重陽子標的によるη中間子光生成反応を介したη中間子-核子散乱Ｓ波有効レンジパラメータの精密決定

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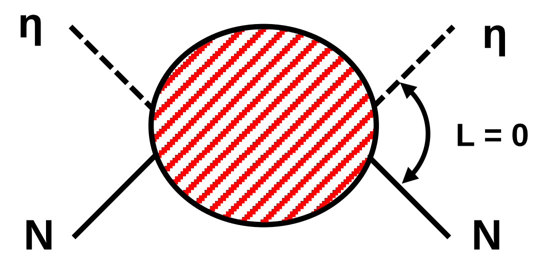
Introduction:
S-wave ηN effective range parameters

✓ **S-wave η-nucleon scattering amplitude [F = (S - 1)/(2ik)]:**

$$F^{l=0}_{\eta N}(k) = \frac{1}{k\cot\delta^{l=0}_{\eta N}(k) - ik}$$

k : magnitude of relative momentum in ηN c.m. frame.



✓ **effective range expansion:**

$$k\cot\delta^{l=0}_{\eta N}(k) = \frac{1}{a_{\eta N}} + r_{\eta N}\times\frac{k^2}{2} + O(k^4)$$

scattering length ($a_{\eta N}$) — effective range ($r_{\eta N}$)

- **A "measure" of attractive/repulsive nature of the S-wave interaction at k ~ 0.**
- **Total cross section at threshold = $4\pi a_{\eta N}^2$**

- **Roughly corresponds to the range of the S-wave interaction.**

Introduction: S-wave ηN effective range parameters

✓ **S-wave η-nucleon scattering amplitude [F = (S - 1)/(2ik)]:**

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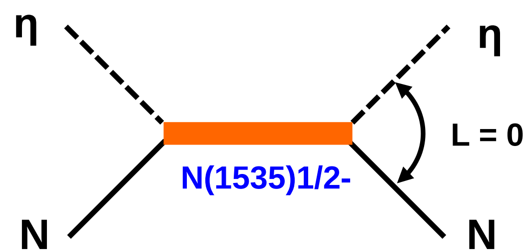
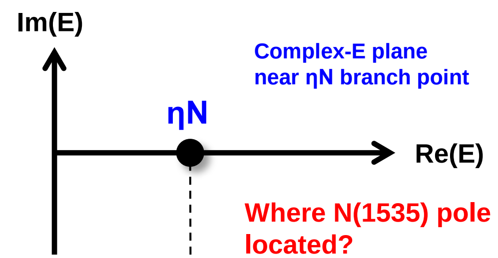


✓ **effective range expansion:**

$$k \cot \delta_{\eta N}^{l=0}(k) = \frac{1}{a_{\eta N}} + r_{\eta N} \times \frac{k^2}{2} + \mathcal{O}(k^4)$$

scattering length ($a_{\eta N}$)

effective range ($r_{\eta N}$)



- **Fundamental quantities of low energy QCD.**
  - ➔ η is regarded as a NG boson for spontaneous breaking of (approximate) chiral symmetry in the 3-flavor (u, d, s) sector (except for mixing from η_0)
- **Strong correlation with possible existence of η-mesic nuclei.**
- **Help precise determination of pole position of the N(1535)1/2$^-$ resonance.**

Introduction:
S-wave ηN effective range parameters

✓ η meson: unstable against the strong interaction & electrically neutral.

× Direct measurement of the ηN scattering

➔ Life time of η is too short to be used as incident beam.

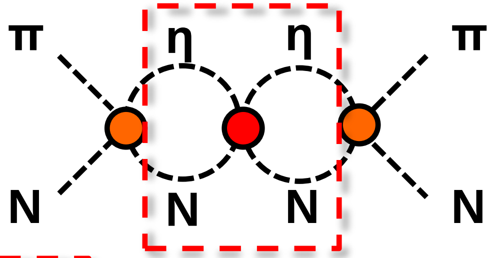
× X-ray measurements of eta-mesic atom

➔ η cannot be bound electromagnetically to form an atom.

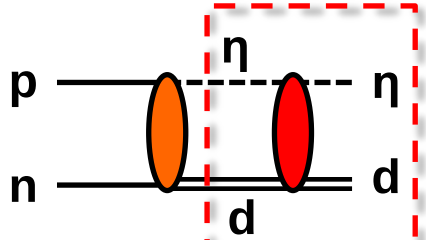
One has to rely on *indirect* information !!

e.g.)

- Analysis of πN→πN, πN→ηN, γN→πN, γN→ηN
  - ➔ ηN interaction appears through coupled-channel effects



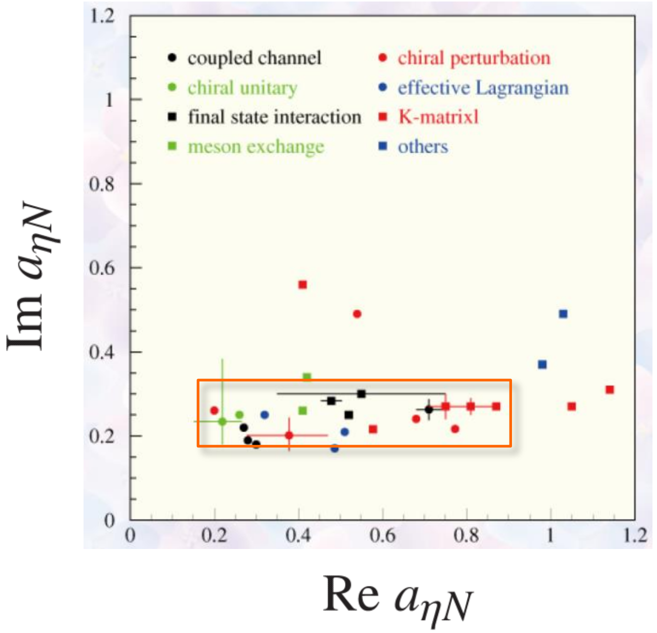
- Analysis of pn → ηd reaction
  - ➔ ηN interaction is embedded in strongly interacting final 3-body ηNN (ηd) system



Introduction:
S-wave ηN effective range parameters

S-wave effective range parameters scatter a lot !!

