

Jülich-Georgia meson-baryon model

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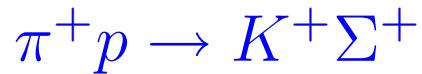
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Contents

The Jülich coupled reaction channels approach

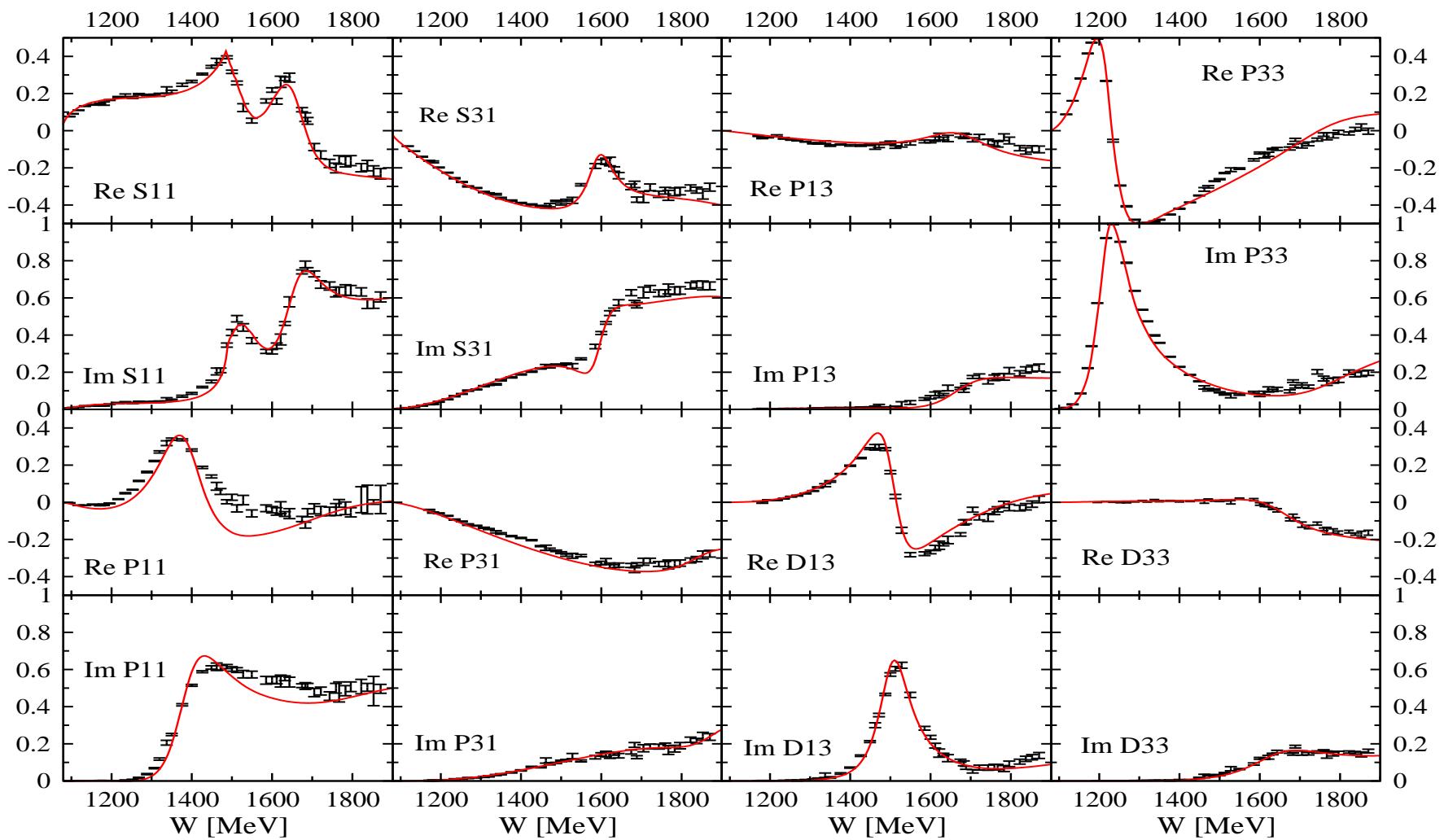
Photoproduction of mesons



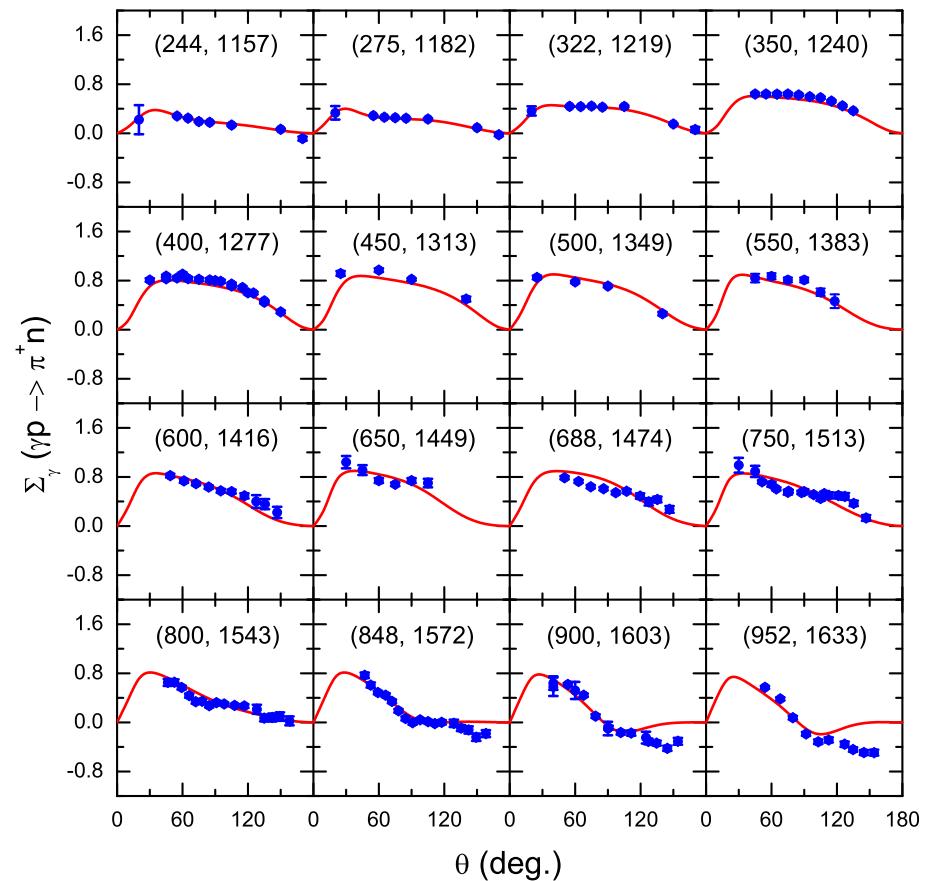
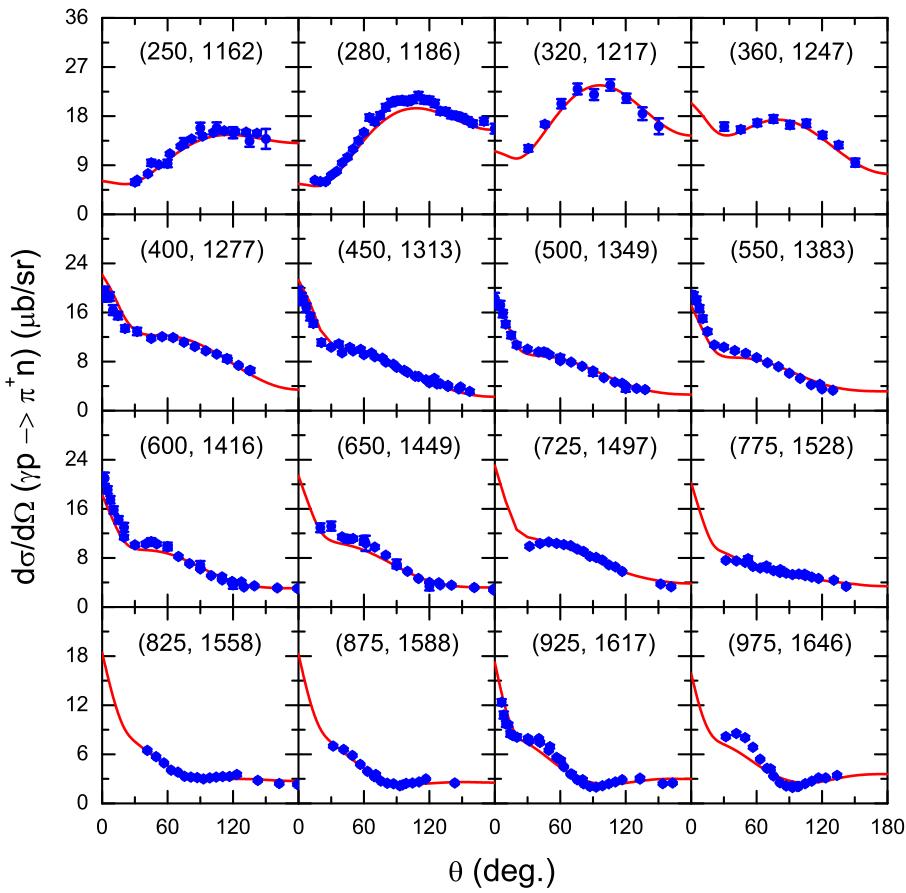
Meeting the lattice

