



**Bonn-Gatchina PWA results of $\pi^- p$
and $K^- p$ reactions**

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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:

$$A(s, t) = \sum_{\beta\beta'n} A_n^{\beta\beta'}(s) Q_{\mu_1 \dots \mu_n}^{(\beta)+} F_{\nu_1 \dots \nu_n}^{\mu_1 \dots \mu_n} Q_{\nu_1 \dots \nu_n}^{(\beta')}$$

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.

Minimization methods

1. The two body final states 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:

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

This method allows us to take into account all correlations in many dimensional phase space. Above **2 000 000 data events** are taken in the fit of pion- and photo-induced reactions.

Table 1: The photoproduction reactions with two pions in the final state, observables and energy ranges.

Reaction	Observable	W (GeV)	
$\gamma p \rightarrow \pi^0 \pi^0 p$	DCS, Tot	1.2 – 1.9	MAMI
$\gamma p \rightarrow \pi^0 \pi^0 p$	E	1.2 – 1.9	MAMI
$\gamma p \rightarrow \pi^0 \pi^0 p$	DCS, Tot	1.4 – 2.38	CB-ELSA
$\gamma p \rightarrow \pi^0 \pi^0 p$	P, H	1.45 – 1.65	CB-ELSA
$\gamma p \rightarrow \pi^0 \pi^0 p$	T, P_x, P_y	1.45 – 2.28	CB-ELSA
$\gamma p \rightarrow \pi^0 \pi^0 p$	P_x, P_x^c, P_x^s (4D)	1.45 – 1.8	CB-ELSA
$\gamma p \rightarrow \pi^0 \pi^0 p$	P_y, P_y^c, P_y^s (4D)	1.45 – 1.8	CB-ELSA
$\gamma p \rightarrow \pi^+ \pi^- p$	DCS	1.7 – 2.3	CLAS
$\gamma p \rightarrow \pi^+ \pi^- p$	I^c, I^s	1.74 – 2.08	CLAS

Charged data only CLAS.

Table 2: pion induced reactions in the fit

Reaction	Observable	W (GeV)	
$\pi N \rightarrow \pi N$	DCS		
$\pi^- p \rightarrow \eta n$	DCS	1.500 – 1.900	
$\pi^- p \rightarrow K^0 \Lambda$	DCS, P	1.630 – 2.300	
$\pi^- p \rightarrow K^0 \Lambda$	β	1.850 – 2.300	
$\pi^- p \rightarrow K^0 \Sigma^0$	DCS, P	1.820 – 2.160	
$\pi^+ p \rightarrow K^+ \Sigma^+$	DCS, P	1.730 – 2.160	
$\pi^- p \rightarrow K^+ \Sigma^-$	DCS	1.740 – 2.240	
$\pi^- p \rightarrow \pi^0 \pi^0 n$	DCS	1.29 – 1.55	Crystal Ball
$\pi^- p \rightarrow \pi^+ \pi^- n$	DCS	1.45 – 1.55	HADES
$\pi^- p \rightarrow \pi^0 \pi^- p$	DCS	1.45 – 1.55	HADES

CBAL data description

Graph

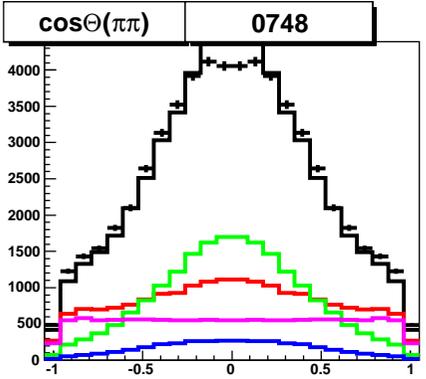
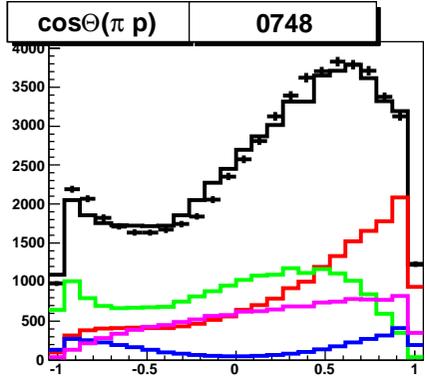
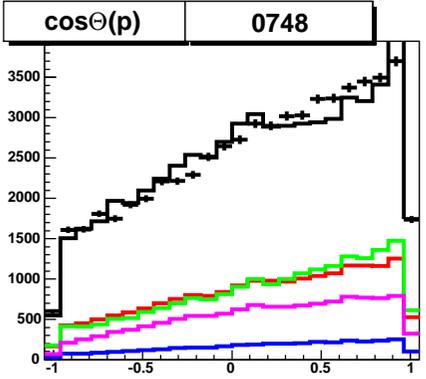
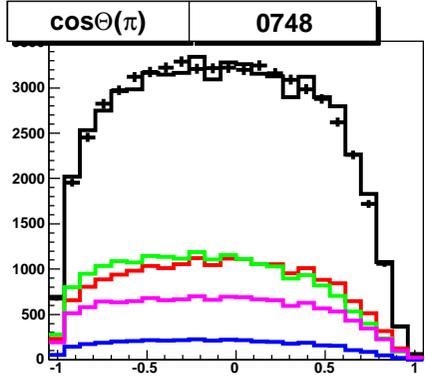
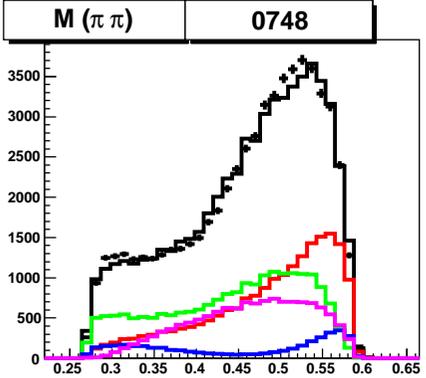
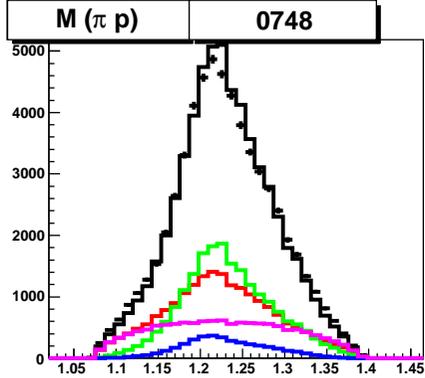
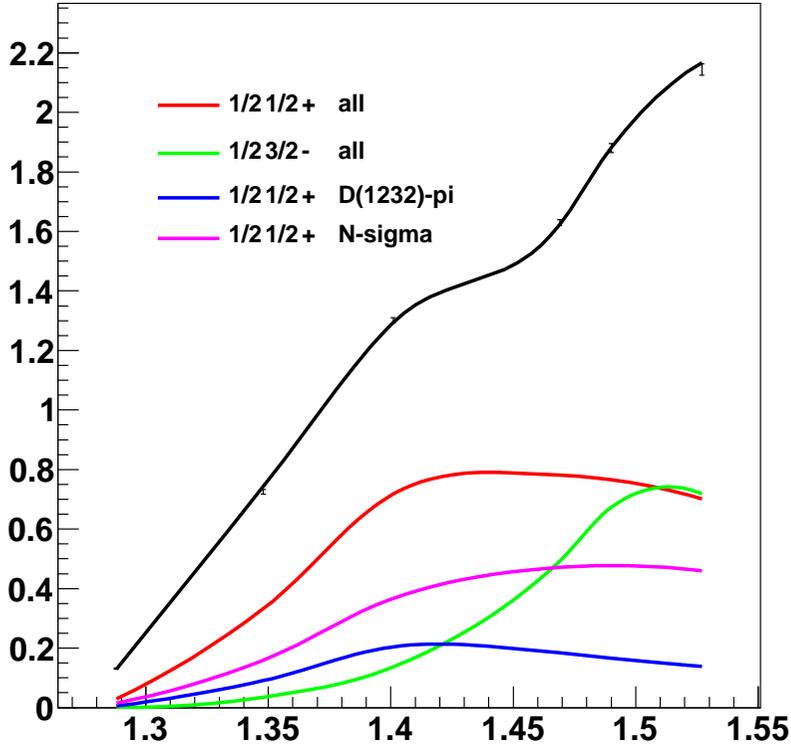
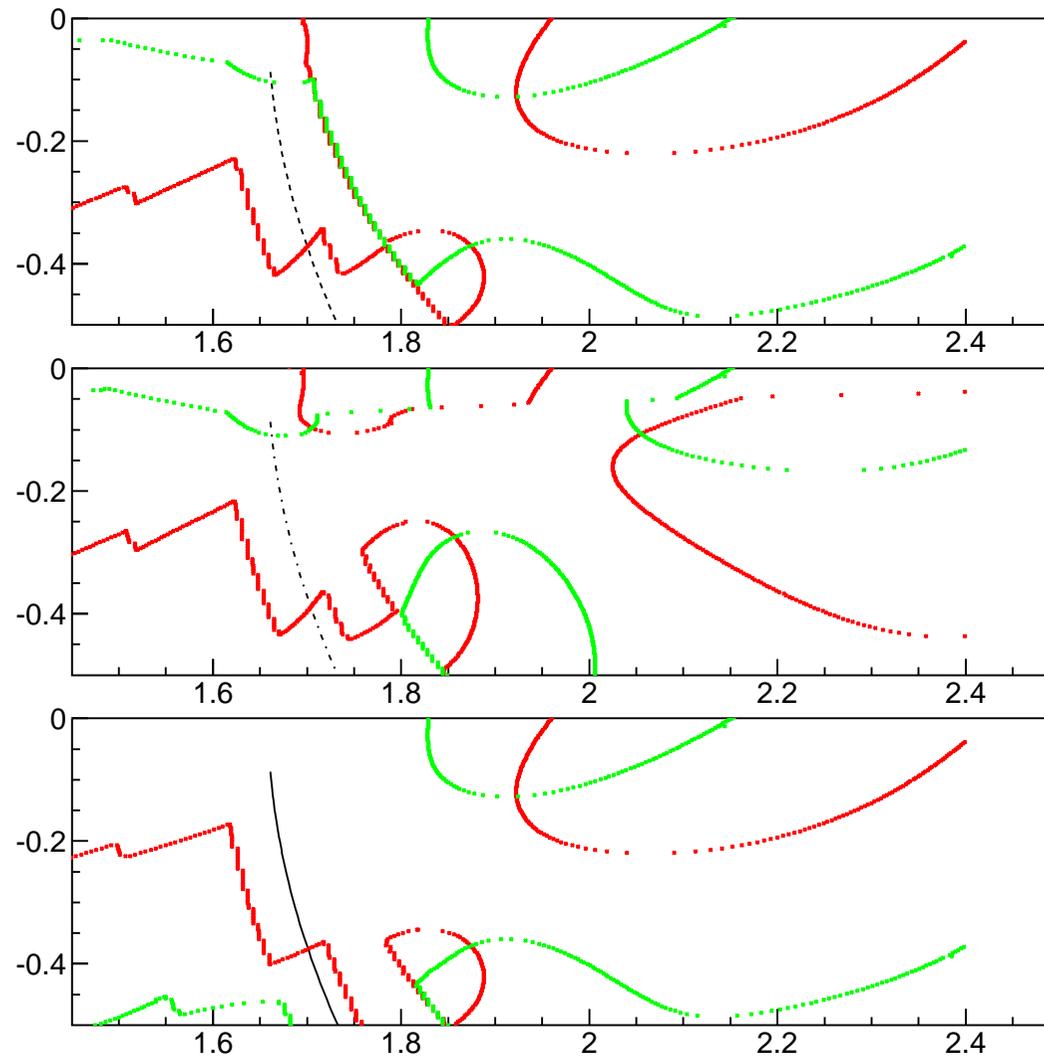


Table 3: Branching ratios for decay of the resonances into $N\rho(770)$ channel (preliminary)

$N(1440)1/2^+$	<1%	$N(1520)3/2^-$	$12\pm 2\%$
$N(1535)1/2^-$	$3\pm 1\%$	$N(1650)1/2^-$	$7\pm 2\%$
$N(1675)5/2^-$	<1%	$N(1685)5/2^+$	$12\pm 2\%$
$N(1710)1/2^+$	$9\pm 3\%$	$N(1700)3/2^-$	$45\pm 15\%$
$N(1720)3/2^+$	$60\pm 18\%$	$N(1880)1/2^+$	$30\pm 8\%$
$N(1895)1/2^-$	$55\pm 10\%$	$N(1875)3/2^-$	$60\pm 14\%$
$N(2060)5/2^-$	$12\pm 8\%$	$N(2120)3/2^-$	$50\pm 20\%$
$N(1860)5/2^+$??	$N(2000)5/2^+$	$65\pm 15\%$
$N(1900)3/2^+$	$25\pm 10\%$	$N(2190)7/2^-$	75%
$\Delta(1600)3/2^+$	5%	$\Delta(1620)1/2^-$	43%
$\Delta(1940)3/2^+$	8%	$\Delta(2200)3/2^+$	22%
$\Delta(1700)3/2^-$	44%	$\Delta(2100)3/2^-$	25%
$\Delta(1750)1/2^+$	2%	$\Delta(1900)1/2^-$	7%
$\Delta(1905)5/2^+$	47%	$\Delta(1950)7/2^+$	$6\pm 4\%$

Quark model predicts two P_{13} states at ~ 1900 MeV.

