



ηA interaction studied in $\gamma d \rightarrow \pi^0 \eta d$

*Interaction between the eta meson and nucleus
studied in coherent neutral-pion and eta-meson
photoproduction on the deuteron*

APCTP Workshop on Nuclear Physics 2022: Physics of Excited Hadrons in the Present and Future Facilities

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Tohoku University, Japan
- T. Ishikawa et al., PRC104, L052201 (2021); PRC105, 045201 (2022).





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$\gamma d \rightarrow \pi^0 \eta d$ reaction

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total cross section ~ final-state interaction

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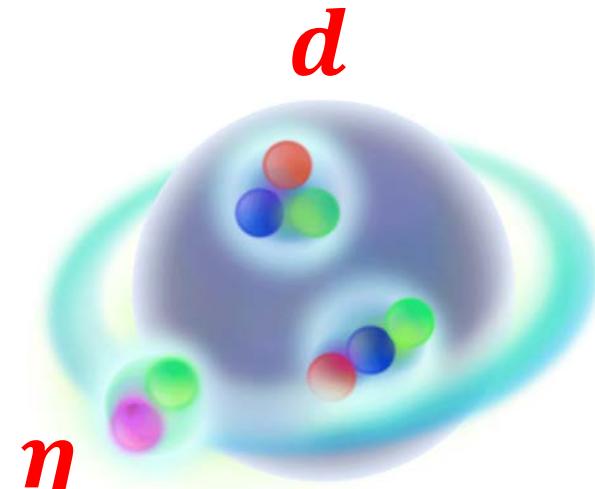
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T. Ishikawa et al., PRC104, L052201 (2021); PRC105, 045201 (2022).



T. Ishikawa





Introduction

Introduction





Meson-nucleus interaction

medium modification

the properties of a **meson** may change in a nucleus
excitation of the QCD vacuum

**due to the partial restoration of chiral symmetry
(decrease of the chiral condensate)**

meson-nucleus interaction reflects this modification

η -nuclear interaction

η - η' mixing S.D. Bass, A.W. Thomas, PLB634, 368 (2006).
S. Hirenzaki, H. Nagahiro, APPB45, 619 (2014).
S.D. Bass, P. Moskal, RMP91, 015003 (2019).

ηN couples to $N(1535)1/2^-$

candidate for the chiral partner of the nucleon

D. Jido et al., PRC66, 045202 (2002); NPA811, 158 (2008);
H. Nagahiro et al., PRC68, 035205 (2003); NPA761, 92 (2005).



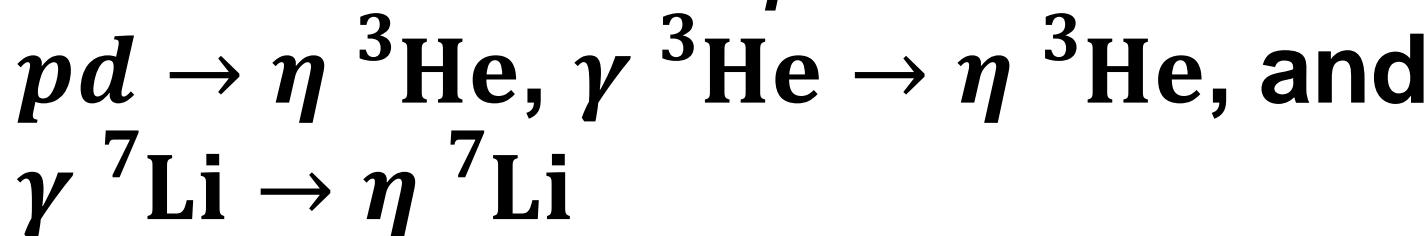


η -nuclear interaction

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



B. Mayer et al., PRC53, 2068 (1996);

J. Smyrski et al., PLB649, 258 (2007);

T. Mersmann et al., PRL98, 242301 (2007);

M. Pfeiffer et al., PRL92, 252001 (2004); PRL94, 049102 (2005);

F. Pheron et al., PLB709, 21 (2012);

B. Krusche and C. Wilkin, PPNP80, 43 (2014);

Y. Marghrbi et al., EPJA49, 38 (2013).





hadronic process

rich information on the low-energy η -nuclear dynamics from $pn \rightarrow \eta d$, $pd \rightarrow \eta pd$

initial-state interaction, and
various two-step mechanisms,

leading to undesirable model dependence

H. Calén et al., PRL79, 2672 (1997); PRL80, 2069 (1998);
F. Hibou et al. EPJA7, 537 (2000);
R. Bilger et al., PRC69, 014003 (2004).

electromagnetic process

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

no initial-state interaction

ηA : low relative-momentum condition

$\pi^0 A$: small absorption

$\pi^0 \eta$: negligibly small below $a_0(980)$

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





η -mesic nucleus

η -meson nucleus bound state

exotic state

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: $M = 2.41 \text{ GeV}$

P.J.G. Mulders, A.Th.M. Aerts, and J.J. de Swart, PRL40, 1543 (1978).

three-body calculation for the $\eta NN-\pi NN$ coupled channels:

T. Ueda, PRL66, 297 (1991).

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

ηNN bound state
 ηd bound state ?



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Experiment

Experiment





Accelerator

Electron Beam

LINAC 150 MeV

Booster Ring 1200 MeV (max)

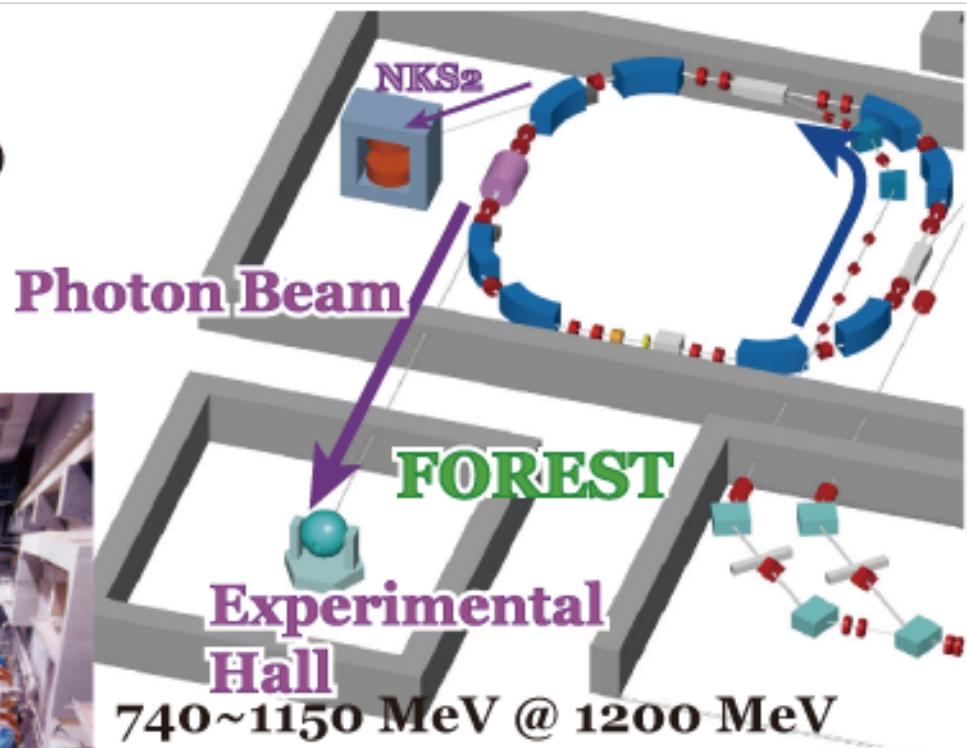
Photon Beam

Bremsstrahlung

Tagged



1.3 GeV Booster STorage Ring



Photon Beam

FOREST

Experimental
Hall

740~1150 MeV @ 1200 MeV

~20 MHz (photon: 10 MHz)

$W_{\gamma d}=2.50\sim2.80 \text{ GeV}$

570~890 MeV @ 930 MeV

~2.8 MHz (photon: 1.2 MHz)

$W_{\gamma d}=2.38\sim2.61 \text{ GeV}$

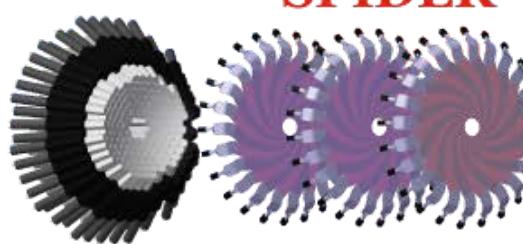
T. Ishikawa et al., NIMA 622, 1 (2010); T. Ishikawa et al., NIMA 811, 124 (2016);
Y. Matsumura et al., NIMA 902, 103 (2018); Y. Obara et al., NIMA 922, 108 (2019).