From Ishikawa-san's talk.



✓ **Scattering length $a_{\eta N}$**

- Re $a_{\eta N}$ ~ 0.2 – 0.9 fm ➔ Δ(Re $a_{\eta N}$) ~ 0.7 fm
- Im $a_{\eta N}$ ~ 0.2 – 0.3 fm ➔ Δ(Im $a_{\eta N}$) ~ 0.1 fm

Relatively small uncertainty in the imaginary part is due to the optical theorem.

✓ **Effective range $r_{\eta N}$**

- Re $r_{\eta N}$ ~ -6 – +1 fm ➔ Δ(Re $r_{\eta N}$) ~ 7 fm
- Im $r_{\eta N}$ ~ -1 – 0 fm ➔ Δ(Im $r_{\eta N}$) ~ 1 fm

c.f.) πN & NN cases:

πN scattering length:

$a^+ = (7.6 \pm 3.1) \cdot 10^{-3} M_\pi^{-1}$ **(isoscalar)**

$a^- = (86.1 \pm 0.9) \cdot 10^{-3} M_\pi^{-1}$ **(isovector)**

NN	a (fm)	r_0 (fm)
nn	-18.9 ± 0.4	2.75 ± 0.11
np	-23.740 ± 0.020	2.77 ± 0.05
pp	-17.3 ± 0.4	2.85 ± 0.04

Introduction:
S-wave ηN effective range parameters

S-wave effective range parameters scatter a lot !!

From Ishikawa-san's talk.

✓ **Clear separation of the ηN interaction from other reaction processes is essential !!**

Highly desirable to utilize reactions (& kinematics) in which

1) mechanisms associated with ηN interaction are significantly enhanced,

2) while other background mechanisms are suppressed.

$a^- = (86.1 \pm 0.9) \cdot 10^{-3} M_\pi^{-1}$ (isovector)

- **Im $r_{\eta N}$ ~ -1 – 0 fm** ➔ **Δ(Im $r_{\eta N}$) ~ 1 fm**

NN	a (fm)	r_0 (fm)
nn	-18.9 ± 0.4	2.75 ± 0.11
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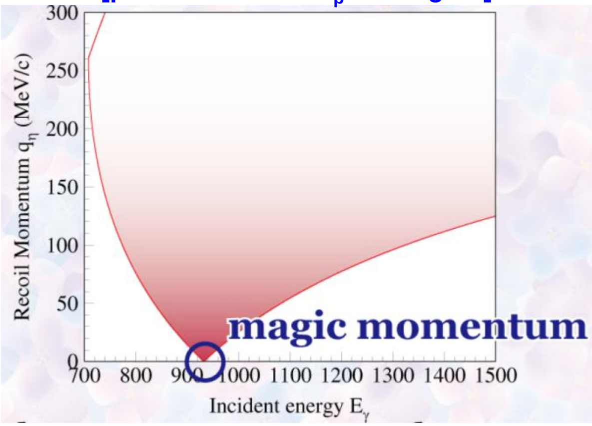
γd→ηpn reaction at the "ELPH kinematics"

✓ New measurement of γd→ηpn at ELPH, Tohoku Univ.
(T. Ishikawa et. al., the ELPH-2844 experiment)

➢ Consider a *special* kinematics with
E_γ ~ 940 MeV and θ_p ~ 0 degree.

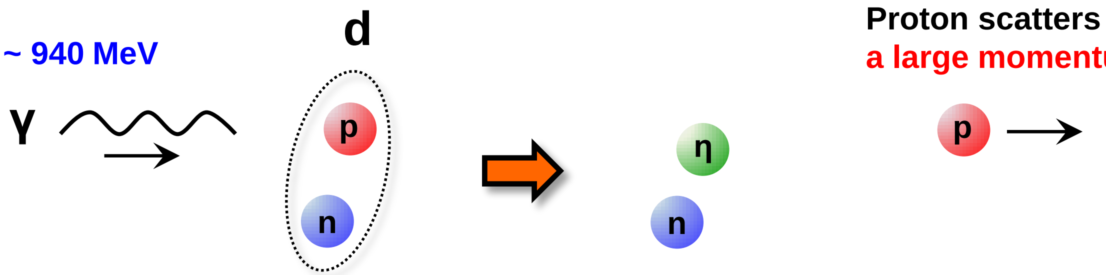
➔ refer to as the "ELPH kinematics"

η-momentum in γp→ηp (Lab frame)
[p is scattered at θ_p = 0 degree]



From Ishikawa-san's talk.

