ηd interaction studied in $\gamma d \to \pi^0 \eta d$

5th Jagiellonian Symposium on Advances in Particle Physics and Medicine

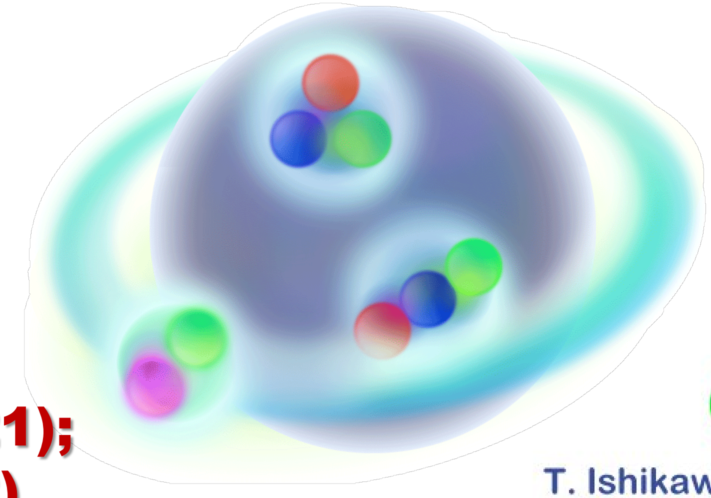
Collegium Novodvorscianum,
Kraków, Poland,
June 29~July 7, 2024

Takatsugu Ishikawa (ishikawa@rcnp.osaka-u.ac.jp)
Research Center for Nuclear Physics (RCNP), Osaka University, Japan

PRC104, L052201 (2021); PRC105, 045201 (2022).

Contents

1. introduction
   η-mesic nucleus
2. experiment
3. results
   total cross section ~ final-state interaction
   differential cross sections ~ ηd scattering
4. summary



T. Ishikawa et al.,
Phys. Rev. C 104, L052201 (2021);
Phys. Rev. C 105, 045201 (2022).

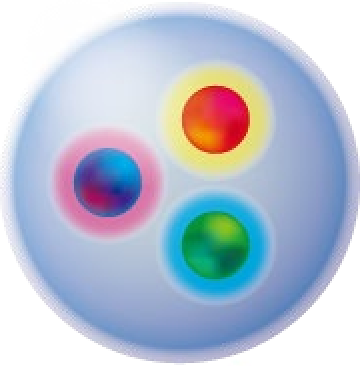
Hadrons

Quarks are the smallest building blocks of matter, or elementary particles.

Quarks form composite particles hadrons, being confined within them.

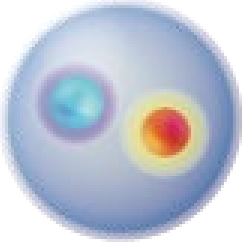
Quarks cannot be observed alone owing to their confinement.

Two kinds of hadrons are observed:



baryons consisting of three quarks,

and

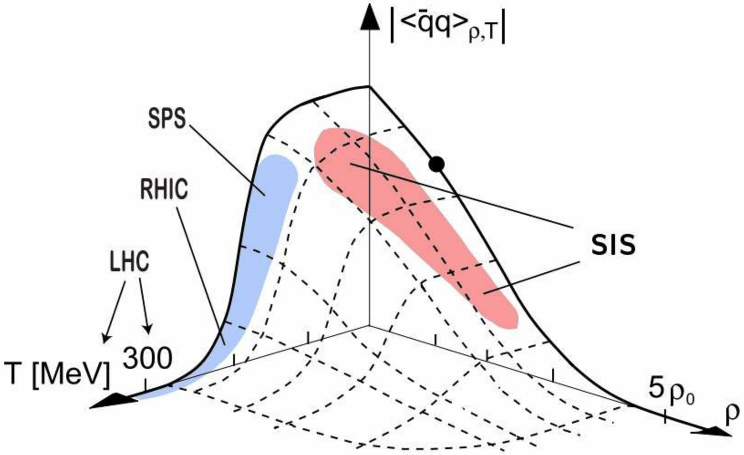


mesons consisting of a quark and anti-quark pair

Mass generation

The mass of a hadron is much larger than the sum of masses of quarks comprising it.

The hadron formation led to generation of a large amount of the matter mass and made the first step in the evolution of matter.



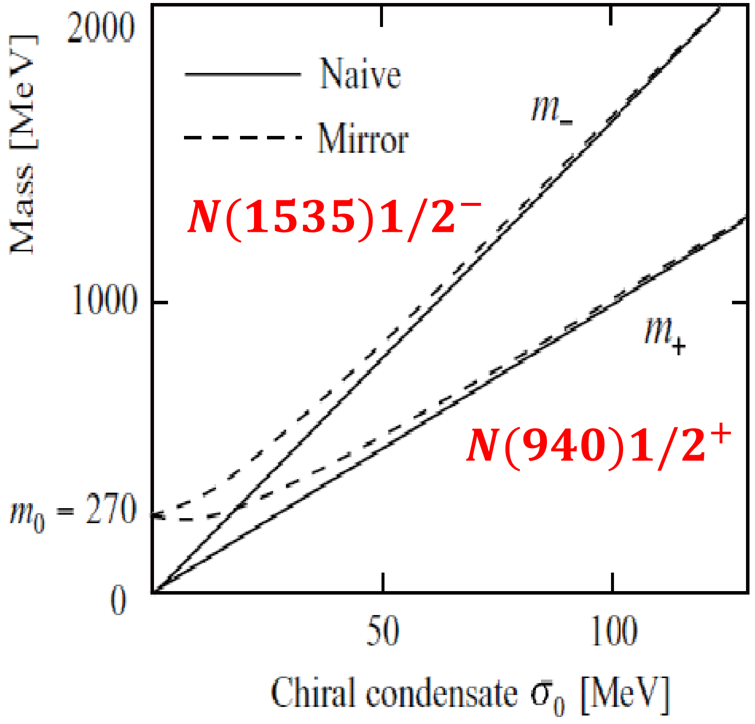
W. Weise, Nucl. Phys. A 553, 59 (1993).

Chiral symmetry breaking is considered to be responsible for mass generation by making $\bar{q}q$ condensate

Chiral partner

This scenario provides the existence of a chiral partner of a hadron with the same mass and same quantum numbers except for the parity if chiral symmetry is not breaking or $\bar{q}q$ condensate is absent.

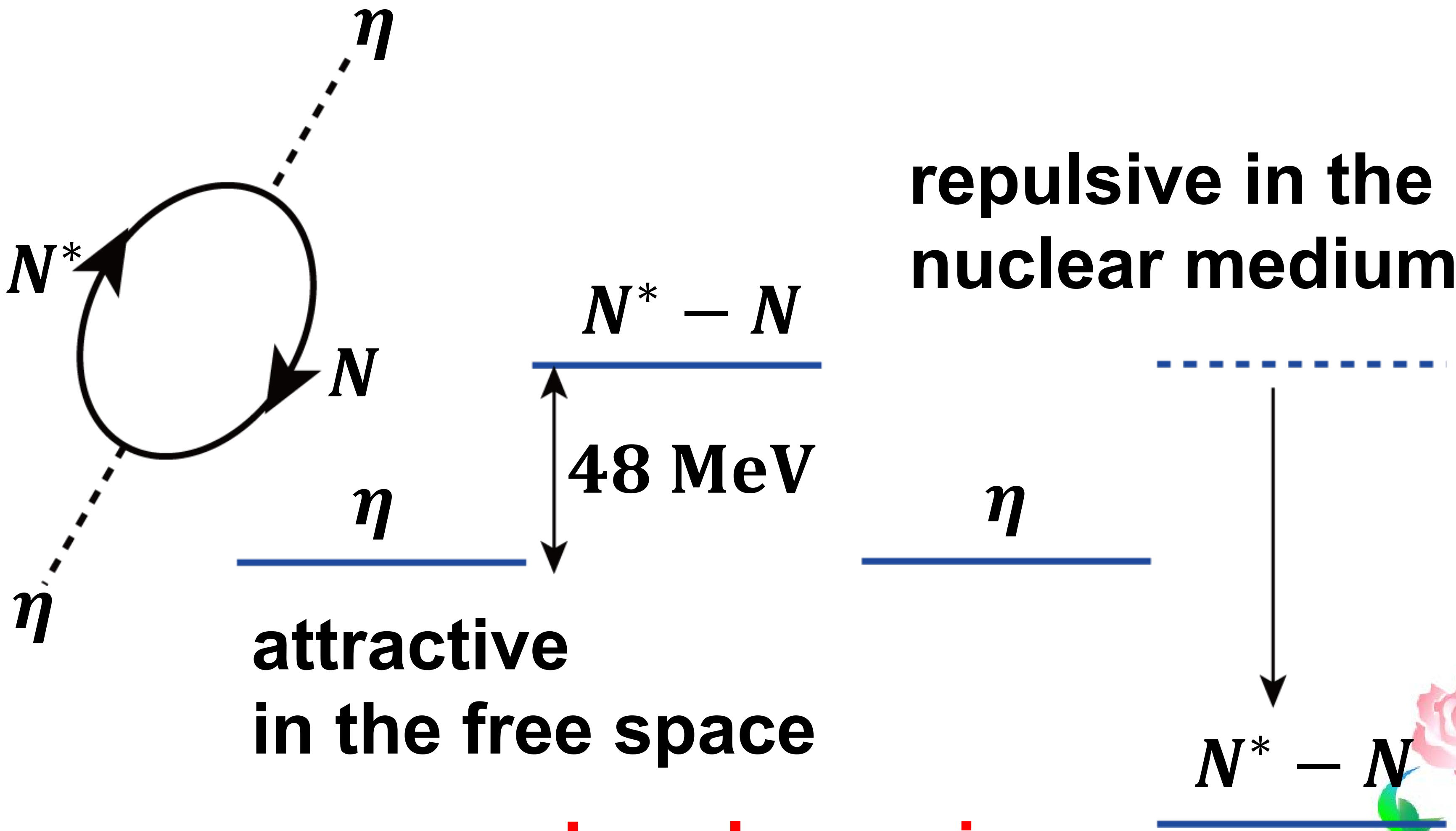
$N(1535)1/2^-$ is speculated to be the chiral partner of the nucleon



