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

EMMI Workshop "Meson and Hyperon Interactions with Nuclei"

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

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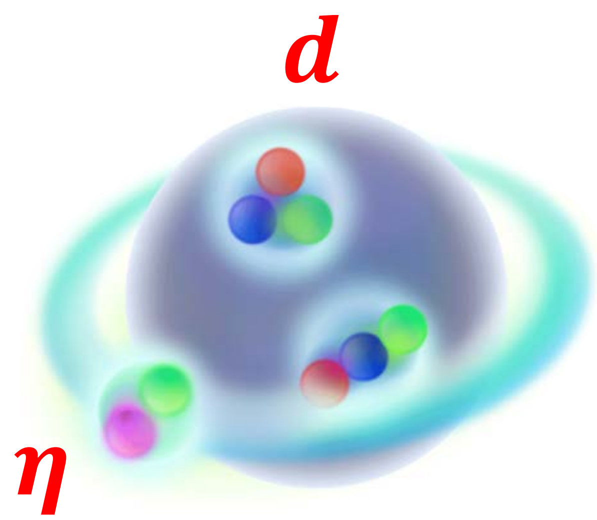

2. experiment

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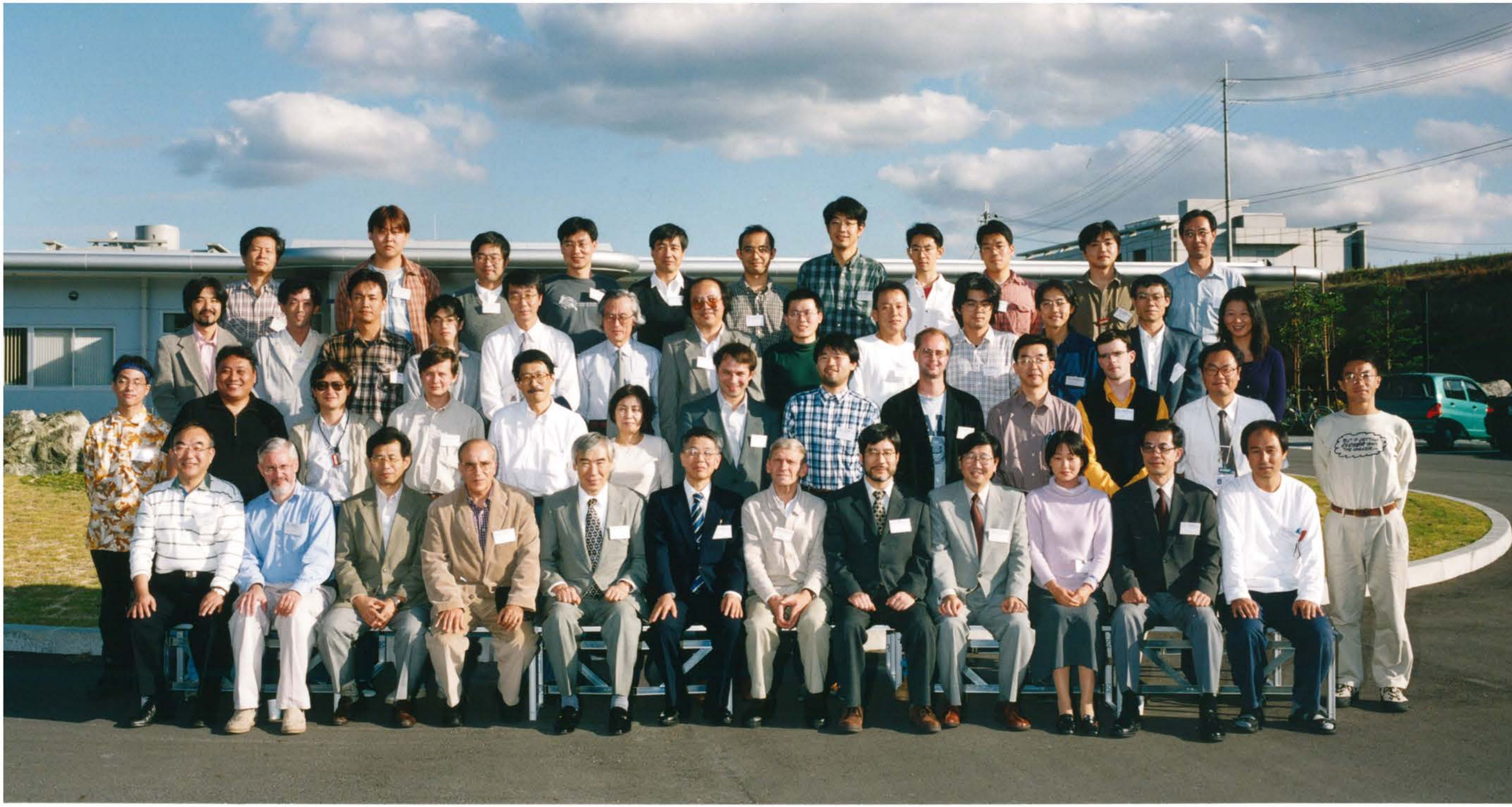
T. Ishikawa et al., PRC104, L052201 (2021); PRC105, 045201 (2022).

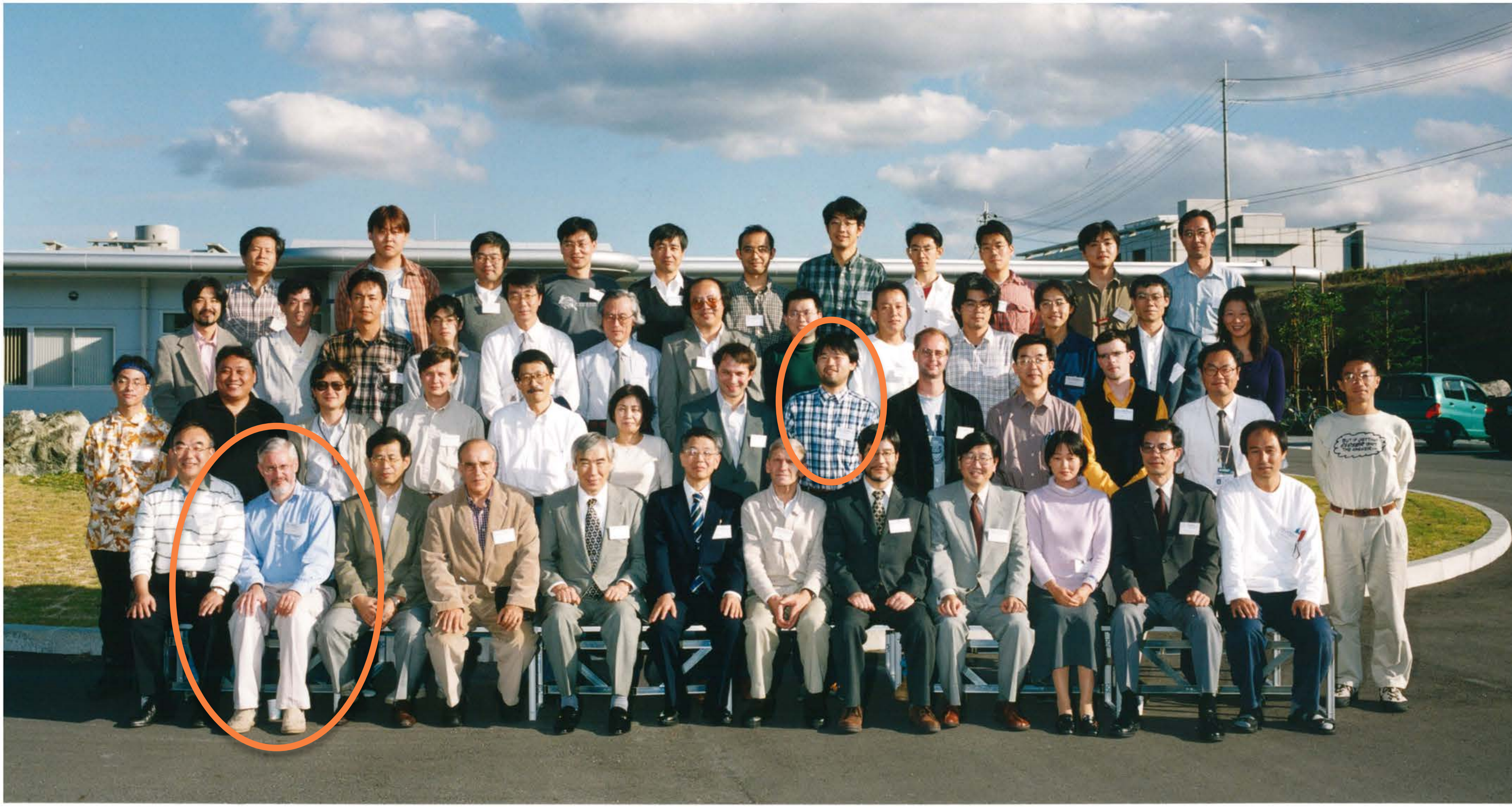
22 years ago at SPring-8



LEPS2000 International Workshop on Laser Electron Photons at SPring-8 Oct 14-15,2000

Bernd Krusche

22 years ago at SPring-8



LEPS2000 International Workshop on Laser Electron Photons at SPring-8 Oct 14-15,2000

T. Ishikawa

Bernd Krusche

Bernd Krusche

He reviewed some of our manuscripts, and gave us fruitful suggestions for improving them.

