Jülich-UGA model for photoproduction

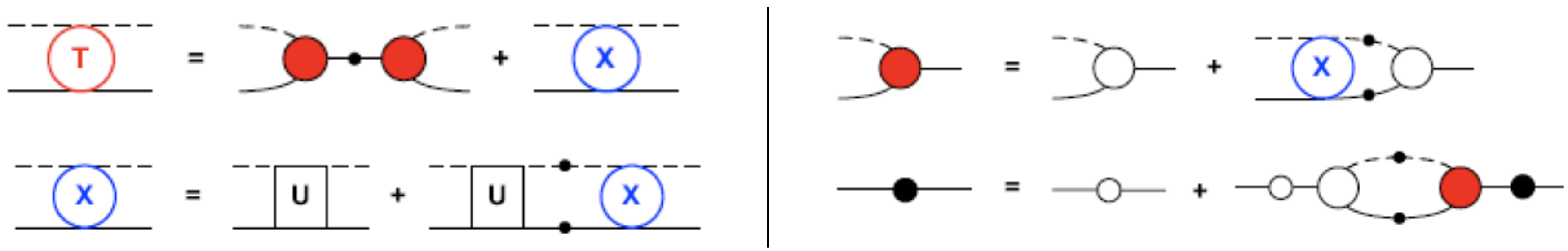
Collaboration:

Fei Huang	*(UGA)*
Michael Döring	*(FZJ)*
S. Krewald	*(FZJ)*
U. -G. Meiβner	*(FZJ)*
H. Haberzettl	*(GWU)*
K. N.	*(UGA/FZJ)*

Reaction Theory: *field theoretical approach*

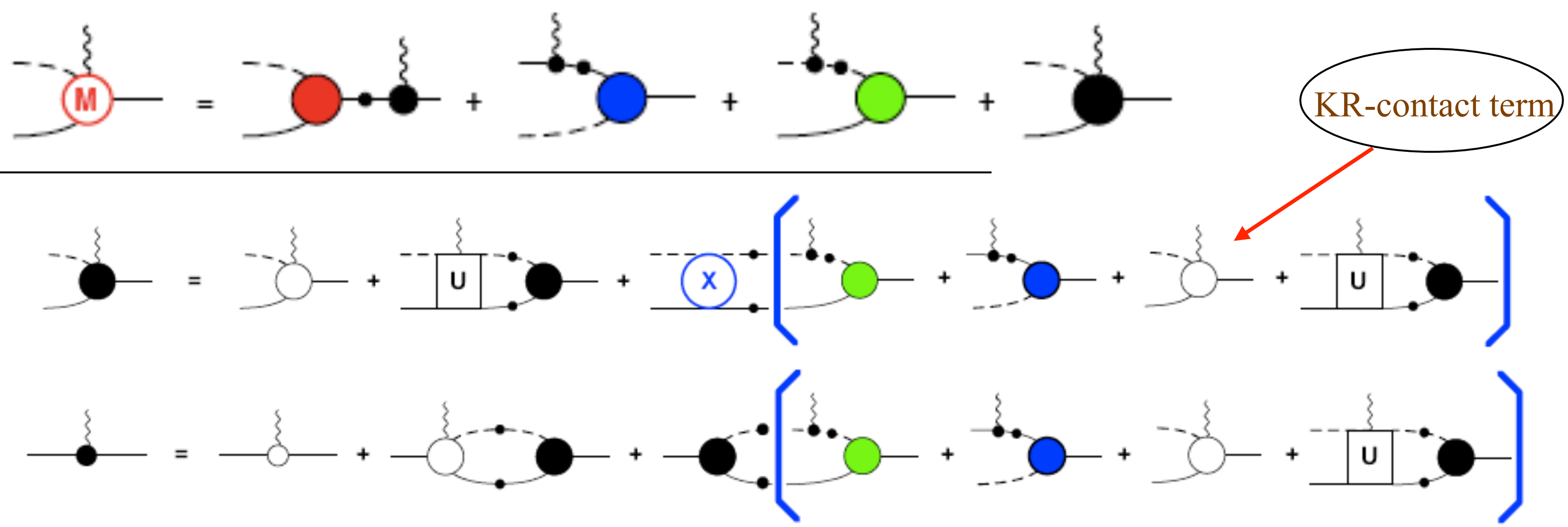
(Haberzettl, PRC56, 2041, '97)

Hadronic Scattering: $\pi N \to \pi N$



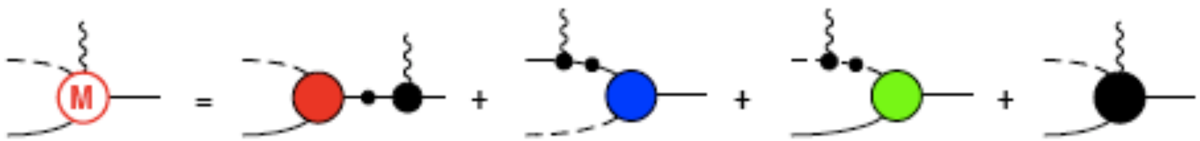
Photoproduction: $\gamma N \to \pi N$

$$M^{\mu} = M_{s}^{\mu} + M_{u}^{\mu} + M_{t}^{\mu} + M_{\text{int}}^{\mu}$$



Reaction Theory: *gauge invariance*

$$M^{\mu} = M_s^{\mu} + M_u^{\mu} + M_t^{\mu} + M_{\text{int}}^{\mu}$$



$F_s\tau$ $F_u\tau$ $F_t\tau$

current conservation: $k_\mu M^\mu = 0$ (all external legs on-shell)

Theory requires off-shell condition (Ward-Takahashi identity):

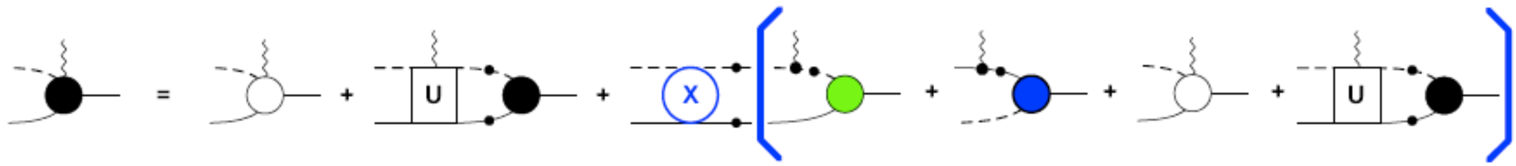
(τ = vertex isospin operator ; Q =charge operator)

$$k_\mu M^\mu = -\,[F_s\tau] S_{p+k}\, Q_i\, S^{-1}_p + S^{-1}_{p'}\, Q_f\, S_{p'-k}\, [F_u\tau] + \Delta^{-1}_{p-p'-k}\, Q_\pi\, \Delta_{p-p'} [F_t\tau]$$

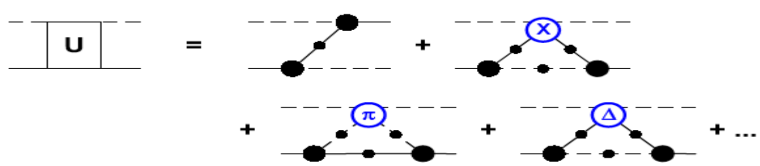
$$k_\mu M^\mu_{int} = -\,[F_s]\, e_i + e_f [F_u] + e_\pi [F_t]$$

$$e_i = \tau Q_i$$
$$e_f = Q_f \tau$$
$$e_\pi = Q_\pi \tau$$

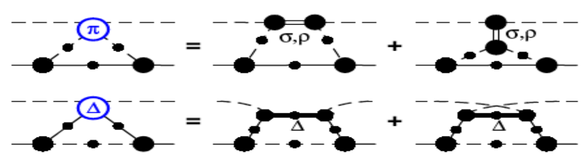
Reaction theory: *gauge invariance* (cont.')



