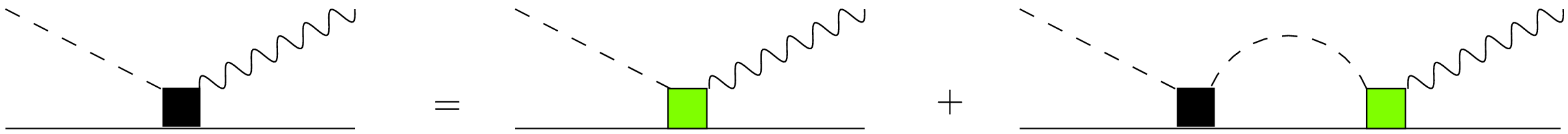
Dynamical coupled-channel approach to ω-meson photoproduction



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Outline

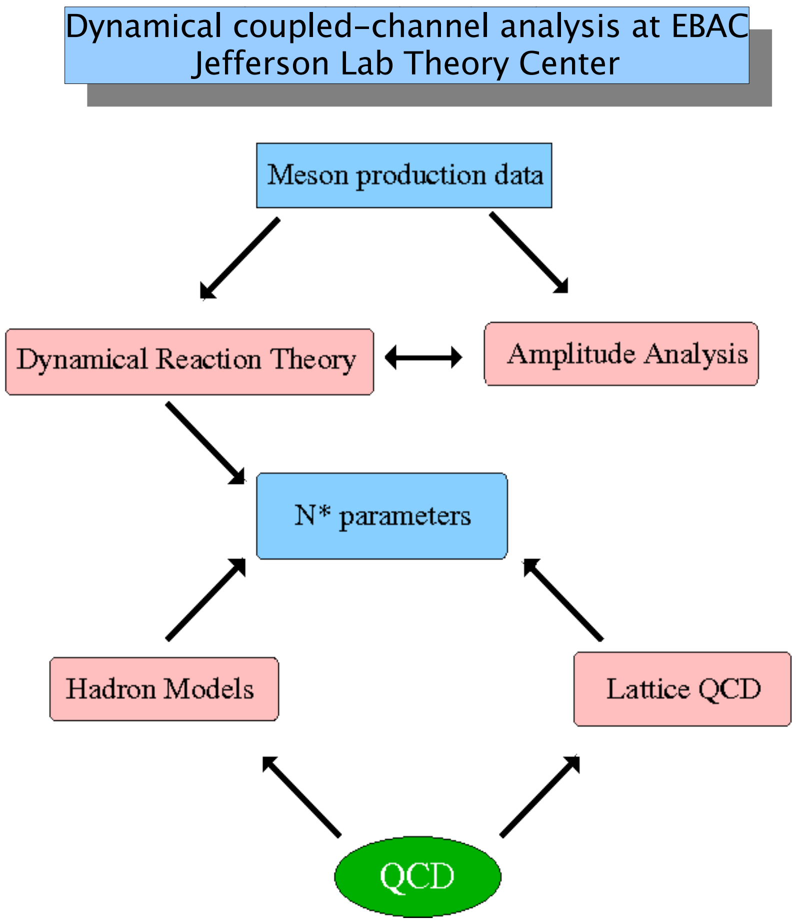
- Motivations
- Formalism
- Experimental observations
- Earlier results
- Preliminary ω–production results
- What next?
- Conclusion

Excited Baryon Analysis Center @ Jefferson Lab Theory Center

Objective: Extraction and *interpretation* of resonance parameters

Projects:

- π & ππ production
- analysis of CLAS data with *Jűlich* model KΛ,KΣ,ωN,ηN
- *EBAC-Saclay* coupled-channel analysis of KN and KY photoproduction
- **ω-production:** preliminary study

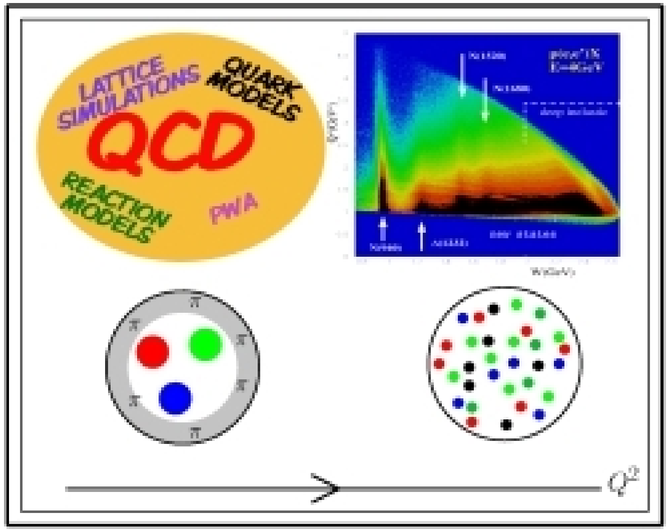


Collaboration: T.-S. Harry Lee, PI (Argonne), A. Matsuyama (Shizuoka U.), T. Sato (Osaka U.), Bruno Julia-Diaz (U.Barcelona), K. Tsushima (U.Salamanca), M. Paris (JLab)

Online: http://ebac-theory.jlab.org

Motivation: fundamental challenges

- baryon resonances offer insight to QCD dynamics
- {confinement} + {many body system} = complex
- scattering observables depend on both the reaction mechanisms and resonance structure:



$$\frac{d\sigma}{d\Omega} = \mathcal{R} \circ \mathcal{S}$$

Reaction
- ISI
- FSI
- channel coupling
- [meson cloud]

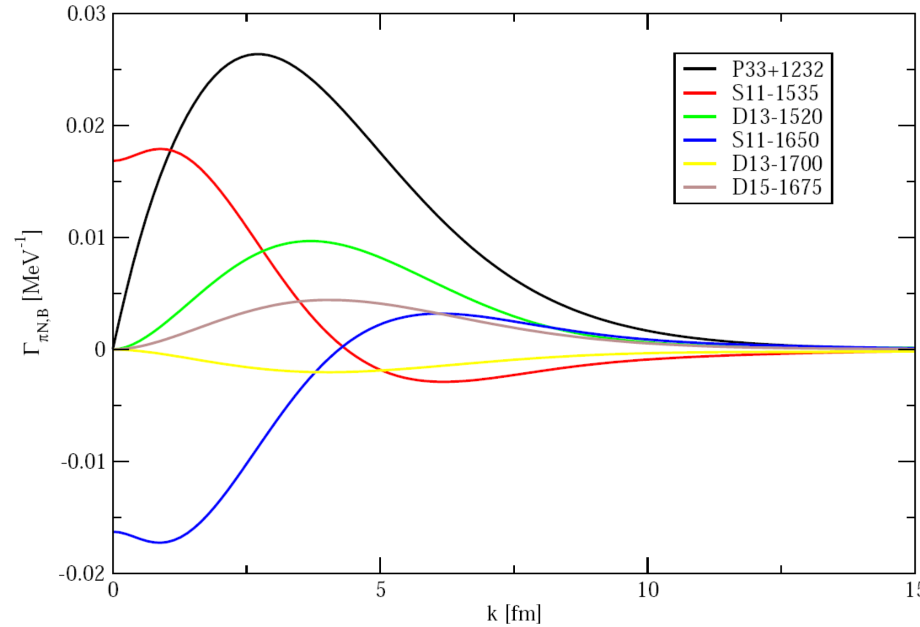
Structure
- Resonance properties

Seek to identify resonance features – in contrast to other (non-resonant) phenomena

Motivation: resonance structures

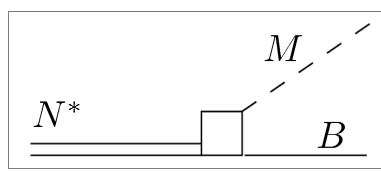
- Extraction of resonance properties:
  - transition form factors
    - width & couplings
    - detailed structure information
  - masses: bare & dressed

Quark model calculation
(via Quantum Monte Carlo)