He also reviewed Ref. [PRC104, L052201 (2021)], which this talk is based on, and encouraged us to publish it.

We would like to thank his support to us and his contribution to hadron physics.

Introduction

Meson-nucleus interaction

QCD in the non-perturbative regime

<u>medium modification</u>

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

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).

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

$$pd \to \eta\, {}^3\mathrm{He},\ \gamma\, {}^3\mathrm{He} \to \eta\, {}^3\mathrm{He}, \text{ and}$$
$$\gamma\, {}^7\mathrm{Li} \to \eta\, {}^7\mathrm{Li}$$

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 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., PRL79, 2672 (1997); PRL80, 2069 (1998);
F. Hibou et al.EPJA7, 537 (2000);
R. Bilger et al., PRC69, 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 $a_0(980)$**

elementary process is rather well understood

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

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: $M = 2.41$ 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 ?

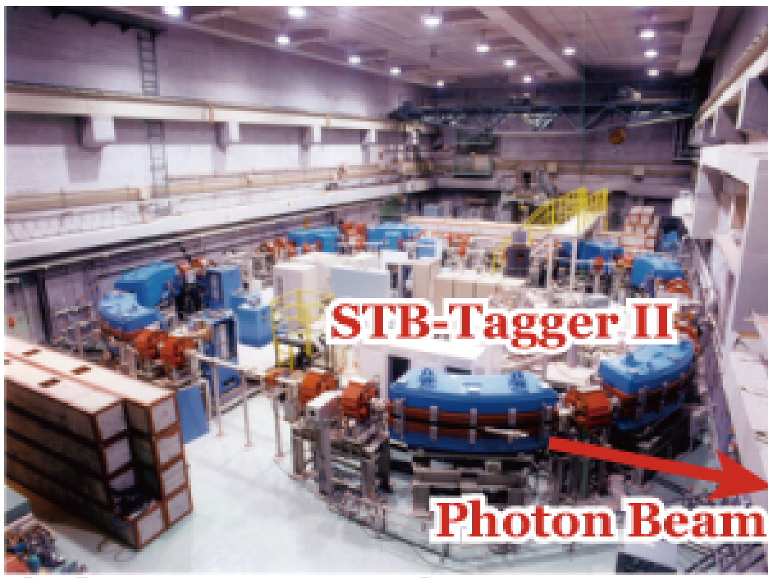
$\gamma d \rightarrow \pi^0 \eta d$ to study ηd

Experiment

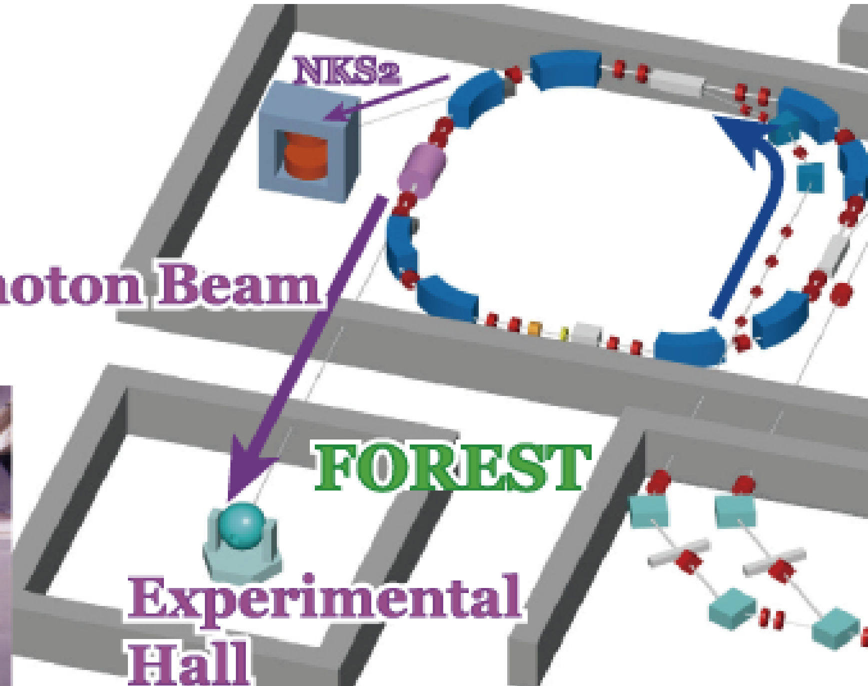
Accelerator

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

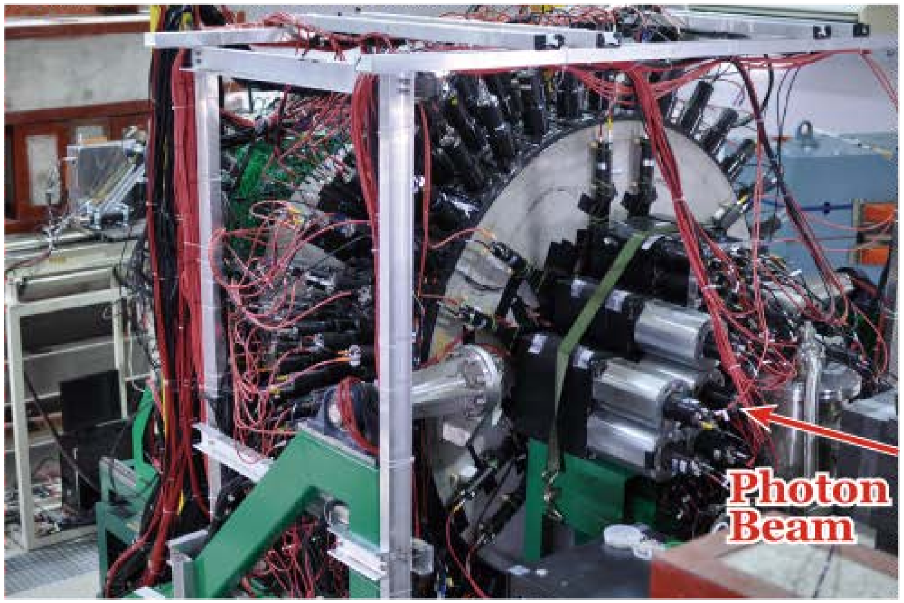
T. Ishikawa et al., NIMA 622, 1 (2010); T. Ishikawa et al., NIMA 811, 124 (2016); Y. Matsumura et al., NIMA 902, 103 (2018); Y. Obara et al., NIMA 922, 108 (2019).

