Search for missing baryon states. Analysis methods and perspective for new experiments.

Petersburg Nuclear Physics Institute

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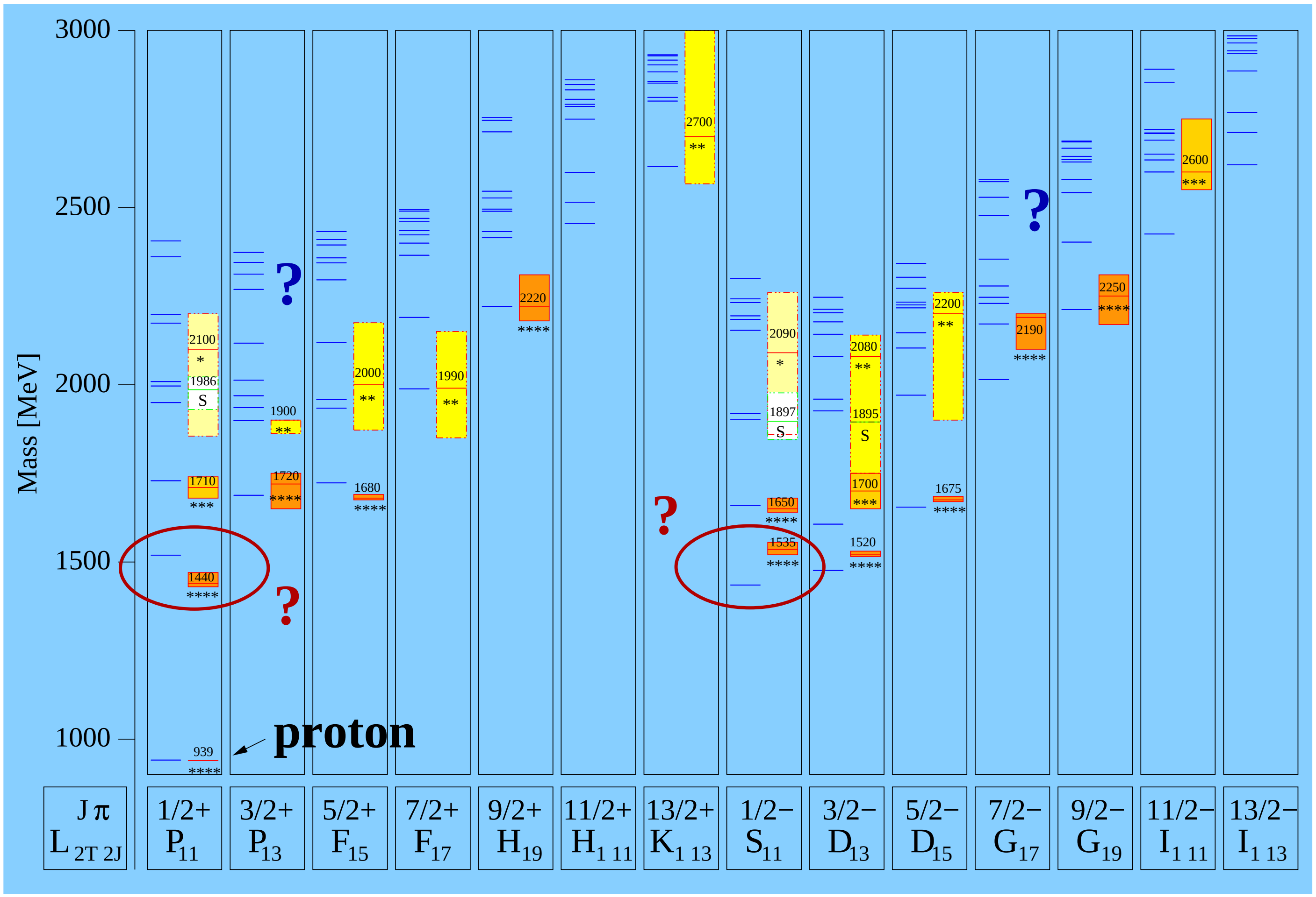
Symposium on Barion resonance production and e^+/e Conversion Decay

14-19 May 2012, Krakow

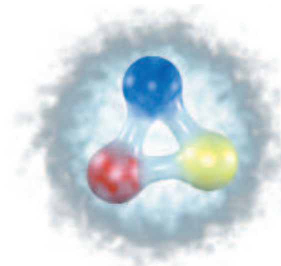
N*- resonances in the quark model

U. Loering, B. Metsch, H. Petry et al. (Bonn)



Nukleon

10^{-15} m



↔

Constituent quarks

Confinement-potential

Residual interaction

The latest analysis of SAID (GWU) of πN elastic data as well as $\gamma p \to \pi^0 p$ and $\gamma p \to \pi^+ n$ did not confirm the set of states observed in earlier analysis of πN elastic data. CLAS (M. Dugger et al.). Phys.Rev.C79:065206,2009.

State	PDG (Pole position)(MeV)		Bonn-Gatchina PWA (MeV)	
	Mass	Width	Mass	Width
$P_{11}(1710)^{***}$	1720 ± 50	230 ± 150	1710 ± 20	200 ± 18
$P_{33}(1600)^{***}$	1550 ± 100	300 ± 100	1510 ± 20	220 ± 45
$P_{33}(1920)^{***}$	1900 ± 50	200^{+100}_{-50}	1900 ± 30	260 ± 60
$D_{13}(1720)^{***}$	1680 ± 50	100 ± 50	1790 ± 40	390 ± 140
$P_{13}(1900)^{*}$	~ 1900	498 ± 78	1905 ± 30	250^{+120}_{-50}

Problem in the baryon spectroscopy and/or quark model:

The number of predicted three quark states exceeds dramatically the number of discovered baryons.

The elastic πN data can provide a reliable information about ground states only. If elastic branching is less than 10% the state is difficult to identify.

Possible solution:

1. **Analysis of the inelastic data from πN collision. There are old data on $\pi N \to K\Lambda$, $\pi N \to K\Sigma$ (Aragon, RAL). Controversial data on $\pi N \to \eta N$, new low energy data on $\pi^- p \to \pi^0 \pi^0 n$ (Crystal Ball) and not available anymore data on $\pi^- p \to \pi^+ \pi^- n$.**

2. **Analysis of photoproduction data taken by CLAS (JLab, USA), GRAAL, LEPS (Japan), MAMI (Mainz) and Crystal Barrel at ELSA (Bonn).**

3. **Analysis of baryon states produced in nuclear-nuclear collisions e.g. meson production in NN interaction.**

Bonn-Gatchina partial wave analysis group:

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

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

Analysis of Other Groups

- SAID
- MAID
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BG PWA

- Publications
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Useful Links

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

CB-ELSA Homepage

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Last changes: January 26th, 2010.

Search for baryon states

1. **Analysis of single 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, MAMI.**
2. **Analysis of single and double meson production in pion-induced reactions.**
   $\pi N \to \pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N$.
3. **Analysis of single and double meson production** $NN \to \pi NN$ **and** $\pi\pi NN$ **(Wasa, PNPI, HADES)**
4. **Analysis of hyperon production** $NN \to K\Lambda p$ **(WASA, HADES)**

Approach:

1. **Energy dependent analysis of the data. Such conditions as analyticity and unitarity can be imposed from the beginning.**
2. **A combined analysis of large data sets.**
3. **In future: an energy fixed partial wave analysis of the data on photoproduction.**

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. **B. S. Zou and D. V. Bugg, Eur. Phys. J. A 16, 537 (2003)**

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. **Anisovich:2001ra A. V. Anisovich, V. V. Anisovich, V. N. Markov, M. A. Matveev and A. V. Sarantsev, J. Phys. G G 28, 15 (2002)**
2. **A. Anisovich, E. Klempt, A. Sarantsev and U. Thoma, Eur. Phys. J. A 24, 111 (2005)**
3. **A. V. Anisovich and A. V. Sarantsev, Eur. Phys. J. A 30, 427 (2006)**
4. **A. V. Anisovich, V. V. Anisovich, E. Klempt, V. A. Nikonov and A. V. Sarantsev, Eur. Phys. J. A 34, 129 (2007).**

Orbital momentum operator

The angular momentum operator is constructed from momenta of particles k_1, k_2 and metric tensor $g_{\mu\nu}$.

For $L=0$ this operator is a constant: $X^0 = 1$

The $L=1$ operator is a vector $X^{(1)}_\mu$, constructed from: $k_\mu = \frac{1}{2}(k_{1\mu} - k_{2\mu})$ and $P_\mu = (k_{1\mu} + k_{2\mu})$. Orthogonality:

$$\int \frac{d^4k}{4\pi} X^{(1)}_{\mu_1} X^{(0)} = \int \frac{d^4k}{4\pi} X^{(n)}_{\mu_1\ldots\mu_n} X^{(n-1)}_{\mu_2\ldots\mu_n} = \xi P_{\mu_1} = 0$$

Then:

$$X^{(1)}_\mu P_\mu = 0 \qquad\qquad X^{(n)}_{\mu_1\ldots\mu_n} P_{\mu_j} = 0$$

and:

$$X^{(1)}_\mu = k^\perp_\mu = k_\nu g^\perp_{\nu\mu}; \qquad\qquad g^\perp_{\nu\mu} = \left(g_{\nu\mu} - \frac{P_\nu P_\nu}{p^2} \right) ;$$

in c.m.s $k^\perp = (0, \vec{k})$

Recurrent expression for the orbital momentum operators $X^{(n)}_{\mu_1\ldots\mu_n}$

$$X^{(n)}_{\mu_1\ldots\mu_n} = \frac{2n-1}{n^2}\sum_{i=1}^{n} k^{\perp}_{\mu_i} X^{(n-1)}_{\mu_1\ldots\mu_{i-1}\mu_{i+1}\ldots\mu_n} - \frac{2k^2_\perp}{n^2}\sum_{\substack{i,j=1\\ i<j}}^{n} g_{\mu_i\mu_j} X^{(n-2)}_{\mu_1\ldots\mu_{i-1}\mu_{i+1}\ldots\mu_{j-1}\mu_{j+1}\ldots\mu_n}$$

Scattering of two spinless particles

Denote relative momenta of particles before and after interaction as q and k, correspondingly. The structure of partial–wave amplitude with orbital momentum $L = J$ is determined by convolution of operators $X^{(L)}(k)$ and $X^{(L)}(q)$:

$$A_L = BW_L(s) X^{(L)}_{\mu_1\ldots\mu_L}(k) O^{\mu_1\ldots\mu_L}_{\nu_1\ldots\nu_L} X^{(L)}_{\nu_1\ldots\nu_L}(q) = BW_L(s) X^{(L)}_{\mu_1\ldots\mu_L}(k) X^{(L)}_{\mu_1\ldots\mu_L}(q)$$

$BW_L(s)$ **depends on the total energy squared only.**

The convolution $X^{(L)}_{\mu_1\ldots\mu_L}(k) X^{(L)}_{\mu_1\ldots\mu_L}(q)$ can be written in terms of Legendre polynomials $P_L(z)$:

$$X^{(L)}_{\mu_1\ldots\mu_L}(k) X^{(L)}_{\mu_1\ldots\mu_L}(q) = \alpha(L) \left(\sqrt{k^2_\perp}\sqrt{q^2_\perp}\right)^L P_L(z)\,,$$

πN interaction

States with $J = L - 1/2$ are called '–' states ($1/2^+$, $3/2^-$,$5/2^+$,...) and states with $J = L + 1/2$ are called '+' states ($1/2^-$, $3/2^+$,$5/2^-$,...).

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

$$A_{\pi N} = \bar{u}(k_1) N^{*\pm}_{\mu_1\ldots\mu_n} F^{\mu_1\ldots\mu_n}_{\nu_1\ldots\nu_n}(P) N^{\pm}_{\nu_1\ldots\nu_n} u(q_1) BW^{\pm}_{\substack{n\\n+1}}(s)$$

$$A_{\pi N} = \omega^* \left[G(s,t) + H(s,t) i(\vec{\sigma}\vec{n})\right]\omega' \qquad n_i = \frac{1}{|\vec{k}||\vec{q}|}\epsilon_{ijm}k_j q_m \ ,$$

$$G(s,t) = \sum_L \Big[(L+1)F^+_L(s) + LF^-_L(s)\Big] P_L(z) \ ,$$

$$H(s,t) = \sum_L \Big[F^+_L(s) - F^-_L(s)\Big] P'_L(z) \ .$$

$$F^+_L = (|\vec{k}||\vec{q}|)^L \sqrt{\chi_i\chi_f}\,\frac{\alpha(L)}{2L+1} BW^+_L(s) \ ,$$

$$F^-_L = (|\vec{k}||\vec{q}|)^L \sqrt{\chi_i\chi_f}\,\frac{\alpha(L)}{L} BW^-_L(s) \ .$$

NN - scattering

Transition of two baryons with momenta p_1 and p_2 into two baryons with p'_1 and p'_2, $s = (p_1 + p_2)^2 = (p'_1 + p'_2)^2$, $k = p_1 - p_2$, $k' = p'_1 - p'_2$. Two baryons with $J^P = \frac{1}{2}^+$ can have spin states $S = 0, 1$.

$$A = \Big(\bar{u}(p'_1) V^{S',L'}_{\mu_1\ldots\mu_J}(k'_\perp) u^c(-p'_2)\Big)\, O^{\mu_1\ldots\mu_n}_{\nu_1\ldots\nu_n} \left(\bar{u}^c(-p_2) V^{S,L}_{\nu_1\ldots\nu_J}(k_\perp) u(p_1)\right) A_{pw}(s)\,.$$

$$u^c_j(-p) \;=\; C\bar{u}^T_j(p) \qquad C = \gamma_2\gamma_0 = \begin{pmatrix} 0 & -\sigma_2 \\ -\sigma_2 & 0 \end{pmatrix}$$

