η-production on the proton *via* electromagnetic and hadronic probes

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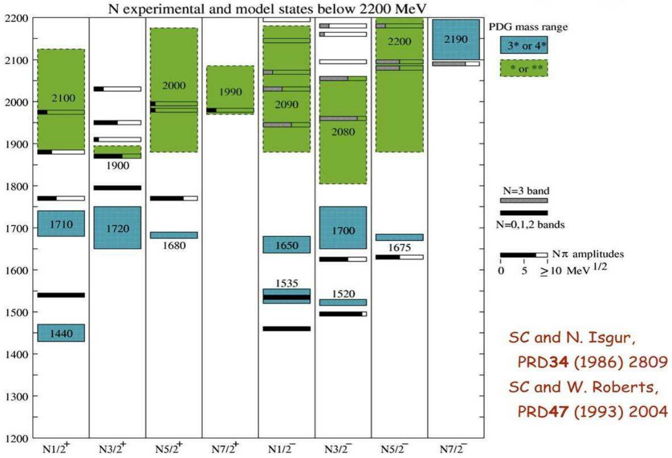
$\pi^- p \to \eta n$ and $\gamma p \to \eta p$

$W \lesssim 2$ GeV

PLAN :

- Introduction
- Chiral constituent quark model ($\gamma p \to \eta p$)
- Dynamical coupled-channels (EBAC)
- Results for $\pi^- p \to MB \to \eta n$ and $\gamma p \to MB \to \eta p$
- Conclusions

- Reactions mechanisms
- Role of nucleon resonances : PDG, "missing", "new"



Investigating $\gamma p \rightarrow MB \rightarrow \eta p$

$$T_{\gamma N \rightarrow \eta N} = (v^{NR}_{\gamma N \rightarrow \eta N} + v^{R}_{\gamma N \rightarrow \eta N})(1 + G_{\eta N} t^{NR}_{\eta N \rightarrow MB \rightarrow \eta N}) + v^{NR}_{\gamma N \rightarrow \pi N} G_{\pi N} t^{NR}_{\pi N \rightarrow MB \rightarrow \eta N}$$

- Direct channel : $\gamma p \rightarrow \eta p$
  CQM : He, Saghai, Li, PR C78, 035204 (2008)
- Coupled-channels $\pi N \rightarrow MB \rightarrow \eta n$, $MB \equiv \pi N, \eta N, \pi \Delta, \sigma N, \rho N$
  Durand, Julia-Diaz, Lee, Saghai, Sato, PR C78, 025204 (2008)
  EBAC : $\pi N \rightarrow MB \rightarrow \pi N$: Julia-Diaz, Lee, Matsuyama, Sato, PR C76, 065201 (2007)
  $\rightarrow$ **JLMS Model**
- $\gamma N \rightarrow \pi N$
  Sato and Lee, PR C54, 2660 (1996).
- Coupled-channels $\gamma p \rightarrow MB \rightarrow \eta p$

Chiral constituent quark model

$$\mathcal{L} = \bar{\psi}[\gamma_\mu(i\partial^\mu + V^\mu + \gamma_5 A^\mu) - m]\psi + \cdots$$

$$\frac{d\sigma^{c.m.}}{d\Omega} = \alpha_e g_{\eta NN} \frac{(E_N + M_N)(E_f + M_f)}{4s(M_f + M_N)^2} \frac{|\mathbf{q}|}{|\mathbf{k}|} |\mathcal{M}_{fi}|^2$$

$$\mathcal{M}_{fi} = \langle N_f | H_{m,e} | N_i \rangle + \sum_j \left\{ \frac{\langle N_f | H_m | N_j \rangle \langle N_j | H_e | N_i \rangle}{E_i + \omega - E_j} + \frac{\langle N_f | H_e | N_j \rangle \langle N_j | H_m | N_i \rangle}{E_i - \omega_m - E_j} \right\} + \mathcal{M}_T$$

$$H_m = \sum_j \frac{1}{f_m} \bar{\psi}_j \gamma_\mu^j \gamma_5^j \psi_j \partial^\mu \phi_m \; ; \; H_e = -\sum_j e_j \gamma_\mu^j A^\mu(\mathbf{k}, \mathbf{r})$$

$$\mathcal{M}_{N^*} = \frac{2M_{N^*}}{s - M_{N^*}^2 - iM_{N^*}\Gamma(\mathbf{q})} e^{-\frac{\mathbf{k}^2 + \mathbf{q}^2}{6\alpha^2}} \mathcal{O}_{N^*}$$

