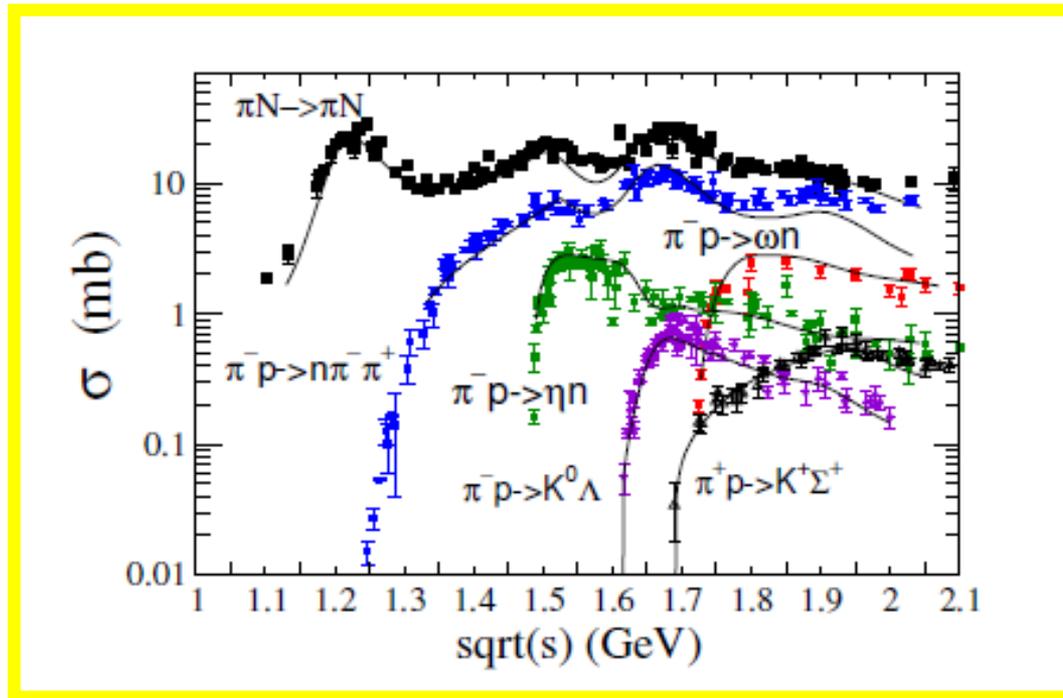


Meson Production on the Nucleon

H. Lenske

**Institut für Theoretische Physik, U. Giessen
and
GSI Darmstadt**

Meson Production on the Nucleon



$$Im T_{\pi N \rightarrow \pi N}^{JP} = \frac{k^2}{4\pi} (\sigma_{\pi N \rightarrow \pi N}^{JP} + \sigma_{\pi N \rightarrow 2\pi N}^{JP} + \sigma_{\pi N \rightarrow \eta N}^{JP} + \sigma_{\pi N \rightarrow \omega N}^{JP} + \sigma_{\pi N \rightarrow K\Lambda}^{JP} + \sigma_{\pi N \rightarrow K\Sigma}^{JP} + \dots)$$

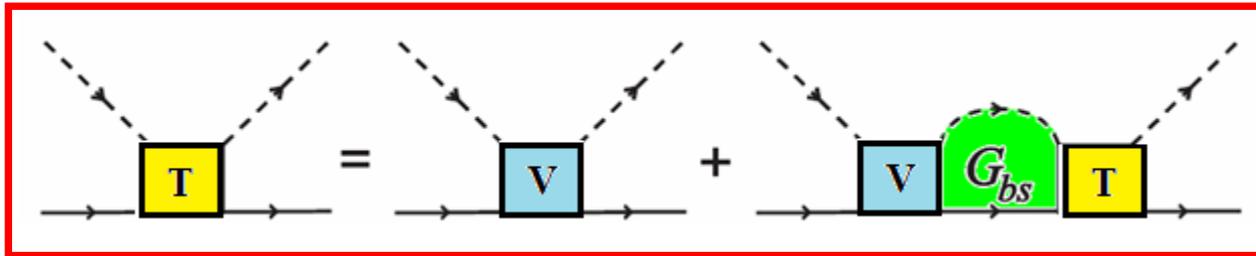
- Reaction dynamics: coupled multi-channel problem
- Lagrangian approach
- Dynamical description of resonances and background
- Meson production on nuclei: π , K , ω , ϕ , ρ ... 2π ...

Agenda

- 1. The Giessen Coupled Channels Approach**
- 2. Kaon Production on the Proton**
- 3. Multi-Meson Production on the Nucleon**
- 4. Outlook: Charm Production in Annihilation Reactions**
- 5. Summary**

The Giessen Model

Coupled Channels Approach to Meson Production on the Nucleon



Coupled-Channels Approach to Meson Production

- ✓ Partial wave (LSJ) T-matrix elements for $a \rightarrow b$ reaction:

$$T_{a,b}^{(LSJ)}(p_a, p_b; E) = V_{a,b}^{(LSJ)}(p_a, p_b; E) + \sum_c \int_0^\infty q^2 dq V_{a,c}^{(LSJ)}(p_a, q; E) G_c(q; E) T_{c,b}^{(LSJ)}(q, p_b; E)$$

channel coupling

- ✓ Choice of Reaction channels:

$$a, b, c = (\gamma^{(*)}N, \pi N, \eta N, \pi\Delta, \sigma N, \rho N, K\Lambda, K\Sigma, \dots)$$

$\pi\pi N$

- ✓ Definition of Transition Potentials:

$$V_{a,b} = V_{a,b}^{\text{bg}} + V_{a,b}^{\text{Z}} + \sum_{N^*} \frac{\Gamma_{N^*,a}^\dagger \Gamma_{N^*,b}}{E - M_{N^*}}$$

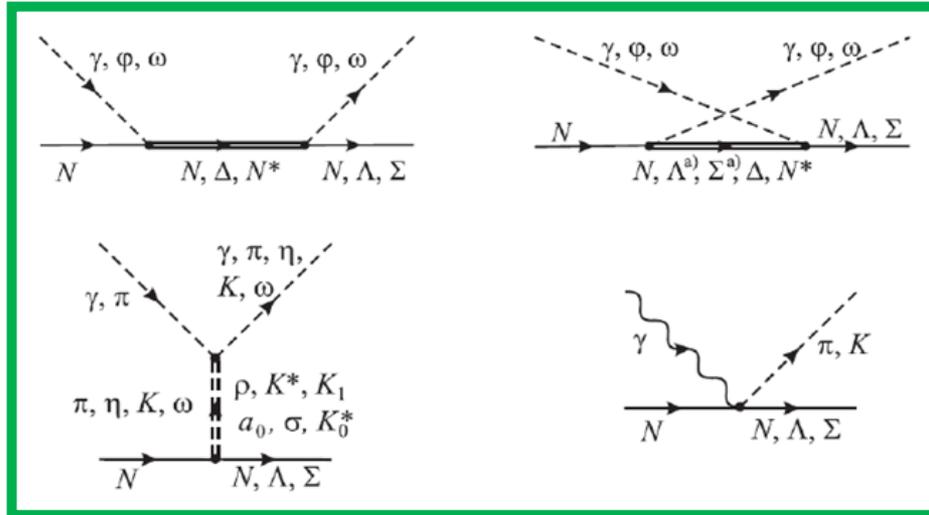
Background potentials

“Z-diagrams”

N^* resonances

Unitary CC K-Matrix Approach

$V_{ab} =$



Solution in K-Matrix Approximation:

$$K_{ab} = V_{ab} + \sum_c P \int V_{ac} G_{cc}^{(r)} K_{cb}$$

Partial Wave T-Matrix:

$$T_{fi}^{IJ\pm} = \left[\left(1 - iK^{IJ\pm} \right)^{-1} K^{IJ\pm} \right]_{fi}$$

Photo-Production Channel in LO

$$T_{\gamma\pi} = V_{\gamma\pi} + \sum_{m \neq \gamma} V_{\gamma m} G_m T_{m\pi}$$

Resulting Multi-Channel T-Matrix

$$T = \begin{pmatrix} T_{\gamma\gamma} & T_{\gamma\pi} & T_{\gamma\eta} & T_{\gamma\rho} \cdots \\ T_{\pi\gamma} & T_{\pi\pi} & T_{\pi\eta} & T_{\pi\rho} \cdots \\ T_{\eta\gamma} & T_{\eta\pi} & T_{\eta\eta} & T_{\eta\rho} \cdots \\ T_{\rho\gamma} & T_{\rho\pi} & T_{\rho\eta} & T_{\rho\rho} \cdots \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix}$$

Applications to Data

$w \leq 2\text{GeV}$ – Results in PDG

- $\gamma N \rightarrow \pi N$
- $\gamma N \rightarrow \omega N$
- $\gamma N \rightarrow \eta N$
- $\gamma N \rightarrow KY$
- $\gamma N \rightarrow \pi^0 \pi^0 N$



- $\pi N \rightarrow \pi N$
- $\pi N \rightarrow \omega N$
- $\pi N \rightarrow \eta N$
- $\pi N \rightarrow KY$
- $\pi N \rightarrow \pi^0 \pi^0 N$

Our Goals

- Identify resonances
- Partial wave analysis
- Predictive power
- Phenomenological field theory for
 - photo-production on the nucleon
 - meson-nucleon interactions

Kaon Production on the Nucleon

The $K\Sigma$ production in photo-induced reactions

① $\gamma p \rightarrow K^0 \Sigma^+$:

SAPHIR, CBELSA, CLAS

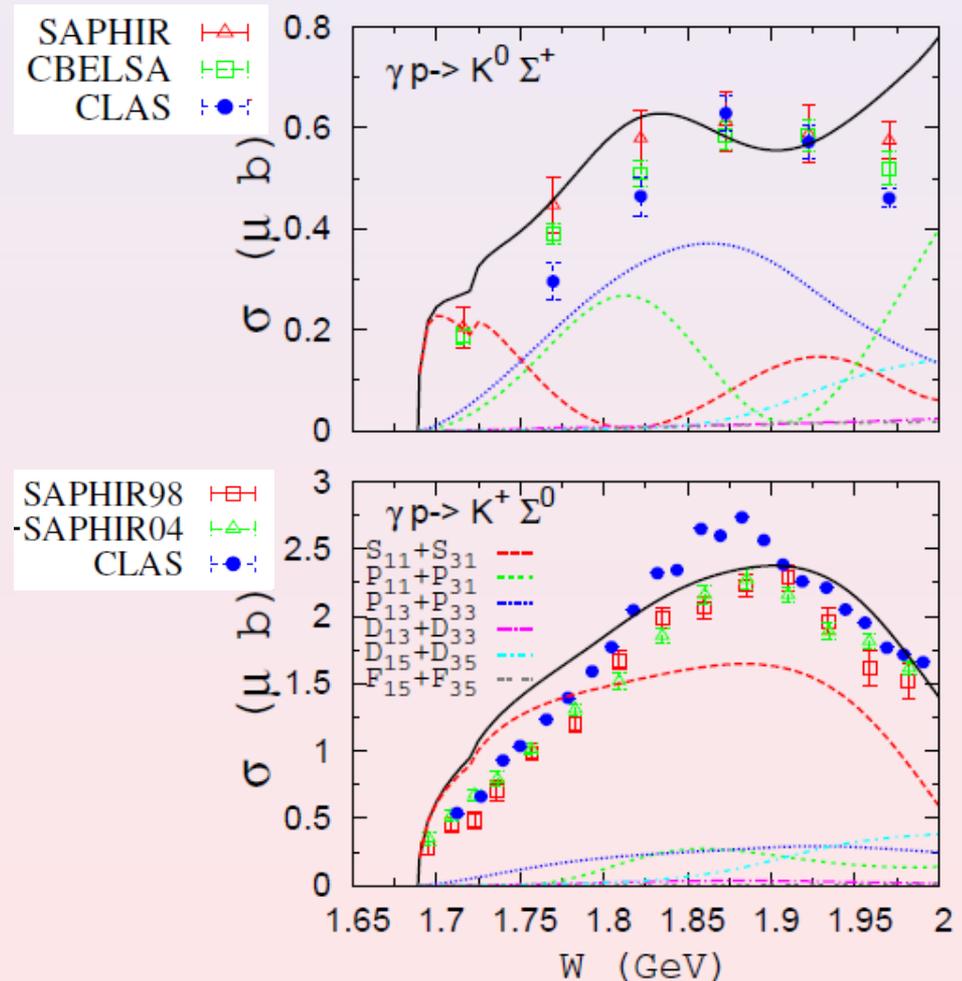
- S_{I1} , P_{I1} and P_{I3}
- Small total cross section. Why?
- the destructive interference of background and resonance contributions!