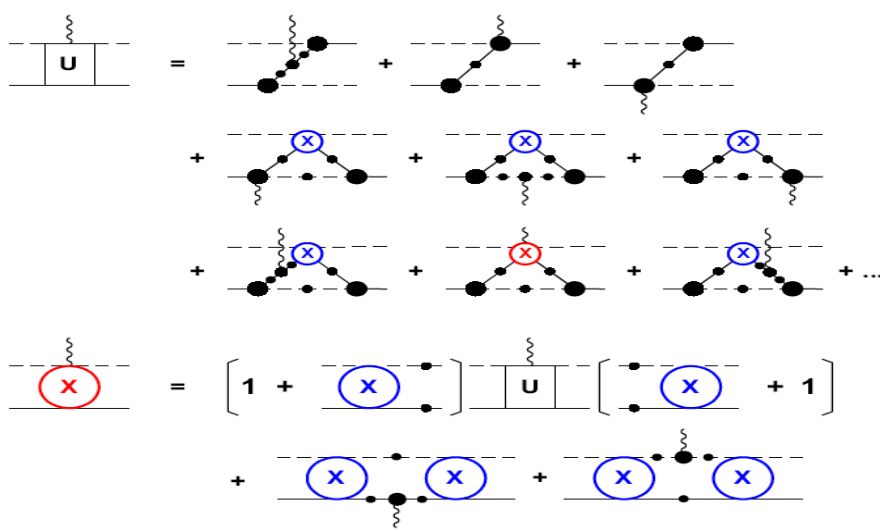
Hadronic Driving Terms:



Box graphs:

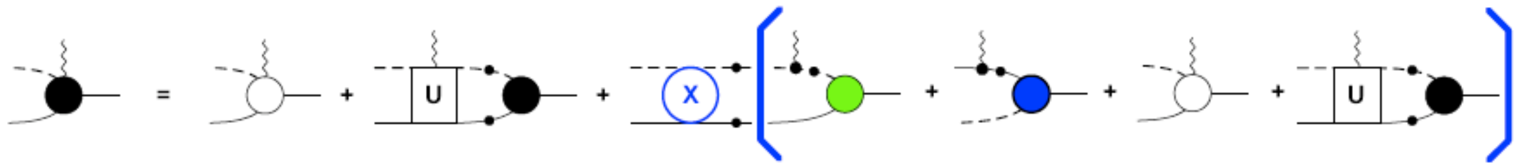


Electromagnetic Couplings to Driving Terms:

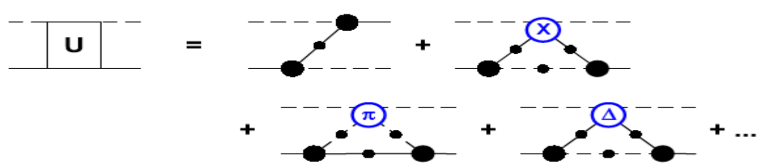


Dressed Nucleon Current:

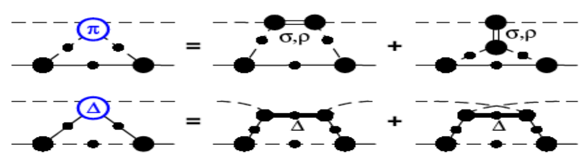
Reaction theory: *gauge invariance* (cont.')



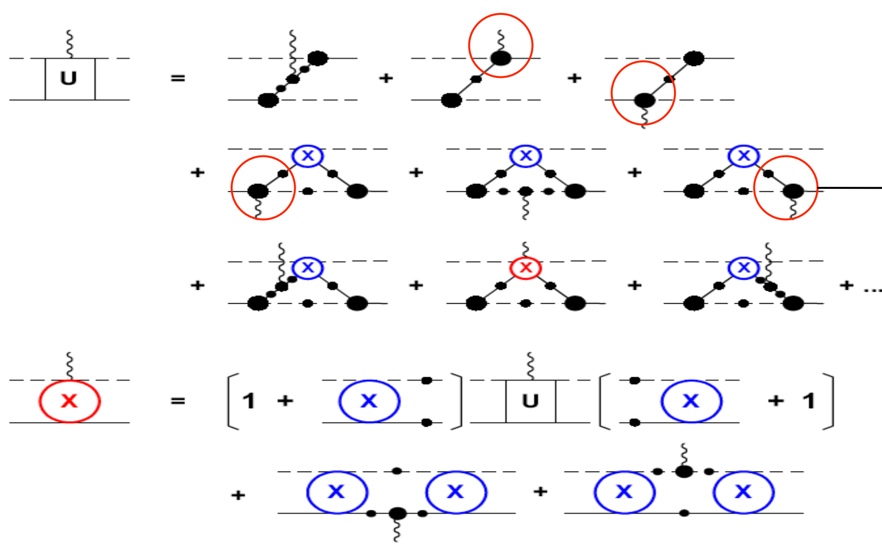
Hadronic Driving Terms:



Box graphs:



Electromagnetic Couplings to Driving Terms:

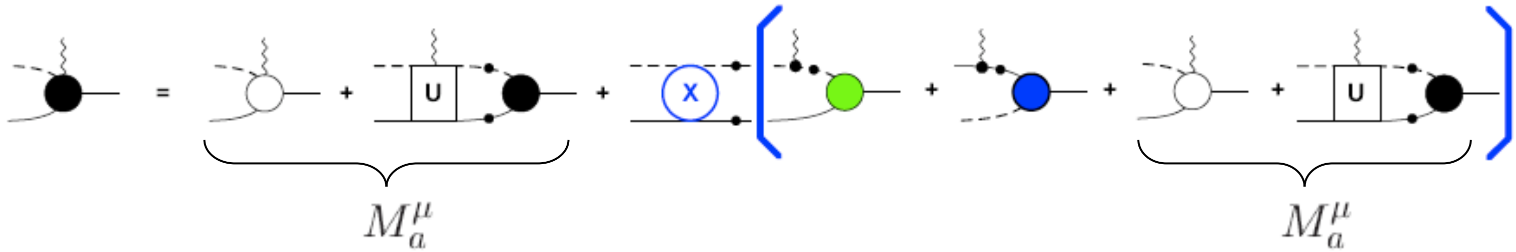


full amplitude
(non-linear effects)

Dressed Nucleon Current:

Reaction Theory: *approx. the interaction current*

(Haberzettl, Nakayama, Krewald, PRC74, '06)



$$M^\mu_{\text{int}} = M^\mu_a + XG[M^\mu_t + M^\mu_u + M^\mu_a]$$

gauge condition on M_a^μ :

$$k_\mu M^\mu_a = (1-UG)\Big(-[F_s]e_i + [F_u]e_f + [F_t]e_\pi\Big) - k_\mu UG\Big(M^\mu_{uL} + M^\mu_{tL}\Big)$$

M^μ_{uL} = longitudinal part of M^μ_u

M^μ_{tL} = longitudinal part of M^μ_t

Ansatz :

$$M^\mu_a = (1-UG)M^\mu_c - UG\Big(M^\mu_{uL} + M^\mu_{tL}\Big) + T^\mu$$

unconstrained transverse contact current ($k_\mu T^\mu=0$)

$$k_\mu M^\mu_c = -[F_s]e_i + [F_u]e_f + [F_t]e_\pi$$

Reaction Theory: *approx. the interaction current*

(cont.')

interaction current:

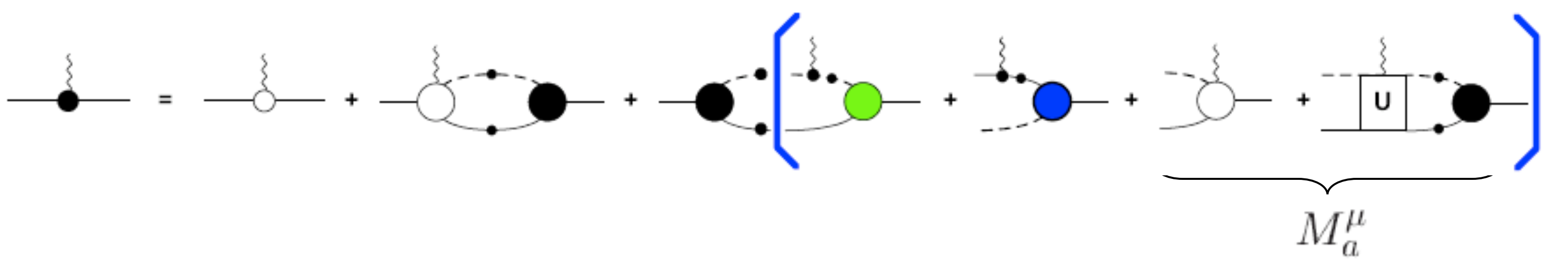
$$M^{\mu}_{\text{int}} = M^{\mu}_{a} + XG[M^{\mu}_{t} + M^{\mu}_{u} + M^{\mu}_{a}]$$

$$= M^{\mu}_{c} + T^{\mu} + XG\left[M^{\mu}_{uT} + M^{\mu}_{tT} + T^{\mu}\right]$$

M^{μ}_{uT} = transverse part of M^{μ}_{u}

M^{μ}_{tT} = transverse part of M^{μ}_{t}

dressed NNγ vertex:



$$\Gamma^{\mu} = \Gamma^{\mu}_{bare} + m_{KR}G[F\tau] + [F_{bare}\tau]G\left(M^{\mu}_{c} + M^{\mu}_{uL} + M^{\mu}_{tL}\right)$$

$$+[F\tau]G\left[M^{\mu}_{uT} + M^{\mu}_{tT} + T^{\mu}\right]$$

Reaction Theory: *approx. the interaction current* *(cont.')*

choosing the contact current M_c^μ :

$$M_c^\mu = \Gamma_{NN\pi}(q) C^\mu + \Gamma_{KR}^\mu f_t$$

$$C^\mu = -e_\pi \frac{(2q-k)^\mu}{t-q^2}(f_t - \hat{F}) - e_f \frac{(2p'-k)^\mu}{u-p'^2}(f_u - \hat{F}) - e_i \frac{(2p+k)^\mu}{s-p^2}(f_s - \hat{F}),$$

$$\hat{F} = 1 - \hat{h}(1-\delta_s f_s)(1-\delta_u f_u)(1-\delta_t f_t) \;, \quad h = \text{free parameter}$$

Genuine contact current
Crossing symmetry
Davidson-Workman (PRC63, 025210)

transverse contact current T^μ :

$$T^\mu = \gamma_5 \sum_{j=1}^{4} A_j T_j^\mu$$

simplest choice:

$$A_j = \frac{a_j}{k_0},$$

a_j=constant (set to zero in actual calculation)

$$T_1^\mu = \frac{i}{m}\sigma^{\mu\nu}k_\nu = \frac{1}{m}(\gamma^\mu \not{k} - k^\mu),$$

$$T_2^\mu = \frac{1}{m^3}\left[P^\mu(2q\cdot k - k^2) - (2q-k)^\mu P\cdot k\right],$$

$$T_3^\mu = \frac{1}{m^2}(\gamma^\mu q\cdot k - q^\mu \not{k}),$$

$$T_4^\mu = \frac{1}{m^2}(\gamma^\mu P\cdot k - P^\mu \not{k}) - T_1^\mu,$$

Reaction Theory: *approx. the interaction current*

(cont.')