$$\mathcal{O}_{N^*} = if_{1l\pm}\sigma \cdot \epsilon + f_{2l\pm}\sigma \cdot \hat{\mathbf{q}}\sigma \cdot (\hat{\mathbf{k}} \times \epsilon) + if_{3l\pm}\sigma \cdot \hat{\mathbf{k}}\hat{\mathbf{q}} \cdot \epsilon + if_{4l\pm}\sigma \cdot \hat{\mathbf{q}}\epsilon \cdot \hat{\mathbf{q}}$$

$f_{kl\pm}$ (k=1,...,4) : partial wave amplitude of resonance $l_{2I,\ 2l\pm1}$

$SU(6) \otimes O(3)$ symmetry

- Underlying $SU(6) \otimes O(3)$ structure of the baryon spectrum established in 70's.
- Configuration mixing among the three-constituent quraks is a consequence of the $SU(6) \otimes O(3)$ breakdown.
- One-gluon-exchange mechanism generates the configuration mixing of the wave-function.

Wave function within the $SU(6) \otimes O(3)$ symmetry for $n \leq 2$ shells as $X^{2S+1} L_\pi J^P$ and configuration mixings, with J^P :

$$
\begin{aligned}
|S_{11}(1535)\rangle &= \cos\theta_S |N^2 P_M \tfrac{1}{2}^-\rangle - \sin\theta_S |N^4 P_M \tfrac{1}{2}^-\rangle \\
|S_{11}(1650)\rangle &= \sin\theta_S |N^2 P_M \tfrac{1}{2}^-\rangle + \cos\theta_S |N^4 P_M \tfrac{1}{2}^-\rangle \\
|Nucleon\rangle &= c_1 |N^2 S_S \tfrac{1}{2}^+\rangle + c_2 |N^2 S'_S \tfrac{1}{2}^+\rangle + c_3 |N^4 D_M \tfrac{1}{2}^+\rangle + c_4 |N^2 S_M \tfrac{1}{2}^+\rangle + c_5 |N^2 P_A \tfrac{1}{2}^+\rangle
\end{aligned}
$$

Coupled-channels (EBAC)

cf. Talks by Hiroyuki Kamano, Turo Sato, & Bruno Julia-Diaz

Schematically, in each partial wave, the MSL model solves

$$t_{MB,M'B'}(E;k,k') = v_{MB,M'B'}(k,k') + \sum_{\alpha} \int_0^{\infty} dk'' v_{MB,\alpha}(k,k'') G_{\alpha}(E,k'') t_{\alpha,M'B'}(E;k'',k')$$

$$t^R_{MB,M'B'}(E) = \sum_{N^*_i,N^*_j} \bar{\Gamma}_{MB\to N^*_i}(E) \frac{1}{(E - M^0_{N^*_i})\delta_{i,j} - \bar{\Sigma}_{ij}(E)} \bar{\Gamma}_{N^*_j\to M'B'}(E)$$

$$\bar{\Gamma}_{MB\to N^*}(E) = \Gamma_{MB\to N^*} + \sum_{M'B'} t_{MB,M'B'}(E) G_{M'B'}(E) \Gamma_{M'B'\to N^*}$$

$$\bar{\Sigma}_{ij}(E) = \sum_{MB} \Gamma_{N^*_i\to MB} G_{MB}(E) \bar{\Gamma}_{MB\to N^*_j}$$

Models

- Ingredients (N*s)
- Adjustable parameters
- Model / data comparisons
- Reaction mechanism

Model for $\pi^- p \to MB \to \eta n$; $W \leq 1.8$ GeV

- $MB \equiv \pi N,\ \eta N,\ \pi\Delta,\ \sigma N,\ \rho N$
- 9 N^* : $S_{11}(1535),\ S_{11}(1650),\ P_{11}(1440),\ P_{11}(1710),\ P_{13}(1720),$

  $D_{13}(1520),\ D_{13}(1700),\ D_{15}(1675),\ F_{15}(1680)$

Adjustable Parameters :