EM calorimeter

SCISSORS III SPIDER



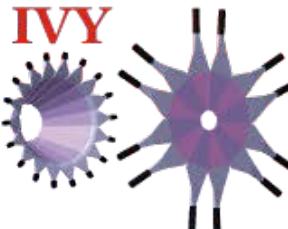
192 CsI crystals
3% @ 1 GeV

Backward Gamma



252 Lead/SciFi modules
7% @ 1 GeV

LOTUS



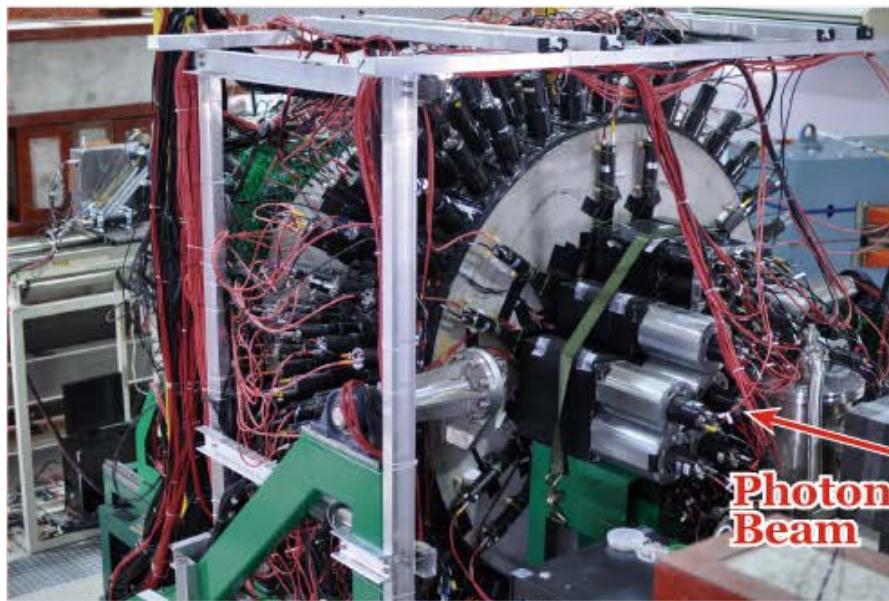
IVY

Rafflesia II

Photon Beam



62 Lead Glasses
5% @ 1 GeV

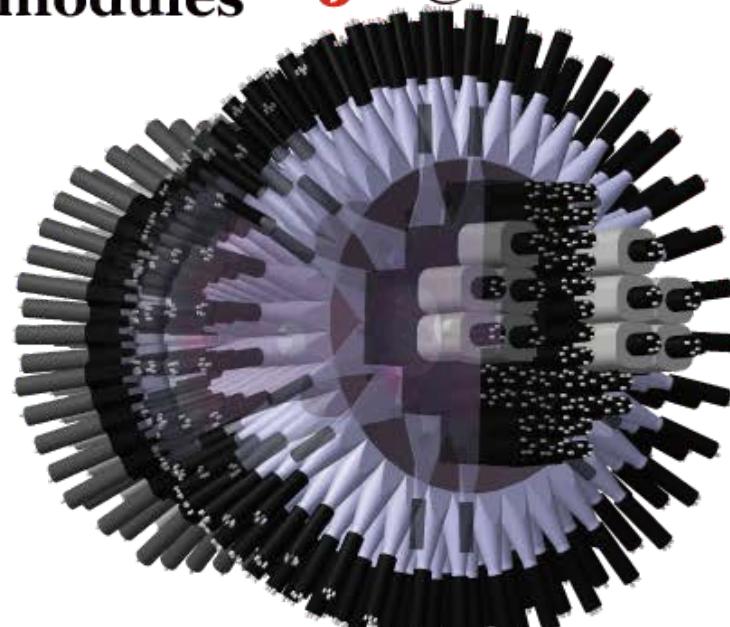


Target: 45 mm thick LH₂ & LD₂

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



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FOREST electro-magnetic
calorimeter

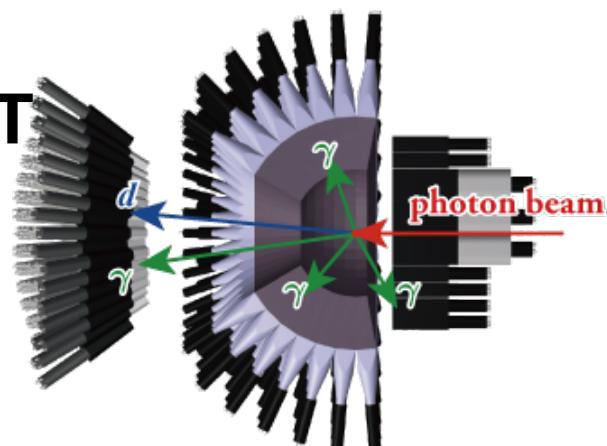


Analysis



Event selection ($\gamma d \rightarrow \pi^0 \eta d$)

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
(response of SCISSORS III is not required)
time delay is larger than 1 ns wrt 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



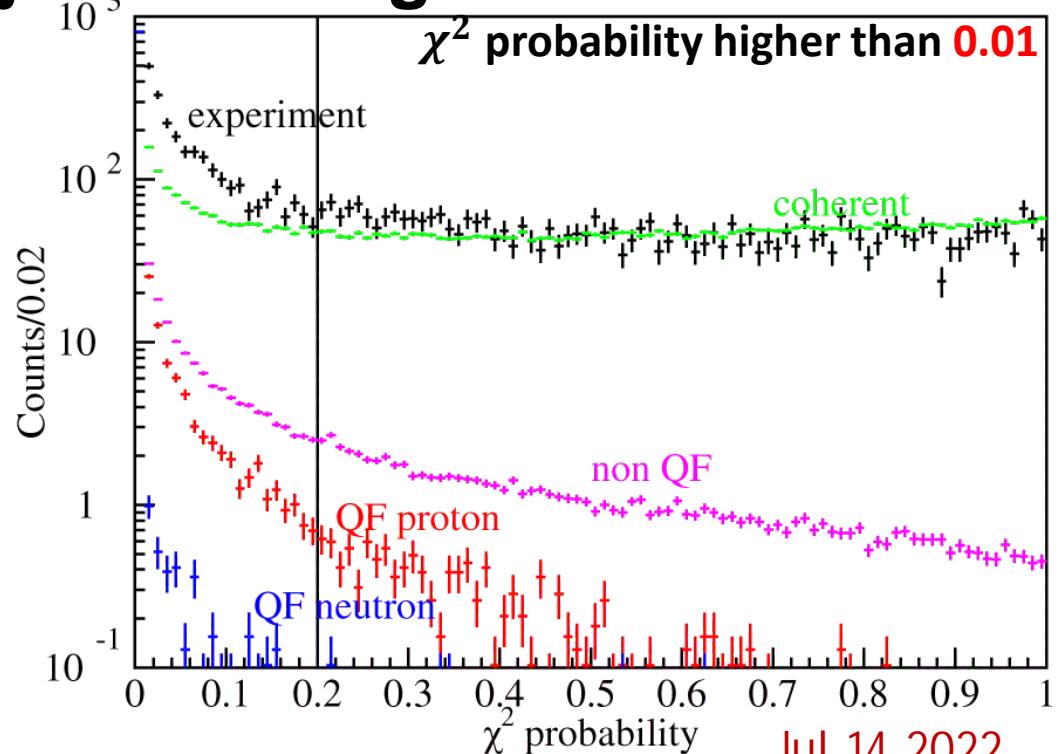
Further event selection

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)