Another choice for the transverse contact current T^{μ} :

$$T^{\mu} = -UG[M^{\mu}_{uT} + M^{\mu}_{tT}] \longrightarrow M^{\mu}_{\text{int}} = M^{\mu}_{c}$$

$$M^{\mu} = M^{\mu}_{s} + M^{\mu}_{u} + M^{\mu}_{t} + M^{\mu}_{c}$$

accounts effectively for the FSI

(suited for study of photoproduction processes where no FSI's are readily available: [η', ϕ, …])

Reaction theory: using the Jülich hadronic model

Juelich Hadronic Model (TOPT):

$$T(\vec{p}',\vec{p};\sqrt{s}) = V(\vec{p}',\vec{p};\sqrt{s}) + \int d\vec{p}''\, V(\vec{p}',\vec{p}'';\sqrt{s}) \frac{1}{\sqrt{s} - E_{p''} - \omega_{p''} + i\eta} T(\vec{p}'',\vec{p};\sqrt{s})$$

Converting to a covariant 3-D reduction like equation:

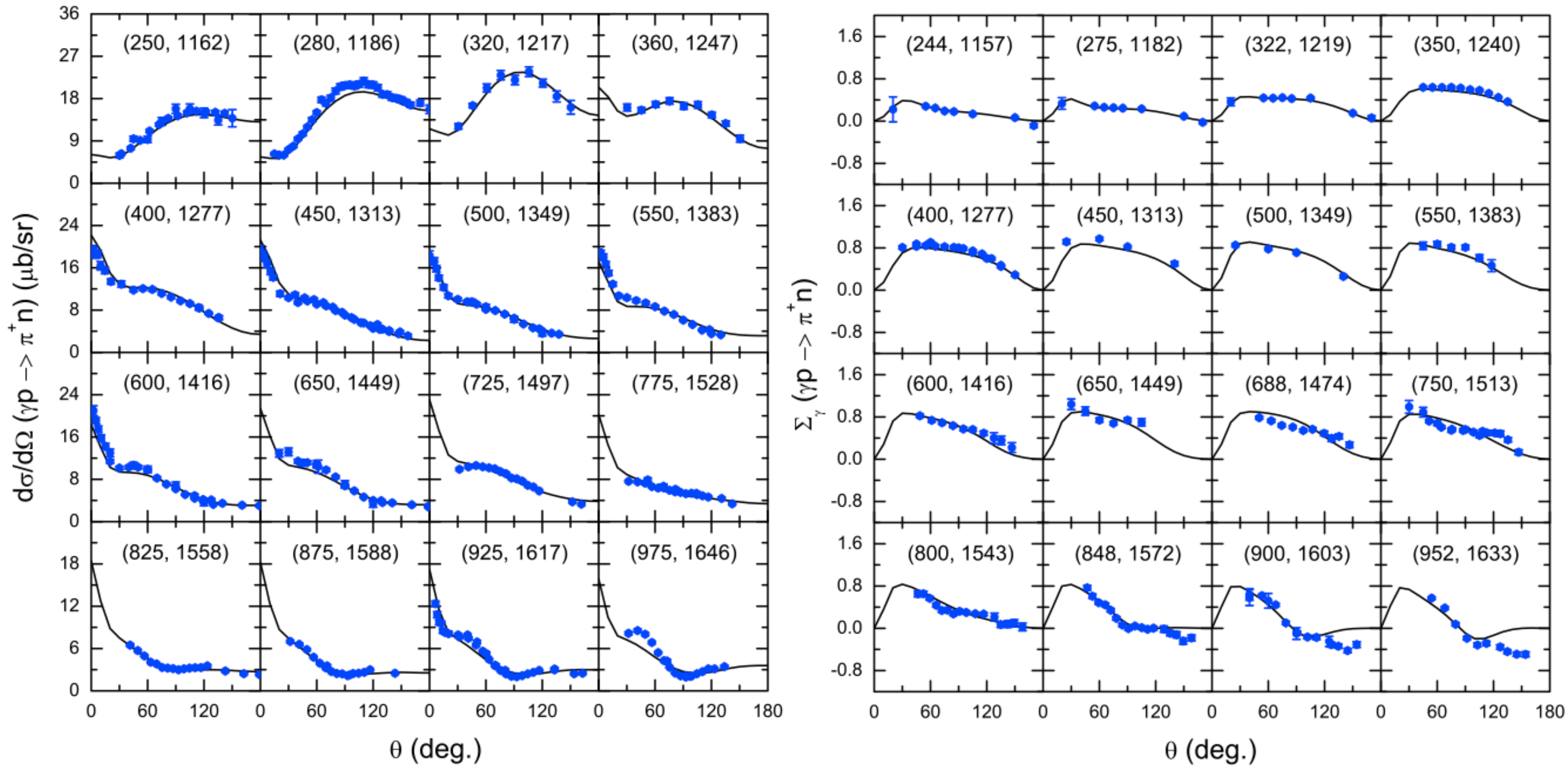
$$\tilde{T}(\vec{p}',\vec{p};\sqrt{s}) = \tilde{V}(\vec{p}',\vec{p};\sqrt{s}) + \int \frac{d\vec{p}''}{(2\pi)^3 2\omega_{p''}} \frac{m}{\varepsilon_{p''}} \tilde{V}(\vec{p}',\vec{p}'';\sqrt{s}) \frac{1}{\sqrt{s} - E_{p''} - \omega_{p''} + i\eta} \tilde{T}(\vec{p}'',\vec{p};\sqrt{s})$$

$$\begin{cases} \tilde{V}(\vec{p}',\vec{p};\sqrt{s}) \equiv (2\pi)^3 \sqrt{\dfrac{\varepsilon_{p'}}{m}} \sqrt{2\omega_{p'}}\, V(\vec{p}',\vec{p};\sqrt{s}) \sqrt{\dfrac{\varepsilon_{p}}{m}} \sqrt{2\omega_{p}} \\ \tilde{T}(\vec{p}',\vec{p};\sqrt{s}) \equiv (2\pi)^3 \sqrt{\dfrac{\varepsilon_{p'}}{m}} \sqrt{2\omega_{p'}}\, T(\vec{p}',\vec{p};\sqrt{s}) \sqrt{\dfrac{\varepsilon_{p}}{m}} \sqrt{2\omega_{p}} \end{cases}$$

(minimal relativity)

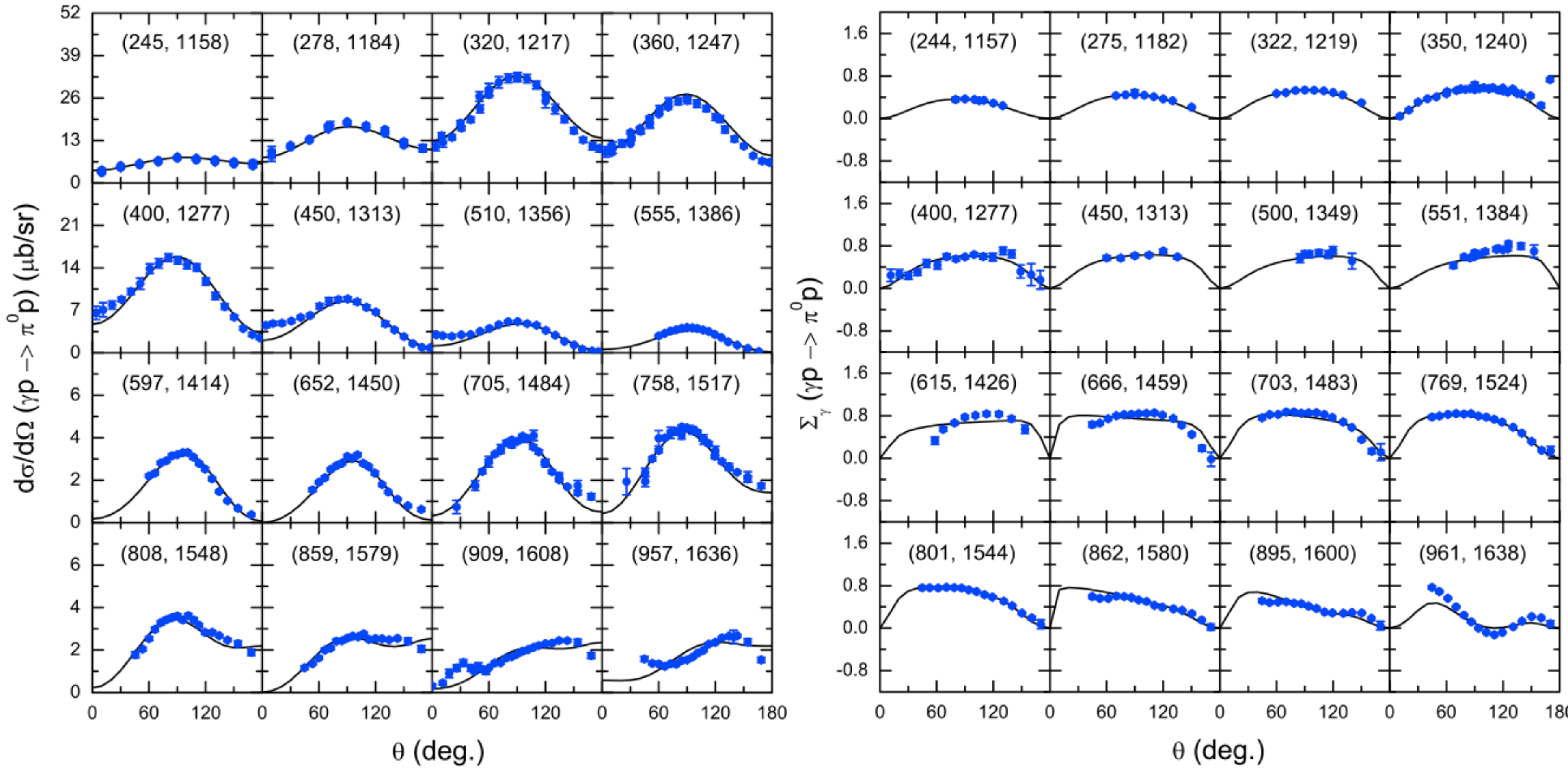
Similarly, make the 3-D reduction of the covariant photoproduction equation.