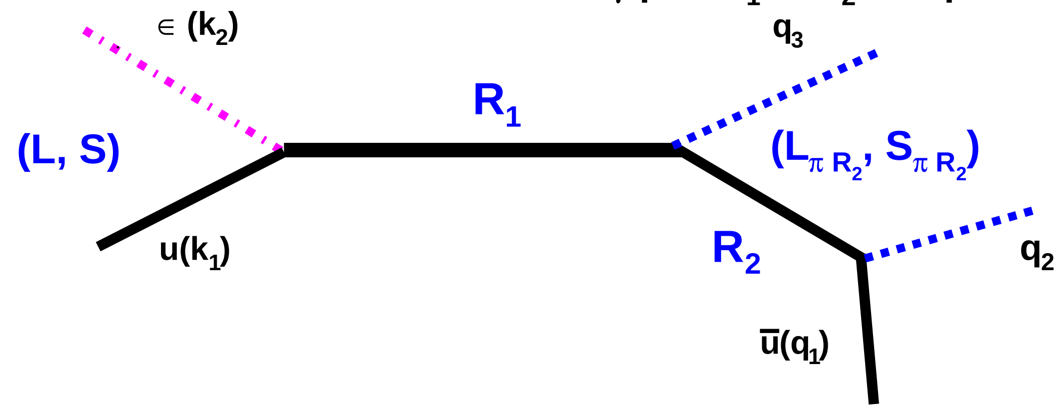
Vertex operators:

$$V^{0,L}_{\mu_1\ldots\mu_J} = i\gamma_5 X^{(J)}_{\mu_1\ldots\mu_J}(k^\perp) \qquad V^{1,L<J}_{\mu_1\ldots\mu_J} = \gamma_{\mu_1} X^{(n-1)}_{\mu_2\ldots\mu_J}(k^\perp)$$

$$V^{1,L=J}_{\mu_1\ldots\mu_J} = \varepsilon_{\mu_1\eta\xi\gamma}\gamma_\eta X^{(J)}_{\xi\mu_2\ldots\nu_J}(k^\perp) P_\gamma \qquad V^{1,L>J}_{\mu_1\ldots\mu_J} = \gamma_\alpha X_{\alpha\mu_1\ldots\mu_J}(k^\perp)$$

The resonance amplitudes for meson photoproduction

$\gamma\, p \to R_1 \to R_2\, \pi \to p\, \pi\, \pi$



The general form of the angular dependent part of the amplitude:

$$\bar u(q_1)\tilde N_{\alpha_1\ldots\alpha_n}(R_2\to\mu N)F^{\alpha_1\ldots\alpha_n}_{\beta_1\ldots\beta_n}(q_1+q_2)\tilde N^{(j)\beta_1\ldots\beta_n}_{\gamma_1\ldots\gamma_m}(R_1\to\mu R_2)$$
$$F^{\gamma_1\ldots\gamma_m}_{\xi_1\ldots\xi_m}(P)V^{(i)\mu}_{\xi_1\ldots\xi_m}(R_1\to\gamma N)u(k_1)\varepsilon_\mu$$

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

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

Parameterization of the partial wave amplitude

1. **Poles: amplitude as a sum of the Breit-Wigner states:**

$$A = \sum_\beta \frac{\Lambda_\beta}{M_\beta^2 - s - i\sum_j g_j^{(\beta)2}\rho_j(s)} \qquad \beta = J, S, L, n\ldots$$

2. **K-matrix approach. (Unitarity and analyticity)**

$$A_{1i} = K_{1j}(I - i\rho K)^{-1}_{ji} \qquad K_{ij} = \sum_\alpha \frac{g_i^\alpha g_j^\alpha}{M_\alpha^2 - s} + f_{ij}(s)$$

3. **N/D-method (Unitarity and correct analytical properties)**

$$A_{jm} = A_{jk}\sum_\alpha B_\alpha^{km}(s)\frac{1}{M_m - s} + \frac{\delta_{jm}}{M_j^2 - s}$$

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

Minimization methods

1. **The two body final states** $\pi N \to \pi N$**,** $\pi\pi \to \pi\pi$**,** $\gamma p \to \pi N$**,** $p\bar{p}(at\, rest) \to 3\pi$**:** χ^2 **method. For** n **measured bins we minimize**

$$\chi^2 = \sum_j^n \frac{(\sigma_j(PWA) - \sigma_j(exp))^2}{(\Delta\sigma_j(exp))^2}$$

2. **Reactions with three or more final states are analyzed with logarithm likelihood method. The minimization function:**

$$f = -\sum_j^{N(data)} ln \frac{\sigma_j(PWA)}{\sum\limits_m^{N(rec\, MC)} \sigma_m(PWA)}$$

This method allows us to take into account all correlations in many dimensional phase space.

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

Baryon Data Base

Kaon photoproduction (χ^2 analysis).

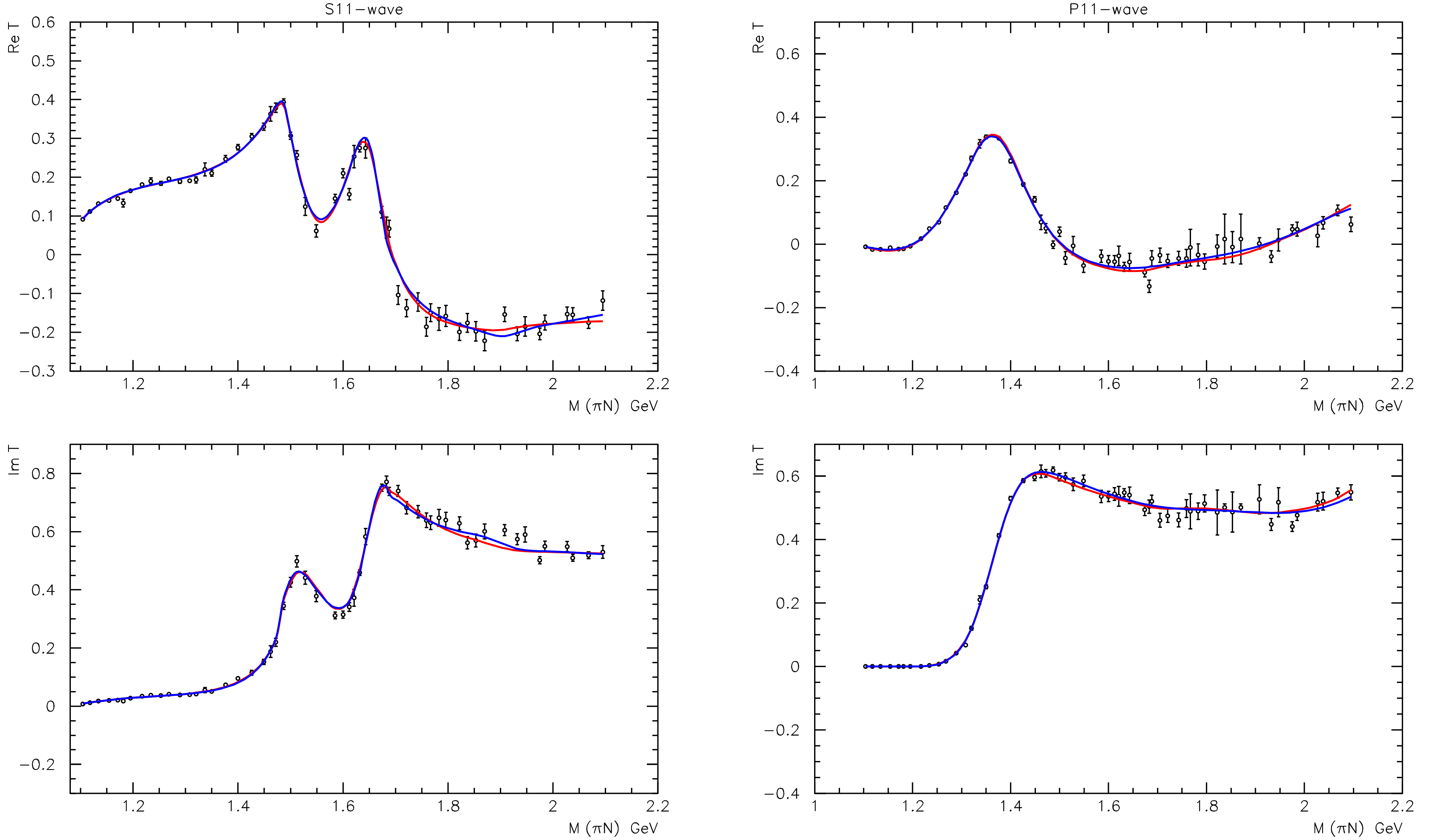
Observable	$N_{\rm data}$	$\frac{\chi^2}{N_{\rm data}}$		Observable	$N_{\rm data}$	$\frac{\chi^2}{N_{\rm data}}$	
$d\sigma/d\Omega(\gamma p \to \Lambda K^+)$	1320	0.78	CLAS09	$d\sigma/d\Omega(\gamma p \to \Sigma^0 K^+)$	1590	1.44	CLAS
$P(\gamma p \to \Lambda K^+)$	1270	1.75	CLAS09	$P(\gamma p \to \Sigma^0 K^+)$	344	2.69	CLAS
$C_x(\gamma p \to \Lambda K^+)$	160	1.44	CLAS	$C_x(\gamma p \to \Sigma^0 K^+)$	94	2.36	CLAS
$C_z(\gamma p \to \Lambda K^+)$	160	1.53	CLAS	$C_z(\gamma p \to \Sigma^0 K^+)$	94	1.62	CLAS
$\Sigma(\gamma p \to \Lambda K^+)$	66	3.32	GRAAL	$\Sigma(\gamma p \to \Sigma^0 K^+)$	42	1.80	GRAAL
$\Sigma(\gamma p \to \Lambda K^+)$	45	2.34	LEP	$\Sigma(\gamma p \to \Sigma^0 K^+)$	45	1.31	LEP
$T(\gamma p \to \Lambda K^+)$	66	1.35	GRAAL 09	$d\sigma/d\Omega(\gamma p \to \Sigma^+ K^0)$	48	3.41	CLAS
$O_x(\gamma p \to \Lambda K^+)$	66	1.70	GRAAL 09	$d\sigma/d\Omega(\gamma p \to \Sigma^+ K^0)$	72	0.67	CB-ELSA 10
$O_z(\gamma p \to \Lambda K^+)$	66	1.66	GRAAL 09	$P(\gamma p \to \Sigma^+ K^0)$	24	1.17	CB-ELSA 10
$P(\gamma p \to \Lambda K^+)$	84	0.60	GRAAL	$\Sigma(\gamma p \to \Sigma^+ K^0)$	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**				
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma p \to p\pi^0\pi^0)$	**CB-ELSA (1.4 GeV)**	$E(\gamma p \to p\pi^0\pi^0)$	**16**	**1.91**	**MAMI**
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma p \to p\pi^0\eta)$	**CB-ELSA (3.2 GeV)**	$\Sigma(\gamma p \to p\pi^0\eta)$	**180**	**2.37**	**GRAAL**
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma p \to p\pi^0\pi^0)$	**CB-ELSA (3.2 GeV)**	$\Sigma(\gamma p \to p\pi^0\pi^0)$	**128**	**0.96**	**GRAAL**
$\mathrm{d}\sigma/\mathrm{d}\Omega(\gamma p \to p\pi^0\eta)$	**CB-ELSA (3.2 GeV)**	$\Sigma(\gamma p \to p\pi^0\eta)$	**180**	**2.37**	**GRAAL**
$I_c(\gamma p \to p\pi^0\eta)$	**CB-ELSA (3.2 GeV)**	$I_s(\gamma p \to p\pi^0\eta)$	**CB-ELSA (3.2 GeV)**		

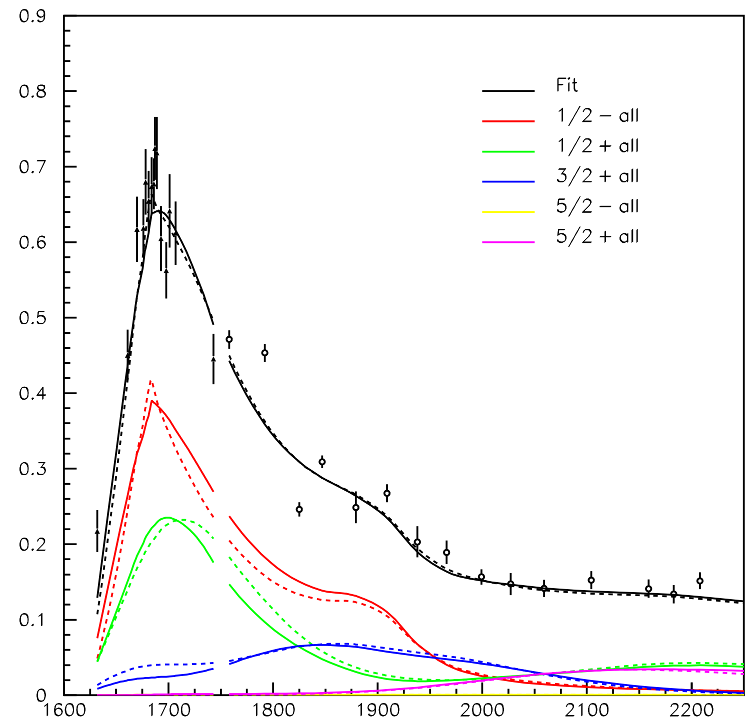
Description of the πN elastic amplitudes (GWU energy independent solution) with K-matrix and D-matrix solutions



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

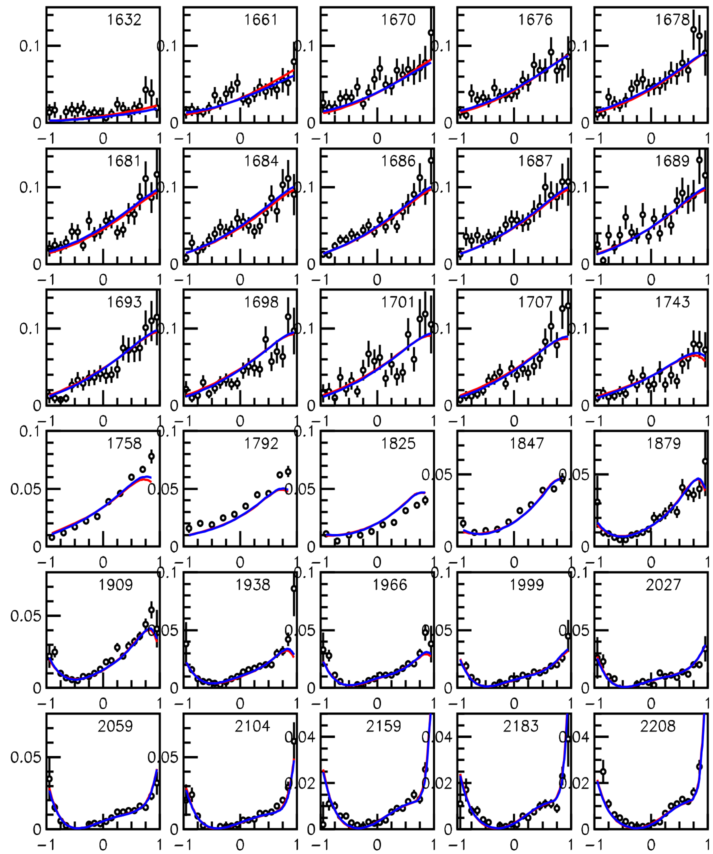
Full experiment for $\pi N \to K\Lambda$: differential cross section, analyzing power, rotation parameter.

