η photoproduction off the deuteron and low-energy η-nucleon interaction

Phys. Rev. C **96**, 042201(R) (2017)

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Collaborators : H. Kamano (RCNP), T. Ishikawa (Tohoku Univ.)

Introduction

ηN scattering length ($a_{\eta N}$)

$$S_{\eta N \to \eta N} = \eta e^{2i\delta} = 1 + 2iF_{\eta N} \qquad F_{\eta N} \approx \frac{p}{\frac{1}{a} + \frac{r}{2}p^2 - ip}$$

a : scattering length

r : effective range

- Governs low-energy behavior of ηN scattering
  → basic feature of meson-baryon dynamics (as with πN scattering)
- Important relevance to the existence of η-mesic nuclei

ηN scattering length ($a_{\eta N}$)

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B.E. of various η-mesic nuclei from theoretical calculations

Nucleus	Nuclear Form Factor [37]	$E - i\Gamma/2$ (MeV)		
		BL model		GW model
		$\overline{a}_{\eta N} = 0.23 + i0.09$	$a_{\eta N} = 0.28 + i0.19$	$\overline{a}_{\eta N} = 0.48 + i0.08$
^{3}He	Hollow exponential	–	–	–
^{4}He	3-parameter Fermi	–	–	$-(6.02 + i3.37)$
^{6}Li	Modified harmonic well	–	–	$-(3.58 + i2.05)$
^{9}Be	Harmonic well	–	–	$-(12.55 + i3.72)$
^{10}B	Harmonic well	$-(0.50 + i2.72)$	$-(0.93 + i8.70)$	$-(14.37 + i3.84)$
^{12}C	Harmonic well	$-(1.71 + i3.51)$	$-(2.91 + i10.22)$	$-(17.71 + i4.07)$
^{16}O	Harmonic well	$-(3.44 + i4.24)$	$-(5.42 + i11.43)$	$-(21.02 + i4.19)$
^{26}Mg	2-parameter Fermi	$-(7.75 + i5.89)$	$-(11.24 + i14.76)$	$-(30.07 + i4.89)$

Q. Haider and L. Liu, Int.J.Mod.Phys. E24 1530009 (2015)

ηN scattering length ($a_{\eta N}$)

$$S_{\eta N\to\eta N} = \eta e^{2i\delta} = 1 + 2iF_{\eta N} \qquad F_{\eta N} \approx \frac{p}{\frac{1}{a}+\frac{r}{2}p^2 - ip}$$

a : scattering length

r : effective range

But not well-determined yet

Current status

- Several coupled-channels analyses of $\pi N \to \pi N$ and $\pi N \to \eta N$ data

  Re[$a_{\eta N}$] = $0.2 \sim 1.1$ fm

  Im[$a_{\eta N}$] = $0.2 \sim 0.3$ fm (optical theorem)

- $pn \to d\eta$ data (WASA/PROMICE@COSY) Eur. Phys. J. A 38, 209 (2008)

  Re[$a_{\eta N}$] = $0.4 \sim 0.6$ fm

$a_{\eta N}$ has been extracted from indirect information → model dependence

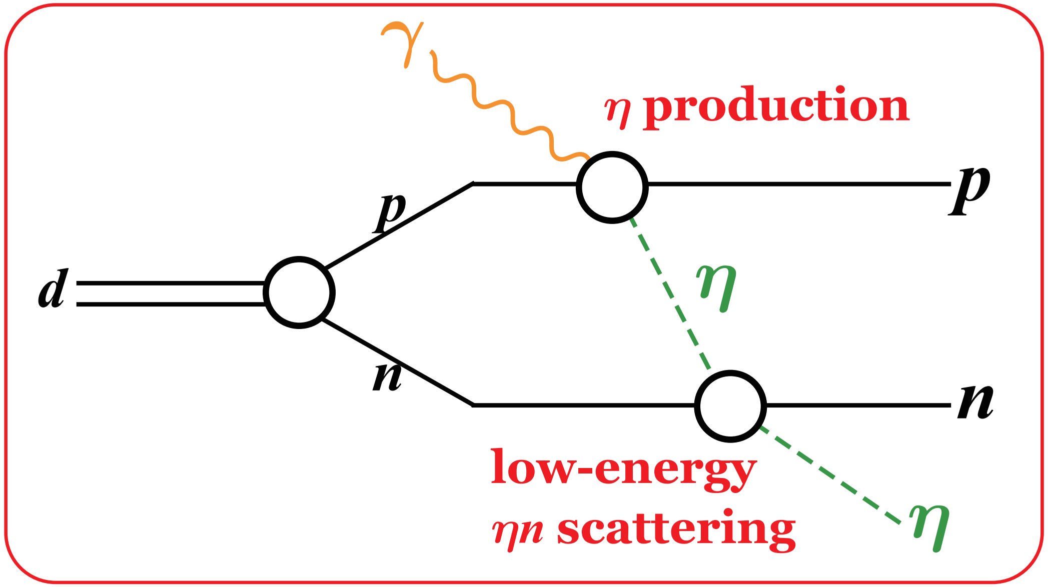
Need process that sensitively probes $\eta N \to \eta N$, with other mechanisms suppressed

Ongoing experiment at ELPH@Tohoku Univ.

$\gamma d \rightarrow \eta n p$ at $E_\gamma \sim 0.95$ GeV and proton detected at 0° (ELPH kinematics)

An ideal kinematical setting for extracting ηN scattering length

- η is produced almost at rest ➔ strong $\eta n \rightarrow \eta n$ rescattering is expected
- $\pi n \rightarrow \eta n$ and NN rescatterings (background) are expected to be suppressed



Data still need to be analyzed with reliable model to extract $a_{\eta N}$

Dynamical Coupled-Channels (DCC) model for meson productions

Kamano, SXN, Lee, Sato, PRC 88, 035209 (2013)
PRC 94, 015201 (2016)

Developed through fully combined analysis of $\gamma N, \pi N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ data, W < 2.1 GeV

→ Ideal building block of $\gamma d \rightarrow \eta\, n\, p$ reaction model for extracting $a_{\eta N}$ from ELPH data

This talk

- Explanation on the DCC model
- $\gamma d \rightarrow \eta\, n\, p$ reaction model based on the DCC model
- Demonstrate model prediction agrees well with $\gamma d \rightarrow \eta\, n\, p$ data
- Predict $\gamma d \rightarrow \eta\, n\, p$ cross sections at ELPH kinematics
- Study sensitivity of ELPH exp. to $a_{\eta N}$ and $r_{\eta N}$

Dynamical Coupled-Channels model for meson productions

DCC (Dynamical Coupled-Channel) model

Matsuyama et al., Phys. Rep. **439**, 193 (2007)

Kamano et al., PRC 88, 035209 (2013)

Coupled-channel Lippmann-Schwinger equation for meson-baryon scattering

$$T_{ab} = V_{ab} + \sum_c V_{ac} G_c T_{cb}$$

$$\{a, b, c\} = \pi N, \ \eta N, \ \pi\pi N, \pi\Delta, \sigma N, \rho N, \ K\Lambda, \ K\Sigma$$

By solving the LS equation, coupled-channel unitarity is fully taken into account

Both on- and off-shell amplitudes are calculated

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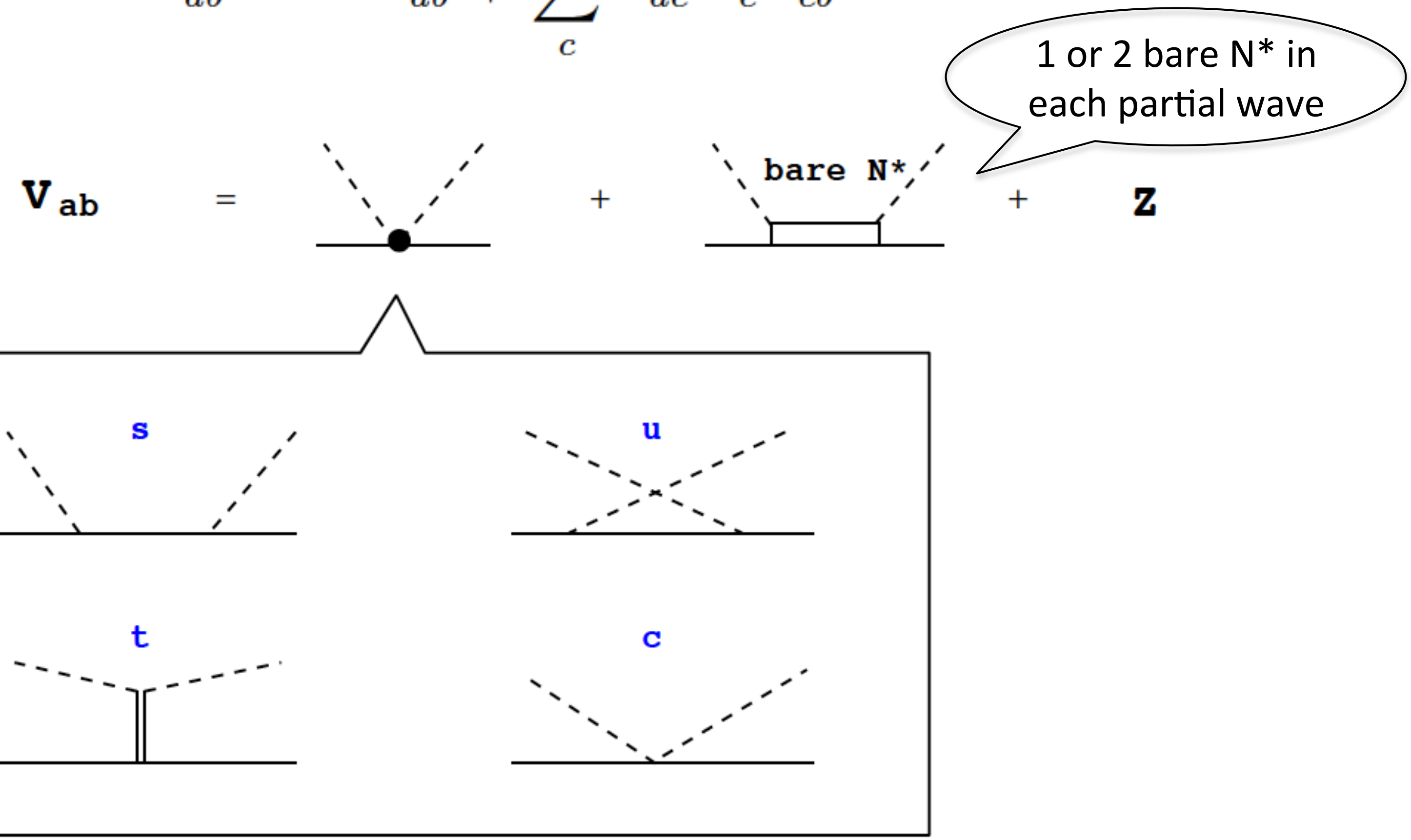