$P_{13} \rightarrow N(1520)\pi$ ($N(1520) \rightarrow \pi N$) decay mode at $W=1700 - 1900$ MeV



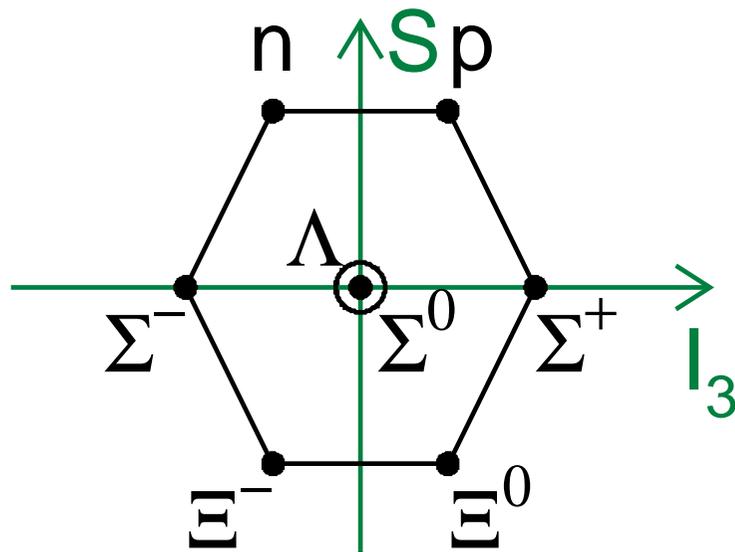
Very interesting reaction $\pi^+ p \rightarrow \pi^0 \pi^+ p$

- **Only Δ^{++} states possible, therefore no isospin mixing problem**
- **search for $\Delta(1750)1/2^+$, key state for quark model**
- **1700 – 1900 MeV**

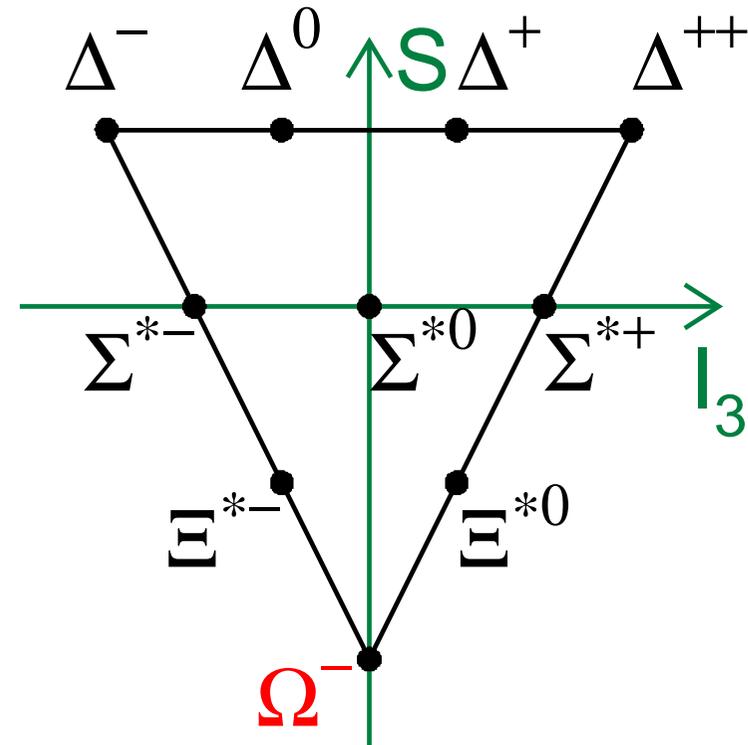
Resonance	Rating	Resonance	Rating	Resonance	Rating
N(1440)1/2 ⁺	****	N(1520)3/2 ⁻	****	N(1535)1/2 ⁻	****
N(1650)1/2 ⁻	****	N(1675)5/2 ⁻	****	N(1680)5/2 ⁺	****
N(1685)	*	N(1700)3/2 ⁻	***	N(1710)1/2 ⁺	***
N(1720)3/2 ⁺	****	N(1860)5/2 ⁺	**	N(1875)3/2 ⁻	***
N(1880)1/2 ⁺	**	N(1895)1/2 ⁻	**	N(1900)3/2 ⁺	***
N(1990)7/2 ⁺	**	N(2000)5/2 ⁺	**	N(2040)3/2 ⁺	*
N(2060)5/2 ⁻	**	N(2100)1/2 ⁺	*	N(2150)3/2 ⁻	**
N(2190)7/2 ⁻	****	N(2220)7/2 ⁻	****	N(2250)9/2 ⁻	****
N(2600)11/2 ⁻	***	N(2700)13/2 ⁺	**		
Δ (1232)	****	Δ (1600)3/2 ⁺	***	Δ (1620)1/2 ⁻	****
Δ (1700)3/2 ⁻	****	Δ (1750)1/2 ⁺	*	Δ (1900)1/2 ⁻	**
Δ (1905)5/2 ⁺	****	Δ (1910)1/2 ⁺	****	Δ (1920)3/2 ⁺	***
Δ (1930)5/2 ⁻	***	Δ (1940)3/2 ⁻	*	Δ (1950)7/2 ⁺	****
Δ (2000)5/2 ⁺	**	Δ (2150)1/2 ⁻	*	Δ (2200)7/2 ⁻	*
Δ (2300)9/2 ⁺	**	Δ (2350)3/2 ⁻	*	Δ (2390)7/2 ⁺	*

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

Octet



Decuplet



Kaon beam motivation

There is a hope to observe the baryon multiplets and therefore to confirm the states observed in the Nucleon and Delta sector.

Table 4: List of reactions used in the partial wave analysis.

$K^- p \rightarrow K^0 n$	$K^- p \rightarrow K^- p$	$K^- p \rightarrow \omega \Lambda$
$K^- p \rightarrow \pi^0 \Lambda$	$K^- p \rightarrow \eta \Lambda$	$K^- p \rightarrow \pi^+ \Sigma^-$
$K^- p \rightarrow \pi^0 \Sigma^0$	$K^- p \rightarrow \pi^- \Sigma^+$	$K^- p \rightarrow \pi^0 \pi^0 \Lambda$
$K^- p \rightarrow K^+ \Xi^-$	$K^- p \rightarrow K^0 \Xi^0$	$K^- p \rightarrow \pi^0 \pi^0 \Sigma^0$

W range is 1.57 – 1.68

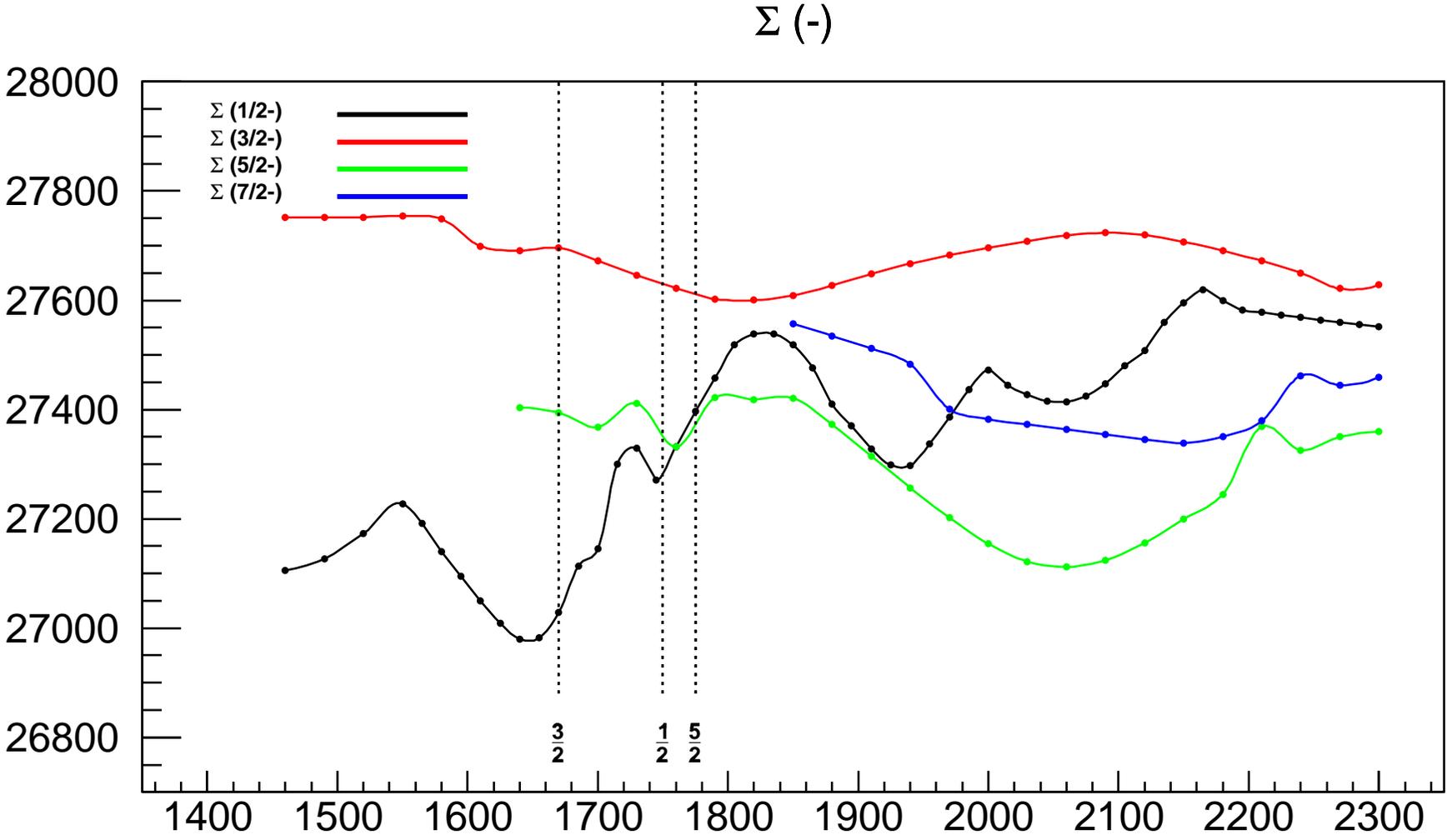
Table 5: Λ -hyperons used in the first fit of the data.

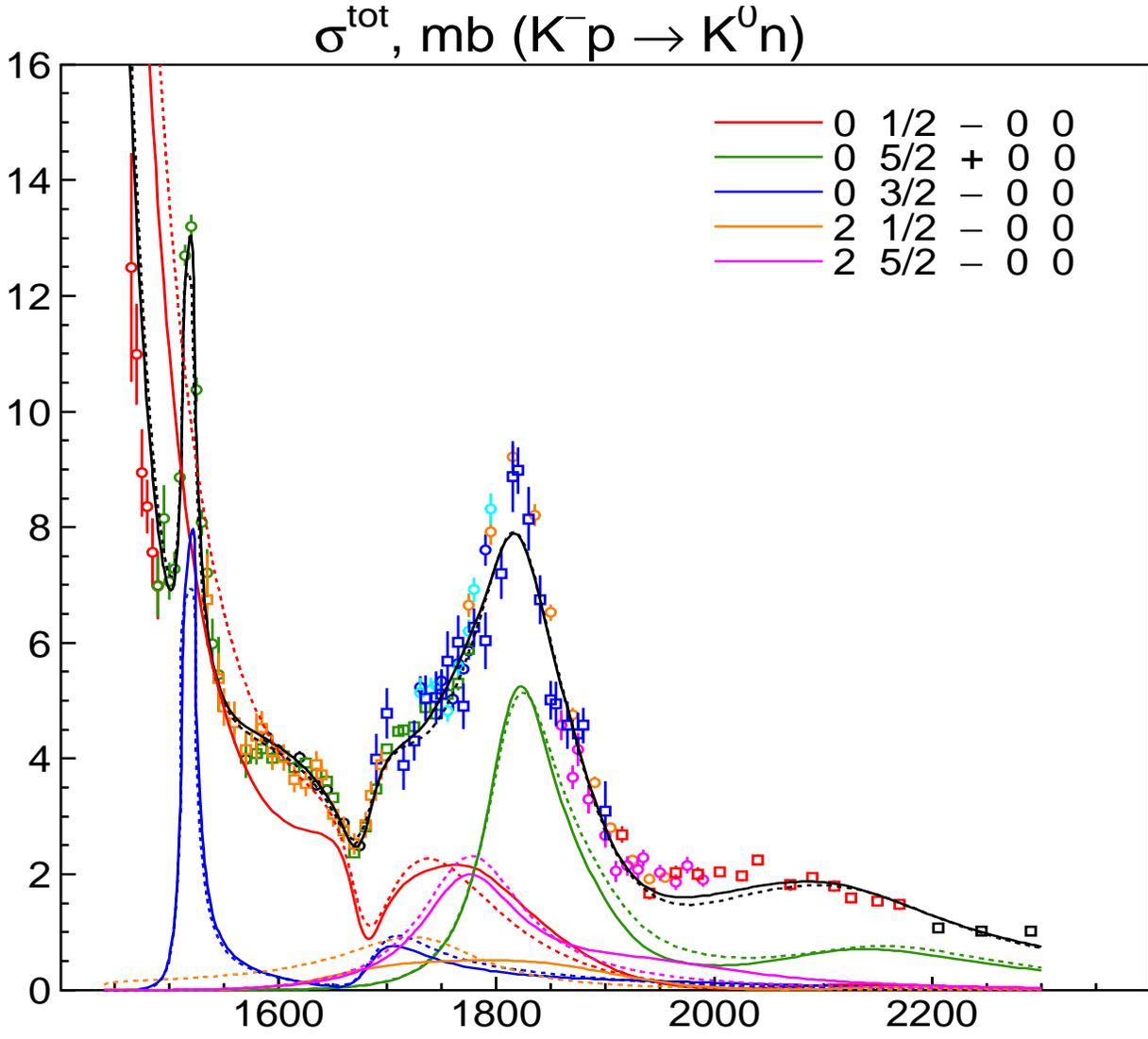
		J^P	Status	Mass	Width
singlet	$\Lambda(1405)$	$1/2^-$	****	$1405^{+1.3}_{-1.0}$	50.5 ± 2.0
$N(1535)$	$\Lambda(1670)$	$1/2^-$	****	$1660 - 1680$	$25 - 50$
$N(1650)$	$\Lambda(1800)$	$1/2^-$	***	$1720 - 1850$	$200 - 400$
singlet	$\Lambda(1520)$	$3/2^-$	****	1519.5 ± 1.0	15.6 ± 1.0
$N(1520)$	$\Lambda(1690)$	$3/2^-$	****	$1685 - 1695$	$50 - 70$
$N(1675)$	$\Lambda(1830)$	$5/2^-$	****	$1810 - 1830$	$60 - 110$
$N(2190)$	$\Lambda(2100)$	$7/2^-$	****	$2090 - 2110$	$100 - 250$
$N(1440)$	$\Lambda(1600)$	$1/2^+$	***	$1560 - 1700$	$50 - 250$
$N(1710)$	$\Lambda(1810)$	$1/2^+$	***	$1750 - 1850$	$50 - 250$
$N(1710)$	$\Lambda(1890)$	$3/2^+$	****	$1850 - 1910$	$60 - 200$
$N(1680)$	$\Lambda(1820)$	$5/2^+$	****	$1815 - 1825$	$70 - 90$
$N(2060)$	$\Lambda(2110)$	$5/2^+$	***	$2090 - 2140$	$150 - 250$

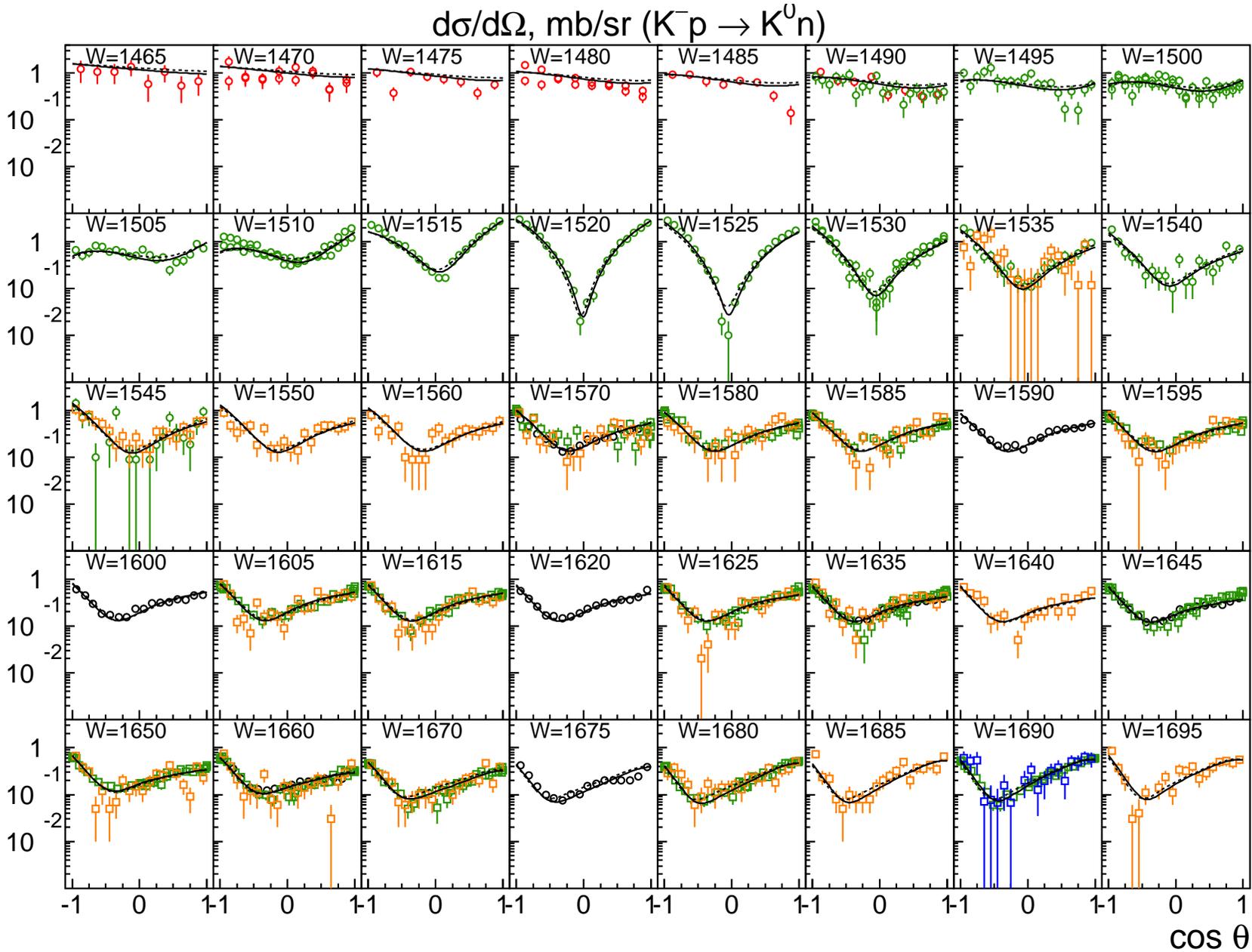
Table 6: Σ -Hyperons used in the first fit of the data.