- Background terms : 2 parameters

  $g_{\eta NN}$
  $V_{\eta NN} \in [600; 1200]$ MeV

- N^*s : 3 parameters per resonance

  $M_{N^*} \in [M - 20MeV; M + 20MeV]$
  $g_{\eta NN^*}$
  Λ

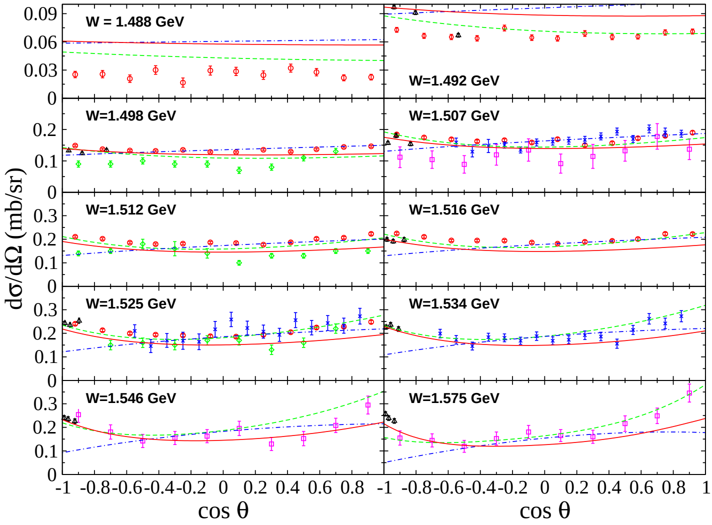
Total of 29 parameters.

Parameters for other intermediate states ($MB \equiv \pi N,\ ,\ \pi\Delta,\ \sigma N,\ \rho N$) fixed to their values determined by JLMS fitting $\pi N \to \pi N$)

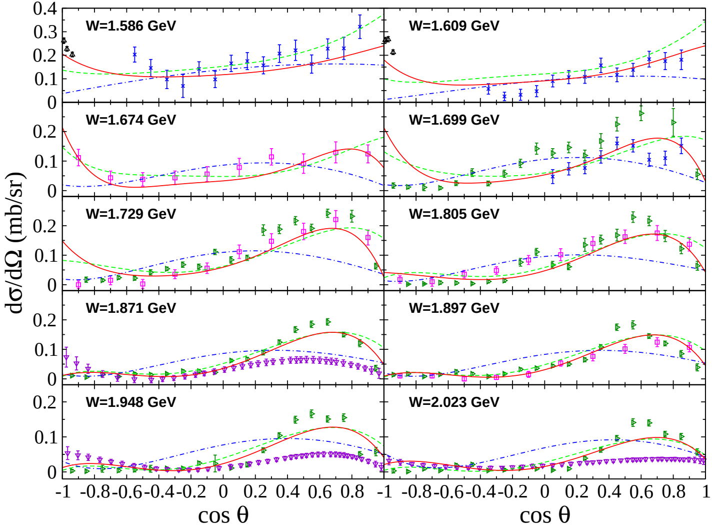
Data base : 255 $d\sigma/d\Omega$

$\chi^2_{pdp} = 2.32$; JLMS : $\chi^2_{pdp} = 6.94$

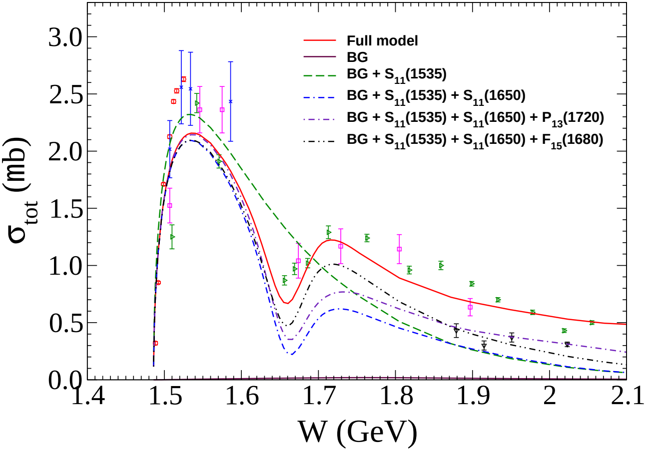
$d\sigma/d\Omega$ for $\pi^- p \to \eta n$



$d\sigma/d\Omega$ for $\pi^- p \to \eta n$



"Postdiction" : σ_{tot} for $\pi^- p \rightarrow \eta n$



Data :