C. DeTar and T. Kunihiro, Phys. Rev. D 39, 28
T. Hatsuda and M. Prakash, Phys. Lett. B 224, 11 (1989);

η-mesic nucleus

$N^* \equiv N(1535)1/2^-$ strongly couples to ηN



repulsive in the nuclear medium

attractive in the free space

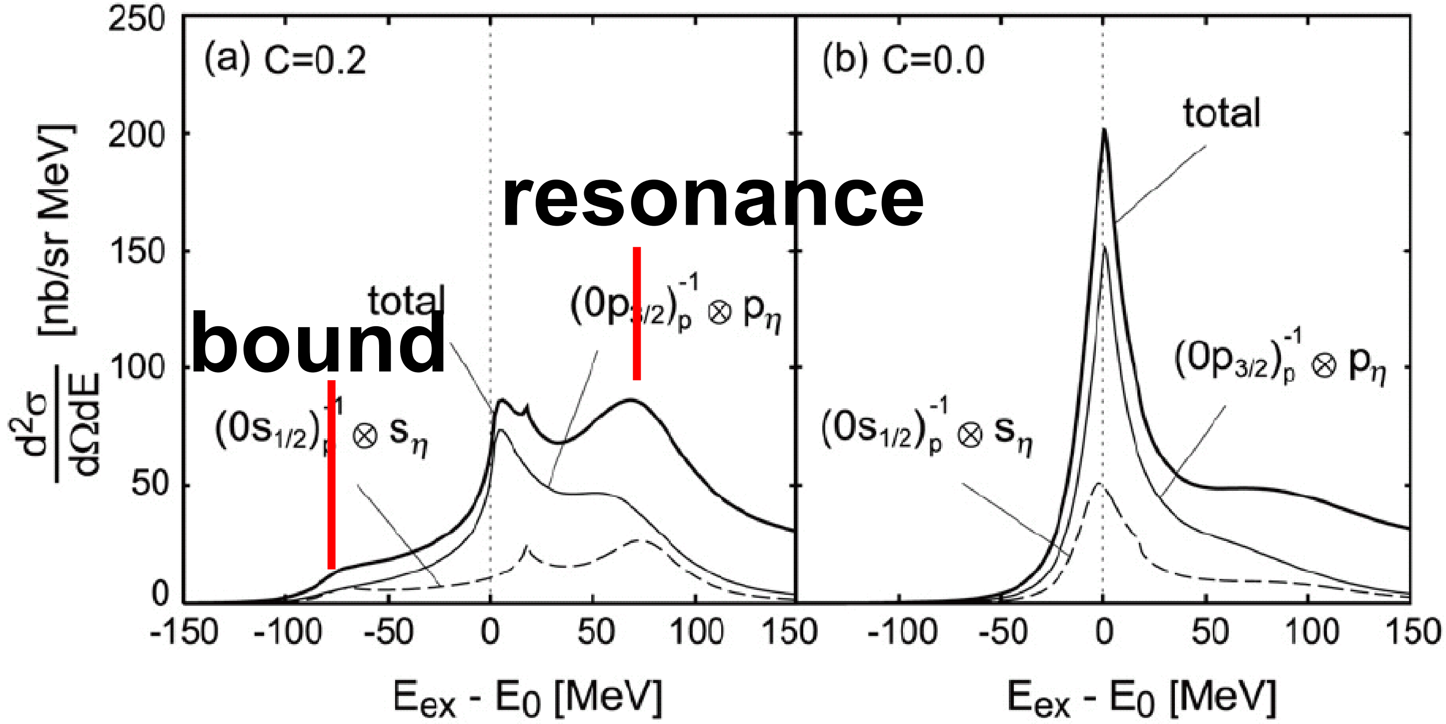
Level crossing

η-mesic nucleus

Excitation spectra for $\gamma\,^{12}\mathrm{C} \to pX$

$$E_{\mathrm{ex}} = M_X - M_\eta - M_{^{11}\mathrm{B}}$$

with level crossing   without level crossing



bound

resonance

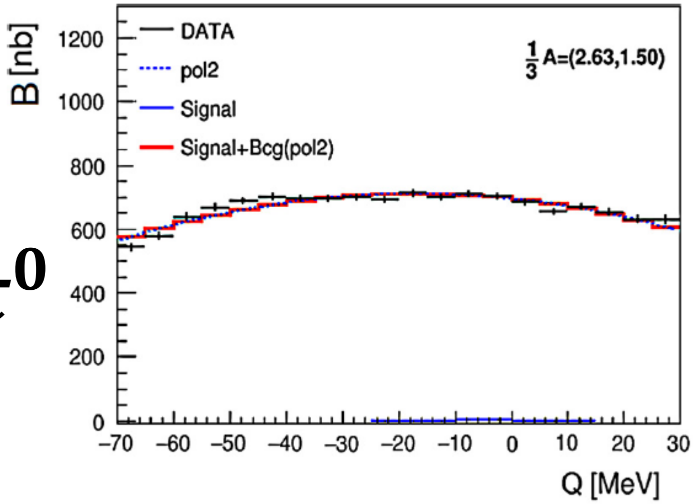
H. Nagahiro et al., Nucl. Phys. A 761, 92 (2005);
D. Jido et al., Nucl. Phys. A 811, 158 (2008).

η-mesic nucleus

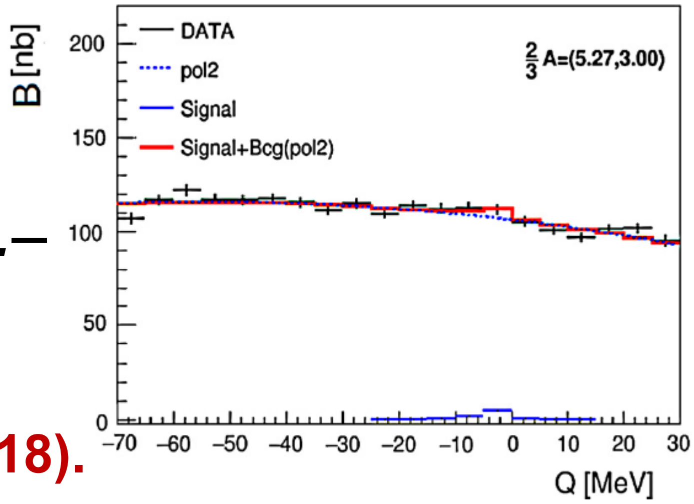
No clear evidence for an η-mesic nucleus

Aleksander Khreptak,
Magdalena Skurzok,
Paweł Moskal,
Front. Phys. 11, 1186457 (2023).

$$dd \to {}^{3}\mathrm{He}n\pi^{0}$$



$$dd \to {}^{3}\mathrm{He}p\pi^{-}$$



M. Skurzok et al.,
Phys. Lett. B 782, 6 (2018).

η-nuclear interaction

Traditional tool

single η production from a nucleus

a significant increase in the η yield at low relative η-nuclear momenta is interpreted as a signature of attractive forces between ηA

$pd \rightarrow \eta\ ^{3}\mathrm{He}$, $\gamma\ ^{3}\mathrm{He} \rightarrow \eta\ ^{3}\mathrm{He}$, and

$\gamma\ ^{7}\mathrm{Li} \rightarrow \eta\ ^{7}\mathrm{Li}$

B. Mayer et al., Phys. Rev. C 53, 2068 (1996);
J. Smyrski et al., Phys. Lett. B 649, 258 (2007);
T. Mersmann et al., Phys. Rev. L 98, 242301 (2007);
M. Pfeiffer et al., Phys. Rev. Lett. 92, 252001 (2004);
Phys. Rev. Lett. 94, 049102 (2005);
F. Pheron et al., Phys. Lett. B709, 21 (2012);
B. Krusche and C. Wilkin, Prog. Part. Nucl. Phys. 80, 43 (2014);
Y. Marghrbi et al., Eur. Phys. J. A 49, 38 (2013).

η-nuclear interaction

Hadronic process

Rich information on the low-energy η-nuclear dynamics has been obtained from the final-state interactions in $pn \to \eta d,\ pd \to \eta pd$

Their analysis can be complicated by various ambiguities associated with

initial-state interaction, and

various two-step mechanisms,

leading to undesirable model dependence

H. Calén et al., Phys. Rev. Lett. 79, 2672 (1997);
Phys. Rev. Lett. 80, 2069 (1998);
F. Hibou et al., Eur. Phys. J. A 7, 537 (2000);
R. Bilger et al., Phys. Rev. C 69, 014003 (2004).

