原子核媒質中のハドロン研究Ⅲ @J-PARC
2015年10月19-20日

(γ,d)反応による η'(958)中間子–原子核束縛状態の生成

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Acknowledgements: 藤岡宏之氏（京都大学），石川貴嗣氏（東北大学）
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1. Introduction

Purpose

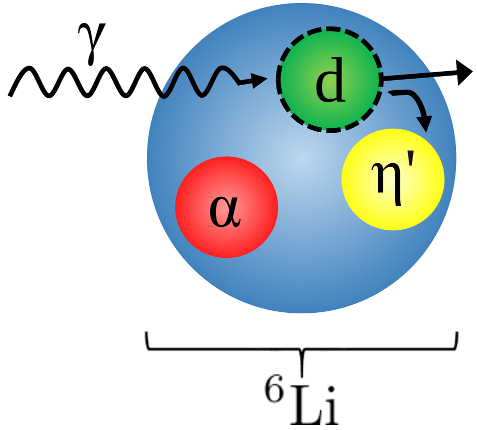
We like to know the possibility of formation of η'(958) mesic nucleus by (γ,d) reaction

ϕ mesic nucleus by (γ,d)

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

⇩

<u>η' mesic nucleus</u> 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)

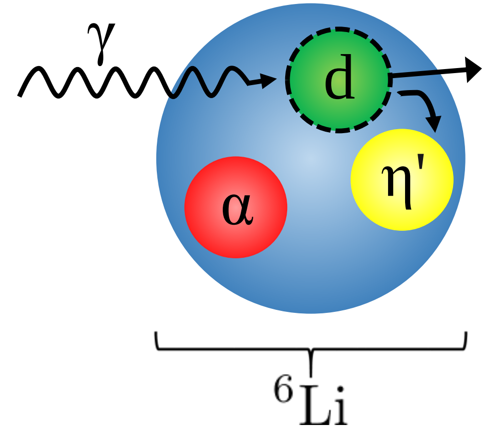
(Hideko Nagahiro, Satoru Hirenzaki, Phys. Rev. Lett. 94 (2005) 232503)
(Kenta Itahashi et al., Prog. Theor. Phys. 128 (2012) 601-613)

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 $^6\mathrm{Li}$ target by effective number (N_{eff}) approach

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



- formation cross section

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

N_{eff} : effective number of deuteron

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

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

$\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{ele}}$: 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)

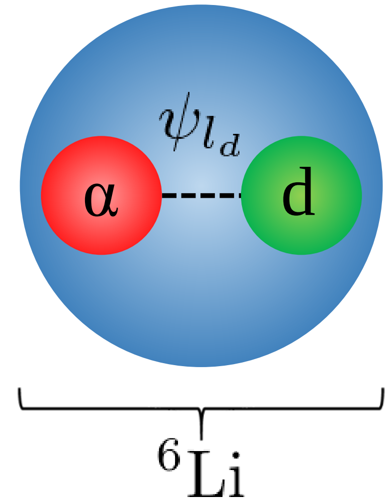
Probability of α+d cluster structure in ^{6}Li is reported to be 73%

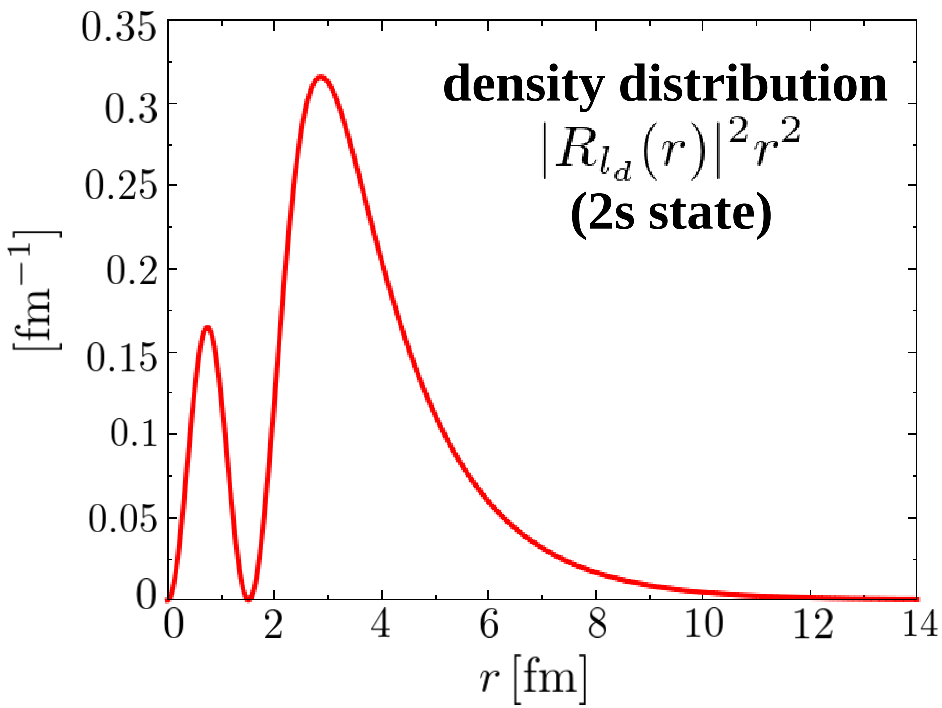
(R. Ent et al., Phys. Rev. Lett. 57, 2367 (1986))

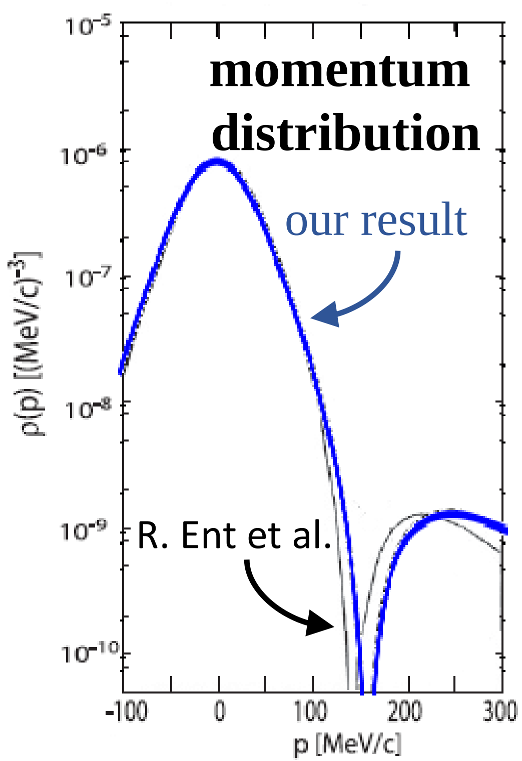
Schrödinger eq.

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

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





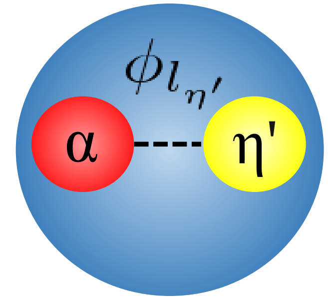


fix two parameters to reproduce $\rho(p)$ in R. Ent et al.

$$V_0 = -75\,[\mathrm{MeV}]$$

$$R = 2.0\,[\mathrm{fm}]$$

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



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

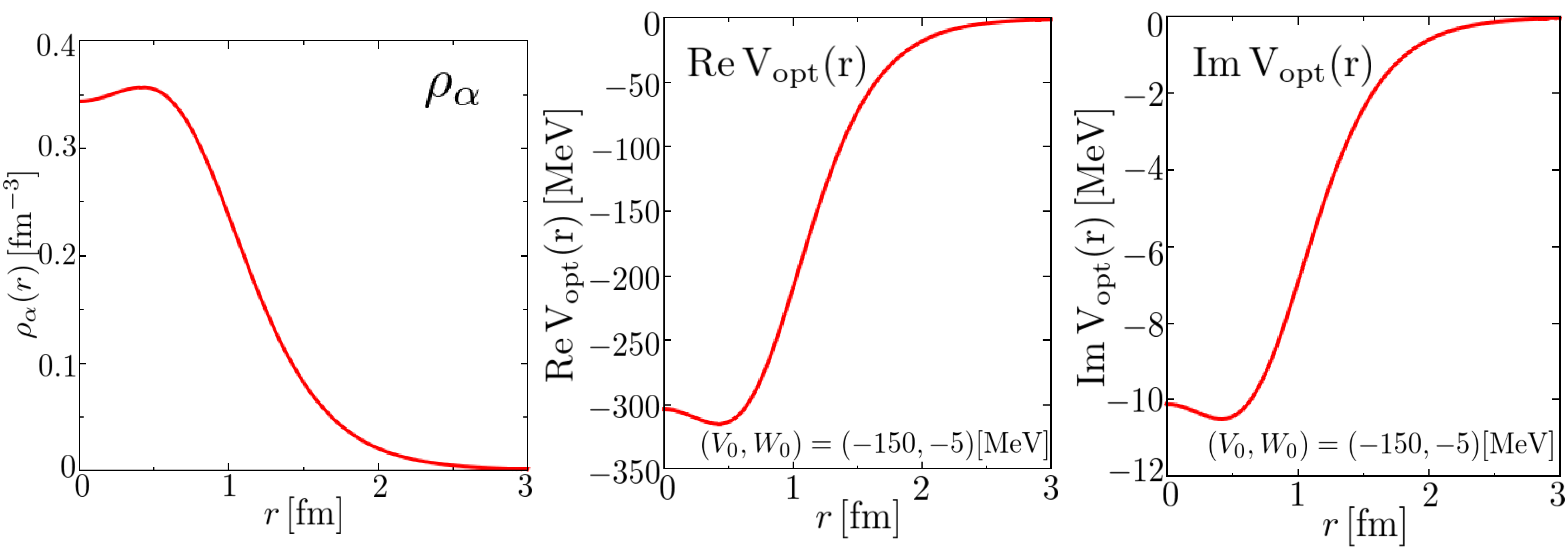
$$V_{\rm opt}(r) = (V_0 + iW_0)\frac{\rho_\alpha(r)}{\rho_0}$$

