Coherent neutral pion and eta meson photoproduction on the deuteron

The 24th International Spin Symposium (SPIN2021), Matsue, Japan, October 18~22, 2021

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   coherent double neutral-meson photoproduction on the deuteron
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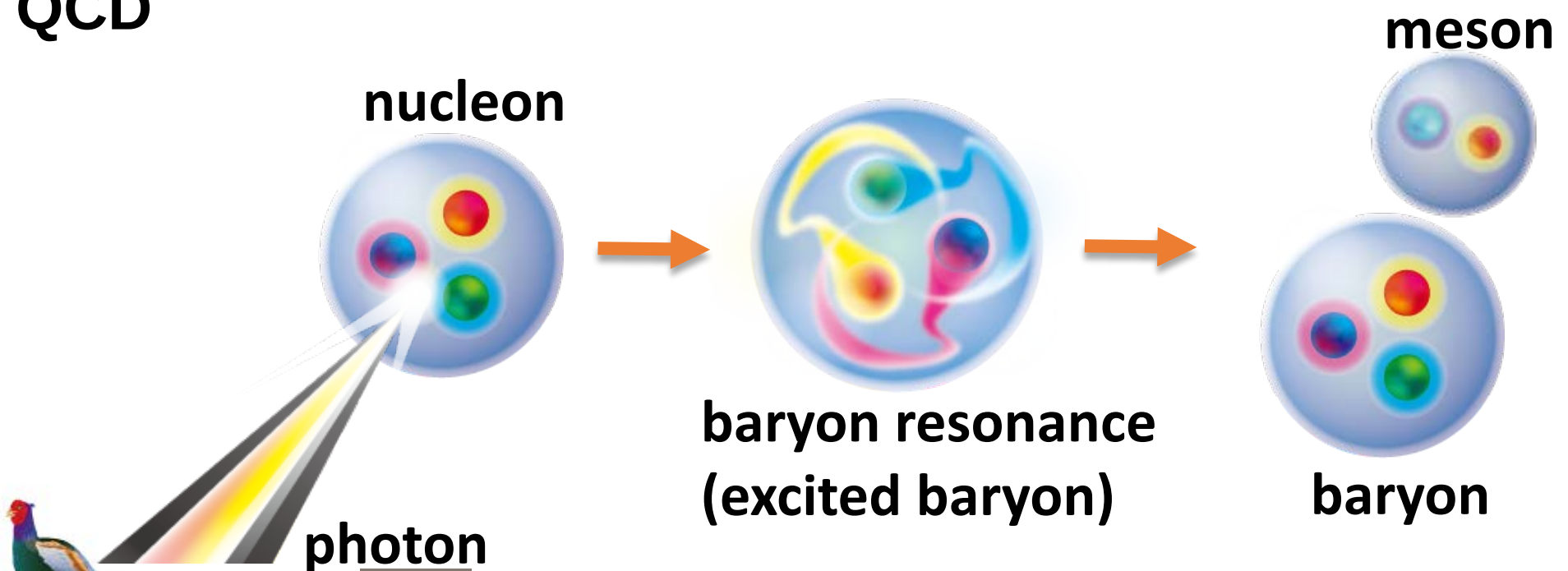
meson photoproduction

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

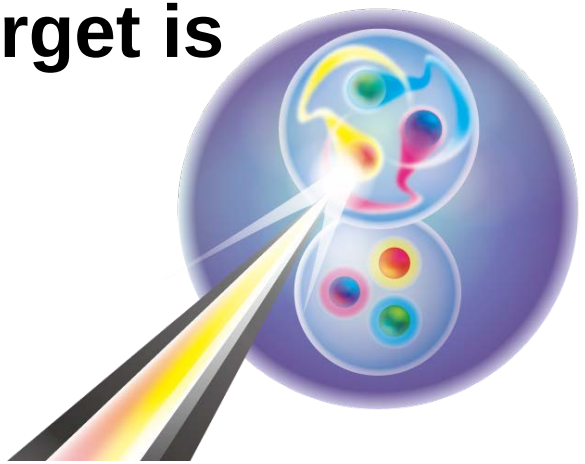
their excitation spectra are important testing ground for understanding the non-perturbative domain of QCD



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

expected mechanism $\gamma N \rightarrow mN$

- **coherent sum of the elementary amplitudes**
- **coalescence of the final-state nucleus**
- **final-state interactions**