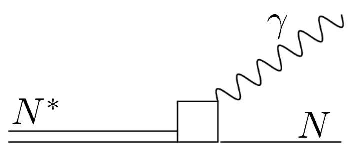


Bare transition form factors

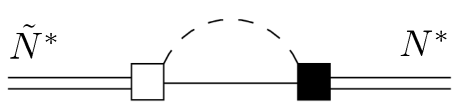
$$\Gamma_{N^*,MB}(\mathbf{k}):$$



$$\Gamma_{N^*,\gamma N}(\mathbf{q},q^0):$$



$$\Sigma(\mathbf{q},E):$$

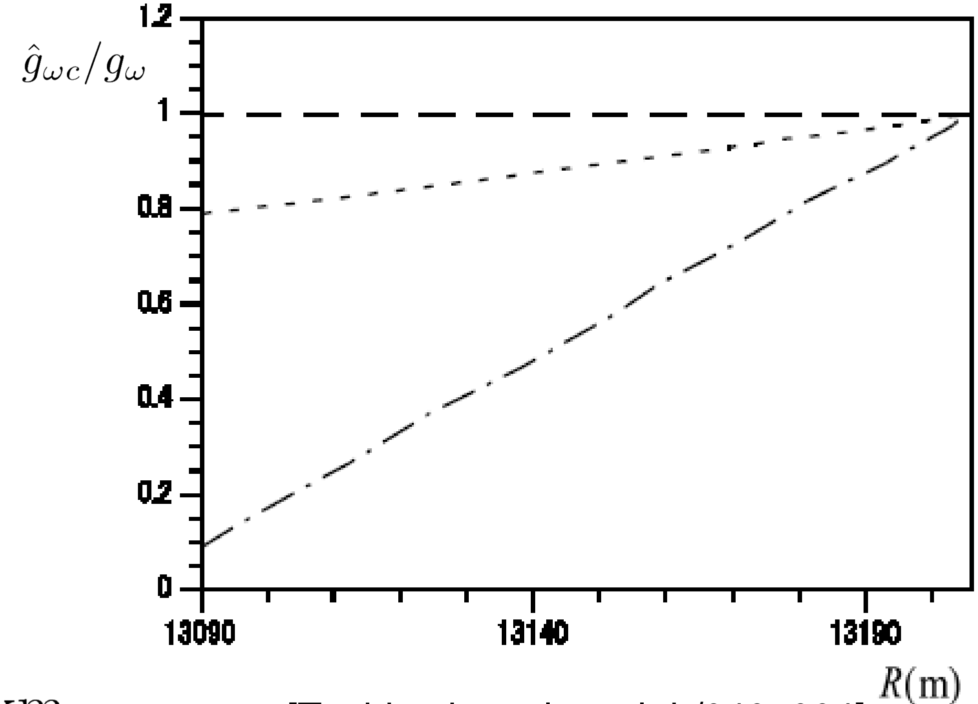


"Missing" resonances?

- can partial widths in *all channels* be fixed with sufficient accuracy?

Motivation: ωN interactions

- ω interactions are poorly determined
  - SU(3):
    - $g_{\omega NN}/g_{\rho NN}=3/2$
  - CD-Bonn realistic NN potential
    - $g_{\omega NN}=8.$ $\kappa_{\omega NN}=0.$
  - Sato-Lee (Δ)
    - $g_{\omega NN}=10.5$ $\kappa_{\omega NN}=0.$
  - Neutron star radii
    - $\delta m_\omega^{*2} \approx 0.1 m_\omega^2 \implies \delta R_{NS} \approx 1\ \mathrm{km}$



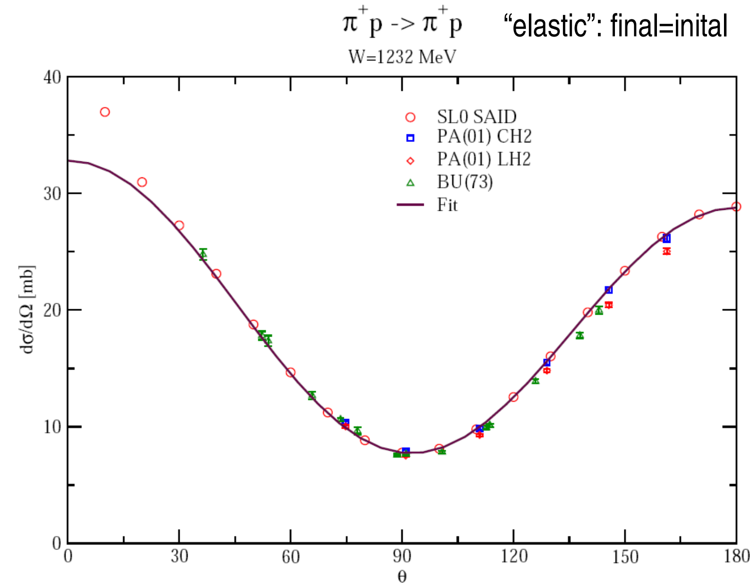
[Tuchitani, et al. nucl-th/0407004]

- More precise determination of ωN scattering length in fits of:

$$\pi N, \gamma N, \gamma^* N \to \omega N$$

- Why isoscalar? $T_\omega=0$ means only T=1/2 N* contribute → simplicity

Formalism: observables



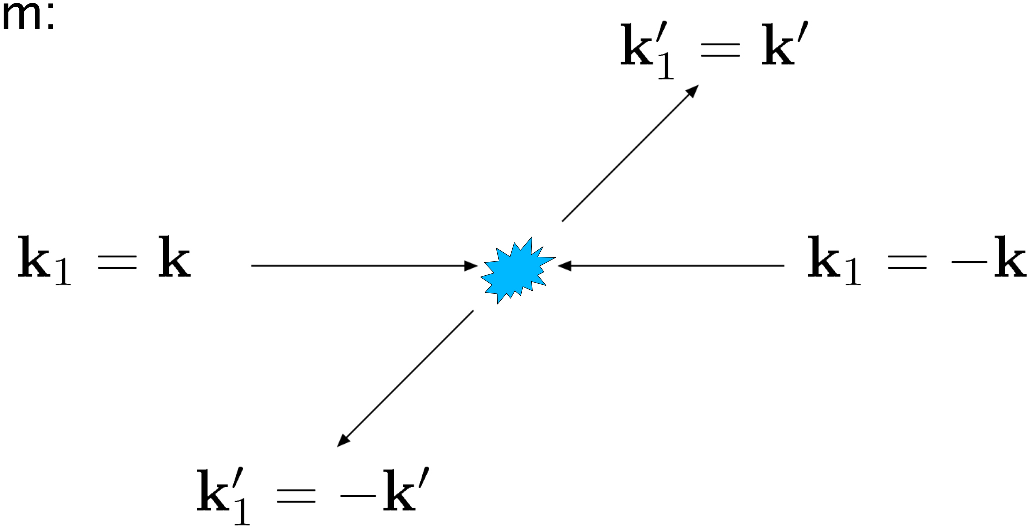
Reaction cross section:

$$\frac{d\sigma}{d\Omega} = \frac{(4\pi)^2}{k^2}\rho_{M'B'}(k')\rho_{MB}(k)|T_{M'B',MB}(\mathbf{k}',\mathbf{k})|^2$$

Strong processes: $\pi N \to \pi N, \pi N \to \omega N$

Electromagnetic: $\gamma N \to \omega N$

Center-of-mass system:



$$\langle \mathbf{k}_1', \mathbf{k}_2' | T_{M'B',MB} | \mathbf{k}_1, \mathbf{k}_2 \rangle = \langle \mathbf{k}' | T_{M'B',MB} | \mathbf{k} \rangle$$

Formalism: S-matrix

S-matrix:

$$S_{\alpha\beta} = \delta(\alpha-\beta) - 2\pi i \delta(E_\alpha - E_\beta) T^{+}_{\alpha\beta}$$
$$= \langle \Psi^{(-)}_\alpha | \Psi^{(+)}_\beta \rangle \rightarrow \langle \mathrm{Out} | \mathrm{In} \rangle$$

$$H = H_0 + V$$
$$H|\Psi^{\pm}_\alpha\rangle = E_\alpha |\Psi^{\pm}_\alpha\rangle$$
$$H_0|\Phi_\alpha\rangle = E_\alpha |\Phi_\alpha\rangle$$