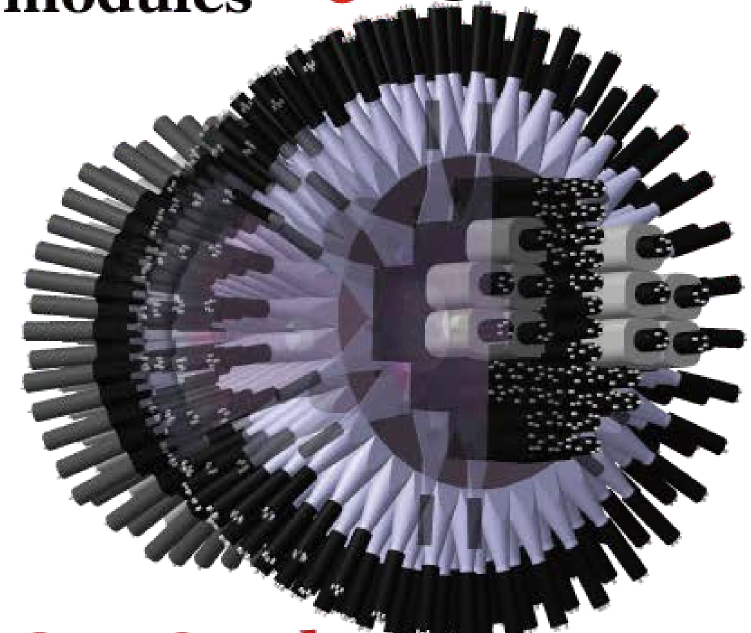
EM calorimeter

192 CsI crystals
3% @ 1 GeV

252 Lead/SciFi modules
7% @ 1 GeV

62 Lead Glasses
5% @ 1 GeV





FOREST electro-magnetic calorimeter

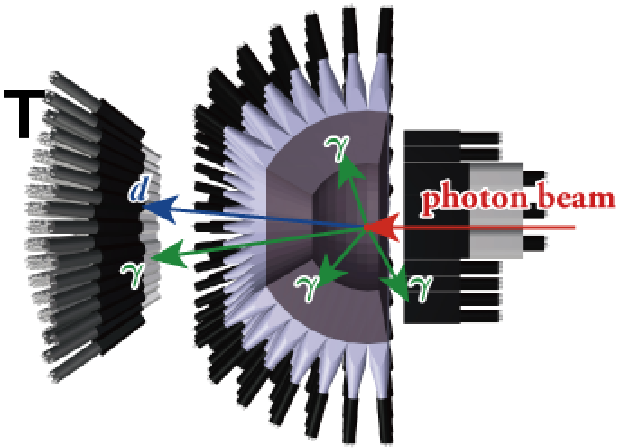
Target: 45 mm thick LH2 & LD2

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

Analysis

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

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

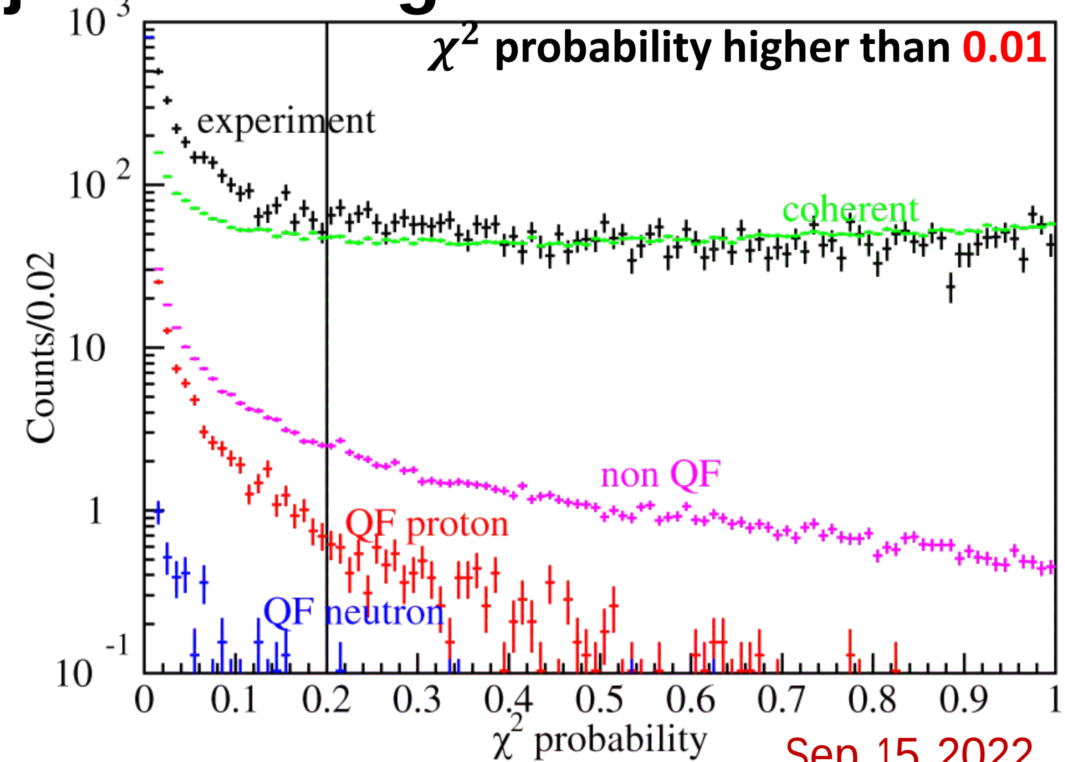


Further event selection

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



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

Further event selection

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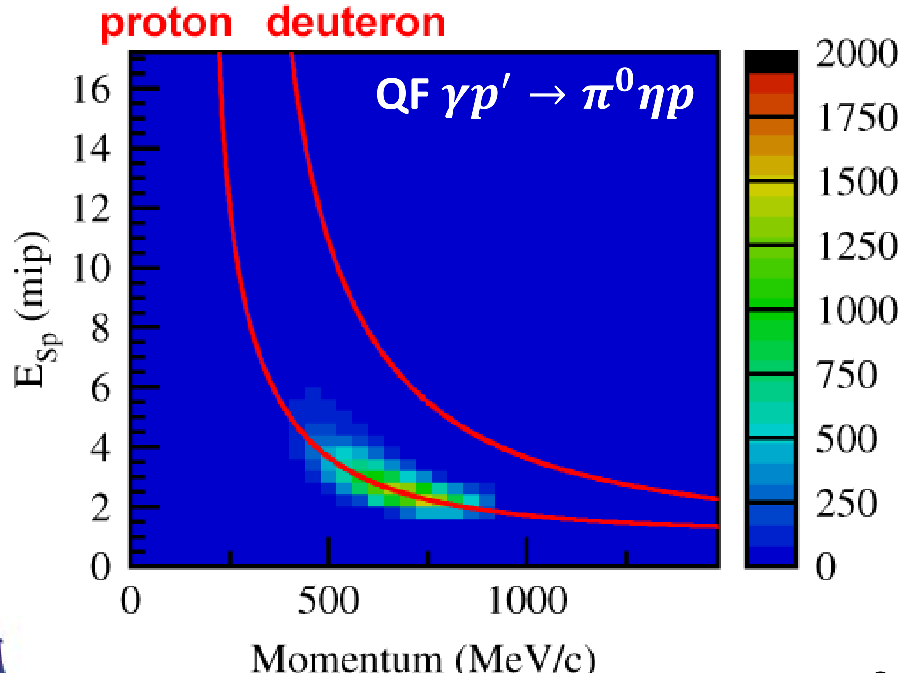
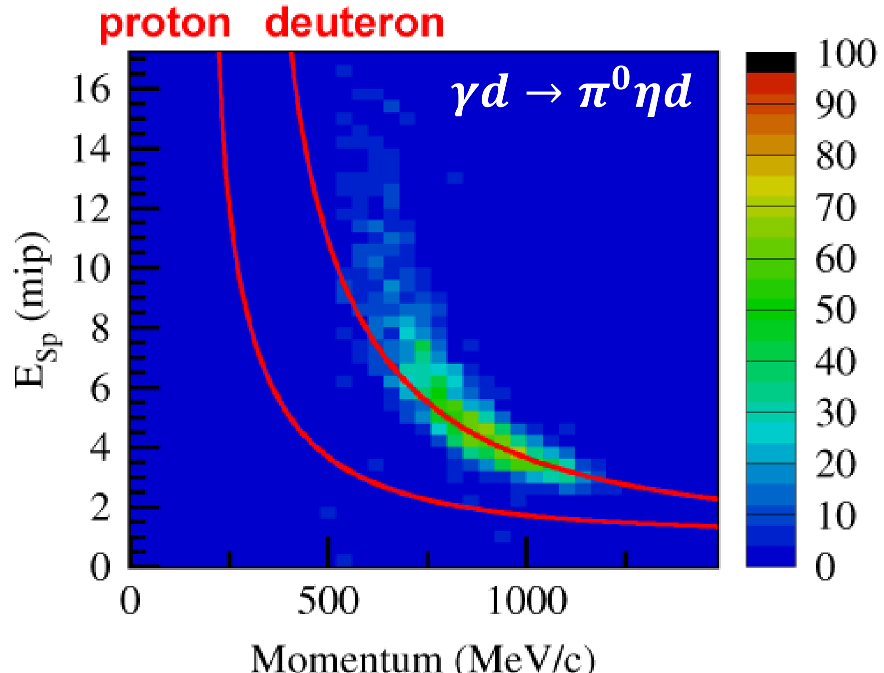




