Pion photoproduction in a dynamical coupled-channels model

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Methodology for N^* study

complete set of data for $\gamma N \rightarrow KY$
$\uparrow$

There are lots of high precision data from JLab, MIT-Bates, BNL-LEGS, Mainz-MAMI, Bonn-ELSA, GRAAL, Spring-8, et al.

N^*'s are unstable and couple strongly to baryon-meson states

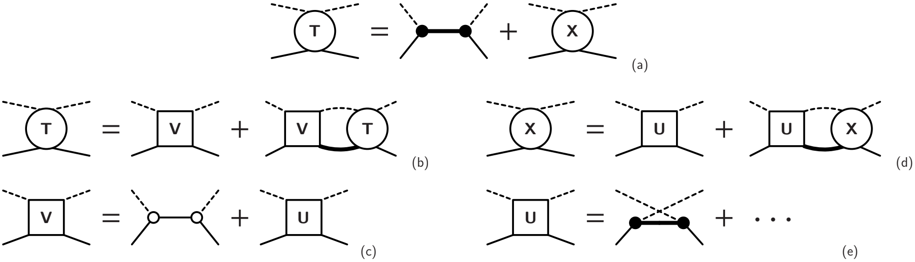
$$\Downarrow$$

Build coupled-channels meson-baryon reaction models to

- analyze the meson production data
- extract N^* parameters
- understand the reaction mechanisms
- understand the structures and dynamical origins of N^*

Most widely used models: K matrix approximation, chiral unitary approach, dynamical coupled-channels model, et al.

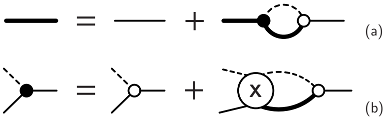
Dynamical model ingredients



(a) $T = |F\rangle\, S\, \langle F| + X$
(b) $T = V + V\, G_0\, T$
(c) $V = |f\rangle\, S_0\, \langle f| + U$
(d) $X = U + U\, G_0\, X$

T: full amplitude
X: non-pole amplitude
U: driving term of X
V: driving term of T

S: dressed res. propagator
S_0: bare res. propagator
$|F\rangle$: dressed res. vertex
$|f\rangle$: bare res. vertex



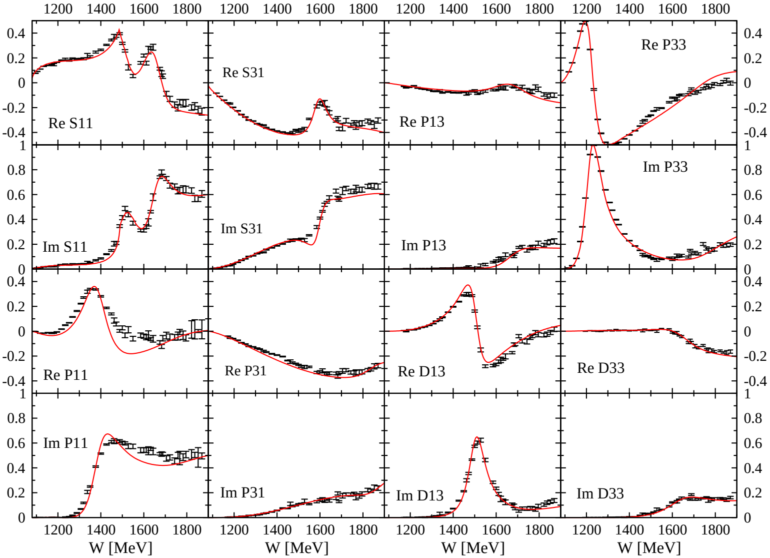
(a) $S = S_0 + S\, \underbrace{\langle F|\, G_0\, |f\rangle}_{\text{“self energy” } \Sigma}\, S_0$

(b) $|F\rangle = |f\rangle + X\, G_0\, |f\rangle$

Jülich model: $\pi N \to \pi N$ [Solution 2002]

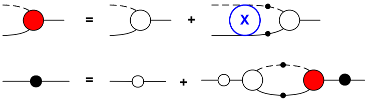
$\pi N \oplus \eta N \oplus \pi\Delta \oplus \rho N \oplus \sigma N$