Model for $\gamma p \rightarrow MB \rightarrow \eta p$; $W \leq 2.1$ GeV

- $MB \equiv \pi N, \eta N, \pi\Delta, \sigma N, \rho N$
- 12 N^* : $S_{11}(1535)$, $S_{11}(1650)$, $P_{11}(1440)$, $P_{11}(1710)$, $P_{13}(1720)$, $P_{13}(1900)$,
  $D_{13}(1520)$, $D_{13}(1700)$, $D_{15}(1675)$, $F_{15}(1680)$, $F_{15}(2000)$, $F_{17}(1990)$
- Higher mass $N^* > 2$ GeV : HM N^*
- 2 new N^* :

$$S_{11} : M = 1707 \text{ MeV}, \Gamma = 222 \text{ MeV}$$
$$D_{13} : M = 1950 \text{ MeV}, \Gamma = 139 \text{ MeV}$$

- No evidence for missing N^*s

Adjustable Parameters :

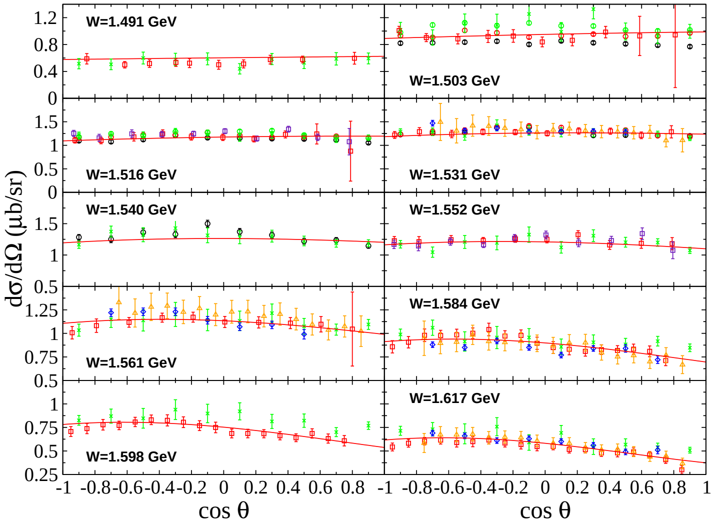
- $g_{\eta NN}$
- m_q : non-strange quarks average mass
- α : harmonic-oscillator strength
- α_s : QCD coupling constant
- Ω, Δ : confinement constants
- $C_{P_{13}}$: Strength of the P_{13}
- Higher mass N^* : 3 parameters (M, Γ, and C_{N^*})
- New N^*s : 3 parameters per new resonance (M, Γ, and C_{N^*})

Total of 10+9=19 parameters.

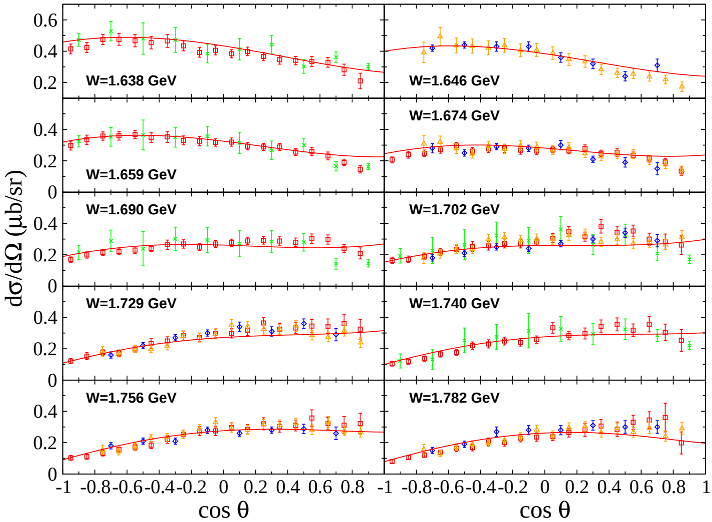
Data base : 751 $d\sigma/d\Omega$, 119 Σ