Results: $\gamma + p \rightarrow \pi^{+} + n$



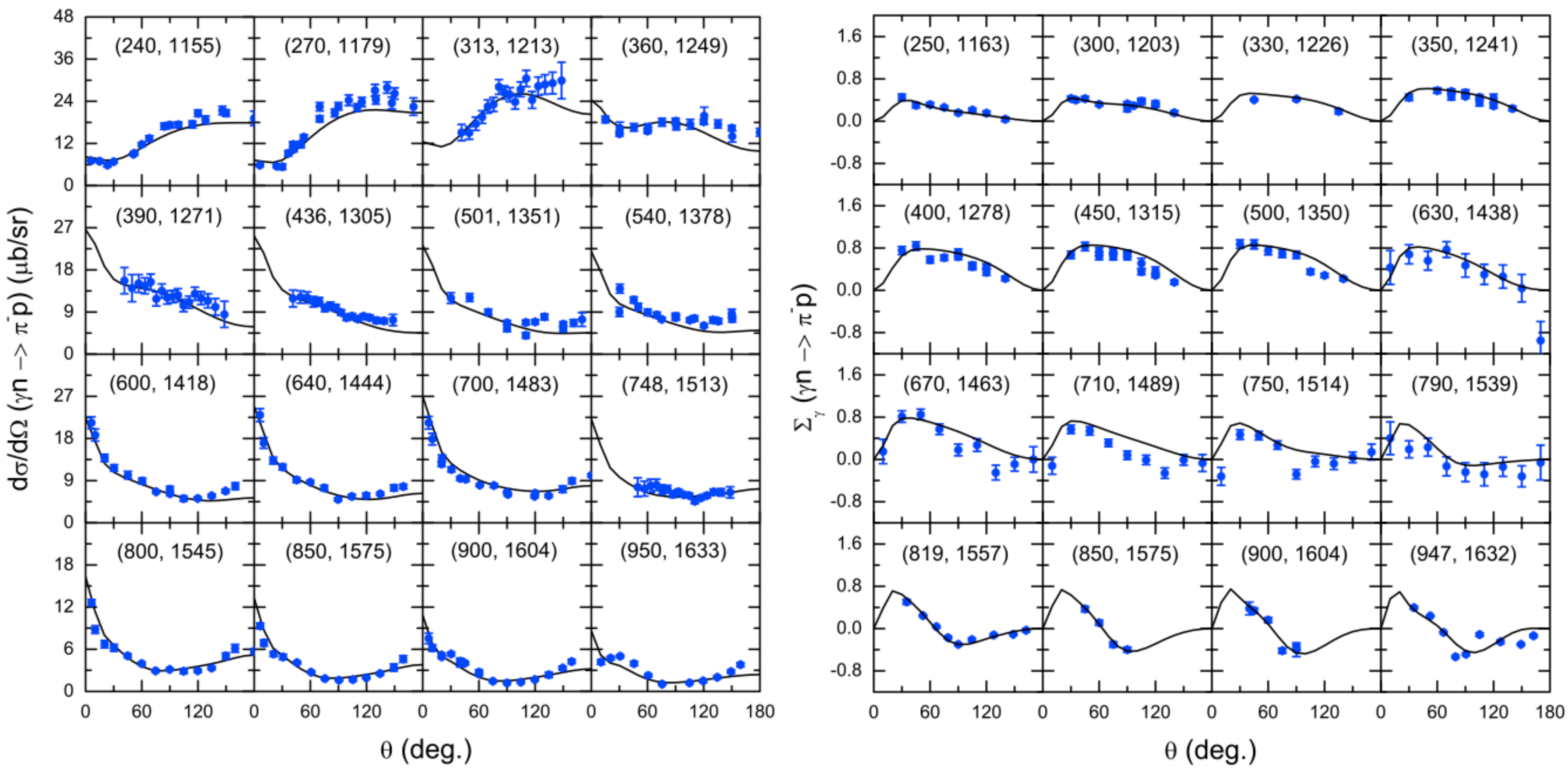
Data: CLAS (2009), MAMI (2004), GRAAL (2000), SAID

Results: $\gamma + p \rightarrow \pi^0 + p$



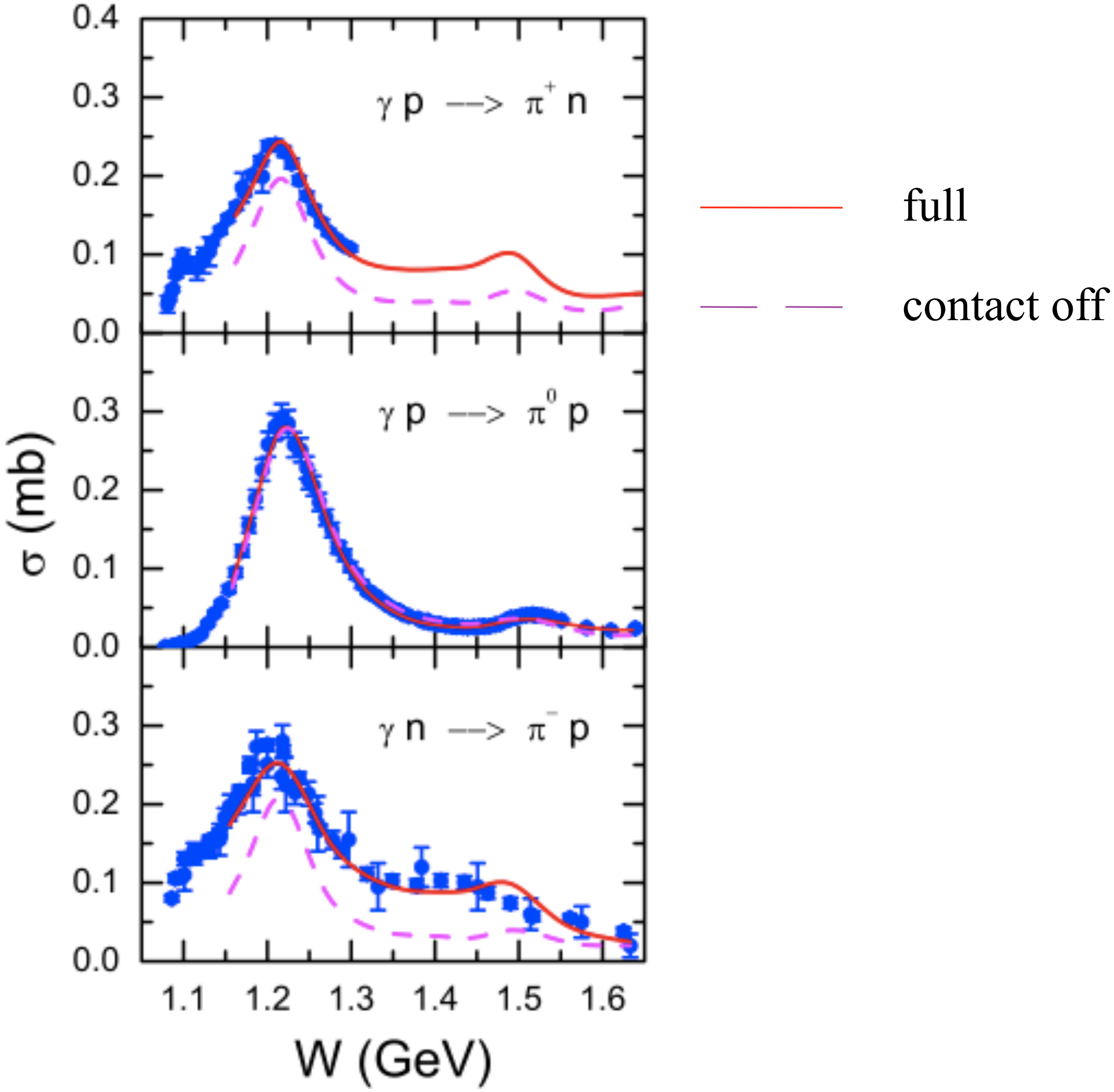
Data: CBELSA/TAPS (2009), GRAAL (2005), SAID

