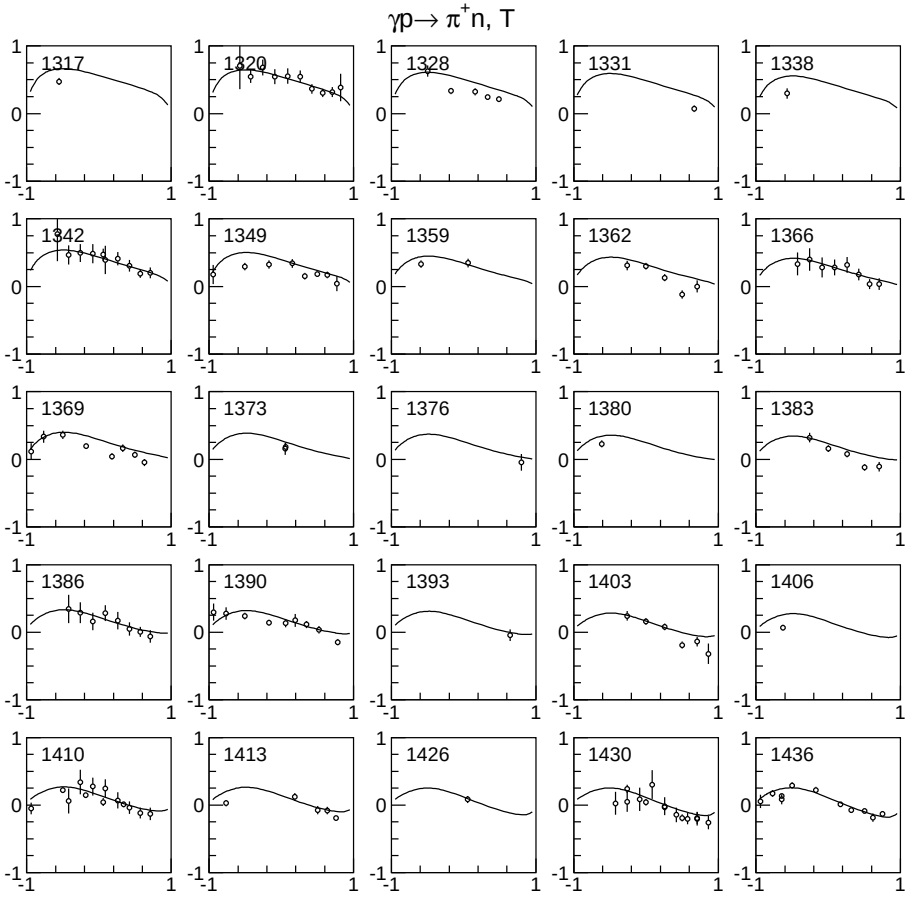

γp→ π+n, G
1217
1232
1240
1262
1481
1513
1543
1573
1603
1632
1660
1674
1702
1730
1757
1783
1809
1835
1860
1885
1910
1934
1959
1982
2006

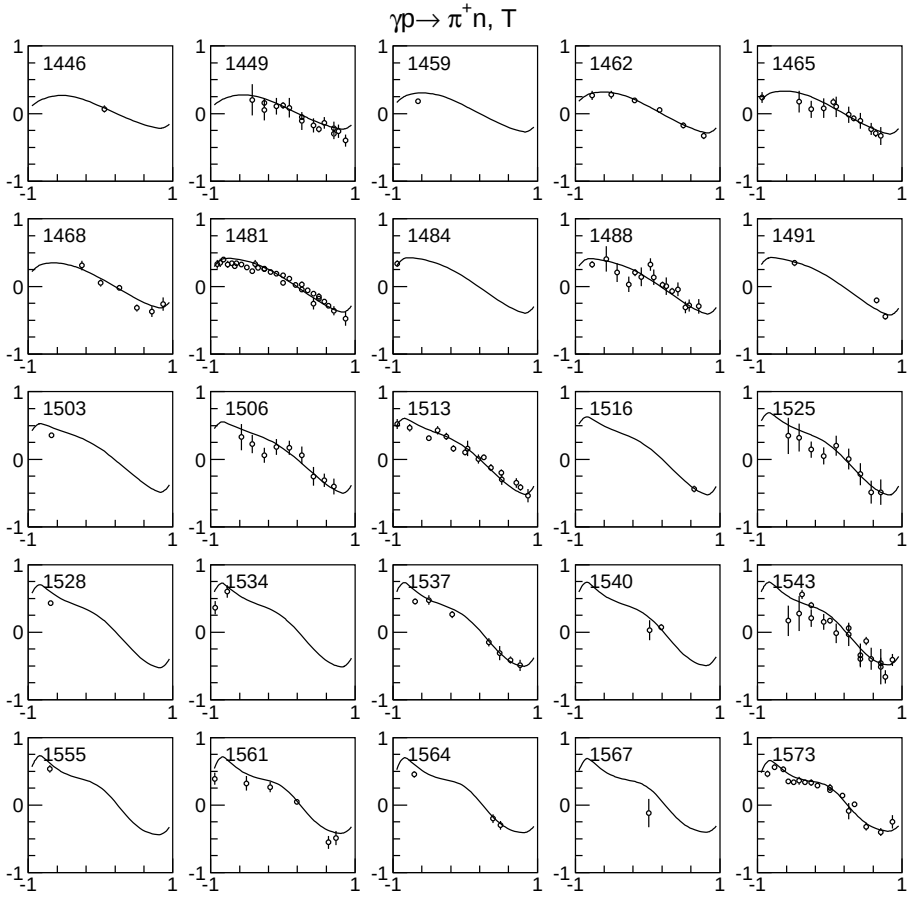

γp→ π+n, G
2029
2052
2075
2097

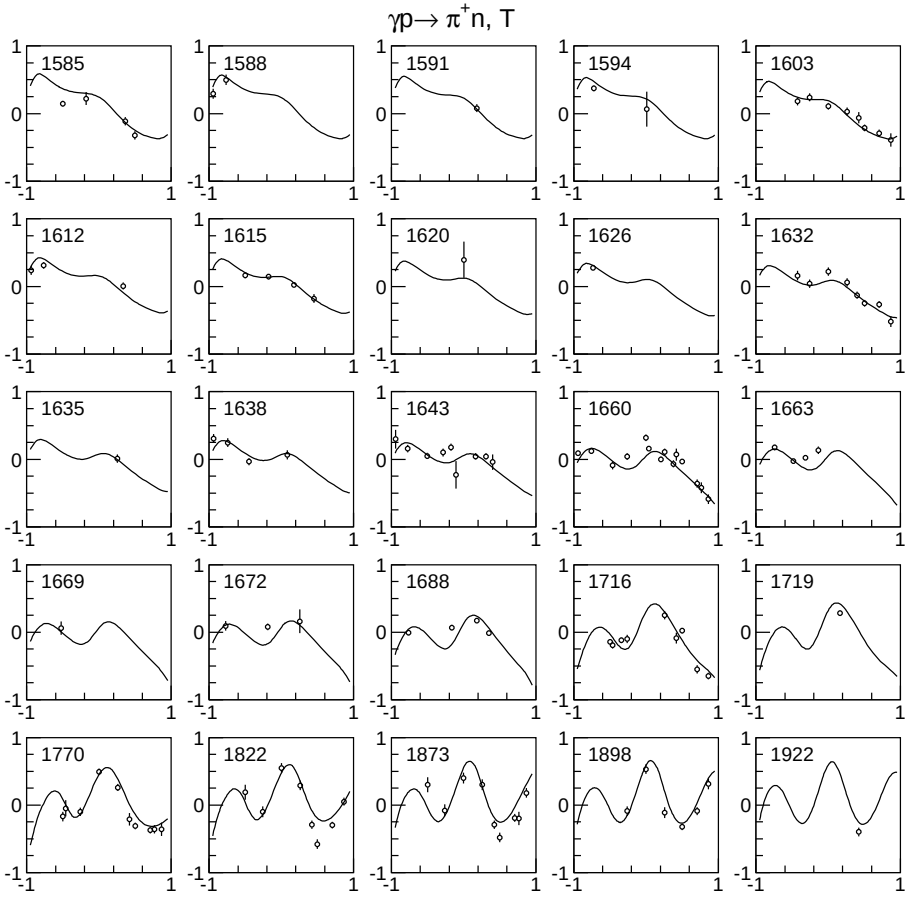

γp→ π+n, H
1217
1240
1262
1413
1416
1449
1481
1513
1516
1528
1540
1543
1573
1588
1603
1632
1635
1660
1674
1702
1730
1757
1788
1809
1835

