The DMT Dynamical Model for Electromagnetic Production of Pions

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DMT dynamical model

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Outline

- Motivation
- Meson-exchange πN model below 400 MeV
- DMT dynamical model for pion e.m. production
- Extension to higher energies
- Conclusions

Motivation

QCD ⟺ Hadronic phenomena

- low energies — ChPT
- high energies, high momentum transfer— pQCD
- medium energies

  □LQCD

  □Phenomenology : hadron models, reaction theory

Aim: To construct a coupled-channel dynamical model to study πN scattering and pion e.m. production

- low energies:

  e.m. threshold pion production, low energy theorems and compare with ChPT

- medium energies:

  N!Δ transition form factors, resonance parameters

- high energy and high momentum transfer:

  transition to pQCD region?

Threshold π^0 electromagnetic production

Photoproduction

	HBChPT $O(p^4)$	Dispersion relation	Exp. ($10^{-3}/m_\pi$)
$E_{0+}\big\vert_{\pi^0 p}$	-1.1	-1.22	-1.33±0.88±0.03
$E_{0+}\big\vert_{\pi^+ n}$	-0.43	-0.56	-0.45±0.06±0.02

- LET (Gauge Inv. + PCAC)□ $E_{0+}(\pi^0 p) = -2.3 \text{ x } 10^{-3}/m_\pi$

$$E_{0+}(\pi^0 p) = -\frac{2.3 \text{ x } 10^{-3}}{m_\pi}(1+O(\mu))$$

ChPT¡ The above expansion in $\mu = m_\pi/m_N$ converges slowly

Electroproduction

HBChPT a low energy effective field theory respecting the symmetries of QCD, in particular, chiral symmetry

perturbative calculation crossing symmetric

DMT Lippman-Schwinger type formulation with potential constructed from chiral effective lagrangian

unitarity loops to all orders

$\boxed{\text{What are the predictions of DMT?}}$

$\gamma^* N \leftrightarrow \Delta$ transition

- In a symmetric SU(6) quark model, the e.m. excitation of the Δ could proceed only via M1 transition

- If the Δ is deformed, then the photon can excite a nucleon into a Δ through electric E2 and Coulomb C2 quadruple transitions

- At $Q^2 = 0$, recent experiments give, R_{EM} = E2/M1 ' -2.5%, ($Q_{N!\Delta}$ = -0.108fm^2 < 0, oblate),

indication of a deformed Δ

Resonance parameters

For example, in the case of the four-star resonance $S_{11}(1535)$,

- Breit-Wigner mass (MeV): 1520 –1555 (¼ 1535)
- Breit-Wigner width (MeV): 100 – 200 (¼ 150)

120 ± 20,	Hoehler	'79	(πN ! πN)
270 ± 50,	Cutkovsky,	'79	(πN ! πN)
66 ,	Arndt	'95	(πN ! πN)
151 ± 27,	Manley	'92	(πN ! πN, ππN)
151 – 198,	Mosel	'98	(πN ! πN, ππN, ηN, KΣ)

- Pole position: (1495-1515, 90-250)
- $A^{p}_{1/2}(10^{-3}\ \mathrm{GeV}^{-1/2})$:

60	, Arndt	'96	(γN!πN)
120	,Krusche	'97	(γN! ηN)

Simultaneous analysis of

(πN ! πN, γN!πN, γN! ηN)

$\gamma^* N \leftrightarrow \Delta$ transition and pQCD

pQCD predicts that as Q^2 !1,

- hadronic helicity conservation: $A_{1/2}$ À $A_{3/2}$
- scaling: $A^{\Delta}_{1/2} : Q^{-3},\ A^{\Delta}_{3/2} : Q^{-5},\ S^{\Delta}_{1/2} : Q^{-3}$

$$R_{EM} = E_{1+}^{(3/2)} / M_{1+}^{(3/2)} \rightarrow 1,$$

$$R_{SM} = S_{1+}^{(3/2)} / M_{1+}^{(3/2)} \rightarrow const.$$

What region of Q^2 corresponds to the transition from nonperturbative to pQCD description?

Meson-exchange π N model below 400 MeV

Bethe-Salpeter equation

$$T_{\pi N} = B_{\pi N} + B_{\pi N} G_0 T_{\pi N},$$

where

$B_{\pi N} =$ sum of all irreducible two-particle Feynman amplitues

$G_0 =$ relativistic free pion-nucleon propagator

can be rewritten as $\Rightarrow$

$$T_{\pi N} = \tilde{B}_{\pi \mathrm{N}} + \tilde{B}_{\pi \mathrm{N}} \tilde{G}_0 T_{\pi N},$$

with

$$\tilde{B}_{\pi \mathrm{N}} = B_{\pi N} + B_{\pi N} (G_0 - \tilde{G}_0) \tilde{B}_{\pi N}.$$

Three-dimensional reduction

Choose a $\tilde{G}_0(k, P)$ such that

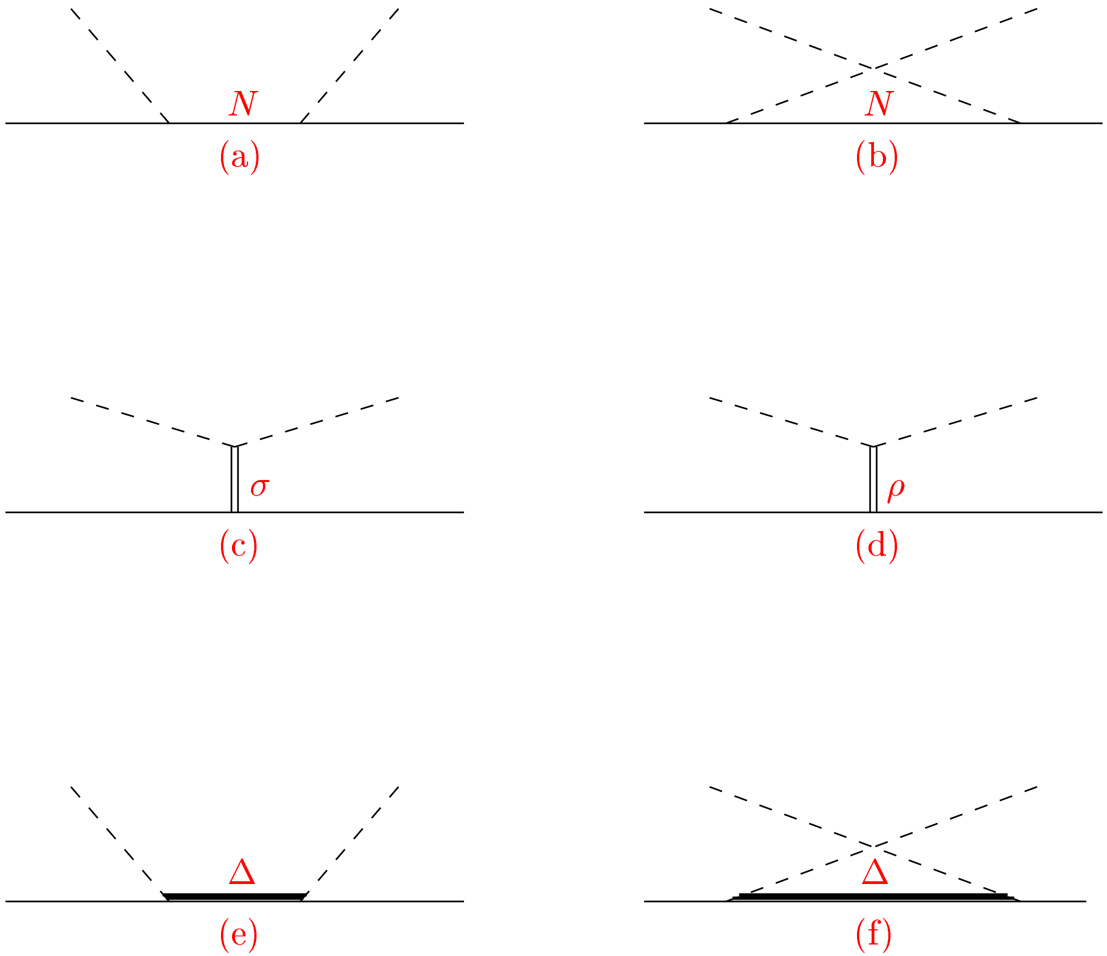
1. $T_{\pi N} = \tilde{B}_{\pi N} + \tilde{B}_{\pi N} \tilde{G}_0 T_{\pi N}$ becomes

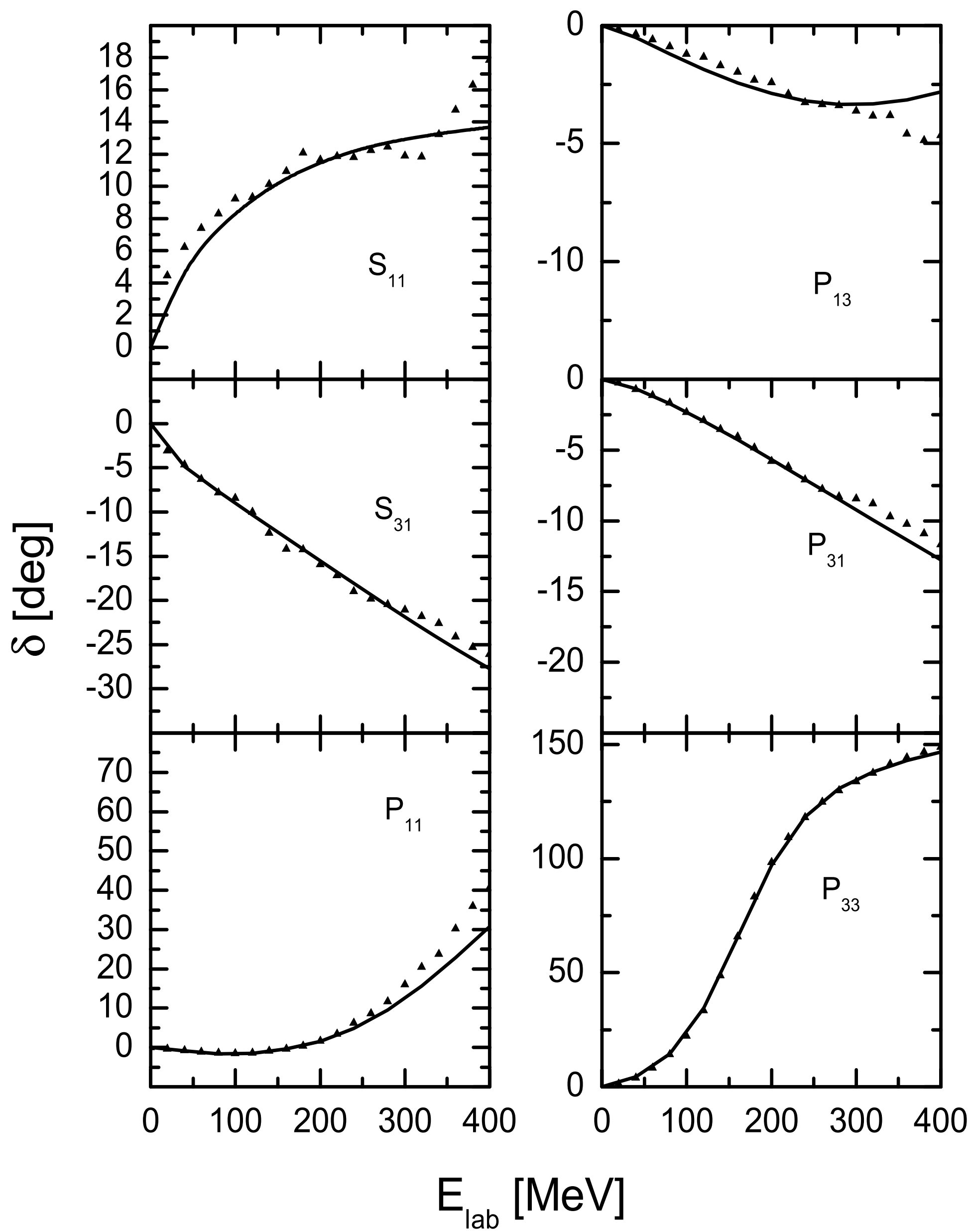
   three-dimensional

2. $\tilde{G}_0$ can reproduce πN elastic cut

Cooper-Jennings reduction scheme

Choose $B_{\pi N}$ to be given by





C.T. Hung, S.N. Yang, and T.-S.H. Lee, Phys. Rev. C64, 034309 (2001)

Dynamical model for γ N ! π N

To order e, the t-matrix for γ N ! π N is written as

$$t_{\gamma\pi}(E) = v_{\gamma\pi} + \Sigma_{\kappa}\, v_{\gamma k}\, g_k(E)\, t_{k\,N}(E), \qquad (1)$$

where,

$$v_{\gamma k} = \text{transition potential,}$$

$$t_{kN}(E) = \text{k N t-matrix,}$$

$$g_k(E) = \frac{1}{E - H_0}.$$

two ingredients

$v_{\gamma\kappa}$, $t_{\kappa N}$

Multipole decomposition of (1) gives the physical amplitude in channel
α=(*ξ*, *l*$_\pi$, *j*), (with η N intermediate states neglected)

Off-shell

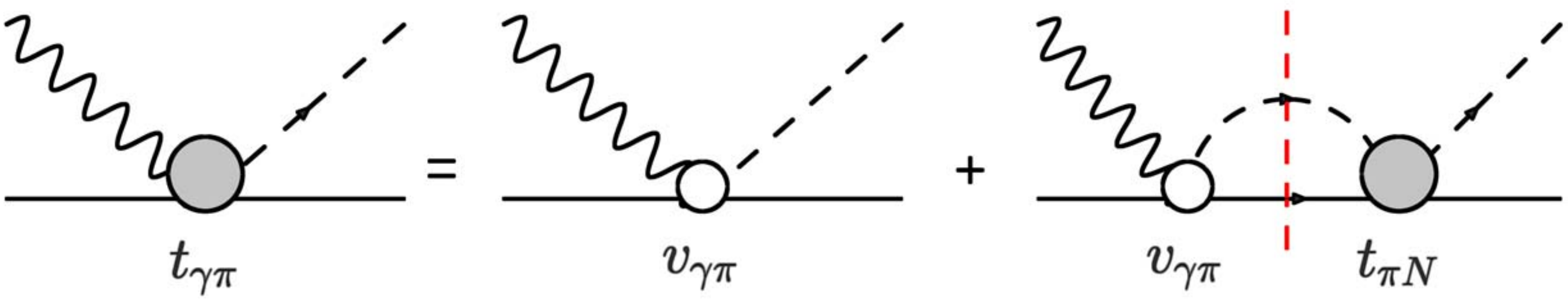
$$t_{\gamma\pi}^{(\alpha)}(q_E, k; E + i\varepsilon) = \exp(i\delta^{(\alpha)})\cos\delta^{(\alpha)} \times \left[v_{\gamma\pi}^{(\alpha)}(q_E, k) + P\int_0^\infty dq' \frac{q'^2\, R_{\pi N}^{(\alpha)}(q_E, q'; E)\, v_{\gamma\pi}^{(\alpha)}(q', k)}{E - E_{\pi N}(q')} \right]$$

where

$\delta^{(\alpha)}$, $R^{(\alpha)}$: π N scattering phase shift and reaction matrix in channel α

k=| k|, q_E : photon and pion on-shell momentum

Both on- & off-shell



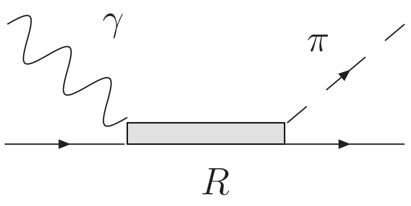
If the transition potential $v_{\gamma\pi}$ consists ot two terms,

$$v_{\gamma\pi}(E) = v^B_{\gamma\pi}(E) + v^R_{\gamma\pi}(E),$$

where

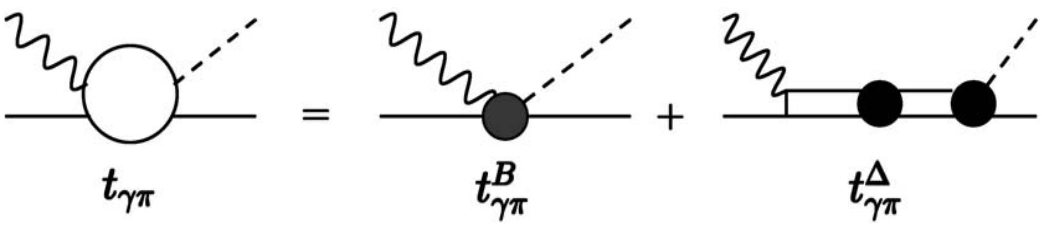
$$v^B_{\gamma\pi} = \text{ background transition potential}$$

$$v^R_{\gamma\pi} = \text{ contribution of a bare resonance } R$$



then one obtains

$$t_{\gamma\pi}(E) = t^B_{\gamma\pi}(E) + t^R_{\gamma\pi}(E),$$



with

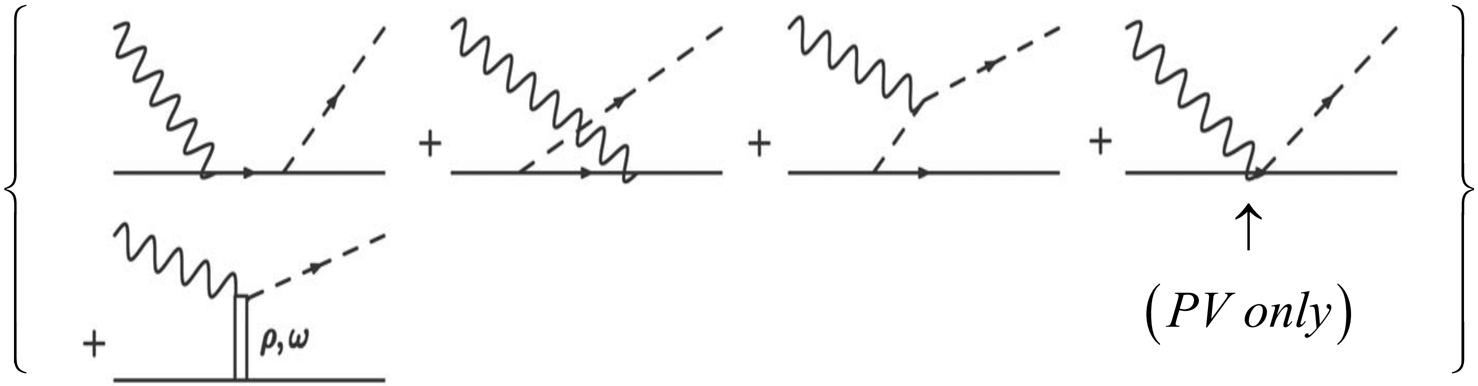
$$t^B_{\gamma\pi}(E) = v^B_{\gamma\pi} + \sum_k v^B_{\gamma k} g_k(E) t_{k\pi}(E)$$

$$t^R_{\gamma\pi}(E) = v^R_{\gamma\pi} + \sum_k v^R_{\gamma k} g_k(E) t_{k\pi}(E)$$

both t^B and t^R satisfy Fermi-Watson theorem, respectively.

