Formation of η’(958) bound states by (γ,d) reaction

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Takatsugu Ishikawa (Tohoku Univ.)
Emiko Hiyama (RIKEN)

1. Introduction

Purpose

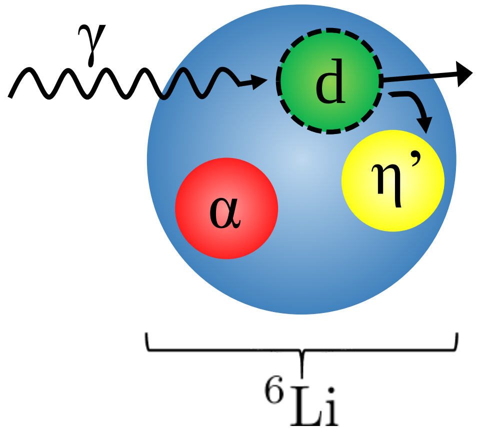
We like to know the possibility of formation of η'(958) mesic nucleus by (γ,d) reaction

ϕ mesic nucleus by (γ,d)

by N. Ikeno et al., Phys. Rev. C 84, 054609(2011)

⇩

η' mesic nucleus by (γ,d)



- In-medium η' properties
  ⇒ Information on $U_A(1)$ anomaly effect
- Possible at photon facilities？
- Formation by (γ,p) and (p,d)

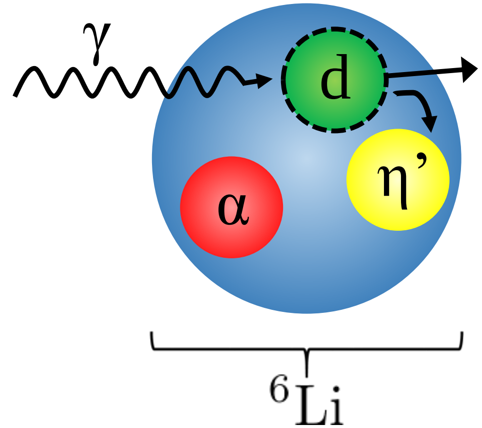
(Hideko Nagahiro, Satoru Hirenzaki, Phys. Rev. Lett. 94 (2005) 232503)
(Kenta Itahashi et al., Prog. Theor. Phys. 128 (2012) 601-613)

Improvements from N. Ikeno et al., Phys. Rev. C 84, 054609 (2011)

- Distortion effect
- Elementary cross section
- Realistic α density distribution
- Recoil effect

2. Two-nucleon pick-up reaction for ^{6}Li target by effective number ($N_{\rm eff}$) approach

^{6}Li has well-developed cluster structure of α+d



- formation cross section

$$\frac{d^2\sigma}{dEd\Omega} = \left(\frac{d\sigma}{d\Omega}\right)^{\rm ele} \sum_f \frac{\Gamma}{2\pi} \frac{1}{\Delta E^2 + \Gamma^2/4} N_{\rm eff}$$

$N_{\rm eff}$: effective number of deuteron

$$N_{\rm eff} = \sum_{JM} \left| \int \chi_d^*(\boldsymbol{r}) \left[\phi_{l_{\eta'}}^*(\boldsymbol{r}) \otimes \psi_{l_d}(\boldsymbol{r}) \right]_{JM} \chi_\gamma(\boldsymbol{r}) d\boldsymbol{r} \right|^2$$

χ_γ , χ_d : incident γ, emitted d wave function

$\phi_{l_{\eta'}}$: α-η’ relative wave function

ψ_{l_d} : α-d relative wave function

$\left(\frac{d\sigma}{d\Omega}\right)^{\rm ele}$: Elementary cross section,

$\Delta E = T_d - E_\gamma + S_d - B_{\eta'} + m_{\eta'}$

Γ : width of η’-meson bound states

2-1. Initial state: α-d relative wave function (2s bound state)

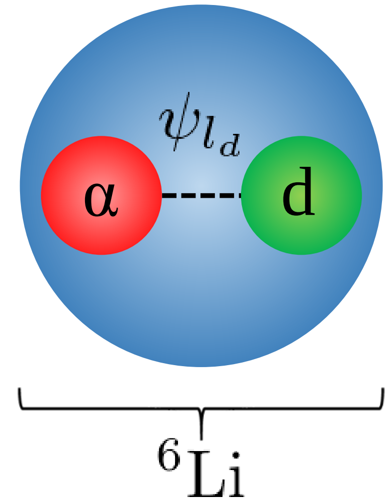
Probability of α+d cluster structure in ^{6}Li is reported to be 73%

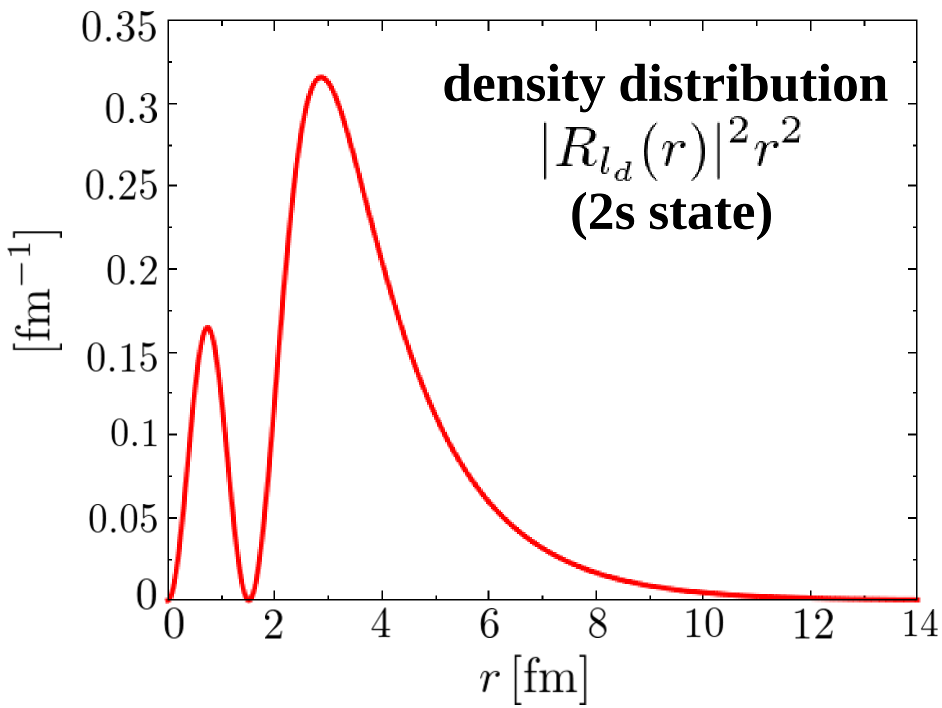
(R. Ent et al., Phys. Rev. Lett. 57, 2367 (1986))

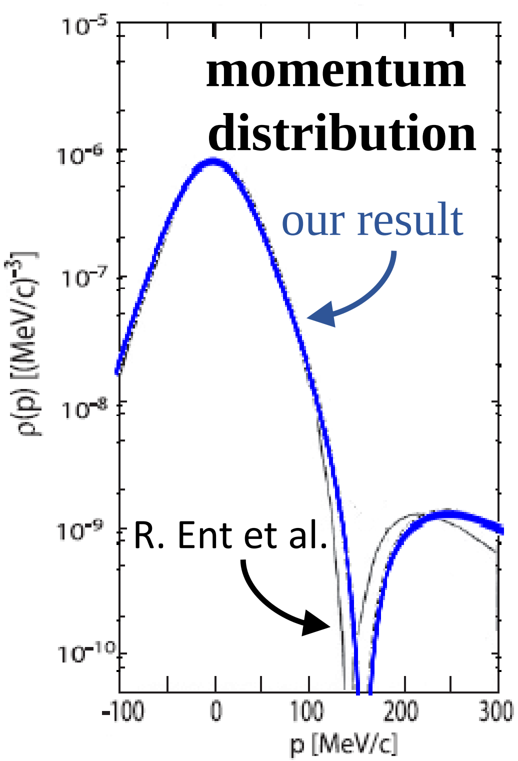
Schrödinger eq.

$$\left[-\frac{1}{2m}\nabla^2 + V(r)\right]\psi_{l_d}(\boldsymbol{r}) = E\psi_{l_d}(\boldsymbol{r})$$

$$V(r) = \frac{V_0}{1+\exp((r-R)/a)}$$: Woods-Saxon-type potential





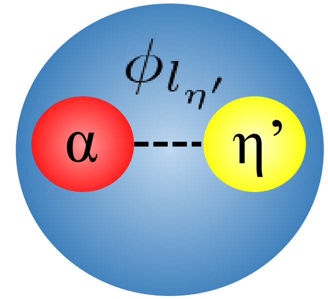


fix two parameters to reproduce $\rho(p)$ in R. Ent et al.