Conclusions

Partial wave amplitudes: $\pi N \rightarrow \pi N$

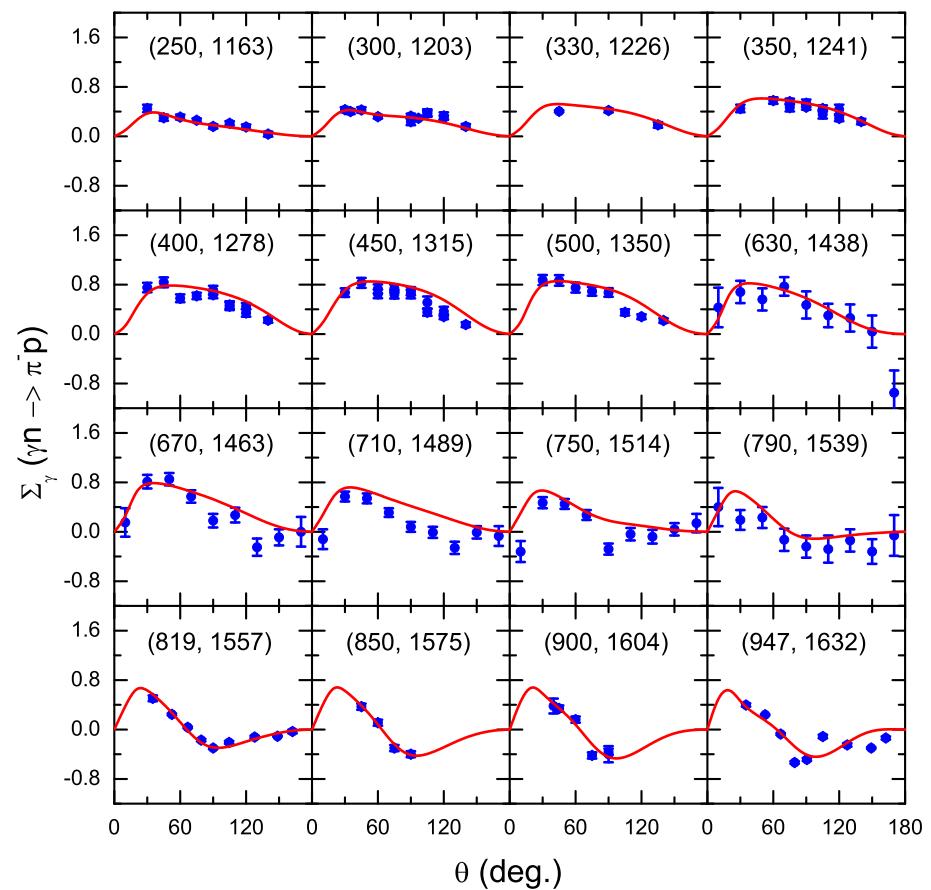
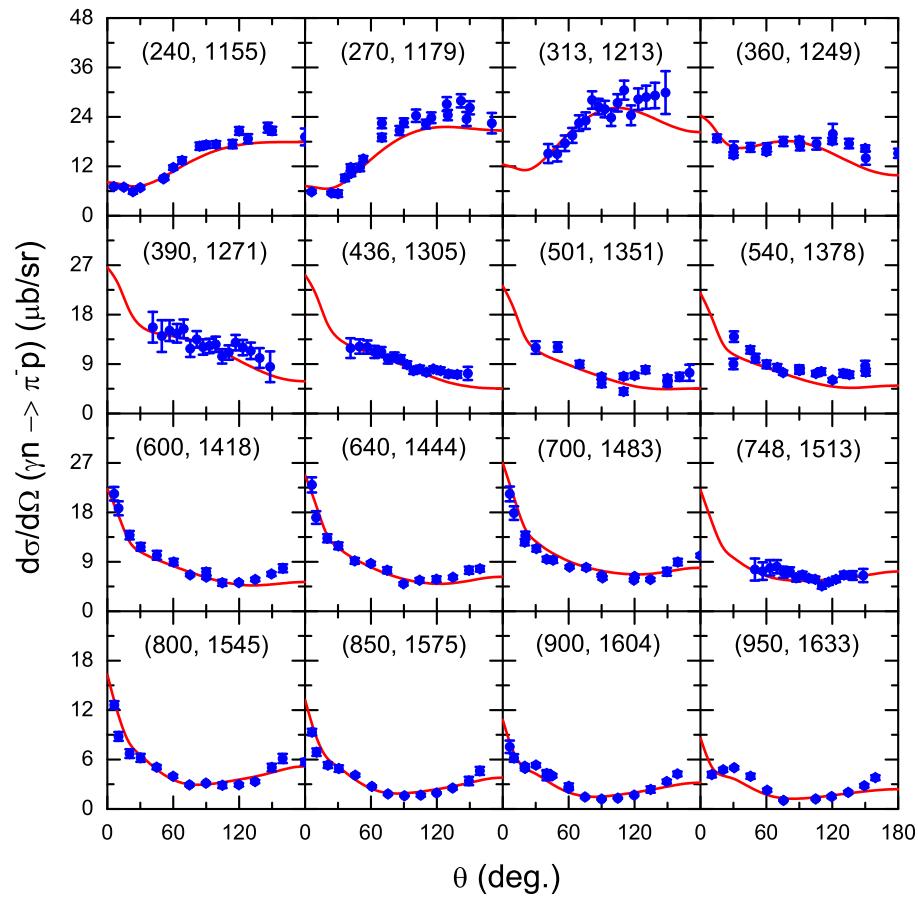


$d\sigma/d\Omega$ and Σ_γ for $\gamma p \rightarrow \pi^+ n$



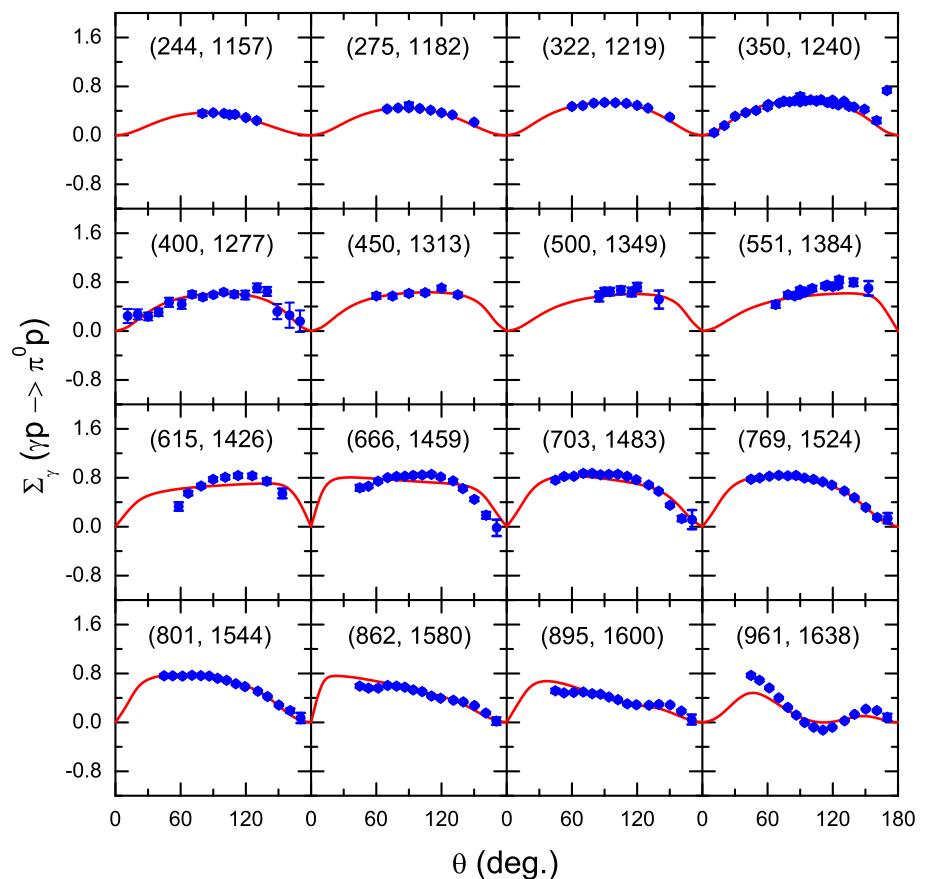
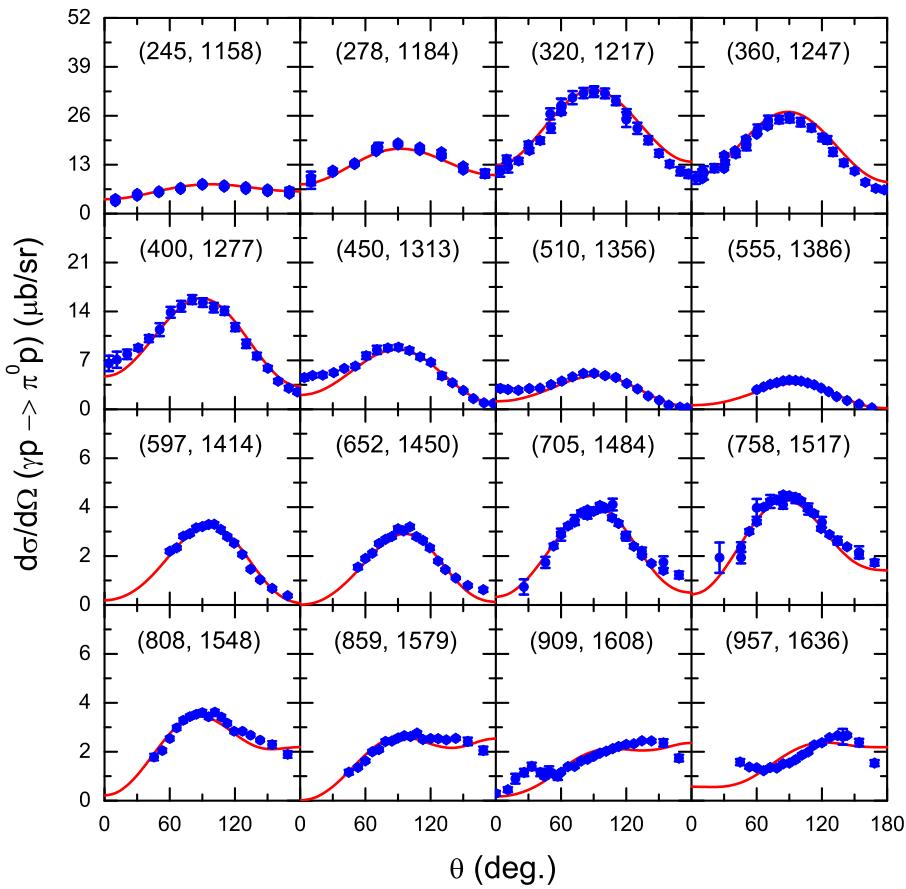
Gauge invariant approach Fei Huang et al., in progress