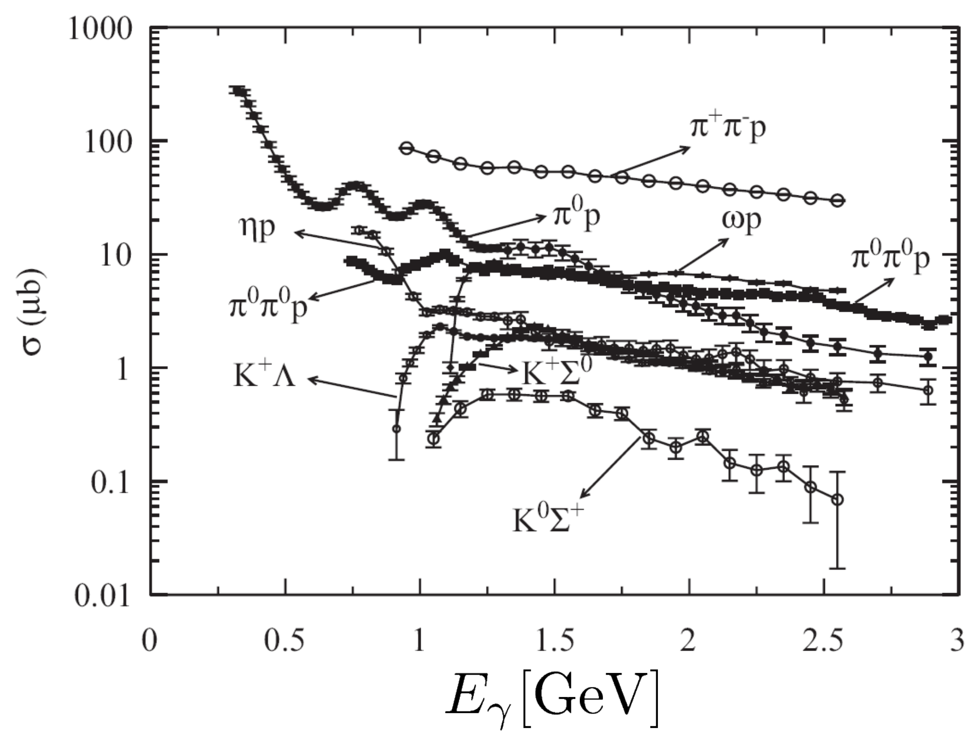
$$G_0^{(\pm)} = \frac{1}{E - H_0 \pm i\epsilon}$$

$$H_0 = \sum_\kappa a^\dagger_\kappa a_\kappa \sqrt{k^2 + m_i^2}$$

$$|\Psi^{(\pm)}\rangle = |\Phi\rangle + V G_0^{(\pm)} |\Psi^{(\pm)}\rangle$$
$$|\Psi\rangle \equiv T|\Phi\rangle$$
$$T = V + V G_0 T = [1 - V G_0]^{-1} V$$

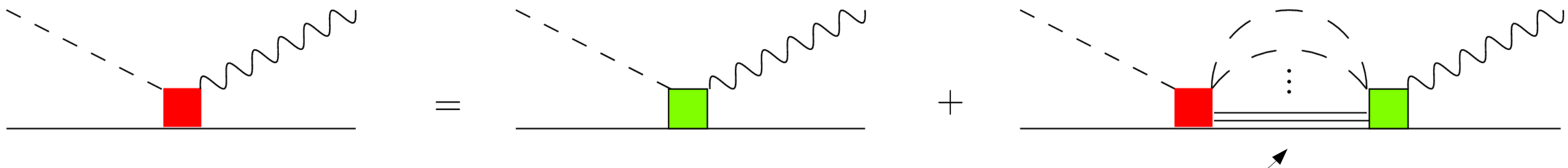
Unitarity condition:

$$i[T_{MB,\gamma N} - T^*_{\gamma N, MB}]$$
$$= \sum_{M'B'} T^*_{\gamma N, M'B'} \rho_{M'B'} T_{\gamma N, M'B'}$$
$$+ T^*_{\gamma N, \pi\pi N} \rho_{\pi\pi N} T_{\gamma N, \pi\pi N}$$



Formalism: model space

Dynamical (Lippman–Schwinger) equation: $T = V + VG_0T$

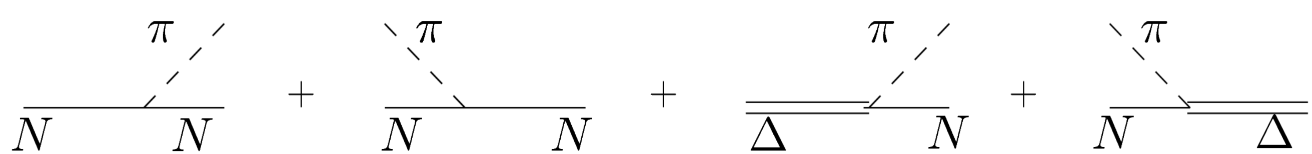


Channel space: $\pi N, \eta N, \omega N, \pi\Delta, \sigma N, \rho N, \pi\pi N$

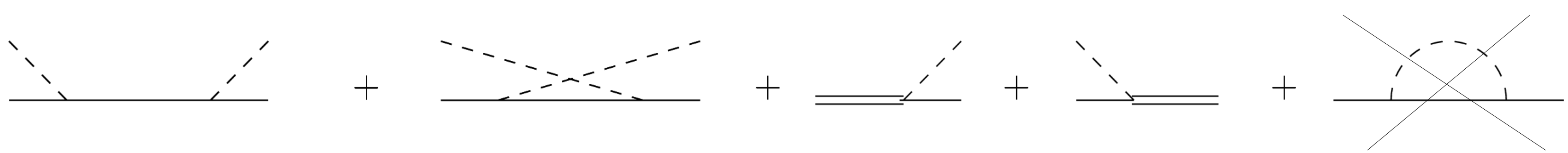
Few–body approach: [After: Amado & Aaron, Sato-Kobayashi-Ohtsubo]

- unitary t–form systematically eliminate “virtual” processes: $V = \int d^3x\, \mathcal{H}_I(x) \rightarrow V'$
- transfers effects of virtual processes to many–body operators
- Advantages:
  - energy independent V'
  - at low energies (<2 GeV COM) only few–body states contribute
- Disadvantages:
  - mass & wave function renormalization treated phenomenologically
  - difficult to estimate higher order terms

- Example: $V =$

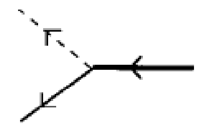


$\longrightarrow V' =$

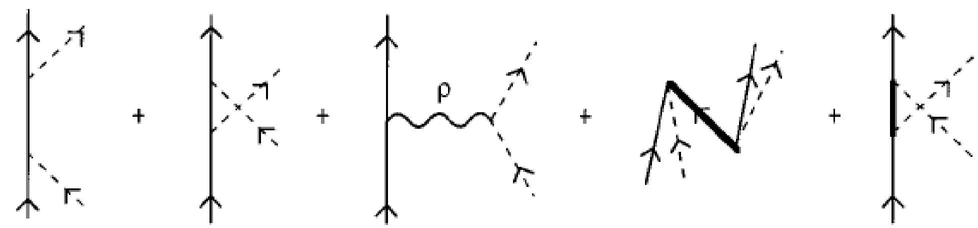


Effective interaction:
$\pi N \to \pi N$

$$V = \Gamma_V + v_{22} + v'$$
$$\Gamma_V = \sum_{N^*, MB} \Gamma_{N^*, MB}$$
$$v_{22} = \sum_{M'B', MB} v_{M'B', MB}$$
$$v' = v_{23} + v_{33}$$



[Hermitian conjugate implied]



For 5 channels: $\pi N, \eta N, \pi\Delta, \sigma N, \rho N \implies$ **42 terms**

Interaction evaluation:
- evaluate diagrams
- project into partial wave basis
- test against plane wave code

Propagators:
- unitary transform modifies Feynman form
- Feynman: off-shell → on-shell

$$\overline{V}_a^{16} = i g_{\omega NN} \frac{f_{\pi NN}}{m_\pi} \Gamma_{\omega'} \frac{1}{2} \left[\frac{1}{\not{p} + \not{k} - m} + \frac{1}{\not{p}' + \not{k}' - m} \right] \tau^i \not{k} \gamma_5$$

$$\overline{V}_b^{16} = i g_{\omega NN} \frac{f_{\pi NN}}{m_\pi} \tau^i \not{k} \gamma_5 \frac{1}{2} \left[\frac{1}{\not{p} - \not{k} - m} + \frac{1}{\not{p}' - \not{k}' - m} \right] \Gamma_{\omega'}$$

$$\overline{V}_e^{16} = g_{\rho NN} \frac{g_{\omega\pi\rho}}{m_\omega} \frac{\tau^i}{2} \Big[\frac{1}{2} \frac{1}{t - m_\rho^2} \epsilon_{\alpha\beta\gamma\delta} \epsilon_{\lambda_\omega}^{\alpha *} (p - p')^\beta k^\gamma \Gamma_\rho^\delta (p - p') + \frac{1}{2} \frac{1}{t' - m_\rho^2} \epsilon_{\alpha\beta\gamma\delta} \epsilon_{\lambda_\omega}^{\alpha *} (k' - k)^\beta k^\gamma \Gamma_\rho^\delta (k' - k) \Big]$$