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

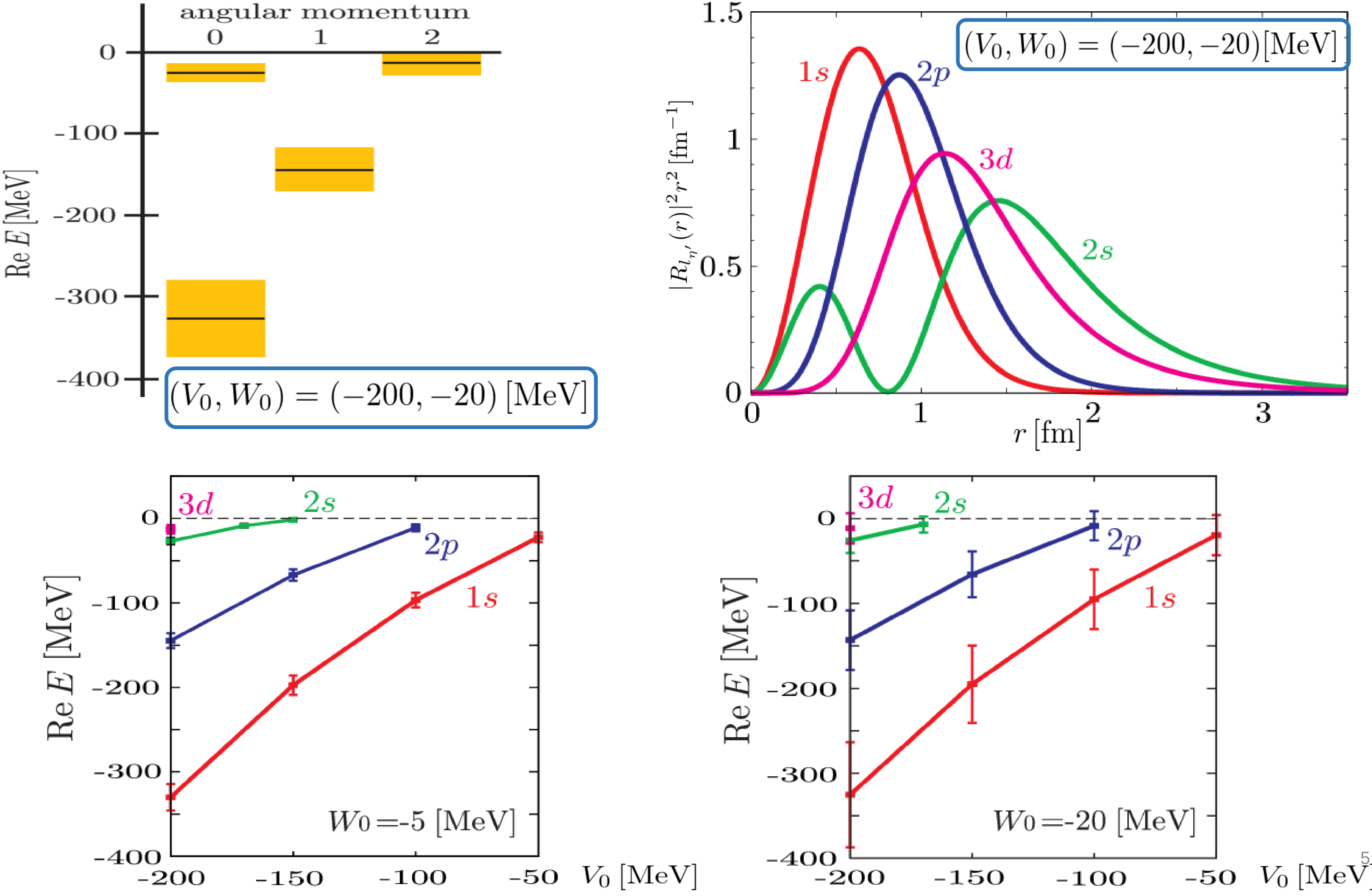
W_0 = -5, -20 [MeV] (H. Nagahiro et al., Phys. Rev. C 87, 045201 (2013))

ρ_α : Realistic α density distribution

Gaussian expansion method by Emiko Hiyama



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



2-3. Scattering waves χ_γ and χ_d

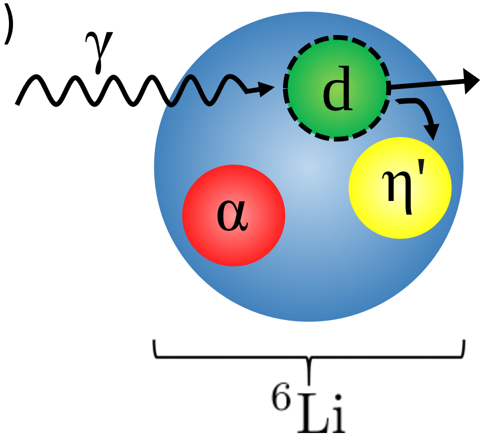
$$N_{\rm eff} = \sum_{JM} \left| \int \underline{\chi_d^*(\boldsymbol{r})} \left[\phi_{l_{\eta'}}^*(\boldsymbol{r}) \otimes \psi_{l_d}(\boldsymbol{r}) \right]_{JM} \underline{\chi_\gamma(\boldsymbol{r})} d\boldsymbol{r} \right|^2$$

1. Distortion effect (DWIA)

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

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

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



2. Recoil effect

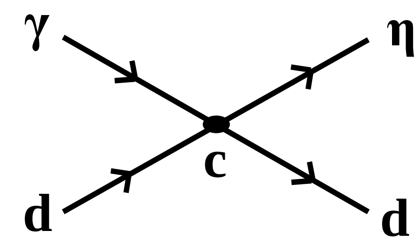
$$\vec{r} \to \boxed{\frac{M_\alpha}{m_{\eta'} + M_\alpha}} \vec{r}$$

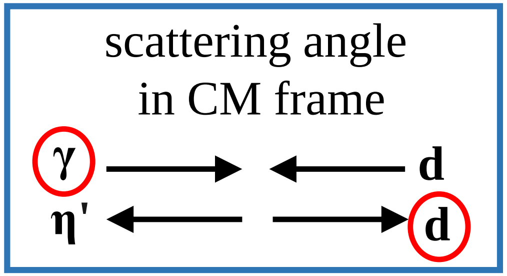
correction factor

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

2-4. Elementary cross section

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





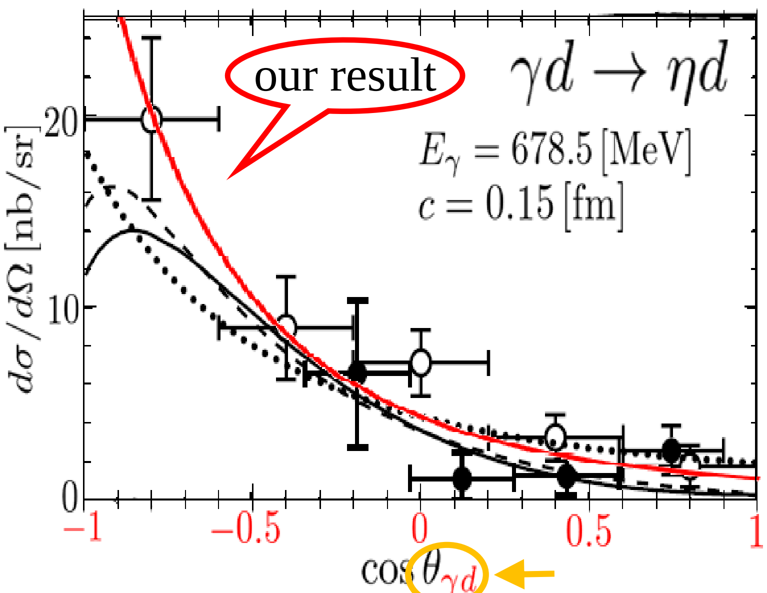
$$F_d(\boldsymbol{q}) = \int \psi_d^*(\boldsymbol{r}) e^{i\boldsymbol{q}\cdot\frac{\boldsymbol{r}}{2}} \psi_d(\boldsymbol{r}) d\boldsymbol{r}$$: Form factor

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

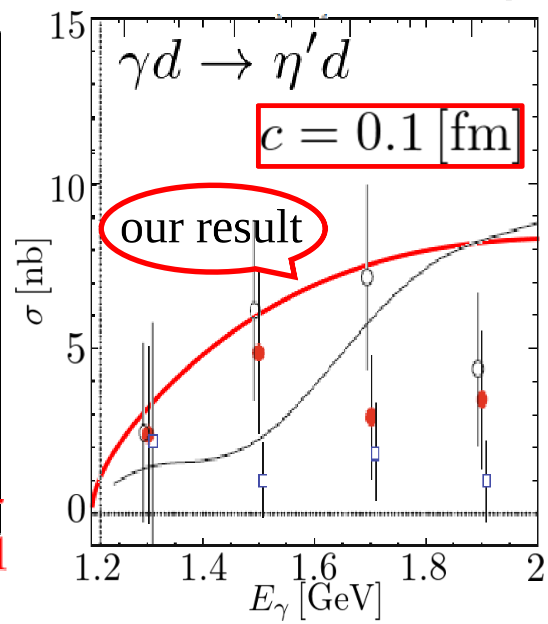
(R. Machleidt et al., Phys. Rep. 149, No.1 (1987) 1-89)

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

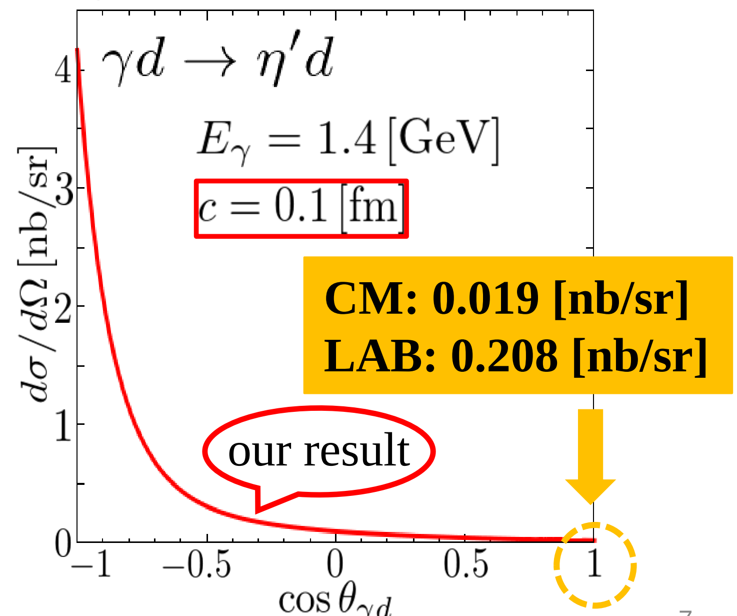
angular distribution of η(548) in CM



total cross section of η'