Introduction

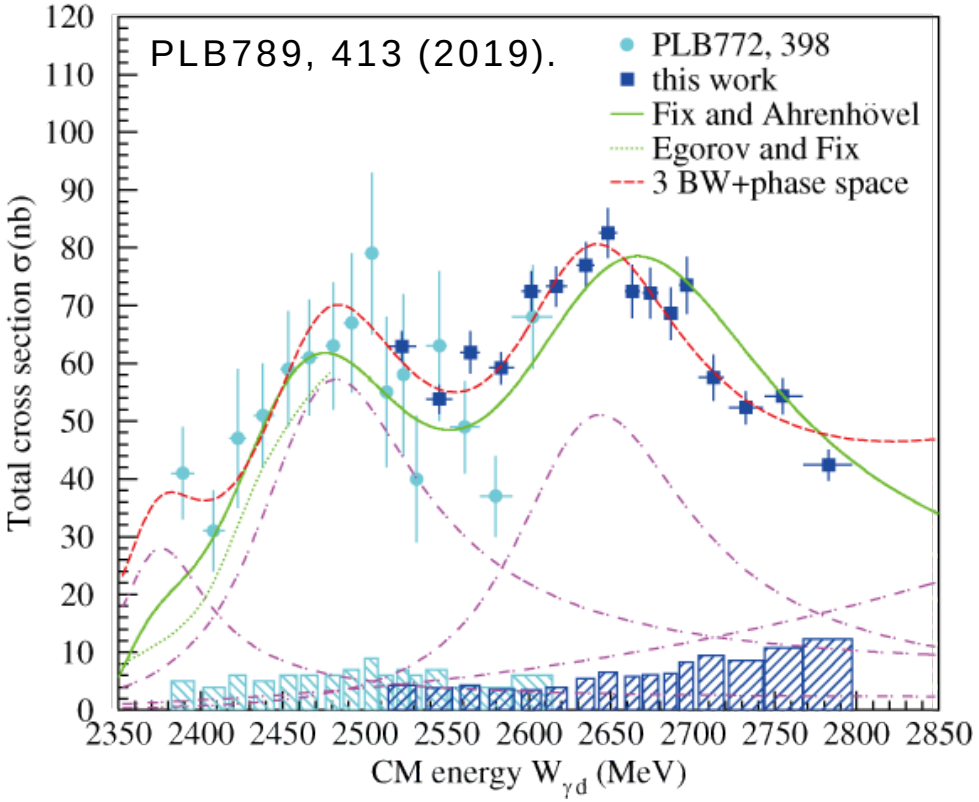
$\gamma d \to \pi^0\pi^0 d$

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

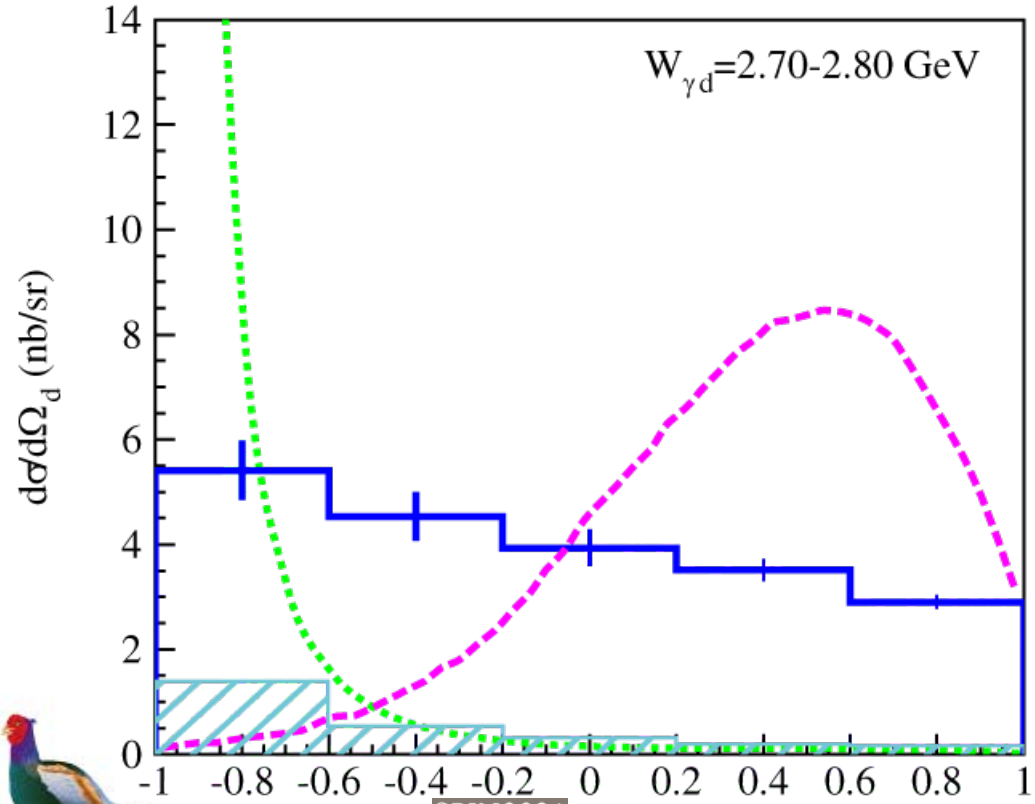


Introduction

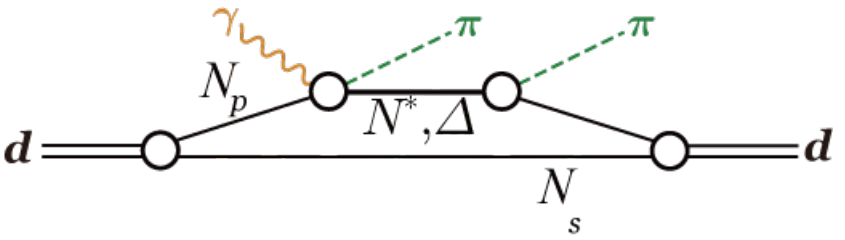
$\gamma d \rightarrow \pi^0 \pi^0 d$

the kinematic condition completely differs from QF process

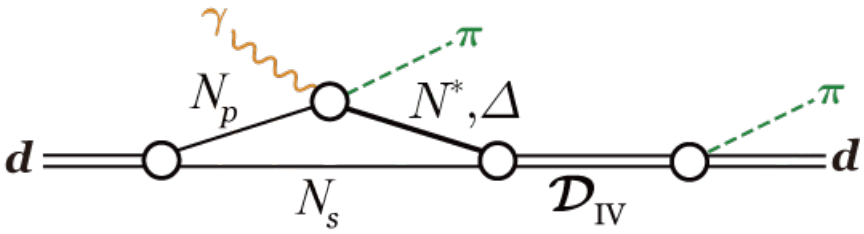
angular distribution of deuteron emission



QF $\pi\pi$ production



QF π production



Introduction

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

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

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

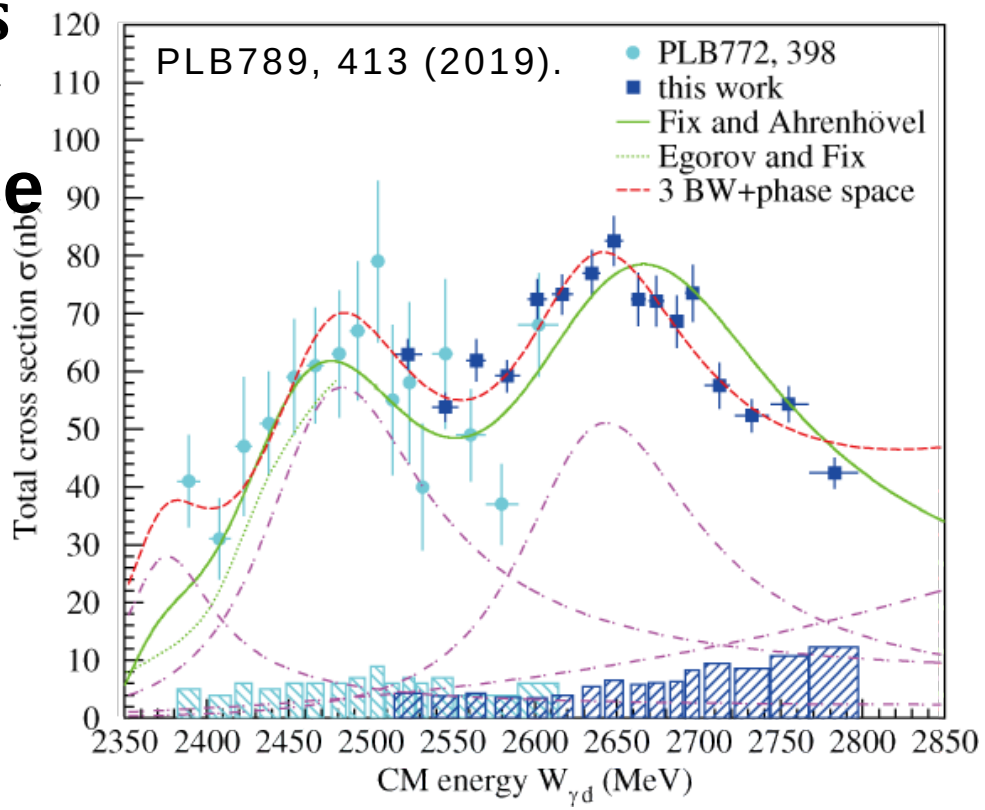
$$\gamma d \to \mathcal{D}_{\text{IS}} \to \pi^0 \mathcal{D}_{\text{IV}} \to \pi^0\pi^0 d$$