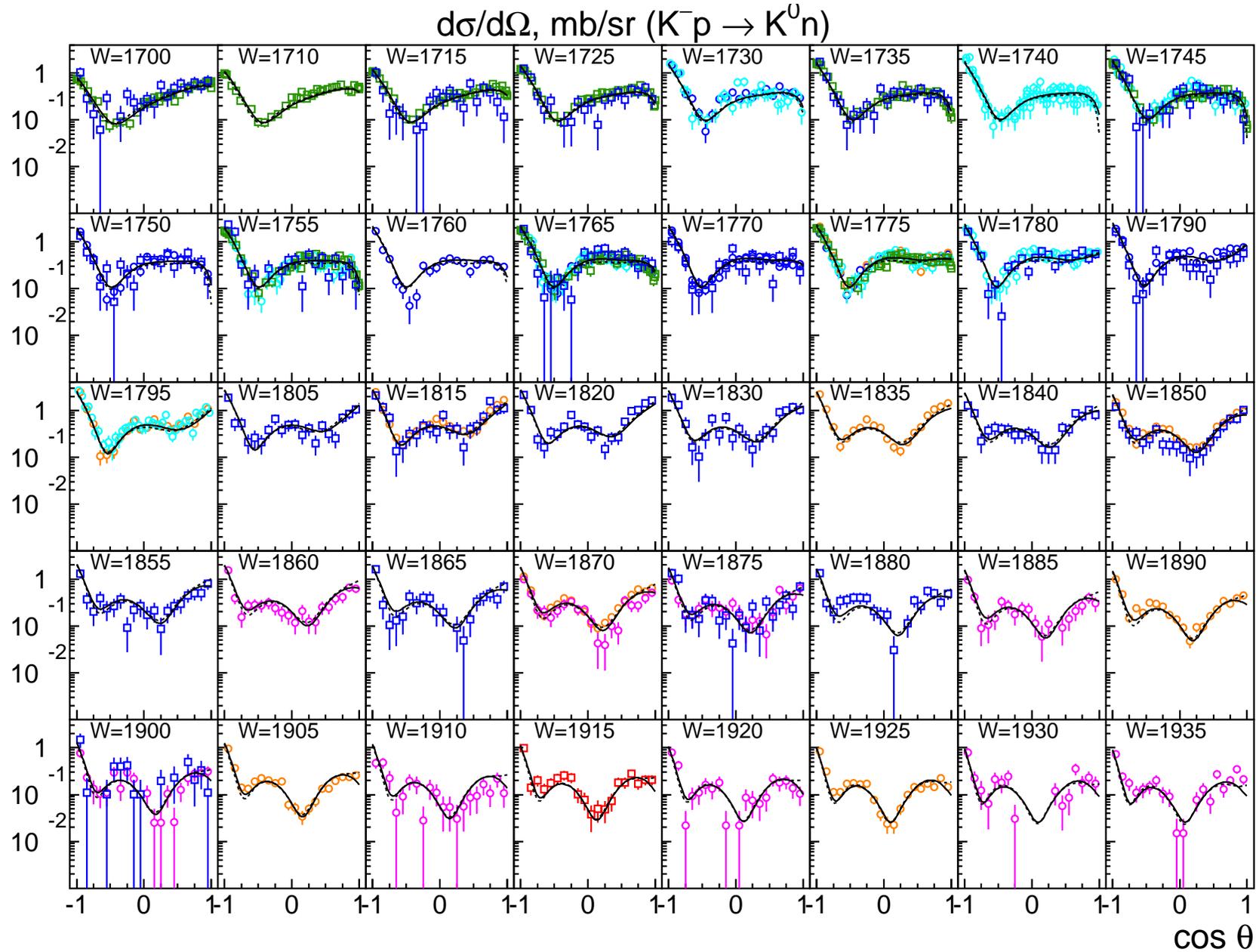
		J^P	Status	Mass	Width
$N(1440)$	$\Sigma(1660)$	$1/2^+$	***	1630 – 1690	36.0 ± 0.7
$\Delta(1230)$	$\Sigma(1385)$	$3/2^+$	****	1382.80 ± 0.35	40 – 200
$N(1680), \Delta(1905)$	$\Sigma(1915)$	$5/2^+$	****	1900 – 1935	80 – 160
$N(1990), \Delta(1950)$	$\Sigma(2030)$	$7/2^+$	****	2025 – 2040	150 – 200
$N(1520)$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

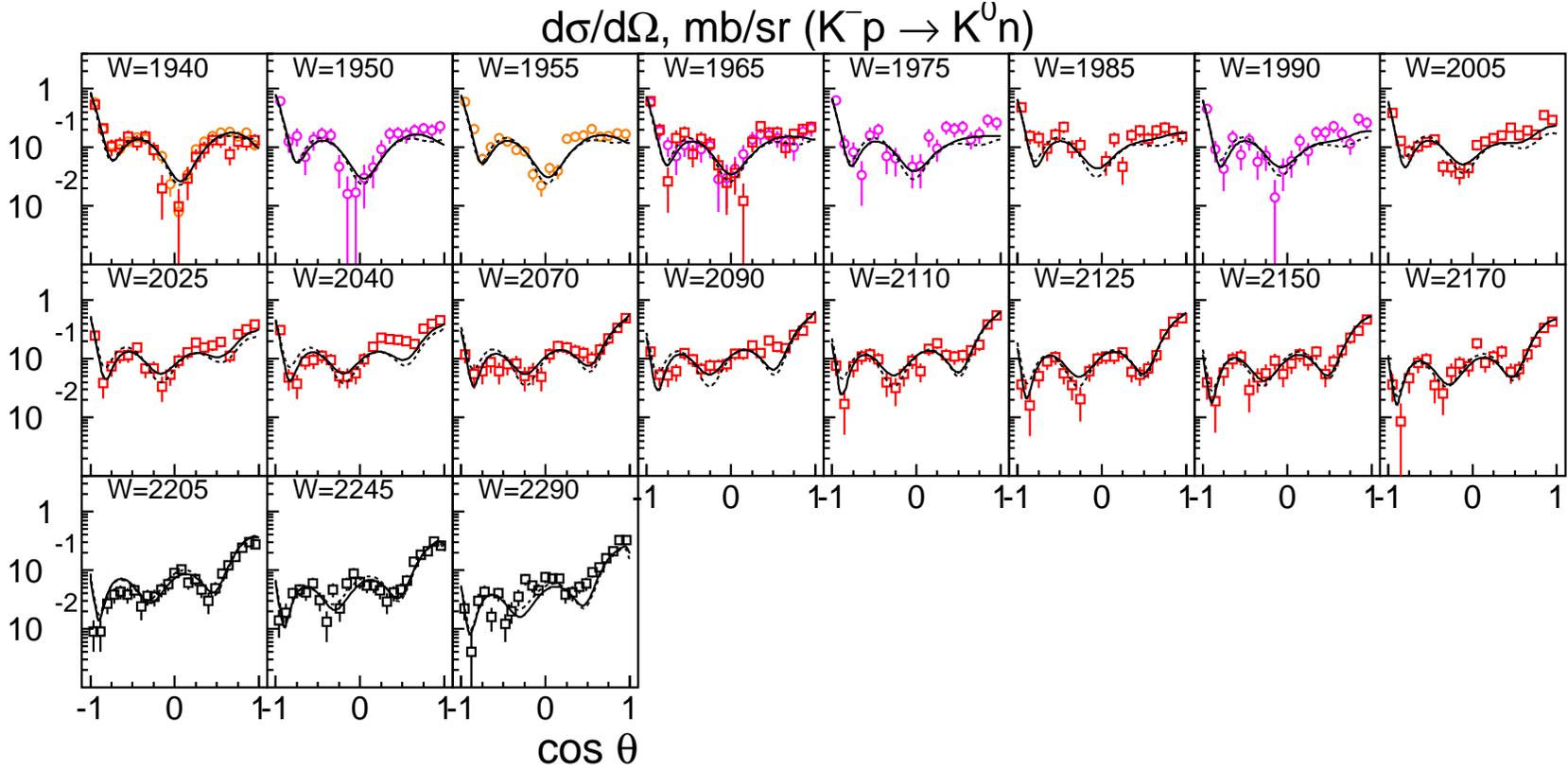
Many Σ states are missing.