Formalism: dynamical equation

Starting model space: neglect $\pi\pi N$

$$\boxed{v^R(E) = \sum_{N_i^*} \frac{\Gamma_i^\dagger \Gamma_i}{E - M_i^0}}$$

$$V_{\alpha\beta} = v_{\alpha\beta} + v^R_{\alpha\beta}$$

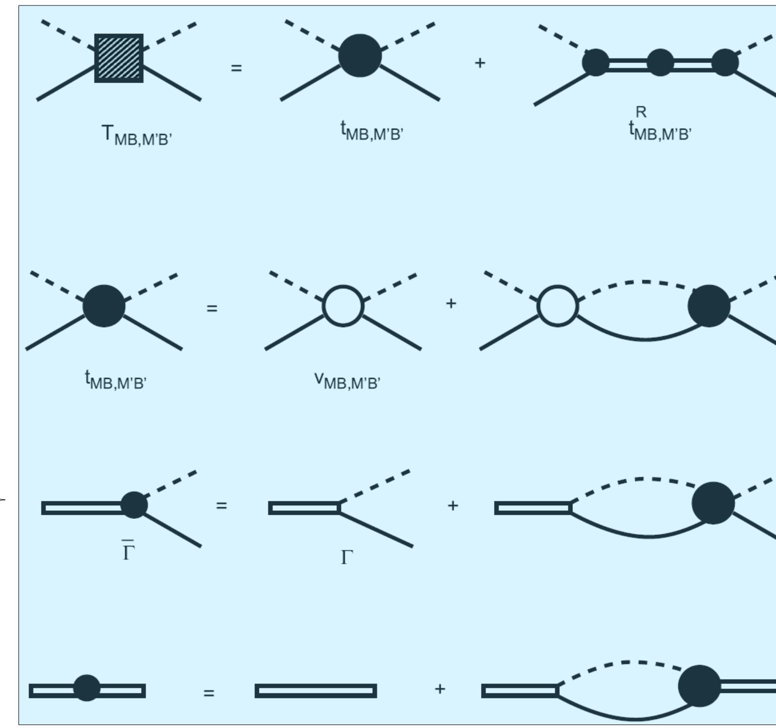
$$T_{\alpha\beta}(E) = t_{\alpha\beta}(E) + t^R_{\alpha\beta}(E)$$

$$t^R_{\alpha\beta}(E) = \sum_{i,j} \overline{\Gamma}_{\alpha,i}[E - H_0 - \Sigma]^{-1}_{ij} \overline{\Gamma}_{j,\beta}$$

$$t_{\alpha\beta}(E) = v_{\alpha\beta} + \sum_\gamma v_{\alpha\gamma} G_{0,\gamma}(E) t_{\gamma\beta}(E)$$

$$\overline{\Gamma}_{i,\beta}(E) = \Gamma_{i,\beta}(E) + \sum_\gamma \Gamma_{i,\gamma} G_{0,\gamma}(E) t_{\gamma\beta}(E)$$

$$\Sigma_{ij} = \sum_\gamma \Gamma_{i,\gamma} G_{0,\gamma} \overline{\Gamma}_{\gamma,j}$$



$$G_{0,MB} = \frac{1}{E - \sqrt{k^2 + m_B^2} - \sqrt{k^2 + m_M^2} - \Sigma_{MB}(E)}$$

$$\Sigma_{MB}(E) = \begin{cases} +i\epsilon & MB = \pi N, \eta N \\ \text{self energy of } p^* & MB = \pi\Delta, \sigma N, \rho N \end{cases}$$

NB sums:

$\sum_\gamma : \gamma = \pi N, \eta N, \pi\Delta, \sigma N, \rho N$

$\sum_{i,j} : i, j =$set of resonances

Resonant T matrix structure

$$t^R_{\alpha\beta}(E) = \sum_{i,j} \overline{\Gamma}_{\alpha,i}(E)[E - H_0 - \Sigma(E)]^{-1}_{ij} \overline{\Gamma}_{j,\beta}(E)$$

$$= \sum_i \tilde{\Gamma}_{\alpha,i}(E) \frac{1}{E - M_i(E) + \frac{i}{2}\Gamma_i(E)} \tilde{\Gamma}_{i,\beta}(E)$$

diagonalized

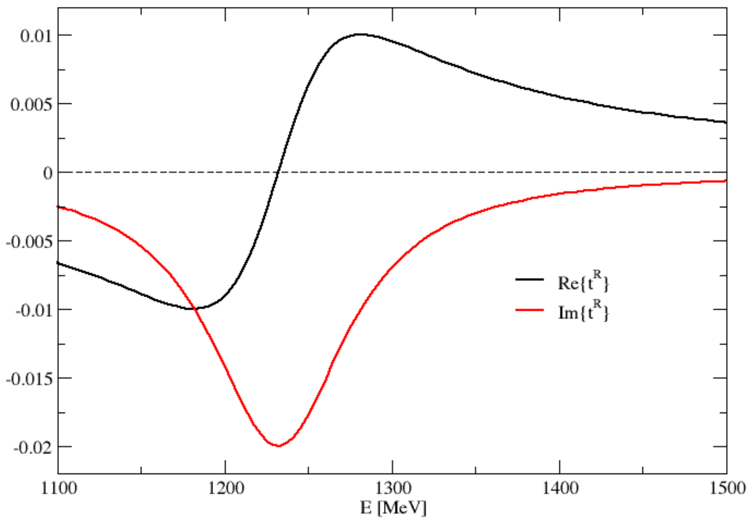
[see ref.Suzuki,Sato,Lee, in prep.]

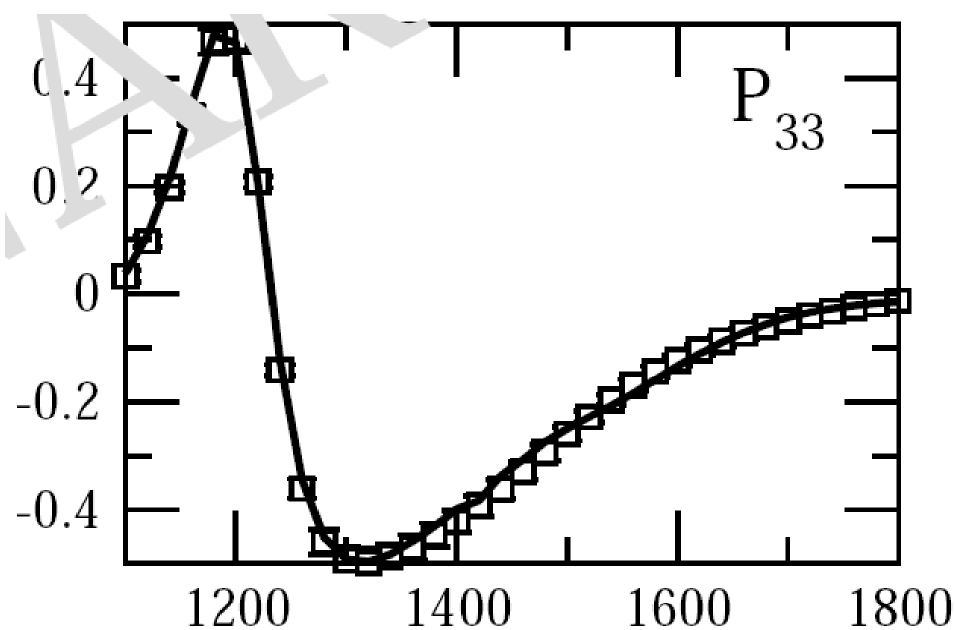
Motivates Breit-Wigner form:

$$\mathcal{A} = \frac{1}{E - M + \frac{i}{2}\Gamma}$$

$$M = 1232 \text{ MeV} \qquad \Gamma = 100 \text{ MeV}$$

$$|\mathcal{A}|^2 = \frac{1}{(E-M)^2 + \Gamma^2/4}$$





Actual fit to SAID from Bruno Julia-Diaz

Alternative formalisms

- Tree-level approximation

$$T_{\alpha\beta}(\text{tree}) = v_{\alpha\beta}(\text{tree}) + \sum_i \frac{\Gamma_{\alpha,i}\Gamma_{i,\beta}}{E - M_i + \frac{i}{2}\Gamma_{\text{tot}}}$$

not unitary

- K-matrix methods

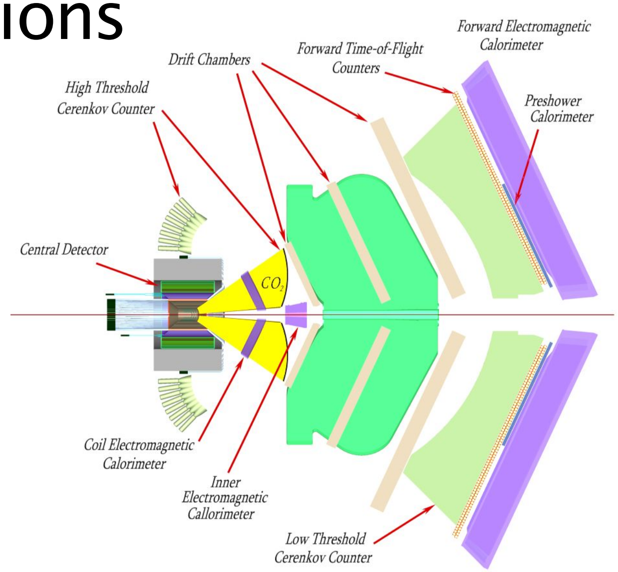
$$G_0(E) = \mathcal{P}\frac{1}{E - H_0} - i\pi\delta(E - H_0)$$

$$K_{\alpha\beta}(E) \equiv V_{\alpha\beta}(E) + \sum_\gamma V_{\alpha\gamma}(E) G_0^{\mathcal{P}}(E) K_{\gamma\beta}(E)$$

$$T_{\alpha\beta}(E) \equiv K_{\alpha\beta}(E) + \sum_\gamma T_{\alpha\gamma}(E)[i\pi\delta(E - H_0)] K_{\gamma\beta}(E)$$

  - Unitary Isobar Model (UIM) → single channel
  - Multi-channel K-matrix → Giessen model (5 channels)

Experimental facilities/observations



- Jefferson Lab: continuous e^- beam @ 6 GeV
  - Approved experiments (relevant sampling):
    - Hall A: HRS^2
      - N->Δ transition via polarization observables
      - Electroproduction of Kaons up to Q^2=3 $(GeV/c)^2$
    - Hall B: CEBAF Large Acceptance Spectrometer
      - Exclusive Kaon electroproduction in Hall B at 6 GeV
      - Search for missing nucleon resonances in the photoproduction of hyperons using a polarized photon beam and a polarized target
      - Measurement of polarization observables in eta-photoproduction with CLAS
      - N* resonances in pseudoscalar-meson photo-production from polarized neutrons in HD and a complete determination of the gn->K0 Lambda amplitude (conditional)
    - Hall C: HMS/SOS
      - Baryon resonance electroproduction at high momentum transfer
      - Precision measurement of the nucleon spin structure functions in the region of the nucleon resonances
      - Measurement of R= σ_L/σ_T in the nucleon resonance region
- MAMI – Mainz
- ELSA – Bonn: SAPHIR data $\gamma p \to \omega p$
- GRAAL – Grenoble; SPRing-8 (~Osaka)

Observables

- From detectors → T-matrices
  - detectors: $\{p_i^\mu\}_{i=1}^n$
  - experimental observable: $\frac{d\sigma}{d\Omega}(\lambda_\gamma, \lambda_N; \ldots)$
  - partial wave analysis (PWA): $T_{\lambda_\gamma, \lambda_N; \ldots}(\mathbf{k}', \mathbf{k})$

$$\frac{d\sigma}{d\Omega}(\lambda_\gamma, \lambda_N; \ldots) = \frac{(4\pi)^2}{q^2} \rho_{M'B'}(k') \rho_{\gamma N}(q) |T_{M'B', \lambda_\gamma, \lambda_N, T_{N,z}}(\mathbf{k}', \mathbf{q})|^2$$

NB: To go from E.O. → T-matrix (PWA)
requires **'complete set'** of observables

- Recent proposed JLab (CLAS) exp. (Klein, Sandorfi, et. al.): $\gamma n \rightarrow K^0 \Lambda$
  - $\#\lambda_\gamma \cdot \#\lambda_N = 4(\mathbb{C}) - 1(\text{phase}) \implies 8$ independent, real amplitudes

$\sigma_0 \rightarrow$ unpol. diff Xsec
$\Sigma \rightarrow$ beam SSA
$T \rightarrow$ target SSA
$P \rightarrow$ recoil SSA
$BT \rightarrow$ beam-target DPA
$TR \rightarrow$ target-recoil DPA
$BR \rightarrow$ beam-recoil DPA

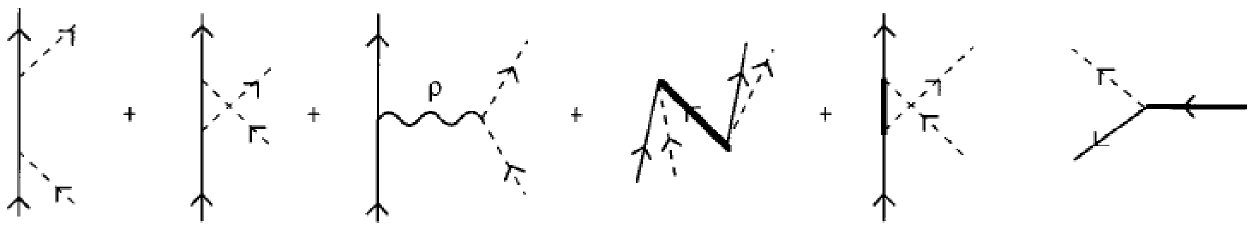
Photon beam		**Target**			**Recoil**			**Target + Recoil**			
					x'	y'	z'	x'	x'	y'	z'
		x	y	z				x	z	x	z
unpolarized γ	σ_0		T			P		$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linearly P_γ	Σ	H	$(-P)$	$-G$	$O_{x'}$	$(-T)$	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$
circular P_γ		F		$-E$	$-C_{x'}$		$C_{z'}$				

Previous results

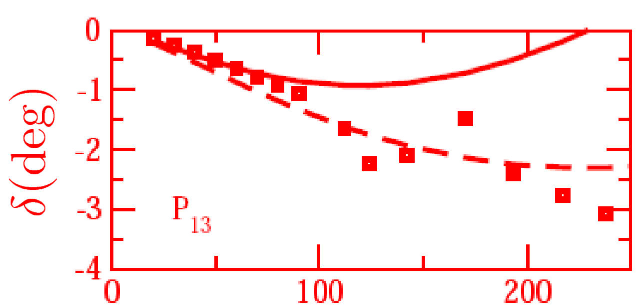
$\pi \to \pi$ and $\gamma \to \pi$

- Sato-Lee ('96) model [PRC **54** p.2660]: Δ resonance region
- πN Interaction:

$$\mathcal{L}_I = \mathcal{L}_{\pi\pi N} + \mathcal{L}_{\pi N \Delta} + \mathcal{L}_{\rho NN} + \mathcal{L}_{\rho\pi\pi} \implies V' :$$