η-nuclear interaction

These disadvantages are overcome when turning to electromagnetic processes

Electromagnetic process

It is not necessary to consider initial-state interaction

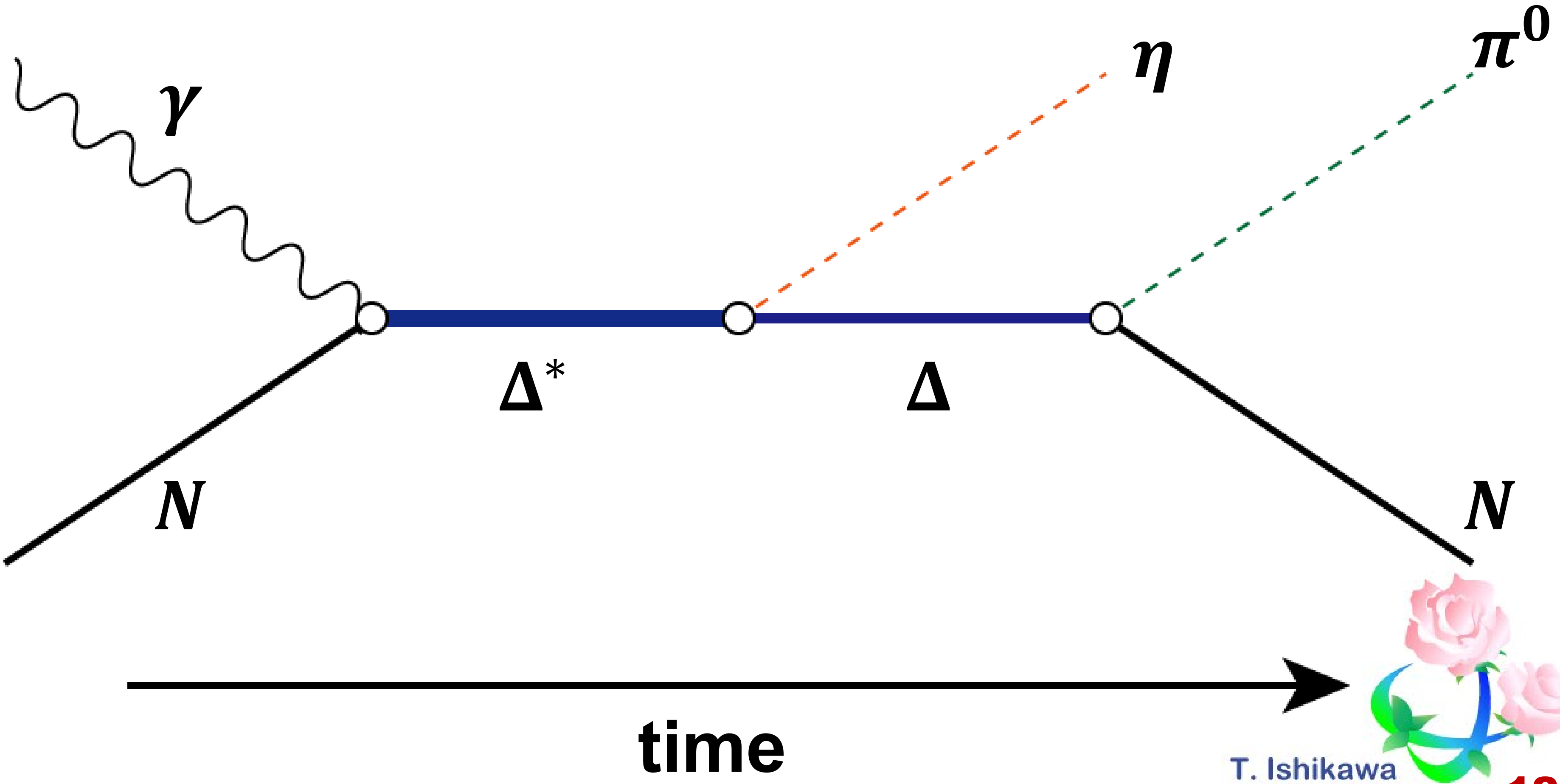
$\gamma A \rightarrow \pi^0 \eta A$ is advantageous

- **ηA: low relative-momentum condition**
- **$\pi^0 A$: small absorption**
- **$\pi^0 \eta$: negligibly small below $a_0(980)$**

η-nuclear interaction

Elementary process is rather well understood

$\gamma N \to \pi^0 \eta N$: $\Delta(1700)3/2^-$, $\Delta(1940)3/2^-$



Experiment

SKIP

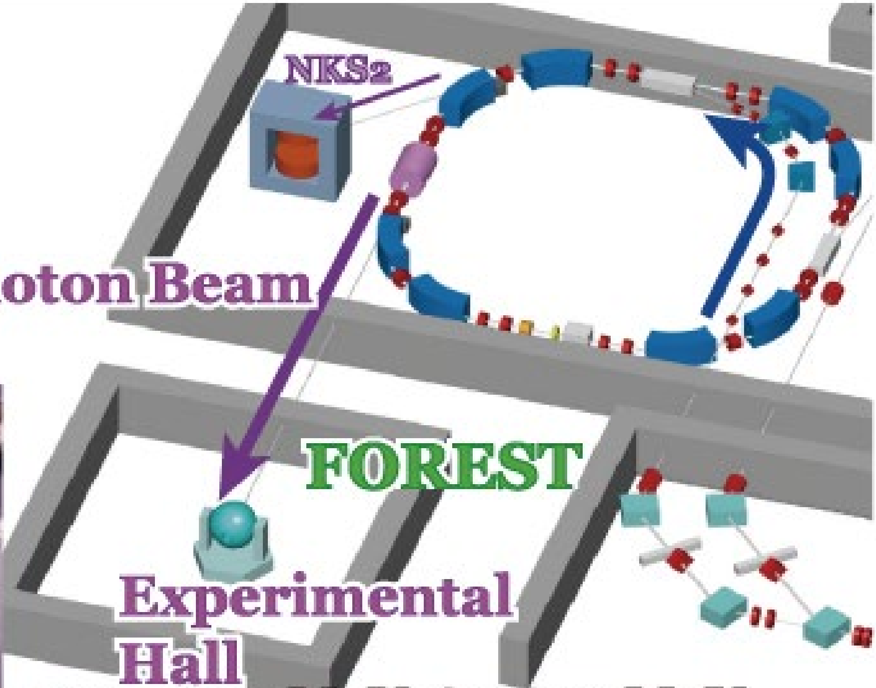
Experiment

Accelerator

SKIP

Electron Beam
- LINAC 150 MeV
- Booster Ring 1200 MeV (max)

Photon Beam
- Bremsstrahlung
- Tagged



1.3 GeV Booster STorage Ring

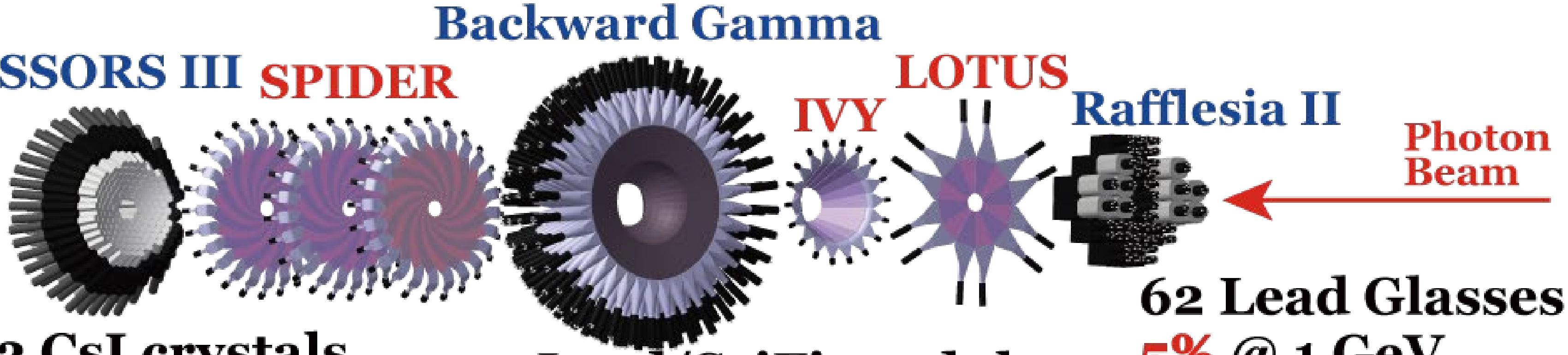
740~1150 MeV @ 1200 MeV
~20 MHz (photon: 10 MHz)
$W_{\gamma d}$=2.50~2.80 GeV

570~890 MeV @ 930 MeV
~2.8 MHz (photon: 1.2 MHz)
$W_{\gamma d}$=2.38~2.61 GeV

T. Ishikawa et al., NIMA 622, 1 (2010); T. Ishikawa et al., NIMA 811, 124 (2016);
Y. Matsumura et al., NIMA 902, 103 (2018); Y. Obara et al., NIMA 922, 108 (2019).