② $\gamma p \rightarrow K^+ \Sigma^0$: CLAS, SAPHIR

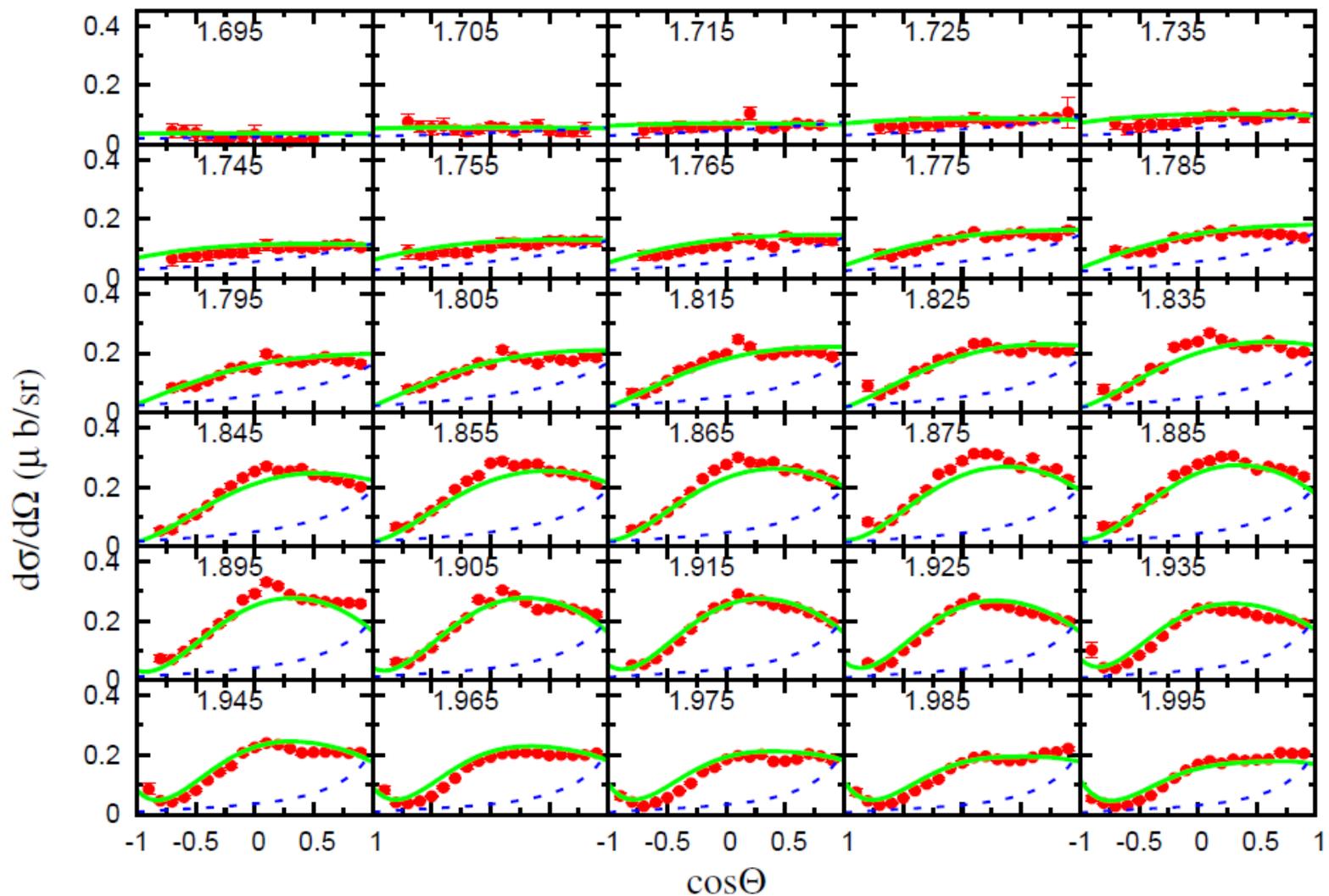
- dominated by the S_{I1} -wave

③ $P_{31}(1750), D_{33}(1700), D_{35}(1930)$ $F_{35}(1905)$

④ $S_{11}(1650), D_{13}(1520), D_{15}(1675)$ $F_{15}(1680)$



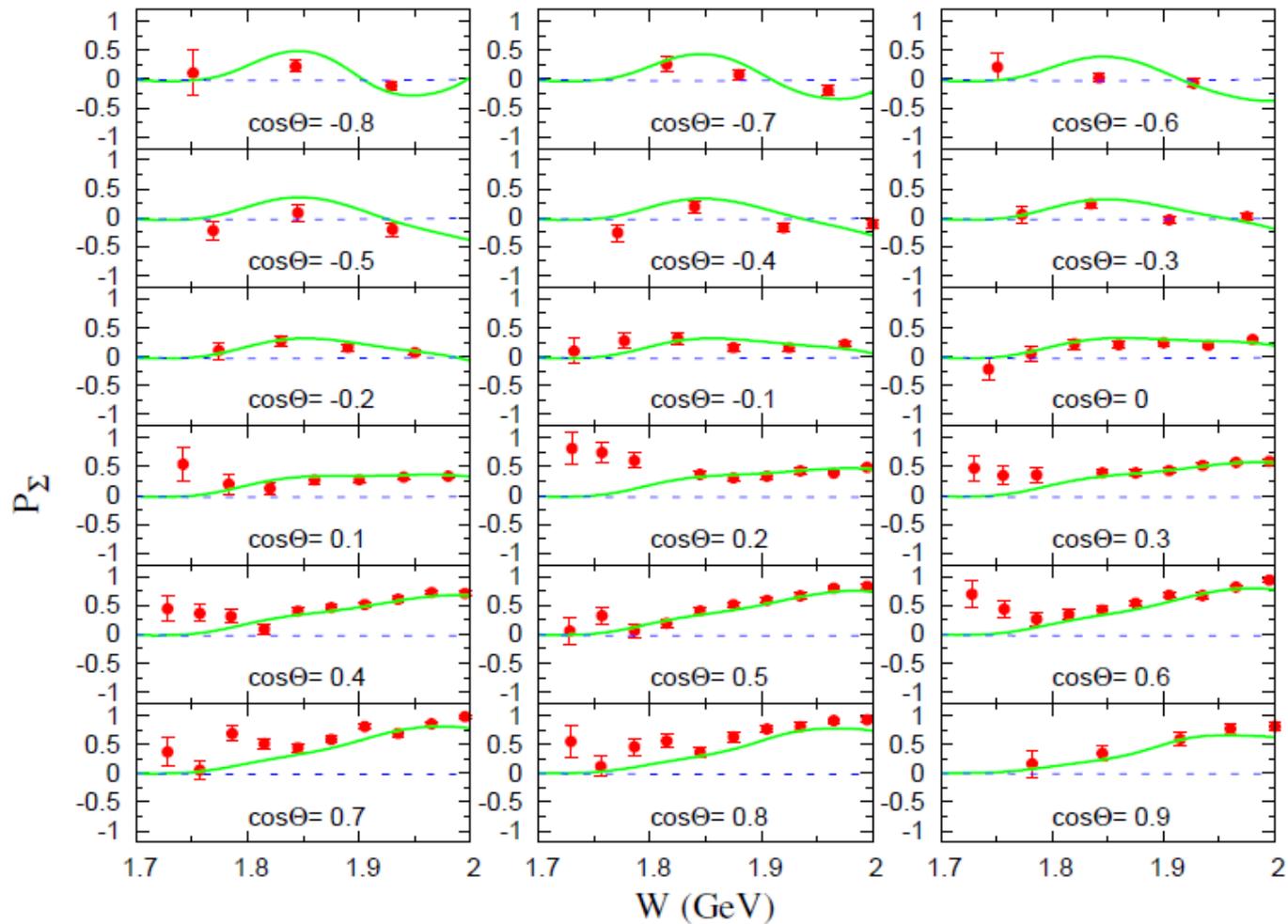
$$\gamma p \rightarrow K^+ \Sigma^0$$



GiM CC-results (green), Born terms (dashed) and CLAS data

Xu Cao et al., Phys. Rev. C 88, 055204 (2013); arXiv:1303.2604

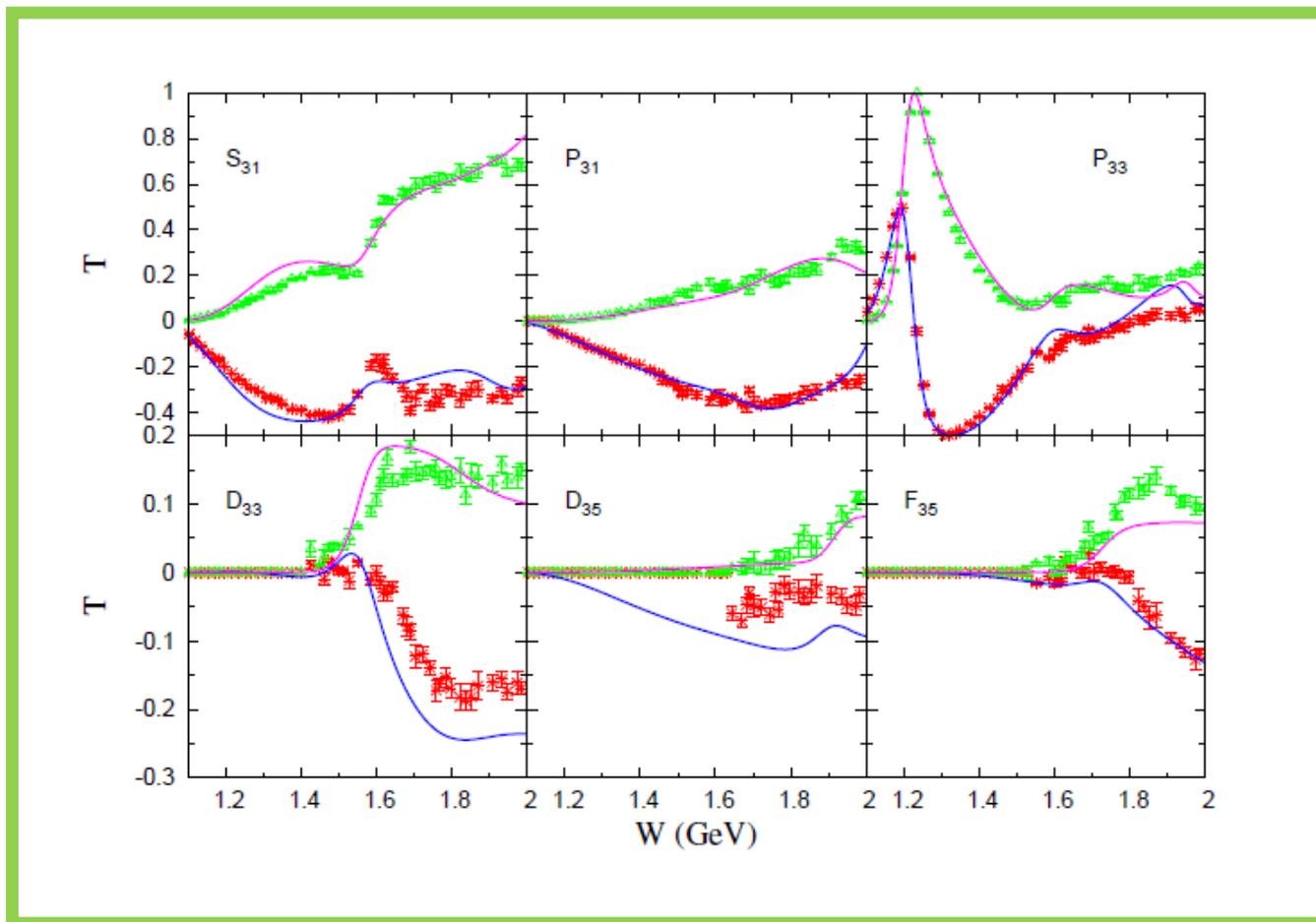
The recoil polarization of $\gamma p \rightarrow K^+ \Sigma^0$ reaction



GiM CC-results (green), Born-terms (dashed) and CLAS data
Xu Cao et al., Phys. Rev. C 88, 055204 (2013); arXiv:1303.2604

