ηd threshold structure from the $\gamma d \to \pi^0 \eta d$ reaction

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1. introduction

η-mesic nucleus
S-wave ηd system
$\gamma d \to \pi^0 \eta d$ reaction

2. experiment

3. event selection

4. results

total cross section
differential cross sections
angular correlations

5. summary

Introduction

η-mesic nucleus

bound by the strong force alone

- ηN interaction A. Fix, O. Kolesnikov, PRC97, 044001 (2018).
- η-η' mixing S.D. Bass, P. Moskal, RMP91, 015003 (2019).
- $N(1535)S_{11}$ in the nuclear medium D. Jido *et al.*, NPA811, 158 (2008).

experimental hints

steep increase from the threshold

- in $pd \to \eta\,^3\mathrm{He}$ B. Mayer et al., PRC53, 2068 (1996). J. Smyrski et al., PLB 649, 258 (2007). T. Mersmann et al., PRL98, 242301 (2007).
- in $\gamma\,^3\mathrm{He} \to \eta\,^3\mathrm{He}$ B. Krusche, and C. Wilkin, PPNP80, 43 (2014).

rather flat angular distribution of η emission

J.-J. Xie . Jido *et al.*, NPA811, 158 (2008).

no convincing evidence

Introduction

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

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, PRL40, 1543 (1978).

ηd bound state

three-body calculation for the ηNN−πNN coupled channels

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

T. Ueda, PRL66, 297 (1991).

ηNN bound state

ηd bound state ?

Introduction

coherent $\gamma d \to \pi^0 \eta d$ reaction

provide a low relative-momentum condition between η and d

produce a possible ηd bound state

similar coherent $\gamma d \to \pi^0 \pi^0 d$ reaction

dominant is a sequential process:

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

with a πd resonance $\mathcal{D}_{12}$ with

$$\mathrm{M} = 2.14\ \mathrm{GeV}, \Gamma = 0.09\ \mathrm{GeV}, I = 1, J^{\pi} = 2^{+}$$

T. Ishikawa et al., PLB789, 413 (2019).

sequential processes for $\gamma d \to \pi^0 \eta d$

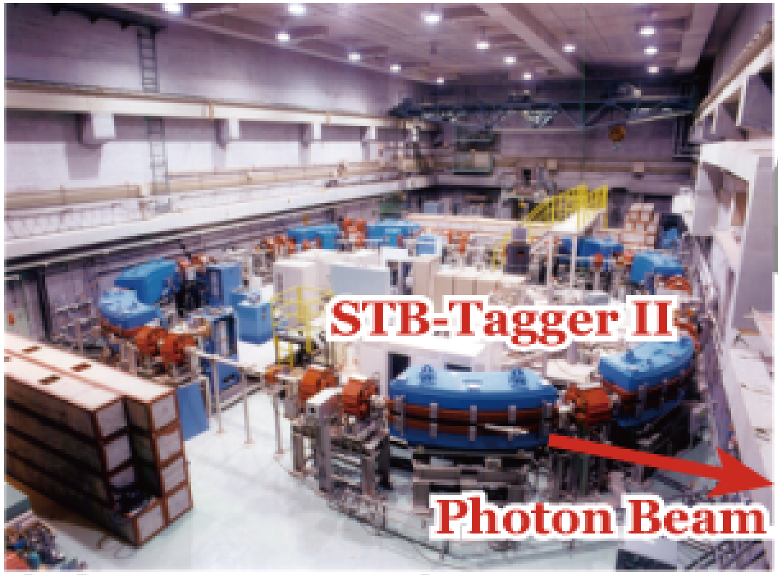
$$\gamma d \to \mathcal{D}_{\mathrm{IV}} \to \pi^0 \mathcal{D}_{\eta d} \to \pi^0 \eta d$$