EM calorimeter

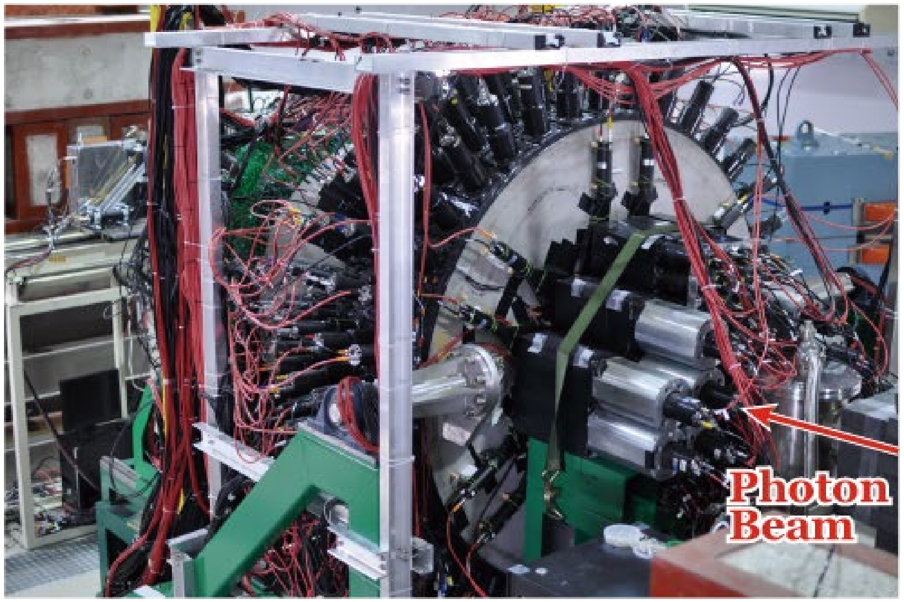
SKIP

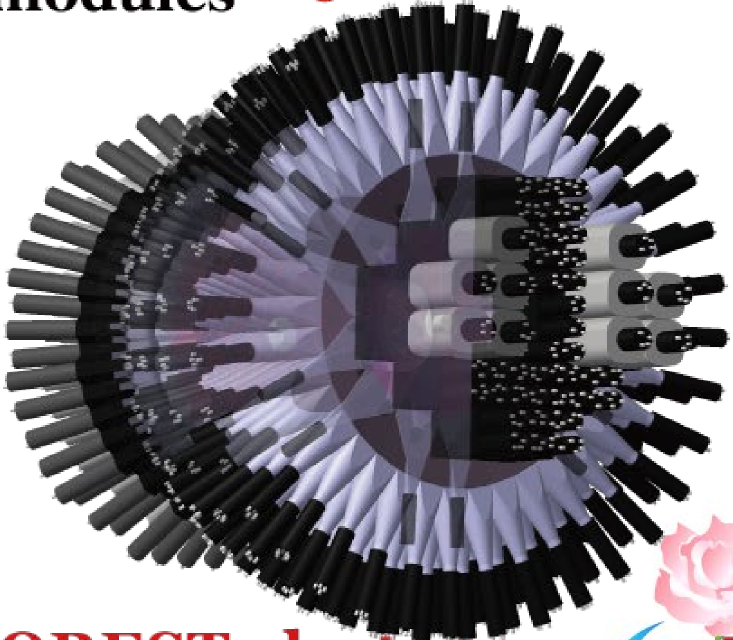


192 CsI crystals
3% @ 1 GeV

252 Lead/SciFi modules
7% @ 1 GeV

62 Lead Glasses
5% @ 1 GeV





FOREST electro-magnetic calorimeter

Target: 45 mm thick LH2 & LD2

T. Ishikawa et al., NIMA 832, 108 (2016).

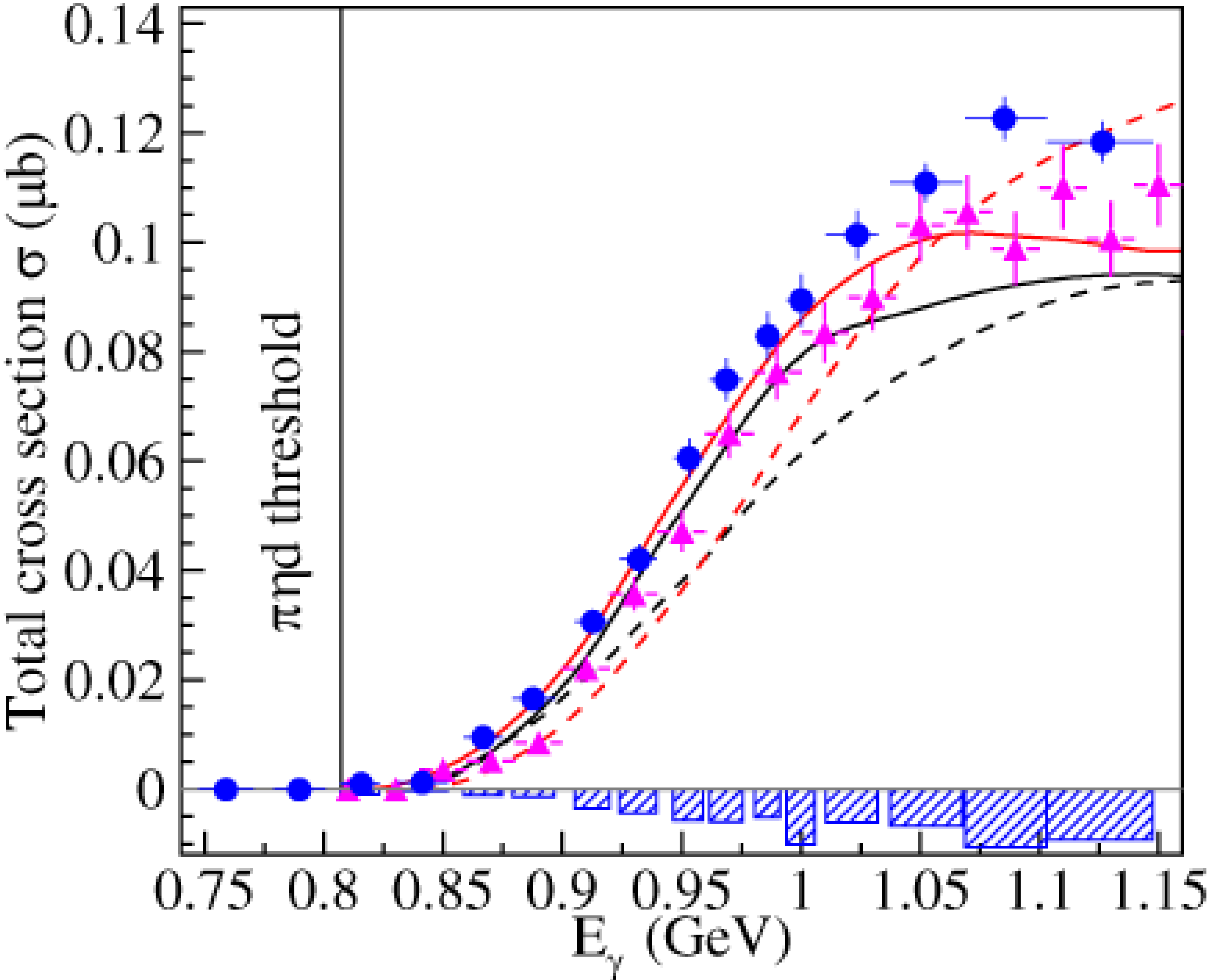
Results

Results

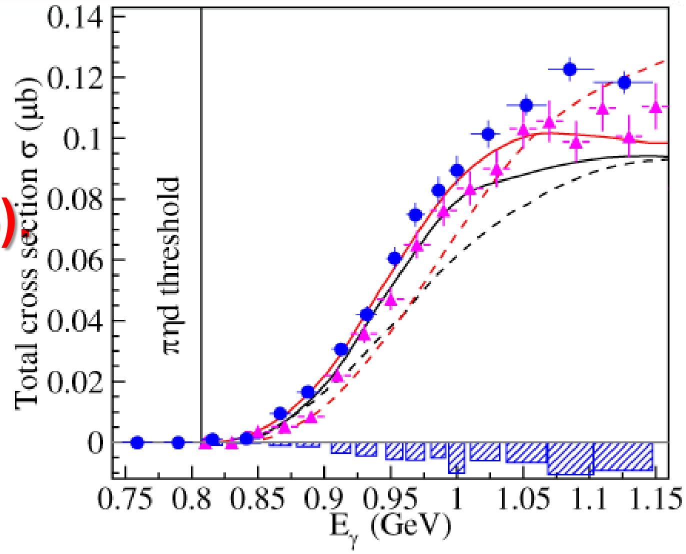
Total cross section

A. Käser et al., Phys. Lett. B 748, 244 (2015).

Excitation function



Total cross section

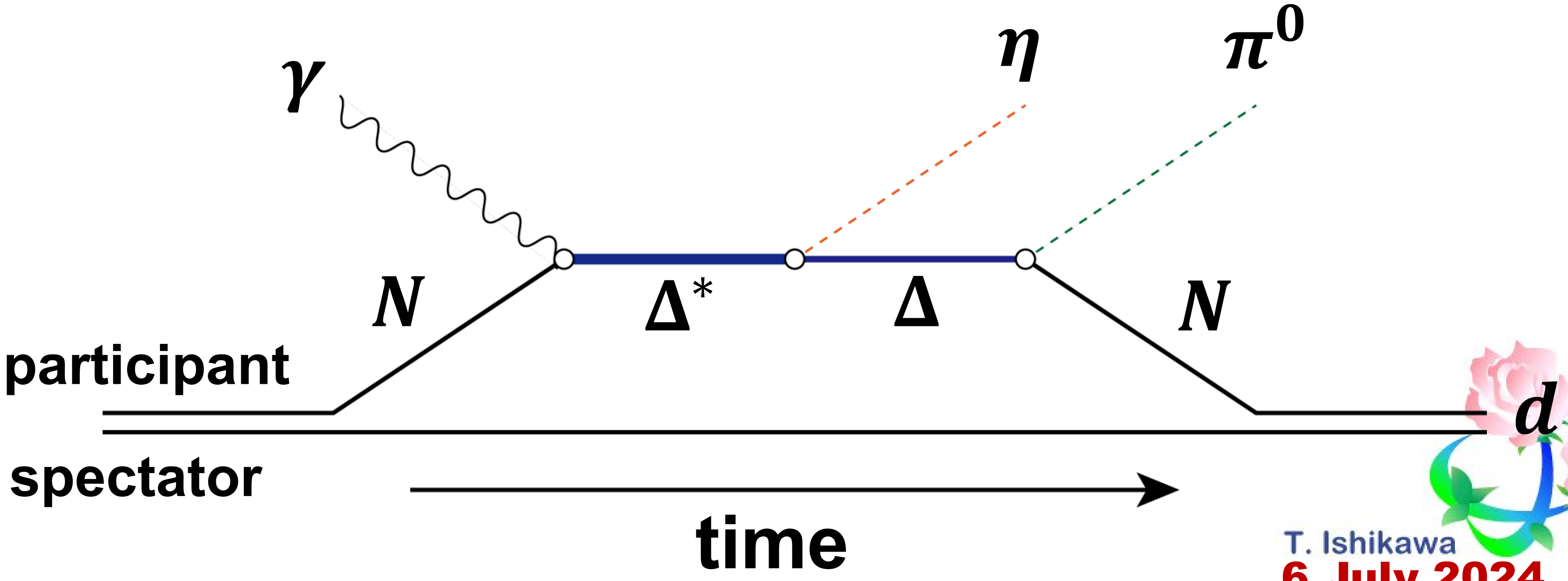