Results: $\gamma + n \rightarrow \pi^- + p$



Data: MAMI (2004), GRAAL (2009), SAID

Results: $\gamma + N \rightarrow \pi + N$



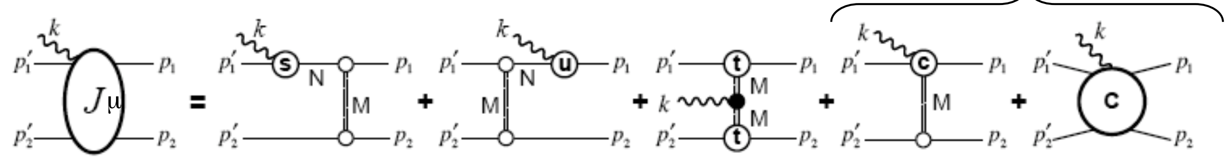
Generalized Contact Current: $NN \rightarrow \gamma NN$

(Nakayama, Haberzettl, PRC80(R),'10)

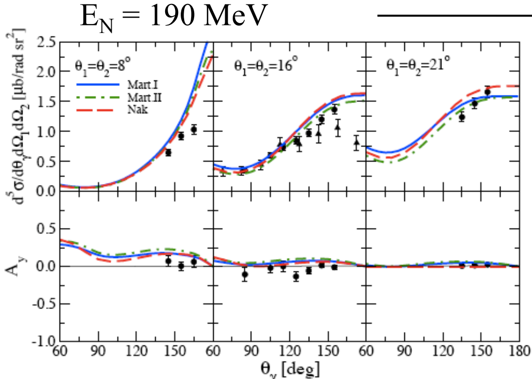
NN → NN scattering: $T = V + VGT$

NN → γNN scattering: $M^{\mu} = (1 + T_f G_f) J^{\mu} (1 + G_i T_i)$

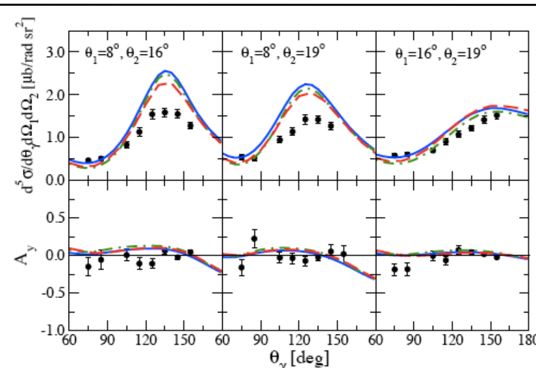
four- and five-point contact current



$E_N = 190$ MeV

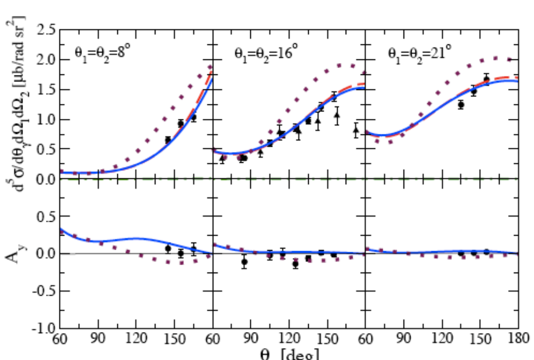


(a)

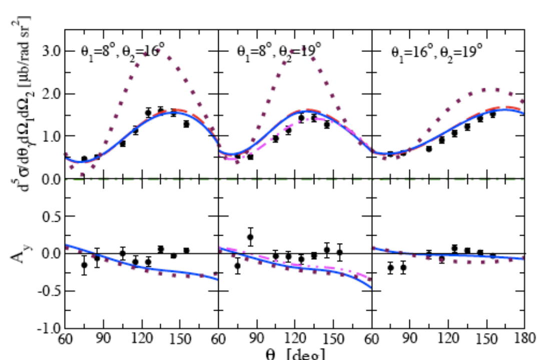


(b)

previously existing calculations (no contact currents)



(c)



(d)

present calculation (with contact currents)

Photoproduction: analytic continuation

Analytic continuation : $M^{\mu}(\sqrt{s}) \rightarrow M^{\mu}(z)$, z = complex energy

$$
\begin{cases}
\text{1st sheet:} & G^{(1)}(z) = \dfrac{1}{z - E_M - E_B + i\epsilon} \\[2ex]
\text{2nd sheet:} & G^{(2)}(z) = G^{(1)}(z) + \underbrace{\dfrac{2\pi i \, q_{\rm on}^{>} \, E_M^{on} \, E_B^{on}}{z}}_{\text{discontinuity of G along the right hand cut}}
\end{cases}
\qquad
q_{\rm on}^{>} = \begin{cases} -q_{\rm on} & \text{if Im } q_{\rm on} < 0 \\ q_{\rm on} & \text{else} \end{cases}
$$

In each partial-wave state:

$$M \equiv \varepsilon_{\mu} M^{\mu} = \varepsilon_{\mu}[M_s^{\mu} + M_u^{\mu} + M_t^{\mu} + M_c^{\mu}] + XG[M_{uT}^{\mu} + M_{tT}^{\mu}]\varepsilon_{\mu}$$

Laurent expansion :

$$M(z) = \frac{a_{-1}}{z - z_o} + a_o + (z - z_o)a_1 + \ldots$$

terms contributing to a_{-1}:

$$M^{P} = \varepsilon_{\mu} M_s^{\mu +} = \Gamma^{a}(z) \frac{1}{z - m - \Sigma(z)} \varepsilon_{\mu} \Gamma^{\mu}(z)$$

$$\overline{M}^{NP} = X(z)G(z)[M_{uT}^{\mu}(z) + M_{tT}^{\mu}(z)]\varepsilon_{\mu}$$

Photoproduction: *extraction of the residues*

In the second Riemann sheet:

$$M^P = \Gamma^{a(2)}(z)\frac{1}{z-m-\Sigma^{(2)}(z)}\varepsilon_\mu \Gamma^\mu(z)$$

$$\overline{M}^{NP} = \int X^{(2)}(z) G^{(2)}(z)[M^\mu_{uT}(z) + M^\mu_{tT}(z)]\varepsilon_\mu$$

$$a_{-1} = a^P_{-1} + a^{NP}_{-1}$$

$$a^P_{-1} = \Gamma^{a(2)}(z_o)\frac{1}{1-[d/dz\Sigma^{(2)}]_{z=z_o}}\varepsilon_\mu \Gamma^\mu(z_o)$$

$$a^{NP}_{-1} = \int a^{NP}_{-1(h)} G^{(2)}(z_o)[M^\mu_{uT}(z_o) + M^\mu_{tT}(z_o)]\varepsilon_\mu$$

half-off-shell hadronic residue

For two resonances case:

$$M^{\mathrm{P}} = \Gamma^{a(2)}(z)\left(D^{(2)}(z)\right)^{-1}\varepsilon_\mu \Gamma^\mu(z)$$

$$\Gamma^{a(2)} = (\Gamma_1^{a(2)}, \Gamma_2^{a(2)}) \qquad \varepsilon_\mu \Gamma^\mu = \begin{pmatrix}\varepsilon_\mu \Gamma_1^\mu \\ \varepsilon_\mu \Gamma_2^\mu\end{pmatrix}$$

$$D^{(2)} = \begin{pmatrix} z - m_1 - \Sigma_{11}^{(2)} & -\Sigma_{12}^{(2)} \\ -\Sigma_{21}^{(2)} & z - m_2 - \Sigma_{22}^{(2)} \end{pmatrix}$$

$$a^{\mathrm{P}}_{-1i} = A\left[\varepsilon_\mu \Gamma^\mu(z_{oi})\right]$$

$$\begin{aligned} A &= \left[\Gamma^{a(2)}\frac{\det D^{(2)}}{d/dz\ \det D^{(2)}}(D^{(2)})^{-1}\right]_{z\to z_{0i}} \\ &= \lim_{z\to z_{0i}}\left\{\left(\Gamma_1^{a(2)}, \Gamma_2^{a(2)}\right)\right. \\ &\times \begin{pmatrix} z - m_2 - \Sigma_{22} & \Sigma_{21} \\ \Sigma_{12} & z - m_1 - \Sigma_{11}\end{pmatrix} \\ &\times \left.\frac{1}{\frac{d}{dz}\left[(z-m_1-\Sigma_{11})(z-m_2-\Sigma_{22}) - \Sigma_{12}\,\Sigma_{21}\right]}\right\} \end{aligned}$$