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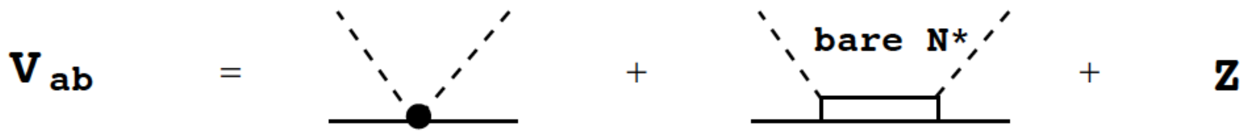
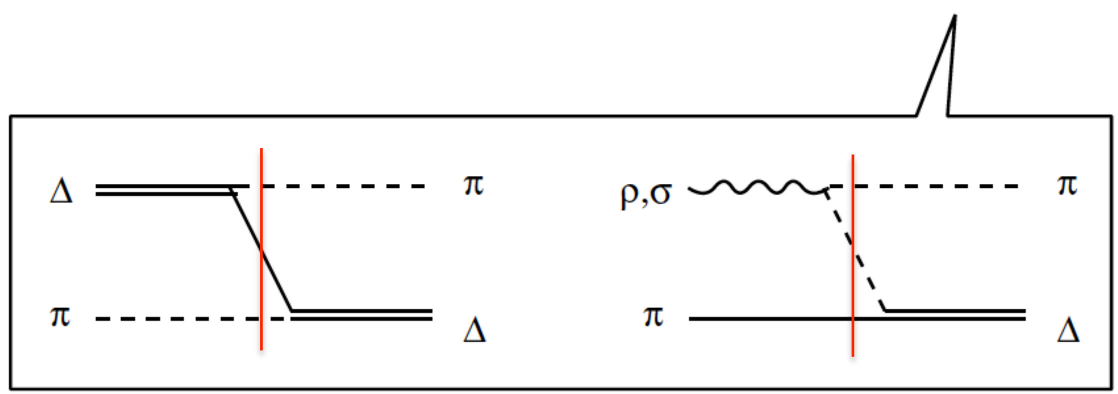


essential for three-body unitarity



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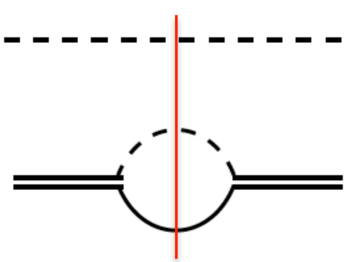
Coupled-channel Lippmann-Schwinger equation for meson-baryon scattering

$$T_{ab} = V_{ab} + \sum_{c} V_{ac}\, G_c\, T_{cb}$$

$G\,c$ =

for stable channels



for unstable channels

DCC (Dynamical Coupled-Channel) model

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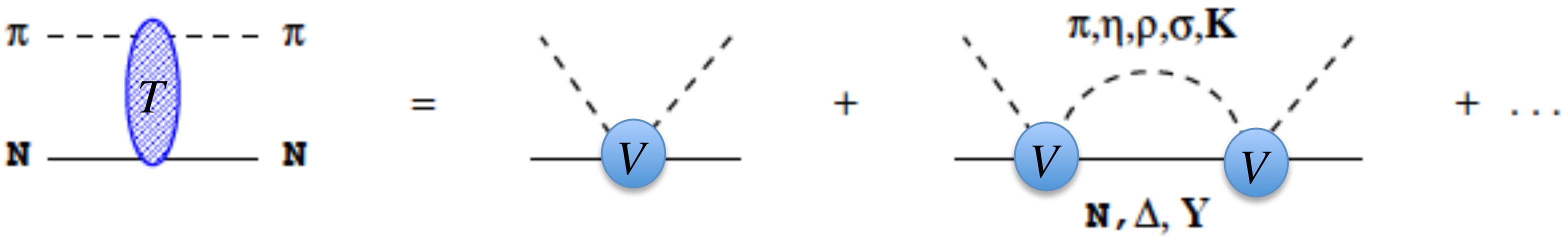
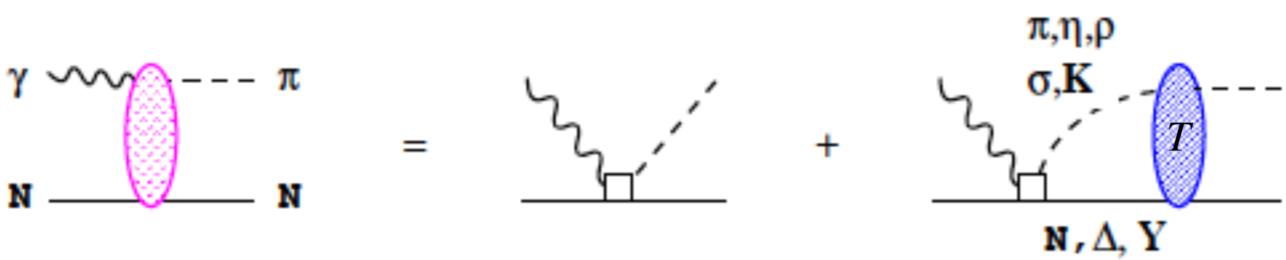
Kamano et al., PRC 88, 035209 (2013)

Coupled-channel Lippmann-Schwinger equation for meson-baryon scattering

$$T_{ab} \quad = \quad V_{ab} + \sum_{c} V_{ac}\, G_c\, T_{cb}$$



In addition, γN channels are included perturbatively



DCC analysis of meson production data

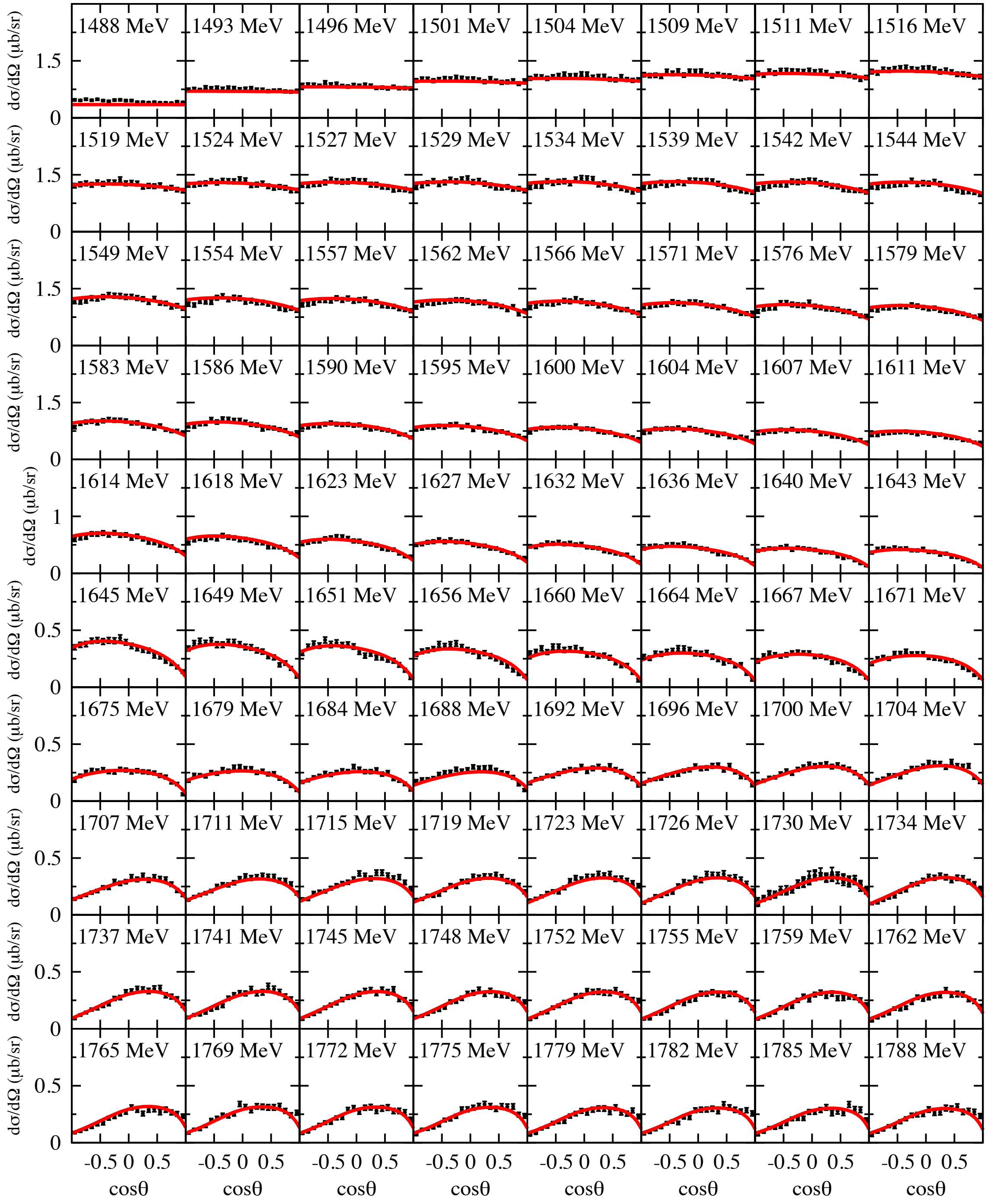
Kamano, Nakamura, Lee, Sato, PRC 88 (2013)
PRC 94 (2016)