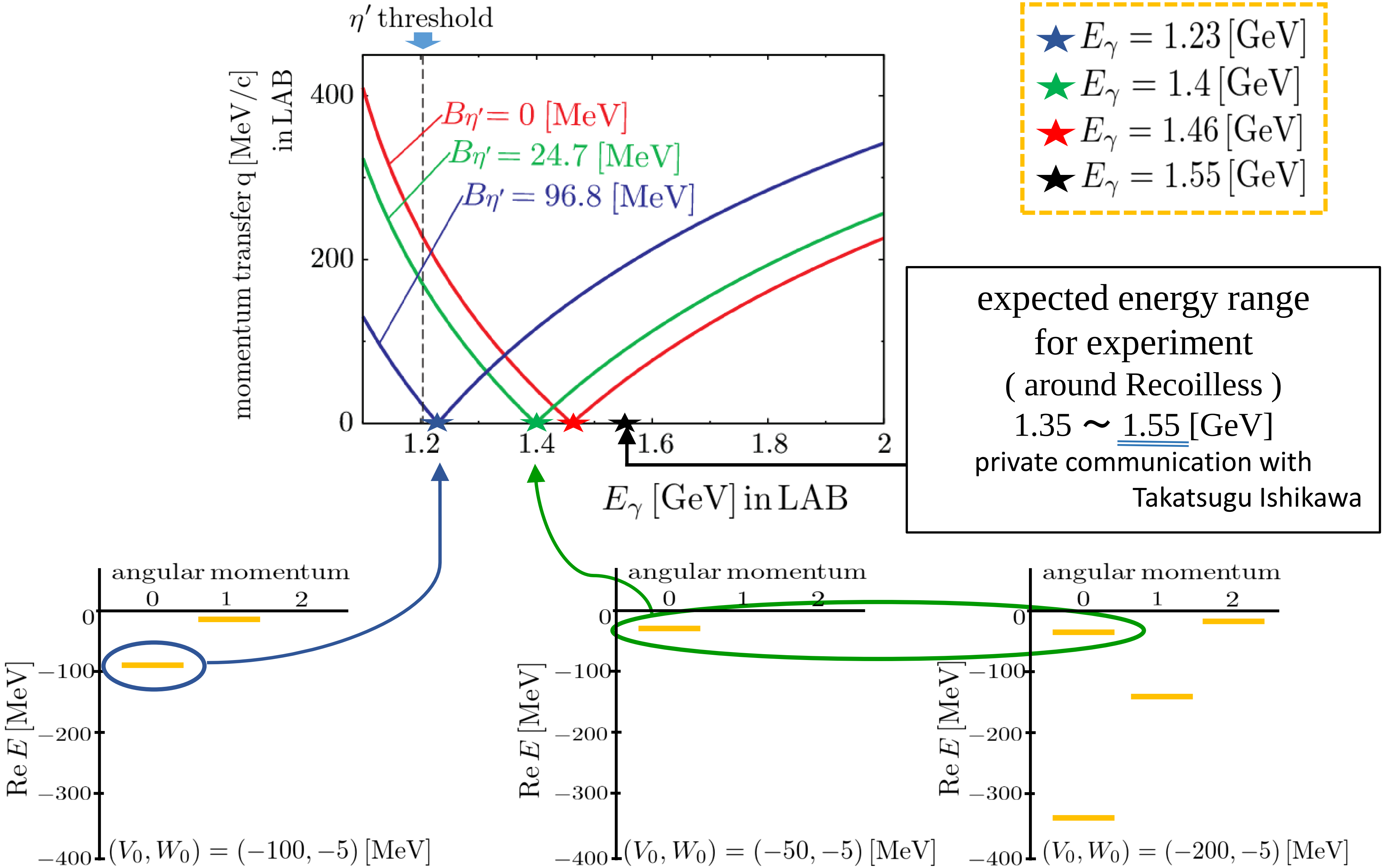
angular distribution of η' in CM



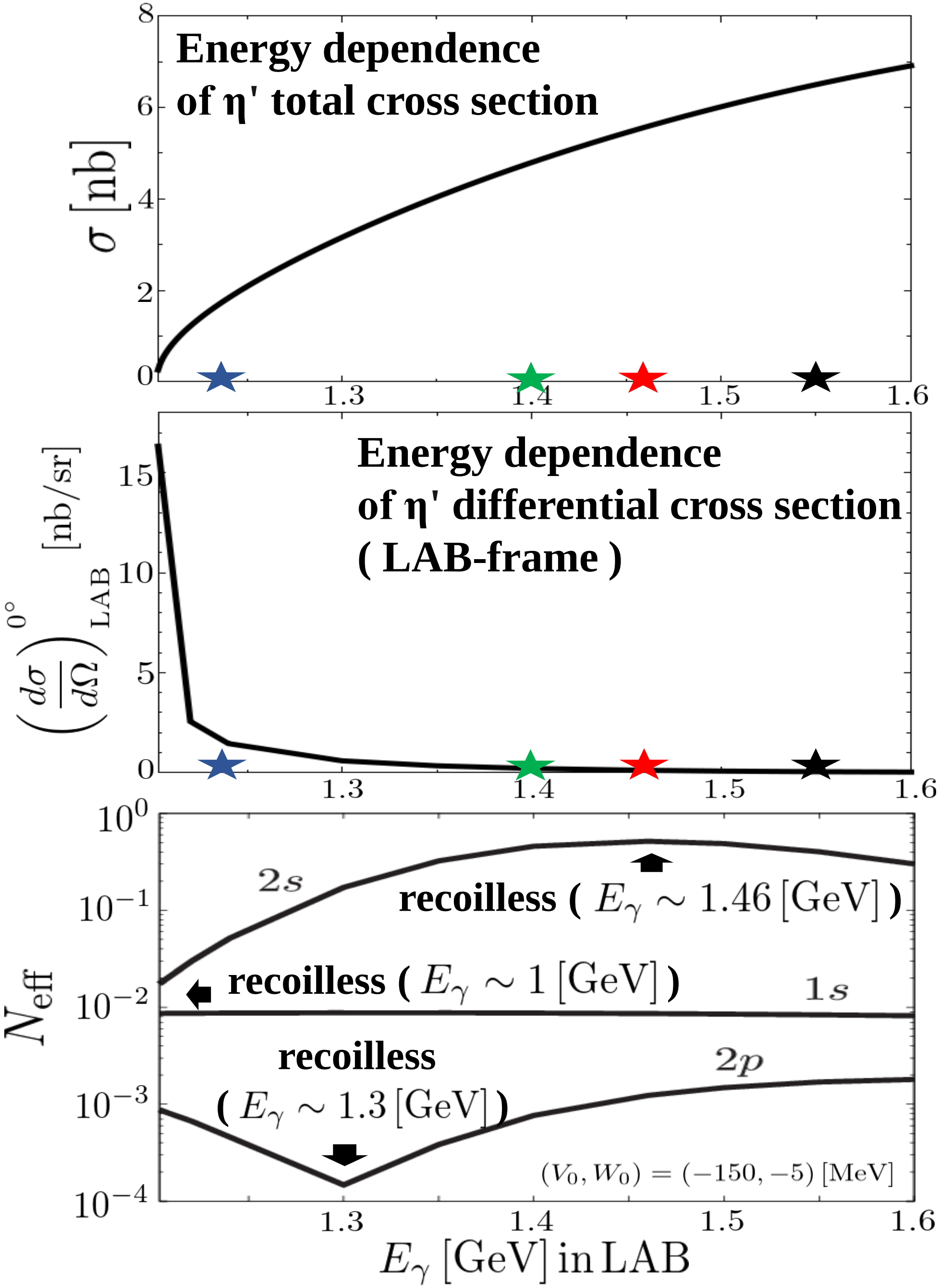
(J. Weiß et al., Eur. Phys. J. A 11, 371-374 (2001)) (I. Jaegle et al., Eur. Phys. J. A (2011) 47: 11)