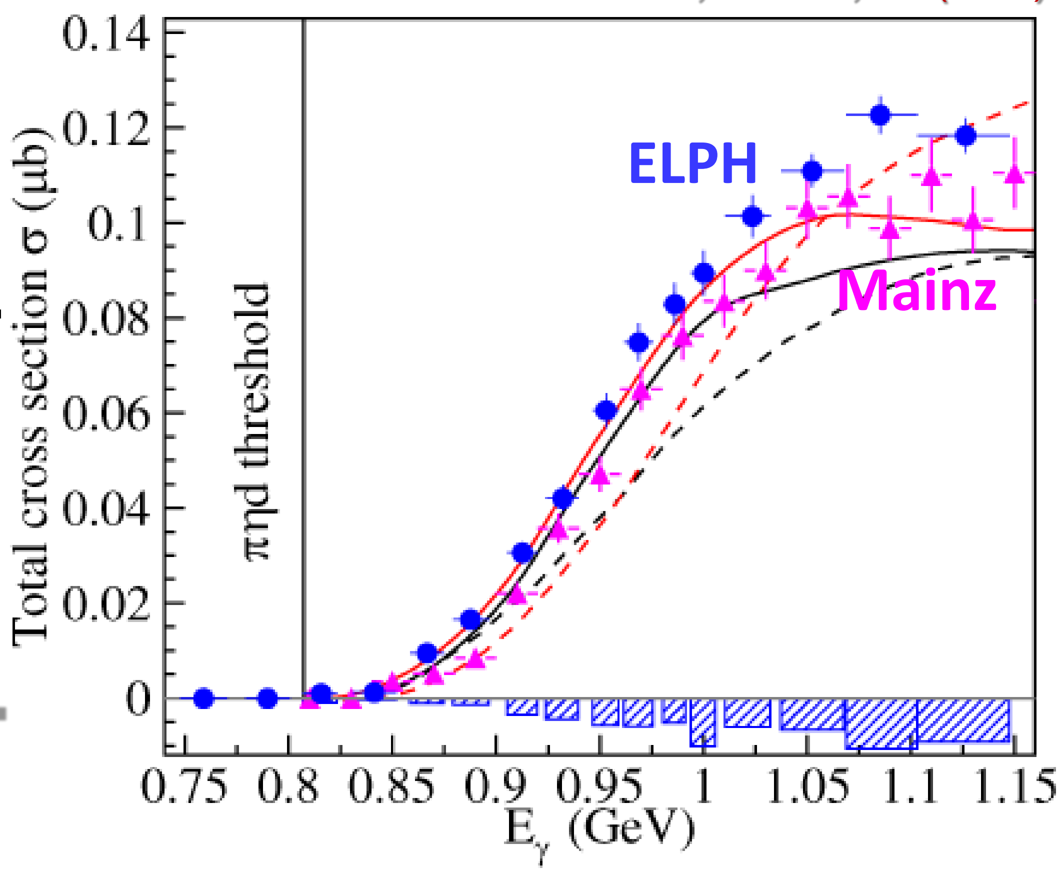
missing momentum $d(\gamma, \pi^0\eta)$ is given for a charged particle

Results

Total cross section

excitation function

A. Käser et al., PLB748, 244(2015).



dashed curves

impulse

solid curves

meson-nucleus final-state interaction

two models

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

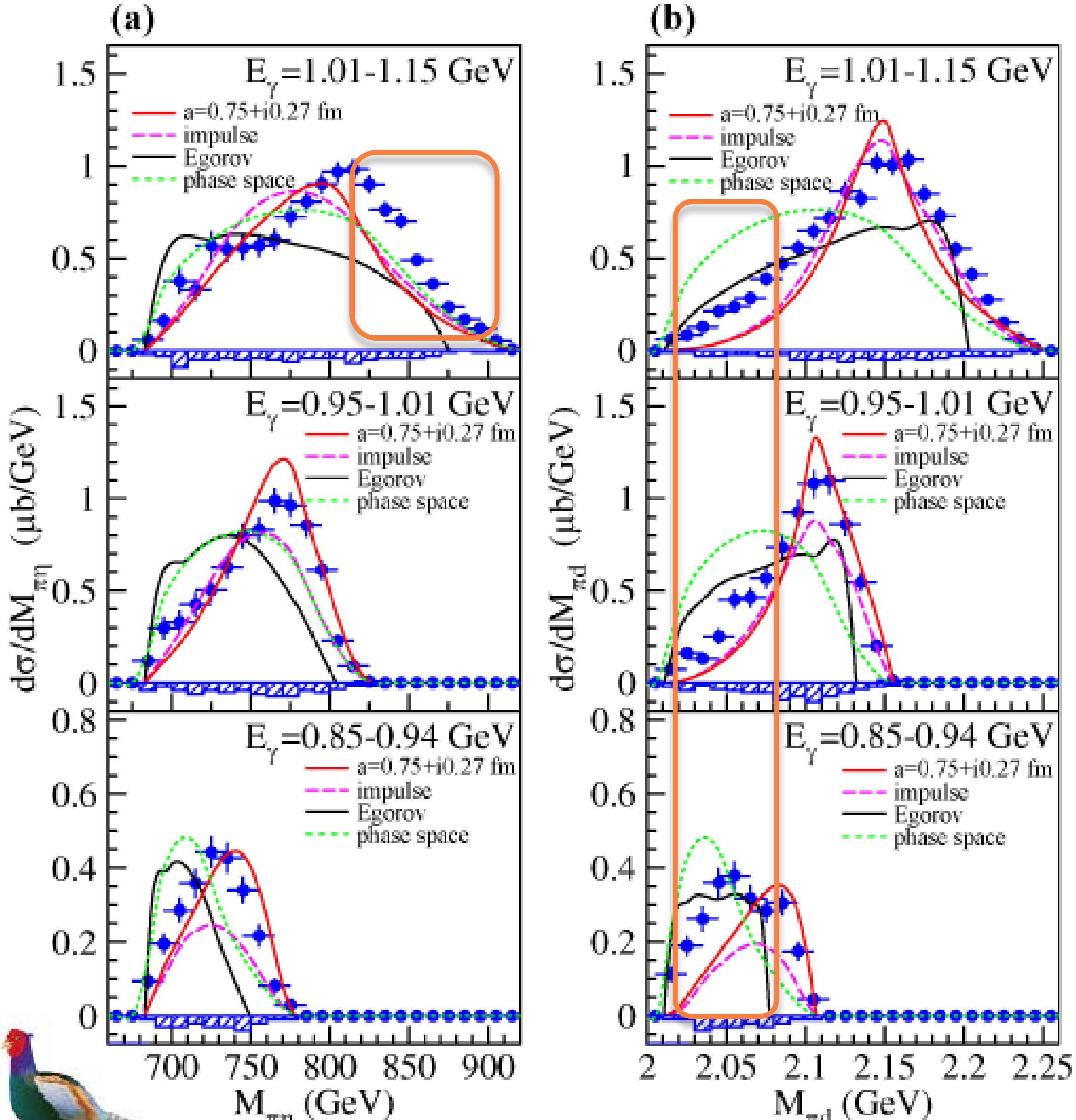
2) M. Egorov, PRC101, 065205 (2020).