$d\sigma/d\Omega$ and Σ_γ for $\gamma n \rightarrow \pi^- p$

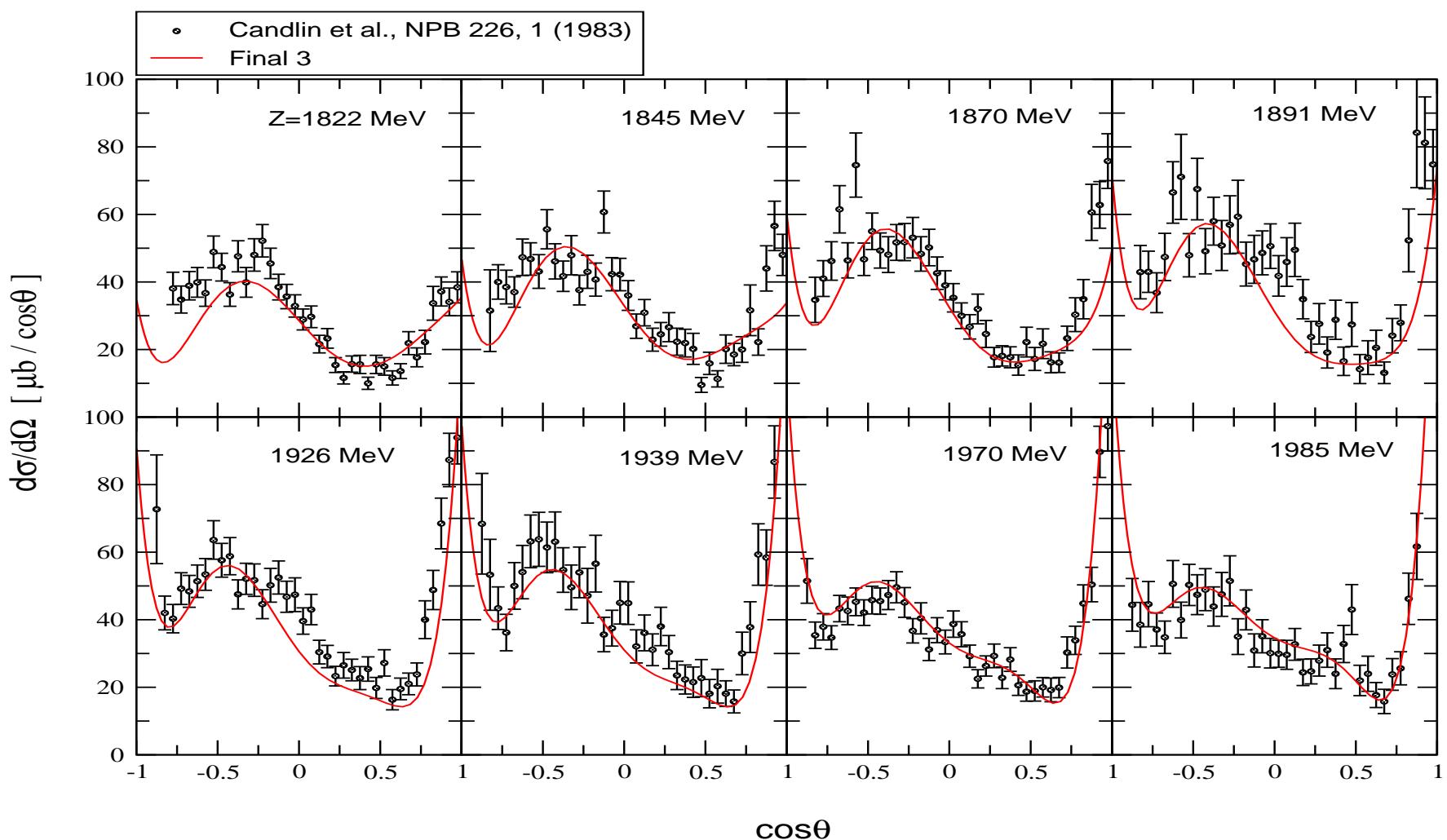


Fei Huang et al., in progress

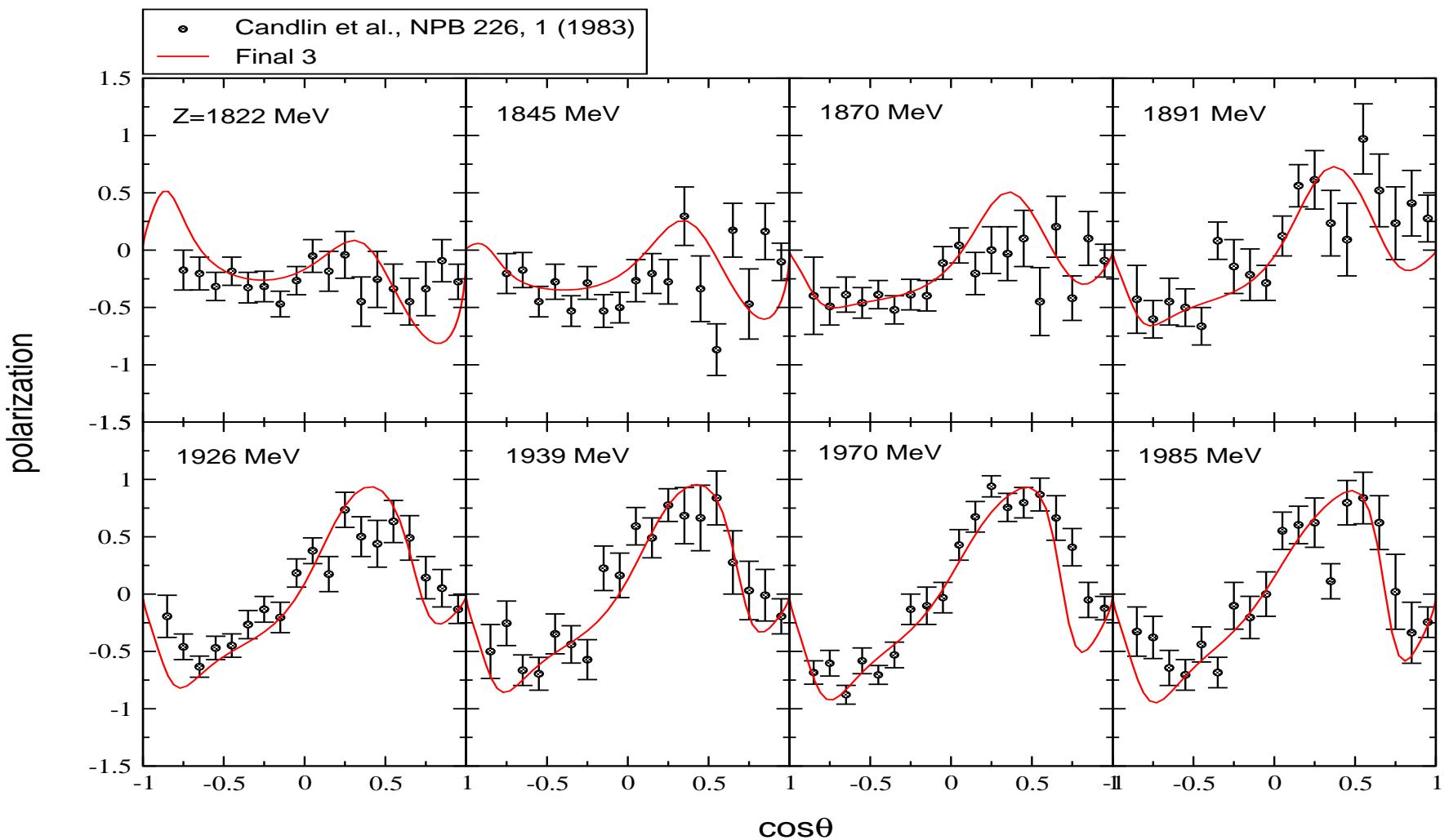
$d\sigma/d\Omega$ and Σ_γ for $\gamma p \rightarrow \pi^0 p$



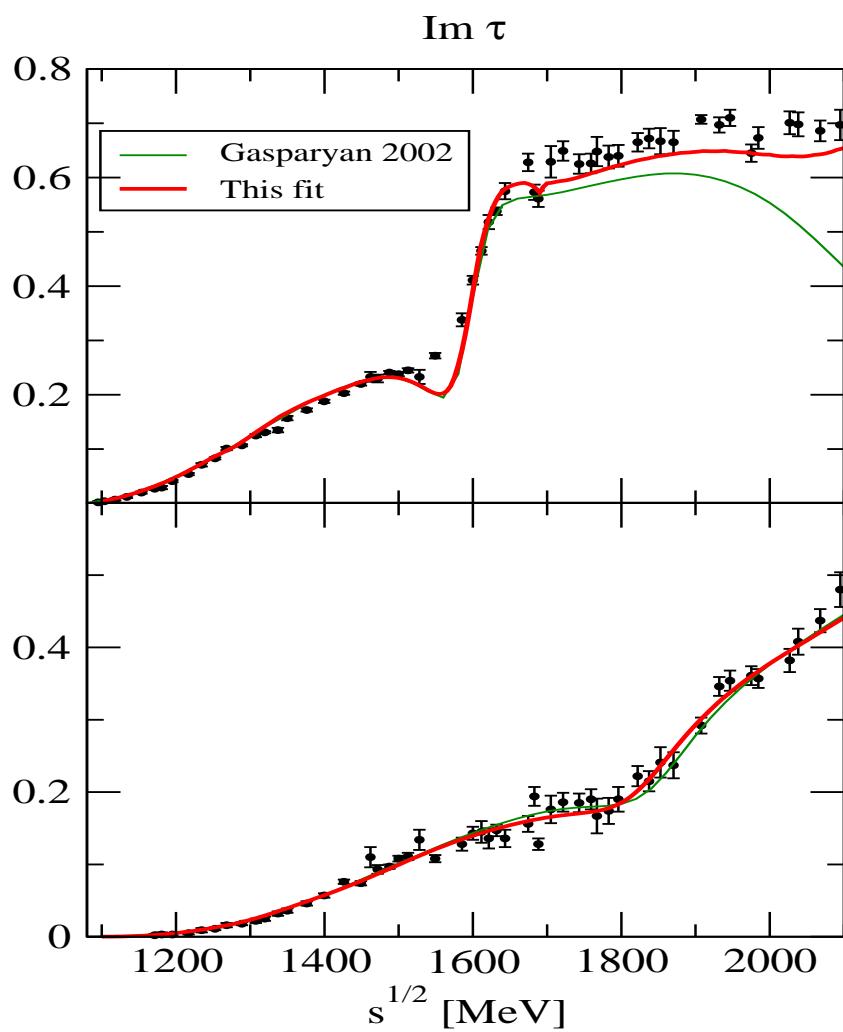
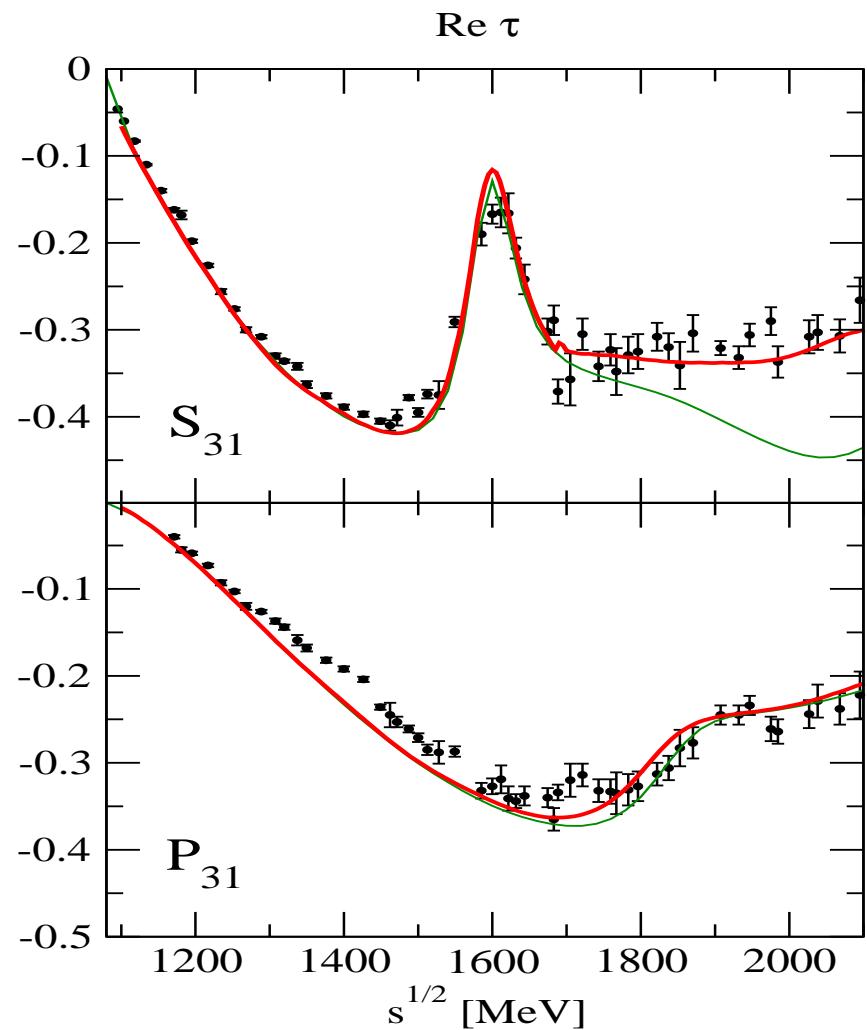
Fei Huang et al., in progress