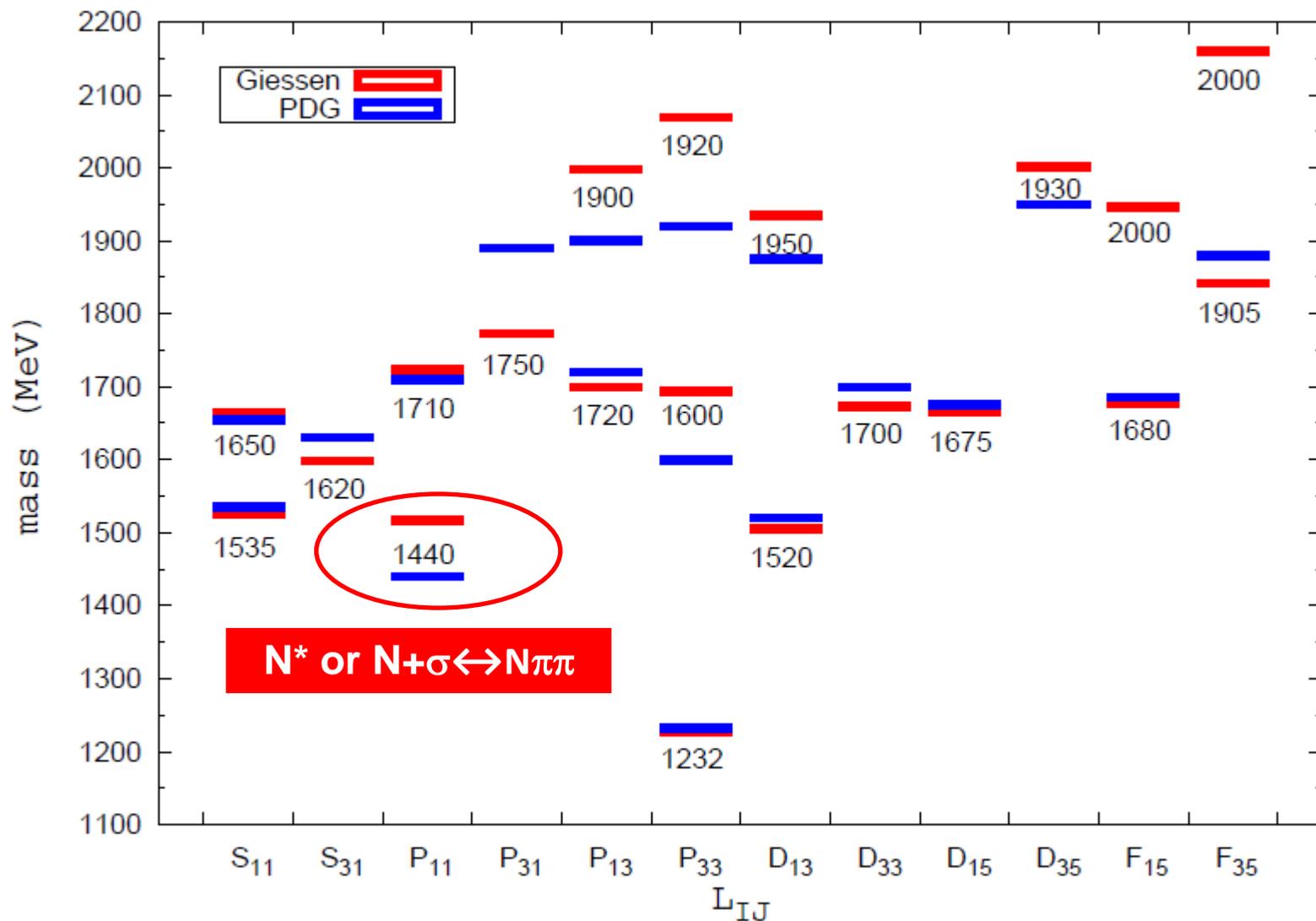
Comparison of Elastic Partial Wave πN T-matrix:

GiM (lines) vs. GWU/SAID (symbols)
(Xu Cao, H.L., PRC 88 (2013); arXiv:1303.2604)



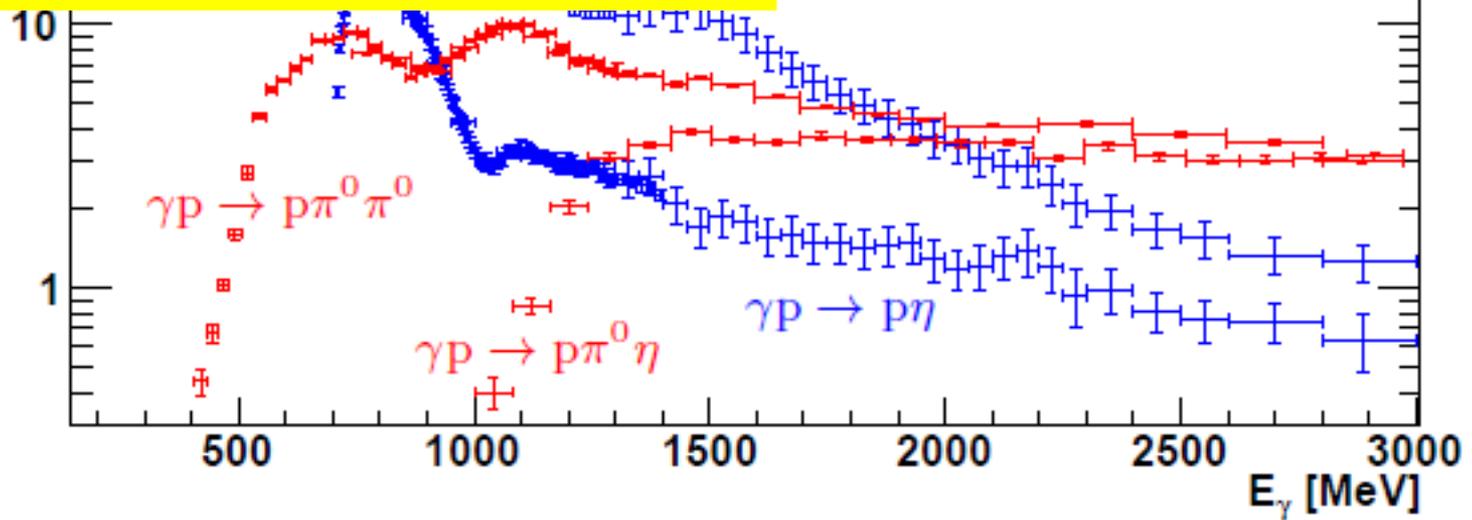
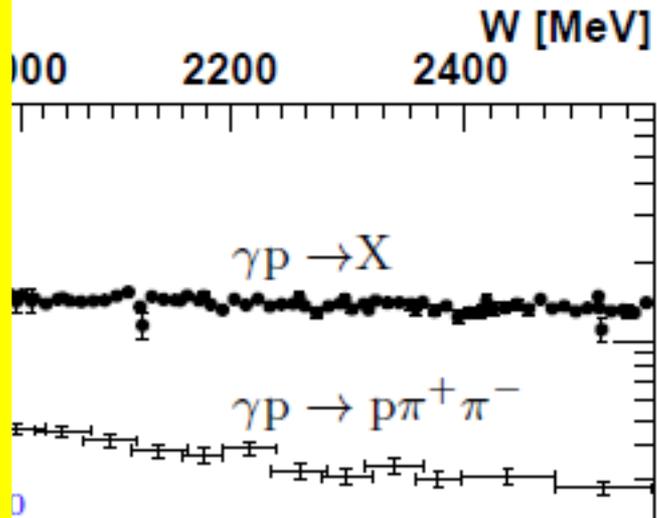
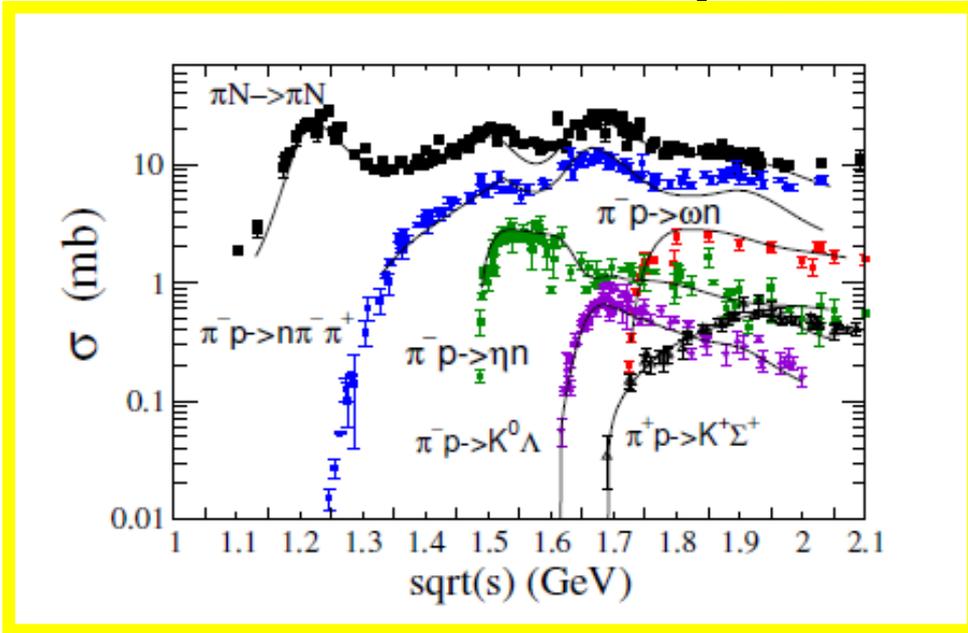
The elastic πN partial waves for $I = 3/2$. The solid lines (magenta) and triangle points (green) are imaginary part of amplitude of our model calculation and GWU/SAID analysis, respectively. The solid line (blue) and star points (red) are the correspondent real part of amplitude.

GiM Resonance Level Scheme



Multi-Meson Production on the Nucleon

2-pion Production

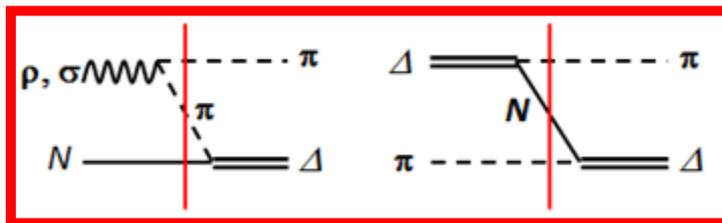
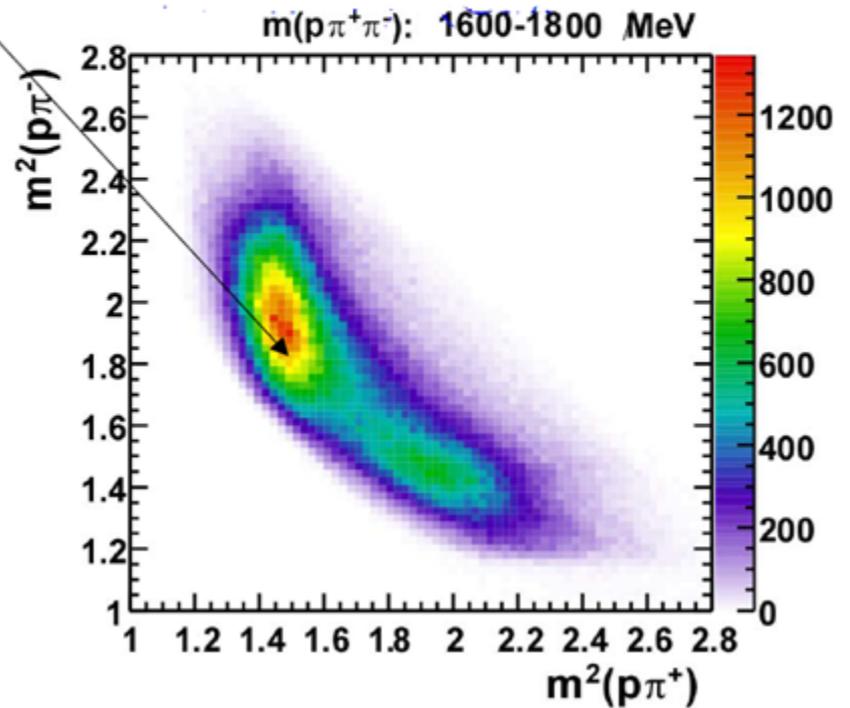
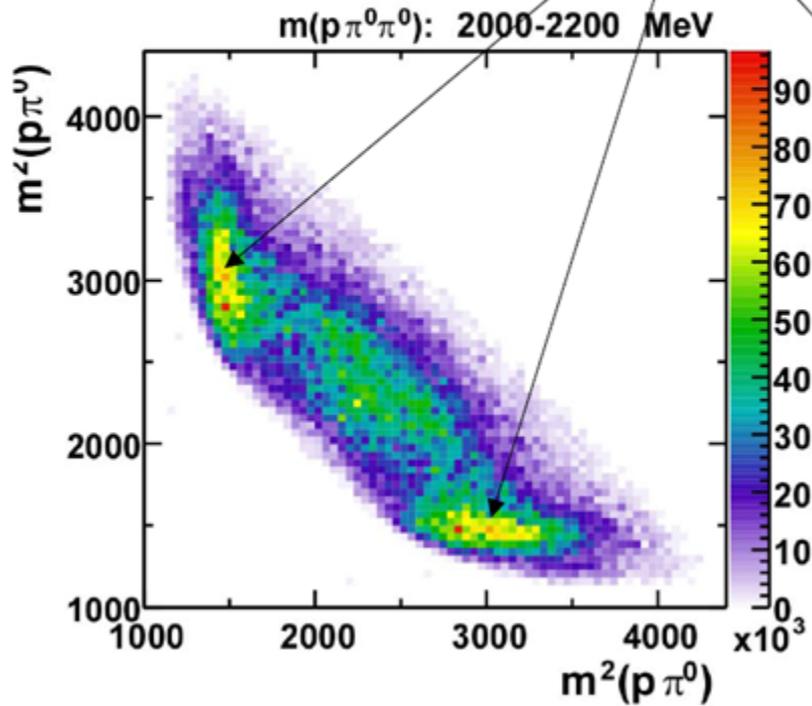