Impulse approximation

M. Egorov, A. Fix, Phys. Rev. C88, 054611 (2013).

M. Egorov, Phys. Rev. C101, 065205 (2020).

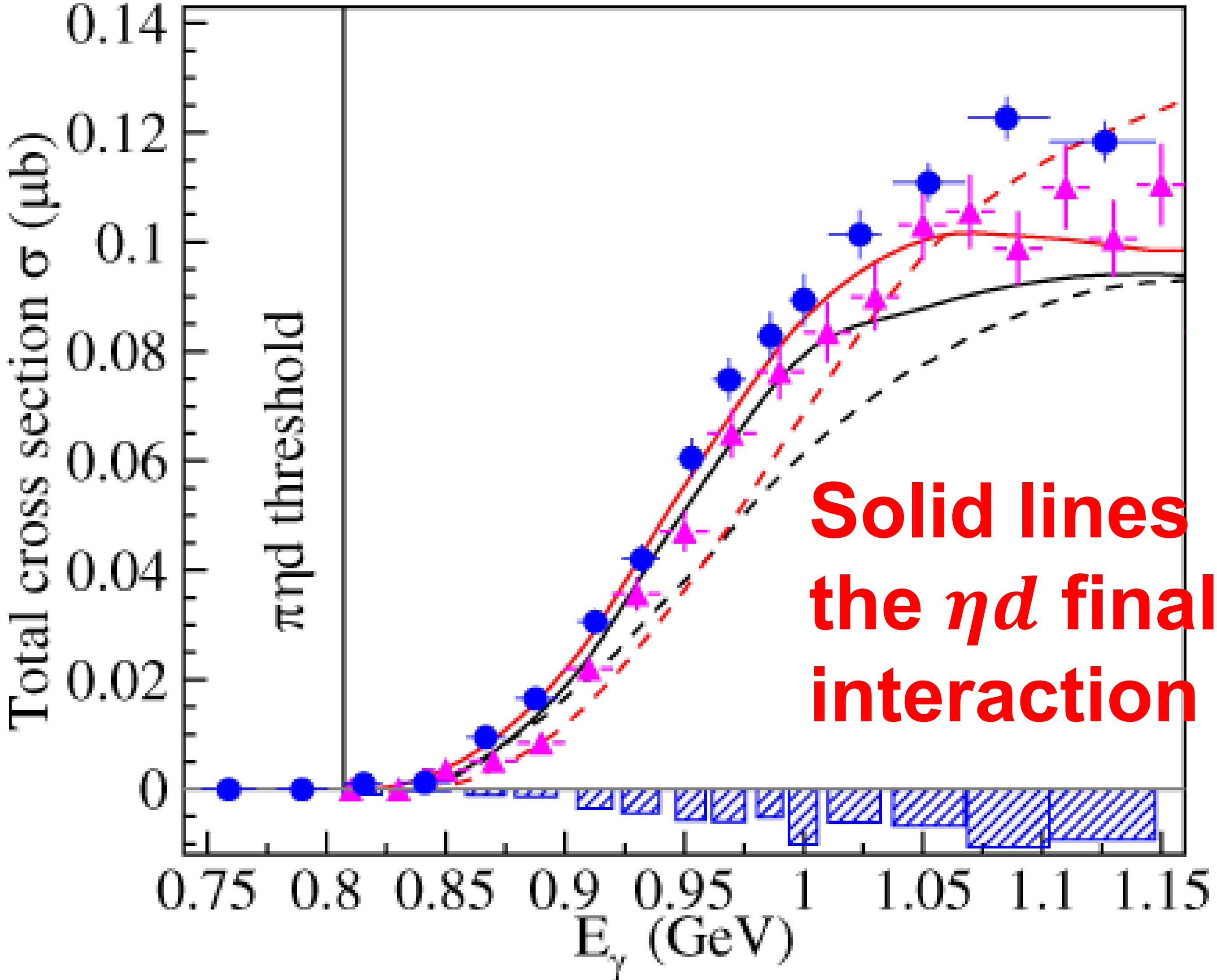
$\pi^{\pm}N \to \eta N$ and $\pi^{\pm}N \to N$
on the spectator nucleon



Total cross section

A. Käser et al., Phys. Lett. B 748, 244 (2015).

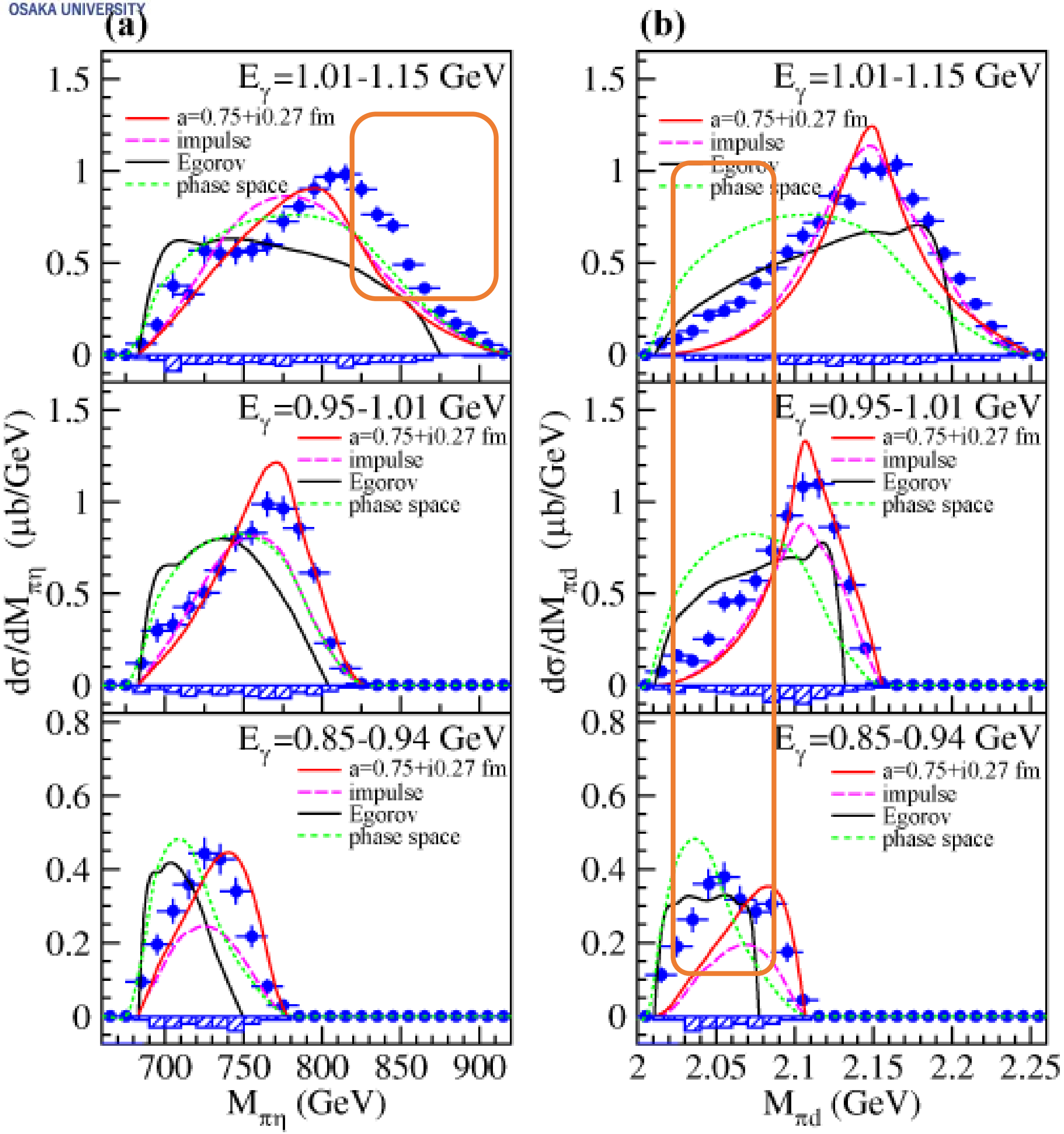
Excitation function



Solid lines incorporating the ηd final-state interaction

Differential cross sections

for the first time



$d\sigma/dM_{\pi\eta}$:

little FSI effects

absence of $a_0(980)$

$d\sigma/dM_{\pi d}$:

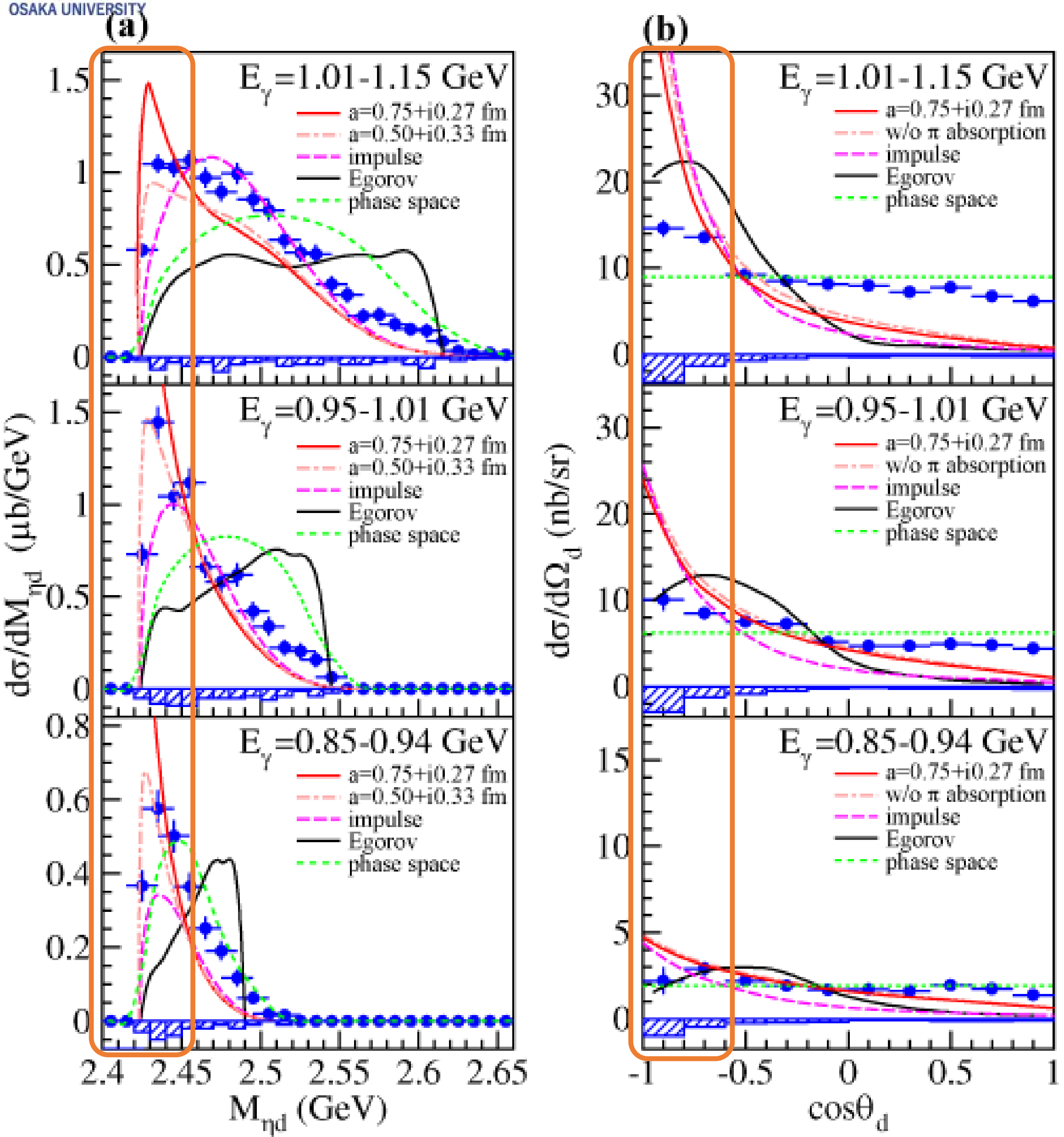
maximum at $M_{\pi d} \approx M_N + M_\Delta$

quasifree Δ prod or ΔN correlated state

discrepancy at low masses

more complicated πd FSI?

Differential cross sections



for the first time

$d\sigma/dM_{\eta d}$:

maximum at $M_{\eta d} \approx M_\eta + M_d$

strong ηd attraction

$a_{\eta N} = 0.50 + i0.33\ \mathrm{fm}$ reproduces the data well

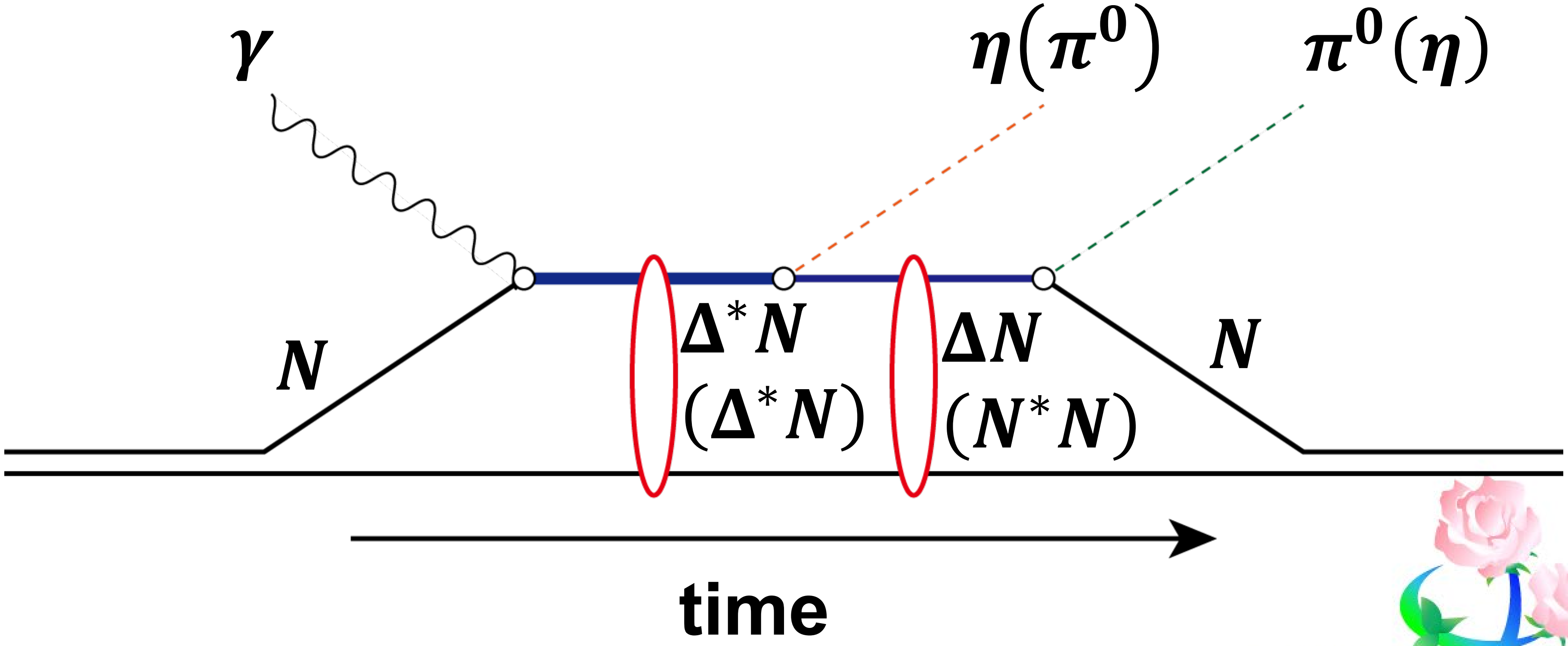
$d\sigma/d\Omega_d$:

rather uniform

coherent sum of elementary amplitudes

Two-baryon correlated state

Rather uniform angular distribution of deuteron emission suggests the formation of correlated state at each step



Phenomenological analysis

Decomposition of the obtained $\pi^0 d$ and ηd invariant mass distributions at two highest incident energies

Two sequential processes

$$\gamma d \to \mathcal{D}_{\mathrm{IV}} \to \pi^0 \mathcal{D}_{\eta d} \to \pi^0 \eta d$$

$$\gamma d \to \mathcal{D}_{\mathrm{IV}} \to \eta \mathcal{D}_{12} \to \pi^0 \eta d$$

$\mathcal{D}_{\eta d}$: *S*-wave ηd system with $I = 0, J^\pi = 1^-$
low-energy ηd scattering parameters: $a_{\eta d}, r_{\eta d}$

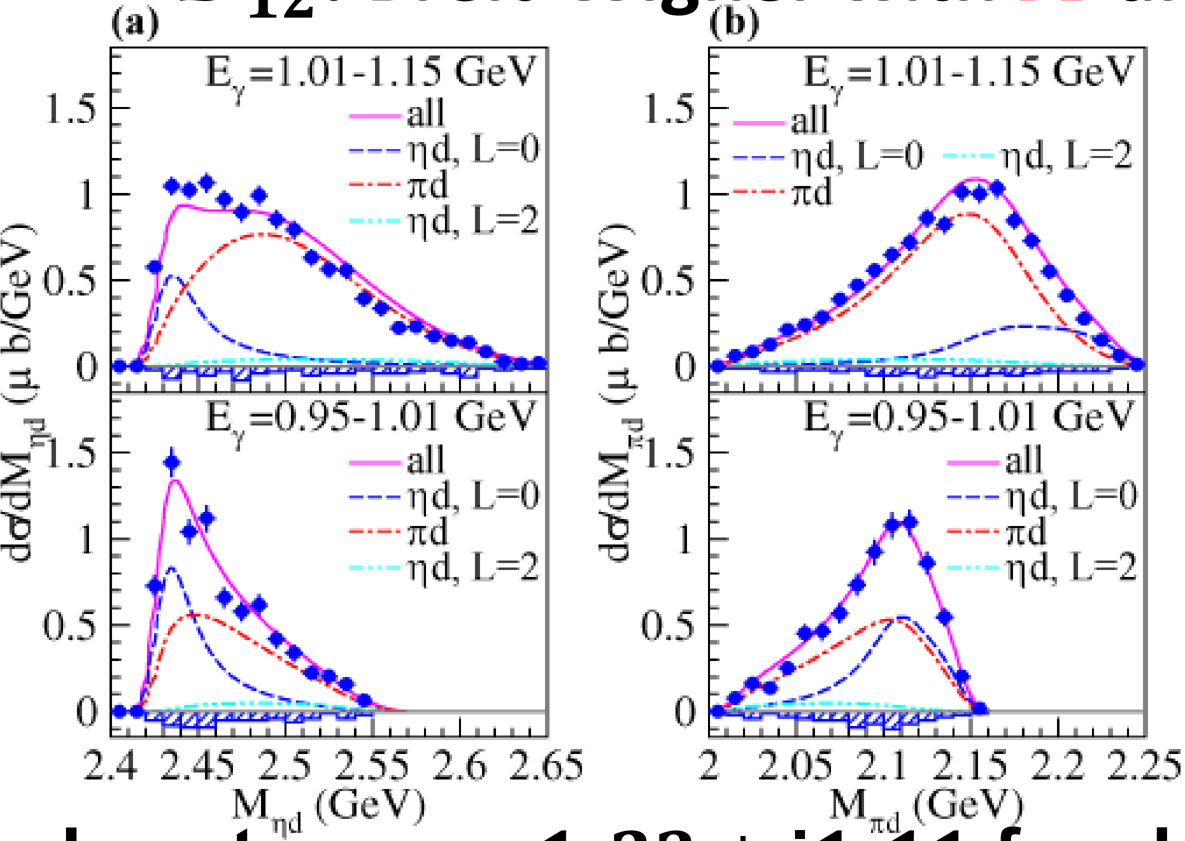
$\mathcal{D}_{12}$: well-known πd resonance with $I = 1, J^\pi = 2^+$
Breit-Wigner with $M \sim 2.14\ \mathrm{GeV}$ and $\underline{\Gamma \sim 0.09\ \mathrm{GeV}}$
constant

simultaneous fit of $d\sigma/dM_{\pi d}$ and $d\sigma/dM_{\eta d}$ distributions to determine 6 parameters