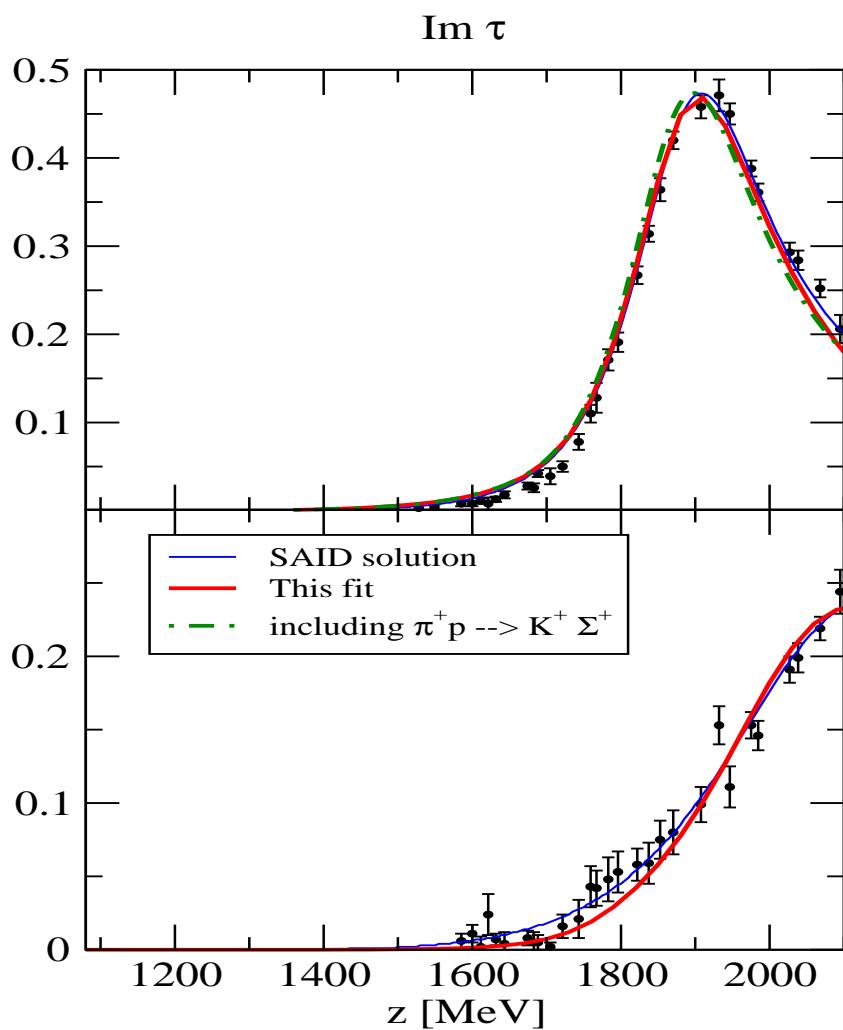
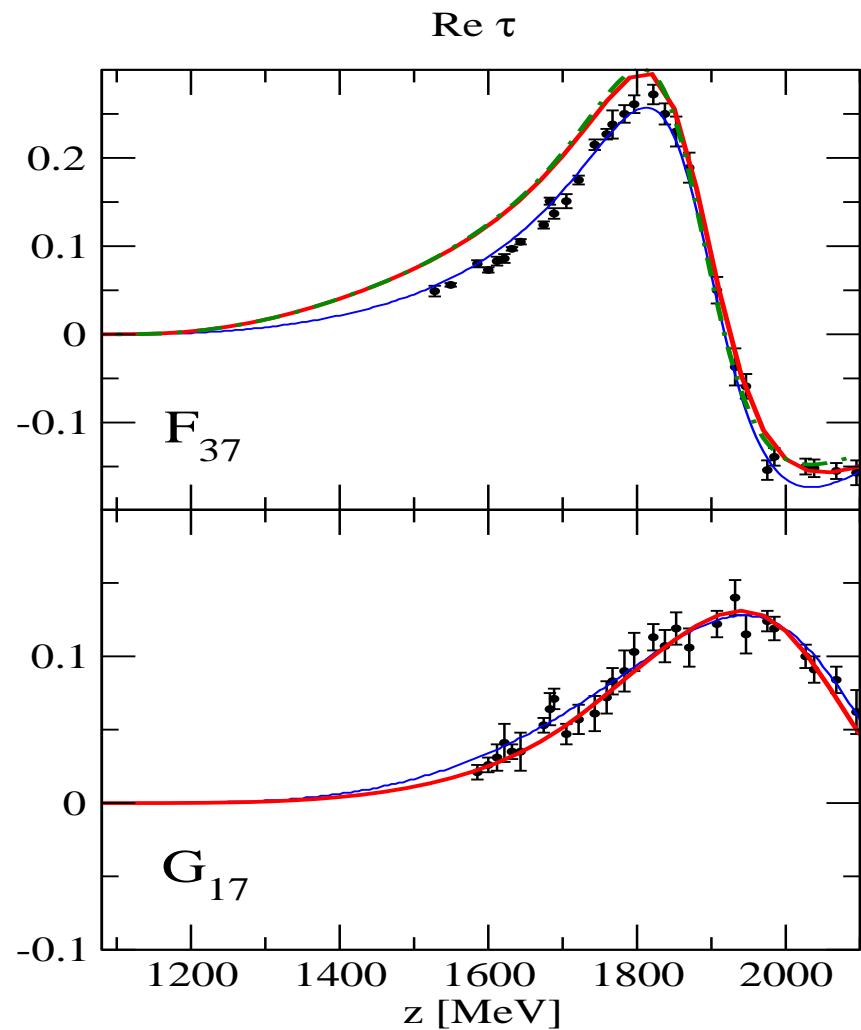
$\pi^+ p \rightarrow K^+ \Sigma^+$, polarization



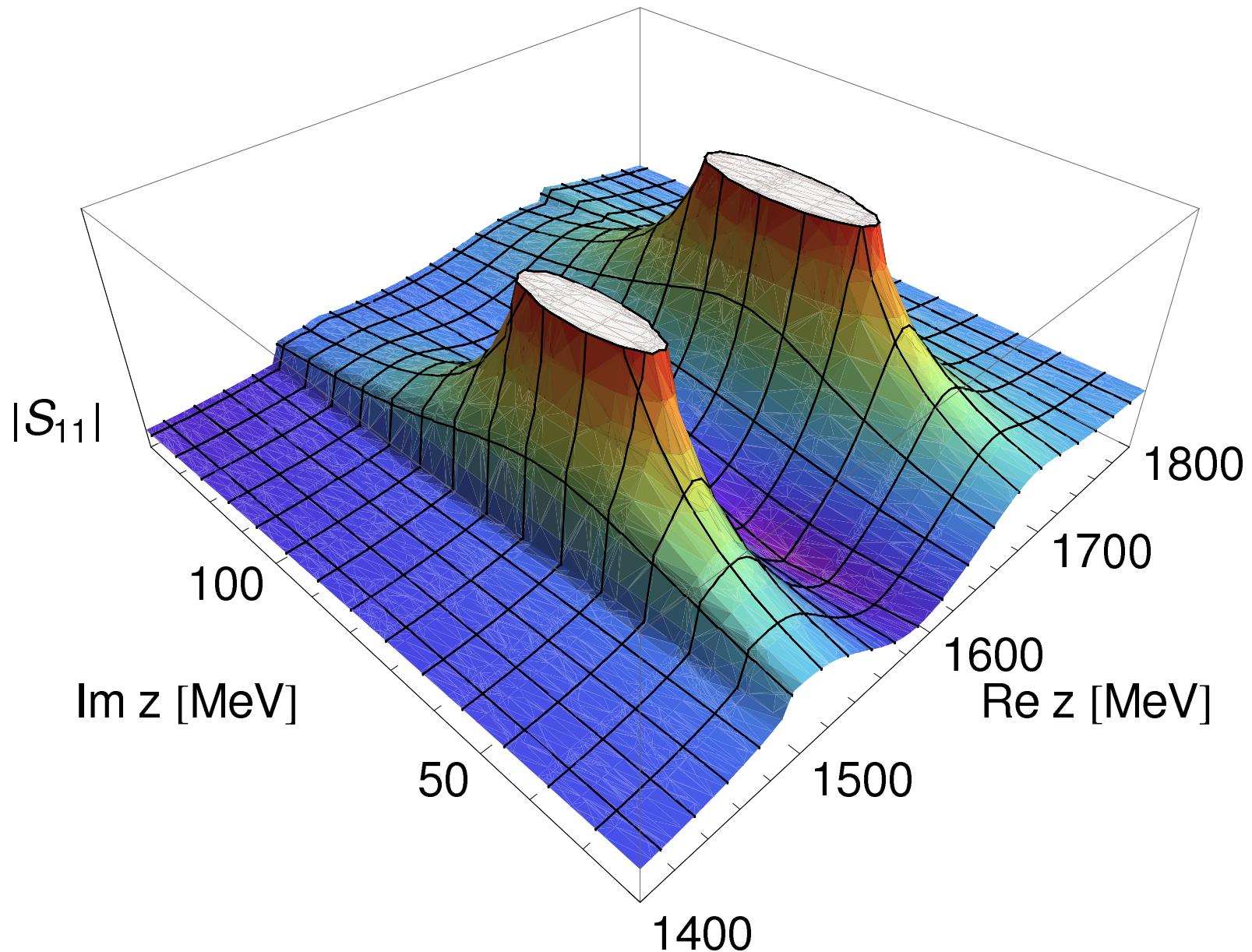
$N\pi$, $S_{3,1}$ and $P_{3,1}$



$N\pi$, $F_{3,7}$ and $G_{1,7}$



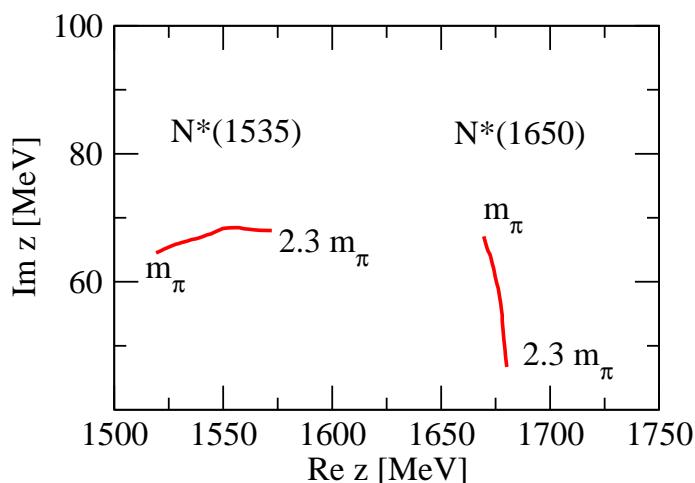
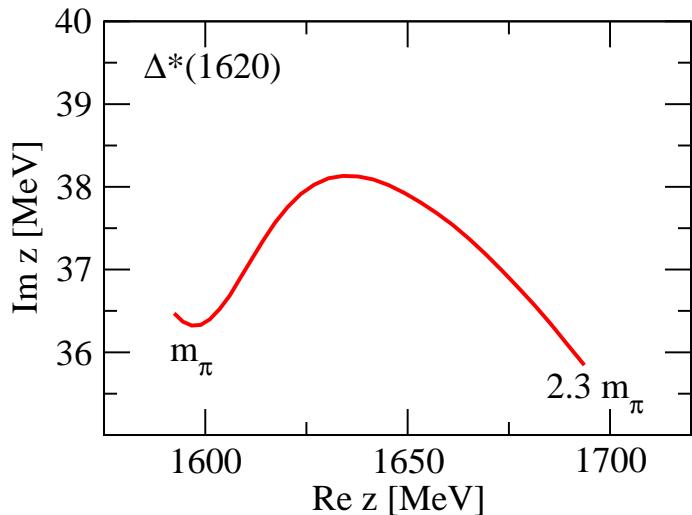
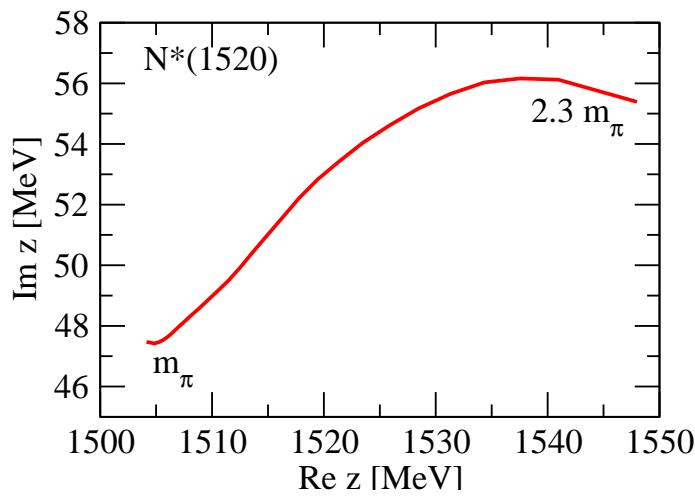
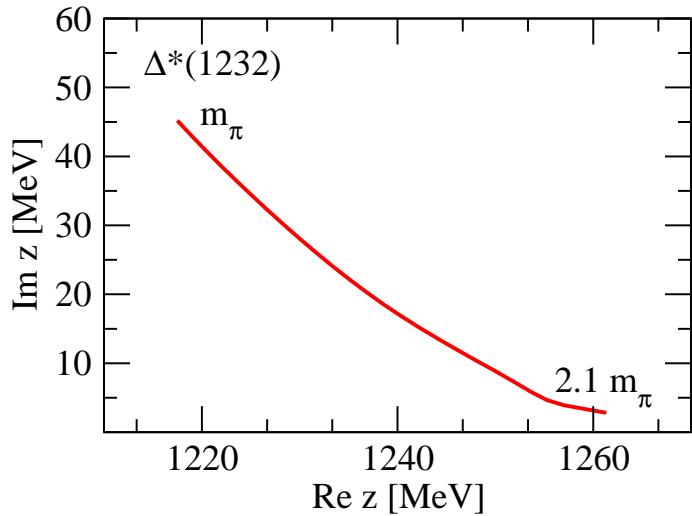
Complex plane: S_{11}