Photoproduction: resonance & background

Hadronic Scattering:

$$T = T^R + T^{BG}$$

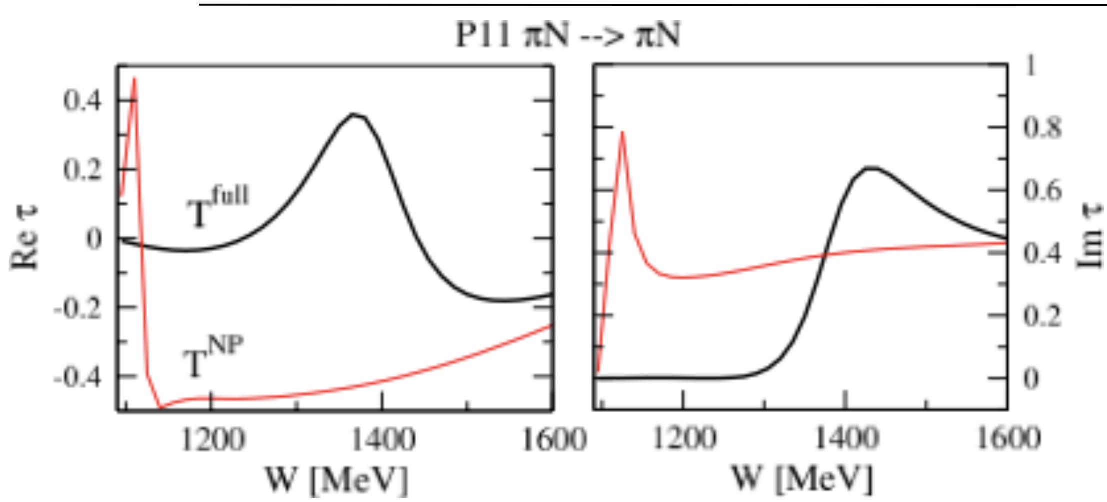
$$\begin{cases} T^R \equiv \sum_r \frac{a_{-1r}}{\sqrt{s} - z_{or}} = \sum_r g_r^{a(h)} \frac{1}{\sqrt{s} - z_{or}} g_r^{c(h)} \\ T^{BG} \equiv T - T^R \end{cases}$$

Overall phase of $g_r^{(h)}$ is fixed by choosing the real part of the πN coupling to be positive

Photoproduction:

$$M \equiv \varepsilon_\mu M^\mu = M^R + M^{BG}$$

$$\begin{cases} M^R \equiv \sum_r \frac{a_{-1r}}{\sqrt{s} - z_{or}} = \sum_r g_r^{a(h)} \frac{1}{\sqrt{s} - z_{or}} g_r^{c(\gamma)} \\ M^{BG} \equiv M - M^R \end{cases}$$



The usual decompositon, $T = T^P + T^{NP}$, is arbitrary and T^P&T^{NP} maybe highly model dependent!

Suggestion: compare T^{BG} & T^R and not T^{NP} & T^P

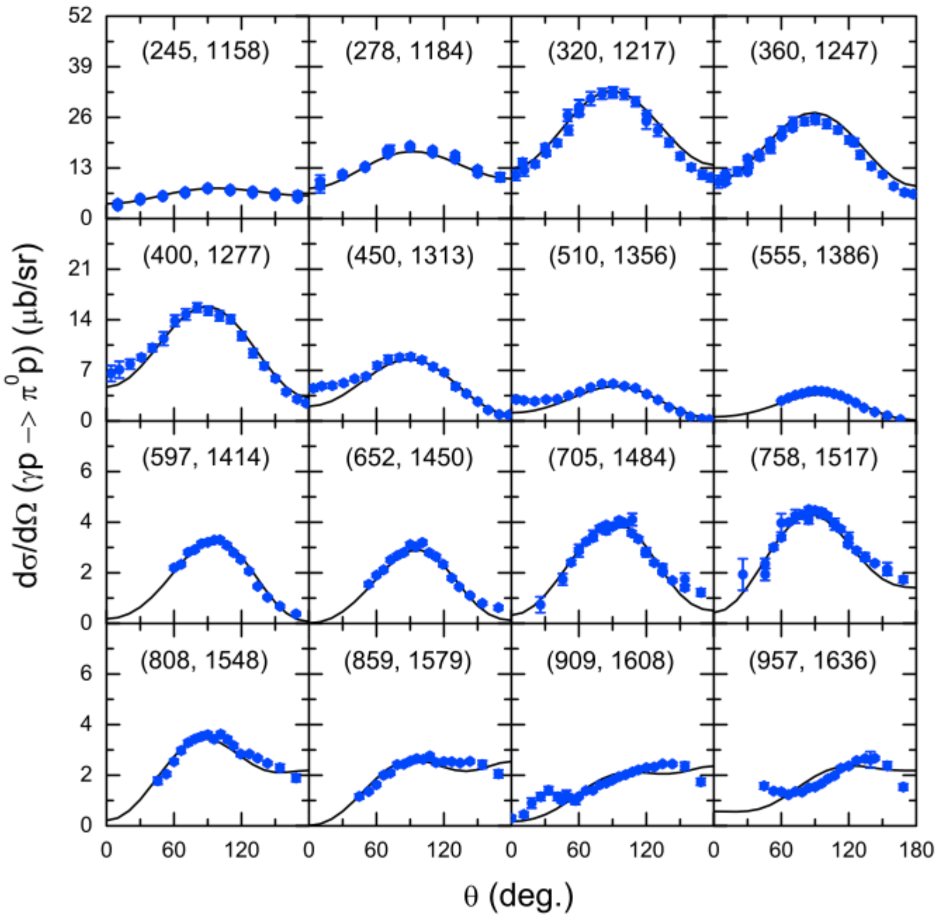
Photoproduction: *poles & residues (couplings)*

Effective electromagnetic couplings g^γ in helicity basis.
The first and second lines for each isospin 1/2 resonance correspond to the results for proton and neutron, respectively.

	Pole position [MeV]	$g^\gamma_{1/2}$ [MeV$^{1/2}$]	$g^\gamma_{3/2}$ [MeV$^{1/2}$]
$P_{33}(1232)$	$1217 - 45\,i$	$0.42 - 0.11\,i$	$4.95 + 1.53\,i$
$P_{11}(1440)$	$1385 - 72\,i$	$-0.07 - 0.26\,i$	
		$-0.92 + 0.08\,i$	
$D_{13}(1520)$	$1503 - 47\,i$	$-3.55 + 2.14\,i$	$2.80 - 1.34\,i$
		$1.99 - 1.84\,i$	$-4.00 + 1.68\,i$
$S_{11}(1535)$	$1520 - 64\,i$	$-1.52 + 1.87\,i$	
		$4.05 - 2.01\,i$	
$S_{31}(1620)$	$1592 - 37\,i$	$-0.43 - 0.19\,i$	
$S_{11}(1650)$	$1666 - 70\,i$	$3.31 + 2.67\,i$	
		$-1.22 - 2.50\,i$	
$D_{33}(1700)$	$1638 - 122\,i$	$0.37 - 8.98\,i$	$-3.91 + 0.81\,i$
$P_{13}(1720)$	$1665 - 101\,i$	$0.11 - 5.41\,i$	$0.54 + 1.55\,i$
		$-0.51 + 2.71\,i$	$0.28 - 3.23\,i$
$P_{31}(1910)$	$1833 - 110\,i$	$59.29 - 31.11\,i$	

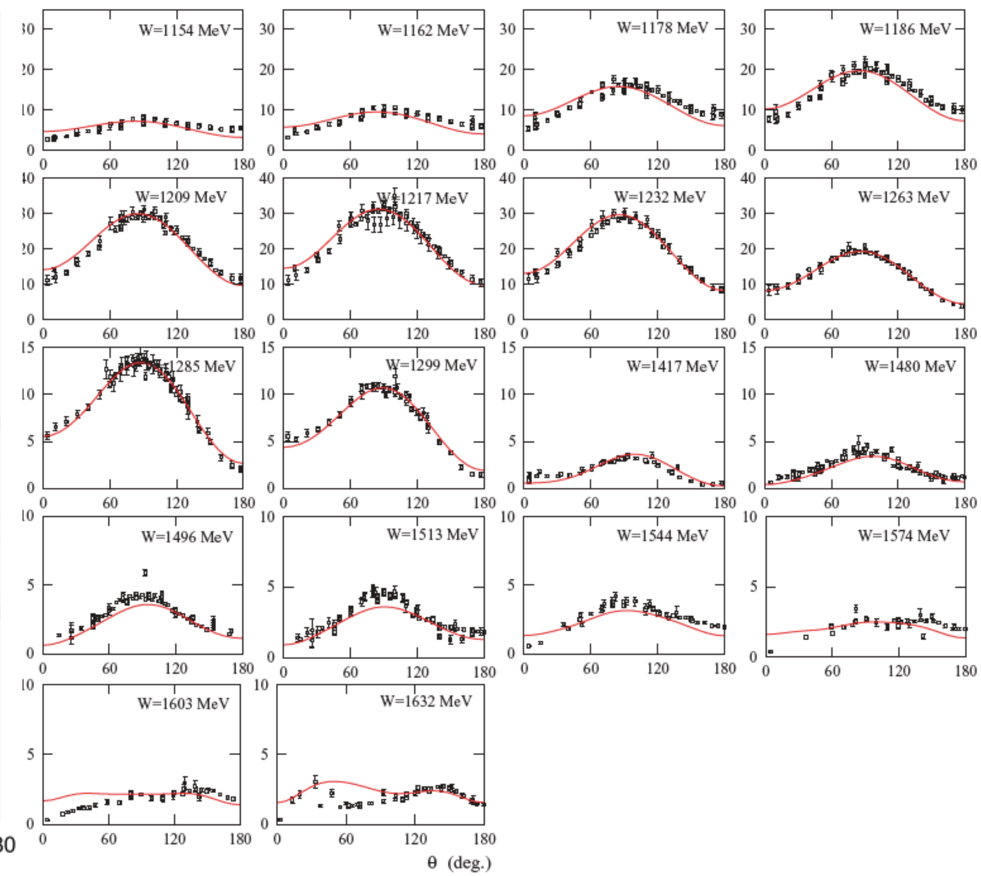
$d\sigma/d\Omega(\gamma + p \rightarrow \pi^0 + p)$: comparison with EBAC (PRC77,'08)