$V_0 = -75$ [MeV]

$R = 2.0$ [fm]

2-2. Final state: α-η’ relative wave function



$$\left[-\nabla^2 + \mu^2 + 2\mu V_{\rm opt}(r)\right] \phi_{l_{\eta'}}(\boldsymbol{r}) = E_{\rm KG}^2 \phi_{l_{\eta'}}(\boldsymbol{r})$$

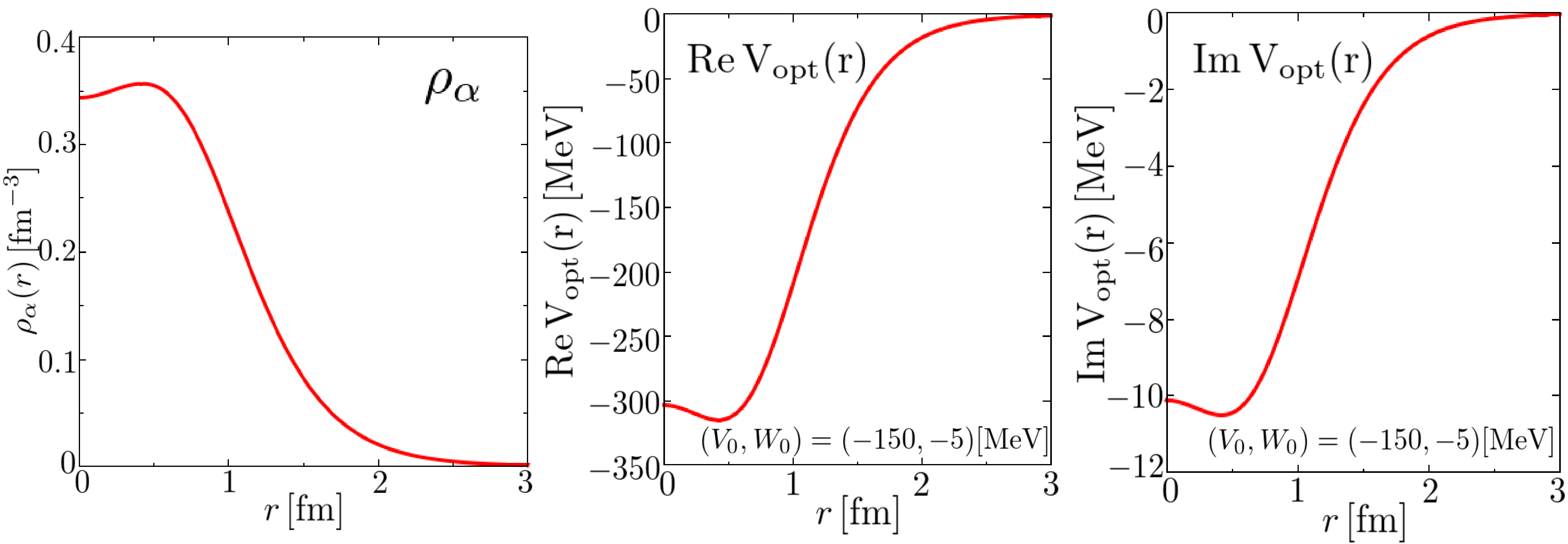
$$V_{\rm opt}(r) = (V_0 + iW_0)\frac{\rho_\alpha(r)}{\rho_0}$$

V_0 = -50, -100, -150, -200 [MeV] , $\rho_0 = 0.17\,[{\rm fm}^{-3}]$

W_0 = -5, -20 [MeV] (H. Nagahiro et al., Phys. Rev. C 87, 045201 (2013))

ρ_α : Realistic α density distribution

Gaussian expansion method by Emiko Hiyama



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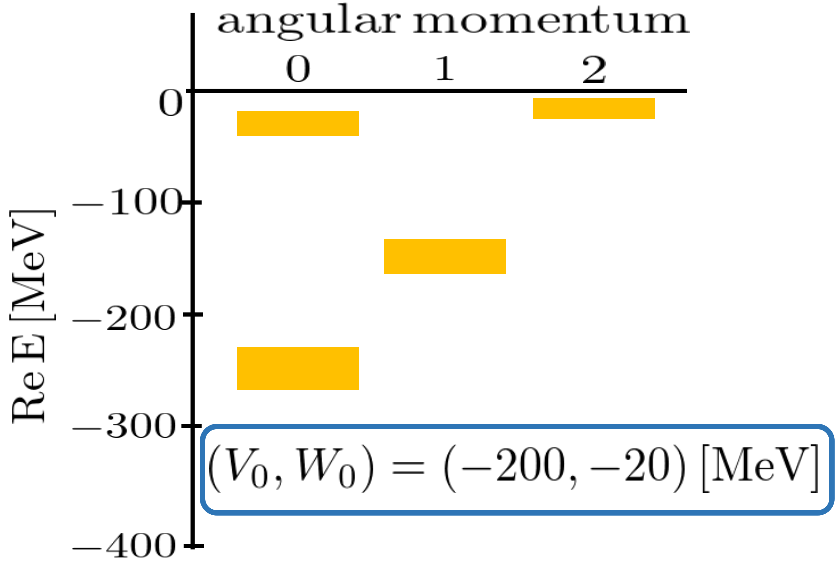