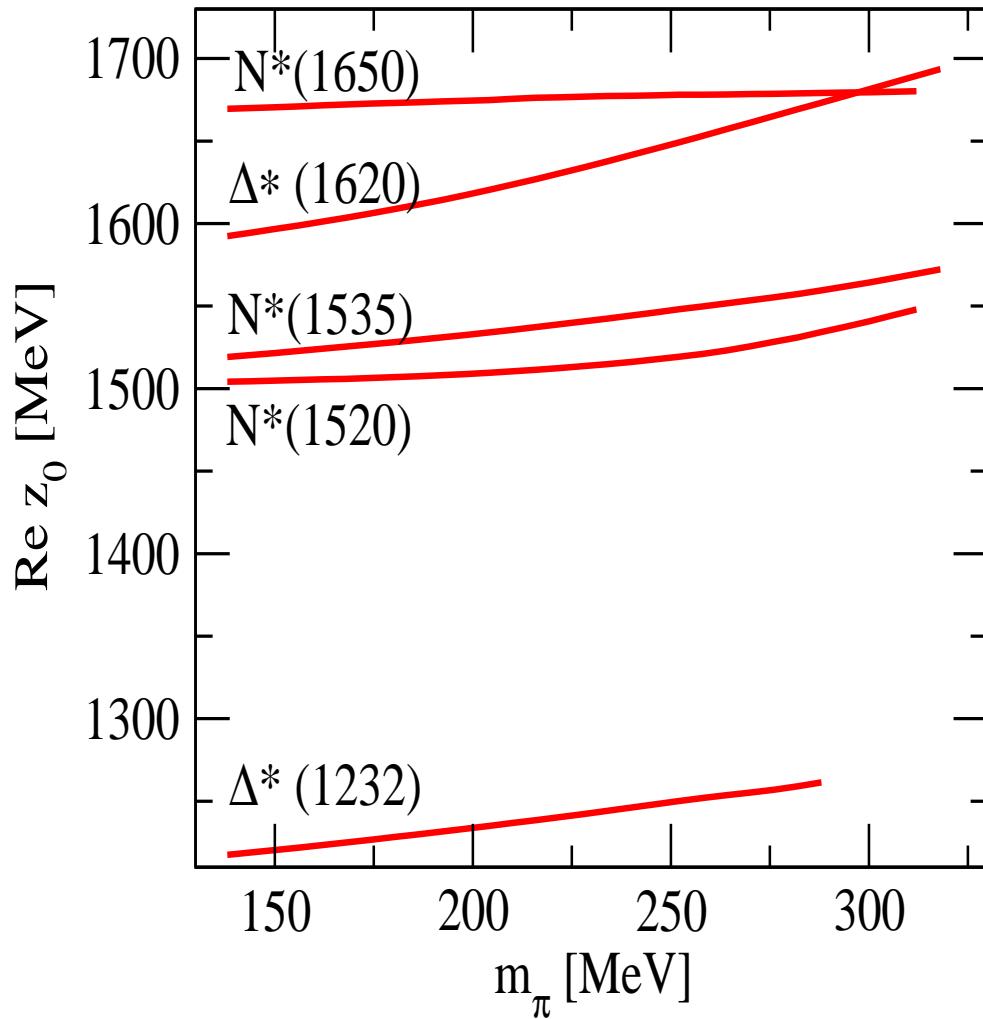
Poles and residues: Delta

	Re z_0 [MeV]	-2 Im z_0 [MeV]	R [MeV]	θ [deg] [0]
$\Delta(1232) P_{33}$	1218	90	47	-37
ARN	1211	99	52	-47
HOE	1209	100	50	-48
CUT	1210 \pm 1	100 \pm 2	53 \pm 2	-47 \pm 1
$\Delta^*(1620) S_{31}$	1593	72	12	-108
ARN	1595	135	15	-92
HOE	1608	116	19	-95
CUT	1600 \pm 15	120 \pm 20	15 \pm 2	-110 \pm 20
$\Delta^*(1910) P_{31}$	1840	221	12	-153
ARN	1771	479	45	+172
HOE	1874	283	38	
CUT	1880 \pm 30	200 \pm 40	20 \pm 4	-90 \pm 30

Meeting the lattice: Pole path



Pion mass dependence



Conclusions

Photoproduction

Combined treatment of $\pi N \rightarrow \pi N$
and $\pi^+ p \rightarrow K^+ \Sigma^+$.

Separation of amplitude into contributions from bare resonances
and background is model dependent.

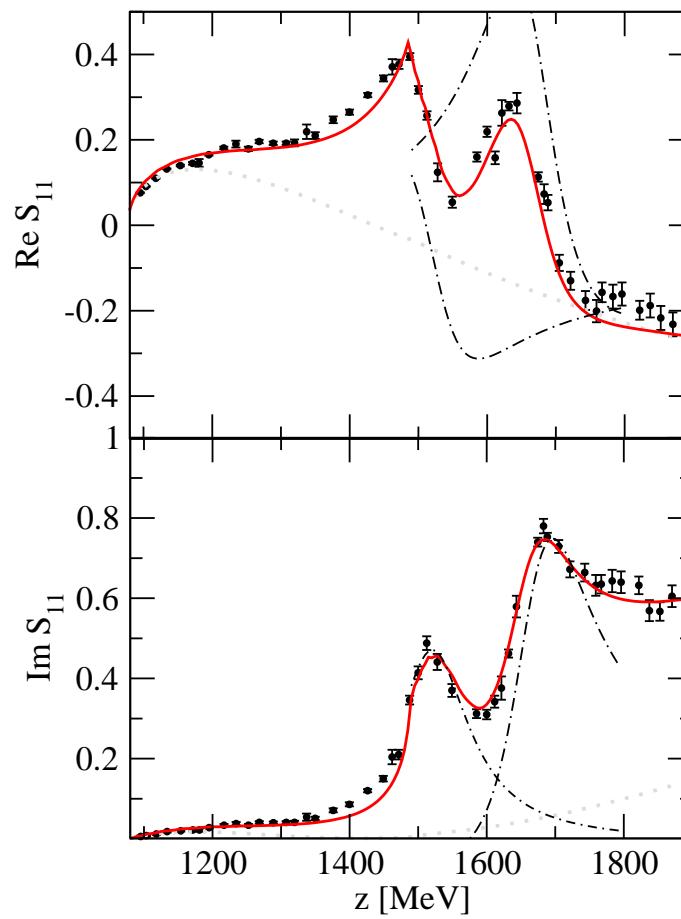
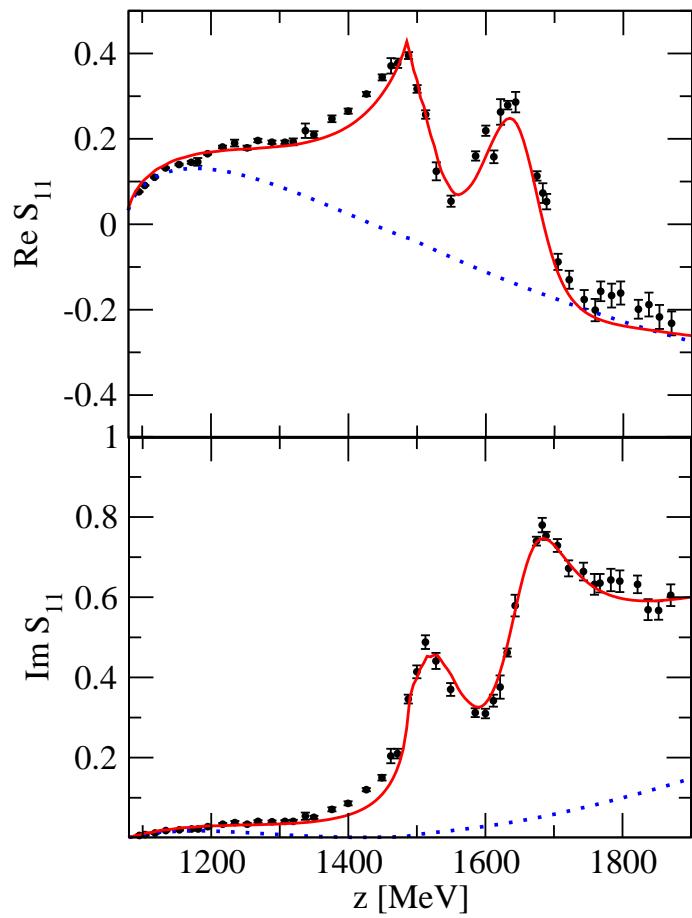
Resonances characterized by poles and residues of the S-matrix
M. Döring et al., NPA829, 170(2009).

Study m_π dependence of poles.

