18th International Workshop on Meson Physics (MESON 2026)

Production cross section of the $\bar{K}NN$ nucleus with two-nucleon absorption in the in-flight $^3\mathrm{He}(K^-, \Lambda p)n$ reaction

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Kyoto Prefectural University
Nuclear-Hadron Physics Lab.

Takuto Jimbo(D1), Takayasu Sekihara

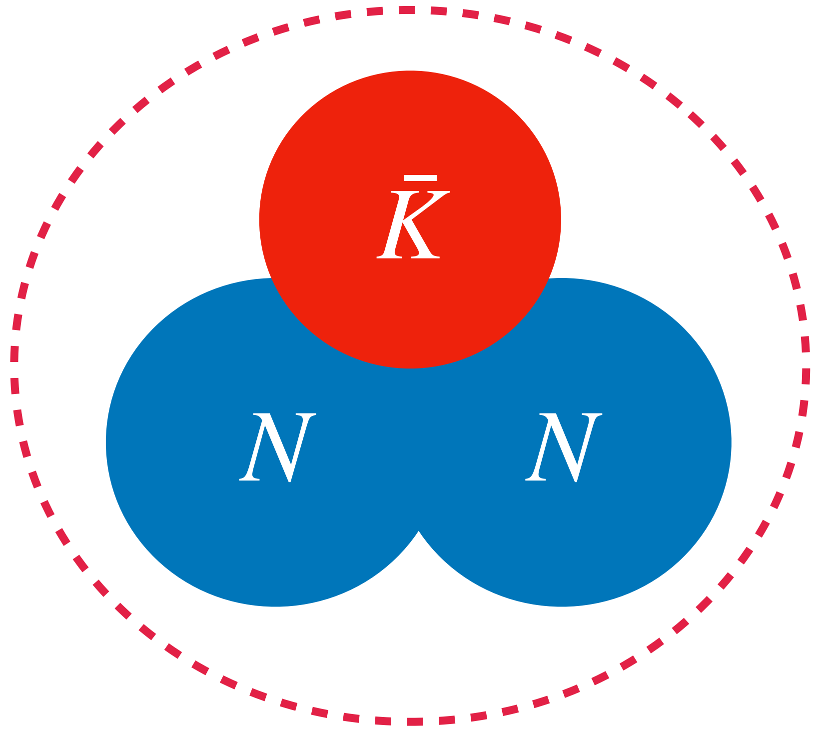
Outline

1. **Introduction**
2. **Spectral calculation for the $\bar{K}NN$ nucleus with two-nucleon absorption**
3. **Formulation in the $^3\mathrm{He}(K^-, \Lambda p)n$ reaction**
4. **Summary and Outlooks**

1. Introduction

1.Introduction

■ What is the $\bar{K}NN$ nucleus ?



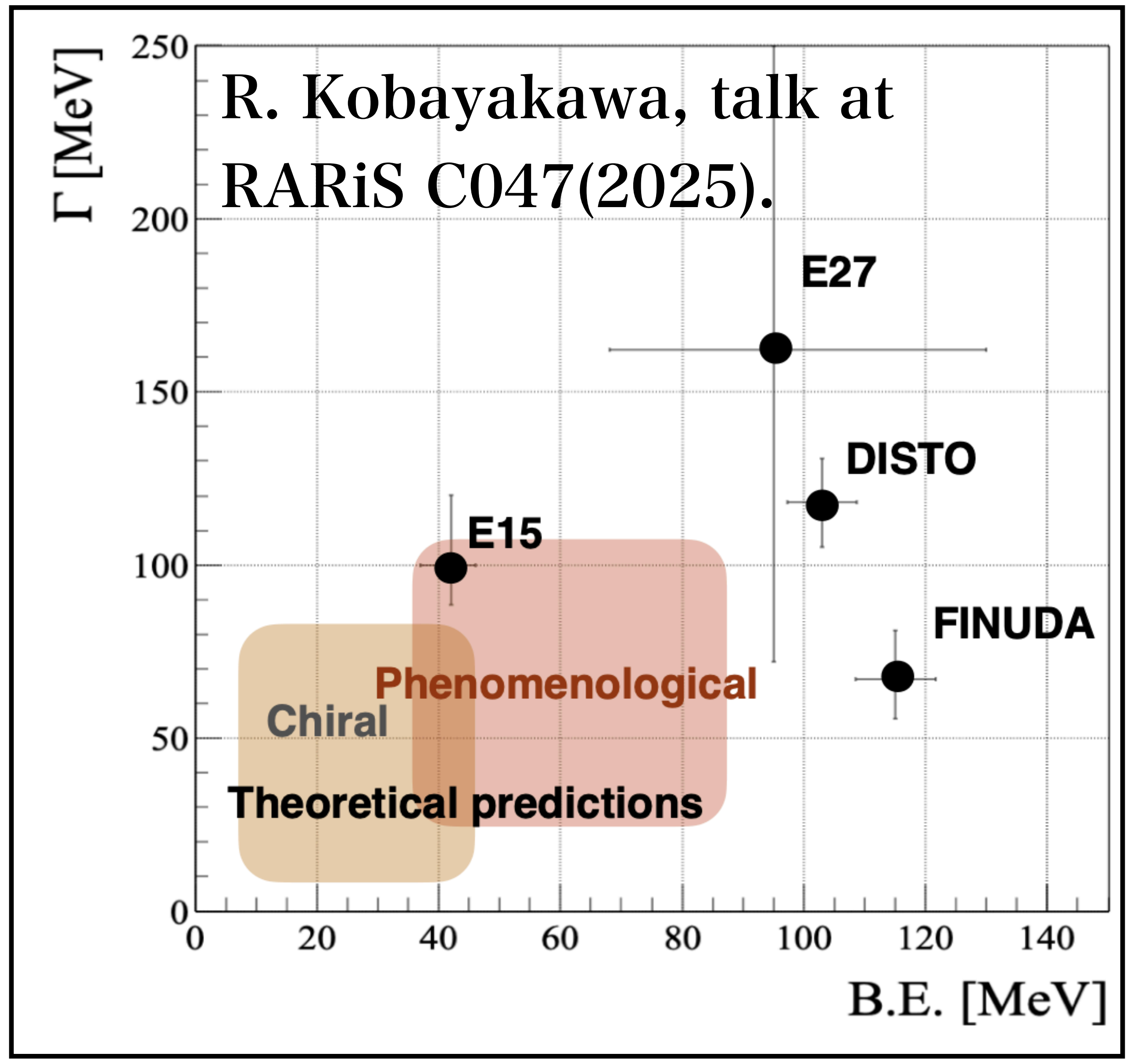
☐ The simplest system of kaonic nuclei.

- the antikaon($\bar{K}$)-nuclear quasibound states via the strong interaction.

☐ $\bar{K}NN$ system has been studied both theoretically and experimentally.

☐ Experimental searches for the $\bar{K}NN$ nucleus.

- J-PARC, SPring-8(Japan)
  - E15, E27(J-PARC), LEPS(SPring-8)
- GSI(Germany)
  - HADES
- SATURNE(France)
  - DISTO
- DAΦNE(Italy)
  - FINUDA, AMADEUS


R. Kobayakawa, talk at RARiS C047(2025).

1.Introduction

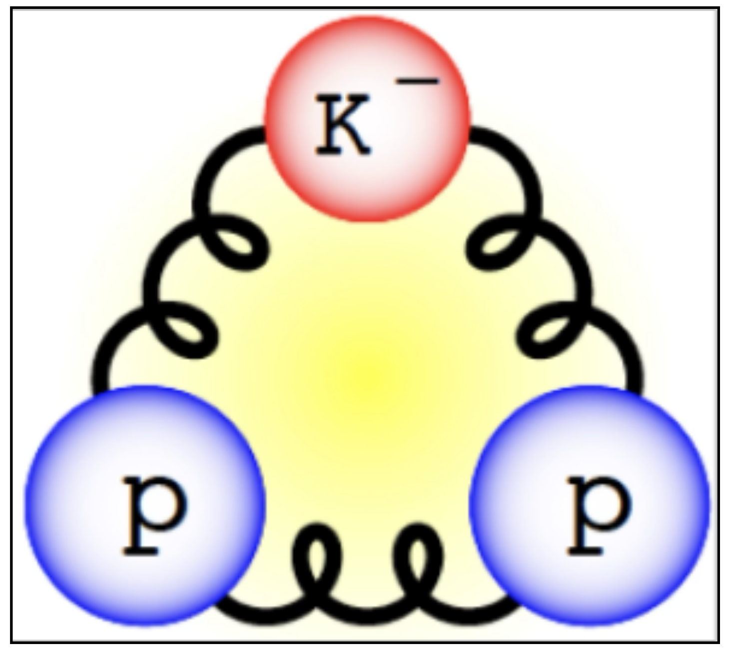
■ Searching for the $\bar{K}NN$ nucleus in the J-PARC E15 experiment

☐ **The peak of $\bar{K}NN$ nucleus was observed in the $^3\mathrm{He}(K^-, \Lambda p)n$ reaction with the K^- beam.**

→ By Reaction calculation in the previous work,

the production of $\bar{K}NN$ nucleus is suggested !

T. Sekihara , E. Oset, and A. Ramos, PTEP 2016 123D03



J-PARC press release

$$\boxed{B_K = 42 \pm 3\,(\mathrm{stat.})^{+3}_{-4}(\mathrm{syst.})\,\mathrm{MeV}}$$