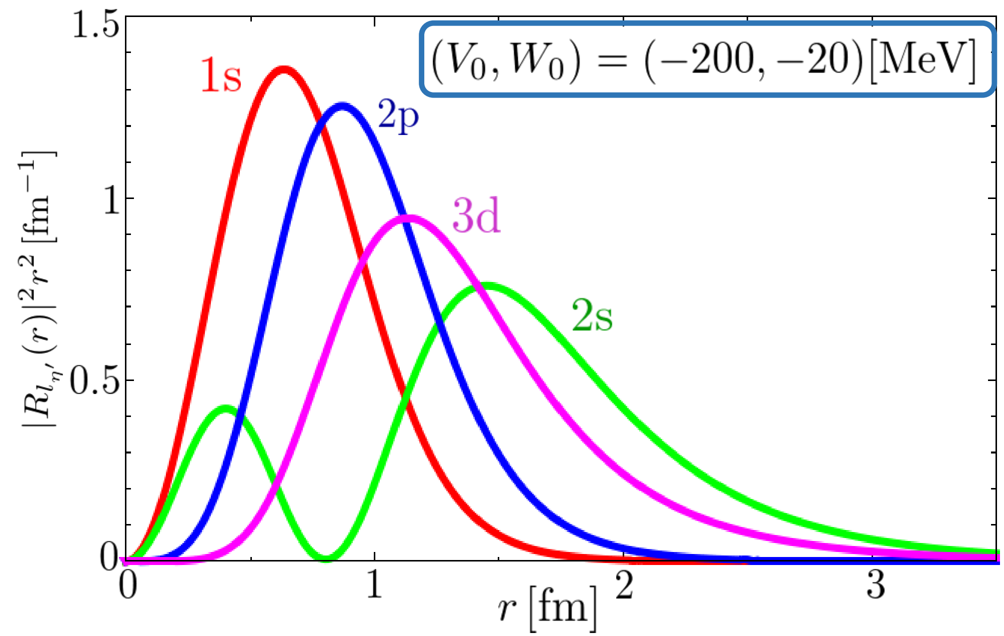

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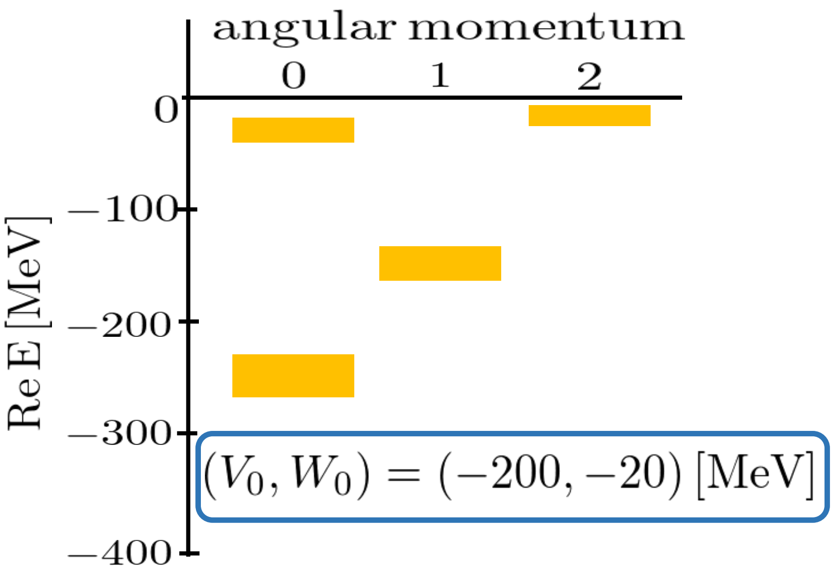
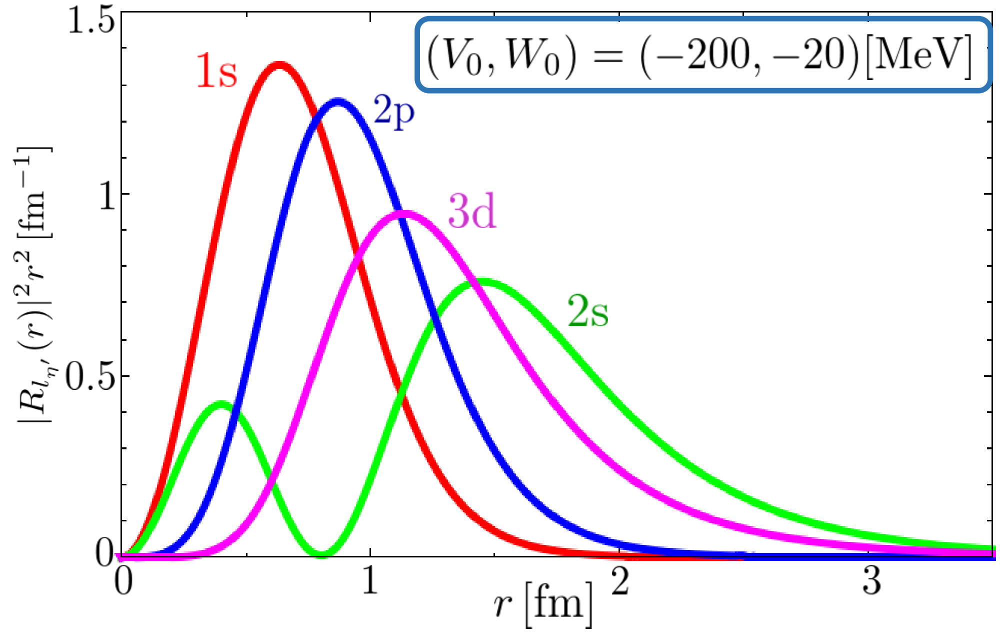
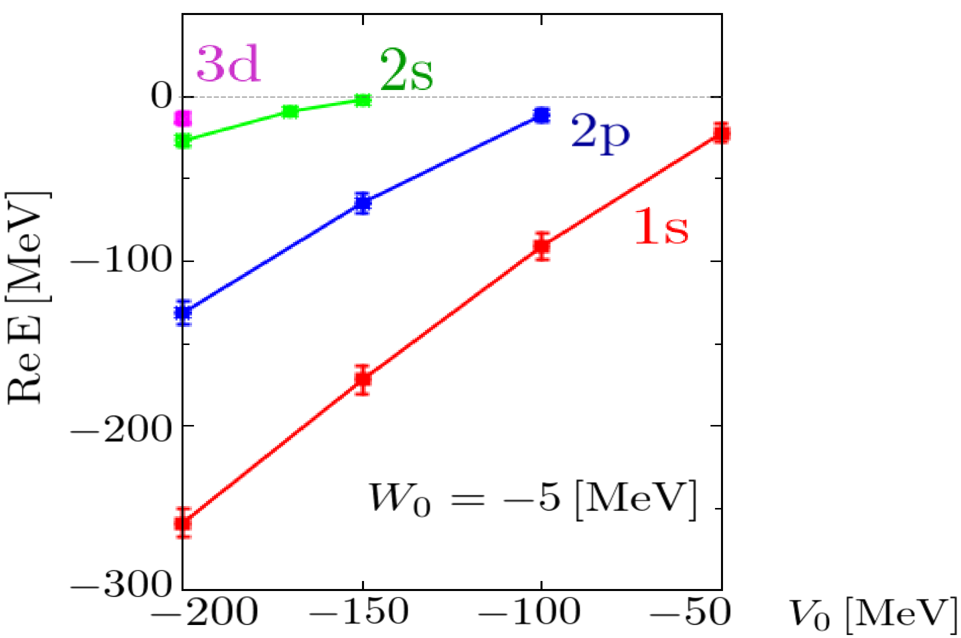
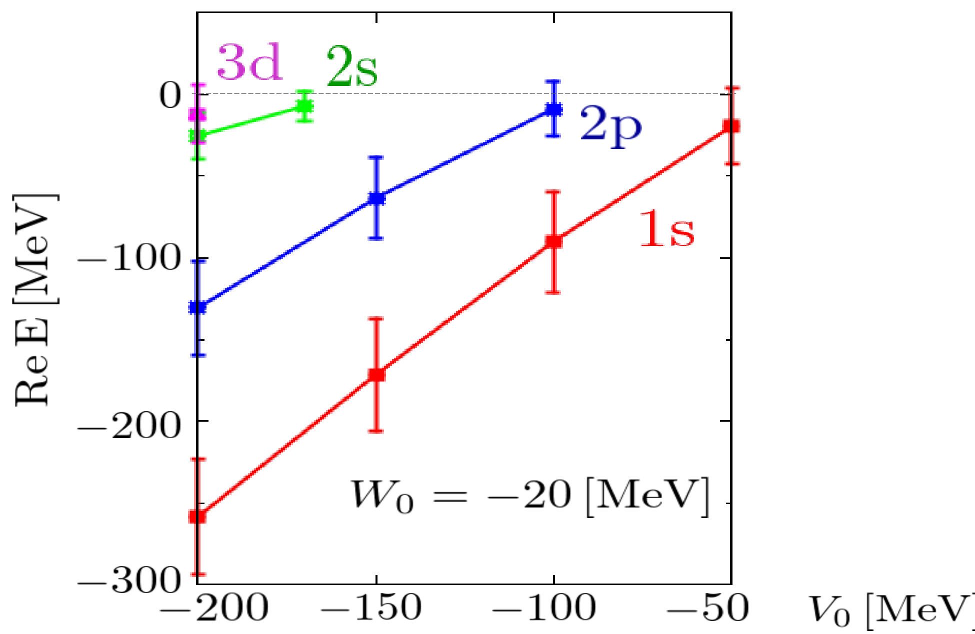








2-3. Scattering waves χ_γ and χ_d

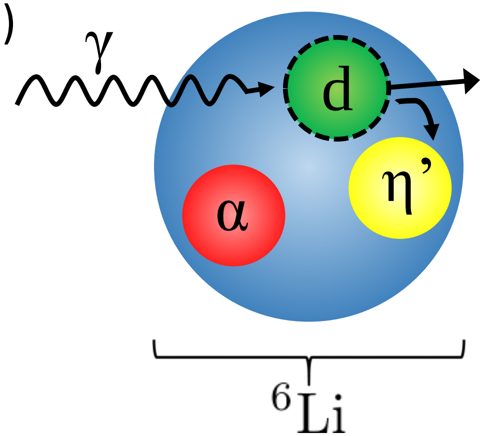
$$N_{\text{eff}} = \sum_{JM} \left| \int \chi_d^*(\boldsymbol{r}) \left[\phi_{l_{\eta'}}^*(\boldsymbol{r}) \otimes \psi_{l_d}(\boldsymbol{r}) \right]_{JM} \chi_\gamma(\boldsymbol{r}) d\boldsymbol{r} \right|^2$$

1. Distortion effect (DWIA)

$$\chi_d^*(\boldsymbol{r})\chi_\gamma(\boldsymbol{r}) = e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \to e^{i\boldsymbol{q}\cdot\boldsymbol{r}} D(\boldsymbol{b}, z)$$

$$D(\boldsymbol{b}, z) = \exp\left[-\frac{\sigma_{\gamma N}}{2} \int_{-\infty}^{z} \rho_{^6\mathrm{Li}}(\boldsymbol{b}, z') dz' - \frac{\sigma_{dN}}{2} \int_{z}^{+\infty} \rho_\alpha(\boldsymbol{b}, z') dz' \right]$$

$$\left[\begin{array}{l} \sigma_{\gamma N} = 0\,[\mathrm{mb}] \\ \sigma_{dN} = 60\,[\mathrm{mb}] \end{array} \right.$$ (taken from σ_{pd} in PDG (2012))



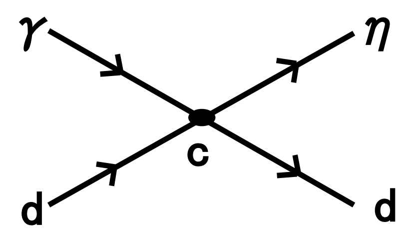
2. Recoil effect

$$\vec{r} \to \boxed{\frac{M_\alpha}{m_{\eta'} + M_\alpha}} \vec{r}$$

correction factor

(the same prescription as in T. Koike, T. Harada, Nucl. Phys. A 804 (2008) 231-273)

2-4. Elementary cross section



$$\left(\frac{d\sigma}{d\Omega}\right)^{\rm ele}_{\rm CM} = \frac{1}{2}\frac{|c|^2}{4\pi}\frac{M_d^2}{\lambda^{\frac{1}{2}}(s, M_d^2, 0)}\frac{1}{p_\gamma}\frac{1}{E_{d'}+\omega_{\eta'}}|F_d(\boldsymbol{q})|^2$$