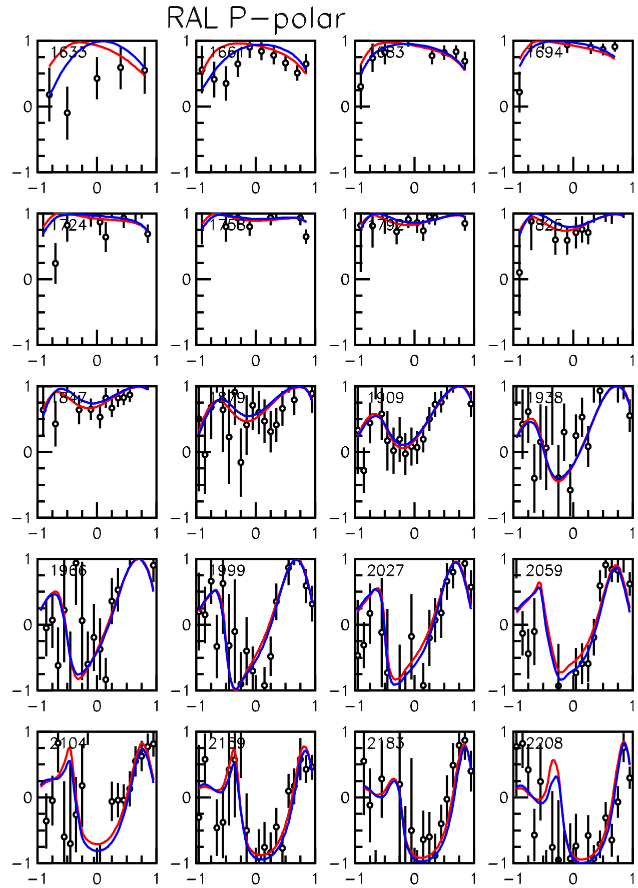
A clear evidence for resonances which are hardly seen (or not seen) in the elastic reactions: $N(1710)P_{11}$, $N(1900)P_{13}$,

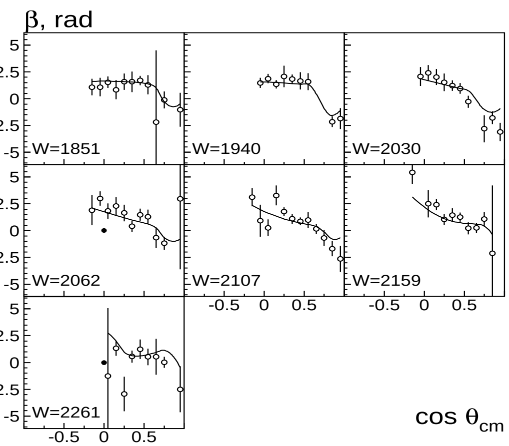


The total cross section for the reaction $\pi^- p \to K^0\Lambda$ and contributions from leading partial waves in K-matrix (full) and D-matrix (dashed) solutions.

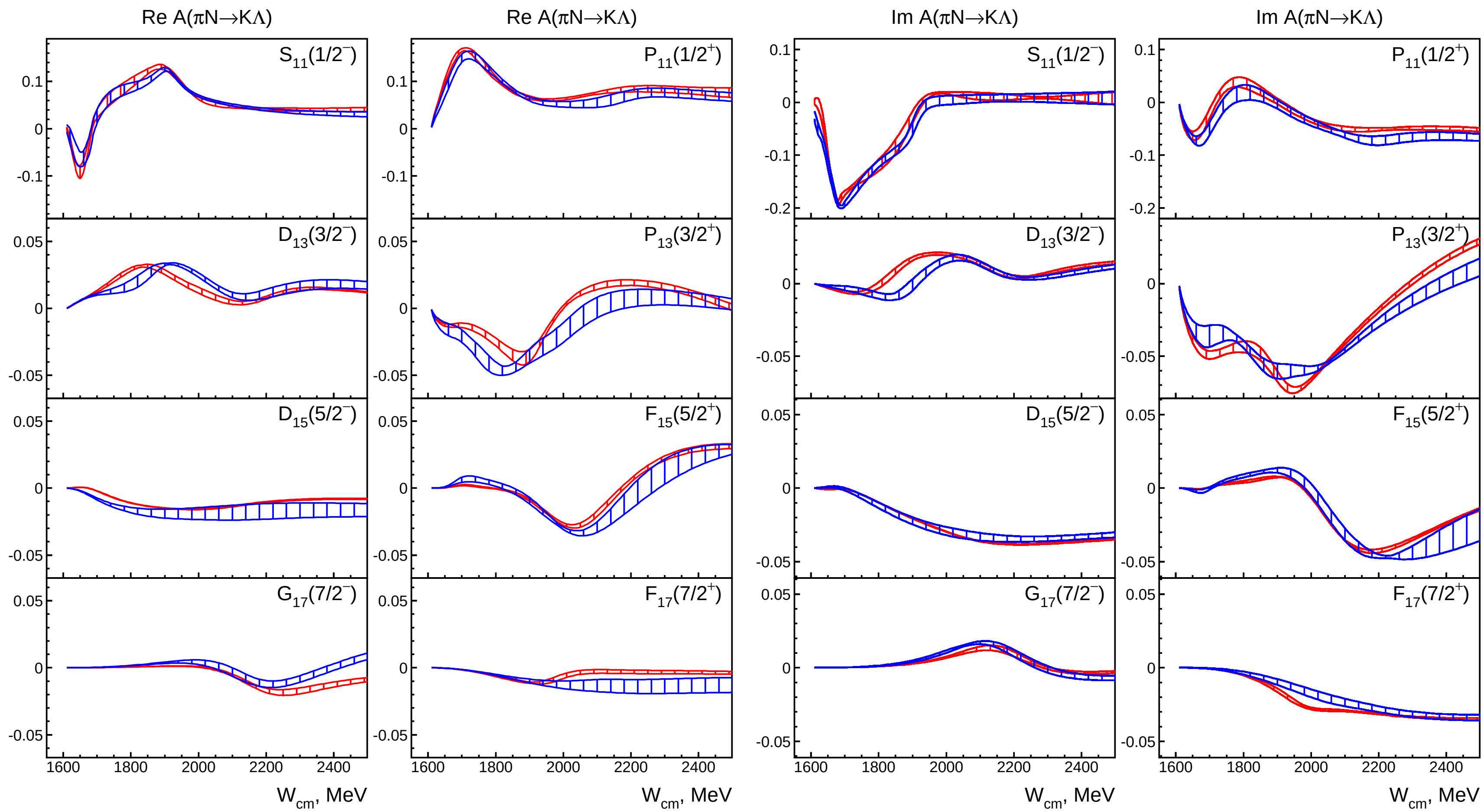
$$\pi^- p \to K\Lambda \, (d\sigma/d\Omega, P)$$