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

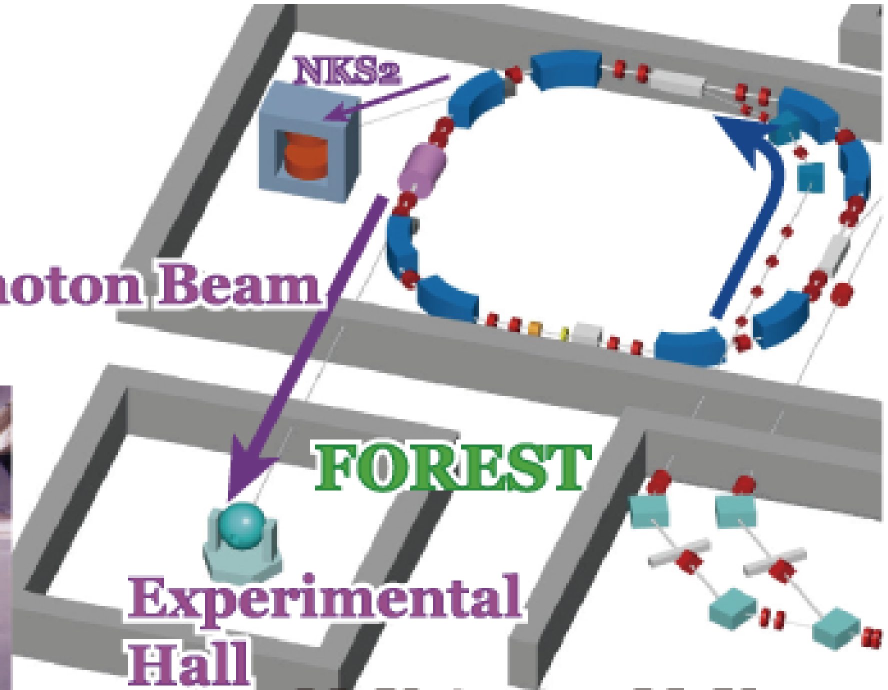
Accelerator

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

Photon Beam
- Bremsstrahlung
- Tagged



1.3 GeV Booster STorage Ring

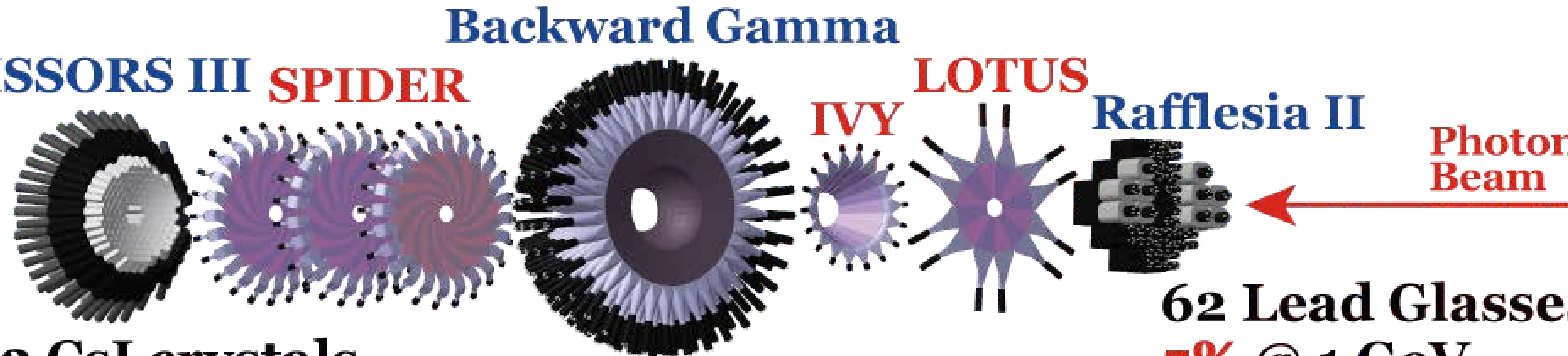


740~1150 MeV @ 1200 MeV
~20 MHz (photon: 10 MHz)
$W_{\gamma d}$=2.50~2.80 GeV

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).