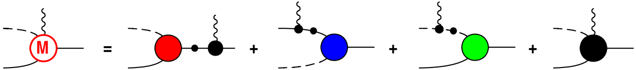
$S_{11}(1535)$, $S_{11}(1650)$, $S_{31}(1620)$, $P_{31}(1910)$, $P_{13}(1720)$, $D_{13}(1520)$, $P_{33}(1232)$, $D_{33}(1700)$ (all are 4-star N^*'s)



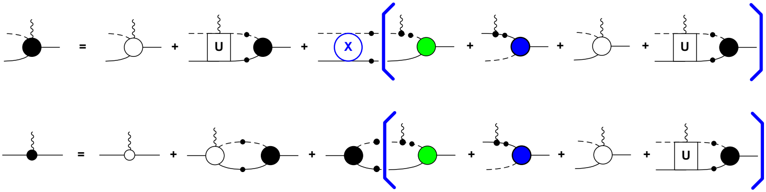
Pion photoproduction [H. Haberzettl, PRC56(1997)2041]

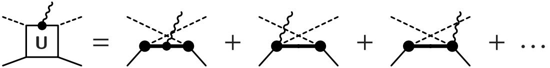
To get M^μ & J^μ, attach a photon everywhere to





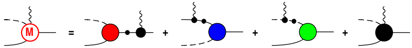
$$M^\mu = M_s^\mu + M_u^\mu + M_t^\mu + M_{\text{int}}^\mu$$

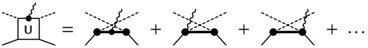


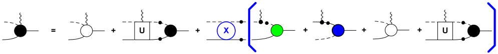


Gauge invariance

- In a full theory (no form factors $\&$ truncations), gauge invariance is respected (minimum coupling, $\partial_\mu \to D_\mu \equiv \partial_\mu + ieA_\mu(x)$)
- Real-world calculations require form factors $\&$ truncations

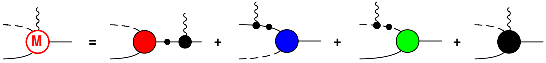




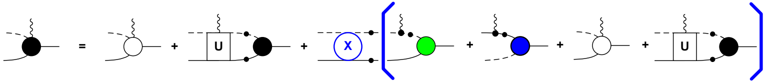


- Inclusion form factors will destroy gauge invariance, since form factors are usually functions of the momenta of exchanged particles
- Truncations usually also destroy gauge invariance
- The vast majority of existing models does not satisfy gauge invariance
- Our model is gauge invariant $\Leftarrow$ we introduce a prescription to restore gauge invariance

Prescription to restore gauge invariance



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



$$M_{\rm int}^\mu = M_c^\mu + X\, G_0 \left(M_u^\mu + M_t^\mu + M_c^\mu\right)_{\rm T}$$

Generalized Ward-Takahashi Identity (GWTI) for M^μ

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

$$\Updownarrow$$

Constraints on M_c^μ & $M_{\rm int}^\mu$

$$k_\mu M_c^\mu \equiv k_\mu M_{\rm int}^\mu = -\left|F_s\tau\right\rangle Q_i + Q_f \left|F_u\tau\right\rangle + Q_\pi \left|F_t\tau\right\rangle$$

Choosing the generalized contact current M_c^μ

- Constraints: gauge invariance; contact term; crossing symmetry
- Choosing the generalized contact current M_c^μ as

$$M_c^\mu = -g_\pi \gamma_5 \left\{ \left[\lambda + (1-\lambda)\frac{\not{q}}{2m} \right] C^\mu + (1-\lambda)\frac{\gamma^\mu}{2m} e_\pi f_t \right\}$$

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

$$\hat{F} = 1 - \hat{h}\,(1-\delta_s f_s)\,(1-\delta_u f_u)\,(1-\delta_t f_t)$$

k, p, q, p': 4-momenta for incoming γ, N & outgoing π, N $\hat{h}$: fit parameter

f_x: form factors for corresponding channels

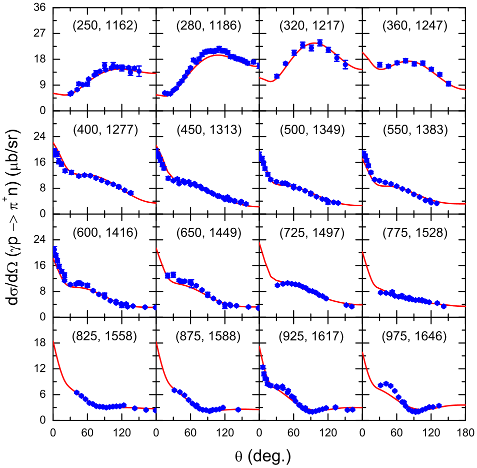
- Check gauge invariance:

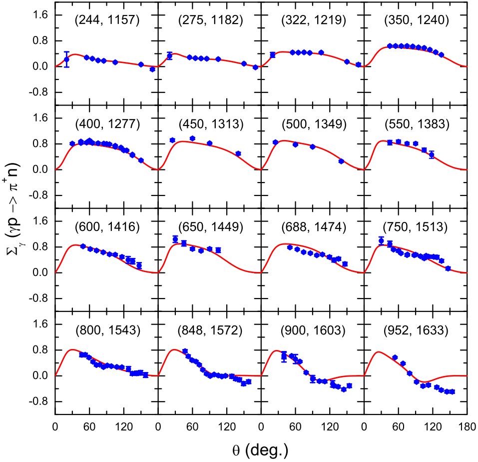
$$k_\mu M_c^\mu = -\left|F_s\right\rangle e_i + \left|F_u\right\rangle e_f + \left|F_t\right\rangle e_\pi$$

- If no form factors, i.e. $f_x = 1$,

$$C^\mu \to 0, \qquad M_c^\mu \to -g_\pi \gamma_5 (1-\lambda)\frac{\gamma^\mu}{2m} e_\pi \quad \text{(Kroll-Ruderman term)}$$

Results: $d\sigma/d\Omega$ & Σ_γ for $\gamma + p \to \pi^+ + n$

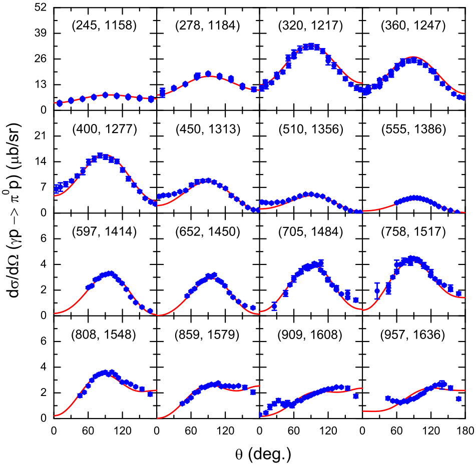




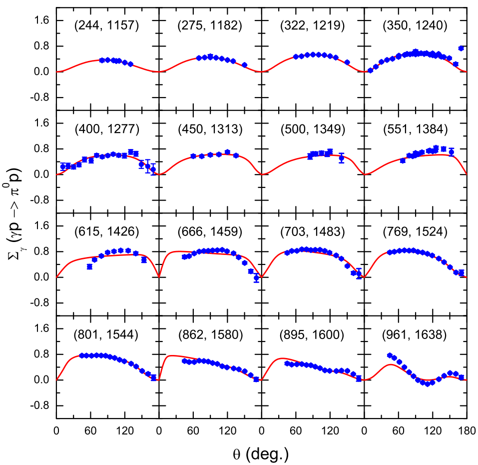
Differential cross sections for $\gamma + p \to \pi^+ + n$

Photon spin asymmetries for $\gamma + p \to \pi^+ + n$

$S_{11}(1535)$, $S_{11}(1650)$, $S_{31}(1620)$, $P_{31}(1910)$, $P_{13}(1720)$, $D_{13}(1520)$, $P_{33}(1232)$, $D_{33}(1700)$