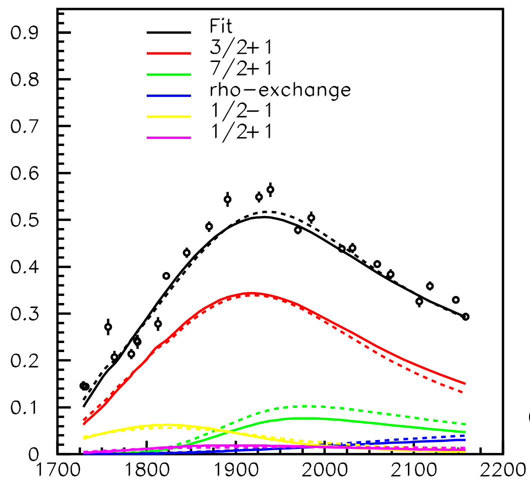


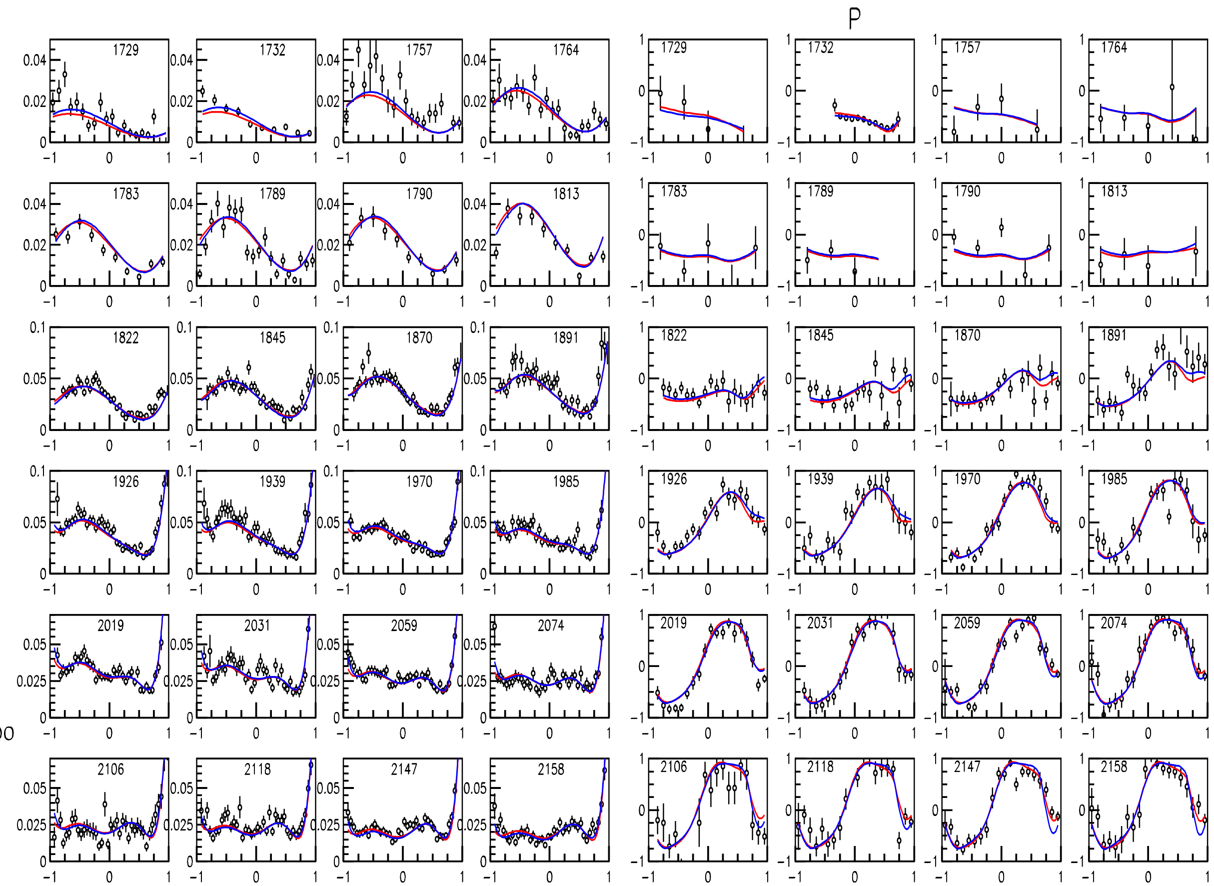


The $\pi N \to K\Lambda$ amplitudes

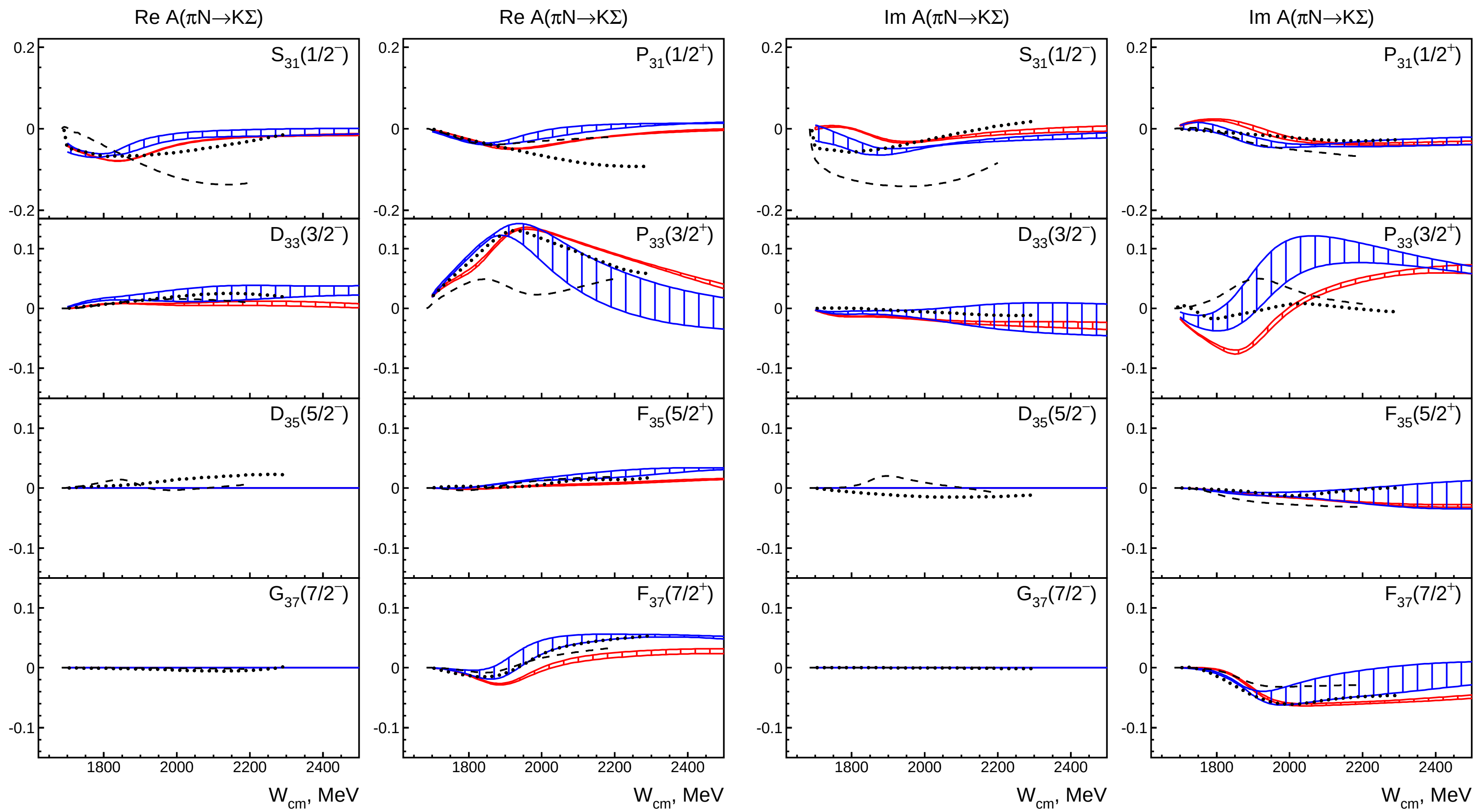


The fit of the the $\pi^+ p \to K^+ \Sigma^+$ reaction

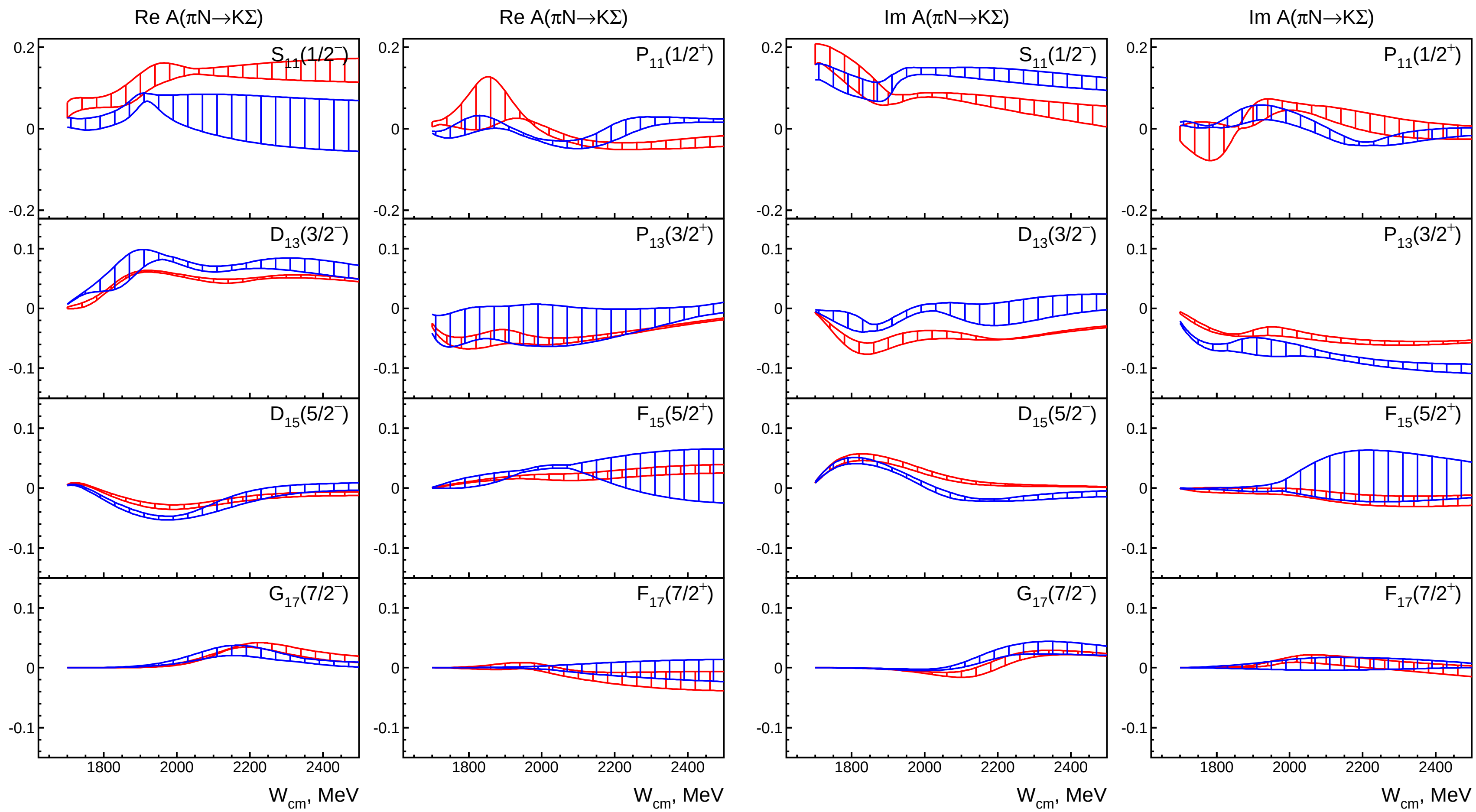




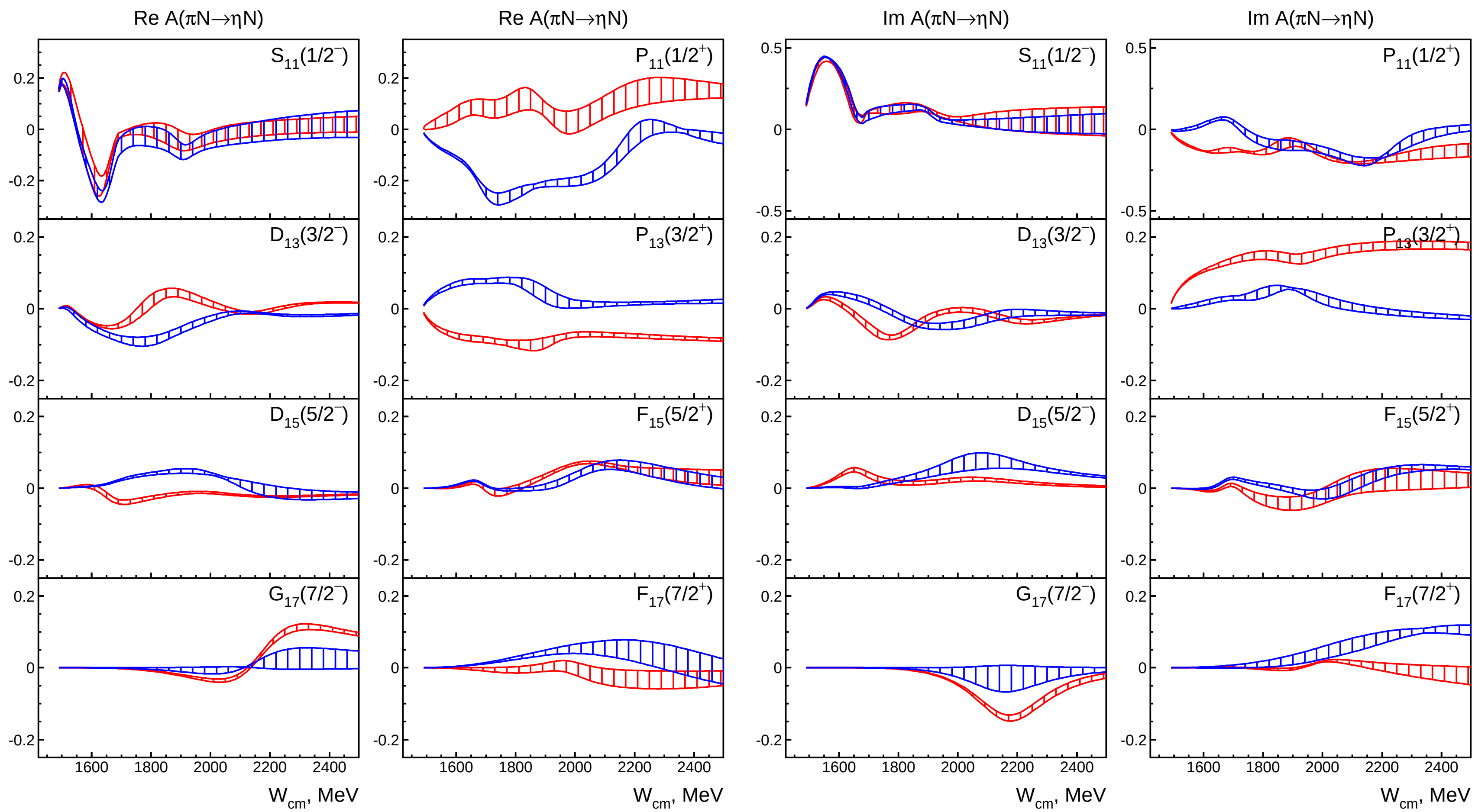
The $\pi N \to K\Sigma$ I=3/2 amplitudes



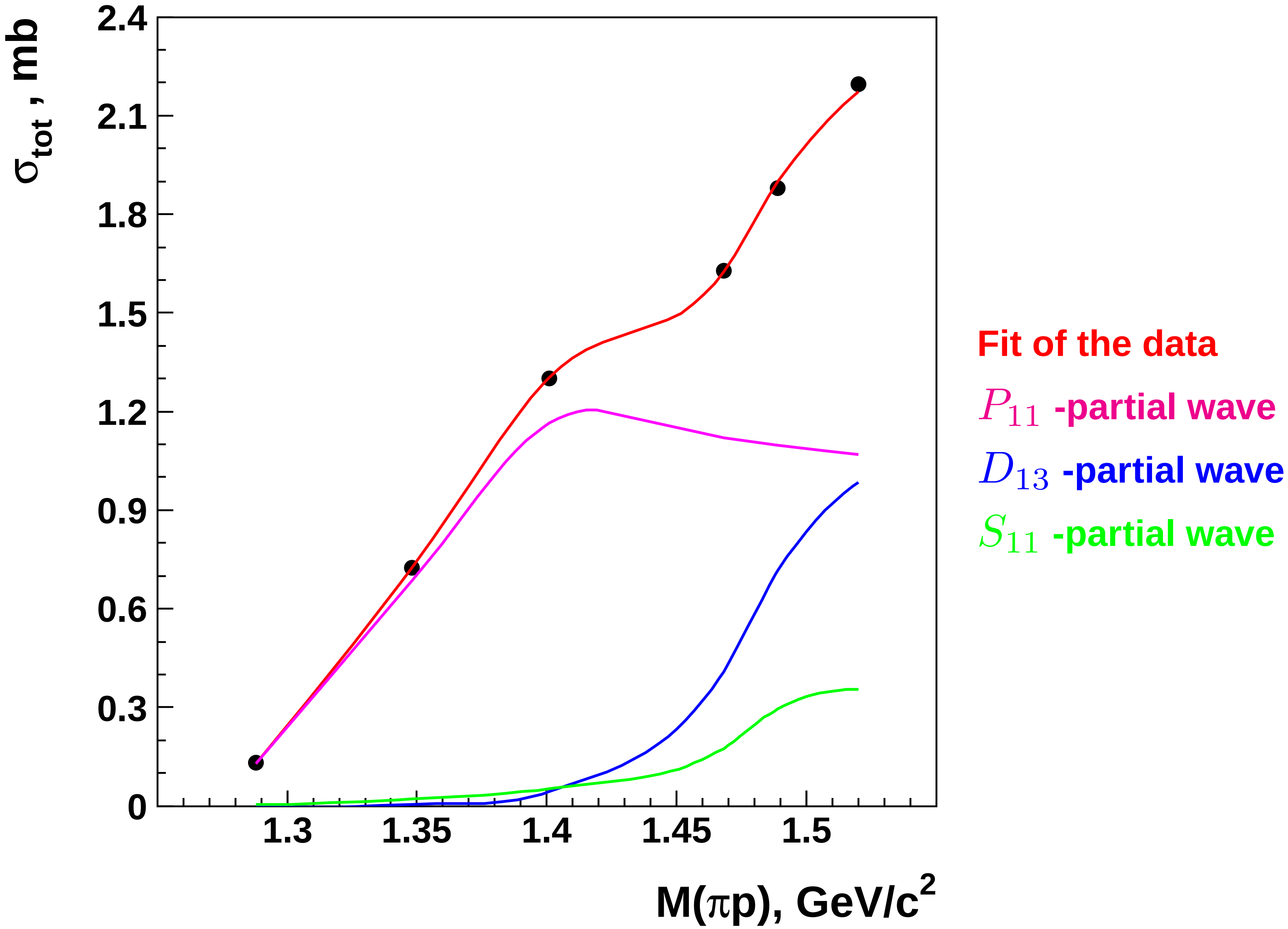
The $\pi N \to K\Sigma$ I=1/2 amplitudes