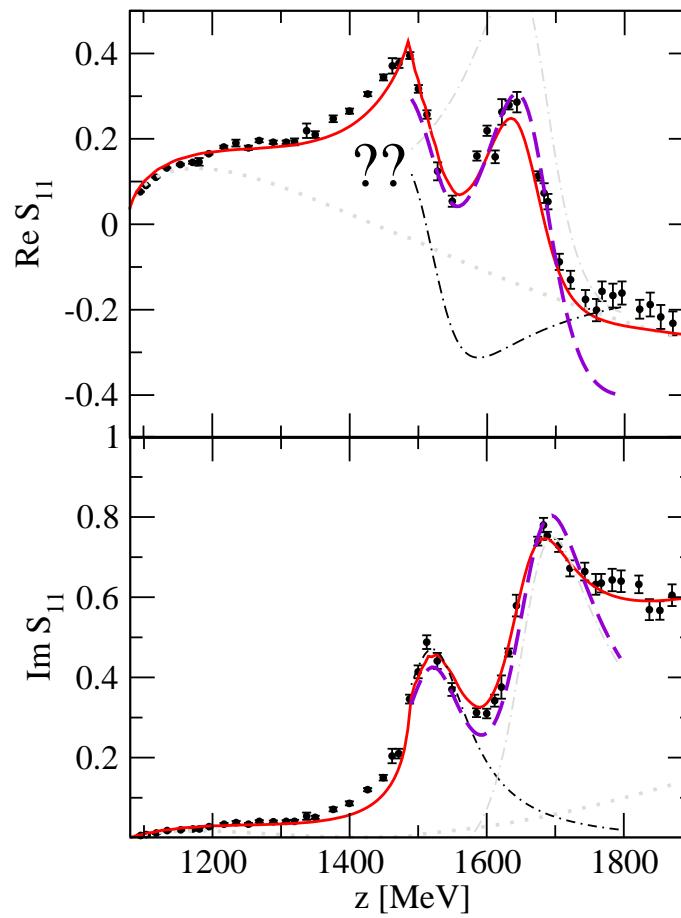
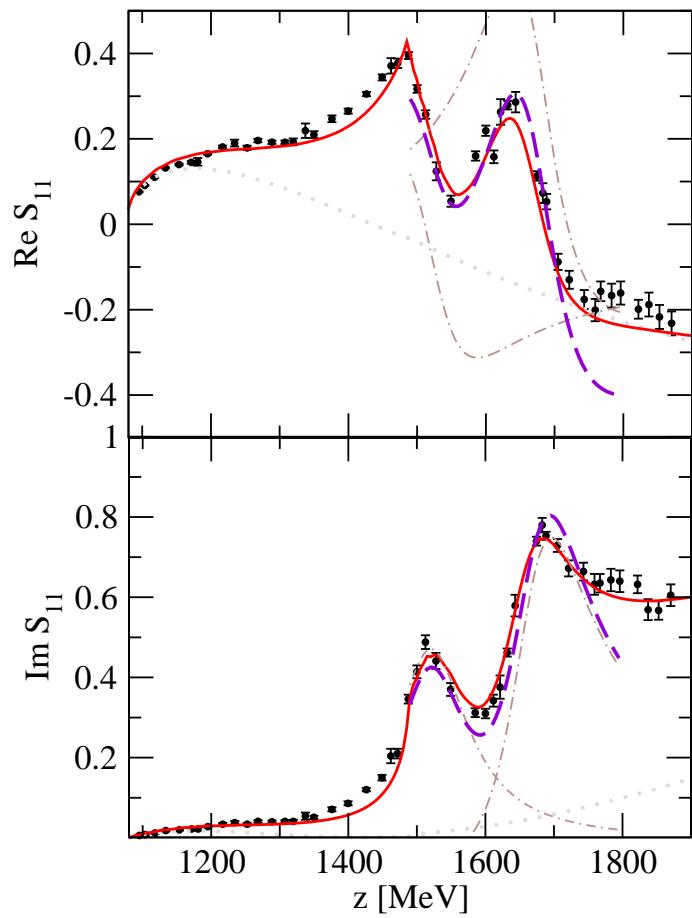
Outlook:

photoproduction of Kaon Hyperon
electroproduction

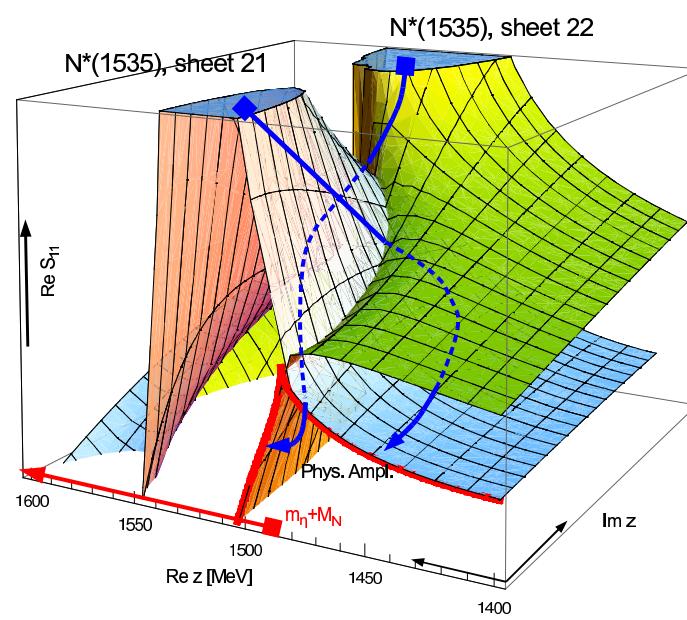
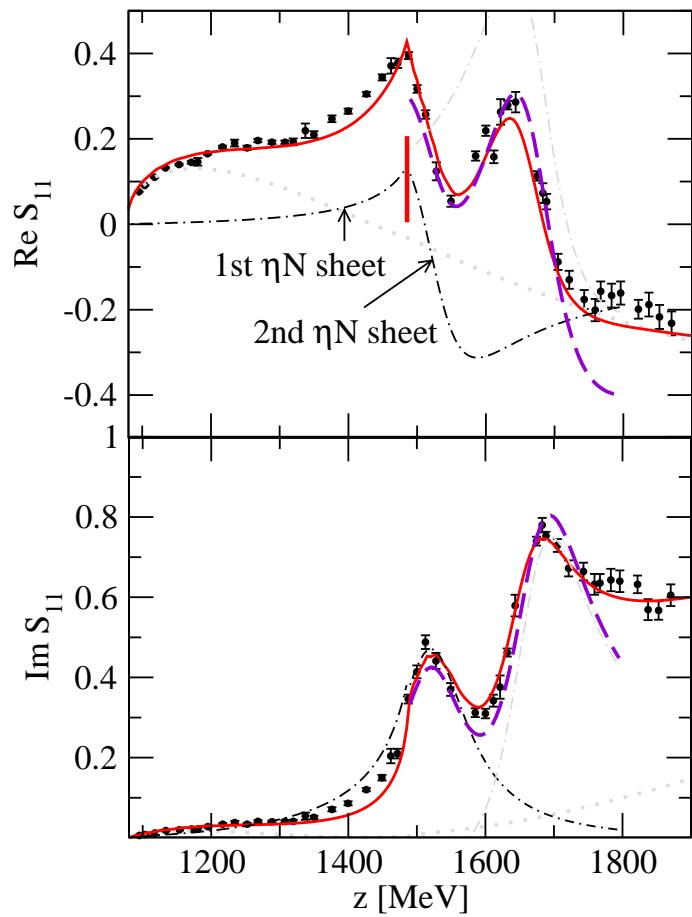
S11: background and poles



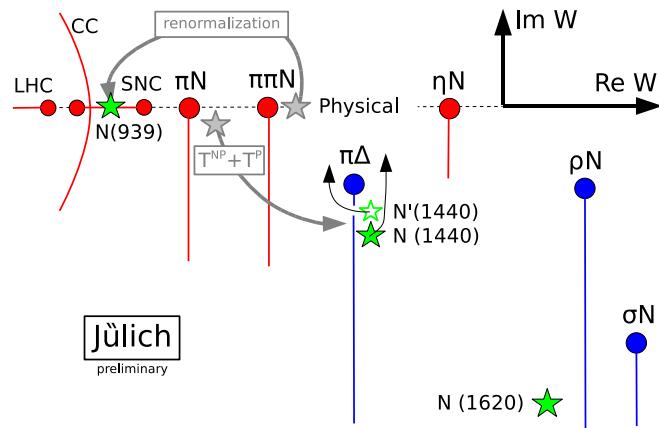
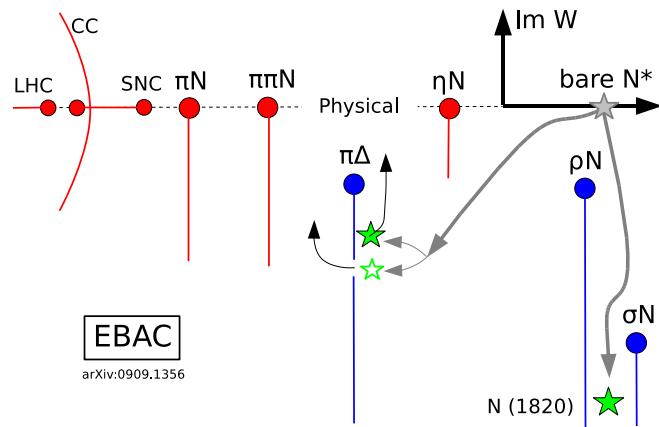
S11: background and poles



S11: cusp



P11: analytical structure



Poles and residues I

	Re Z_0 [MeV]	-2 Im Z_0 [MeV]	R [MeV]	θ [deg] $[^{\circ}]$
$N^*(1520) D_{13}$	1505	95	32	-18
Arndt06	1515	113	38	-5
Hohler93	1510	120	32	-8
Cutkosky79	1510±5	114±10	35±2	-12±5
$\Delta(1232) P_{33}$	1218	90	47	-37
Arndt06	1211	99	52	-47
Hohler93	1209	100	50	-48
Cutkosky79	1210±1	100±2	53±2	-47±1
$\Delta^*(1700) D_{33}$	1637	236	16	-38
Arndt06	1632	253	18	-40
Hohler93	1651	159	10	
Cutkosky79	1675±25	220±40	13±3	-20±25

Poles and residues II

	Re Z_0 [MeV]	-2 Im Z_0 [MeV]	R [MeV]	θ [deg] $[^{\circ}]$
$N^*(1535) S_{11}$	1519	129	31	-3
Arndt06	1502	95	16	-16
Hohler93	1487			
Cutkosky79	1510±50	260±80	120±40	+15±45
$N^*(1650) S_{11}$	1669	136	54	-44
Arndt06	1648	80	14	-69
Hohler93	1670	163	39	-37
Cutkosky79	1640±20	150±30	60±10	-75±25
$N^*(1440) P_{11}$	1387	147	48	-64
Arndt06	1359	162	38	-98
Hohler93	1385	164	40	
Cutkosky79	1375±30	180±40	52±5	-100±35

