# Low-energy scattering parameters between the eta meson and nucleon from eta photoproduction on the deuteron

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*2nd Jagiellonian Symposium*
*on Fundamental and Applied Subatomic Physics*
*June 4~9, 2017.*

# Contents




**1.3 GeV bremsstrahlung photon beam**

# $\eta N$ interaction

**Interaction between mesons and nucleons**

**fundamental & important**

**Neutral mesons:**

**not precisely determined (except for $\pi^0$)**

**scattering experiments: impossible**

**life time is very short**

**no beam is available**

**X-ray measurements: impossible**

**no electro-magnetic attraction**

**no mesic atom**

**$\eta N$ - $S_{11}(1535)$: lowest negative parity**

# $\eta N$ interaction

$\eta N$ low-energy scattering parameters

**combined theoretical analyses** of

differential and total cross sections for

$\pi N \rightarrow \eta N$ transition, $\gamma N \rightarrow \eta N$ photoproduction

together with

$\pi N \rightarrow \pi N$ scattering, $\gamma N \rightarrow \pi N$ photoproduction

obtained scattering length $a_{\eta N}$

– Im $a_{\eta N}$: ~0.26 fm (optical theorem)

– **Re $a_{\eta N}$: 0.2~1.1 fm**

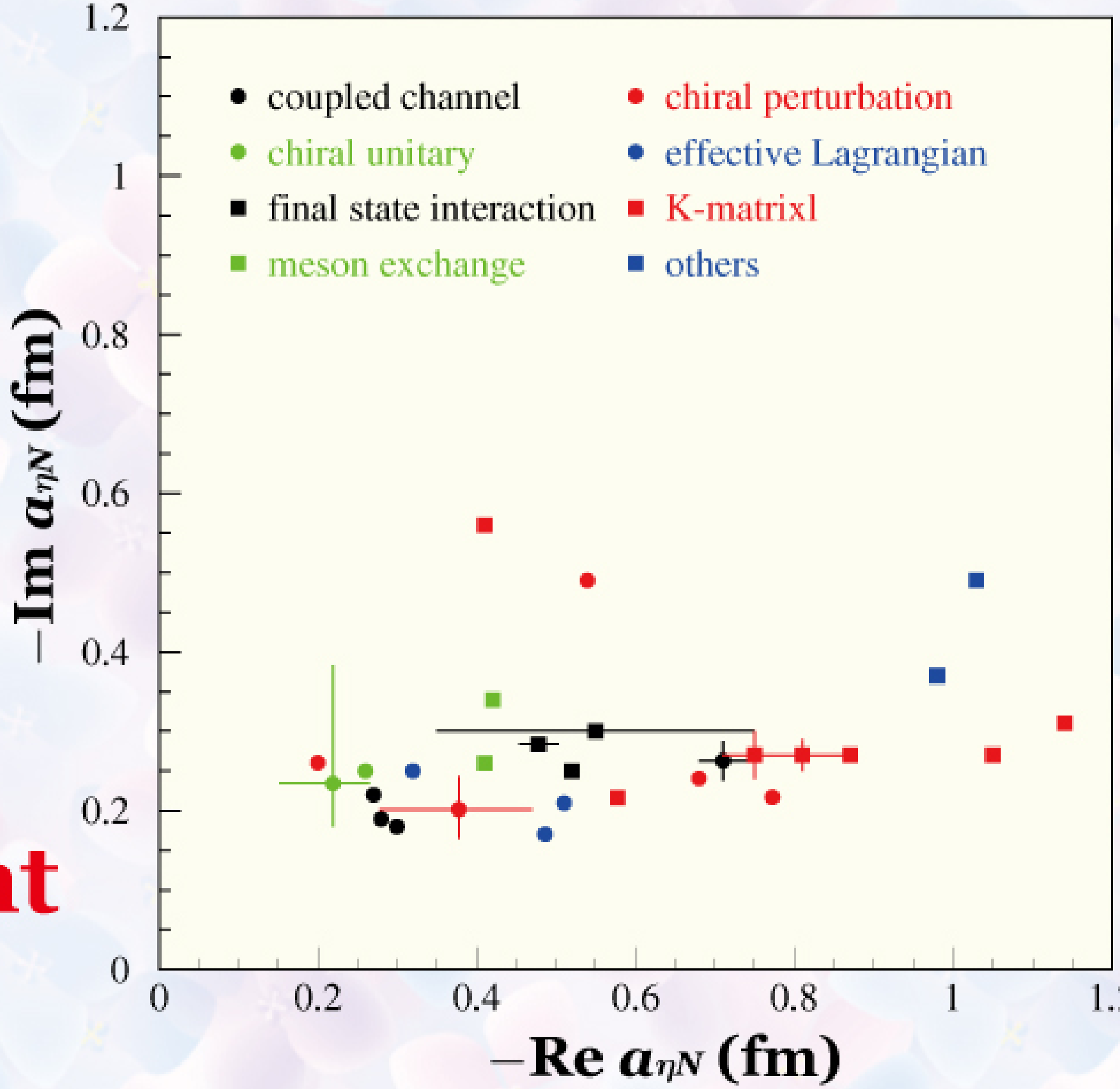
# $\eta N$ interaction

**scattering length $a_{\eta N}$**

**indirectly determined**

**real part is scattered**

**a direct measurement of $a_{\eta N}$ is desired**



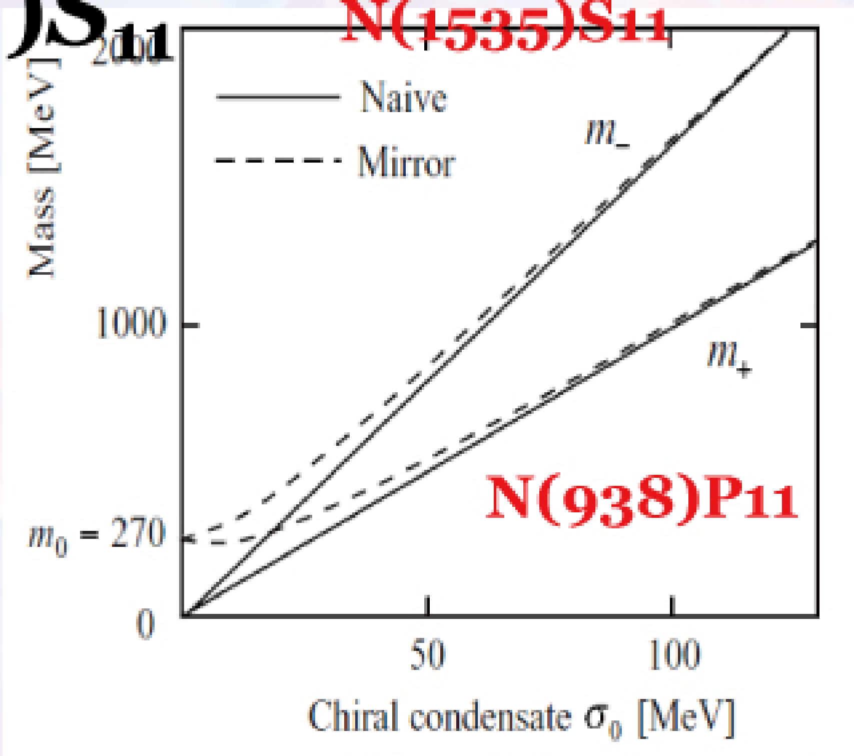

**Q. Haider and L.C. Liu, J. Mod. Phys. E 24, 1530009 (2015).**

# $\eta$-mesic nuclei

**Scattering length $a_{\eta N}$ affects**
- **the existence of an exotic nuleus:**
  - **$\eta$-nucleus bound state ($\eta$-mesic nucleus)**
  - **pure strong interaction**

**first prediction** Q. Haider and L.C. Liu, Phys. Lett. B 172 (1986) 257; B 174 (1986) 465E.

**search for $\eta$-mesic nuclei**
- **in-medium properties of $N(1535)S_{11}$**
  - **strongly couples to $\eta N$**
  - **chiral partner of the nucleon**




C. DeTar and T. Kunihiro, Phys. Rev. D 39, 2805 (1989);
T. Hatsuda and M. Prakash, Phys. Lett. B 224, 11 (1989)

# $\eta$-mesic nuclei

## $\eta$ meson in free space

$N^*$–$N$

48 MeV

$\eta$

**attractive**


## $\eta$ meson in a nucleus

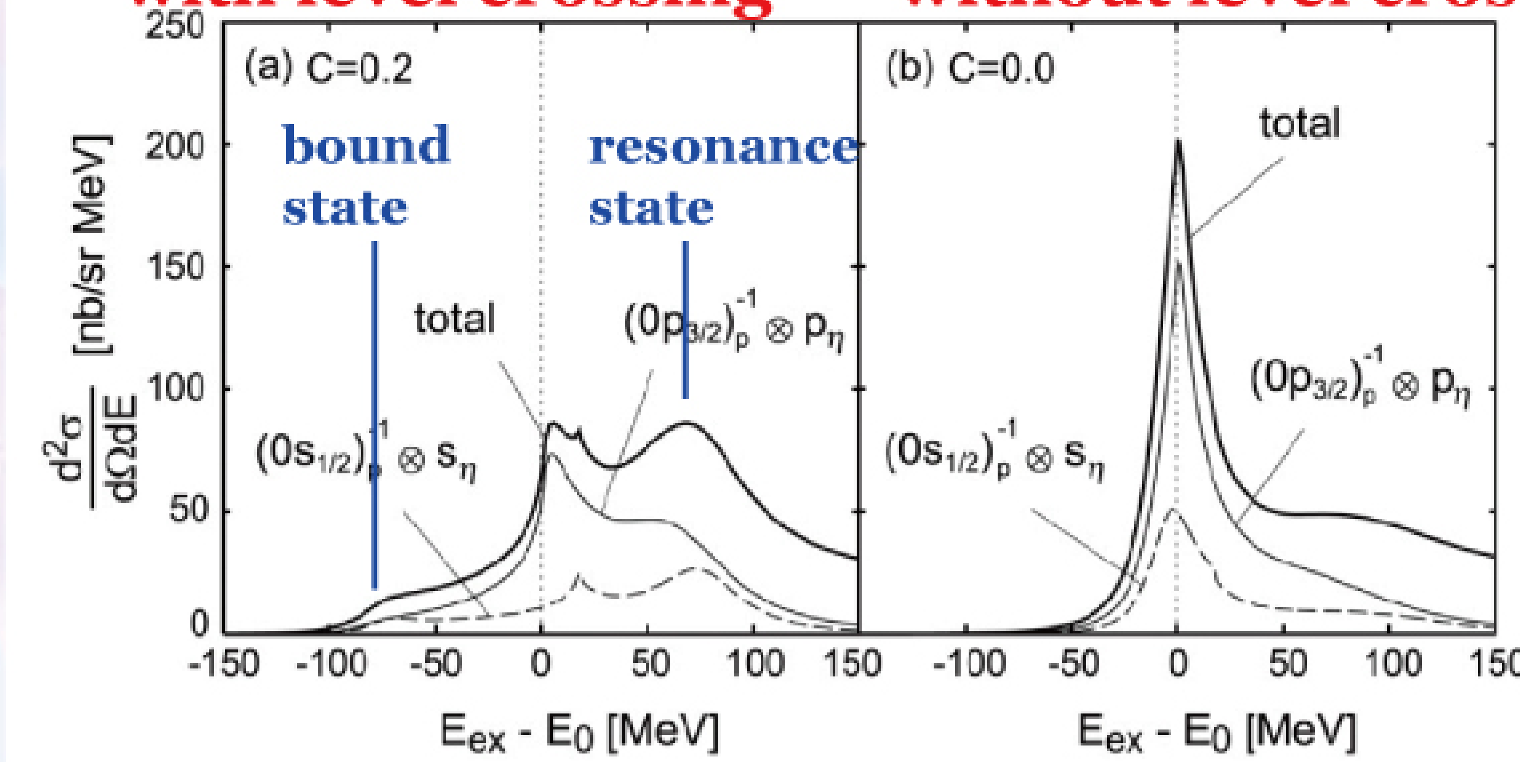
$\eta$

**repulsive**
**medium effect**

$N^*$–$N$

**level crossing**

with level crossing | without level crossing



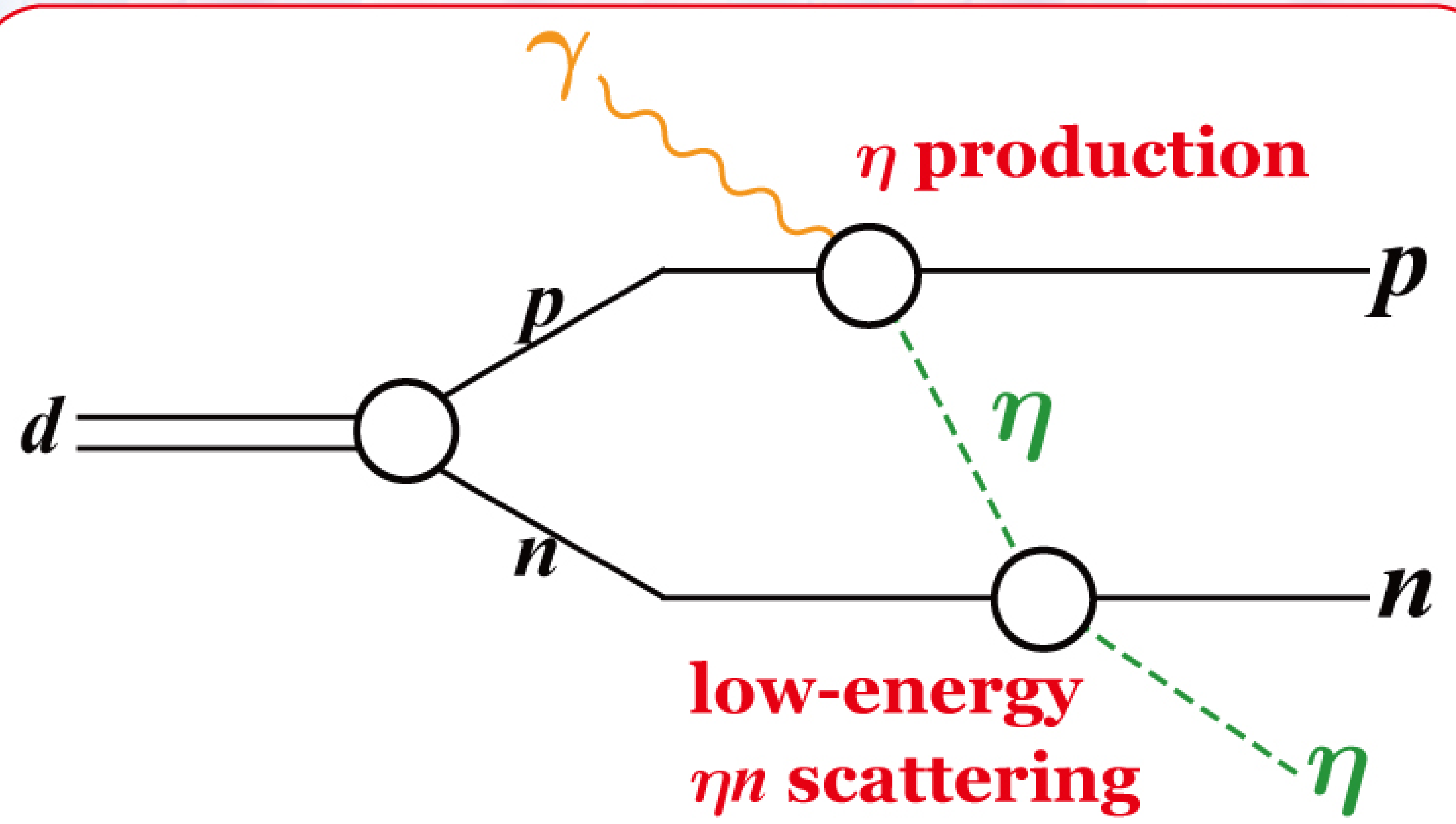

**Expected spectra for the $\gamma^{12}C \to pX$ reaction**

$E_0 = m_{^{11}B} + m_\eta$

H. Nagahiro, D. Jido, S. Hirenzaki, Nucl. Phys. A 761, 92 (2005);
D. Jido, E.E. Kolomeitsev, H. Nagahiro, S. Hirenzaki, Nucl. Phys. A 811, 158 (2008).