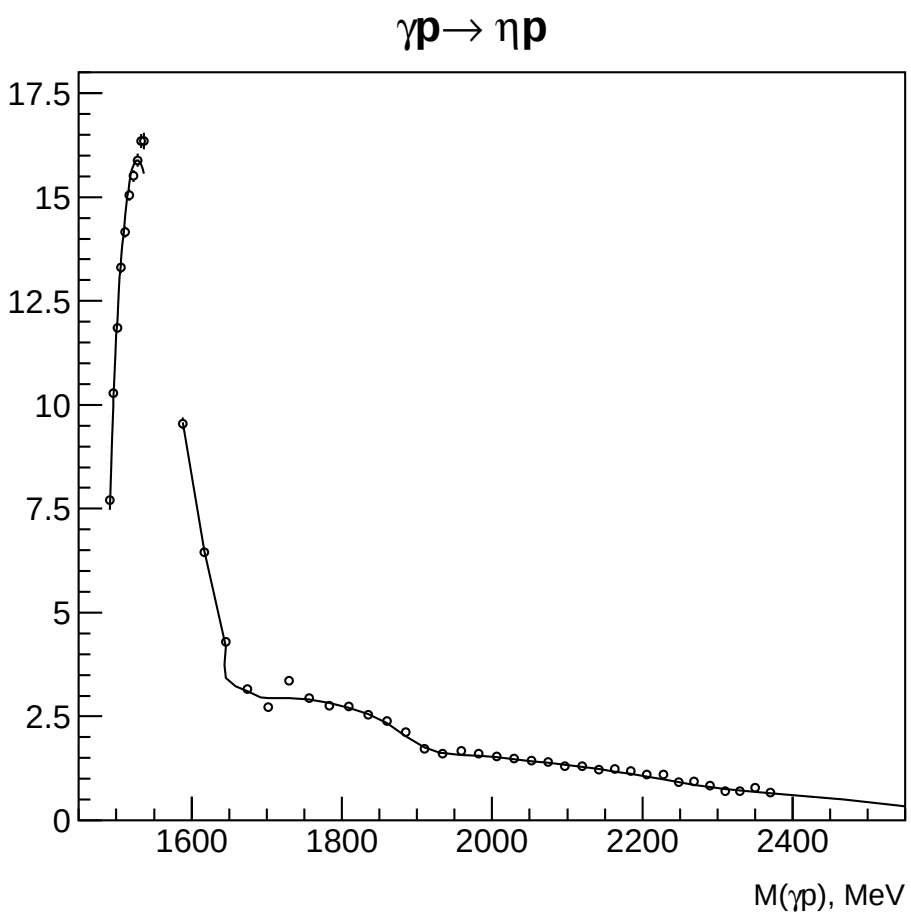

γp→ π+n, H
1860
1885
1910
1934
1959
1982
2006
2029
2052

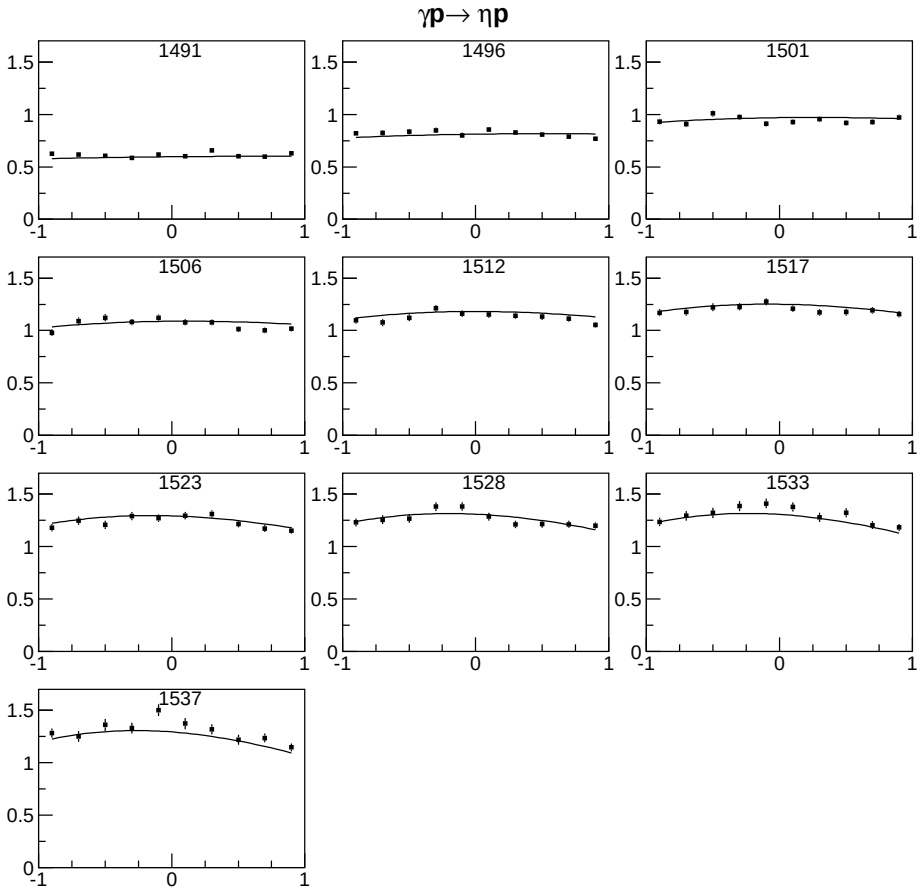

γp→ π+n, T
1201
1205
1213
1217
1221
1225
1232
1236
1244
1247
1251
1255
1262
1266
1270
1273
1277
1281
1284
1288
1292
1295
1303
1306
1313

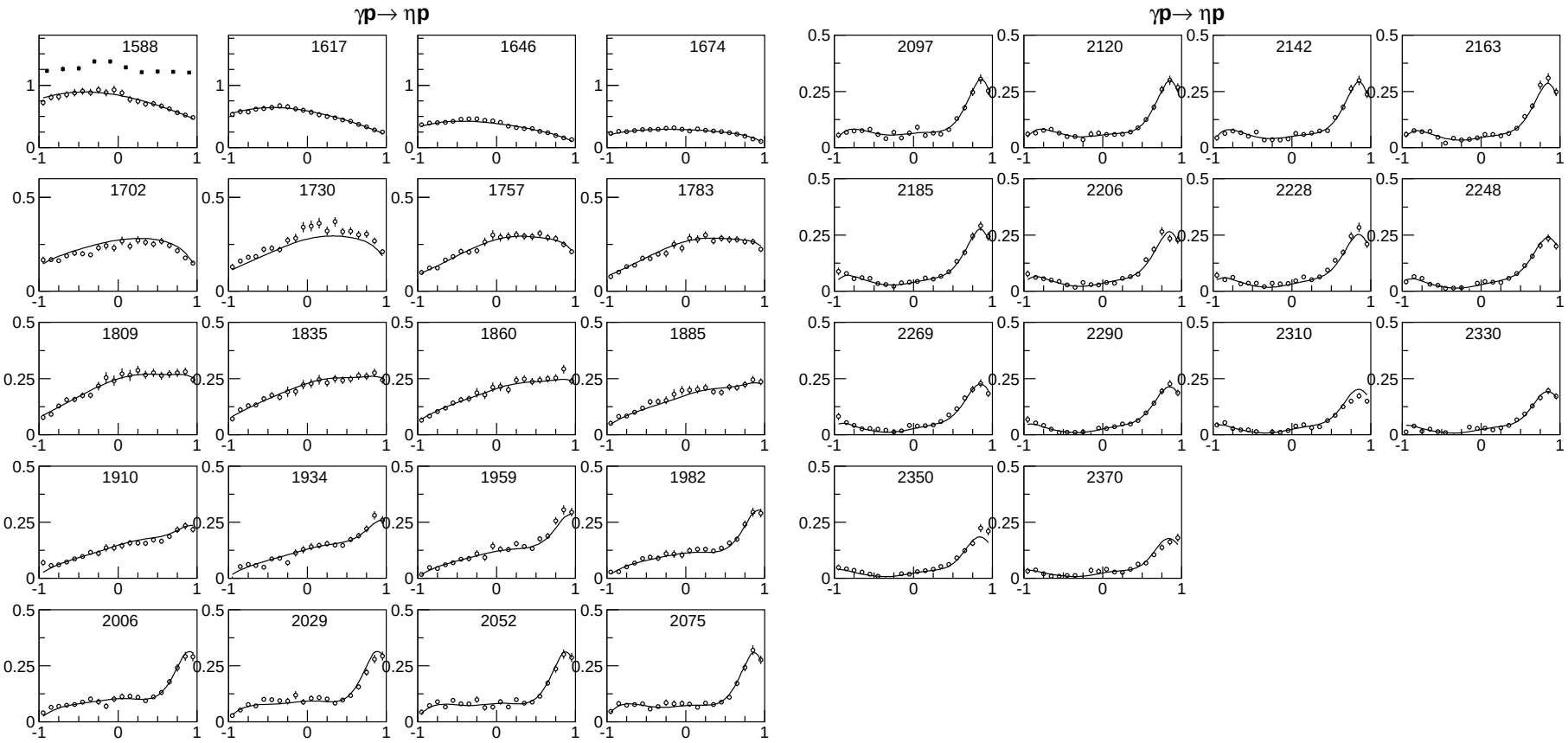

γp→ π+n, T
1317
1320
1328
1331
1338
1342
1349
1359
1362
1366
1369
1373
1376
1380
1383
1386
1390
1393
1403
1406
1410
1413
1426
1430
1436

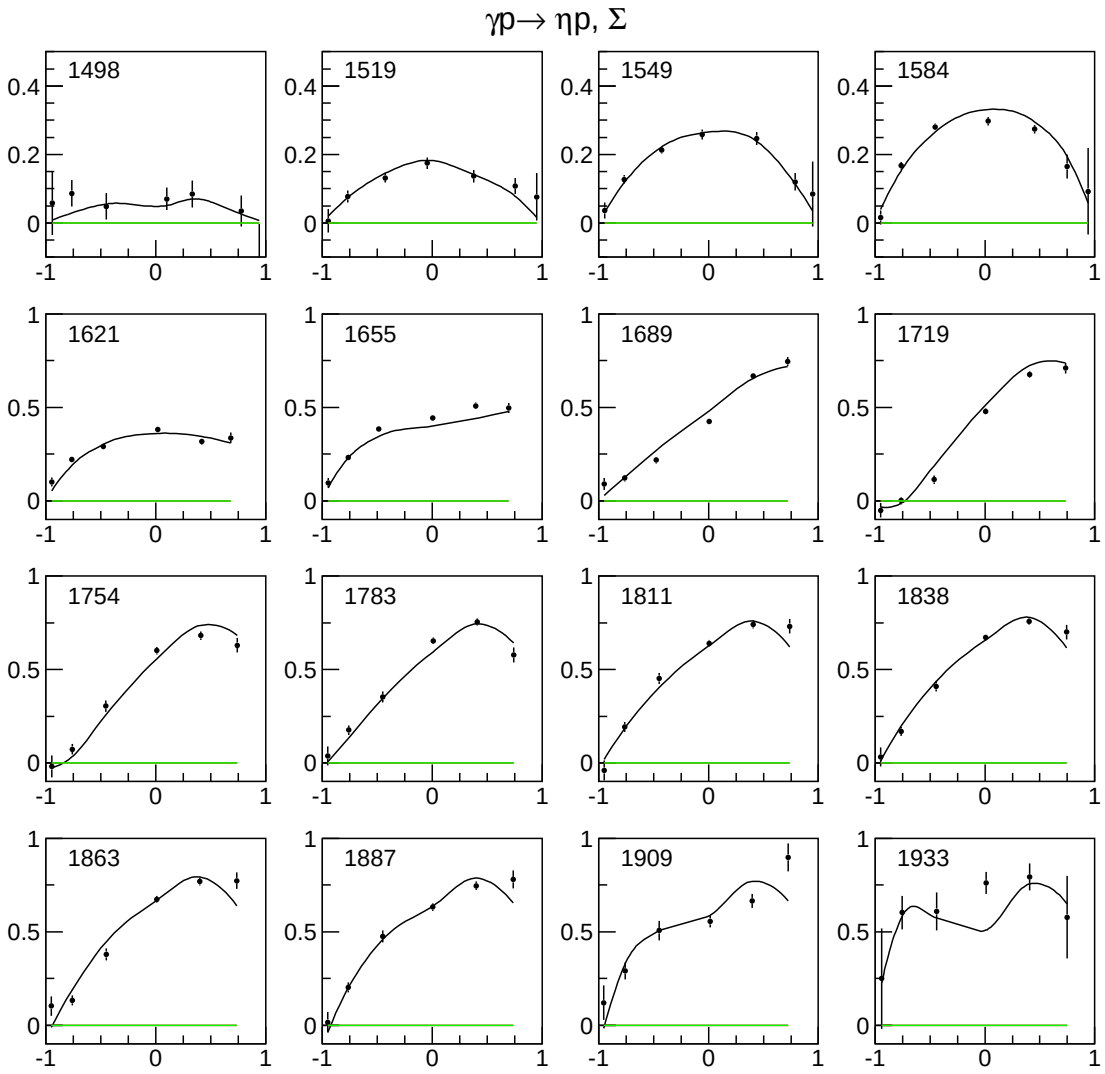

γp→ π+n, T
1446
1449
1459
1462
1465
1468
1481
1484
1488
1491
1503
1506
1513
1516
1525
1528
1534
1537
1540
1543
1555
1561
1564
1567
1573

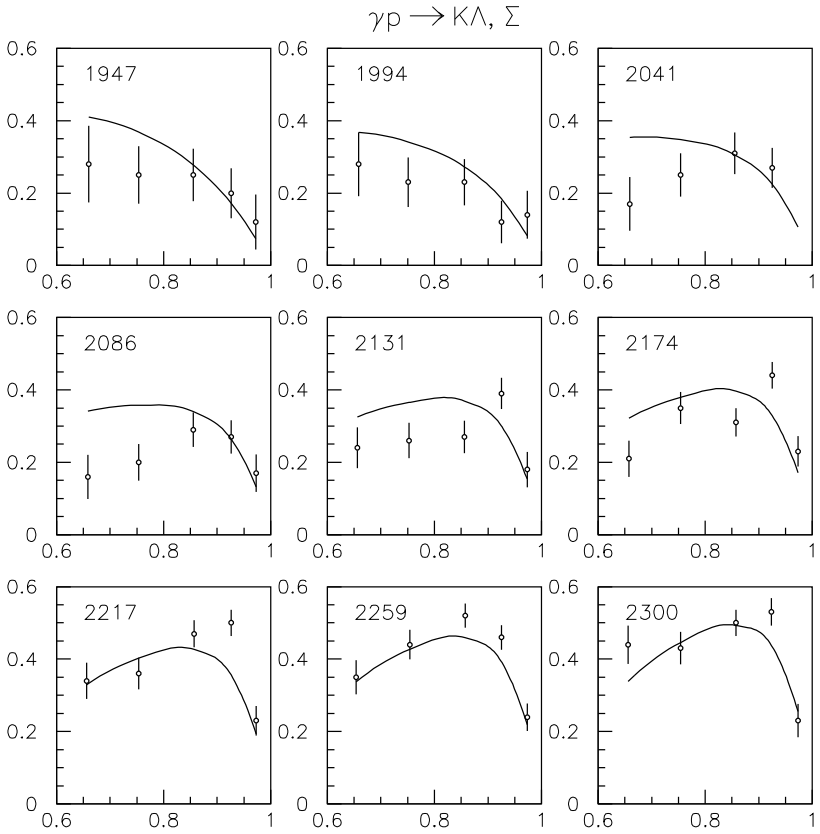

γp→ π+n, T
1585
1588
1591
1594
1603
1612
1615
1620
1626
1632
1635
1638
1643
1660
1663
1669
1672
1688
1716
1719
1770
1822
1873
1898
1922