Differential cross sections for $\gamma + p \to \pi^0 + p$



Photon spin asymmetries for $\gamma + p \to \pi^0 + p$

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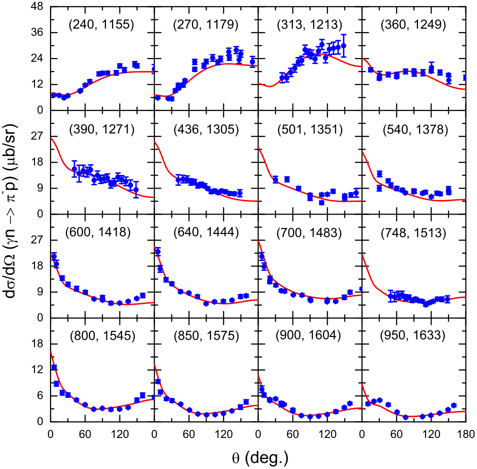
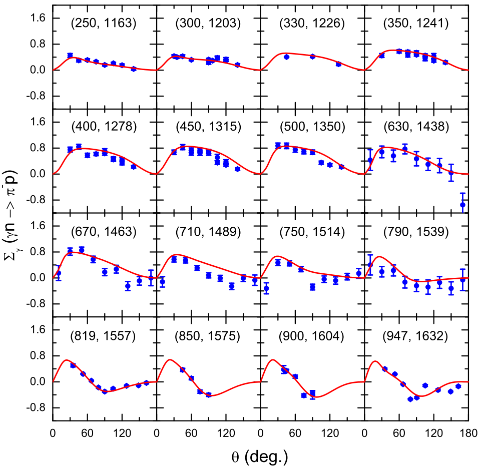
Results: $d\sigma/d\Omega$ & Σ_γ for $\gamma + n \to \pi^- + p$



Differential cross sections for $\gamma + n \to \pi^- + p$



Photon spin asymmetries for $\gamma + n \to \pi^- + p$

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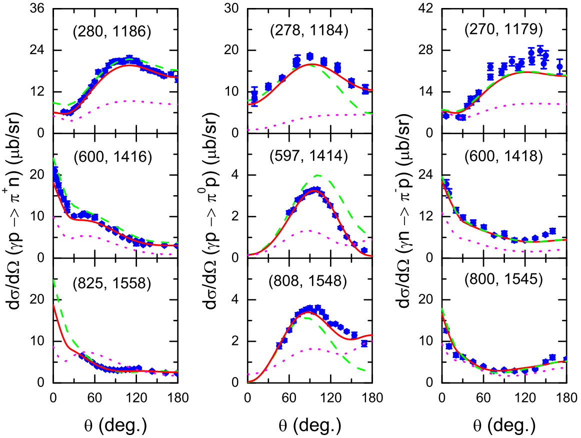
Contributions from loop integral & M_c^μ



$$M^\mu = |F\rangle\, S\, \tilde{J}_s^\mu + M_u^\mu + M_t^\mu + M_c^\mu + T\, G_0 \left(M_u^\mu + M_t^\mu + M_c^\mu\right)_{\mathrm{T}}$$

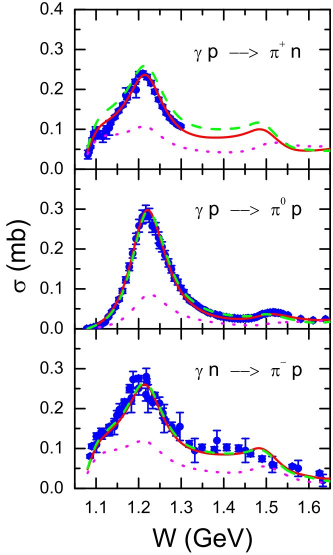
——: full calculation

· · · ·: no loop integral

- - - -: no M_c^μ apart from K.R.

- Contribution from the loop integral is important
- The terms apart from the Kroll-Ruderman term in M_c^μ give significant effects
  $\Rightarrow$ keeping gauge invariance is important

Results: $\gamma N \to \pi N$ total cross sections



——: full calculation

· · · ·: no loop integral

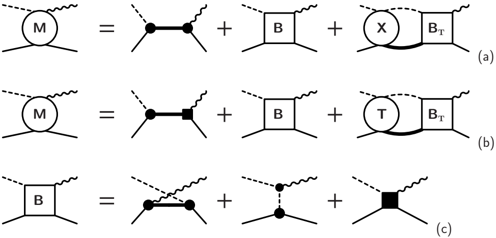
- - - -: no M_c^μ apart from Kroll-Ruderman term

- Data not included in the fit
- Contribution from the loop integral is important
- Effect of the terms apart from Kroll-Ruderman term in M_c^μ is significant for $\gamma p \to \pi^+ n$
- For $\gamma p \to \pi^0 p$, the effect of M_c^μ on $\mathrm{d}\sigma/\mathrm{d}\omega$ is largely suppressed at backward angles by $\sin\theta$