Fully combined analysis of $\gamma N, \pi N$ ➔ $\pi N, \eta N, K\Lambda, K\Sigma$ data

$d\sigma / d\Omega$ and polarization observables (W ≤ 2.1 GeV)

~ 27,000 data points are fitted

by adjusting parameters (N^* mass, N^* ➔ MB couplings, cutoffs)



$\gamma p \rightarrow \eta p$

Kamano, Nakamura, Lee, Sato, PRC 88 (2013)

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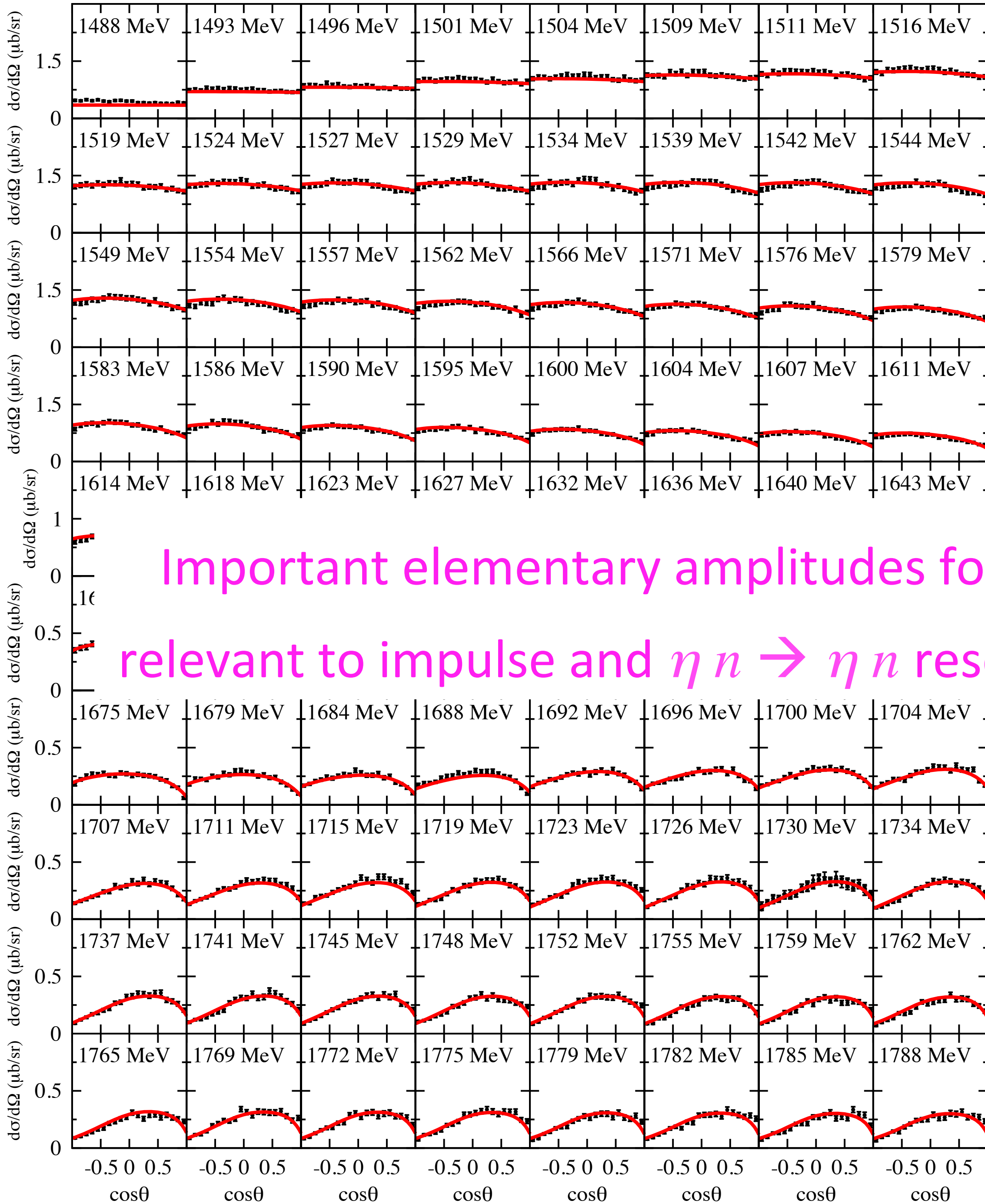


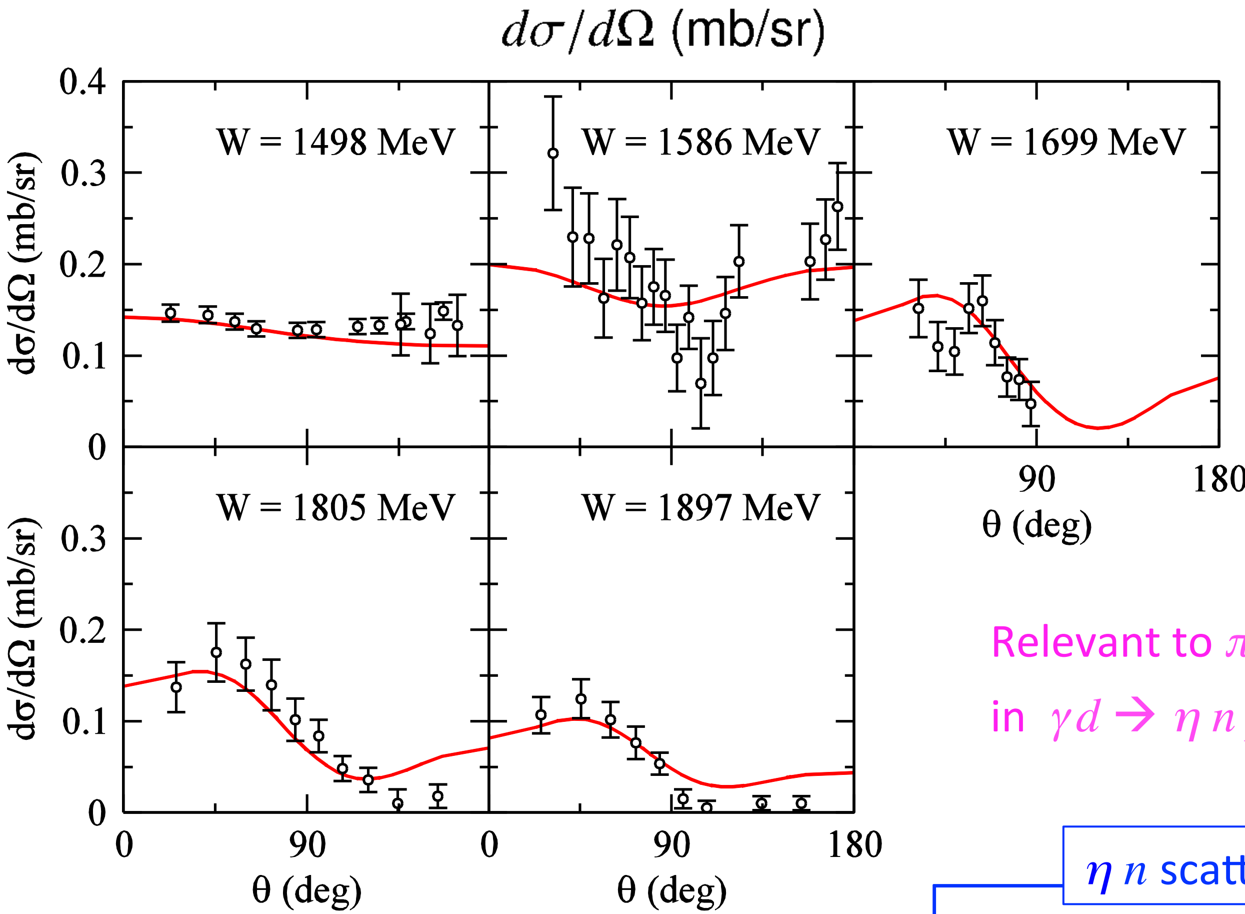
Important elementary amplitudes for $\gamma d \rightarrow \eta n p$ tested

relevant to impulse and $\eta n \rightarrow \eta n$ rescattering mechanisms

Eta production reactions

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

Database carefully selected in Durand et al. PRC (2008)