2-pion Production and Nucleon Resonances

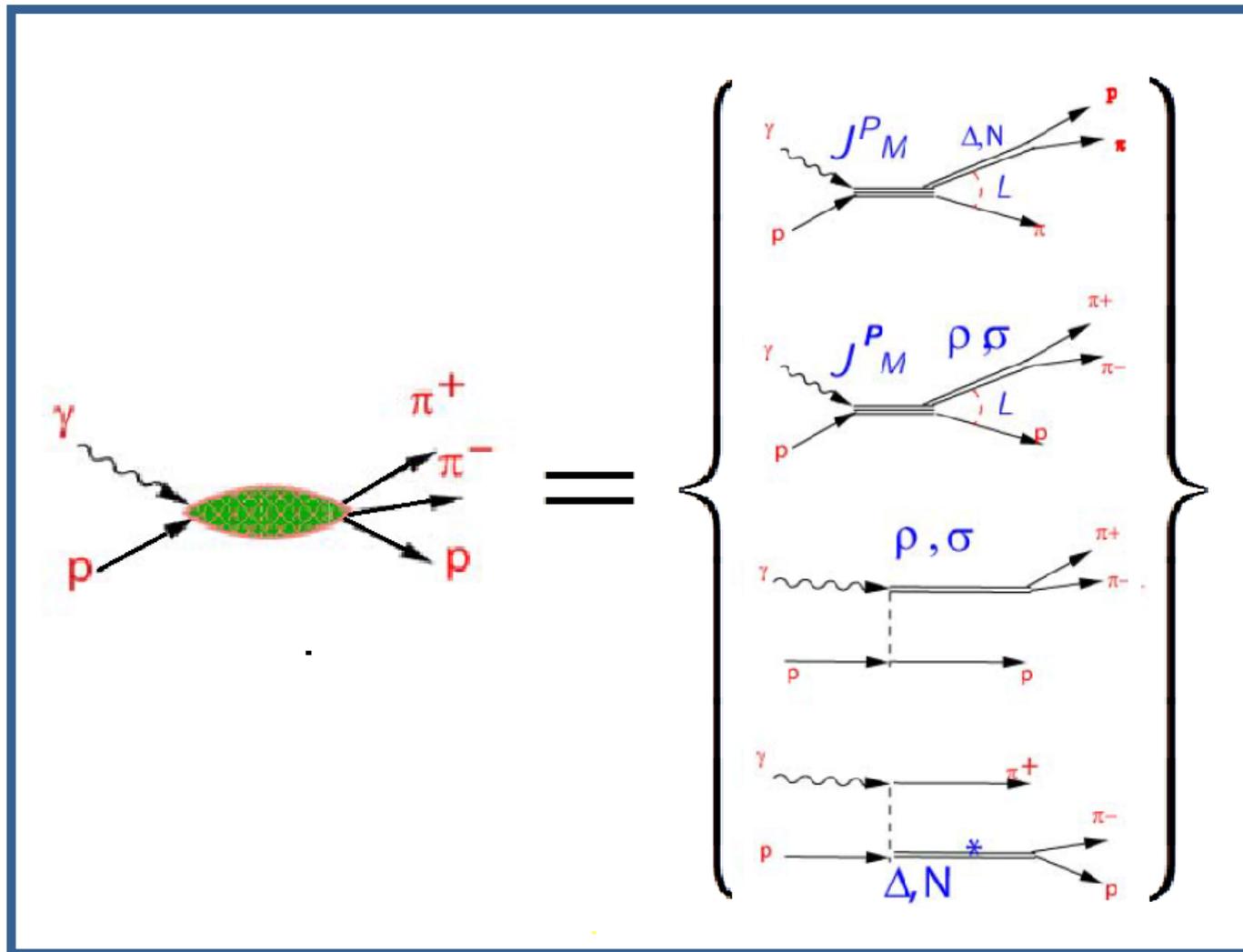
$\Delta(1232)\pi$ decays dominate

$\gamma p \rightarrow \pi^0 \pi^0 p$ (Bonn)

$\gamma p \rightarrow \pi^+ \pi^- p$ (CLAS)



Building Blocks of 2-pion Photo-Production



GiM Lagrangian for 2-pion Dynamics

Meson-Meson Interactions

$$\mathcal{L}_{\pi\pi\sigma} = g_{\pi\pi\sigma} m_\sigma \sigma(\pi\pi).$$

$$\mathcal{L}_{\pi N \Delta} = \frac{g_{\pi N \Delta}}{m_\pi} \bar{u}_\Delta^\mu \mathbf{T} u_N \partial_\mu \pi + h.c.,$$

$$\mathcal{L}_{\pi N^* \Delta} = \frac{g_{\pi N^* \Delta}}{m_\pi} \bar{u}_\Delta^\mu \mathbf{T} \begin{pmatrix} 1 \\ i\gamma_5 \end{pmatrix} u_{N^*} \partial_\mu \pi + h.c.,$$

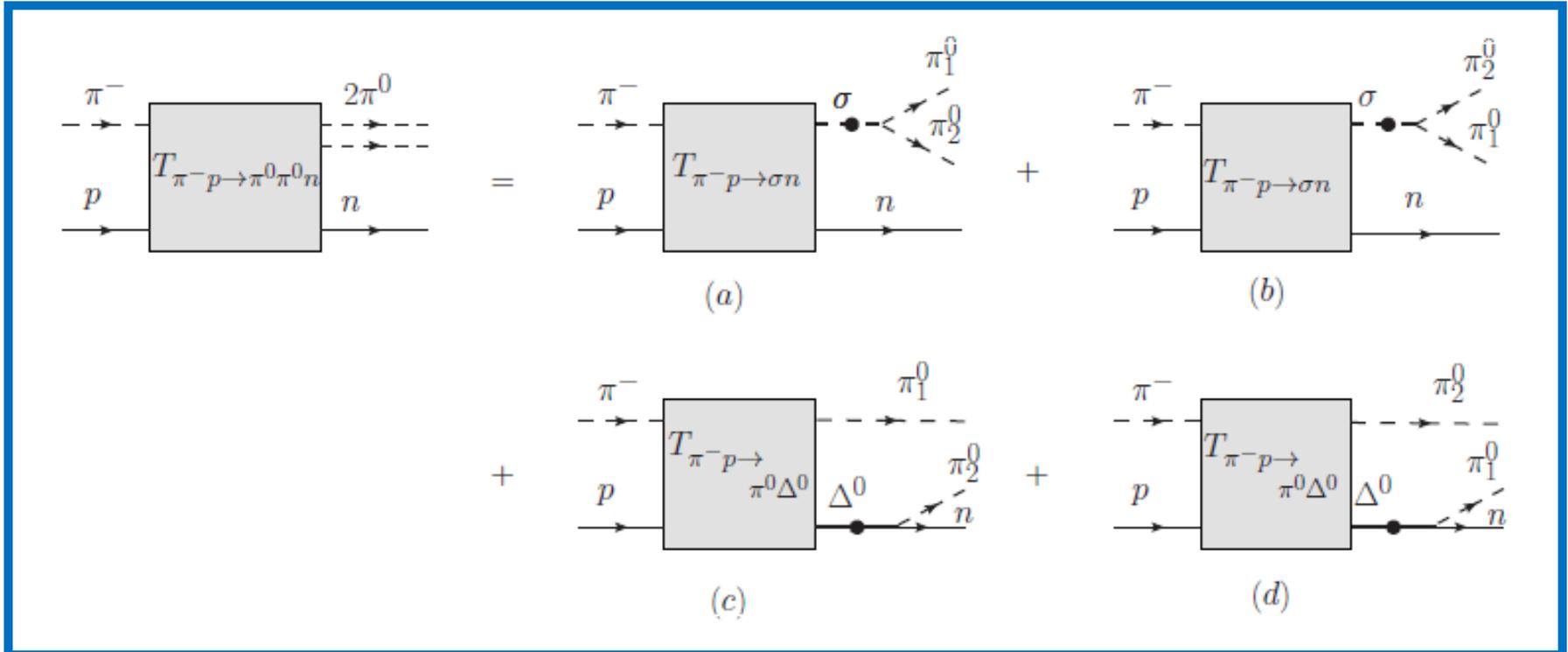
$$\mathcal{L}_{\pi NN} = \frac{f_{\pi NN}}{m_\pi} \bar{u}_N [\gamma_\mu \gamma_5 \boldsymbol{\tau}] u_N \partial^\mu \pi.$$

$$J^P = \frac{1}{2}^+ \quad \mathcal{L}_{\varphi NN^*} = \frac{g_{\varphi NN^*}}{m_\varphi} \bar{u}_{N^*} \begin{pmatrix} \gamma_5 \\ i \end{pmatrix} \gamma^\mu \boldsymbol{\tau}_\varphi u_N \partial_\mu \varphi + h.c.;$$

$$J^P = \frac{1}{2}^- \quad \mathcal{L}_{\varphi NN^*} = \frac{g_{\varphi NN^*}}{m_\varphi} \bar{u}_{N^*} \begin{pmatrix} 1 \\ i\gamma_5 \end{pmatrix} \boldsymbol{\tau}_\varphi u_N \varphi + h.c.,$$

Baryon-Meson Interactions

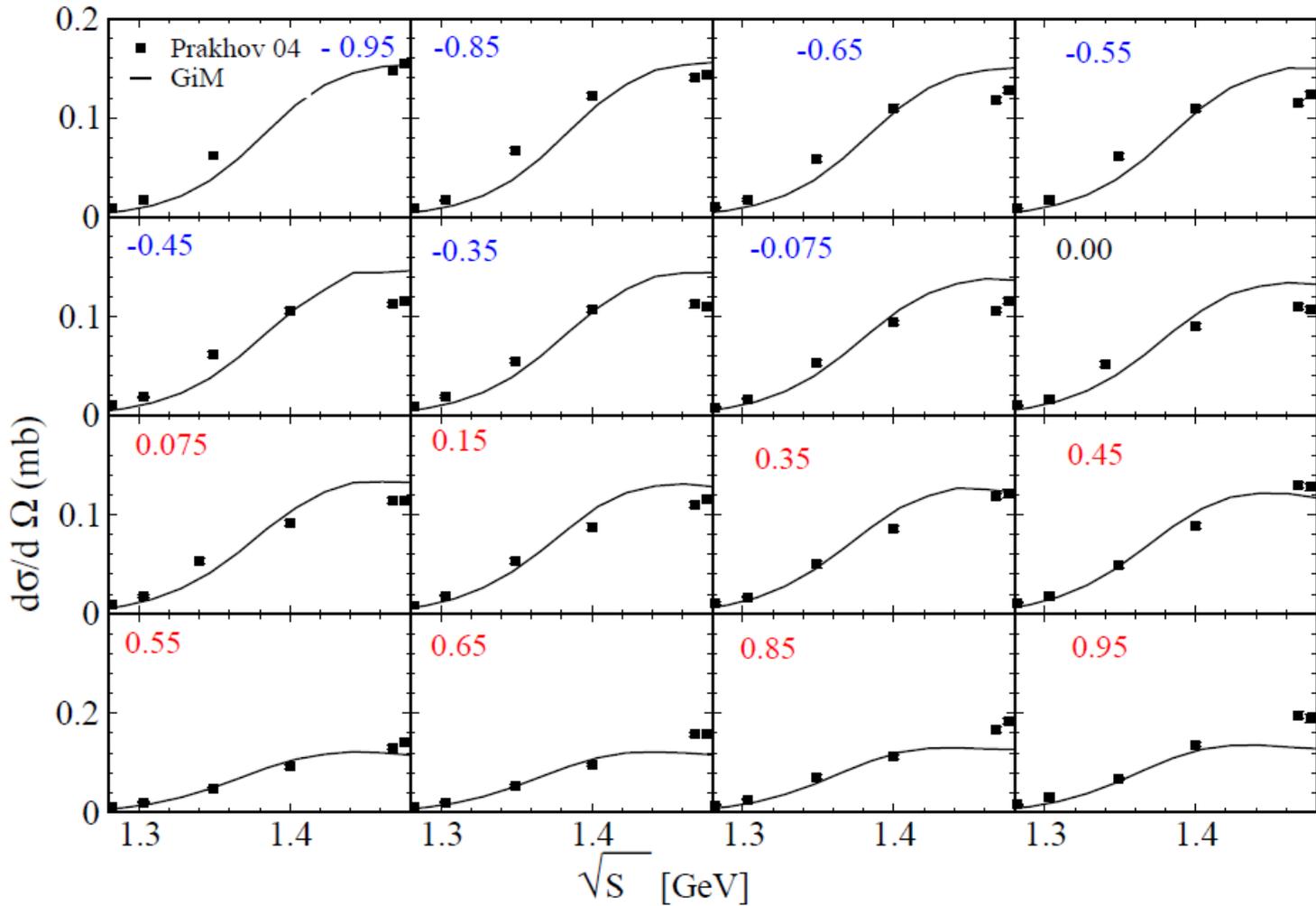
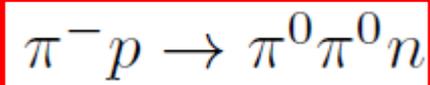
The 2-pion Exit Channels