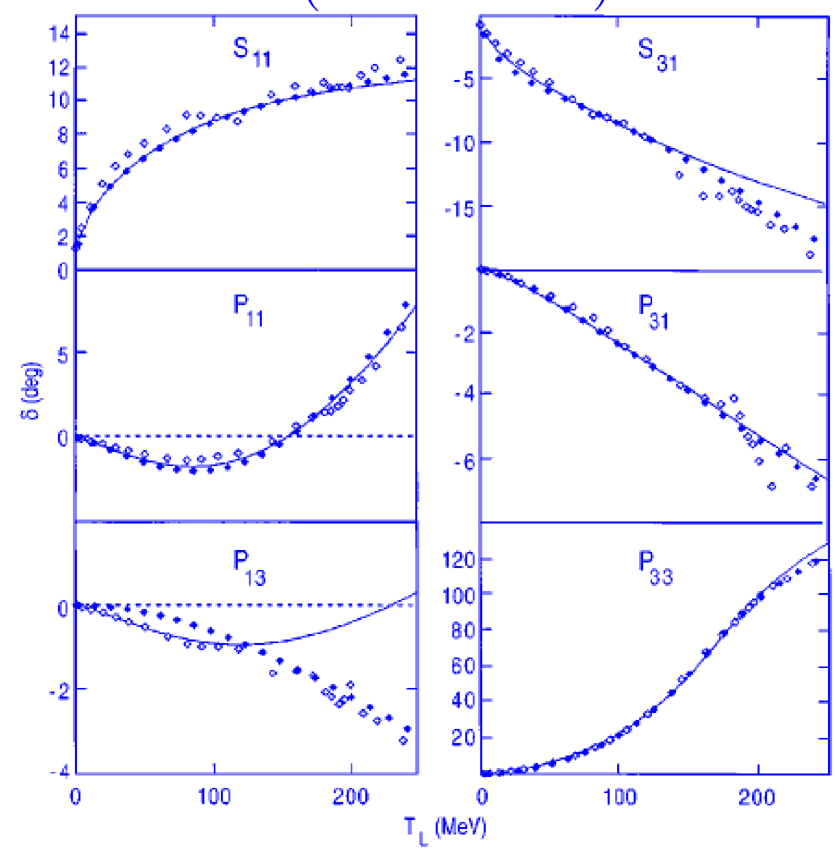


  - 7 parameter fit:
  $$\{g_\rho^2 = g_{\rho\pi\pi} g_{\rho NN}, \kappa_\rho, f_{\pi N\Delta}, \Lambda_{\pi NN},$$
  $$\Lambda_{\pi N\Delta}, \Lambda_\rho(\rho NN, \rho\pi\pi), m_\Delta^{(0)}\}$$
  - recent fits by B.Julia-Diaz have cured P_{13}



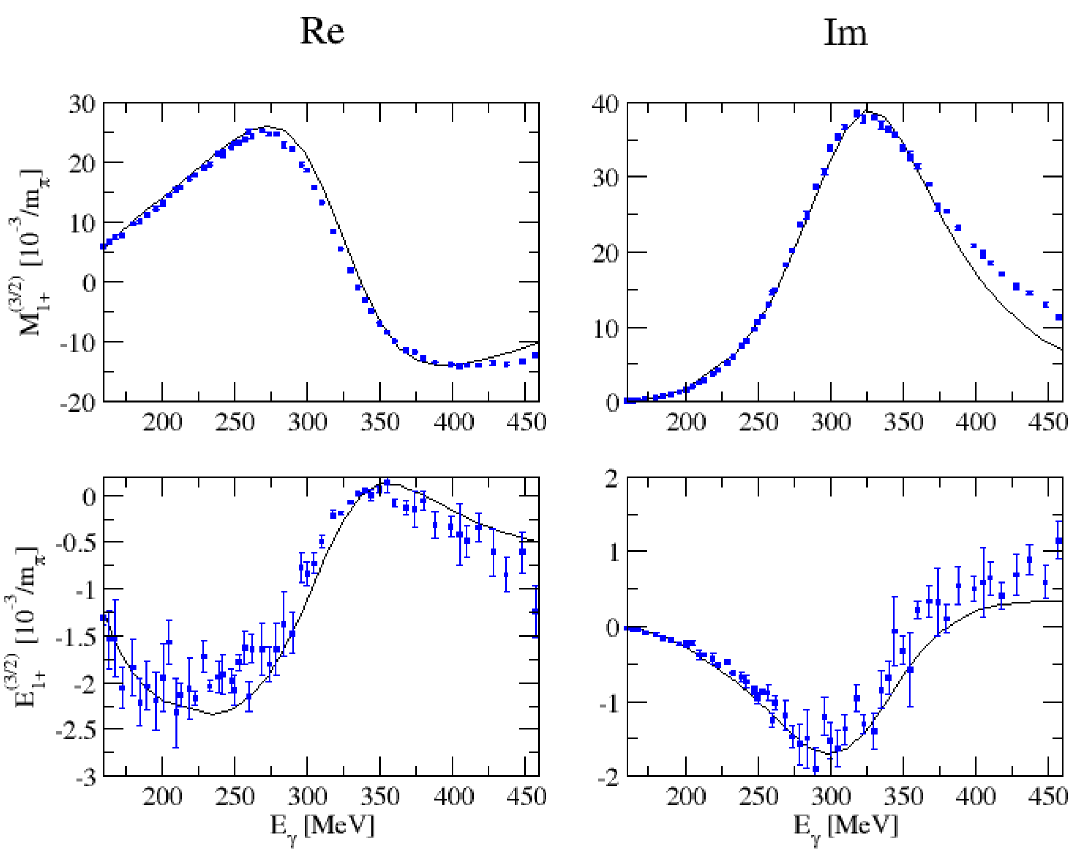
[Julia-Diaz,Lee,Sato,Smith Phys.Rev. C75 (2007) 015205]

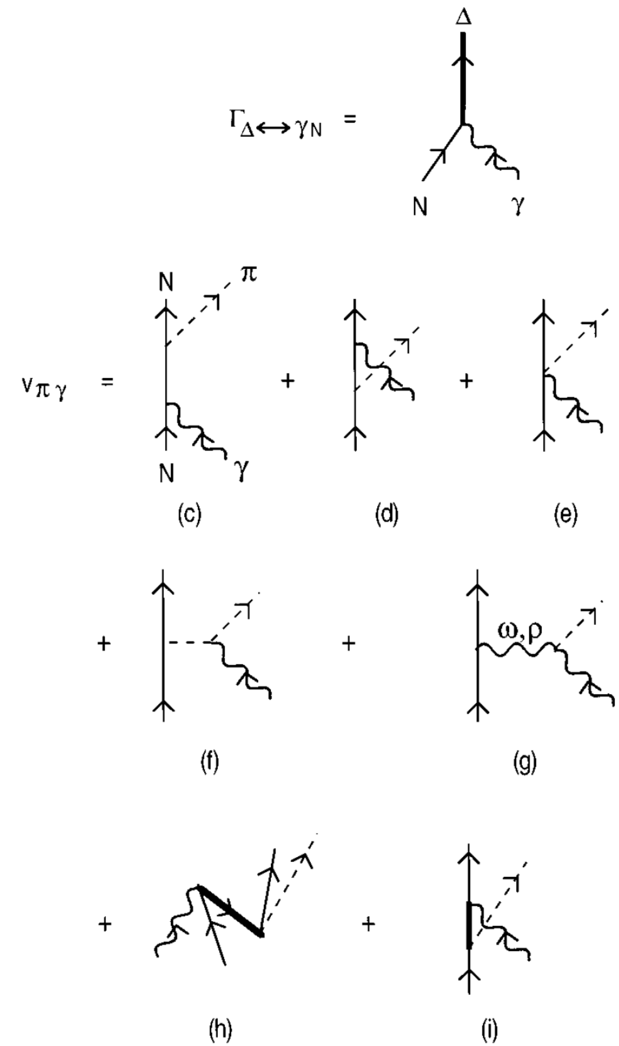
$\delta(\pi N \to \pi N)$



Sato-Lee model: photoproduction in Δ region

- Multipole amplitudes
  - linear superposition of helicity amplitudes
  - coeffs of angle-dependent X-sec functions
  - compared with SAID analysis





- 3 parameters:

$$g_{\omega NN}, G_M(0), G_E(0)$$

ω–production [desiderata]

- Formalism:
  - define projection operators:

$$\alpha = 1,\ldots,6 \rightarrow \omega N, \pi N, \eta N, \pi\Delta, \sigma N, \rho N$$

$$P_0 = \sum_{\alpha\neq 1} |\alpha\rangle\langle\alpha|, \qquad P_1 = |\omega N\rangle\langle\omega N|$$