E_γ ~ 940 MeV



Proton scatters forward with a large momentum

940 MeV photon strikes the proton inside the deuteron

produced η is almost at rest

γd→ηpn reaction at the "ELPH kinematics"

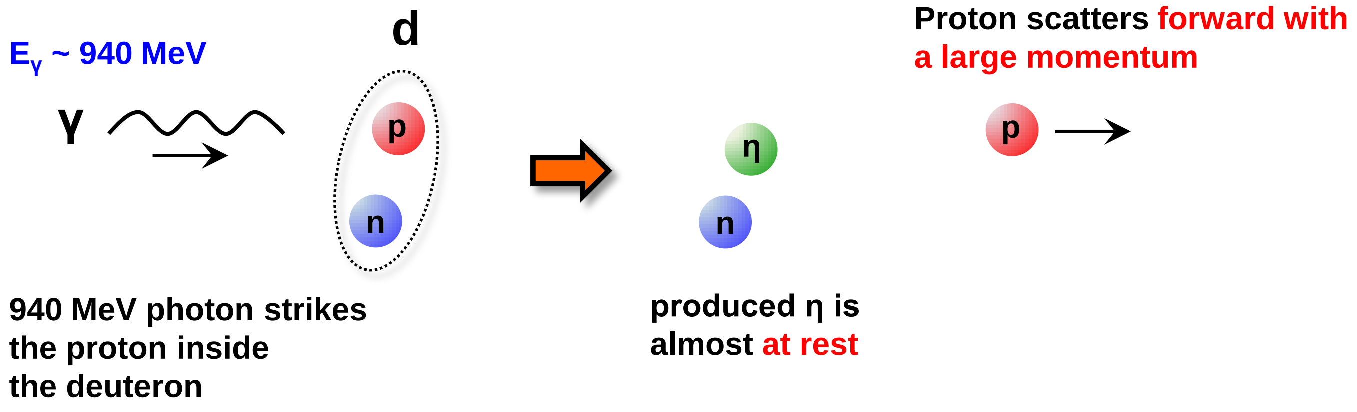
✓ New measurement of γd→ηpn at ELPH, Tohoku Univ. (T. Ishikawa et. al., the ELPH-2844 experiment)

- Consider a *special* kinematics with E_γ ~ 940 MeV and θ_p ~ 0 degree.

  ➔ refer to as the "ELPH kinematics"

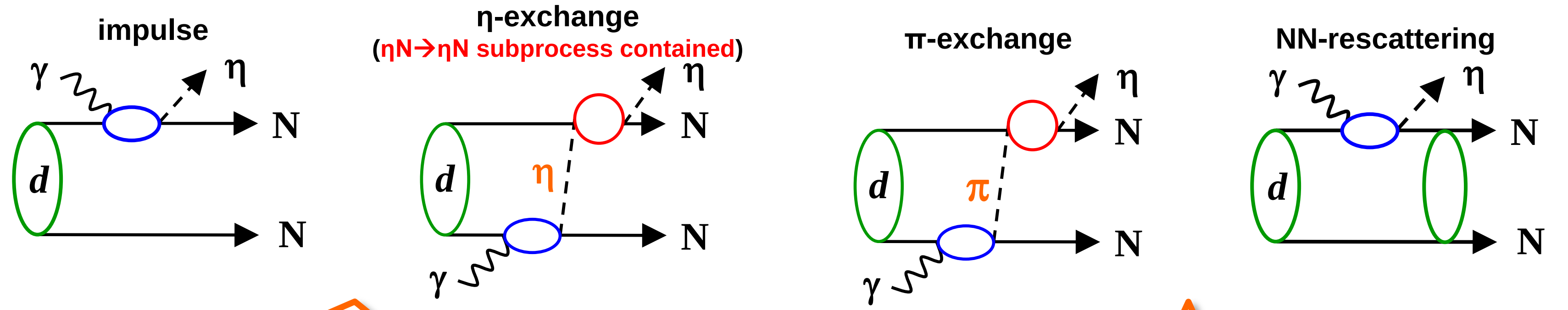
- Produced η will strongly interact with the spectator neutron.
- Scattered proton has little chance to interact with the η & neutron.

Ideal kinematical condition to extract η-nucleon effective range parameters !!



Model for γd → ηpn

✓ Reaction mechanisms for γd → ηpn



Deuteron wave function & (off-shell) NN amplitudes
➔ from realistic NN potential (e.g., CD-Bonn)

(Off-shell) ηN→ηN, πN→ηN, γN→ηN, γN→πN amplitudes
➔ from our Dynamical Coupled-Channels (DCC) model.

Dynamical Coupled-Channels (DCC) approach to meson production reactions

Dynamical Coupled-Channels (DCC) model:

[Matsuyama et al., PR439(2007)193; HK, et al., PRC88(2013)035209; 90(2014)065204; 94(2016)015201]

$$T^{(LSJ)}_{a,b}(p_a, p_b; E) = V^{(LSJ)}_{a,b}(p_a, p_b; E) + \underbrace{\sum_c}_{\text{CC effect}} \underbrace{\int_0^\infty q^2 dq}_{\text{off-shell effect}} V^{(LSJ)}_{a,c}(p_a, q; E) G_c(q; E) T^{(LSJ)}_{c,b}(q, p_b; E)$$

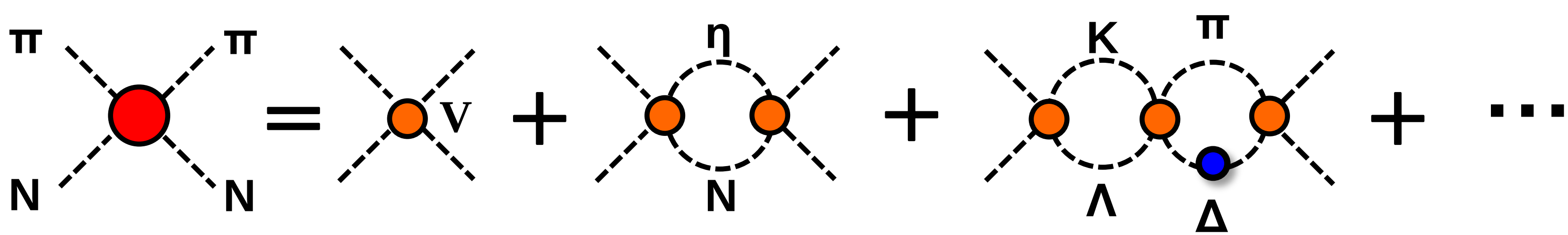
CC effect off-shell effect

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

quasi two-body channels of three-body ππN

✓ **Summing up all possible transitions between reaction channels !!**
(➔ satisfies multichannel two- and *three*-body unitarity)