3. Result of η' mesic nucleus formation reaction

3-1. Incident γ energy and momentum transfer

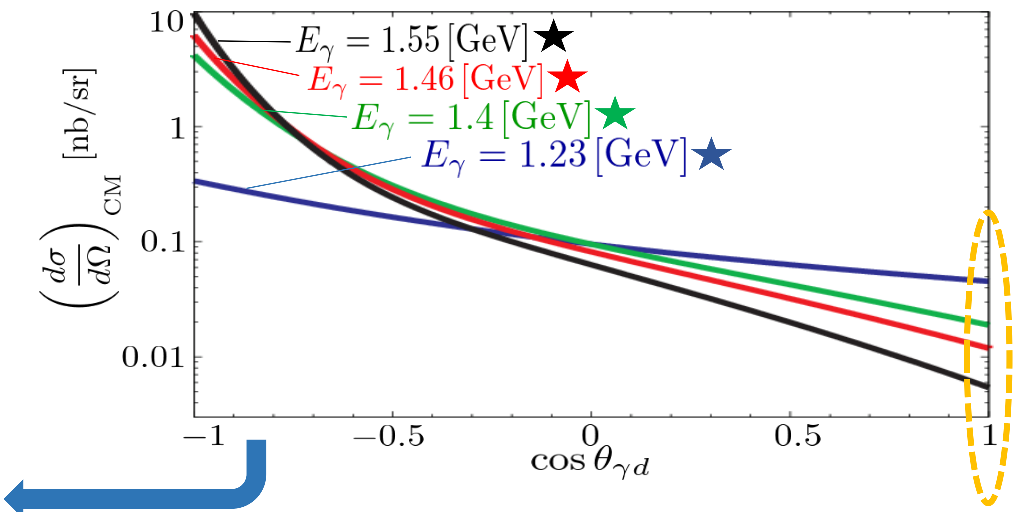


3-2. Incident γ energy dependence



Formation cross section

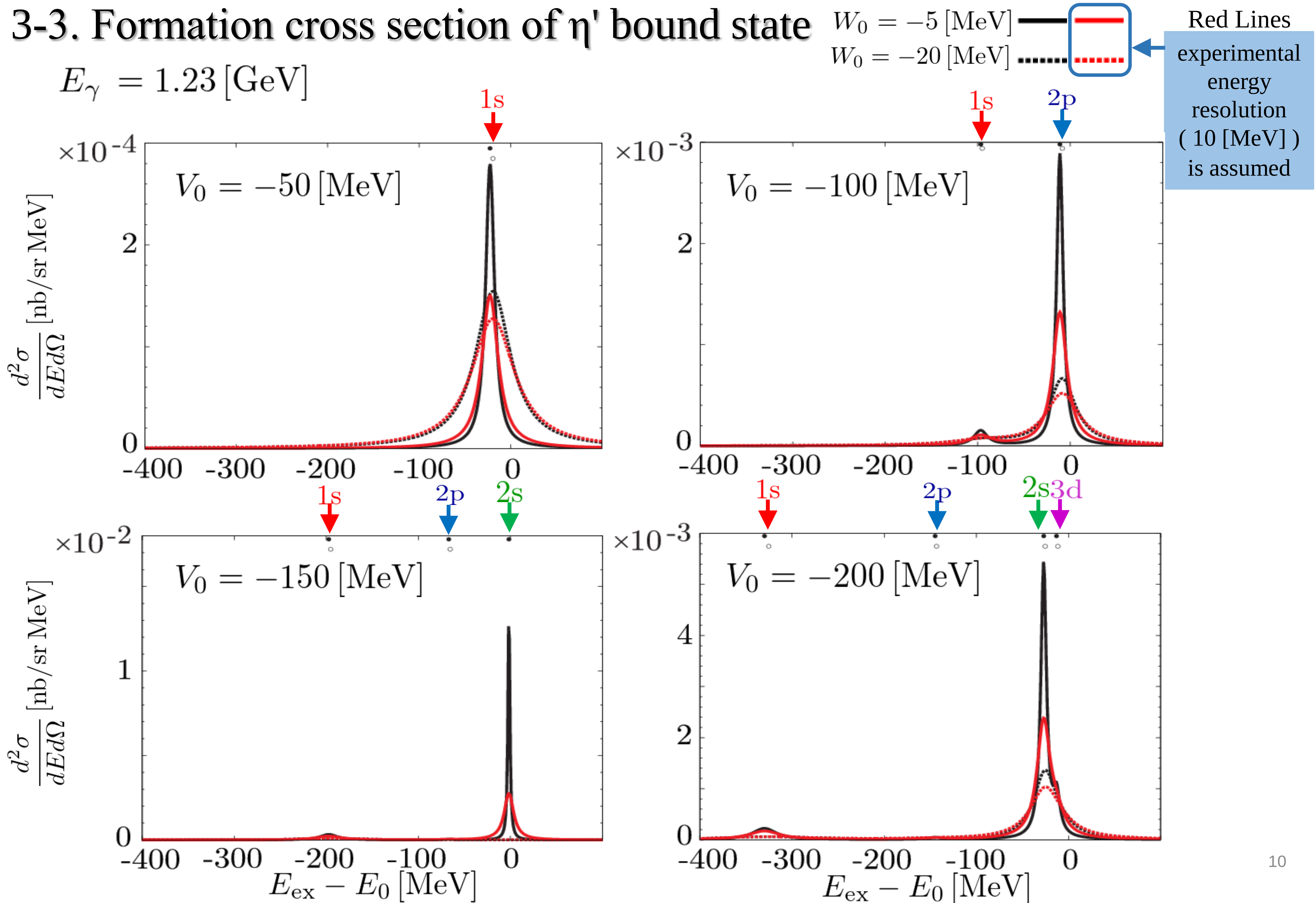
$$\frac{d^2\sigma}{dE d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{ele}} \sum_f \frac{\Gamma}{2\pi} \frac{1}{\Delta E^2 + \Gamma^2/4} N_{\mathrm{eff}}$$



E_γ → larger

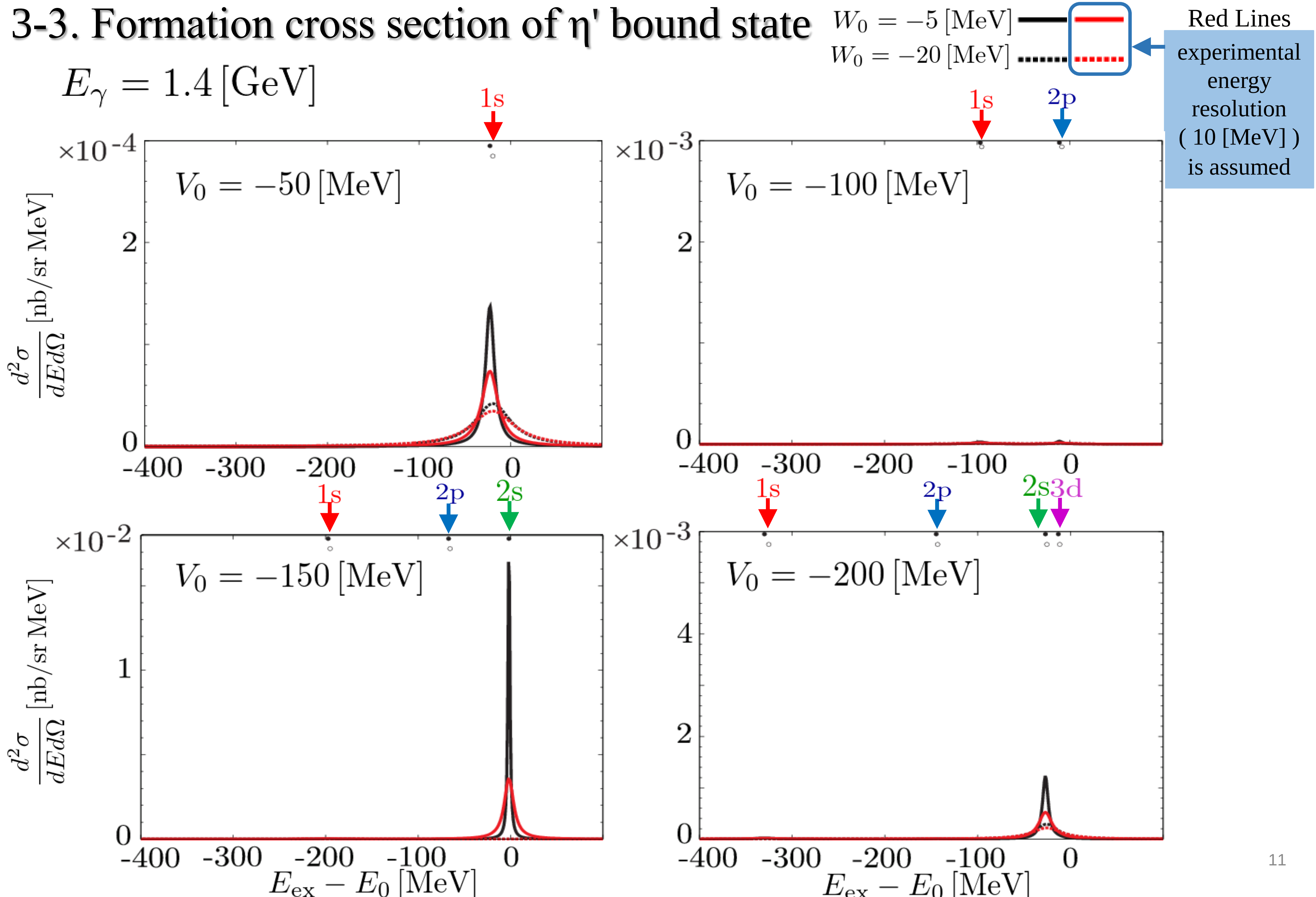
- ✓ η' total cross section (σ) increases
- ✓ elementary cross section $\left(\frac{d\sigma}{d\Omega}\right)$
  → decreases at $\theta_{\gamma d} = 0^\circ$
- ✓ N_{eff} vary
  according to the matching condition