Relevant to $\pi n \to \eta n$ rescattering

in $\gamma d \to \eta n p$ reaction

Kamano, Nakamura, Lee, Sato, PRC 88 (2013)

ηn scattering parameters

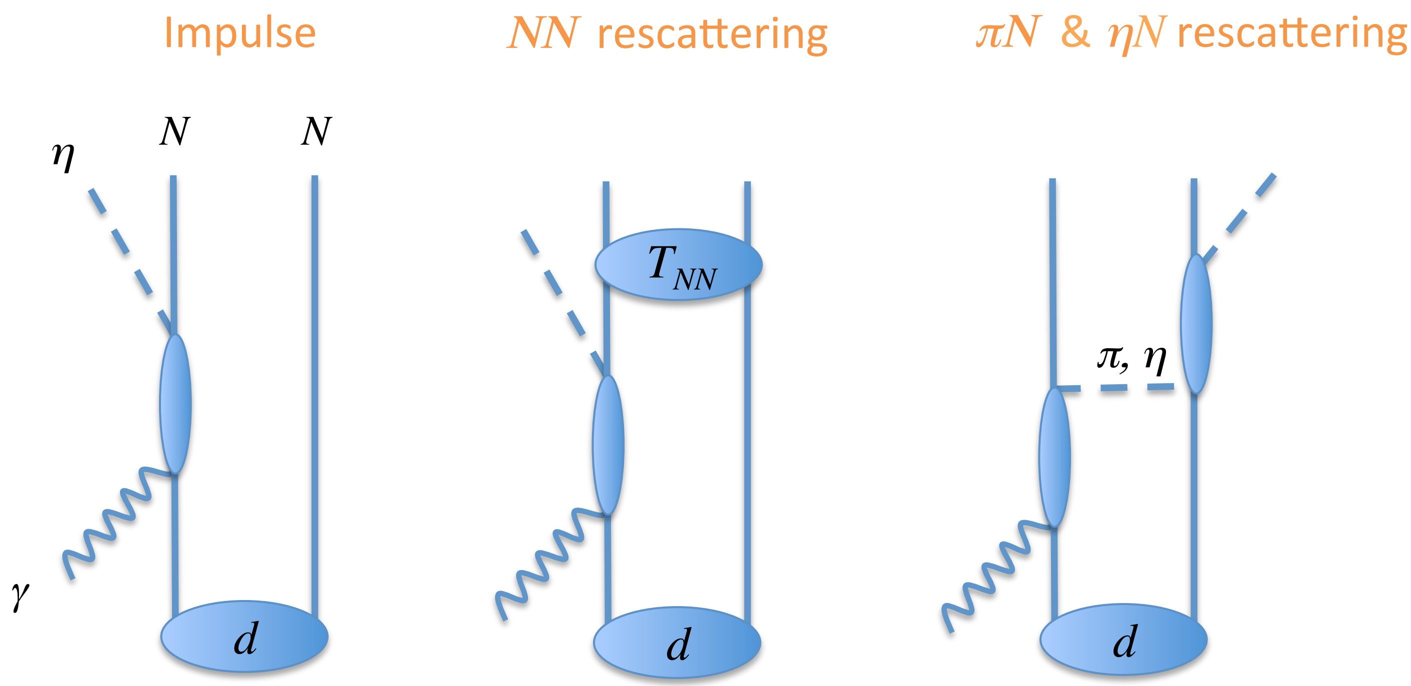
DCC (2016)

$$a_{\eta N} = 0.75 + 0.26\, i \ \text{fm}$$
$$r_{\eta N} = -1.6 - 0.6\, i \ \text{fm}$$

Application of DCC model to

$\gamma d \rightarrow \eta n p$ reaction

Model for $\gamma d \rightarrow \eta\, n\, p$



$\gamma N \rightarrow \pi N, \eta N$ amplitude ← DCC model

$\pi N, \eta N \rightarrow \eta N$ amplitude ← DCC model

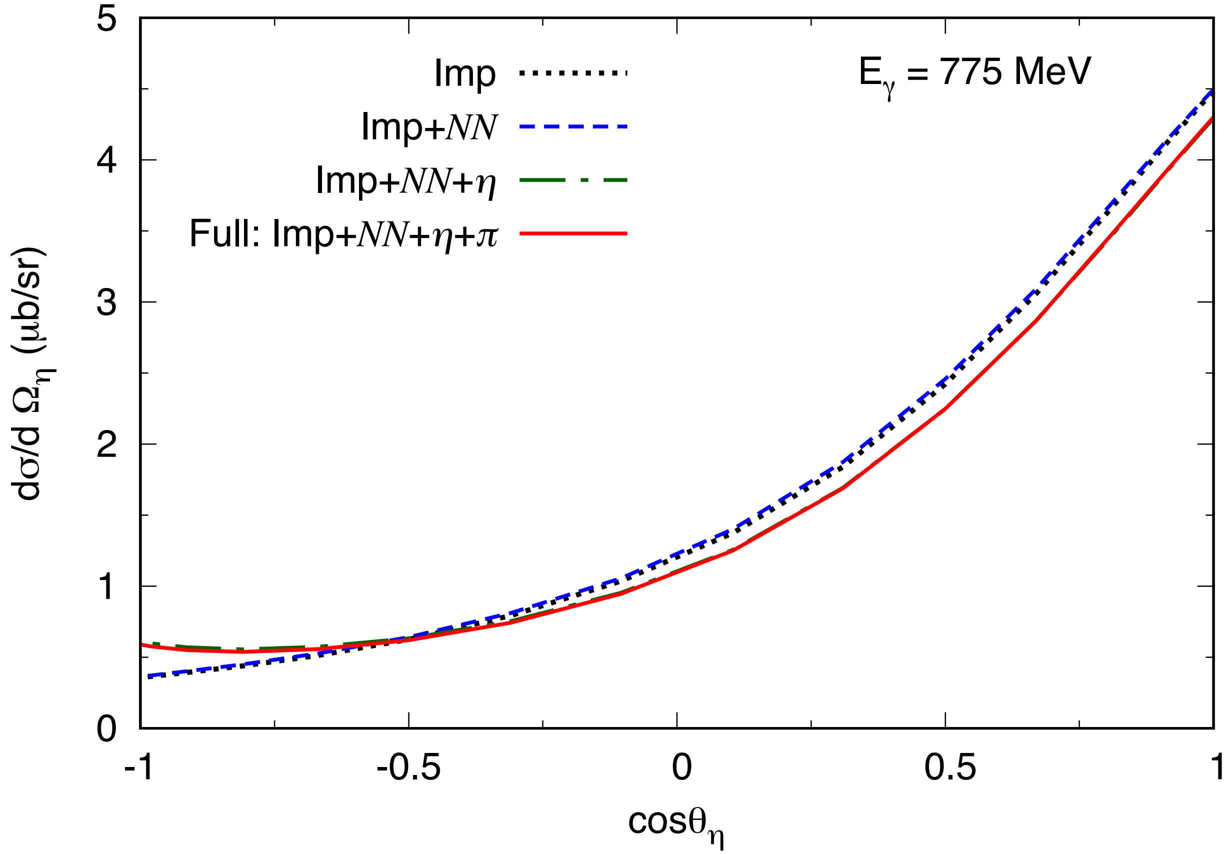
T_{NN}, deuteron w.f. ← CD-Bonn potential (PRC 63, 024001 (2001))

Off-shell effects are taken into account

Numerical results for $\gamma d \rightarrow \eta n p$

Comparison with data for η angular distribution in $\gamma d \to \eta X$

($\gamma d \to \eta d$ is small)