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

dibaryon: $B = 2$ resonance

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

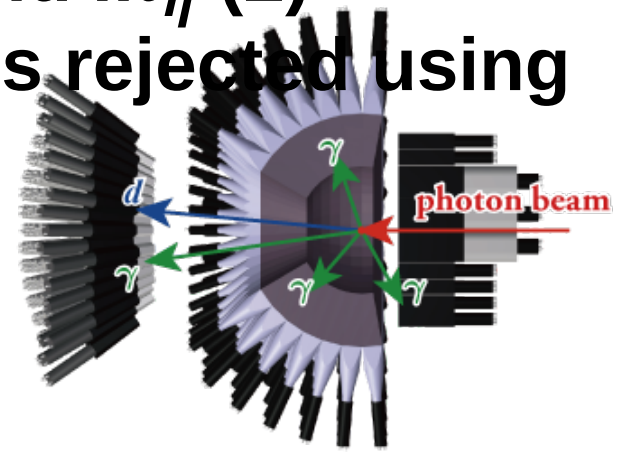
How is $\gamma d \to \pi^0\eta d$?



Experiment & Event selection

1. **bremsstrahlung tagged photon beam is used ranging from 0.75 to 1.15 GeV at ELPH**
2. **four photons from the π^0 and η decays, and a charged particle are detected with the FOREST electromagnetic calorimeter**
3. **kinematic fit is applied to select the $\gamma d \to \pi^0 \eta d$ events**
   - **energy and momentum conservation (4)**
   - **$\gamma\gamma$ invariant masses are m_{π^0} and m_η (2)**

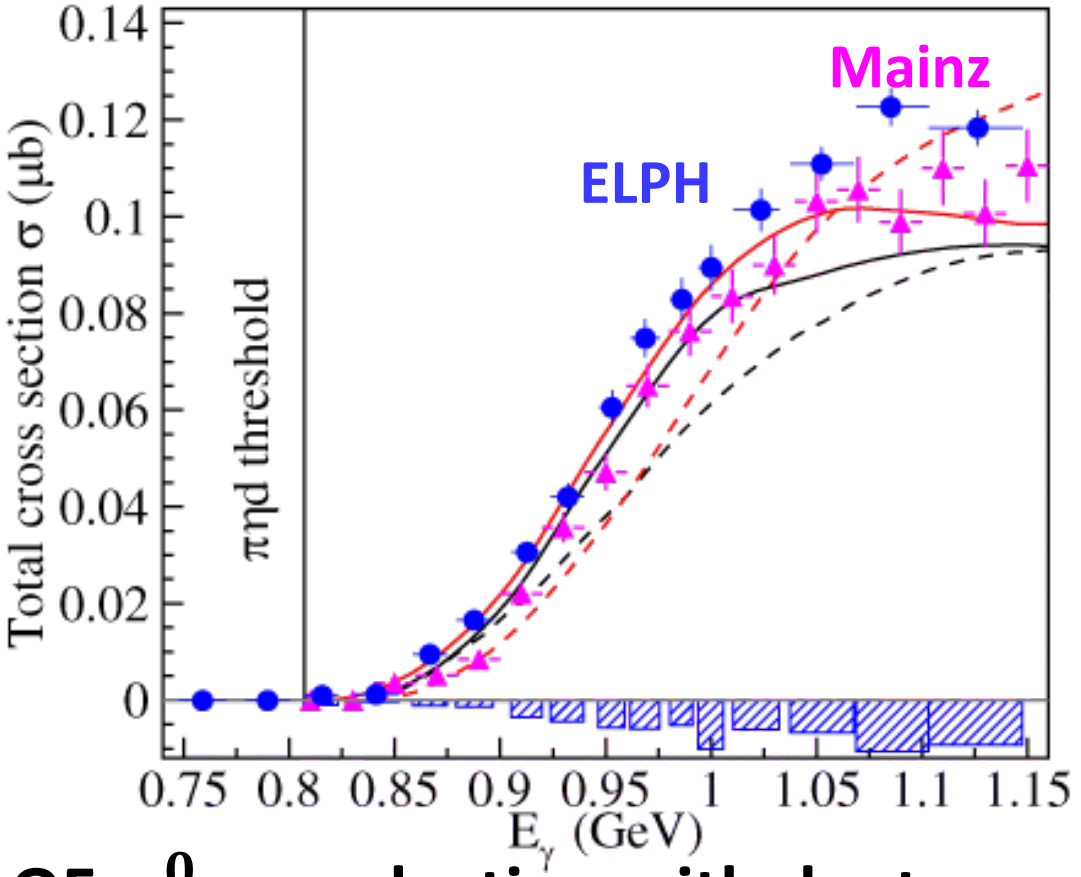
   quasifree $\gamma p' \to \pi^0 \eta p$ possibility is rejected using another kinematic fit



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).