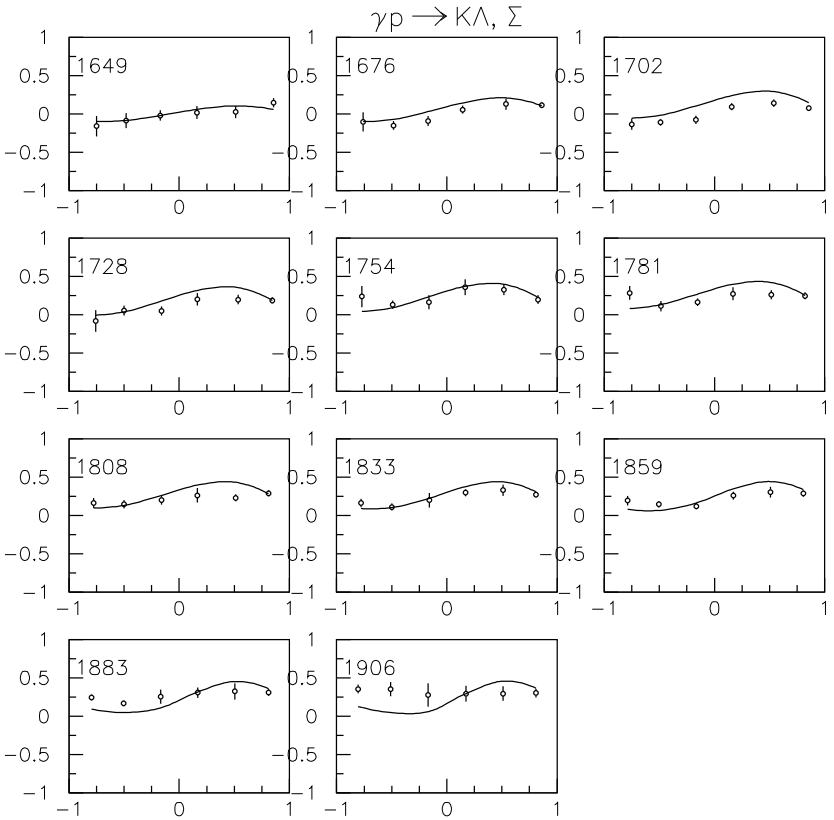

γp→ ηp
17.5
15
12.5
10
7.5
5
2.5
0
1600
1800
2000
2200
2400
M(γp), MeV

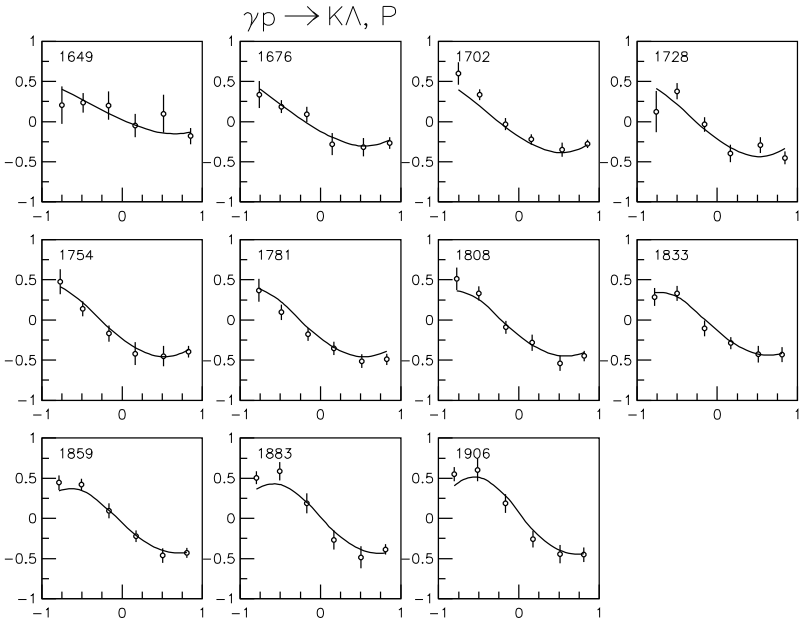

γp→ ηp
1491
1496
1501
1506
1512
1517
1523
1528
1533
1537

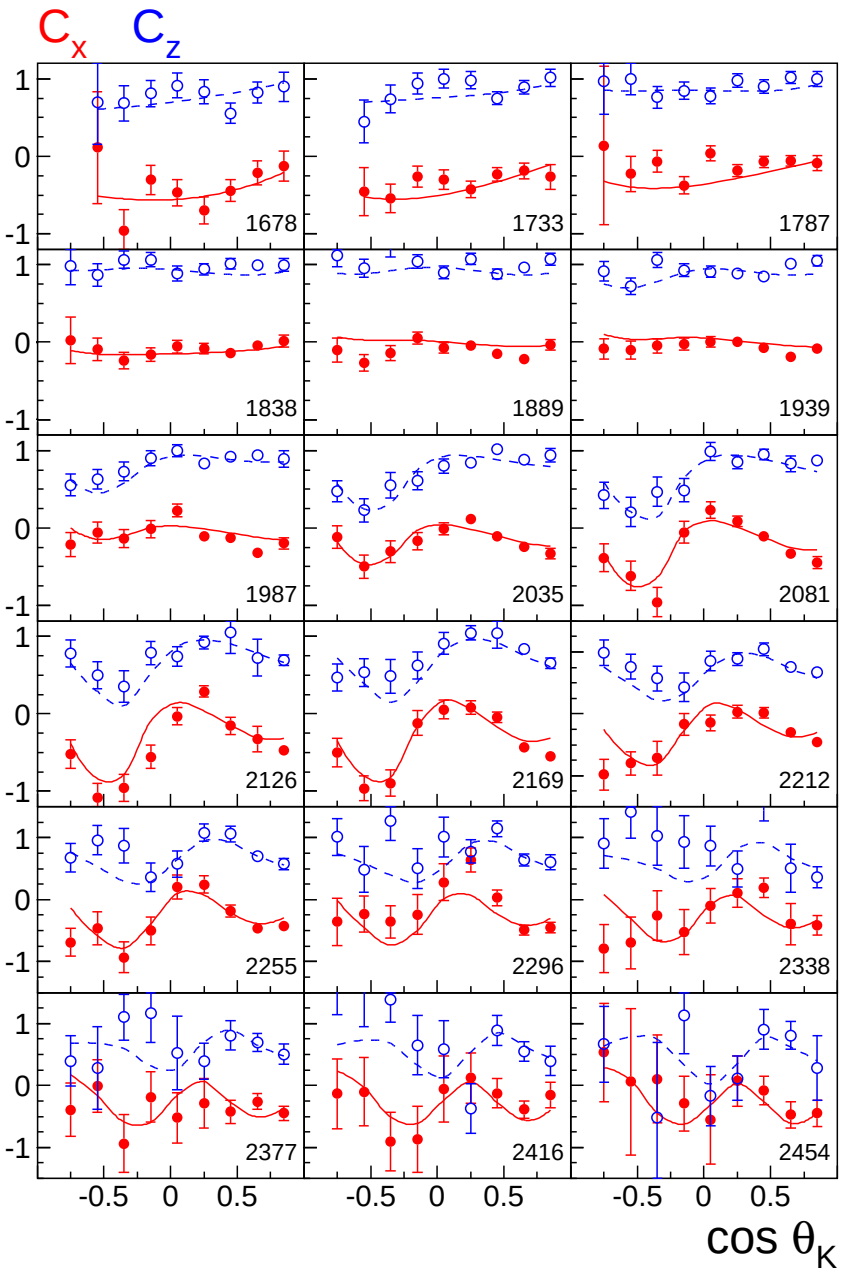

γp→ ηp
1588
1617
1646
1674
1702
1730
1757
1783
1809
1835
1860
1885
1910
1934
1959
1982
2006
2029
2052
2075
γp→ ηp
2097
2120
2142
2163
2185
2206
2228
2248
2269
2290
2310
2330
2350
2370

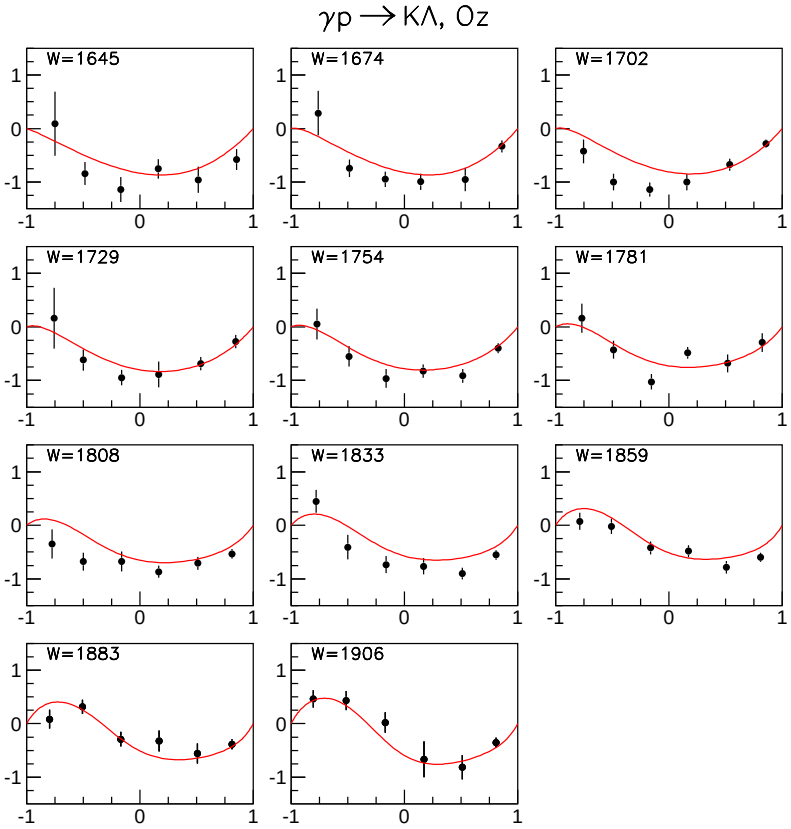

γp→ ηp, Σ
1498
1519
1549
1584
1621
1655
1689
1719
1754
1783
1811
1838
1863
1887
1909
1933