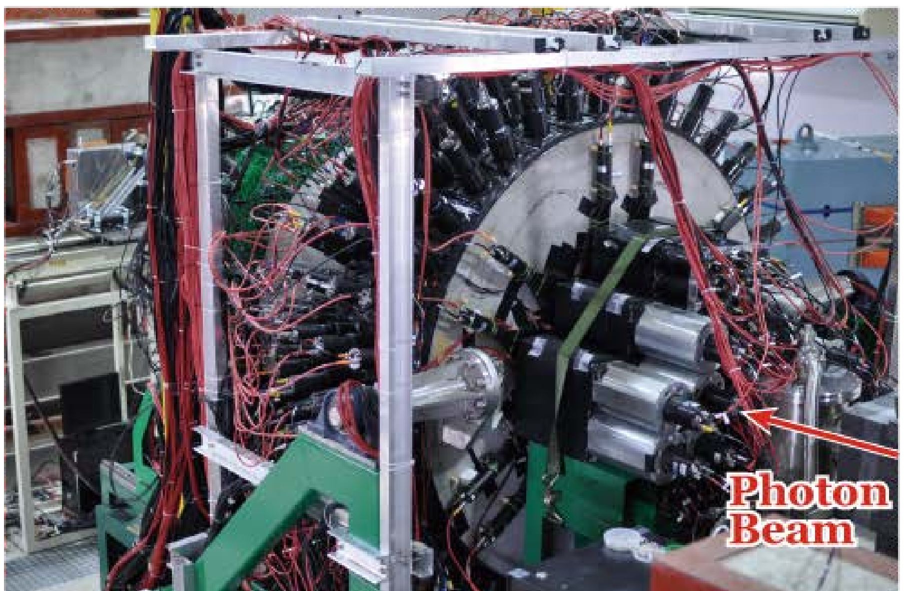
EM calorimeter

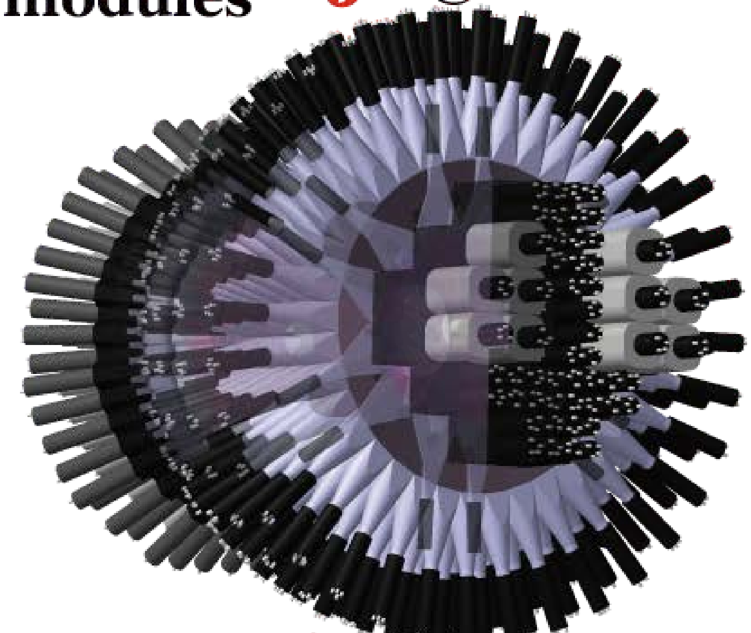


192 CsI crystals
3% @ 1 GeV

252 Lead/SciFi modules
7% @ 1 GeV

62 Lead Glasses
5% @ 1 GeV



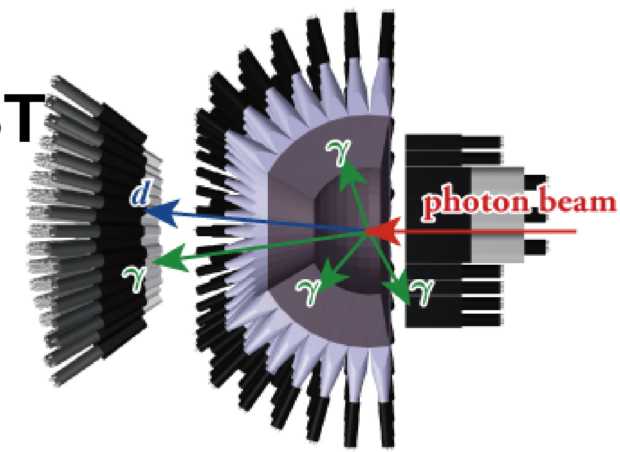


FOREST electro-magnetic calorimeter

Target: 45 mm thick LH2 & LD2
T. Ishikawa et al., NIMA 832, 108 (2016).

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 $2E_{\mathrm{mip}}$
4. **sideband background subtraction**
   to remove accidental coincidence
   between STB-Tagger II and FOREST

