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

Exotic multi-quark states and baryon spectroscopy workshop

Universitätsclub Bonn, the University of Bonn, Bonn, Germany,

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Takatsugu Ishikawa (ishikawa@rcnp.osaka-u.ac.jp)

Research Center for Nuclear Physics (RCNP), Osaka University, Japan

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

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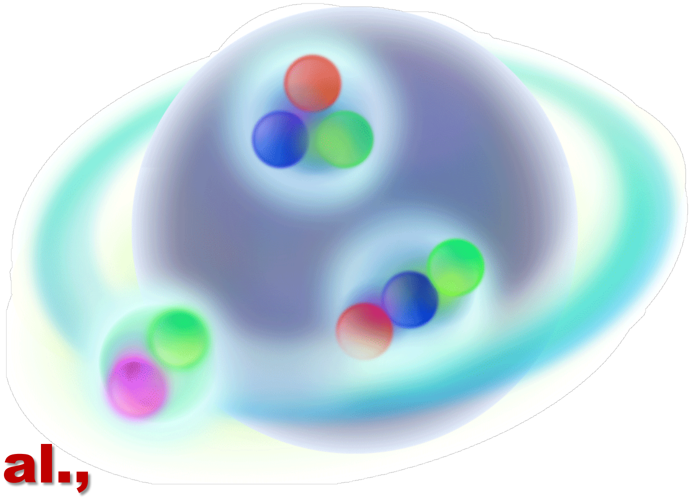

T. Ishikawa et al.,
Phys. Rev. C 104, L052201 (2021);
Phys. Rev. C 105, 045201 (2022).

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 $N(1535)1/2^-$

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-nuclear interaction

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<u>Traditional tool</u>

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

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

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

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: $M = 2.41\ \mathrm{GeV}$ 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 ?

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

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Experiment

@ Research Center for Electron Photon Science (ELPH), Tohoku University

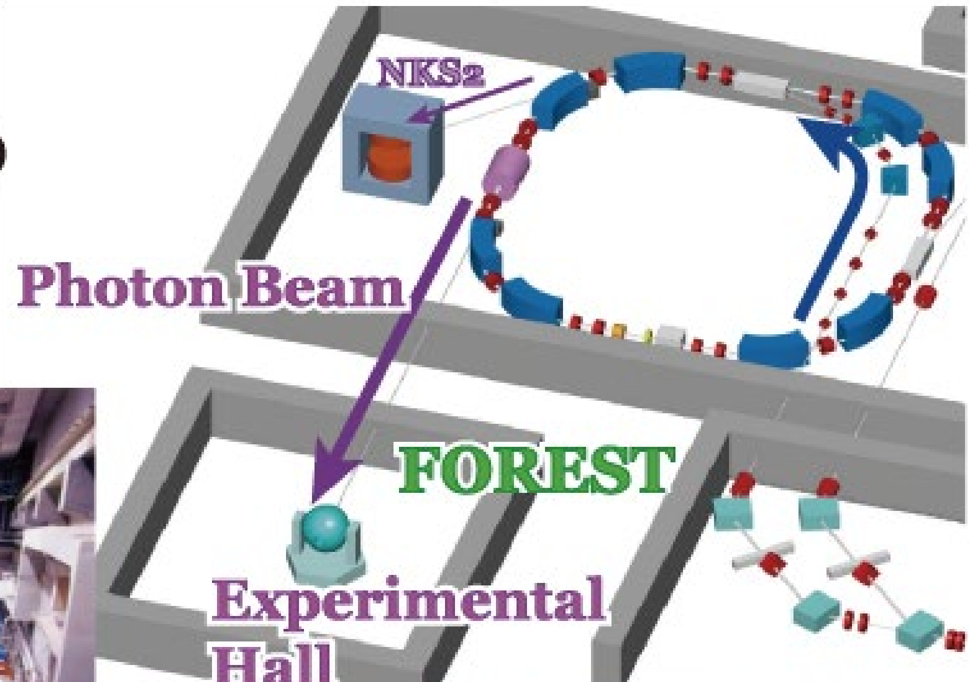
Accelerator

Electron Beam

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

Photon Beam

- Bremsstrahlung
- Tagged



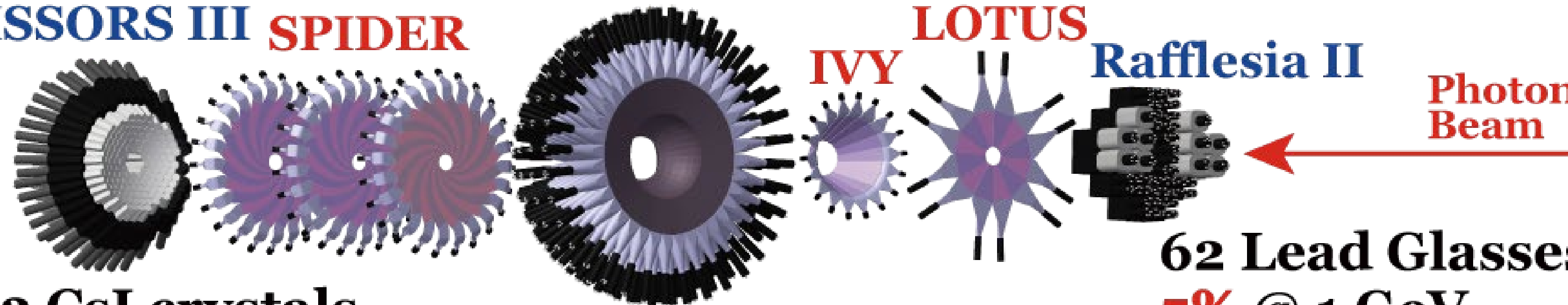
1.3 GeV Booster STorage Ring

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).

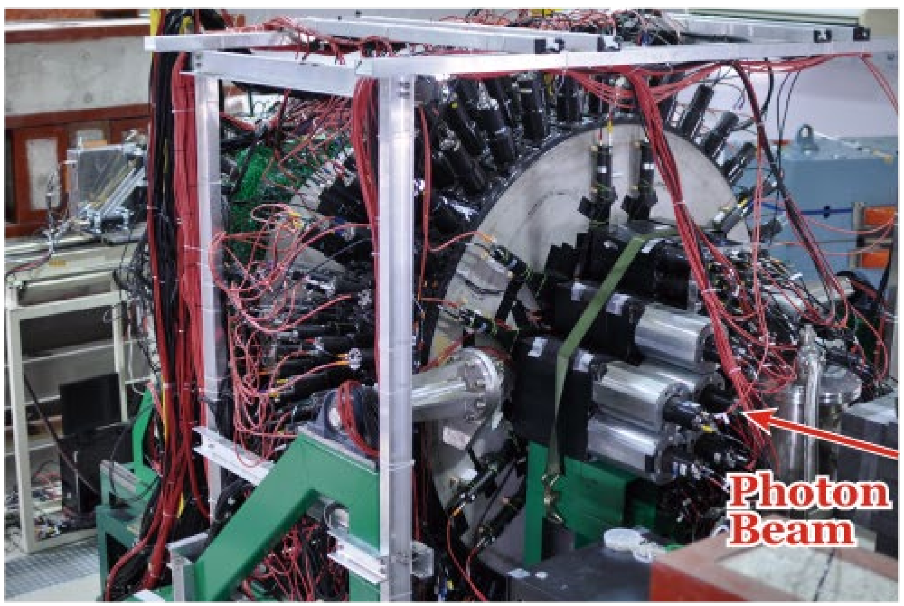
EM calorimeter



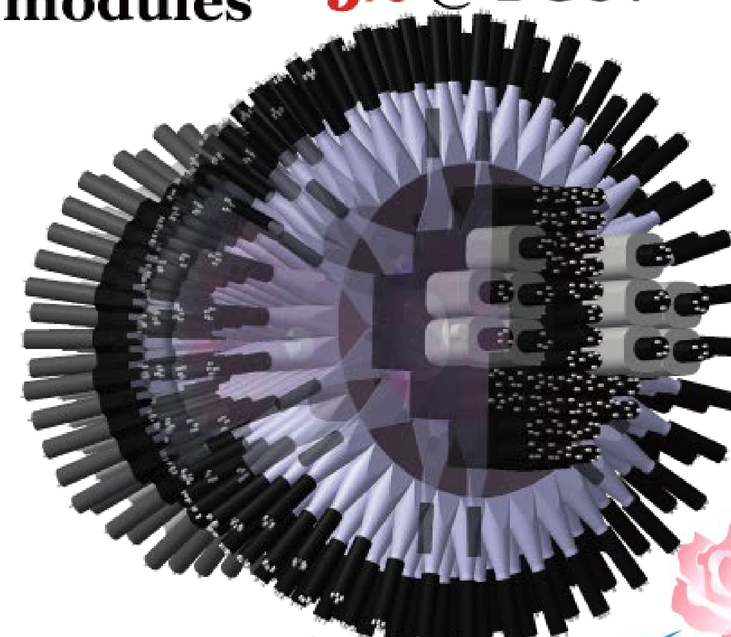
192 CsI crystals
3% @ 1 GeV

252 Lead/SciFi modules
7% @ 1 GeV

62 Lead Glasses
5% @ 1 GeV



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

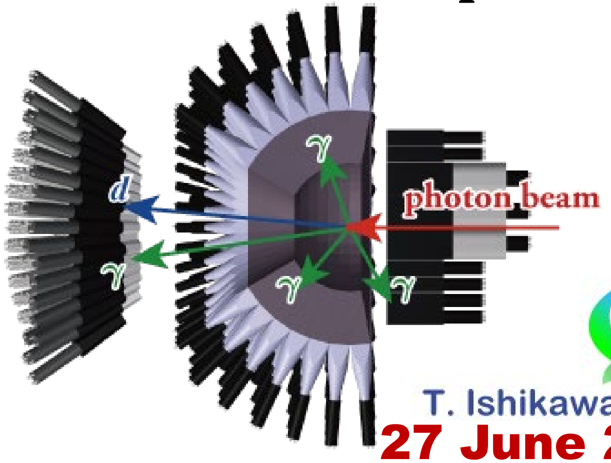


FOREST electro-magnetic calorimeter

Analysis

Event selection

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



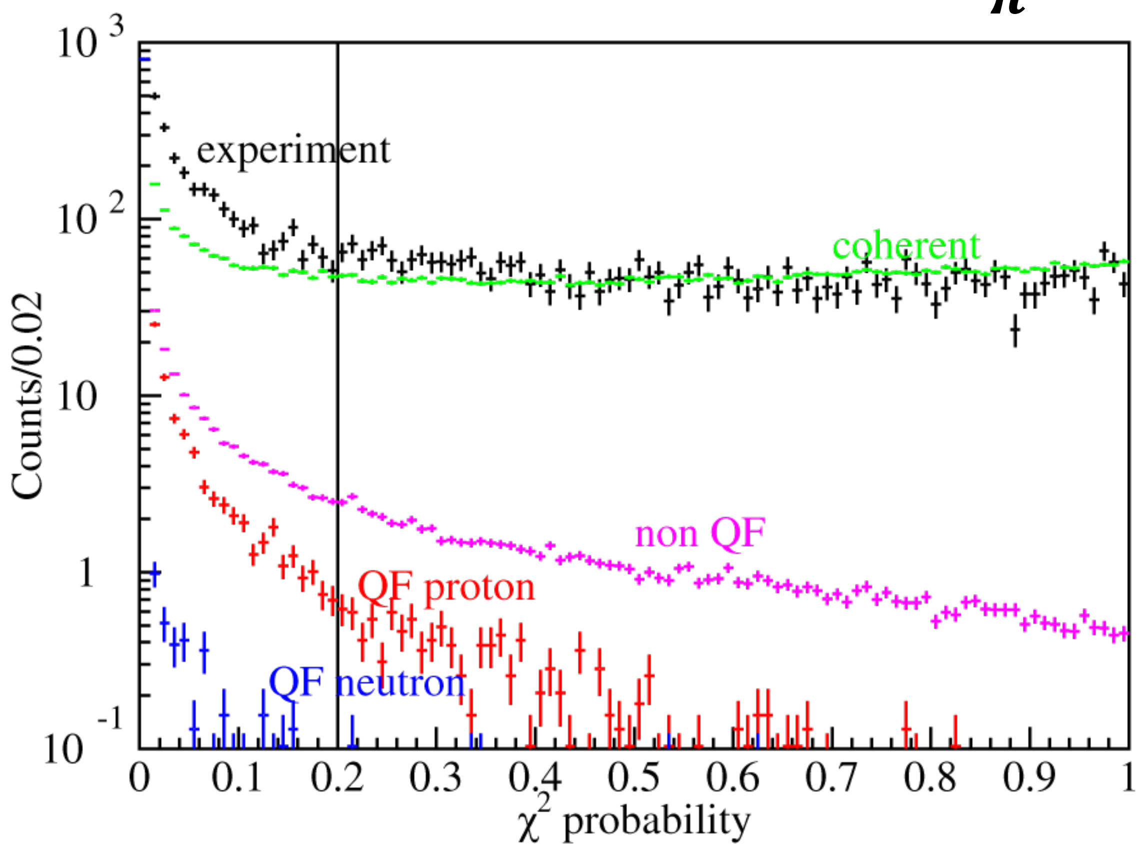
Event selection

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)