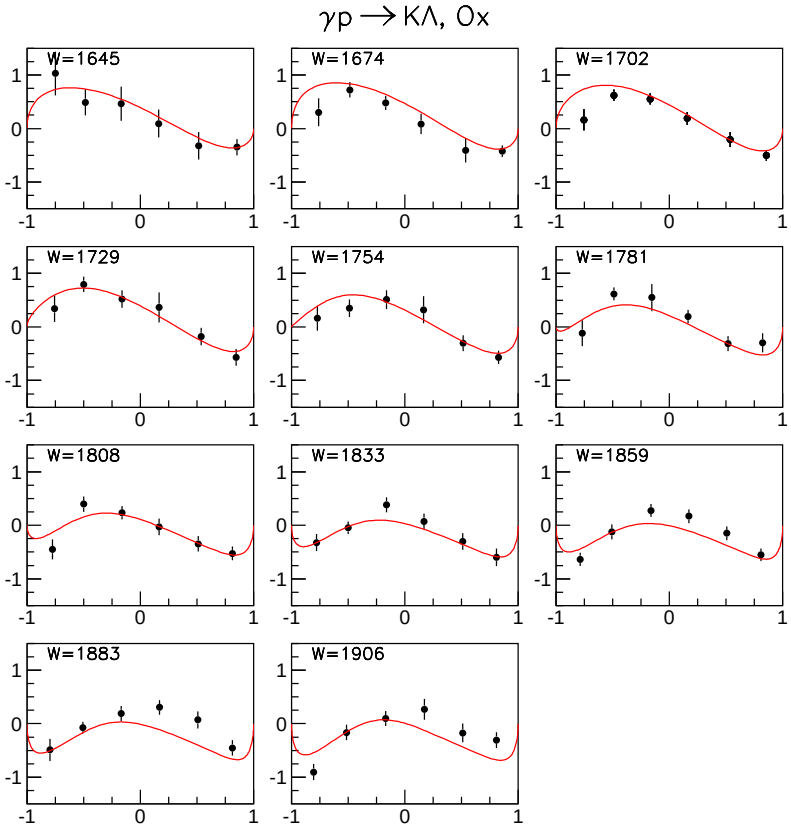

γp ⟶ KΛ, Σ
1947
1994
2041
2086
2131
2174
2217
2259
2300

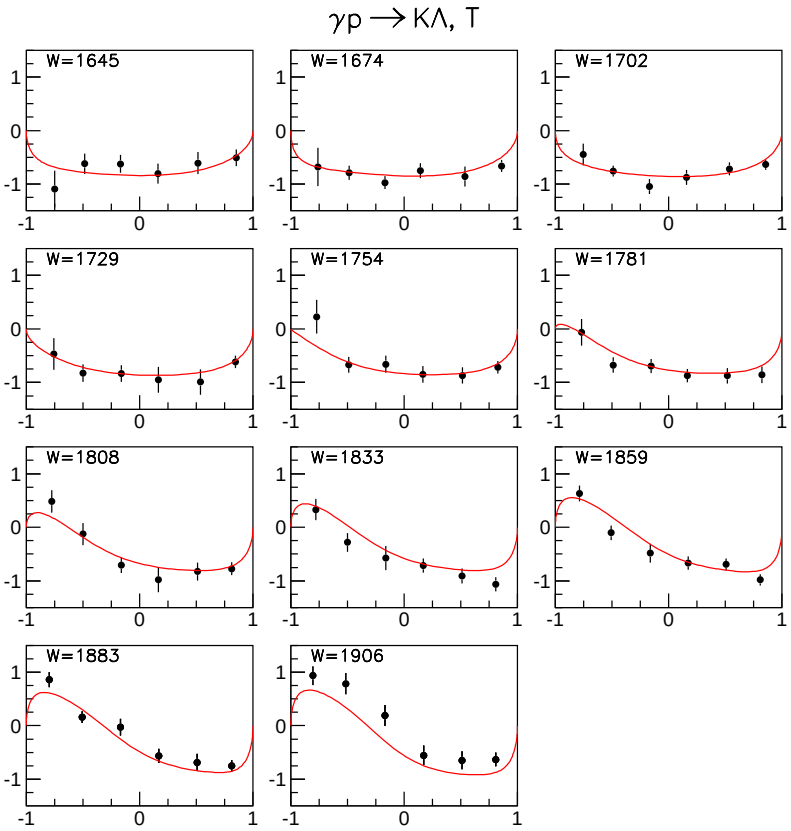

γp ⟶ KΛ, Σ
1649
1676
1702
1728
1754
1781
1808
1833
1859
1883
1906

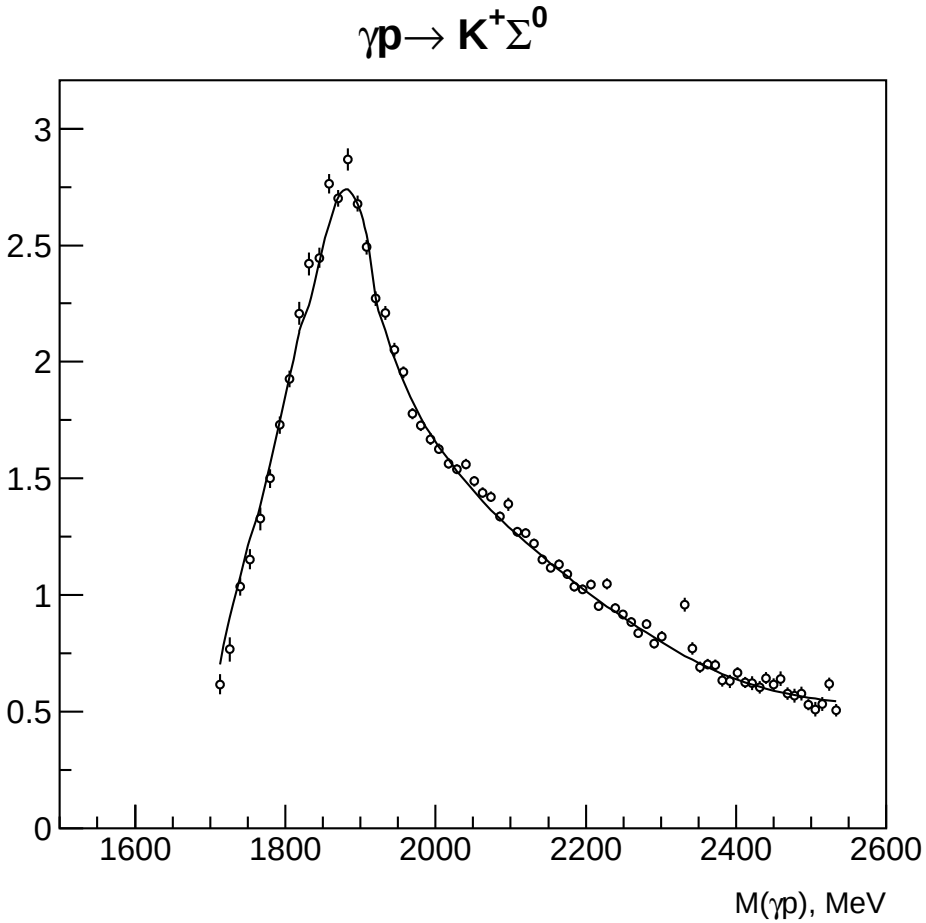

γp → KΛ, P
1649
1676
1702
1728
1754
1781
1808
1833
1859
1883
1906

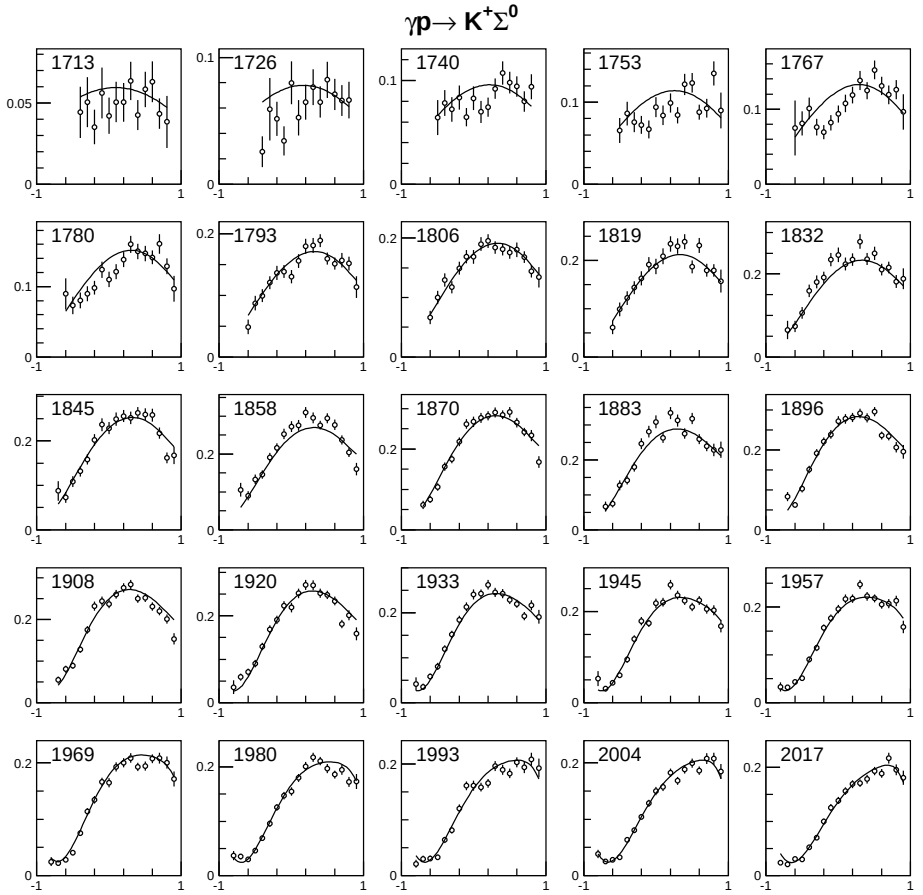

C_x C_z
1678
1733
1787
1838
1889
1939
1987
2035
2081
2126
2169
2212
2255
2296
2338
2377
2416
2454
cos θ_K