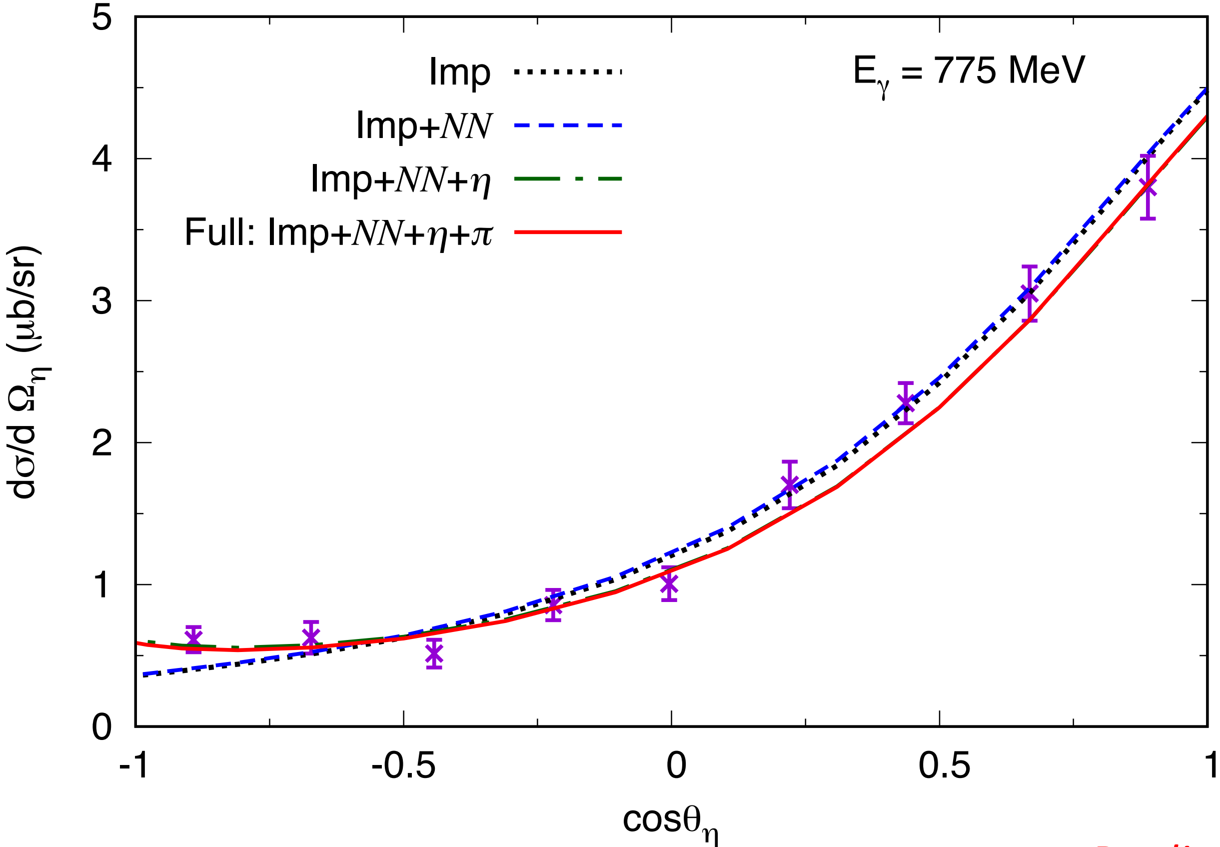


Mechanisms

- IA term dominates
- NN rescattering contribution is small
- η rescattering effect is not large but important

Comparison with data for η angular distribution in $\gamma d \to \eta X$

($\gamma d \to \eta d$ is small)



Data: Phys. Lett. B 358 40 (1995)

Mechanisms

- IA term dominates
- NN rescattering contribution is small
- η rescattering effect is not large but important

Prediction excellently agrees with data

- $\eta N \to \eta N$ rescattering is essential
- Soundness of model demonstrated !

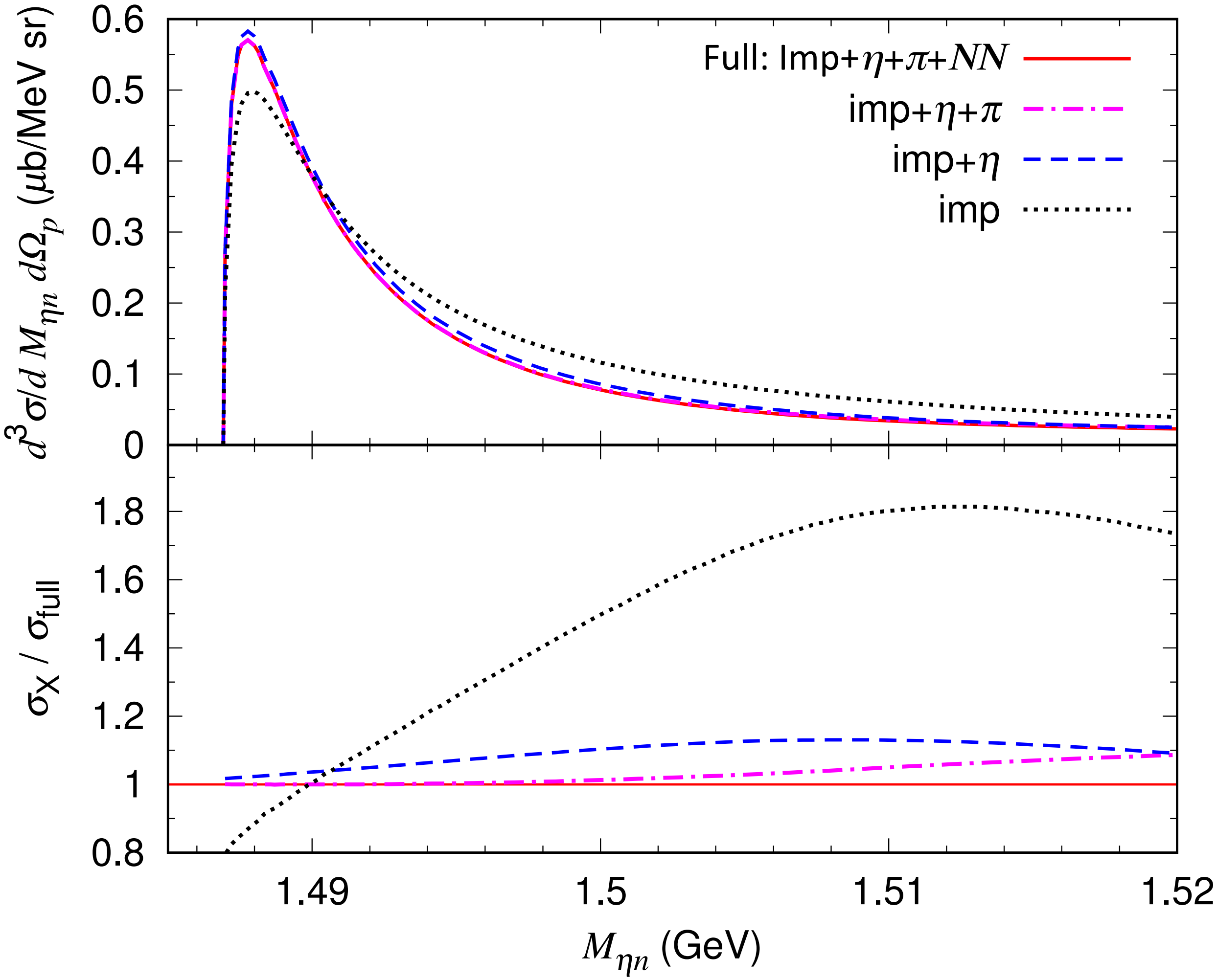
Numerical results for

$\gamma d \rightarrow \eta n p$ cross sections

at ELPH kinematics

$\gamma d \rightarrow \eta\, n\, p$ at ELPH kinematics

E_γ = 950 MeV, $\theta_p \sim 0^{o}$



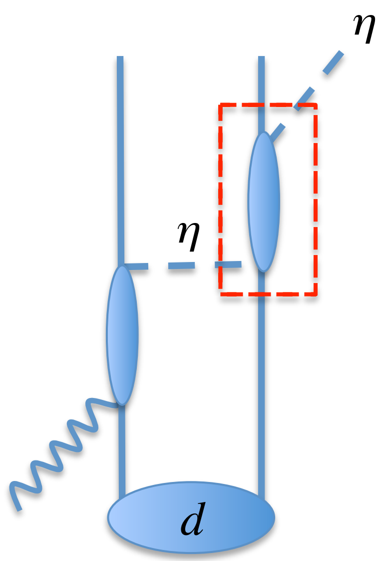
- η production suppressed for $M_{\eta\, n} \gtrsim$ 1.5 GeV ← deuteron wave function
- Impulse current dominates
- $\eta\, n$ rescattering (~ s-wave) gives sizable (−40% ~ +20%) contribution
- Small $\pi N \rightarrow \eta N$ rescattering → controllable contribution (data exist)

- NN rescattering negligible for $M_{\eta\, n}$< 1.5 GeV → more multiple rescattering negligible

→ Data for $M_{\eta\, n}$< 1.5 GeV will be useful to study $\eta N \rightarrow \eta N$ scattering

Study sensitivity of $\gamma d \rightarrow \eta n p$ to $a_{\eta N}$ and $r_{\eta N}$