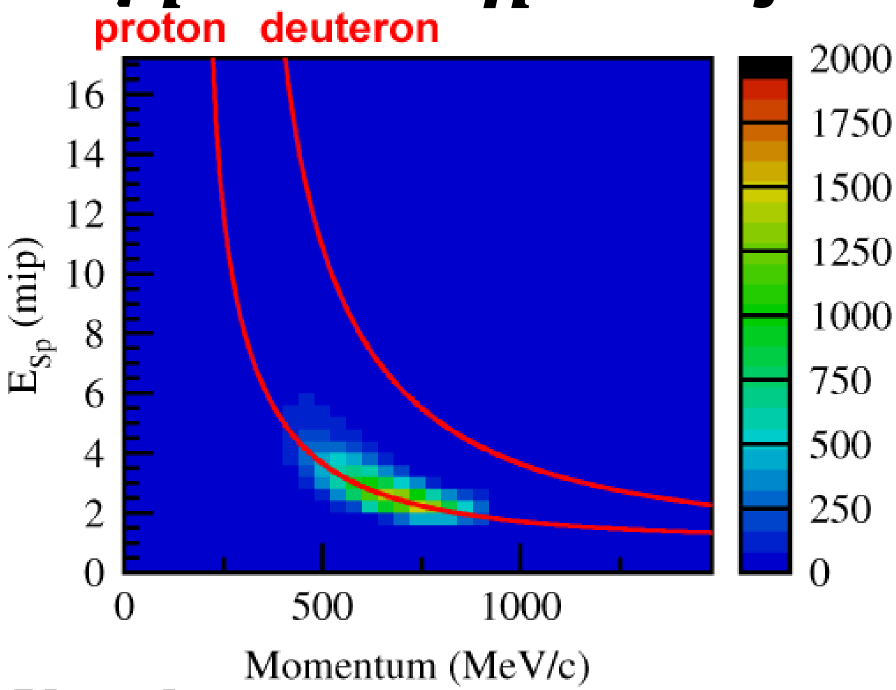


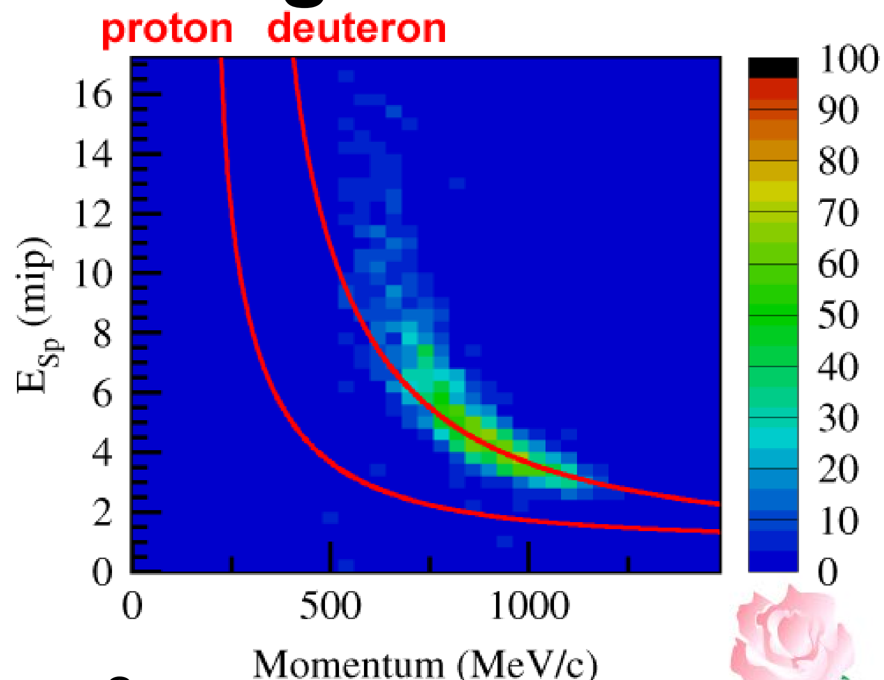
Event selection

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

Results

Results

Total cross section

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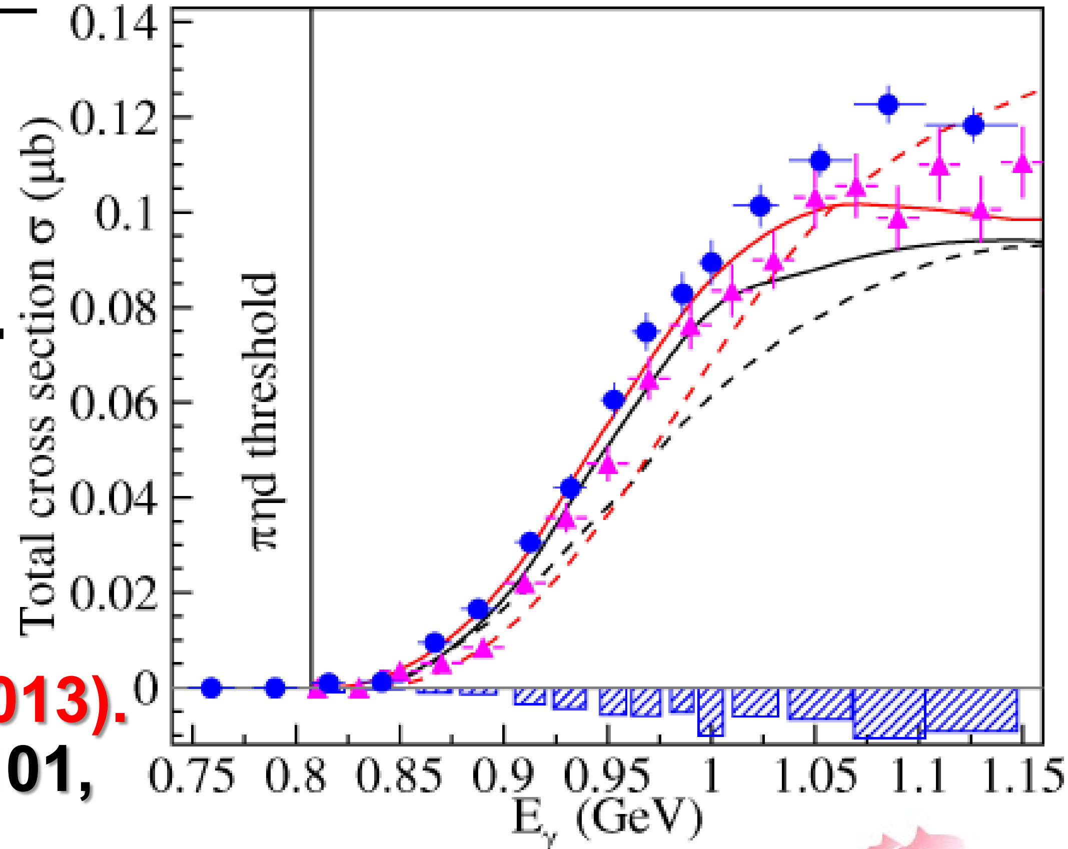
A. Käser et al., Phys. Lett. B 748, 244 (2015).

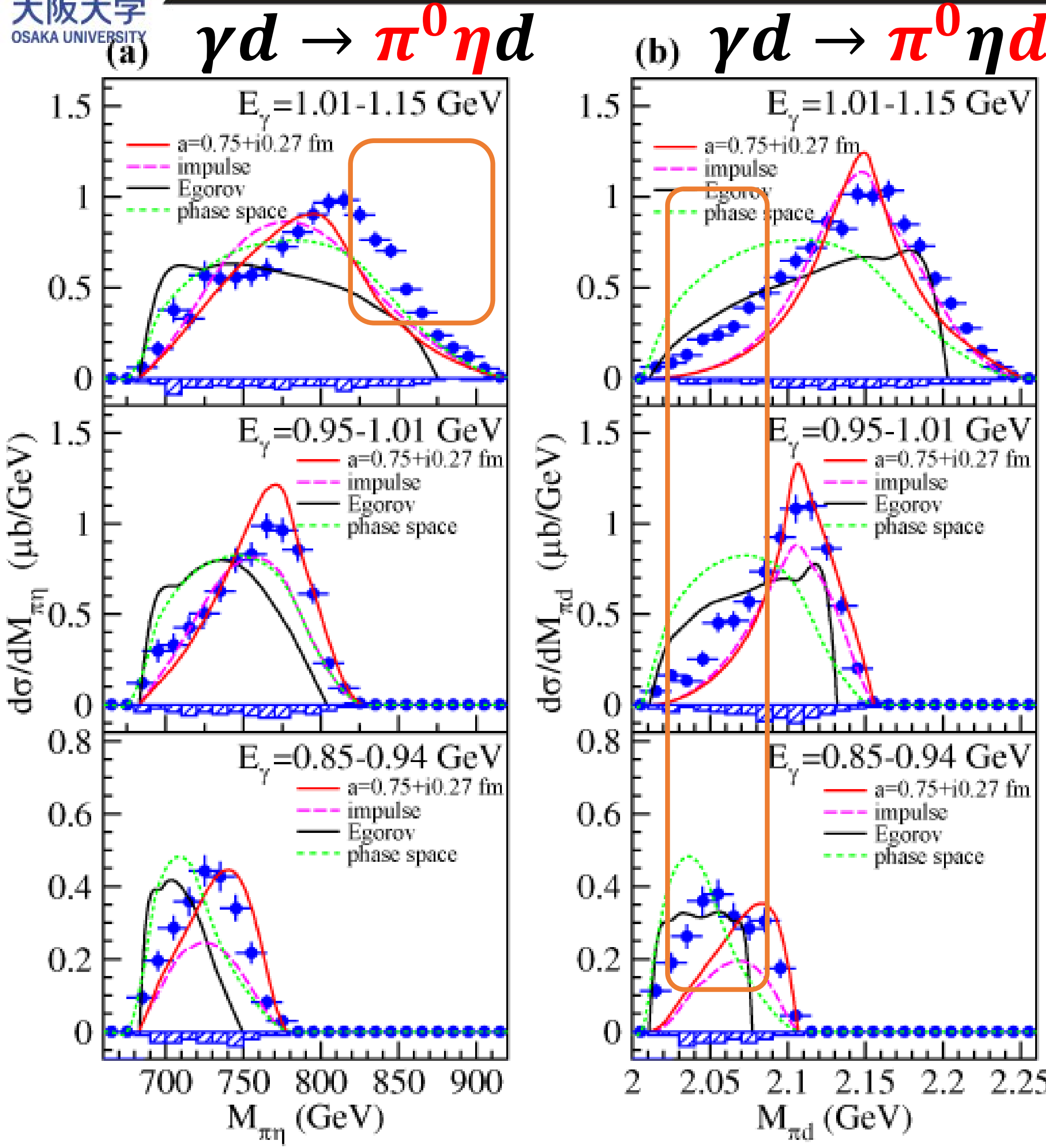
Excitation function

Dashed curves
  impulse
Solid curves
  meson-nucleus final-state interaction



Two models
1) M. Egorov, A. Fix, Phys. Rev. C88, 054611 (2013).
2) M. Egorov, Phys. Rev. C101, 065205 (2020).
  unified microscopic approach
  $\pi^{\pm}N \to \eta N$ and $\pi^{\pm}N \to N$ 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>