Jülich-UGA



fit to newer data

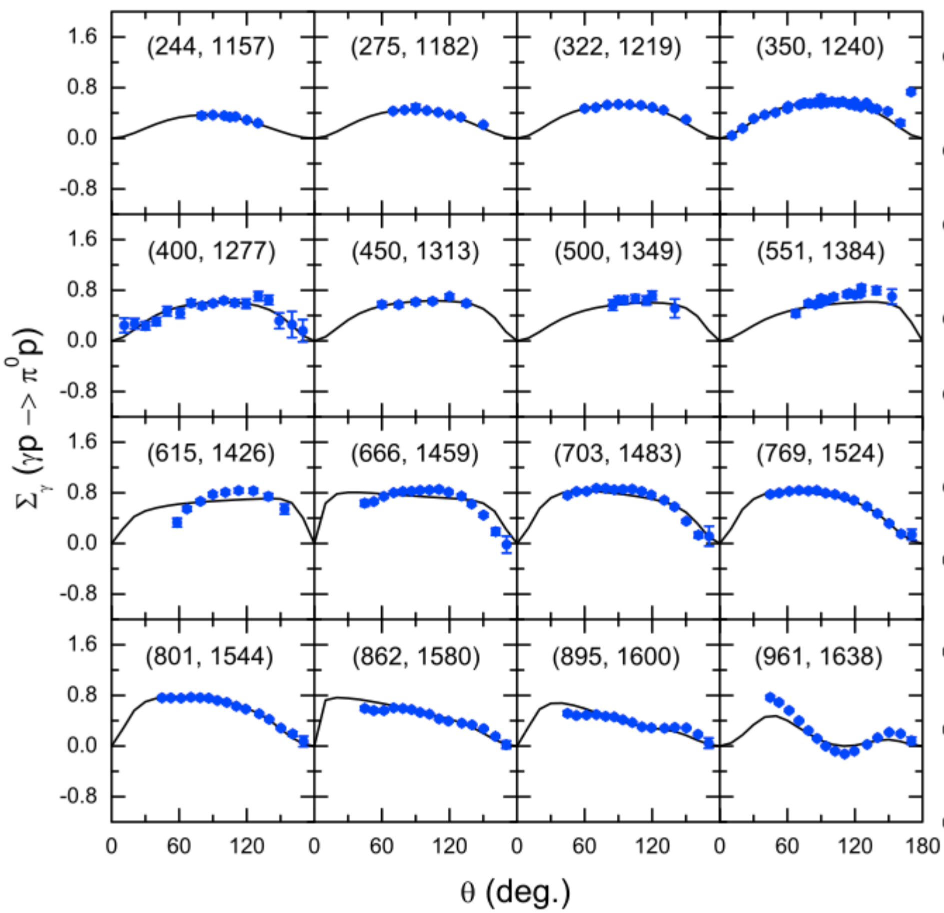
EBAC



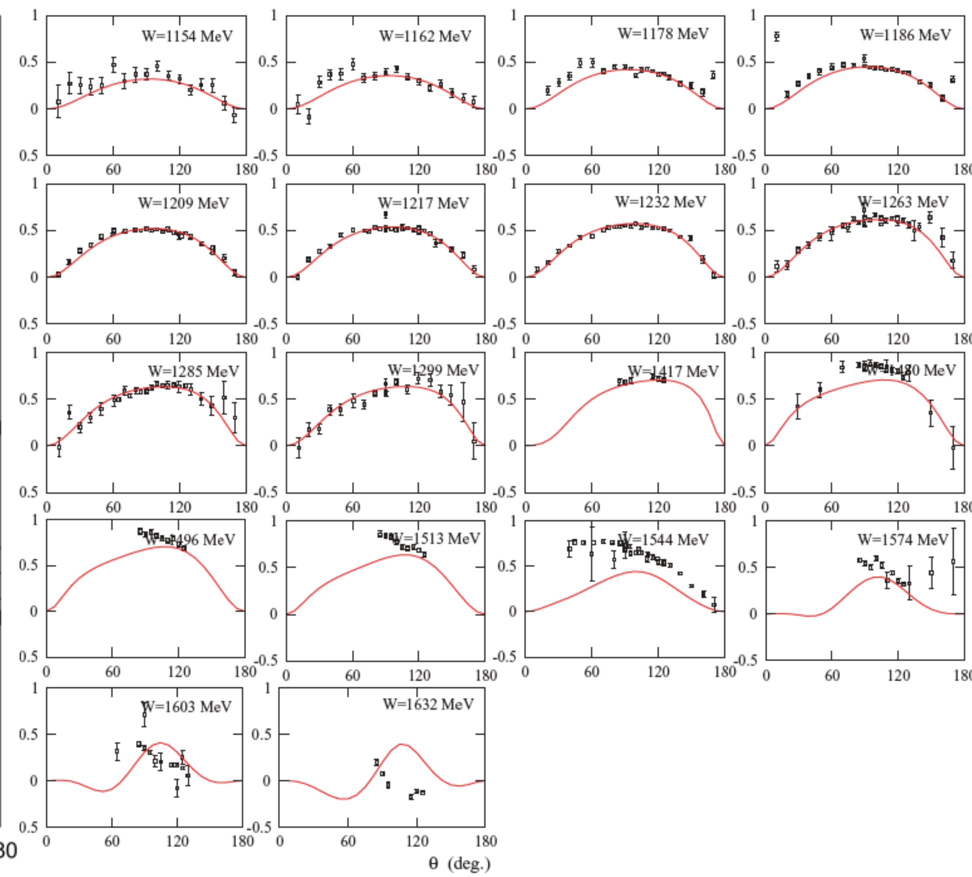
fit to older data

$\Sigma(\gamma + p \rightarrow \pi^0 + p)$: comparison with EBAC (PRC77,'08)