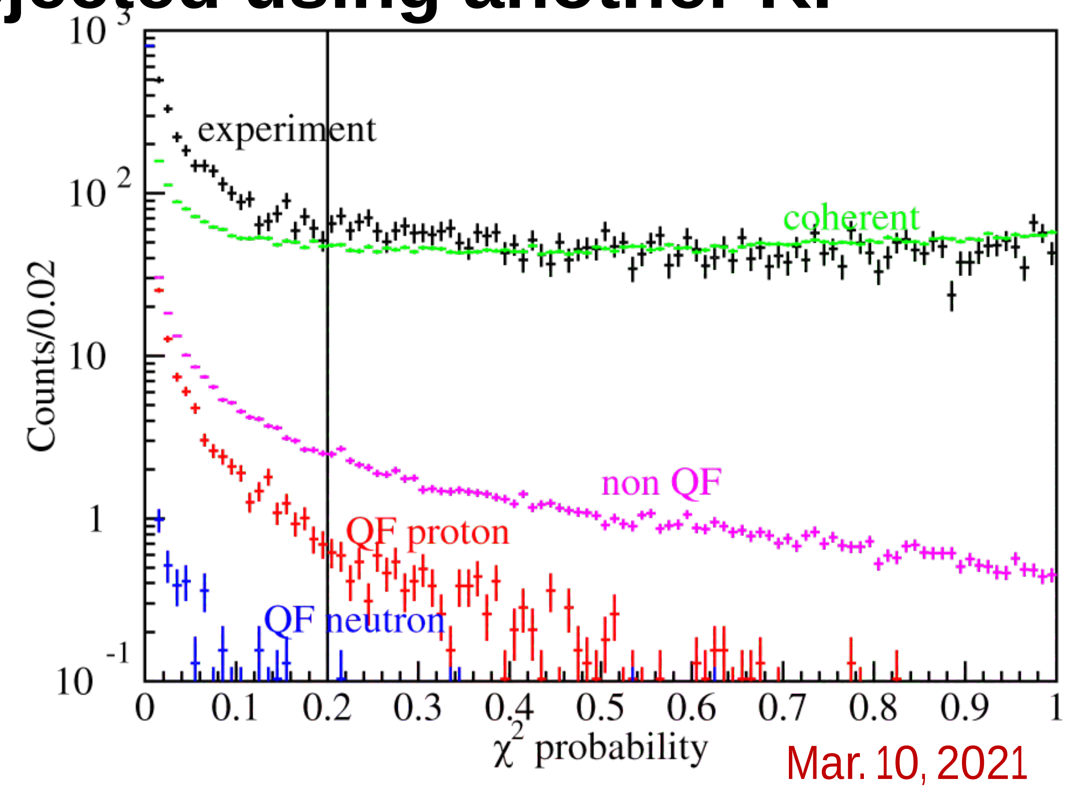


Further event selection

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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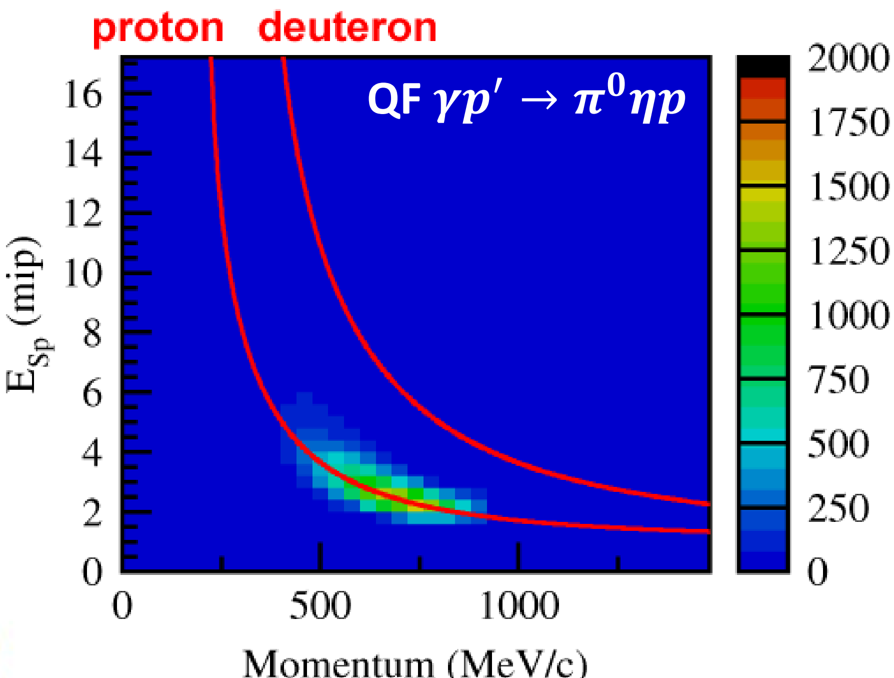
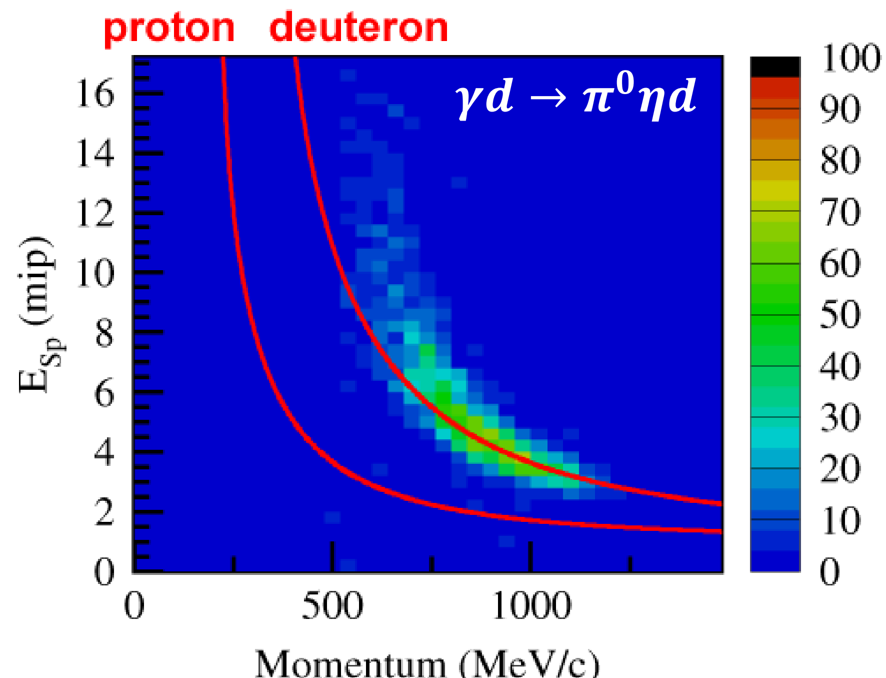