  - $t_{10} = P_1 t P_0, \ldots$

$$t_{10} = [1 + \bar{t}_{11} G_{0,1}] v_{10} [1 + G_{0,0} \bar{t}_{00}]$$

$$\bar{t}_{00} = v_{00} + v_{00} G_{0,0} \bar{t}_{00}$$

From πN fits

$$\bar{t}_{11} = \bar{v}_{11} + \bar{v}_{11} G_{0,1} \bar{t}_{11}$$

$$\bar{v}_{11} = v_{11} + v_{10} [G_{0,0} + G_{0,0} \bar{t}_{00} G_{0,0}] v_{01}$$

  - "Doorway" approximation

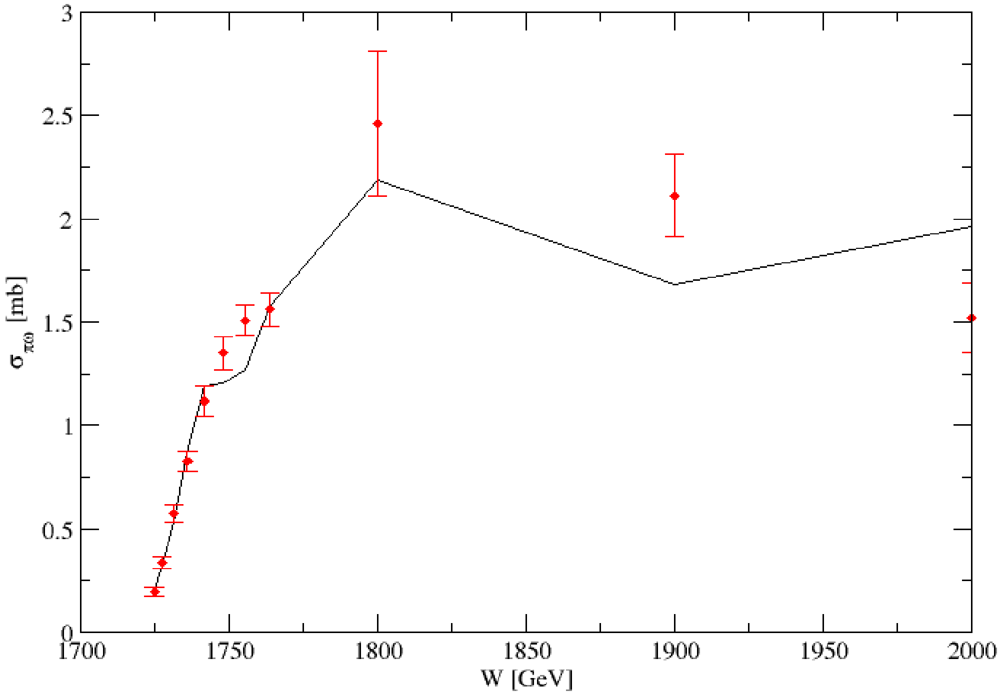
$$v_{\omega N,\alpha} \propto \delta_{\alpha,\pi N}$$

→since the coupling ωN → ηN, for example, isn't well known and probably small

$\pi N \to \omega N$

- Fit differential cross section data
  - Fit data from
    - Karami et. al. [NPB 154, 503 (1979)]:
      - $\pi^- p \longrightarrow \omega n$
      - 1.7249 GeV < W < 1.76380 GeV
    - Danburg et. al. [PRD **2** p.2564]:
      - $\pi^+ d \longrightarrow (p) p \pi^+ \pi^- \pi^0$
      - W = 1.80,1.90,2.00 GeV

total cross section

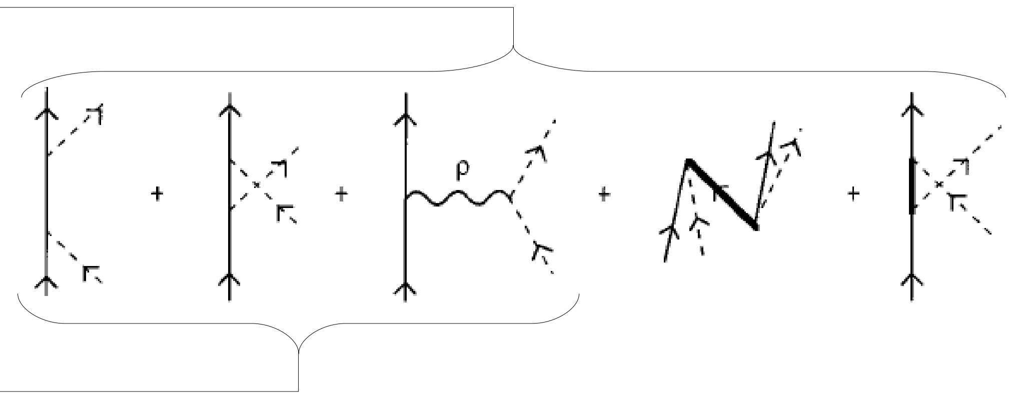


Model for ω-production

- First stage: assume only two channels are important
  - non-resonant terms: $\pi \longrightarrow \omega$

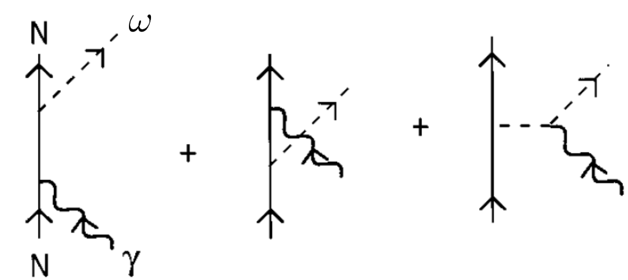
parameters: $g_{MBB}, g_{MMM}, \Lambda_M$

$$v = \begin{pmatrix} v_{\pi N,\pi N} & v_{\pi N,\omega N} \\ v_{\omega N,\pi N} & v_{\omega N,\omega N} \end{pmatrix}$$



- non-resonant terms: $\gamma \longrightarrow \omega$

$$t_{\omega N,\gamma N} = v_{\omega N,\gamma N} + \sum_{\alpha=\pi N,\omega N} t_{\omega N,\alpha} G_{0,\alpha} v_{\alpha,\gamma N}$$

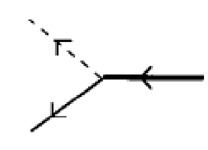


- resonant contributions: after Giessen [PRC **71** 055206]

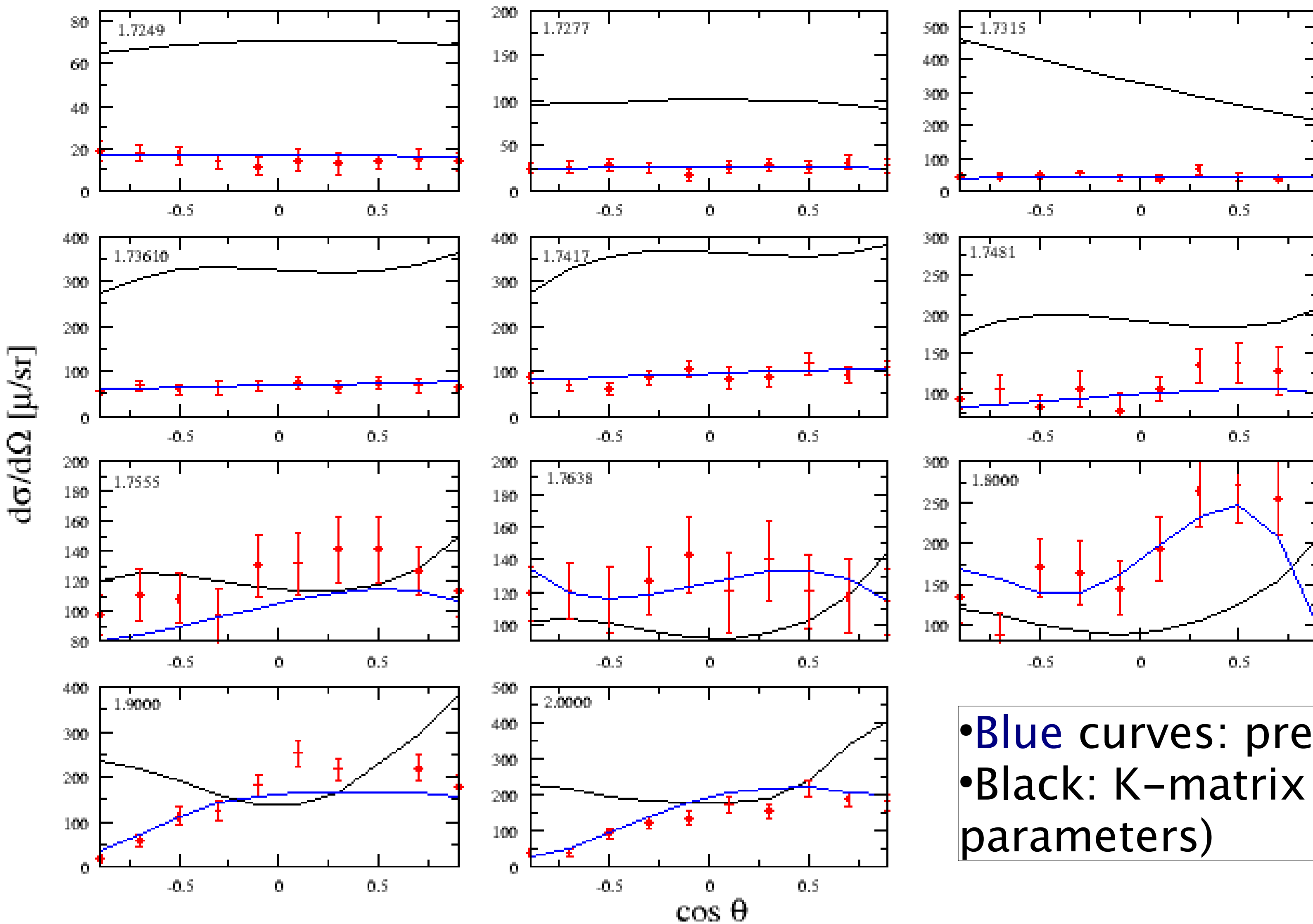
$S_{11}(1535), S_{11}(1650)$
$P_{11}(1440), P_{11}(1710)$
$P_{13}(1720), P_{13}(1900)$
$D_{13}(1520), D_{13}(1950)$
$D_{15}(1675),$
$F_{15}(1680), F_{15}(2000)$