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



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

$E_\gamma = 1.4\,[\mathrm{GeV}]$



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

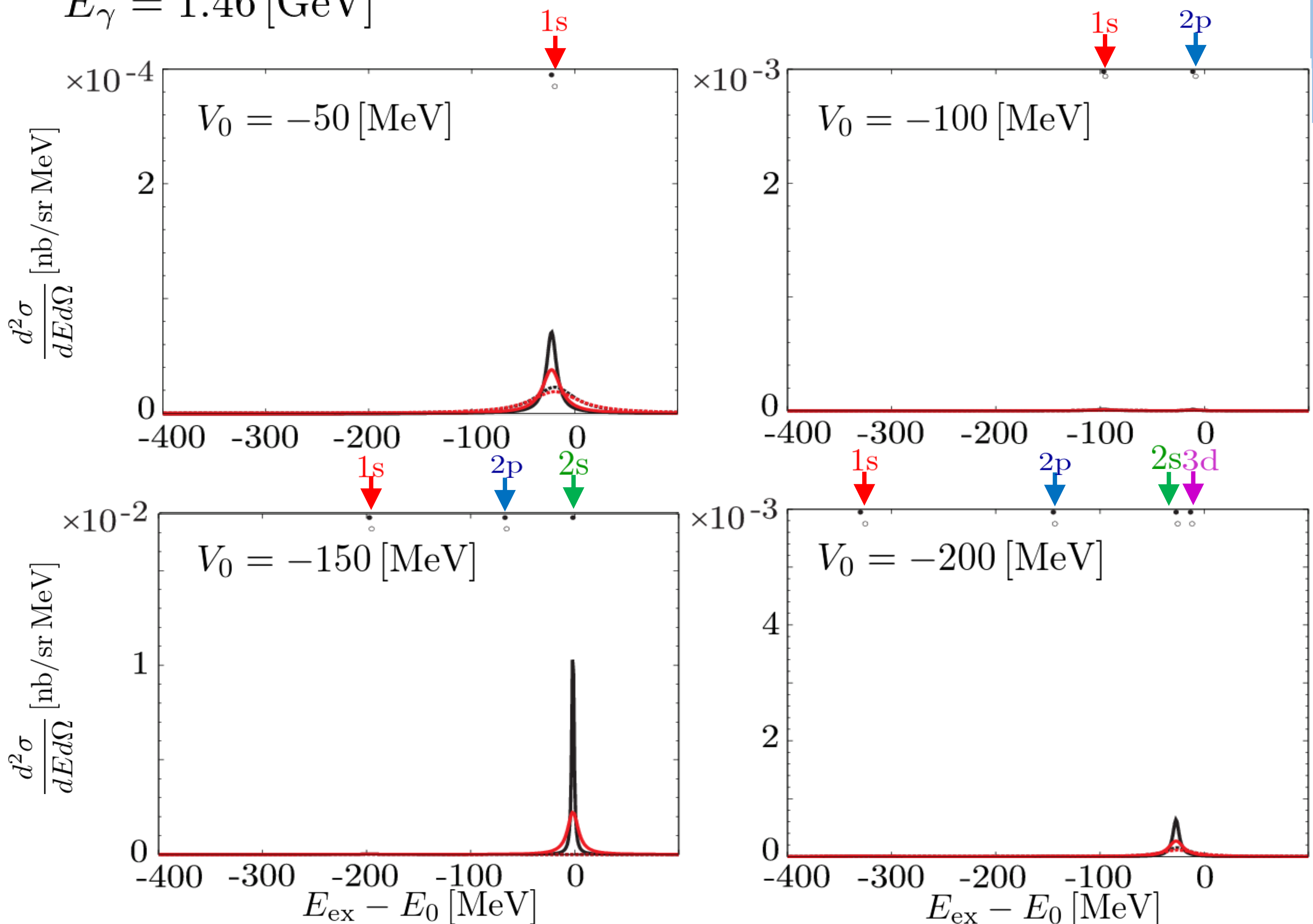
$W_0 = -5\,[\mathrm{MeV}]$

$W_0 = -20\,[\mathrm{MeV}]$

Red Lines

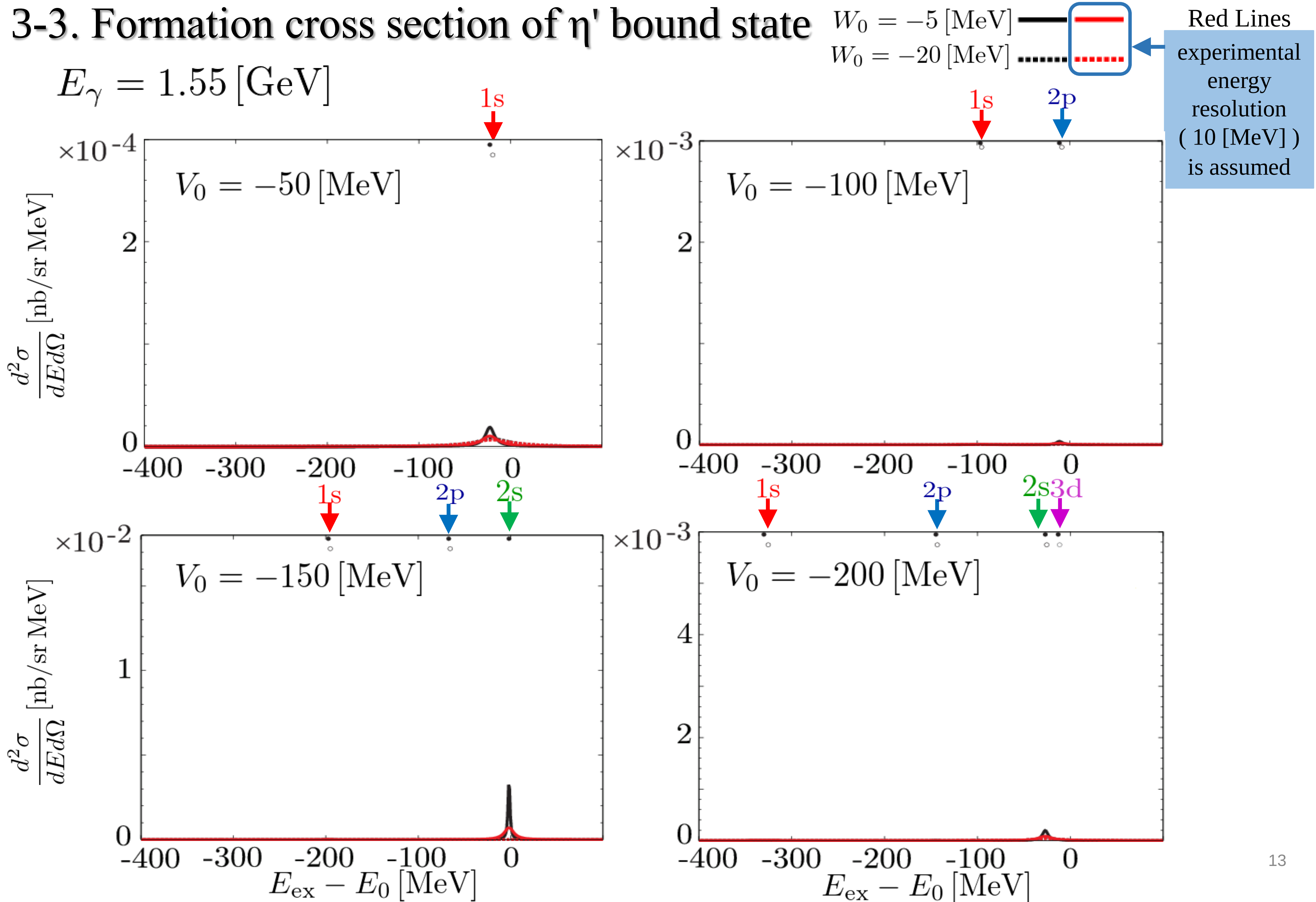
experimental energy resolution (10 [MeV]) is assumed

$E_\gamma = 1.46\,[\mathrm{GeV}]$



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

$E_\gamma = 1.55$ [GeV]



ここまでで分かったこと

✓ $E_\gamma \rightarrow$ 大 の時、η' 中間子束縛状態の生成断面積→小さくなる

➔ deuteronの形状因子が大きく影響している

より大きい生成断面積を得るために

^{6}Li 標的内での
deuteronのshrinkの効果

さらに低い
入射エネルギー E_γ での計算

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入射エネルギー E_γ での計算

3-4. Effects of shrinkage of quasi-deuteron in $^6\mathrm{Li}$ target

- Deuteron wave function

$$\psi_d(\boldsymbol{r}) = \psi_S(\boldsymbol{r}) + \psi_D(\boldsymbol{r})$$

S-wave part D-wave part

- Radial wave function

$$R_S(r) = \frac{u(r)}{r}, \quad R_D(r) = \frac{w(r)}{r}$$

$$1 = \int_0^\infty dr\,\left(u^2(r) + w^2(r)\right)$$: Normalization

- Parameterization

$$\begin{cases} u(r) = \sum_j C_j \exp(-m_j r) \\ w(r) = \sum_j D_j \exp(-m_j r)\left(1 + \frac{3}{m_j r} + \frac{3}{(m_j r)^2}\right) \end{cases}$$

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

- Form factor

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

- Elementary cross section

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

Scale (Shrink) factor α

$0 < \alpha < 1$

$$m_j \to \frac{1}{\alpha} m_j$$

$$(C_j,\ D_j) \to \frac{1}{\sqrt{\alpha}}(C_j,\ D_j)$$

- Normalization: invariant
- $\sqrt{\langle r^2 \rangle} \to \alpha\sqrt{\langle r^2 \rangle}$

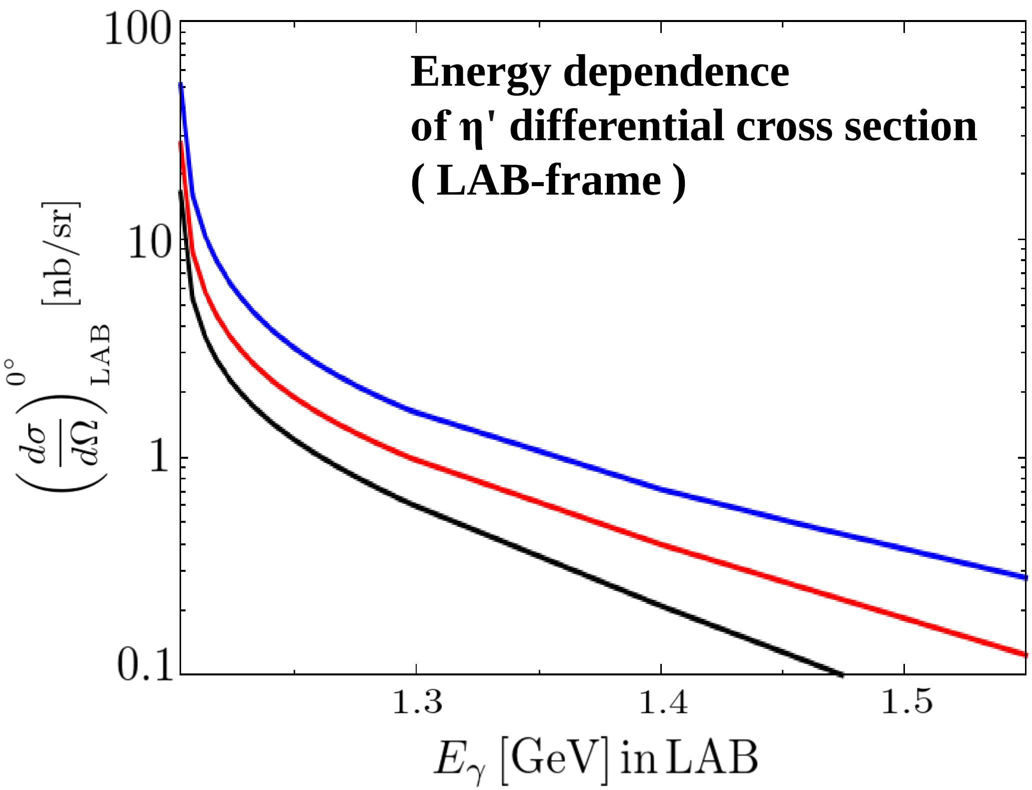
3-4. Effects of shrinkage of quasi-deuteron

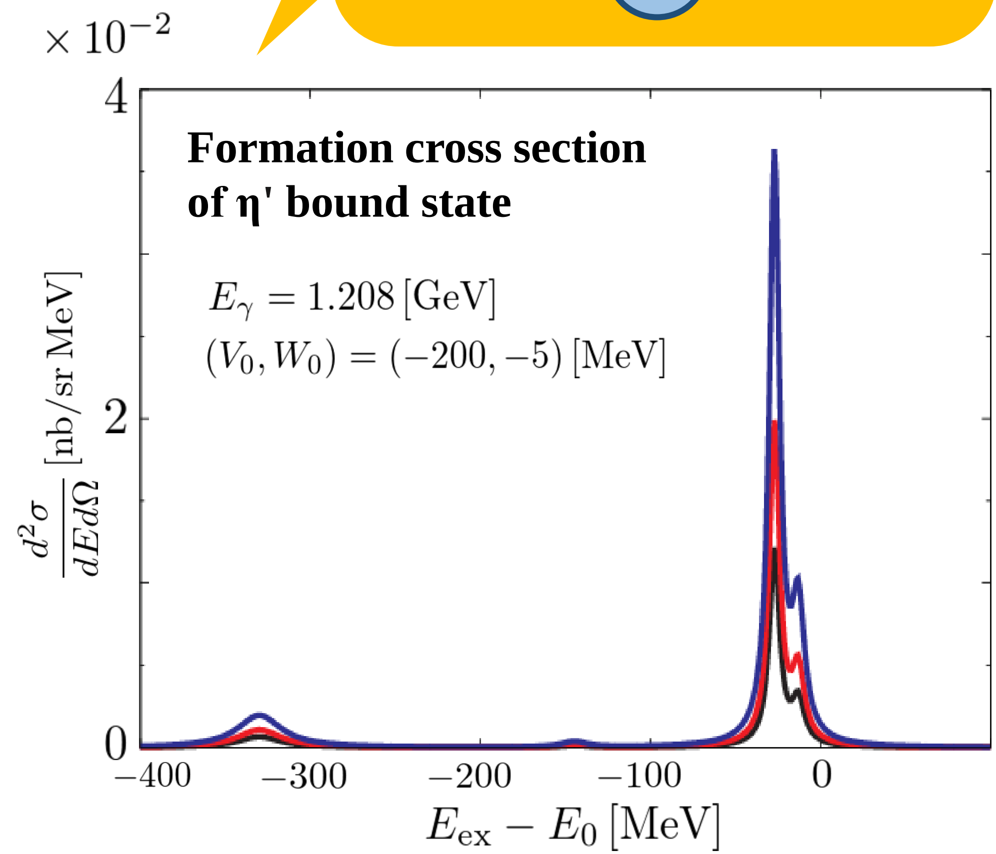
Scale (Shrink) factor $\alpha = 1.0$ (black), $\alpha = 0.9$ (red), $\alpha = 0.8$ (blue)