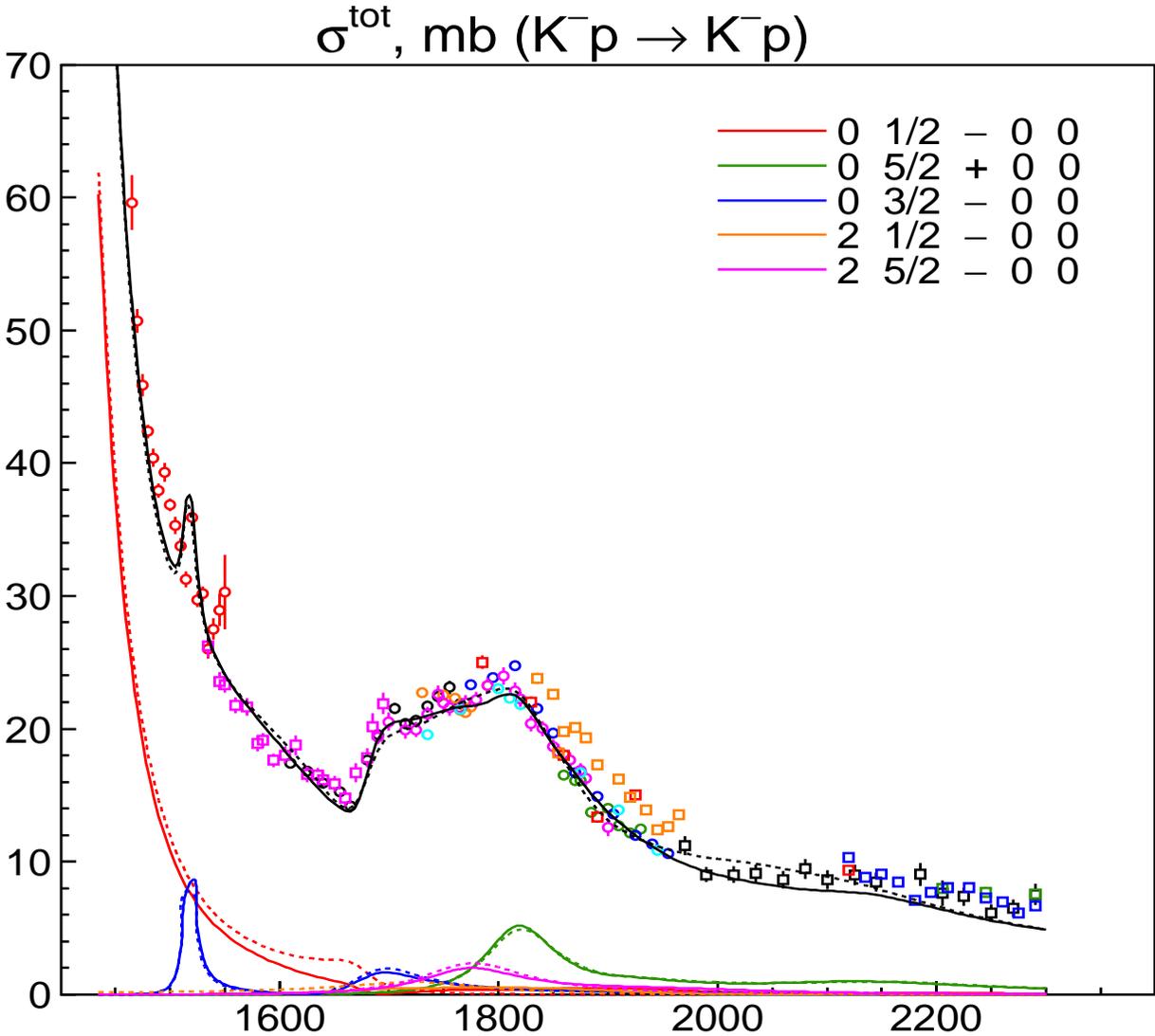


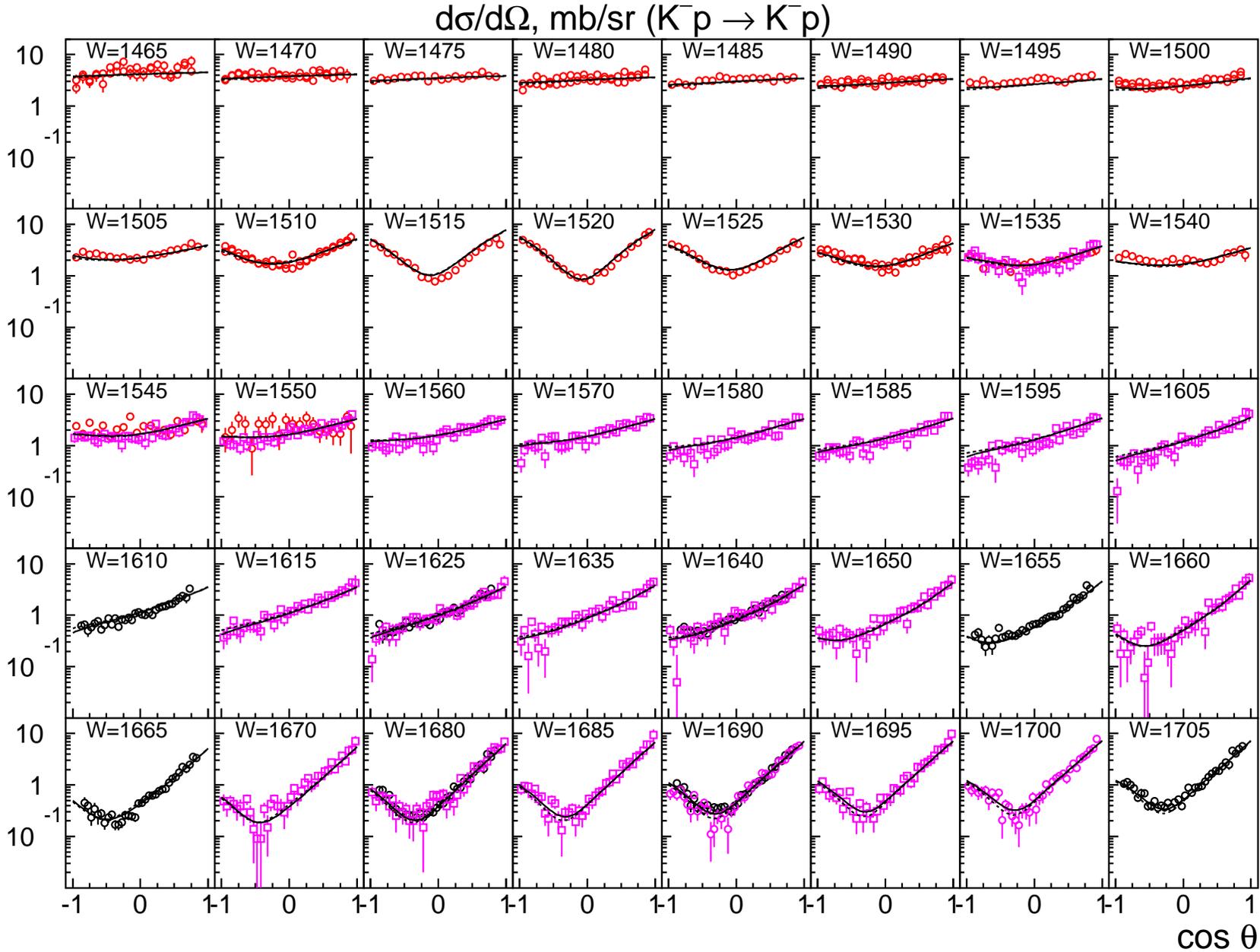


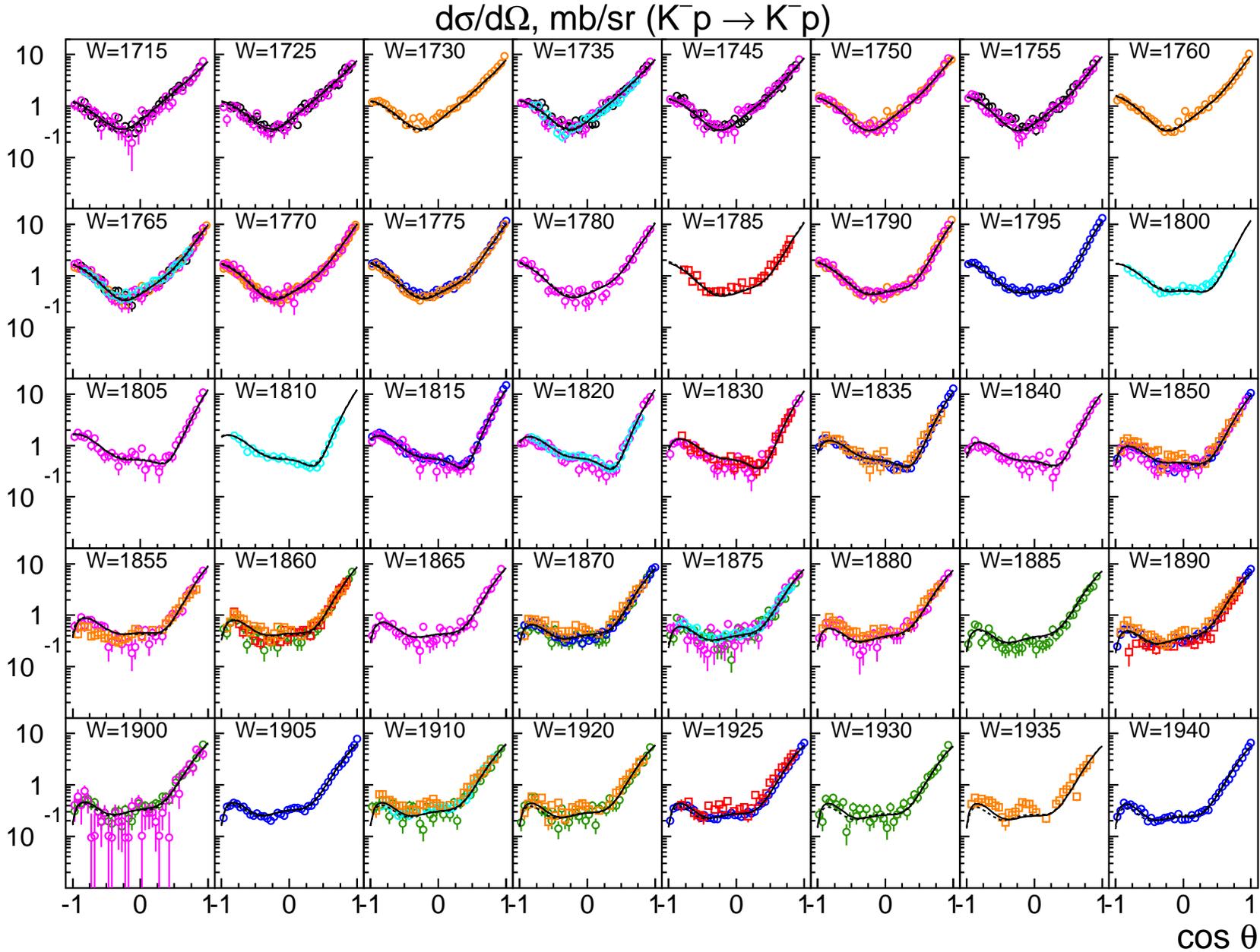


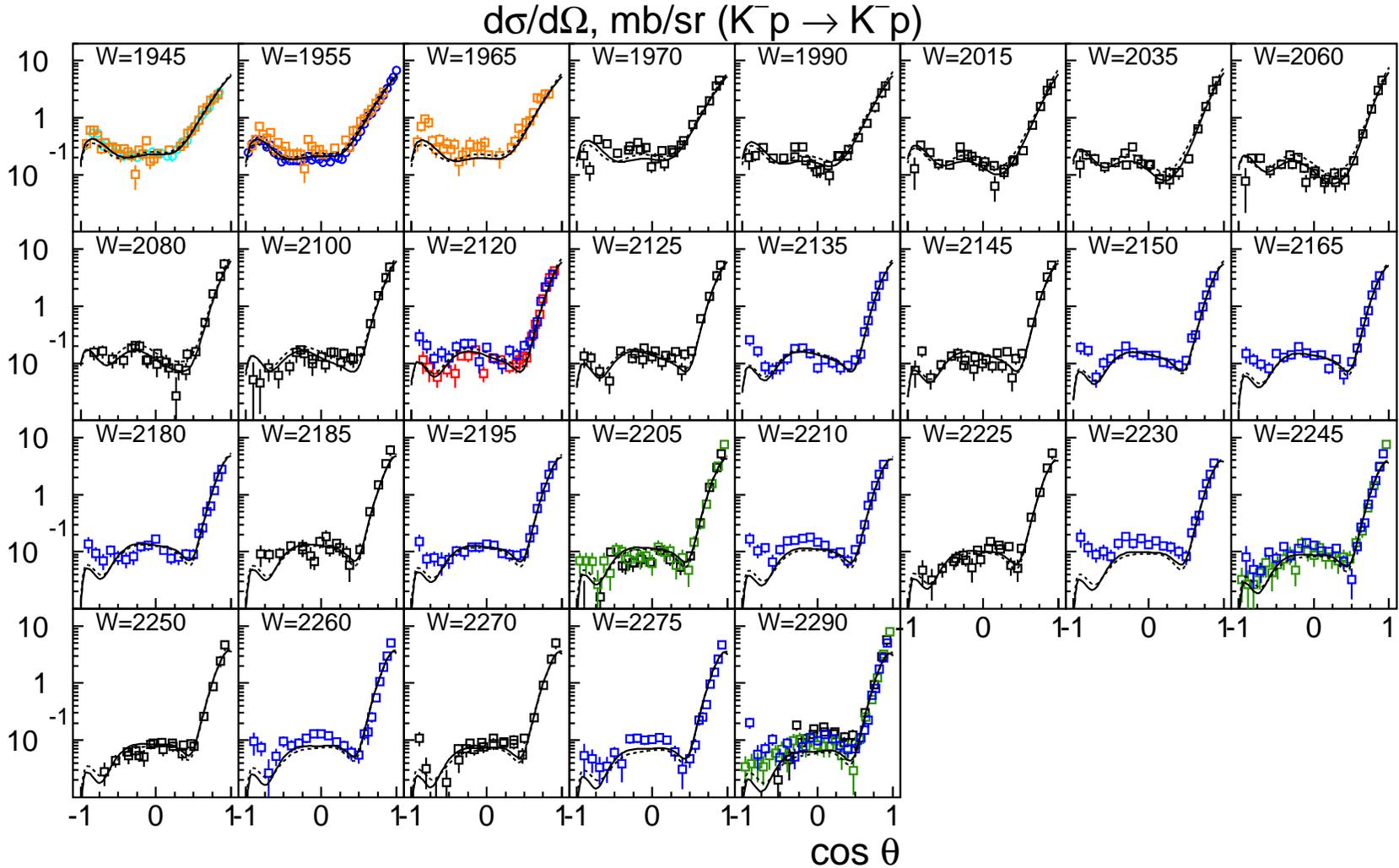


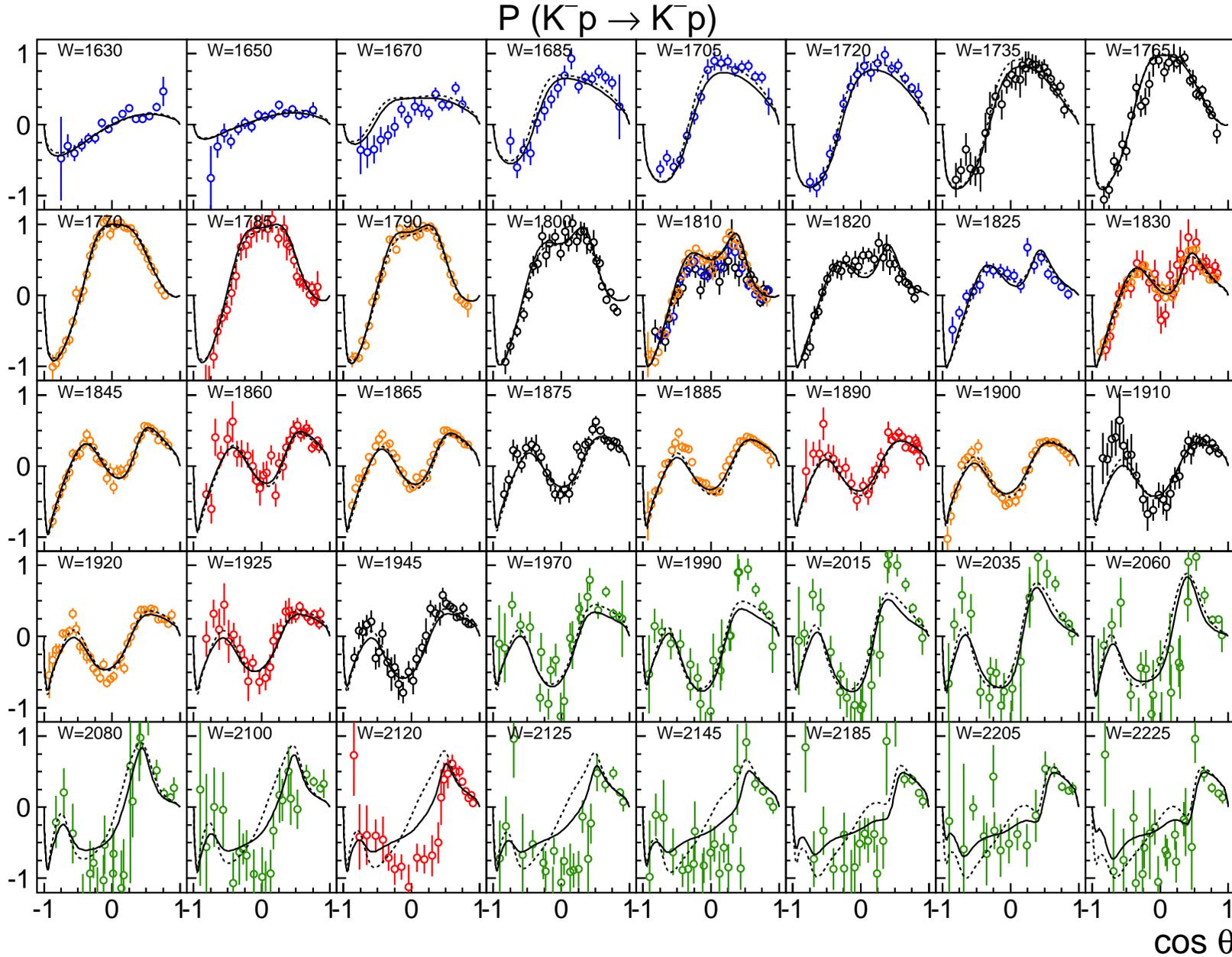


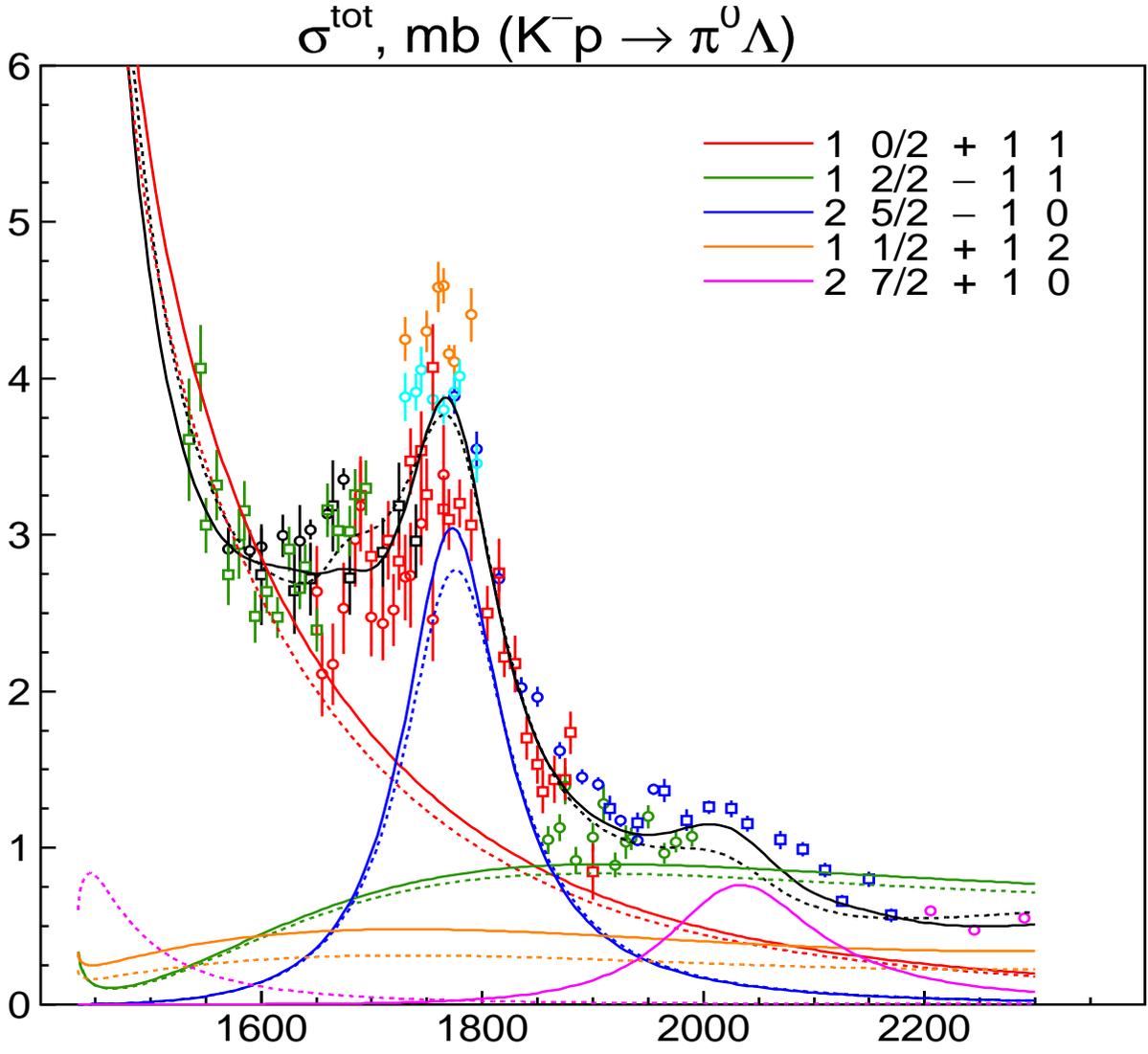


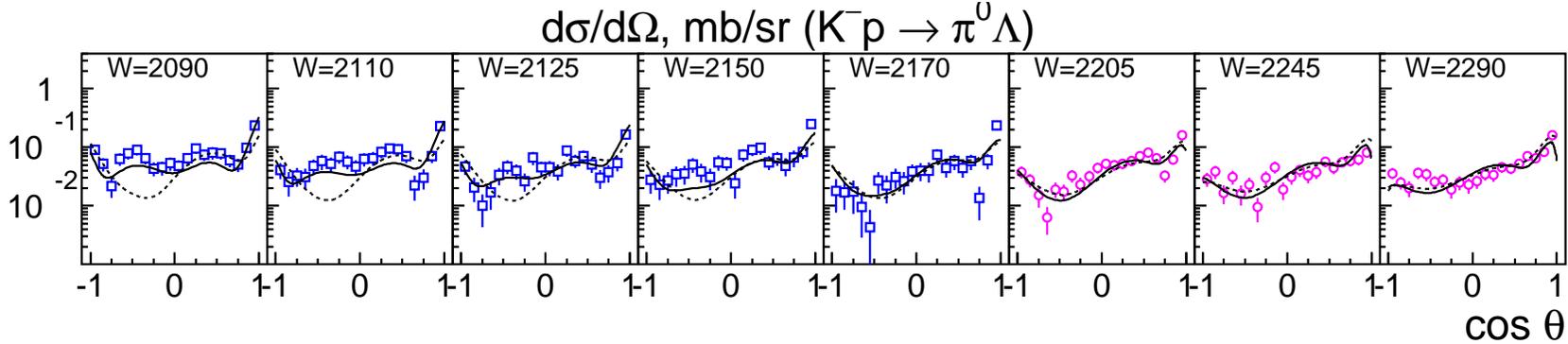


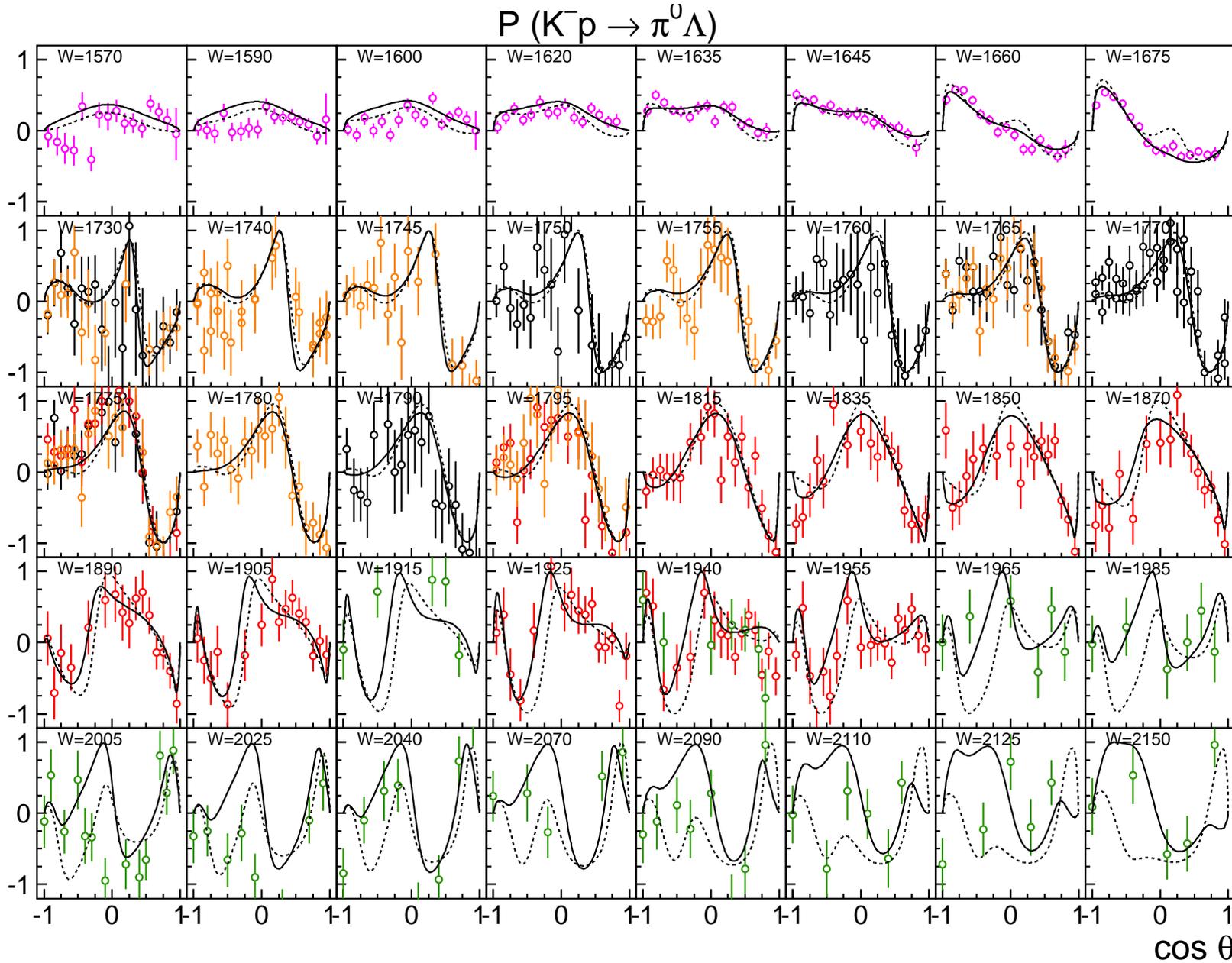


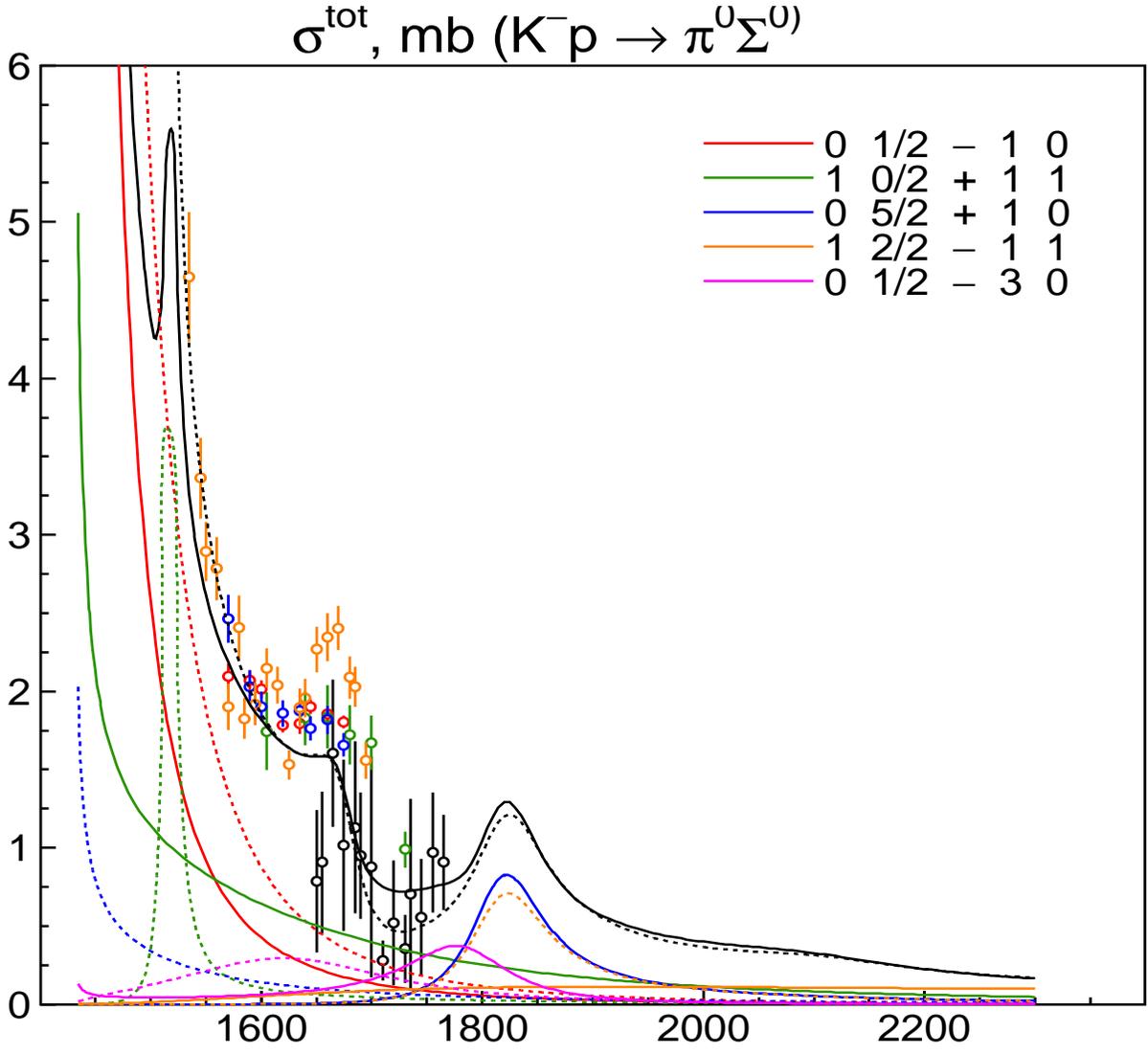


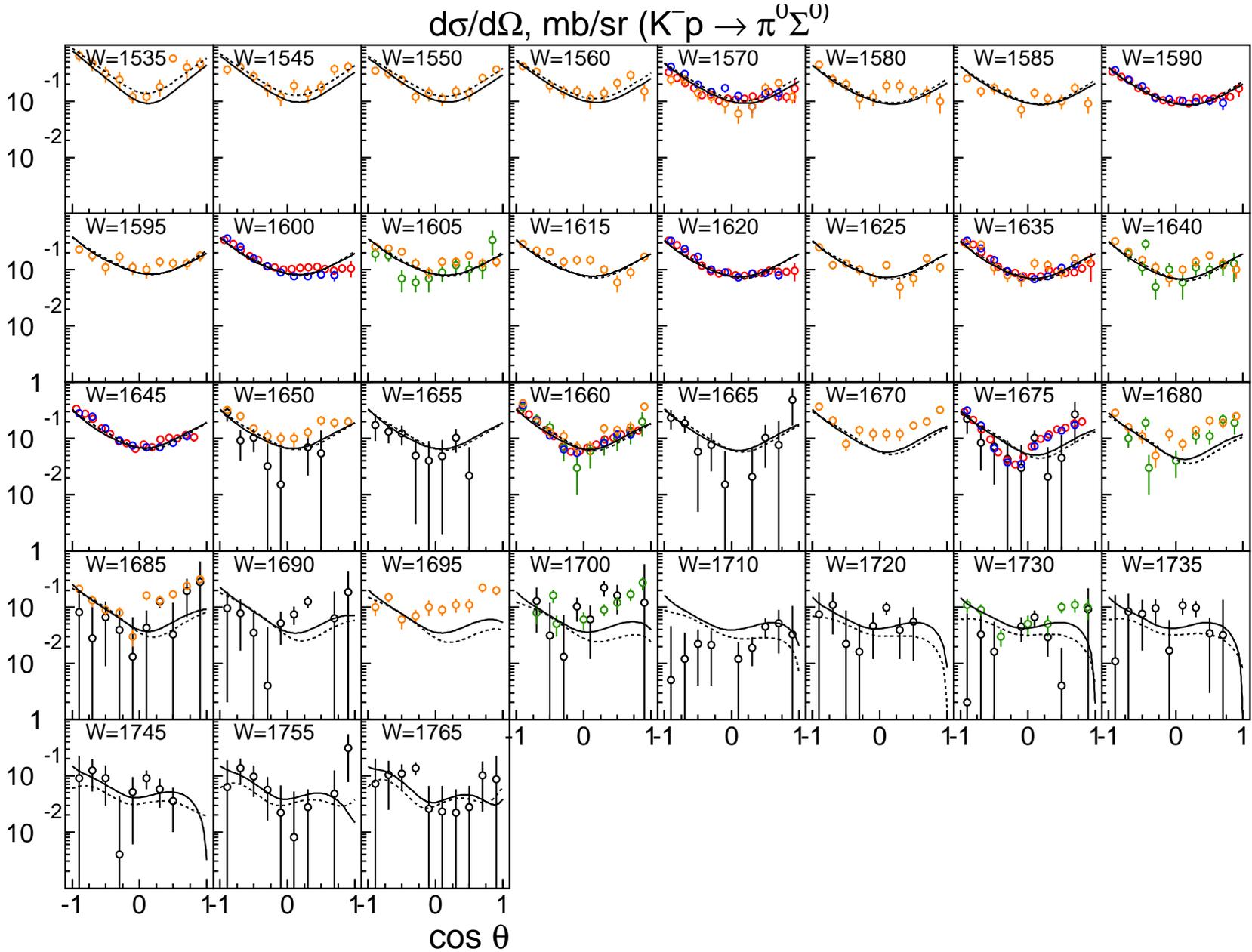


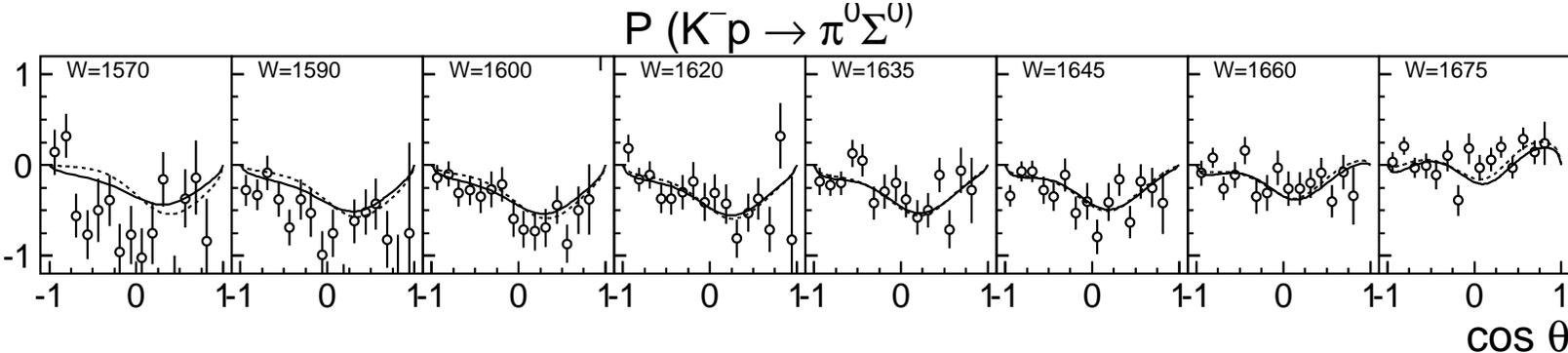


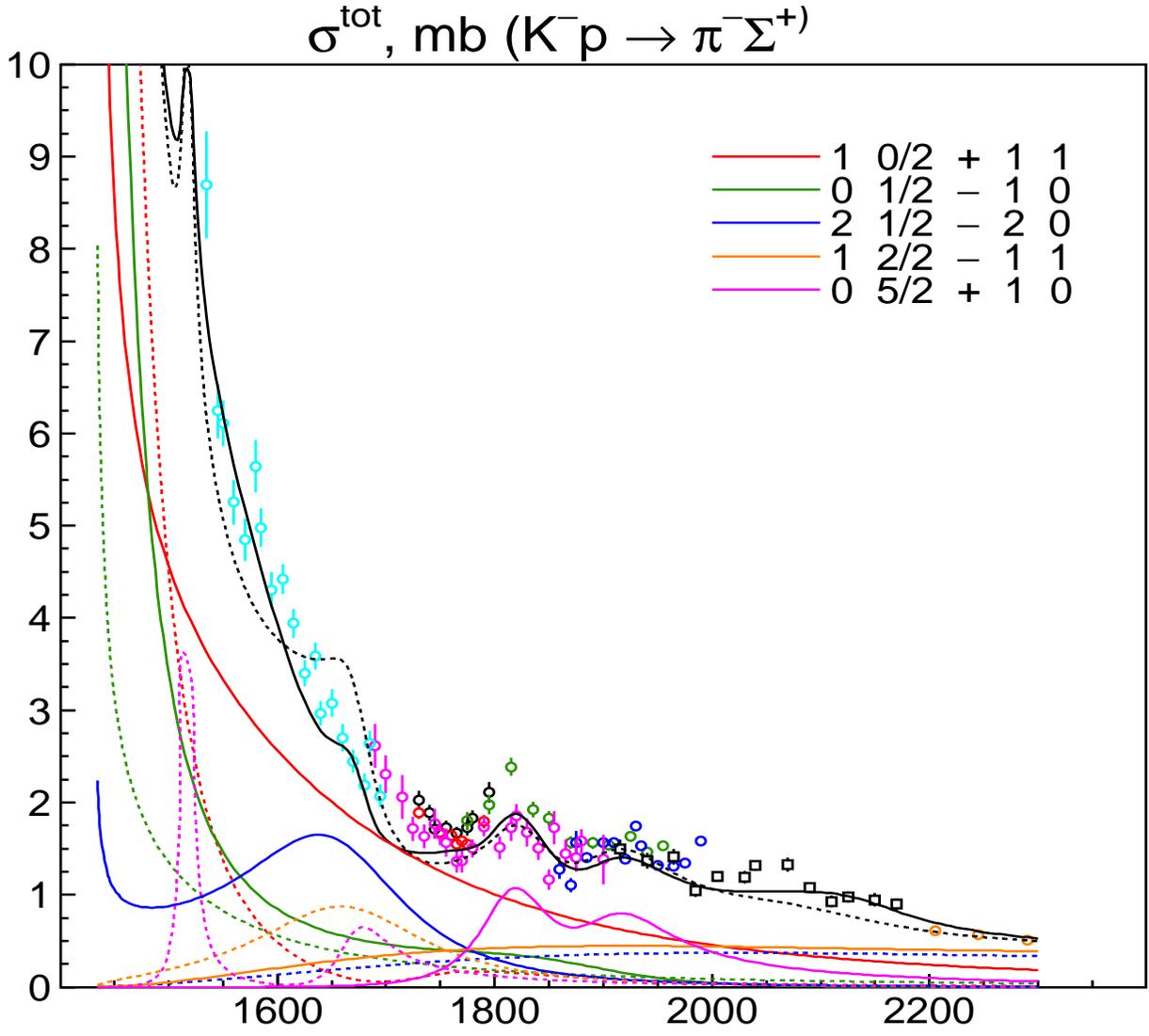


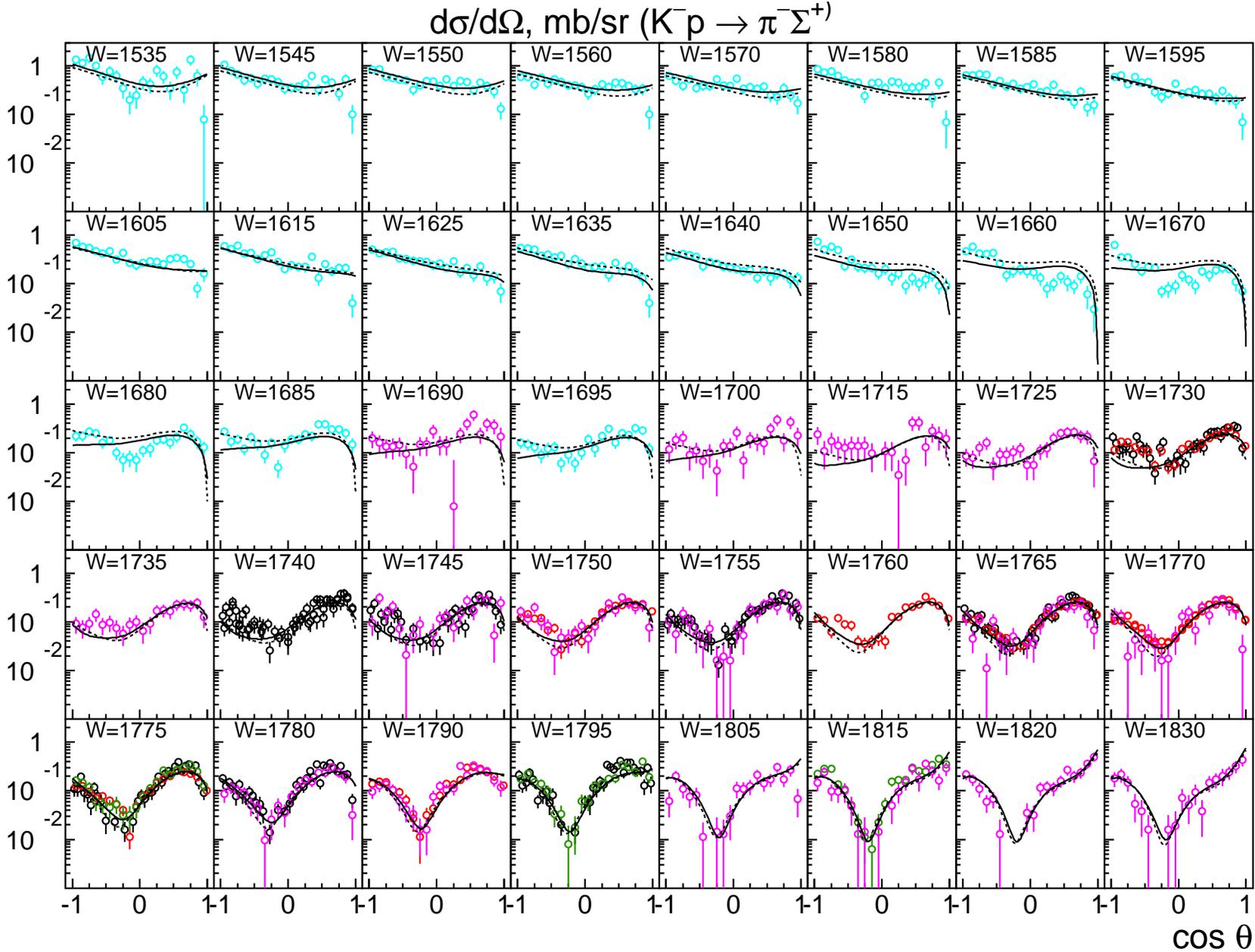


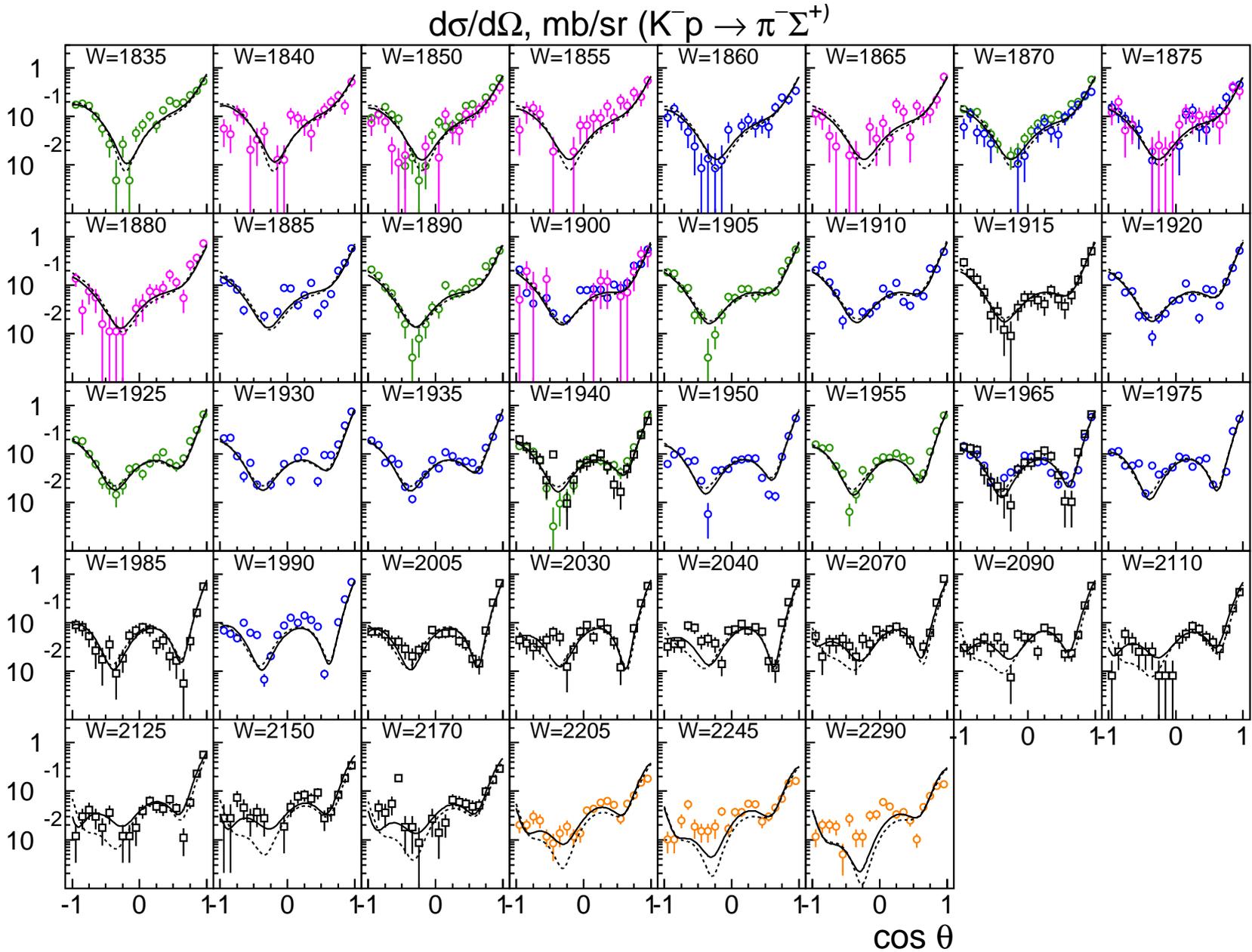


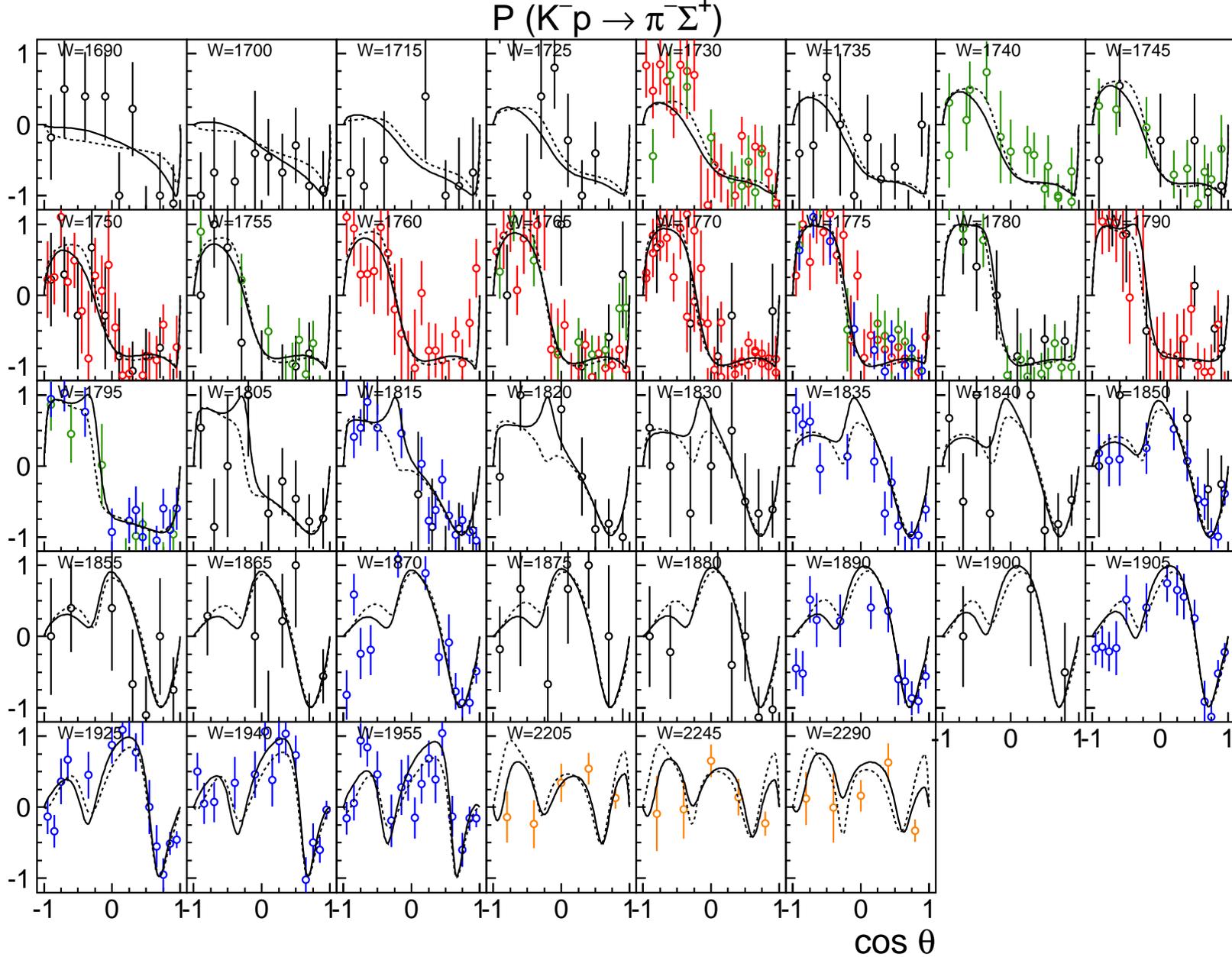


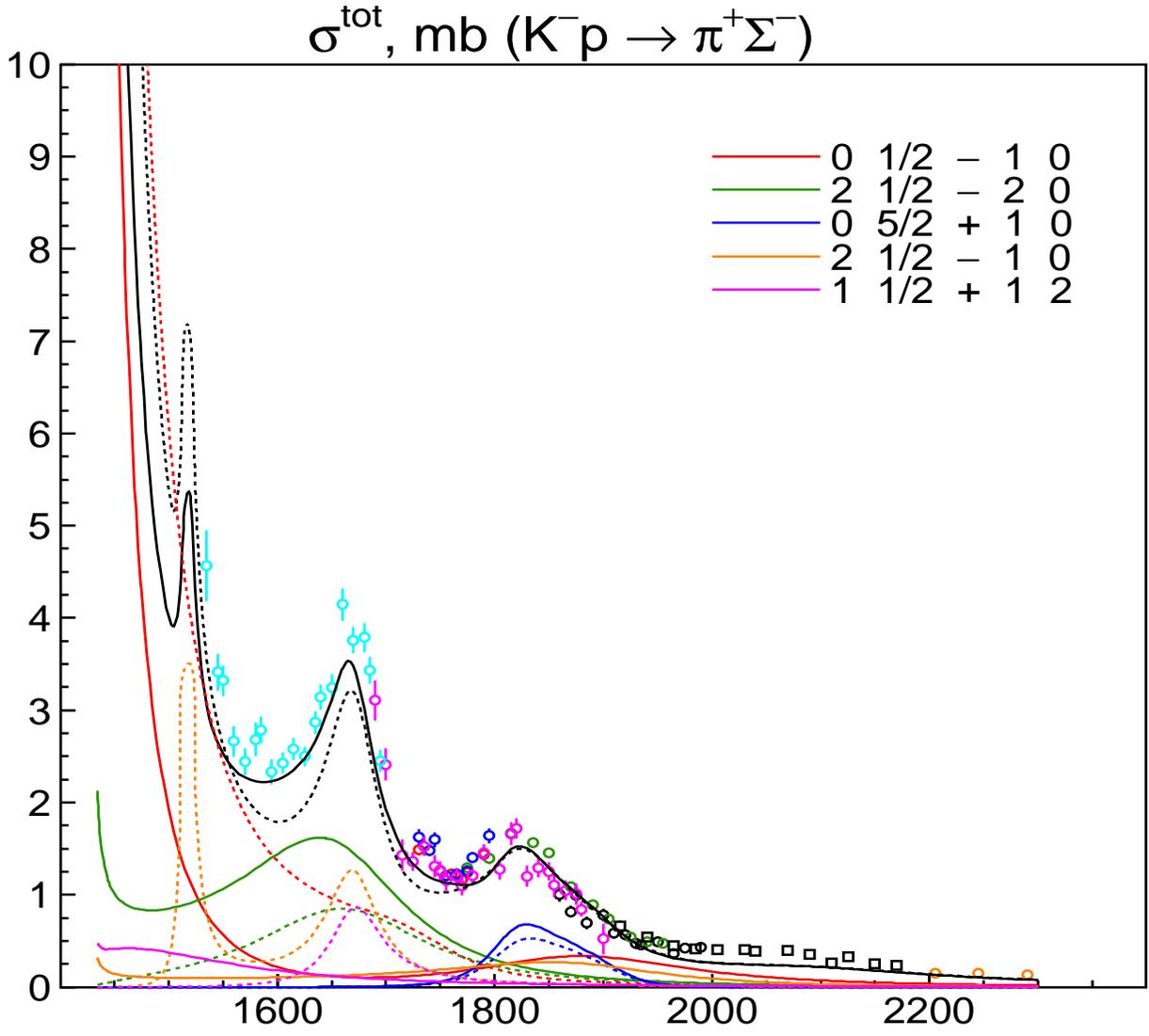