# $\gamma d \to p \eta n$ reaction at $E_\gamma$~0.94 GeV

**Proposed reaction to extract $\eta n$ scattering length**

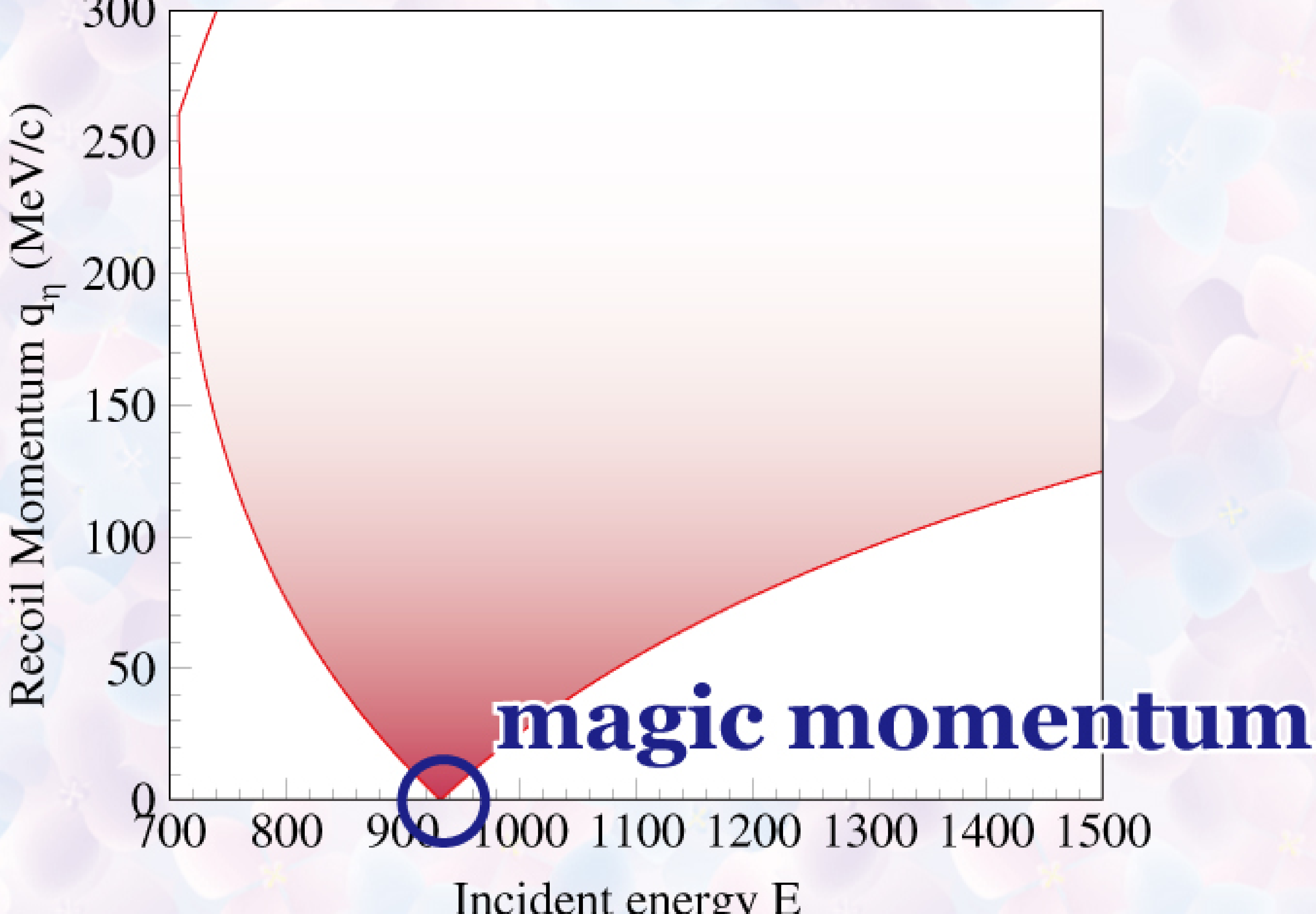



**To be considered:**

**contirbution of the $\eta n \to \eta n$ reaction**

# $\gamma d \to p\eta n$ reaction at $E_\gamma \sim 0.94$ GeV

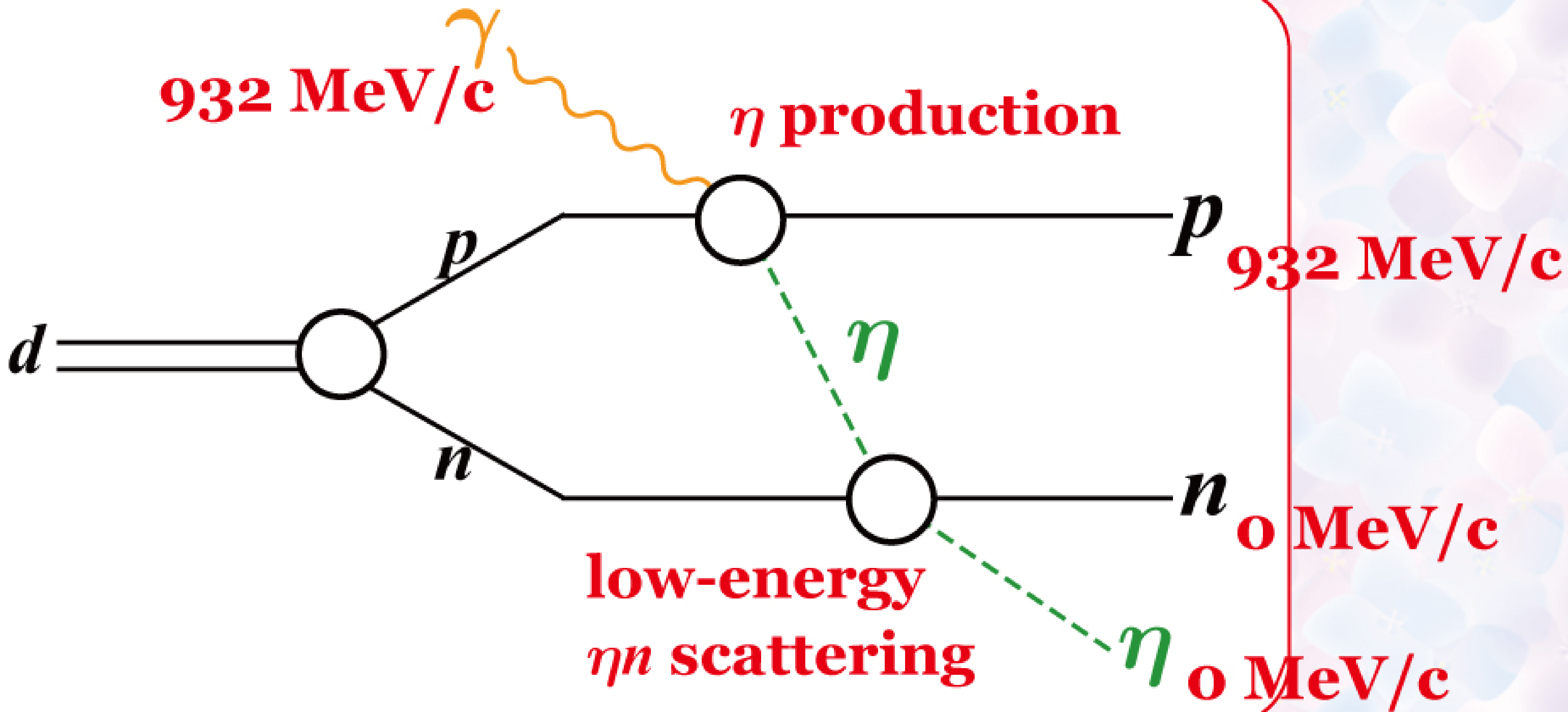
**recoil momentum of $\eta$ for the $\gamma p \to p\eta$ reaction**




**The $\eta$ mesons are at rest when**
**the incident photon energy is 932 MeV, and**
**protons are detected at 0°.**

# $\gamma d \to p\eta n$ reaction at $E_\gamma$~0.94 GeV

**Proposed reaction to extract $\eta n$ scattering length**

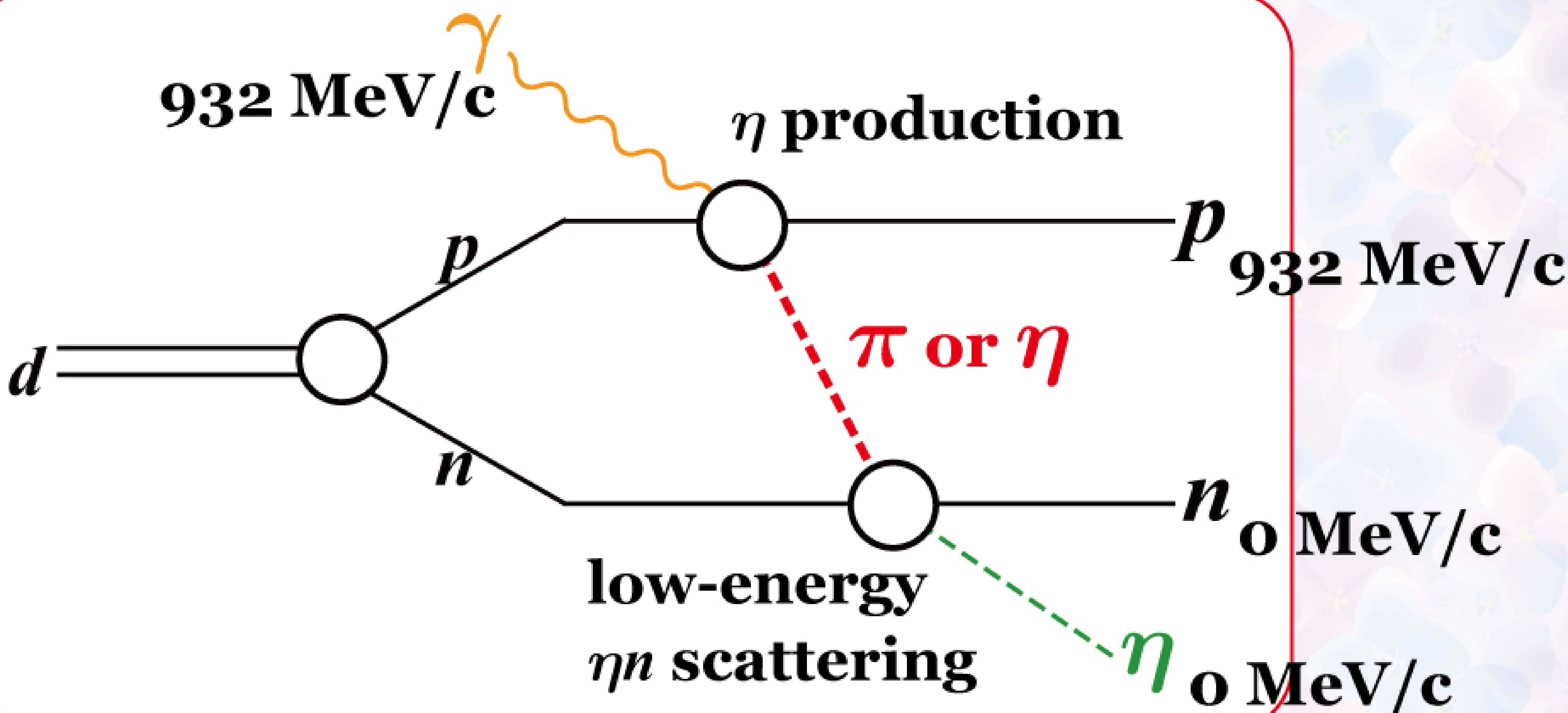



**The final-state interaction (FSI)**
**between $\eta p$ and $pn$ is expected to be suppressed.**

**The Fermi motion should be taken into account though.**

# $\gamma d \to p\eta n$ reaction at $E_\gamma$~0.94 GeV

**Proposed reaction to extract $\eta n$ scattering length**




**Which is dominant between $\pi$ and $\eta$ exchange amplitude?**

**The mass of the exchange particle is close to the $\eta$ rest mass**

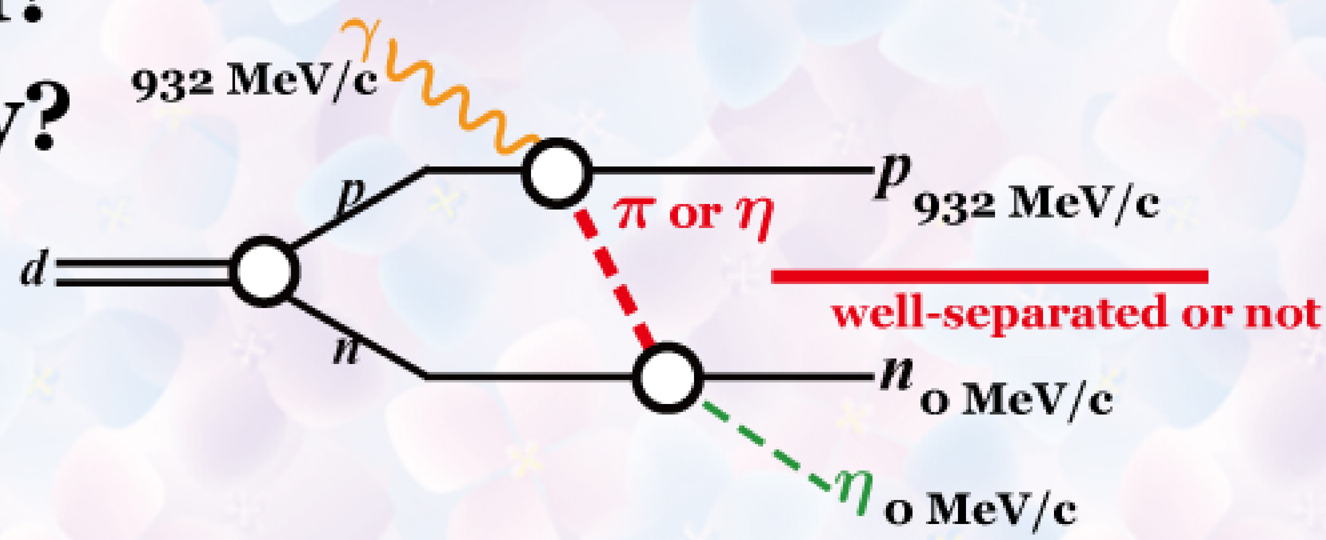
# $\gamma d \to p\eta n$ reaction at $E_\gamma$~0.94 GeV

**Sensitivity to $\eta n$ scattering length**

**dynamical coupled channel (DCC) model is applied to $\gamma d$ reactions**

**to be checked:**

1. $\eta$ exchange is dominant?
2. $pn$ FSI is suppressed?
3. how is the sensitivity?




S.X. Nakamura, H. Kamano, and T. Ishikawa,
Low-energy η-nucleon interaction studied with η photoproduction off the deuteron,
arXiv:1704.07029.

# $\gamma d \to p\eta n$ reaction at $E_\gamma$~0.94 GeV

**DCC model**

**coupled channel Lippman-Schwinger equation for meson-baryon scattering**

A. Matsuyama, T. Sato, T.-S.H. Lee, Phys. Rept. 439, 193 (2007).
H. Kamano et al., Phys. Rev. C 88, 035209 (2013).

$$T_{ab} = V_{ab} + \sum_c V_{ac} G_c T_{cb}$$

- $\sum_c$: coupled channel
- $G_c$: meson-baryon Green function including quasi two-body channels
- $V_{ab}$, $V_{ac}$: transition potential
  - exchange (*s*, *t*, *u*, and contact)
  - Z-diagrams (transition between quasi two-body channels)
  - bare N* states

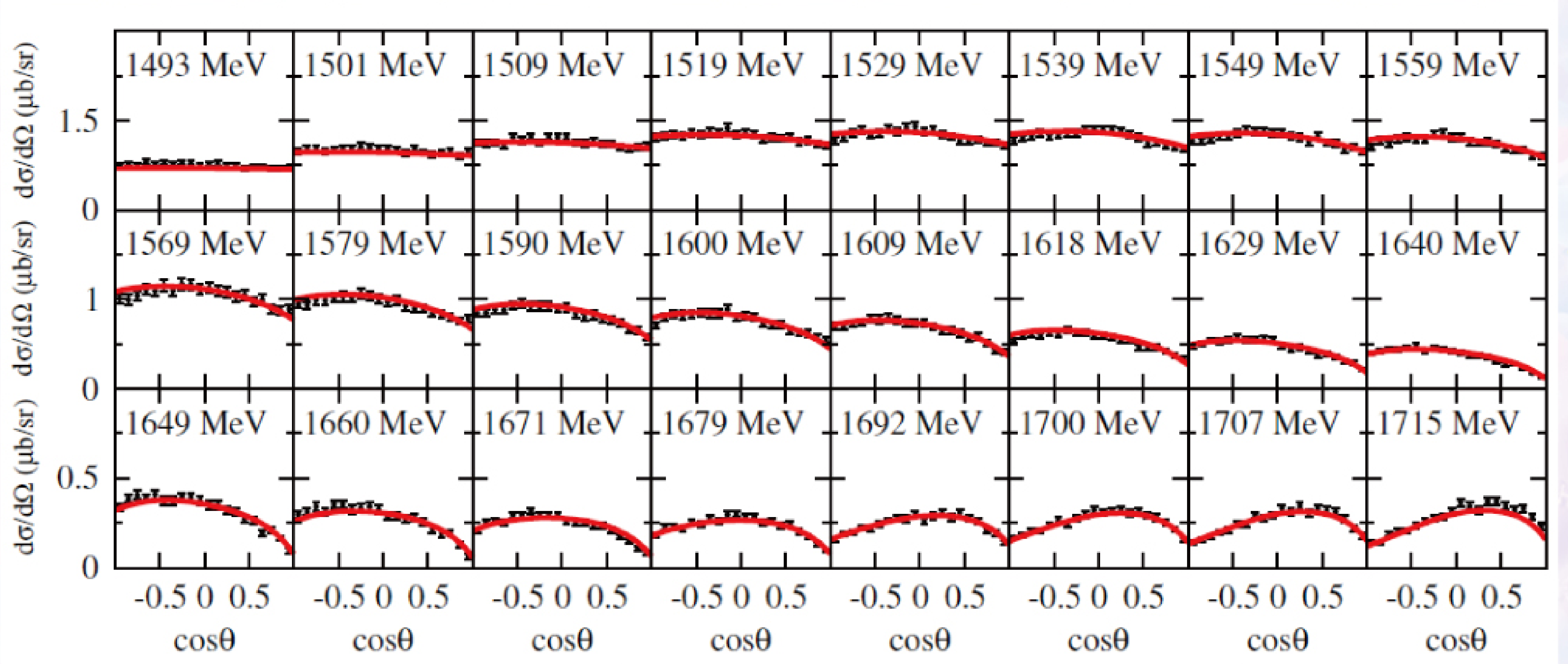
**full consideration**
- coupled-channel unitarity
- on- and off-shell amplitudes

$$\{a,b,c\} = \gamma^{(*)}N, \pi N, \eta N, \pi\Delta, \sigma N, \rho N, K\Lambda, K\Sigma, \ldots$$

($\pi\Delta, \sigma N, \rho N$: $\pi\pi N$)