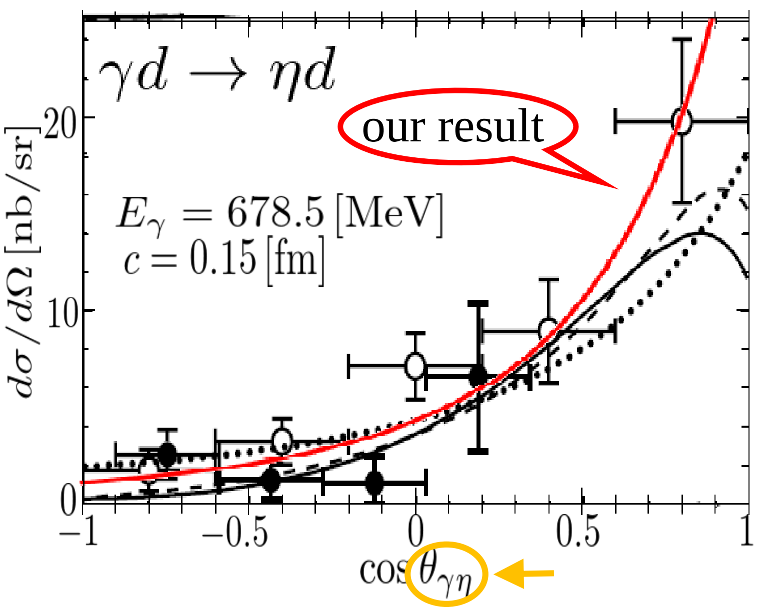
$F_d(\boldsymbol{q}) = \int \psi_d^*(\boldsymbol{r}) e^{i\boldsymbol{q}\cdot\frac{\boldsymbol{r}}{2}} \psi_d(\boldsymbol{r}) d\boldsymbol{r}$: Form factor

$\psi_d(\boldsymbol{r})$: proton-neutron relative wave function in deuteron by Bonn potential

(R. Machleidt et al., Phys. Rep. 149, No.1 (1987) 1-89)

$\boldsymbol{q}$: momentum transfer in deuteron rest frame

angular distribution of η(548) in CM



(J. Weiß et al., Eur. Phys. J. A 11, 371-374 (2001))

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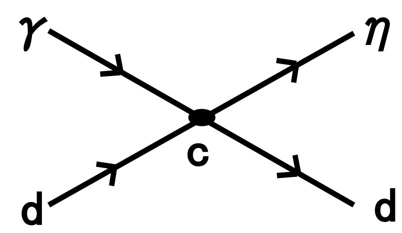

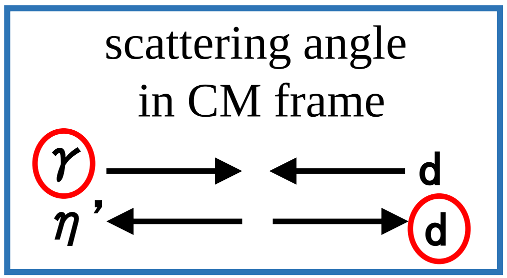

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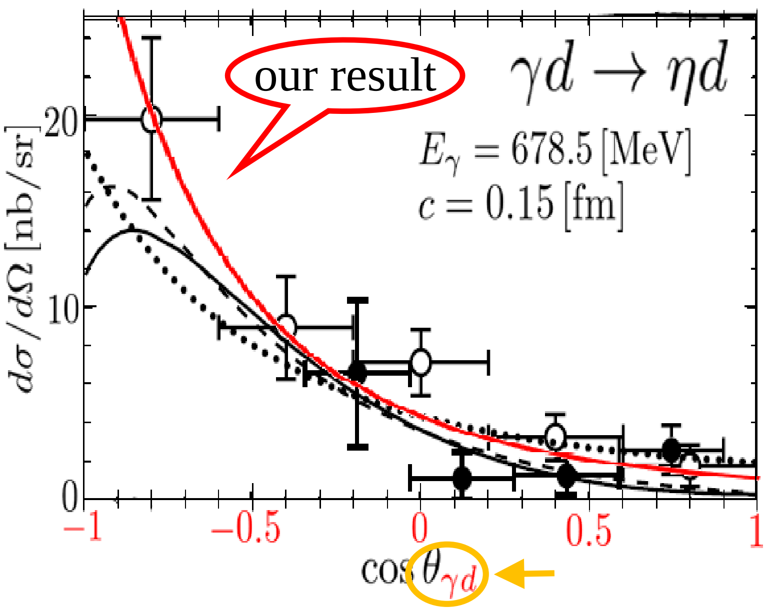

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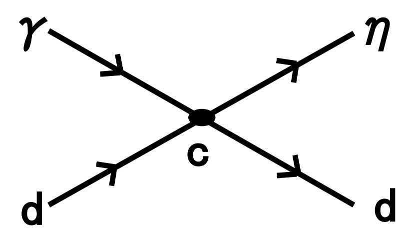

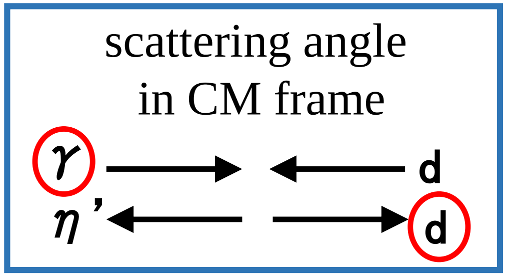

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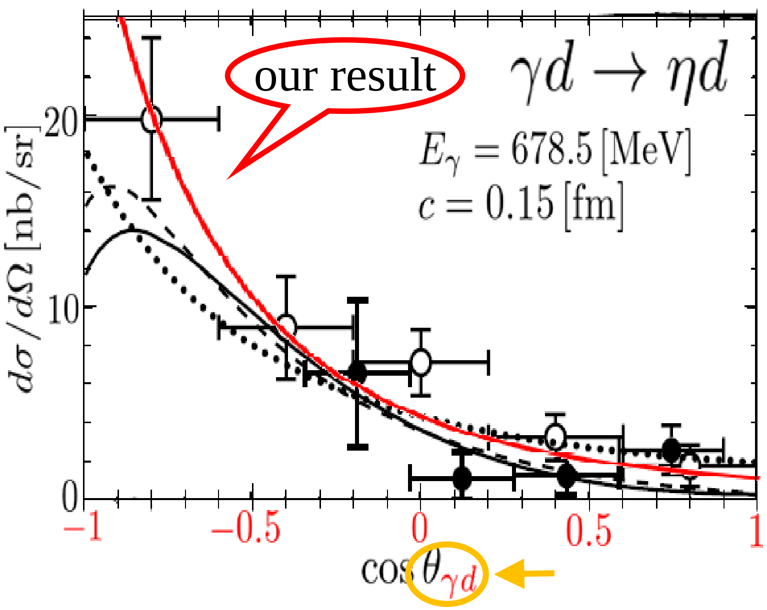
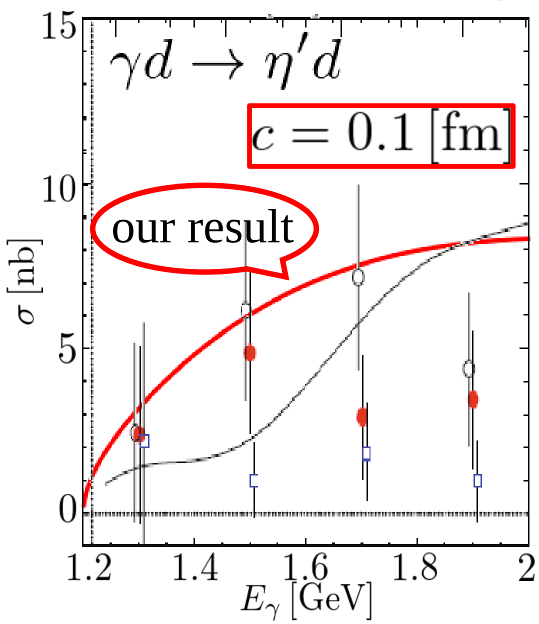


total cross section of η'



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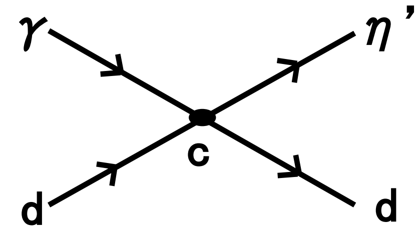

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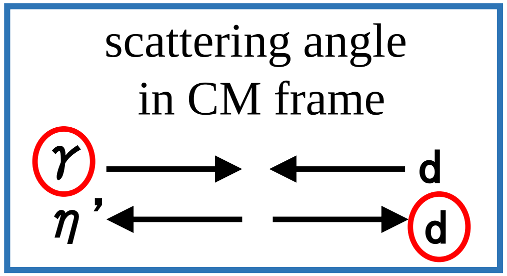