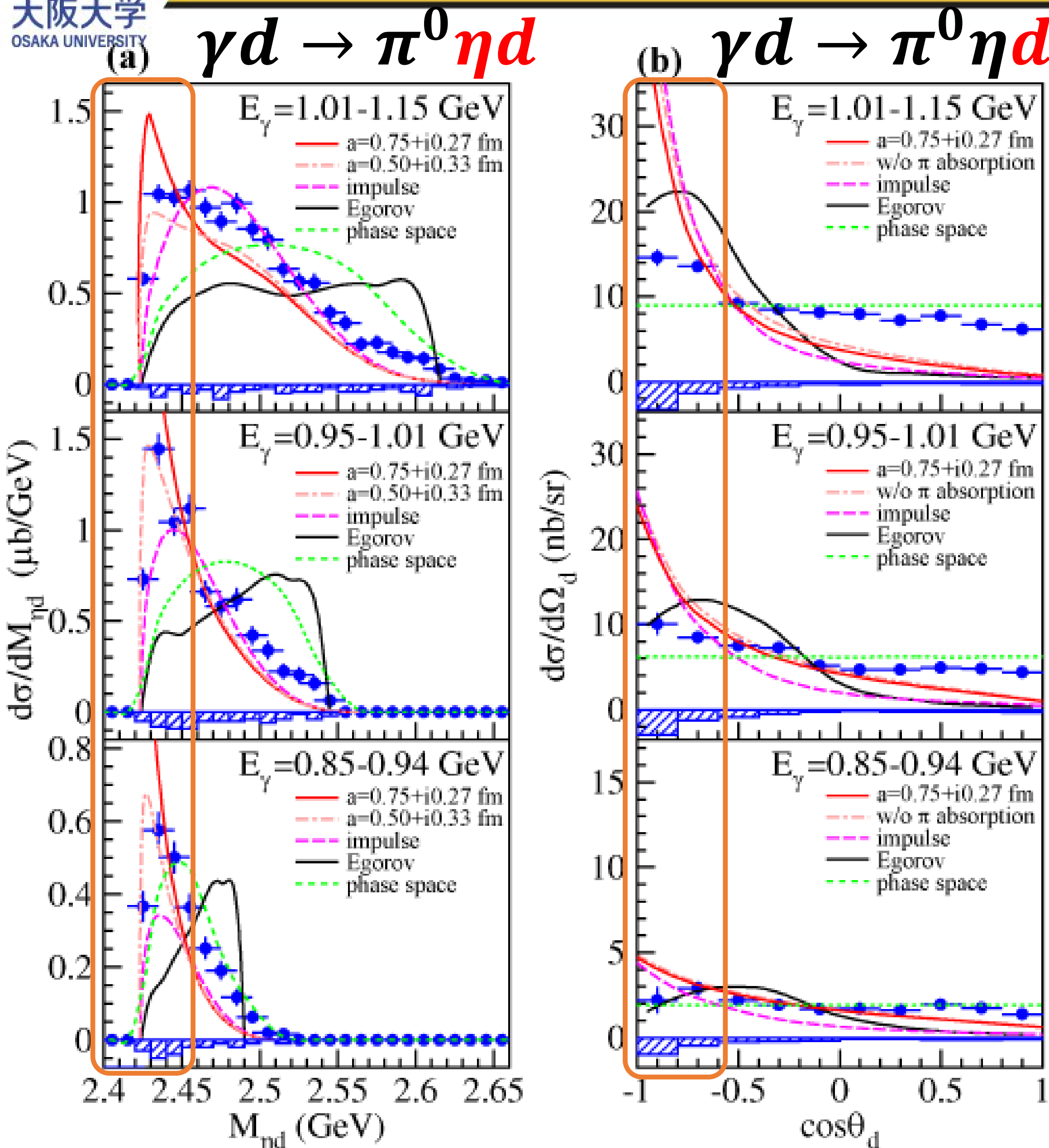
maximum at $M_{\pi d} \approx M_N + M_\Delta$

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

$\to$ ηd attraction

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

$d\sigma/d\Omega_d$:

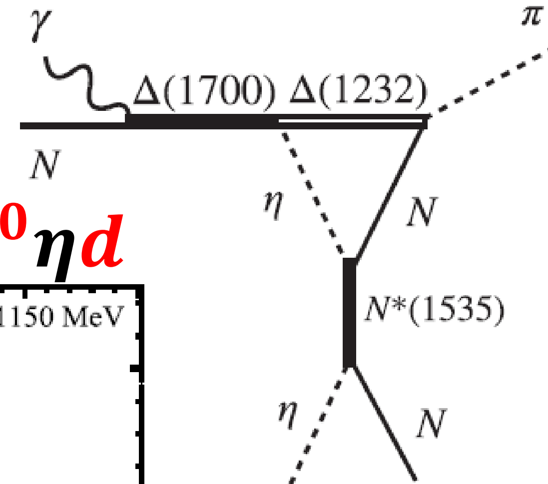
rather uniform

coherent sum of elementary amplitudes

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

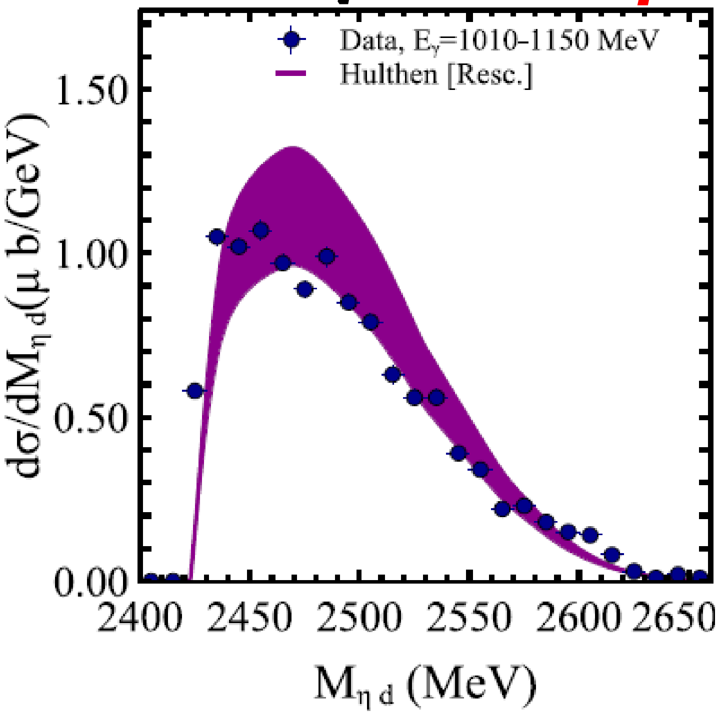
New interpretation of $\gamma d \to \pi^0 \eta d$

Martinez Torres, K. P. Khemchandani and E. Oset, PRC107, 025202 (2023) [triangle singularity].

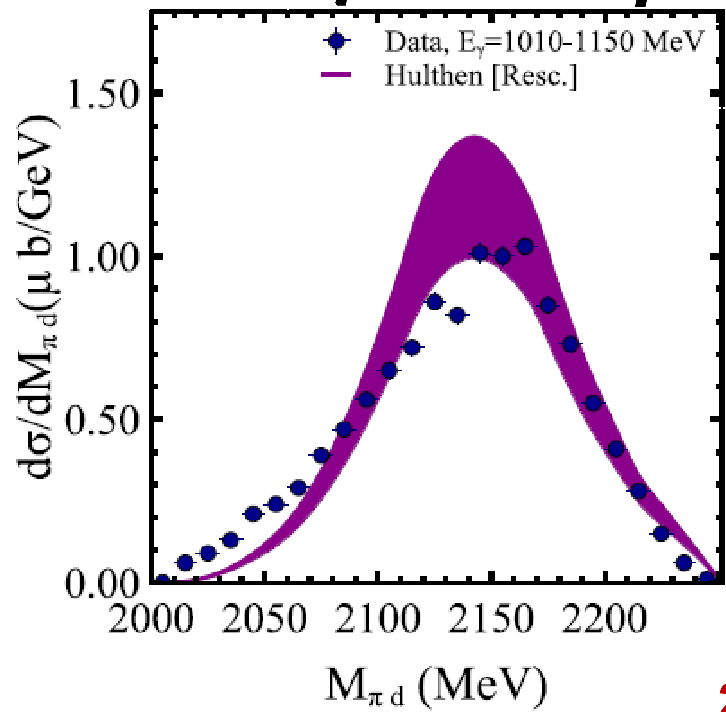


The features of the mass distributions are reproduced.

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



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

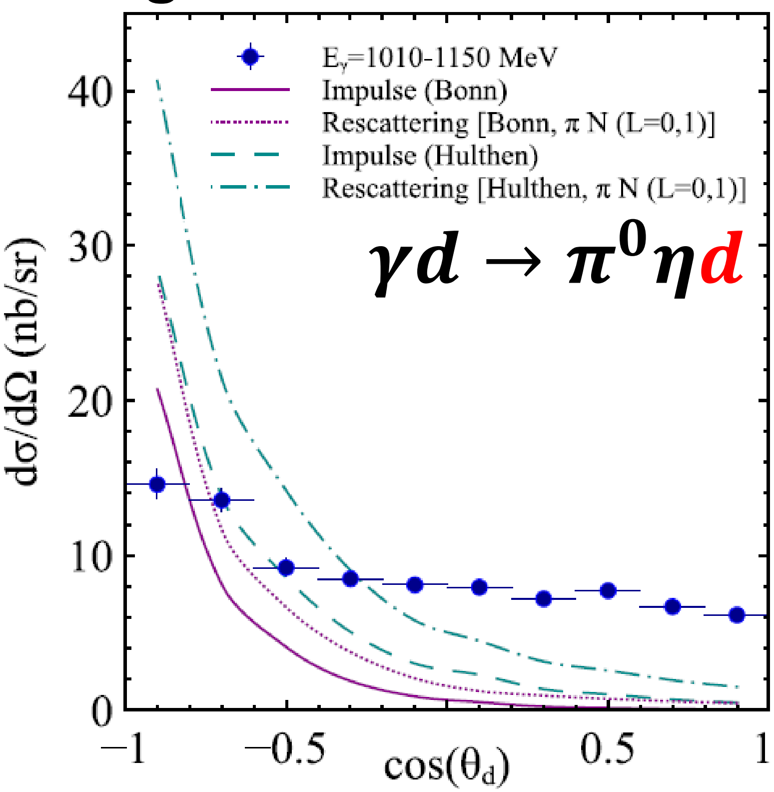


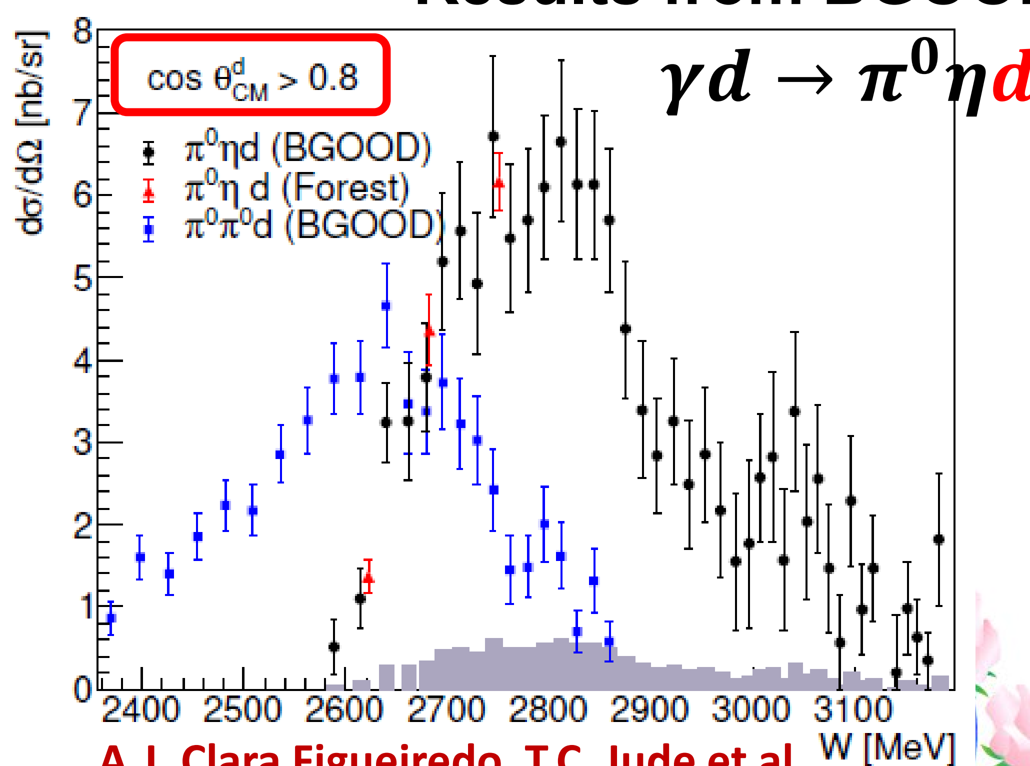
Mystery in $\gamma d \to \pi^0 \eta d$

no theoretical calculations reproduce unexpected large cross sections at forward angles of deuteron emission

Results from BGOOD

Triangular calculation





A.J. Clara Figueiredo, T.C. Jude et al., arXiv: 2405.09392 (2024).