# $\gamma d \to p\eta n$ reaction at $E_\gamma$~0.94 GeV

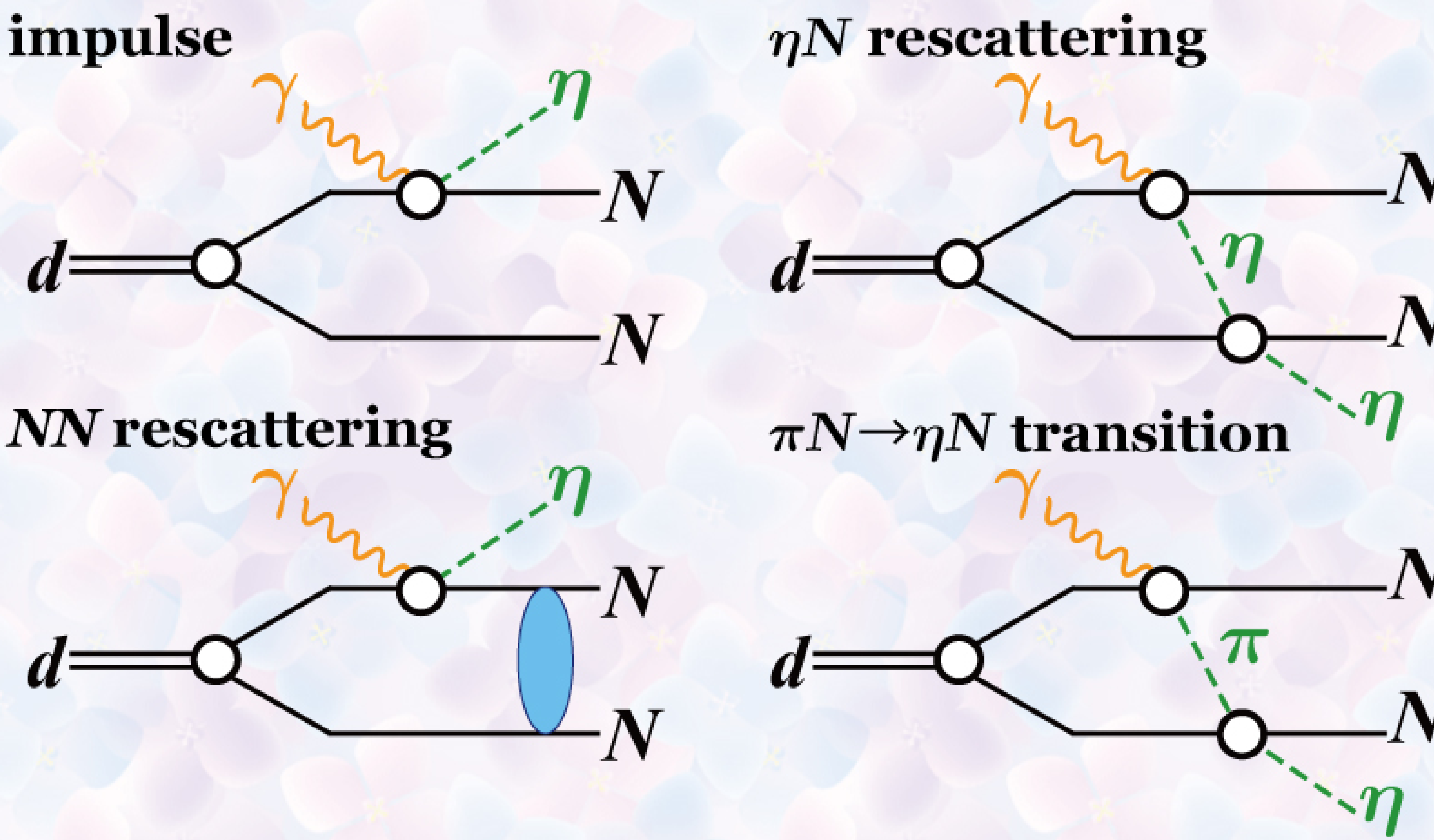
**DCC model well reproduces $\gamma p \to \eta p$ cross sections over the energy region relevant to the calculations of $\gamma d \to p\eta n$.**




data: O. Bartholomy et al., Eur. Phys. J. A 33, 133 (2007); V. Crede et al., Phys. Rev. C 80, 055202 (2009); E. F. McNicoll et al., Phys. Rev. C 82, 035208 (2010).

# $\gamma d \to p\eta n$ reaction at $E_\gamma$~0.94 GeV

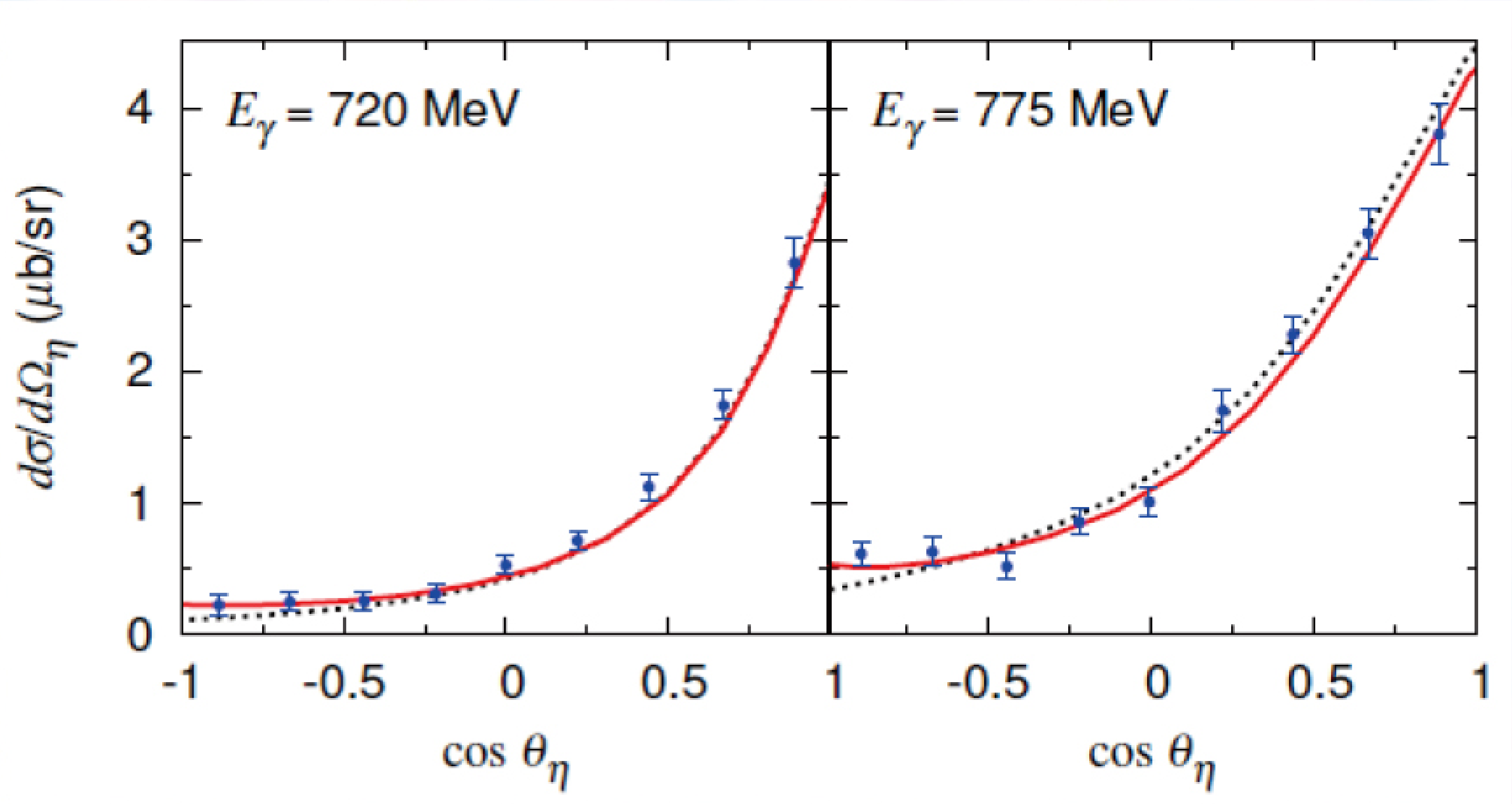
## Model for $\gamma d \to \eta np$




$\gamma N \to \pi N$, $\gamma N \to \eta N$, $\pi N \to \eta N$ amplitudes (DCC model)
*NN* FSI and deteron wave function (CD-Bonn potenial)
off-shell effects

# $\gamma d \rightarrow p\eta n$ reaction at $E_\gamma$~0.94 GeV

**Differential cross section for $\gamma d \rightarrow \eta p n$ as a function of the $\eta$ emission angle**

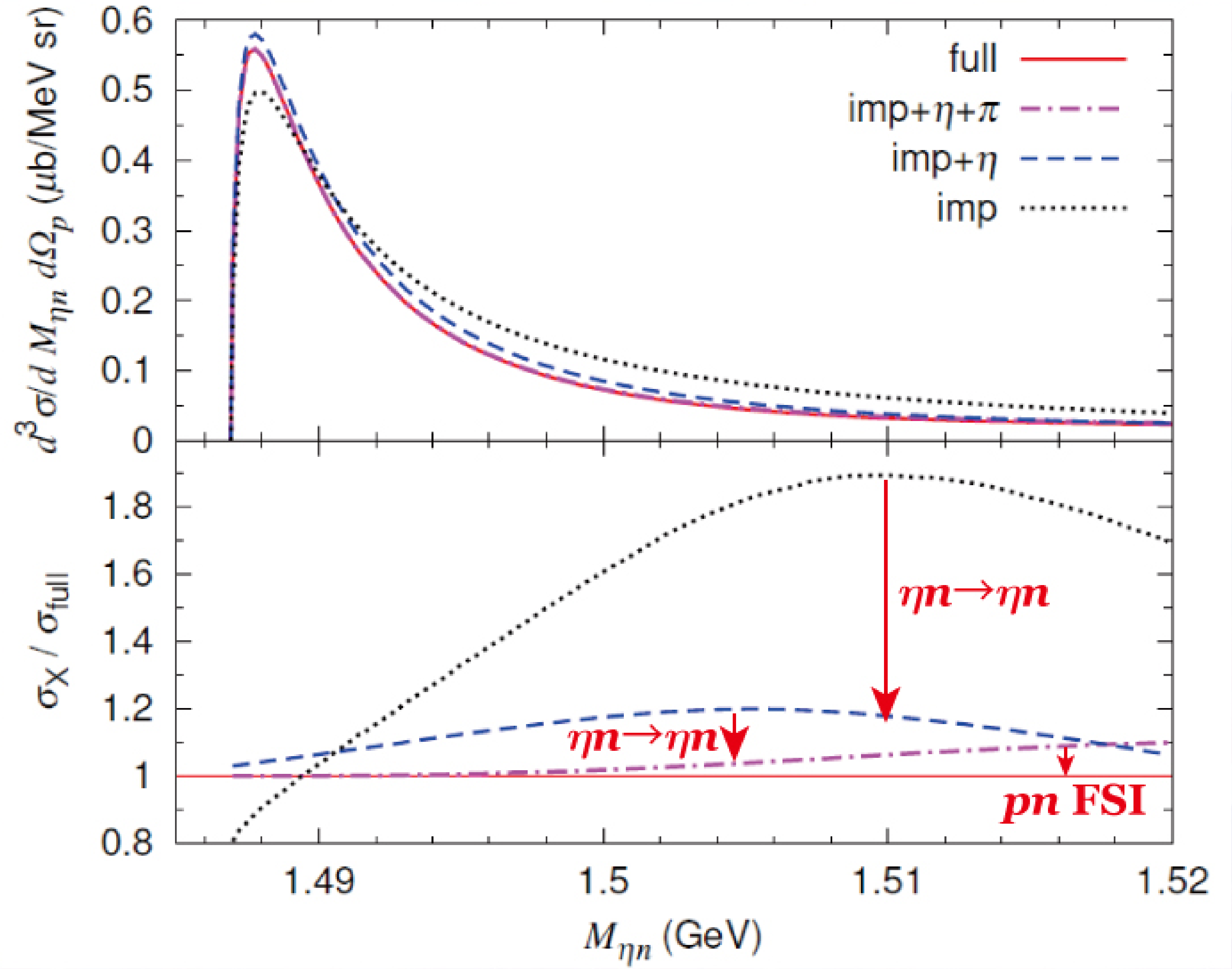



data: B. Krusche *et al.*, Phys. Lett. B 357, 40 (1995).

**Full calculation (solid)**
**impulse mechanism only (dotted)**

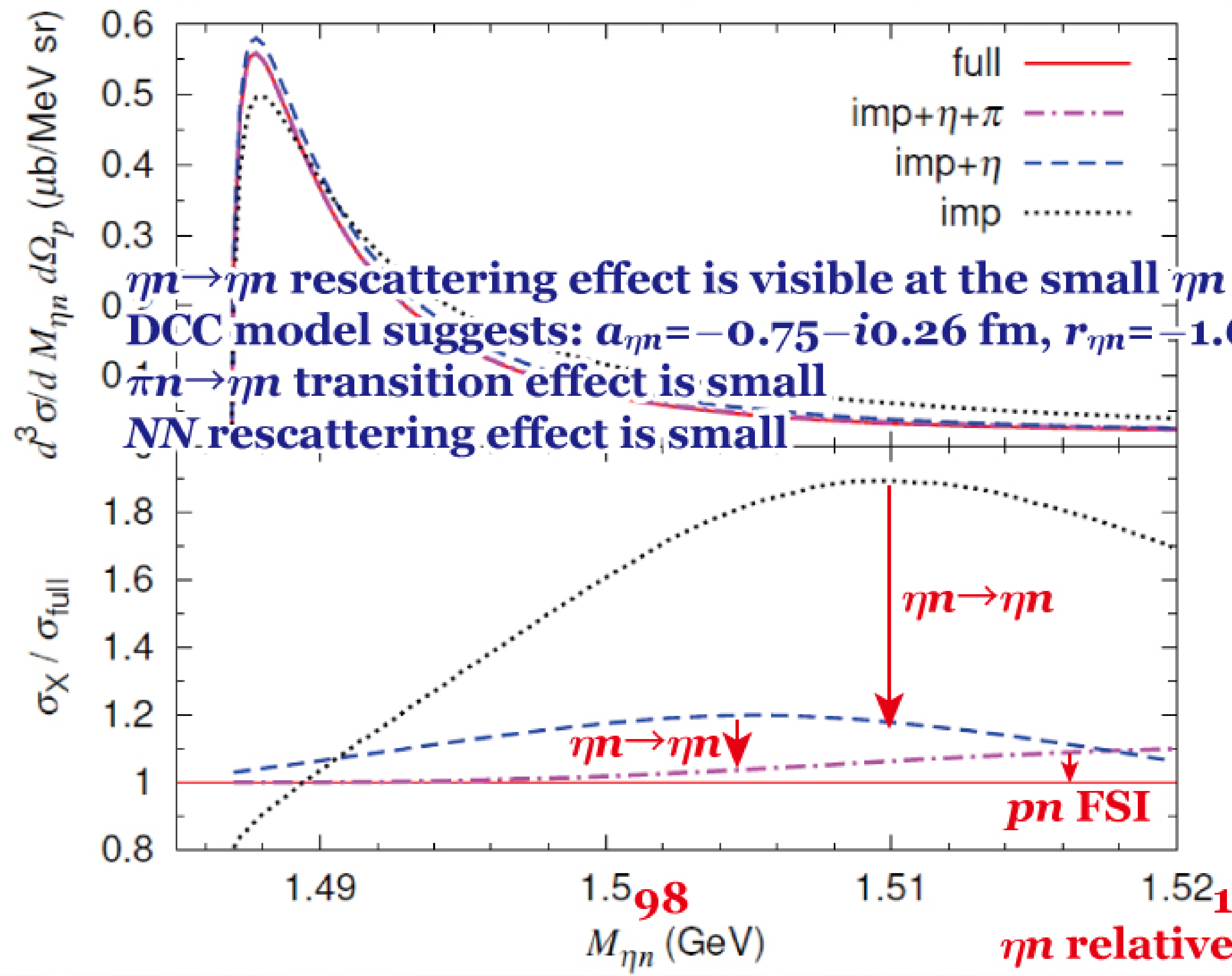
# $\gamma d \to p\eta n$ reaction at $E_\gamma \sim 0.94$ GeV

**Differential cross section for $\gamma d \to \eta p n$ as a function of the $\eta n$ invariant mass**



# $\gamma d \to p\eta n$ reaction at $E_\gamma$~0.94 GeV

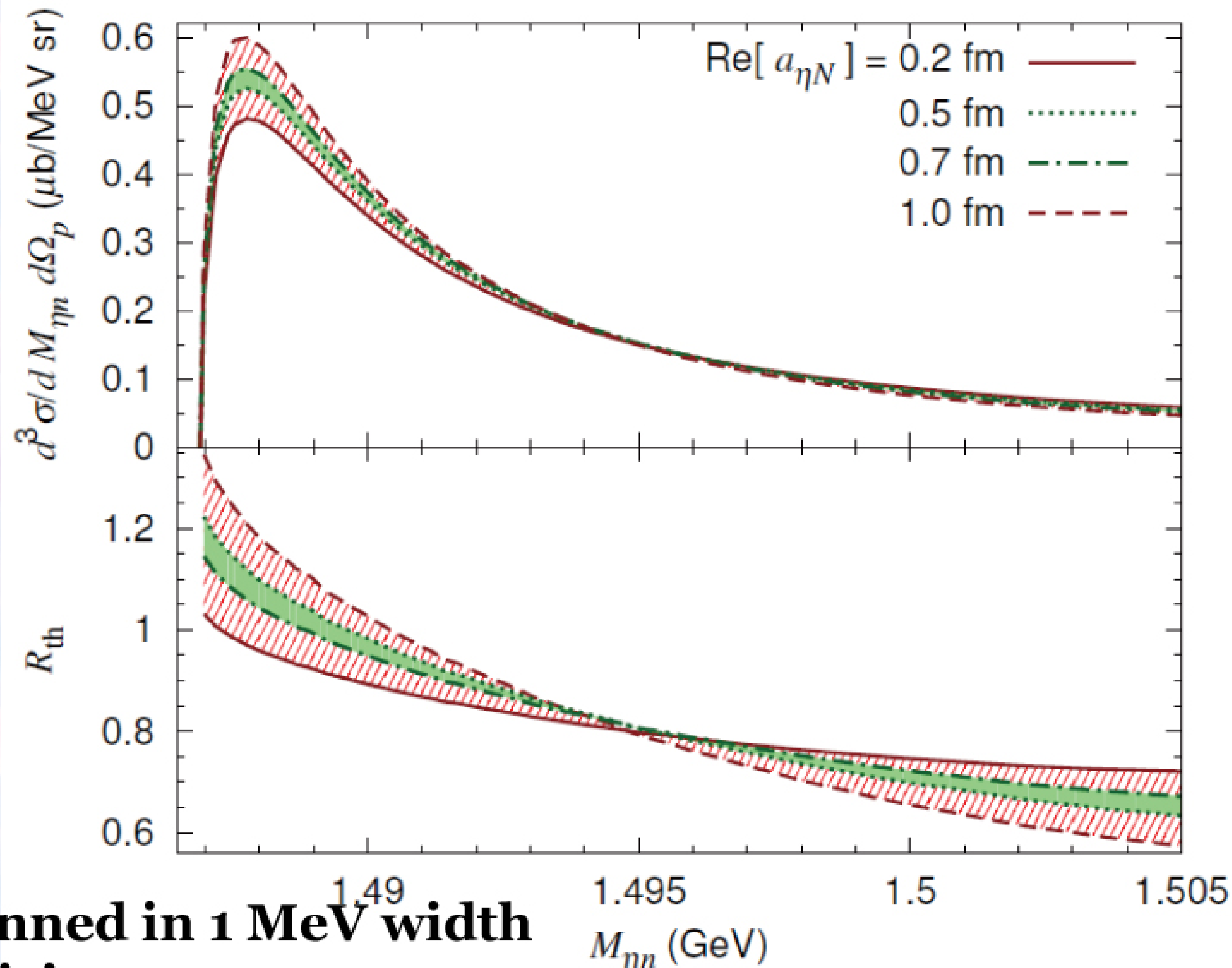
## Differential cross section for $\gamma d \to \eta pn$ as a function of the $\eta n$ invariant mass