unified microscopic approach

$\pi^{\pm}N \rightarrow \eta N$ **and** $\pi^{\pm}N \rightarrow N$ **reaction**

on the spectator nucleon

Differential cross sections



for the first time

<u>$d\sigma/dM_{\pi\eta}$:</u>

little FSI effects

absence of $a_0(980)$

<u>$d\sigma/dM_{\pi d}$:</u>

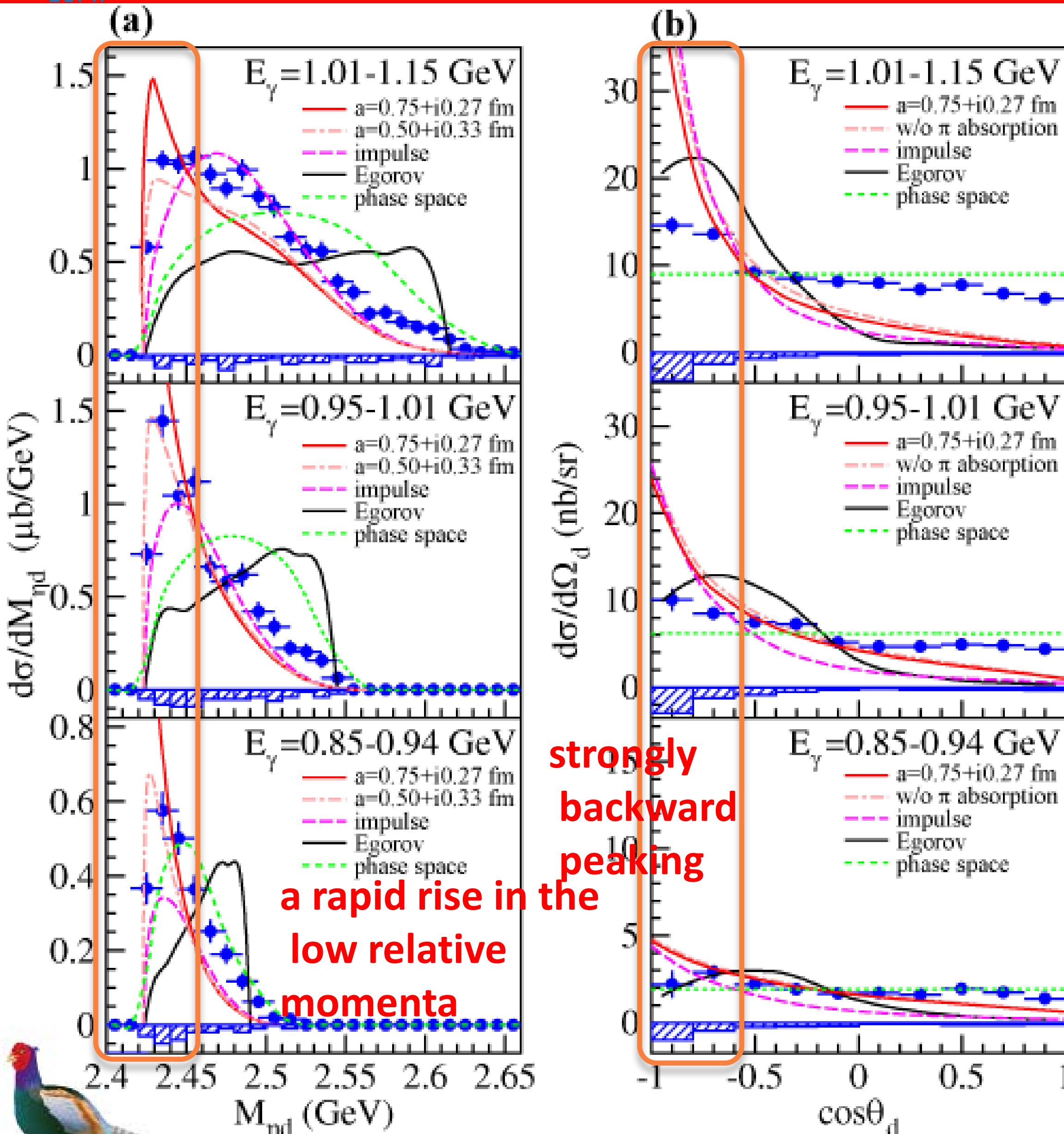
maximum at $M_{\pi d} \approx M_N + M_\Delta$

quasifree Δ prod or D_{12} dibaryon

discrepancy at low masses

more complicated πd FSI?

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~~

T. Ishikawa

Phenomenological analysis 1

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

<u>two sequential processes</u>

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

$\mathcal{D}_{\eta d}$: *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 $I = 1, J^\pi = 2^+$

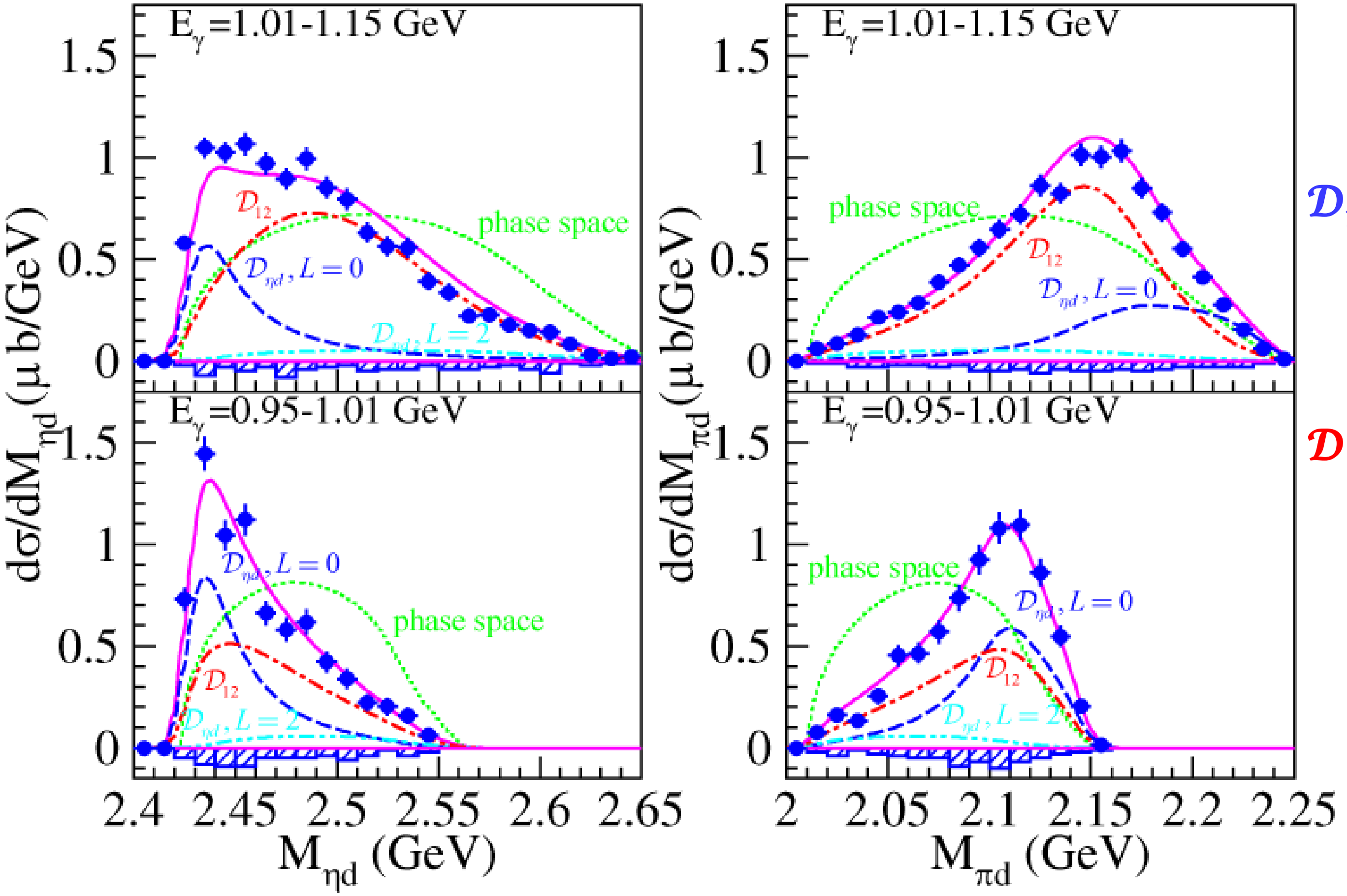
mass ~2.14 GeV, width ~0.09 GeV

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

Phenomenological analysis 1

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



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

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

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

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

$\mathcal{D}_{12}$:

$M = 2.158^{+0.003}_{-0.003}$ GeV

$\Gamma = 0.116^{+0.005}_{-0.011}$ GeV

$\mathcal{D}_{\eta d}$ ($M \sim 2.43$ GeV, $\Gamma \sim 0.03$ GeV) & $\mathcal{D}_{12}$($M \sim 2.16$ GeV, $\Gamma \sim 0.12$ GeV)