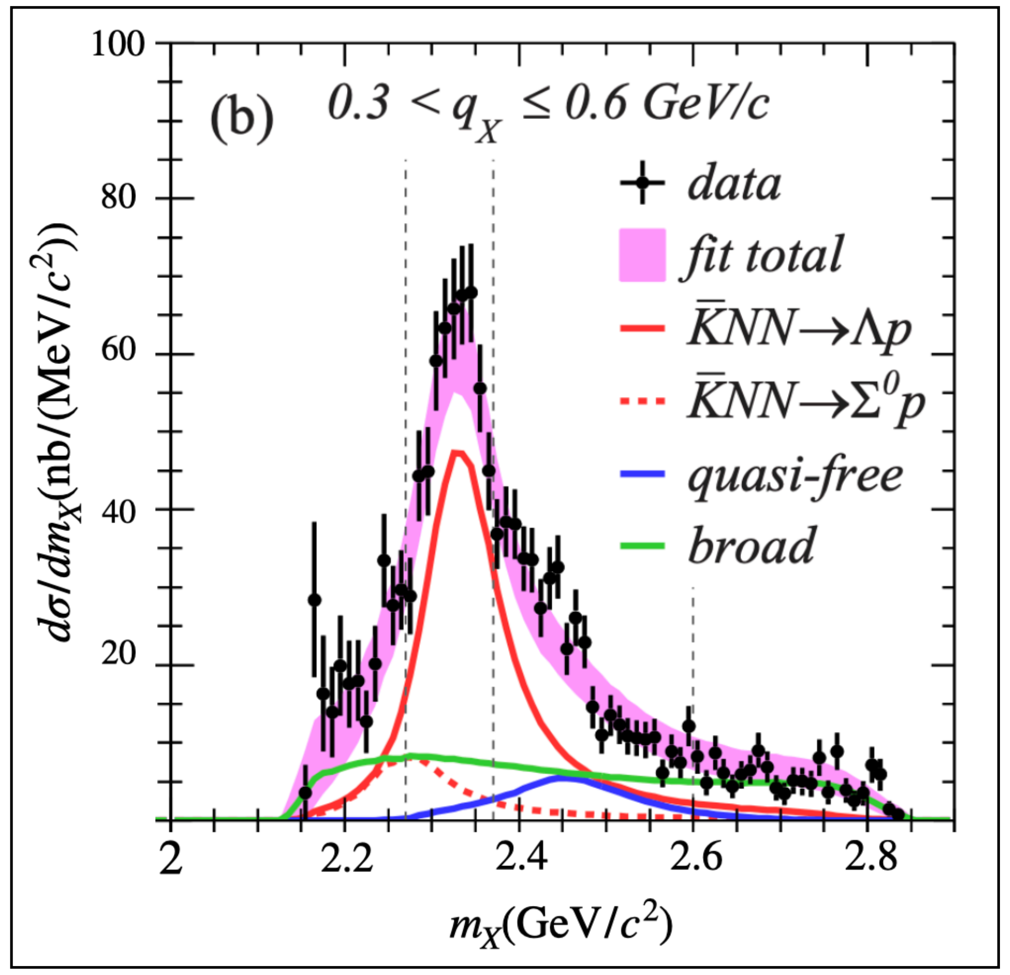
$$\boxed{\Gamma_K = 100 \pm 7\,(\mathrm{stat.})^{+19}_{-9}(\mathrm{syst.})\,\mathrm{MeV}}$$

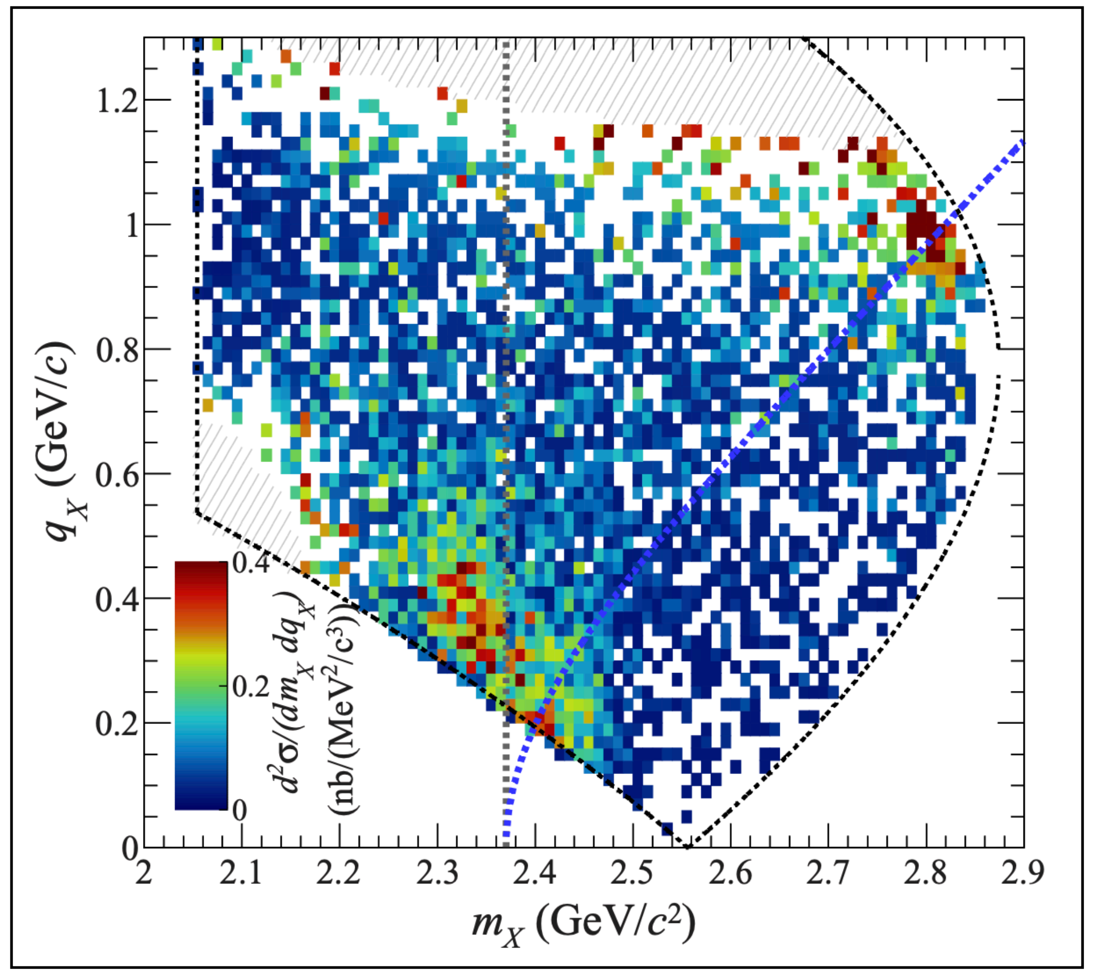
☐ **Important issue in theoretical calculation**

→ **Two-nucleon absorption (2NA).**

- The peak was observed through this process.

- But, there are only few calculations incorporating it.





T. Yamaga, et al, Phys. Rev. C102 (2020) 044002.

1.Introduction

■ Our research goals

1. **Structure and Reaction calculations of the $\bar{K}NN$ nucleus with two-nucleon absorption.**
   - **Structure** : binding energy, decay width, spin/parity, …
   - **Reaction** : How is $\bar{K}NN$ nucleus produced? Cross section?

2. **Compare our results with the Exp. Data at J-PARC.**
   - Can we support the production of the $\bar{K}NN$ nucleus strongly?
   - What did we observed in the J-PARC E15 experiment ?

We want to determine the spin/parity and pole position of the $\bar{K}NN$ nucleus through reaction calculation !

1.Introduction

■ Today's presentation contents

☐ As a first step for Reaction calculation, we performed spectral calculation for the $\bar{K}NN$ nucleus

- Formulation two-nucleon absorption(2NA) in a framework of Faddeev equation
- Results : $\bar{K}NN \to \Lambda N$ scattering amplitude, ΛN invariant mass spectrum

 - the spin/parity(not 2NA), relatively comparison with Exp. Data(2NA)

☐ Overview of our model for Reaction calculation

 - We are in progress !

2. Spectral calculation for the $\bar{K}NN$ nucleus with two-nucleon absorption

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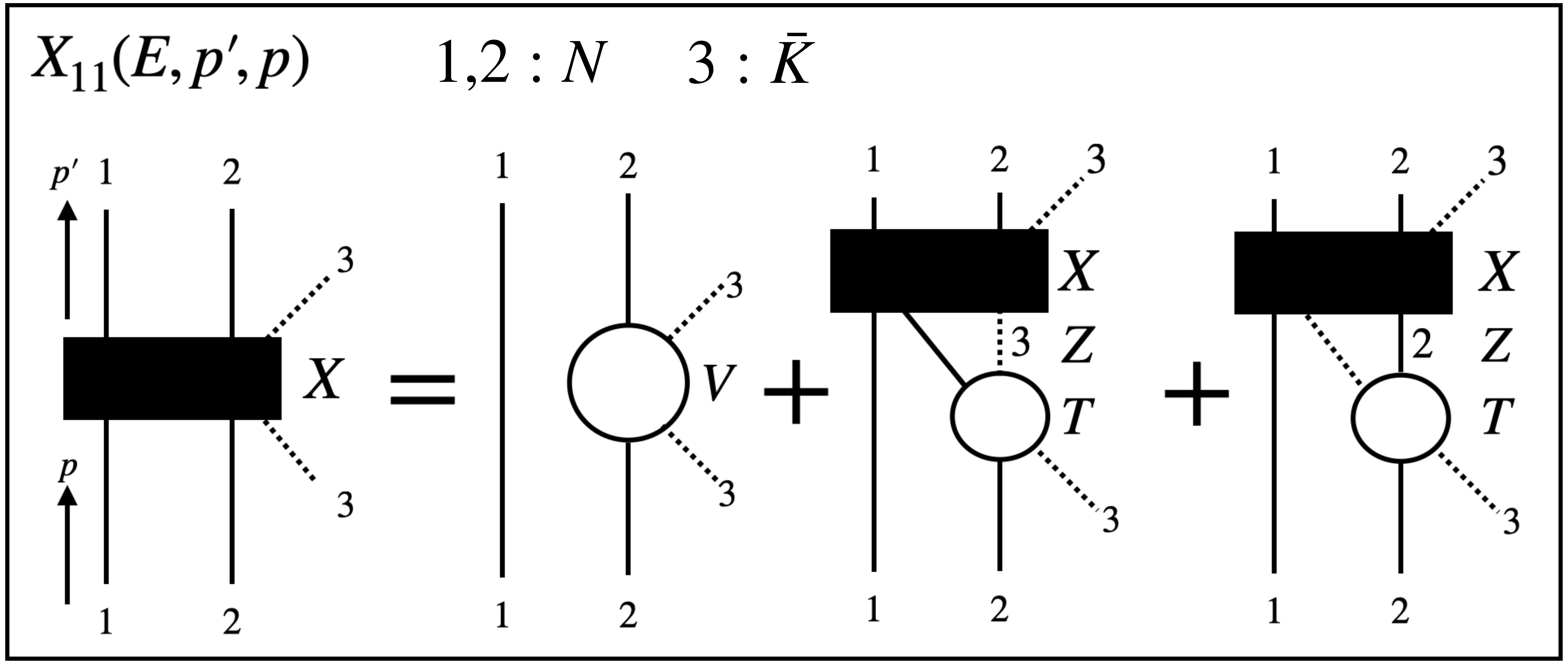
■ Faddeev equation

☐ A method of three-body calculation in quantum mechanics.