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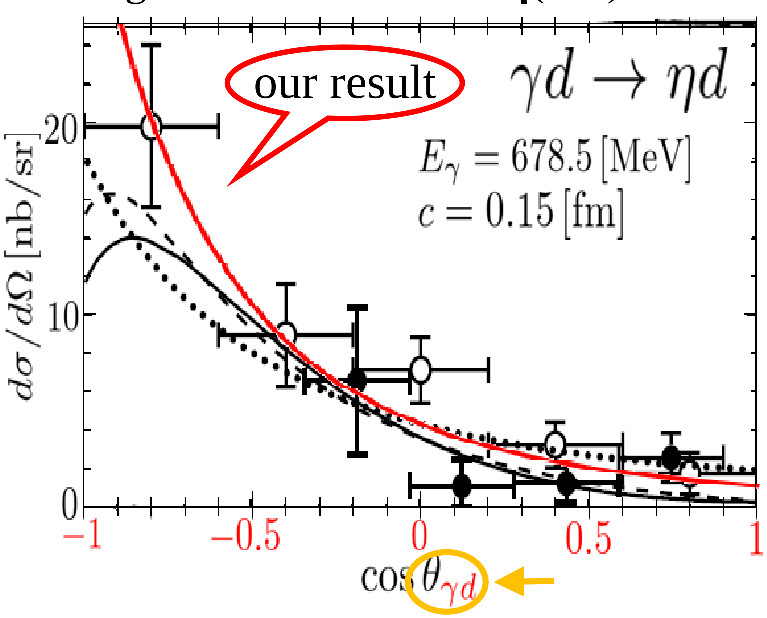

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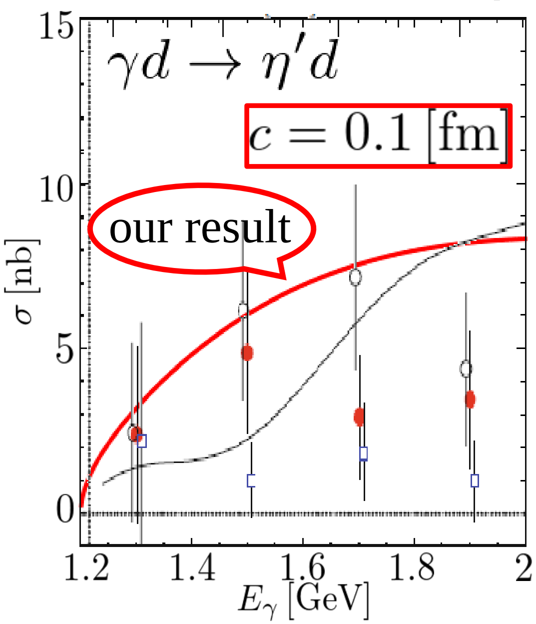
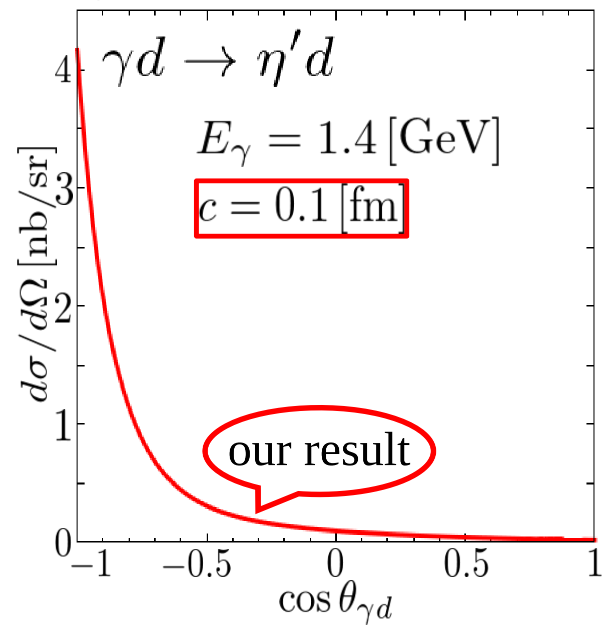


angular distribution of η' in CM



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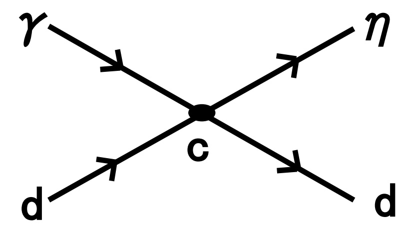

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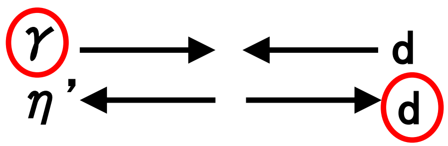
scattering angle
in CM frame



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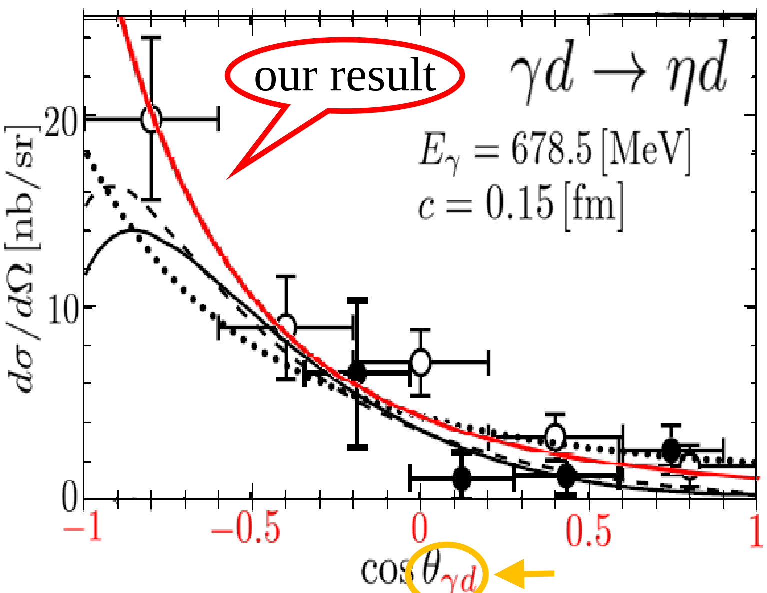
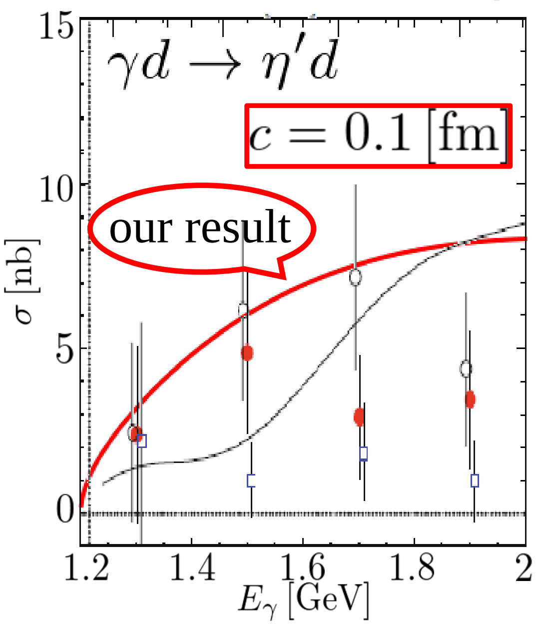
angular distribution of η(548) in CM



total cross section of η'



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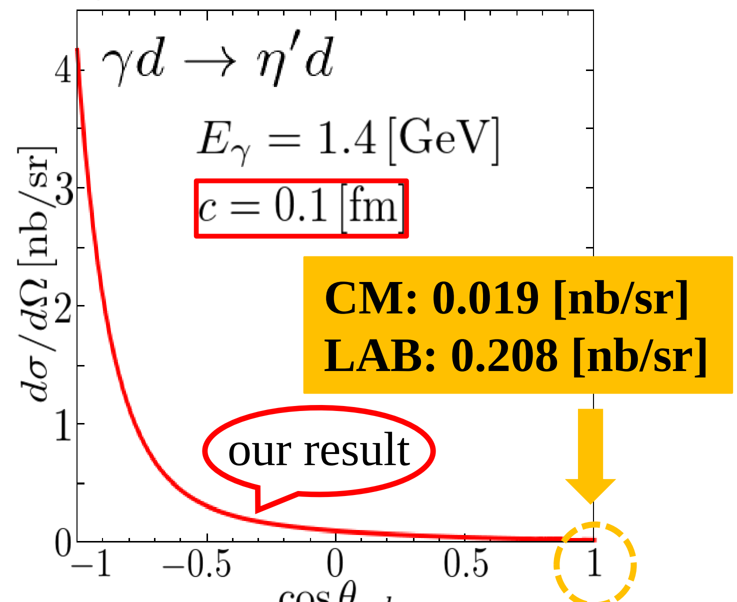