Other coherent reactions

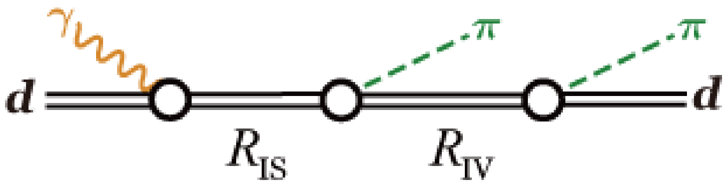
$\gamma d \to \pi^0 \pi^0 d$ to study dibaryons

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

Coherent photoproduction

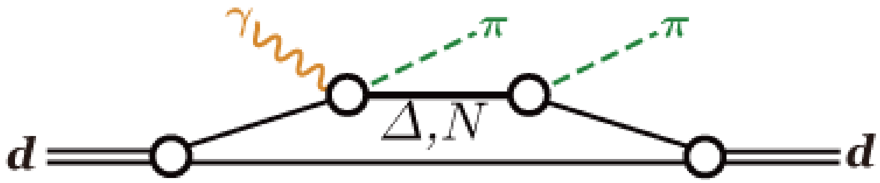
angular distribution of deuteron emission

(1) dibaryon production



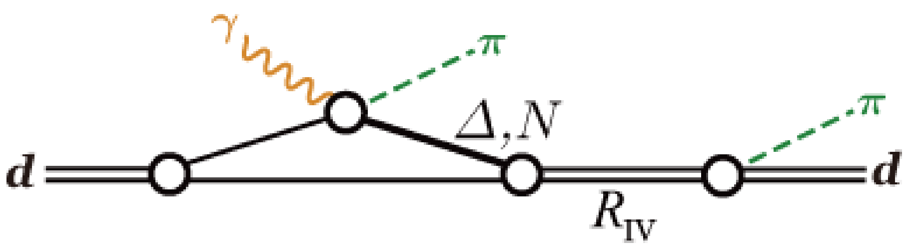
almost flat

(2) QF $\pi\pi$ production



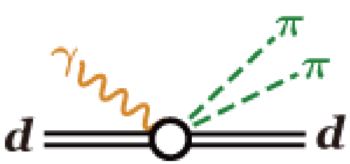
backward peaking

(3) QF $\pi\pi$ production



sideway peaking

(4) QF $\pi\pi$ production



almost flat

kinematically separable!

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

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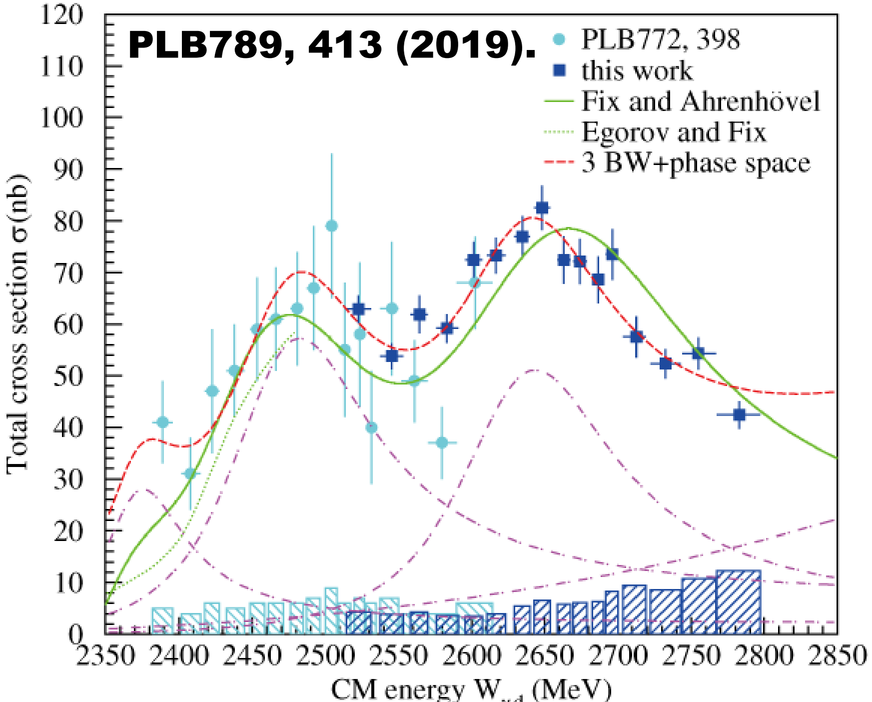
Total cross section σ

at incident energies 0.55~1.15 GeV

Two resonance-like peaks around 2.47 and 2.63 GeV

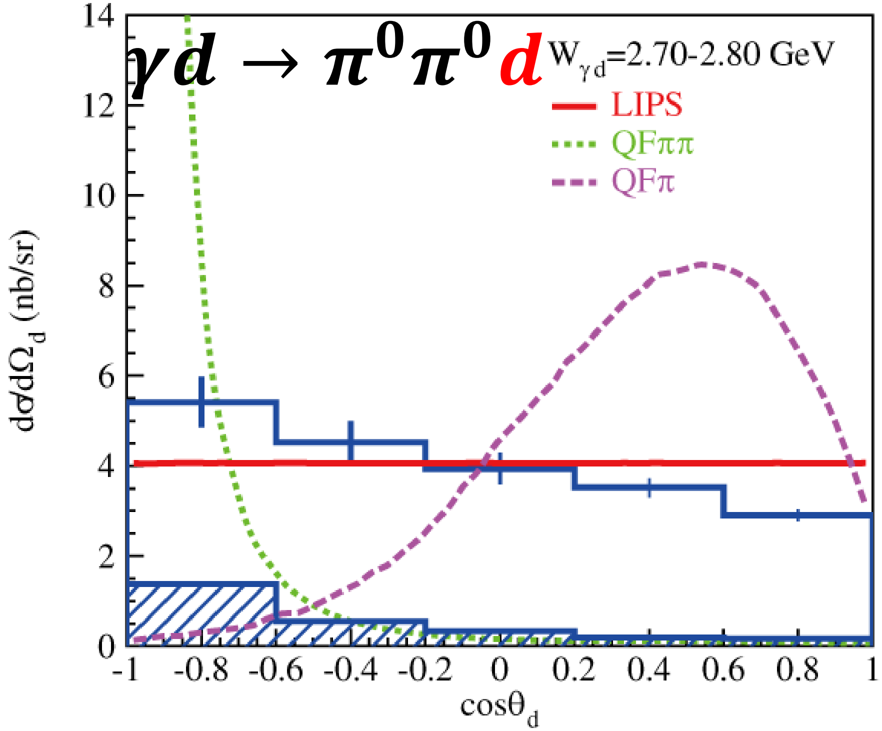
similar to the excitation function of the elementary $\gamma N \to \pi^0\pi^0 N$



naiive interpretation:
quasi-free excitation of the nucleon in the deuteron.

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

Angular distribution of deuteron emission



QF $\pi\pi$ production (FA calculation)

QF π production

pure phase space (direct $\pi\pi$ production)

PLB789, 413 (2019).

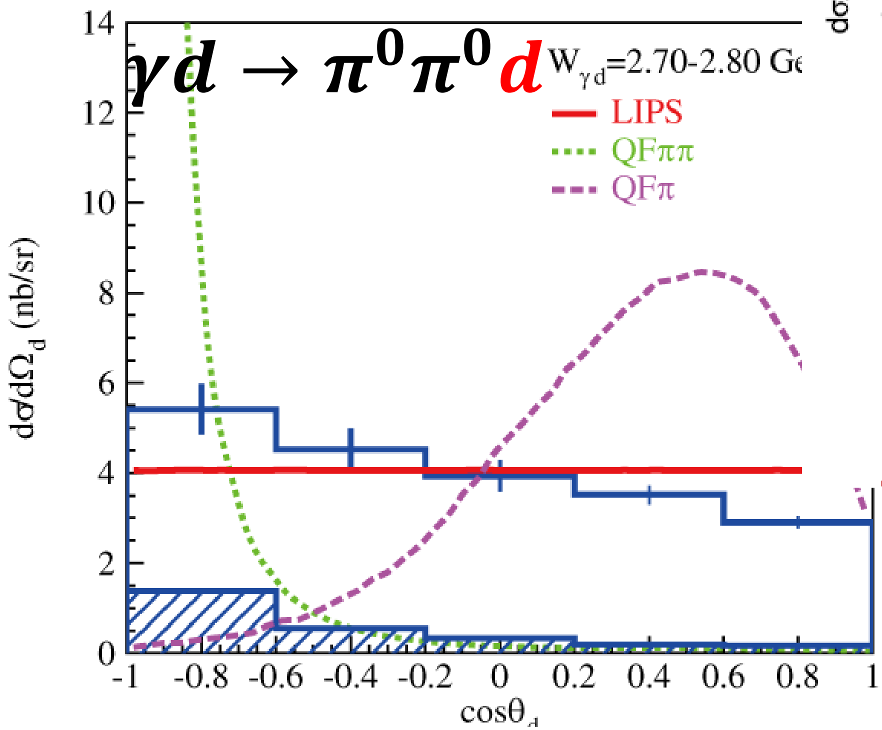
exeperimental data suggests a sequential process:

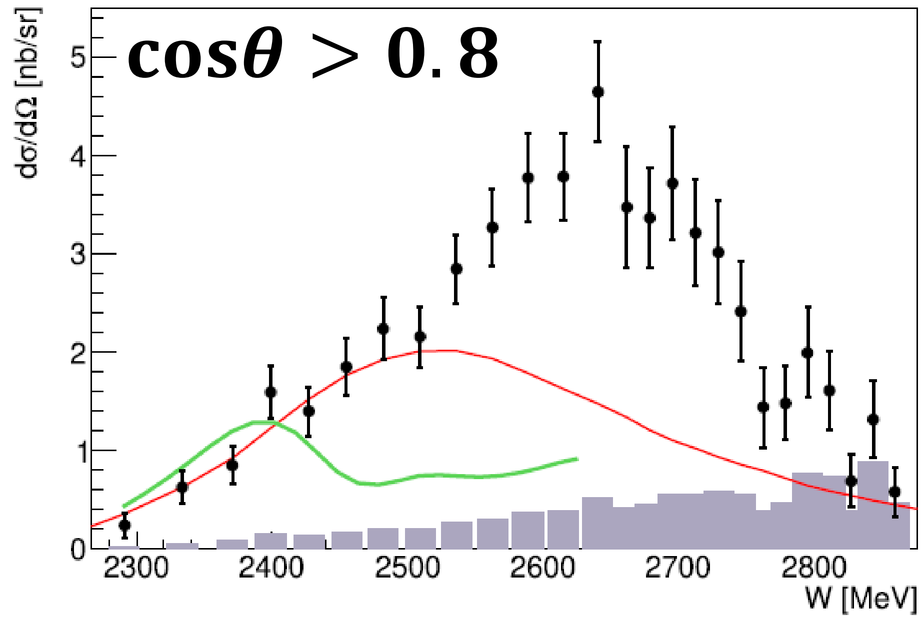
$$\gamma d \to R_{IS} \to \pi^0 R_{IV} \to \pi^0 \pi^0 d$$

(rather flat angular distribution & 2.15-GeV peak in $M_{\pi d}$)

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

Angular distribution of





T.C. Jude et al., PLB832, 137277 (2022).

PLB789, 413 (2019).

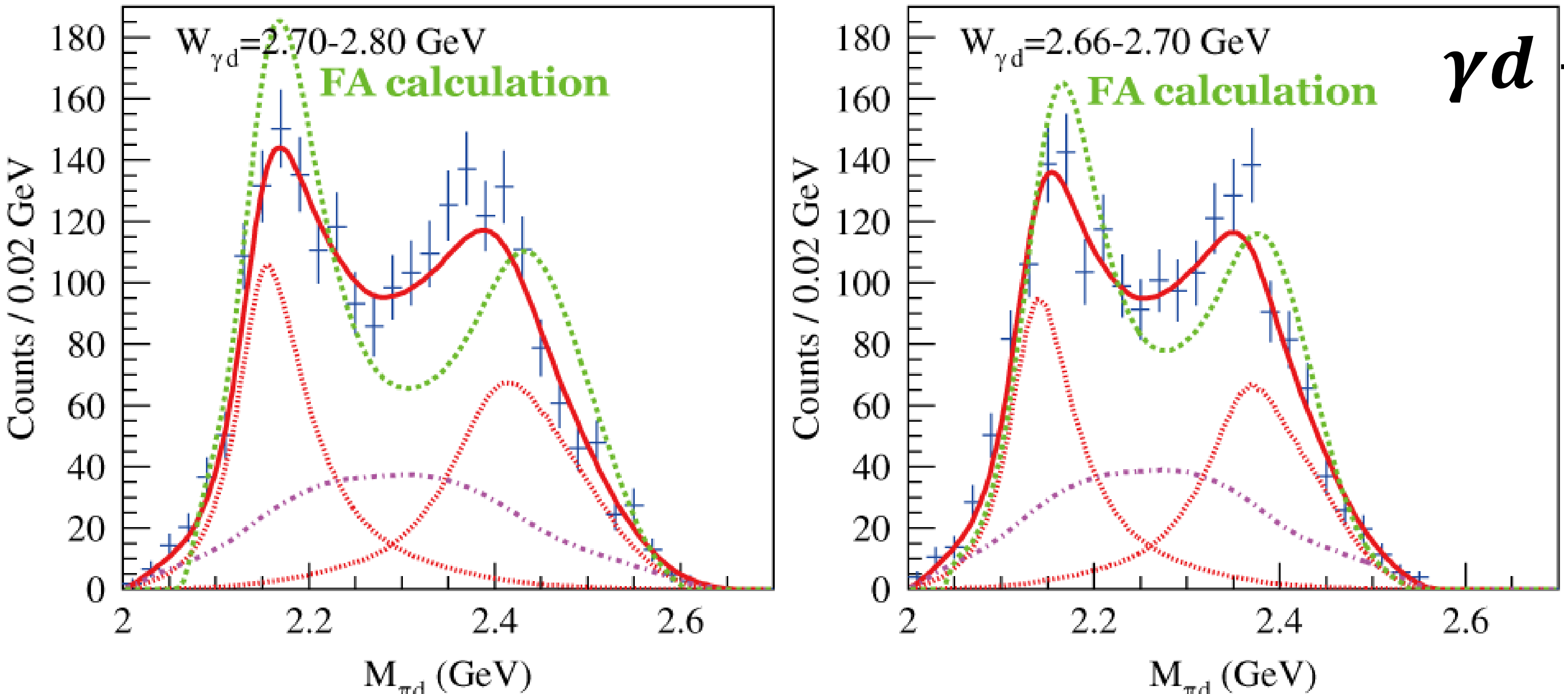
Although the angular coverages are different, large differential cross sections are obtained at forward angles of deuteron emission

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

πd invariant mass distribution

PLB789, 413 (2019).