The $\pi N \to \eta N$ amplitudes

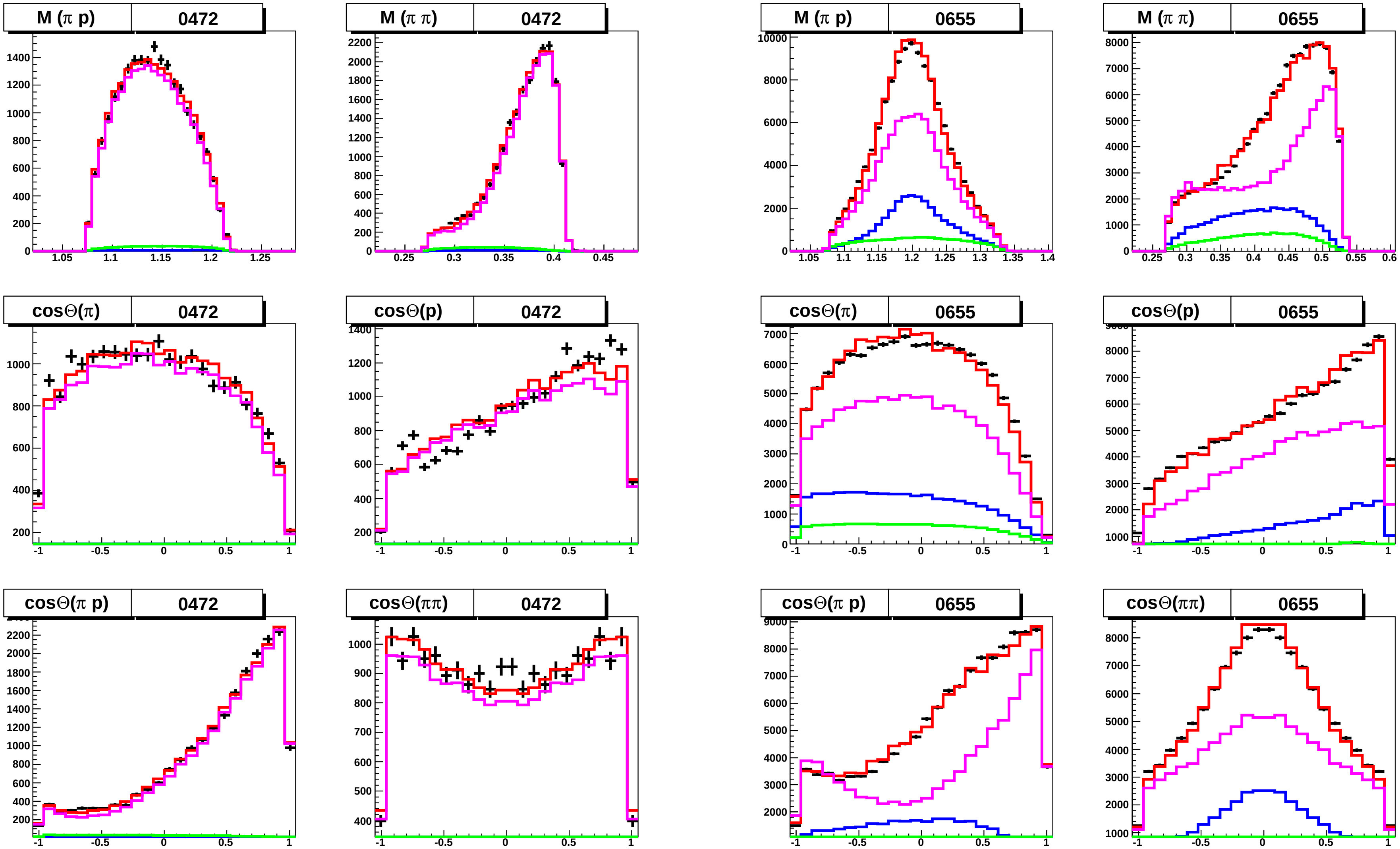


$\pi^- p \rightarrow n\pi^0\pi^0$ (Crystal Ball) total cross section

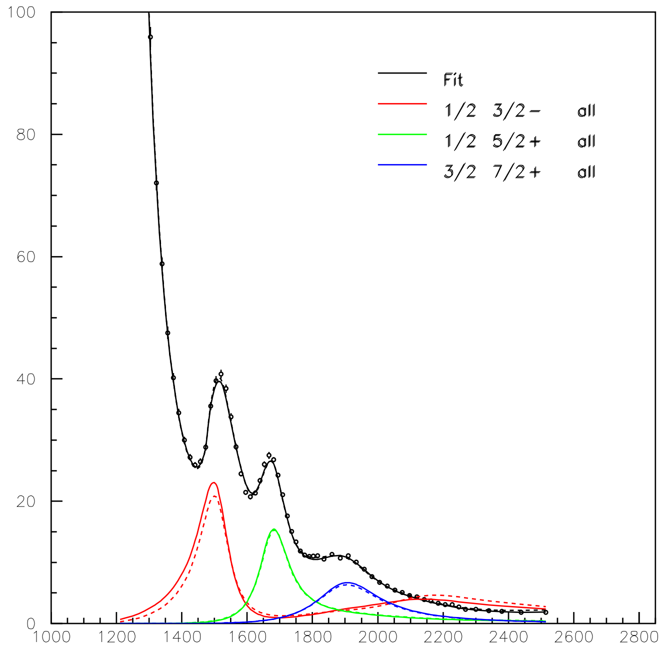


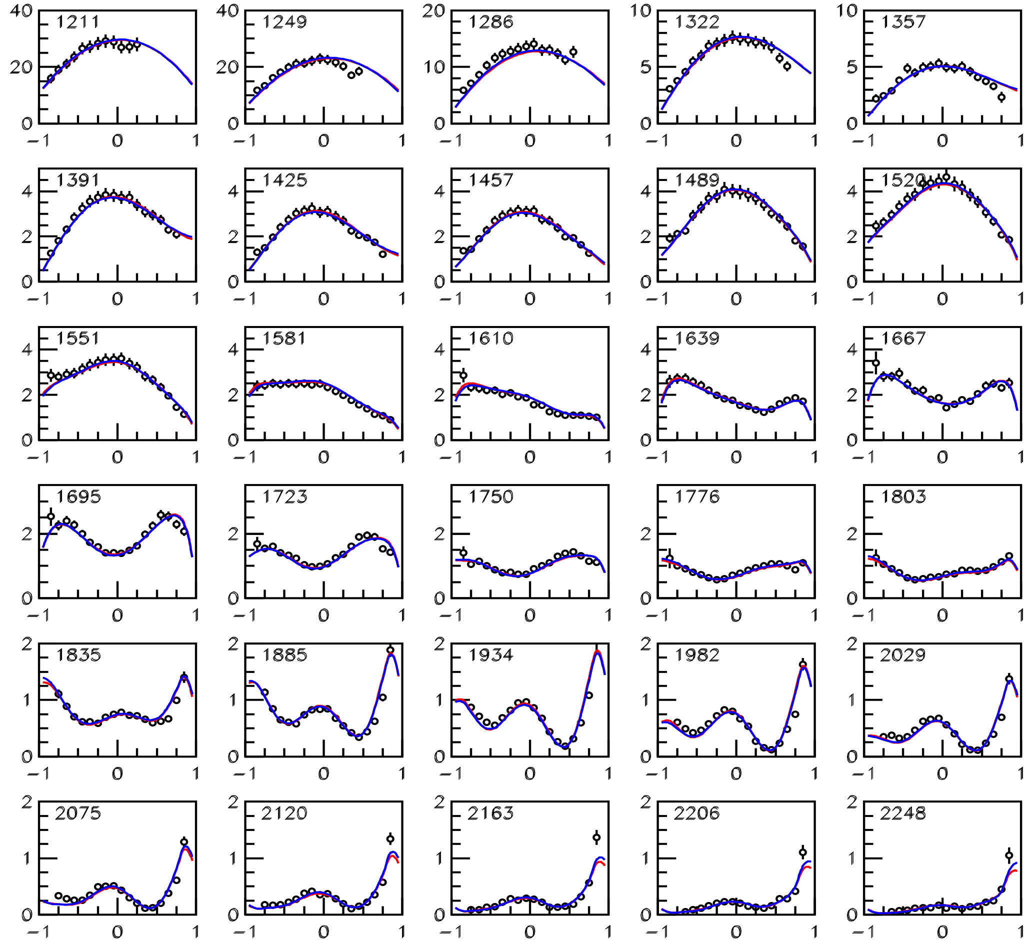
$\pi^- p \to n\pi^0\pi^0$ (Crystal Ball)

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

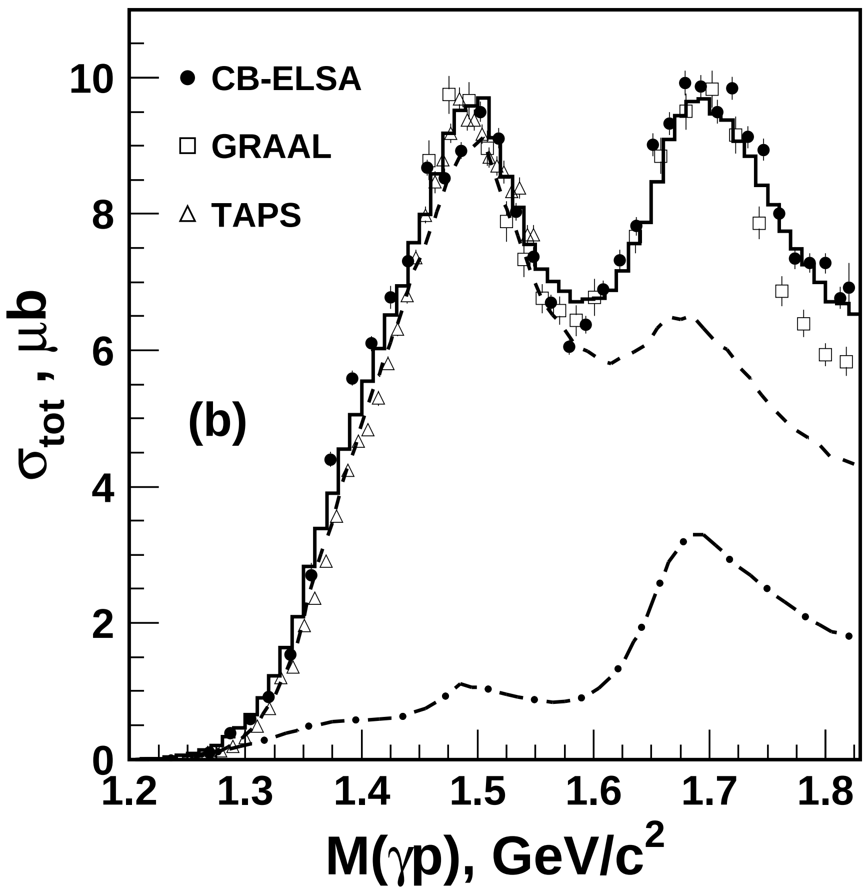


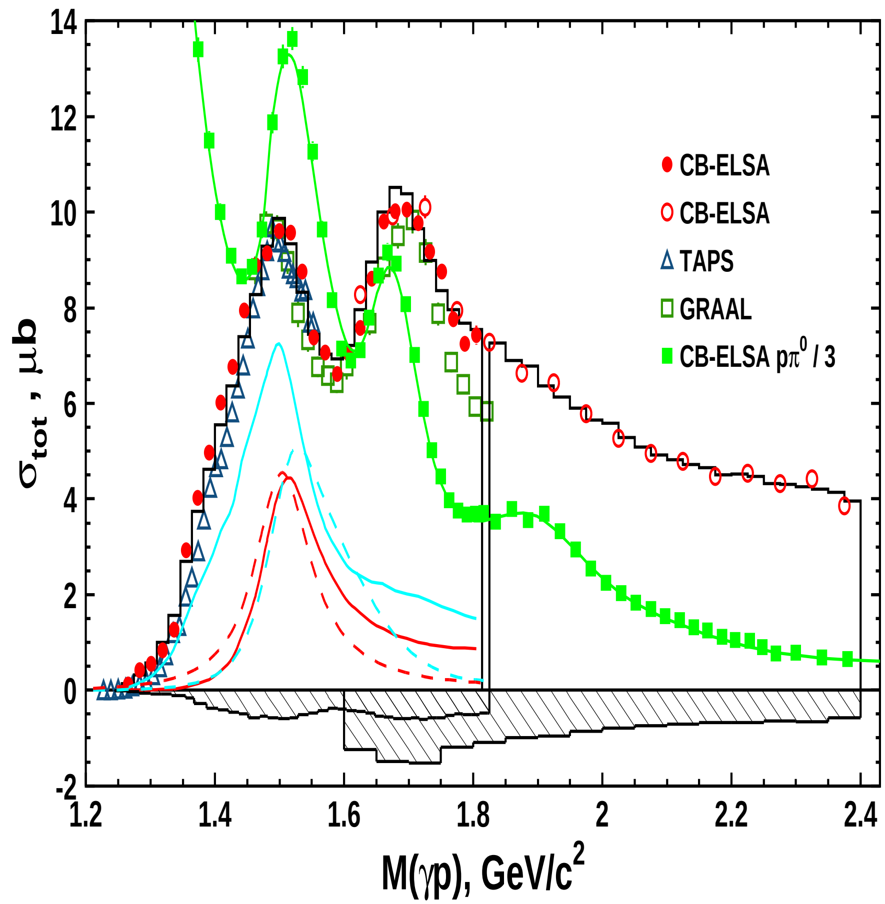
Photoproduction reactions: $\gamma p \rightarrow \pi^0 p$





$\gamma p \rightarrow p\pi^0\pi^0$ (CB-ELSA) M.Fuchs et al.





PWA corrected cross section and contributions from $\Delta(1232)\pi$ (dashed) and $N\sigma$ (dashed-dotted) final states.

Contributions from D_{33} (dotted), P_{11} (dashed) and D_{13} (dashed-dotted) partial waves.