χ^2 probability is higher than **0.2**

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



Further event selection

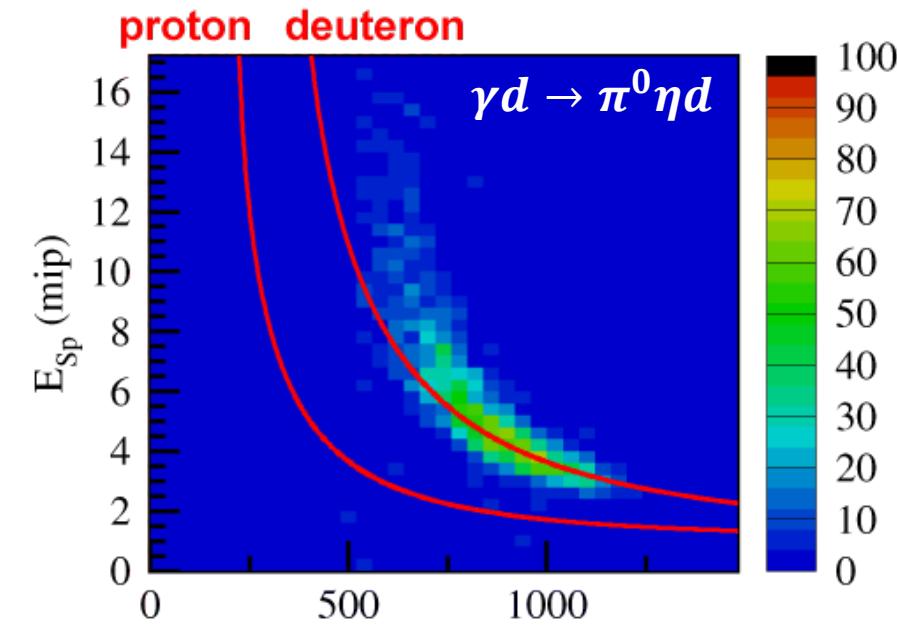
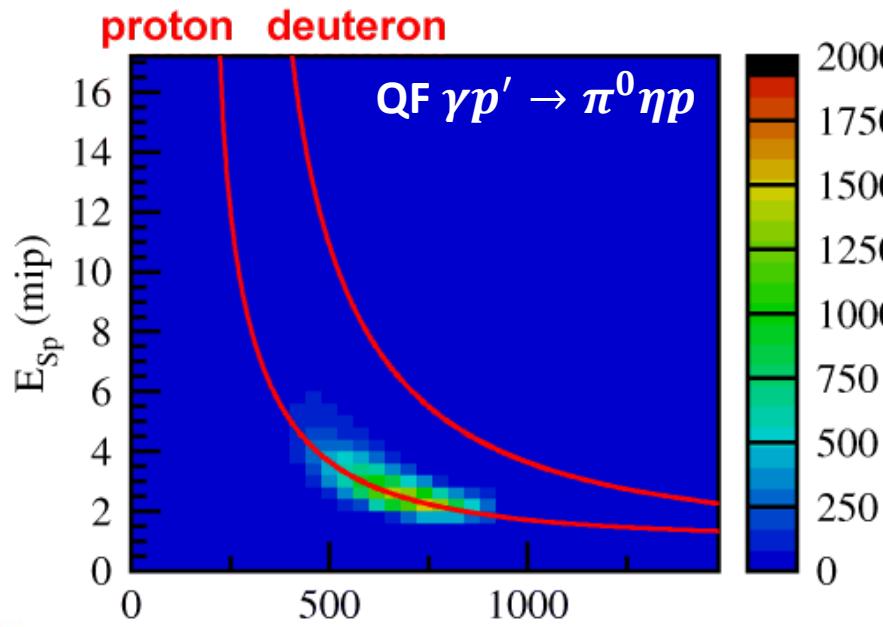
a kinematic fit (KF) with 6 constraints is applied

energy and momentum conservation (4)

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

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



Results

Results



Total cross section

excitation function

dashed curves

impulse

solid curves

meson-nucleus final-state interaction

two models

- 1) M. Egorov, A. Fix, PRC88, 054611 (2013).
- 2) M. Egorov, PRC101, 065205 (2020).

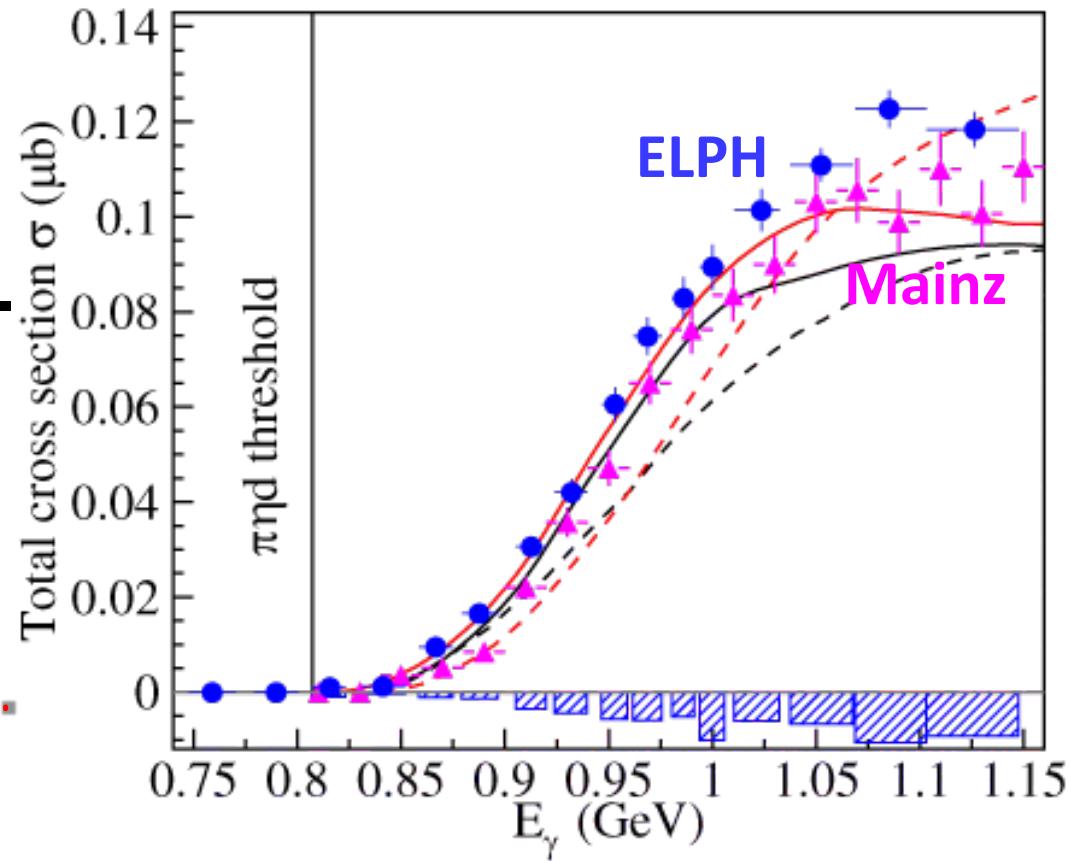
unified microscopic approach

$\pi^\pm N \rightarrow \eta N$ and $\pi^\pm N \rightarrow N$ reaction
on the spectator nucleon



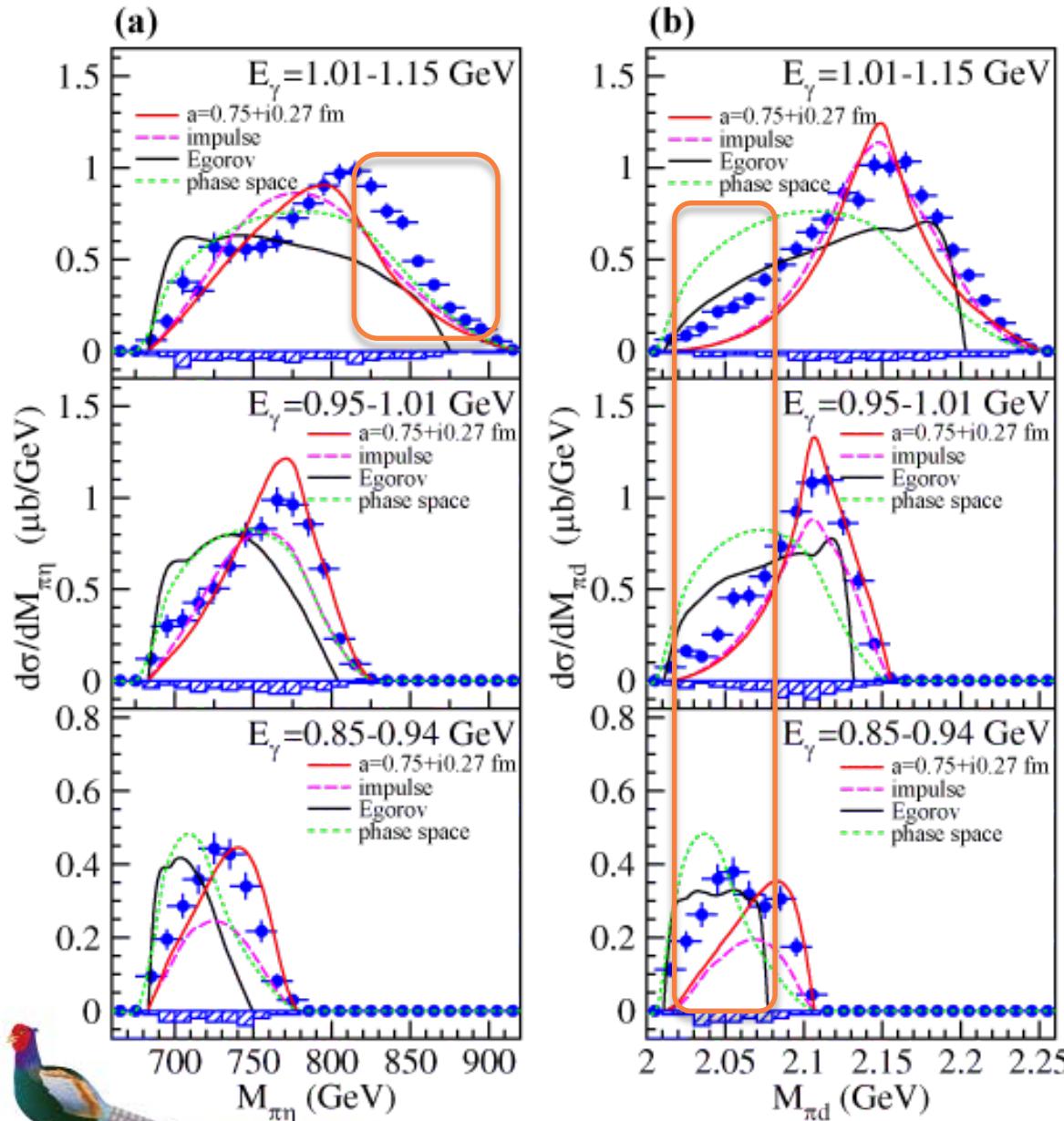
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A. Käser et al., PLB748, 244(2015)