Phenomenological analysis 2

$\mathcal{D}_{\eta d}$: scattering parameters $\sim|k\cot\delta|^{-2}$

$\mathcal{D}_{12}$: Breit-Wigner with M and Γ (constant)



$$a_{\eta d} = \pm\left(0.7^{+0.8}_{-0.6}\right) + i\left(0.0^{+1.5}_{-0.0}\right)\ \mathrm{fm}$$

$$r_{\eta d} = \mp\left(4.3^{+8.6}_{-2.9}\right) + i\left(6.7^{+6.0}_{-8.4}\right)\ \mathrm{fm}$$

close to $a_{\eta d} = 1.23 + \mathrm{i}1.11$ fm obtained in a three-body calculation using $a_{\eta N} = 0.50 + \mathrm{i}0.33$ fm

M. Egorov, A. Fix, Phys. Rev. C 88, 054611 (2013).

Summary

Summary

Summary

1. cross sections are measured at $E_\gamma < 1.15\ \mathrm{GeV}$ for $\gamma d \to \pi^0 \eta d$
2. $\sigma(E_\gamma)$ is well-reproduced by the existing theoretical calculations with ηd FSI
3. $d\sigma/dM_{\eta d}$ and $d\sigma/dM_{\pi d}$ are decomposed to $\gamma d \to \mathcal{D}_{\mathrm{IV}} \to \pi^0 \mathcal{D}_{\eta d}/\eta \mathcal{D}_{12} \to \pi^0 \eta d$
   $\mathcal{D}_{\eta d}$: $I = 0, J^\pi = 1^-, M \sim 2.42\ \mathrm{GeV}, \Gamma \sim 0.03\ \mathrm{GeV}$
   a predicted bound state or a virtual state
4. another phenomenological analysis shows $a_{\eta d} = \pm\left(0.7^{+0.8}_{-0.6}\right) + i\left(0.0^{+1.5}_{-0.0}\right)$ fm, suggesting rather weak ηd attraction ($a_{\eta N} = 0.50 + \mathrm{i}0.33$ fm)
5. no theoretical calculations reproduce a rather flat angular distributions of deuteron emission

大阪大学
OSAKA UNIVERSITY

Hadron 2025

The 21st International Conference on Hadron Spectroscopy and Structure

HADRON2025

Toyonaka Campus, Osaka University, Japan, March 27 - 31, 2025

HADRON2025

Toyonaka Campus, Osaka University, Japan, March 27 - 31, 2025

This series of conferences started in 1985 in Maryland, USA. It brings together experimentalists and theorists every other year to review the status and progress in hadron spectroscopy, structure and related topics and to exchange ideas for future explorations.

The main physics topics of this conference include:

Hadron: 27~31 March 2025
HIN: 2~4 April 2025

Backup

Backup

Meson-nucleus interaction

QCD in the non-perturbative regime

Medium modification

Meson: excitation of the QCD vacuum described by various nonvanishing condensates

The properties of a meson: may change in a nucleus due to the partial restoration of chiral symmetry (decrease of the chiral condensate)

Meson-nucleus interaction reflects this modification

Meson-nucleus interaction

η-nuclear interaction

η-η' mixing

S.D. Bass, A.W. Thomas, Phys. Lett. B634, 368 (2006).
S. Hirenzaki, H. Nagahiro,
Acta Phys. Polon. B45, 619 (2014).
S.D. Bass, P. Moskal, Rev. Mod. Phys. 91, 015003 (2019).

ηN couples to $\underline{N(1535)1/2^{-}}$

candidate for the chiral partner of the nucleon

D. Jido et al., Phys. Rev. C 66, 045202 (2002);
Nucl. Phys. A 811, 158 (2008);
H. Nagahiro et al., Phys. Rev. C68, 035205 (2003);
Nucl. Phys. A761, 92 (2005).

η-mesic nucleus

η-meson nucleus bound state

Exotic: bound by the strong force alone
Strong ηA attraction is required

S-wave ηd system $\mathcal{D}_{\eta d}$ with $I = 0, J^{\pi} = 1^{-}$

The lightest η-mesic nucleus if bound

Bag model in a q^2−q^4 configuration: $M = 2.41\ \mathrm{GeV}$

P.J.G. Mulders, A.Th.M. Aerts, and J.J. de Swart, Phys. Rev. Lett. 40, 1543 (1978).

Three-body calculation for the ηNN−πNN coupled channels:

T. Ueda, Phys. Rev. Lett. 66, 297 (1991).

$$M \simeq M_{\eta} + M_{d},\ \Gamma = 0.01 \sim 0.02\ \mathrm{GeV}$$

ηNN bound state, ηd bound state ?

Analysis

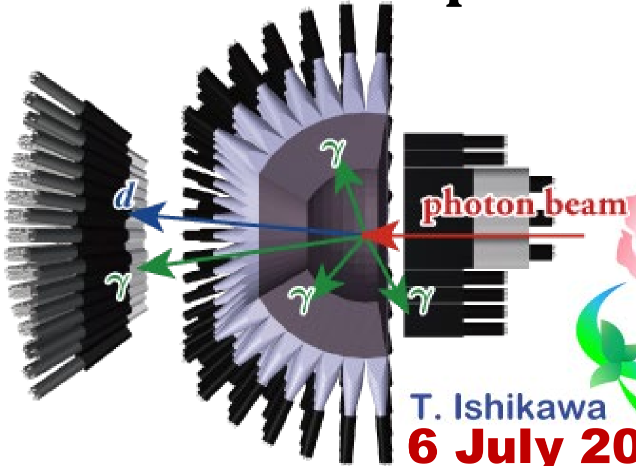
SKIP

Analysis

Event selection

SKIP

1. 4 neutral particles and 1 charged particle
2. π^0 and η: $\gamma\gamma$ decay
   time difference is less than $3\sigma_t$
   between every 2 neutral clusters out of 4
3. d is detected with SPIDER
   time delay is larger than 1 ns with respect to average $\gamma\gamma\gamma\gamma$ time
   Energy deposit is higher than $2E_{\text{mip}}$
4. Sideband background subtraction to remove accidental coincidence between STB-Tagger II and FOREST



Event selection

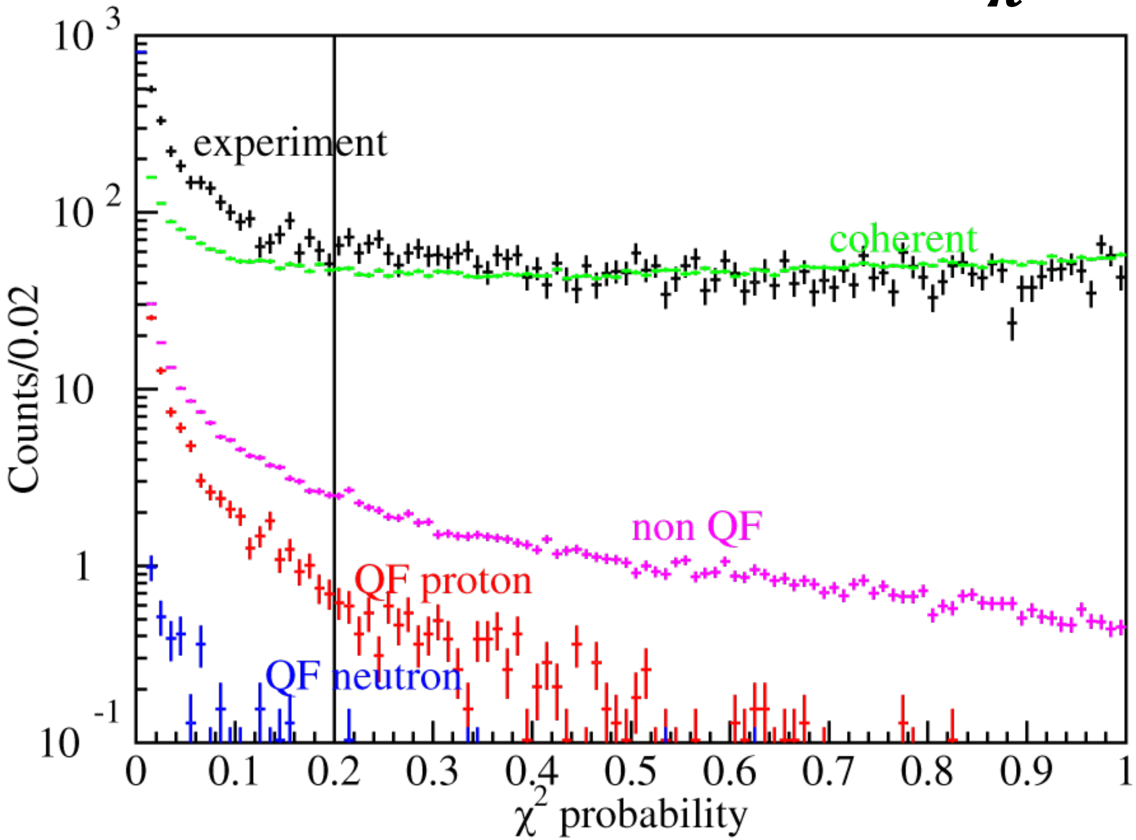
SKIP

Further event selection

a kinematic fit (KF) with 6 constraints is applied

energy and momentum conservation (4)