**$\eta n \to \eta n$ rescattering effect is visible at the small $\eta n$ relative momentum**
**DCC model suggests: $a_{\eta n}$=−0.75−i0.26 fm, $r_{\eta n}$=−1.6−i0.6 fm**
**$\pi n \to \eta n$ transition effect is small**
**$NN$ rescattering effect is small**

# $\gamma d \to p\eta n$ reaction at $E_\gamma$~0.94 GeV

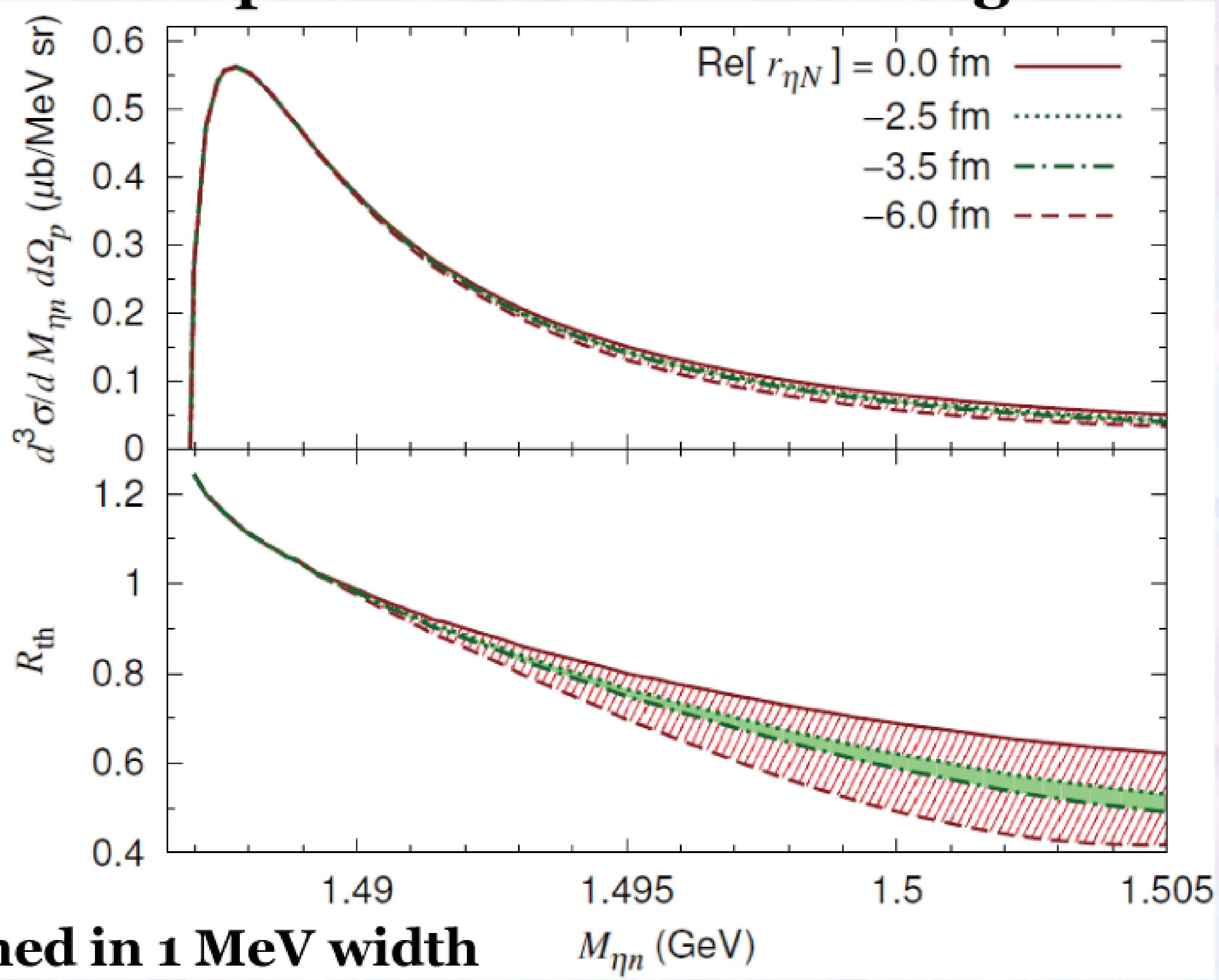
## Sensitivity to the real part of the scattering length




**5% yield error binned in 1 MeV width gives 0.1 fm precision**

# $\gamma d \to p\eta n$ reaction at $E_\gamma \sim 0.94$ GeV

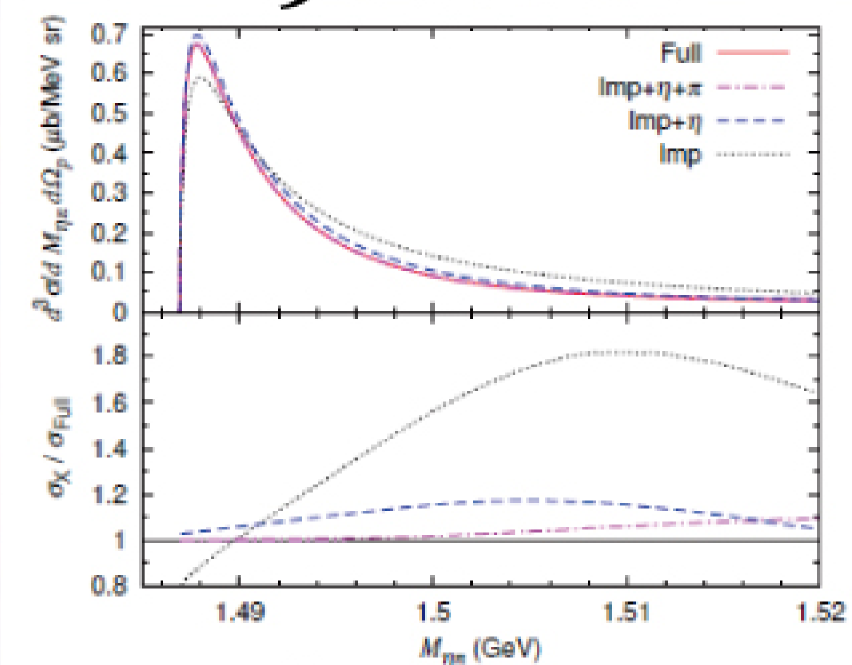
## Sensitivity to the real part of the effective range