Differential cross sections

for the first time



$d\sigma/dM_{\pi\eta}$:
little FSI effects
absence of $a_0(980)$

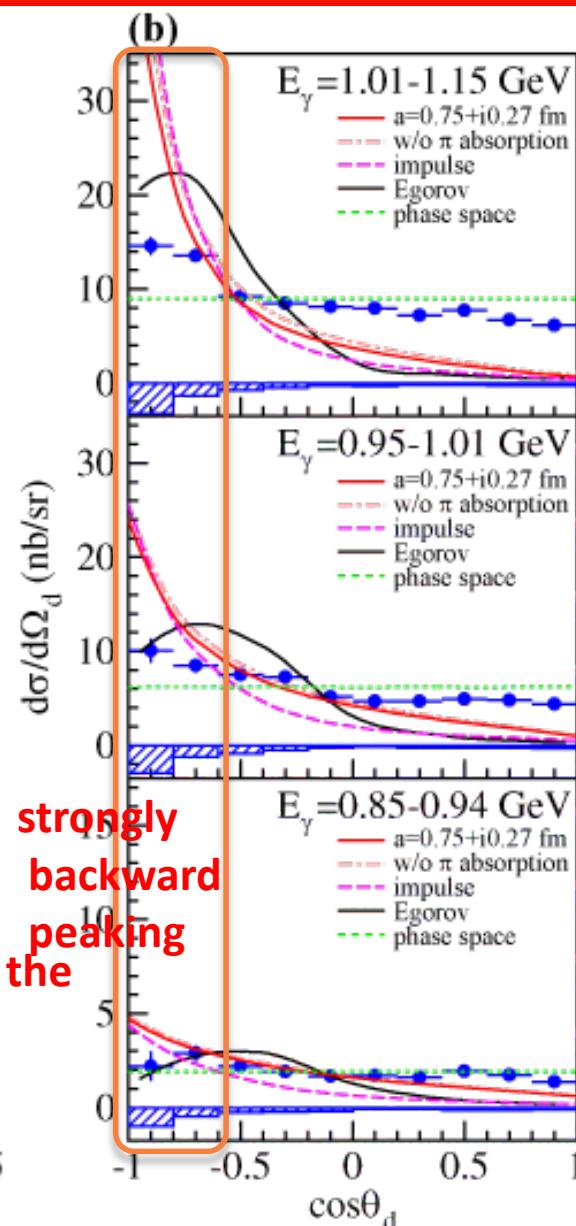
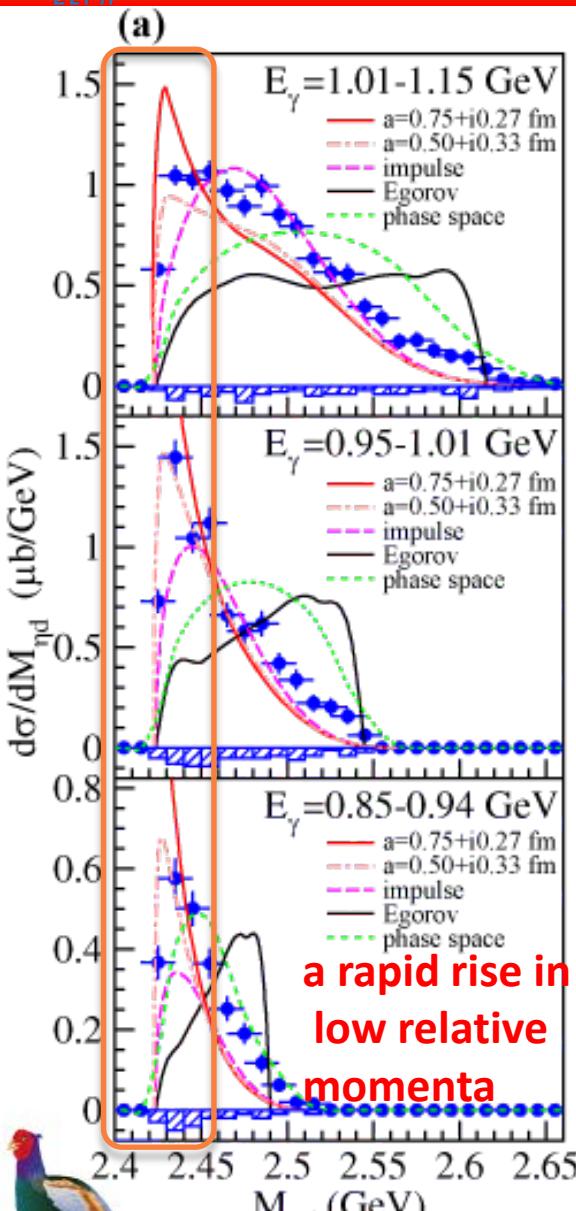
$d\sigma/dM_{\pi d}$:
maximum at $M_{\pi d} \approx M_N + M_\Delta$
quasifree Δ prod or D_{12} dibaryon
discrepancy at low masses
more complicated πd FSI?



T. Ishikawa



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

$d\sigma/d\Omega_d$:
rather uniform
coherent sum of elementary amplitudes

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

two sequential processes

$$\gamma d \rightarrow \mathcal{D}_{\text{IV}} \rightarrow \pi^0 \mathcal{D}_{\eta d} \rightarrow \pi^0 \eta d$$

$$\gamma d \rightarrow \mathcal{D}_{\text{IV}} \rightarrow \eta \mathcal{D}_{12} \rightarrow \pi^0 \eta d$$

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

Flatté: Breit-Wigner with M and $\Gamma = \Gamma_0 + gp_\eta$

\mathcal{D}_{12} : well-known πd resonance with $I = 1, J^\pi = 2^+$

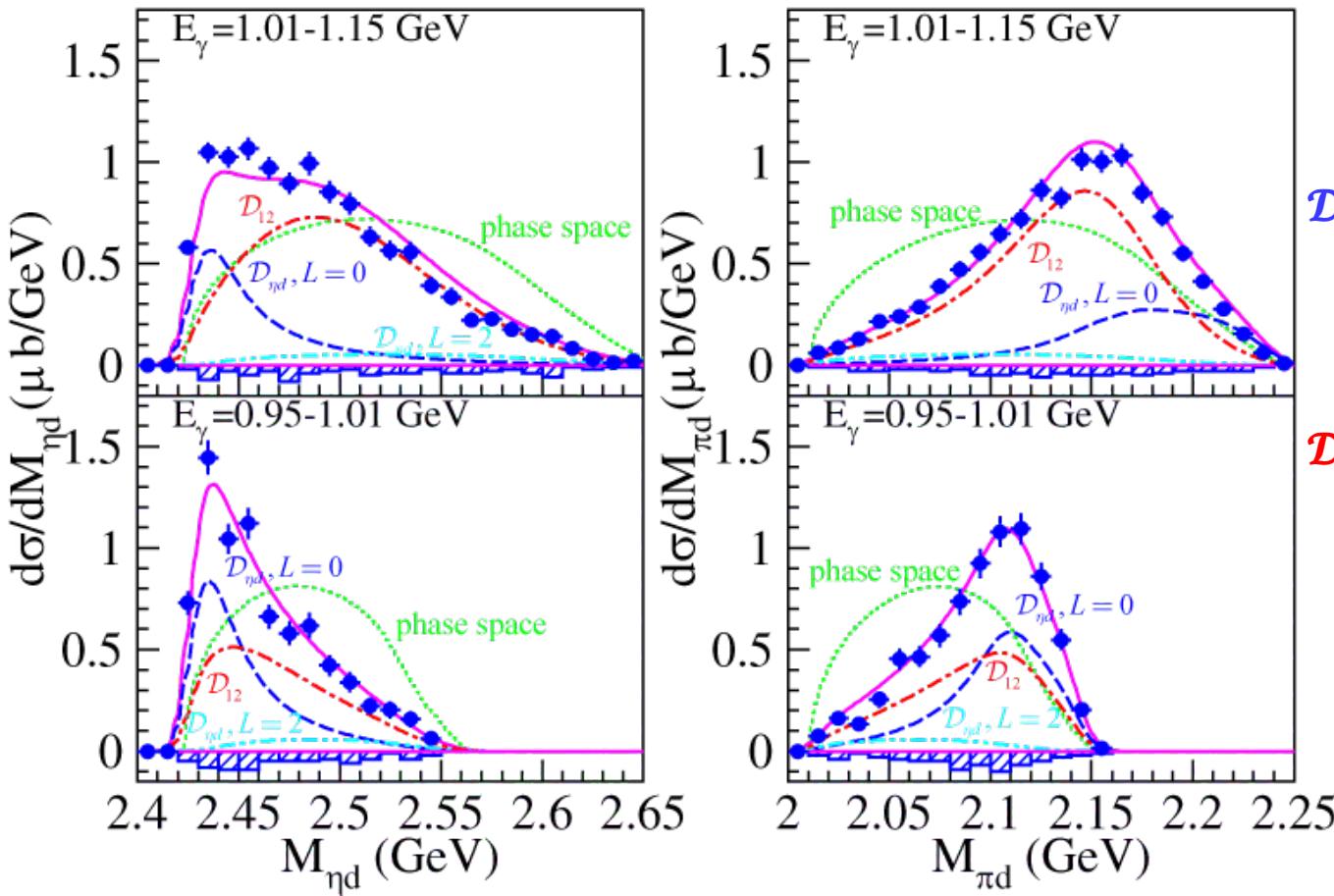
mass ~ 2.14 GeV, width ~ 0.09 GeV

Breit-Wigner with M and Γ (constant)

simultaneous fit of $d\sigma/dM_{\pi d}$ and $d\sigma/dM_{\eta d}$
distributions at two highest incident photon
energies to determine five parameters