DMT Model

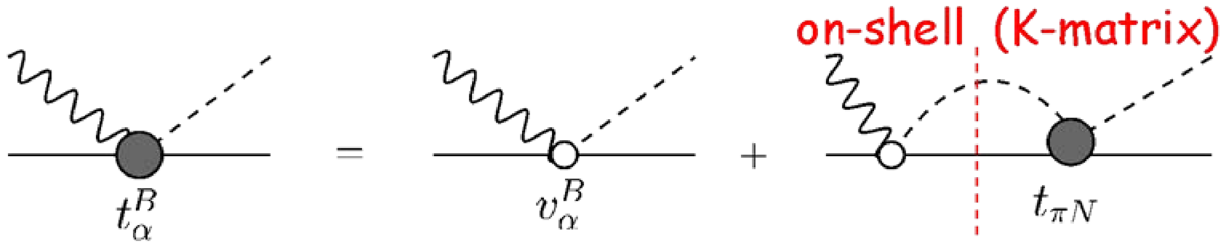
$$v_{\gamma\pi}^{B} = \left\{ \right.$$



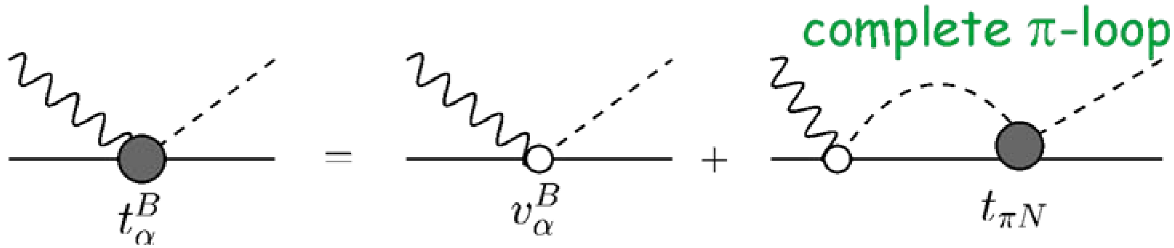
$$t_{\gamma\pi}^{B,\alpha} = \exp(i\delta^{(\alpha)})\cos\delta^{(\alpha)} \begin{cases} v_{\gamma\pi}^{B,\alpha}(W,Q^2) + P\int_0^\infty dq'\,\dfrac{q'^2\, R_{\pi N}^{(\alpha)}(q_E,q';E)\,v_{\gamma\pi}^{B,\alpha}(q',k)}{E-E_{\pi N}(q')}, & DM \\ v_{\gamma\pi}^{B,\alpha}(W,Q^2), & MAID \end{cases}$$

in the dynamical approach the background is differently defined:

K-matrix:
(MAID/SAID)



dynamical
approach:

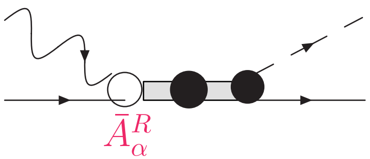


$$t_\alpha^B(DM) = v_\alpha^B\, e^{i\delta_\alpha} \cos\delta_\alpha + P\int_0^\infty dq' \frac{q'^2\, t_{\pi N}^{(\alpha)}(q_E, q')\, v_\alpha^B(q')}{E - E_{\pi N}(q')}$$

additional contribution from explicit π-loop integration

In DMT, we approximate the resonance contribution $A^R{}_\alpha(W,Q^2)$ by the following Breit-Winger form

$$A_\alpha^R(W,Q^2) = \bar{A}_\alpha^R(Q^2)\frac{f_{\gamma R}(W)\Gamma_R M_R f_{\pi R}(W)}{M_R^2 - W^2 - iM_R\Gamma_R}e^{i\phi},$$



with

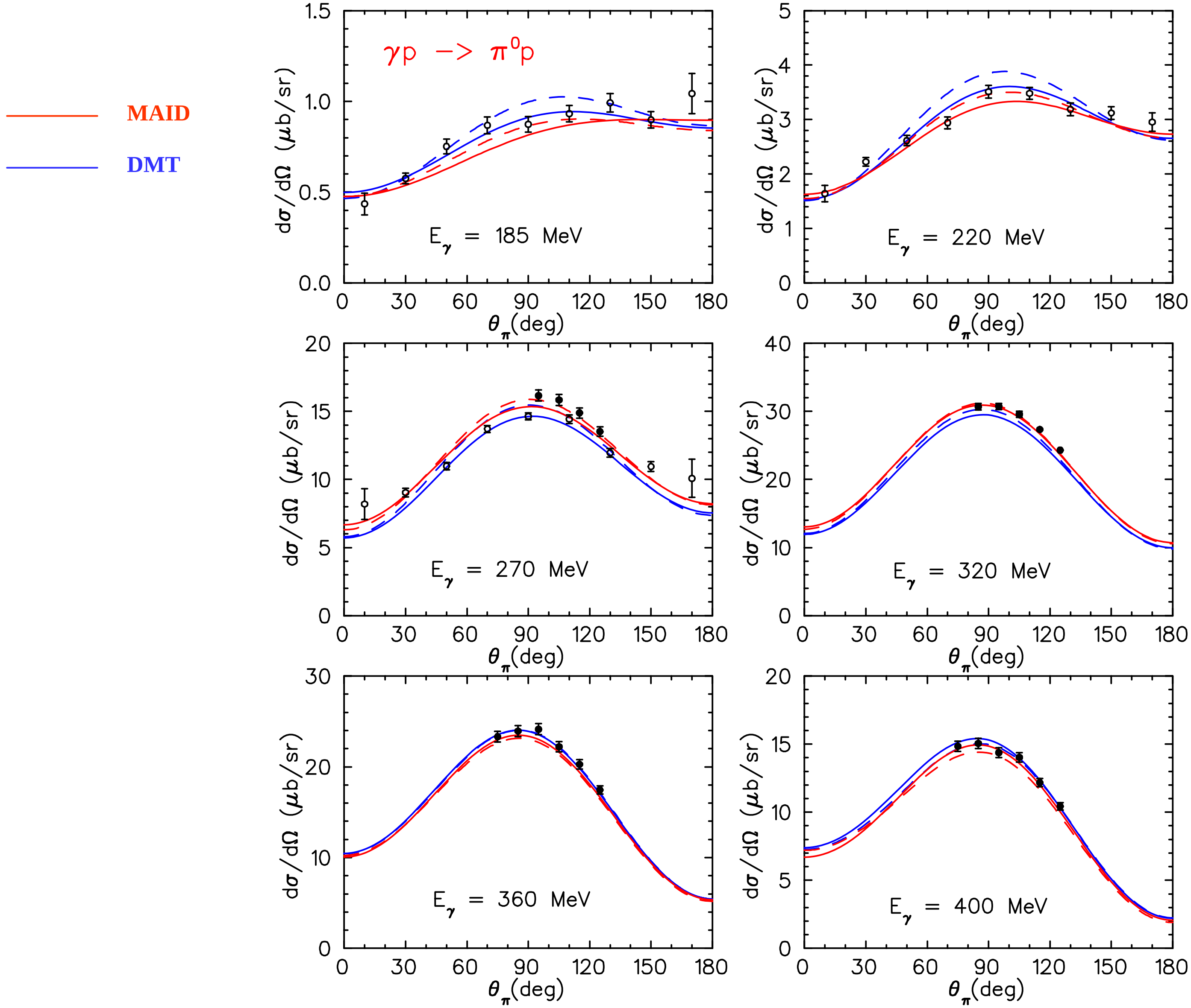
$f_{\pi R}$ = Breit-Winger factor describing the decay of the resonance R

$\Gamma_R(W)$ = total width

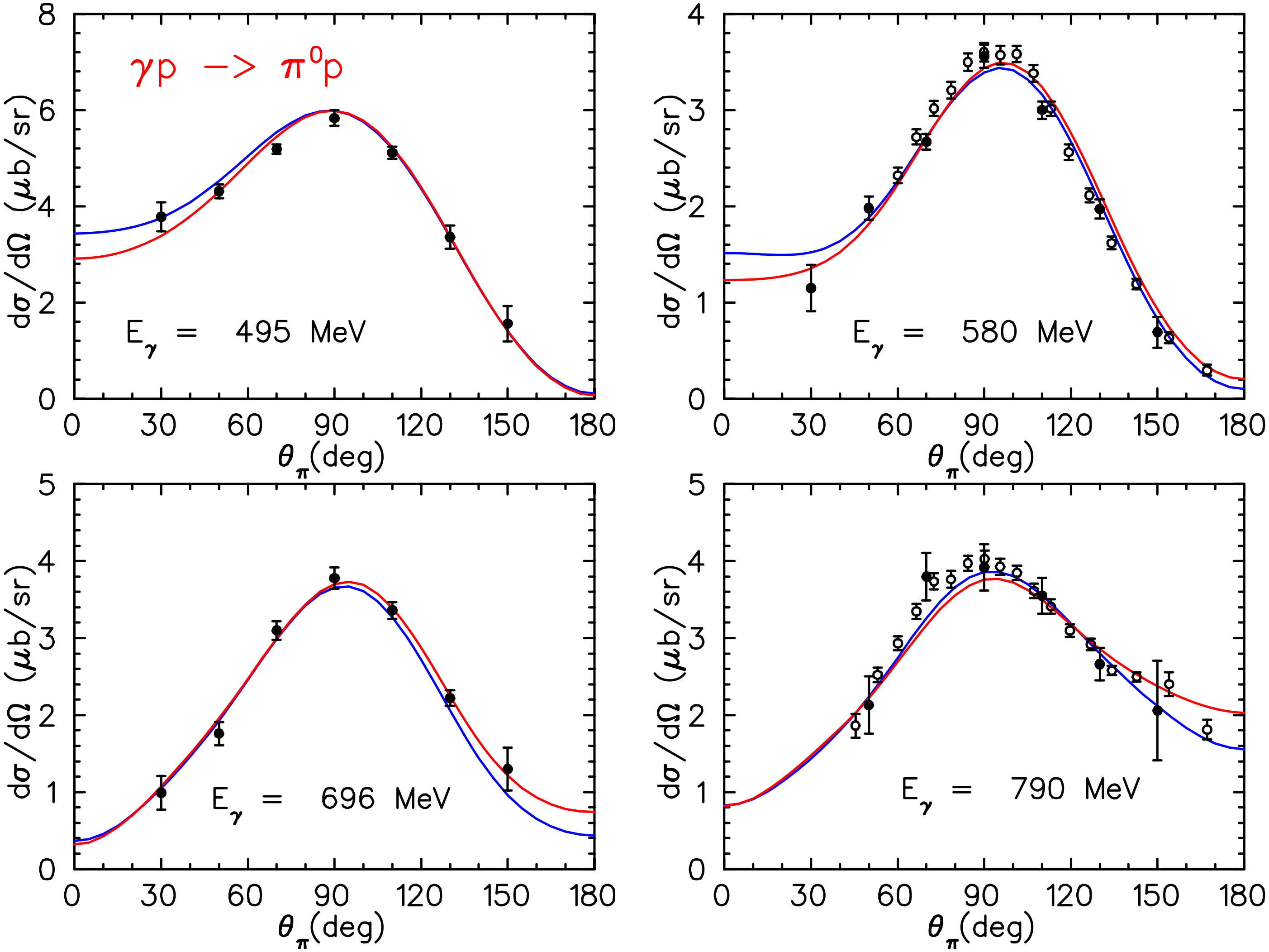
M_R = physical mass

$\phi(W)$ = to adjust the phase of the total multipole to be equal to the corresponding π N phase shift $\delta^{(\alpha)}$.

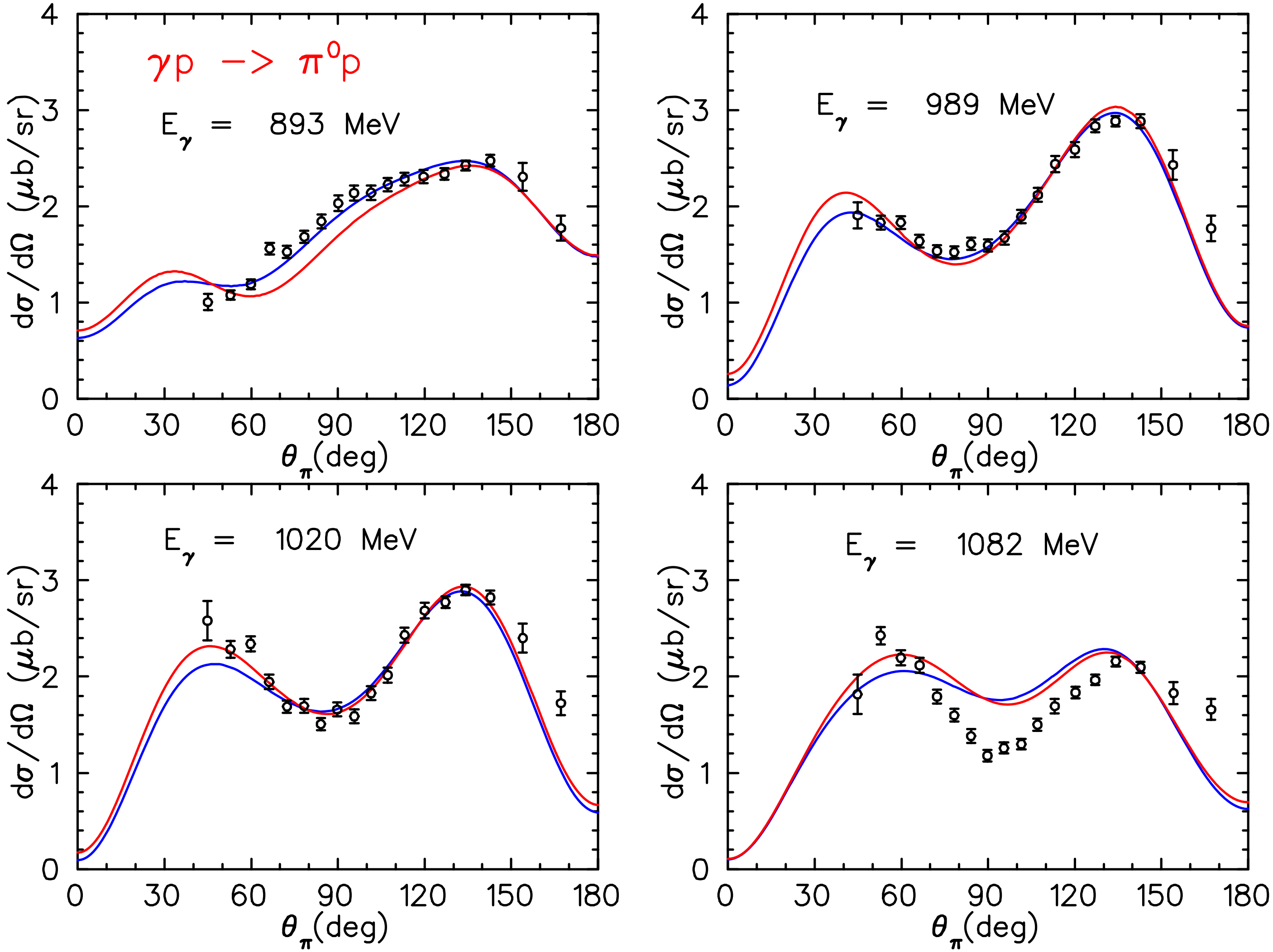
Note that $$\bar{A}_\alpha^R(Q^2) = \begin{cases} \text{bare, DMT} \\ \text{dressed, MAID} \end{cases}$$



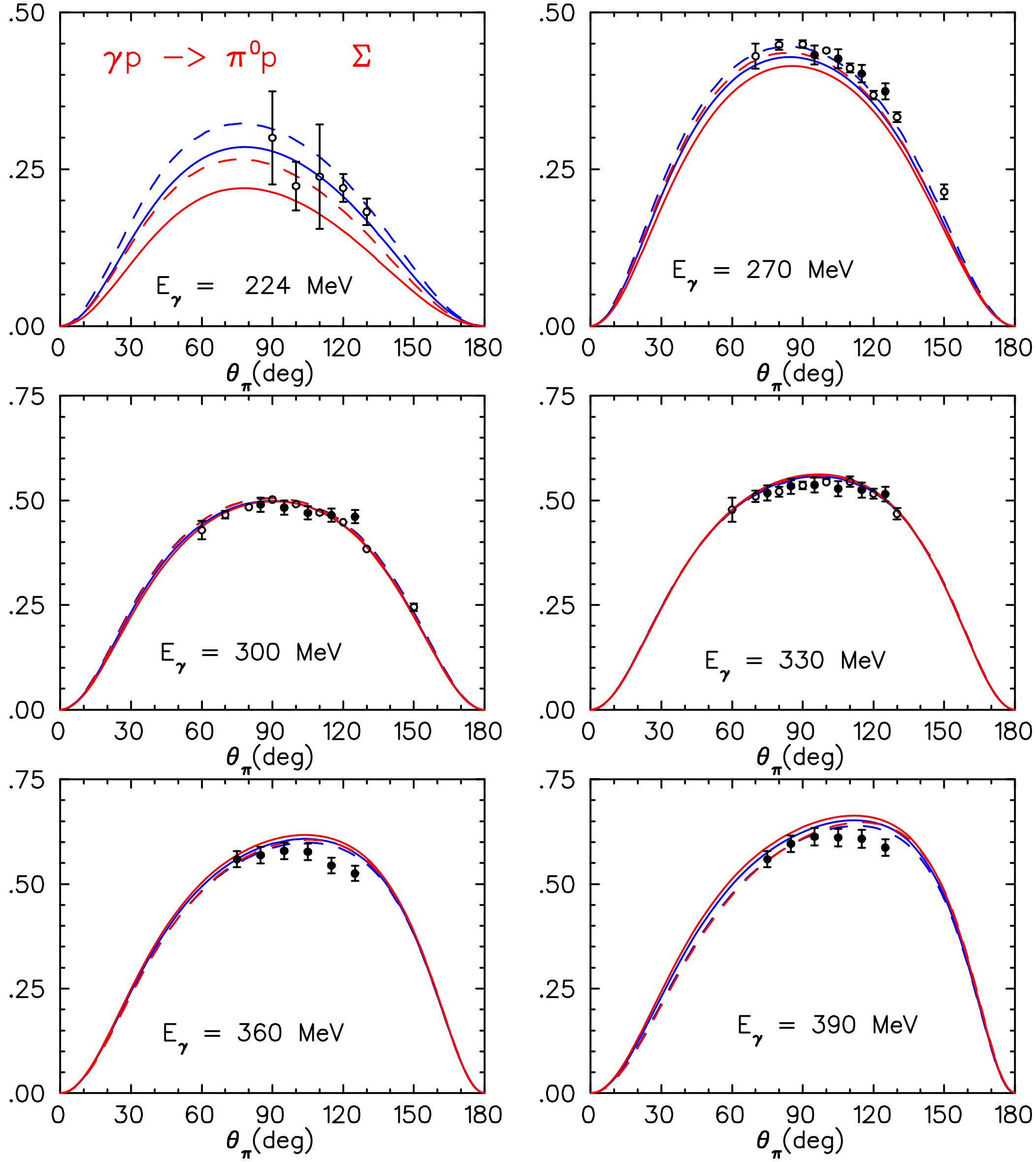
MAID
DMT
γp -> π⁰p
dσ/dΩ (μb/sr)
E_γ = 185 MeV
E_γ = 220 MeV
E_γ = 270 MeV
E_γ = 320 MeV
E_γ = 360 MeV
E_γ = 400 MeV
θ_π(deg)



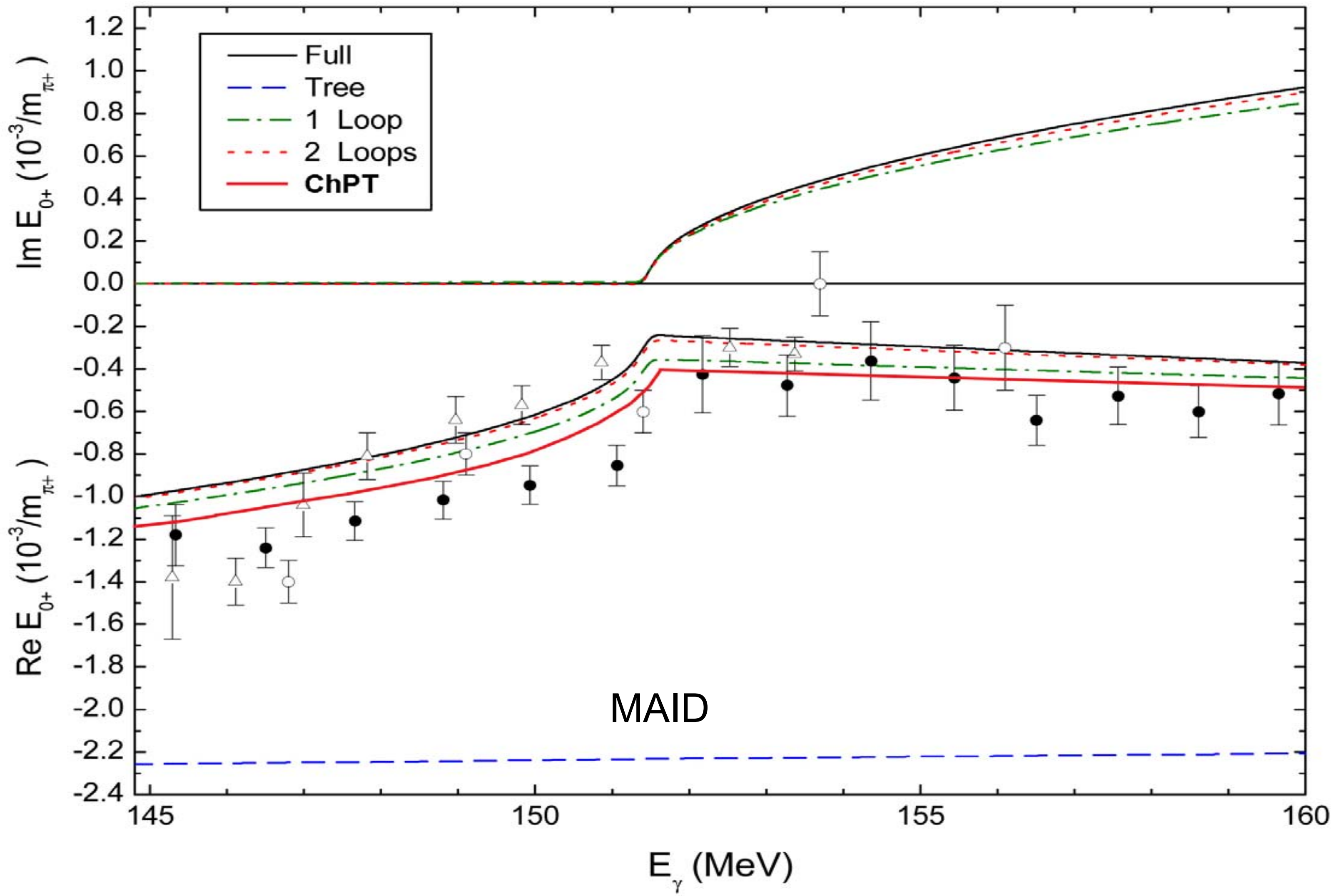
γp -> π⁰p
dσ/dΩ (μb/sr)
θπ(deg)
Eγ = 495 MeV
Eγ = 580 MeV
Eγ = 696 MeV
Eγ = 790 MeV



γp -> π⁰p
E_γ = 893 MeV
E_γ = 989 MeV
E_γ = 1020 MeV
E_γ = 1082 MeV
dσ/dΩ (μb/sr)
θ_π(deg)
0
1
2
3
4
0
30
60
90
120
150
180


γp -> π⁰p Σ
E_γ = 224 MeV
E_γ = 270 MeV
E_γ = 300 MeV
E_γ = 330 MeV
E_γ = 360 MeV
E_γ = 390 MeV
θ_π(deg)
.00
.25
.50
.75
0
30
60
90
120
150
180

$\gamma\, p \rightarrow \pi^0\, p$



Threshold values of E_{0+} (in units of $10^{-3}/m_\pi$) for different channels predicted by DMT ($Q^2 = 0$)