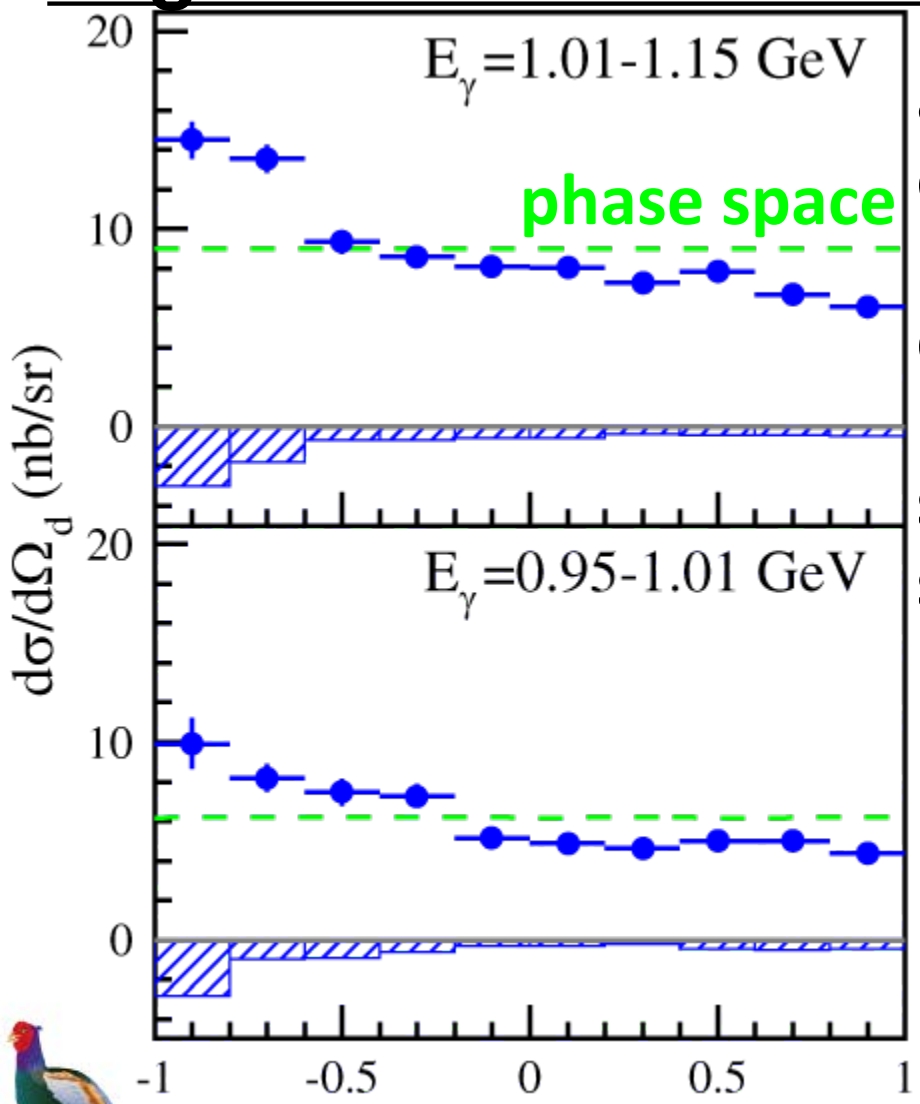
M. Egorov, PRC101, 065205 (2020).

unified microscopic approach

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

Differential cross sections

angular distributions $d\sigma/d\Omega_d$ for the first time



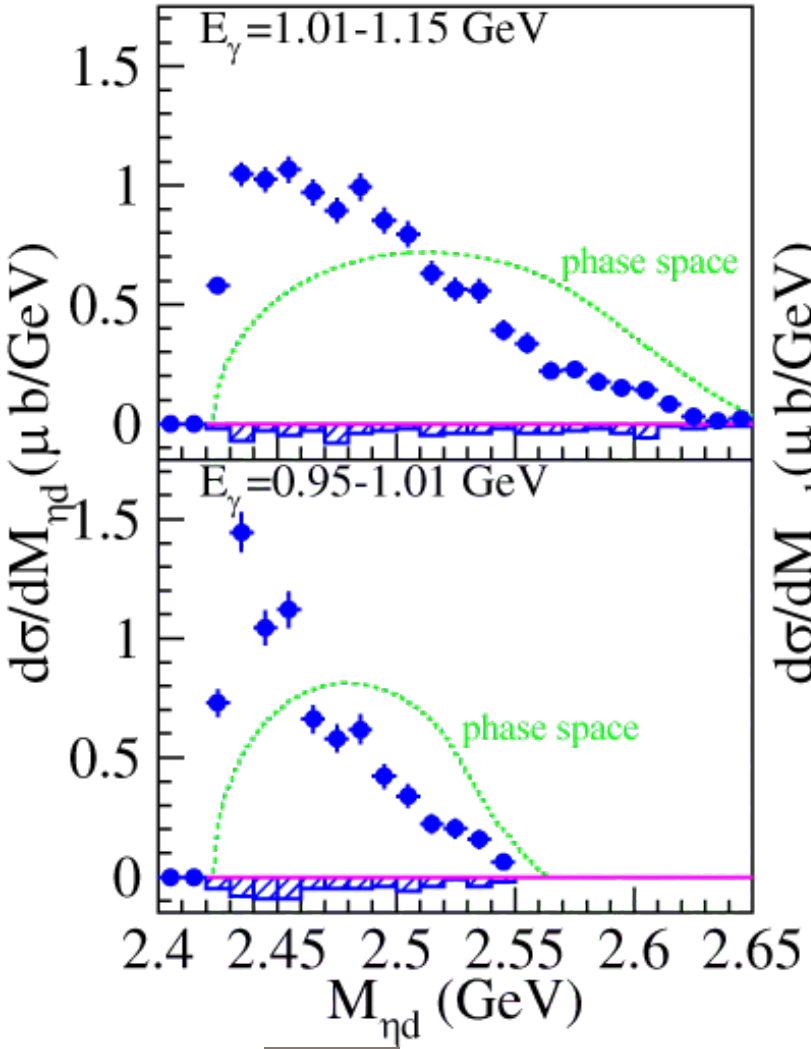
phase space

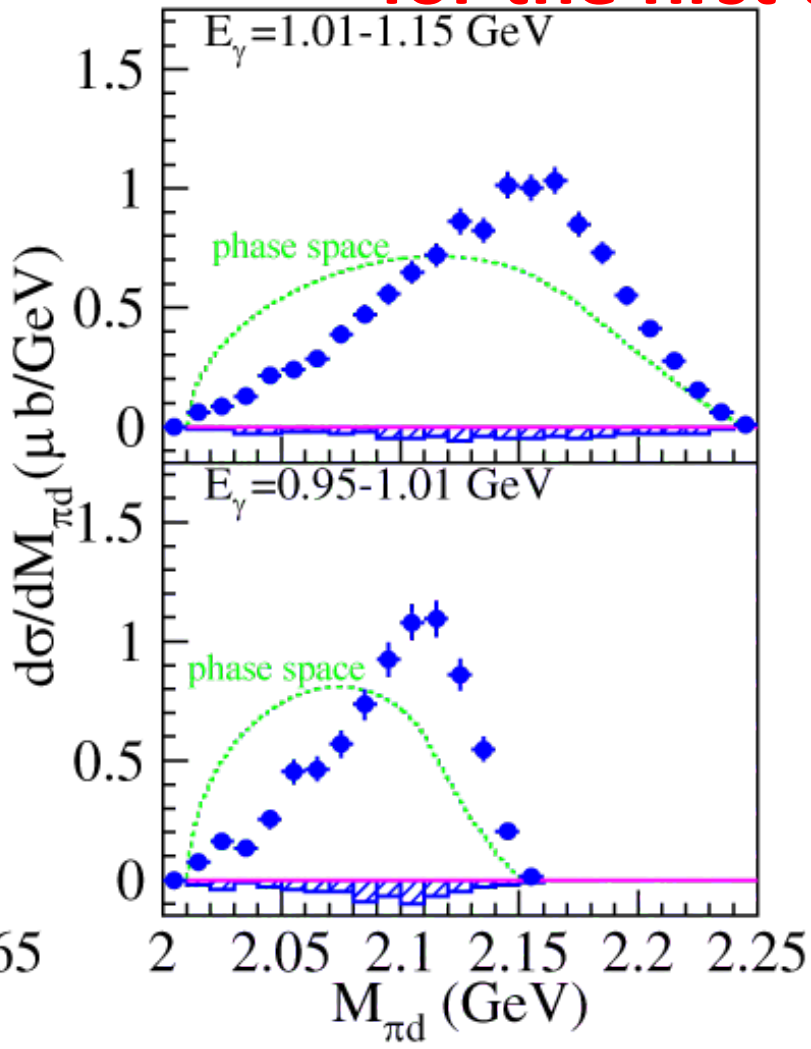
angular distribution of deuteron emission in the γd CM frame