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

Phenomenological analysis 1

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 ηNN–πNN

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

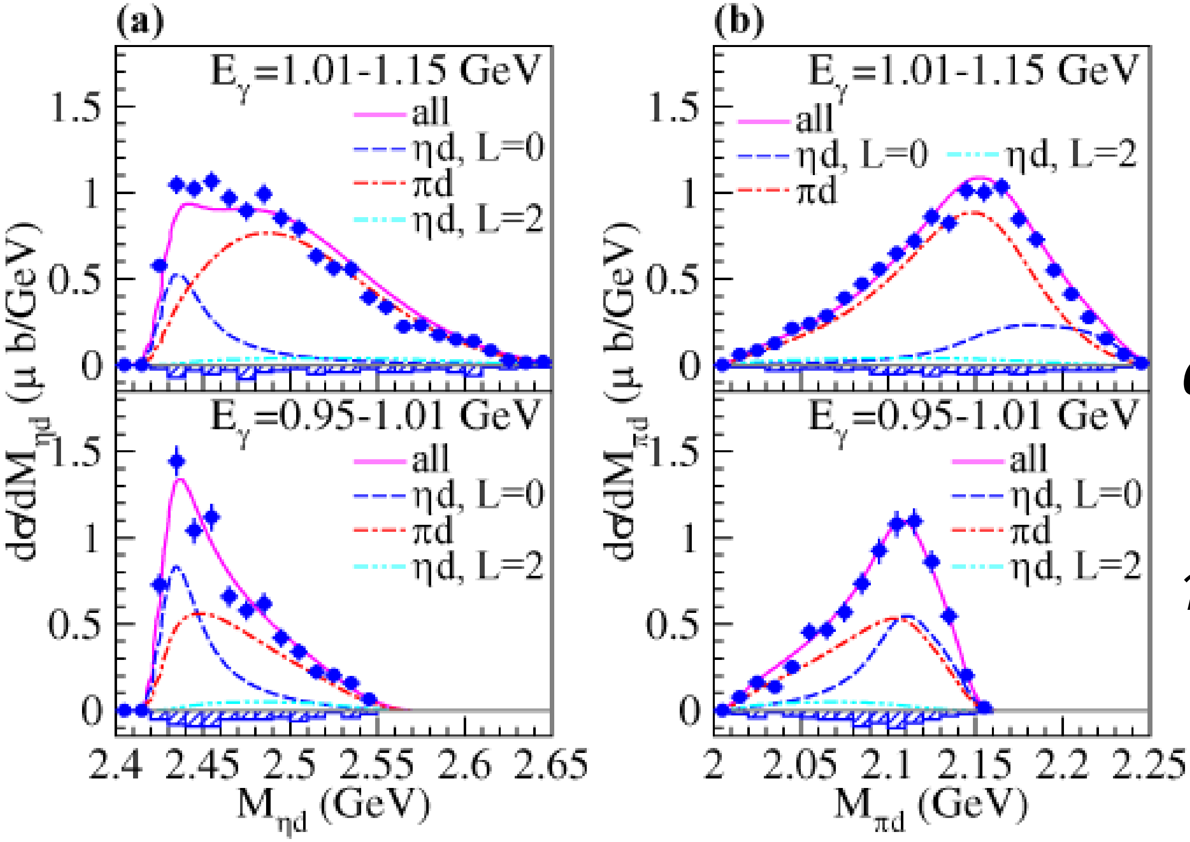
T. Ueda, PRL66, 297 (1991).

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

Phenomenological analysis 2

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

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



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

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

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, PRC88, 054611 (2013).

Summary

Summary

1. cross sections are measured at $E_\gamma < 1.15$ GeV for $\gamma d \to \pi^0 \eta d$
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: $\gamma d \to \mathcal{D}_{\mathrm{IV}} \to \pi^0 \mathcal{D}_{\eta d}(\eta \mathcal{D}_{12}) \to \pi^0 \eta d$ in a phenomenological analysis
   $\mathcal{D}_{\eta d}$: $I = 0, J^\pi = 1^-, M \sim 2.42$ GeV, $\Gamma \sim 0.03$ 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)

T. Ishikawa

Summary

5. **no theoretical calculations reproduce a rather flat angular distributions of deuteron emission in $\gamma d \to \pi^0 \eta d$ ($\gamma d \to \pi^0 \pi^0 d$)**
    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: 2205.00948v2 [triangle singularity].
6. **coherent $\pi^0 \eta$ from a nucleus is suitable for studying the η-nuclear interaction**

<u>$\gamma d \to \pi^0 \pi^0 d$</u>

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).

<u>$\gamma d \to \pi^0 \eta d$</u>

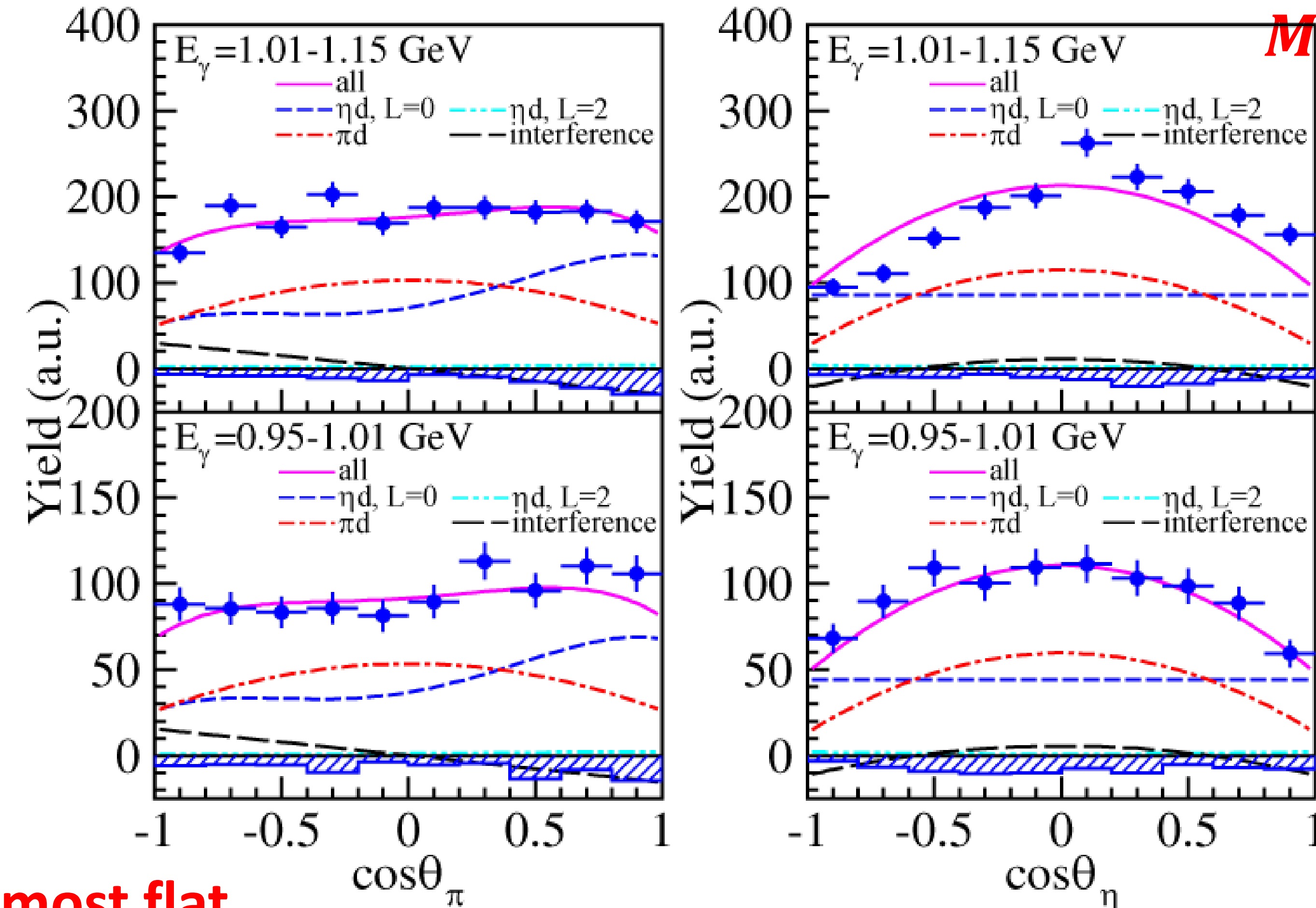
A2: Käser *et al.*, PLB748, 244(2015);
ELPH: T. Ishikawa et al., PRC104, L052201 (2021); PRC105, 045201 (2022).

Backup

Angular correlations

angular distributions for the ηd correlated state

$M_{\eta d} < 2.47$ GeV



convex upward

almost flat

γ–π in the γd-CM frame

π–η in the ηd rest frame (opposite sign)

decomposed to the two sequential processes

Observed states

angular distribution & correlation

similar yields

$$L = 1, 2 \qquad L = 0, 1, 2 \qquad L = 0, 2$$

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

47%

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

$$L = 1, 2 \qquad L = 1 \qquad L = 1$$

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).