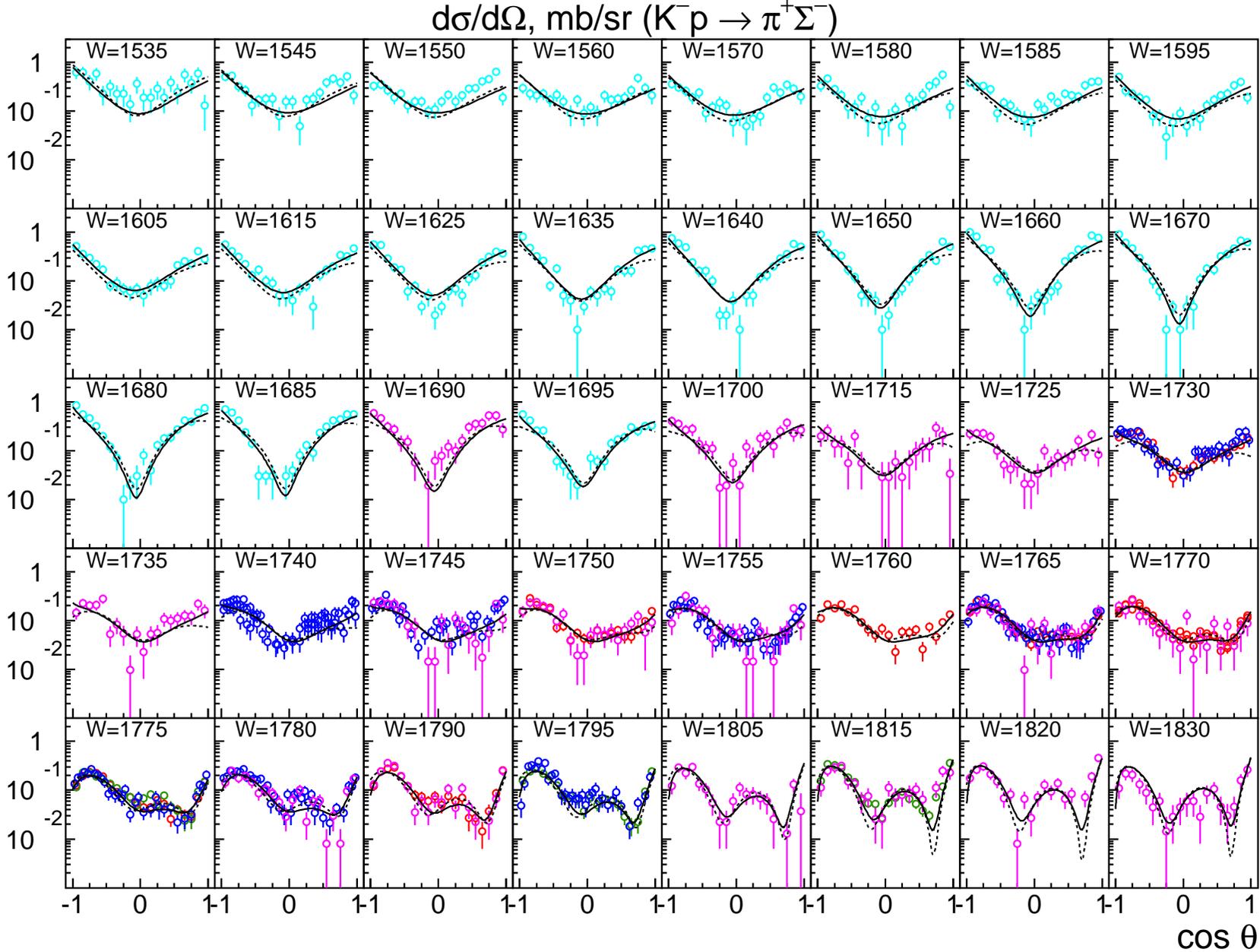


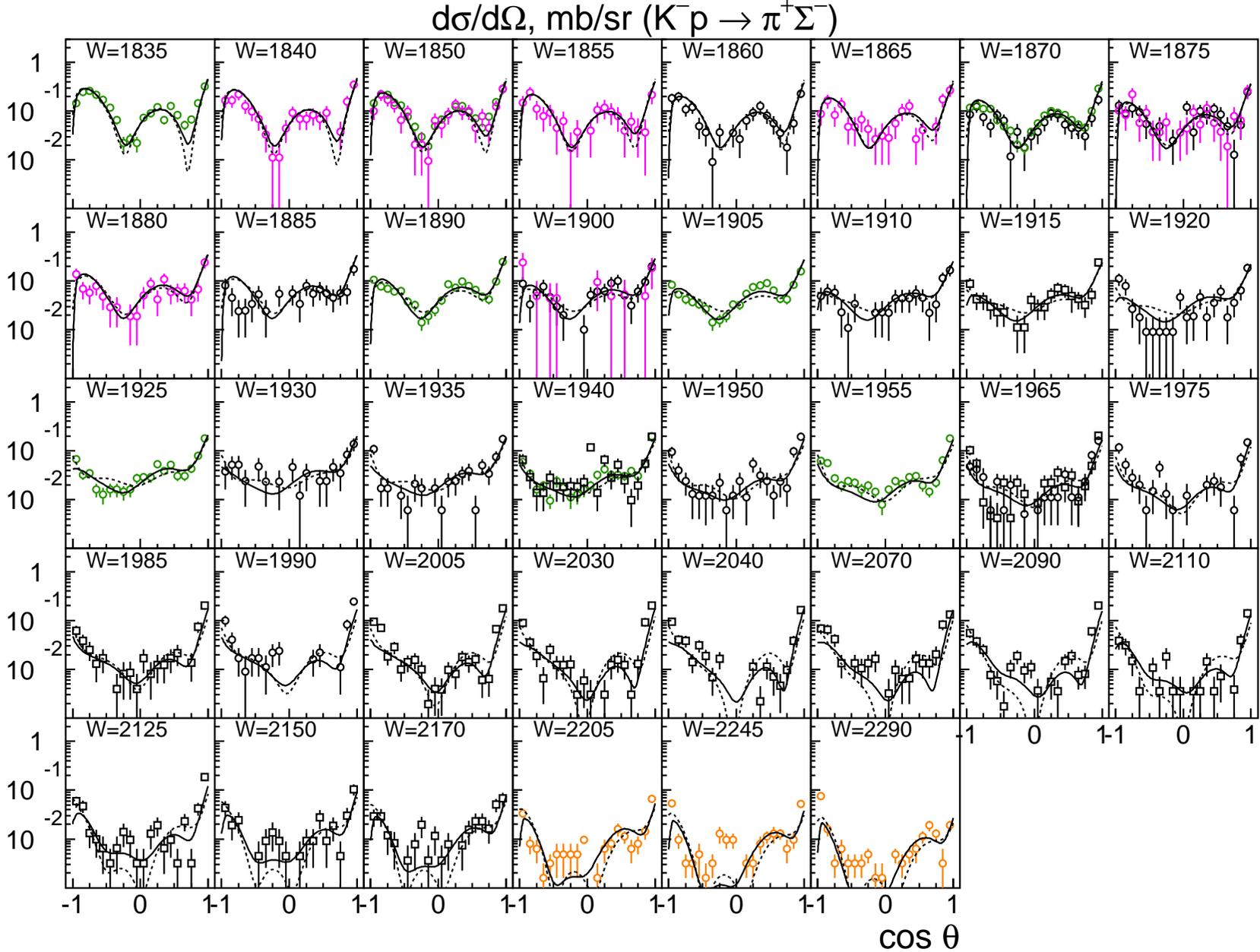




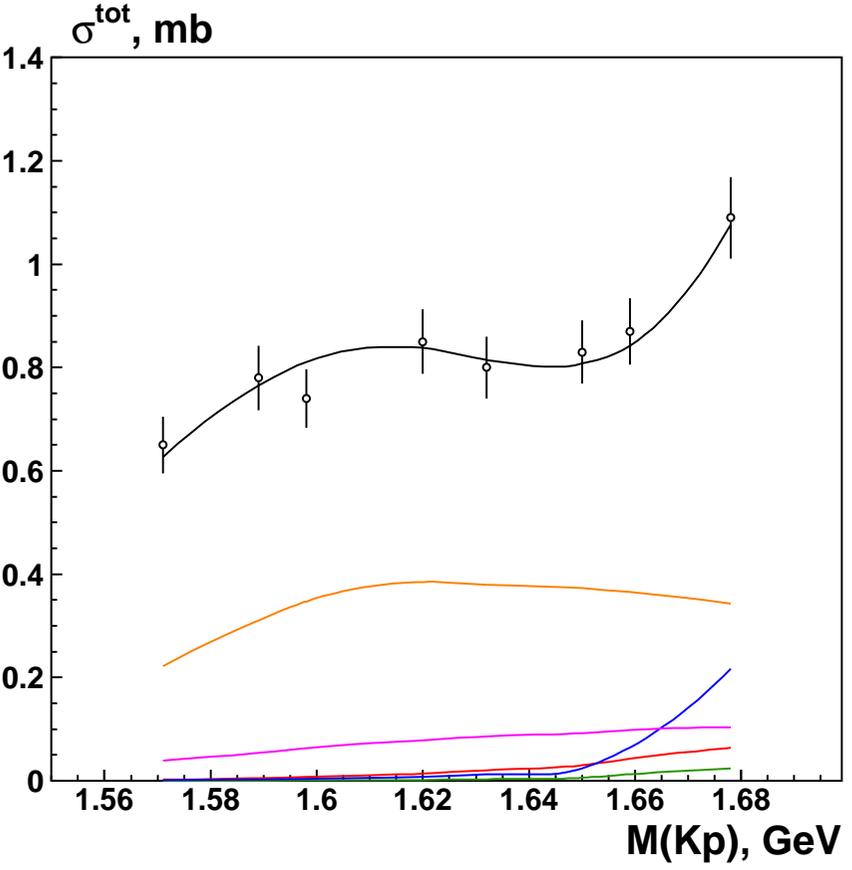




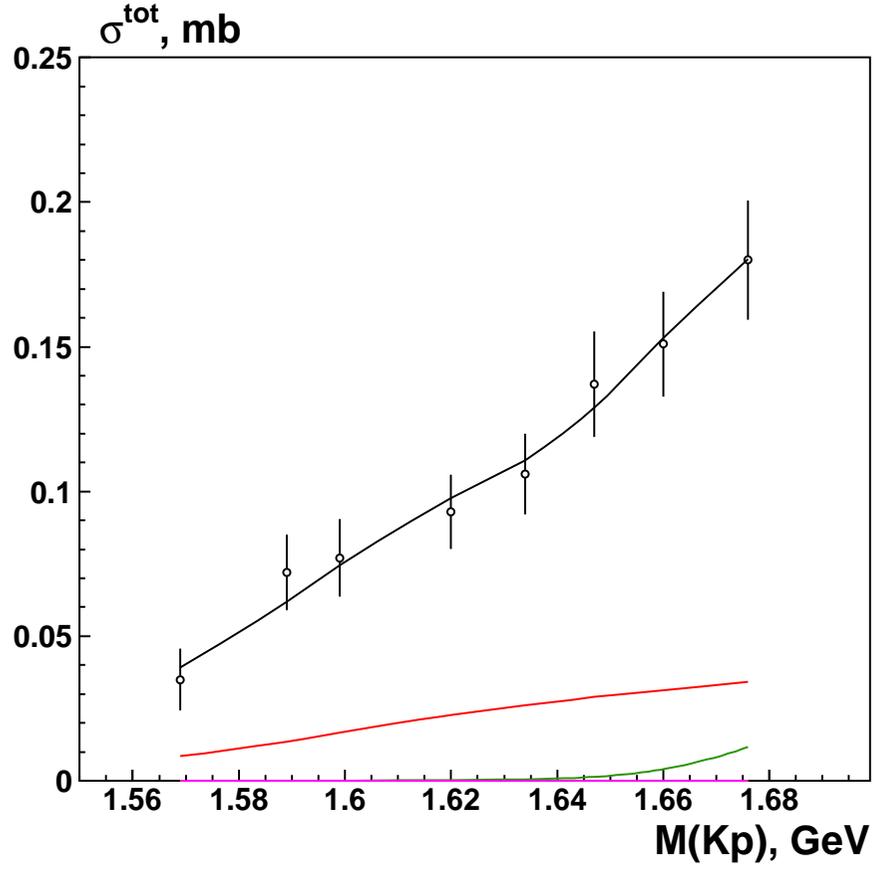




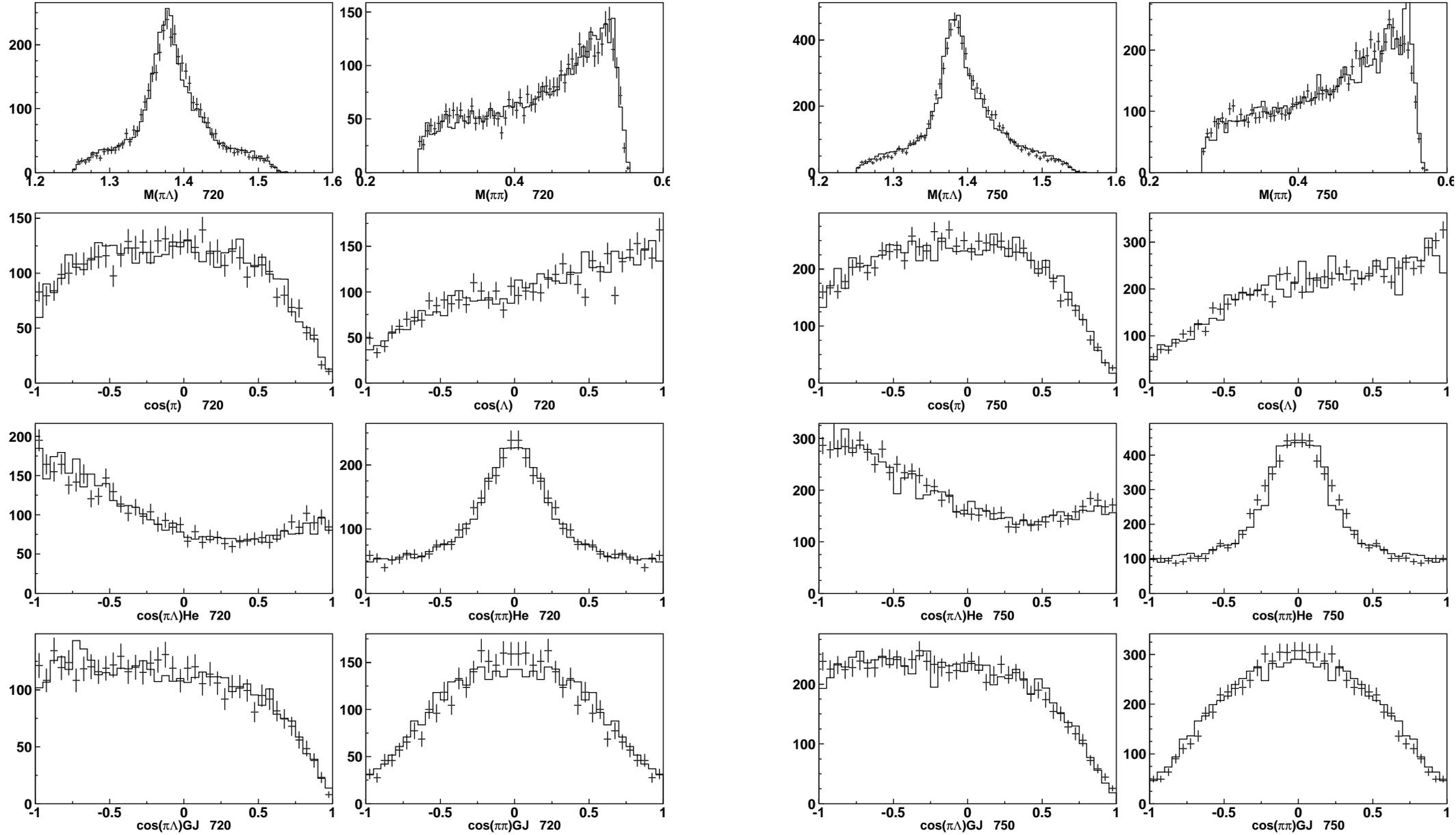
$$K^- p \rightarrow \pi^0 \pi^0 \Lambda$$



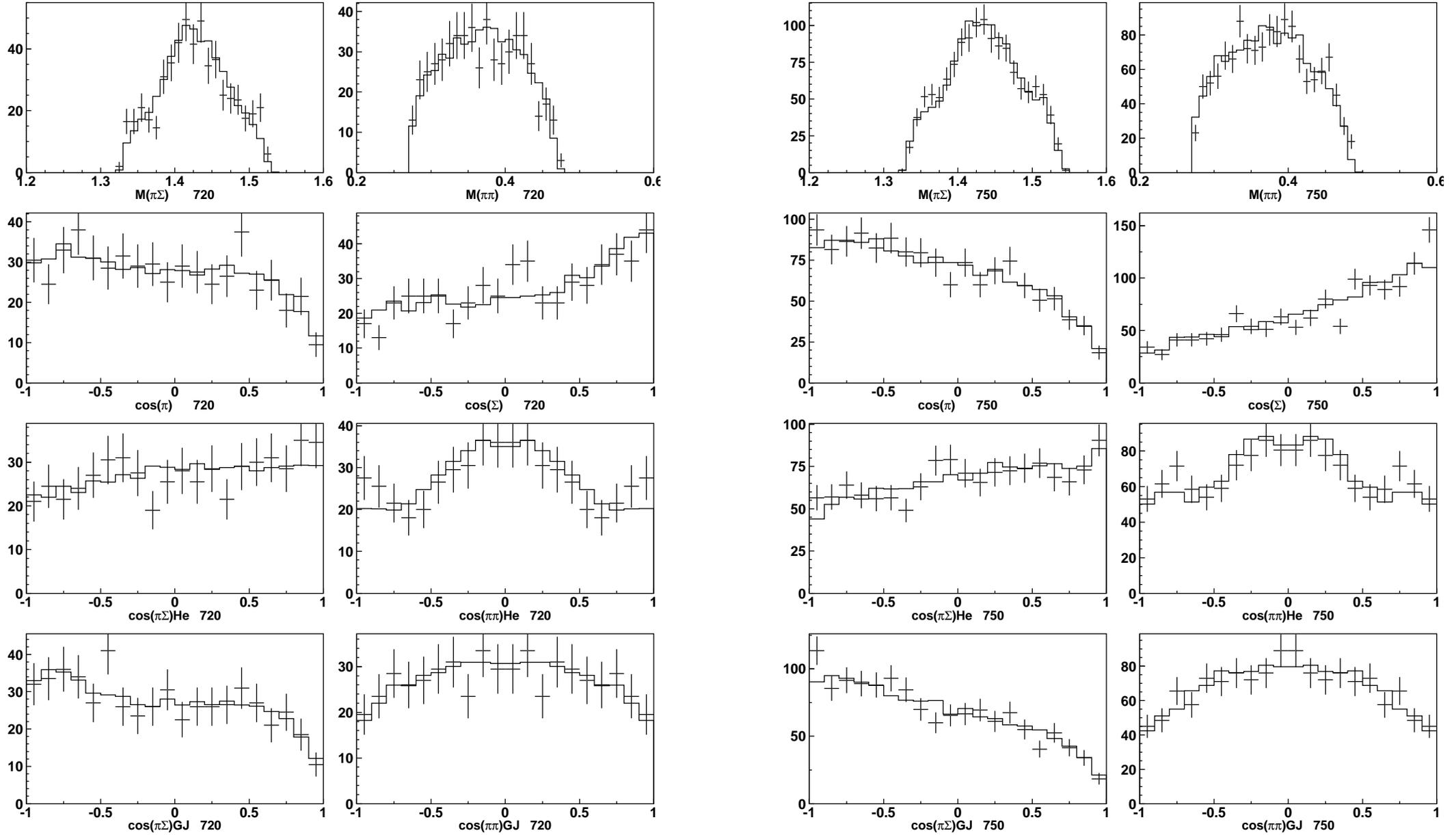
$$K^- p \rightarrow \pi^0 \pi^0 \Sigma^0$$



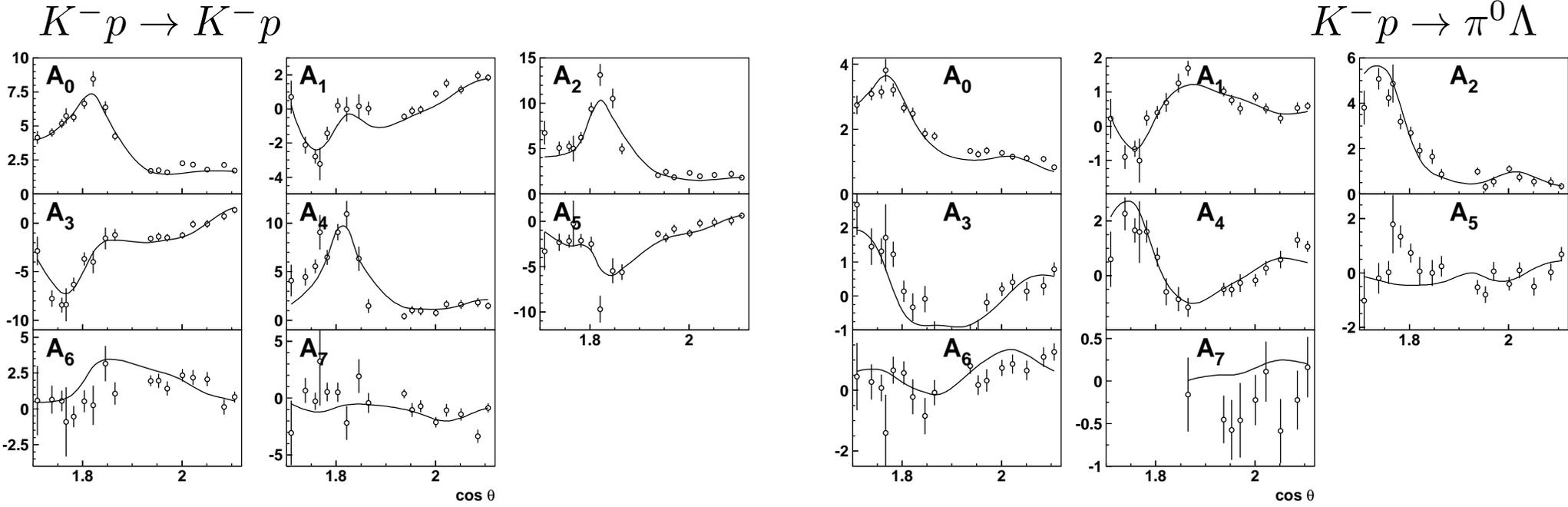
$K^- p \rightarrow \pi^0 \pi^0 \Lambda$ (beam momenta 720 and 750 MeV/c)



$K^- p \rightarrow \pi^0 \pi^0 \Sigma^0$ (beam momenta 720 and 750 MeV/c)



Some data were presented as Legendre polynomial coefficients



		ANL-Osaca	Bn-Ga	Model A	Model B	Bn-Ga
$K^- p \rightarrow K^- p$	$d\sigma/d\Omega$	3962	5495	3.07	2.98	2.28