	Tree	1-loop	2-loop	Full	ChPT	Exp.
π□p	-2.26	-1.06 (53.1%)	-1.01 (2.2%)	-1.00	-1.1	-1.33±0.11
π□n	27.72	28.62 (3.2%)	28.82 (0.7%)	28.85	28.2±0.6	28.3±0.3
π□n	0.46	2.09 (354.3%)	2.15 **(13.0%)**	2.18	2.13	
π□p	-31.65	-32.98 (4.2%)	-33.27 (0.9%)	-33.31	-32.7±0.6	-31.8±1.9

	DMT	HBChPT
chiral symmetry	yes	yes
crossing symmetry	no	yes
unitarity	yes	no
counting	loop($g_{\pi N}$)	chiral power

Threshold values of $E_{0+}\,(10^{-3}/m_\pi)$ at $Q^2 = 0.05(\mathrm{GeV/c})^2$ for different channels predicted by DMT

	Tree	1-loop	2-loop	Full	ChPT	Exp.
π□p	-0.19	0.96	1.02	**1.03**	**0.27**	**0.57±0.11**
π□n	23.92	24.86	25.09	25.12		
π□n	1.53	3.00	3.07	3.09		
π□p	-26.42	-27.69	-27.96	-28.00		

Threshold values of $E_{0+}\,(10^{-3}/m_\pi)$ at $Q^2 = 0.1(\mathrm{GeV/c})^2$ for different channels predicted by DMT

	Tree	1-loop	2-loop	Full	ChPT	Exp.
π□p	1.30	2.37	2.43	**2.44**	**1.42**	**0.58±0.18**
π□n	20.89	21.88	22.10	22.13		
π□n	2.27	3.57	3.64	3.66		
π□p	-22.33	-23.51	-23.75	-23.79		

H. Merkel et. al., PRL 88 (2002) 012301

Threshold values of $L_{0+}\,(10^{-3}/m_\pi)$ at $Q^2 = 0.05(\text{GeV/c})^2$ for different channels predicted by DMT

	Tree	1-loop	2-loop	Full	ChPT	Exp.
π□p	-1.97	-16.7	-1.67	**-1.67**	**-1.55**	**-1.29±0.02**
π□n	4.96	5.06	5.10	5.11		
π□n	0.05	0.54	0.56	0.57		
π□p	-7.92	-8.33	-8.42	-8.43		

Threshold values of $L_{0+}\,(10^{-3}/m_\pi)$ at $Q^2 = 0.1(\text{GeV/c})^2$ for different channels predicted by DMT

	Tree	1-loop	2-loop	Full	ChPT	Exp.
π□p	-1.32	-1.15	-1.15	**-1.15**	**-1.33**	**-1.38±0.01**
π□n	2.32	2.35	2.37	2.38		
π□n	0.06	0.36	0.37	0.37		
π□p	-4.37	-4.61	-4.66	-4.67		

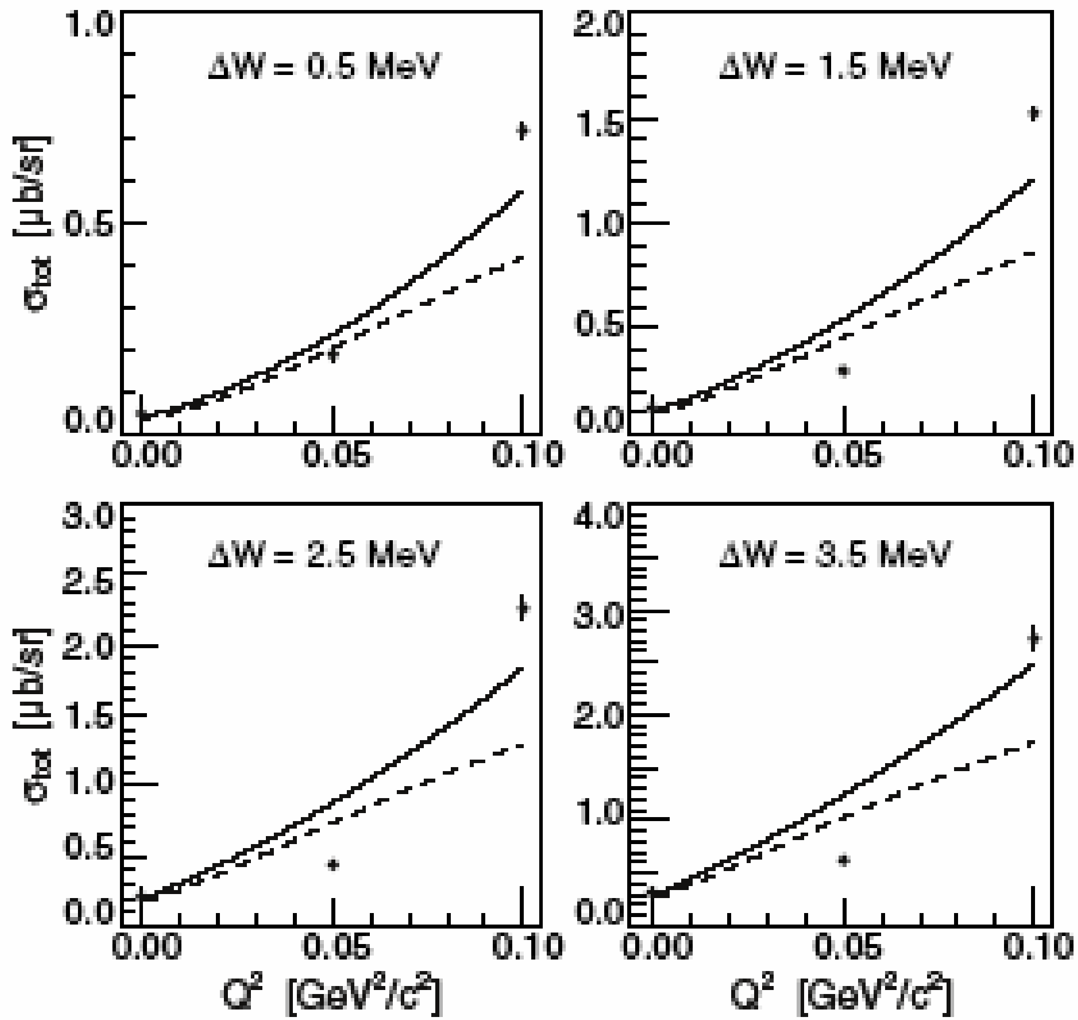


FIG. 3. The total cross section σ_{tot} versus Q^2, at a value of $\epsilon = 0.8$. The solid (dashed) line is the prediction of ChPT (MAID), data points at $Q^2 = 0$ and 0.1 GeV^2/c^2 from [6,11].

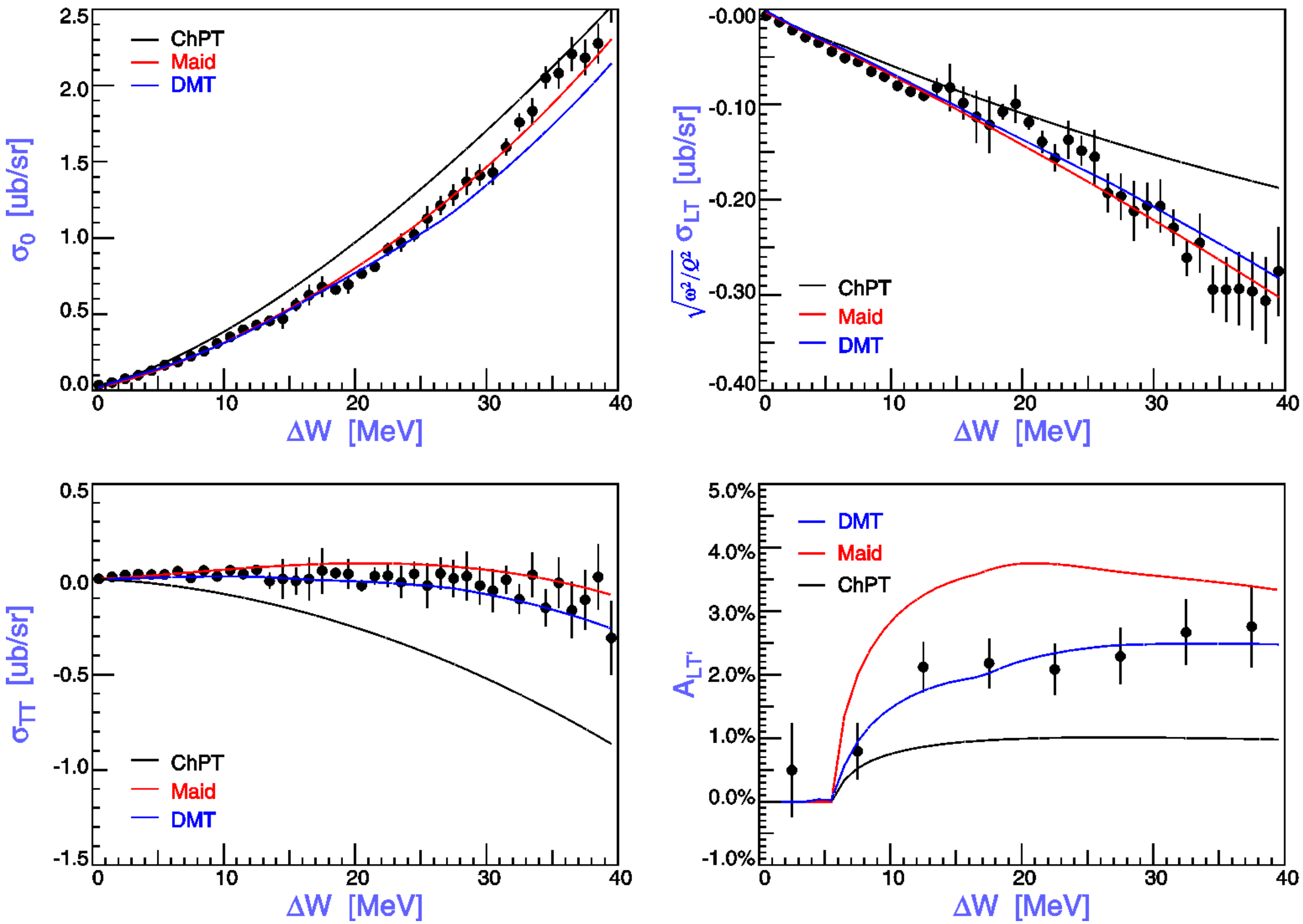
Merkel et. al., PRL 88 (2002) 012301.

$p(\vec{e},e'p)\pi^0$ Electroproduction near Threshold

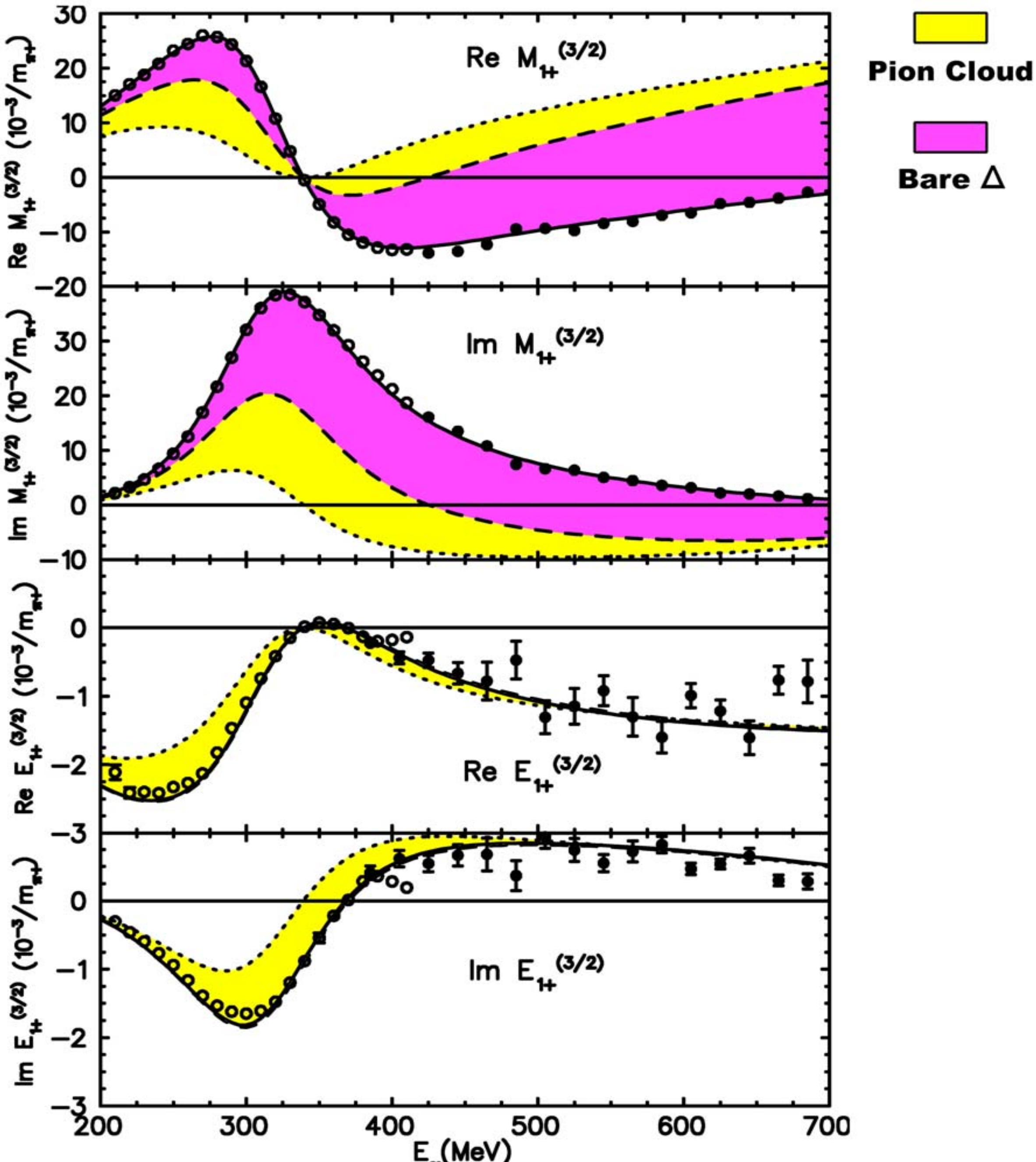
E_0=854.5 MeV, Q^2=0.05 GeV²/c², ε=0.03, θ=90°, ϕ=90°

exp. data: M. Weis, Mainz 2003

$$\frac{d\sigma_v}{d\Omega} = \frac{d\sigma_T}{d\Omega} + \varepsilon\frac{d\sigma_L}{d\Omega} + \sqrt{2\varepsilon(1+\varepsilon)}\frac{d\sigma_{LT}}{d\Omega}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{d\Omega}\cos 2\phi + h\sqrt{2\varepsilon(1-\varepsilon)}\frac{d\sigma_{LT'}}{d\Omega}\sin\phi$$



$$A_{LT'} = \frac{\sqrt{2\varepsilon(1-\varepsilon)}\,\sigma_{LT'}}{\sigma_T + \varepsilon\,\sigma_L - \varepsilon\,\sigma_{TT}}$$



Pion Cloud
Bare Δ
Re $M_{1+}^{(3/2)}$
Im $M_{1+}^{(3/2)}$
Re $E_{1+}^{(3/2)}$
Im $E_{1+}^{(3/2)}$
Re $M_{1+}^{(3/2)}$ $(10^{-3}/m_{\pi^+})$
Im $M_{1+}^{(3/2)}$ $(10^{-3}/m_{\pi^+})$
Re $E_{1+}^{(3/2)}$ $(10^{-3}/m_{\pi^+})$
Im $E_{1+}^{(3/2)}$ $(10^{-3}/m_{\pi^+})$
E_γ(MeV)

	$A_{1/2}$ $(10^{-3}GeV^{-1/2})$	$A_{3/2}$	$Q_{N\,!\,\Delta}$ (fm^2)	$\mu_N\,!\,\Delta$
PDG	**-135**	**-255**	**-0.072**	**3.512**
LEGS	**-135**	**-267**	**-0.108**	**3.642**
MAINZ	**-131**	**-251**	**-0.0846**	**3.46**
DMT	**-134** (-80)	**-256** (-136)	**-0.081** (0.009)	**3.516** (1.922)
SL	**-121** (-90)	**-226** (-155)	**-0.051** (0.001)	**3.132** (2.188)

Comparison of our predictions for the helicity amplitudes, $Q_{N\,!\,\Delta}$, and $\mu_{N\,!\,\Delta}$ with experiments and Sato-Lee's prediction. The numbers within the parenthesis in red correspond to the bare values.

$$\bar{A}_\alpha^\Delta(Q^2) = X_\alpha^\Delta(Q^2)\bar{A}_\alpha^\Delta(0)\frac{k}{k_w}F(Q^2), \quad \alpha = M,\ E,\ S$$

$$F(Q^2) = (1+\beta Q^2)e^{-\gamma Q^2}G_D(Q^2), \quad G_D(Q^2) = 1/(1+Q^2/0.71)^2.$$

β and γ were determined by setting $X_M^\Delta(Q^2) \equiv 1$,

and fitting $\bar{A}_\alpha^\Delta(Q^2)$ to the data for G_M^*.

$\bar{A}_M^\Delta(0)$ and $\bar{A}_E^\Delta(0)$ were determined by fitting to the multipoles.

fitting to Jlab $d\sigma/d\Omega$ data of $p(e,e'p)\pi^0$ (751+867 pts)

$\Rightarrow$

$$X_E^\Delta(\mathrm{DMT}) = 1 + Q^4/2.4, \quad X_S^\Delta(\mathrm{DMT}) = 1 - 10Q^2.$$