Summary & perspectives

- Jülich dynamical coupled-channels model
  - $\pi N \oplus \eta N \oplus \pi\Delta \oplus \rho N \oplus \sigma N$; analyticity & unitarity respected
  - Wess & Zumino chiral Lagrangian $+ \Delta, \omega, \eta, a_0, \sigma$
  - Nucleon pole & dynamically generated Roper
  - $S_{11}(1535)$, $S_{11}(1650)$, $S_{31}(1620)$, $P_{31}(1910)$, $P_{13}(1720)$, $D_{13}(1520)$, $P_{33}(1232)$, $D_{33}(1700)$
- π photoproduction
  - Field-theoretical approach
  - Gauge invariance strictly respected
  - $d\sigma/d\Omega$ & Σ_γ described quite well up to 1.65 GeV
  - Loop integral & M_c^μ (apart from K.R.) are important
- Next step work:
  - Resonances' electromagnetic couplings
  - ΛK & ΣK ($I = 1/2$) channels, ωN channel
  - Photoproduction of η, K, ω
  - Electroproduction of π

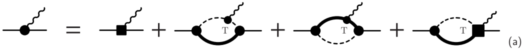
Photoproduction amplitudes: summary



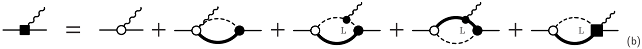
$$M^\mu = |F\rangle\, S\, J^\mu + B^\mu + X\, G_0\, B^\mu_{\mathsf{T}}$$

$$M^\mu = |F\rangle\, S\, \tilde{J}^\mu_s + B^\mu + T\, G_0\, B^\mu_{\mathsf{T}}$$

$$B^\mu = M^\mu_u + M^\mu_t + M^\mu_c$$



$$J^\mu = \tilde{J}^\mu_s + \langle F|\, G_0\, B^\mu_{\mathsf{T}}$$



$$\tilde{J}^\mu_s = J^\mu_0 + \langle m^\mu_{\mathsf{KR}}|G_0|F\rangle + \langle f|\, G_0\, B^\mu_{\mathsf{L}}$$

For details about $\tilde{J}^\mu_s$, see:

H. Haberzettl, F. Huang, and K. Nakayama, arXiv:1103.2065

Covariance & 3-D integral equation

- Jülich πN model — TOPT

$$T_{\mathrm{TO}}(\mathbf{p}',\mathbf{p};\sqrt{s}) = V_{\mathrm{TO}}(\mathbf{p}',\mathbf{p};\sqrt{s}) + \int d^3p''\, V_{\mathrm{TO}}(\mathbf{p}',\mathbf{p}'';\sqrt{s})\, G_{\mathrm{TO}}(\mathbf{p}'',\sqrt{s}) T_{\mathrm{TO}}(\mathbf{p}'',\mathbf{p};\sqrt{s})$$

$$G_{\mathrm{TO}}(\mathbf{p}'',\sqrt{s}) = \frac{1}{\sqrt{s} - E(\mathbf{p}'') - \omega(\mathbf{p}'') + i0}$$

- Converting to a covariant 3-D reduction like equation

$$V(\mathbf{p}',\mathbf{p};\sqrt{s}) \equiv (2\pi)^3 \sqrt{2E(\mathbf{p}')\,2\omega(\mathbf{p}')}\sqrt{2E(\mathbf{p})\,2\omega(\mathbf{p})}\; V_{\mathrm{TO}}(\mathbf{p}',\mathbf{p};\sqrt{s})$$

$$T(\mathbf{p}',\mathbf{p};\sqrt{s}) \equiv (2\pi)^3 \sqrt{2E(\mathbf{p}')\,2\omega(\mathbf{p}')}\sqrt{2E(\mathbf{p})\,2\omega(\mathbf{p})}\; T_{\mathrm{TO}}(\mathbf{p}',\mathbf{p};\sqrt{s})$$

$$T(\mathbf{p}',\mathbf{p};\sqrt{s}) = V(\mathbf{p}',\mathbf{p};\sqrt{s}) + \int \frac{d^3p''}{(2\pi)^3}\, V(\mathbf{p}',\mathbf{p}'';\sqrt{s})\, G_0(\mathbf{p}'',\sqrt{s})\, T(\mathbf{p}'',\mathbf{p};\sqrt{s})$$

$$G_0(\mathbf{p}'',\sqrt{s}) \equiv \frac{1}{2E(\mathbf{p}'')\,2\omega(\mathbf{p}'')}\;\frac{1}{\sqrt{s} - E(\mathbf{p}'') - \omega(\mathbf{p}'') + i0}$$

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