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

Differential cross sections

mass distributions $d\sigma/dM_{\eta d}$ and $d\sigma/dM_{\pi d}$ for the first time





Observed 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** $I = 0, J^{\pi} = 1^{-}$

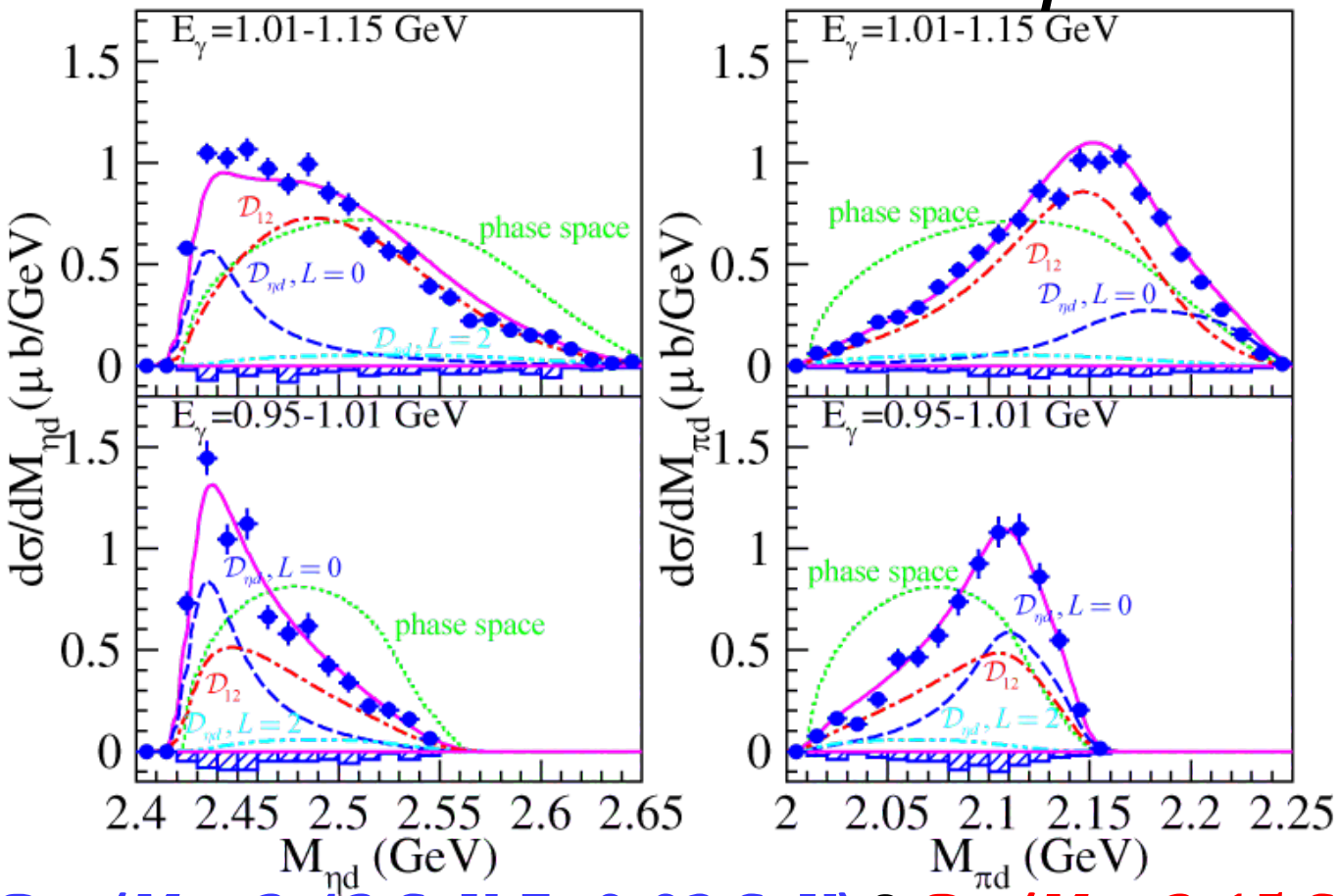
$\mathcal{D}_{12}$: **well-known** πd **resonance with** $I = 1, J^{\pi} = 2^{+}$

mass ~2.14 GeV

width ~0.09 GeV

Observed states

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

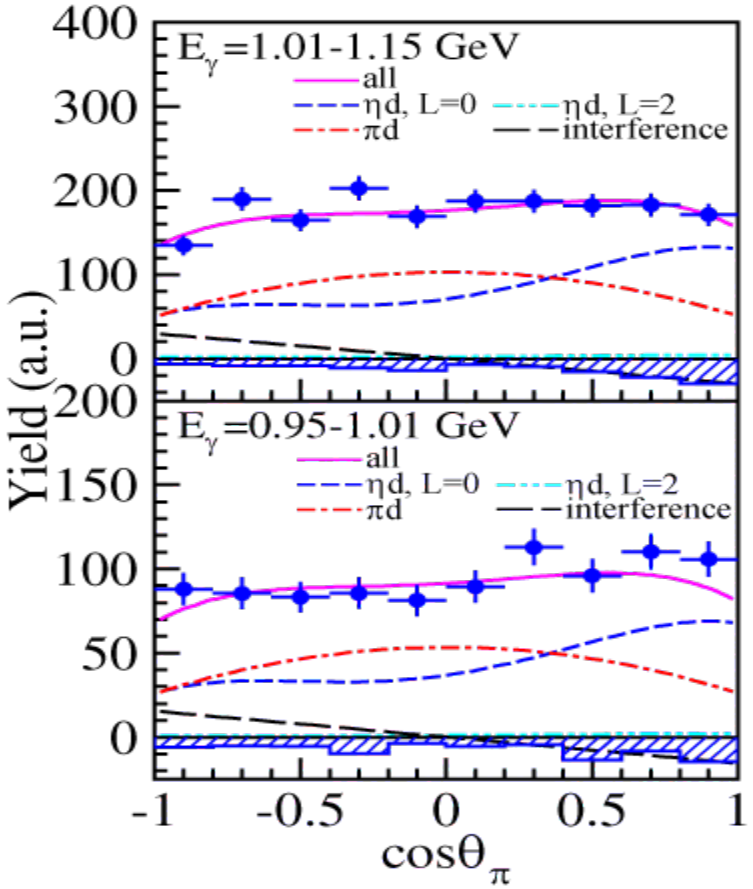


$\mathcal{D}_{\eta d}$ ($M \sim 2.42$ GeV, $\Gamma \sim 0.03$ GeV) & $\mathcal{D}_{12}$($M \sim 2.15$ GeV, $\Gamma \sim 0.11$ GeV)
consistent with isoscalar ηNN state (ηNN–πNN coupled channel calculation): $M \simeq M_\eta + M_d, \Gamma = 0.01 \sim 0.02$ GeV