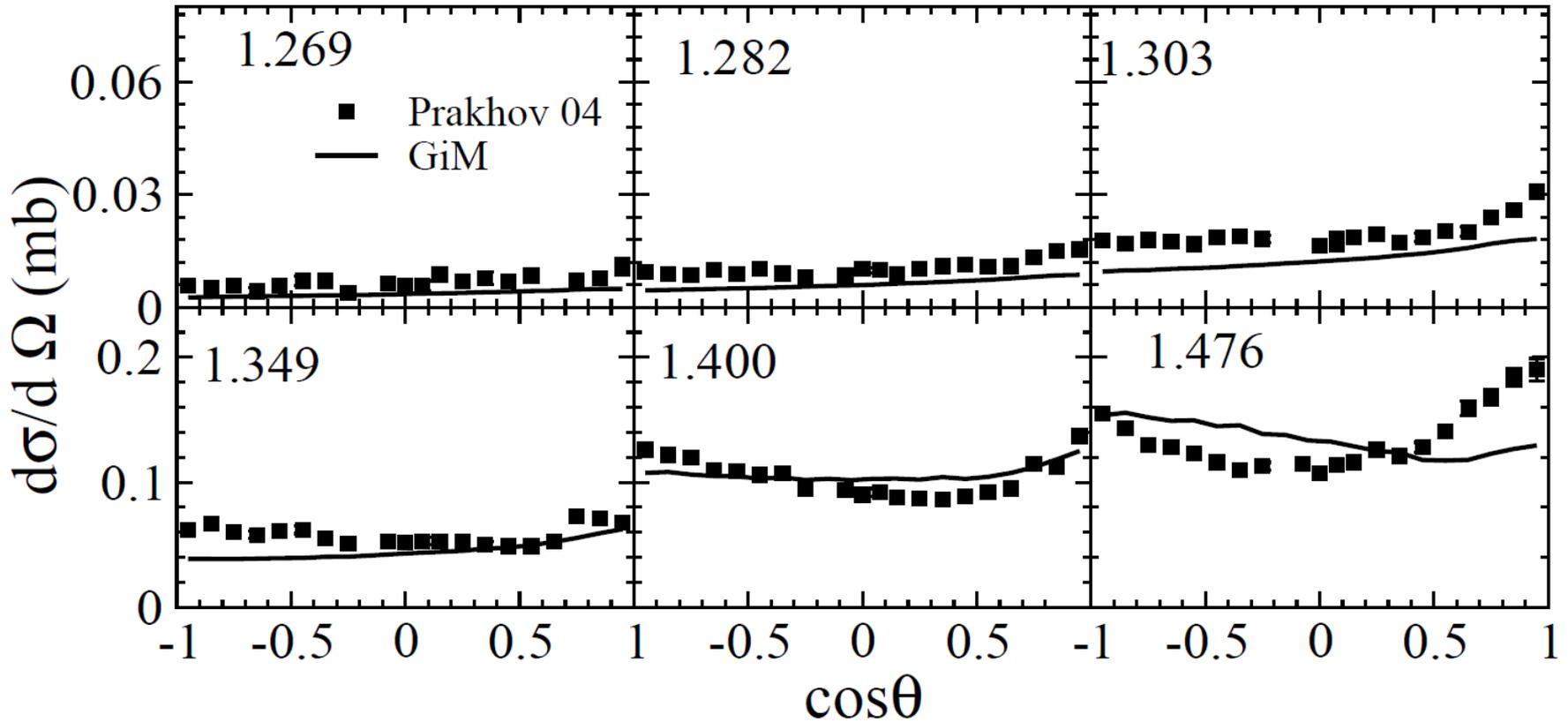
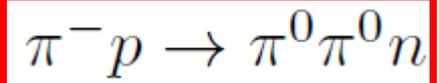
The $\pi^- p \rightarrow \pi^0 \pi^0$ reaction expressed via the isobar production amplitudes.

2-pion (3-body) Unitarity:

$$T_{\pi\pi N, \gamma N}(E) = \hat{T}_{\pi\pi N, \gamma N}^{dir}(E) + \hat{T}_{\pi\pi N, \gamma N}^{\pi\Delta}(E) + \hat{T}_{\pi\pi N, \gamma N}^{\rho N}(E) + \hat{T}_{\pi\pi N, \gamma N}^{\sigma N}(E)$$



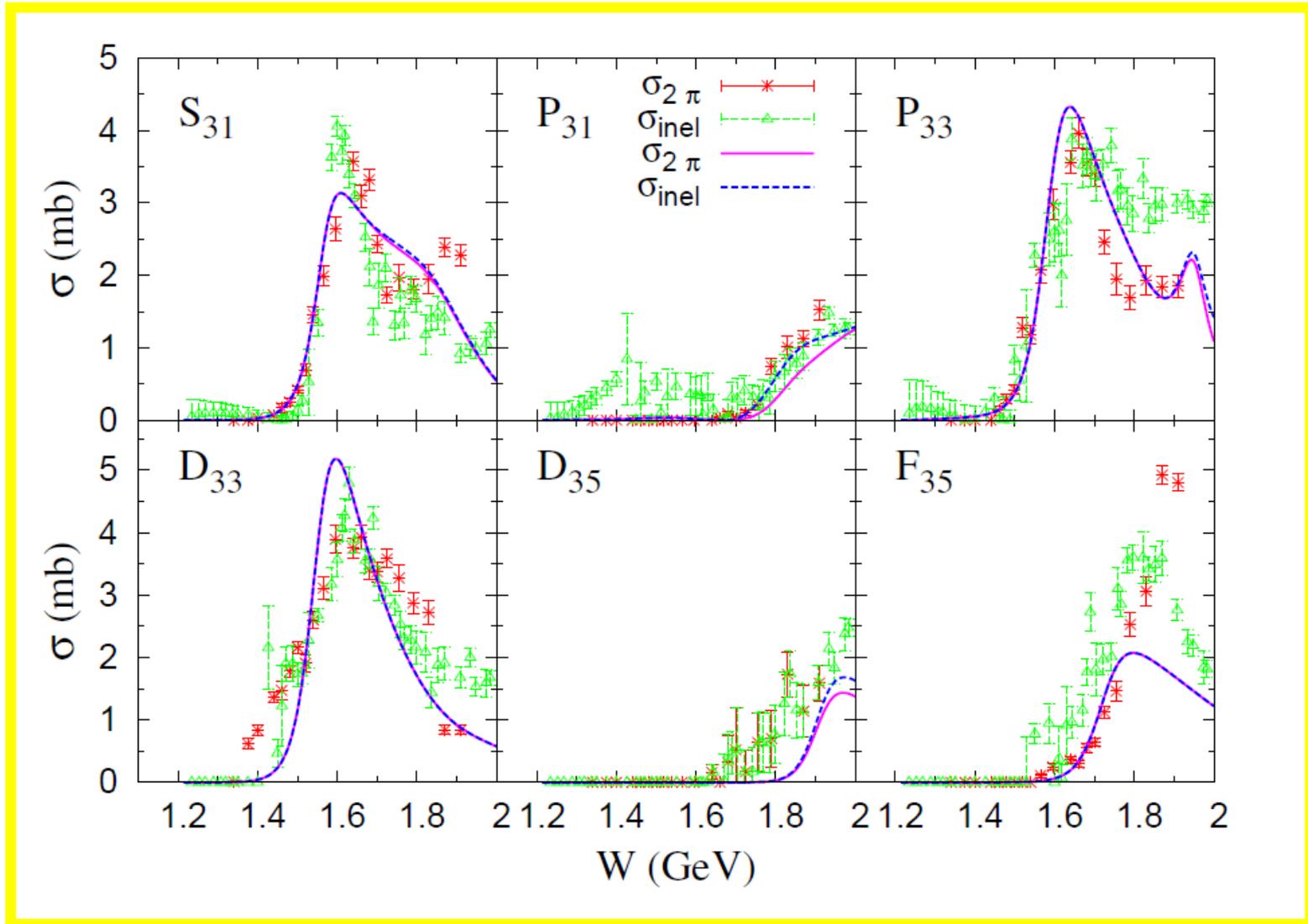
2-pion Spectra at fixed neutron scattering angle ($\cos\theta$)
(Crystal Ball Data, BNL/AGS)

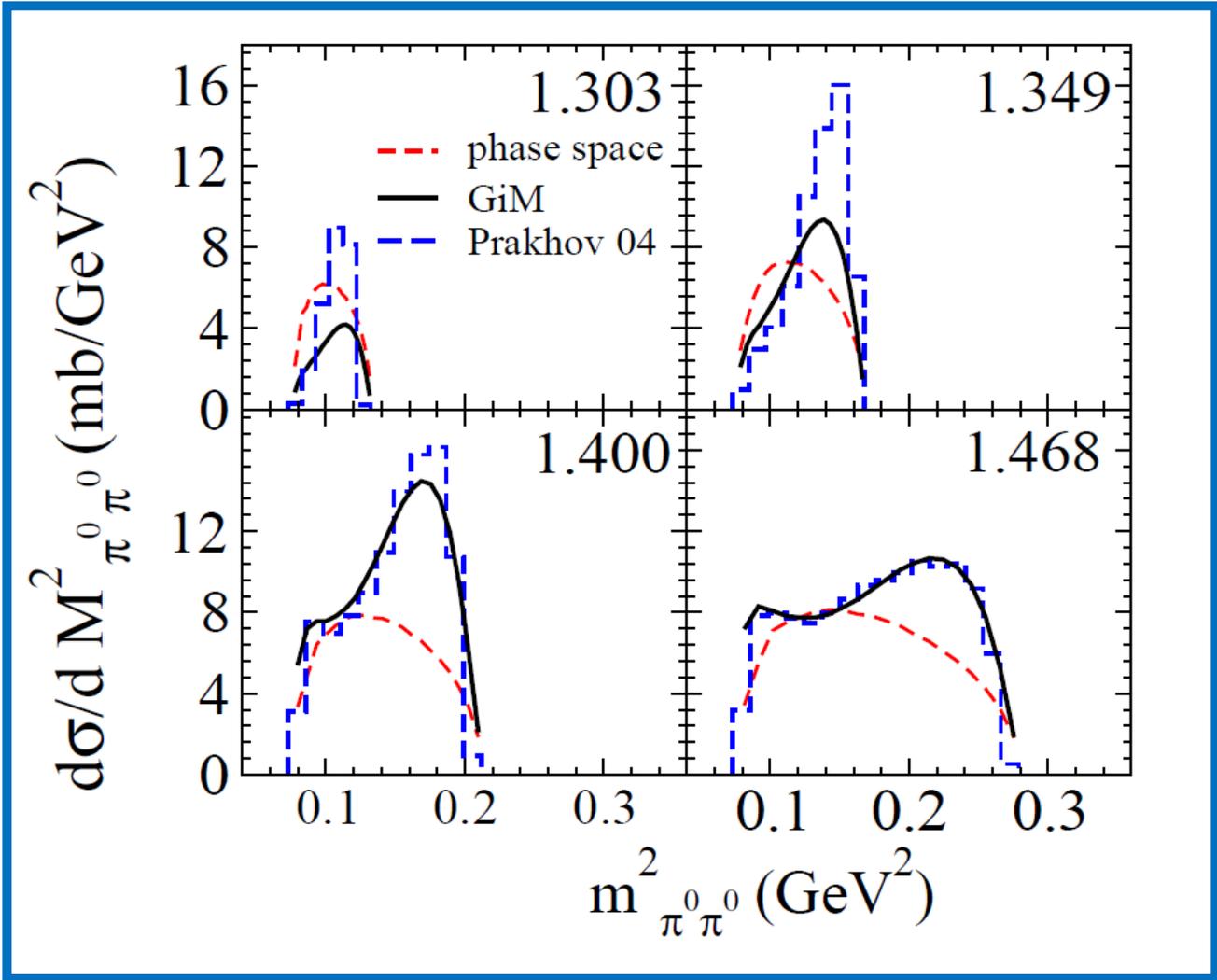
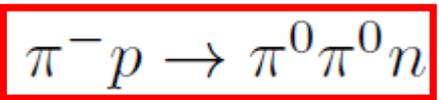