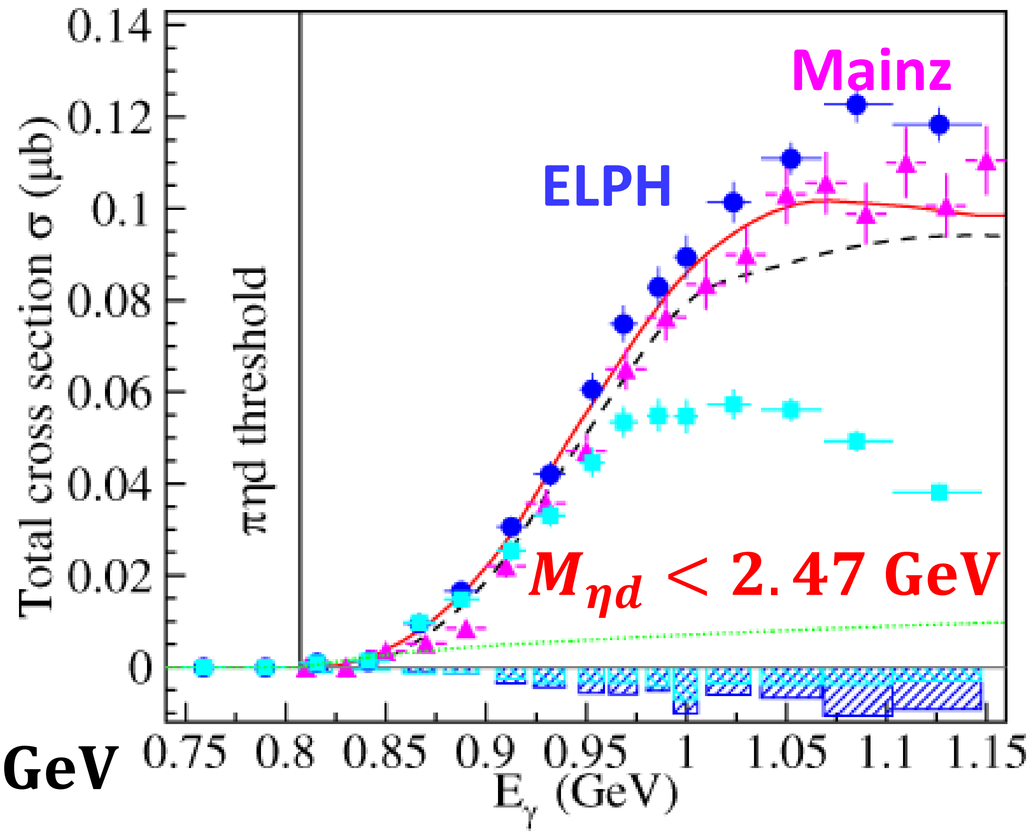
Intermediate state

total cross section

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

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

M. Egorov, PRC101,
065205 (2020).
unified microscopic approach



The events with $M_{\eta d} < 2.47$ 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 $\eta\mathcal{D}_{12}$

$\mathcal{D}_{12}(2^+) \sim N\Delta(1232)P_{33}$

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

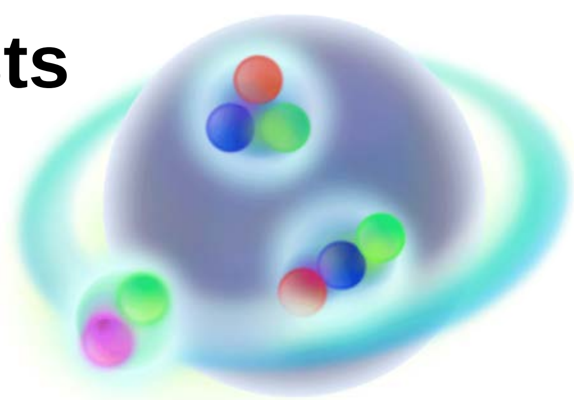
the lightest η-mesic nucleus if it exists

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

predicted near the ηd threshold with

$\Gamma = 0.01 \sim 0.02$ GeV

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

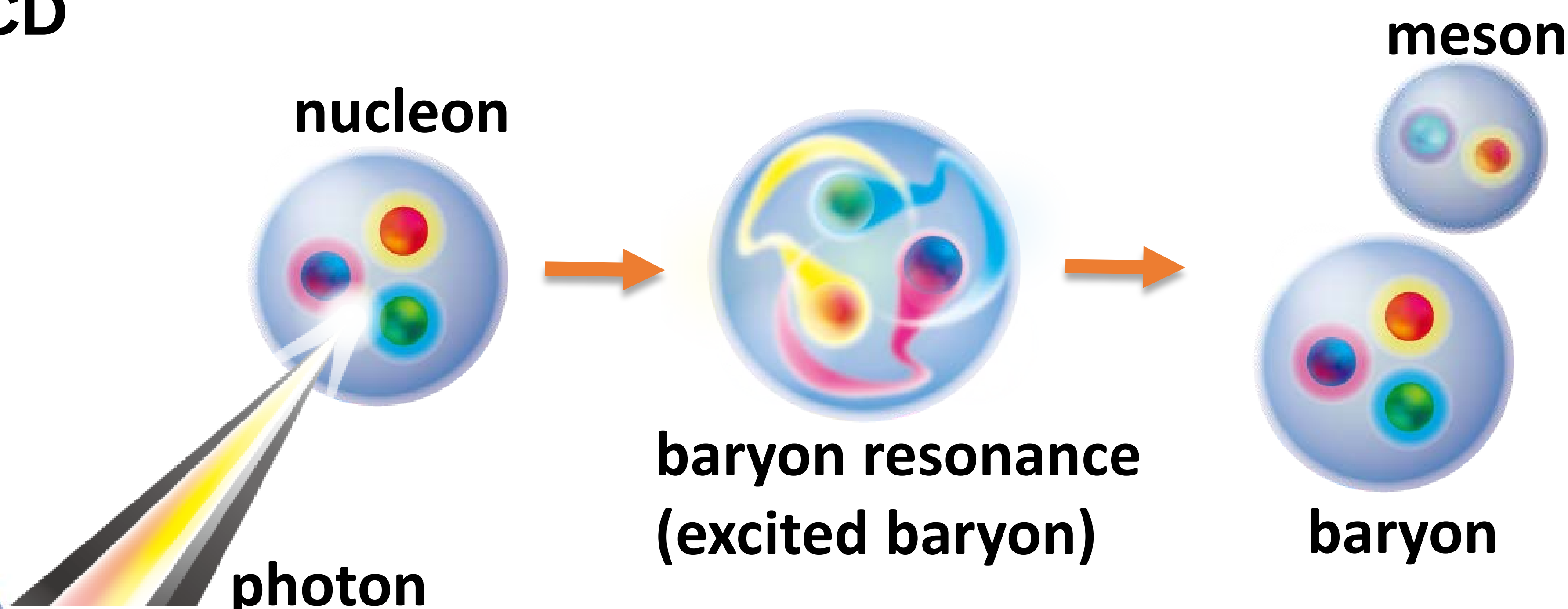


Clusters & Hierarchies

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



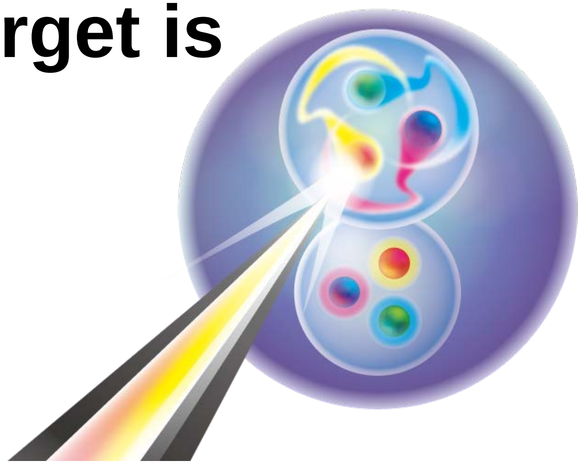
Introduction

Clusters & Hierarchies

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.

N^*



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

Clusters & Hierarchies

$\underline{\gamma d \to \eta d}$ **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

$\underline{\gamma d \to \pi^0 \pi^0 d}$ **PLB789, 413 (2019).**

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

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

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

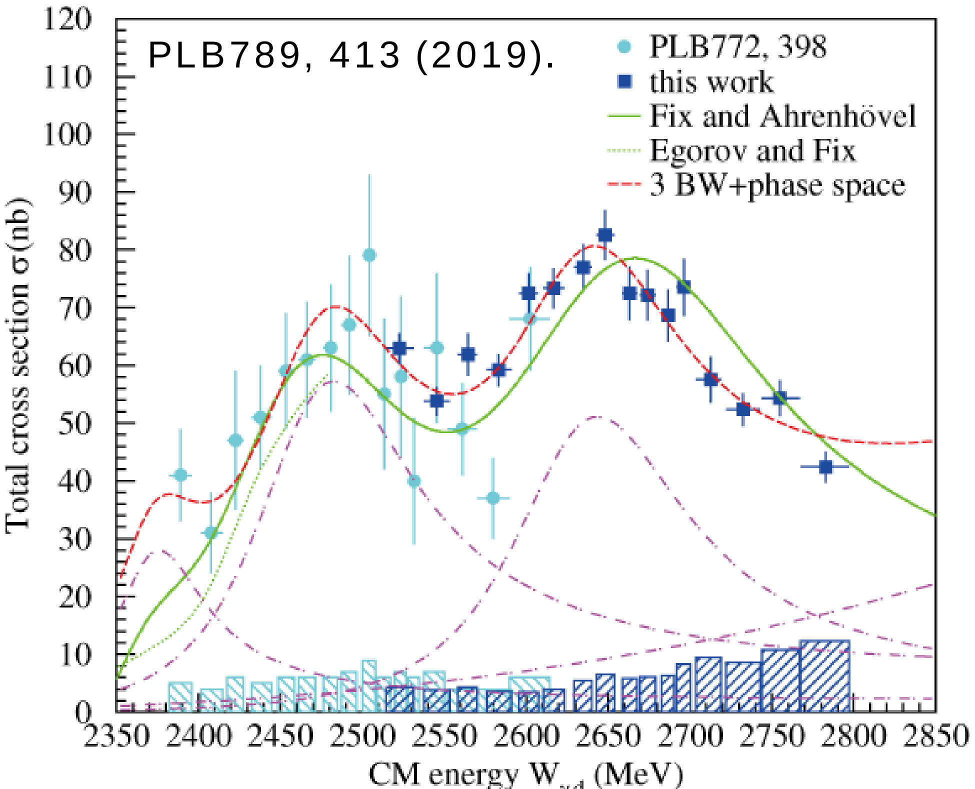
$\gamma d \to \pi^0 \pi^0 d$

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 $\gamma N' \to \pi^0 \pi^0 N$