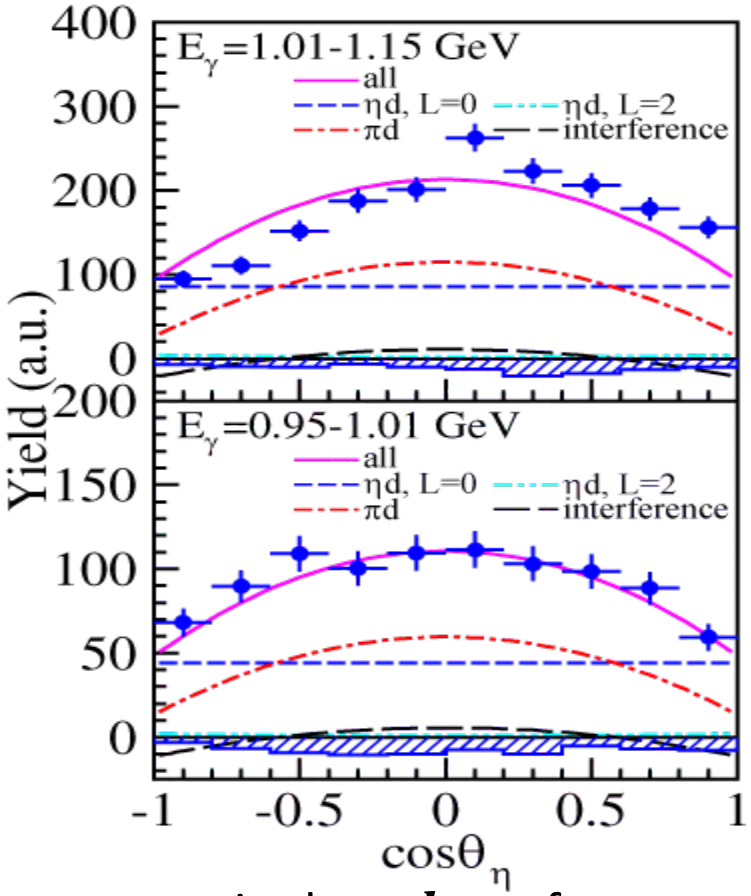
T. Ueda, PRL66, 297 (1991).

Angular correlations

angular distribution & correlation



γ–π in the γd-CM frame



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

$M_{\eta d} < 2.47$ GeV

Observed states

angular distribution & correlation

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

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

47%

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

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

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).

Summary

1. neither $\gamma d \to \pi^0\pi^0 d$ nor $\gamma d \to \pi^0\eta d$ is described by a coherent sum of the elementary amplitudes with deuteron coalescence

2. a sequential process in $\gamma d \to \pi^0\pi^0 d$
   $\gamma d \to \mathcal{D}_{\rm IS} \to \pi^0\mathcal{D}_{12} \to \pi^0\pi^0 d$
   $\mathcal{D}_{12}$: $I = 1, J^\pi = 2^+, M = 2.14$ GeV, $\Gamma = 0.09$ GeV

3. two sequential processes in $\gamma d \to \pi^0\eta d$
   $\gamma d \to \mathcal{D}_{\rm IV} \to \pi^0\mathcal{D}_{\eta d} \to \pi^0\eta d$
   $\gamma d \to \mathcal{D}_{\rm IV} \to \eta\mathcal{D}_{12} \to \pi^0\eta d$
   $\mathcal{D}_{\eta d}$: $I = 0, J^\pi = 1^-, M \sim 2.42$ GeV, $\Gamma \sim 0.03$ GeV consistent with a theoretical prediction:
   three-body calculation for the ηNN–πNN coupled channels
   $M \simeq M_\eta + M_d, \Gamma = 0.01 \sim 0.02$ GeV T. Ueda, PRL66, 297 (1991).
   also interpreted as an ηd virtual state

4. the N^* contribution appears in $\gamma N \to \pi^0\eta N$

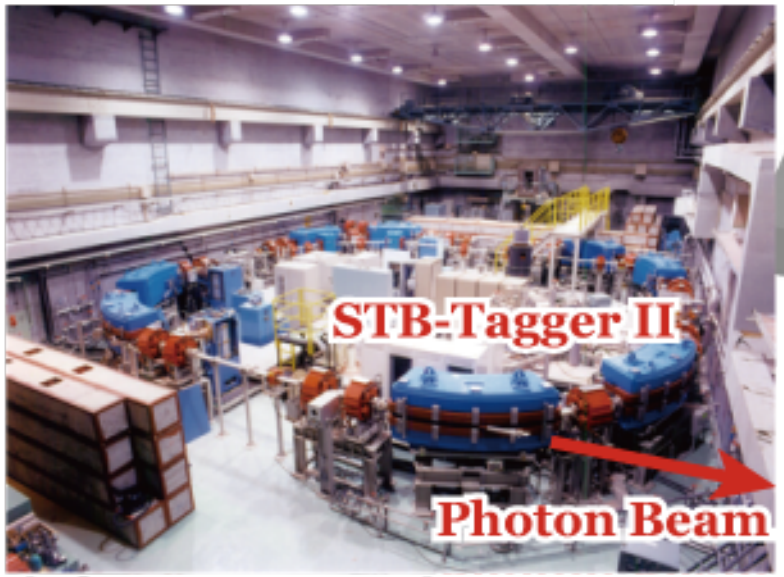
5. Detailed discussion can be found in arXiv: 2105.10887