e.g.) πN scattering



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CC effect

off-shell effect

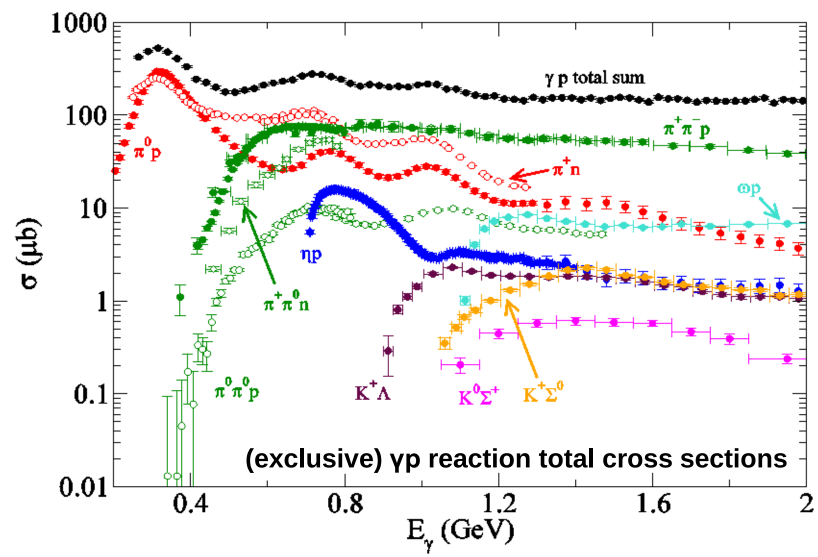
$$a,b,c = (\gamma^{(*)}N,\ \pi N,\ \eta N,\ \boxed{\pi\Delta,\ \sigma N,\ \rho N},\ K\Lambda,\ K\Sigma,\ \omega N\cdots)$$

quasi two-body channels of three-body ππN

✓ **Current developing model:**

- **Constructed by simultaneous analysis of**
  - **πN scattering (W < 2.3 GeV)**
  - **πp → ηN, KΛ, KΣ (W < 2.1 GeV)**
  - **γp → πN, ηN, KΛ, KΣ (W < 2.1 GeV)**
  - **γ'n' → πN, ηN (W < 2 GeV, ongoing)**
  - **ep → e'πN, (W < 2 GeV, Q^2 < 6 GeV^2, ongoing)**
- **Single- and double-spin polarization data are also taken into account.**
- **Results in fitting total ~50,000 data points.**

Region our model can cover



Dynamical Coupled-Channels (DCC) approach to meson production reactions

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CC effect

$$a,b,c = (\gamma^{(*)}N,\ \pi N,\ \eta N,\ \pi$$

quasi t

t

✓ **Current developing model:**

➢ **Constructed by simultaneous analysis of**

- **πN scattering (W < 2.3 GeV)**
- **πp → ηN, KΛ, KΣ (W < 2.1 GeV)**
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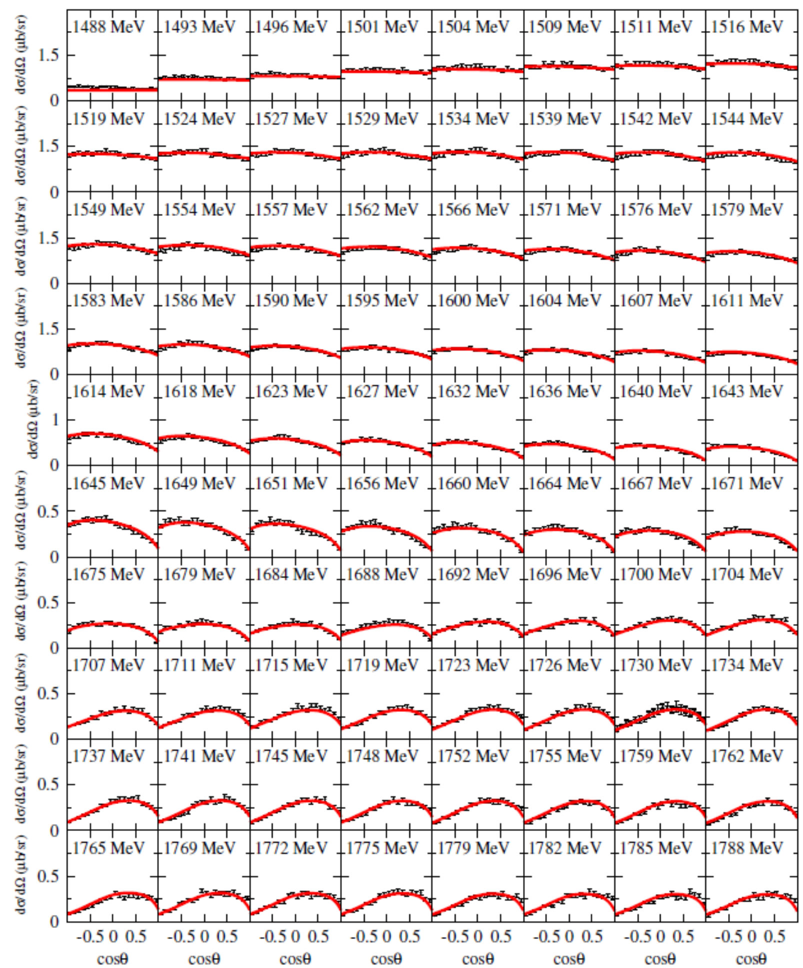
- **γ'n' → πN, ηN (W < 2 GeV, ongoing)**
- **ep → e'πN, (W < 2 GeV, Q^2 < 6 GeV^2, ongoi**