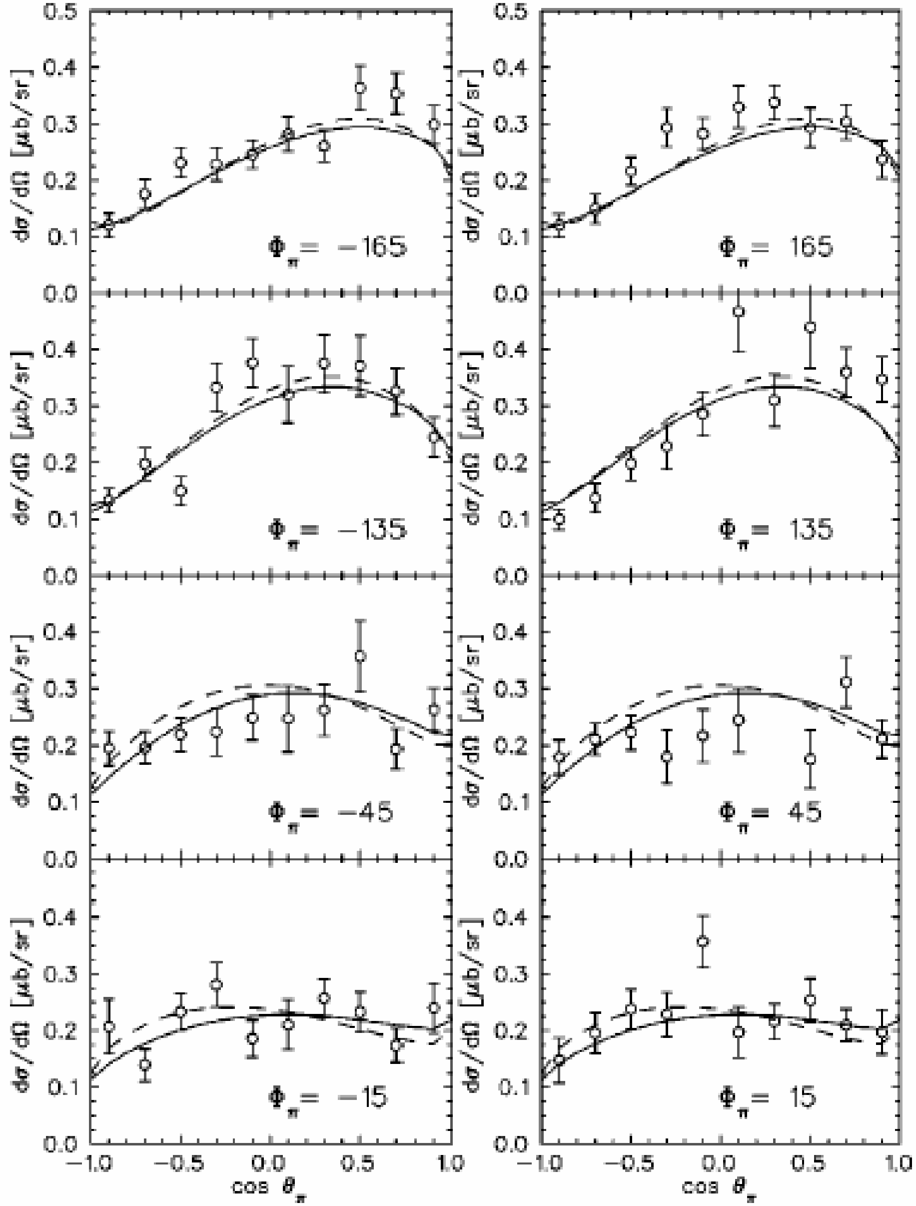
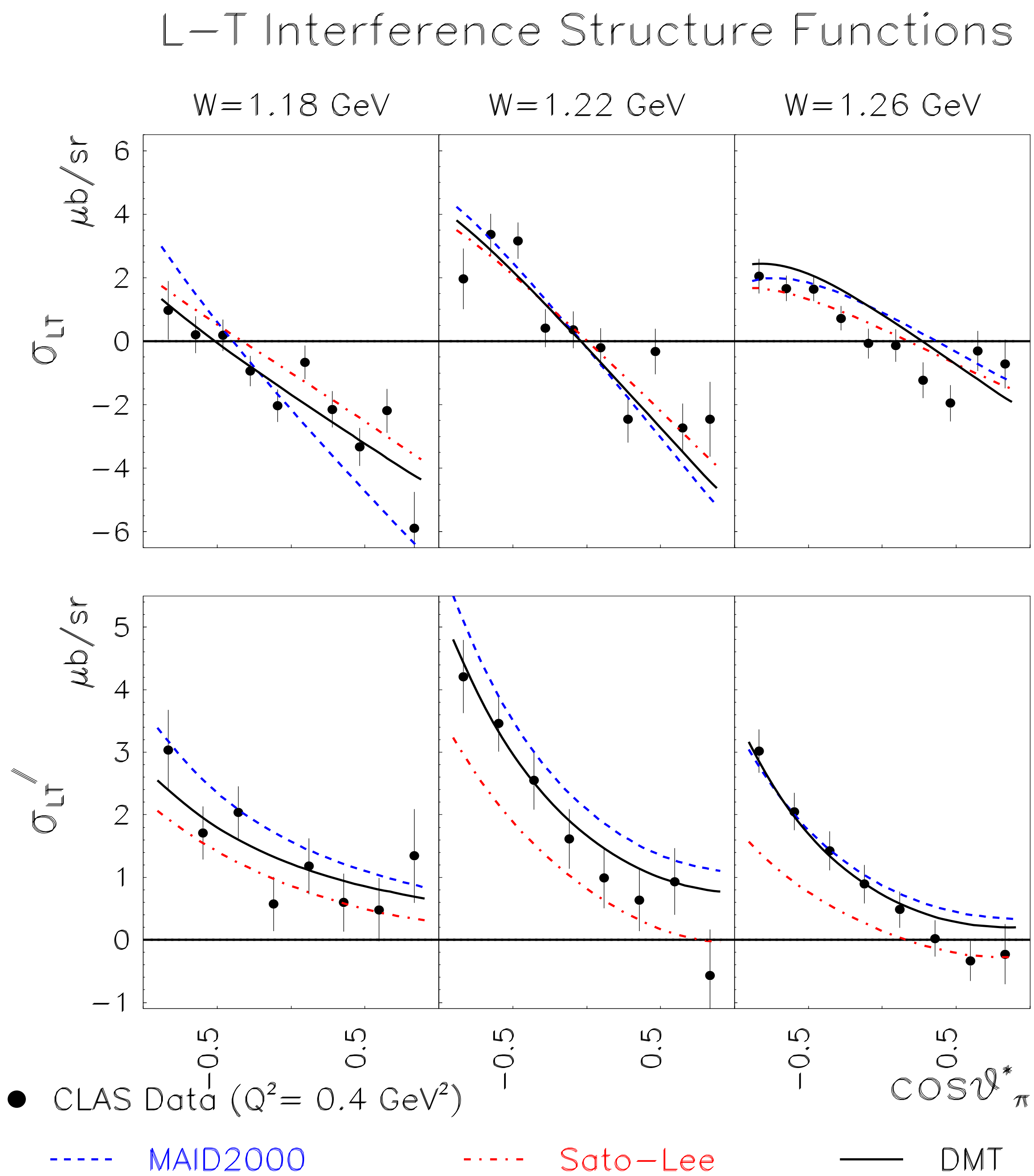
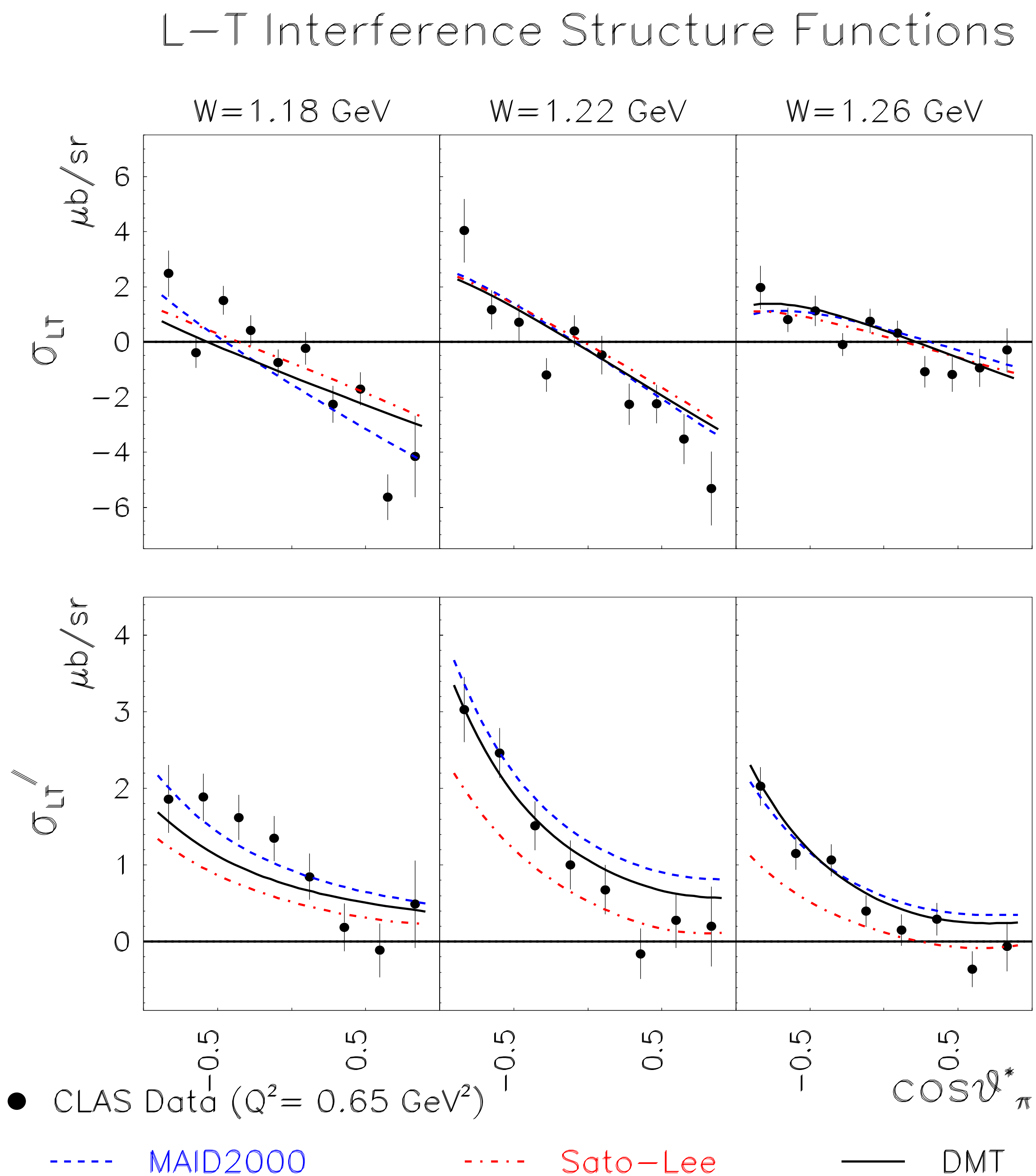
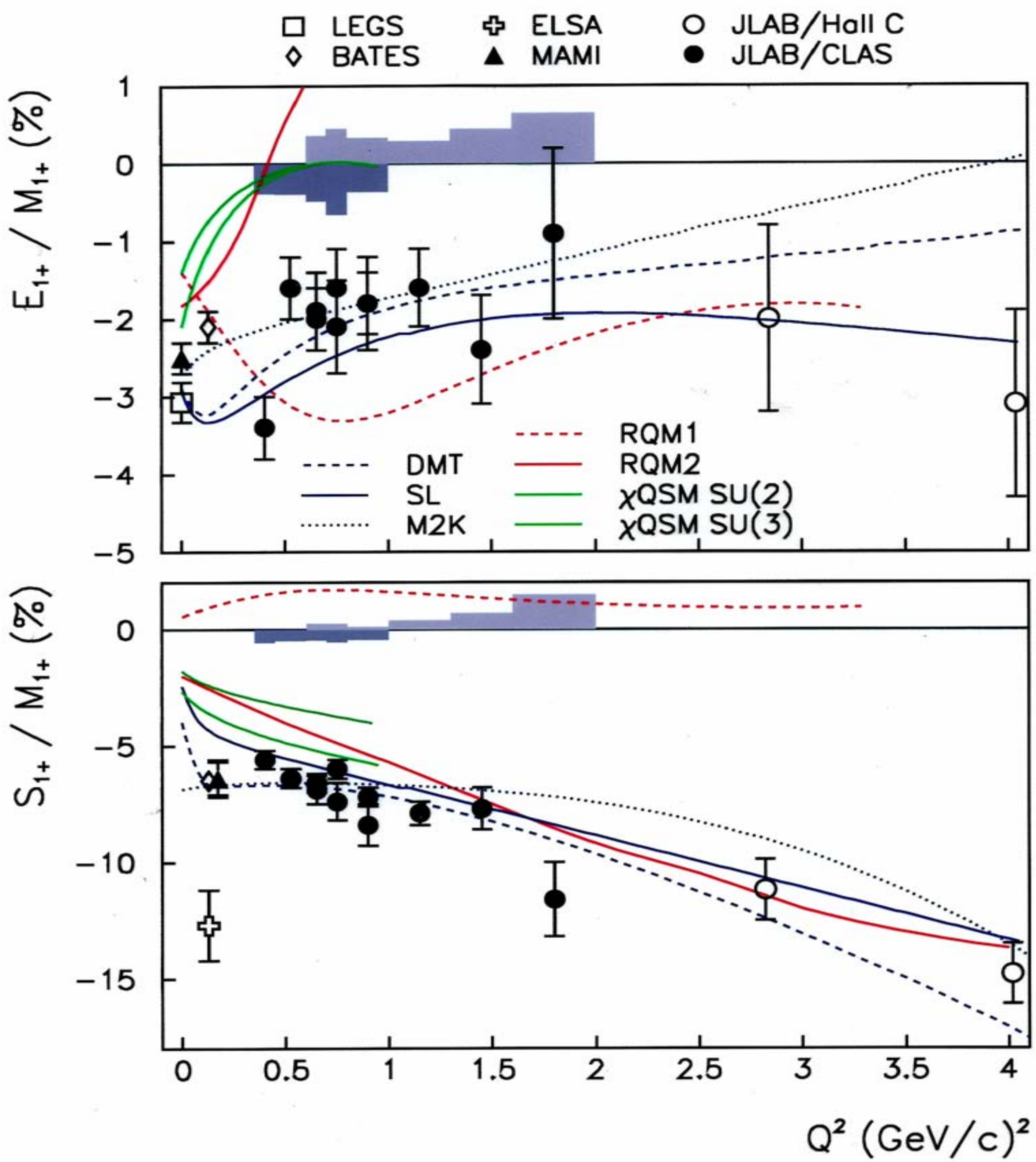


FIG. 1. The virtual photons differential cross sections at $Q^2 = 4.03\ (\mathrm{GeV}/c)^2$ and $W = 1232$ MeV. The full and dashed curves are the results from the MAID and DM analysis, respectively. Data are from Ref. [1].



L−T Interference Structure Functions
W=1.18 GeV
W=1.22 GeV
W=1.26 GeV
μb/sr
σ_{LT}
σ_{LT}'
6
4
2
0
−2
−4
−6
5
3
1
−1
−0.5
0.5
$\cos\vartheta^*_\pi$
CLAS Data (Q^2= 0.4 GeV^2)
MAID2000
Sato−Lee
DMT


L−T Interference Structure Functions
W=1.18 GeV
W=1.22 GeV
W=1.26 GeV
σLT
μb/sr
6
4
2
0
−2
−4
−6
σ'LT
μb/sr
4
3
2
1
0
−0.5
0.5
cos ϑ*π
CLAS Data (Q²= 0.65 GeV²)
MAID2000
Sato−Lee
DMT



LEGS
BATES
ELSA
MAMI
JLAB/Hall C
JLAB/CLAS
E_{1+} / M_{1+} (%)
1
0
−1
−2
−3
−4
−5
DMT
SL
M2K
RQM1
RQM2
χQSM SU(2)
χQSM SU(3)
S_{1+} / M_{1+} (%)
0
−5
−10
−15
0
0.5
1
1.5
2
2.5
3
3.5
4
Q^2 $(GeV/c)^2$

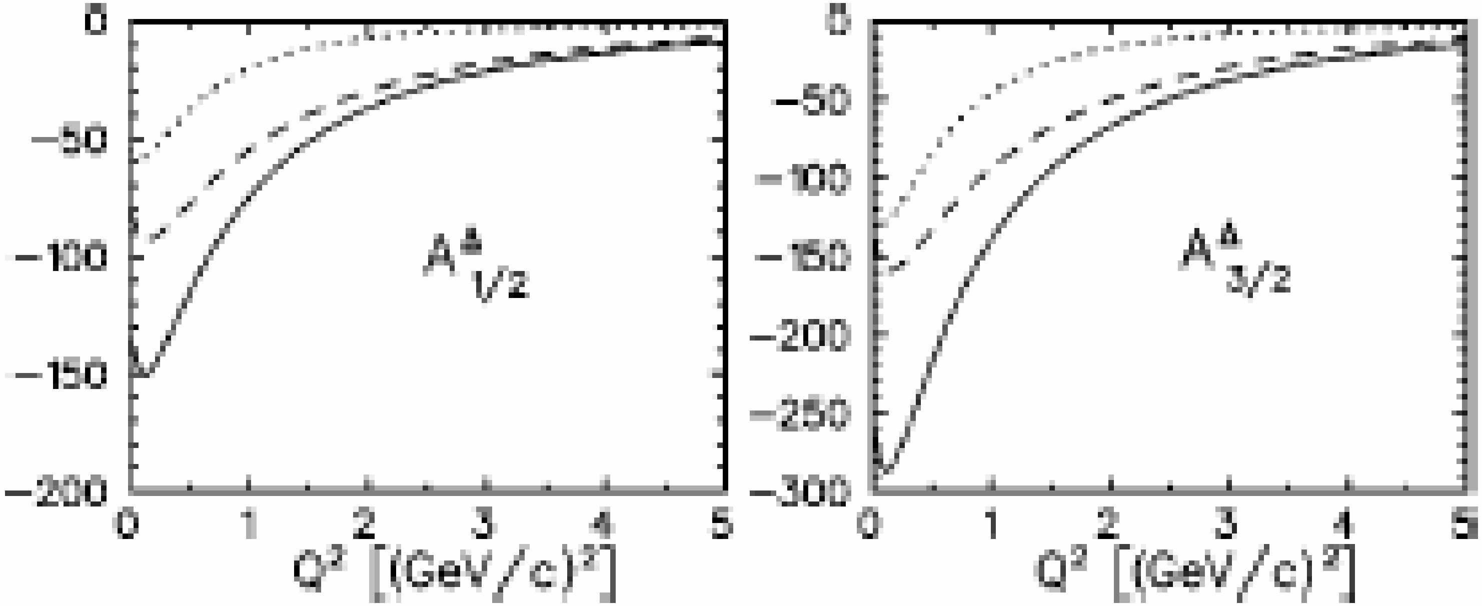


FIG. 4. The Q^2 dependence of the bare (dashed curves) and dressed (solid curves) helicity amplitudes $A_{1/2}$ and $A_{3/2}$ (in units of 10^{-3} $\mathrm{GeV}^{-1/2}$) extracted with DM. The dotted curves are the pion cloud contributions.

$A_{1/2}$ ¼ $A_{3/2}$, hadron helicity conservation not yet observed

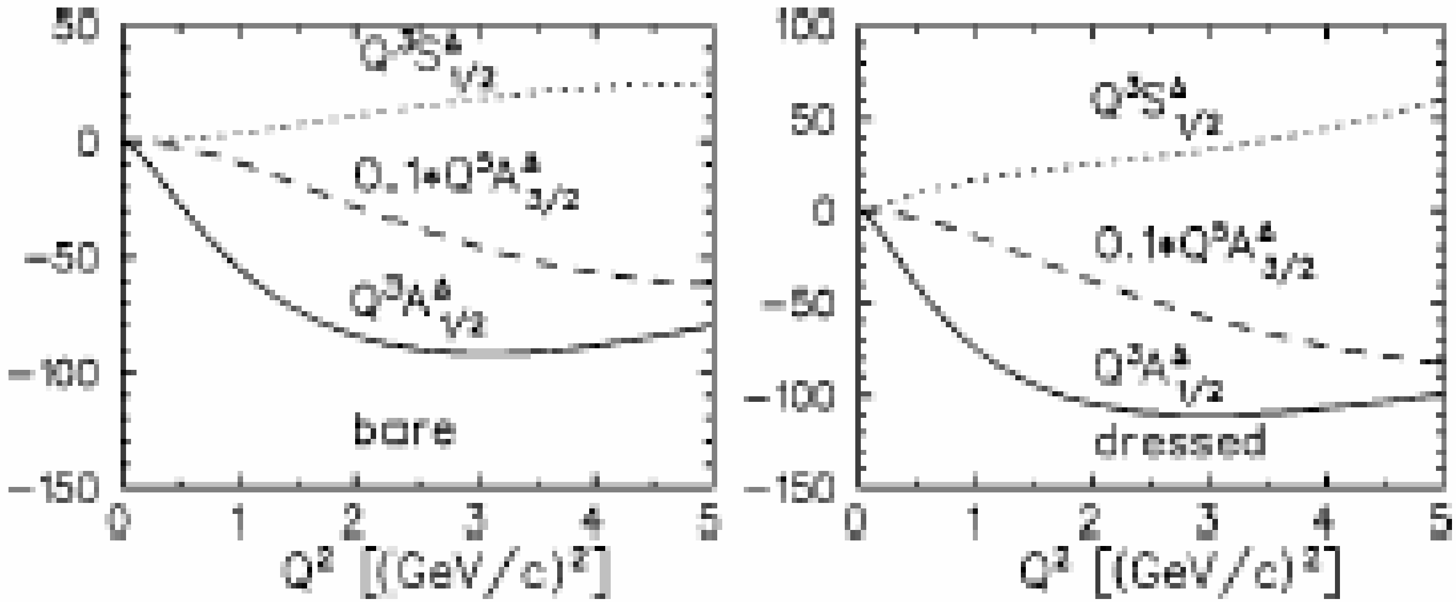


FIG. 5. The Q^2 dependence of the $Q^3A^{\Delta}_{1/2}$ (solid curve), $Q^5A^{\Delta}_{3/2}$ (dashed curve), and $Q^3S^{\Delta}_{1/2}$ (dotted curve) amplitudes (in units of 10^{-3} GeV$^{m/2}$) obtained with DM.

bare $S^{\Delta}_{1/2}$ and $A^{\Delta}_{1/2}$ start exhibiting pQCD scaling behavior

Extension to higher energies

- coupled π, η, 2π channels

$$t_{ij}(E) = v_{ij} + \sum_k v_{ik} g_k(E) t_{kj}(E),$$

$$(i,\ j,\ k = \pi,\ \eta)$$

- Include resonances R's with couplings to π, η, 2π channels

$$v_{ij}(E) = v_{ij}^B(E) + v_{ij}^R(E)$$

Non-resonant background v_{ij}^B :

$$v_{\pi\pi}^B \text{ as given before,}$$

$$v_{\pi\eta}^B = v_{\eta\pi}^B = v_{\eta\eta}^B = 0.$$

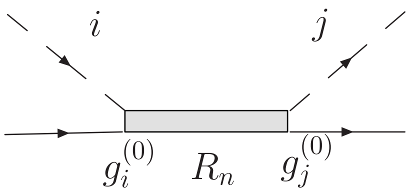
$$L_I = i g_{\pi NR}^{(0)} \bar{R} \vec{\tau} \cdot \vec{\pi} N + i g_{\eta NR}^{(0)} \bar{R} \eta N + \text{h.c.}$$

Resonance contribution v_{ij}^{R} :

$$v_{ij}^{R} = \sum_{n=1}^{N} v_{ij}^{R_n}(q', q; E),$$

for N overlapping resonances.