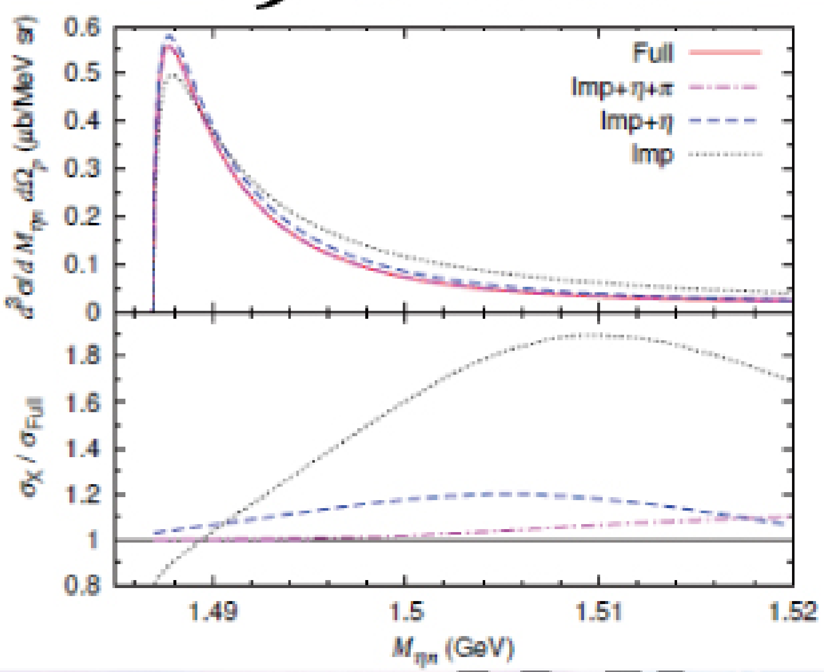

**5% yield error binned in 1 MeV width gives 0.5 fm precision**

# $\gamma d \to p\eta n$ reaction at $E_\gamma$~0.94 GeV

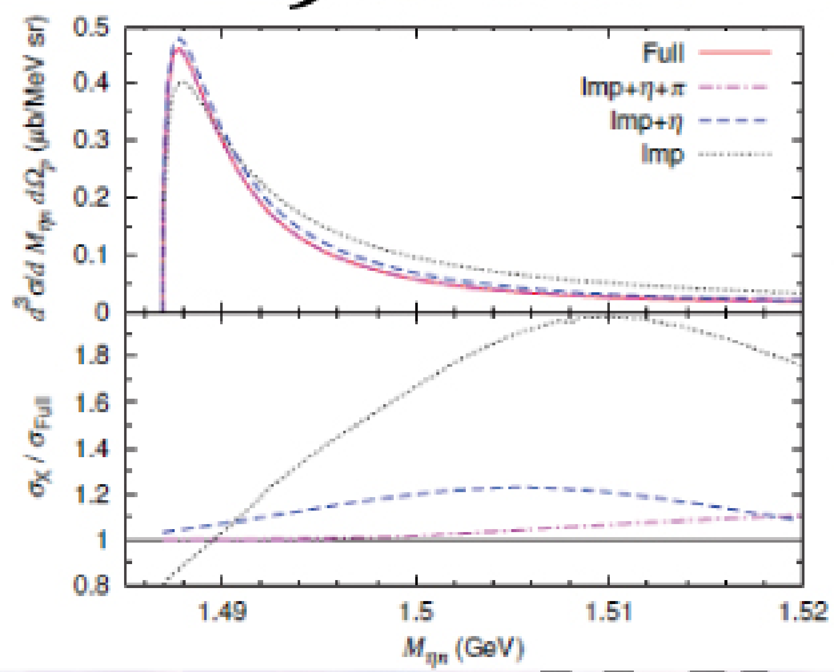
**900 MeV**



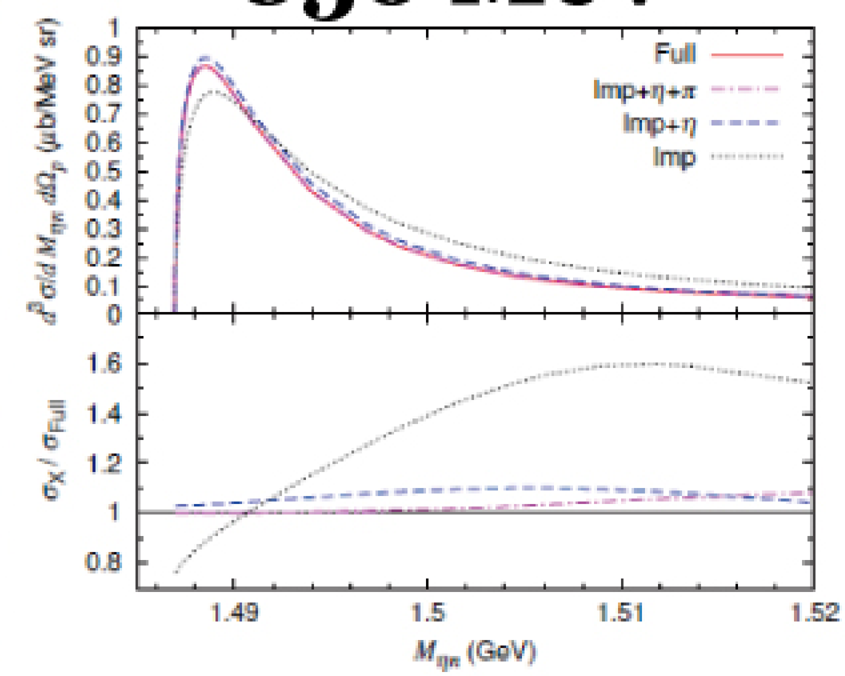

**920 MeV**



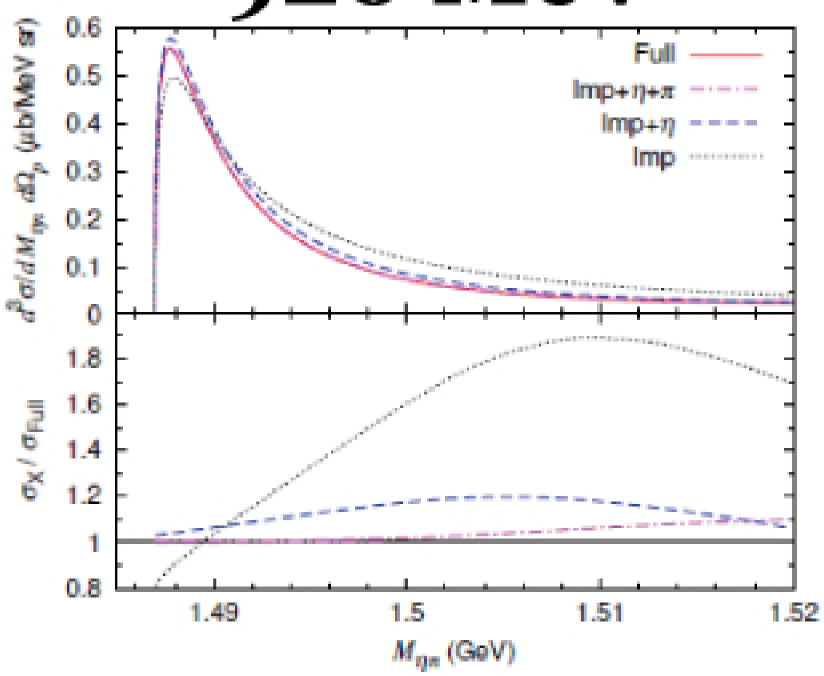

**960 MeV**



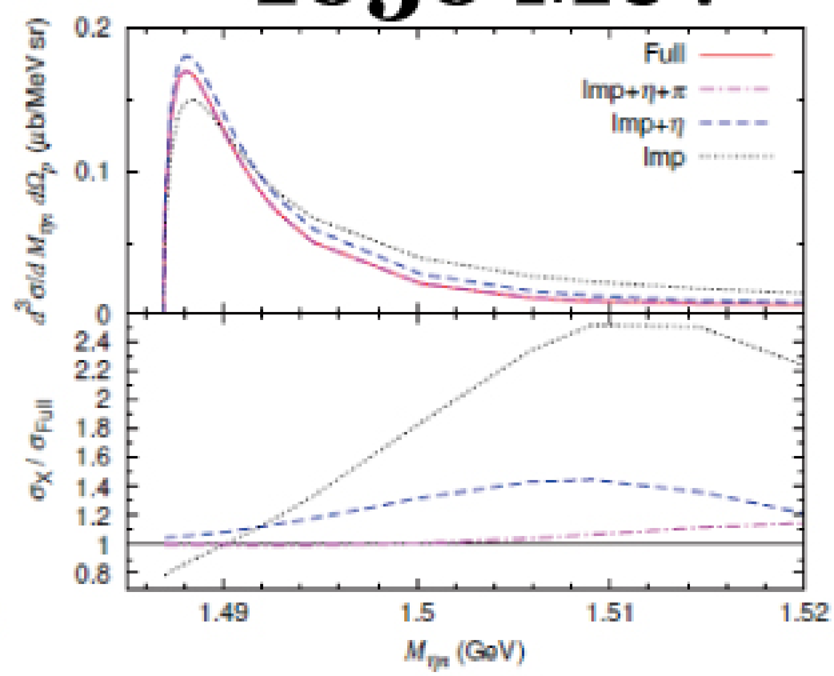

**850 MeV**




**920 MeV**




**1050 MeV**



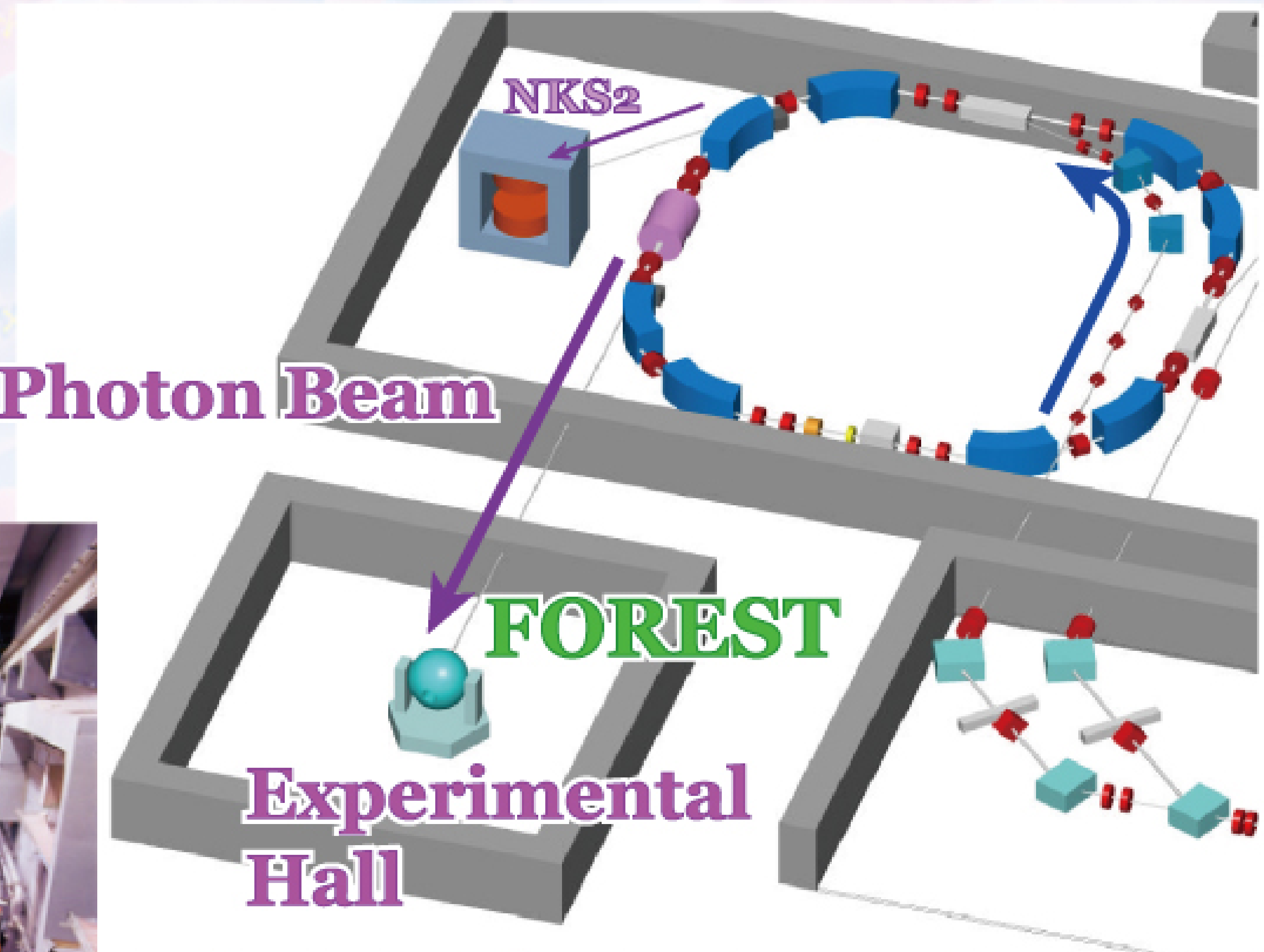

**similar behaviors for different incident energies**

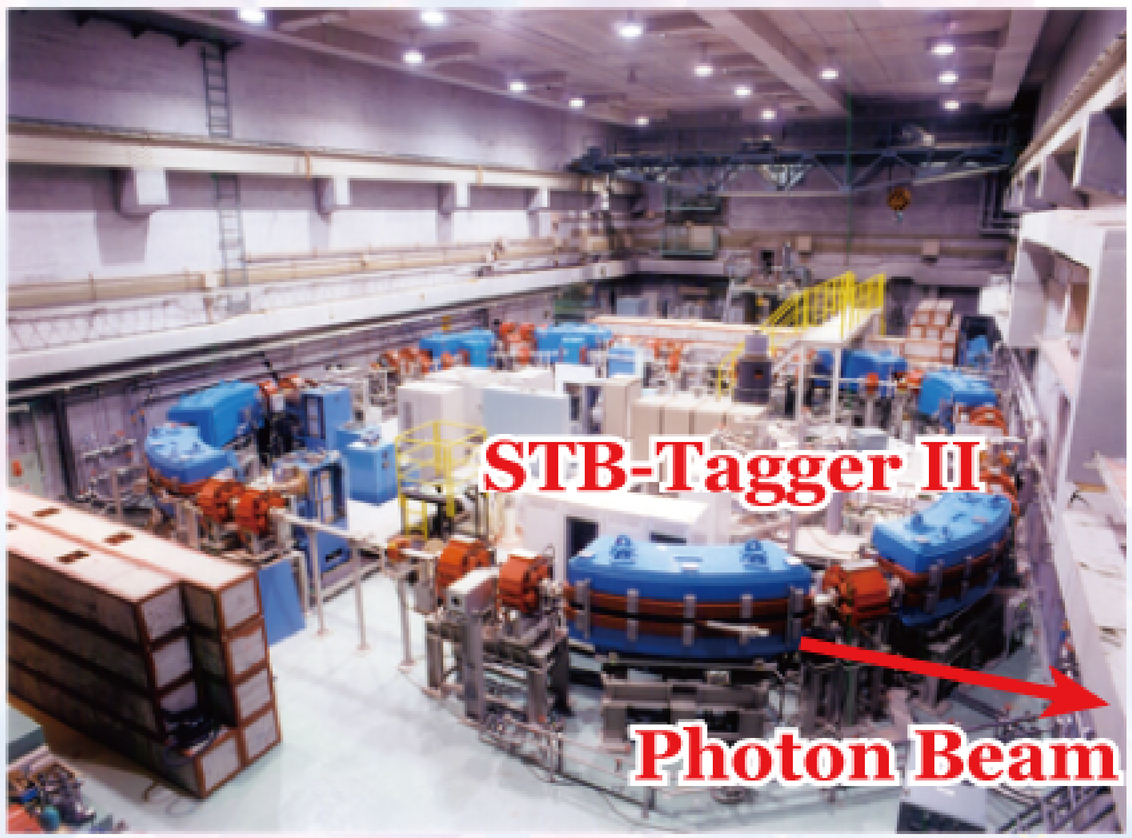
**→we can use a photon beam with a finite energy range.**

# Experimental setup ~ accelerator

**Electron Beam**
- LINAC 93 MeV
- Booster Ring 1.32 GeV (max)

**Photon Beam**
- Bremsstrahlung
- Tagged




**1.3 GeV Booster STorage Ring**

Typical Tagging Rate
- 20 MHz (photon: 10 MHz)

Bremsstrahlung Tagged Photon Beam
- 740~1150 MeV @ 1200 MeV
- 570~890 MeV @ 930 MeV

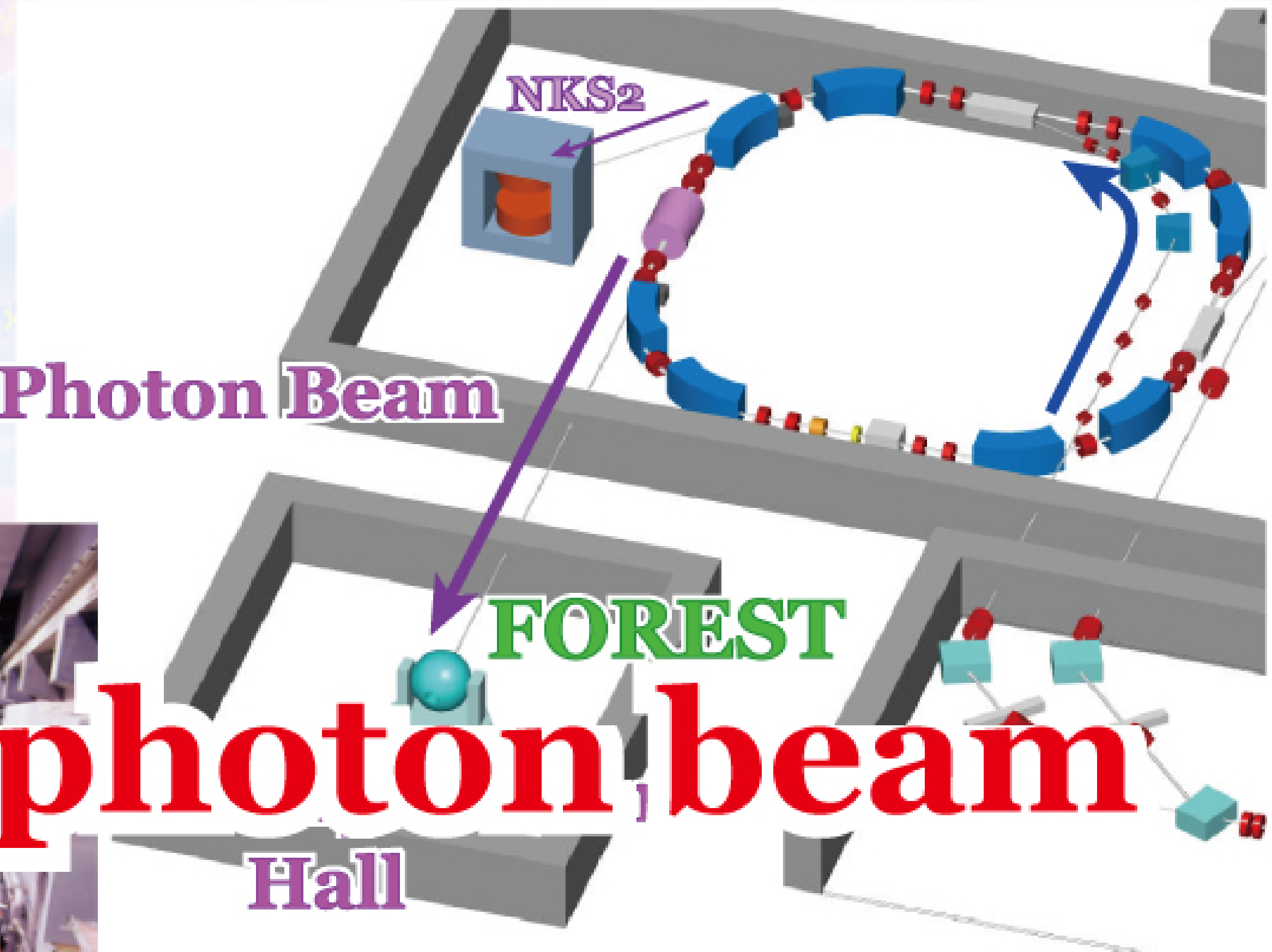
$\delta E$: 1~2 MeV

**T. Ishikawa et al., Nucl. Instr. Meth. A 622, 1 (2010);**
**T. Ishikawa et al., Nucl. Instr. Meth. A 811, 124 (2016).**

# Experimental setup ~ accelerator

**Electron Beam**
- LINAC 93 MeV
- Booster Ring 1.32 GeV (max)

**Photon Beam**
- Bremsstrahlung
- Tagged





1.3 GeV Booster STorage Ring

## 940 MeV photon beam

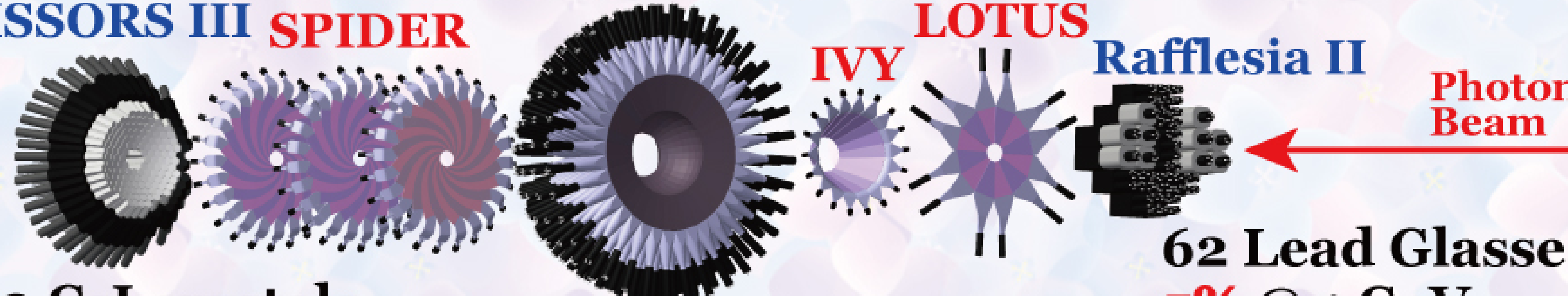
Typical Tagging Rate
- 20 MHz (photon: 10 MHz)

Bremsstrahlung Tagged Photon Beam
- 740~1150 MeV @ 1200 MeV
- 570~890 MeV @ 930 MeV