➢ **Single- and double-spin polarization data are also taken into account.**

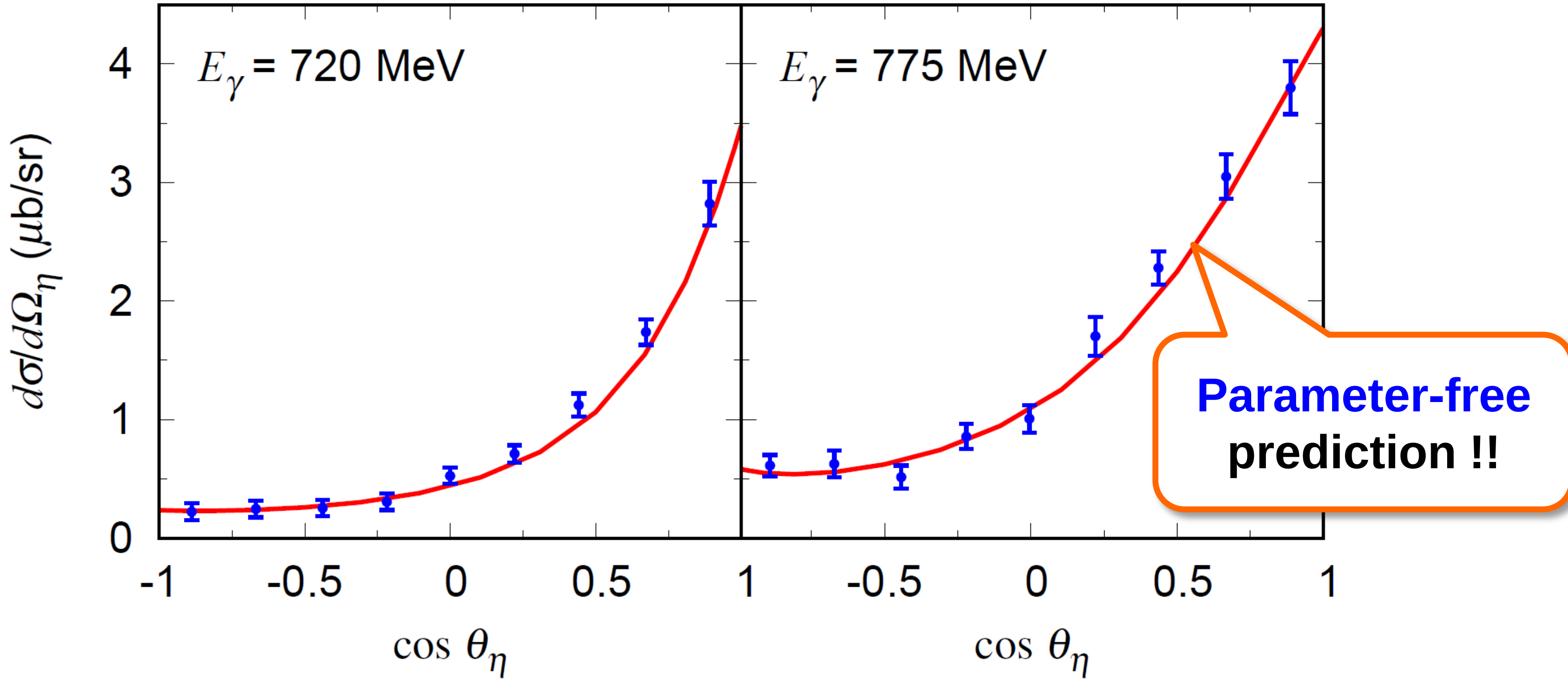
➢ **Results in fitting total ~50,000 data points.**