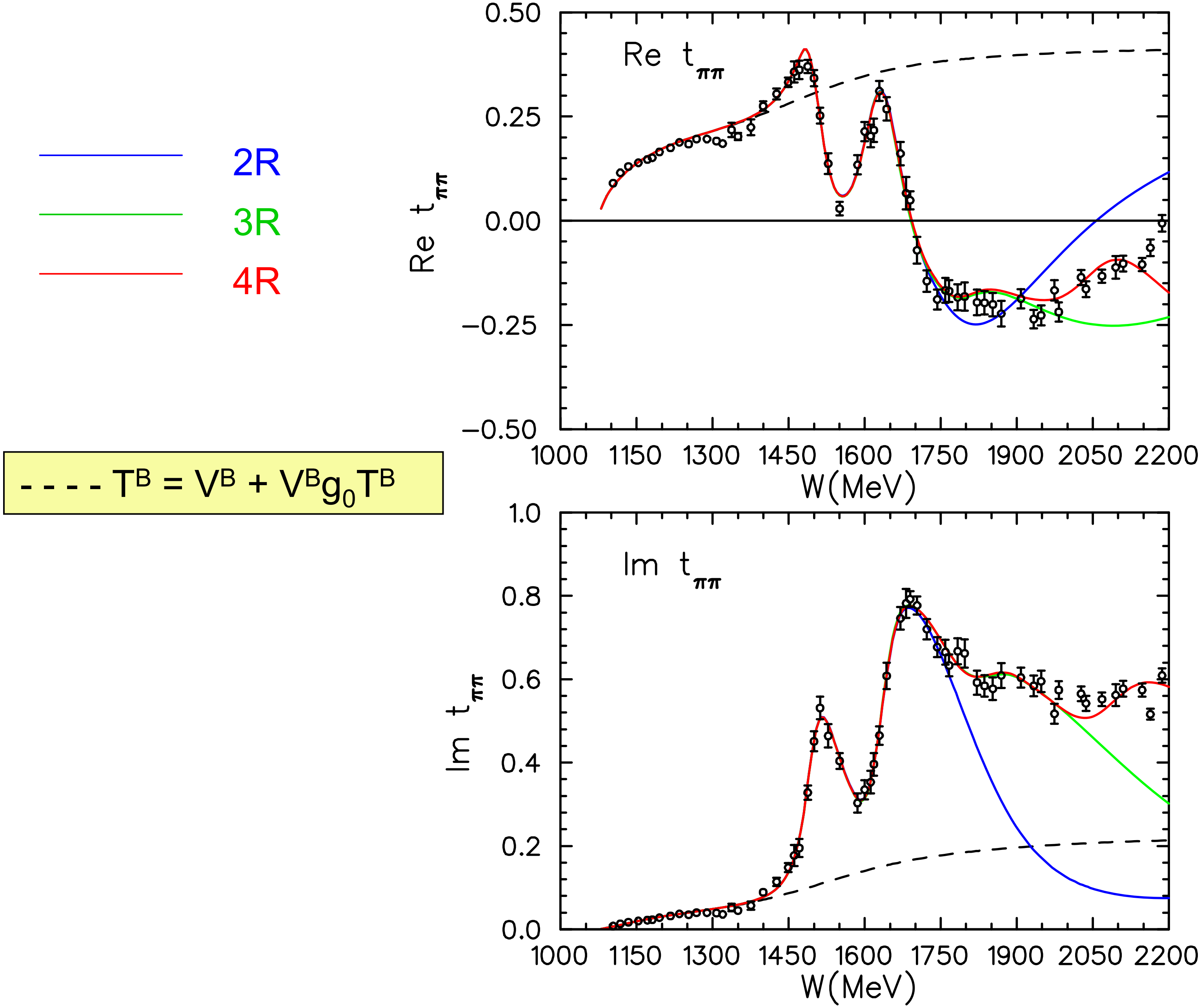
$$v_{ij}^{R_n} = \frac{f(\Lambda_i^{(n)}, q'; E)\, g_i^{(0)} g_j^{(0)} f(\Lambda_j^{(n)}, q : E)}{E - M_{R_n}^{(0)} + i\frac{1}{2}\Gamma_{2\pi}^{(n)}(E)},$$



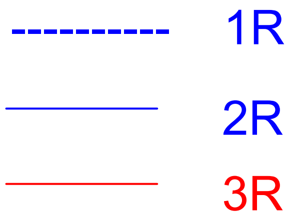
$M_{R_n}^{(0)}$ = bare mass of resonance $\mathrm{R_n}$,

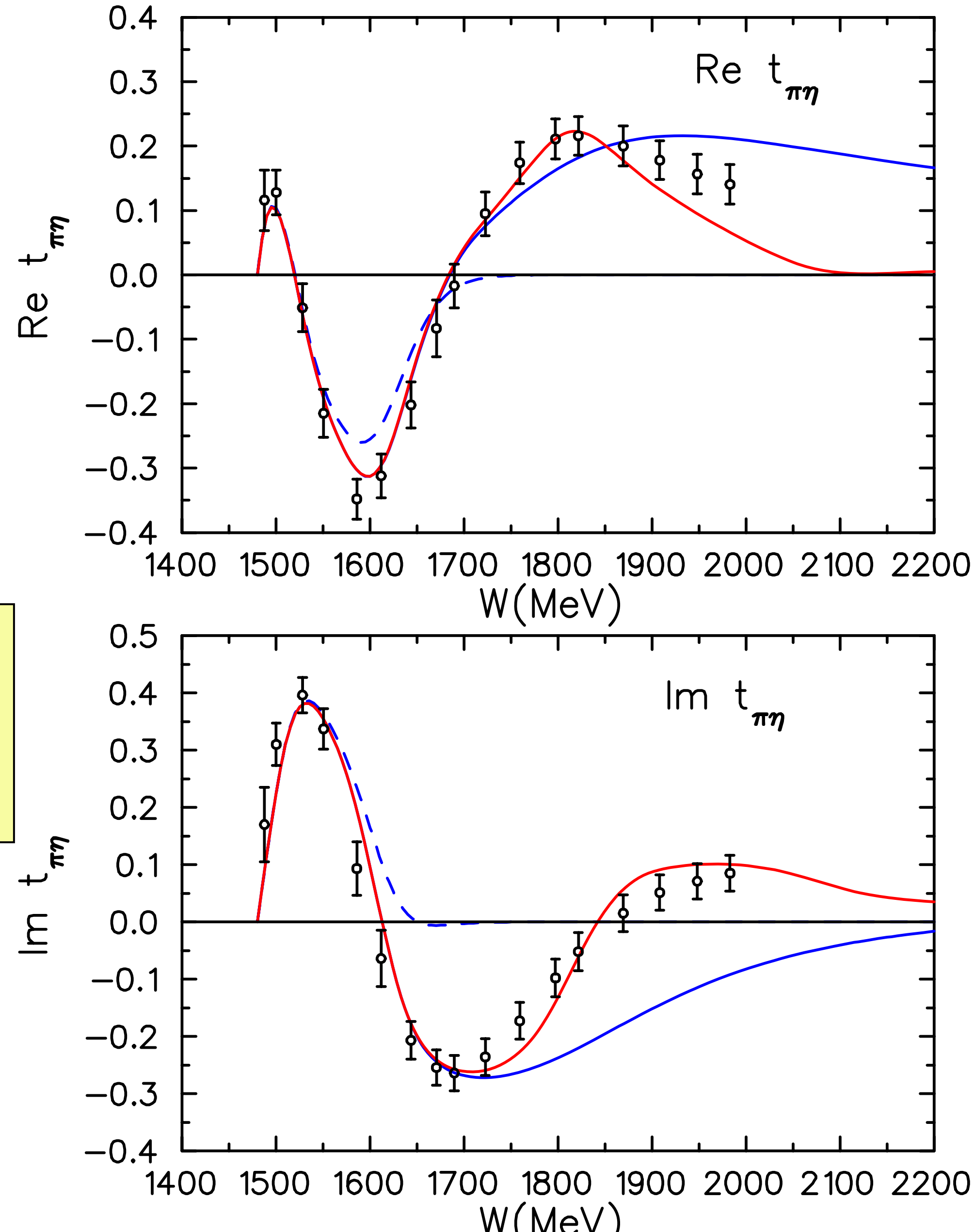
$$\Gamma_{2\pi}^{(n)} = \Gamma_{2\pi}^{0,n}\left(\frac{q_{2\pi}}{q_{0,n}}\right)^{2l+4}\left(\frac{X^2 + q_{0,n}^2}{X^2 + q_{2\pi}^2}\right)^{l+2}$$

= effects of $\pi\pi$N decay channel



2R
3R
4R
- - - - $T^B = V^B + V^B g_0 T^B$
Re $t_{\pi\pi}$
0.50
0.25
0.00
−0.25
−0.50
1000 1150 1300 1450 1600 1750 1900 2050 2200
W(MeV)
Im $t_{\pi\pi}$
1.0
0.8
0.6
0.4
0.2
0.0
1000 1150 1300 1450 1600 1750 1900 2050 2200
W(MeV)

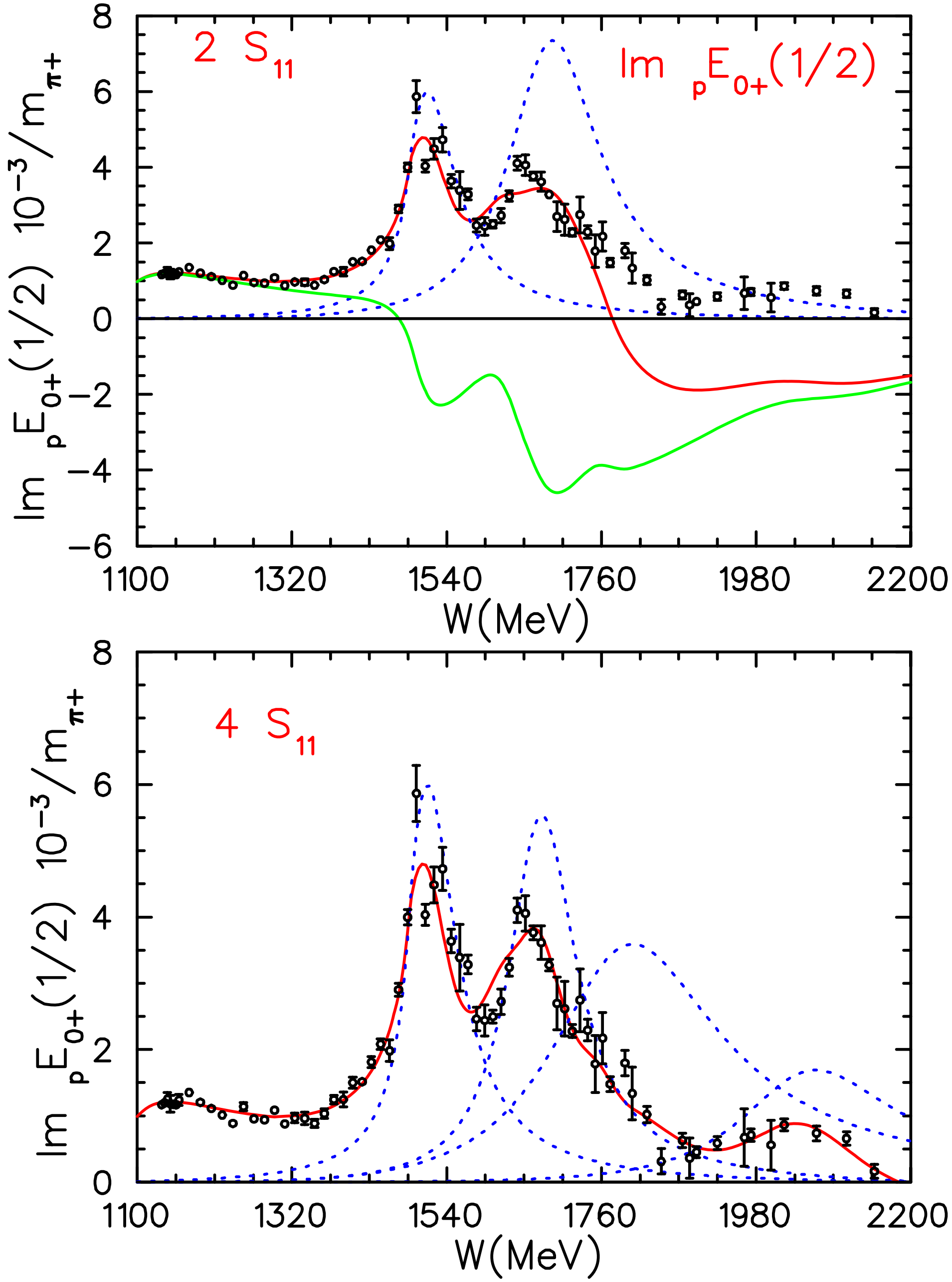




No evidence for the 4th S_{11} resonance in

π N ! η N

$t^{B}_{\gamma\pi}$
$t^{R}_{\gamma\pi}$
full

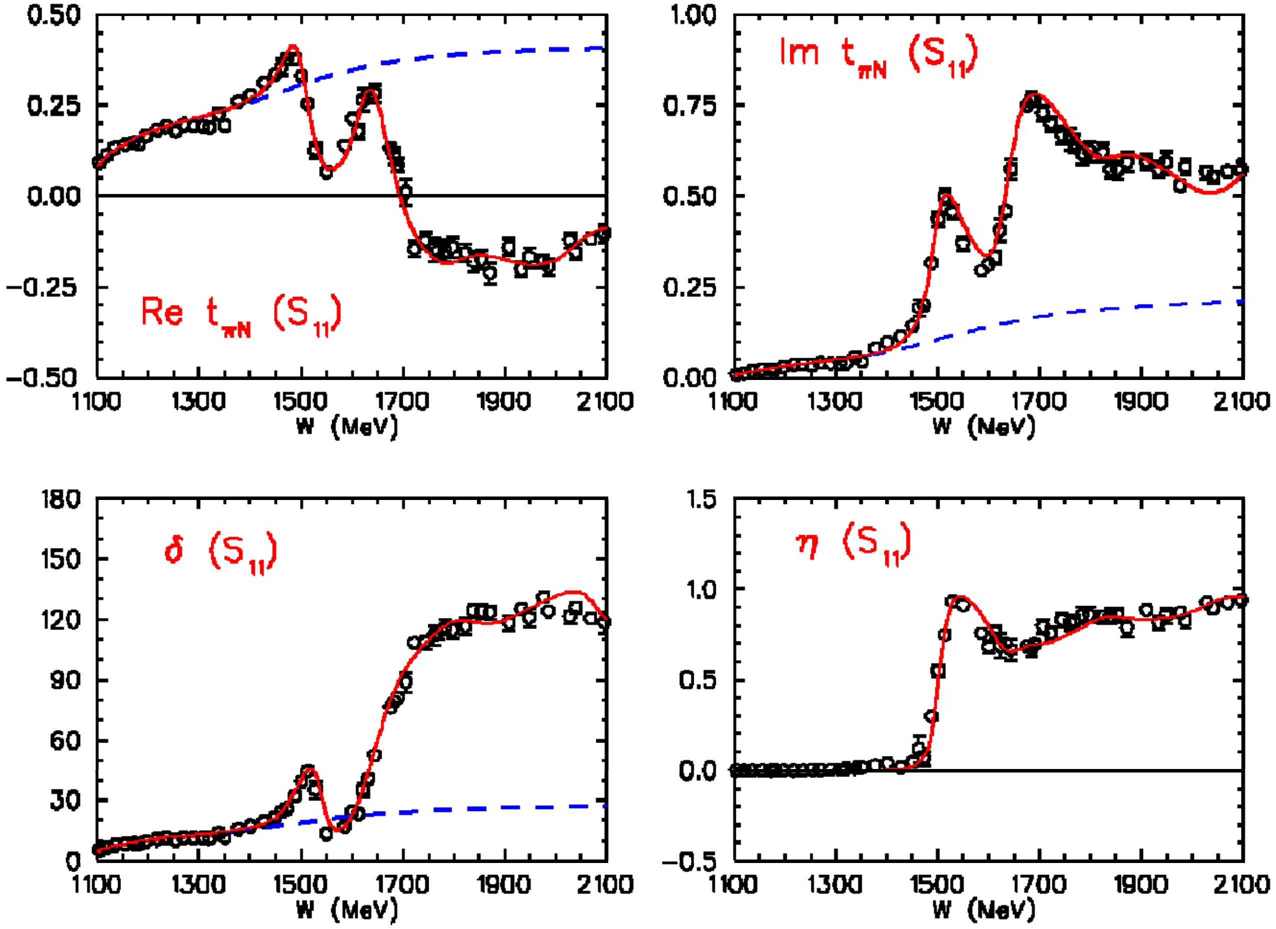


χ^2=64

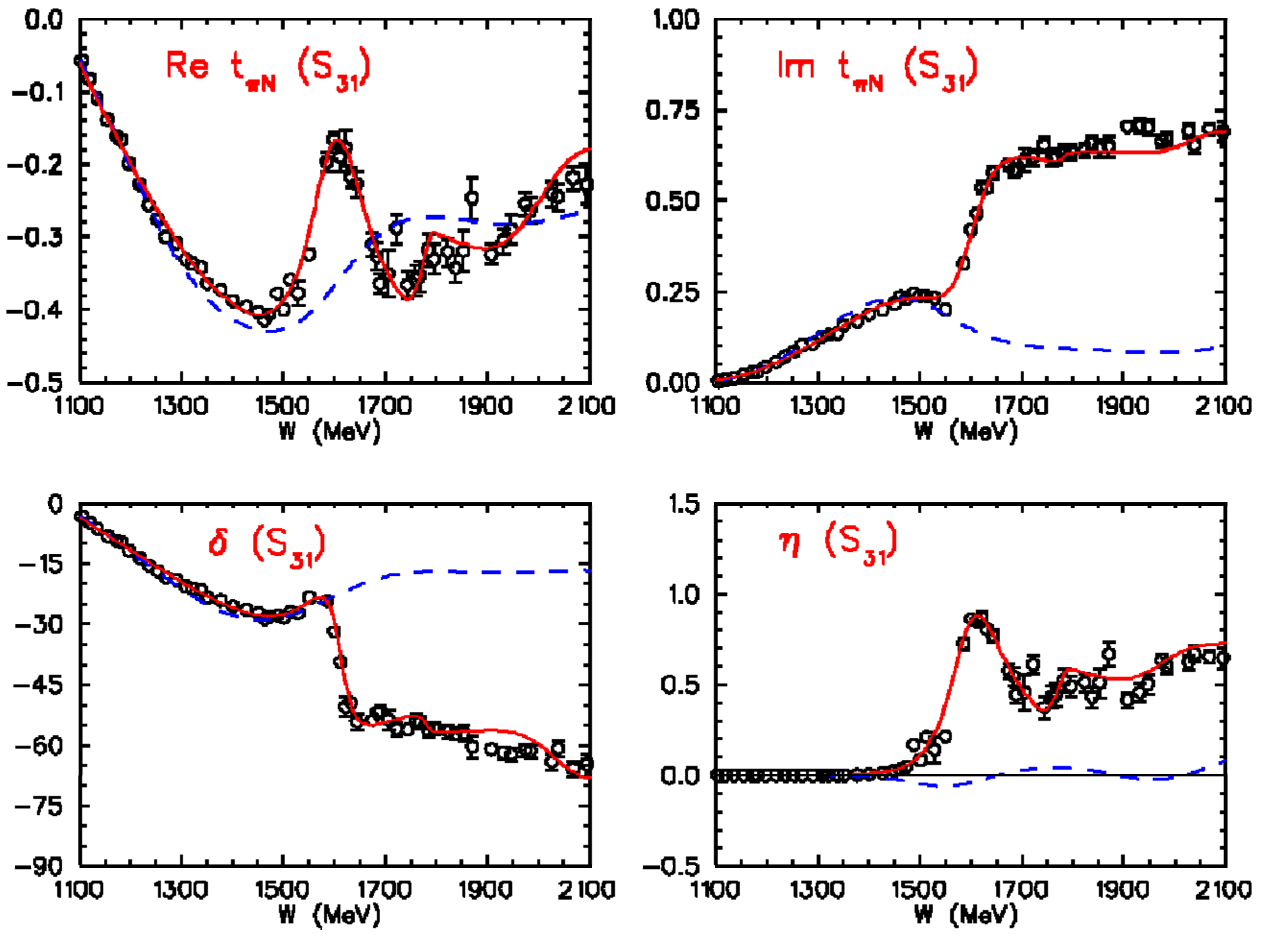
χ^2=3.5

Need 4 S_{11} Resonances

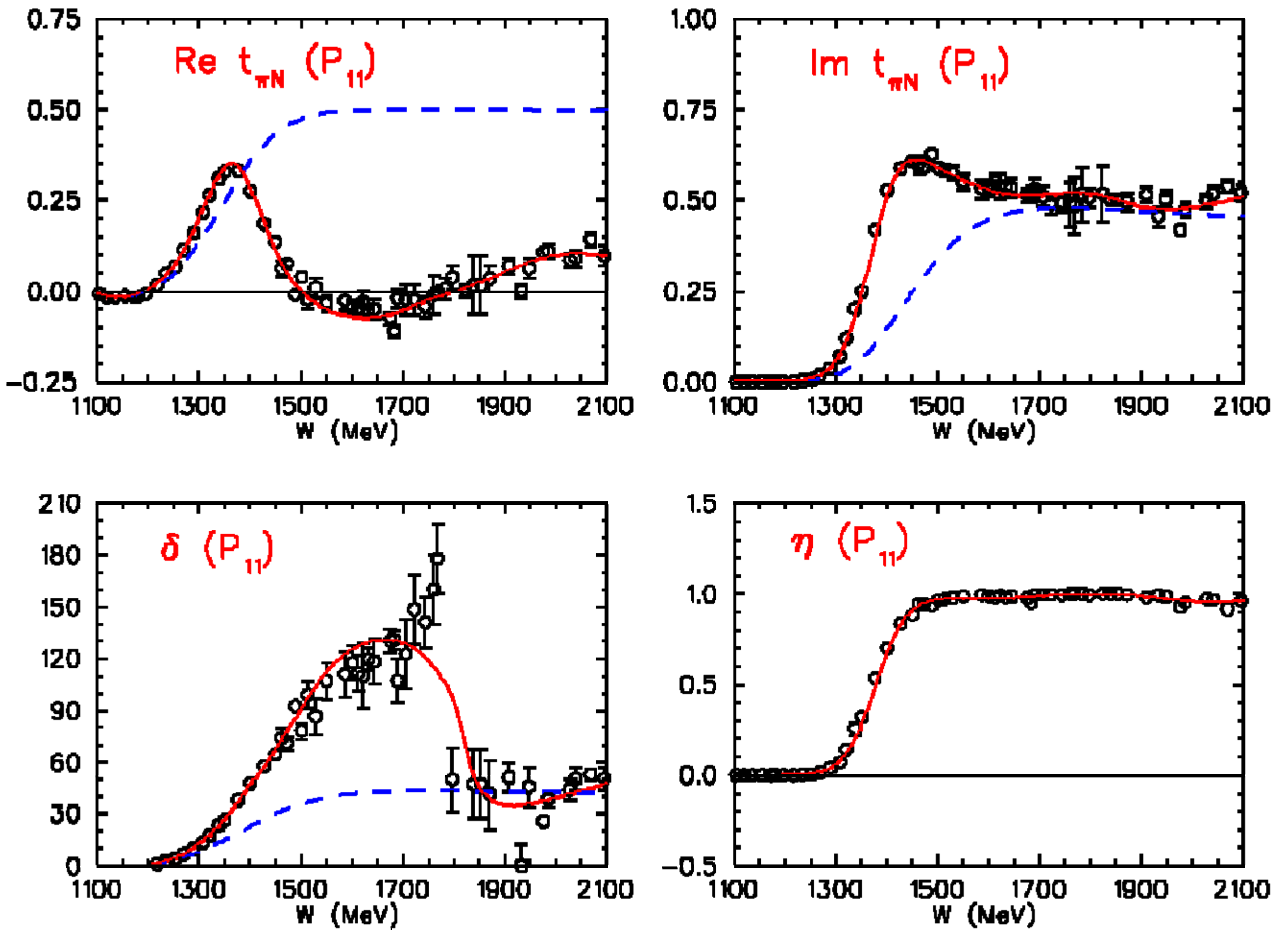
(3,4), red- PDG, blue- DMT



(3,3)