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



$\mathcal{D}_{\eta d}$:

$$\begin{aligned} M &= 2.427^{+0.013}_{-0.006} \text{ GeV} \\ \Gamma_0 &= 0.029^{+0.006}_{-0.029} \text{ GeV} \\ g &= 0.00^{+0.41}_{-0.00} \end{aligned}$$

\mathcal{D}_{12} :

$$\begin{aligned} M &= 2.158^{+0.003}_{-0.003} \text{ GeV} \\ \Gamma &= 0.116^{+0.005}_{-0.011} \text{ GeV} \end{aligned}$$

$\mathcal{D}_{\eta d} (M \sim 2.43 \text{ GeV}, \Gamma \sim 0.03 \text{ GeV})$ & $\mathcal{D}_{12} (M \sim 2.16 \text{ GeV}, \Gamma \sim 0.12 \text{ GeV})$
consistent with the \mathcal{D}_{12} parameters obtained in $\gamma d \rightarrow \pi^0 \pi^0 d$



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

$\mathcal{D}_{\eta d}$:

$$M = 2.427^{+0.013}_{-0.006} \text{ GeV}$$

$$\Gamma_0 = 0.029^{+0.006}_{-0.029} \text{ GeV}$$

$$g = 0.00^{+0.41}_{-0.00}$$

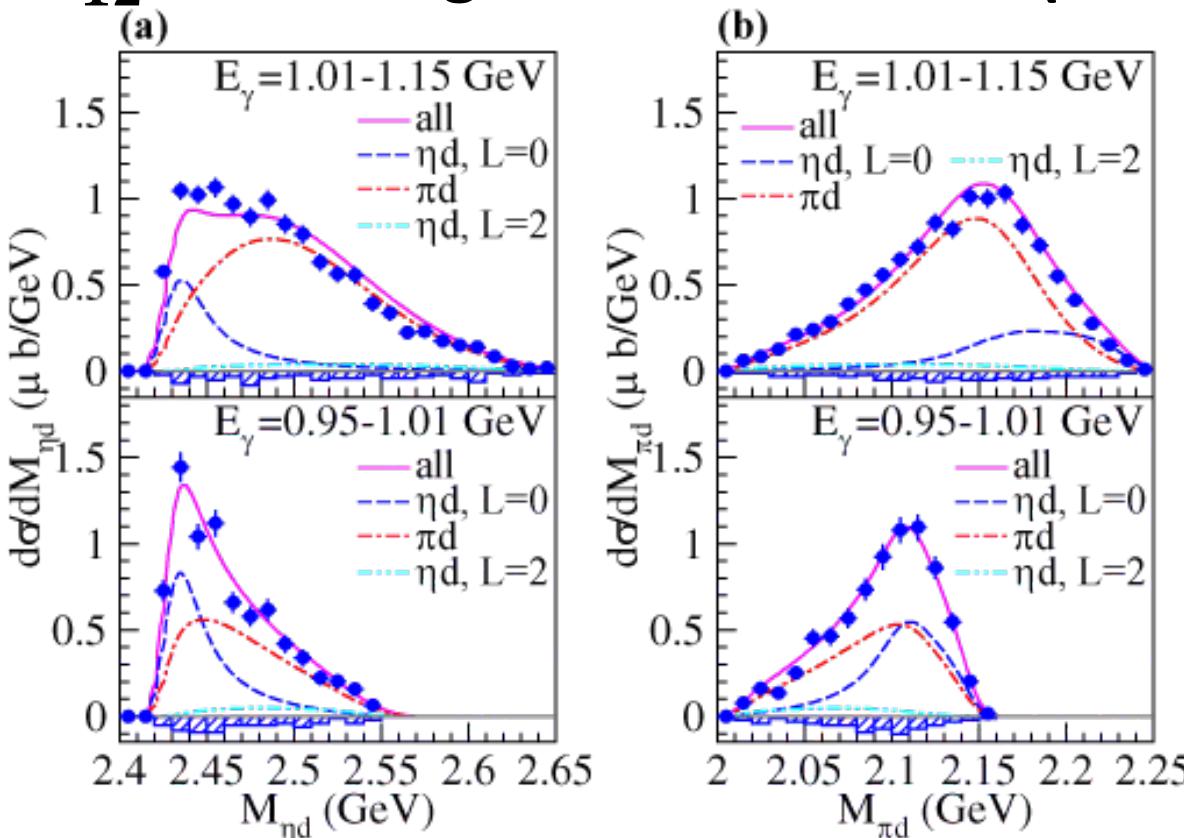
- 1) **S -wave ηd resonance with a width broader than 0.05 GeV is ruled out**
- 2) **$g = 0$ gives a predicted ηd bound state isoscalar ηNN state from $\eta NN - \pi NN$**
 $M \simeq M_\eta + M_d, \Gamma = 0.01 \sim 0.02 \text{ GeV}$
- 3) **$\Gamma_0 = 0$ gives an ηd virtual state**

T. Ueda, PRL66, 297 (1991).



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

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



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

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

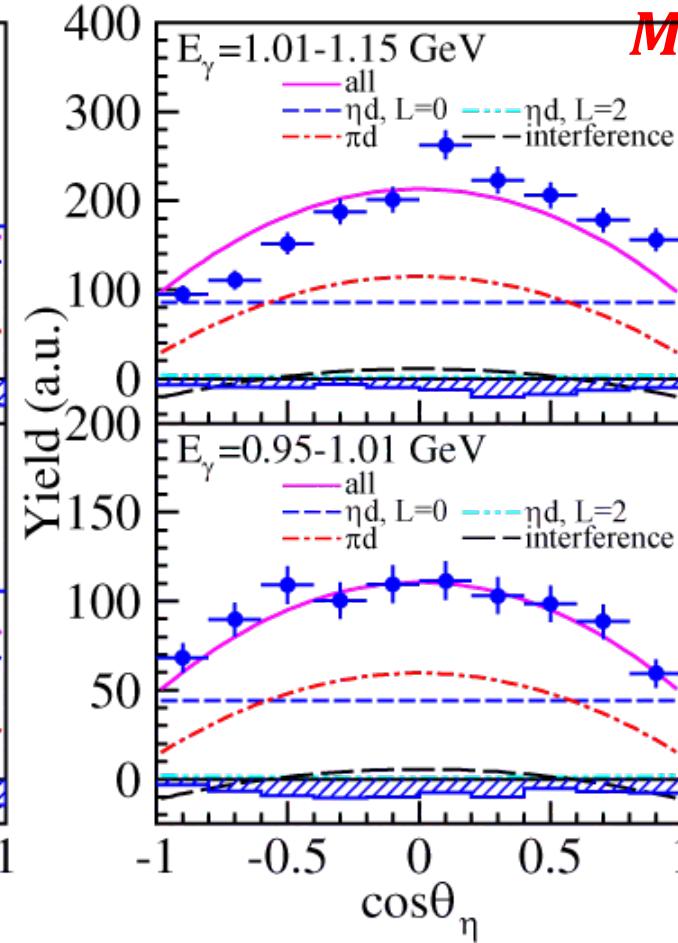
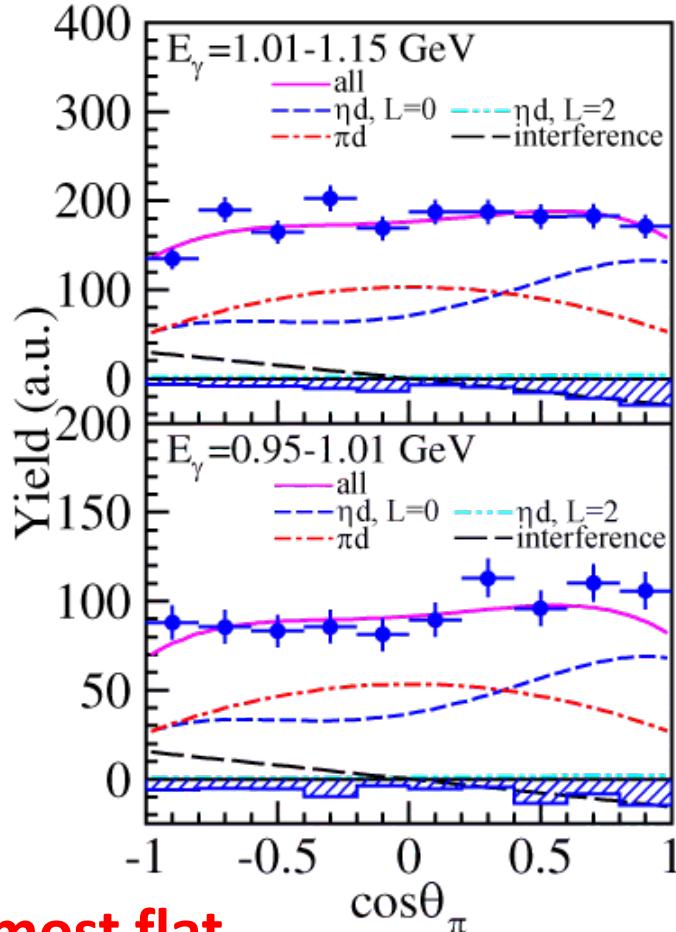
close to $a_{\eta d} = 1.23 + i1.11 \text{ fm}$ obtained in a three-body calculation using $a_{\eta N} = 0.50 + i0.33 \text{ fm}$