Backup slides

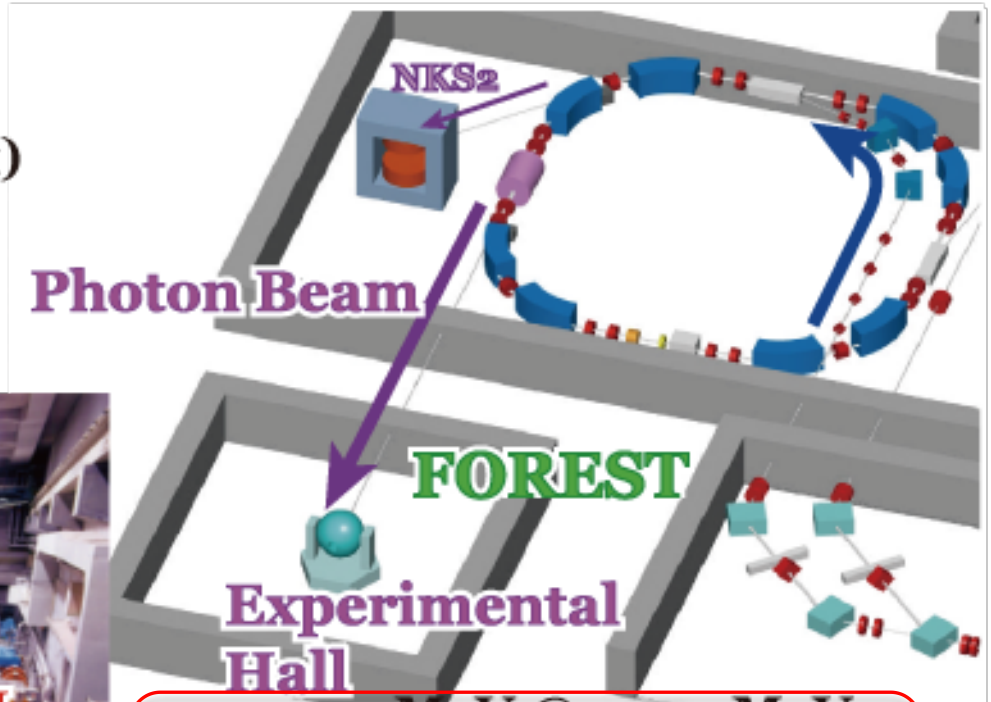
Accelerator

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

Photon Beam
- Bremsstrahlung
- Tagged



1.3 GeV Booster STorage Ring

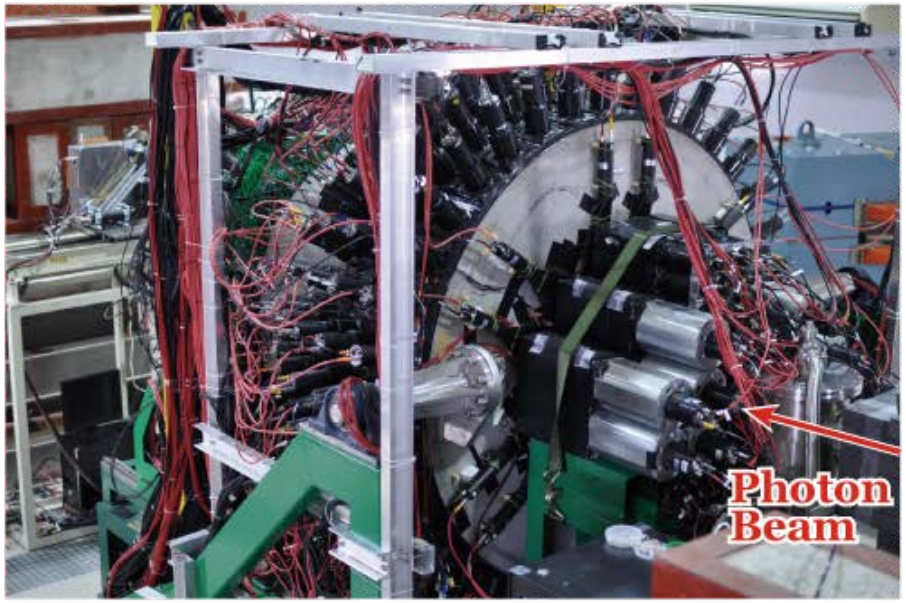


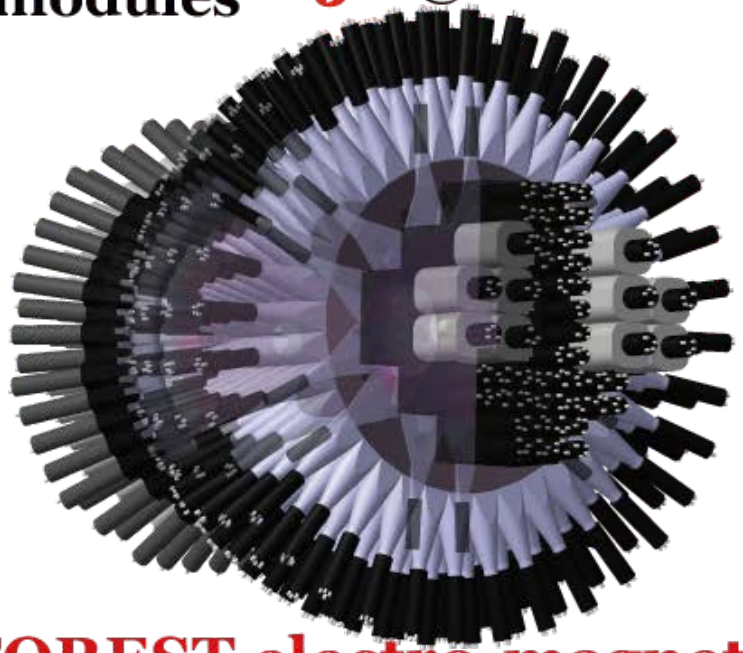
740~1150 MeV @ 1200 MeV
~20 MHz (photon: 10 MHz)
$W_{\gamma d}$=2.50~2.80 GeV