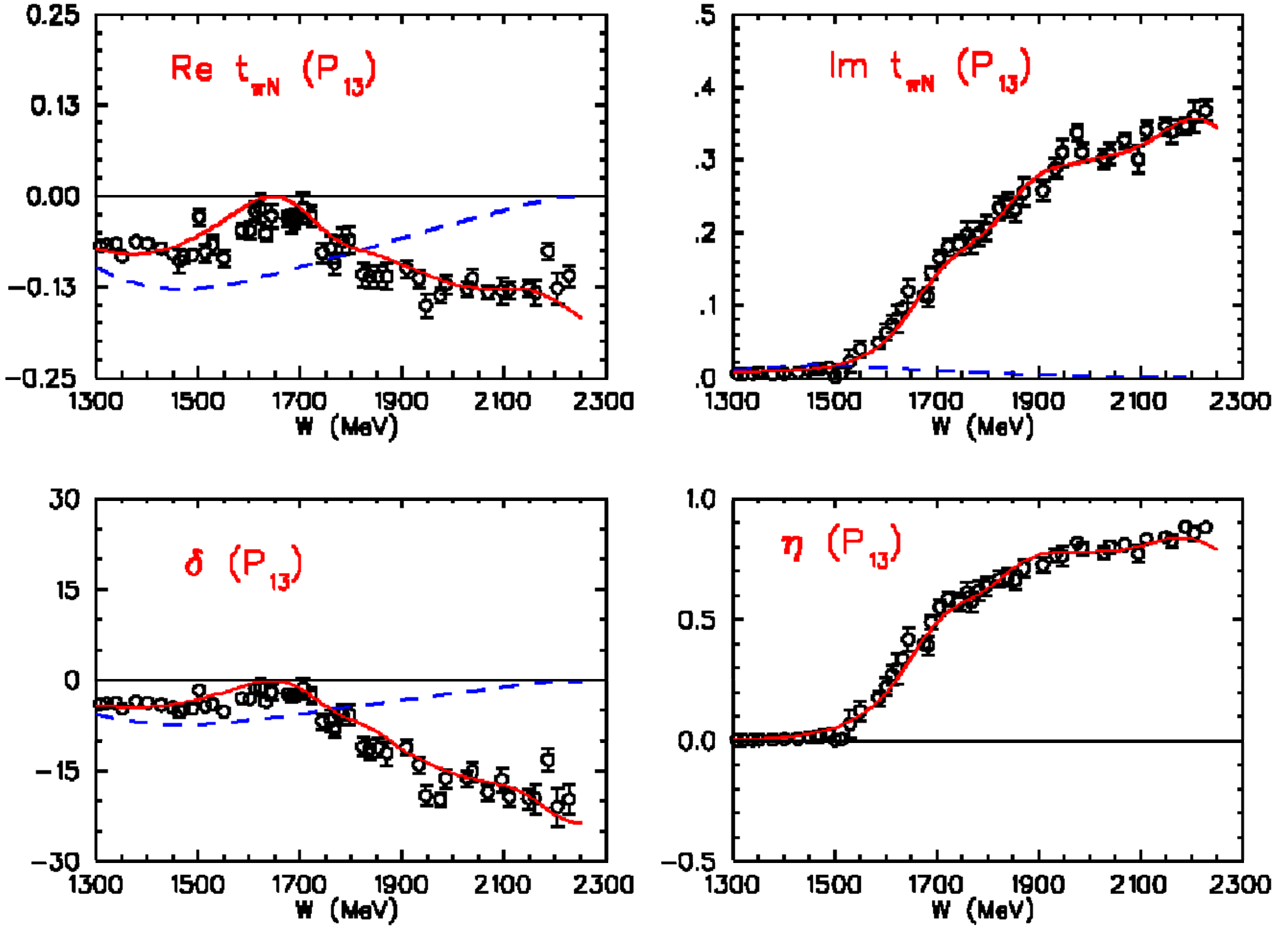


(3,3)



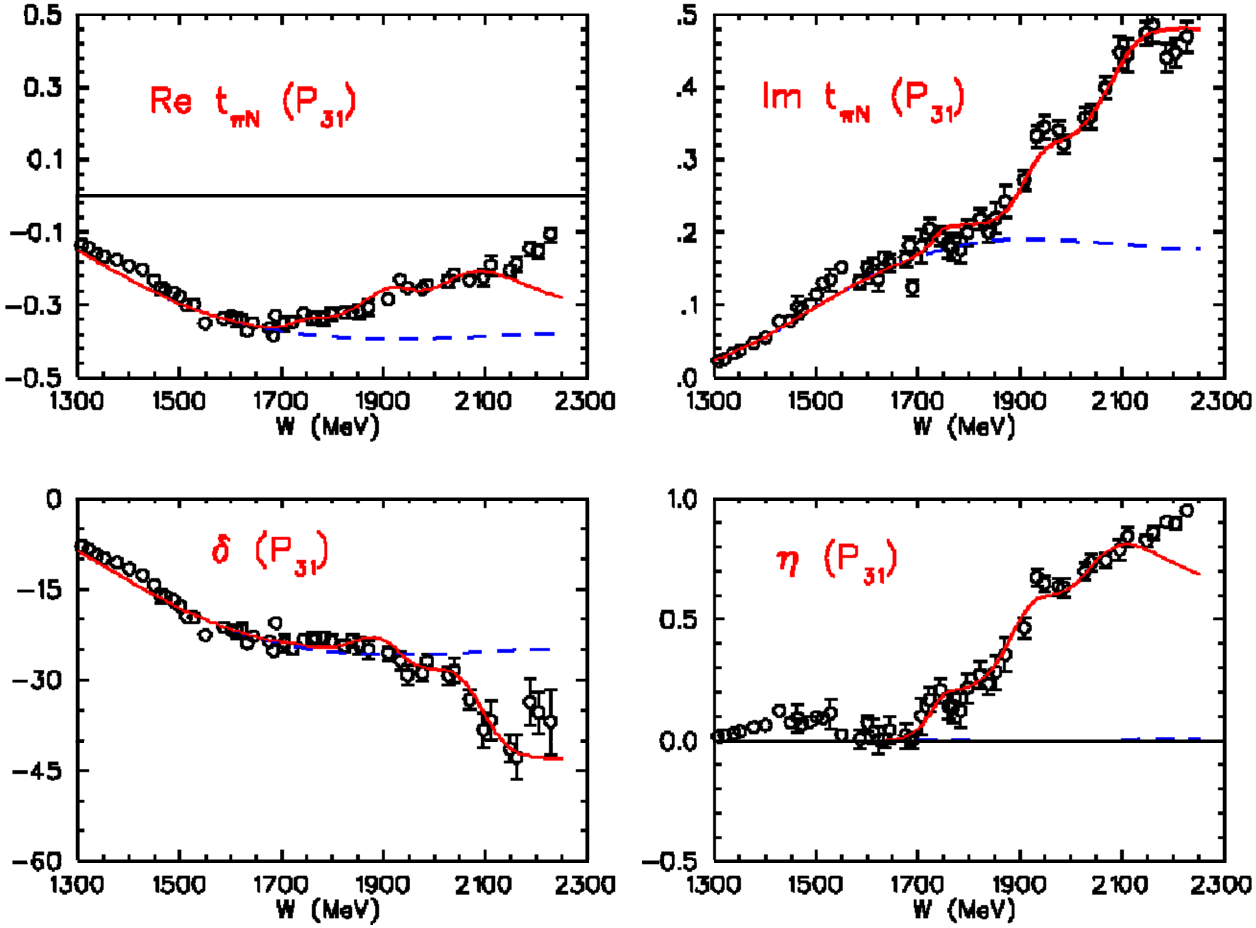
Re $t_{\pi N}$ (P_{11})
Im $t_{\pi N}$ (P_{11})
δ (P_{11})
η (P_{11})
W (MeV)
0.75
0.50
0.25
0.00
−0.25
1.00
210
180
150
120
90
60
30
0
1.5
1.0
0.5
0.0
−0.5
1100
1300
1500
1700
1900
2100

(2,2)

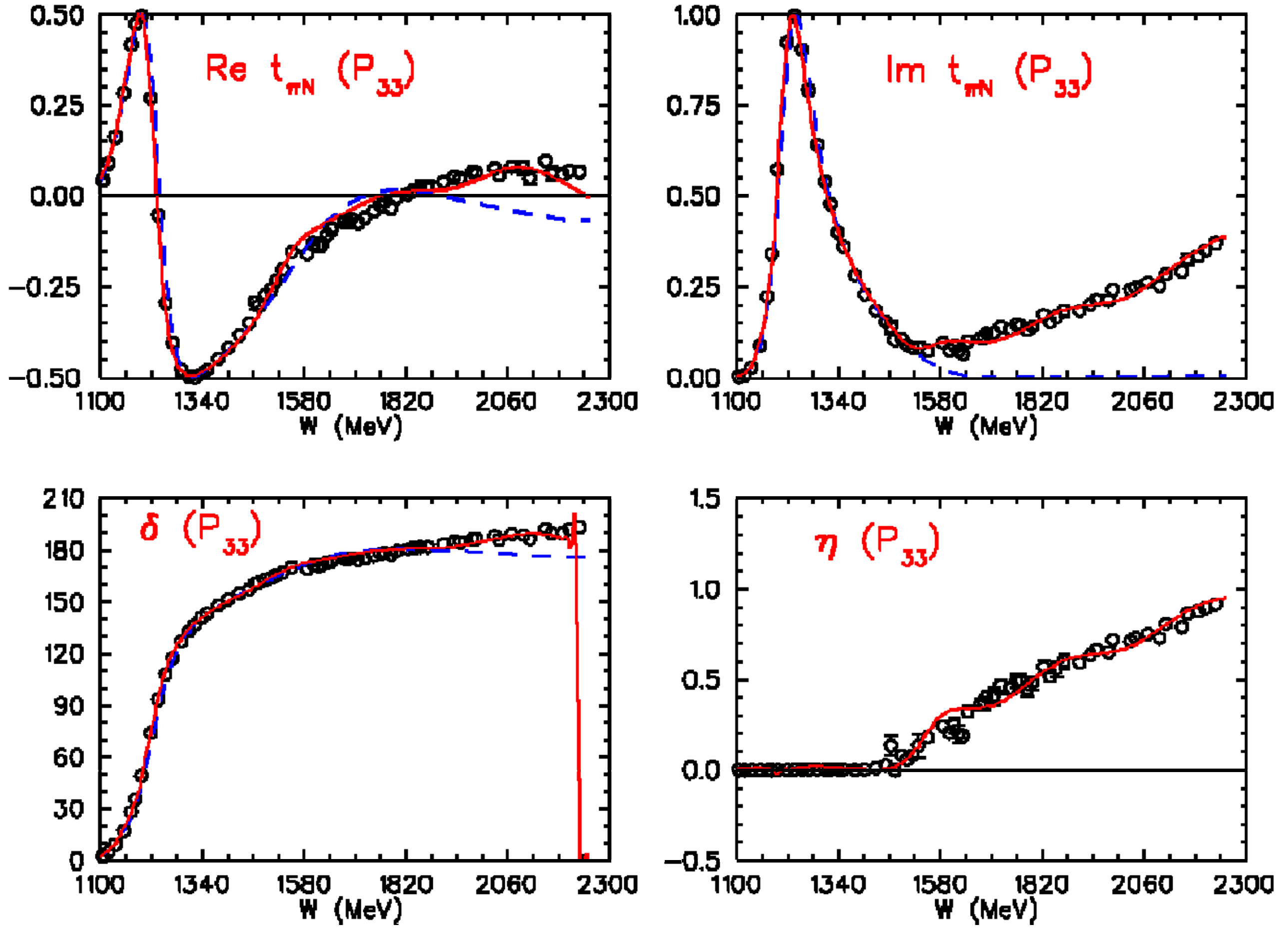


Re $t_{\pi N}$ (P_{13})
Im $t_{\pi N}$ (P_{13})
δ (P_{13})
η (P_{13})
W (MeV)
0.25
0.13
0.00
−0.13
−0.25
.5
.4
.3
.2
.1
.0
30
15
0
−15
−30
1.0
0.5
0.0
−0.5
1300
1500
1700
1900
2100
2300

(2,3)

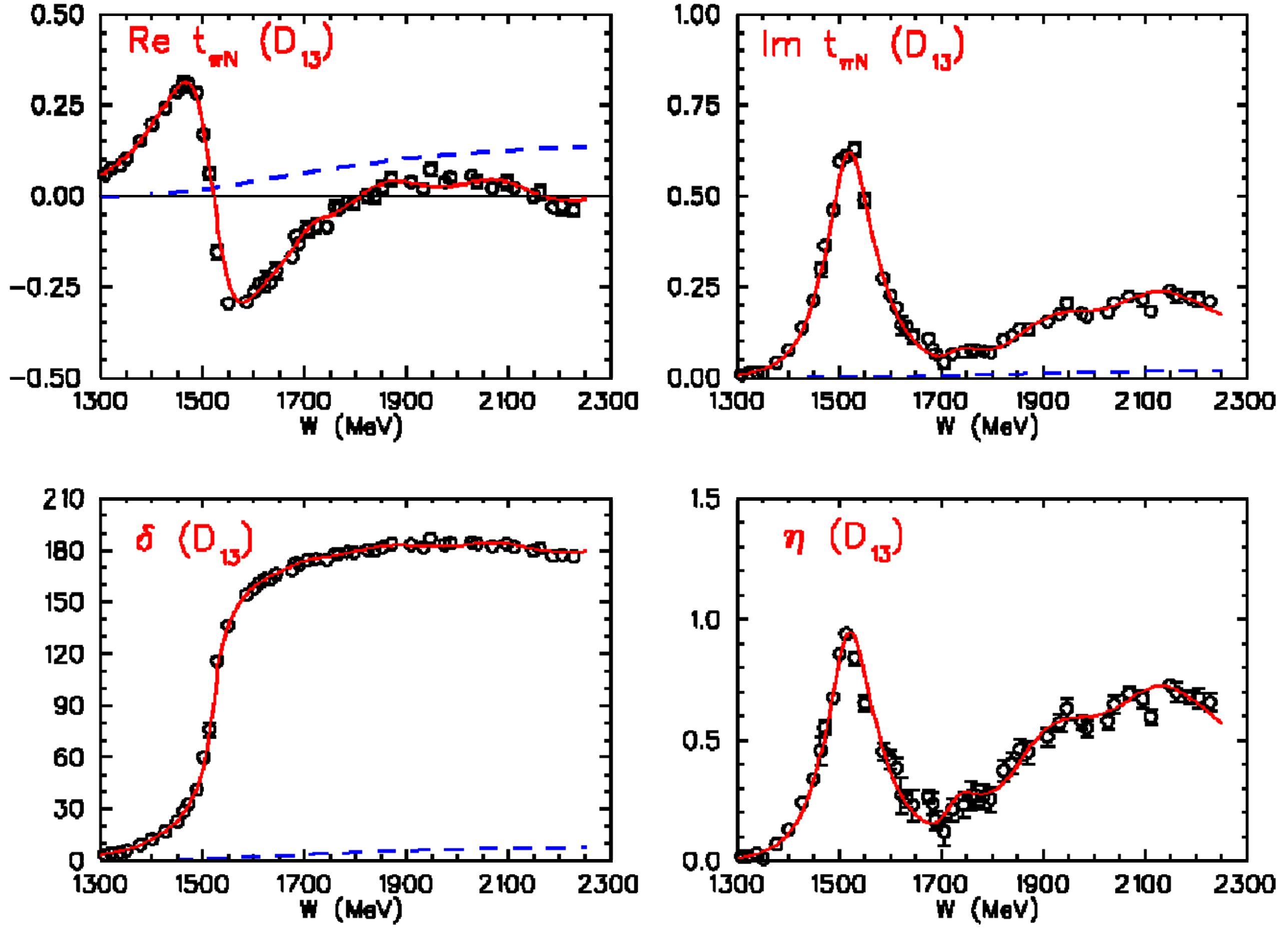


(3,3)

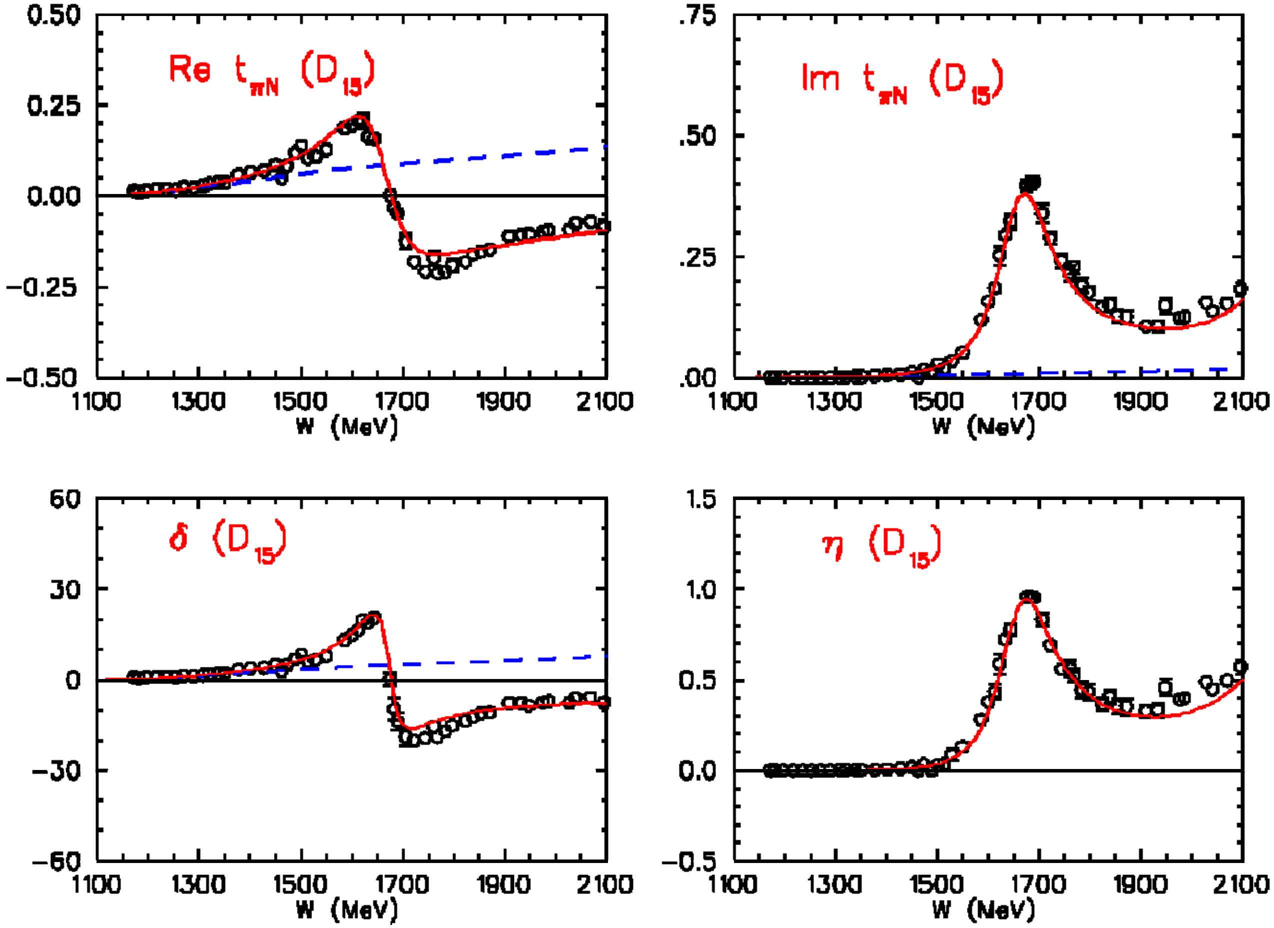


Re $t_{\pi N}$ (P_{33})
Im $t_{\pi N}$ (P_{33})
δ (P_{33})
η (P_{33})
W (MeV)
0.50
0.25
0.00
−0.25
−0.50
1.00
0.75
210
180
150
120
90
60
30
0
1.5
1.0
0.5
0.0
−0.5
1100
1340
1580
1820
2060
2300