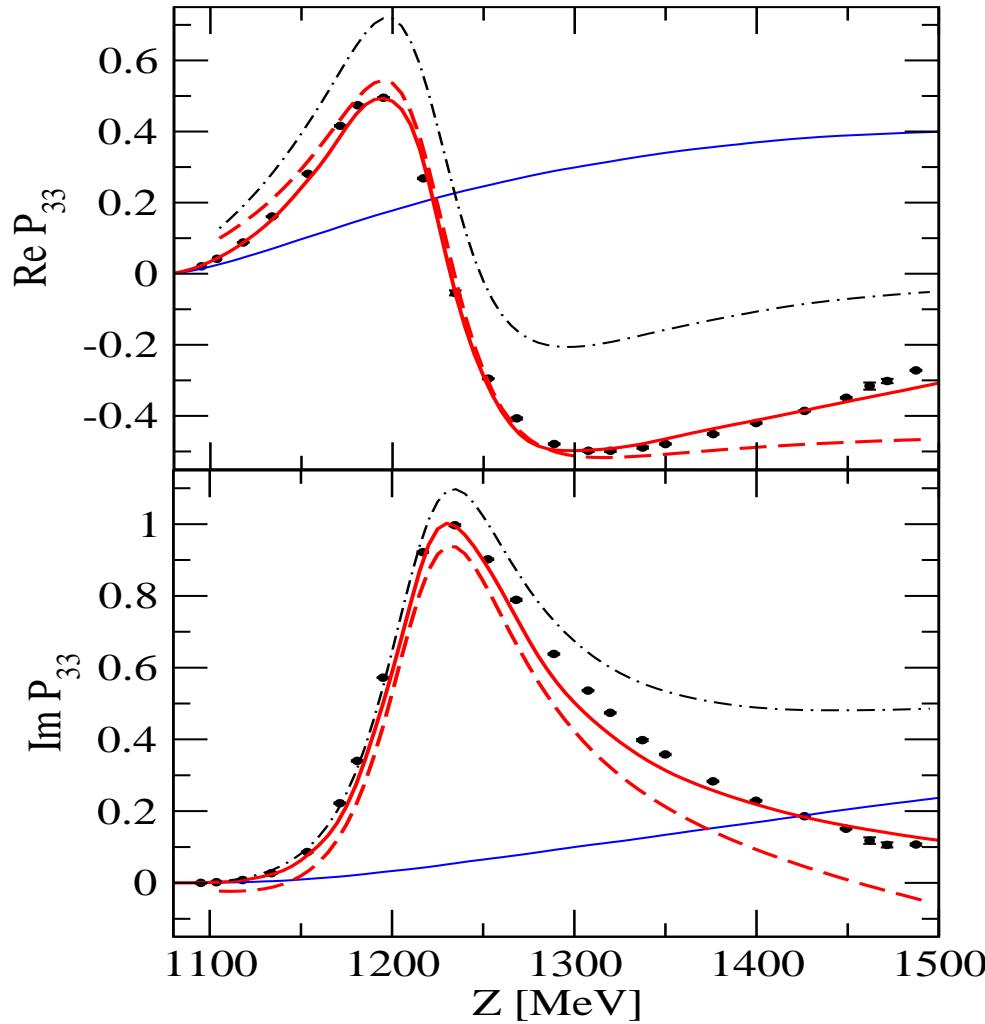
Poles and residues III

	Re Z_0 [MeV]	-2 Im Z_0 [MeV]	R [MeV]	θ [deg] $[^{\circ}]$
$\Delta^*(1620) S_{31}$	1593	72	12	-108
Arndt06	1595	135	15	-92
Hohler93	1608	116	19	-95
Cutkosky79	1600 \pm 15	120 \pm 20	15 \pm 2	-110 \pm 20
$\Delta^*(1910) P_{31}$	1840	221	45	-153
Arndt06	1771	479	38	+172
Hohler93	1874	283	19	
Cutkosky79	1880 \pm 30	200 \pm 40	20 \pm 4	-90 \pm 30
$N^*(1720) P_{13}$	1663	212	14	-82
Arndt06	1666	355	25	-94
Hohler93	1686	187	15	
Cutkosky79	1680 \pm 30	120 \pm 40	8 \pm 12	-160 \pm 30

Background

	T^{NP}	a_0^{P}	Ratio
$N^*(1440) P_{11}$	$15.3 - 7.60i$	$-10.9 + 7.92i$	0.26
$\Delta^*(1620) S_{31}$	$9.01 - 6.37i$	$-1.21 + 0.24i$	0.9
$\Delta^*(1910) P_{31}$	$4.58 - 2.76i$	$-0.78 + 0.24$	0.9
$N^*(1720) P_{13}$	$1.76 - 0.10i$	$0.45 - 0.56i$	1.3
$N^*(1520) D_{13}$	$-4.62 - 0.56i$	$3.03 + 1.23i$	0.4
$\Delta(1232) P_{33}$	$-16.7 - 3.57i$	$17.1 + 10.6i$	0.4
$\Delta^*(1700) D_{33}$	$0.80 - 0.52i$	$0.40 + 0.11i$	1.3

Poles and background P_{33}

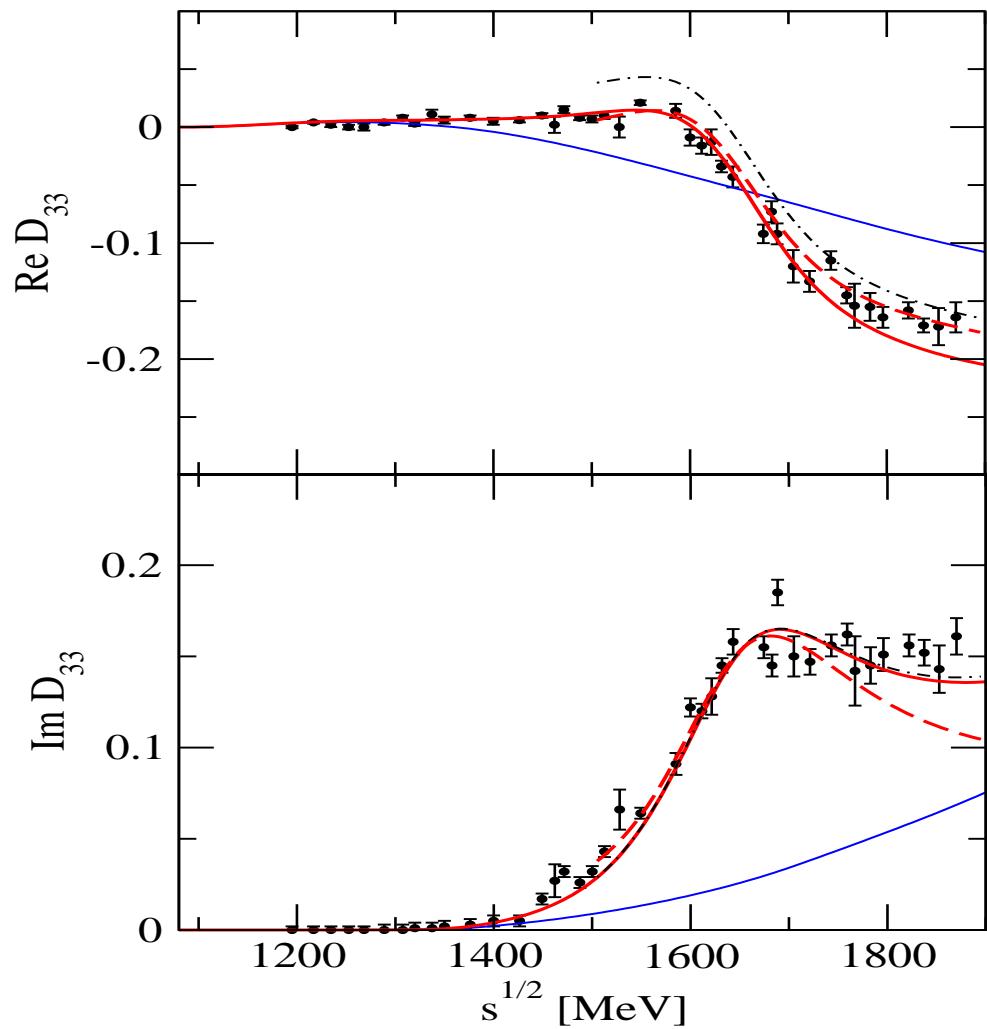


Vicinity of Pole:

$$T(Z) \sim \frac{a_{-1}}{Z-Z_0} + T^{NP}(Z)$$

$$T(Z) \sim \frac{a_{-1}}{Z-Z_0} + a_0$$

Poles and background D_{33}

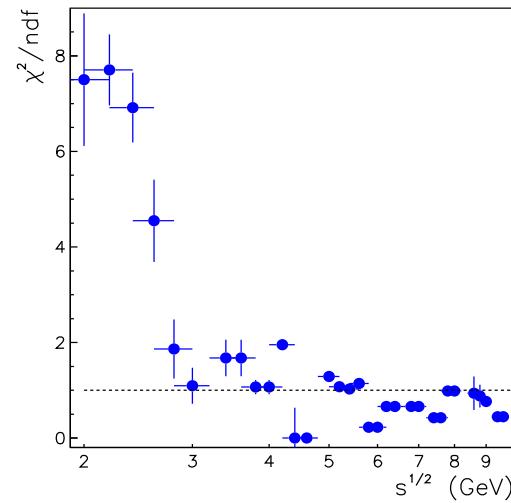
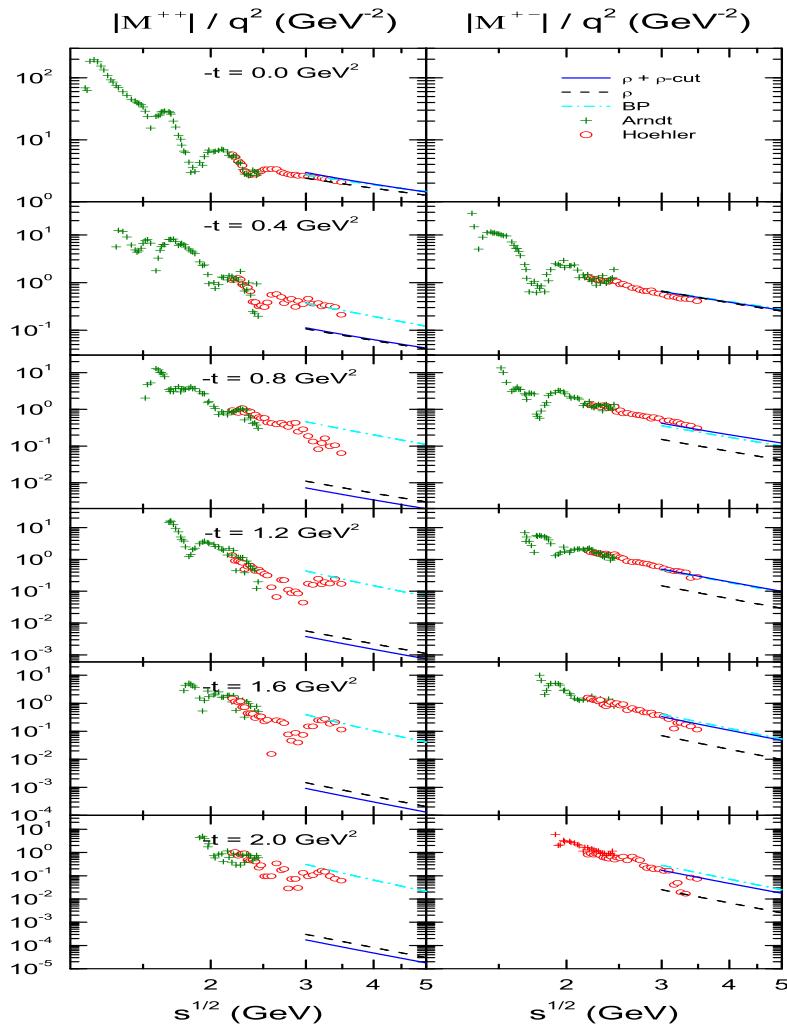