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





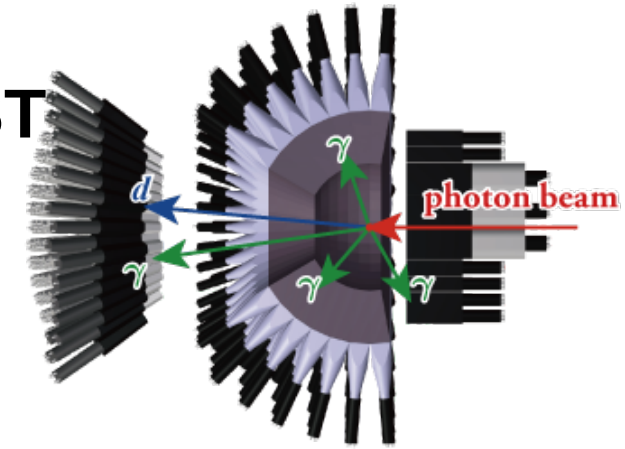
FOREST electro-magnetic calorimeter

Target: 45 mm thick LH2 & LD2

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

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



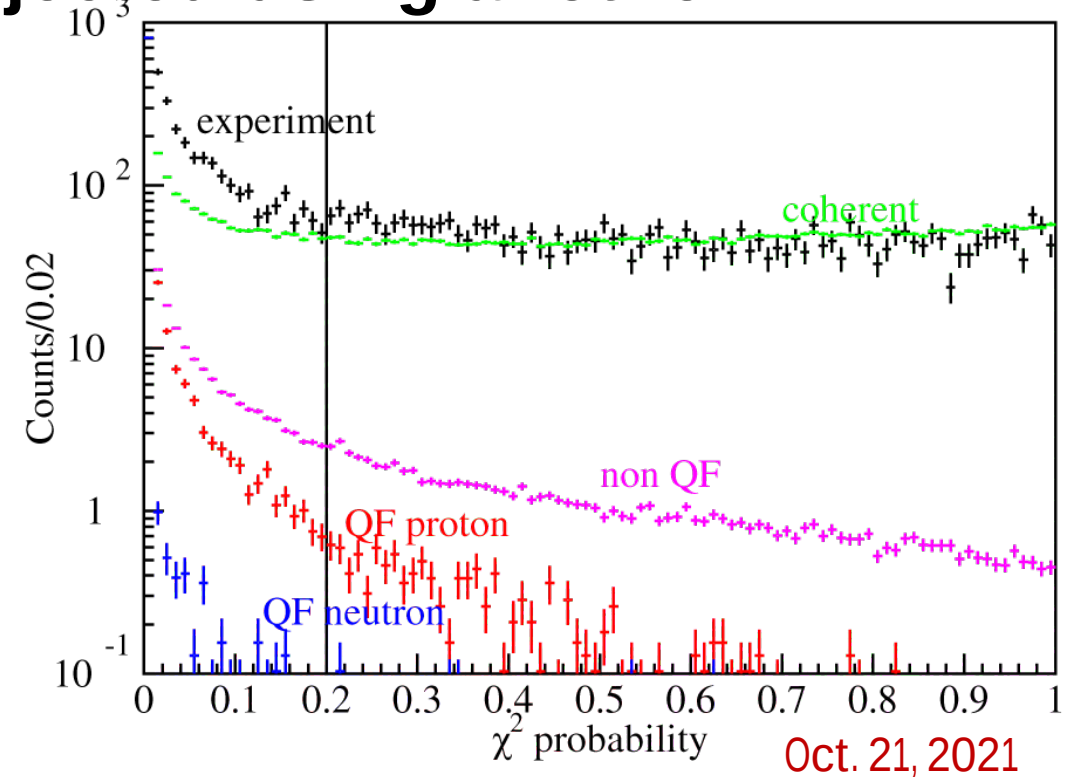
Event selection ($\gamma d \to \pi^0 \eta d$)

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



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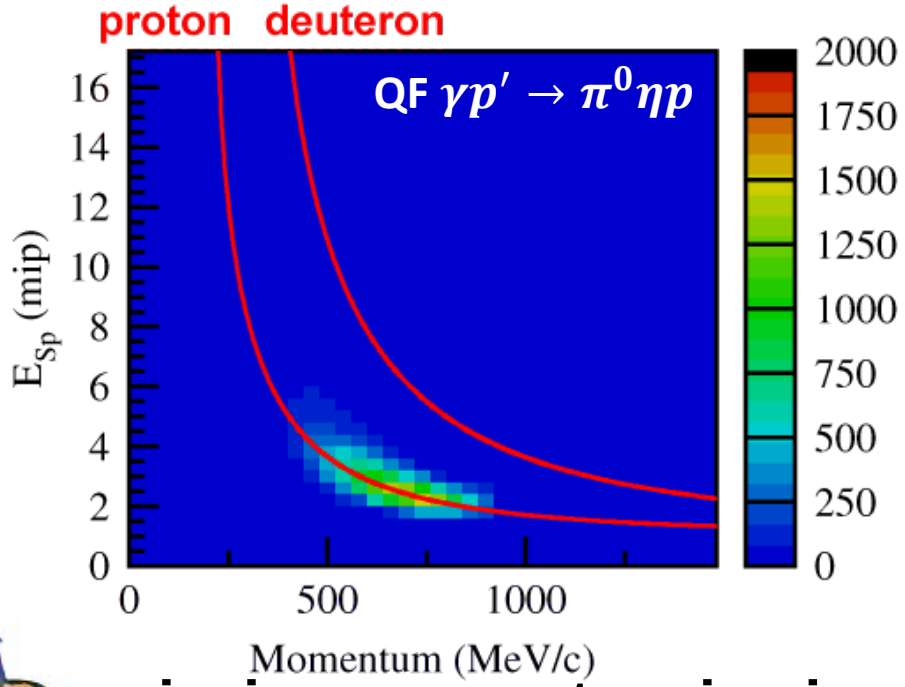

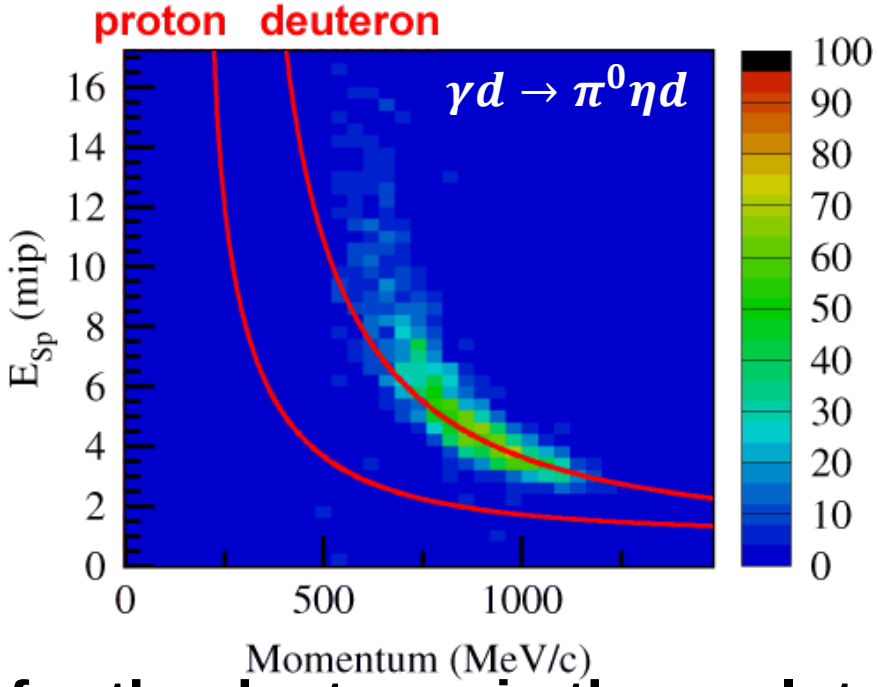

missing momentum is given for the deuteron in these plots

Correlation plot