e.g.) dσ/dΩ for γp → ηp



Examining validity of our model

✓ Angular distributions of η meson for γd → ηpn

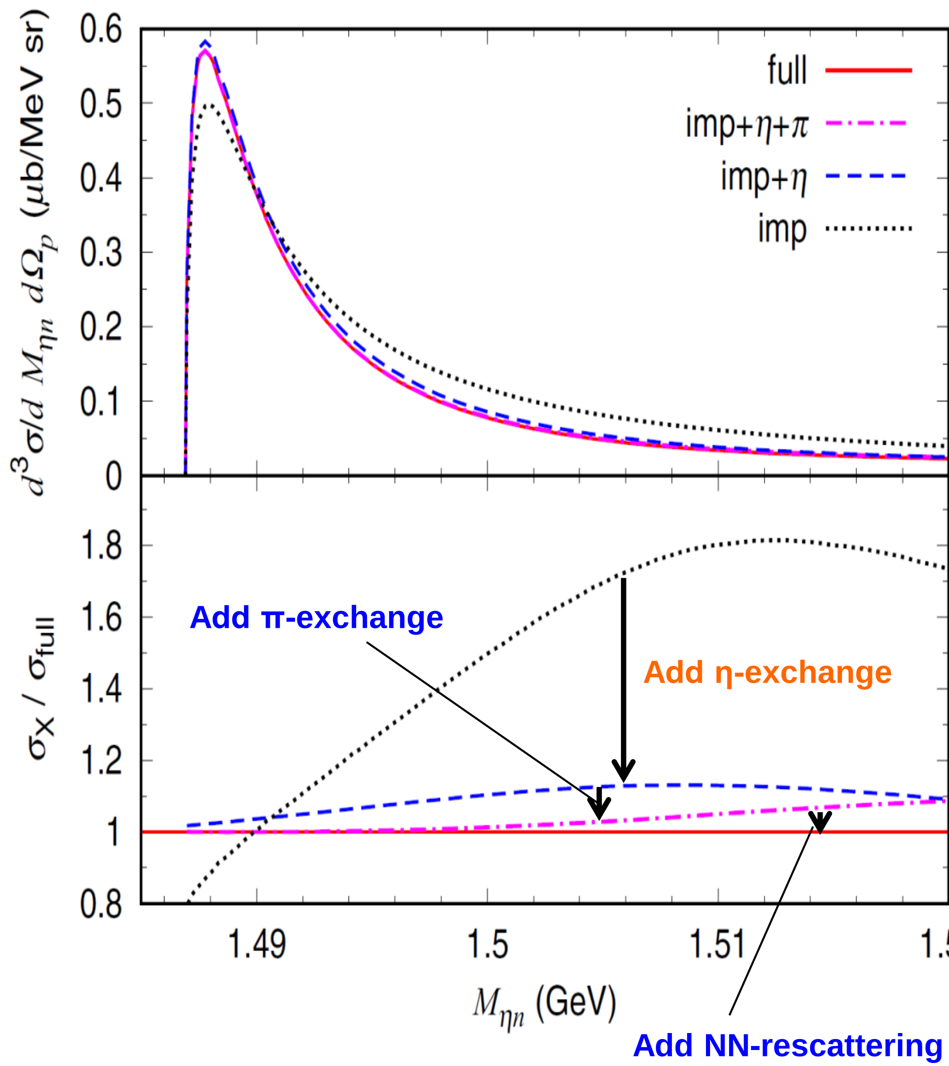


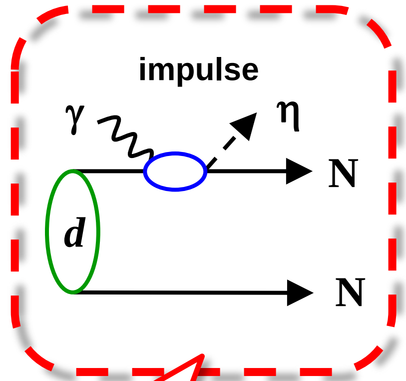
➢ Our prediction is in excellent agreement with the existing data !!

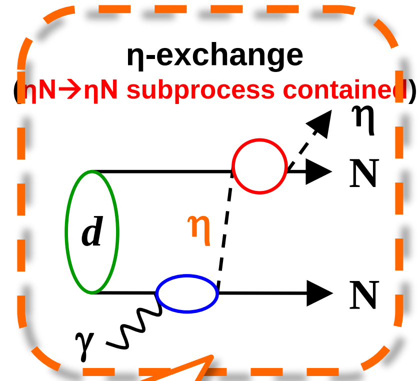
➔ Reliable study of ηN effective range parameters is possible.

Contribution of each mechanism

3-fold DCS for γd → ηpn at the ELPH kinematics (E_γ = 940 MeV & θ_p = 0 deg.)

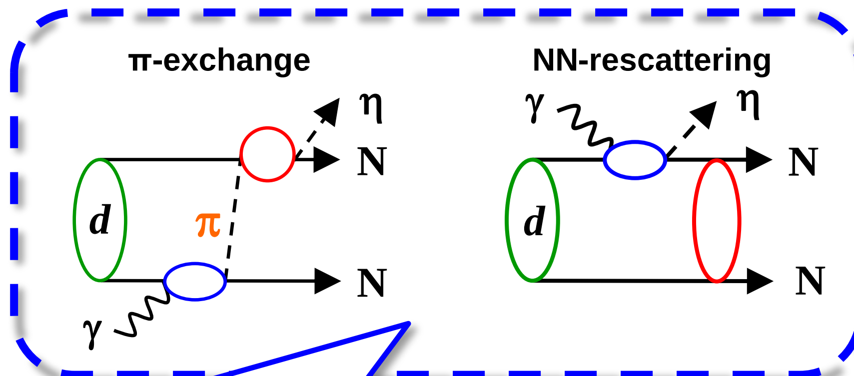






Dominant contribution

Change impulse result by -20% to +60%



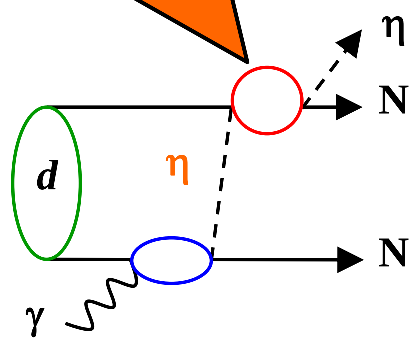
Less than 10% contribution (highly suppressed)
(NN-rescattering is negligible below $M_{\eta N}$ = 1.5 GeV.)
➔ Higher-order multiple scatterings are safely dropped.