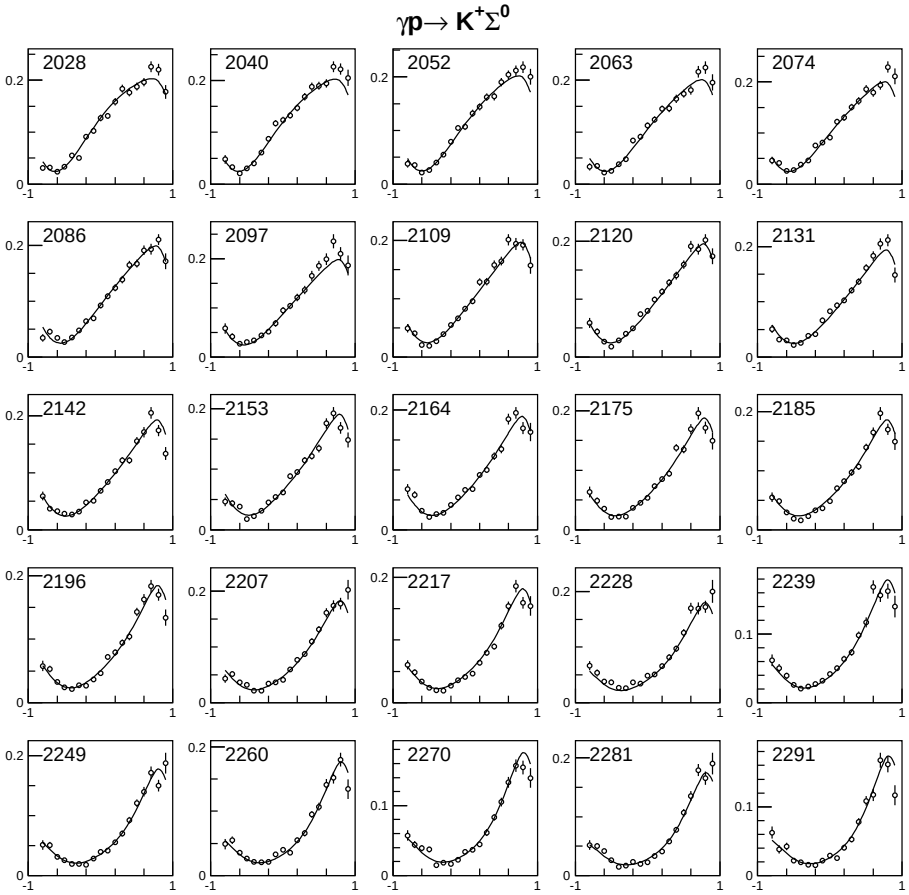

γp → KΛ, Oz
W=1645
W=1674
W=1702
W=1729
W=1754
W=1781
W=1808
W=1833
W=1859
W=1883
W=1906

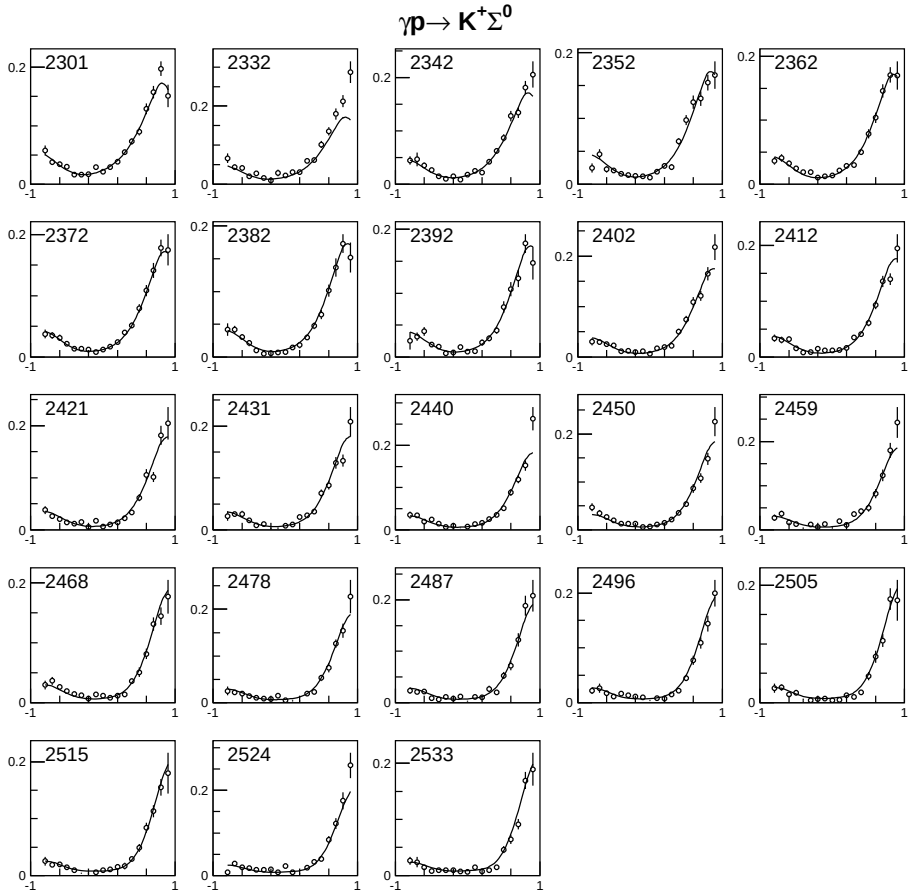

γp → KΛ, Ox
W=1645
W=1674
W=1702
W=1729
W=1754
W=1781
W=1808
W=1833
W=1859
W=1883
W=1906

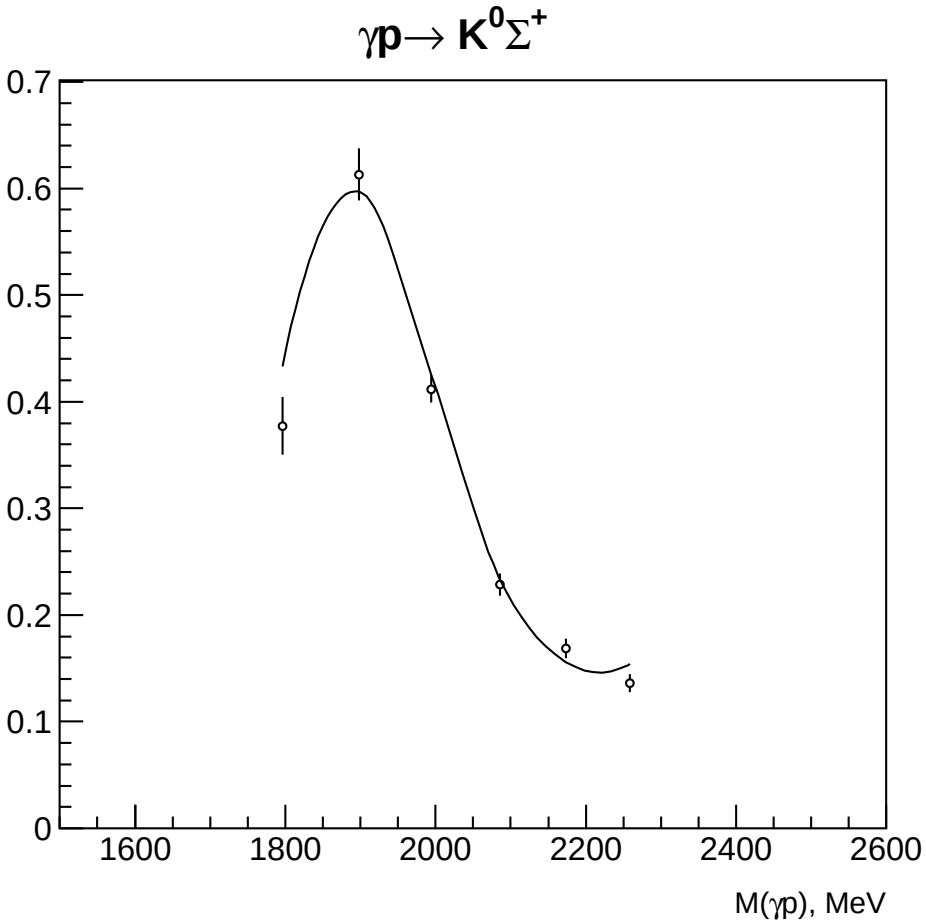

γp → KΛ, T
W=1645
W=1674
W=1702
W=1729
W=1754
W=1781
W=1808
W=1833
W=1859
W=1883
W=1906

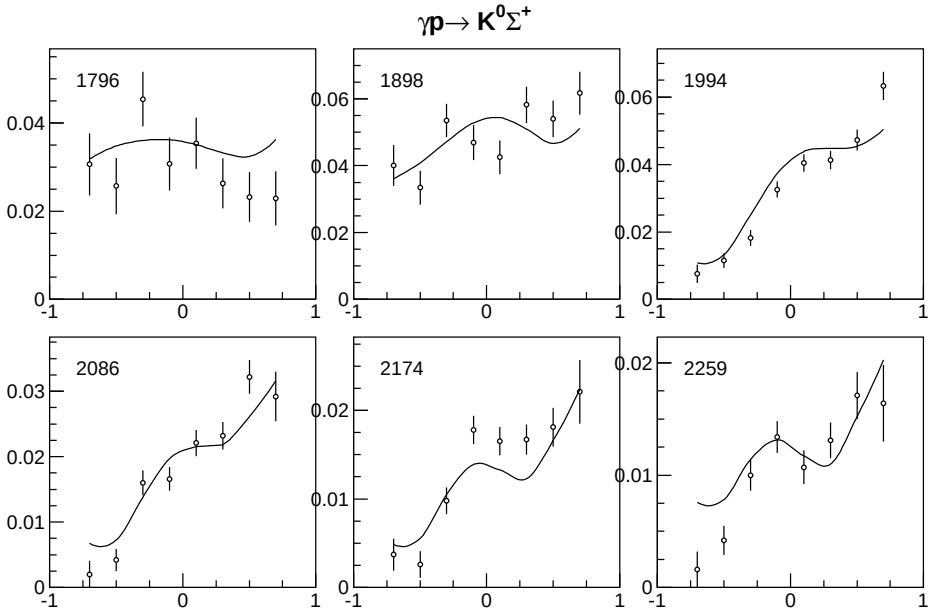

γp→ K+Σ0
3
2.5
2
1.5
1
0.5
0
1600
1800
2000
2200
2400
2600
M(γp), MeV

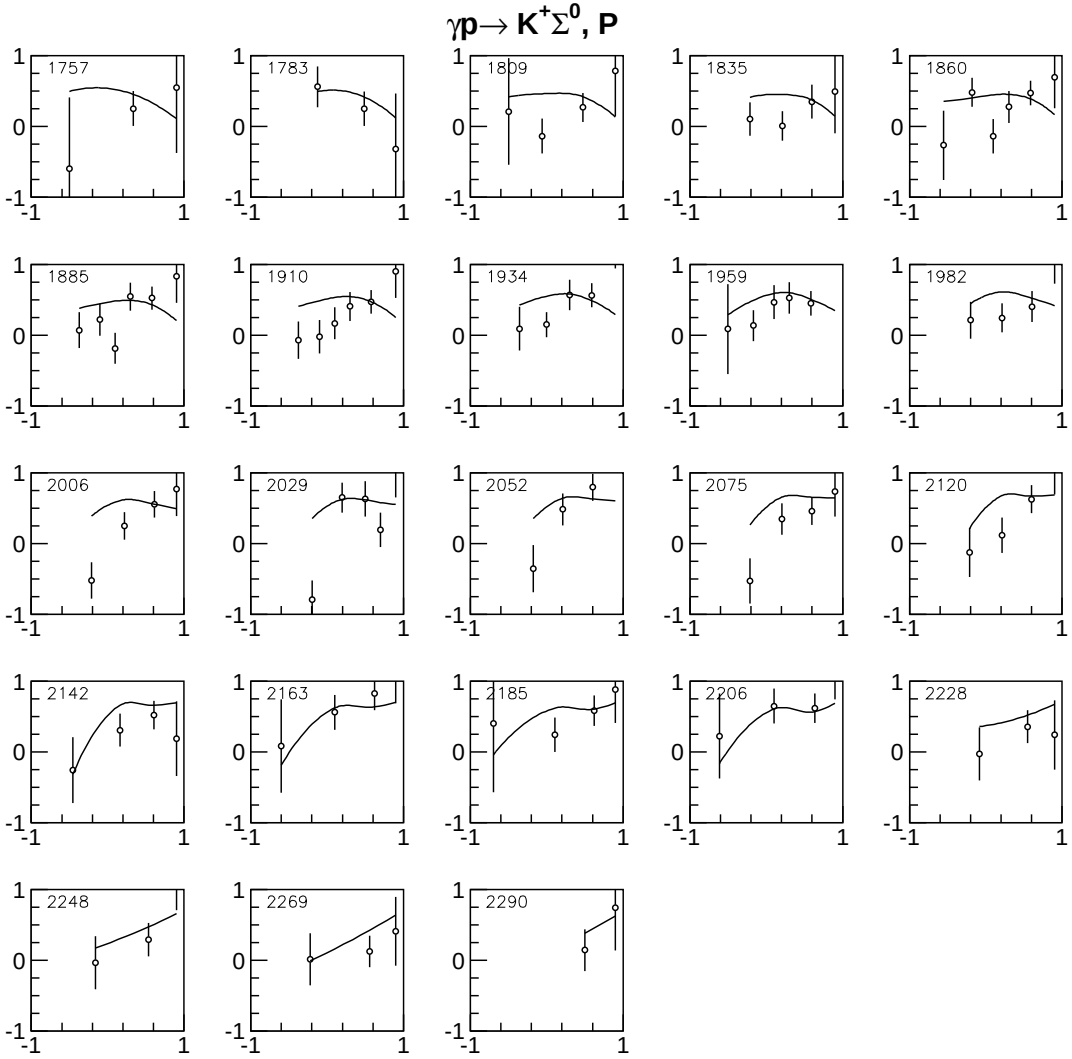

γp→ K+Σ0
1713
1726
1740
1753
1767
1780
1793
1806
1819
1832
1845
1858
1870
1883
1896
1908
1920
1933
1945
1957
1969
1980
1993
2004
2017