2-pion Angular distributions at fixed c.m. energy
(Crystal Ball Data, BNL/AGS)

$\pi N \rightarrow 2\pi N$ partial wave cross sections for $I = 3/2$

GiM (line) vs. Manley- and GWU-Analysis (symbols)





2-Pion Mass distributions at fixed c.m. energy

2-pion Production and Resonance Parameters

N^*	mass	Γ_{tot}	$R_{\pi N}$	$R_{\sigma N}$	$R_{\pi\Delta(1232)}$	Reference
$N^*(1535) \frac{1}{2}^-$	1.544_{-23}^{+6}	127_{-9}^{+30}	36_{-3}^{+4}	0^{+1}	0^{+1}	this work
	1.526_{-2}^{+2}	131_{-12}^{+12}	35_{-3}^{+3}	ng	ng	GiM12 [7]
	1.535_{-10}^{+10}	150_{-25}^{+25}	45_{-10}^{+10}	2_{-1}^{+1}	0^{+1}	PDG12[20]
	1.519_{-5}^{+5}	128_{-14}^{+14}	54_{-5}^{+5}	ng	$2.5_{-1.5}^{+1.5}$	BoGa12[19]
	1.538_{-1}^{+1}	141_{-4}^{+4}	37_{-1}^{+1}	$1.5_{-0.5}^{+0.5}$	$2.5_{-1.5}^{+1.5}$	KSU[28]
$N^*(1440) \frac{1}{2}^+$	1.478_{-27}^{+17}	569_{-240}^{+30}	61_{-7}^{+2}	27_{-9}^{+4}	12_{-3}^{+5}	this work
	1.515_{-15}^{+15}	605_{-90}^{+90}	56_{-2}^{+2}	ng	ng	GiM12 [7]
	1.440_{-20}^{+30}	300_{-100}^{+150}	65_{-10}^{+10}	15_{-5}^{+5}	25_{-5}^{+5}	PDG12[20]
	1.430_{-8}^{+8}	365_{-35}^{+35}	62_{-3}^{+3}	17_{-7}^{+7}	21_{-8}^{+8}	BoGa12[19]
	1.412_{-2}^{+2}	248_{-5}^{+5}	$64.8_{-0.9}^{+0.9}$	27_{-1}^{+1}	$6.5_{-0.8}^{+0.8}$	KSU[28]
	1.458_{-12}^{+12}	363_{-39}^{+39}	ng	ng	$40.5_{-17.5}^{+17.5}$	JM [53]

Summary

- **Coupled channels approach to meson production on the nucleon**
- **Strangeness production on the nucleon**
- **[η -Photoproduction \rightarrow Phys. Rev. C 87:015201 (2013)]**
- **2-pion photoproduction: isobar description**
- **Outlook: Charmonium production in annihilation reactions**

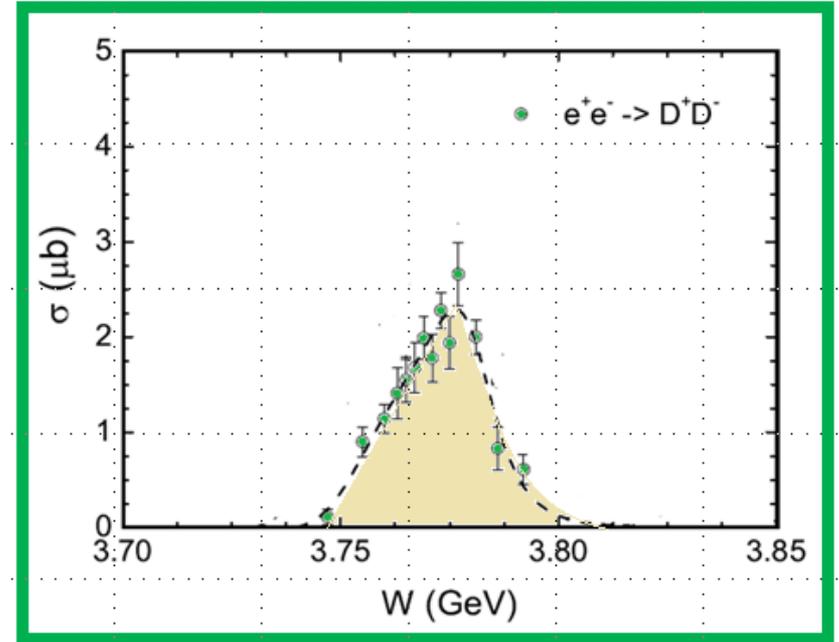
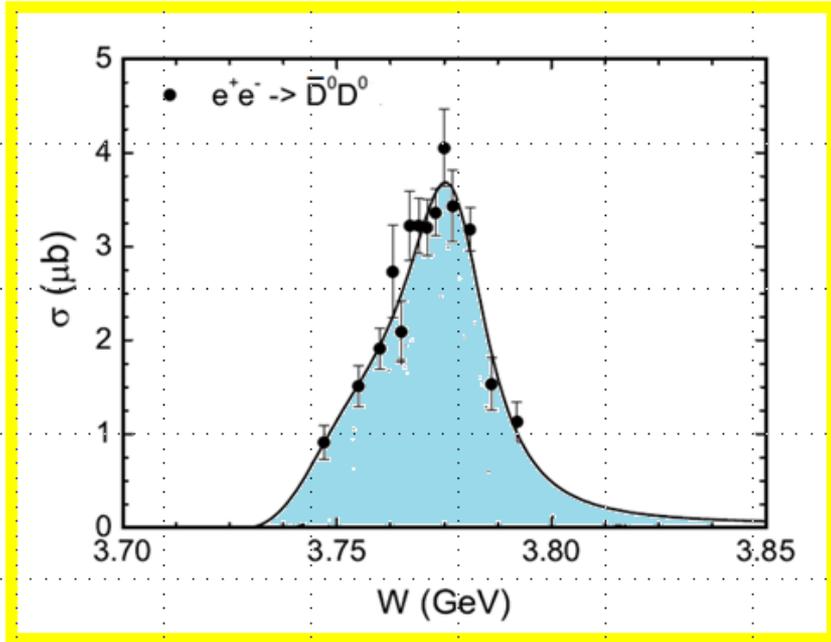
...with essential contributions by:

Xu Cao, Vitaliy Shklyar, and Radhey Shyam

Supported by: GSI, DFG, SFB/TR 16, HIC for FAIR, LOEWE

Outlook:
**Charm Production in Annihilation
Reactions**

$\psi''(3770)$ Production in $e^+e^- \rightarrow D\bar{D}$ Annihilation (Data: BES Collaboration)

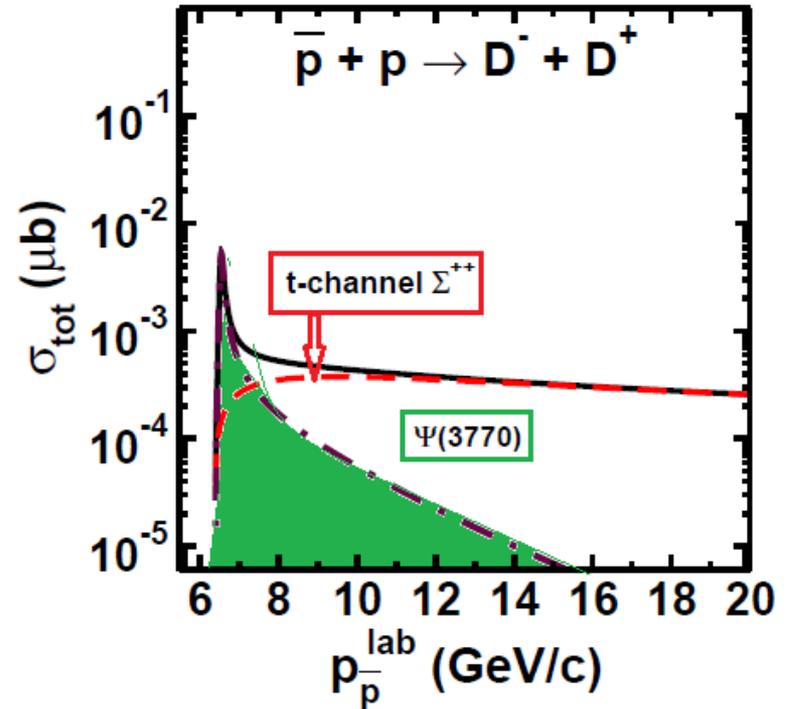
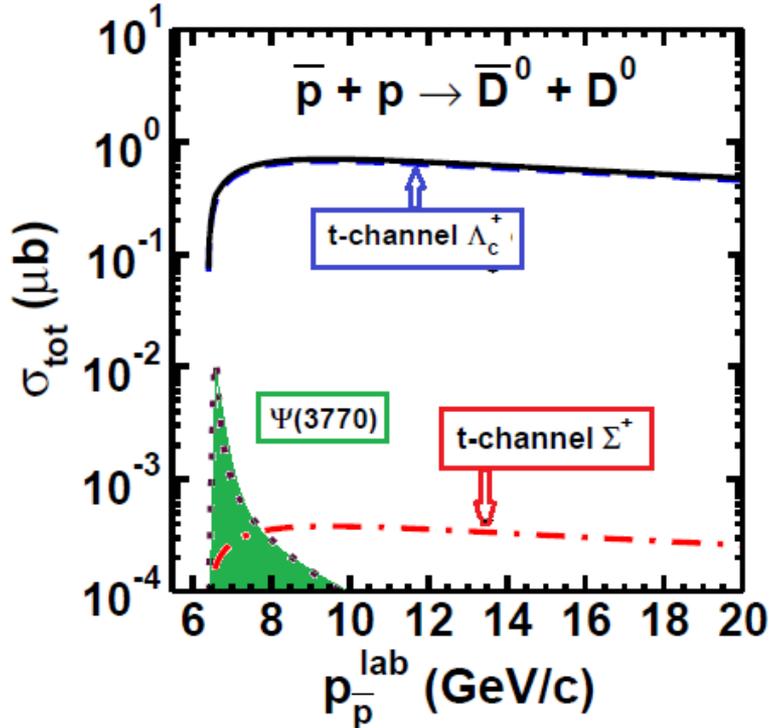
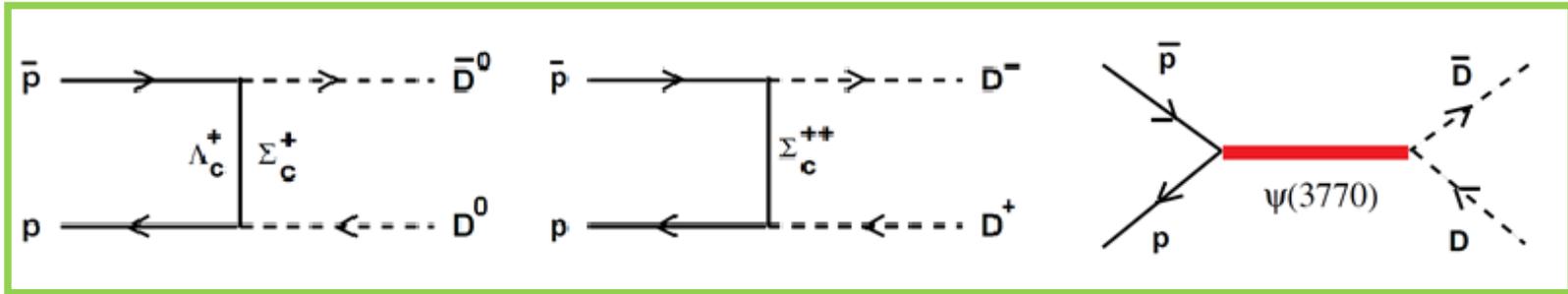