for $\alpha = 0.8$

$\left(\sqrt{\langle r^2 \rangle} \to 0.8\sqrt{\langle r^2 \rangle}\right)$

$\sim \times$ ③



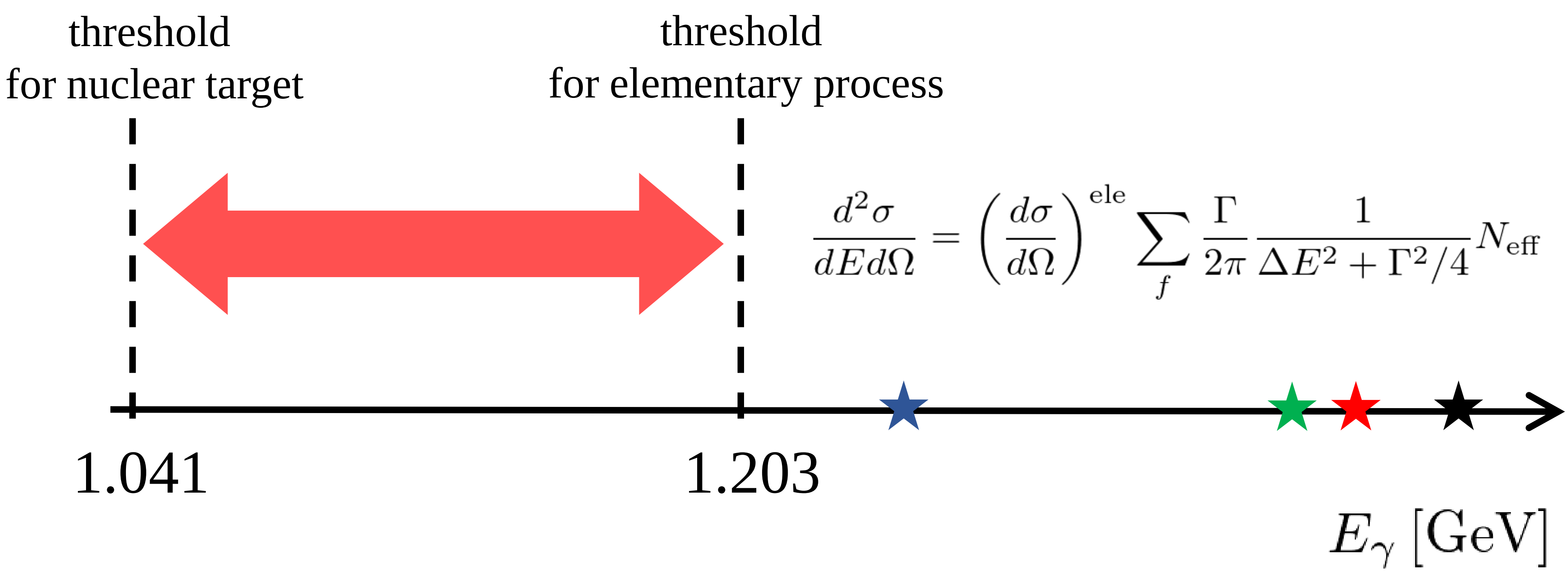


3-5.

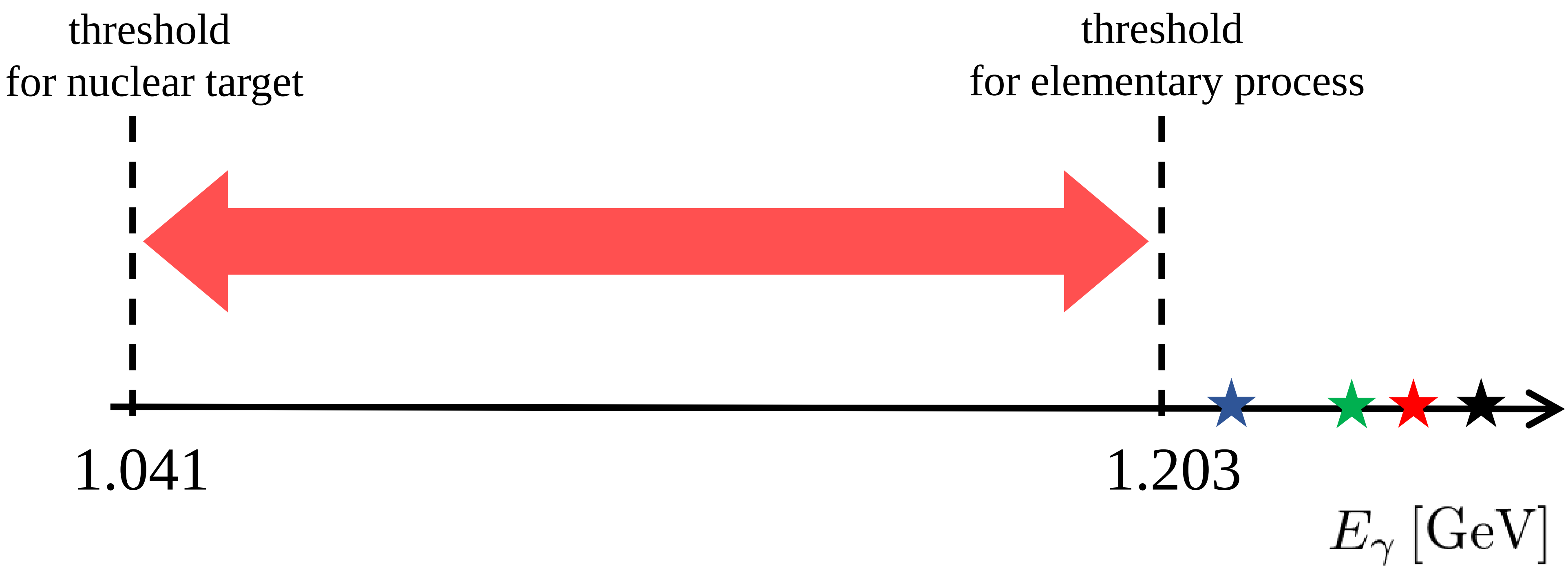
より大きい生成断面積を得るために

^{6}Li 標的内での
deuteronのshrinkの効果

さらに低い
入射エネルギーE_γでの計算

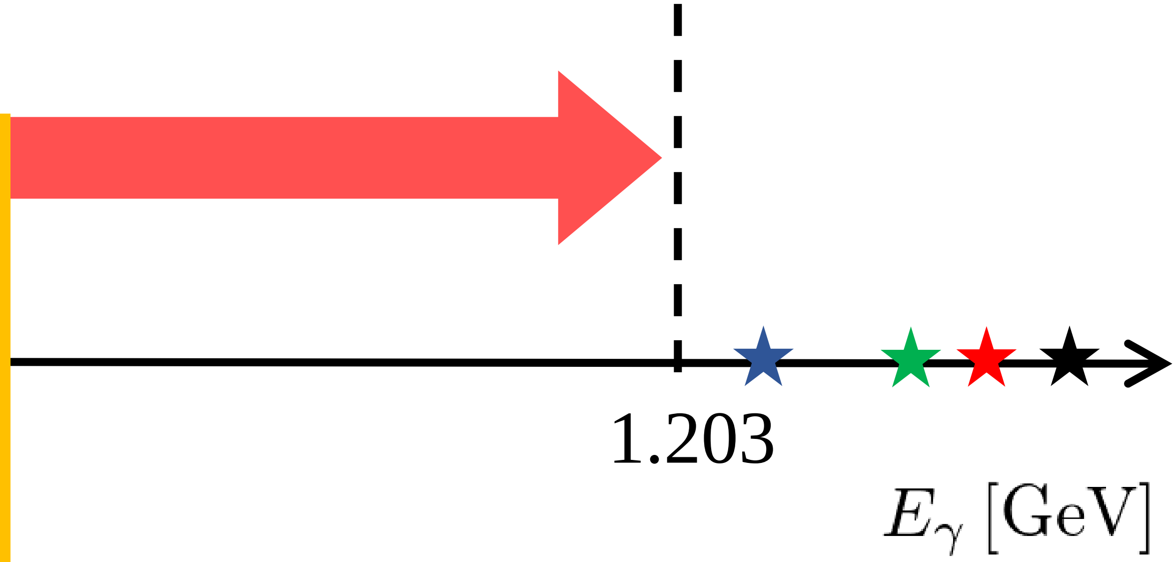


$$\frac{d^2\sigma}{dE\,d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{ele}} \sum_f \frac{\Gamma}{2\pi} \frac{1}{\Delta E^2 + \Gamma^2/4} N_{\mathrm{eff}}$$

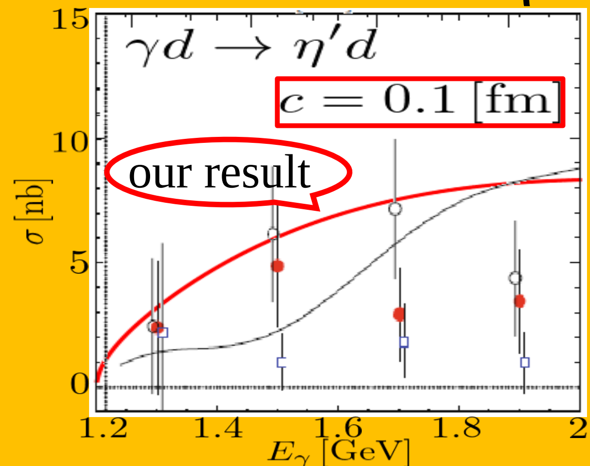


□ 生成断面積の新たな定式化

$$\frac{d^2\sigma}{dE d\Omega} = \sum_f \frac{|c|^2 M_d\, p_{d'}}{16\pi^2 m_{\eta'} p_\gamma} \frac{\Gamma}{2\pi} \frac{1}{\Delta E^2 + \Gamma^2/4} N_{\rm eff} |F_d(\boldsymbol{q})|^2$$