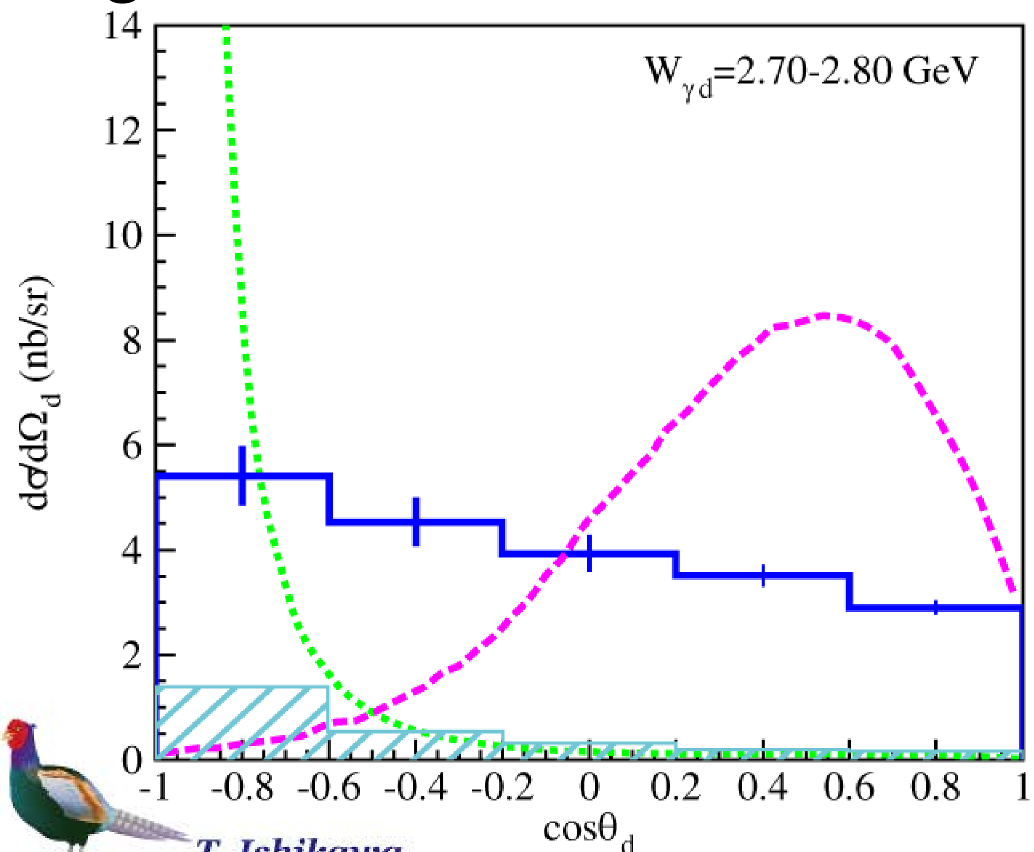
naïve interpretation is QF excitation of the nucleon in the deuteron



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

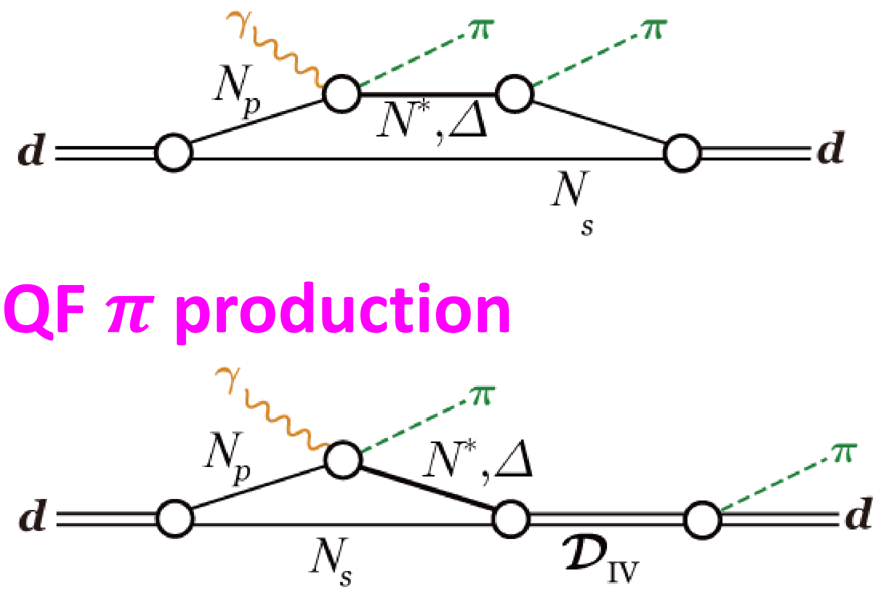
the kinematic condition completely differs from QF process

angular distribution of deuteron emission



QF $\pi\pi$ production

QF π production



Introduction

$\underline{\gamma d \to \pi^0\pi^0 d}$ $\qquad I = 1, J^\pi = 2^+,$

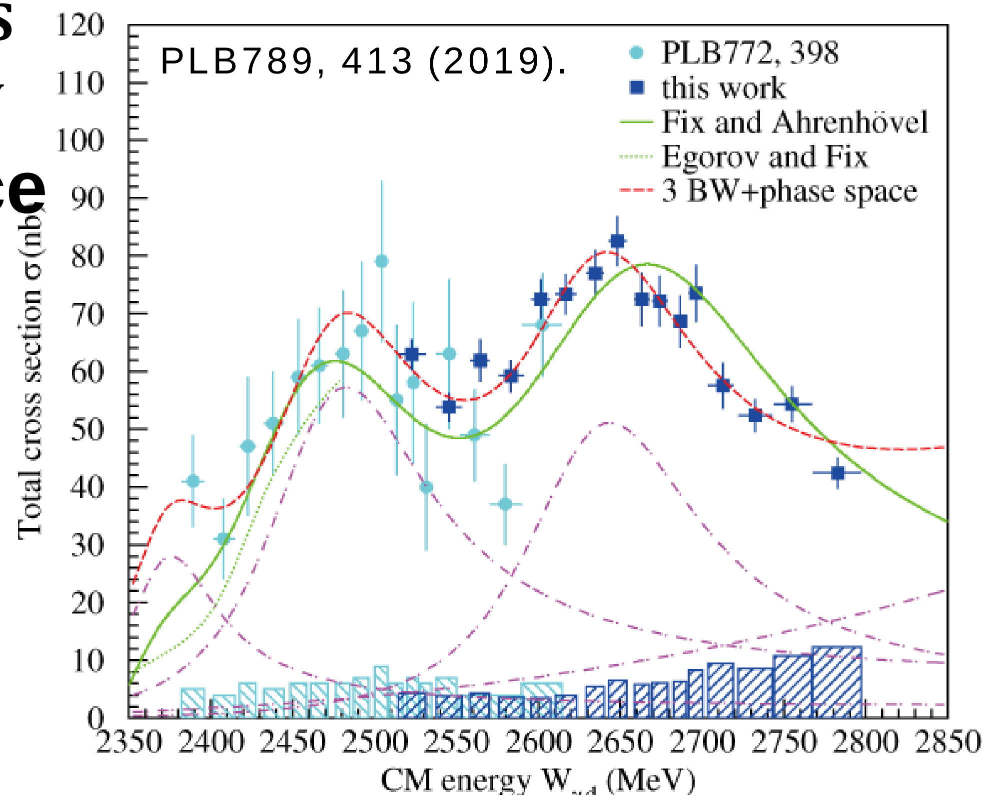
sequential process: $M = 2.14\ \mathrm{GeV}, \Gamma = 0.09\ \mathrm{GeV}$

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

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

dibaryon: $B = 2$ resonance

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



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