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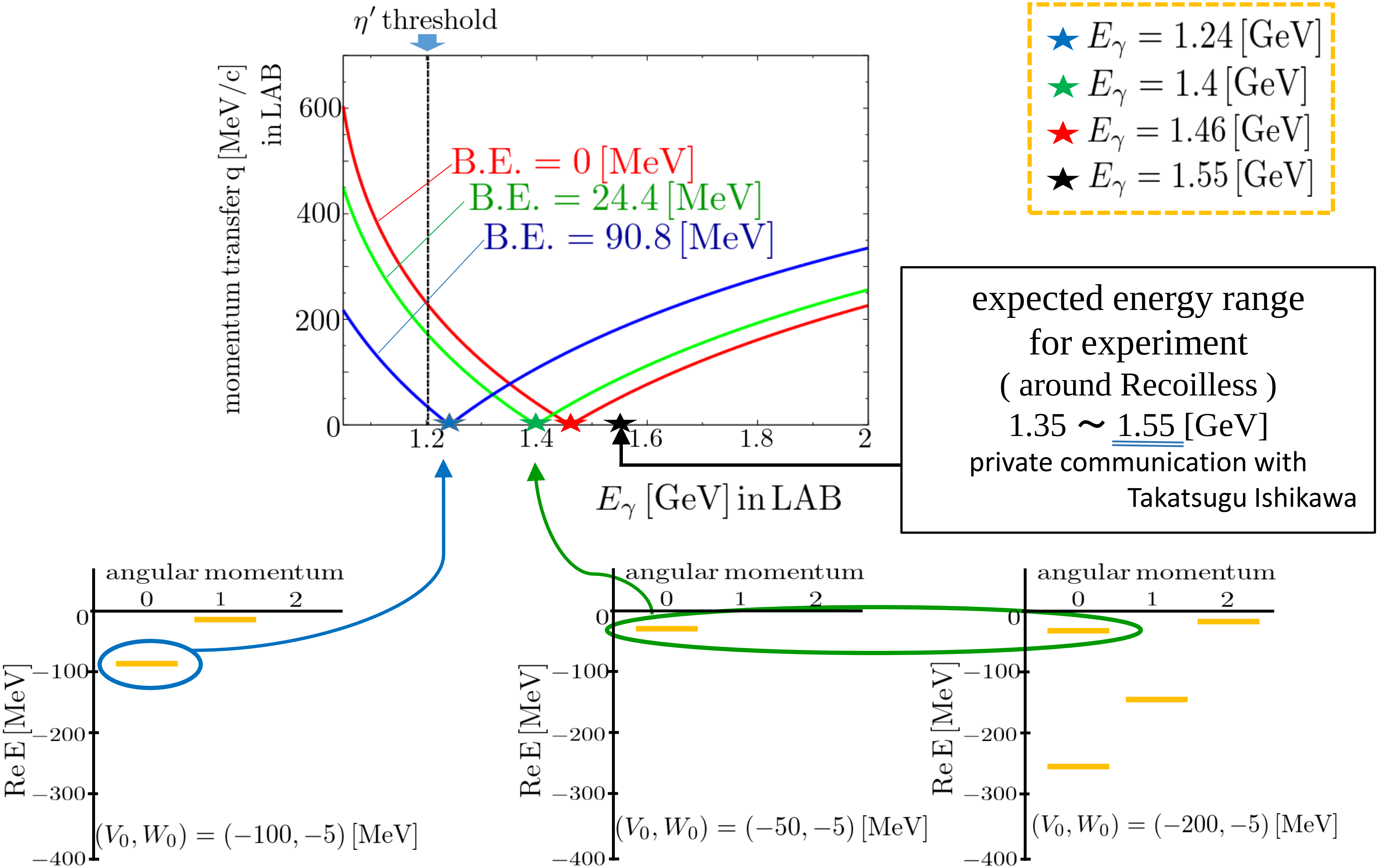
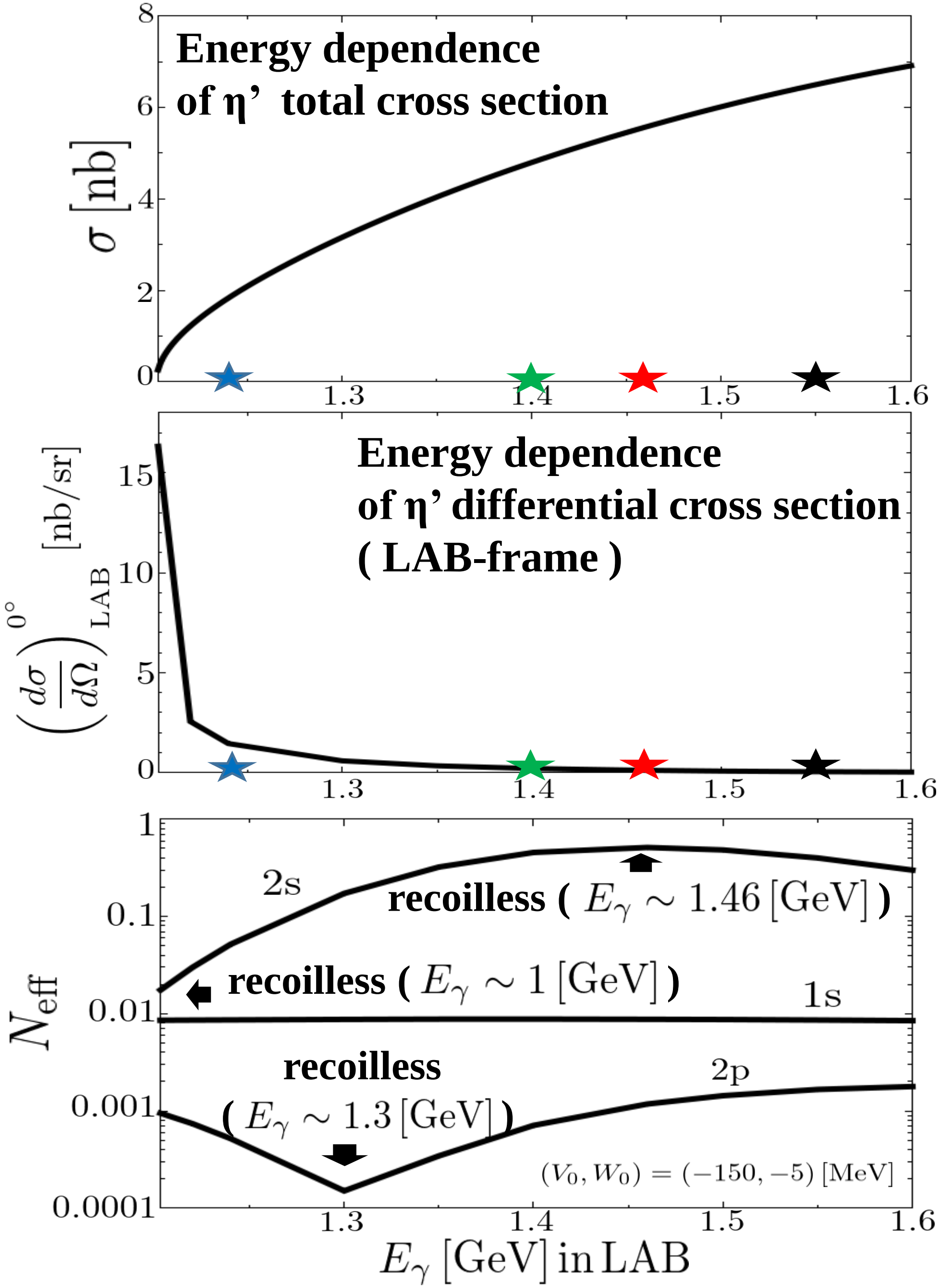
3. Result of η’ mesic nucleus formation reaction
3-1. Incident γ energy and momentum transfer