	P	510	859	2.04	2.08	1.79
$K^- p \rightarrow \bar{K}^0 n$	$d\sigma/d\Omega$	2950	3445	2.67	2.75	1.62
$K^- p \rightarrow \pi^- \Sigma^+$	$d\sigma/d\Omega$	1792	2095	3.37	3.49	3.17
	P	418	578	1.30	1.28	2.06
$K^- p \rightarrow \pi^0 \Sigma^0$	$d\sigma/d\Omega$	580	581	3.68	3.50	3.57
	P	196	124	6.39	5.80	1.51
$K^- p \rightarrow \pi^+ \Sigma^-$	$d\sigma/d\Omega$	1786	2082	2.56	2.18	1.80
$K^- p \rightarrow \pi^0 \Lambda$	$d\sigma/d\Omega$	2178	2478	2.59	3.71	1.82
	P	693	732	1.41	1.73	1.73
$K^- p \rightarrow \eta \Lambda$	$d\sigma/d\Omega$	160	160	2.69	2.03	1.52
	P	18	—	0.94	3.83	—
$K^- p \rightarrow K^0 \Xi^0$	$d\sigma/d\Omega$	33	67	1.24	1.61	1.20
$K^- p \rightarrow K^+ \Xi^-$	$d\sigma/d\Omega$	92	193	2.05	1.74	1.38