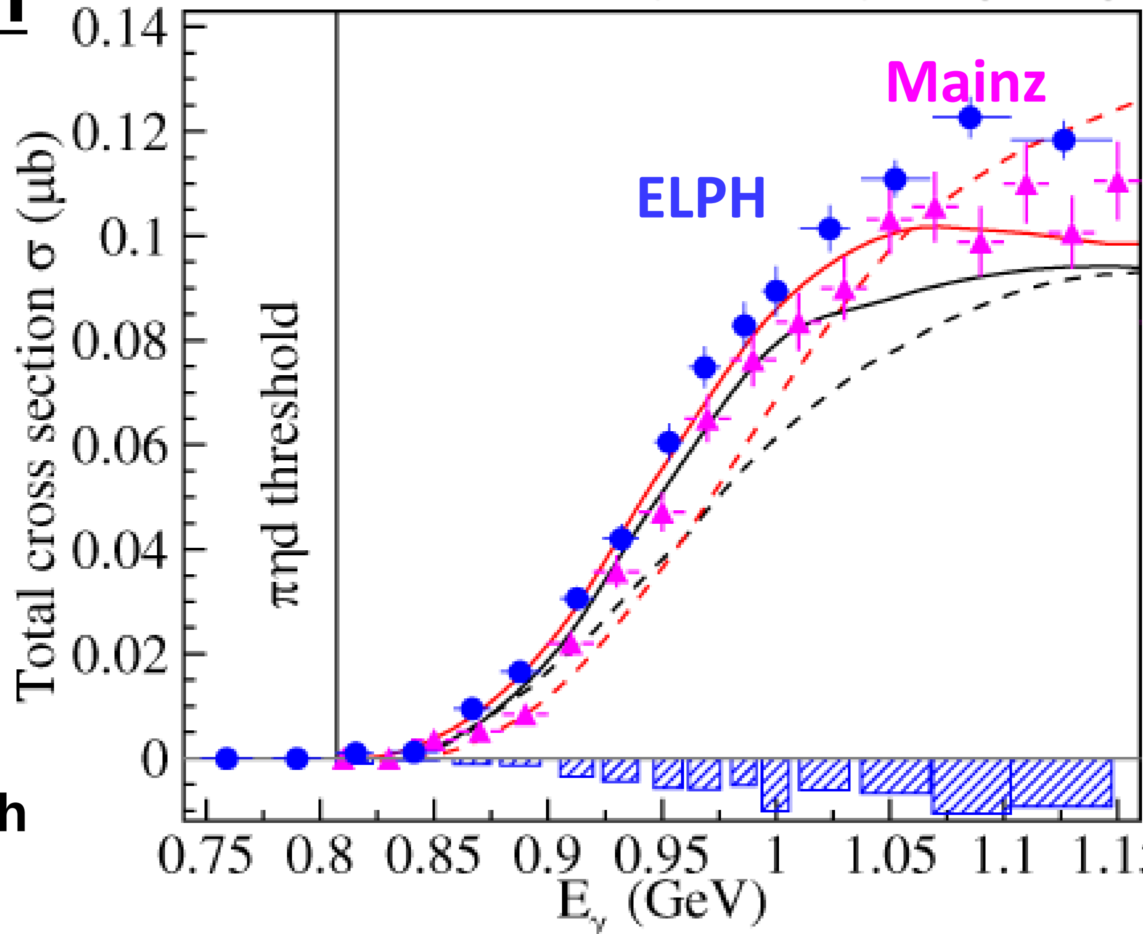


missing momentum is given for the deuteron in these plots

Total cross section

excitation function

A. Käser *et al.*, PLB748, 244(2015).



dashed curves
impulse
solid curves
including ηd final-state interaction

two models

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

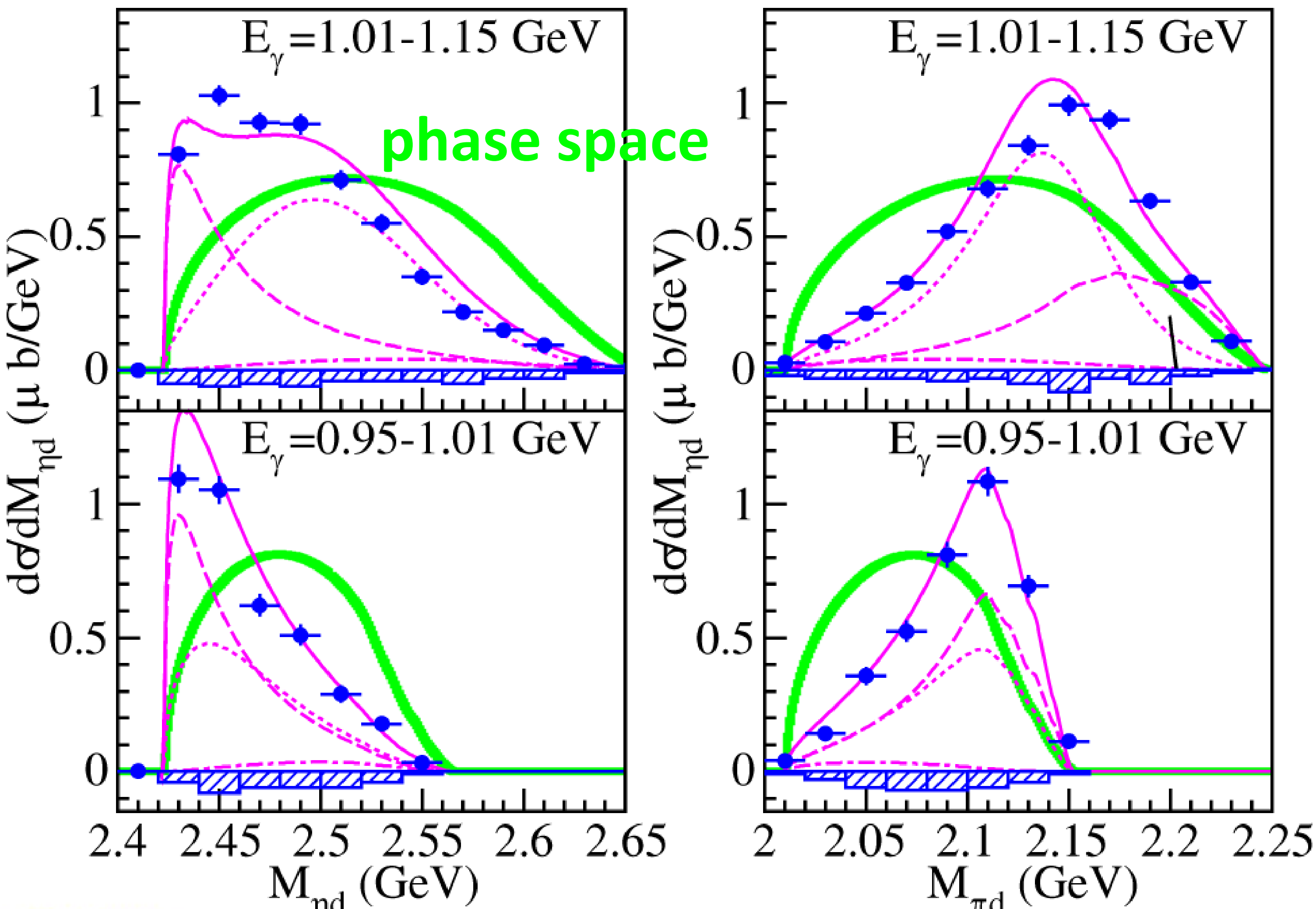
M. Egorov, PRC101, 065205 (2020).
unified microscopic approach

Both models are based on QF $\pi^0\eta$ production with deuteron coalescence but different approaches are adopted to incorporate the ηd final-state interaction