Matrix Form

$$\boxed{X = V + TZX}$$

X : **Three-body amplitude,**

T : **Two-body amplitude,**

Z : **Change spectator,**

V : T × **(the factor of spectator particle).**

☐ **Two-body amplitude** T

- we determine parameters to reproduce,

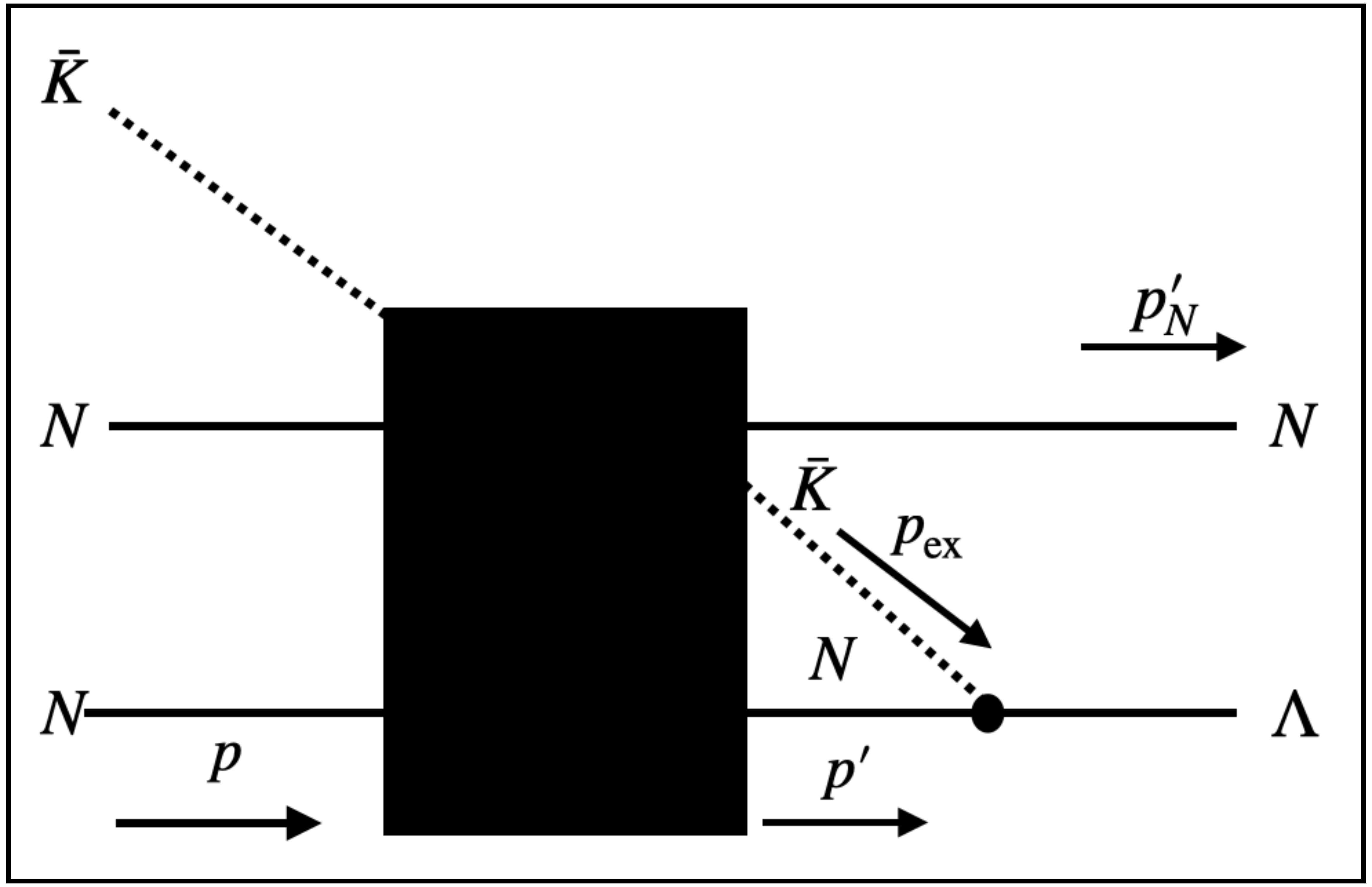
$\bar{K}N$ ← Y. Ikeda, T. Hyodo, and W. Weise, Nucl. Phys. A881 (2012) 98.

NN ← the phase shift of NN ($^3S_1$, $^1S_0$) .

2. Spectral calculation for the $\bar{K}NN$ nucleus with two-nucleon absorption

- $\bar{K}NN \to \Lambda N$ **scattering amplitude,** ΛN **mass spectrum**

☐ Next, We calculate the $\bar{K}NN \to \Lambda N$ scattering amplitude, considering the final state Λp in the $^3\mathrm{He}(K^-, \Lambda p)n$ reaction.



☐ For simplicity, we use only $p = 0$.

☐ $\bar{K}NN \to \Lambda N$ scattering amplitude.

$$\boxed{X_{\bar{K}NN\to\Lambda N} = \int_0^\infty dp' \frac{p'^2}{2\pi^2} X_{11}(E, p', p) Z_{\Lambda N}(E, p')}$$

☐ p'_N : on-shell momentum of nucleon in the final state.

☐ ΛN mass spectrum.

$$\boxed{\frac{d\sigma}{dM_{\Lambda N}} = p'_N \left| X_{\bar{K}NN\to\Lambda N}(E) \right|^2}$$

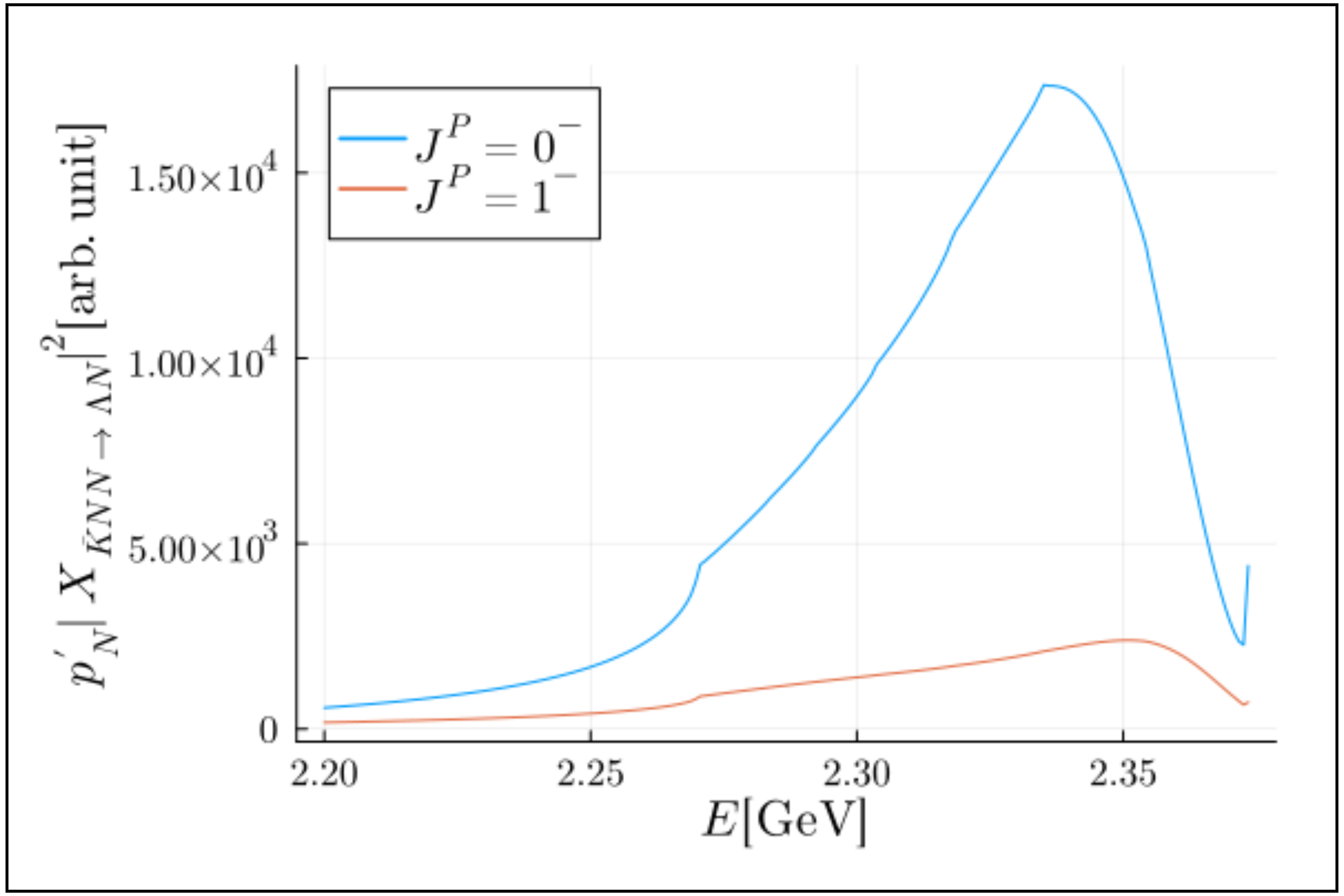
E. Oset, A. Ramos, Nucl. Phys. A, 635, 99 (1998).

2. Spectral calculation for the $\bar{K}NN$ nucleus with two-nucleon absorption

■ Result : ΛN mass spectrum for the spin/parity

☐ To determine the spin/parity for the future, we calculate ΛN mass spectrum for $J^P = 0^-, 1^-$

- **not considering two-nucleon absorption**



$$|\bar{K}NN(J^P = 0^-)\rangle = \sqrt{\frac{2}{3}}|K^-pp\rangle + \frac{1}{\sqrt{3}}\left|\bar{K}^0\frac{pn+np}{\sqrt{2}}\right\rangle$$

$$|\bar{K}NN(J^P = 1^-)\rangle = \frac{1}{\sqrt{2}}|\bar{K}^0pn\rangle - \frac{1}{\sqrt{2}}|\bar{K}^0np\rangle$$

- Difference weights for the $\bar{K}N$ $(I = 0,1)$ int.

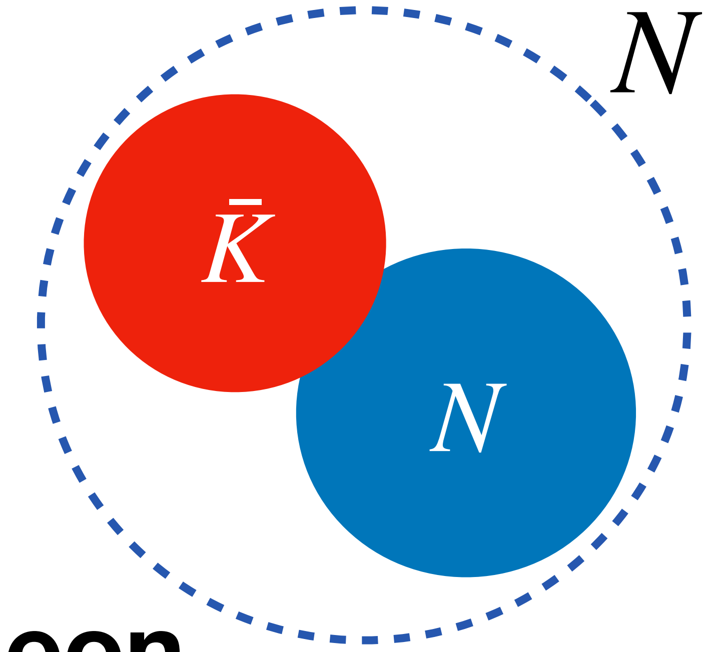
☐ Contribution from $J^P = 0^-$ is large for ΛN mass spectrum.