Examining sensitivity of ηN scattering effective range parameters to the $\gamma d \to \eta p n$ cross section

1) **Off-shell S-wave $\eta N \to \eta N$ amplitude from our DCC model is replaced by the on-shell parametrization [up to $O(k^2)$ in denominator]:**

$$\frac{1}{(1/a_{\eta N}) + r_{\eta N}\,(k^2/2) - ik}$$

scattering length ($a_{\eta N}$) — effective range ($r_{\eta N}$)



η-exchange

2) **Vary scattering length ($a_{\eta N}$) & effective range ($r_{\eta N}$) freely, and see how the $\gamma d \to \eta p n$ cross section at the ELPH kinematics changes.**

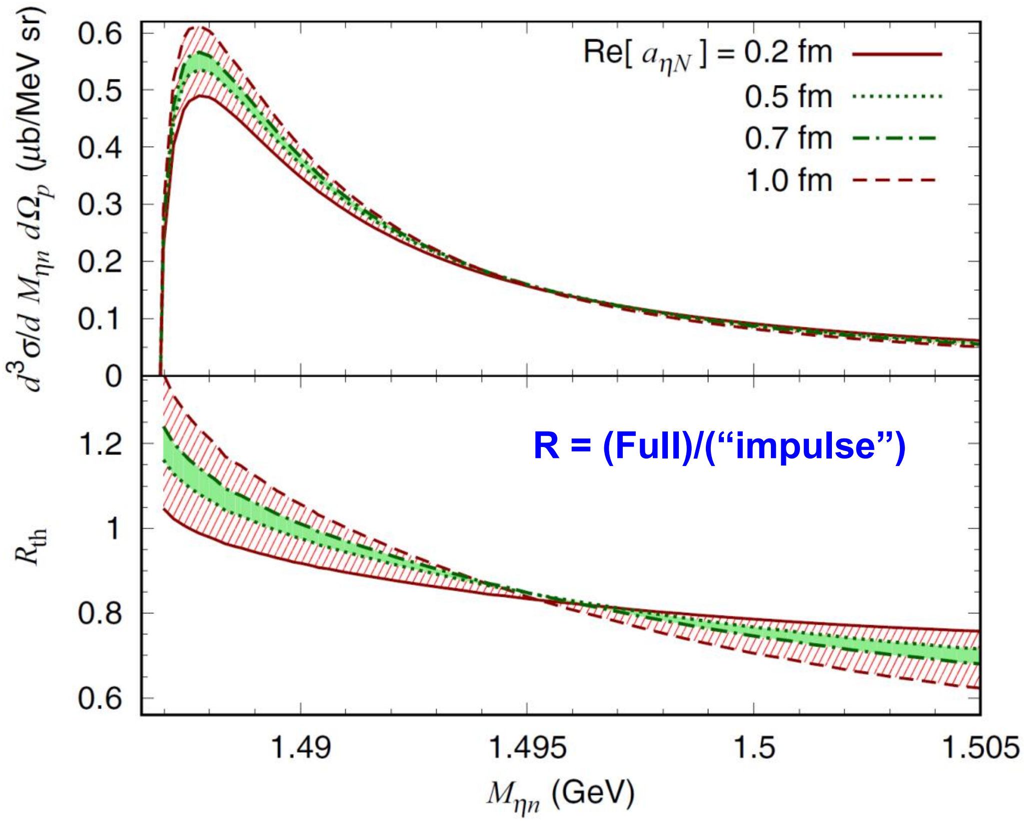
NOTE: We have confirmed that at this special kinematics, the off-shell effect of $\eta N \to \eta N$ rescattering process is negligibly small and safely replaced with the on-shell amplitude.

Sensitivity of scattering length

3-fold DCS for γd → ηpn at the ELPH kinematics (E_γ = 940 MeV & θ_p = 0 deg.)

DCS with Re [$a_{\eta N}$] varied from 0.2 fm to 1.0 fm

(Fixed as Im [$a_{\eta N}$] = 0.25 fm & $r_{\eta N}$ = 0 fm)



✓ Current estimated range for $a_{\eta N}$:

- Re $a_{\eta N}$ ~ 0.2 – 0.9 fm
  [Δ(Re $a_{\eta N}$) ~ 0.7 fm]
- Im $a_{\eta N}$ ~ 0.2 – 0.3 fm
  [Δ(Im $a_{\eta N}$) ~ 0.1 fm]

Once "R" data of 5% error binned in 1 MeV are given, we have

Δ(Re $a_{\eta N}$) ~ 0.7 fm → 0.2 fm

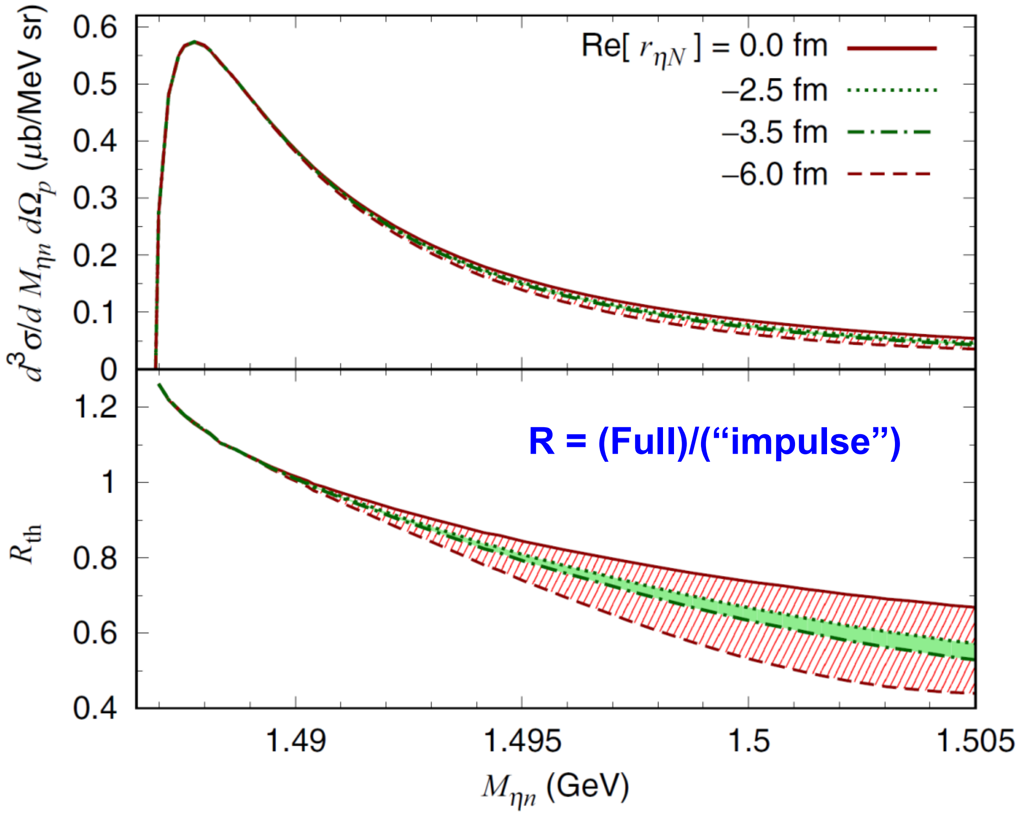
To reduce Δ(Im $a_{\eta N}$), one needs better accuracy of R data.