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



$$N(m_1) = \int_{m_2} \left(\alpha \left| L_{M,\Gamma}(m_1) + L_{M,\Gamma}(m_2) \right|^2 + C \right) V_{\mathrm{PS}}(m_1, m_2)\ dm_2$$

convoluted with 11-MeV-σ Gaussian

Breit-Wigner amplitude:

$$L_{M,\Gamma}(m) = \left(m^2 - M^2 + iM\Gamma \right)^{-1}$$

mass 2140±11 MeV & width 91±11 MeV

$\mathcal{D}_{12}$ or $\Delta + N$

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

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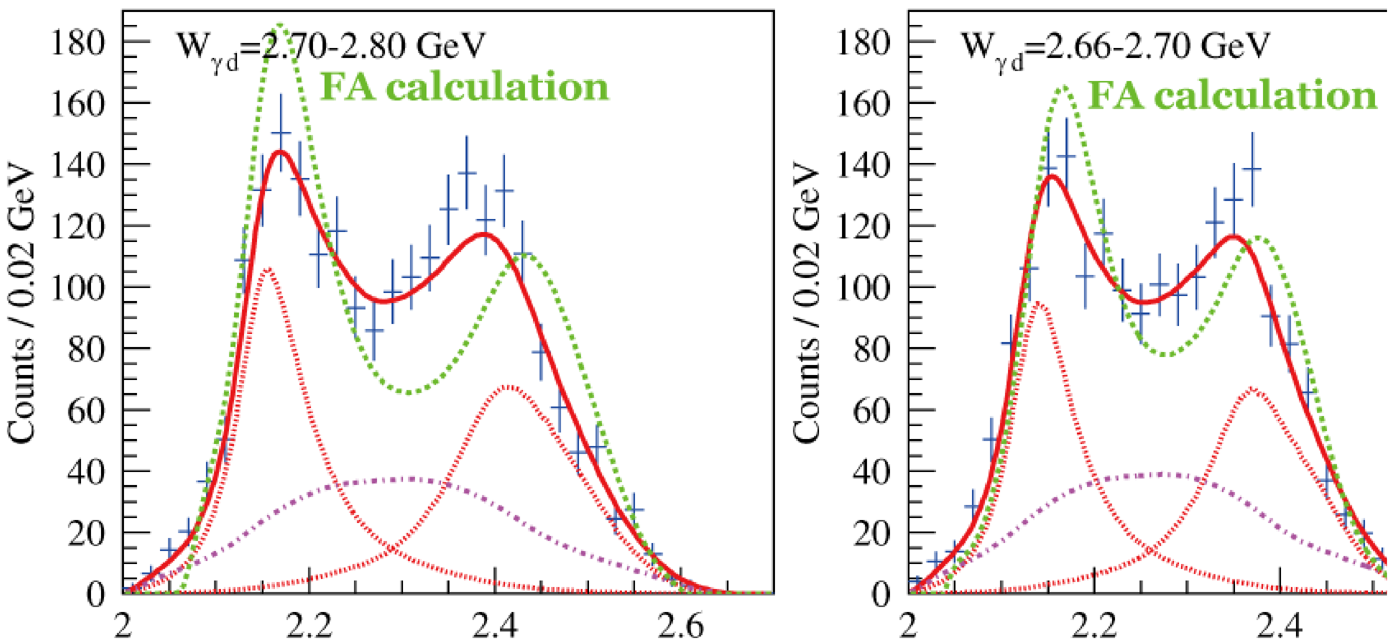
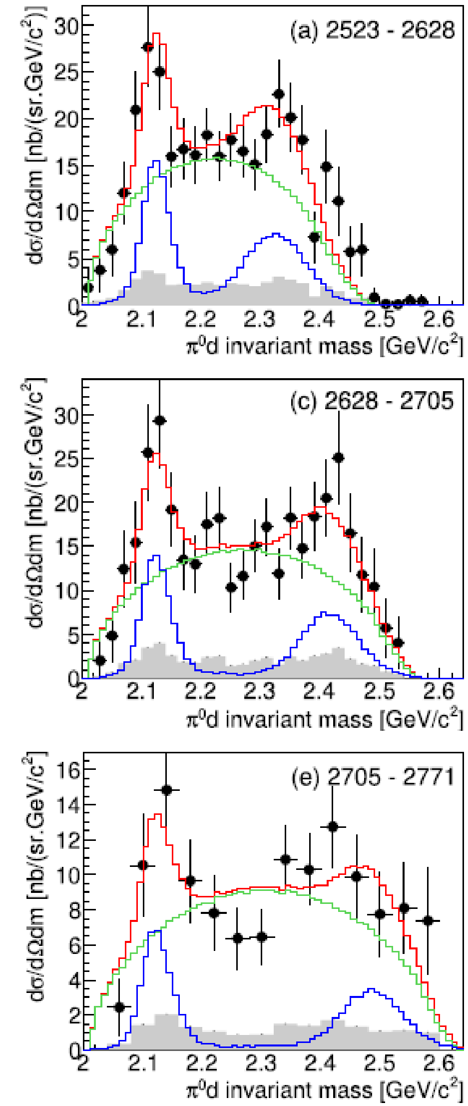
T.C. Jude et al., PLB832, 137277 (2022).

πd invariant mass distribution



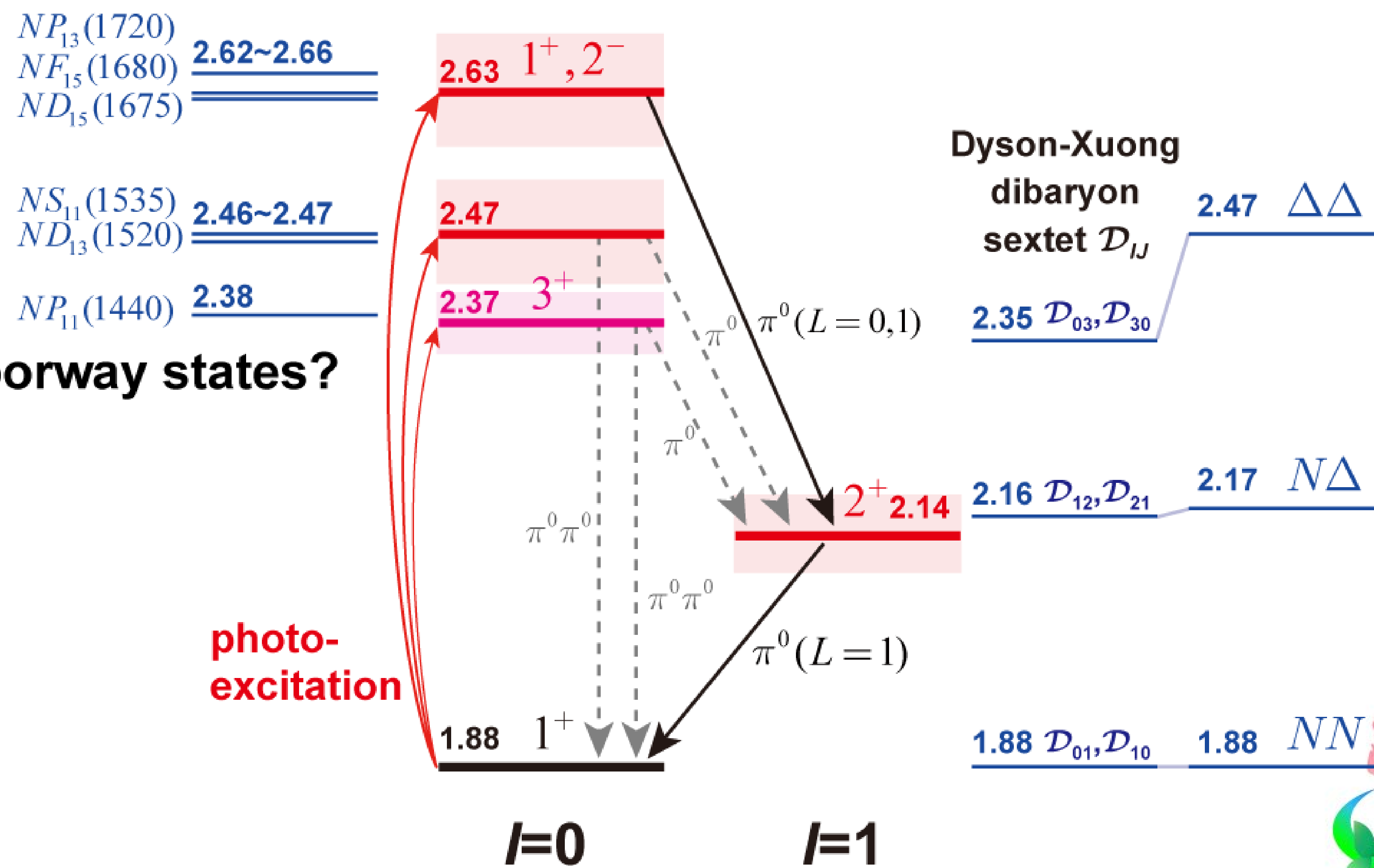


A much narrower width of 20 MeV is observed at BGOOD than that of 91 MeV

mass 2140±11 MeV & width 91±11 MeV

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

Excitation spectra



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

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

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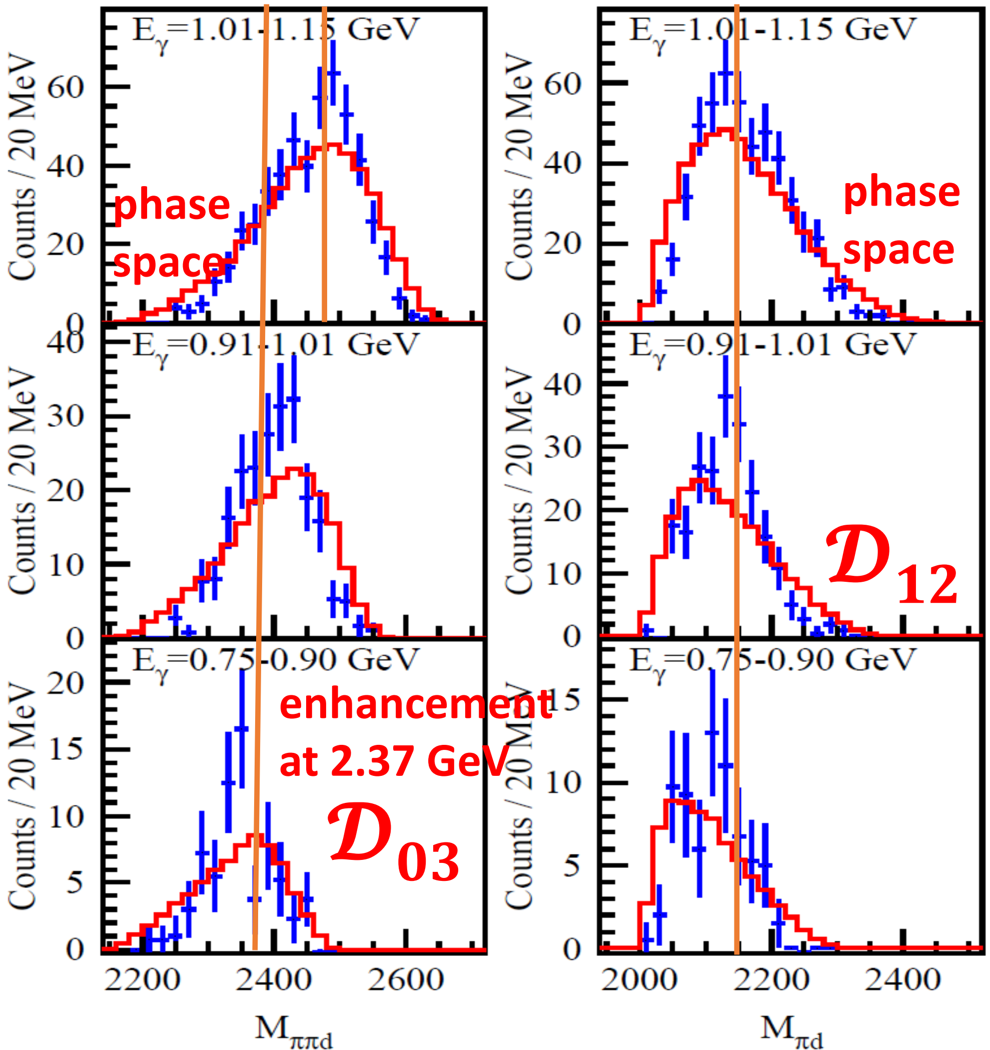
πd and $\pi\pi d$ invariant mass distributions