Angular correlations

angular distributions for the ηd correlated state



$\pi\text{--}\eta$ in the ηd rest frame
(opposite sign)

decomposed to the two sequential processes





Observed states

angular distribution & correlation

similar yields

$$L = 1, 2$$

$$L = 0, 1, 2$$

$$L = 0, 2$$

$$d(1^+) \rightarrow \mathcal{D}_{\text{IV}}(0^-, 1^\pm, 2^\pm) \rightarrow \mathcal{D}_{\eta d}(1^-) \rightarrow d(1^+)$$

47%

$$d(1^+) \rightarrow \mathcal{D}_{\text{IV}}(2^+) \rightarrow \mathcal{D}_{12}(2^+) \rightarrow d(1^+)$$

$$L = 1, 2$$

$$L = 1$$

$$L = 1$$

The major 0^- contribution suggests that not a $N\Delta^*$ but a NN^* molecule-like state plays a role as a doorway.
This seems **inconsistent** with the fact that the $\Delta(1700)3/2^-$ is the main contributor for the elementary $\pi\eta$ photoproduction

M. Döring et al., PRC73, 045209 (2006); J. Ajaka et al., PRL100, 052003 (2008);
A. Fix et al., PRC82, 035207 (2010); E. Gutz et al., EPJA50, 74 (2014);
V. Sokhoyan et al., PRC97, 055212 (2018).



total cross section

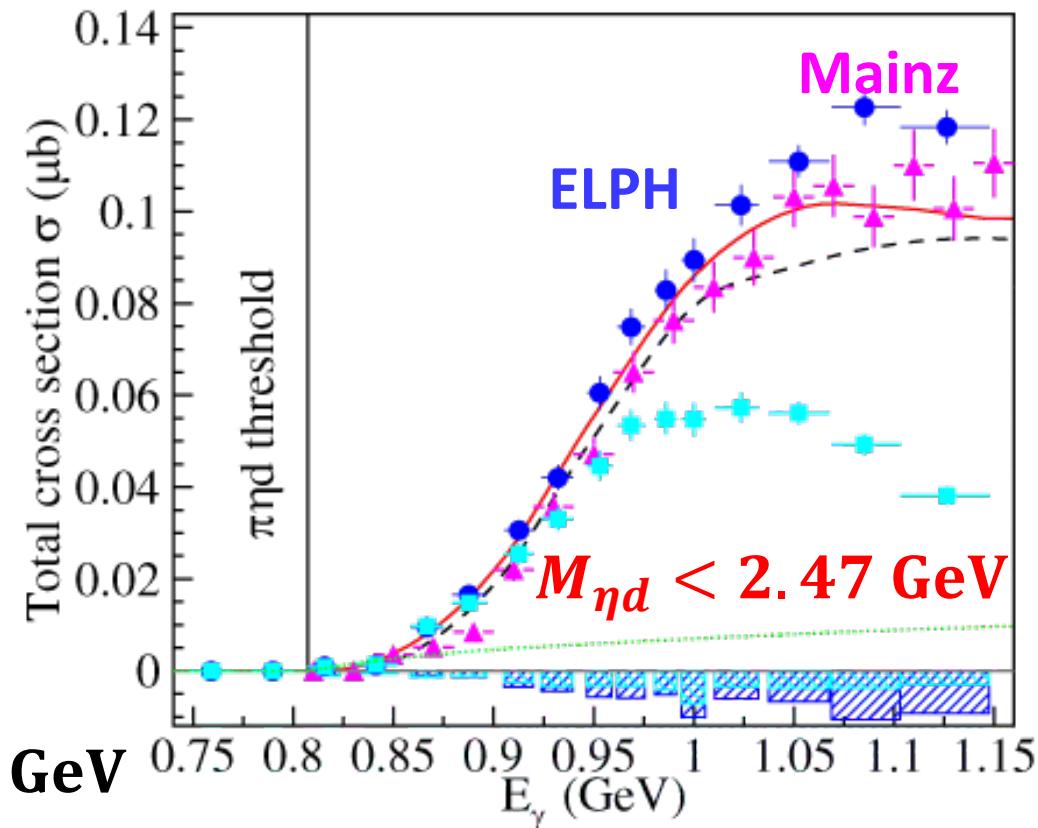
two models

M. Egorov, A. Fix,
PRC88, 054611 (2013).

M. Egorov, PRC101,
065205 (2020).

unified microscopic approach

A. Käser *et al.*, PLB748, 244 (2015).



The events with $M_{\eta d} < 2.47 \text{ GeV}$

form a bump around 1 GeV

$0^- N\Delta(1620)S_{31}$, $NN(1650)S_{11}$, $NN(1700)D_{13}$ for $\pi^0 \mathcal{D}_{\eta d}$

$\mathcal{D}_{\eta d}(1^-) \sim NN(1535)S_{11}$

$2^+ NN(1720)P_{13}$, $N\Delta(1600)P_{33}$ for $\eta \mathcal{D}_{12}$
 $\mathcal{D}_{12}(2^+) \sim N\Delta(1232)P_{33}$