→ **It is likely to be $J^P = 0^-$?**

2. Spectral calculation for the $\bar{K}NN$ nucleus with two-nucleon absorption

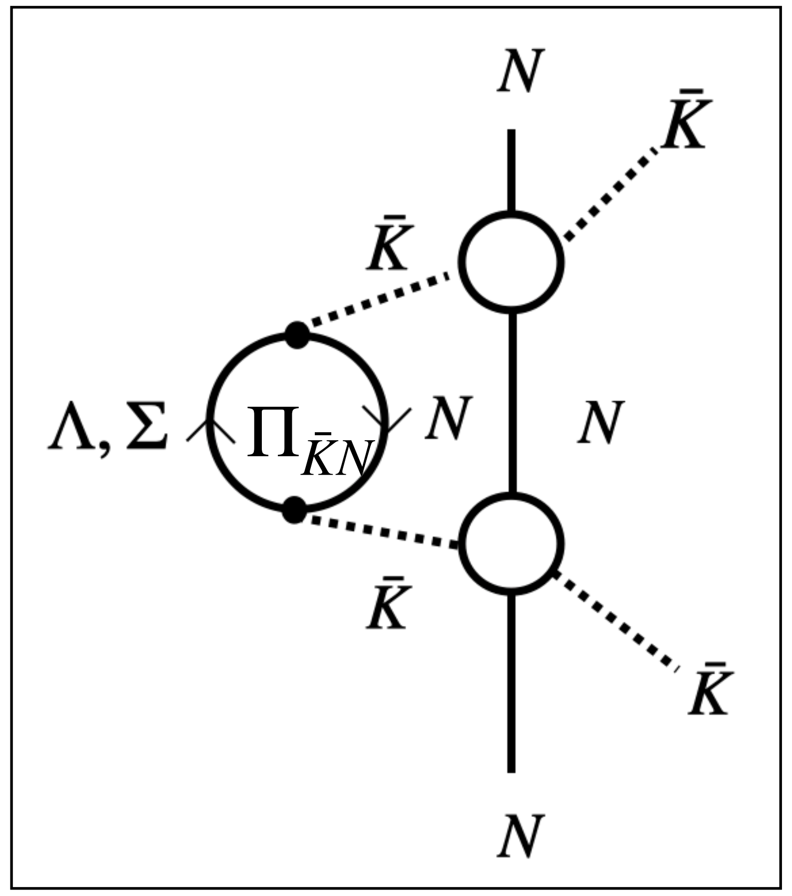
■ Two-nucleon absorption(2NA)

☐ the process of changing the particle number as $\bar{K}NN \rightarrow YN$ $(Y : \Lambda, \Sigma)$ in scattering.



$\Pi_{\bar{K}N}$

- $\bar{K}N\Lambda$ vertex $\tilde{V}_{\bar{K}N\Lambda}$.
- $\bar{K}N\Sigma$ vertex $\tilde{V}_{\bar{K}N\Sigma}$.
- the wave function of spectator nucleon : $\varphi_N(r)$.

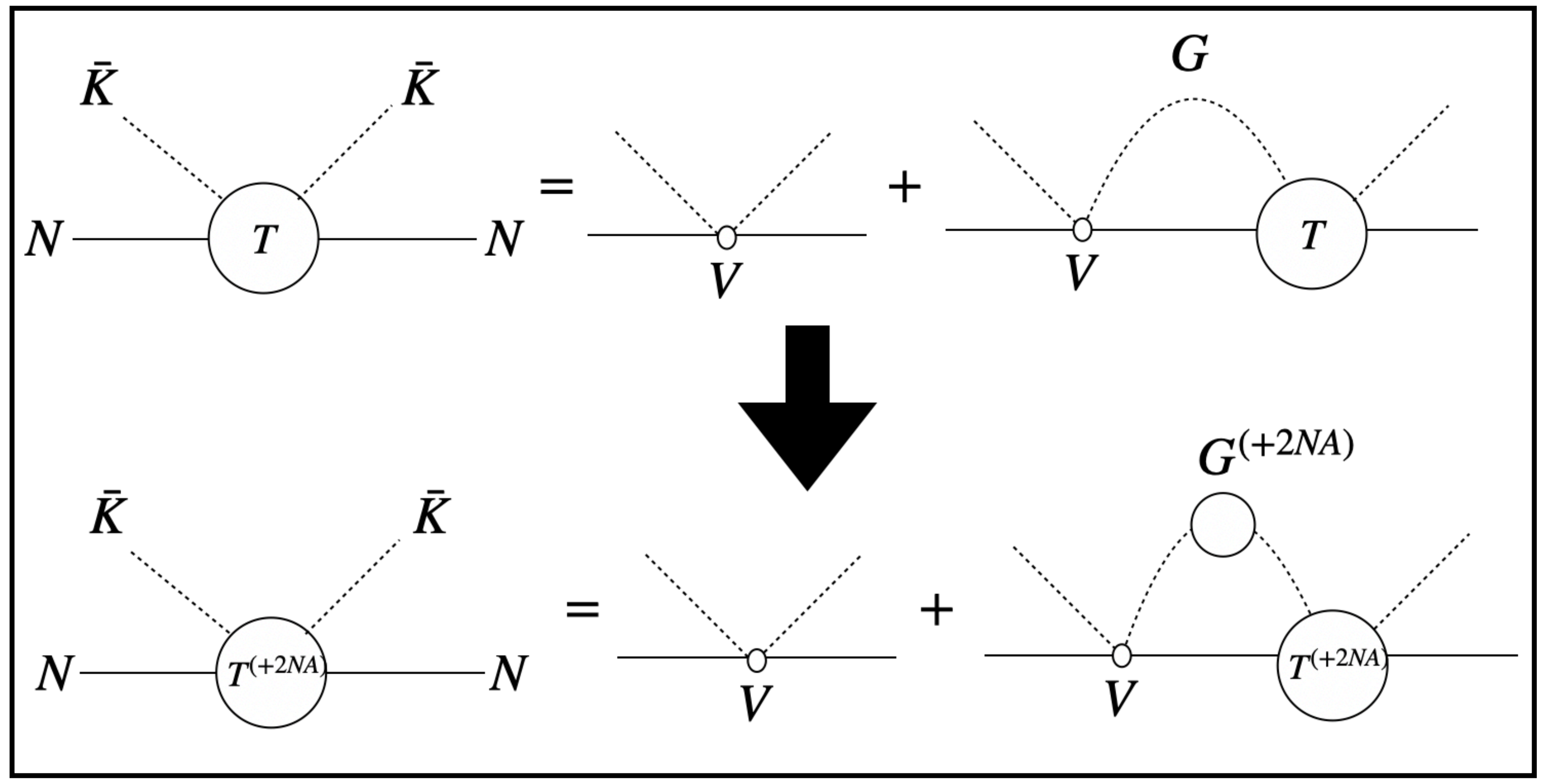


☐ the wave function of spectator nucleon.

- assumption !

$$\varphi_N(r) = \left(\frac{1}{R}\sqrt{\frac{2}{\pi}}\right)^{\frac{3}{2}} \exp\left(-\frac{r^2}{R^2}\right)$$

- Contribution of 2NA for the range of w.f. R ?