ηN rescattering

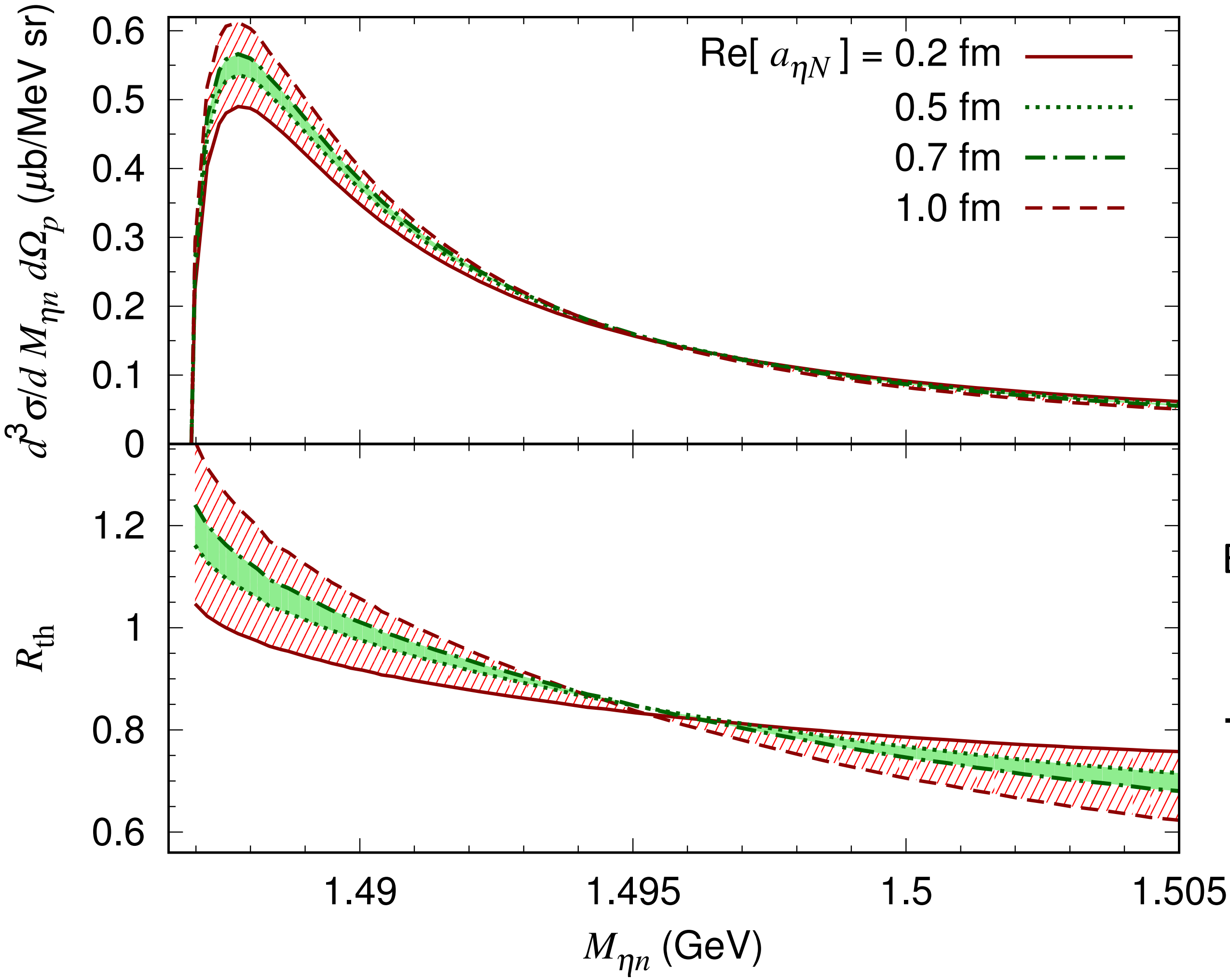


DCC amplitude → $T_{\eta N \to \eta N} \propto \dfrac{1}{\dfrac{1}{a_{\eta N}} + \dfrac{r_{\eta N}}{2} p^2 - ip}$

Vary $a_{\eta N}$ and $r_{\eta N}$

→ how sensitively $\gamma d \rightarrow \eta n p$ cross sections at ELPH kinematics change

Re[$a_{\eta N}$]-dependence of $\gamma d \to \eta\, n\, p$ at ELPH kinematics



E_γ = 950 MeV, $\theta_p \sim 0^{\rm o}$

$$R_{\rm th} \equiv \frac{d^3\sigma_{\rm full} / dM_{\eta n} d\Omega_p}{d^3\sigma_{\rm IA} / dM_{\eta n} d\Omega_p}$$

at ELPH kinematics

ELPH measures both

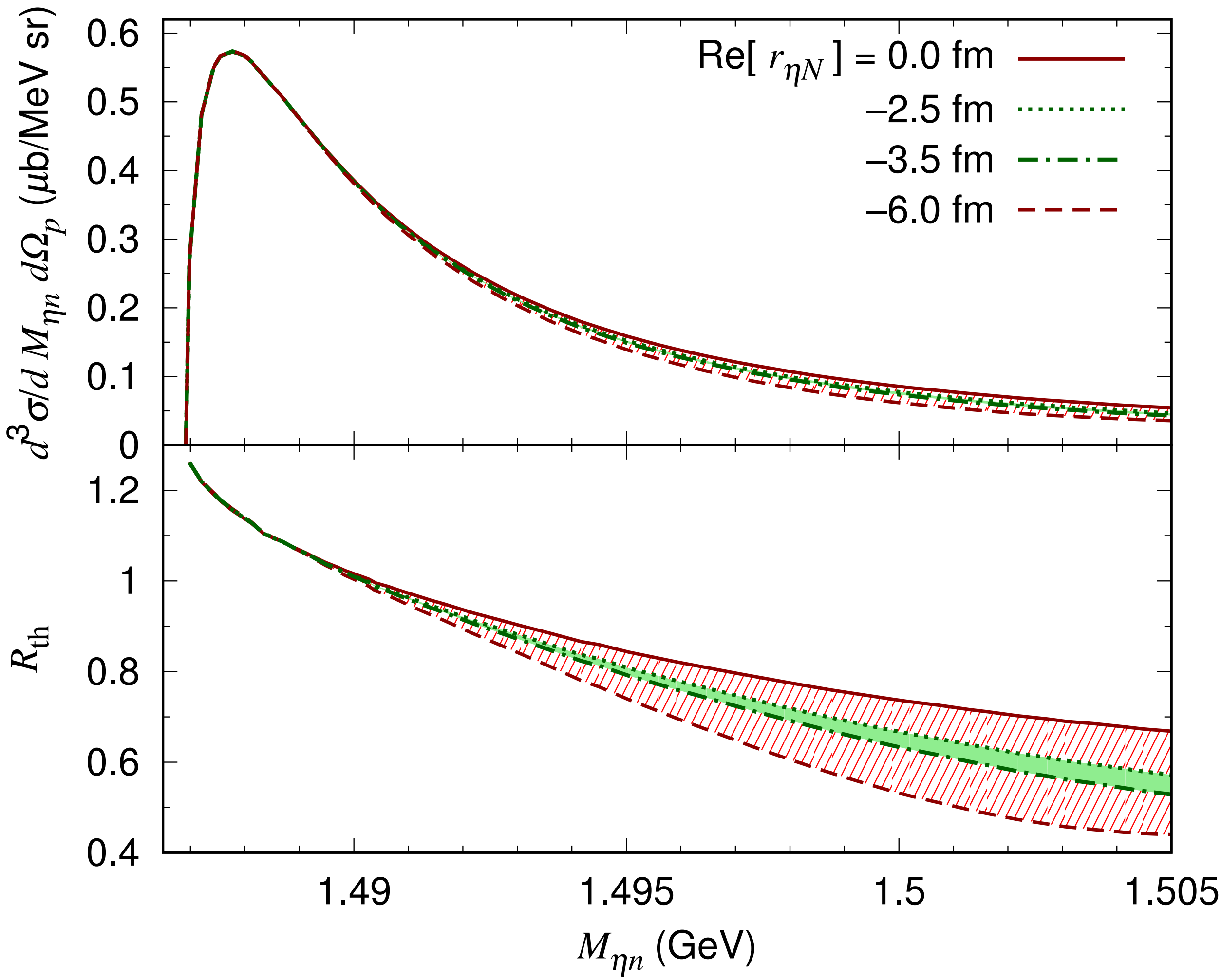
$\sigma(\gamma d \to \eta\, n\, p)$ & $\sigma(\gamma p \to \eta\, p)$

→ $R_{\rm exp}$ will be measured

$\gamma d \to \eta\, n\, p$ at ELPH exp. kinematics has a good sensitivity to Re[$a_{\eta N}$]

5% precision measurement of $R_{\rm exp}$ → Δ(Re[$a_{\eta N}$]) ~ 0.2 fm (current: Δ(Re[$a_{\eta N}$]) ≈ 1.3 fm)

Re[$r_{\eta N}$]-dependence of $\gamma d \to \eta\, n\, p$ at ELPH kinematics



E_γ = 950 MeV, $\theta_p \sim 0^{\rm o}$

$$R_{\rm th} \equiv \frac{d^3\sigma_{\rm full} \,/\, dM_{\eta n} d\Omega_p}{d^3\sigma_{\rm IA} \,/\, dM_{\eta n} d\Omega_p}$$

at ELPH kinematics

ELPH measures both

$\sigma(\gamma d \to \eta\, n\, p)$ & $\sigma(\gamma p \to \eta\, p)$

→ $R_{\rm exp}$ will be measured

$\gamma d \to \eta\, n\, p$ at ELPH exp. kinematics has sensitivity to Re[$r_{\eta N}$]

5% precision measurement of $R_{\rm exp}$ → Δ (Re[$r_{\eta N}$]) ~ 1 fm (current: Δ(Re[$r_{\eta N}$]) ≈ 7 fm)

Conclusion

Conclusion

✓ Dynamical coupled-channels (DCC) model applied to $\gamma d \to \eta n p$

* DCC model well reproduces $\gamma N,\ \pi N \to \pi N, \eta N, K\Lambda, K\Sigma$ data

* impulse, NN and meson-nucleon rescattering mechanisms considered

* $\gamma d \to \eta n p$ data are well reproduced for $E_\gamma = 700 \sim 800$ MeV

✓ $\gamma d \to \eta n p$ at ELPH kinematics studied with the DCC-based $\gamma d \to \eta n p$ model

* impulse dominates; $\gamma p \to \eta p$ elementary amplitude needs solid validation

* $\eta n \to \eta n$ rescattering effect is sizable (−40% ~ +20%) at low $M_{\eta n}$