$\chi^2_{pdp} = 1.44$

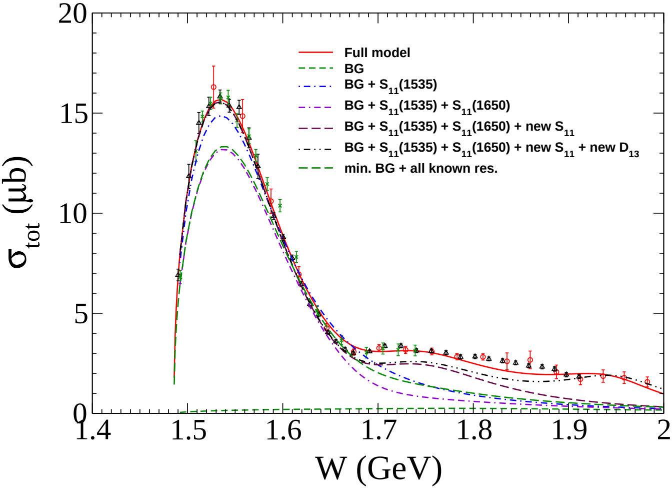
$d\sigma/d\Omega$ for $\gamma p \rightarrow \eta p$



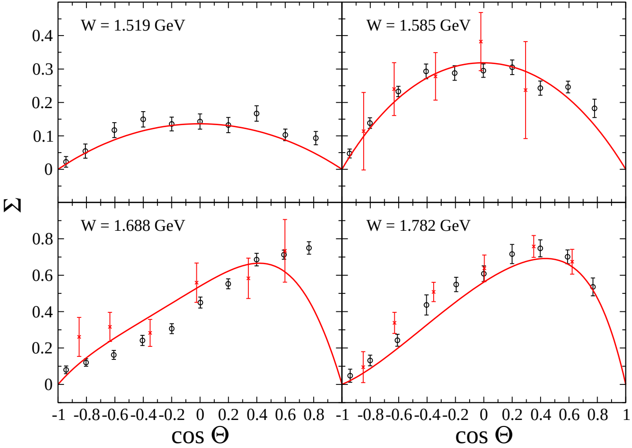
$d\sigma/d\Omega$ for $\gamma p \to \eta p$



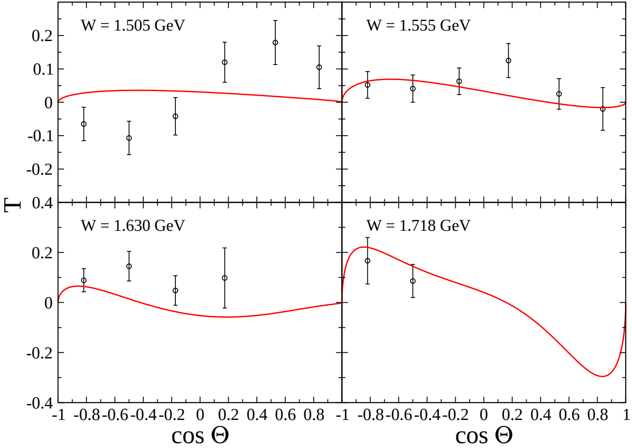
"Postdiction" : σ_{tot} for $\gamma p \rightarrow \eta p$



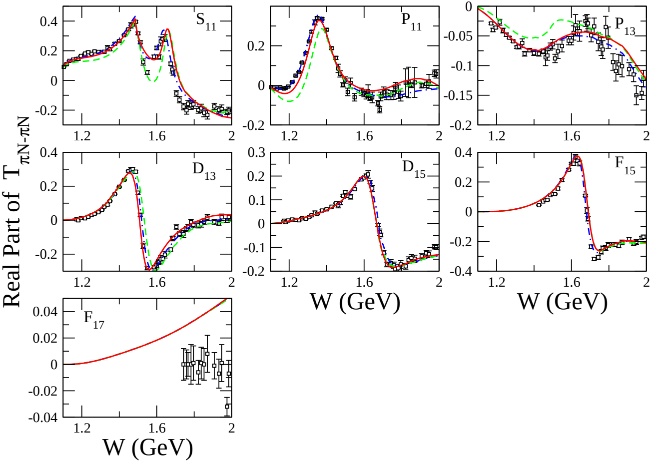
Σ for $\vec{\gamma}p \rightarrow \eta p$