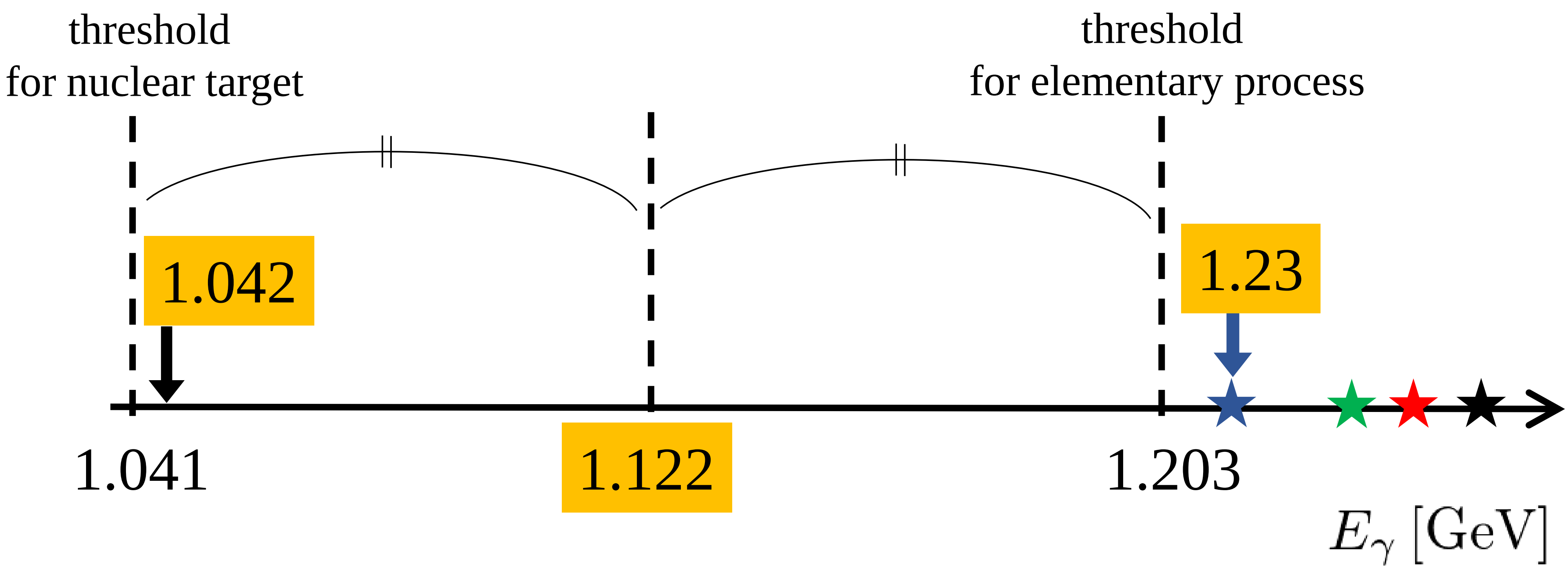
total cross section of η'



(I. Jaegle et al., Eur. Phys. J. A (2011) 47: 11)

化

$$\frac{d^2\sigma}{dE d\Omega} = \sum_f \frac{|c|^2 M_d\, p_{d'}}{16\pi^2 m_{\eta'} p_\gamma} \frac{\Gamma}{2\pi} \frac{1}{\Delta E^2 + \Gamma^2/4} N_{\mathrm{eff}} |F_d(\boldsymbol{q})|^2$$



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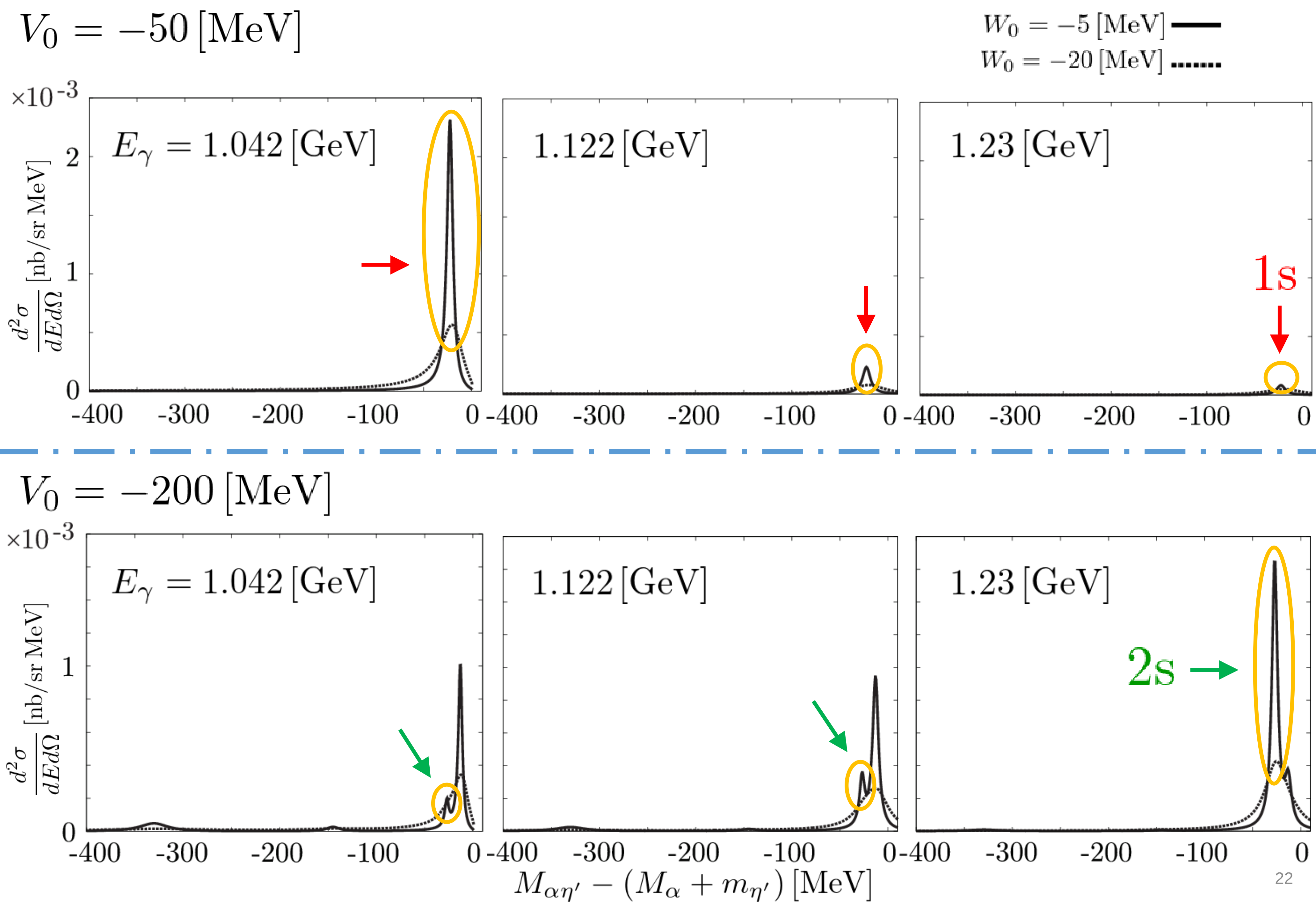
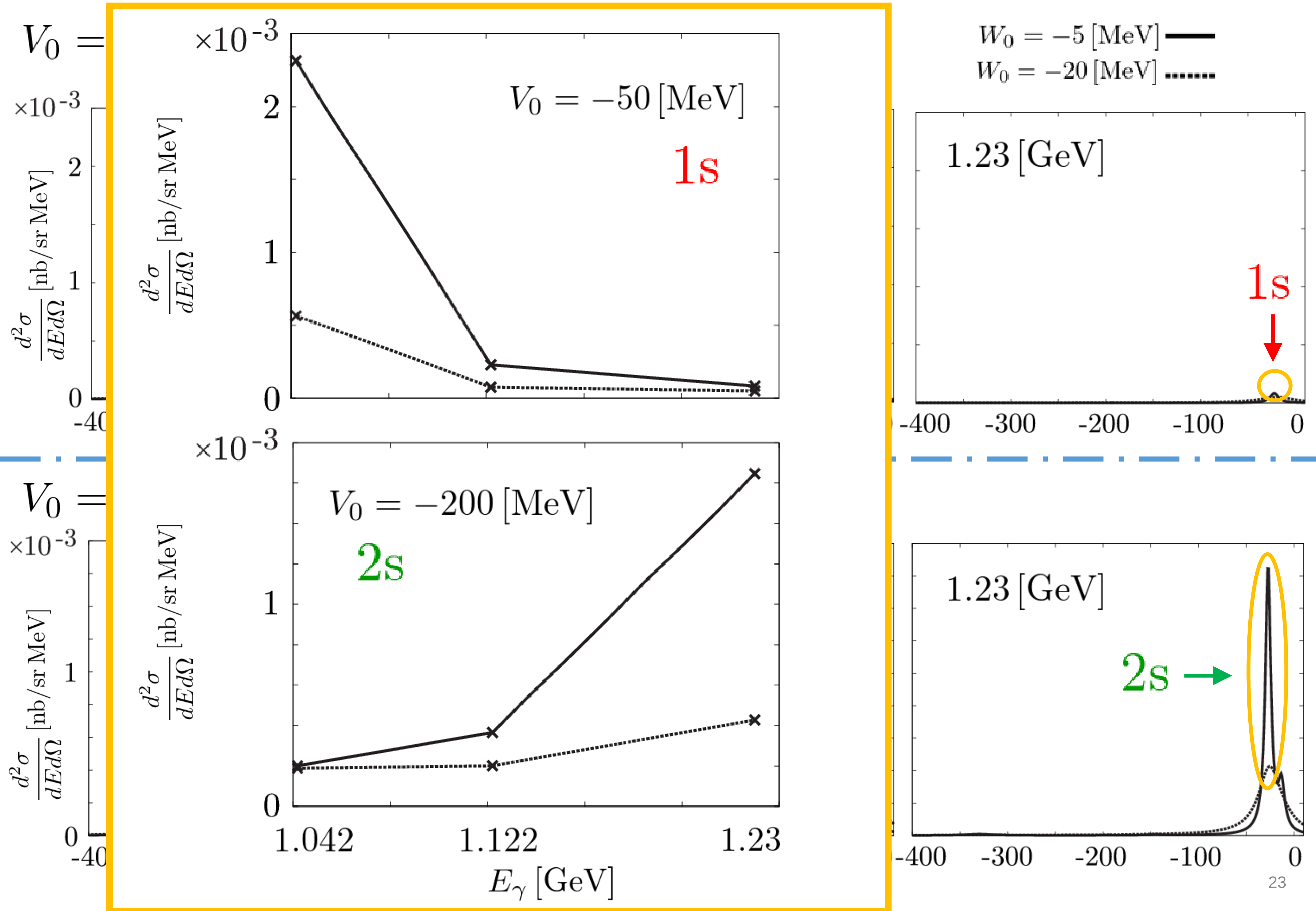
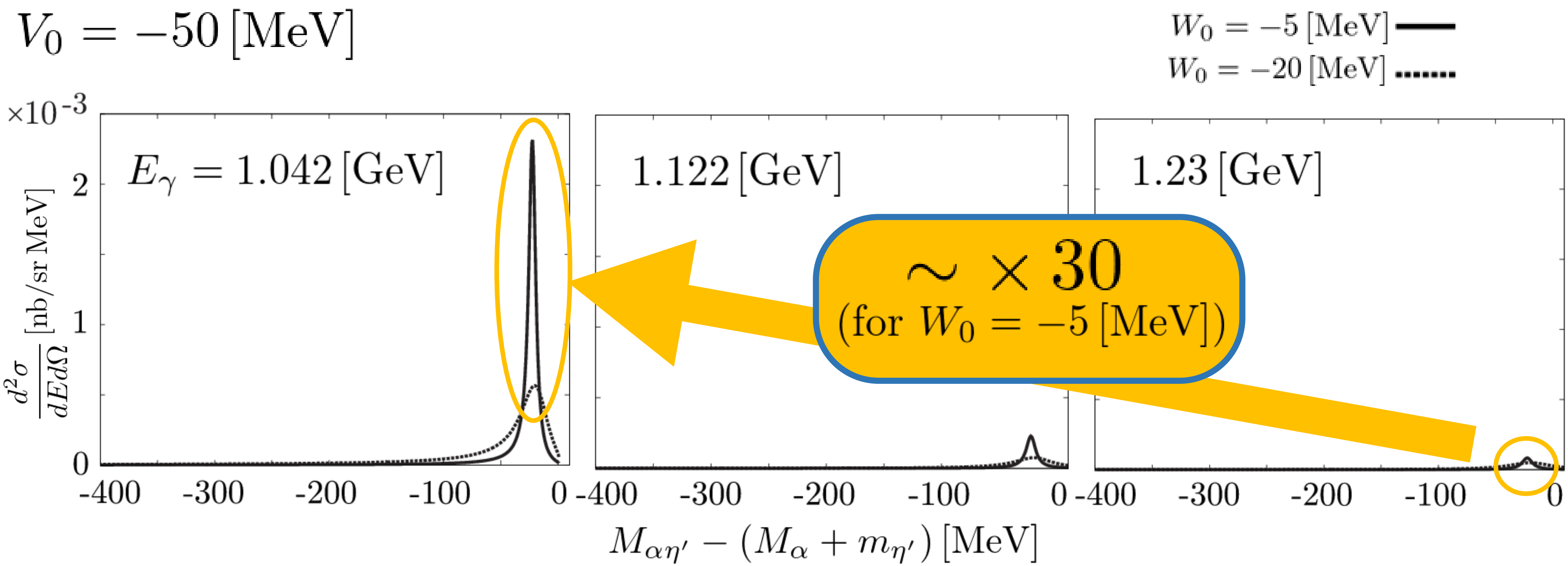