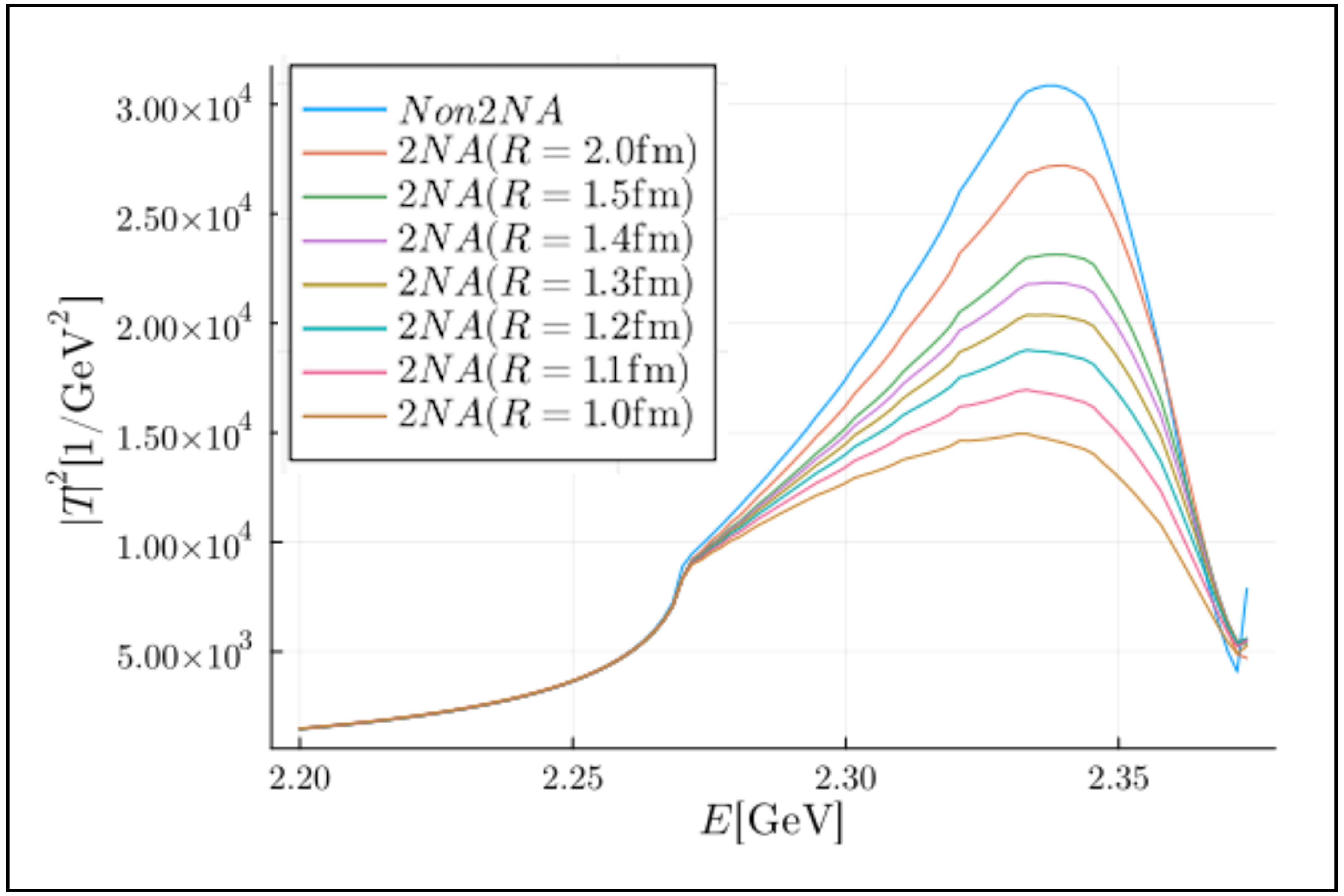


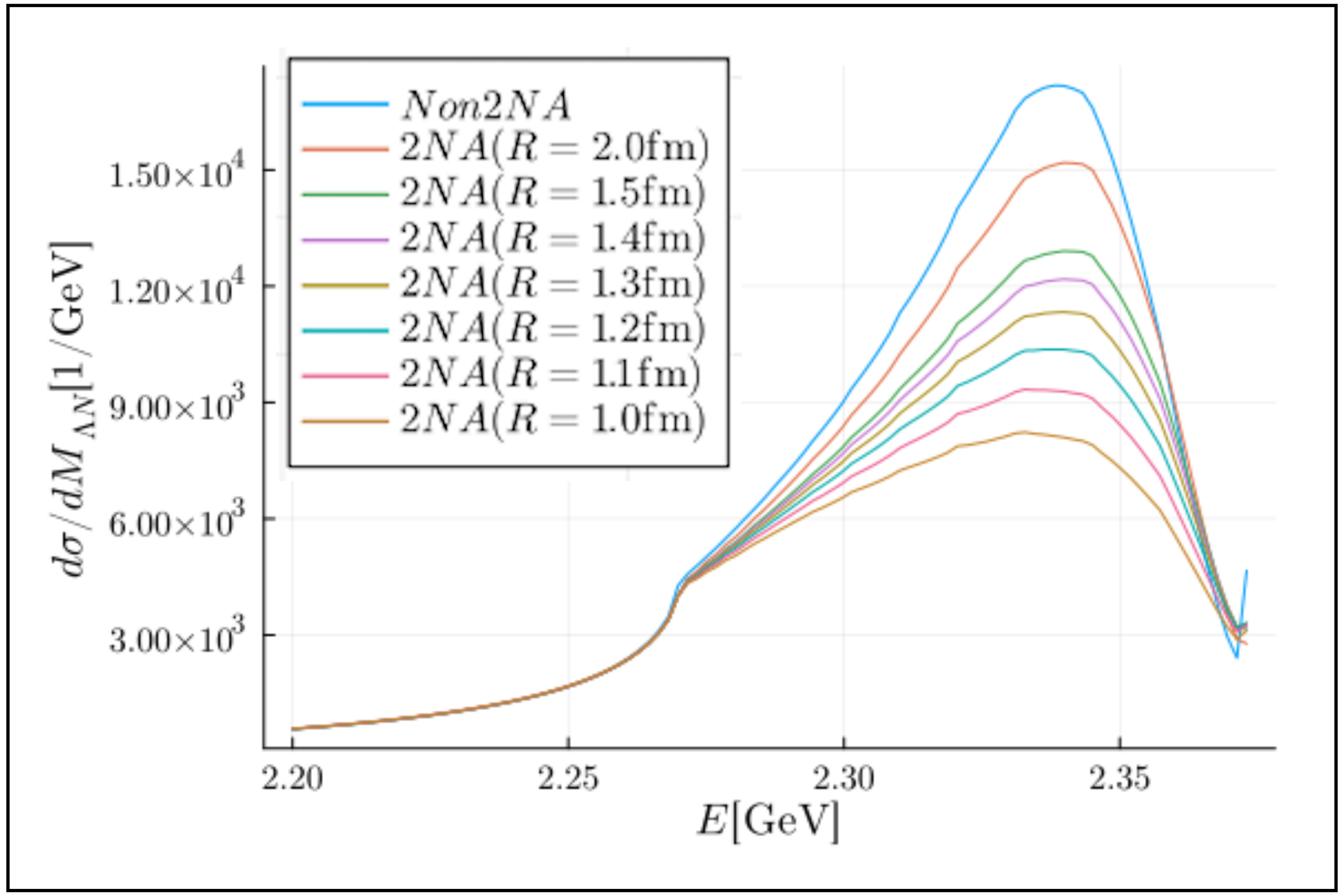
☐ We introduce it into Loop function G in LS equation of $\bar{K}N$ channel

$$G^{(+2NA)}_{\bar{K}N} = \frac{1}{2\pi^2}\int_0^{\infty} dp \frac{p^2 m_{\rm N}}{2\varepsilon_{\rm N}(p)\omega_{\bar{K}}(p)} \frac{f(\Lambda_{\bar{K}N}, p)}{E_{\bar{K}N} - \varepsilon_{\rm N}(p) - \omega_{\bar{K}}(p) - \underline{\frac{\Pi_{\bar{K}N}}{2\omega_{\bar{K}}(p)}}}$$

2. Spectral calculation for the $\bar{K}NN$ nucleus with two-nucleon absorption

■ Results : $\bar{K}NN \to \Lambda N$ scattering amplitude, ΛN mass spectrum $(J^P = 0^-)$





☐ **The range of wave function R is smaller, spectrums are broader !**

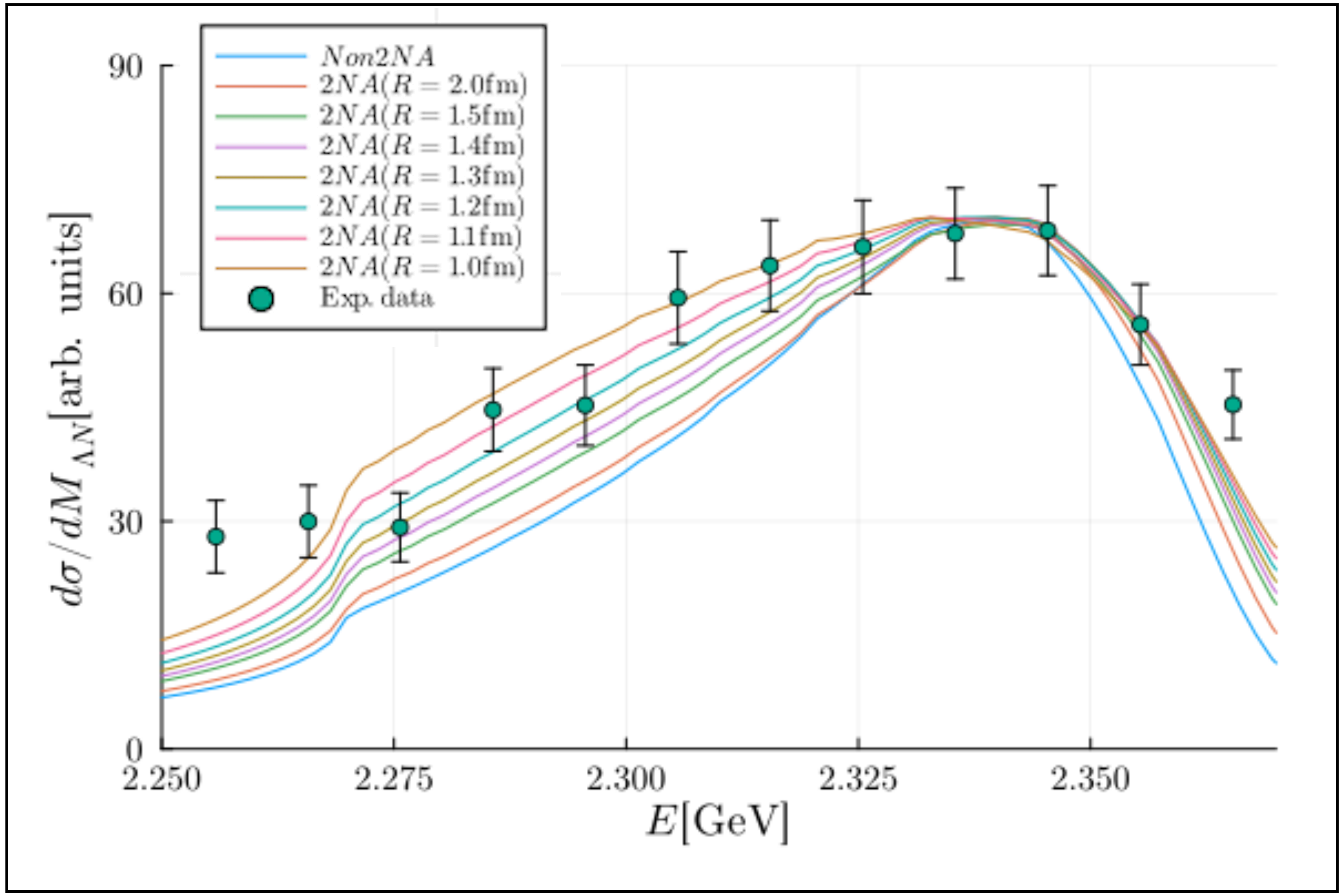
☐ **Since $\bar{K}$ and N are closer by R, 2NA is more likely to occur.**

→ We can see the contribution of 2NA !

2. Spectral calculation for the $\bar{K}NN$ nucleus with two-nucleon absorption

■ Comparison with Exp. data (ΛN mass spectrum)

☐ **We compare with the Exp. Data relatively by multiplying the constant C to match the height of peak.**



$$\boxed{\frac{d\sigma}{dM_{\Lambda N}} = C\, p'_N |X(E)|^2}$$

☐ **The Exp. Data is from previous research.**

T. Yamaga, et al, Phys. Rev. C102 (2020) 044002.

☐ The range of w.f. R : **smaller**

→ **It is more consistent with the Exp. Data !**

☐ **It matches well with the Exp. data**

→ $1.0 \leq R \leq 1.5$ [fm].

- It is importance of 2NA !

3. Formulation in the ${}^{3}\mathrm{He}(K^{-}, \Lambda p)n$ reaction

3. Formulation in the $^{3}\mathrm{He}(K^{-},\Lambda p)n$ reaction

■ The model of our calculation

☐ We aim to construct a precise model to investigate the spin/parity and pole position.