$\delta E$: 1~2 MeV

T. Ishikawa et al., Nucl. Instr. Meth. A 622, 1 (2010);
T. Ishikawa et al., Nucl. Instr. Meth. A 811, 124 (2016).

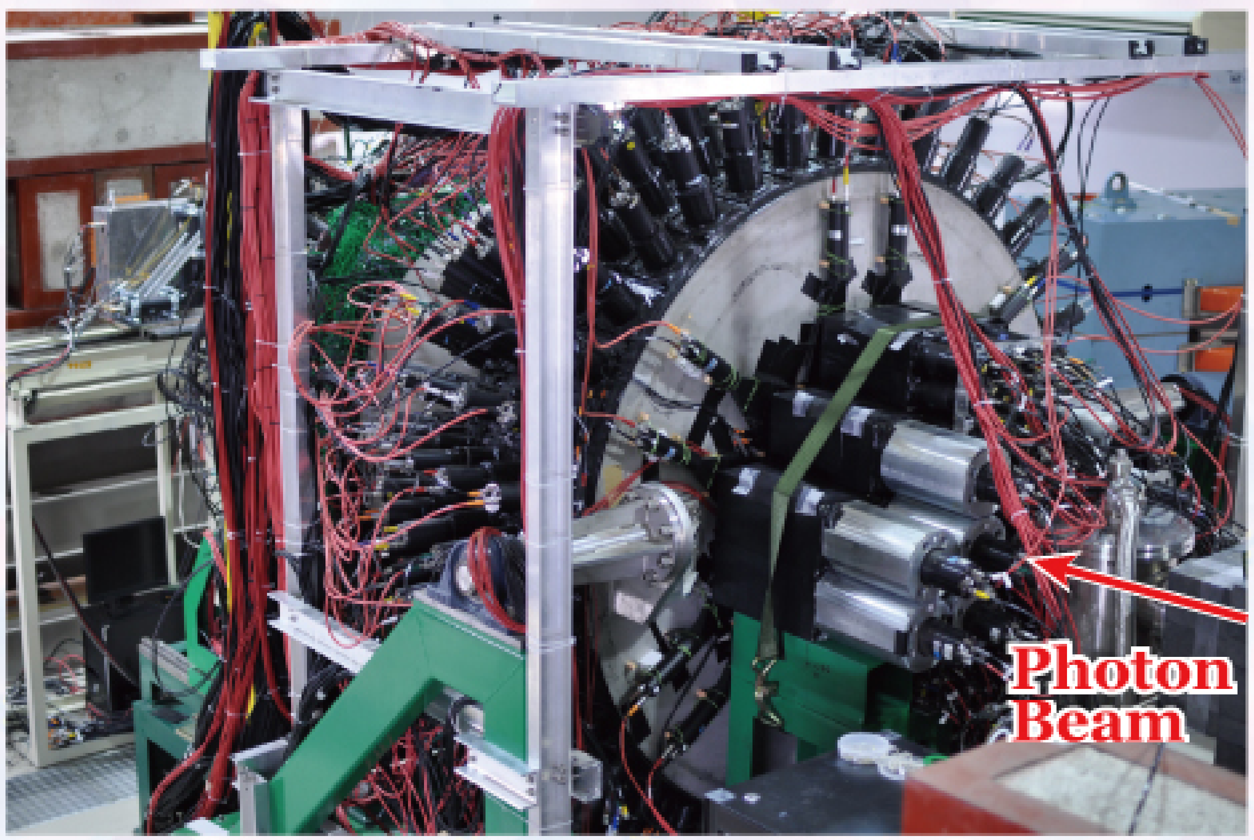
# Experimental setup ~ EM calorimeter



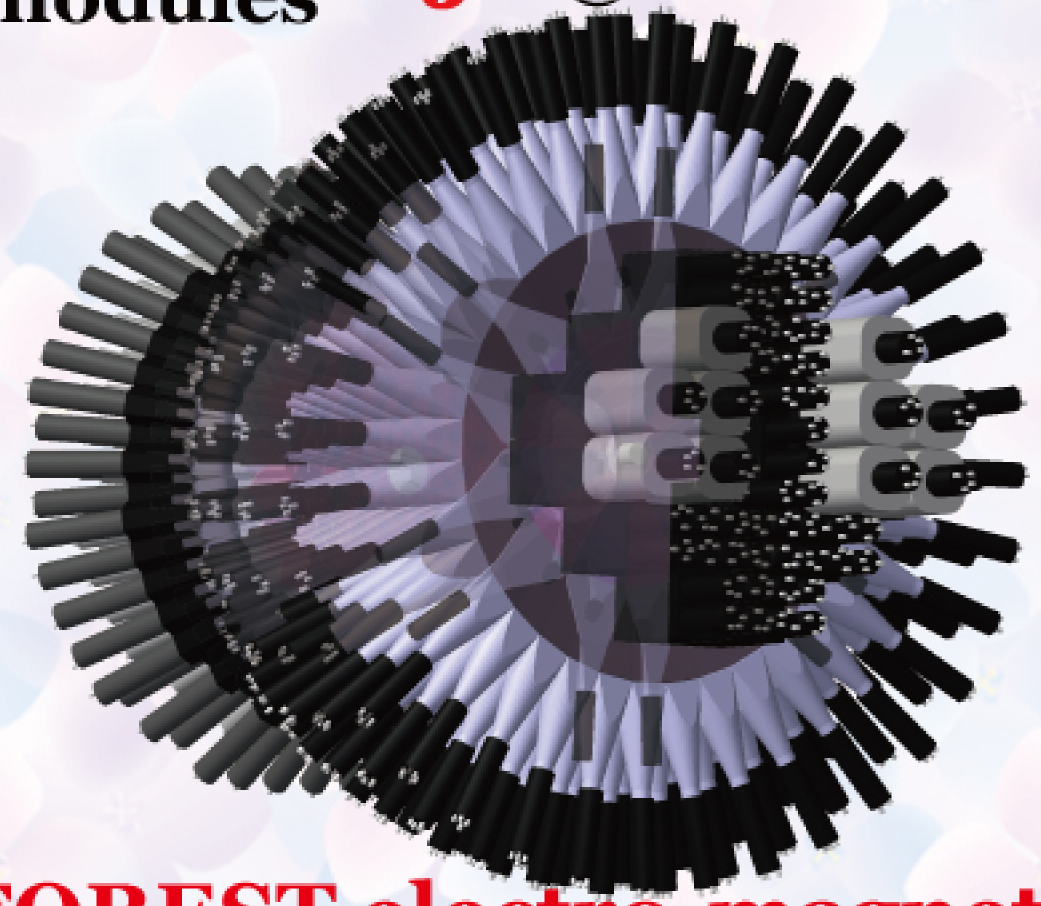

192 CsI crystals
**3%** @ 1 GeV

252 Lead/SciFi modules
**7%** @ 1 GeV

62 Lead Glasses
**5%** @ 1 GeV




Target: 45 mm thick $LH_2$ & $LD_2$



**FOREST electro-magnetic calorimeter**

**T. Ishikawa et al., Nucl. Instr. Meth. A 832, 108 (2016).**

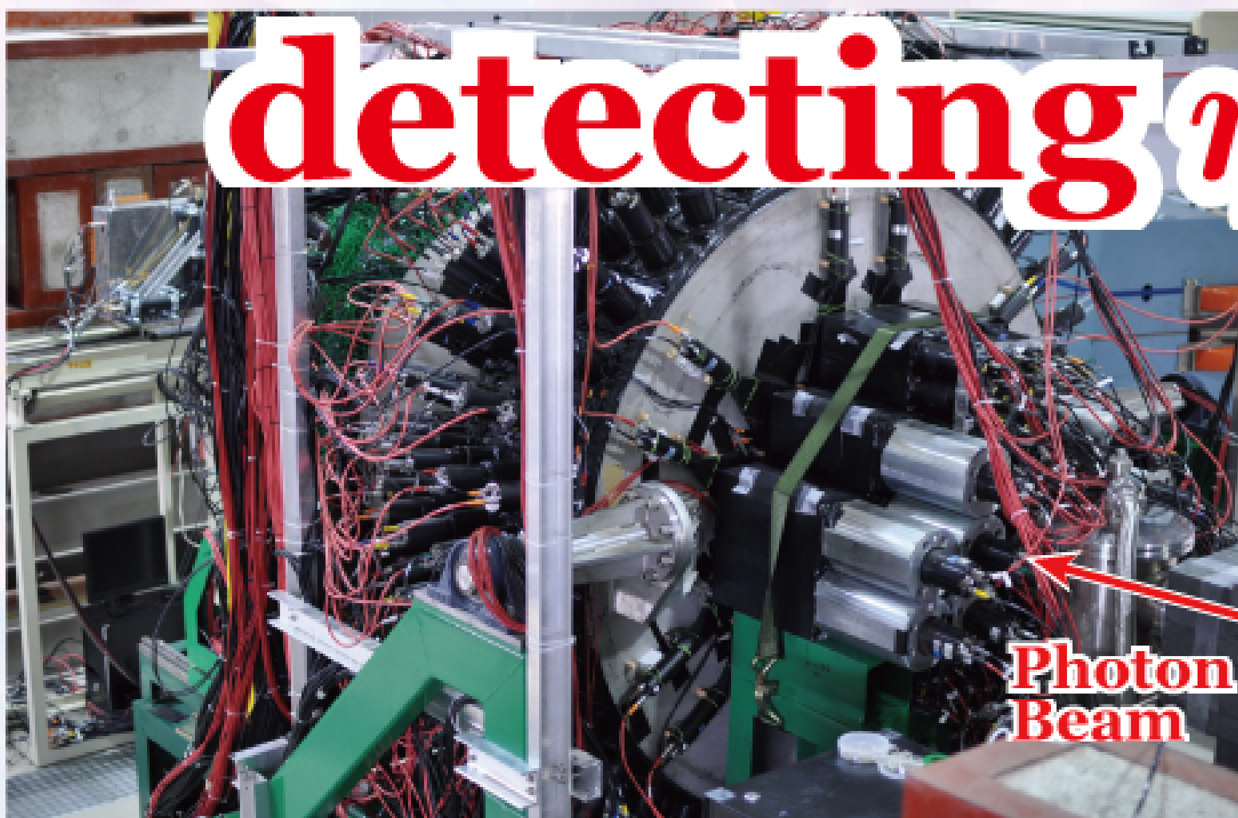
# Experimental setup ~ EM calorimeter


192 CsI crystals
3% @ 1 GeV

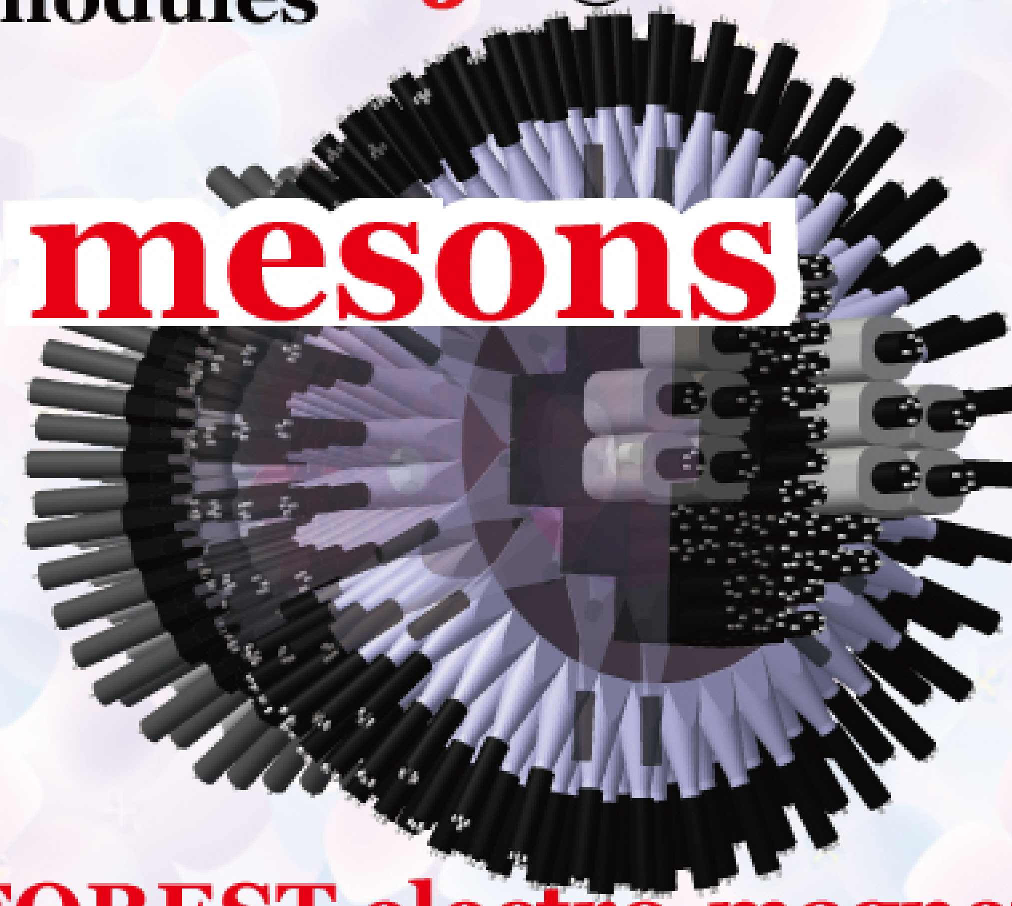
252 Lead/SciFi modules
7% @ 1 GeV

62 Lead Glasses
5% @ 1 GeV

**detecting $\eta$ mesons**




Target: 45 mm thick LH2 & LD2

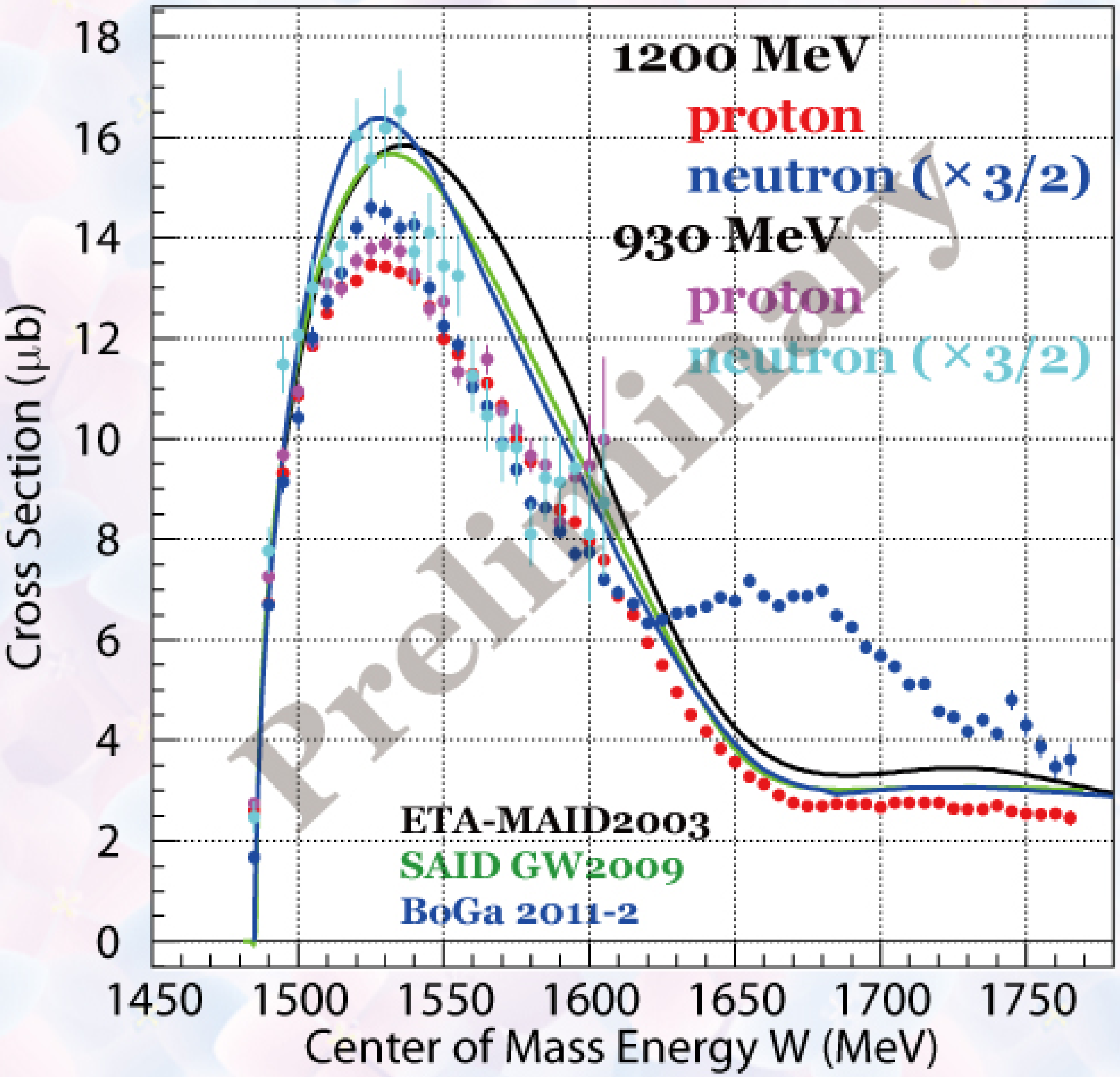


FOREST electro-magnetic calorimeter

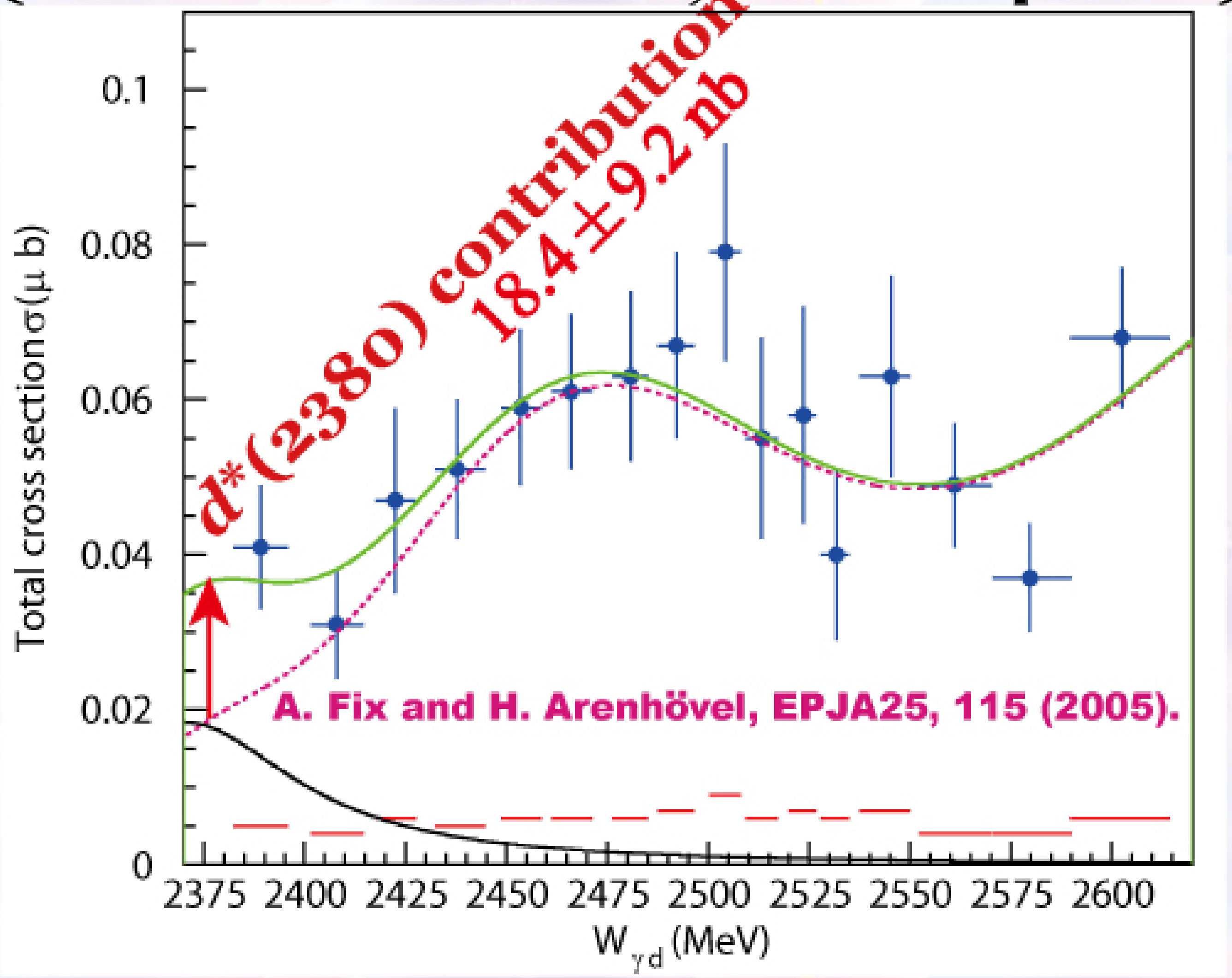
T. Ishikawa et al., Nucl. Instr. Meth. A 832, 108 (2016).