$\gamma\gamma$ invariant masses are m_{π^0} and m_η (2)



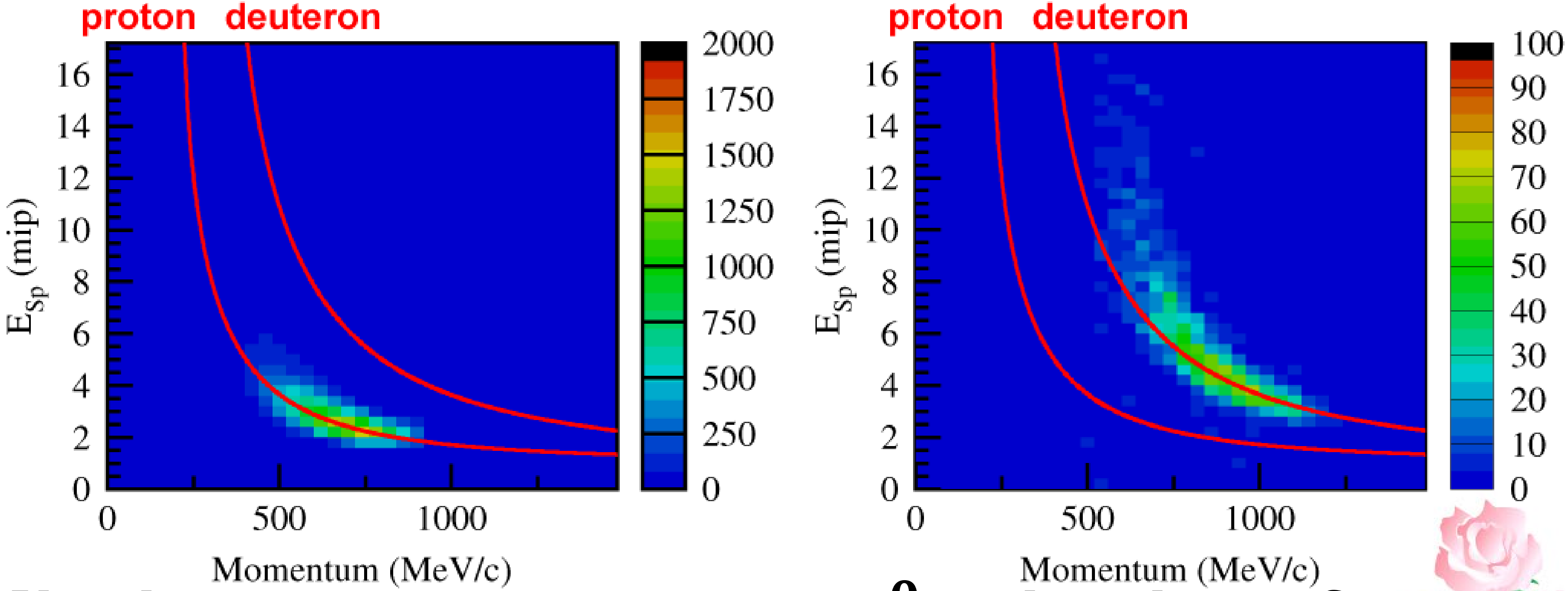
Event selection

SKIP

Further event selection

χ^2 probability is higher than 0.2

QF $\gamma p' \rightarrow \pi^0 \eta p$ is rejected using another KF



Missing momentum $d(\gamma, \pi^0 \eta)$ is given for a charged particle

Phenomenological analysis 1

Decomposition of the obtained $\pi^0 d$ and ηd invariant mass distributions at two highest incident energies

Two sequential processes

$$\gamma d \to \mathcal{D}_{\mathrm{IV}} \to \pi^0 \mathcal{D}_{\eta d} \to \pi^0 \eta d$$

$$\gamma d \to \mathcal{D}_{\mathrm{IV}} \to \eta \mathcal{D}_{12} \to \pi^0 \eta d$$

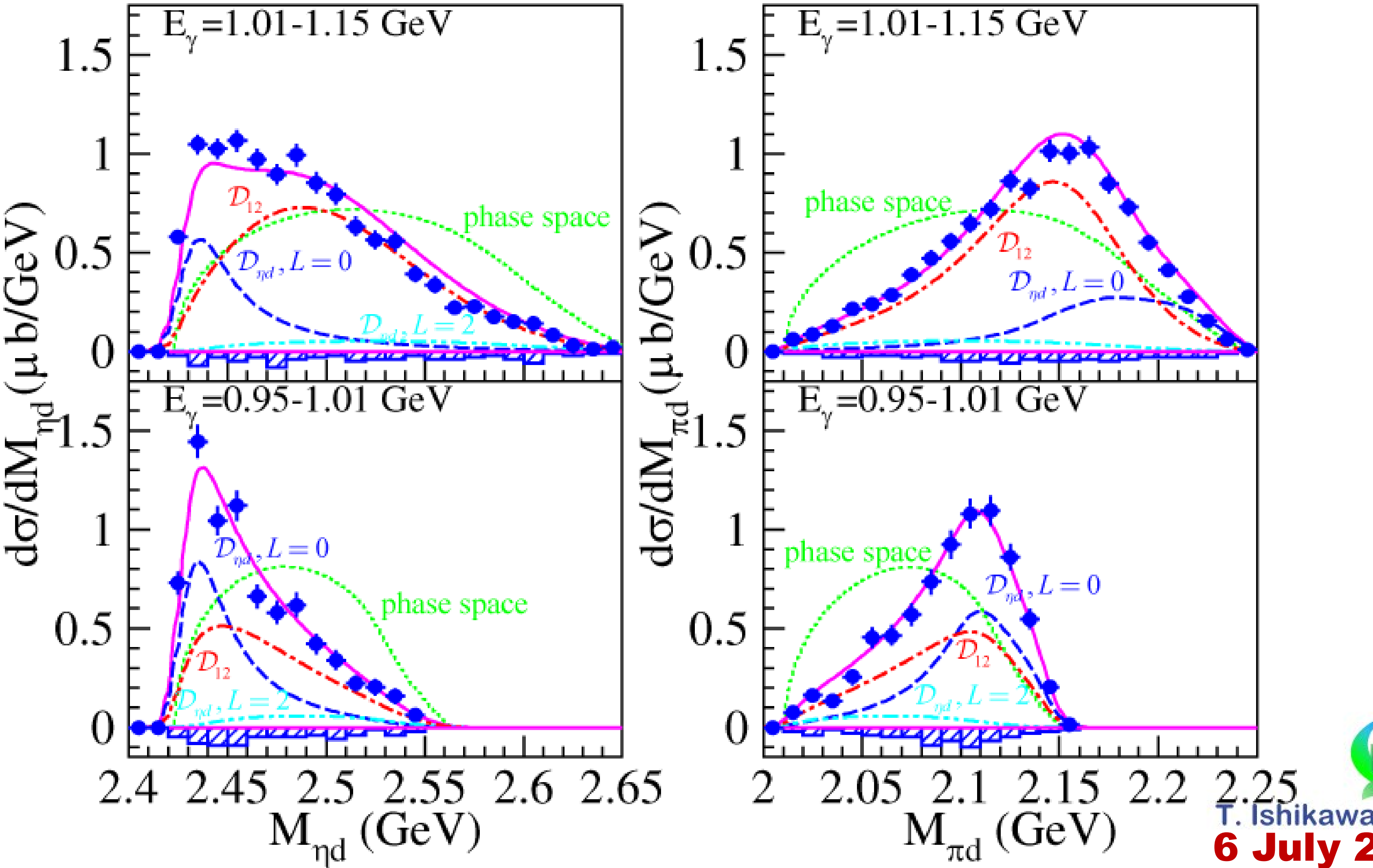
$\mathcal{D}_{\eta d}$: *S*-wave ηd system with $I = 0, J^{\pi} = 1^{-}$
Flatté: Breit-Wigner with M and $\Gamma = \Gamma_0 + g p_{\eta}$

$\mathcal{D}_{12}$: well-known πd resonance with $I = 1, J^{\pi} = 2^{+}$
Breit-Wigner with $M \sim 2.14\ \mathrm{GeV}$ and $\underline{\Gamma \sim 0.09\ \mathrm{GeV}}$
constant

simultaneous fit of $d\sigma/dM_{\pi d}$ and $d\sigma/dM_{\eta d}$ distributions to determine five parameters

Phenomenological analysis 1

$d\sigma/dM_{\eta d}$ and $d\sigma/dM_{\pi d}$



Phenomenological analysis 1

$\mathcal{D}_{\eta d}$: $\mathrm{M} = 2.427^{+0.013}_{-0.006}$ GeV, $\Gamma_0 = 0.029^{+0.006}_{-0.029}$ GeV,
$g = 0.00^{+0.41}_{-0.00}$

1) S-wave ηd resonance with a width broader than 0.05 GeV is ruled out

2) $g = 0$ gives a predicted ηd bound state isoscalar ηNN state from ηNN−πNN

$$M \simeq M_\eta + M_d, \Gamma = 0.01 \sim 0.02\ \text{GeV}$$

3) $\Gamma_0 = 0$ gives an ηd virtual state

$\mathcal{D}_{12}$: $\mathrm{M} = 2.158^{+0.003}_{-0.003}$ GeV, $\Gamma = 0.116^{+0.005}_{-0.011}$ GeV

4) consistent with the $\mathcal{D}_{12}$ parameters obtained in $\gamma d \to \pi^0\pi^0 d$