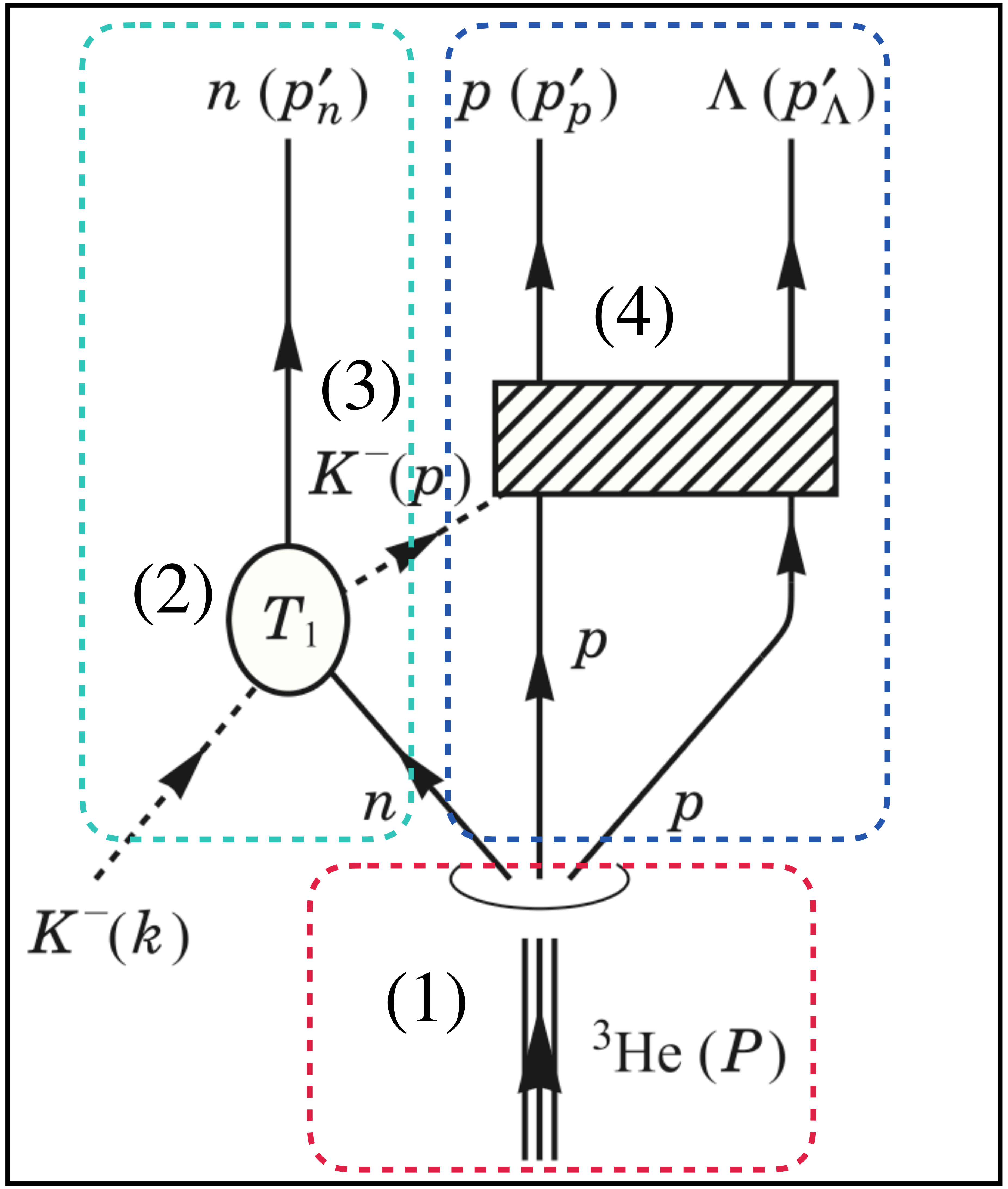
☐ Contributions

(1) $^{3}\mathrm{He}$ wave function.

(2) Two-body amplitude T_1 ($\bar{K}N \to \bar{K}N,\ p_K = 1.0\,\mathrm{GeV}$).

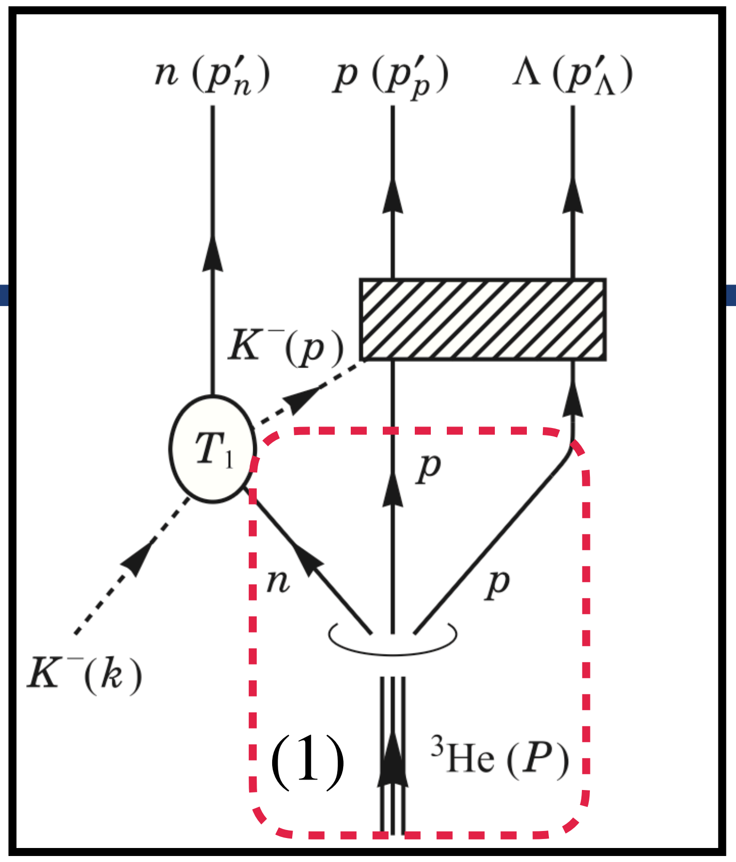
(3) $\bar{K}$ propagator.

(4) Three-body amplitude X ($\bar{K}NN \to \Lambda N$).



T. Sekihara , E. Oset, and A. Ramos, PTEP 2016 123D03

3. Formulation in the $^3\mathrm{He}(K^-, \Lambda p)n$ reaction



■ ^{3}He wave function

V. Baru, J. Haidenbauer, C. Hanhart, and J. A. Niskanen,
Eur. Phys. J. A16(2003) 437.

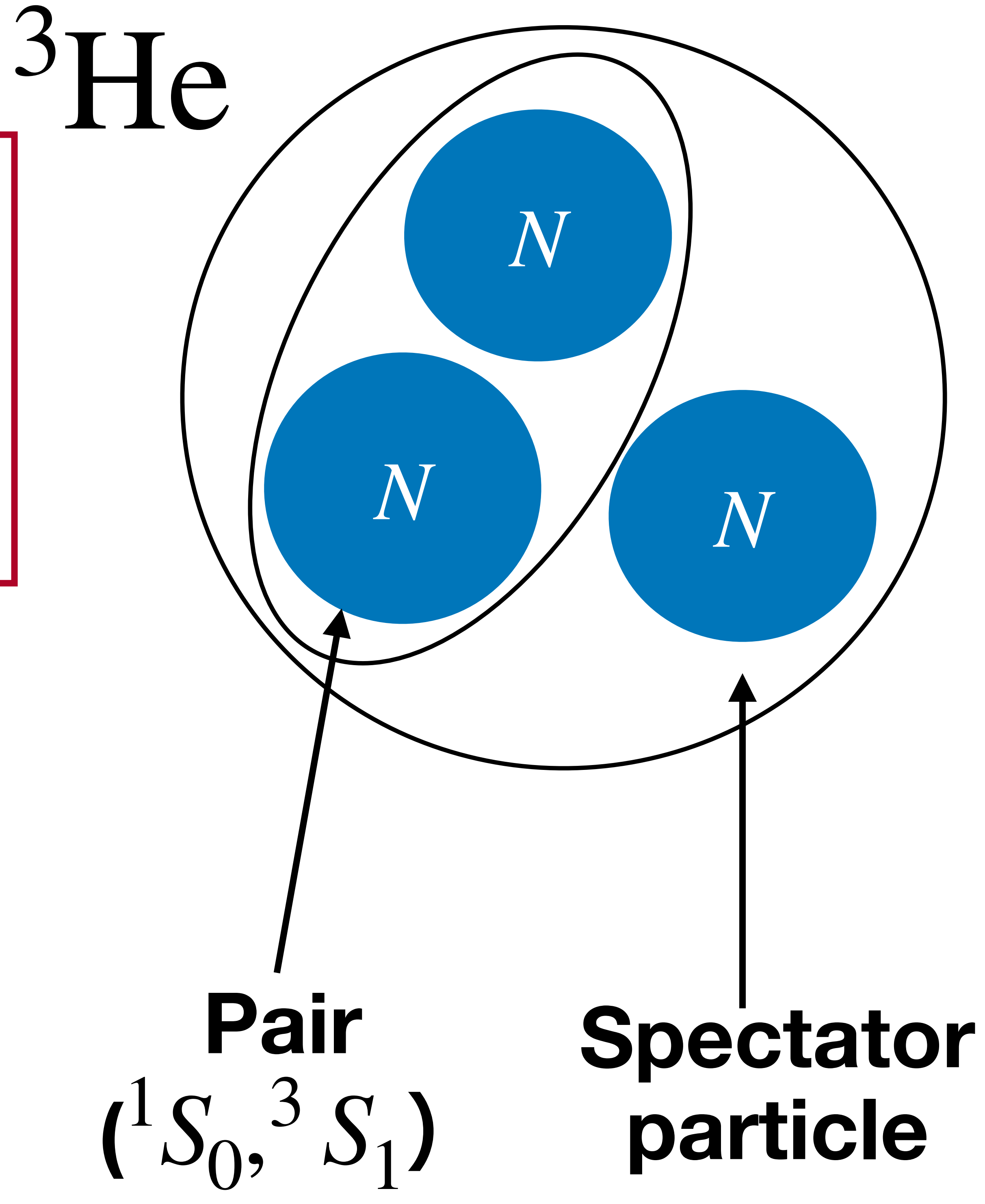
☐ **Precise wave function of three nucleons by a few parameters with CD-Bonn potential(s-wave ~ 90%)**