Derived Parameters:

	$D^0 \bar{D}^0$	$D^+ D^-$
$m_{\psi'}$ (MeV)	3782.1 ± 1.6	3784.0 ± 2.0
$g_{\psi' D\bar{D}}$	11.8 ± 0.9	10.7 ± 1.3
q	-2.1 ± 0.3	-1.6 ± 0.3
$\chi^2/d.o.f$	0.83	0.90

Xu Cao, H.L., PRD (2015)

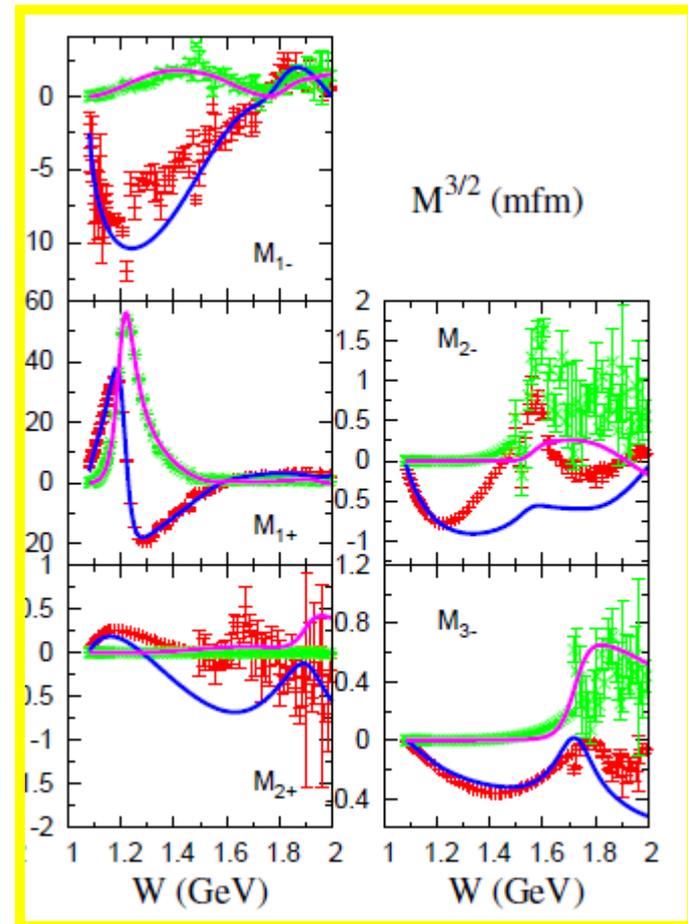
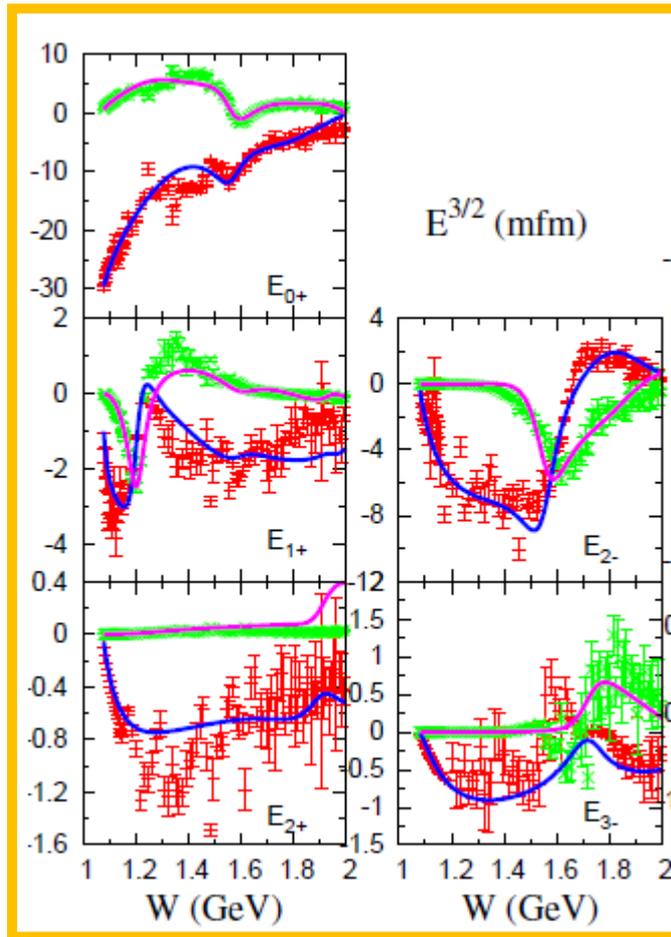
$\psi''(3770)$ Production in $p\bar{p} \rightarrow D\bar{D}$ Annihilation



Backups

Multipole Decomposition for $\gamma N \rightarrow \pi N$:

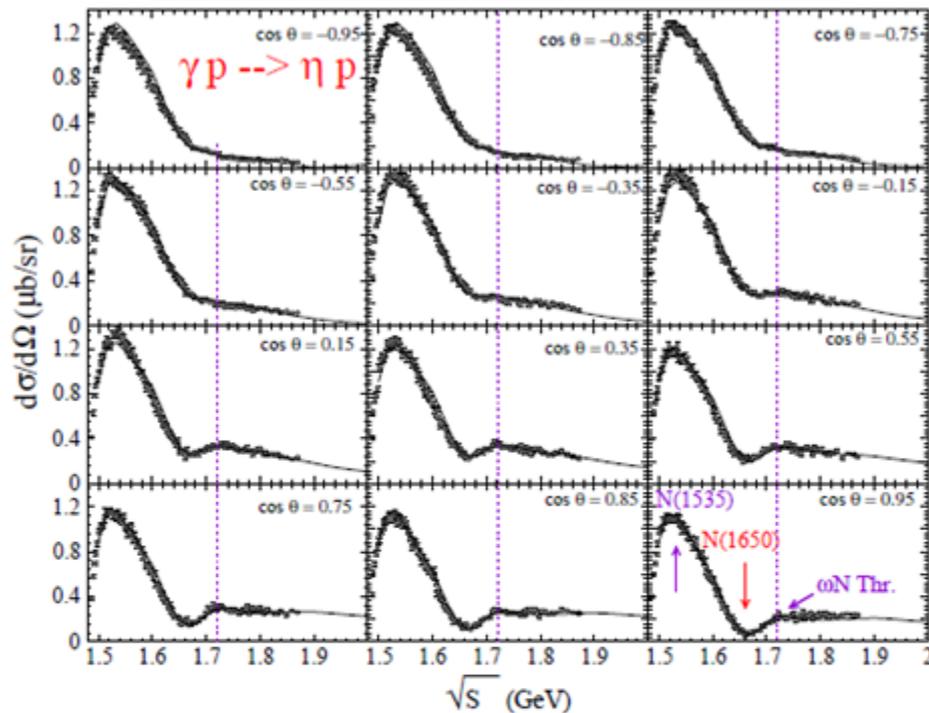
GiM (lines) vs. GWU/SAID (symbols)



The $\gamma N \rightarrow \pi N$ multipoles for $I = 3/2$. The solid lines (magenta) and triangle points (green) are imaginary part of amplitude of our model calculation and SAID analysis, respectively. The solid line (blue) and star points (red) are the correspondent real part of amplitude.

Eta Photo-Production

Results for $\gamma p \rightarrow \eta p$

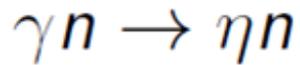


$\gamma p \rightarrow \eta p$: updated Giessen analysis vs. MAMI 2010 data
 We corroborate our previous conclusions: Shklyar et al PLB650,172

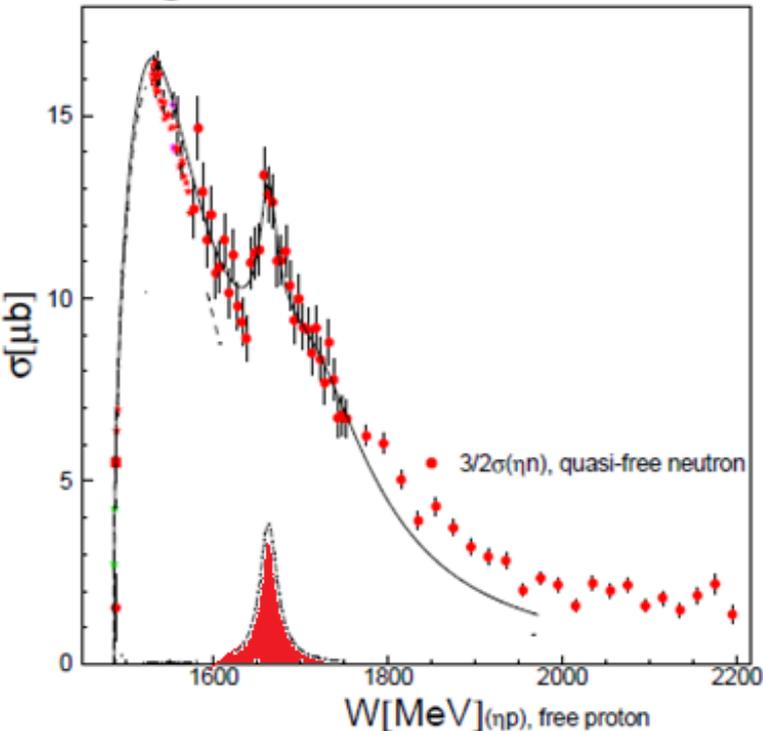
- $S_{11}(1535)$ and $S_{11}(1650)$: destructive interference - dip at 1.68 GeV; effect from $P_{11}(1710)$ is small
- ωN threshold: 50 MeV above the dip position- not decisive
- no room for narrow state of 15...20 MeV width

V. Shklyar, H.L. et al., Phys. Rev. C 87:015201 (2013)

η -photoproduction on the neutron



I. Jeagle, B. Krusche EPJA47, 89



First peak: $S_{11}(1535)$

- recent measurements (I. Jeagle et al) EPJA47,89: **clean second peak!**
Looks very narrow

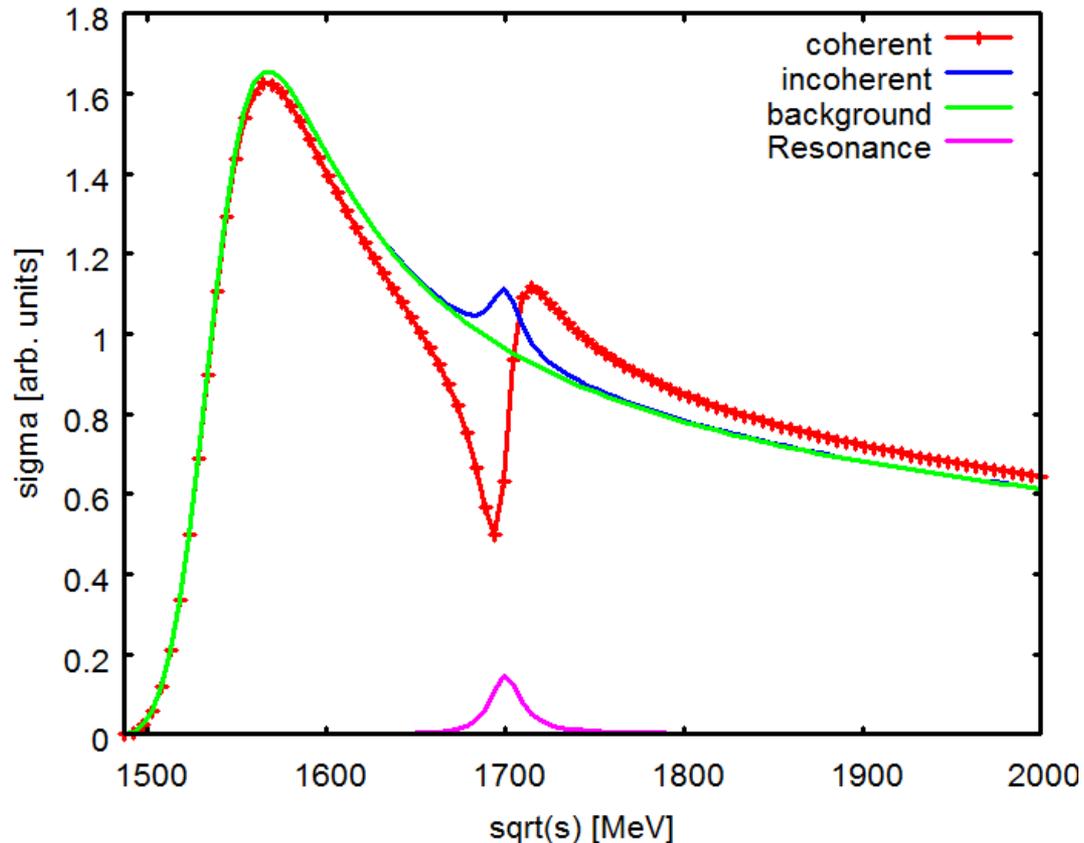
Other explanations

- Shklyar, Mosel, Lenske PLB650 (2007),172: **well known $S_{11}(1650)$, $S_{11}(1535)$ and $S_{11}(1650)$:**
- Doering, Nakayama PLB683(2010),145 : pole due to **$K\Sigma$ and $K\Lambda$ rescattering**

...evidence for a new state?