Differential cross sections

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

for the first time



Observes states

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

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 $I = 0, J^\pi = 1^-$

mass and width: free parameters

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

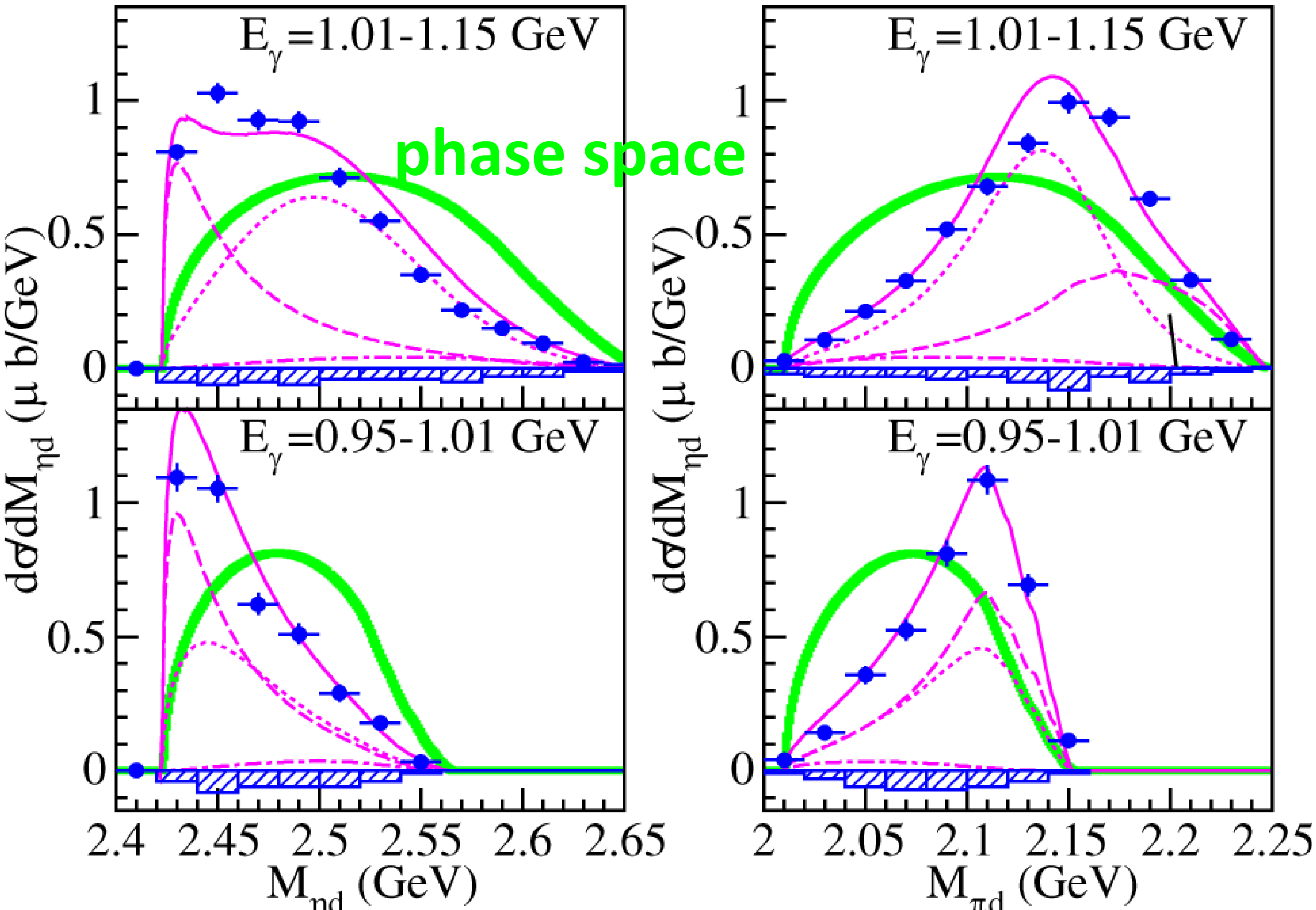
mass 2.14 GeV

width 0.09 GeV

simultaneous fit of four distributions

Observes states

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



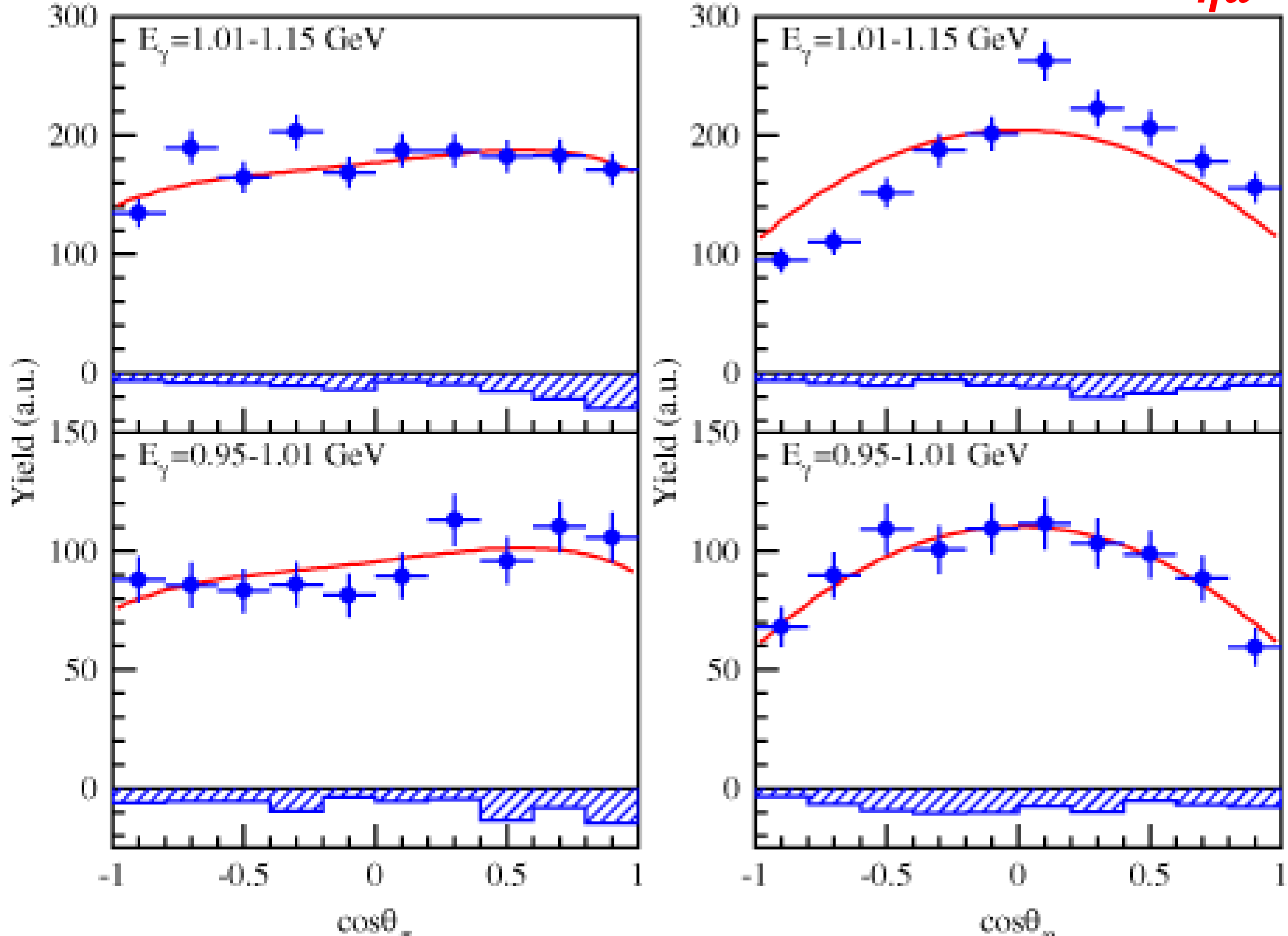
dashed: $\mathcal{D}_{\eta d}$ ($M\sim 2.40$ GeV, $\Gamma = 0.02$ GeV) &