$\pi^0\pi^0 d$ invariant mass $\pi^0 d$ invariant mass



A peak corresponding to $\mathcal{D}_{03}$ is observed at around **2.37 GeV** in the $\pi^0\pi^0 d$ invariant mass distribution

A peak corresponding to $\mathcal{D}_{12}$ is observed at around **2.16 GeV** in the $\pi^0 d$ invariant mass distribution

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

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Excitation spectra

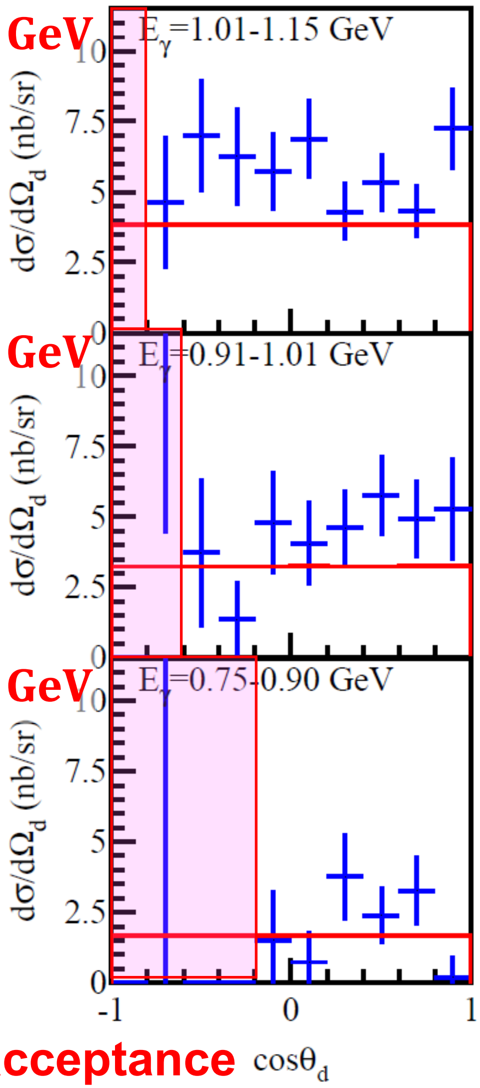
angular distribution of deuteron emission in the CM frame:

isotropic

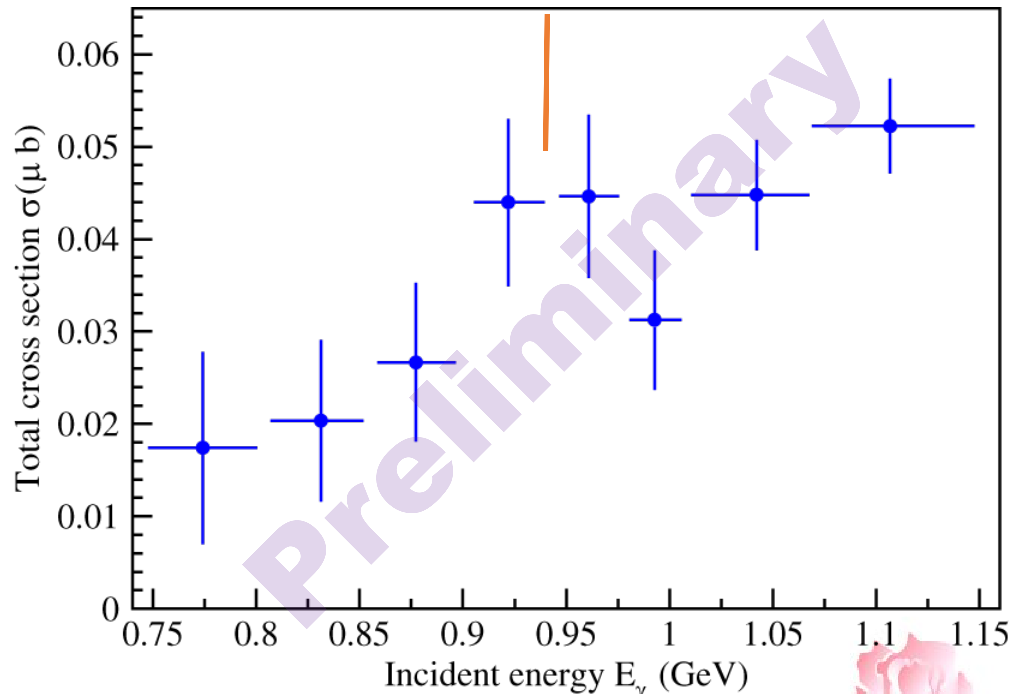
E_γ=1.01~1.15 GeV

E_γ=0.91~1.01 GeV

E_γ=0.75~0.90 GeV



no acceptance



enhancement at 0.94 GeV

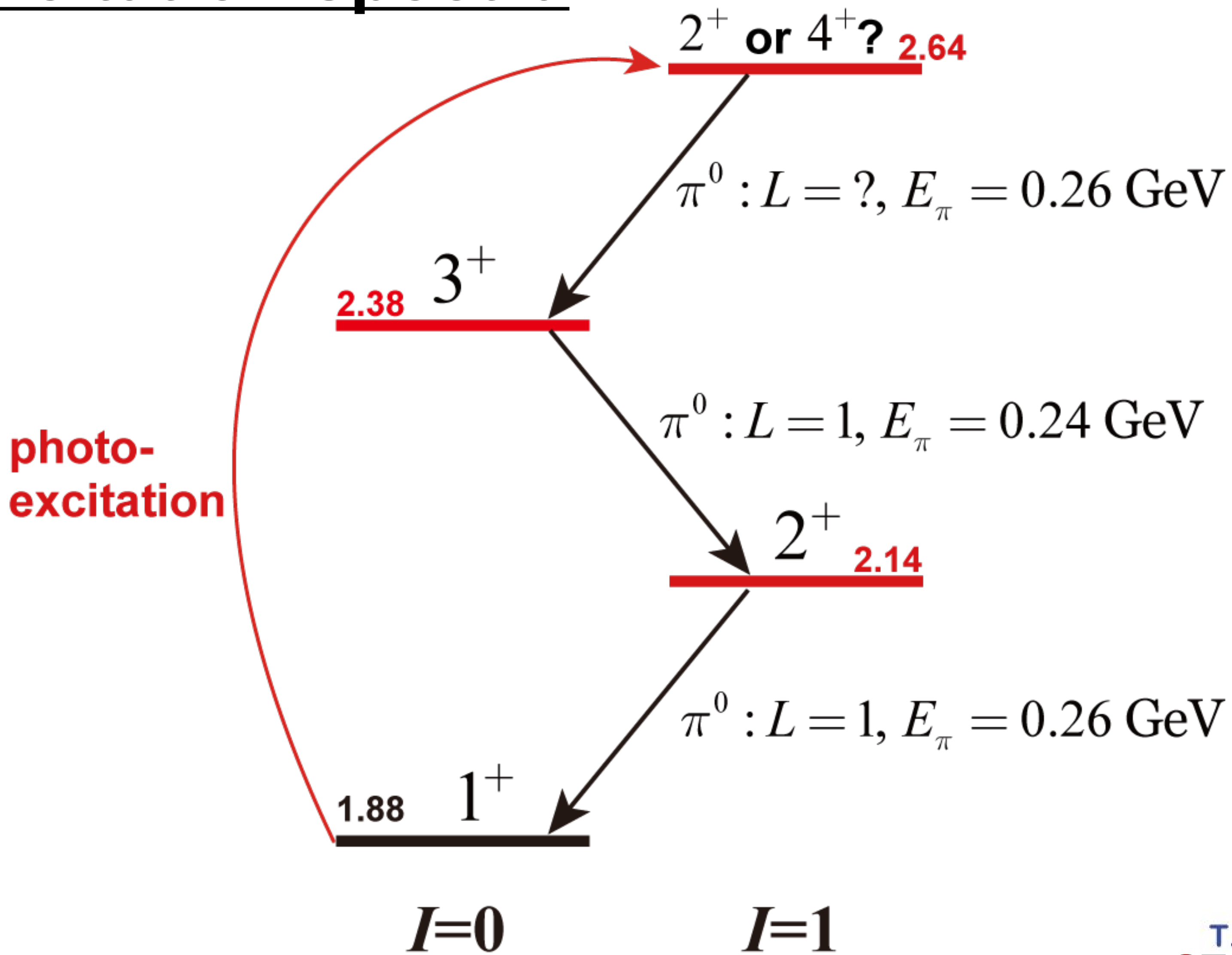
$W_{\gamma d} = M_{\pi\pi\pi d} \sim 2.64$ GeV

T. Ishikawa

27 June 2024

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

Excitation spectra



$\mathcal{D}_{30}$ dibaryon

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To understand the internal structure of dibaryons, it is important to establish their excitation spectrum

Non-strange dibaryon sextet

F.J. Dyson and N.-H. Xuong, PRL13, 815 (1964).

spin-flavor SU(6) symmetry

observed — J-PARC E79

$\mathcal{D}_{IJ}$	$\mathcal{D}_{01}$	$\mathcal{D}_{10}$	$\mathcal{D}_{12}$	$\mathcal{D}_{21}$	$\mathcal{D}_{03}$	$\mathcal{D}_{30}$
BB	NN	NN	ΔN	ΔN	$\Delta\Delta$	$\Delta\Delta$
M [MeV]	1878	1878	2160	2160	2348	2348

$^3S_1$ deuteron

$^1S_0$ NN virtual state

observed in $pp \to \pi^-\pi^+pp$?
P. Adlarson et al., PRL121, 052001 (2018).

observed in $\pi^+d \to pp$
B.S. Neganov and L.B. Parfenov, JETP7, 528 (1958).

$\mathcal{D}_{30}$ dibaryon

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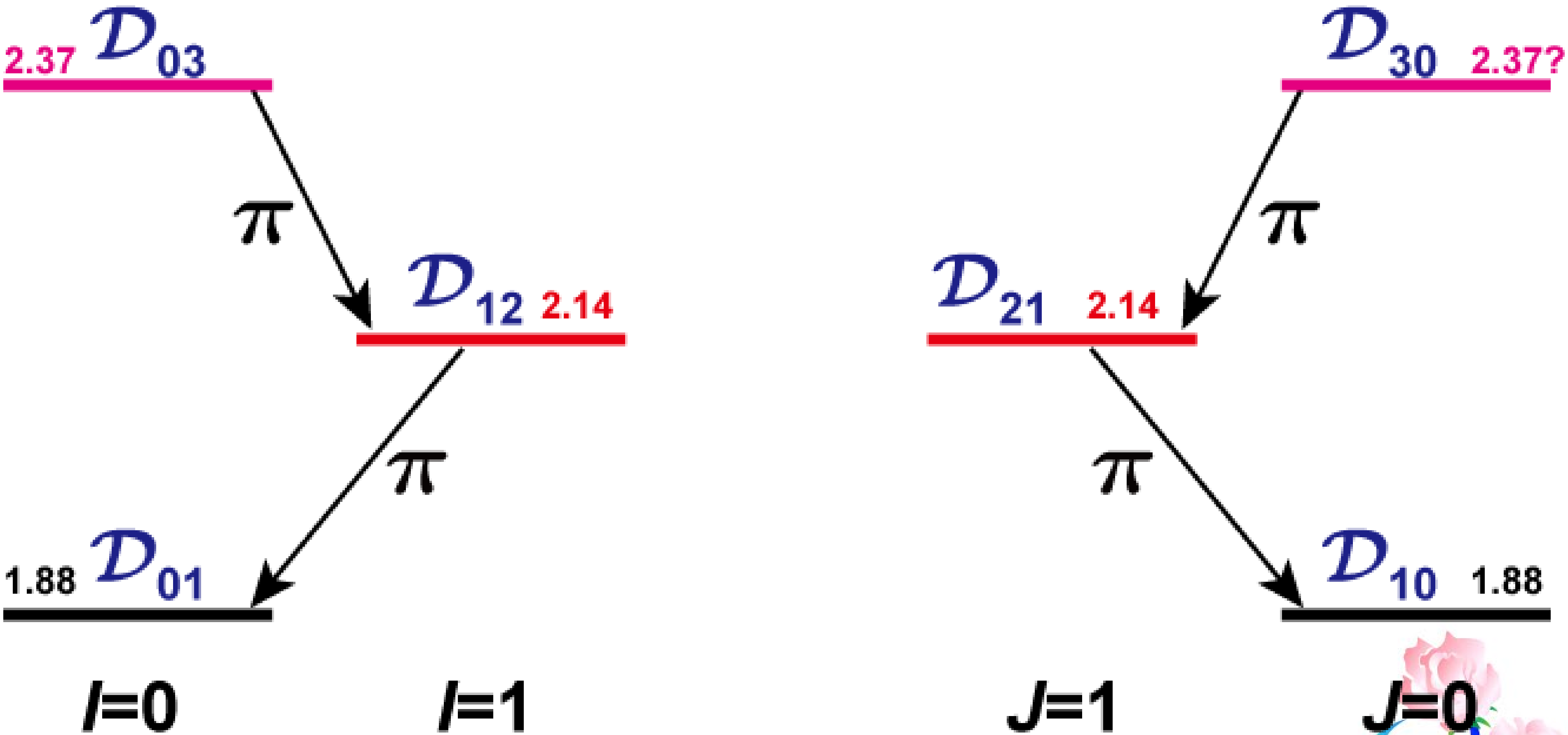
Decay chains for $\mathcal{D}_{03}$ and $\mathcal{D}_{30}$