# Experimental setup ~ EM calorimeter

**pentaquark candidate observed in $\gamma n \to \eta n$**

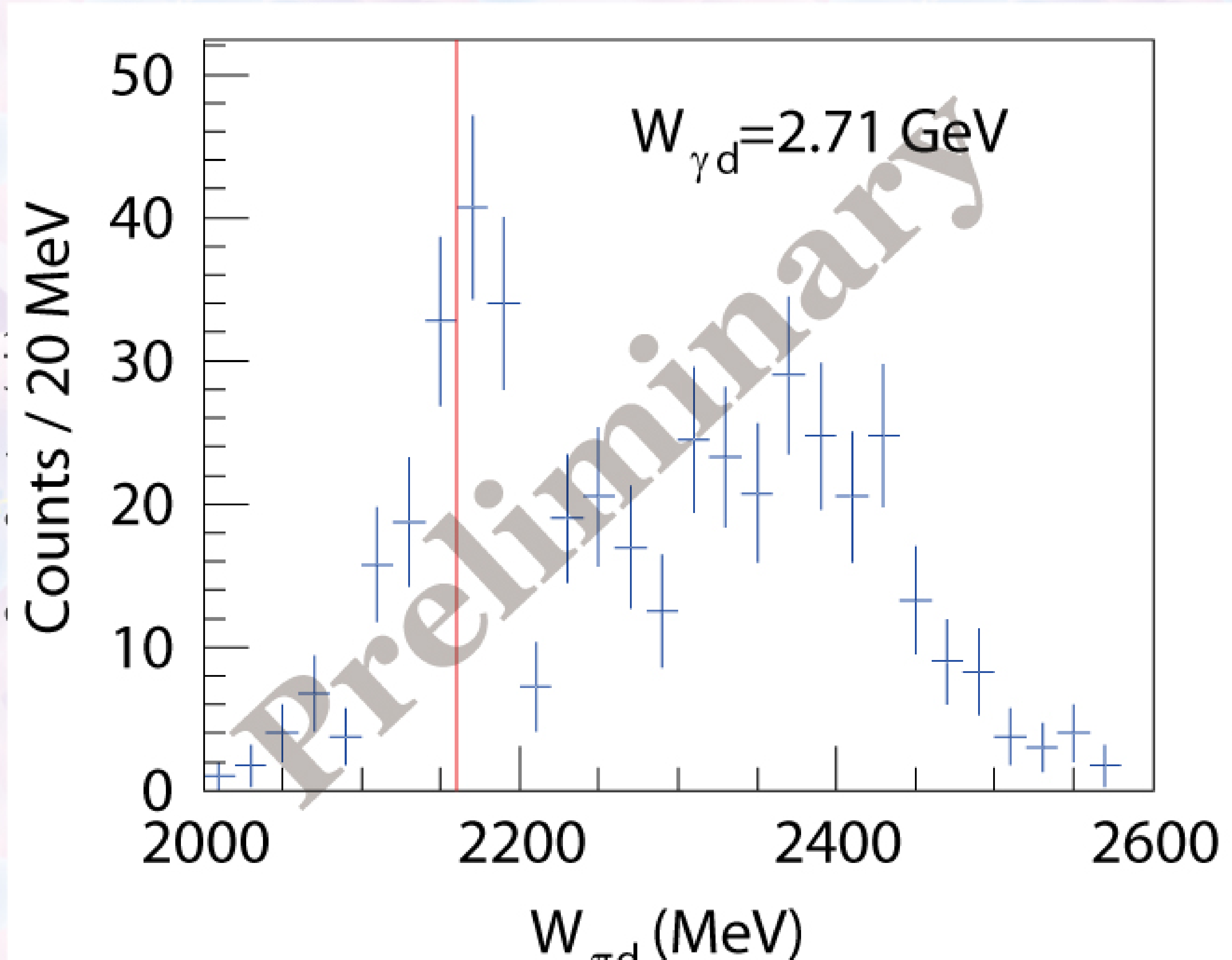



**dibaryon candidate observed in $\gamma d \to \pi^0 \pi^0 d$ (T. Ishikawa *et al.*, PLB in press)**



# Experimental setup ~ EM calorimeter

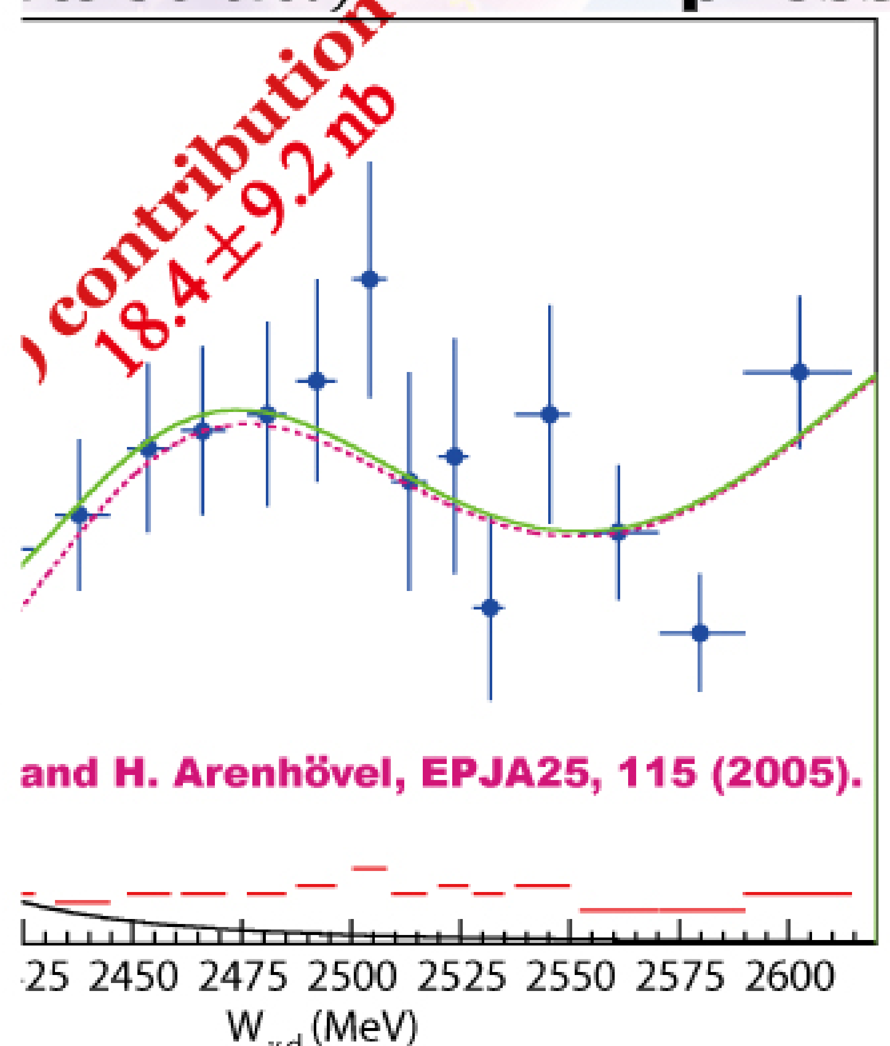
**pentaquark candidate**




**andidate**

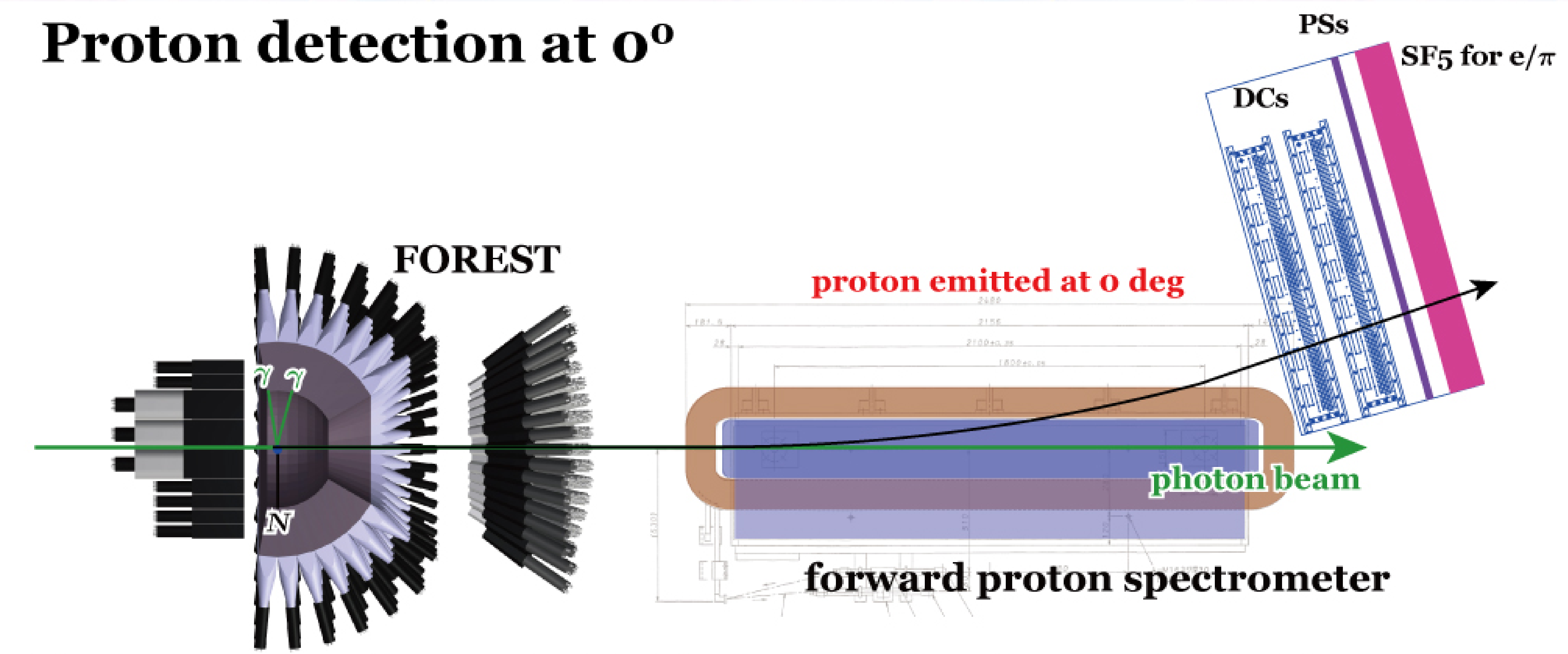
**n $\gamma d \to \pi^0 \pi^0 d$**

**va *et al.*, PLB in press)**




## $\Delta N$ quasi-bound state?

# Experimental setup ~ spectrometer




beding magnet from the KEKB low energy ring

plastic hodoscopes (PSs) for the TOF measurement

drift chambers (DCs) for the momentum measurement

SF5 lead glass Counters for $e/\pi$ separation

# Experimental setup ~ spectrometer

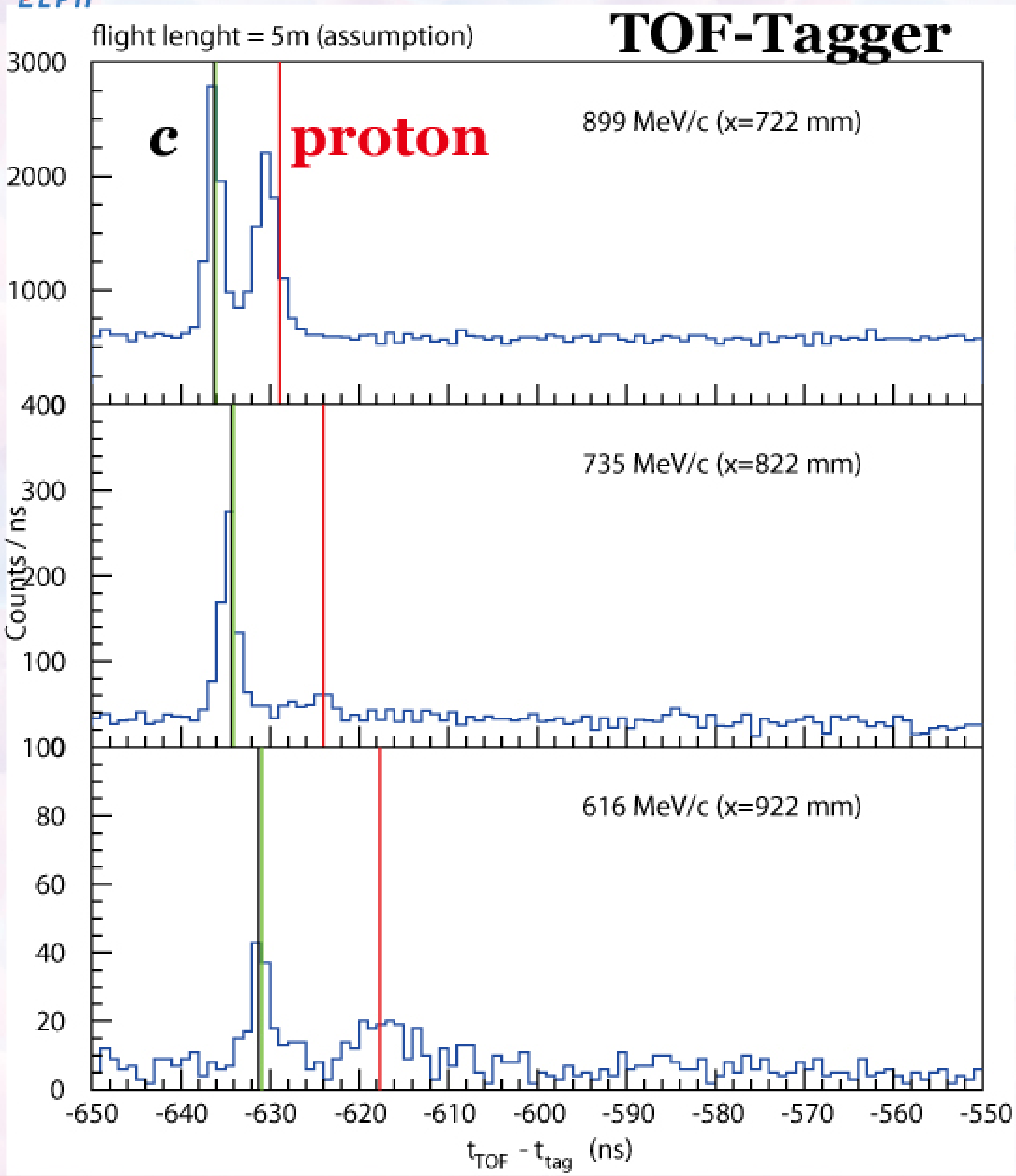
Proton detection at 0°

Proton missing mass resolution: 3.8~ 6.1 MeV
corresponding to $\eta N$ invariant mass resolution
photon tagging: 0.5~2.5 MeV
emitted proton measurement:
uncertainty of the vertex z point
8 ps($\sigma$) for 20 mm target thickness
time resolution of PS hodoscopes 50~100 ps
flight length ~5 m giving 4~8 MeV/c

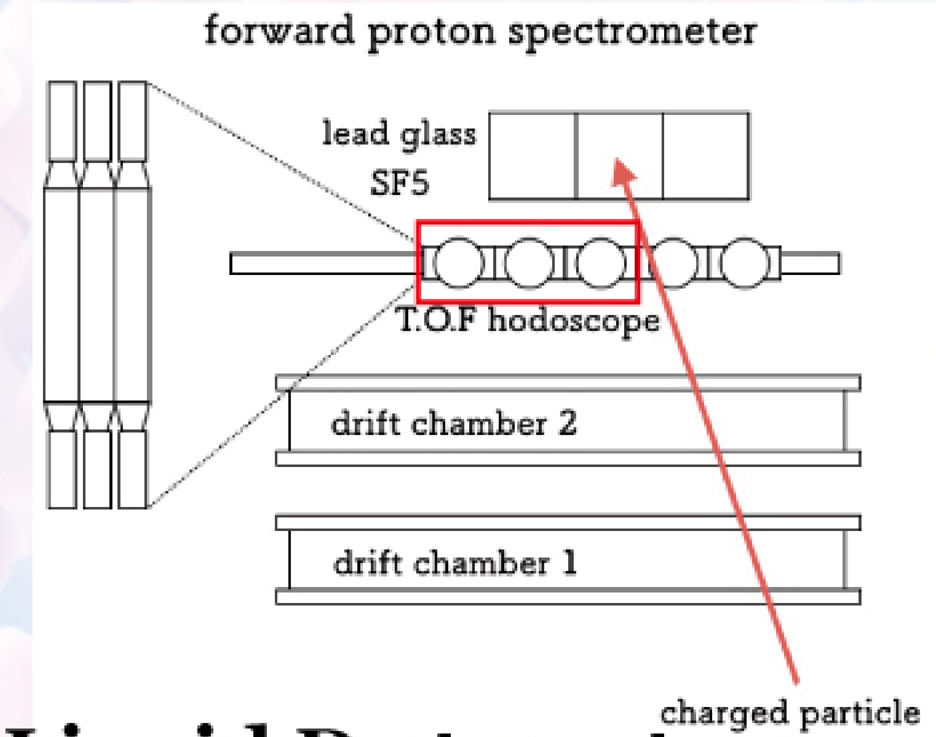
TOF start: RF signal of the STB ring

$\eta N$ relative momentum:
8~13 MeV/c for 3.8 MeV $m_{\eta N}$ mass resolution
12~20 MeV/c for 6.1 MeV $m_{\eta N}$ mass resolution
performance of the new detector system is on-going.
required beamtime estimation is also on-going
(approximately 100 days)

# Current status




**Commissioning (1st)**
**13~16 January 2017**




**Liquid D2 target**
**two peaks corresponding to the positive pions and protons are observed clearly**

**Commissioning (2nd)**
**22~31 May 2017**
**Experiment**
**October/November 2017~**

# ELPH-2844 (New FOREST experiment)

T. Ishikawa, Y. Honda, Y. Inoue, M. Miyabe, Y. Matsumura, N. Muramatsu, H. Ohnishi, M. Sasagawa, H. Shimizu, K. Shiraishi, A.O. Tokiyasu, H. Yamazaki
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H. Fujioka
*Department of Physics, Kyoto University*

T. Hotta, H. Kanda
*Research Center for Nuclear Physics, Osaka University*

K. Itahashi, T. Nishi
*Nishina Center, RIKEN*

K. Maeda
*Department of Physics, Tohoku University*

H. Kawai, M. Tabata
*Department of Physics, Chiba University*

S. Miyata
*Department of Physics, University of Tokyo*

Y. Tsuchikawa
*Department of Physics, Nagoya University*

# Summary

Low-energy $\eta n$ scattering parameters:

- fundamental & important
- little is known

ELPH-2844 (T. Ishikawa et al.)

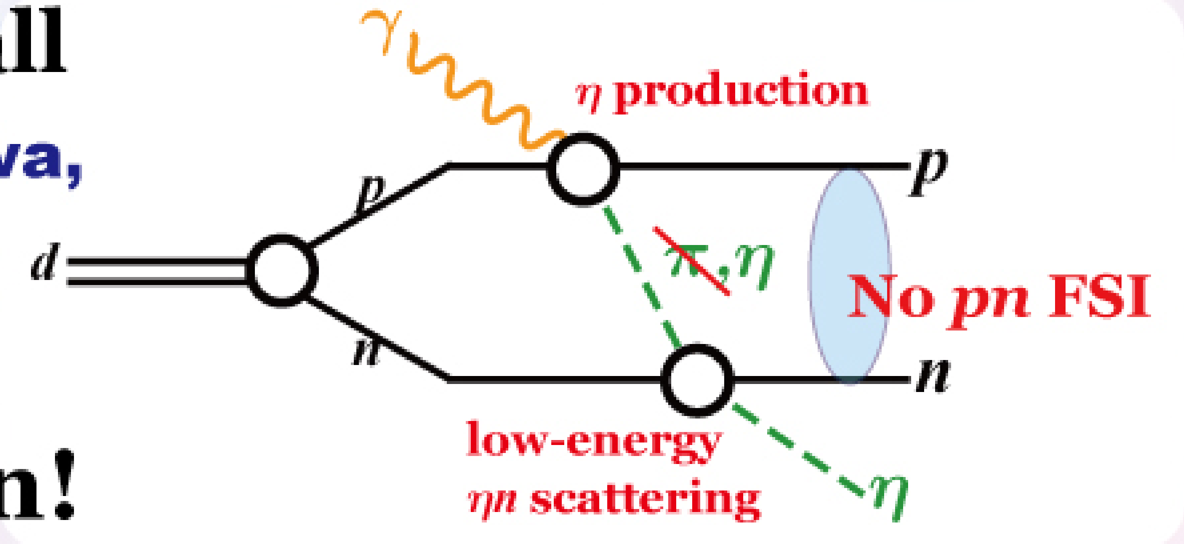
$\gamma p \to p \eta n$ experiment is proposed
using the FOREST detector at ELPH to extract $a_{\eta n}$

$E_\gamma$=940 MeV and $\theta_p$=0° is the ideal condition:

- minimum $\eta n$ relative momentum
- $pn$ rescattering effect is small
- $\pi n \to \eta n$ transition effect is small

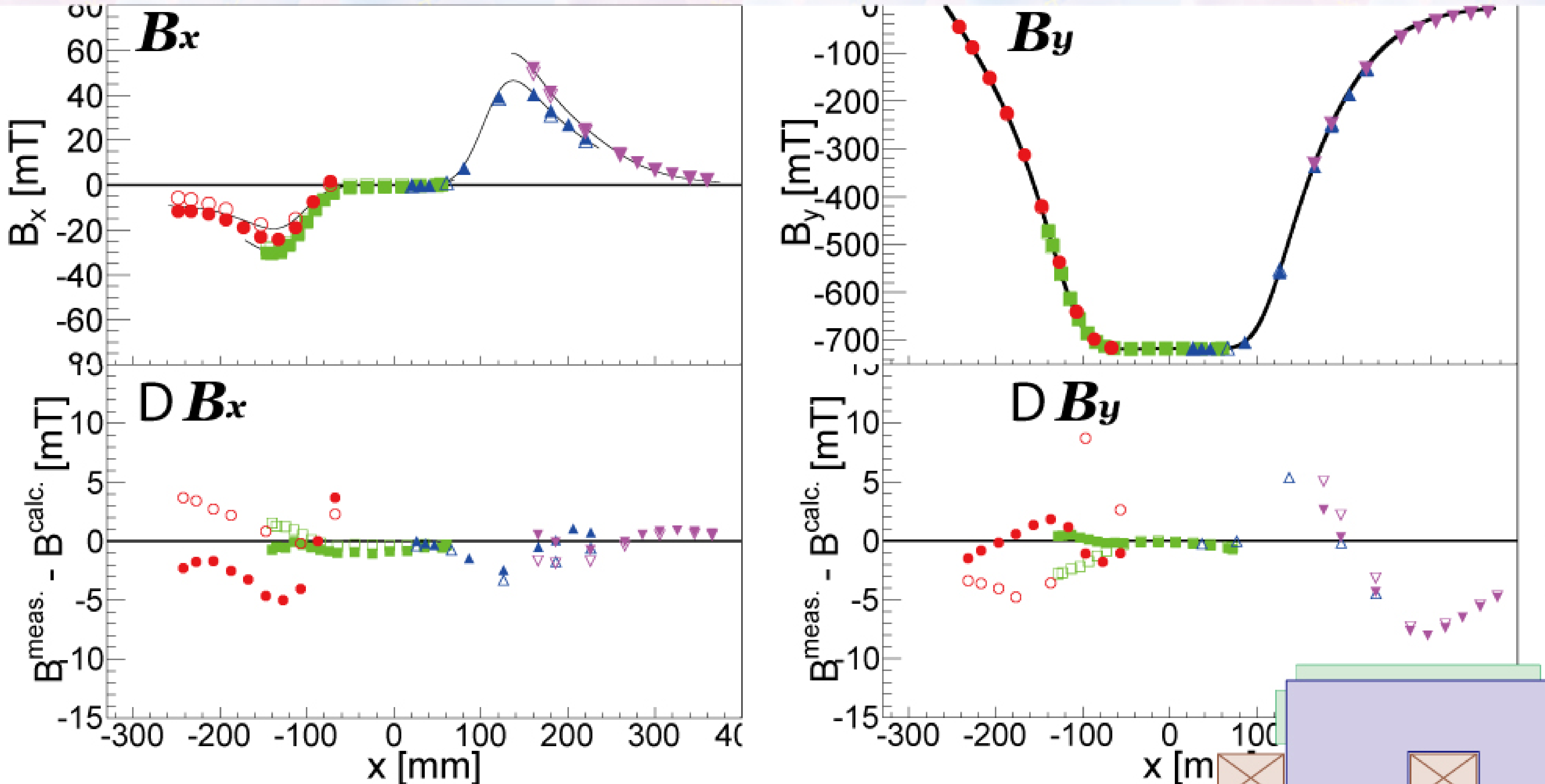
S. X. Nakamura, H. Kamano, T. Ishikawa, arXiv:1704.07029.