* $\pi n \to \eta n$ effect is small and NN rescattering effect is negligible for $M_{\eta n} \lesssim 1.5$ GeV

* $\gamma d \to \eta n p$ at ELPH kinematics has good sensitivity
  to ηn scattering length & effective range

* 5% precision measurement of $R_{\exp}$ (achievable at ELPH exp.)
  → significantly narrowing down the currently estimated range of Re[$a_{\eta N}$] and Re[$r_{\eta N}$]

Thank you very much for your attention

Acknowledgments

- Financial support for this work

  FAPESP 2016/15618-8

  KAKENHI JP25105010

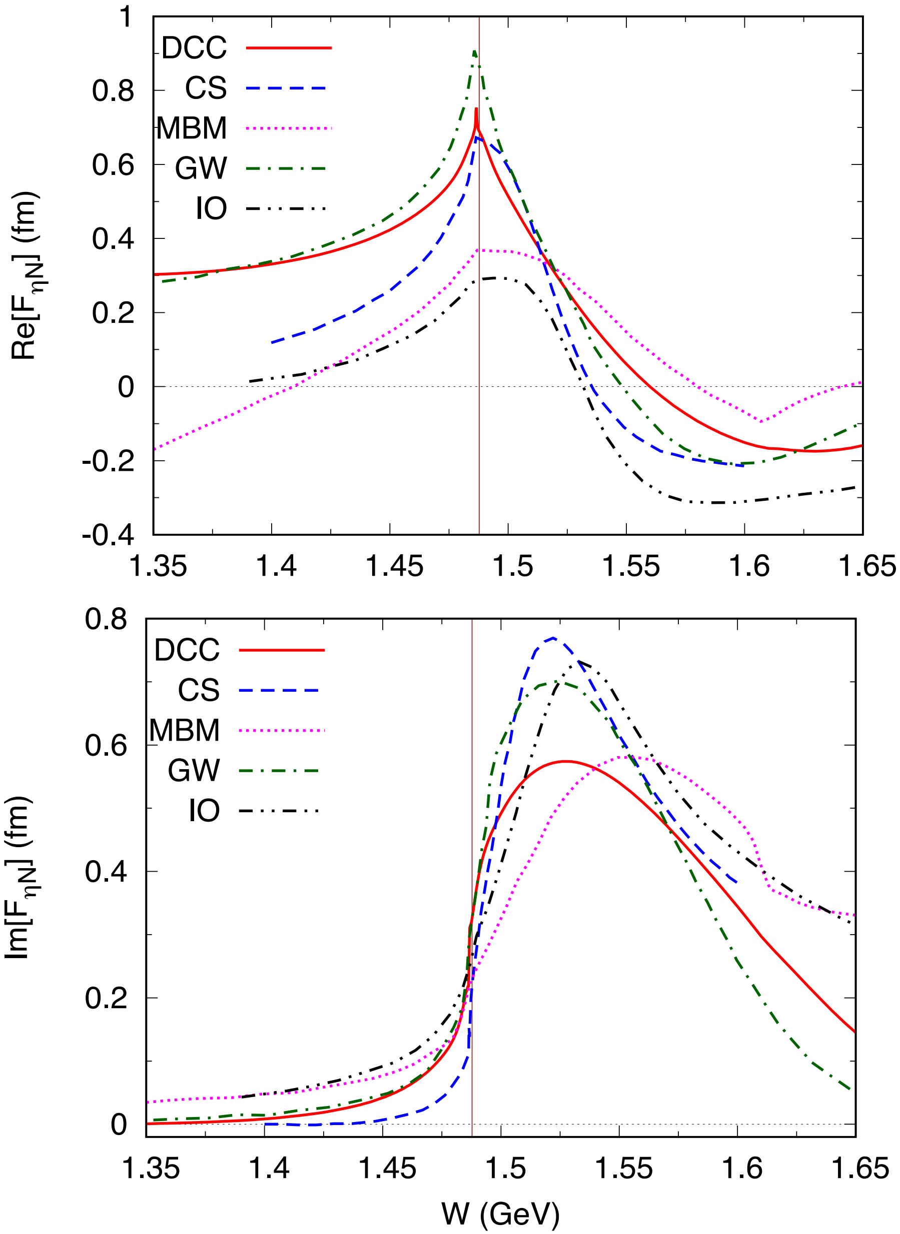
- Computing resource

  LCRC at Argonne National Lab

  NERSC

BACKUP

$\eta N \rightarrow \eta N$ S-wave amplitude



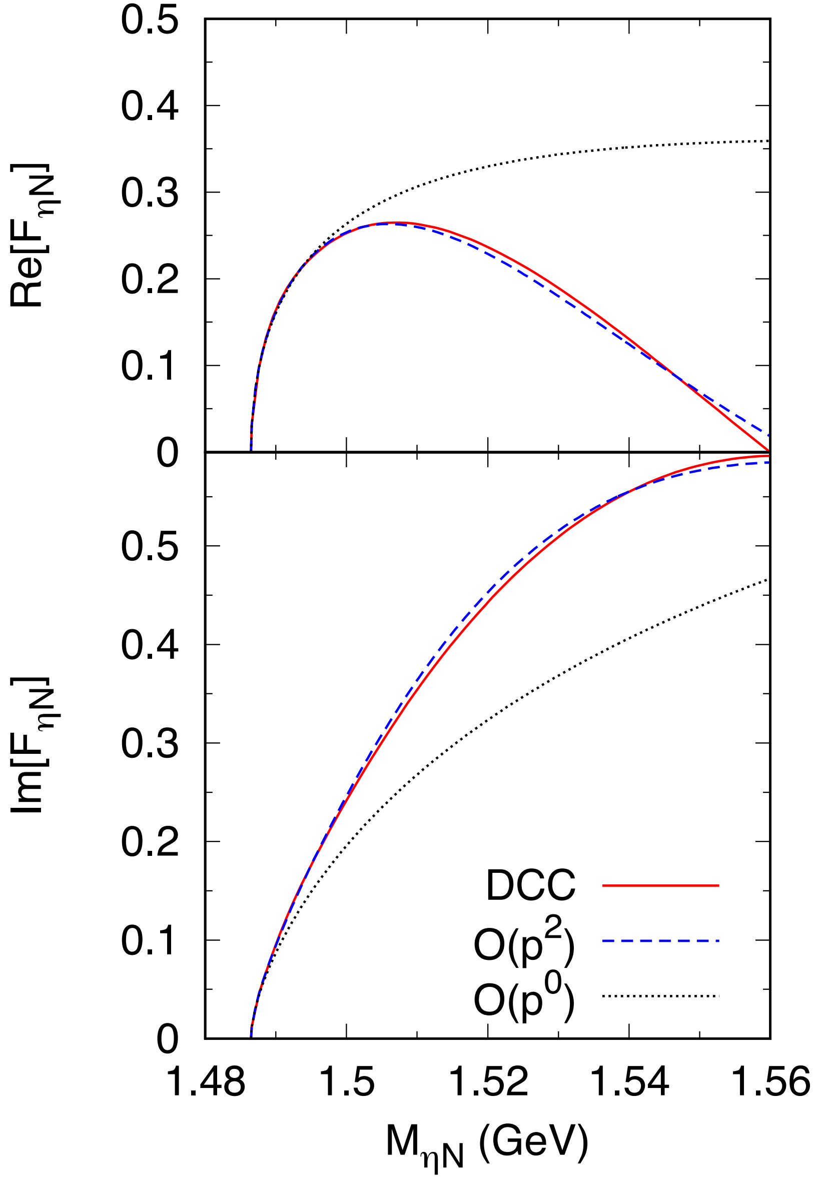
CS	Cieplý et al. NPA 919 (2013)
MBM	Mai et al. PRD 86 (2012)
GW	Green et al. PRC 71 (2005)
IO	Inoue et al. NPA 710 (2002)

- $\eta N \rightarrow \eta N$ S-wave amplitude is rather model dependent
- DCC analysis covered data much more extensive than the others
  → meson-baryon dynamics could be better constrained

DCC (2016)

$$a_{\eta N} = 0.75 + 0.32\, i$$
$$r_{\eta N} = -1.6 - 0.6\, i$$

$\eta\, n \rightarrow \eta\, n$ s-wave amplitude



Definition $S = \eta e^{2i\delta} = 1 + 2iF_{\eta N}$

Effective range expansion (ERE)