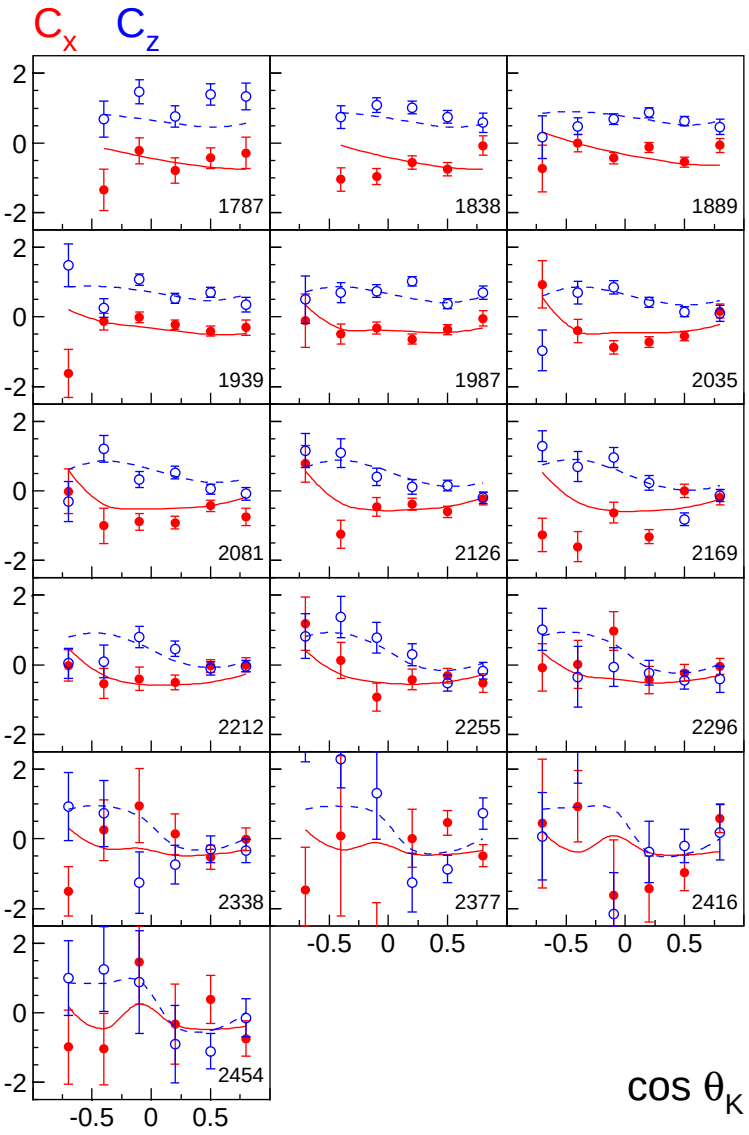

γp→ K+Σ0
2028
2040
2052
2063
2074
2086
2097
2109
2120
2131
2142
2153
2164
2175
2185
2196
2207
2217
2228
2239
2249
2260
2270
2281
2291

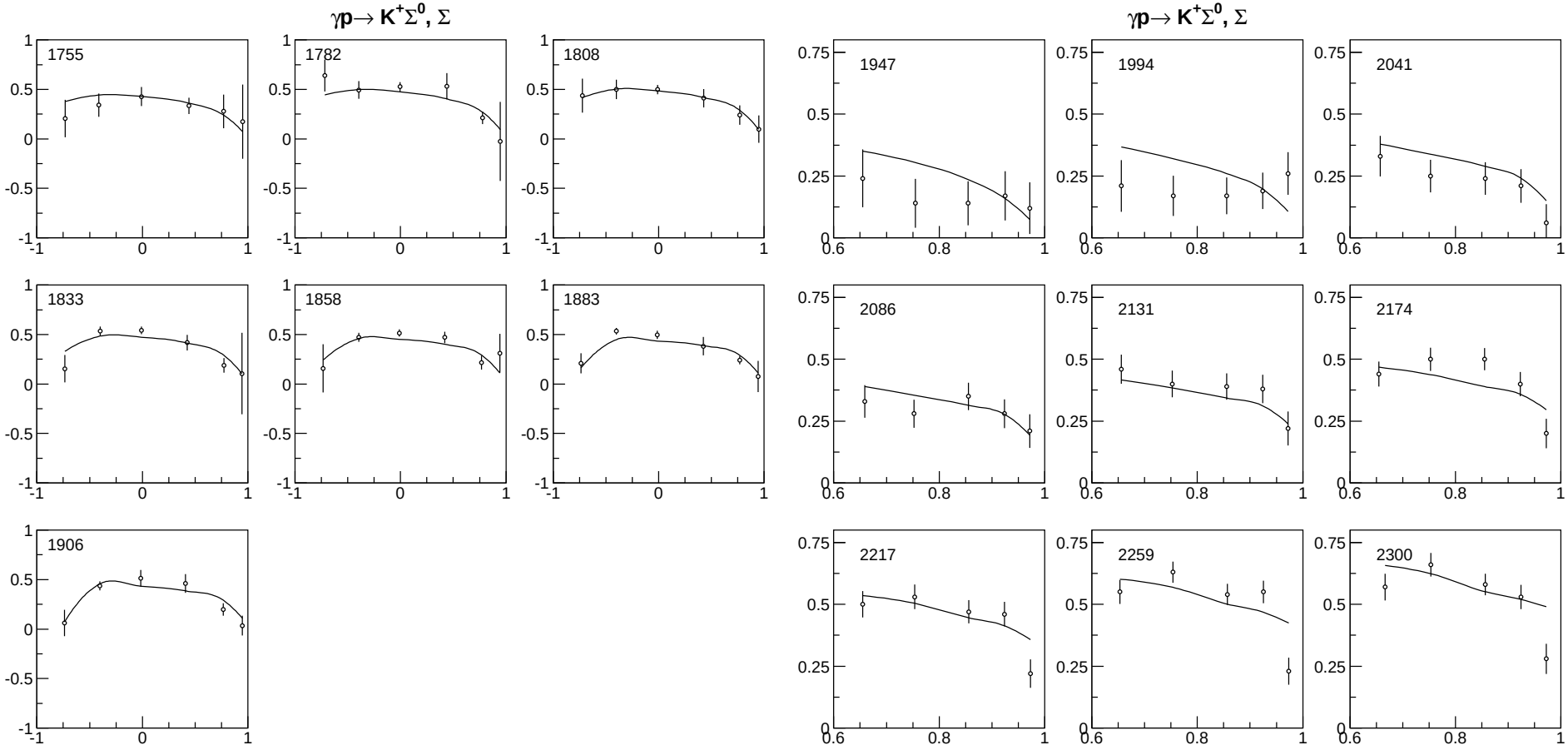

γp→ K+Σ0
2301
2332
2342
2352
2362
2372
2382
2392
2402
2412
2421
2431
2440
2450
2459
2468
2478
2487
2496
2505
2515
2524
2533


γp→ K⁰Σ⁺
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1600
1800
2000
2200
2400
2600
M(γp), MeV

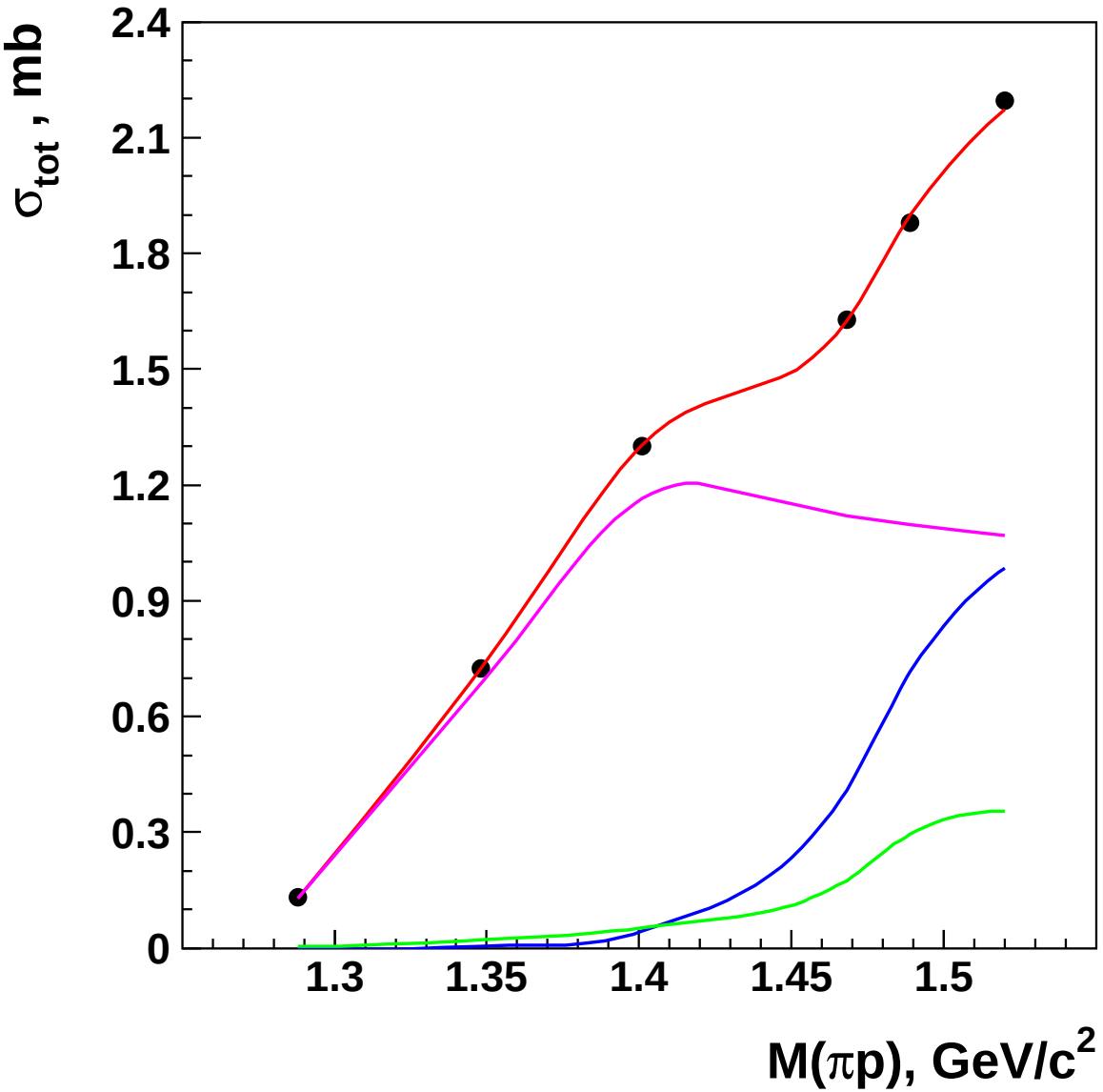

γp→ K⁰Σ⁺
1796
1898
1994
2086
2174
2259


γp→ K+Σ0, P
1757
1783
1809
1835
1860
1885
1910
1934
1959
1982
2006
2029
2052
2075
2120
2142
2163
2185
2206
2228
2248
2269
2290


Cx Cz
1787
1838
1889
1939
1987
2035
2081
2126
2169
2212
2255
2296
2338
2377
2416
2454
cos θK


γp→ K+Σ0, Σ
1755
1782
1808
1833
1858
1883
1906
γp→ K+Σ0, Σ
1947
1994
2041
2086
2131
2174
2217
2259
2300