Nucleon spectrum

$N(1440)\frac{1}{2}^+$ or $N(1440)P_{11}$

$N(1440)\frac{1}{2}^+$ pole parameters (MeV)			
$M_{\rm pole}$	1370±4	$\Gamma_{\rm pole}$	190±7
Elastic pole residue	48±3	Phase	-(78±4)°
Residue $\pi N \to N\sigma$	20±5	Phase	-(135±7)°
Residue $\pi N \to \Delta\pi$	26±3	Phase	(40±5)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.044±0.007	Phase	(142±5)°

$N(1440)\frac{1}{2}^+$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	1430±8	$\Gamma_{\rm BW}$	365±35
Br(πN)	62±3%		
Br($N\sigma$)	17±7%	Br($\Delta\pi$)	21±8%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	-0.061±0.008		

$N(1520)\frac{3}{2}^-$ or $N(1520)D_{13}$

$N(1520)\frac{3}{2}^-$ pole parameters (MeV)			
$M_{\rm pole}$	1507±3	$\Gamma_{\rm pole}$	111±5
Elastic pole residue	36±3	Phase	-(14±3)°
Residue $\pi N \to \Delta\pi_{L=0}$	18±4	Phase	(150±20)°
Residue $\pi N \to \Delta\pi_{L=2}$	14±3	Phase	(100±20)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	-0.021±0.004	Phase	(0±5)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	0.132±0.009	Phase	(2±4)°

$N(1520)\frac{3}{2}^-$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	1517±3	$\Gamma_{\rm BW}$	114±5
Br(πN)	62±3%		
Br($\Delta\pi_{L=0}$)	19±4%	Br($\Delta\pi_{L=2}$)	9±2%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	-0.022±0.004	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.131±0.010

Nucleon spectrum

$\boldsymbol{N(1535)\frac{1}{2}^-}$ or $N(1535)S_{11}$

$N(1535)\frac{1}{2}^-$ pole parameters (MeV)			
$M_{\rm pole}$	1501±4	$\Gamma_{\rm pole}$	134±11
Elastic pole residue	31±4	Phase	-(29±5)°
Residue $\pi N \to N\eta$	29±4	Phase	-(76±5)°
Residue $\pi N \to \Delta\pi$	8±3	Phase	(145±17)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.116±0.010	Phase	(7±6)°

$N(1535)\frac{1}{2}^-$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	1519±5	$\Gamma_{\rm BW}$	128±14
Br(πN)	54±5%		
Br($N\eta$)	33±5%	Br($\Delta\pi$)	2.5±1.5%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.105±0.010		

$\boldsymbol{N(1650)\frac{1}{2}^-}$ or $N(1650)S_{11}$

$N(1650)\frac{1}{2}^-$ pole parameters (MeV)			
$M_{\rm pole}$	1647±6	$\Gamma_{\rm pole}$	103±8
Elastic pole residue	24±3	Phase	-(75±12)°
Residue $\pi N \to N\eta$	15±2	Phase	(134±10)°
Residue $\pi N \to \Lambda K$	11±3	Phase	(85±9)°
Residue $\pi N \to \Delta\pi$	12±3	Phase	-(30±20)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.033±0.007	Phase	-(9±15)°

$N(1650)\frac{1}{2}^-$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	1651±6	$\Gamma_{\rm BW}$	104±10
Br($N\pi$)	51±4%	Br($N\eta$)	18±4%
Br(ΛK)	10±5%	Br($\Delta\pi$)	19±6%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.033±0.007		

Nucleon spectrum

$N(1675)\frac{5}{2}^-$ or $N(1675)D_{15}$

$N(1675)\frac{5}{2}^-$ pole parameters (MeV)			
M_{pole}	1654±4	Γ_{pole}	151±5
Elastic pole residue	28±1	Phase	-(26±4)°
Residue $\pi N \to \Delta\pi$	25±5	Phase	(82±10)°
Residue $\pi N \to N\sigma$	11±4	Phase	(132±18)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.024±0.003	Phase	-(16±5)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	0.026±0.008	Phase	-(19±6)°

$N(1675)\frac{5}{2}^-$ Breit-Wigner parameters (MeV)			
M_{BW}	1664±5	Γ_{BW}	152±7
Br($N\pi$)	40±3%		
Br($\Delta\pi$)	33±8%	Br($N\sigma$)	7±3%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.024±0.003	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.025±0.007

$N(1680)\frac{5}{2}^+$ or $N(1680)F_{15}$

$N(1680)\frac{5}{2}^+$ pole parameters (MeV)			
M_{pole}	1676±6	Γ_{pole}	113±4
Elastic pole residue	43±4	Phase	-(2±10)°
Residue $\pi N \to \Delta\pi_{L=1}$	8±3	Phase	-(70±45)°
Residue $\pi N \to \Delta\pi_{L=3}$	13±3	Phase	(85±15)°
Residue $\pi N \to N\sigma$	14±3	Phase	-(56±15)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	-0.013±0.004	Phase	-(25±22)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	0.134±0.005	Phase	-(2±4)°

$N(1680)\frac{5}{2}^+$ Breit-Wigner parameters (MeV)			
M_{BW}	1689±6	Γ_{BW}	118±6
Br($N\pi$)	64±5%	Br($N\sigma$)	14±7%
Br($\Delta\pi_{L=1}$)	10±3%	Br($\Delta\pi_{L=3}$)	5±3%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	-0.013±0.003	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.135±0.006

Nucleon spectrum

$\boldsymbol{N(1700)\frac{3}{2}^-}$ or $N(1700)D_{13}$

$N(1700)\frac{3}{2}^-$ pole parameters (MeV)			
M_{pole}	1770±40	Γ_{pole}	420±180
Elastic pole residue	50±40	Phase	-(100±40)°
Residue $\pi N \to \Delta\pi_{L=0}$	75±50	Phase	-(60±40)°
Residue $\pi N \to \Delta\pi_{L=2}$	18±12	Phase	(90±35)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.044±0.020	Phase	(85±45)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	-0.037±0.012	Phase	(0±30)°

$N(1700)\frac{3}{2}^-$ Breit-Wigner parameters (MeV)			
M_{BW}	1790±40	Γ_{BW}	390±140
Br(πN)	12±5%		
Br($\Delta\pi_{L=0}$)	72±16%	Br($\Delta\pi_{L=2}$)	5±4%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.041±0.017	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	-0.034±0.013

$\boldsymbol{N(1710)\frac{1}{2}^+}$ or $N(1710)P_{11}$

$N(1710)\frac{1}{2}^+$ pole parameters (MeV)			
M_{pole}	1687±17	Γ_{pole}	200±25
Elastic pole residue	6±4	Phase	(120±70)°
Residue $\pi N \to N\eta$	11±4	Phase	(0±45)°
Residue $\pi N \to \Lambda K$	17±7	Phase	-(110±20)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.055±0.018	Phase	-(10±65)°

$N(1710)\frac{1}{2}^+$ Breit-Wigner parameters (MeV)			
M_{BW}	1710±20	Γ_{BW}	200±18
Br($N\pi$)	5±4%	Br($N\eta$)	17±10%
Br(ΛK)	23±7%		
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.052±0.015		

Confirmed, but ambiguous

Confirmed

Nucleon spectrum

$N(1720)\frac{3}{2}^+$ or $N(1720)P_{13}$

$N(1720)\frac{3}{2}^+$ pole parameters (MeV)			
$M_{\rm pole}$	1660±30	$\Gamma_{\rm pole}$	450±100
Elastic pole residue	22±8	Phase	-(115±30)°
Residue $\pi N \to N\eta$	7±5	Phase	not defined
Residue $\pi N \to \Lambda K$	14±10	Phase	-(150±45)°
Residue $\pi N \to \Delta\pi_{L=1}$	64±25	Phase	(80±40)°
Residue $\pi N \to \Delta\pi_{L=3}$	8±8	Phase	not defined
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.110±0.045	Phase	(0±40)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	0.150±0.035	Phase	(65±35)°

$N(1720)\frac{3}{2}^+$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	1690^{+70}_{-35}	$\Gamma_{\rm BW}$	420±100
Br($N\pi$)	10±5%	Br($N\eta$)	3±2%
Br($\Delta\pi_{L=1}$)	75±15%	Br($\Delta\pi_{L=3}$)	2±2%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.110±0.045	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.150±0.030

$N(1860)\frac{5}{2}^+$ or $N(1860)F_{15}$

$N(1860)\frac{5}{2}^+$ pole parameters (MeV)			
$M_{\rm pole}$	1830^{+120}_{-60}	$\Gamma_{\rm pole}$	250^{+150}_{-50}
Elastic pole residue	50±20	Phase	-(80±40)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.020±0.012	Phase	(120±50)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	0.050±0.020	Phase	-(80±60)°

$N(1860)\frac{5}{2}^+$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	1860^{+120}_{-60}	$\Gamma_{\rm BW}$	270^{+140}_{-50}
Br($N\pi$)	20±6%		
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	-0.019±0.011	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.048±0.018

Needs confirmation

Nucleon spectrum

$N(1875)\frac{3}{2}^-$ or $N(1875)D_{13}$

$N(1875)\frac{3}{2}^-$ pole parameters (MeV)			
M_{pole}	1860±25	Γ_{pole}	200±20
Elastic pole residue	2.5±1.0	Phase	not defined
Residue $\pi N \to \Lambda K$	1.5±1.0	Phase	not defined
Residue $\pi N \to \Sigma K$	5±3	Phase	not defined
Residue $\pi N \to N\sigma$	8±3	Phase	-(170±65)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.018±0.008	Phase	-(100±60)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	0.010±0.004	Phase	(180±30)°

$N(1875)\frac{3}{2}^-$ Breit-Wigner parameters (MeV)			
M_{BW}	1880±20	Γ_{BW}	200±25
Br($N\pi$)	3±2%	Br($N\eta$)	5±2%
Br(ΛK)	4±2%	Br(ΣK)	15±8%
Br($\Delta\pi$)	20±12%	Br($N\sigma$)	60±12%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.018±0.010	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	-0.009±0.005

$N(1880)\frac{1}{2}^+$ or $N(1880)P_{11}$

$N(1880)\frac{1}{2}^+$ pole parameters (MeV)			
M_{pole}	1860±35	Γ_{pole}	250±70
Elastic pole residue	6±4	Phase	(80±65)°
Residue $\pi N \to \eta N$	13±8	Phase	-(75±55)°
Residue $\pi N \to K\Lambda$	4±3	Phase	(40±40)°
Residue $\pi N \to K\Sigma$	13±7	Phase	(95±40)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.014±0.004 $^{(01)}$	Phase	-(130±60)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.036±0.012 $^{(02)}$	Phase	(15±20)°

$N(1880)\frac{1}{2}^+$ Breit-Wigner parameters (MeV)			
M_{BW}	1870±35	Γ_{BW}	235±65
Br(πN)	5±3%	Br(ηN)	25^{+30}_{-20}%
Br($K\Lambda$)	2±1%	Br($K\Sigma$)	17±7%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)			-0.013±0.003 $^{(01)}$
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)			0.034±0.011 $^{(02)}$

Observed by BG group (needs confirmation)

Nucleon spectrum

$\boldsymbol{N(1895)\frac{1}{2}^-}$ or $N(1895)S_{11}$

$N(1895)\frac{1}{2}^-$ pole parameters (MeV)			
$M_{\rm pole}$	1900±15	$\Gamma_{\rm pole}$	90^{+30}_{-15}
Elastic pole residue	1±1	Phase	not defined
Residue $\pi N \to \eta N$	3±2	Phase	(40±20)°
Residue $\pi N \to K\Lambda$	2±1	Phase	-(90±30)°
Residue $\pi N \to K\Sigma$	3±2	Phase	(40±30)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.012±0.006	Phase	(120±50)°
$N(1895)\frac{1}{2}^-$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	1895±15	$\Gamma_{\rm BW}$	90^{+30}_{-15}
Br(πN)	2±1%	Br(ηN)	21±9%
Br($K\Lambda$)	18±5%	Br($K\Sigma$)	13±7%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	-0.011±0.006		

Observed by BG (needs confirmation)

$\boldsymbol{N(1900)\frac{3}{2}^+}$ or $N(1900)P_{13}$

$N(1900)\frac{3}{2}^+$ pole parameters (MeV)			
$M_{\rm pole}$	1900±30	$\Gamma_{\rm pole}$	260^{+100}_{-60}
Elastic pole residue	3±2	Phase	(10±35)°
Residue $\pi N \to \eta N$	6±3	Phase	(70±60)°
Residue $\pi N \to K\Lambda$	9±5	Phase	(135±25)°
Residue $\pi N \to K\Sigma$	5±3	Phase	(110±30)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.026±0.015	Phase	(60±40)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	0.060±0.030	Phase	(185±60)°
$N(1900)\frac{3}{2}^+$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	1905±30	$\Gamma_{\rm BW}$	250^{+120}_{-50}
Br(πN)	3±2%	Br(ηN)	10±4%
Br($K\Lambda$)	16±5%	Br($K\Sigma$)	5±2%
Br($\Delta\pi_{L=1}$)	38±10%	Br($\Delta\pi_{L=3}$)	11±10%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.026±0.015	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	-0.065±0.030

Observed by BG (Confirmed)

Nucleon spectrum

$N(1990)\frac{7}{2}^+$ or $N(1990)F_{17}$

$N(1990)\frac{7}{2}^+$ pole parameters (MeV)			
$M_{\rm pole}$	2030±65	$\Gamma_{\rm pole}$	240±60
Elastic pole residue	2±1	Phase	(125±65)°
Residue $\pi N\to\Delta\pi_{L=3}$	8±5	Phase	(80±50)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.042±0.014	Phase	-(30±20)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	0.058±0.014	Phase	-(35±25)°

$N(1990)\frac{7}{2}^+$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	2060±65	$\Gamma_{\rm BW}$	240±50
Br(πN)	2±1%	Br($\Delta\pi_{L=3}$)	20±15%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.040±0.012	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.057±0.012

$N(2000)\frac{5}{2}^+$ or $N(2000)F_{15}$

$N(2000)\frac{5}{2}^+$ pole parameters (MeV)			
$M_{\rm pole}$	2030±110	$\Gamma_{\rm pole}$	480±100
Elastic pole residue	35^{+80}_{-15}	Phase	-(100±40)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.035±0.015	Phase	(15±40)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	0.050±0.014	Phase	-(130±40)°

$N(2000)\frac{5}{2}^+$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	2090±120	$\Gamma_{\rm BW}$	460±100
Br(πN)	9±4%	Br(ΔN)	50±20%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.032±0.014	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.048±0.014

Two solutions

Nucleon spectrum

$\boldsymbol{N(2060)\frac{5}{2}^-}$ or $N(2060)D_{15}$

$N(2060)\frac{5}{2}^-$ pole parameters (MeV)			
$M_{\rm pole}$	2040±15	$\Gamma_{\rm pole}$	390±25
Elastic pole residue	19±5	Phase	-(125±20)°
Residue $\pi N\to\eta N$	15±8	Phase	(40±25)°
Residue $\pi N\to K\Lambda$	1±0.5	Phase	not defined
Residue $\pi N\to K\Sigma$	7±4	Phase	-(70±30)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.065±0.015	Phase	(15±8)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	0.055^{+15}_{-35}	Phase	(15±10)°
$N(2060)\frac{5}{2}^-$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	2060±15	$\Gamma_{\rm BW}$	375±25
Br(πN)	8±2%	Br(ηN)	4±2%
Br($K\Sigma$)	3±2%		
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.067±0.015	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.055±0.020