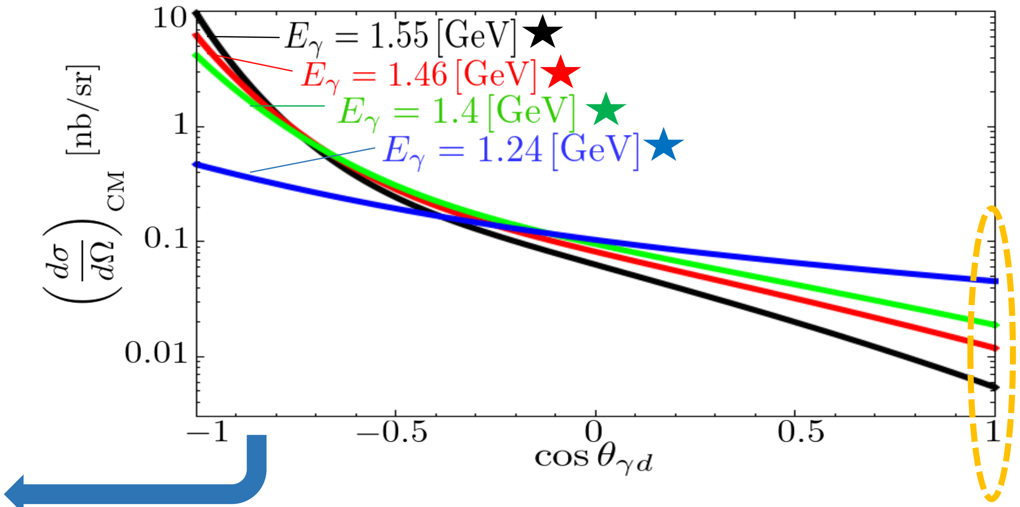


3-2. Incident γ energy dependence



Formation cross section

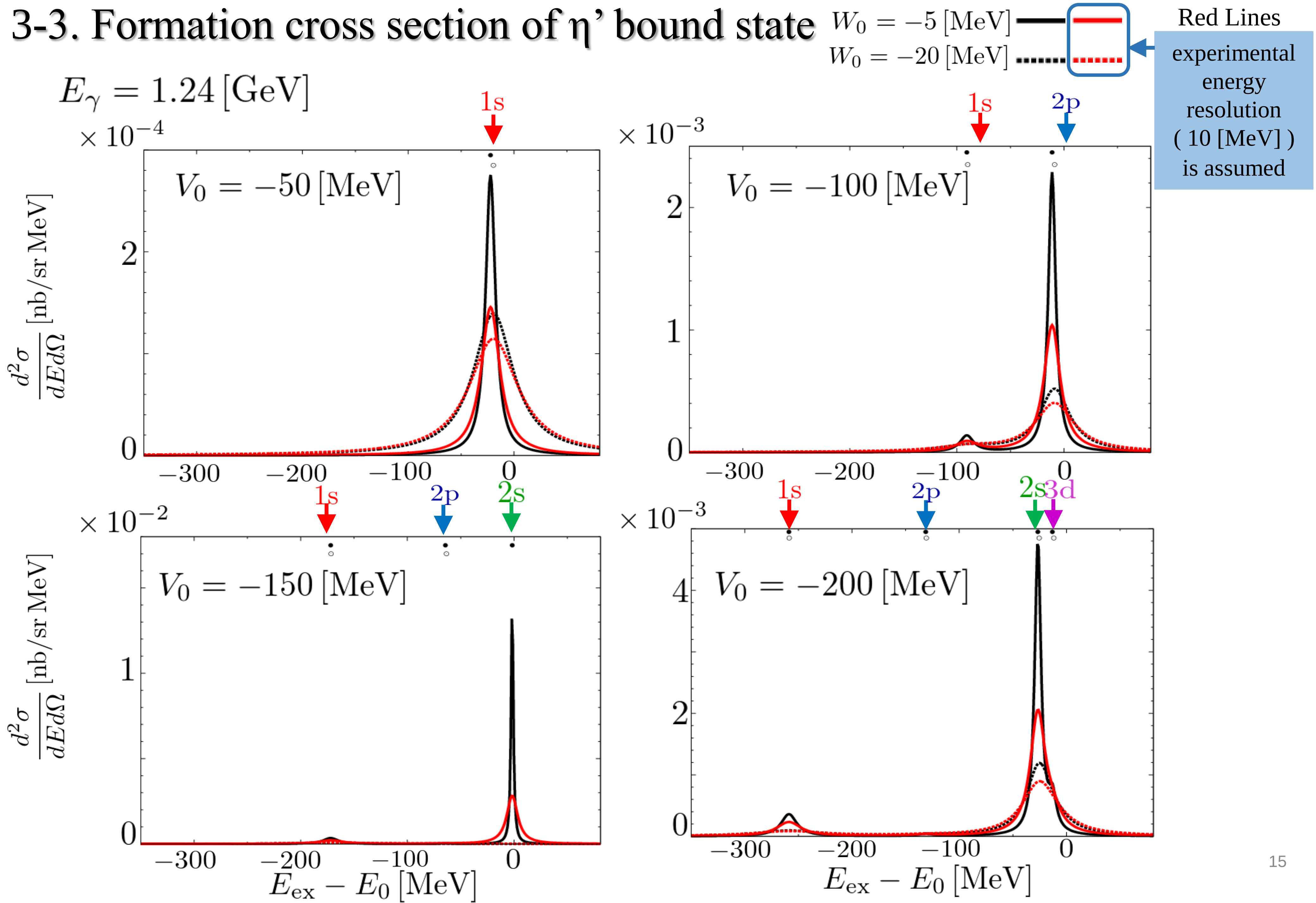
$$\frac{d^2\sigma}{dEd\Omega} = \left(\frac{d\sigma}{d\Omega}\right)^{\rm ele} \sum_f \frac{\Gamma}{2\pi} \frac{1}{\Delta E^2 + \Gamma^2/4} N_{\rm eff}$$



E_γ → larger

- ✓ η' total cross section (σ) increases
- ✓ elementary cross section $\left(\frac{d\sigma}{d\Omega}\right)$
  → decreases at $\theta_{\gamma d} = 0^\circ$
- ✓ $N_{\rm eff}$ vary
  according to the matching condition

3-3. Formation cross section of η' bound state



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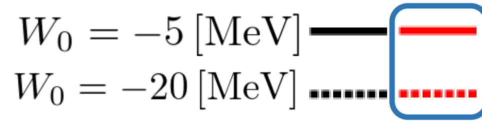
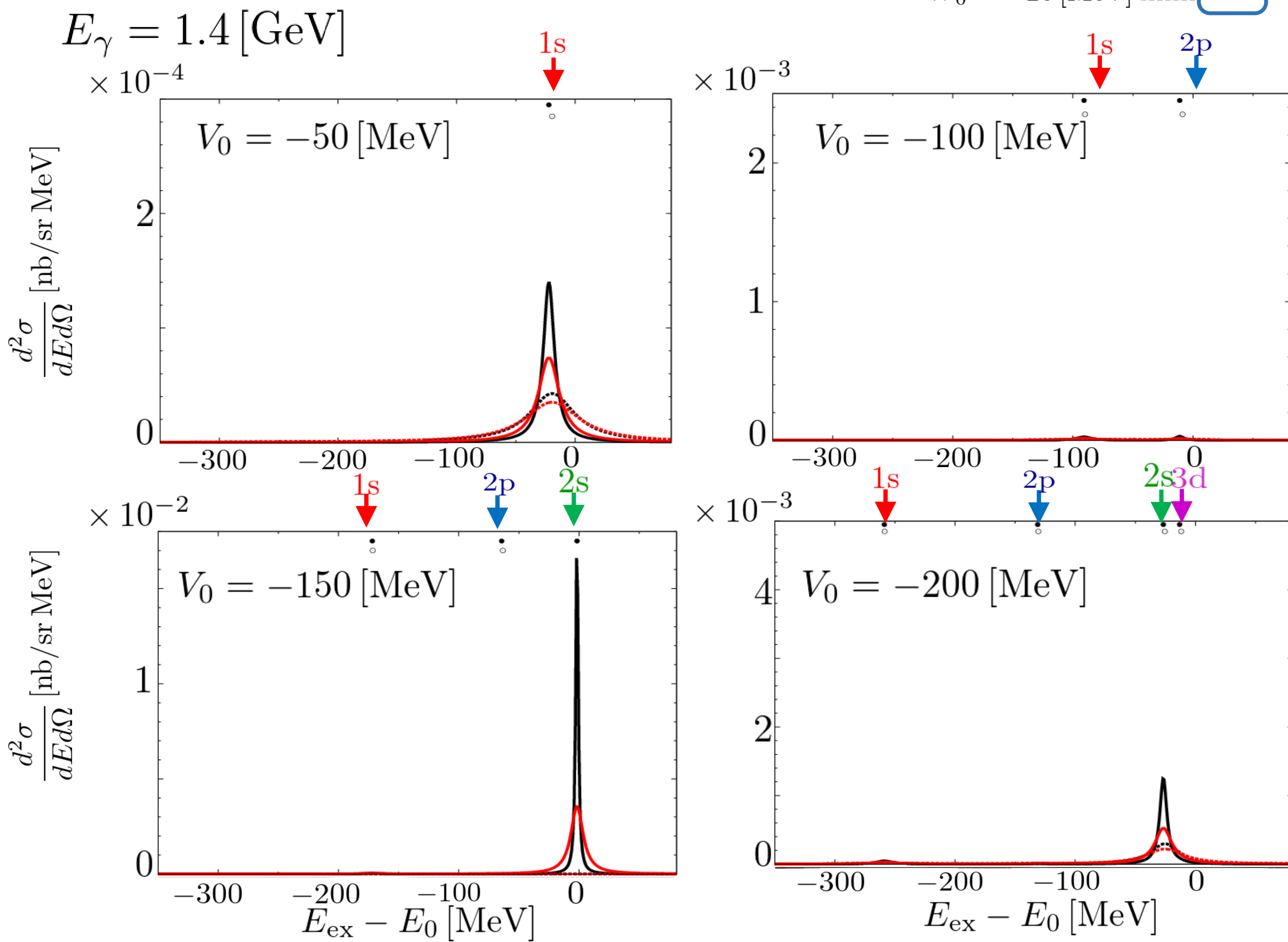