Sensitivity of effective range

3-fold DCS for γd → ηpn at the ELPH kinematics (E_γ = 940 MeV & θ_p = 0 deg.)

DCS with Re [$r_{\eta N}$] varied from -6 fm to 0 fm

(Fixed as $a_{\eta N}$ = 0.75+0.26i fm & Im[$r_{\eta N}$] = 0 fm)



✓ **Current estimated range for $r_{\eta N}$:**

- **Re $r_{\eta N}$ ~ -6 – +1 fm**
  [Δ(Re $r_{\eta N}$) ~ 7 fm]
- **Im $r_{\eta N}$ ~ -1 – 0 fm**
  [Δ(Im $r_{\eta N}$) ~ 1 fm]

Once “R” data of 5% error binned in 1 MeV are given, we have

Δ(Re $r_{\eta N}$) ~ 7 fm → 1 fm

To reduce Δ(Im $r_{\eta N}$), one needs better accuracy of R data.

Summary

- ✓ Examined a possible extraction of S-wave ηN scattering effective range parameters ($a_{\eta N}$ & $r_{\eta N}$) using the γd → ηpn data from forthcoming experiment at ELPH [Ishikawa et al., ELPH-2844 exp.]

- ✓ Dynamical Coupled-Channels (DCC) model is used for (off-shell) γ-nucleon and meson-baryon elementary amplitudes.
  - ➔ parameter-free prediction gives excellent agreement with currently available γd → ηpn data
  - ➔ enable a reliable investigation of γd → ηpn

Achievable *IF* the requested beam time of the ELPH-2844 experiment is *FULLY* adopted !!

- ✓ Once "R" data with 5% error binned in 1 MeV width are given, uncertainties in real parts of $a_{\eta N}$ & $r_{\eta N}$ are significantly reduced as

$$\Delta(\mathrm{Re}\ a_{\eta N}) \sim 0.7\ \mathrm{fm} \rightarrow 0.2\ \mathrm{fm} \quad (\sim 70\%\ \mathrm{reduced})$$

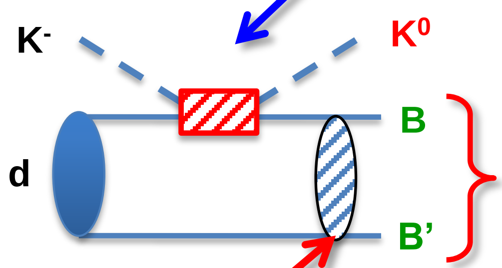
$$\Delta(\mathrm{Re}\ r_{\eta N}) \sim 7\ \mathrm{fm} \rightarrow 1\ \mathrm{fm} \quad (\sim 85\%\ \mathrm{reduced})$$

Ongoing works

✓ **Study of S=-2 baryon-baryon interaction & H dibaryons with $K^- d \rightarrow K^0 (BB)_{S=-2,Q=0}$**

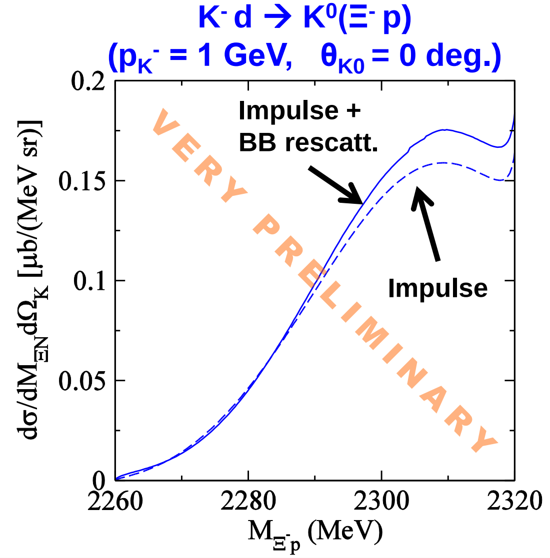
➢ <u>$K^- d \rightarrow K^0 (BB)_{S=-2,Q=0}$ reaction</u>

(off-shell) amplitudes from our
DCC model of $\bar{K}N$ reaction
HK et al., PRC90(2014)065204



Total strangeness S= -2
Total charge Q = 0

$(BB)_{S=-2}$ interaction:
Phenomenological model
Chiral EFT
Lattice QCD, ...



Once the data are available, we do partial-wave analysis, and

➢ Determine $(BB)_{S=-2}$ interaction
➢ Search for H dibaryon