Jülich-UGA

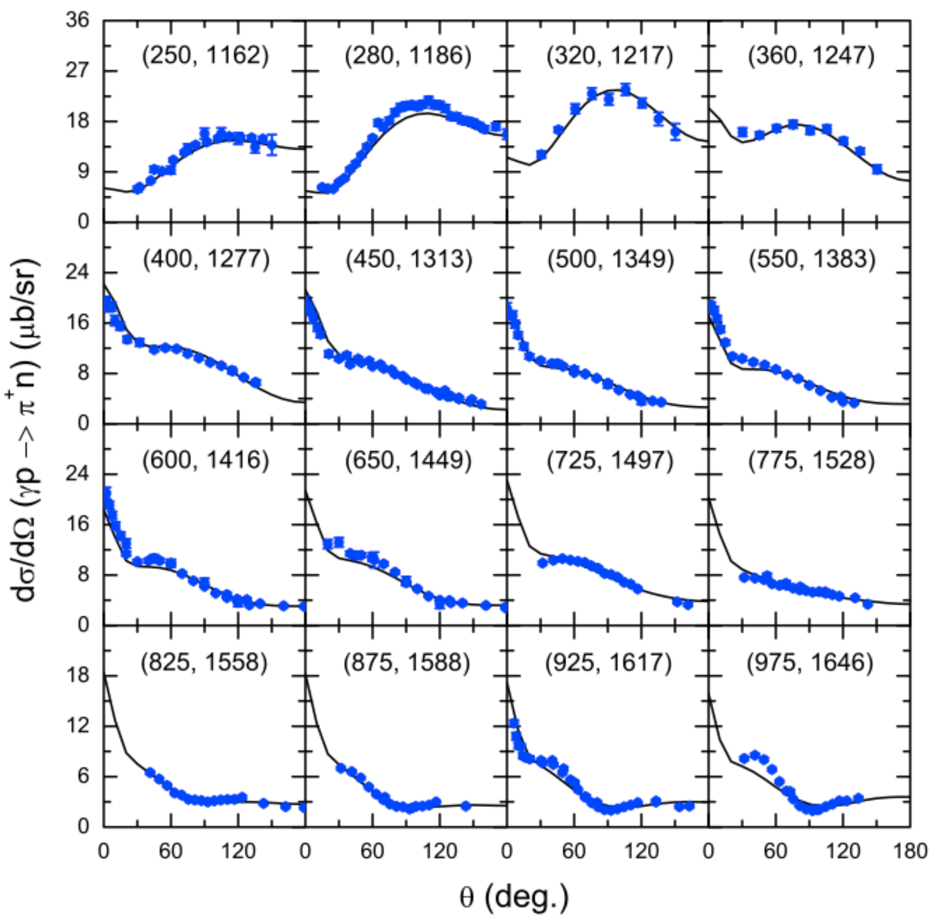


EBAC

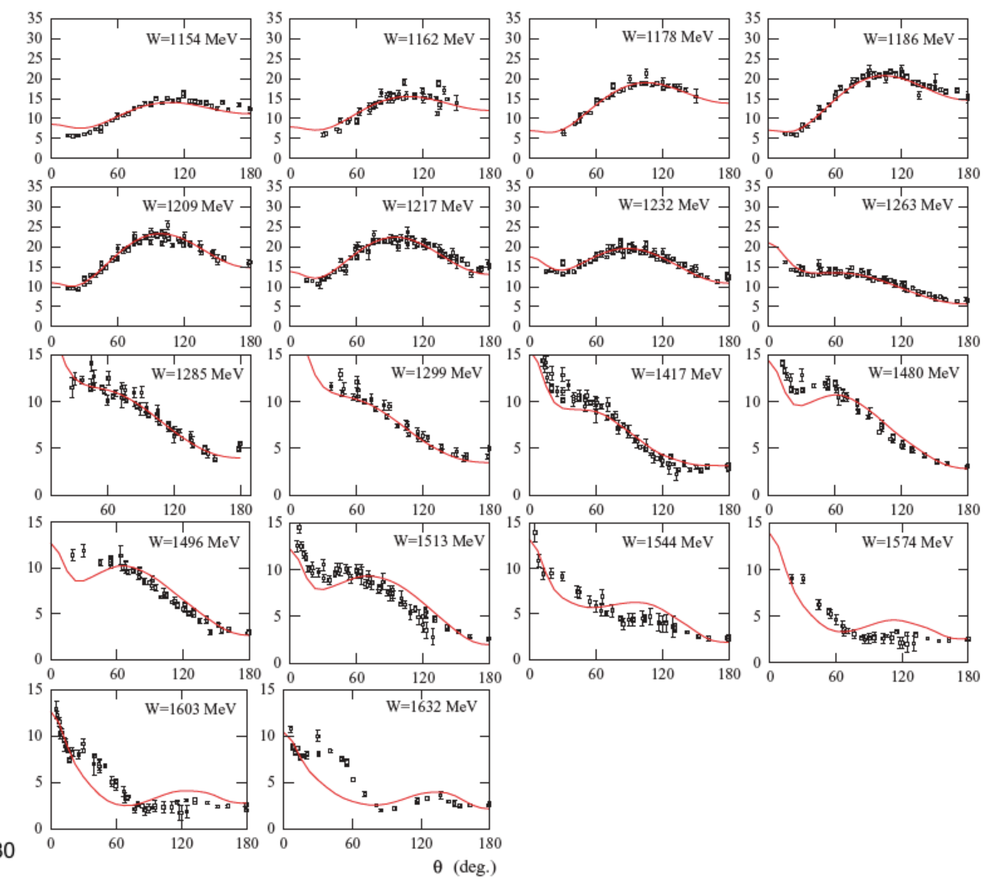


$d\sigma/d\Omega(\gamma + p \rightarrow \pi^+ + n)$: comparison with EBAC (PRC77,’08)

Jülich-UGA

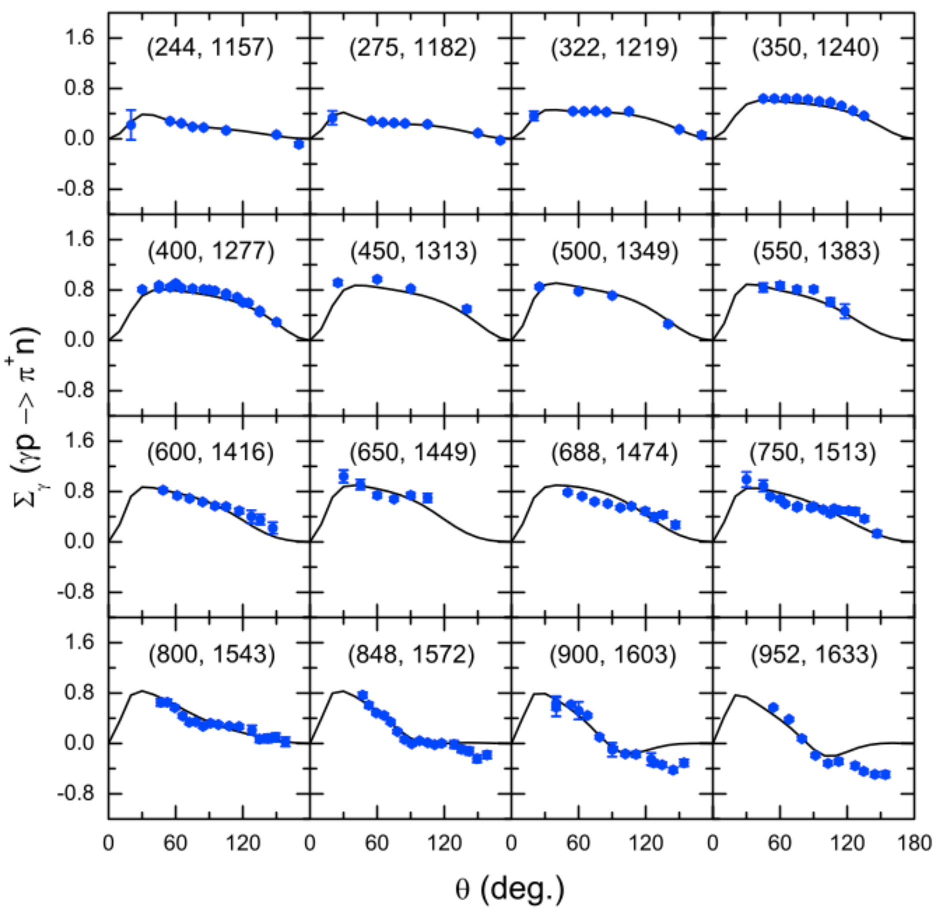


EBAC

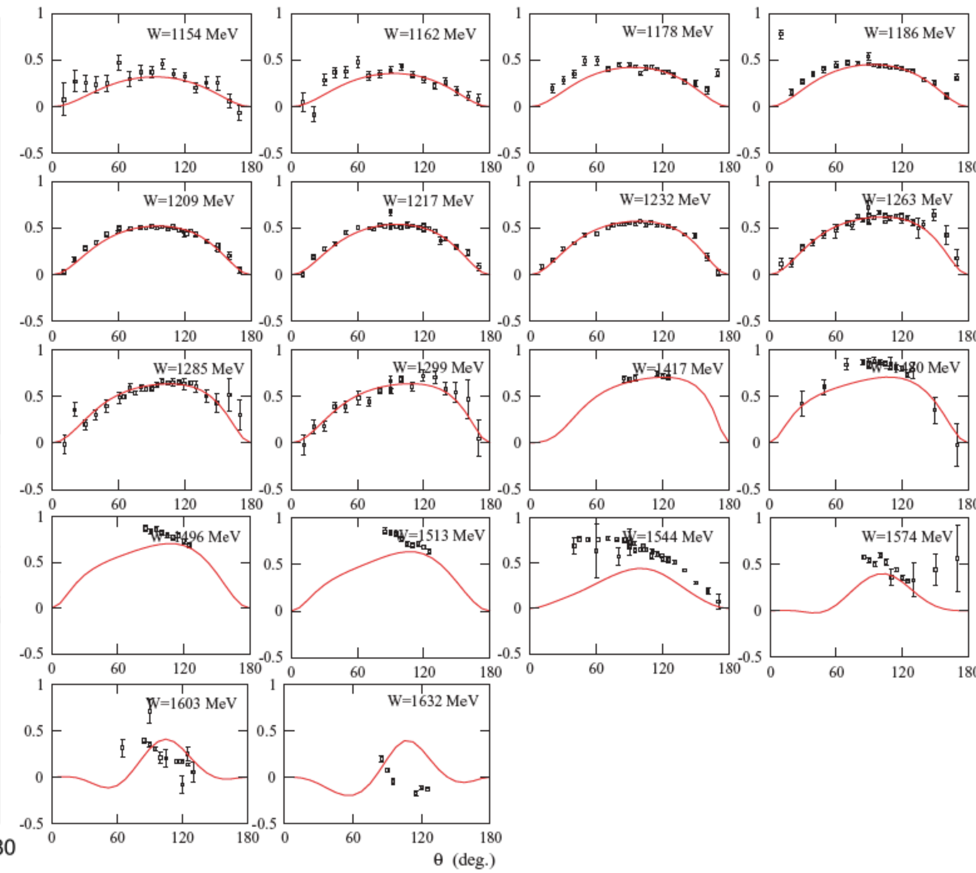


$\Sigma(\gamma + p \rightarrow \pi^+ + n)$: comparison with EBAC (PRC77,'08)

Jülich-UGA



EBAC



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