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

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

angular distribution & correlation

$M_{\eta d} < 2.47$ GeV



γ–π in the γd-CM frame

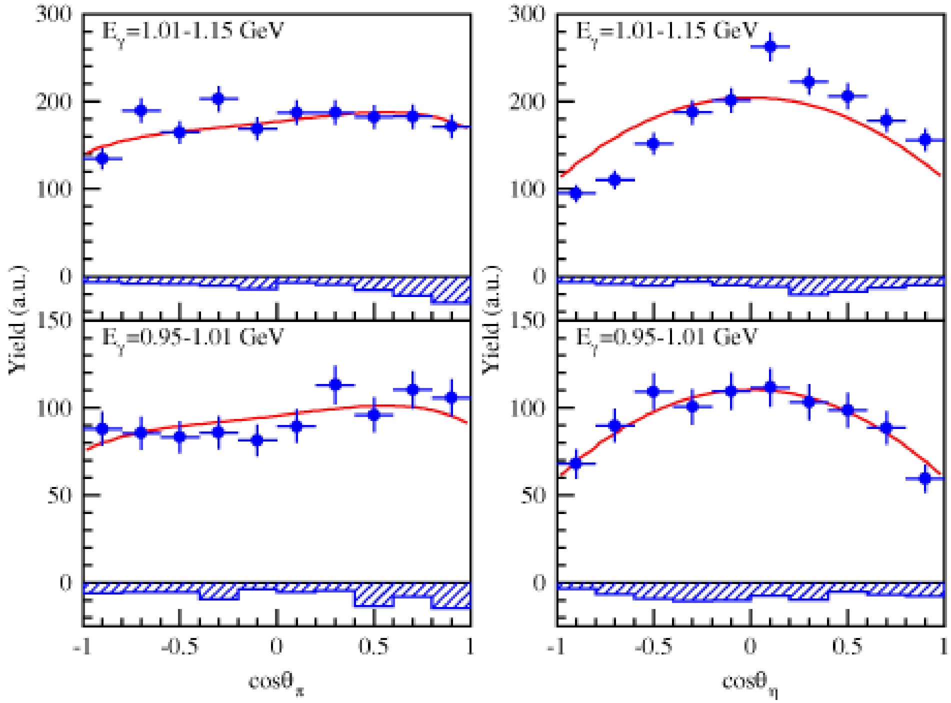
π–η in the ηd rest frame (opposite sign)

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

fit of angular distributions $M_{\eta d} < 2.47$ GeV

2/3 $d(1^+) \xrightarrow{L=1,2} \mathcal{D}_{IV}(0^-, 1^\pm, 2^\pm) \xrightarrow{L=0,1,2} \mathcal{D}_{\eta d}(1^-) \xrightarrow{L=0} d(1^+)$ (2/3)

1/3 $d(1^+) \xrightarrow{L=1} \mathcal{D}_{IV}(2^+) \xrightarrow{L=1} \mathcal{D}_{12}(2^+) \xrightarrow{L=1} d(1^+)$