$\boldsymbol{N(2150)\frac{3}{2}^-}$ or $N(2150)D_{13}$

$N(2150)\frac{3}{2}^-$ pole parameters (MeV)			
$M_{\rm pole}$	2110±50	$\Gamma_{\rm pole}$	340±45
Elastic pole residue	13±3	Phase	-(20±10)°
Residue $\pi N\to K\Lambda$	5±2	Phase	(100±30)°
Residue $\pi N\to K\Sigma$	3±2	Phase	-(50±40)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.125±0.045	Phase	-(55±20)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	0.150±0.060	Phase	-(35±15)°
$N(2150)\frac{3}{2}^-$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	2150±60	$\Gamma_{\rm BW}$	330±45
Br(πN)	6±2%	Br($\Delta\pi$)	60±20%
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.130±0.045	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.150±0.055

Observed by BG (Confirmed)

Observed by BG (needs confirmation)

Baryon spectrum

$N(2190)\frac{7}{2}^-$ or $N(2190)G_{17}$

$N(2190)\frac{7}{2}^-$ pole parameters (MeV)			
$M_{\rm pole}$	2150±25	$\Gamma_{\rm pole}$	330±30
Elastic pole residue	30±5	Phase	(30±10)°
Residue $\pi N \to \Delta\pi_{L=2}$	45±10	Phase	-(160±30)°
Residue $\pi N \to K\Lambda$	4.5±2	Phase	(20±15)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	0.063±0.007	Phase	-(170±15)°
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	0.035±0.020	Phase	(25±10)°
$N(2190)\frac{7}{2}^-$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	2180±20	$\Gamma_{\rm BW}$	335±40
Br(πN)	16±2%	Br($\Delta\pi_{L=2}$)	25±11%
Br($K\Lambda$)	0.5±0.3%		
$A^{1/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	-0.065±0.008	$A^{3/2}_{BW}$ (GeV$^{-\frac{1}{2}}$)	0.035±0.017

$N(2250)\frac{9}{2}^-$ or $N(2250)G_{19}$

$N(2250)\frac{9}{2}^-$ pole parameters (MeV)			
$M_{\rm pole}$	2195±45	$\Gamma_{\rm pole}$	470±50
Elastic pole residue	26±5	Phase	-(38±25)°
$A^{1/2}$ (GeV$^{-\frac{1}{2}}$)	< 0.010	Phase	not defined
$A^{3/2}$ (GeV$^{-\frac{1}{2}}$)	< 0.010	Phase	not defined
$N(2250)\frac{9}{2}^-$ Breit-Wigner parameters (MeV)			
$M_{\rm BW}$	2280±40	$\Gamma_{\rm BW}$	520±50
Br(πN)	12±4%		
$\lvert A^{1/2}_{BW}\rvert$ (GeV$^{-\frac{1}{2}}$)< 0.010		$\lvert A^{3/2}_{BW}\rvert$ (GeV$^{-\frac{1}{2}}$)< 0.010	

Holographic QCD (AdS/QCD)

L, S, N	κ_{gd}	Resonance					Pred.
0,$\frac{1}{2}$,0	$\frac{1}{2}$	$N(940)$				input:	0.94
0,$\frac{3}{2}$,0	0	$\Delta(1232)$					1.27
0,$\frac{1}{2}$,1	$\frac{1}{2}$	$N(1440)$					1.40
1,$\frac{1}{2}$,0	$\frac{1}{4}$	$N(1535)$	$N(1520)$				1.53
1,$\frac{3}{2}$,0	0	$N(1650)$	$N(1700)$	$N(1675)$			1.64
1,$\frac{1}{2}$,0	0	$\Delta(1620)$	$\Delta(1700)$		L, S, N=0,$\frac{3}{2}$,1:	$\Delta(1600)$	1.64
2,$\frac{1}{2}$,0	$\frac{1}{2}$	$N(1720)$	$N(1680)$		L, S, N=0,$\frac{1}{2}$,2:	$N(1710)$	1.72
1,$\frac{1}{2}$,1	$\frac{1}{4}$	$N(1890)$	$N(1880)$				1.82
1,$\frac{3}{2}$,1	0	$\Delta(1900)$	$\Delta(1940)$	$\Delta(1930)$			1.92
2,$\frac{3}{2}$,0	0	$\Delta(1910)$	$\Delta(1920)$	$\Delta(1905)$	$\Delta(1950)$		1.92
2,$\frac{3}{2}$,0	0	$N(1875)$	$N(1900)$	$N(1880)$	$N(1980)$		1.92
0,$\frac{1}{2}$,3	$\frac{1}{2}$	$N(????)$					2.03
3,$\frac{1}{2}$,0	$\frac{1}{4}$	$N(2075)$	$N(2185)$	L, S, N=1,$\frac{1}{2}$,2:	$N(????)$	$N(????)$	2.12
3,$\frac{3}{2}$,0	0	$N(2200)$	$N(2250)$	L, S, N=1,$\frac{1}{2}$,2:	$\Delta(2223)$	$\Delta(2200)$	2.20
4,$\frac{1}{2}$,0	$\frac{1}{2}$	$N(2220)$					2.27
4,$\frac{3}{2}$,0	0	$\Delta(2390)$	$\Delta(2300)$	$\Delta(2420)$	L, N=3,1:	$\Delta(2400)$ $\Delta(2350)$	2.43
5,$\frac{1}{2}$,0	$\frac{1}{4}$	$N(2600)$					2.57

Parity doublets of N and Δ resonances at high mass region

Parity doublets must not interact by pion emission

and could have a small coupling to πN.

$J=\frac{1}{2}$	$N_{1/2+}(1880)$	*	$N_{1/2-}(1890)$	*	$\Delta_{1/2+}(1910)$	****	$\Delta_{1/2-}(1900)^a$	**
$J=\frac{3}{2}$	$N_{3/2+}(1900)$	**	$N_{3/2-}(1875)$	**	$\Delta_{3/2+}(1940)^a$	***	$\Delta_{3/2-}(1990)^a$	*
$J=\frac{5}{2}$	$N_{5/2+}(1880)$	**	$N_{5/2-}(2070)$		$\Delta_{5/2+}(1940)$	****	$\Delta_{5/2-}(1930)^a$	***
$J=\frac{7}{2}$	$N_{7/2+}(1980)$	**	$N_{7/2-}(2170)$	****	$\Delta_{7/2+}(1920)$	****	$\Delta_{7/2-}(2200)$	*
$J=\frac{9}{2}$	$N_{9/2+}(2220)$	****	$N_{9/2-}(2250)$	****	$\Delta_{9/2+}(2300)$	**	$\Delta_{9/2-}(2400)^a$	**

$J=\frac{5}{2}$	$N_{5/2+}(2100)$	**	$N_{5/2-}(2070)$		$\Delta_{5/2+}(1940)$	****	$\Delta_{5/2-}(1930)^a$	***
$J=\frac{7}{2}$	$N_{7/2+}(2100)$	**	$N_{7/2-}(2160)$	****	$\Delta_{7/2+}(1920)$	****	$\Delta_{7/2-}(2200)$	*
$J=\frac{9}{2}$	$N_{9/2+}(2220)$	****	$N_{9/2-}(2250)$	****	$\Delta_{9/2+}(2300)$	**	$\Delta_{9/2-}(2400)^a$	**

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.**
- **The low spin states in this mass region fit very well the AdS/QCD prediction as well as with the idea about chiral restoration at high energies.**
- **New, high precision data on πN collision (especially into ηN and $\pi^+\pi^- N$ final) can confirm and probably discover new baryon states.**
- **Analysis of NN collision can supply an information about baryons with week photo and πN couplings.**

The analysis of PNPI data on meson production in pp and np collisions (maximum likelihood approach)

n	Reaction	p_{beam}	N_{data}	Origin
1	$pp \to \pi^0 pp$	1683 MeV/c	1094	Gatchina
2	$pp \to \pi^0 pp$	1581 MeV/c	903	Gatchina
3	$pp \to \pi^0 pp$	1536 MeV/c	1319	Gatchina
4	$pp \to \pi^0 pp$	1485 MeV/c	997	Gatchina
5	$pp \to \pi^0 pp$	1437 MeV/c	918	Gatchina
6	$pp \to \pi^0 pp$	1389 MeV/c	996	Gatchina
7	$pp \to \pi^0 pp$	1341 MeV/c	883	Gatchina
8	$pp \to \pi^0 pp$	1279 MeV/c	621	Gatchina
9	$pp \to \pi^0 pp$	1217 MeV/c	544	Gatchina
10	$np \to \pi^- pp$	1-1.9 GeV/c	8210	Gatchina
11	$pp \to \pi^0 pp$	950 MeV/c	154972	Tübingen
13	$pp \to \pi^0 pp$	σ_{tot} 1217-1683 MeV	9	Gatchina

Parameterization

$$d\sigma = \frac{(2\pi)^4|A|^2}{4|\vec{k}|\sqrt{s}}\, d\Phi_3(P, q_1, q_2, q_3)\ ,$$

$$A = \sum_\alpha A^\alpha_{tr}(s) Q^{in}_{\mu_1\ldots\mu_J}(SLJ) A_{2b}(i, S_2L_2J_2)(s_i) Q^{fin}_{\mu_1\ldots\mu_J}(i, S_2L_2J_2S'L'J)\ .$$

Angular-spin momentum operators $Q_{\mu_1\ldots\mu_J}(SLJ)$ are given in

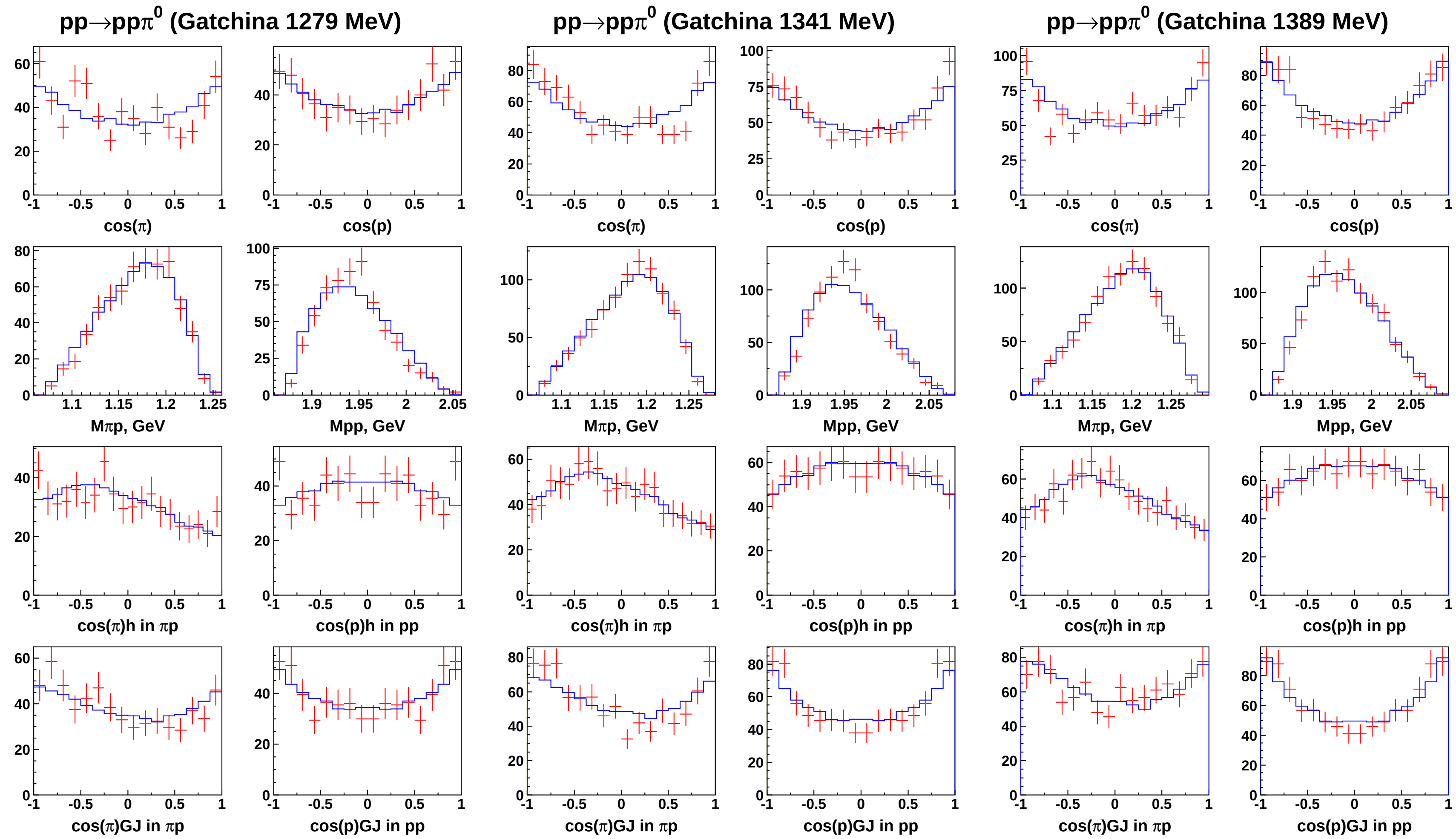
A. V. Anisovich et. al Eur.Phys.J. A34 (2007) 129.

$$A^\alpha_{tr}(s) = \frac{a^\alpha_1 + a^\alpha_3\sqrt{s}}{s - a^\alpha_4}\, e^{ia^\alpha_2}\,,$$