expected decay chain for $\mathcal{D}_{30}$

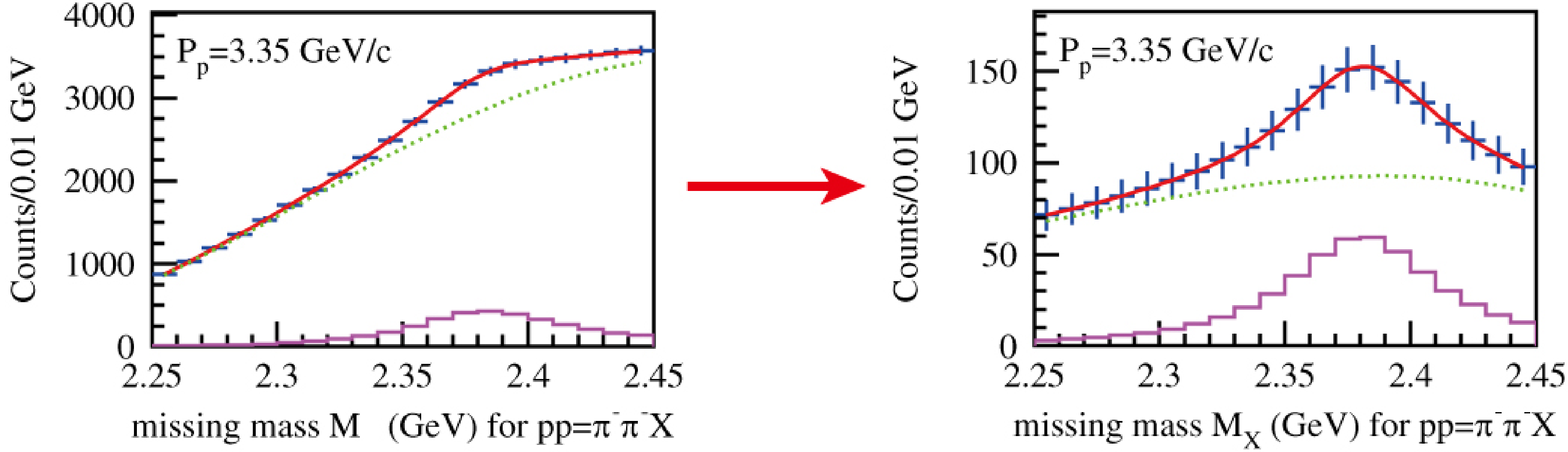


decay chain for $d^*(2380) \equiv \mathcal{D}_{03}$

$\mathcal{D}_{30}$ dibaryon

P79 experiment at J-PARC

$$pp \rightarrow \pi^-\pi^-\mathcal{D}_{30}^{++++} \rightarrow \pi^-\pi^-(\pi^+\pi^+pp)$$



$$^{2}\text{He tagging}: \mathcal{D}_{30}^{++++} \rightarrow \pi^+\mathcal{D}_{21}^{+++} \rightarrow \pi^+\pi^{+2}\text{He}$$

hexaquark state: much heavier mass

ΔΔ molecule-like state: unbound

π cloud-like state: similar mass

Summary

Summary

Summary

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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. $d\sigma/dM_{\eta d}$ shows ηd attraction, suggesting rather weak ηd attraction ($a_{\eta N} = 0.50 + \mathrm{i}0.33$ fm)
4. no theoretical calculations reproduce a rather flat angular distributions of deuteron emission
6. Equally spaced energy levels for dibaryons are suggested from $\gamma d \to \pi^0\pi^0 d$ and $\gamma d \to \pi^0\pi^0\pi^0 d$ data: pion is a degree of freedom?
7. Observation or non-observation of $\mathcal{D}_{30}$ at J-PARC (E79) would reveal the structure of dibaryons.

Hadron 2025

大阪大学
OSAKA UNIVERSITY

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:

Backup

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 $\Gamma = \Gamma_0 + g p_\eta$

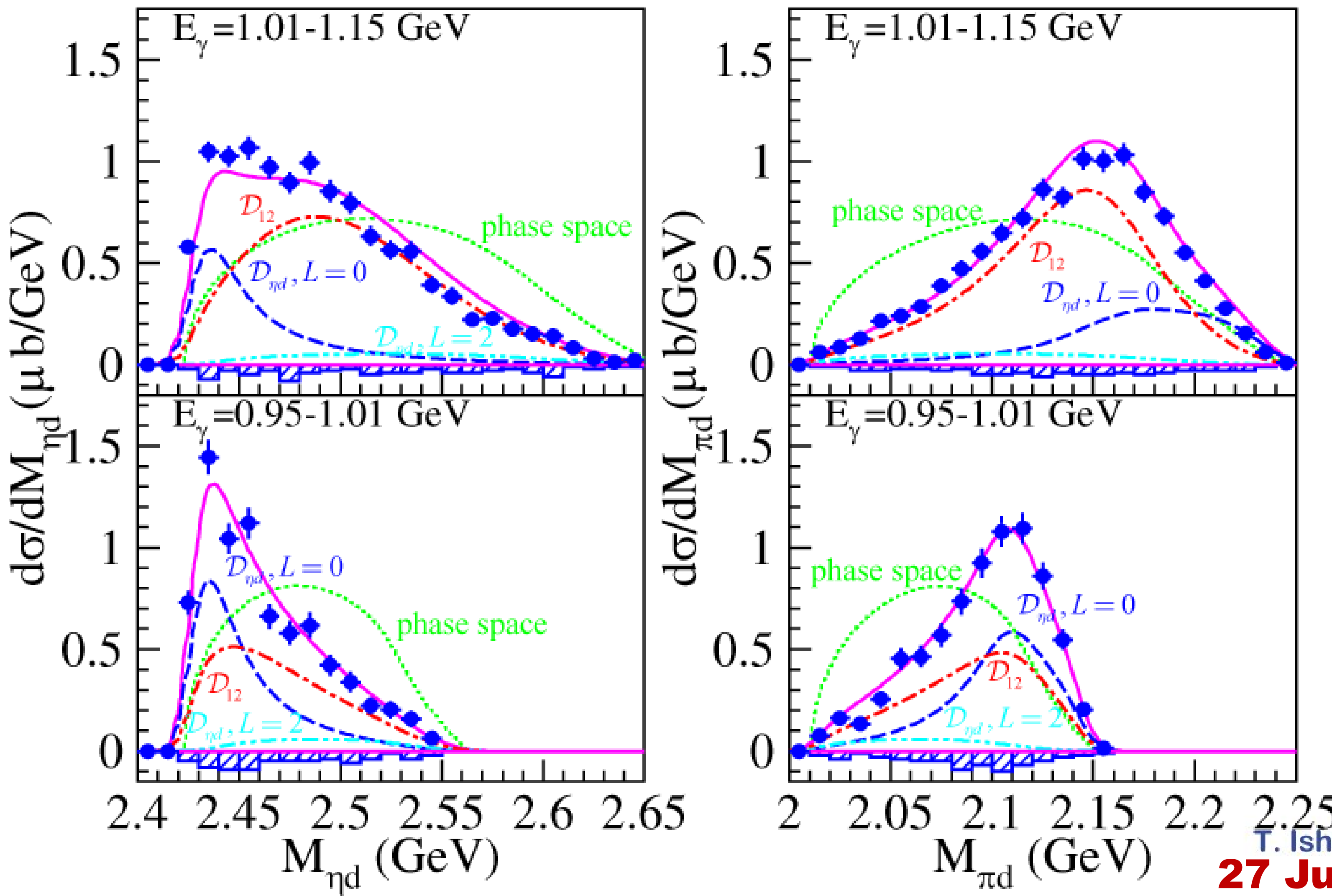
$\mathcal{D}_{12}$: well-known πd resonance with $I = 1, J^\pi = 2^+$

Breit-Wigner with $M \sim 2.14\ \mathrm{GeV}$ and $\Gamma \sim 0.09\ \mathrm{GeV}$ 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

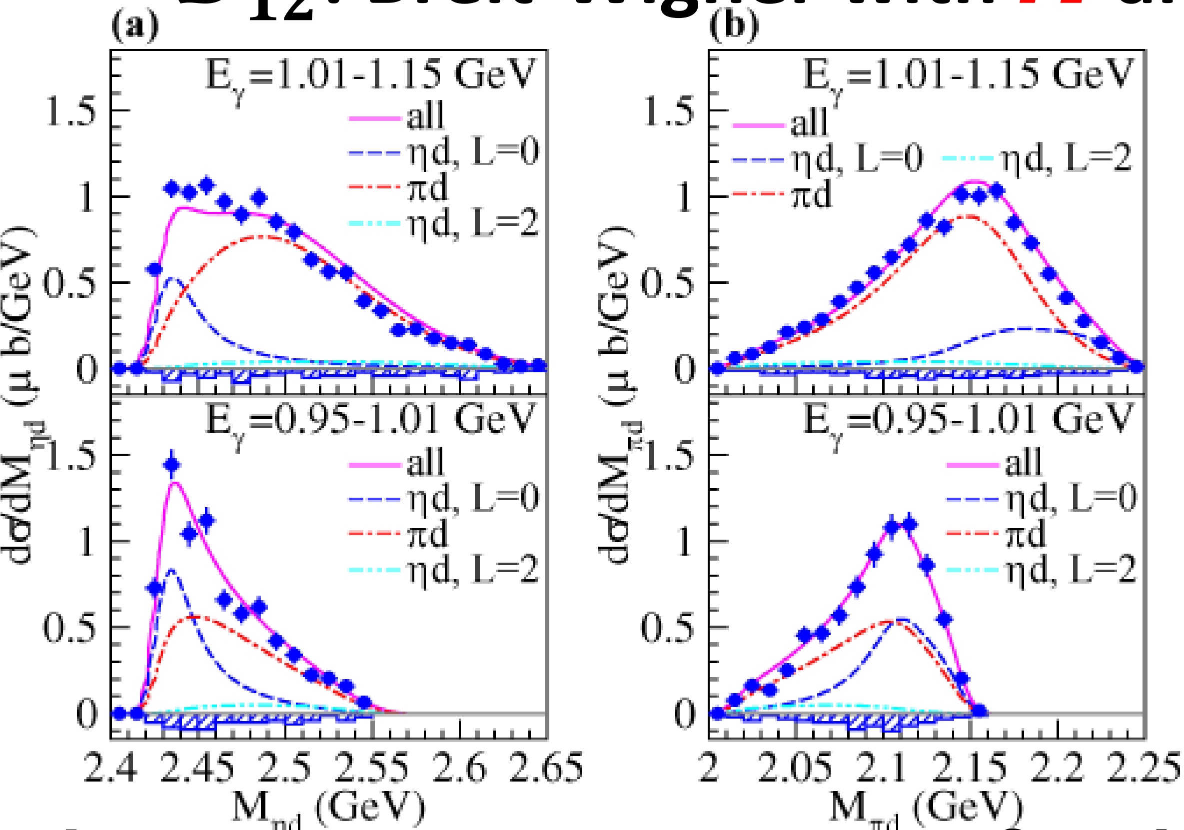
$\mathcal{D}_{12}$: $\mathrm{M} = 2.158^{+0.003}_{-0.003}$ GeV, $\Gamma = 0.116^{+0.005}_{-0.011}$ GeV