$$F_{\eta N} = \frac{p}{\frac{1}{a} + \frac{r}{2}p^2 - ip}$$

a : scattering length

r : effective range

$a = 0.7 + 0.3\,i$ fm

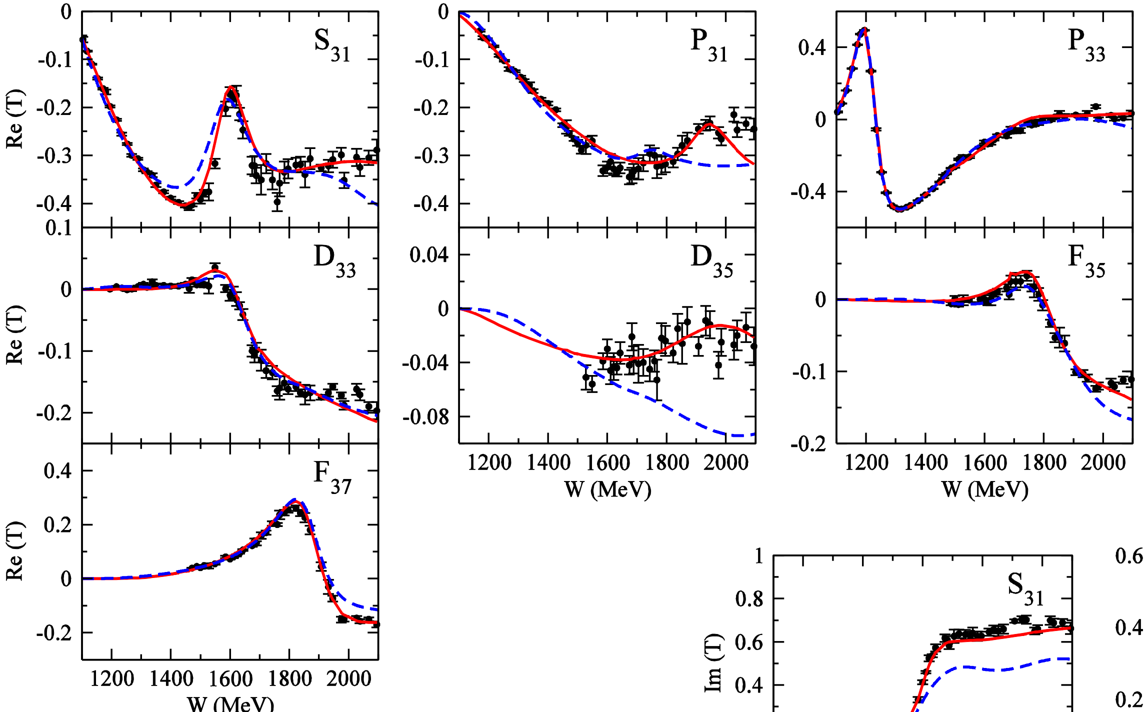
$r = -1.9 - 0.5\,i$ fm

(DCC model)

- ERE is valid for W $\lesssim$ 1550 MeV where $\eta\, n$ rescattering is important
- off-shell-ness of $\eta\, n \rightarrow \eta\, n$ s-wave amplitude turns out to be small effect on $\gamma d \rightarrow \eta\, n\, p$ at ELPH kinematics

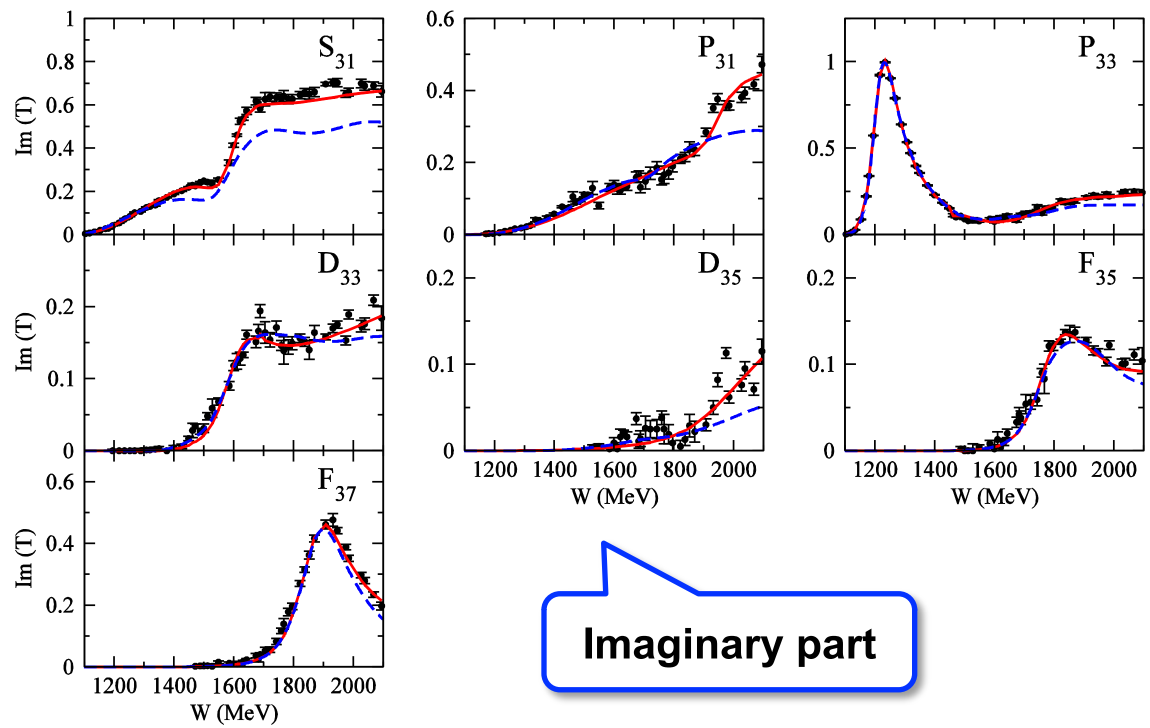
$\eta n \rightarrow \eta n$ amplitude in $\gamma d \rightarrow \eta\, n\, p$ can be replaced with ERE and study ER parameter dependence

Partial wave amplitudes of π N scattering



Real part

$$I = \frac{3}{2}$$



Imaginary part

Kamano, Nakamura, Lee, Sato, PRC 88 (2013)

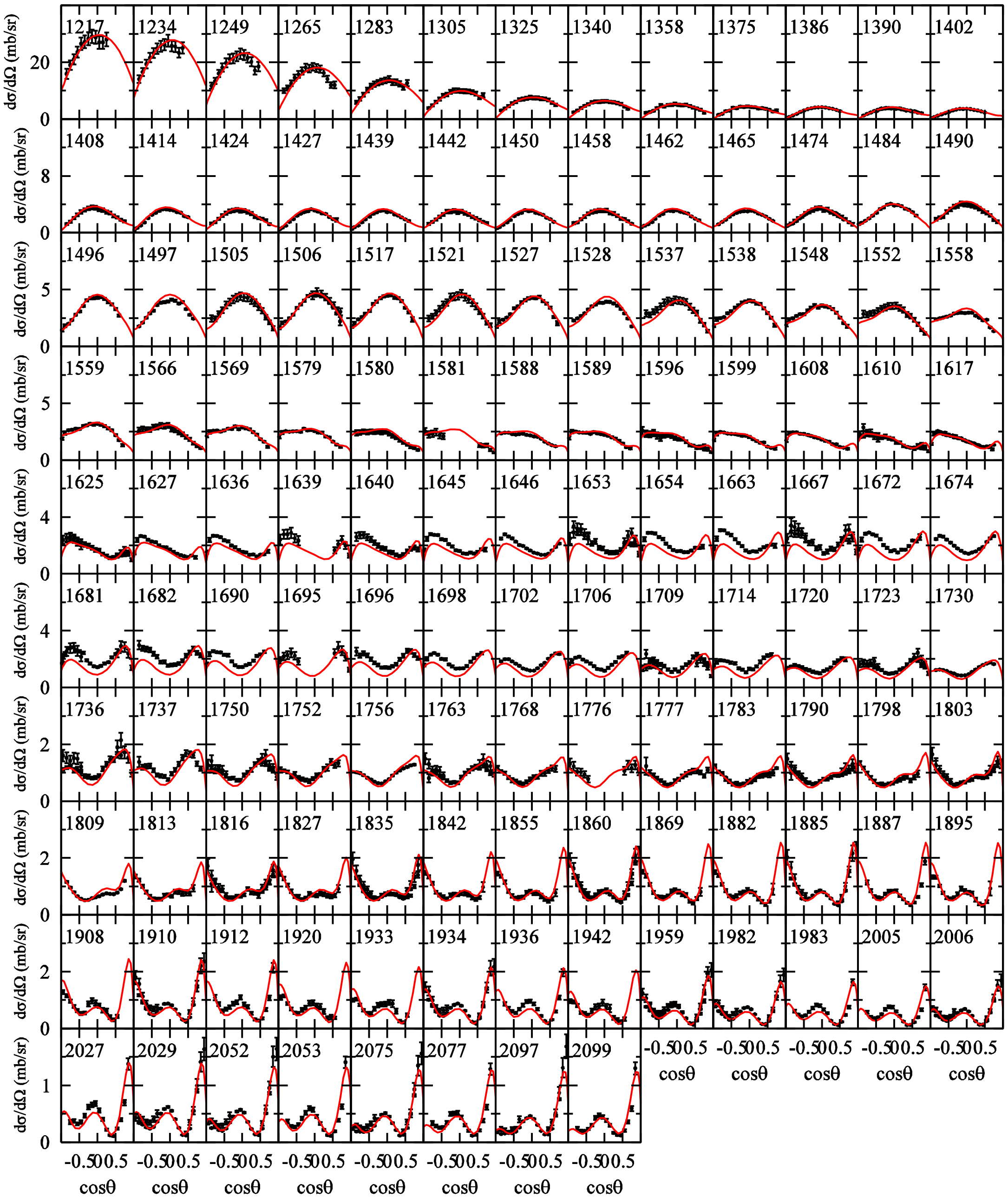
Previous model (fitted to πN → πN data only) [PRC76 065201 (2007)]

Data: SAID πN amplitude

γp → π^0p

dσ/dΩ for W < 2.1 GeV

Kamano, Nakamura, Lee, Sato, PRC 88 (2013)



- Relevant to π exchange mechanism in $\gamma d \to \eta n p$ reaction