$\pi^- p \to n\pi^0\pi^0$ (Crystal Ball) total cross section



Fit of the data

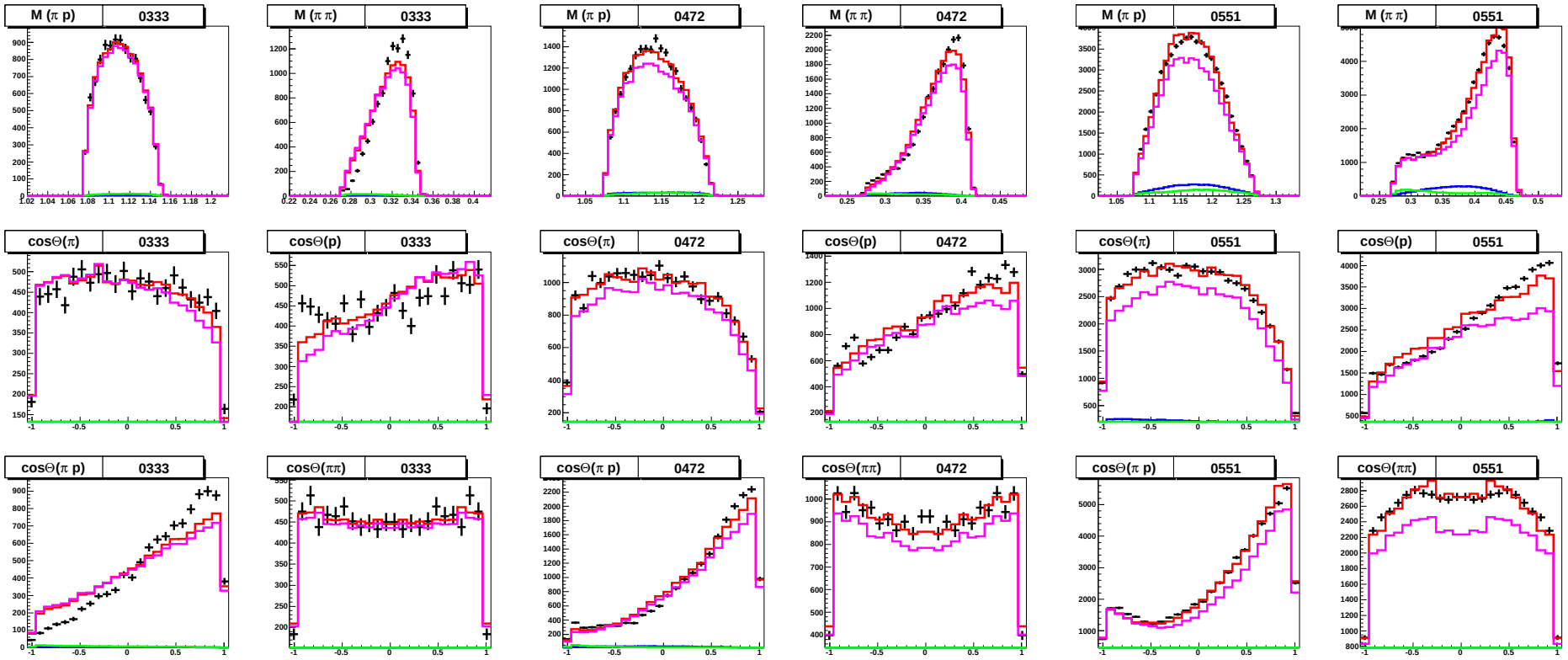
P_{11} **-partial wave**

D_{13} **-partial wave**

S_{11} **-partial wave**

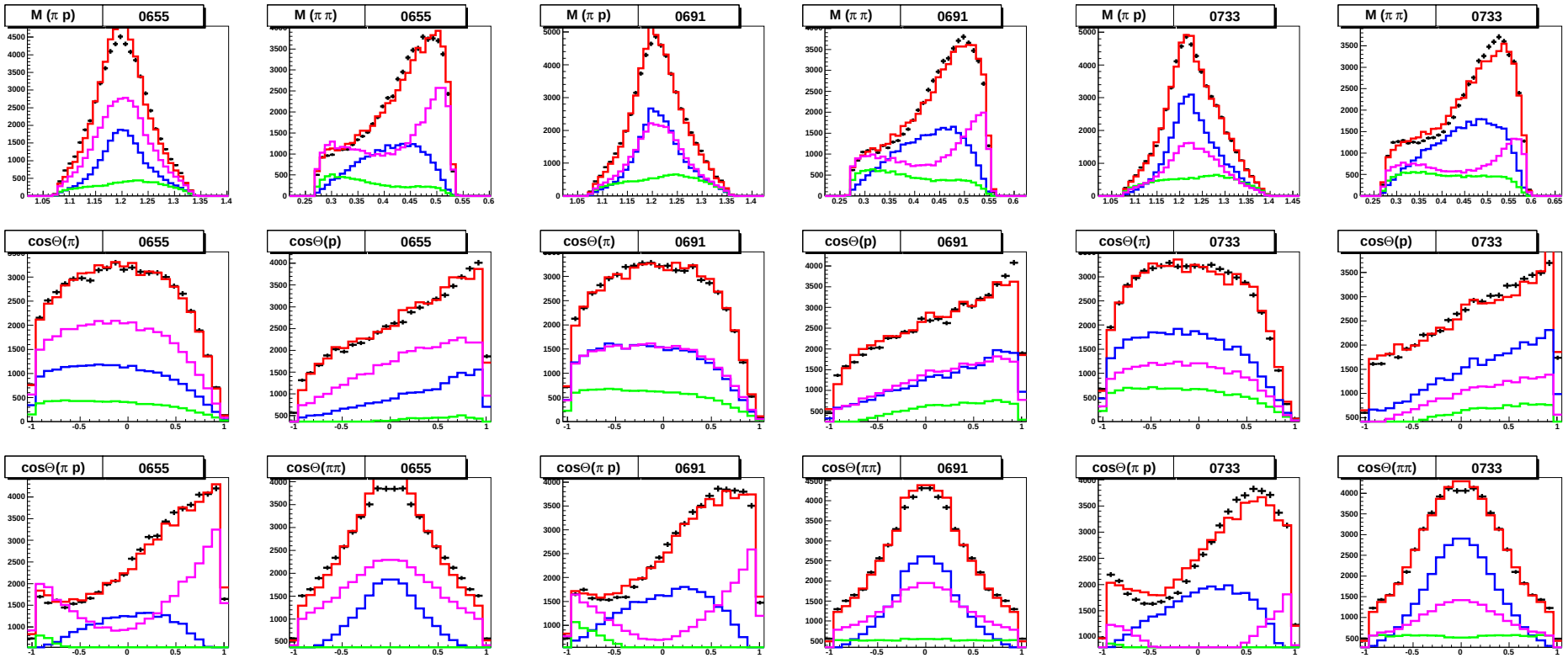
$\pi^- p \to n\pi^0\pi^0$ (Crystal Ball)

Differential cross sections for 333,472 and 551 MeV/c data.



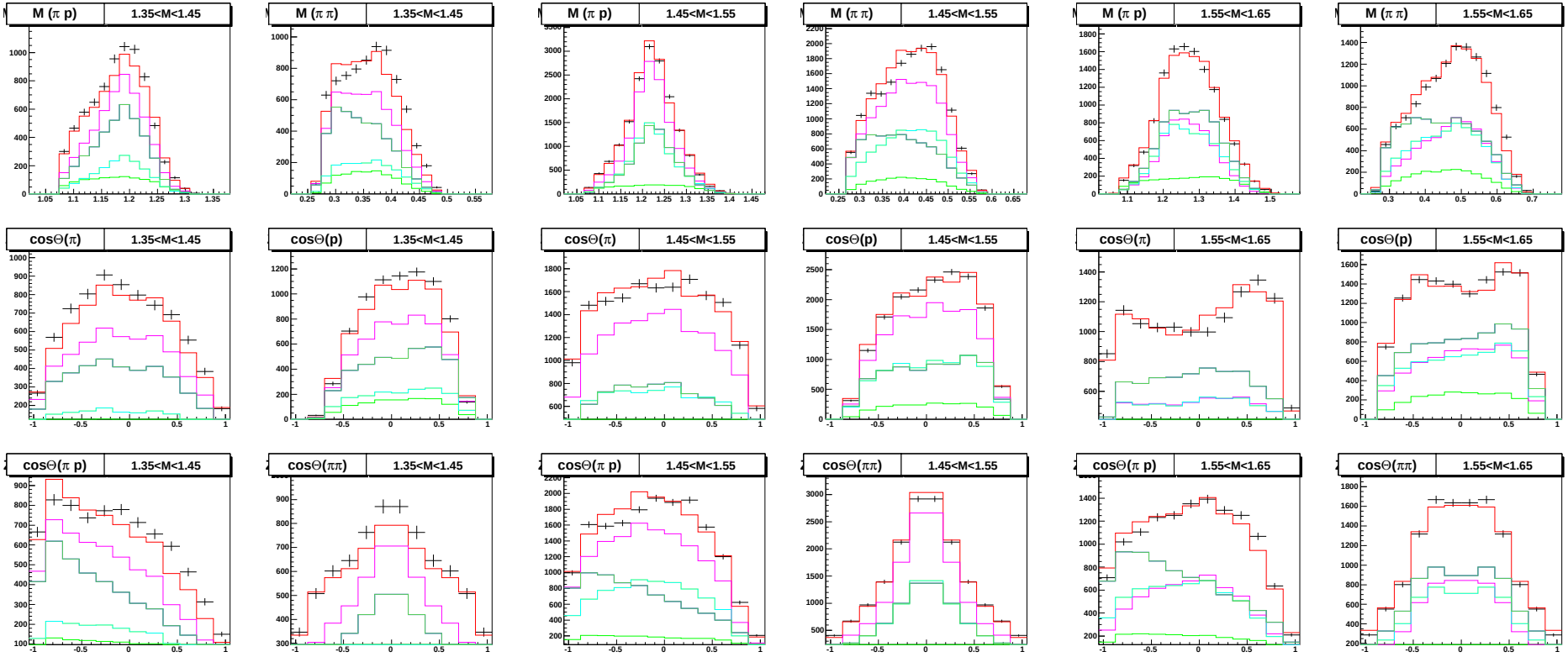
$\pi^- p \to n\pi^0\pi^0$ (Crystal Ball)

Differential cross sections for 655, 691 and 733 MeV/c data.



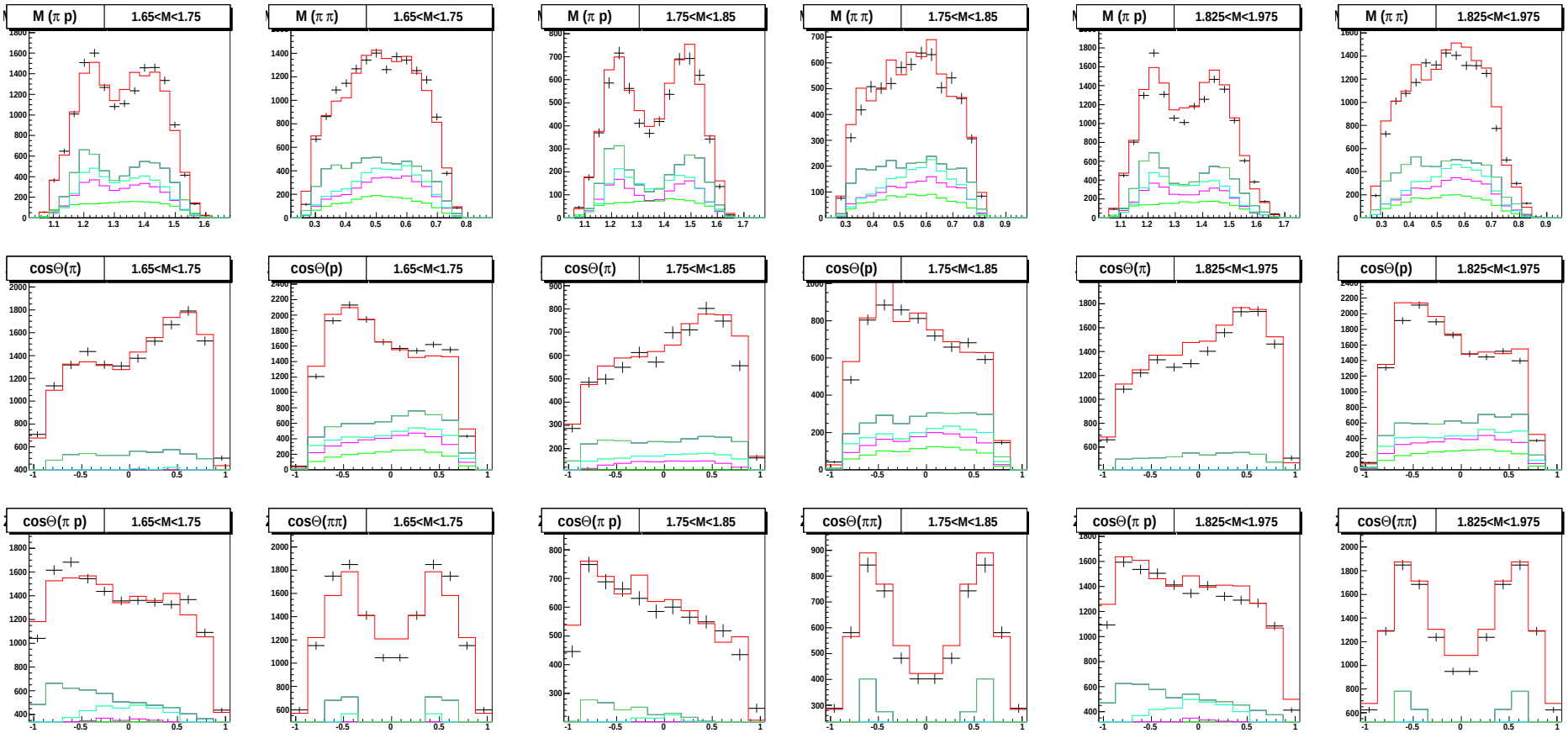
$\gamma p \to p\pi^0\pi^0$ (CB-ELSA)

Differential cross sections for W=1400, 1500 and 1600 MeV data.