Red Lines

experimental energy resolution (10 [MeV]) is assumed



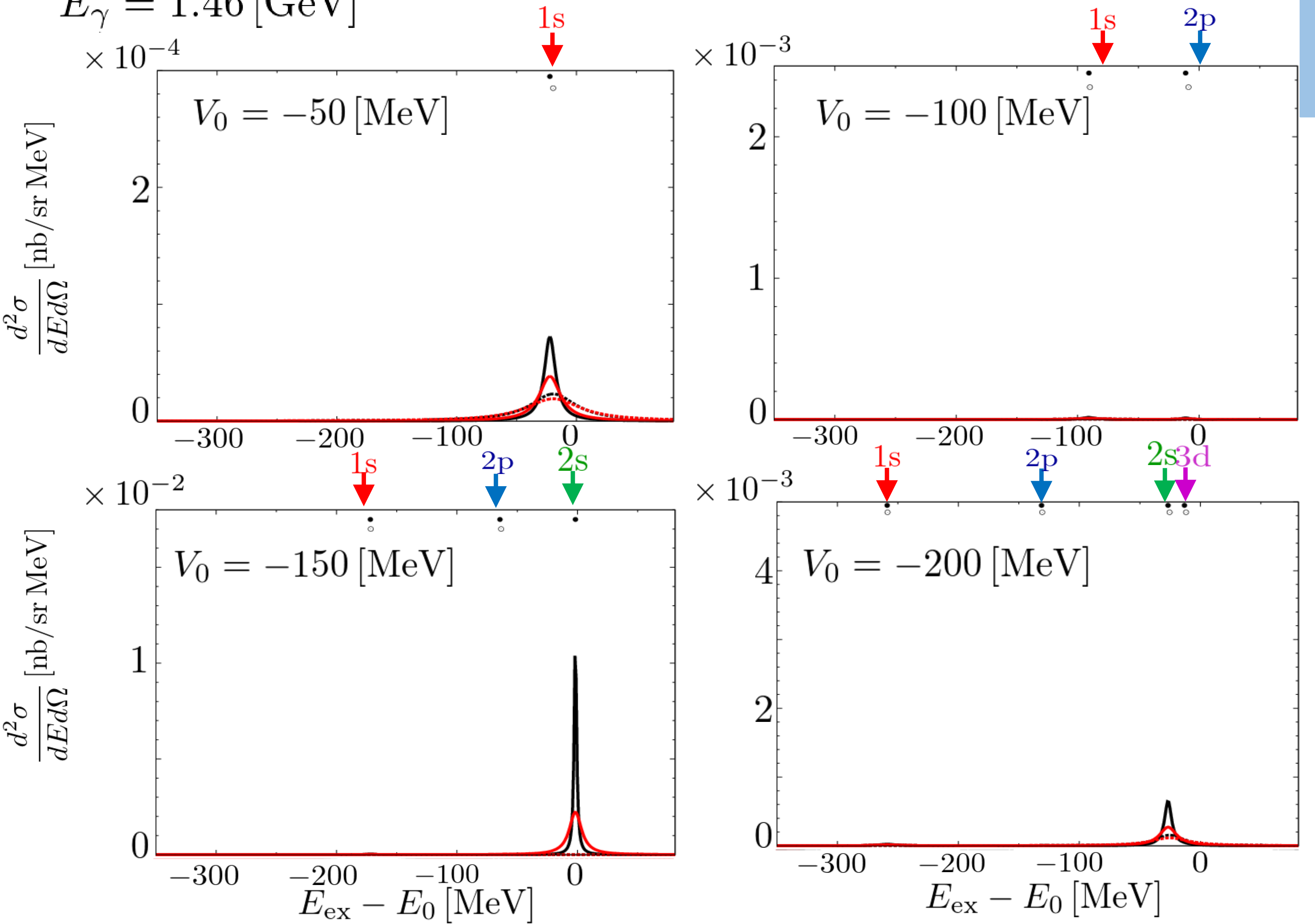
3-3. Formation cross section of η' bound state

$W_0 = -5$ [MeV]
$W_0 = -20$ [MeV]

Red Lines

experimental energy resolution (10 [MeV]) is assumed

$E_\gamma = 1.46$ [GeV]



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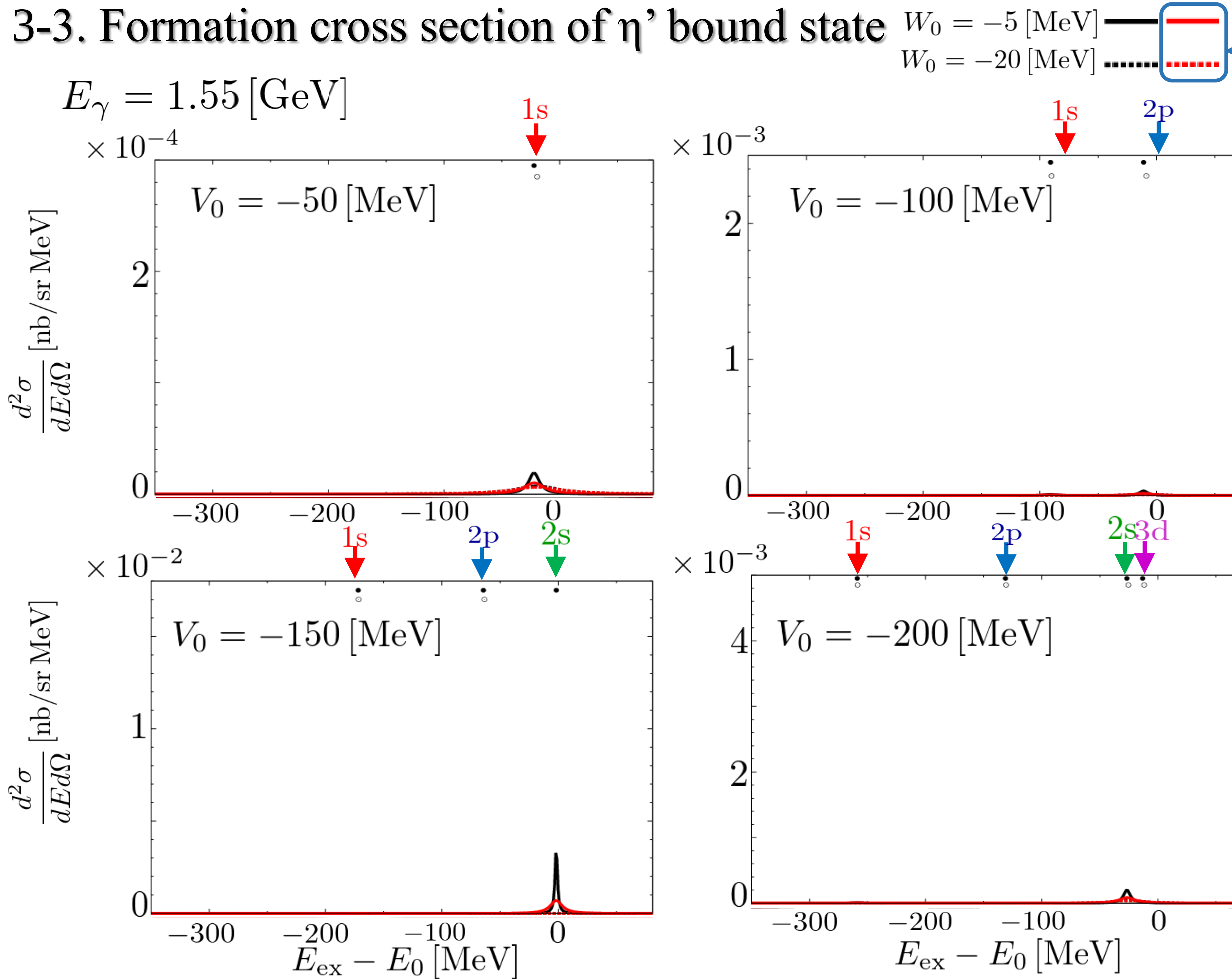

Red Lines

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4. Summary

Purpose of this work

To know the possibility of formation of η'(958) mesic nucleus by (γ,d) reaction

Formalism

- Effective number approach
- Improvements from N. Ikeno et al., Phys. Rev. C 84, 054609 (2011) ' Formation of ϕ mesic nucleus '
  - Distortion effect
  - Elementary cross section
  - Realistic α density distribution
  - Recoil effect

Numerical results

- Formation of the η' mesic nucleus in recoilless kinematics is possible
- Formation cross section
  - Peak height is smaller than $0.01\,[\mathrm{nb/sr\,MeV}]$ for almost all cases
  - Larger cross sections at $E_\gamma = 1.24\,[\mathrm{GeV}]$ than other energies considered here
  - The bound η' states form well-separated peak structures in the spectra

Discussions

- **Effects of the deuteron form factor**

  Large effects for the formation cross section of η' mesic nucleus

  $\Rightarrow$ For larger E_γ , $\left(\frac{d\sigma}{d\Omega}\right)^{\text{ele}}$ decreases at $\theta_{\gamma d} = 0^\circ$

  $\Rightarrow$ Experiments with photon energy

  around η' production threshold ($E_\gamma \sim 1.2\,[\text{GeV}]$) could be better

- Incident photon energy

  - for larger elementary cross section
  - for recoilless kinematics ($E_\gamma \sim 1.46\,[\text{GeV}]$)

  are different !!

  $\Rightarrow$ We need to consider optimum incident γ energy

Future plan

- Discussion for the feasibility of the experiments with experimentalists

  (Ishikawa, Fujioka, …)
- Systematic theoretical calculations
- Optimum condition determination
- …..