Vicinity of Pole:

$$T(Z) \sim \frac{a_{-1}}{Z-Z_0} + T^{NP}(Z)$$

$$T(Z) \sim \frac{a_{-1}}{Z-Z_0} + a_0$$

Amplitudes for charge exchange



Analyticity and Unitarity

Pole and Non-Pole T-Matrix

$$T = T^P + T^{NP}$$

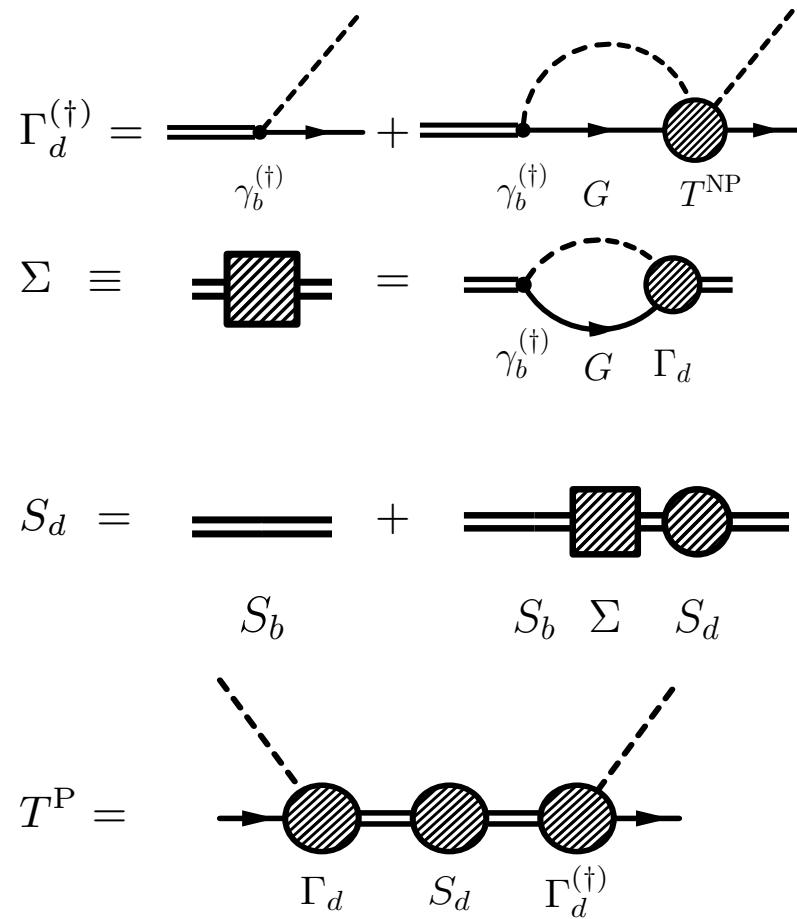
$$T = \frac{a_{-1}}{Z - Z_0} + a_0 + O(Z - Z_0)$$

$$a_{-1} = \frac{\Gamma_d \Gamma_d^{(\dagger)}}{1 - \frac{\partial}{\partial Z} \Sigma}$$

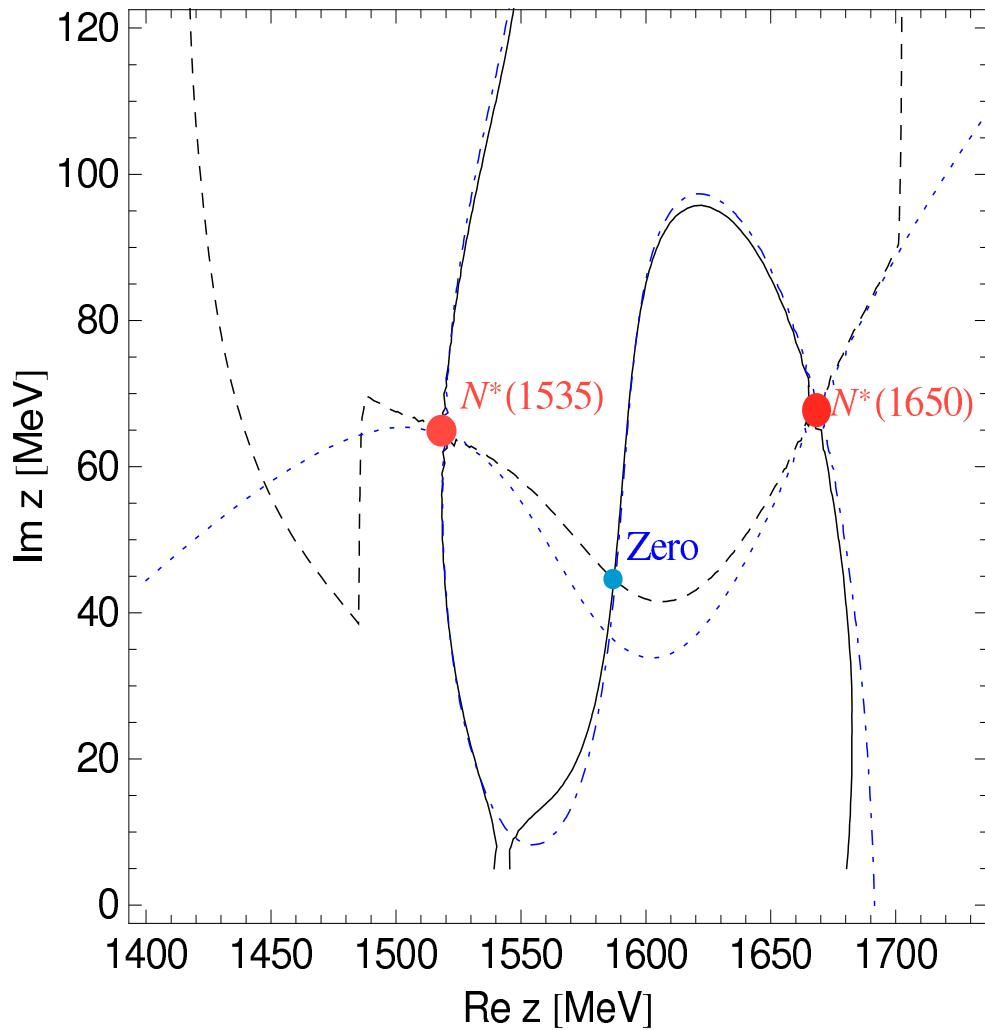
$$a_0 = T^{NP} + a_0^P$$

$$a_0^P = \frac{a_{-1}}{\Gamma_d \Gamma_d^{(\dagger)}} *$$

$$* \left(\frac{\partial}{\partial Z} (\Gamma_d \Gamma_d^{(\dagger)}) + \frac{a_{-1}}{2} \frac{\partial^2}{\partial Z^2} \Sigma \right)$$



Tool: X-ray plot (Gauss)



$$\text{Re}[\mathcal{T}(z)] = 0$$

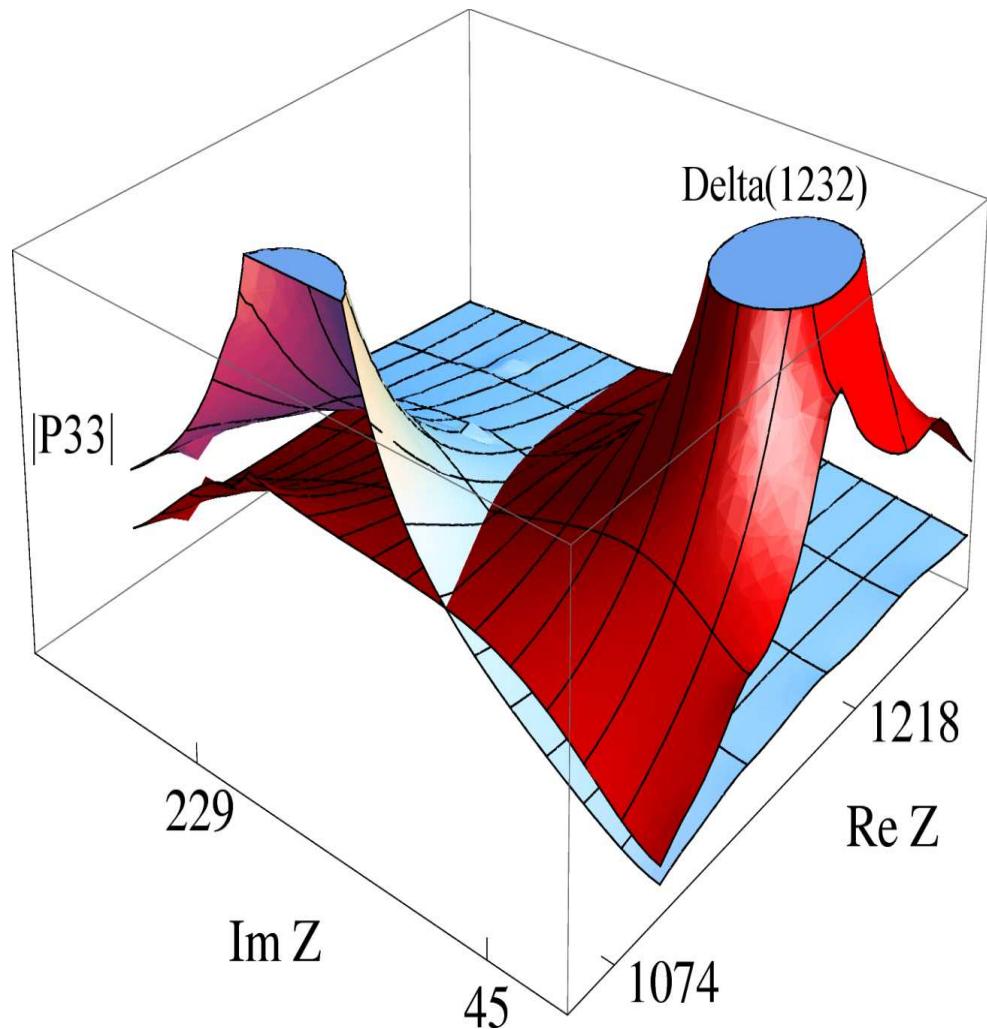
$$\text{Im}[\mathcal{T}(z)] = 0$$

$$\frac{1}{x-iy} = \frac{x+iy}{x^2+y^2}$$

$$T^{[2]}(Z) = \frac{a_{-1}(1535)}{Z - Z_0(1535)}$$

$$+ \frac{a_{-1}(1650)}{Z - Z_0(1650)}$$

Second Riemann sheet: P₃₃



$$T^{NP}$$

$$T^P + T^{NP}$$

$\gamma N \rightarrow \pi N$ Gauge invariance

Hadronic scattering:

$$\begin{aligned} \textcircled{r} &= \textcircled{o} + \textcircled{x} \\ \textcircled{b} &= \textcircled{o} + \textcircled{o} \textcircled{o} \\ \textcircled{x} &= \boxed{\textcircled{u}} + \boxed{\textcircled{u}} \textcircled{x} \\ \textcircled{T} &= \textcircled{r} \textcircled{r} + \textcircled{x} \end{aligned}$$

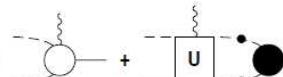
Photo-production:

$$\begin{aligned} \textcircled{M} &= \textcircled{r} + \textcircled{b} + \textcircled{g} + \textcircled{c} \\ &= \textcircled{r} + \textcircled{b} + \textcircled{g} + \boxed{\textcircled{u}} + \boxed{\textcircled{u}} \textcircled{c} \\ &\quad \boxed{\textcircled{x}} + \boxed{\textcircled{x}} \textcircled{c} \end{aligned}$$

Gauge invariance: Generalized Ward-Takahashi identity (WTI)

(Note the condition of current conservation $k_\mu M^\mu = 0$ is necessary but not sufficient!)

$$k_\mu M^\mu = -|F_s\tau\rangle S_{p+k} Q_i S_p^{-1} + S_{p'}^{-1} Q_f S_{p'-k} |F_u\tau\rangle + \Delta_{p-p'+k}^{-1} Q_\pi \Delta_{p-p'} |F_t\tau\rangle$$

Strategy: Replace  by phenomenological contact term such that the generalized WTI is satisfied

Haberzettl, PRC56 (1997), Haberzettl, Nakayama, Krewald, PRC74 (2006)