$K^- p \rightarrow \Lambda \omega$	$d\sigma/d\Omega$	—	300	—	—	1.08

Table 7: Σ -Hyperons used in the final fit to the data.

	J^P	Status	Mass	Width
$\Sigma(1660)$	$1/2^+$	***	1630 – 1690	36.0 ± 0.7
$\Sigma(1385)$	$3/2^+$	****	1382.80 ± 0.35	40 – 200
$\Sigma(1915)$	$5/2^+$	****	1900 – 1935	80 – 160
$\Sigma(2030)$	$7/2^+$	****	2025 – 2040	150 – 200
$\Sigma(1670)$	$3/2^-$	****	1665 – 1685	40 – 80
$\Sigma(1750)$	$1/2^-$	***	1730 – 1800	60 – 160
$\Sigma(1775)$	$5/2^-$	****	1770 – 1780	105 – 135
$\Sigma(1940)$	$3/2^-$	***	1900 – 1950	150 – 300
$\Sigma(1665)$	$1/2^-$		1670 ± 15	210 ± 20
$\Sigma(2150)$	$1/2^-$		2160 ± 20	220 ± 25
$\Sigma(2250)$	$5/2^-$		2250 ± 30	330 ± 40

SUMMARY

- There is lack of the data with charged pions above 1700 MeV. New data with two pions in the final state would be very useful.
- The number of the states should be still found or confirmed ($\Delta(1750)1/2^+$, $N(1875)3/2^+$, number of Λ and Σ states).
- We perform the first combined analysis of the $Kp \rightarrow \pi\pi\Lambda$ and $Kp \rightarrow \pi\pi\Sigma$ together with the data on reactions with two body final states and with the data presented as Legendre polynomial coefficients.
- The combined analysis of the Kp collision reactions shows the presence of the unknown Σ -hyperons. There is a hope to find new hyperon states in the analysis of the two pion production data if they are available in the future.