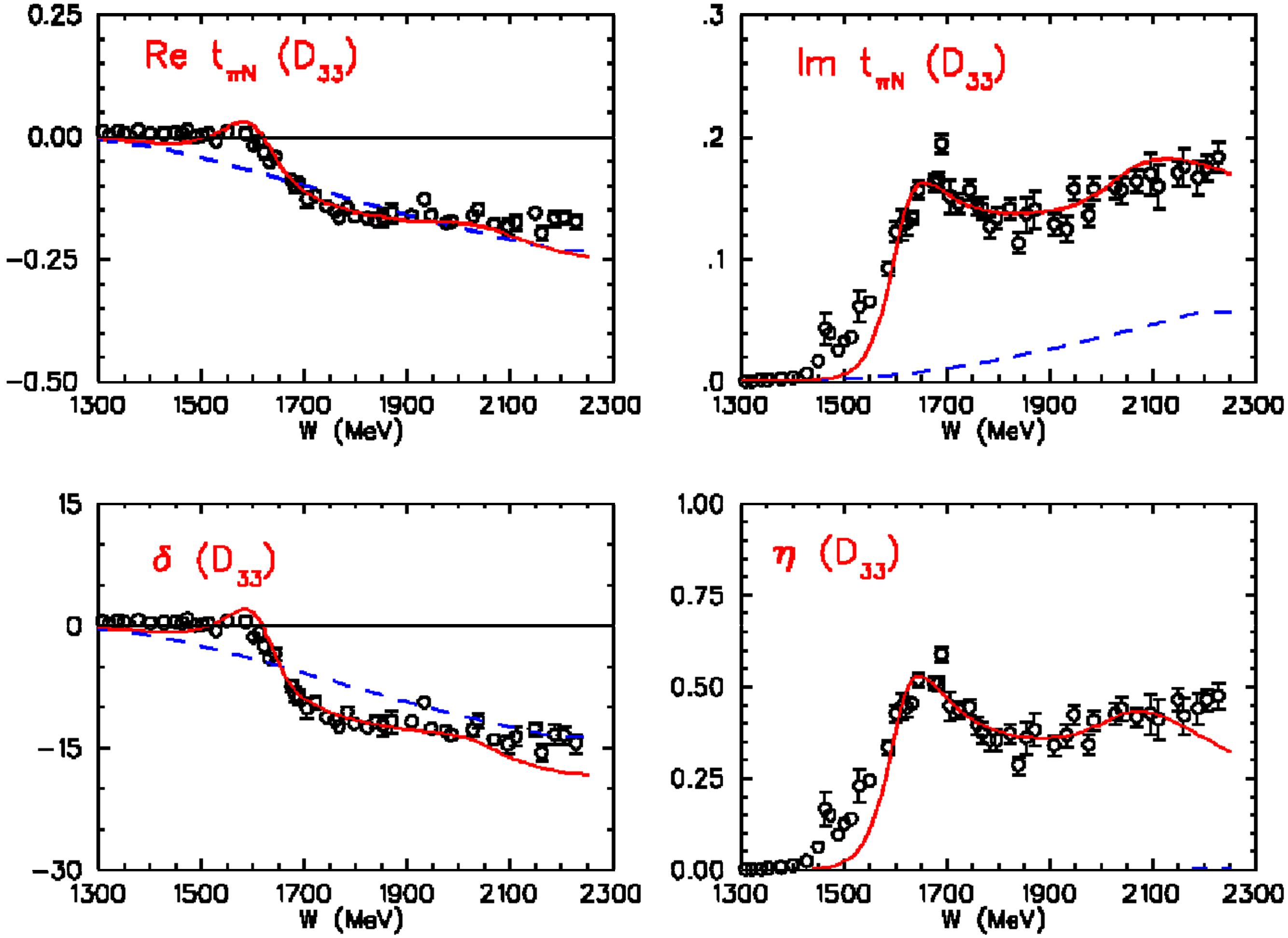
(3,3)


Re $t_{\pi N}$ (D_{13})
Im $t_{\pi N}$ (D_{13})
δ (D_{13})
η (D_{13})
W (MeV)
0.50
0.25
0.00
−0.25
−0.50
1.00
0.75
210
180
150
120
90
60
30
0
1.5
1.0
0.5
0.0
1300
1500
1700
1900
2100
2300

(2,2)

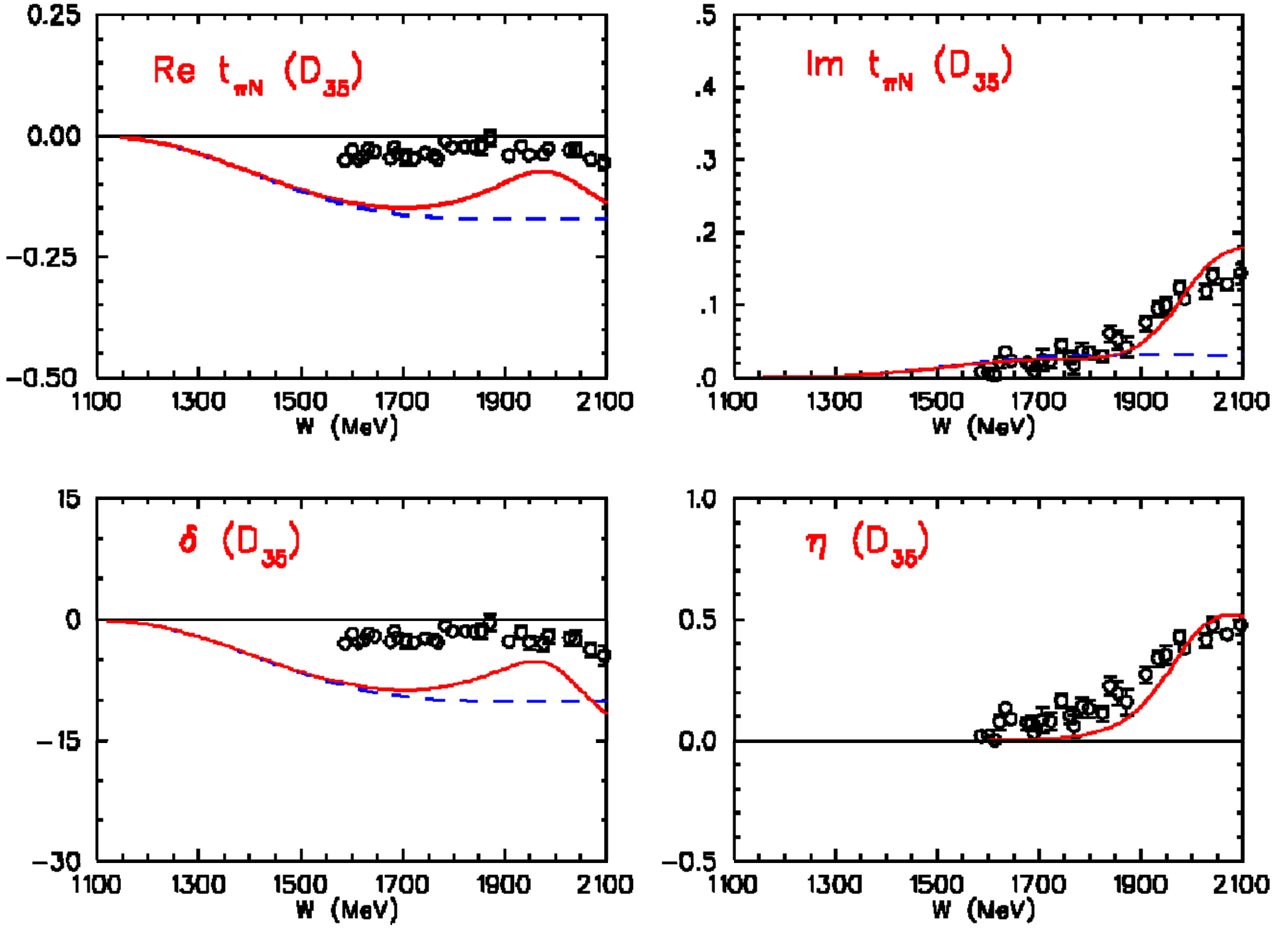


(2,2)

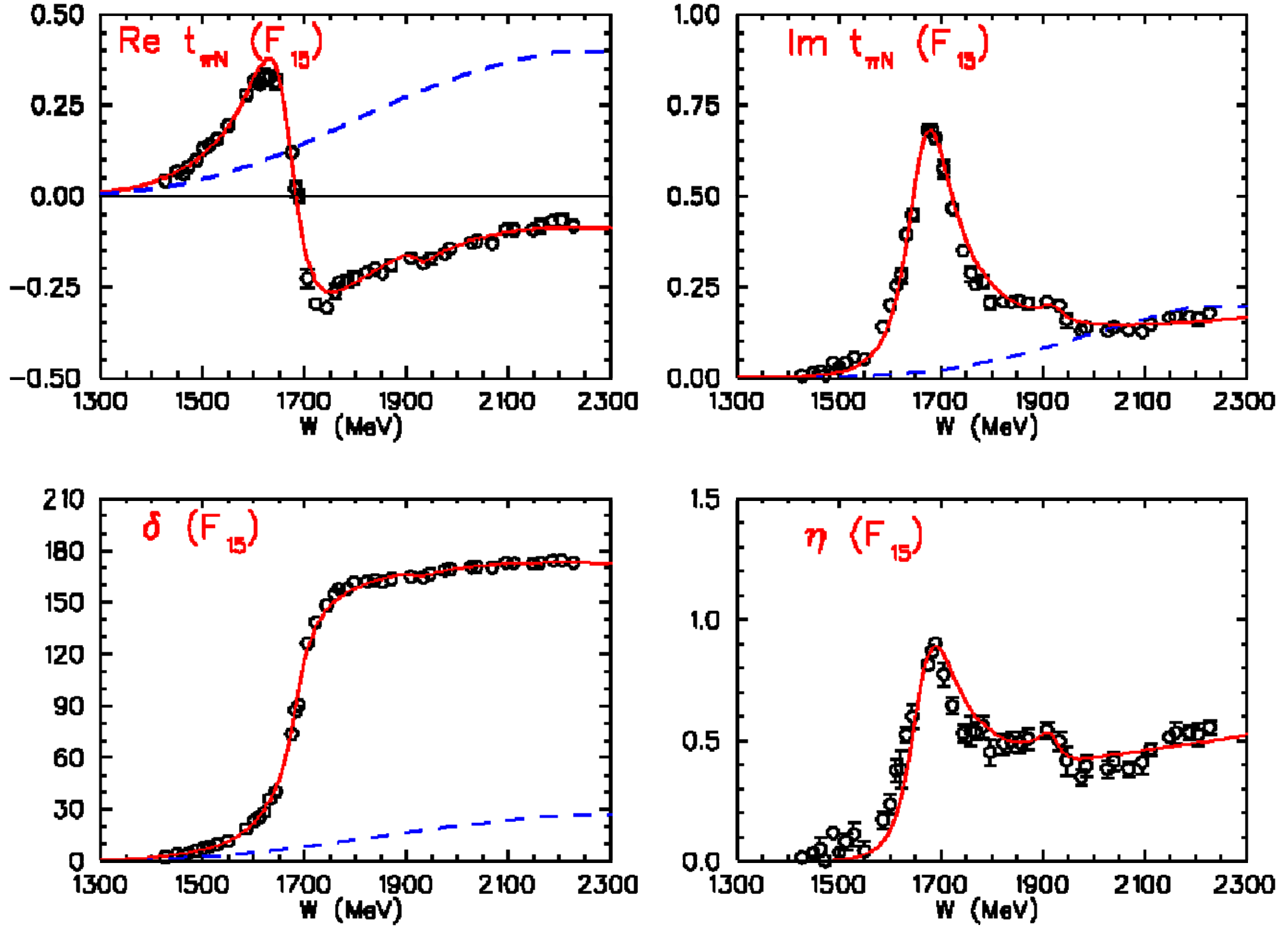


Re $t_{\pi N}$ (D_{33})
0.25
0.00
−0.25
−0.50
1300
1500
1700
1900
2100
2300
W (MeV)
Im $t_{\pi N}$ (D_{33})
.3
.2
.1
.0
1300
1500
1700
1900
2100
2300
W (MeV)
δ (D_{33})
15
0
−15
−30
1300
1500
1700
1900
2100
2300
W (MeV)
η (D_{33})
1.00
0.75
0.50
0.25
0.00
1300
1500
1700
1900
2100
2300
W (MeV)

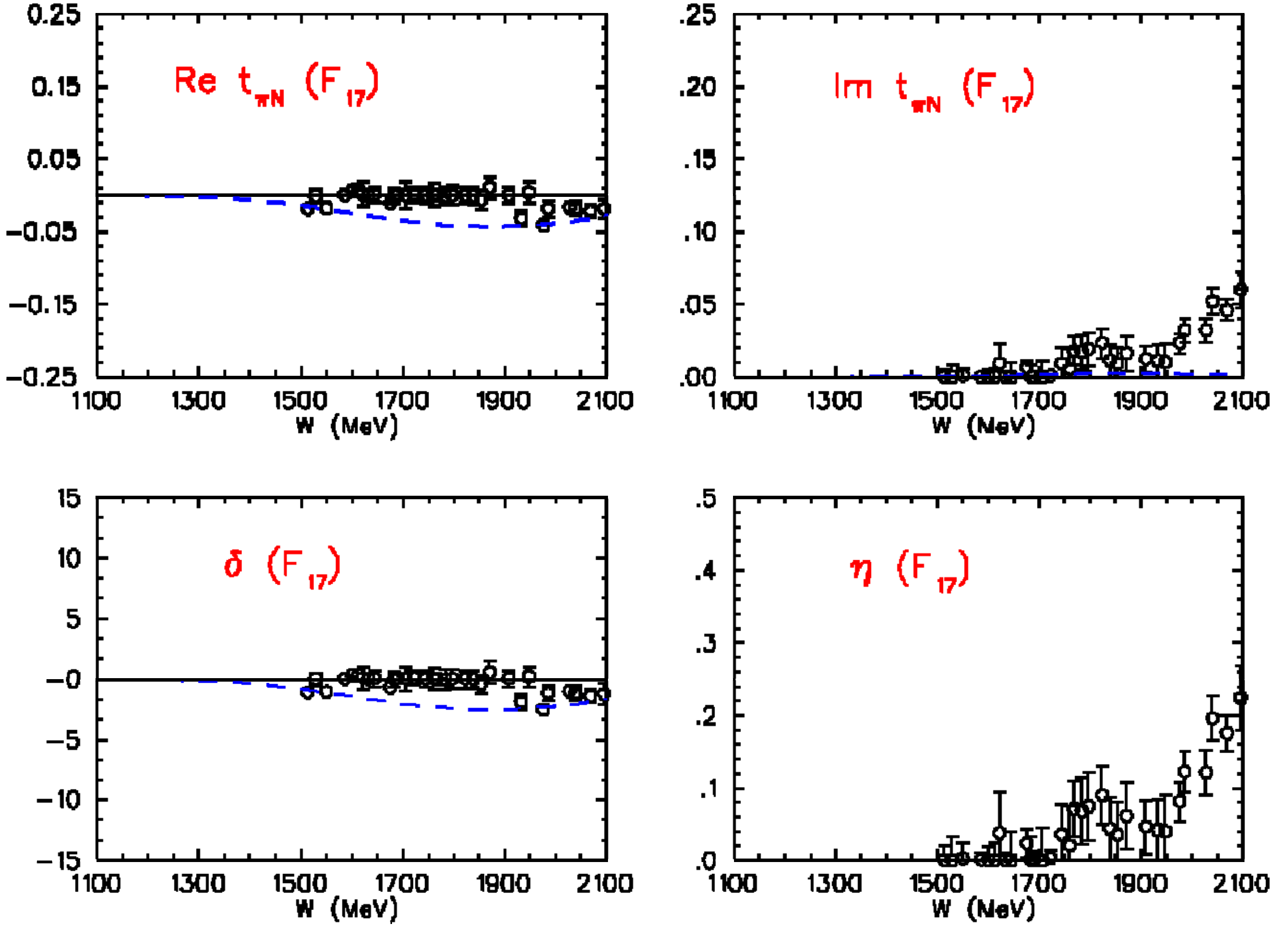
(2,1)



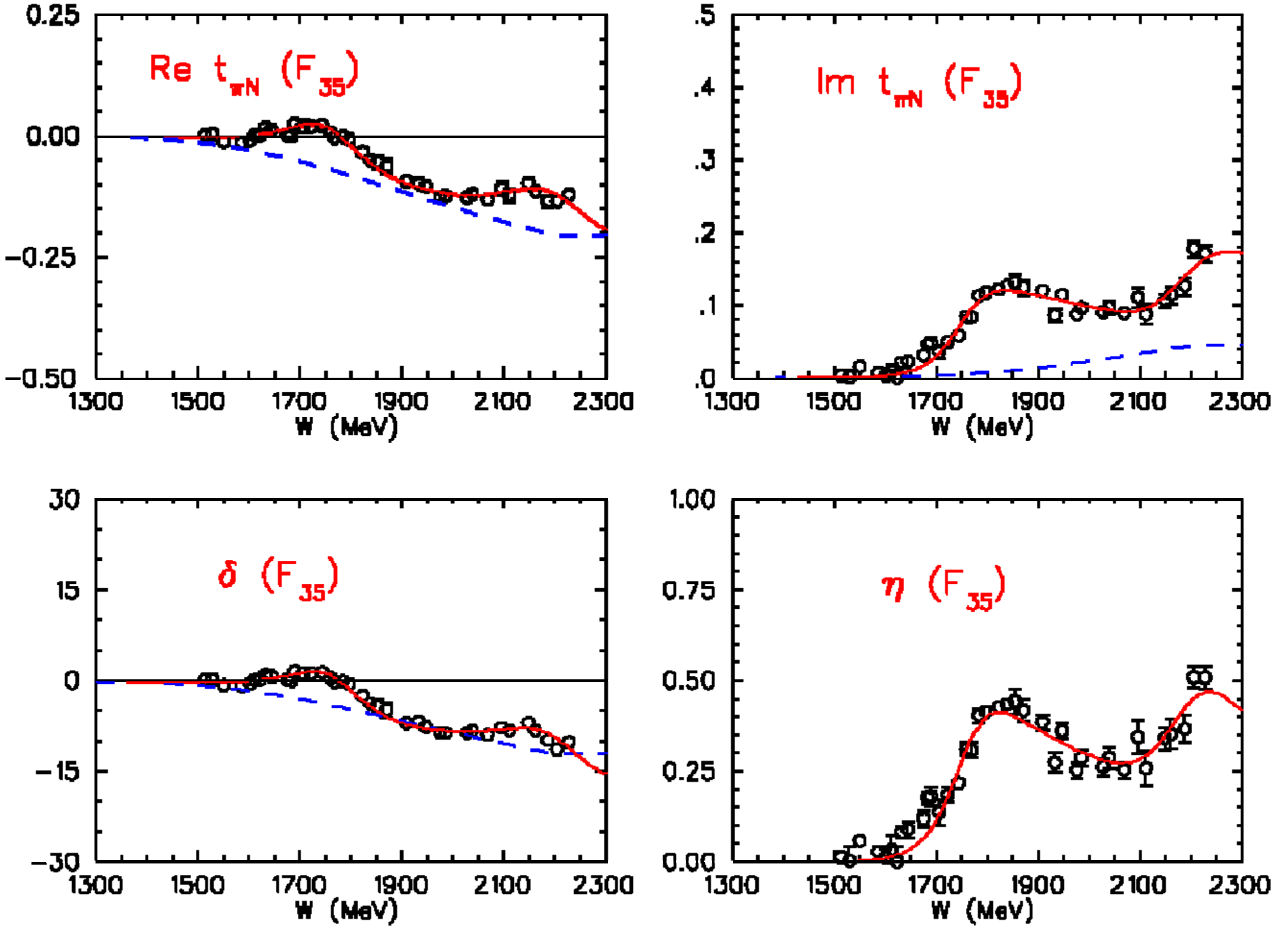
(2,2)



(1,0)

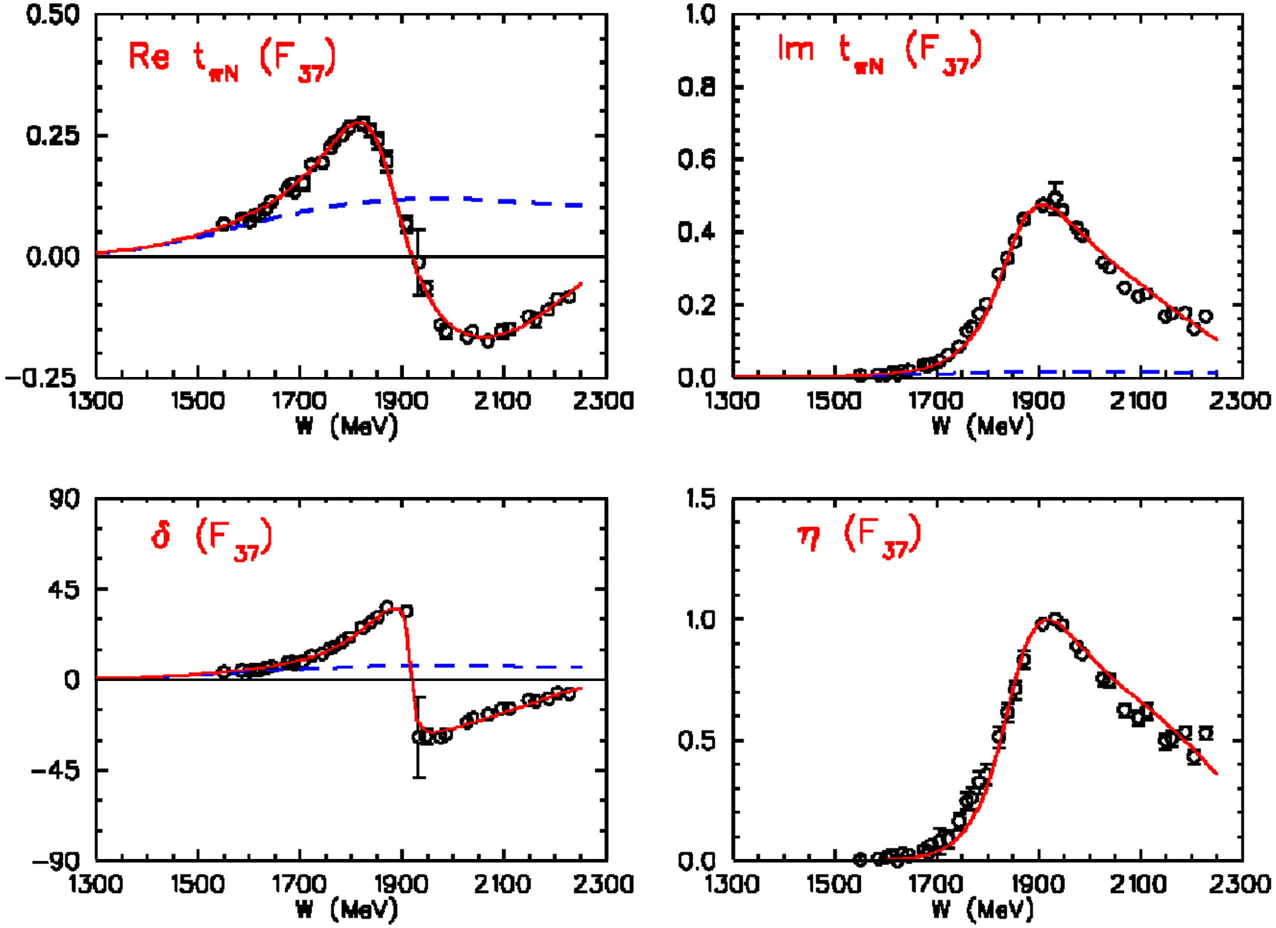


(2,2)