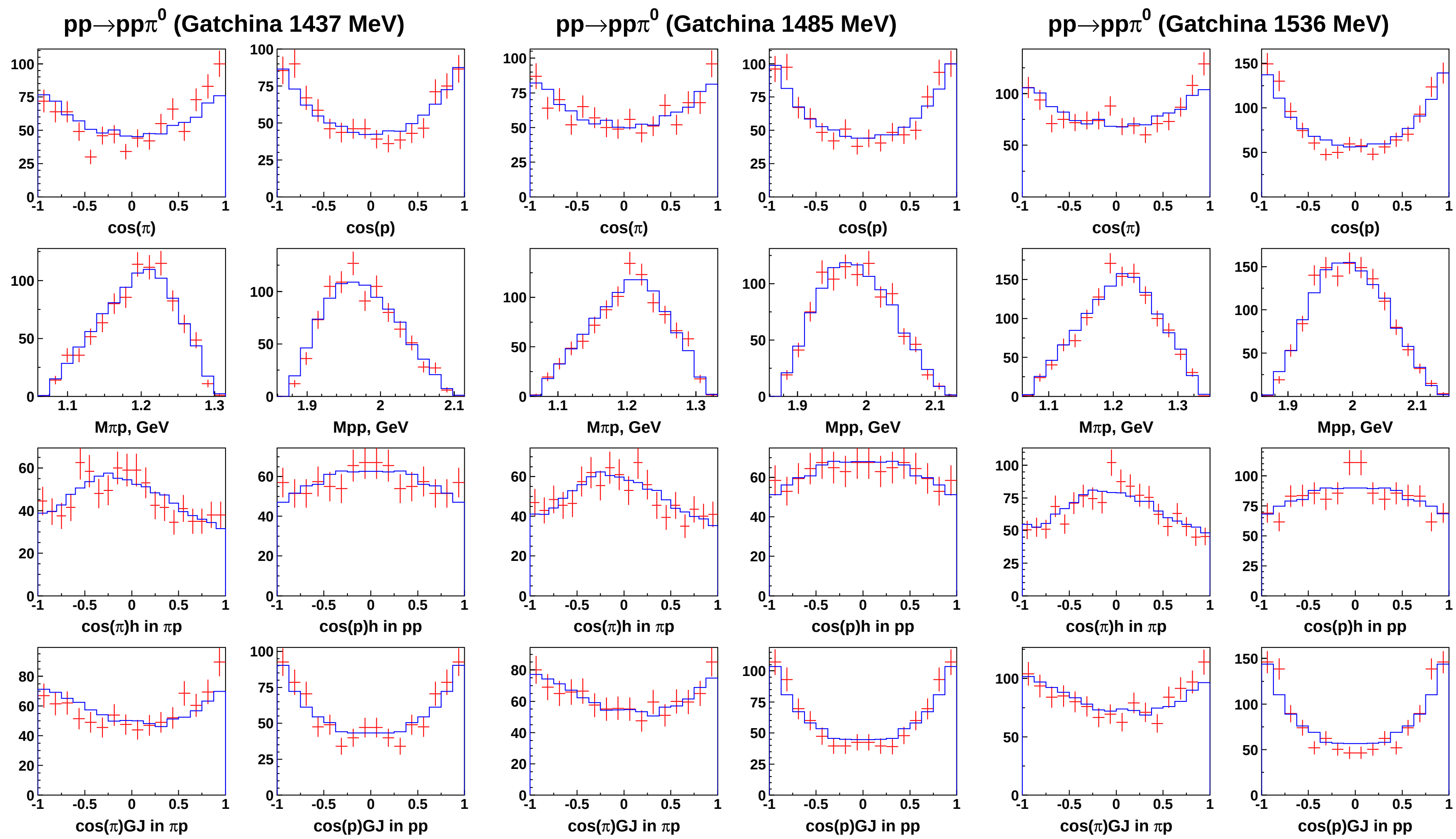
Decay modes: $\Delta(1232)N$, $P_{11}(1440)N$ and $\pi(NN)$. In NN channel amplitude was parameterized with generalized Watson-Migdal formula:

$$A^\beta_{2b}(s_i) = \frac{\sqrt{s_i}}{1 - \frac{1}{2}r^\beta q^2 a^\beta_{pp} + iqa^\beta_{pp}q^{2L}/F(q, r^\beta, L)}\,,$$

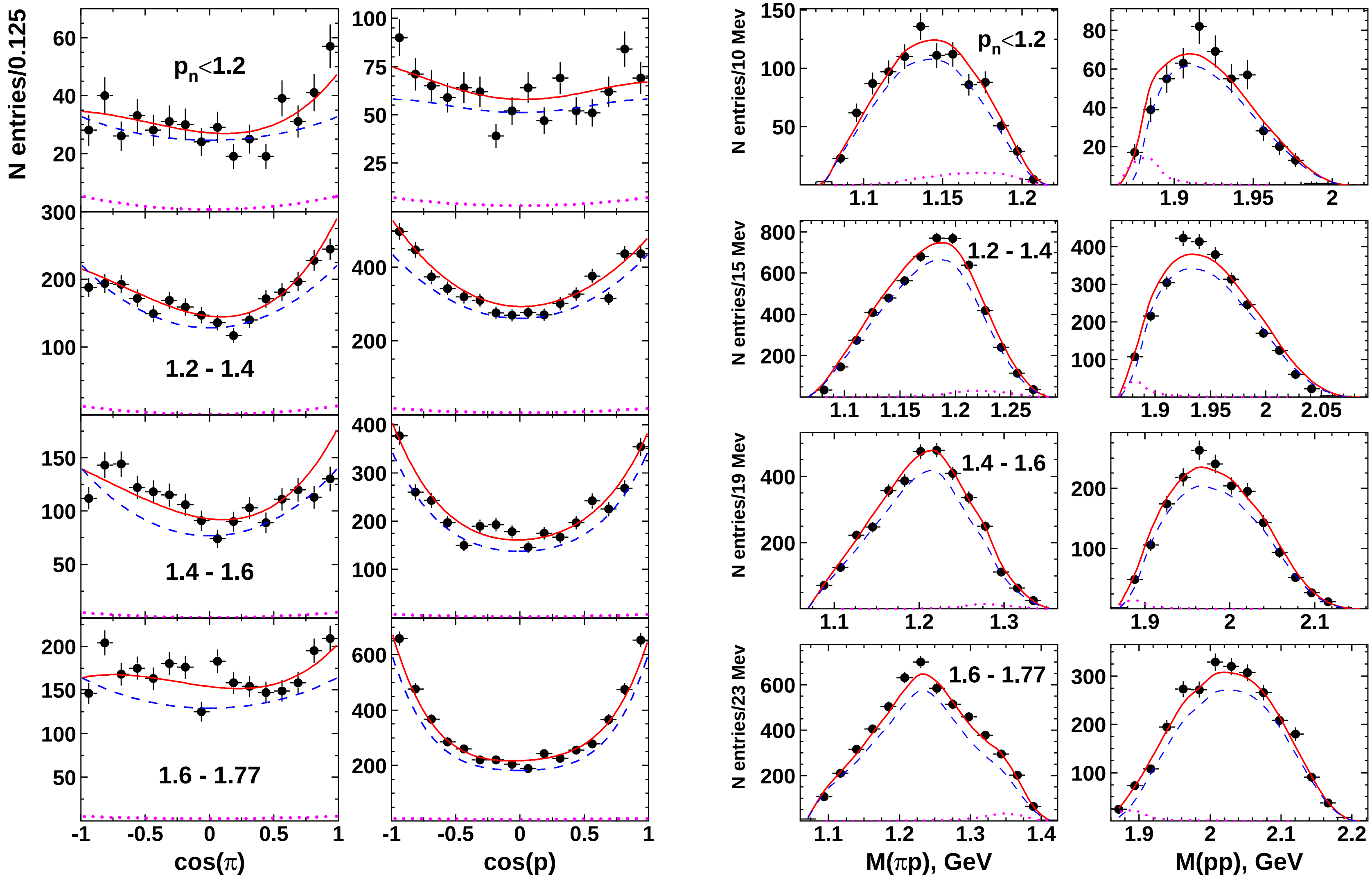
Description of $pp \to pp\pi^0$:



Description of $pp \rightarrow pp\pi^0$:



$$np \longrightarrow \pi^- pp$$

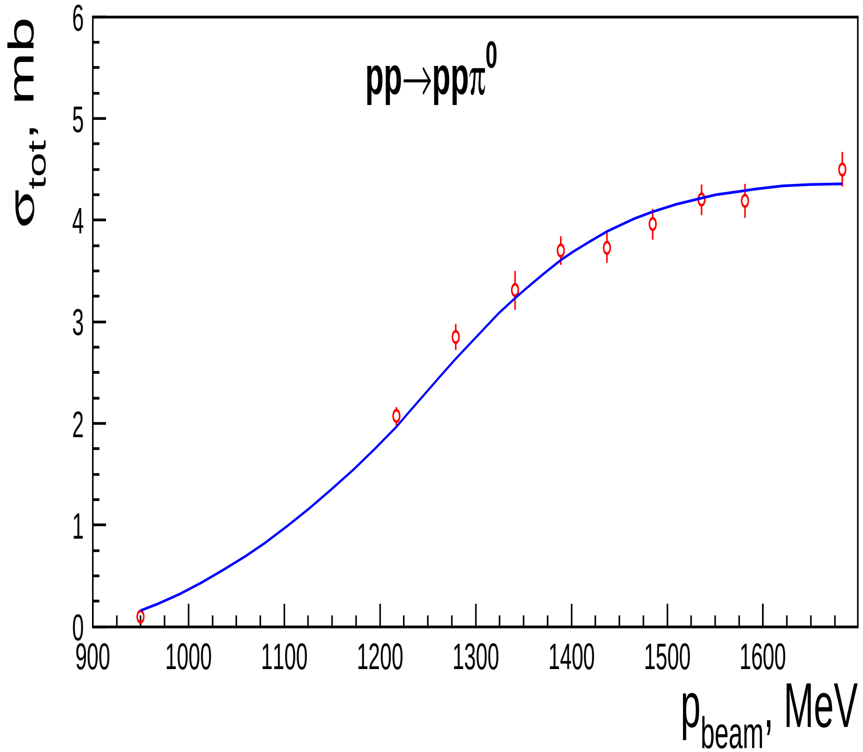


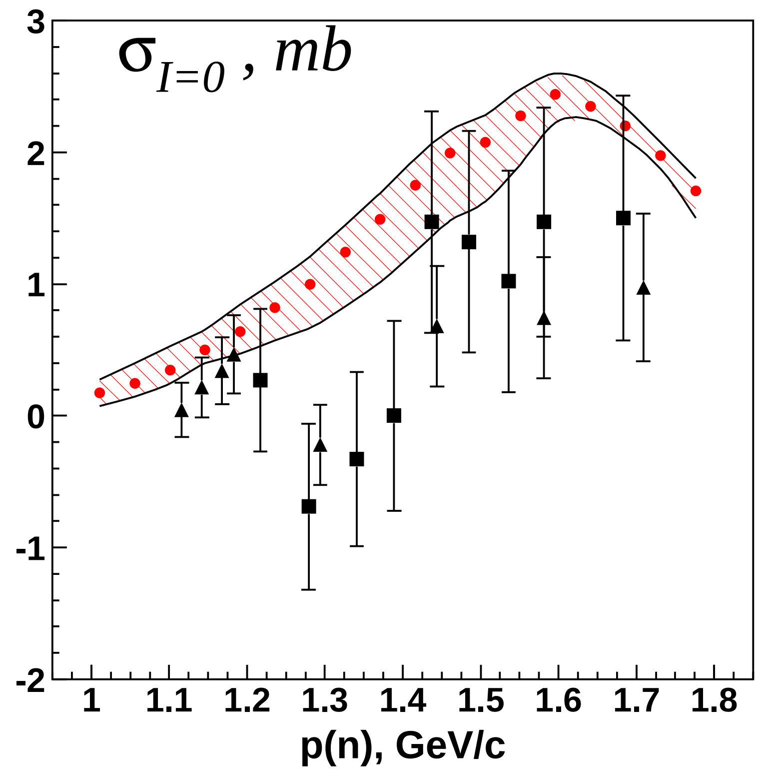
Dashed lines - $I = 1$, **dotted lines** - $I = 0$

The cross section for pion production in nucleon-nucleon collision with $I = 1$ is well known. However there are very poor data about $I = 0$ cross section.

$$\sigma(I = 0) = 3[2\sigma(np \to pp\pi^-) - \sigma(pp \to pp\pi^0)]$$

$$\sigma(I = 1) = \sigma(pp \to pp\pi^0)$$

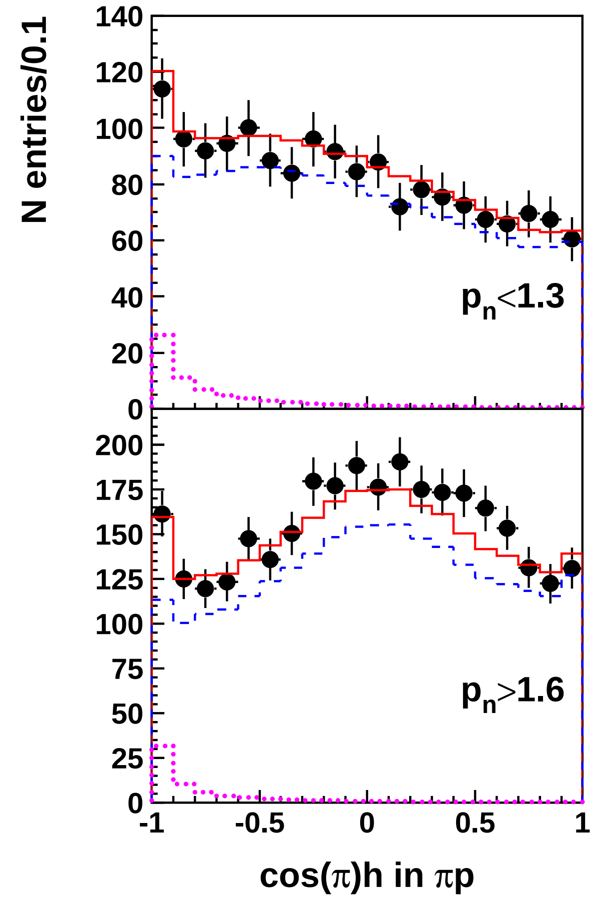




Scattering length

$$A_{2b}^{\beta}(s_i) = \frac{\sqrt{s_i}}{1 - \frac{1}{2} r^{\beta} q^2 a_{pp}^{\beta} + i q a_{pp}^{\beta} q^{2L} / F(q, r^{\beta}, L)},$$

$a_{pp}^{\beta} = -7.5 \pm 0.3$ **fm**



The isoscalar initial channel provides us a good tool for the determination of scattering length of the final pp system in the pion production reactions.