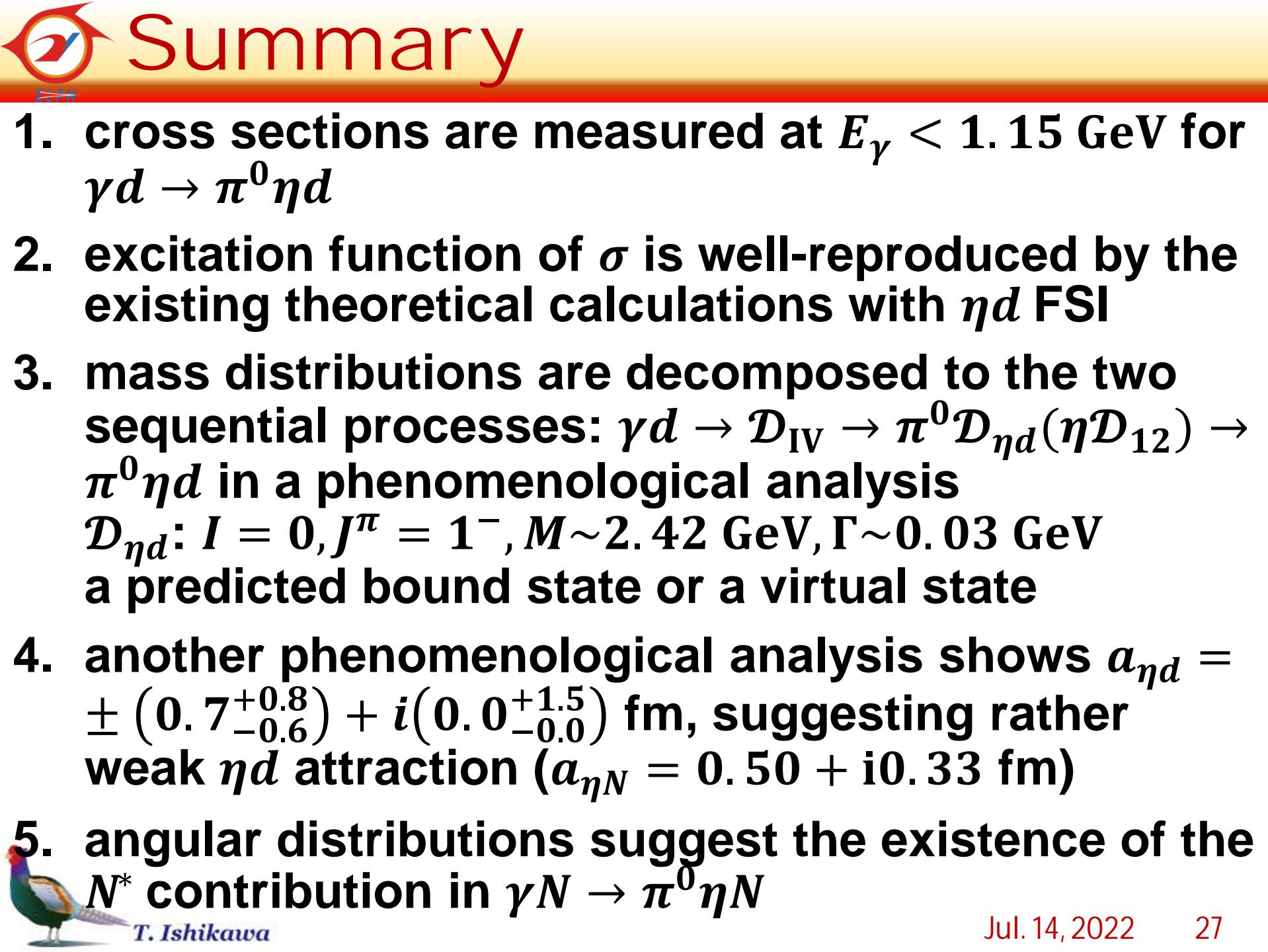




Summary

Summary





Summary

1. cross sections are measured at $E_\gamma < 1.15 \text{ GeV}$ for $\gamma d \rightarrow \pi^0 \eta d$
2. excitation function of σ is well-reproduced by the existing theoretical calculations with ηd FSI
3. mass distributions are decomposed to the two sequential processes: $\gamma d \rightarrow \mathcal{D}_{\text{IV}} \rightarrow \pi^0 \mathcal{D}_{\eta d} (\eta \mathcal{D}_{12}) \rightarrow \pi^0 \eta d$ in a phenomenological analysis
 $\mathcal{D}_{\eta d}$: $I = 0, J^\pi = 1^-$, $M \sim 2.42 \text{ GeV}$, $\Gamma \sim 0.03 \text{ GeV}$
a predicted bound state or a virtual state
4. another phenomenological analysis shows $a_{\eta d} = \pm (0.7^{+0.8}_{-0.6}) + i(0.0^{+1.5}_{-0.0}) \text{ fm}$, suggesting rather weak ηd attraction ($a_{\eta N} = 0.50 + i0.33 \text{ fm}$)
5. angular distributions suggest the existence of the N^* contribution in $\gamma N \rightarrow \pi^0 \eta N$





Summary

5. no theoretical calculations reproduce a rather flat angular distributions of deuteron emission in $\gamma d \rightarrow \pi^0 \eta d$ ($\gamma d \rightarrow \pi^0 \pi^0 d$)

1. M. Egorov and A. Fix, PRC88, 054611 (2013);
2. M. Egorov, PRC101, 065205 (2020);
3. A. Martinez Torres, K. P. Khemchandani and E. Oset, arXiv: 2205.00948.

6. coherent $\pi^0 \eta$ from a nucleus is suitable for studying the η -nuclear interaction

$\gamma d \rightarrow \pi^0 \pi^0 d$

ELPH: T. Ishikawa et al., PLB772, 398 (2017); PLB789, 413 (2019);

A2: M.S. Günther, PoS(Hadron2017) 051 (2018);

BGOOD: T.C. Jude et al., arXiv: 2202.08594 (2022).

$\gamma d \rightarrow \pi^0 \eta d$

A2: Käser *et al.*, PLB748, 244(2015);

ELPH: T. Ishikawa et al., PRC104, L052201 (2021); PRC105, 045201 (2022).





Backup



exotic η -mesic nucleus

η meson is bound to the nucleus by the strong force alone **Q. Haider and L.C. Liu, PLB172, 257 (1986).**

behavior of η in a dense nuclear environment
in-medium properties of $N(1535)1/2^- \equiv N^*$
strongly couples to η and N
the chiral partner of the nucleon (?)

ηd bound state

the lightest η -mesic nucleus if it exists

$$\eta d \leftrightarrow NN^*$$

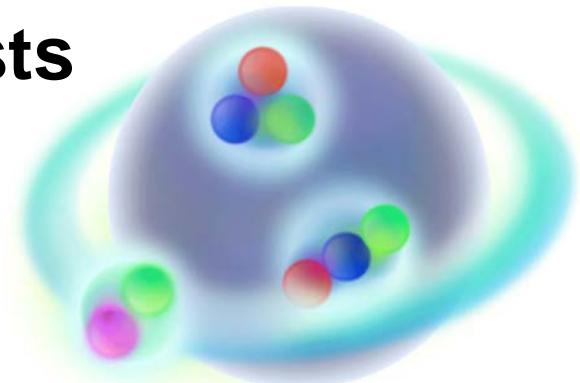
predicted near the ηd threshold with

$$\Gamma = 0.01 \sim 0.02 \text{ GeV}$$

T. Ueda, PRL66, 297 (1991); PLB291, 228 (1992).



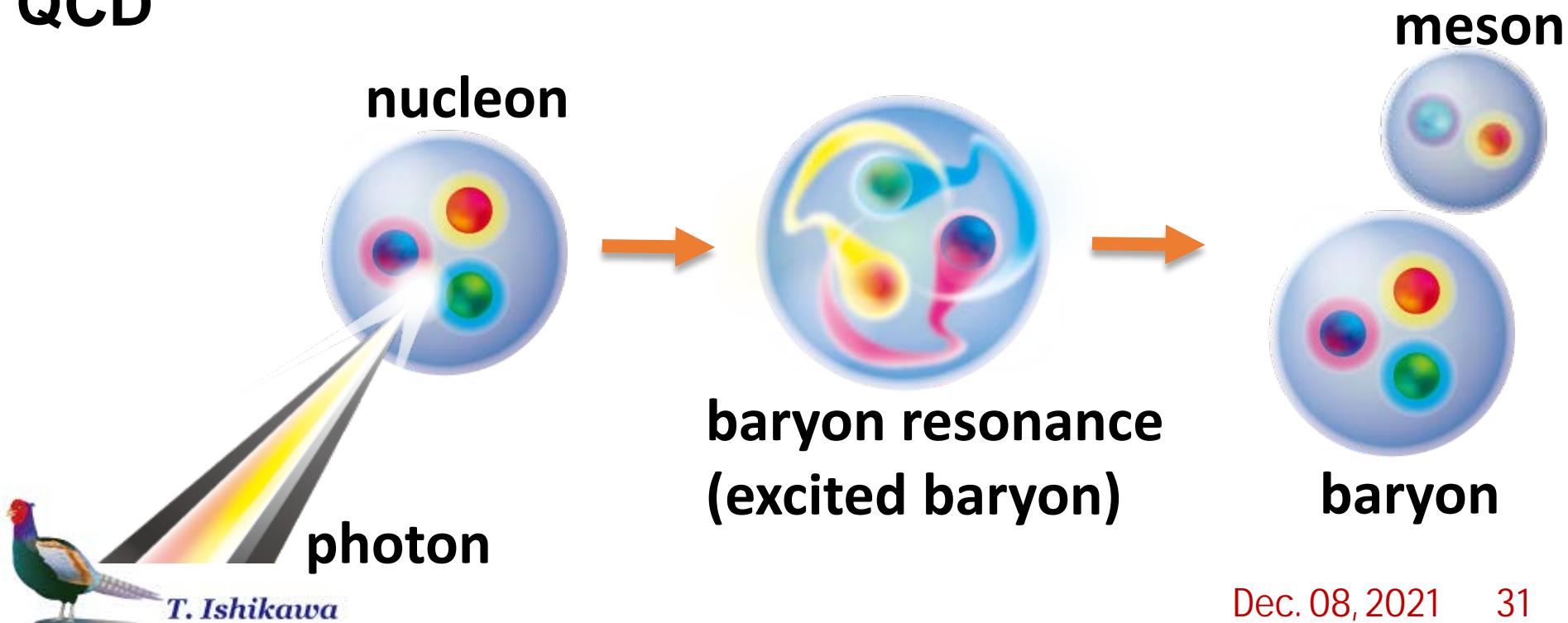
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meson photoproduction

a GeV photon beam has a function to **produce baryon resonances** from the nucleon

their excitation spectra are important testing ground for understanding the non-perturbative domain of QCD

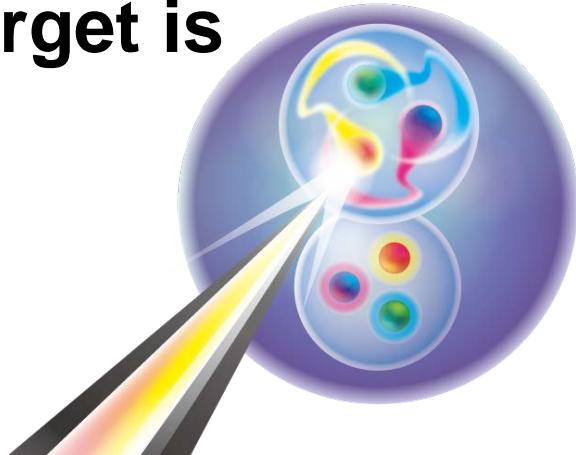


Introduction

meson photoproduction from a nucleus

baryon resonances are produced **from the quasi-free (QF) nucleon** even when a nuclear target is irradiated with a GeV photon beam.

the QF nucleon is a participant, and
the residual nucleus is a spectator



coherent meson photoproduction

the same nucleus appears in the final state

no spectator

meson-nucleus system



Introduction

$\gamma d \rightarrow \eta d$ P. Hoffmann-Rothe et al., PRL78, 4697 (1997);
J. Weiß et al., EPJA11, 371 (2001).

no indication of the ηd bound state

expressed by

coherent sum of the elementary amplitudes
coalescence of the deuteron

angular distribution of deuteron emission shows
strongly backward peaking

$\gamma d \rightarrow \pi^0 \pi^0 d$ PLB789, 413 (2019).

rather uniform angular distribution of deuteron
emission suggests the sequential process:

$\gamma d \rightarrow D_{IS} \rightarrow \pi^0 D_{IV} \rightarrow \pi^0 \pi^0 d$

How about $\gamma d \rightarrow \pi^0 \eta d$?