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

Phenomenological analysis

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

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



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

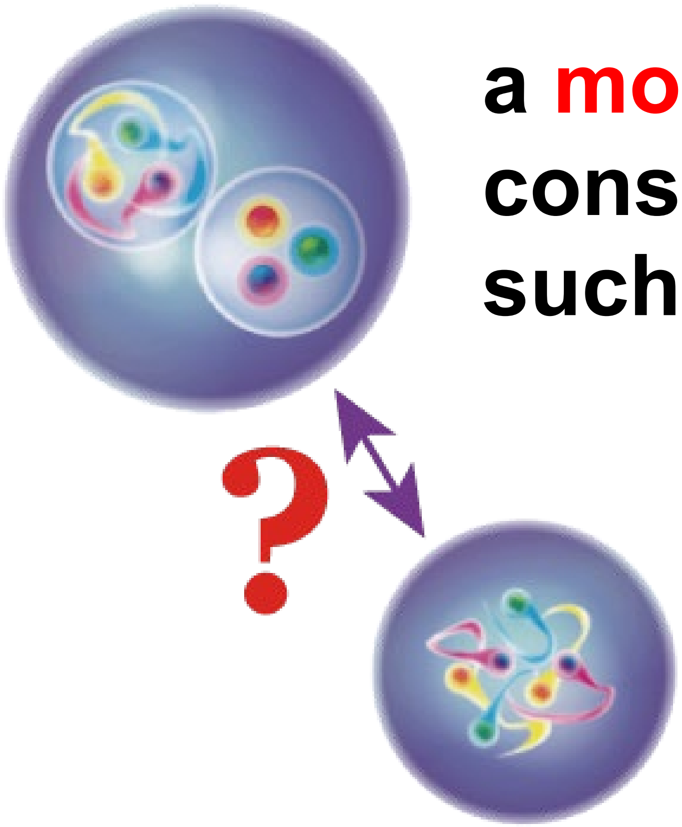
$$r_{\eta d} = \mp\left(4.3^{+8.6}_{-2.9}\right) + i\left(6.7^{+6.0}_{-8.4}\right)\ \mathrm{fm}$$

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

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

Dibaryons

The internal structure of a dibaryon ($B = 2$ system):



a **molecule-like** state consisting of two baryons such as the deuteron

a spatially-compact **hexaquark** hadron state

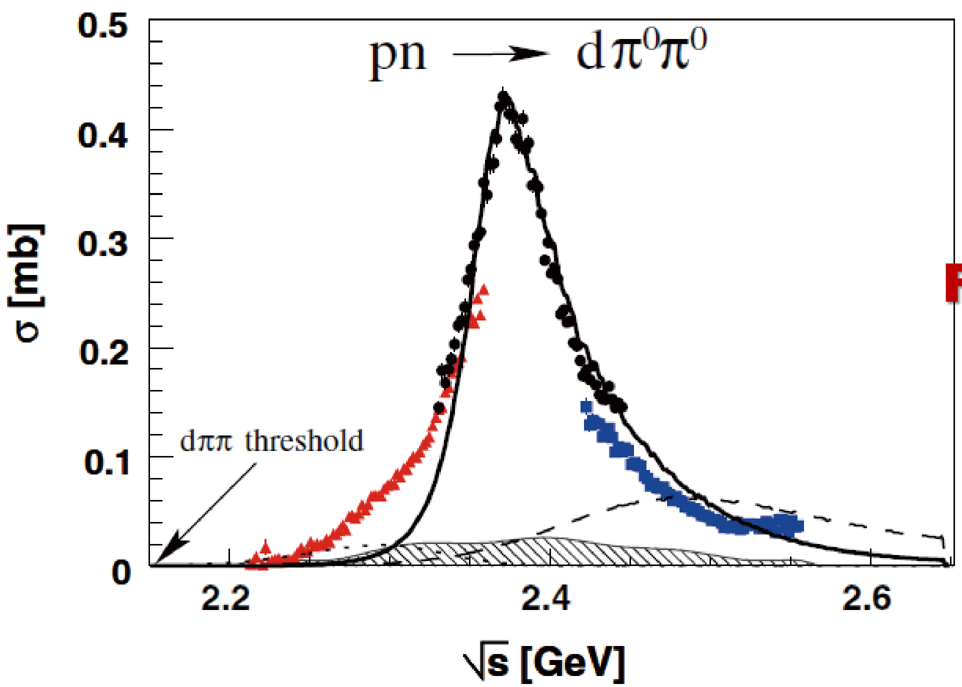
The current problem in hadron physics

$d^*(2380)$ dibaryon

observed in $pn \to d^*(2380) \to \pi^0\pi^0 d$

$$m = 2.37\ \mathrm{GeV}, \Gamma = 0.07\ \mathrm{GeV}, I = 0, J^\pi = 3^+$$

T. Kamae, PRL38, 468 (1977);
M. Bashkanov *et al.* (CELSIUS/WASA), PRL102, 052301 (2009);
P. Adlarson *et al.* (WASA-at-COSY), PRL106, 242302 (2011).



hexaquark state

$$R = \frac{\hbar c}{\sqrt{2\mu B}} \sim 0.6\ \mathrm{fm}$$

μ: reduced mass
B: binding energy

F. Piccini, School in Erice (2015).

and/or

isoscalar $\Delta\Delta$ quasi-bound state $\mathcal{D}_{03}$

F.J. Dyson and N.-H. Xuong, PRL13, 815 (1964).

$d^*(2380)$ dibaryon

To understand the internal structure of dibaryons, it is important to establish their excitation spectrum

Non-strange dibaryon sextet

F.J. Dyson and N.-H. Xuong, PRL13, 815 (1964).

spin-flavor SU(6) symmetry

observed

$\mathcal{D}_{IJ}$	$\mathcal{D}_{01}$	$\mathcal{D}_{10}$	$\mathcal{D}_{12}$	$\mathcal{D}_{21}$	$\mathcal{D}_{03}$	$\mathcal{D}_{30}$
BB	NN	NN	ΔN	ΔN	$\Delta\Delta$	$\Delta\Delta$
M [MeV]	1878	1878	2160	2160	2348	2348

$^3S_1$ deuteron

$^1S_0$ NN virtual state

observed in $pp \to \pi^-\pi^+ pp$?

P. Adlarson et al., PRL121, 052001 (2018).

observed in $\pi^+ d \to pp$

B.S. Neganov and L.B. Parfenov, JETP7, 528 (1958).

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

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Corresponding peaks were clearly observed
Partial wave analysis (PWA) shows 2^+

$\pi^+ d \to pp$ **R. Arndt et al., PRC48, 1926 (1993).**

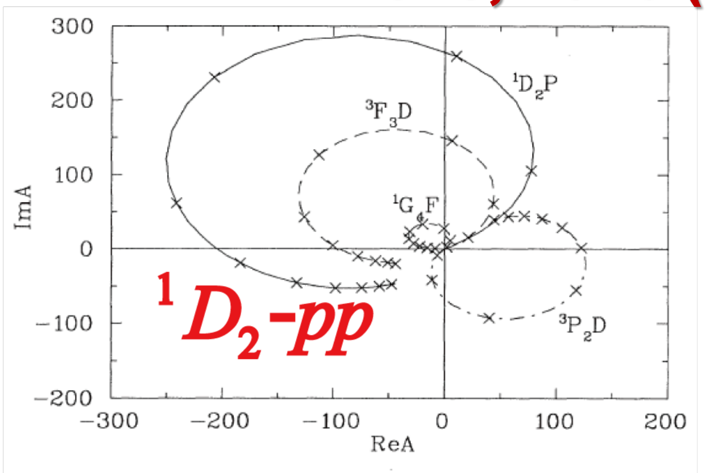


FIG. 7. Argand plot of dominant partial-wave amplitudes. The X points denote 50 MeV steps. All amplitudes have been multiplied by a factor of 10^3.

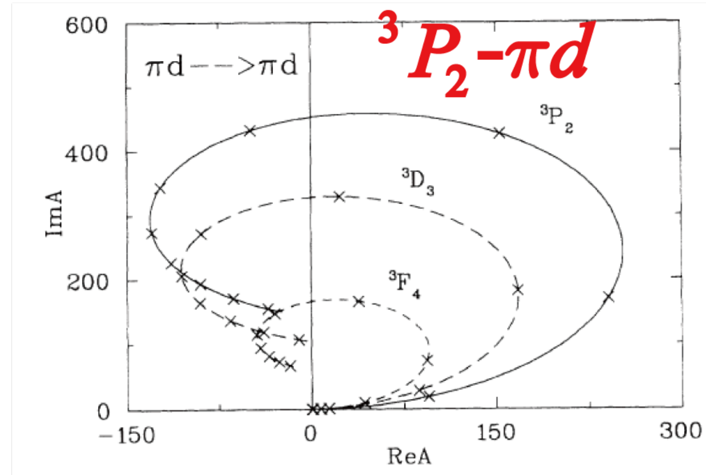


FIG. 7. Argand plot of the dominant πd partial-wave amplitudes $^3P_2$, $^3D_3$, and $^3F_4$ which correspond to the $^1D_2$, $^3F_3$, and $^1G_4$ pp states, respectively. (Compare Fig. 7 of Ref. [3]). The X points denote 50 MeV steps. All amplitudes have been multiplied by a factor of 10^3.

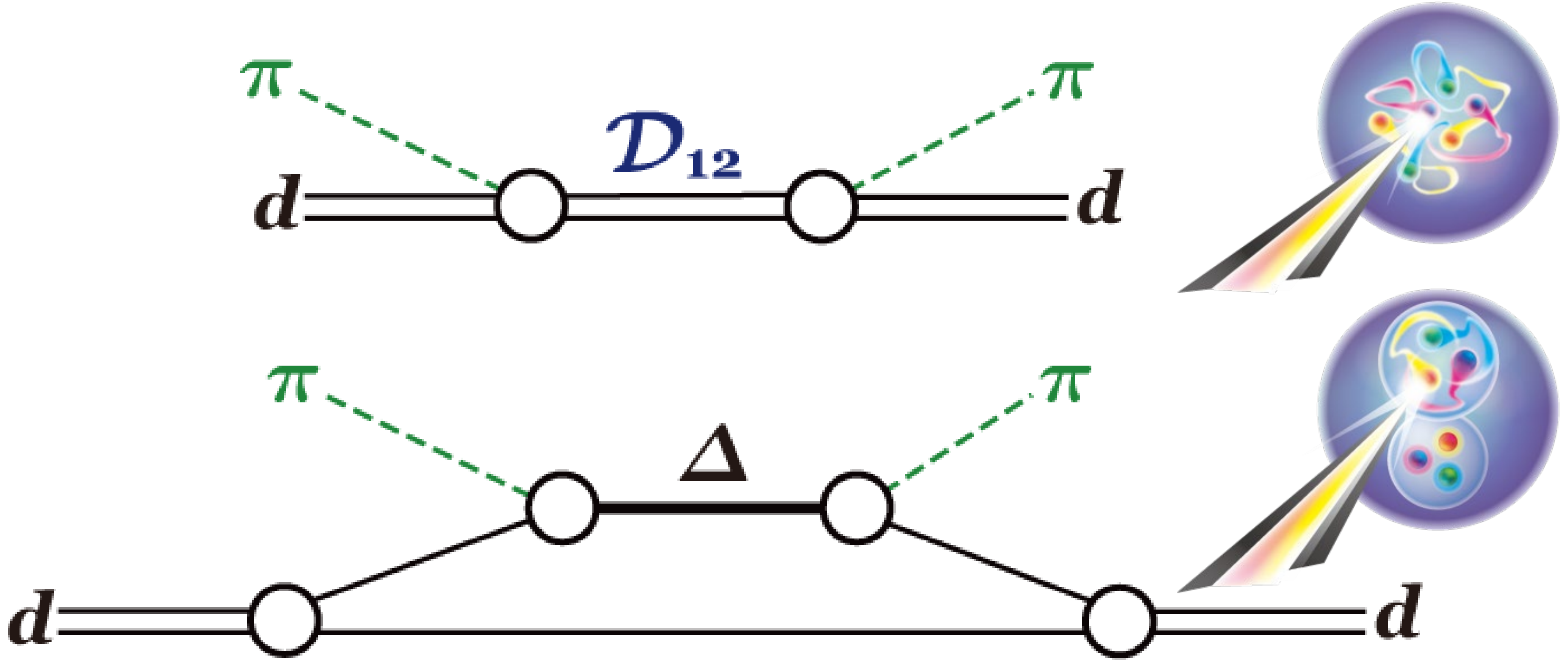
R. Arndt et al., PRC50, 1796 (1994). $\pi^\pm d \to \pi^\pm d$

SAID group provides a pole for $\mathcal{D}_{12}$ from a combined analysis including $pp \to pp$.

C.H. Oh et al., PRC56, 635 (1997).

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

Dibaryonic interpretation is still questionable



quasi-free (QF) *Δ* excitation cannot be kinematically separated