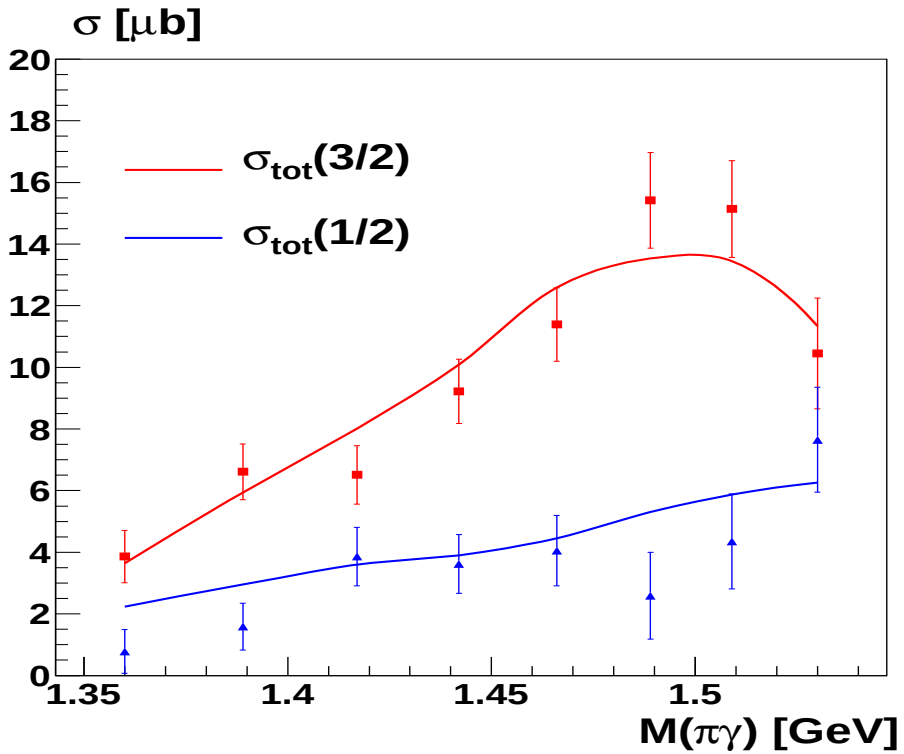
$\gamma p \to p\pi^0\pi^0$ (CB-ELSA)

Differential cross sections for W=1700, 1800 and 1900 MeV data.



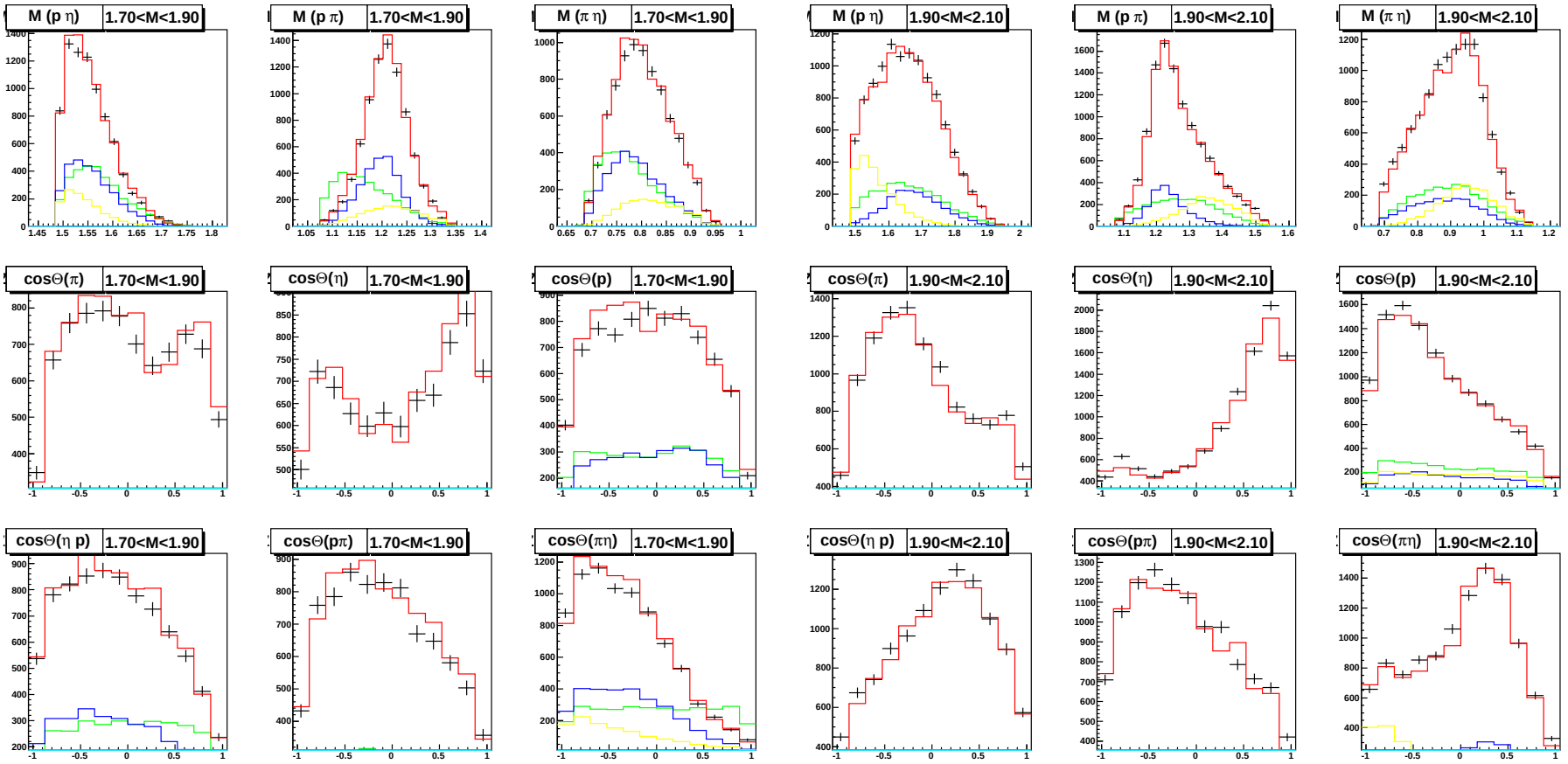
$\gamma p \to p\pi^0\pi^0$ (MAMI)

Differential cross sections $S = 3/2$ and $S = 1/2$.



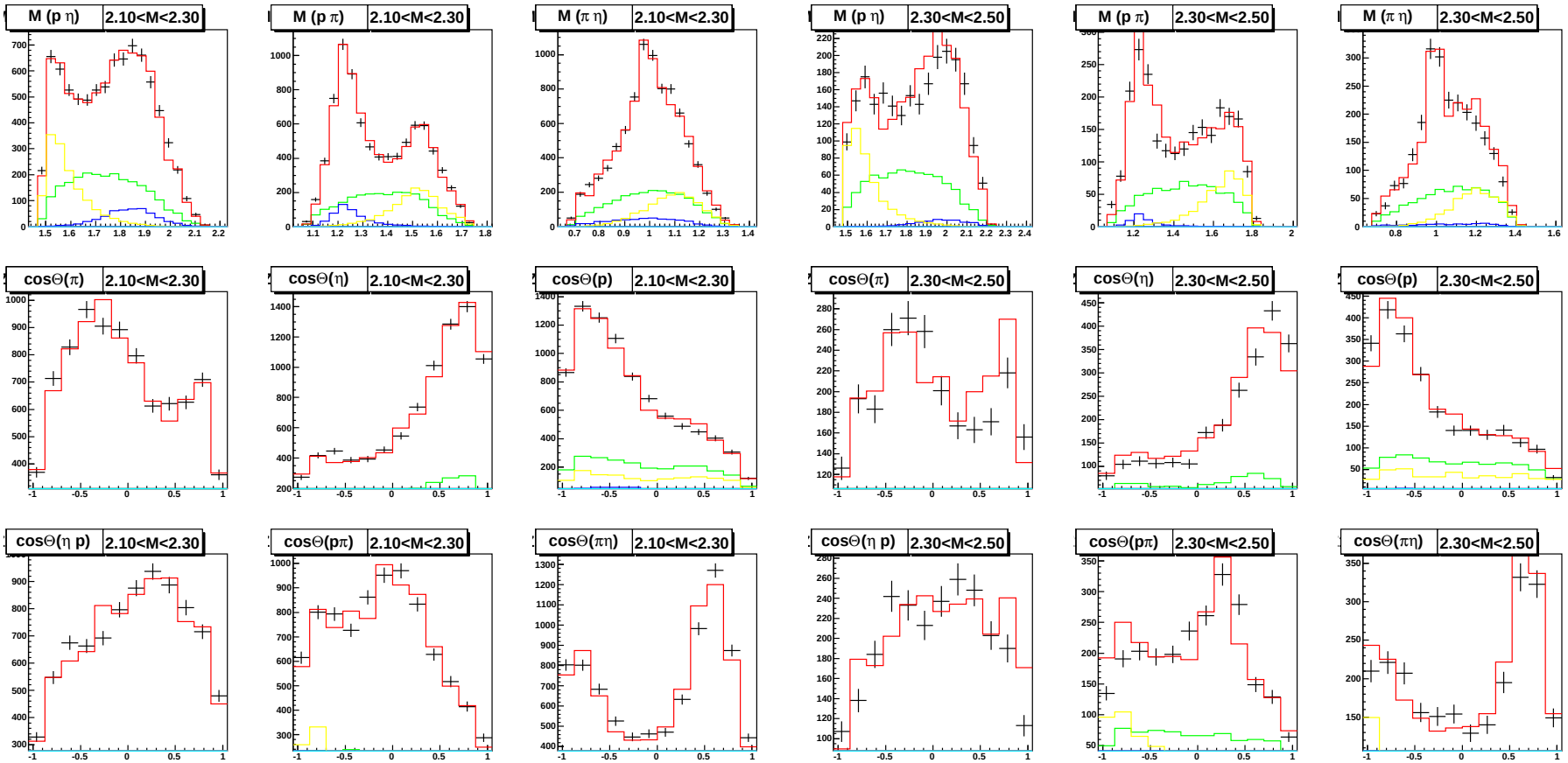
$\gamma p \to p\eta\pi^0$ (CB-ELSA)

Differential cross sections for W=1700 and 1800 MeV data.



$\gamma p \to p\eta\pi^0$ (CB-ELSA)

Differential cross sections for W=1900 and 2000 MeV data.



$\gamma p \to p\eta\pi^0$ (CB-ELSA)

Beam asymmetry data.