Introduction ~ $\gamma d \rightarrow \pi^0 \eta d$

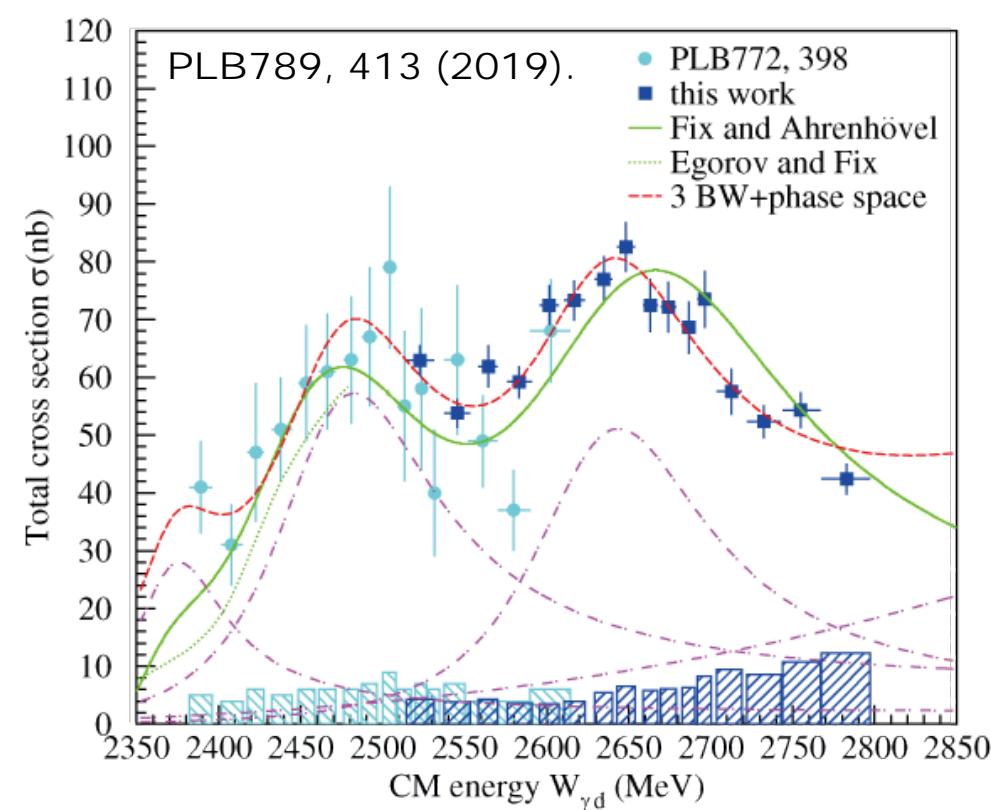
$\gamma d \rightarrow \pi^0 \pi^0 d$

total cross section as a function of the γd CM energy
(excitation function) at $E_\gamma < 1.2$ GeV

resonance-like behavior peaked at around 2.47 and
2.63 GeV

similar to the excitation
function of $\gamma N' \rightarrow \pi^0 \pi^0 N$

naïve interpretation is
QF excitation of the
nucleon in the deuteron



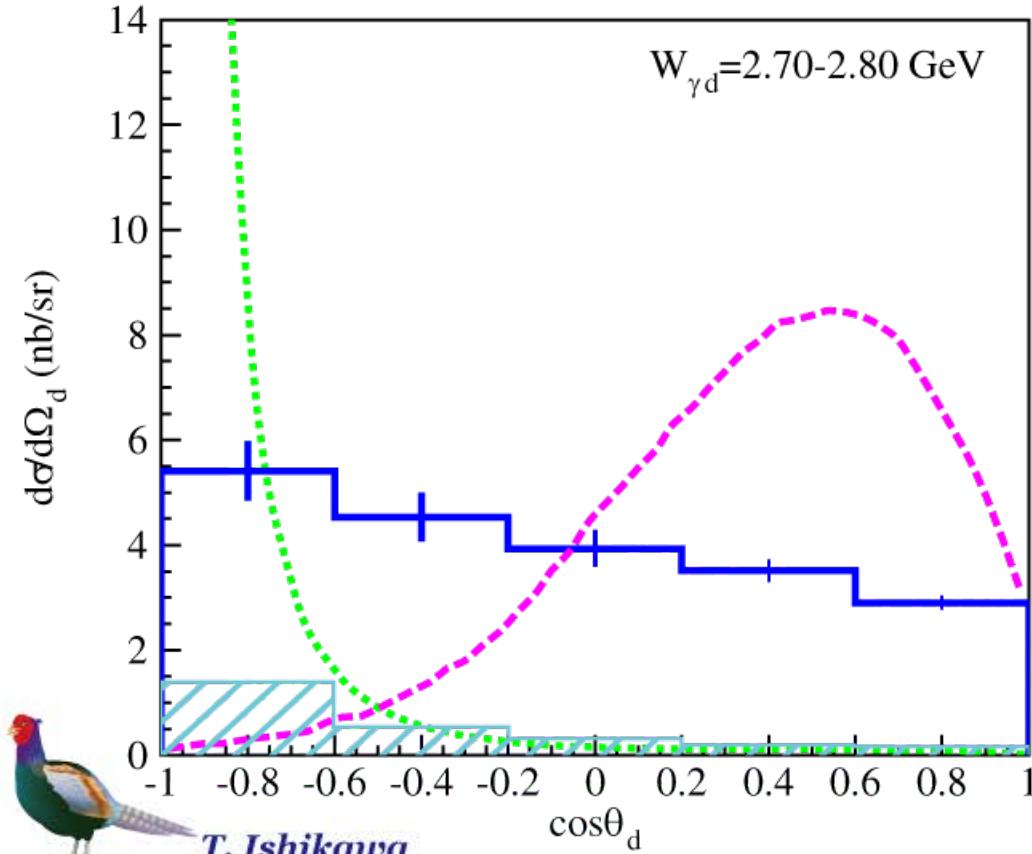


Introduction ~ $\gamma d \rightarrow \pi^0 \eta d$

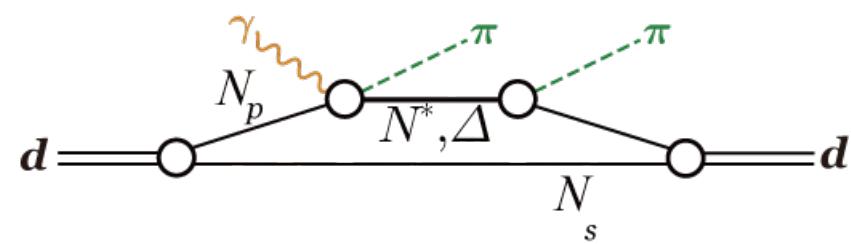
$\gamma d \rightarrow \pi^0 \pi^0 d$

the kinematic condition completely differs from QF process

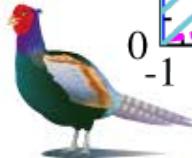
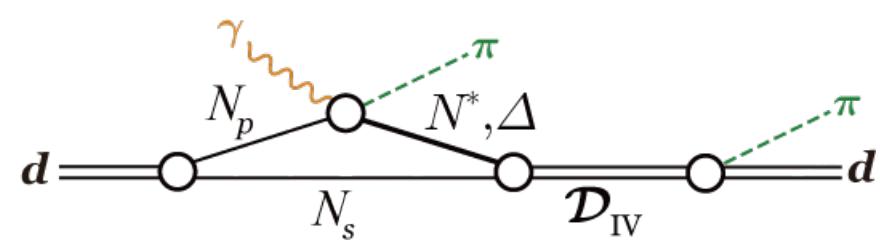
angular distribution of deuteron emission



QF $\pi\pi$ production



QF π production





Introduction

$$\gamma d \rightarrow \pi^0 \pi^0 d$$

$$I = 1, J^\pi = 2^+,$$

sequential process: $M = 2.14 \text{ GeV}, \Gamma = 0.09 \text{ GeV}$

$$\gamma d \rightarrow \mathcal{D}_{\text{IS}} \rightarrow \pi^0 \mathcal{D}_{\text{IV}} \rightarrow \pi^0 \pi^0 d$$

with an $I = 0$ dibaryon \mathcal{D}_{IS}
and an $I = 1$ dibaryon \mathcal{D}_{IV}

dibaryon: $B = 2$ resonance

two \mathcal{D}_{IS} s are observed
in the excitation function

How is $\gamma d \rightarrow \pi^0 \eta d$?