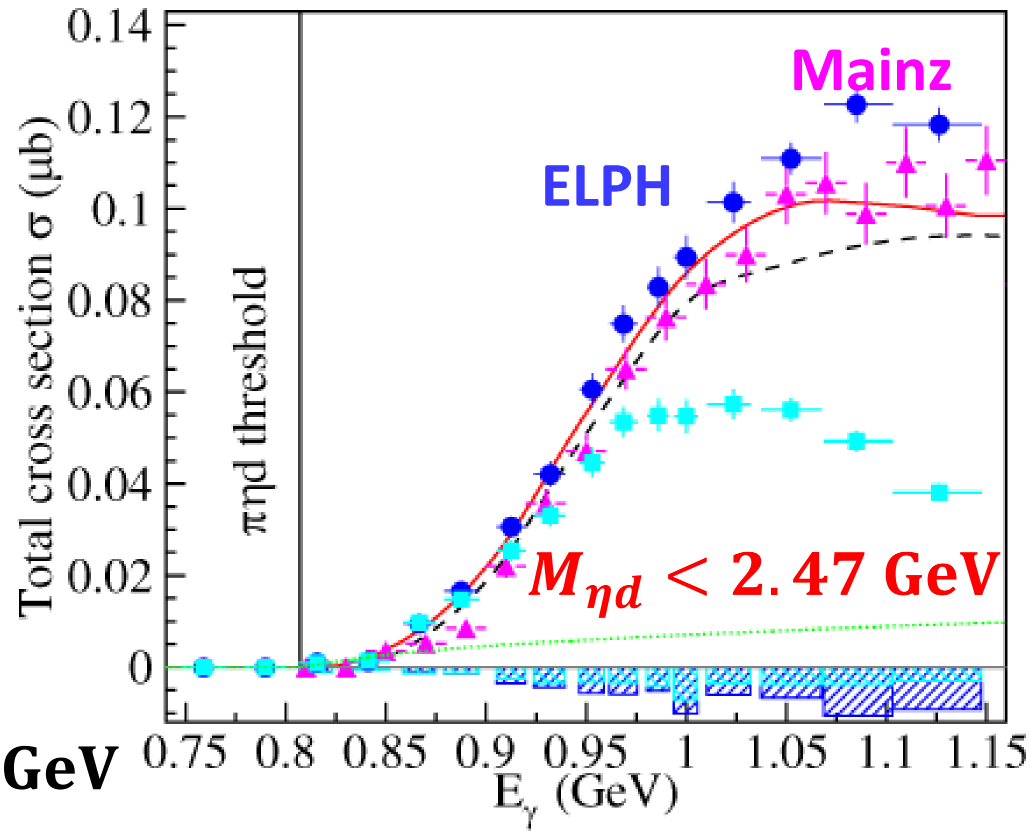
Coherent $\gamma d \to \pi^0 \eta d$

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

$\bar{s}s$ $N\Delta(1620)S_{31}$, $NN(1650)S_{11}$, $NN(1700)D_{13}$
for $\mathcal{D}_{01}(1^-) \sim NN(1535)S_{11}$
$NN(1720)P_{13}$, $N\Delta(1600)P_{33}$ for $\mathcal{D}_{12}(2^+) \sim N\Delta(1232)P_{33}$
$\bar{s}s$? 1%~5% $N\eta$ decay

Summary

1. **Cross sections are measured at $E_\gamma < 1.15\ \mathrm{GeV}$ 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**

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

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

   $\mathcal{D}_{\eta d}$: $I = 0, J^\pi = 1^-, M = 2.40 \pm 0.01\ \mathrm{GeV}, \Gamma < 0.03\ \mathrm{GeV}$ **below the ηd threshold**

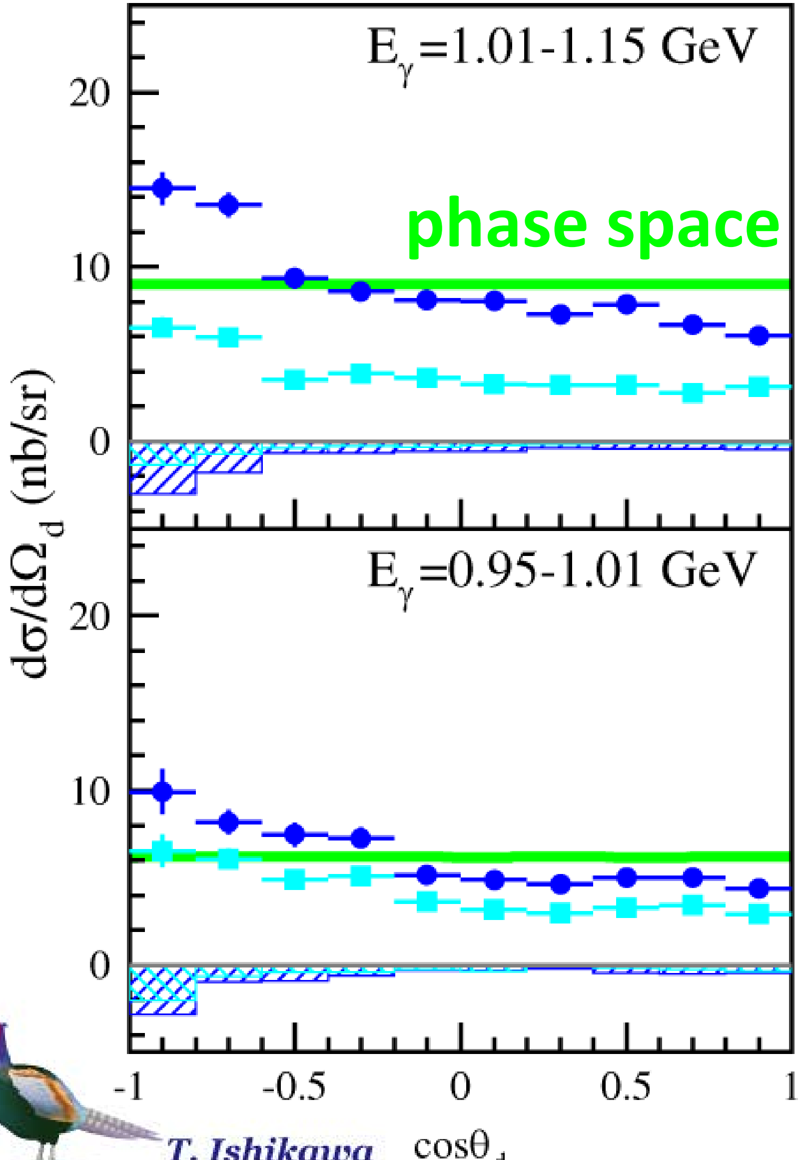
   $\mathcal{D}_{12}$: $I = 1, J^\pi = 2^+, M = 2.14\ \mathrm{GeV}, \Gamma = 0.09\ \mathrm{GeV}$
4. **doorway states for the first $\mathcal{D}_{\mathrm{IV}}$ state would be $NN(1650)S_{11}$ for $\pi^0 \mathcal{D}_{\eta d}$ and $NN(1720)P_{13}$ for $\eta \mathcal{D}_{12}$**

Backup

Differential cross sections

angular distributions $d\sigma/d\Omega_d$

for the first time



angular distribution of deuteron emission in the γd CM frame

does not show a strongly backward-peaking behavior but shows a rather flat distribution, suggesting a sequential process

—: $M_{\eta d} < 2.47$ GeV