Re $t_{\pi N}$ (F_{35})
Im $t_{\pi N}$ (F_{35})
δ (F_{35})
η (F_{35})
0.25
0.00
−0.25
−0.50
.5
.4
.3
.2
.1
.0
30
15
0
−15
−30
1.00
0.75
0.50
0.25
0.00
1300 1500 1700 1900 2100 2300
W (MeV)

(2,1)



Re $t_{\pi N}$ (F_{37})
Im $t_{\pi N}$ (F_{37})
δ (F_{37})
η (F_{37})
0.50
0.25
0.00
−0.25
1.0
0.8
0.6
0.4
0.2
0.0
90
45
0
−45
−90
1.5
1.0
0.5
0.0
1300 1500 1700 1900 2100 2300
W (MeV)

Pole Positions and Residues in [MeV] (preliminary)

	1st Resonance		2nd Resonance		3rd Resonance	
N*	**Wp**	**Γp**	**Wp**	**Γp**	**Wp**	**Γp**
S_{11} (3,4)	1499 (1505, 1501)	67 (170, 124)	1642 (1660, 1673)	97 (160, 82)	2065 (2150±70)	223 (350±100)
S_{31} (3,3)	1598 (1600, 1585)	136 (115, 104)	1775 (1870±40)	36 (1850±50)	2012 (2140±80)	148 (200±80)
P_{11} (3,3)	1366 (1365, 1346)	179 (210, 176)	1721 (1720, 1770)	185 (230, 378)	1869 (2120±40, 1810)	238 (240±80, 622)
P_{13} (2,2)	1683 (1700, 1717)	239 (250, 388)	1846 (not listed)	180 (not listed)		
P_{31} (2,3)	1729 (1714)	70 (68)	1896 (1855, 1810)	130 (350, 494)	2065	161
P_{33} (3,3)	1218 (1210, 1211)	90 (100, 100)	1509 (1600, 1675)	236 (300, 386)	2149 (1900, 1900±80)	400 (300, 300±100)

Red□PDG04 Blue□Arndt95

Green□Cutkovsky80 Orange□Vrana00

obtained with speed plot

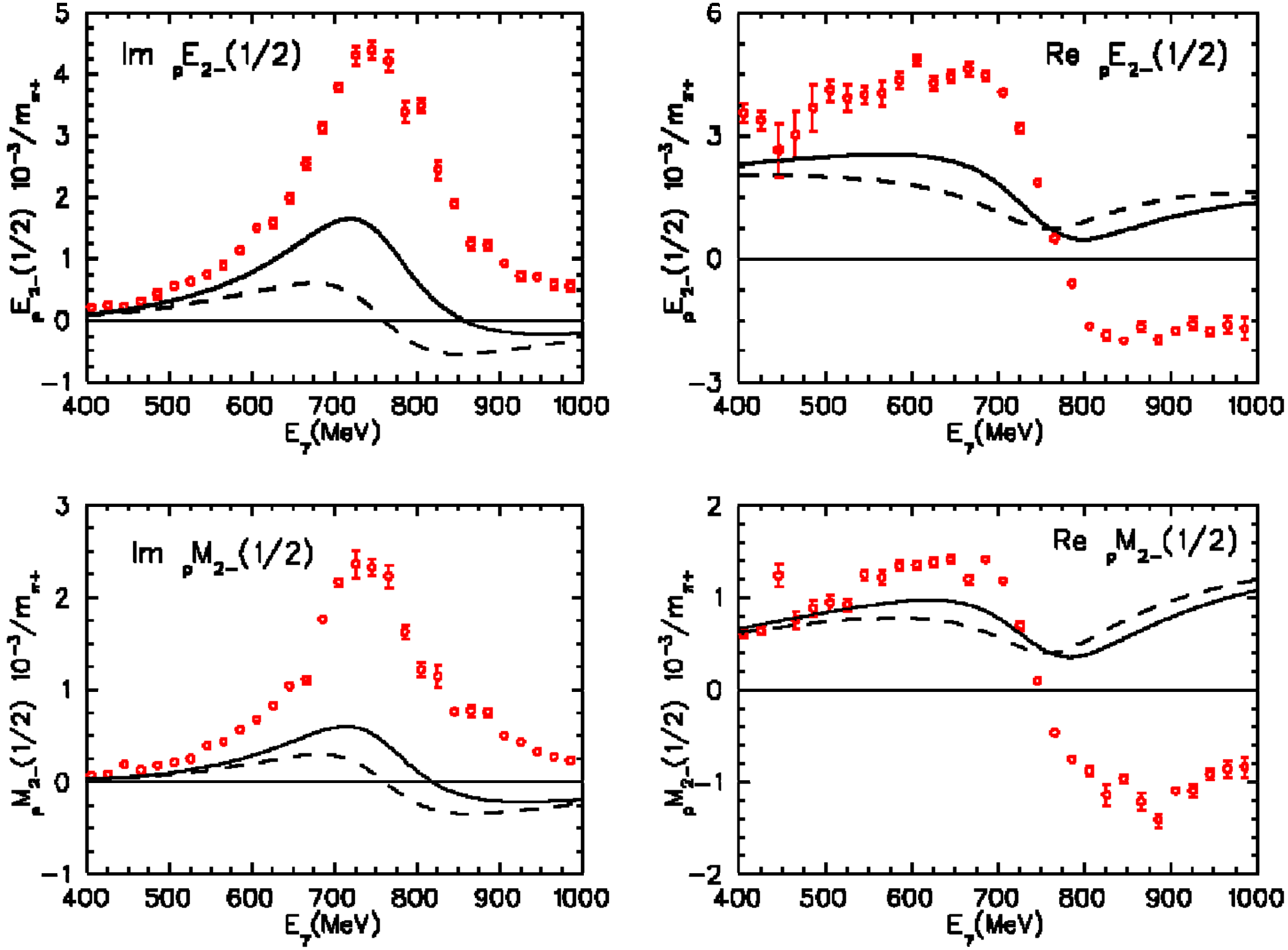
Pole Positions and Residues in [MeV] (preliminary)

	1st Resonance		2nd Resonance		3rd Resonance	
N*	**Wp**	**Γp**	**Wp**	**Γp**	**Wp**	**Γp**
D_{13} (3,3)	1516 (1510, 1515)	123 (115, 110)	not seen (1680, not seen)	not seen (100, not seen)	1834 (1880±100)	210 (160±80)
D_{33} (2,2)	1609 (1660, 1655)	133 (200, 242)	2070 (1900±100)	267 (200±60)		
D_{15} (2,2)	1657 (1660, 1663)	132 (140, 152)	2188 (2100±60)	238 (360±80)		
D_{35} (2,1)	1992 (1890, 1913)	270 (250, 246)	not seen (2400±60)	not seen (400±150)		
F_{15} (2,2)	1663 (1670, 1670)	115 (120, 120)	1931 (not listed)	62 (not listed)		
F_{35} (2,2)	1771 (1830, 1832)	190 (280, 254)	2218 (2150±100, 1697)	219 (350±100, 112)		
F_{37} (2,1)	1860 (1885, 1880)	201 (240, 236)	2207 (2350±100)	439 (260±100)		

Red□PDG04 Blue□Arndt95

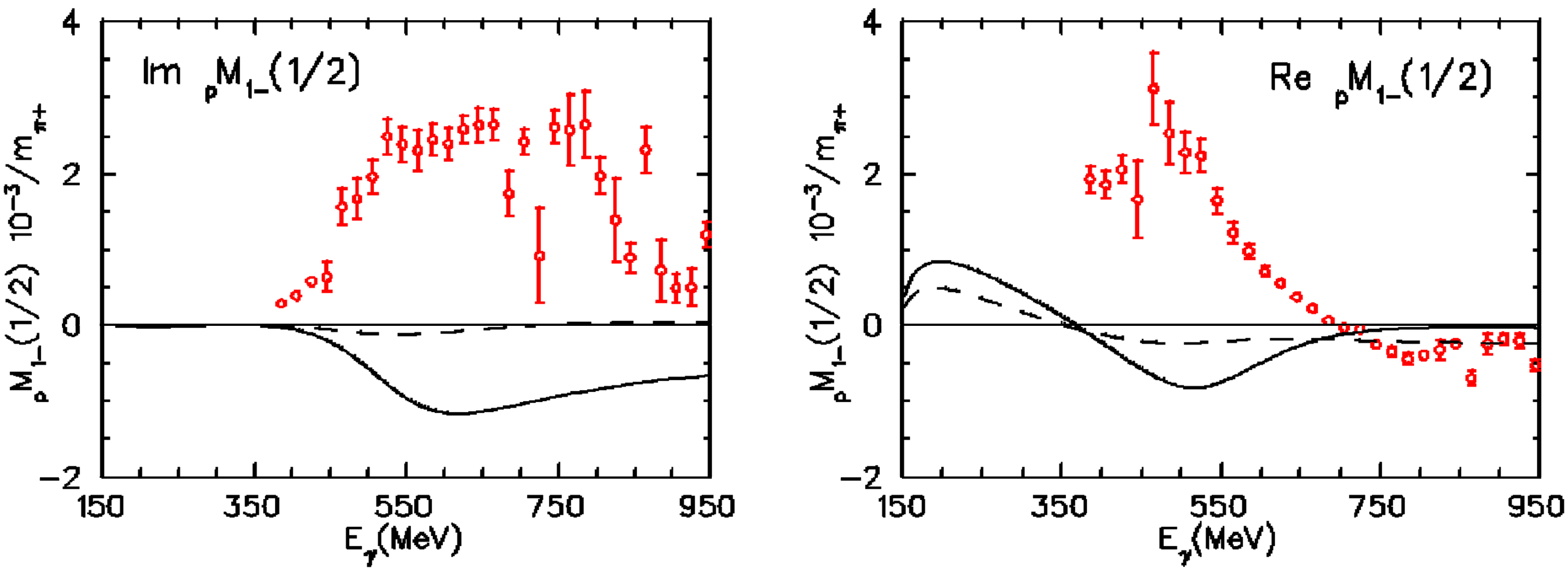
Green□Cutkovsky80 Orange□Vrana00

pion cloud effects: D_{13}



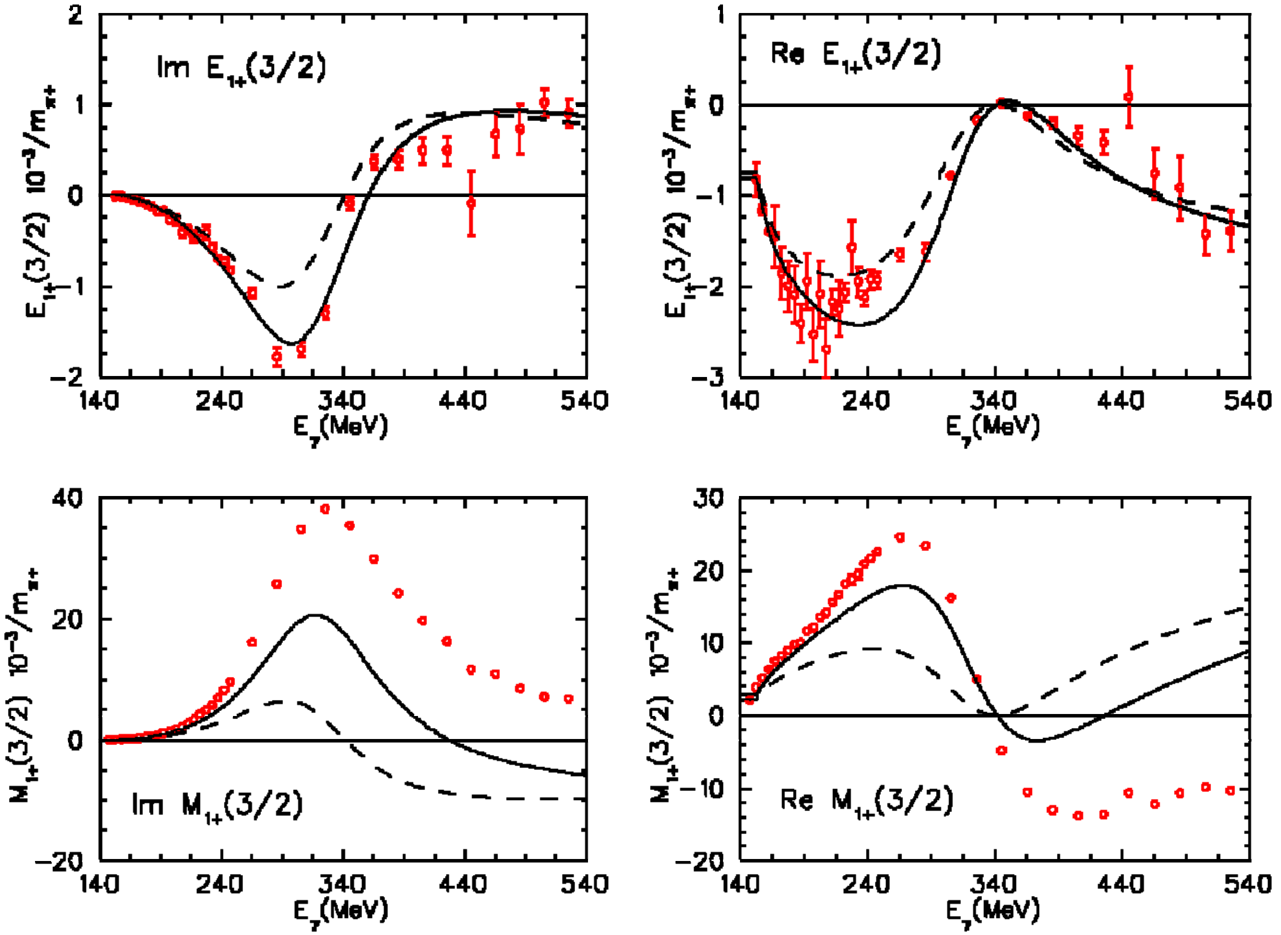
Dashed lines: K-matrix, solid lines: K-matrix + pion clouds

P_{11}



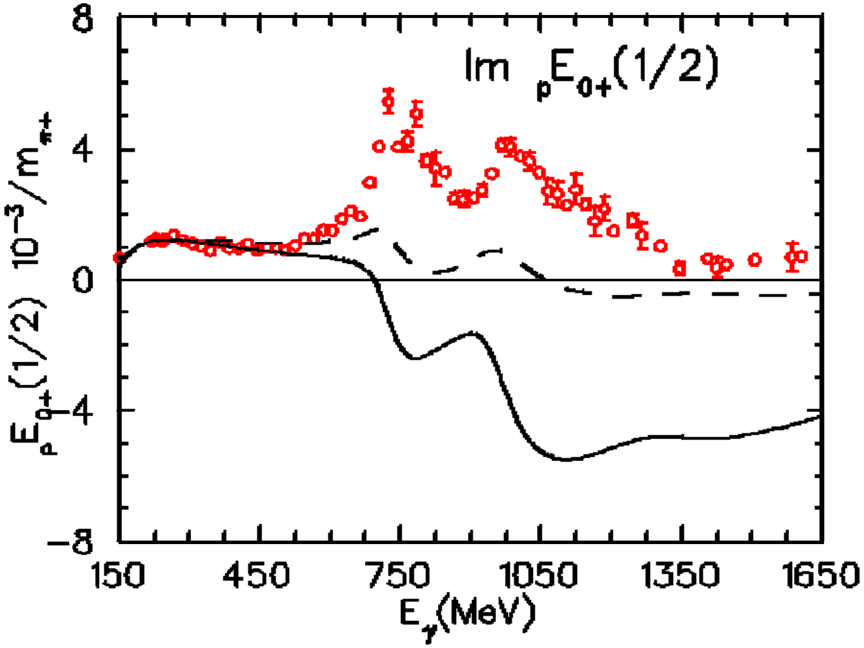
Im $_pM_{1-}(1/2)$
Re $_pM_{1-}(1/2)$
$_pM_{1-}(1/2)$ $10^{-3}/m_{\pi^+}$
E_γ(MeV)
4
2
0
−2
150
350
550
750
950

P_{33}

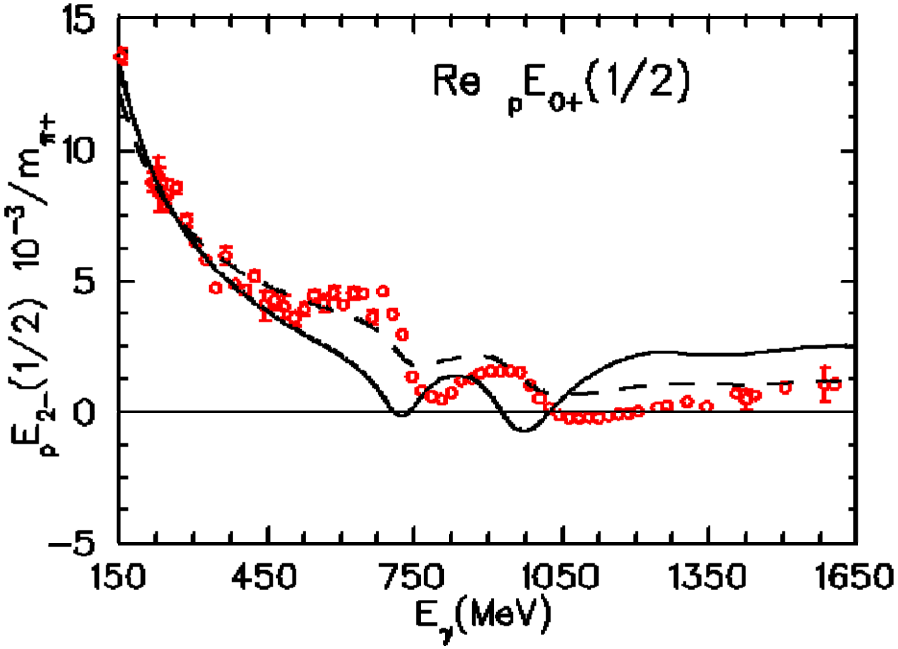


Im $E_{1+}(3/2)$
Re $E_{1+}(3/2)$
Im $M_{1+}(3/2)$
Re $M_{1+}(3/2)$
$E_{1+}(3/2)$ $10^{-3}/m_{\pi^+}$
$M_{1+}(3/2)$ $10^{-3}/m_{\pi^+}$
E_γ(MeV)
140
240
340
440
540

S_{11}



Im $_pE_{0+}(1/2)$
$_pE_{0+}(1/2)$ $10^{-3}/m_{\pi+}$
8
4
0
−4
−8
150
450
750
1050
1350
1650
E_γ(MeV)



Re $_pE_{0+}(1/2)$
$_pE_{2-}(1/2)$ $10^{-3}/m_{\pi+}$
15
10
5
0
−5
150
450
750
1050
1350
1650
E_γ(MeV)

Summary

- The DMT coupled-channel dynamical model gives excellent description of the pion scattering and pion e.m. production data from threshold to first resonance region

  - Excellent agreement with π^0 threshold production data. Two-loop contributions small. For electroproduction, ChPT needs to go at least to $O(p^4)$.

  - DMT predicts $\mu_{N!\Delta}$ = 3.514 μ_N, $Q_{N!\Delta}$=-0.081 fm^2, and R_{EM}=-2.4%, all in close agreement with the experiments.
    $\Rightarrow$ dressed Δ is oblate

  - Bare Δ is almost spherical. The oblate deformation of the dressed Δ arises almost exclusively from pion cloud

- We have re-analyzed the recent Jlab data for the electroproduction of the $\Delta(1232)$ via $p(e,e'p)\pi^0$ with DMT and MAID. In contrast with the previous findings, we find

  - At $Q^2=4.0\ (GeV/c)^2$, hadronic helicity conservation is still not yet observed.
  - R_{EM}, starting from a small and negative value at the real photon point, actually exhiits a clear tendency to cross zero and change sign as Q^2 increases.
  - $S_{1/2}$ and $A_{1/2}$, but not $A_{3/2}$, start exhibiting scaling behavior at about $Q^2 > 2.5\ (GeV/c)^2$.

$\Rightarrow$ the onset of scaling might take place at a lower momentum transfer than that of hadronic helicity conservation.

Extension to 2.2 GeV gives (prelminary)

- Even pole positions and the number of resonance could be sensitive w.r.t. different analysis tools.
- The pion cloud effects for the pion photoproduction are, in general important, in many channels.

Work in progress (completely dynamical)

- extraction of dressed masses, widths, Q^2 evolution of helicity amplitudes ($\gamma\pi$)

Further theoretical improvements

- Consistent treatment for πN and $\gamma\pi$
- Gauge invariance
- Sensitivity w.r.t. the πN interaction model
- Effects of other channels like ρN, $\pi\Delta$, σN et. al.