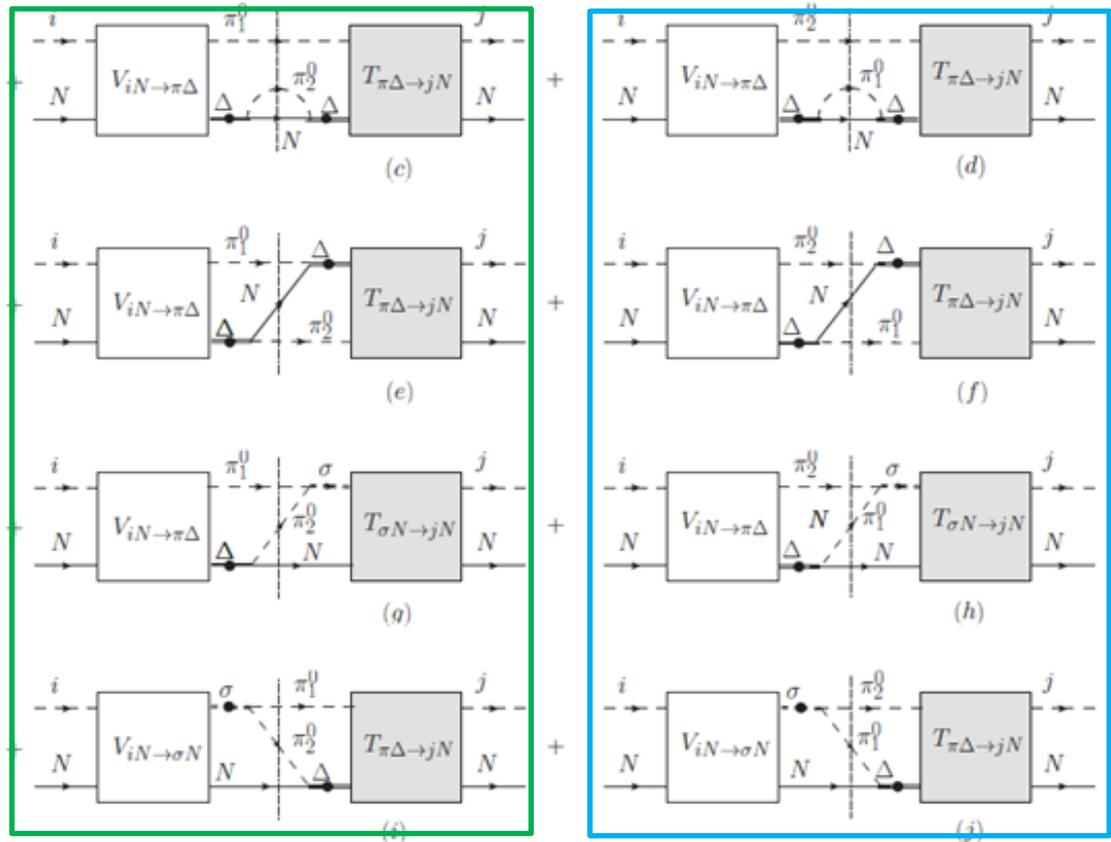
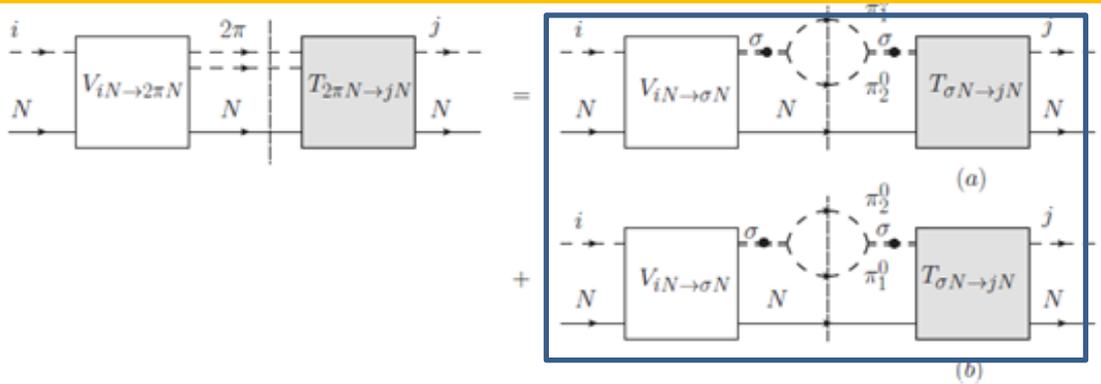
Interference: a toy model:

- Background amplitude $M_b(\sqrt{s})$
- Resonant amplitude $M_r(\sqrt{s}) \sim M_0 e^{i\phi} / (s - m_r^2 - i\sqrt{s}\Gamma(\sqrt{s}))$
- $\sigma_{\text{coh.}} \sim |M_b(\sqrt{s}) + M_r(\sqrt{s})|^2$
- $\sigma_{\text{incoh.}} \sim |M_b(\sqrt{s})|^2 + |M_r(\sqrt{s})|^2$



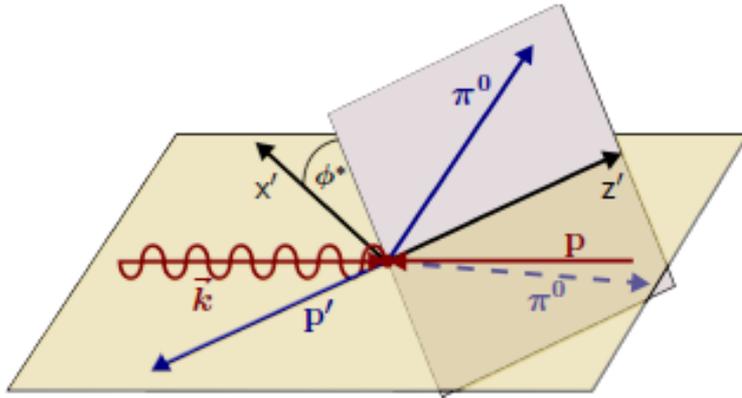
„Isobar“ Approach to $\pi^0 \pi^0 N$ production

$$\pi + N \rightarrow \begin{cases} \pi + N \\ \sigma + N \rightarrow 2\pi + N \\ \pi + \Delta \rightarrow 2\pi + N \end{cases}$$



Three-Body Kinematics

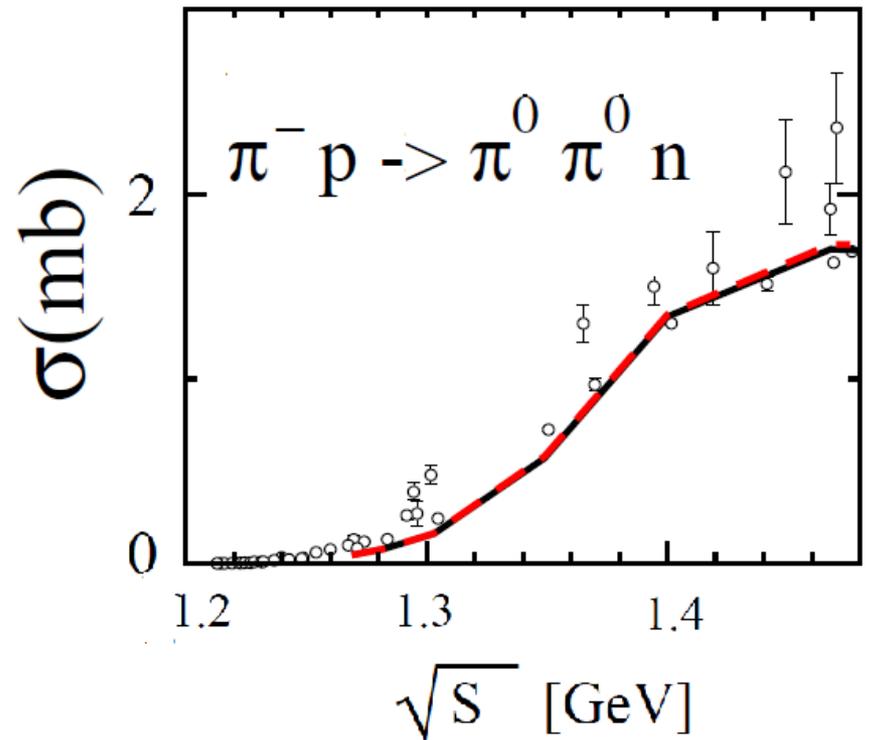
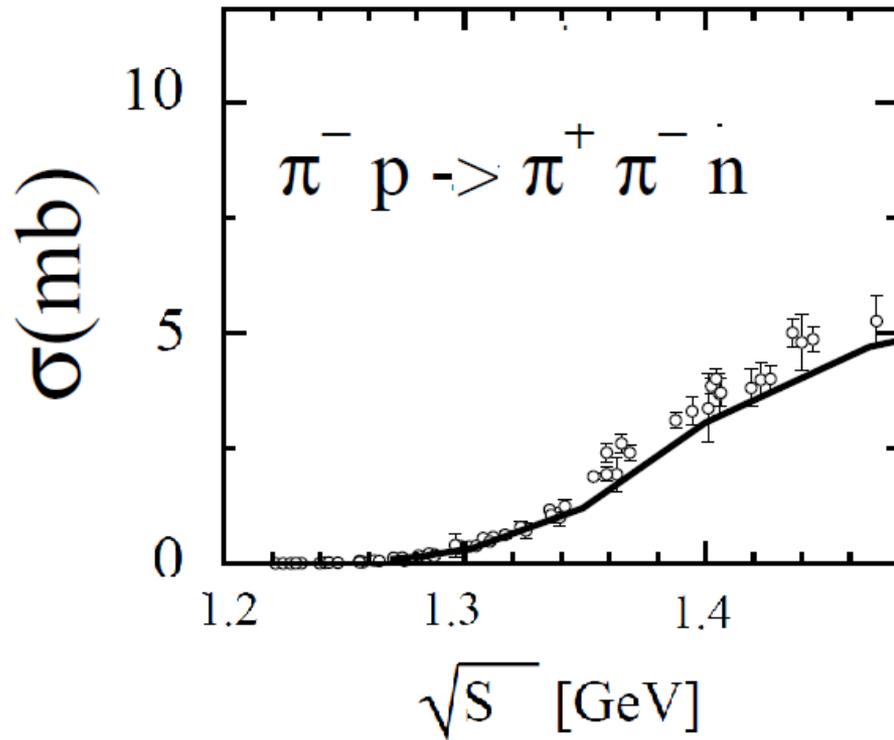
W. Roberts, T. Oed, Phys. Rev. C 71 (2005)



$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \cdot \left\{ (1 + \Lambda_x P_x + \Lambda_y P_y) \right. \\ \left. + \delta_\ell \cdot \left[\sin(2\phi) \cdot (I^s + \Lambda_x P_x^s + \Lambda_y P_y^s) \right. \right. \\ \left. \left. + \cos(2\phi) \cdot (I^c + \Lambda_x P_x^c + \Lambda_y P_y^c) \right] \right\}$$

Photon Pol.		Target Pol. Axis		
		<i>x</i>	<i>y</i>	<i>z</i>
unpolarised	σ	P_x	P_y	P_z
linear $\sin(2\phi)$	I^s	P_x^s	P_y^s	P_z^s
linear $\cos(2\phi)$	I^c	P_x^c	P_y^c	P_z^c
circular	I^\odot	P_x^\odot	P_y^\odot	P_z^\odot

2-pion Total Cross Sections



Extending the Model Space to Multi-Meson Production

$$\gamma(\pi) + N \rightarrow \left\{ \begin{array}{l} \pi + N \\ \sigma + N \rightarrow \pi + \pi + N \\ \rho + N \rightarrow \pi + \pi + N \\ K^* + Y \rightarrow \pi + \pi + N \\ \pi + \Delta \rightarrow \pi + \pi + N \\ \pi + N^* \rightarrow \pi + \pi + N \\ K + Y^* \rightarrow \pi + \pi + N \end{array} \right.$$

...and many other channels, constrained only by energy!