We will give Re $a_{\eta n}$
with a 0.1 fm precision!

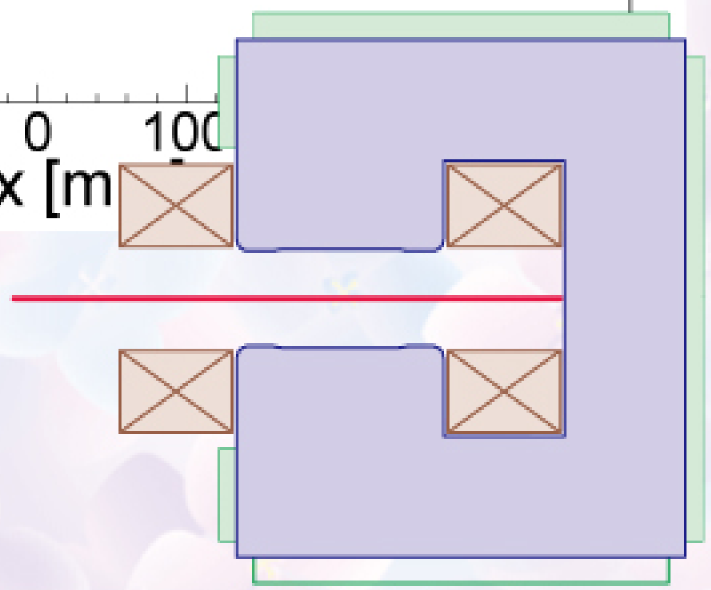


# Backup slides

# Magnetic flux density




**measurement (markers) and calculation (line)**



**Y. Inoue**

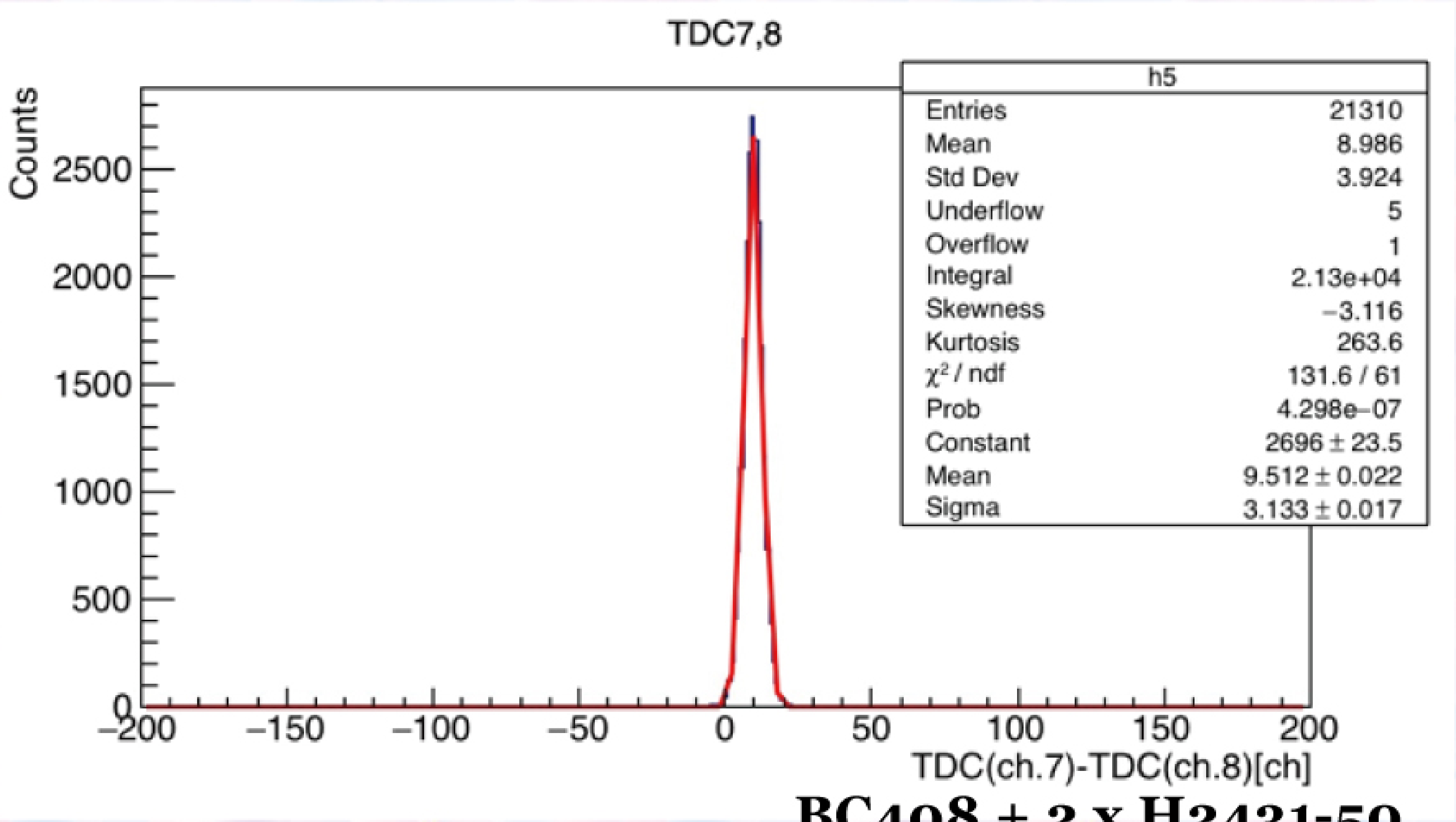
# Detector performance ~ DC

| | residual including plance of interest σ [um] | residual without plance of interest σ [um] | position resolution σ [um] |
|---|---|---|---|
| DC1x (layer1) | 205 | 470 | 310 |
| DC1x' (layer2) | 225 | 464 | 323 |
| DC2x (layer3) | 223 | 407 | 301 |
| DC2x' (layer4) | 202 | 423 | 292 |

**The position resolution is approximately 0.3 mm.**

**S. Miyata**

# Detector performance ~ PS

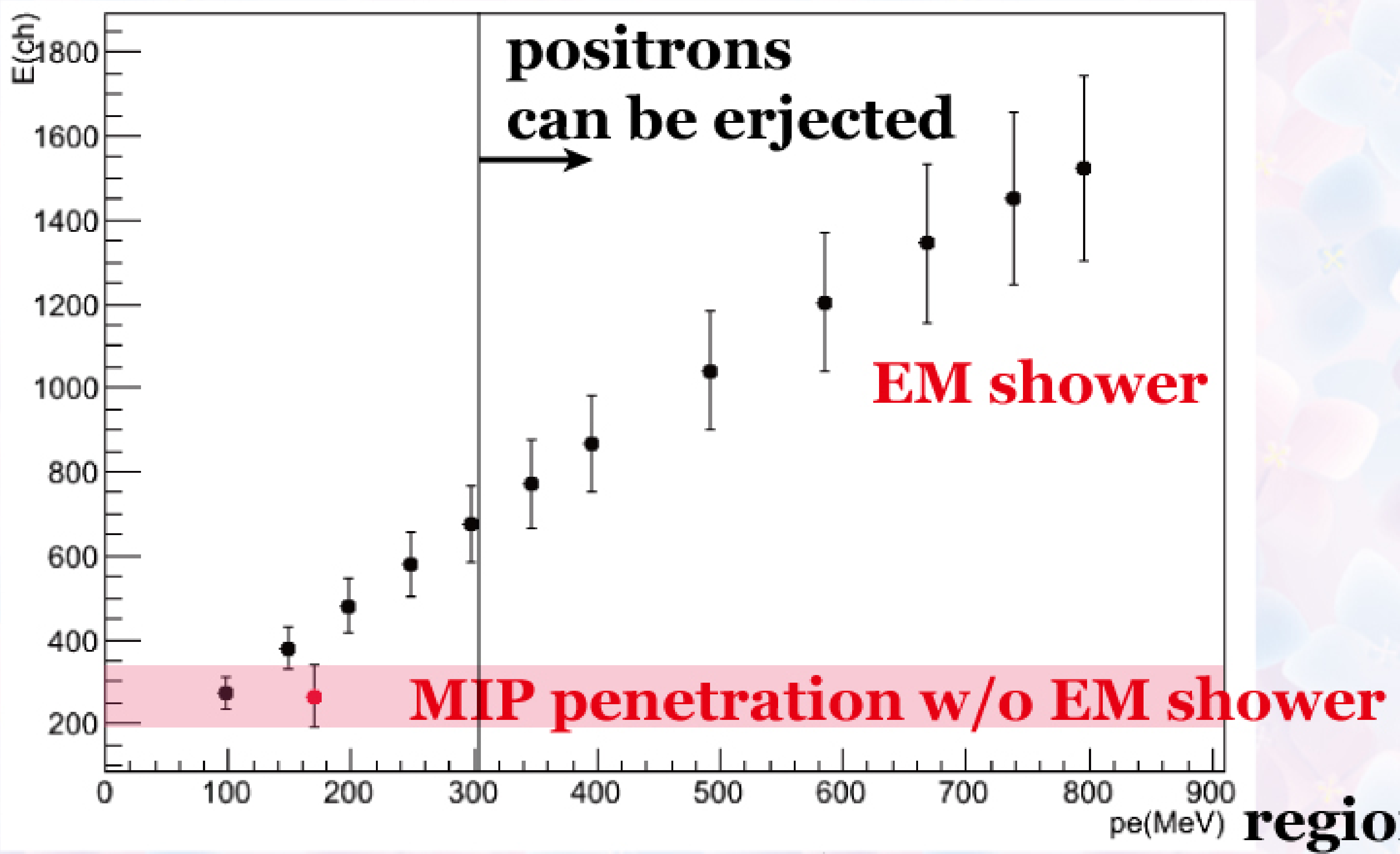



**BC408 + 2 x H2431-50**

**The time resolution for the difference is 80~130 ps, corresponding to that for the average 40~65 ps.**

**S. Miyata**

# Detector performance ~ PS

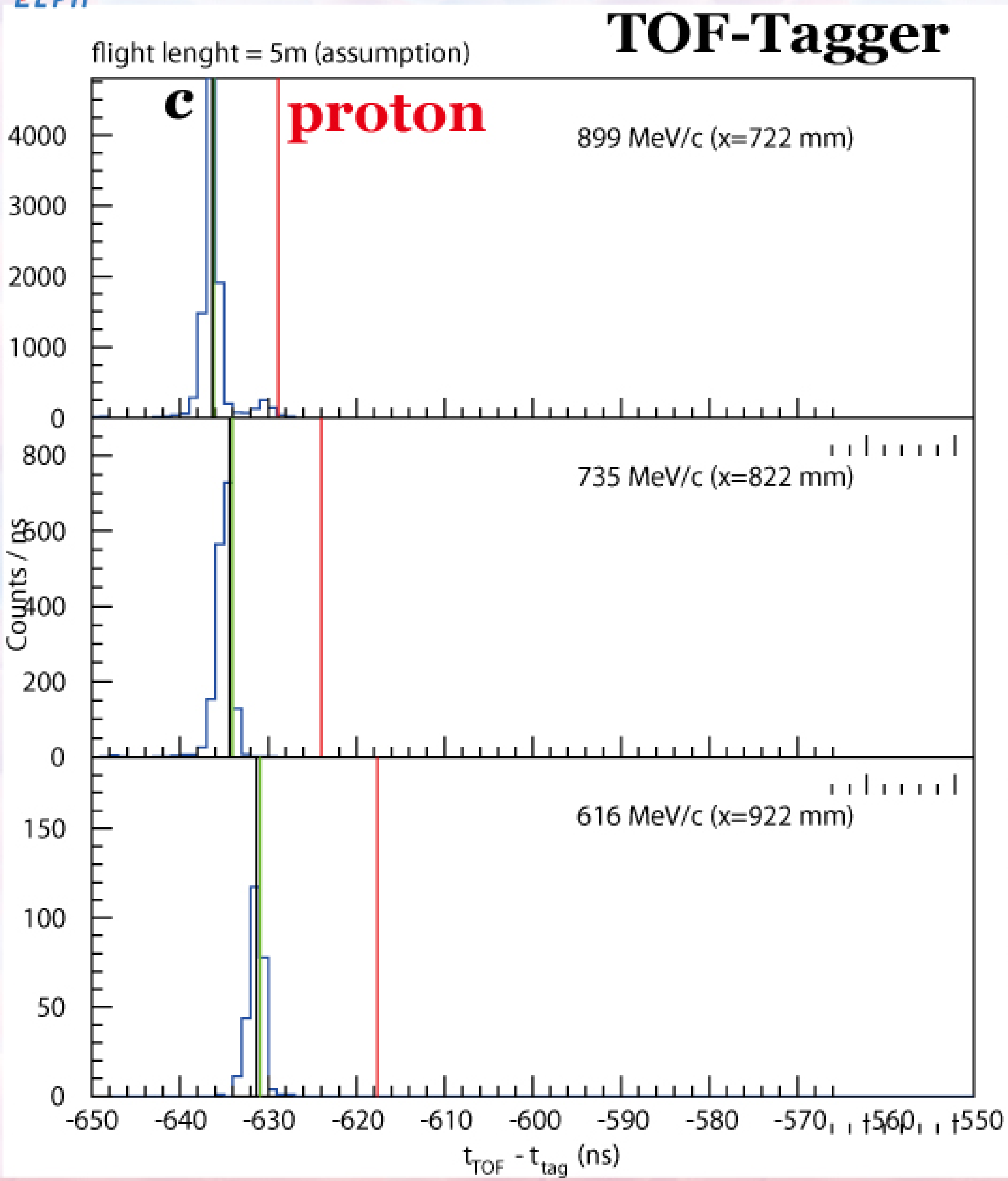



**region of interest**

**The measured energies in response to the positrons are much higher than those for the charged hadrons.**

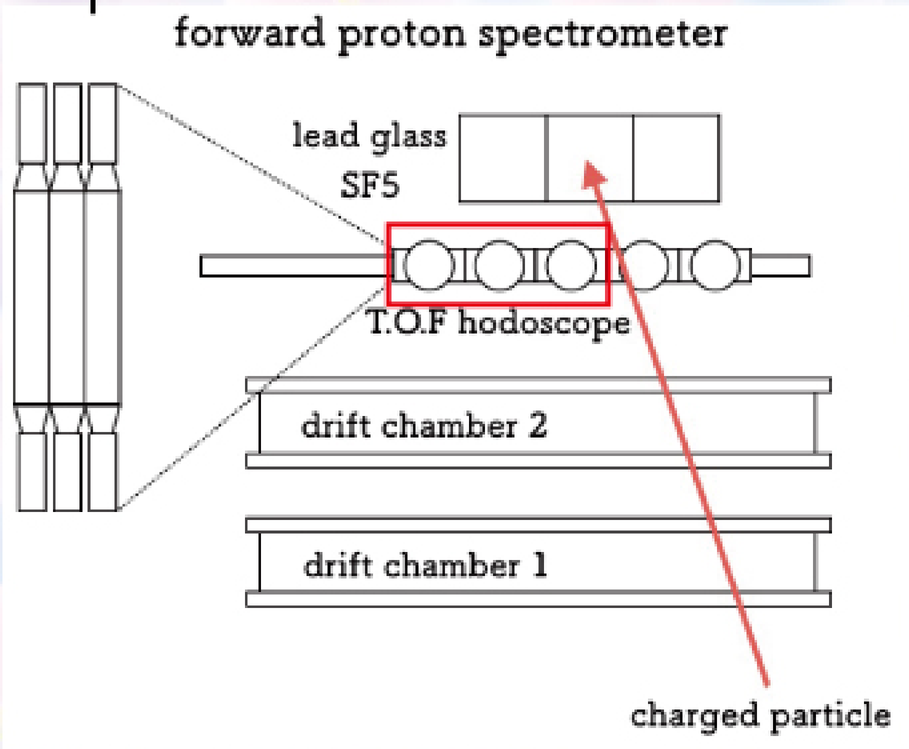
**R. Shirai**

# Commisionning of BLC




## Commissioning (1st)

## 13~16 January 2017




**A thick converter is placed in front of BLC.**

**Almost all the particles are positrons, giving the 0 timing of PS counters.**