☐ **Wave function**

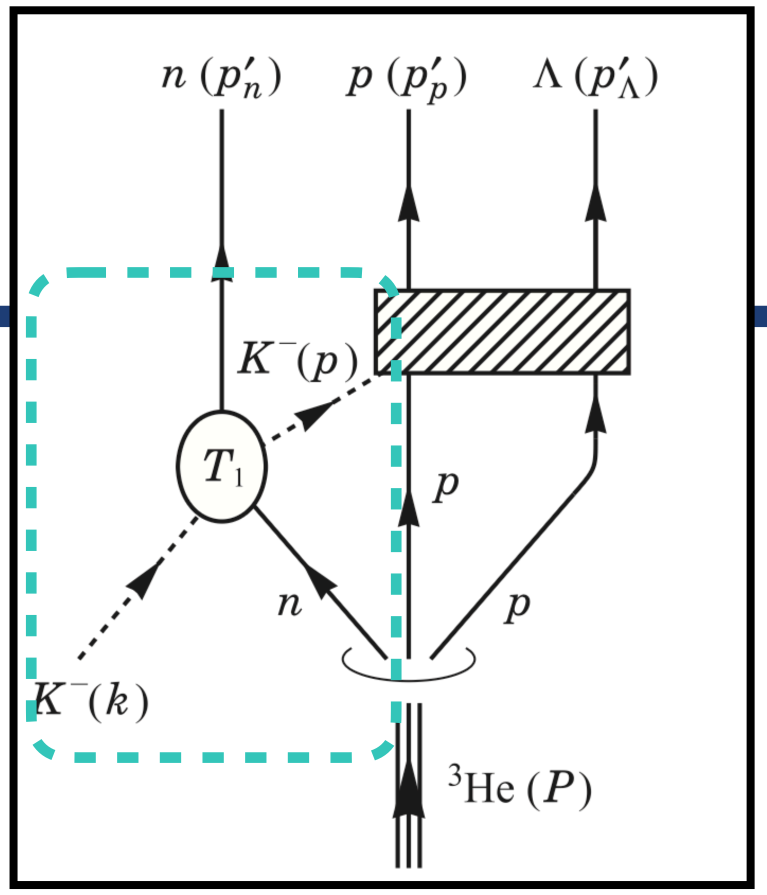
$$\left|^3\mathrm{He}_\uparrow\right\rangle = v^{^1S_0}(p_\rho)\,w^{^1S_0}(p_\lambda)\left|-\frac{1}{\sqrt{3}}n_\uparrow(p_\uparrow p_\downarrow - p_\downarrow p_\uparrow) + \frac{1}{2\sqrt{3}}p_\uparrow(p_\uparrow n_\downarrow + n_\uparrow p_\downarrow - p_\downarrow n_\uparrow - n_\downarrow p_\uparrow)\right\rangle$$
$$+\, v^{^3S_1}(p_\rho)\,w^{^3S_1}(p_\lambda)\left|-\frac{1}{\sqrt{3}}p_\downarrow(p_\uparrow n_\uparrow - n_\uparrow p_\uparrow) + \frac{1}{2\sqrt{3}}p_\uparrow(p_\uparrow n_\downarrow - n_\uparrow p_\downarrow + p_\downarrow n_\uparrow - n_\downarrow p_\uparrow)\right\rangle$$

- functions v, w of pair and spectator particle given by 5 term expansion

$$v^\nu_\lambda(p) = \sum_{n=1}^{5}\frac{a^\nu_{n,\lambda}}{p^2 + (m^\nu_{n,\lambda})^2}, \quad w^\nu_\lambda(q) = \sum_{n=1}^{5}\frac{b^\nu_{n,\lambda}}{q^2 + (M^\nu_{n,\lambda})^2} \quad (\nu = {}^1\mathrm{S}_0, {}^3\mathrm{S}_1)$$



3. Formulation in the $^3\mathrm{He}(K^-, \Lambda p)n$ reaction

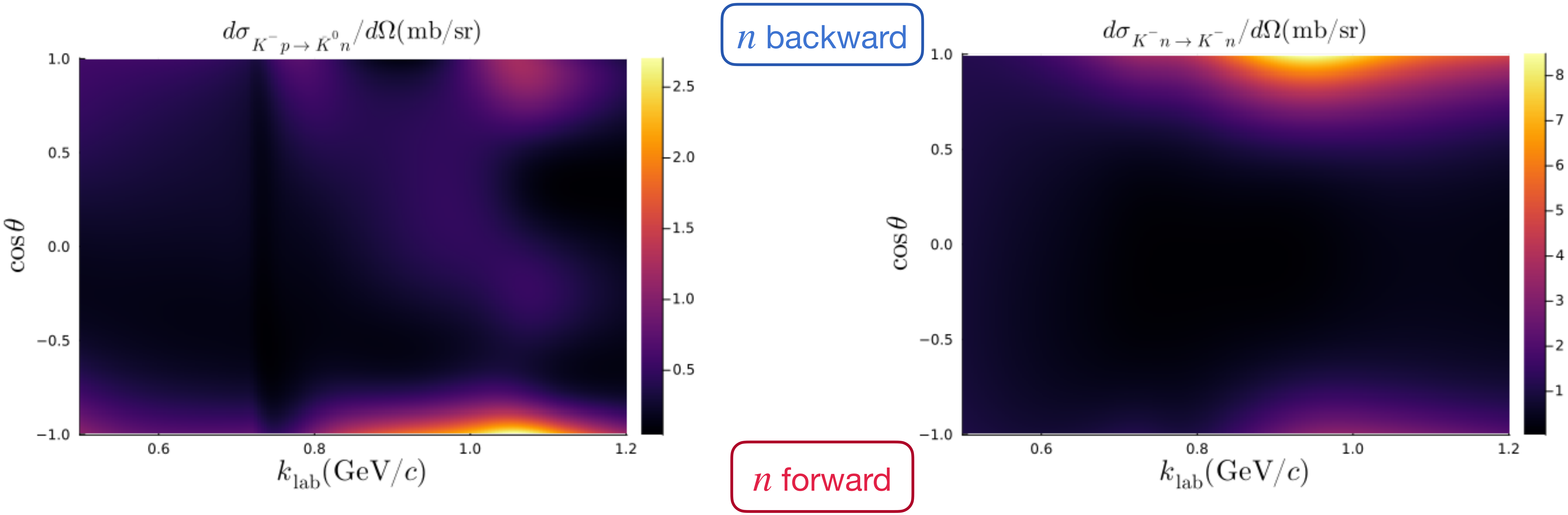


- **Two-body amplitude T_1 ($\bar{K}N \to \bar{K}N$)**

H. Kamano, S. X. Nakamura, T. -S. H. Lee, and T. Sato, Phys. Rev. C90 (2014) 065204.

□ $\bar{K}N$ **interaction → Kamano amplitude** T_{Kamano}

- calculate $K^-p \to \bar{K}^0 n$, $K^-n \to K^-n$ cross section.



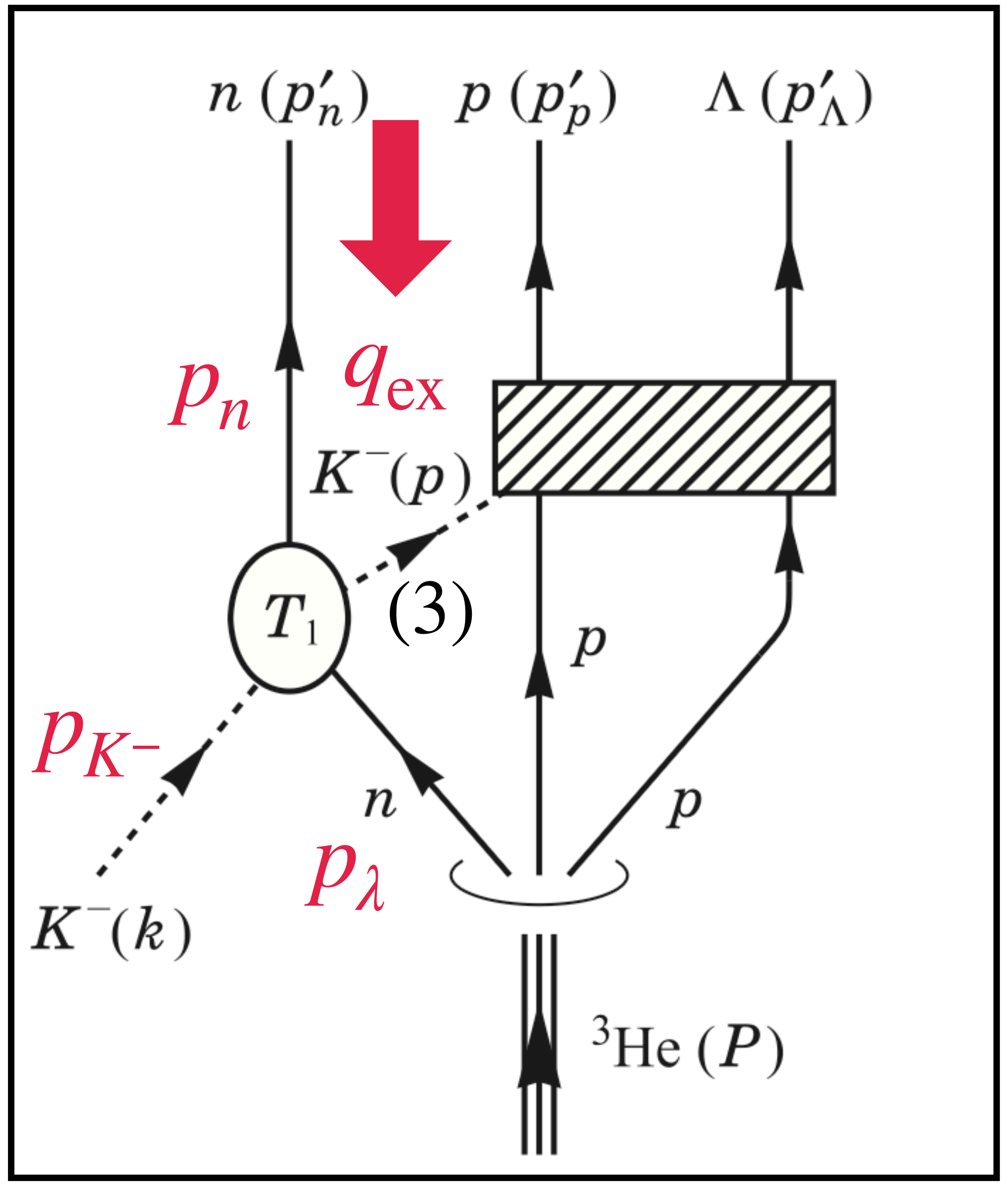
—it is likely that these reaction occur around $(k_{\mathrm{lab}}, \cos\theta) = (1.0\,\mathrm{GeV}, \pm 1.0)$.