$$\tilde{\Gamma}^{JT}_{N^*,LSMB}(k) = \frac{1}{(2\pi)^{3/2}} \frac{1}{\sqrt{2E_M(k)}} \sqrt{\frac{m_B}{E_B(k)}} \sqrt{\frac{8\pi^2 M_{N^*}}{m_B k_R}} \left[G^{JT}_{LS,MB}\right] f^{JT}_{LS}(k, k_R) \left(\frac{k}{k_R}\right)^L$$

$$\tilde{\Gamma}^{JT}_{N^*,\lambda_\gamma \lambda_N m_{\tau_N}}(q) = \frac{1}{(2\pi)^{3/2}} \sqrt{\frac{m_N}{E_N(q)}} \frac{1}{\sqrt{2q}} \left[\sqrt{2q_R} A^{JT}_{\lambda, m_{\tau_N}}\right] g^{JT}_{\lambda}(q, q_R) \delta_{\lambda,(\lambda_\gamma - \lambda_N)},$$



π→ω differential cross section fit



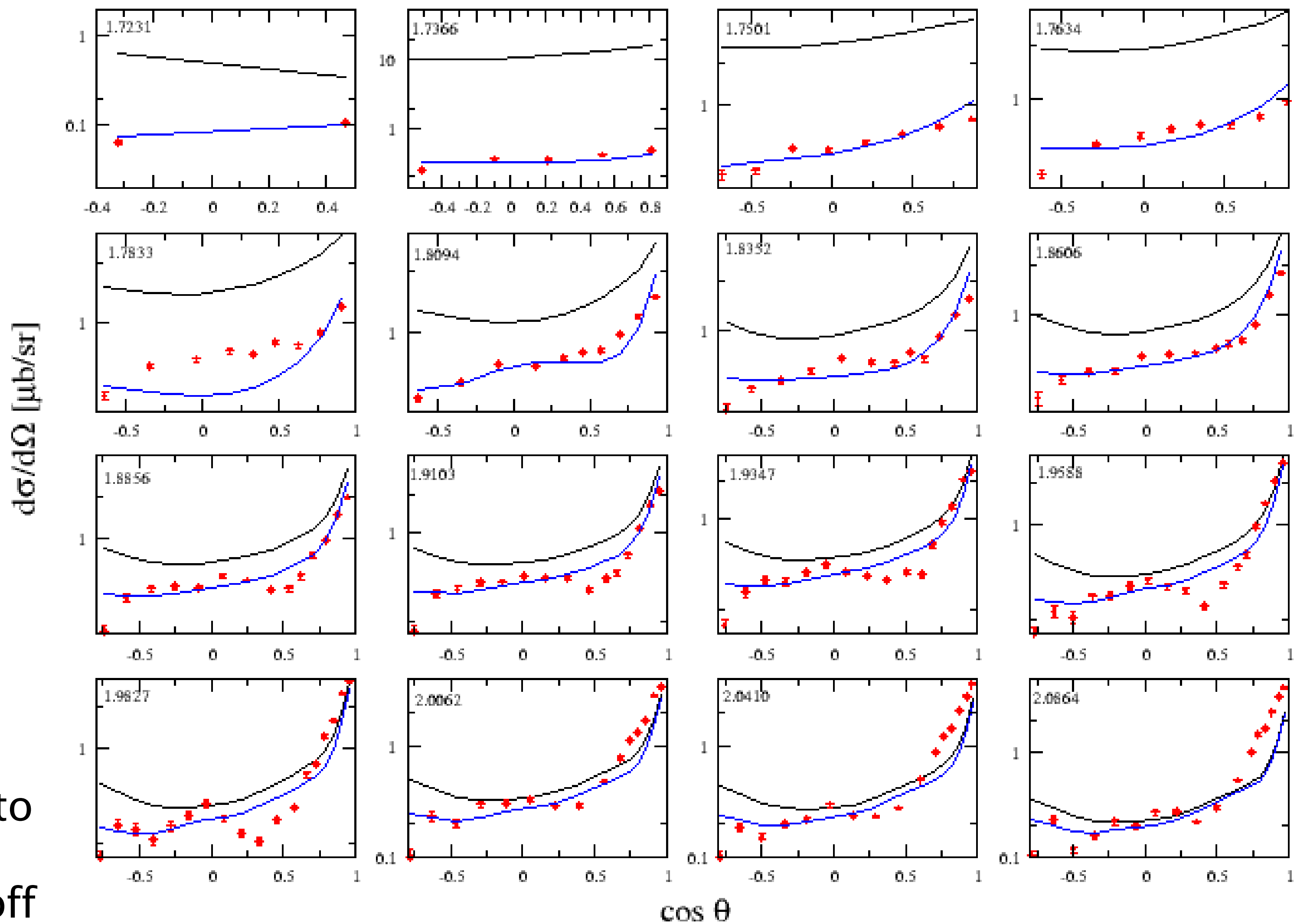
- Blue curves: present fit
- Black: K-matrix (same parameters)

Variable parameters:

- non-resonant: $\Lambda_{\pi NN}, g_{\rho NN}, \Lambda_{\rho NN}, g_{\omega NN}, \Lambda_{\omega NN}, \kappa_\omega$
- resonant: all ωN coup's/cut's (πN fixed to PDG values)

γ→ω differential cross section

- current fit (blue curve) compared to K-matrix fit (same parameters)



•vary only resonance couplings to ωN
•same cutoff for all resonances

What is to be done.

- ωN data
  - complete 2 channel (πN⊕ωN) fits
  - global fit to π→ω & γ→ω data
    - explore full parameter space
  - extend fits to γ→ω W ≈ 2.4 GeV
  - implement full (off-shell) in "doorway approximation"

$$t_{\pi N,\pi N} \,\&\, t_{\omega N,\pi N}$$

  - electo-production; weak interactions

- Extraction of bare/dressed transition form factors
  - given fitted data, what bare form factors reproduce data?
  - meson cloud effects
  - model calculations

Conclusion

- Coupled-channel approach
  - sufficiently rich & flexible to fit large meson production data sets
  - significant off-shell contributions → contrast with K-matrix approaches
  - unitarity effects are not neglible
- Model implications
  - can model dependencies be identified & controlled?
  - connection to model independent results of χPT?
  - can contact with Lattice QCD be made?
    - "valence" QCD (K.-F. Liu et. al.)

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