$V_0 = -50$ [MeV]
$W_0 = -5$ [MeV]
$W_0 = -20$ [MeV]
×10⁻³
$\frac{d^2\sigma}{dEd\Omega}$ [nb/sr MeV]
$E_\gamma = 1.042$ [GeV]
1.122 [GeV]
1.23 [GeV]
1s
$V_0 = -200$ [MeV]
×10⁻³
$\frac{d^2\sigma}{dEd\Omega}$ [nb/sr MeV]
$E_\gamma = 1.042$ [GeV]
1.122 [GeV]
1.23 [GeV]
2s
$M_{\alpha\eta'} - (M_\alpha + m_{\eta'})$ [MeV]

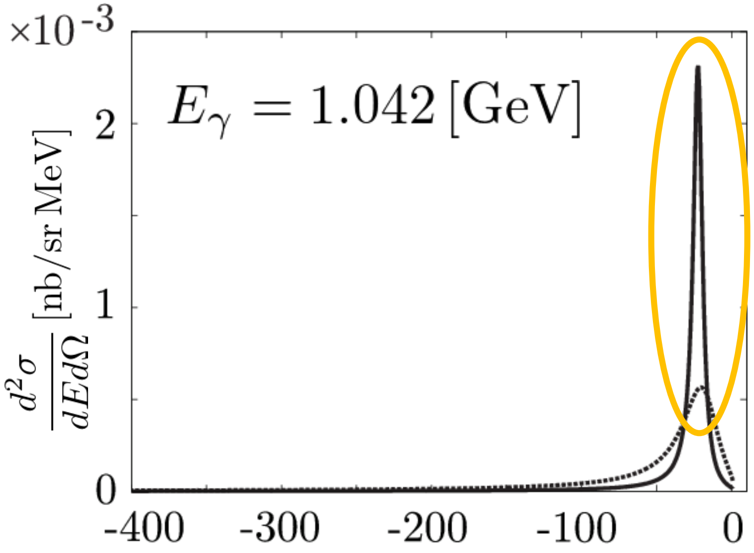

$V_0 = -50$ [MeV]
1s
$V_0 = -200$ [MeV]
2s
$\times 10^{-3}$
$\frac{d^2\sigma}{dEd\Omega}$ [nb/sr MeV]
E_γ [GeV]
1.042
1.122
1.23
$W_0 = -5$ [MeV]
$W_0 = -20$ [MeV]
1.23 [GeV]
-400
-300
-200
-100
0



$V_0 = -50$ [MeV]
$W_0 = -5$ [MeV]
$W_0 = -20$ [MeV]
×10^-3
$\frac{d^2\sigma}{dEd\Omega}$ [nb/sr MeV]
$E_\gamma = 1.042$ [GeV]
1.122 [GeV]
1.23 [GeV]
$\sim \times 30$
(for $W_0 = -5$ [MeV])
$M_{\alpha\eta'} - (M_\alpha + m_{\eta'})$ [MeV]

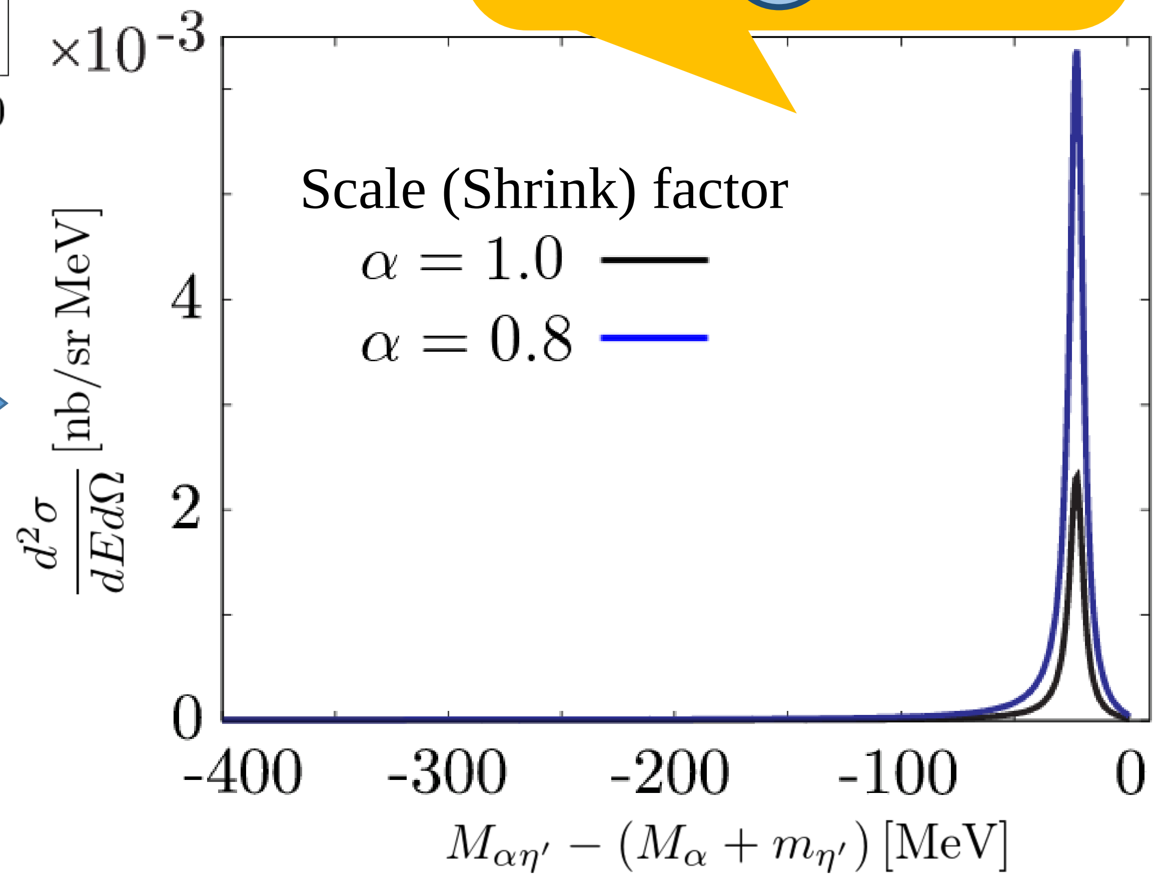
$V_0 = -50\,[\mathrm{MeV}]$

$W_0 = -5\,[\mathrm{MeV}]$ (solid)
$W_0 = -20\,[\mathrm{MeV}]$ (dotted)



Effects of
possible deuteron shrinkage

for $\alpha = 0.8$
$\left(\sqrt{\langle r^2 \rangle} \to 0.8\sqrt{\langle r^2 \rangle}\right)$
$\sim \times$ 3



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 at $E_\gamma = 1.23 \sim 1.55\,[\mathrm{GeV}]$ (above γ+d→η'+d threshold)

- 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 $E_\gamma = 1.23\,[\mathrm{GeV}]$ than other energies considered here
  - The bound η' states form well-separated peak structures in the spectra

Discussions

- <u>Effects of the deuteron form factor</u>

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

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

  ⇒ Experiments with photon energy around η' production threshold ($E_\gamma \sim 1.2\,[\mathrm{GeV}]$) could be better

- To get larger cross section
  - Possible deuteron shrinkage effects

    ⇒ For 0.8 times shorter $\sqrt{\langle r^2 \rangle}$, cross section becomes about 3 times larger
  - Lower incident γ energy

    (nuclear target threshold ⬄ elementary process threshold)

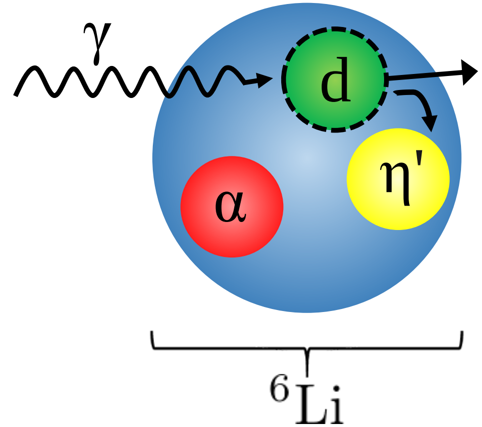
$\times 100$ Enhancement for 1s state for $(V_0, W_0) = (-50, -5)\,[\mathrm{MeV}]$ case

$8.3 \times 10^{-5}\,[\mathrm{nb/sr\,MeV}]$ $\left(E_\gamma = 1.23\,[\mathrm{GeV}] \right)$ → $6.4 \times 10^{-3}\,[\mathrm{nb/sr\,MeV}]$ $\left(E_\gamma = 1.042\,[\mathrm{GeV}],\ \alpha = 0.8 \right)$

Lower incident γ energy
Deuteron shrinkage effects

Conclusion

^{6}Li (γ,d) reaction — pick-up quasi-deuteron in target



➢ $$\frac{d^2\sigma}{dE d\Omega} \le 0.01 \text{ [nb/sr MeV]}$$

for all cases considered here
including possible deuteron shrinkage in ^{6}Li
and optimizing the incident γ energy