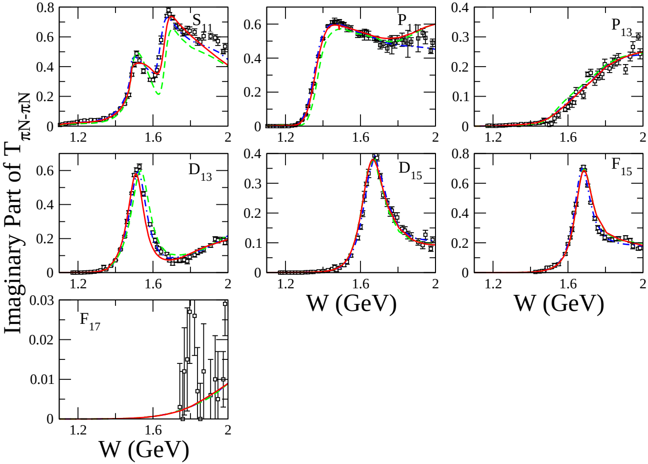
Prediction : T for $\gamma\vec{p} \rightarrow \eta p$



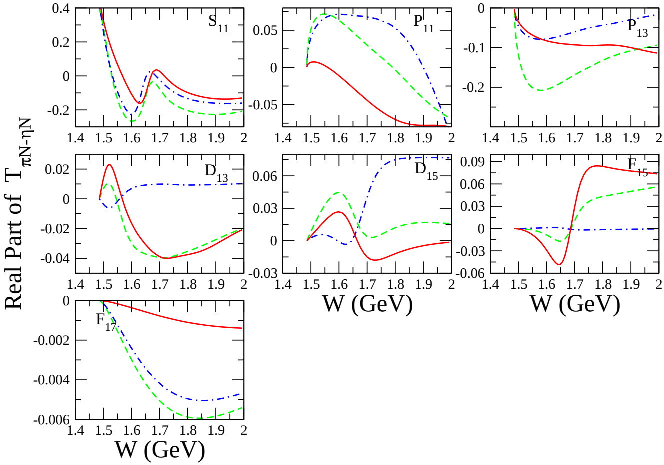
Real parts of the $\pi N \to \pi N$ T-matrices for isospin 1/2 partial waves



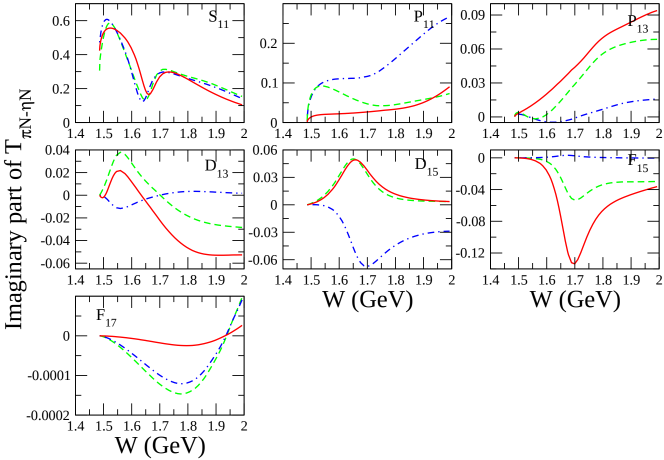
Imaginary parts of the $\pi N \to \pi N$ T-matrices for isospin 1/2 partial waves



Real parts of the $\pi N \rightarrow \eta N$ T-matrices for isospin 1/2 partial waves



Imaginary parts of the $\pi N \to \eta N$ T-matrices for isospin 1/2 partial waves



Concluding remarks

- EBAC's Dynamical coupled-channels apprach complemented with a CQM
- Reasonable agreement with data for both strong and electromagnetic initial states for $W \lesssim 2$ GeV
- Reaction mechanisms dominated by : $S_{11}(1535)$, $S_{11}(1650)$, $P_{13}(1720)$, $D_{13}(1520)$, $F_{15}(1680)$
- S_{11} : M = 1707 MeV, Γ= 222 MeV ; D_{13} : M=1950 MeV, Γ = 139 MeV

Forthcoming improvements :

- Extension of the CQM to $n \leq 6$-shell $\rightarrow$ $W \leq 2.5$ GeV for $\gamma p \rightarrow \eta p$
  He, Li, Saghai, Zhao, *in preparation*
- extend the EBAC approach to $\pi\pi N$ channel
  Kamano, Julia-Diaz, Lee, Matsuyama, Sato, PR C79, 025206 (2009)
- Embody the $\pi\pi N$ channel in the $\pi N \rightarrow MB \rightarrow \pi N$ code
- Go back to $\gamma p \rightarrow MB \rightarrow \eta p$

Data :

- Badly missing $\pi N \rightarrow \eta N$
- Double polarization $\vec{\gamma}\vec{p} \rightarrow \eta p$ measurements at ELSA and JLab

Thank you for your attention !