3. Formulation in the $^3\mathrm{He}(K^-, \Lambda p)n$ reaction

■ $\bar{K}$ propagator

□ Scattering amplitude

$$T = \int \frac{d^3 p_\lambda}{(2\pi)^3} \frac{w^\nu(p_\lambda)}{(q_{\mathrm{ex}}^0)^2 - \boldsymbol{q}_{\mathrm{ex}}^2 - m_{\bar{K}}^2 + i\varepsilon}$$

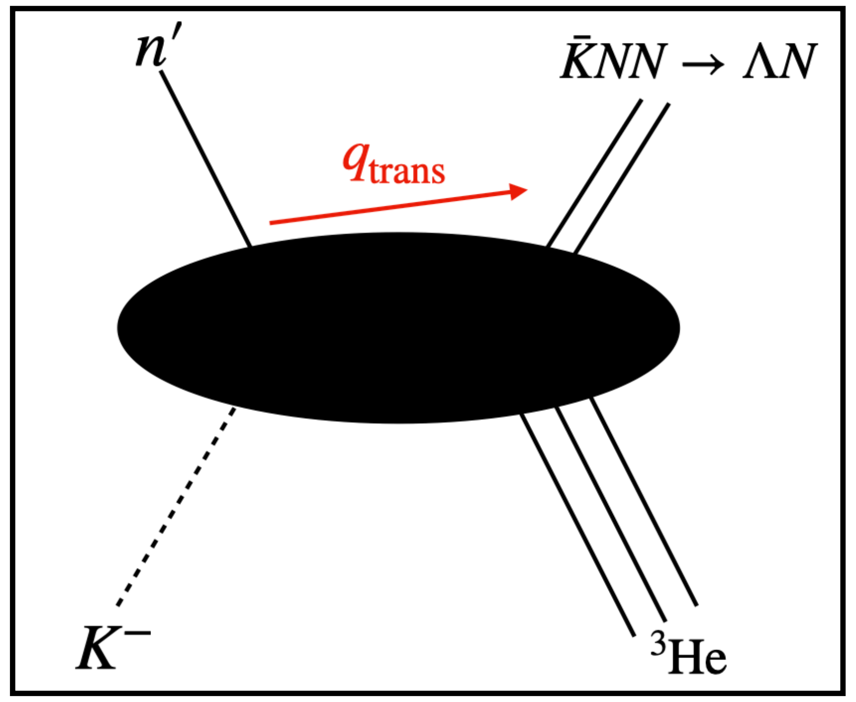


- $\bar{K}$ momentum in final state

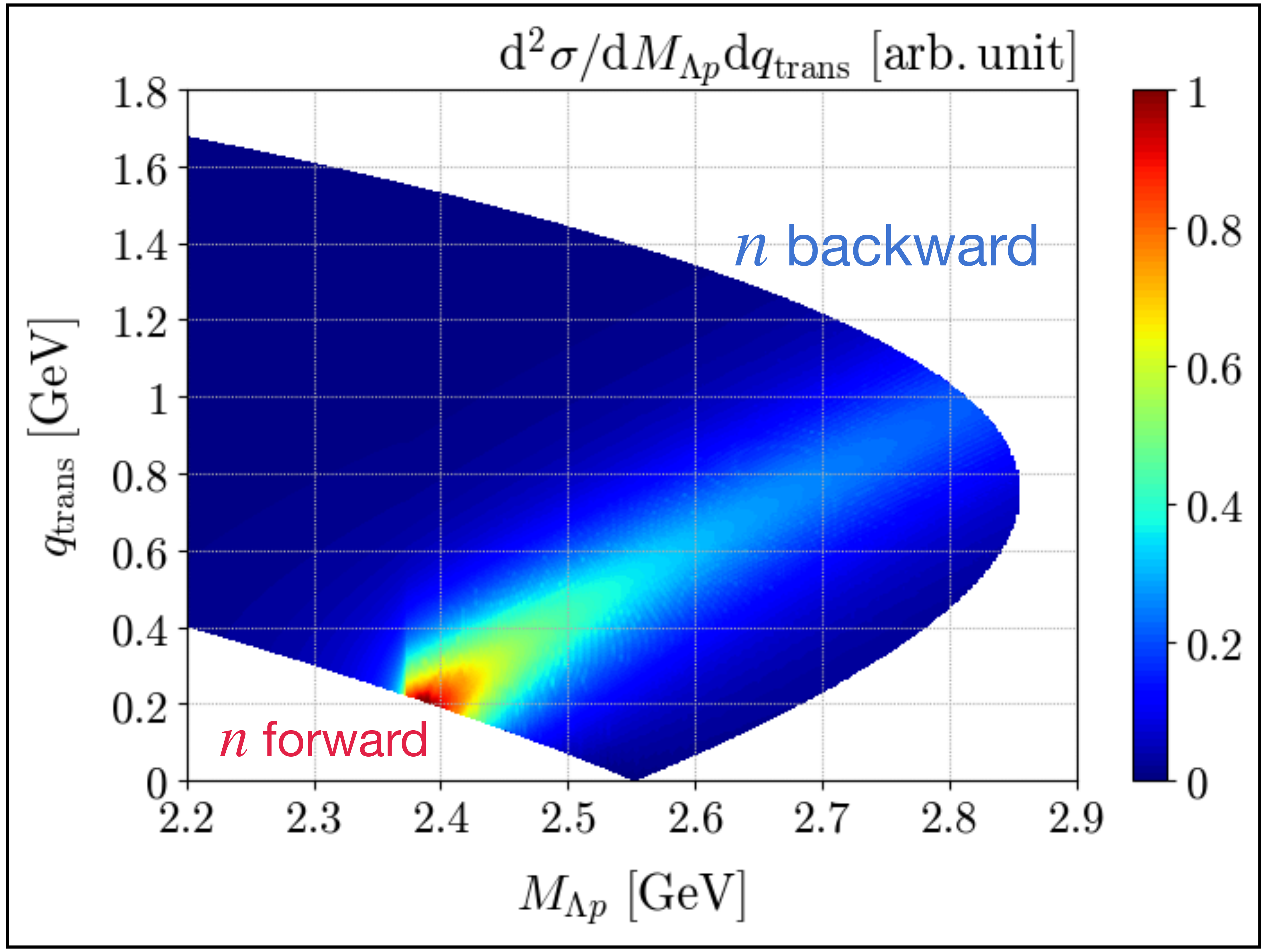
$$\boldsymbol{q}_{\mathrm{ex}} = \boldsymbol{p}_{K^-} + \boldsymbol{p}_\lambda - \boldsymbol{p}_n$$

- momentum transfer

$$\boldsymbol{q}_{\mathrm{trans}} = \boldsymbol{p}_{K^-} - \boldsymbol{p}_n$$

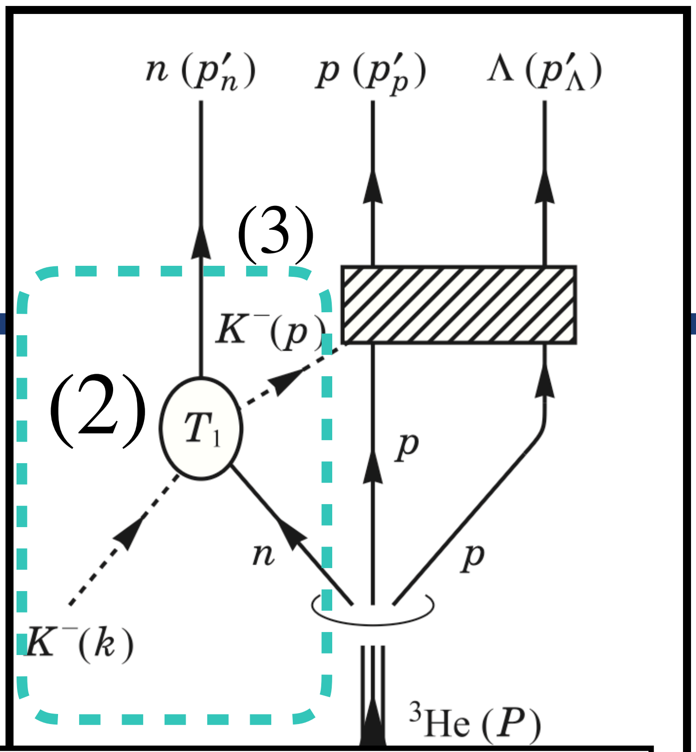


□ Differential cross section



- Band structure：**the propagating $\bar{K}$ as (almost) on-shell particle**

3. Formulation in the $^{3}\mathrm{He}(K^{-}, \Lambda p)n$ reaction

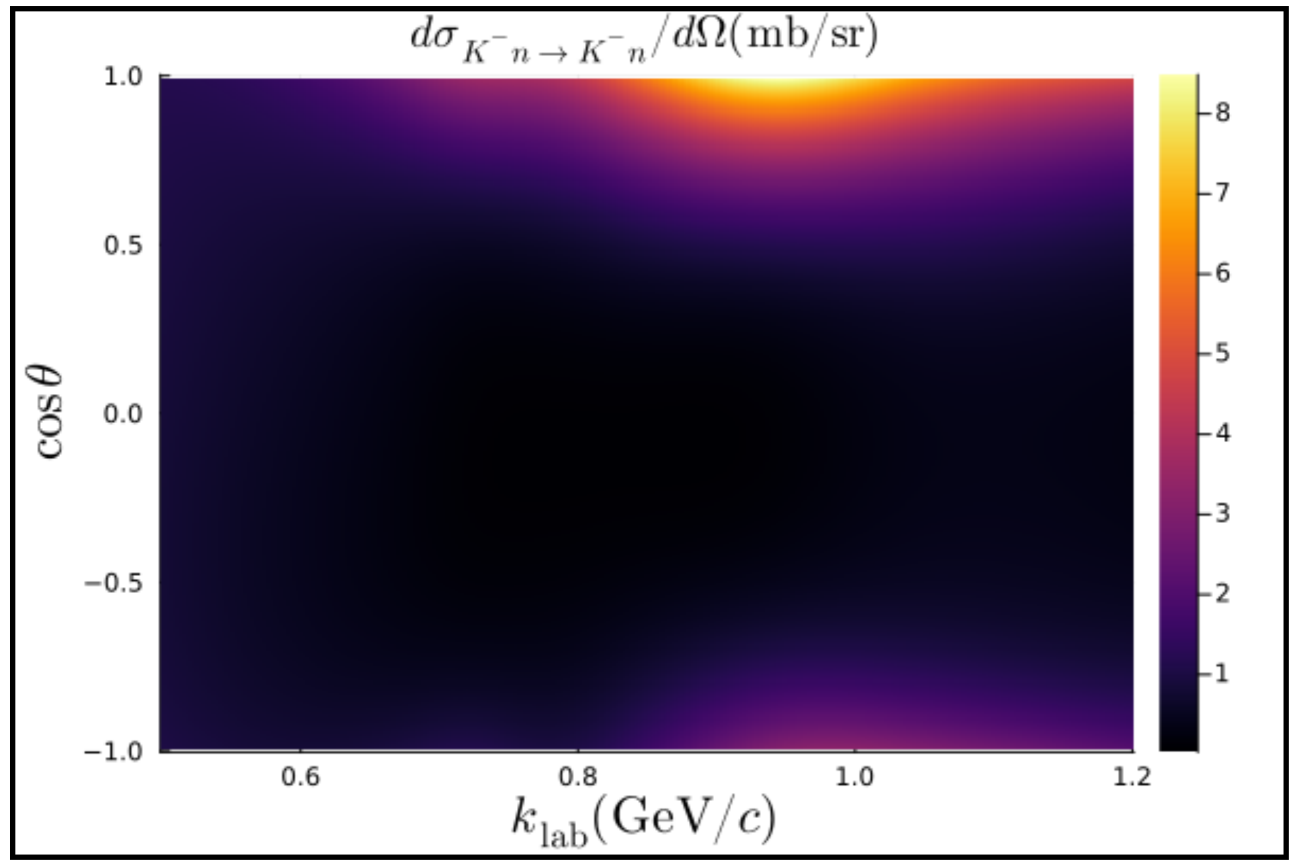


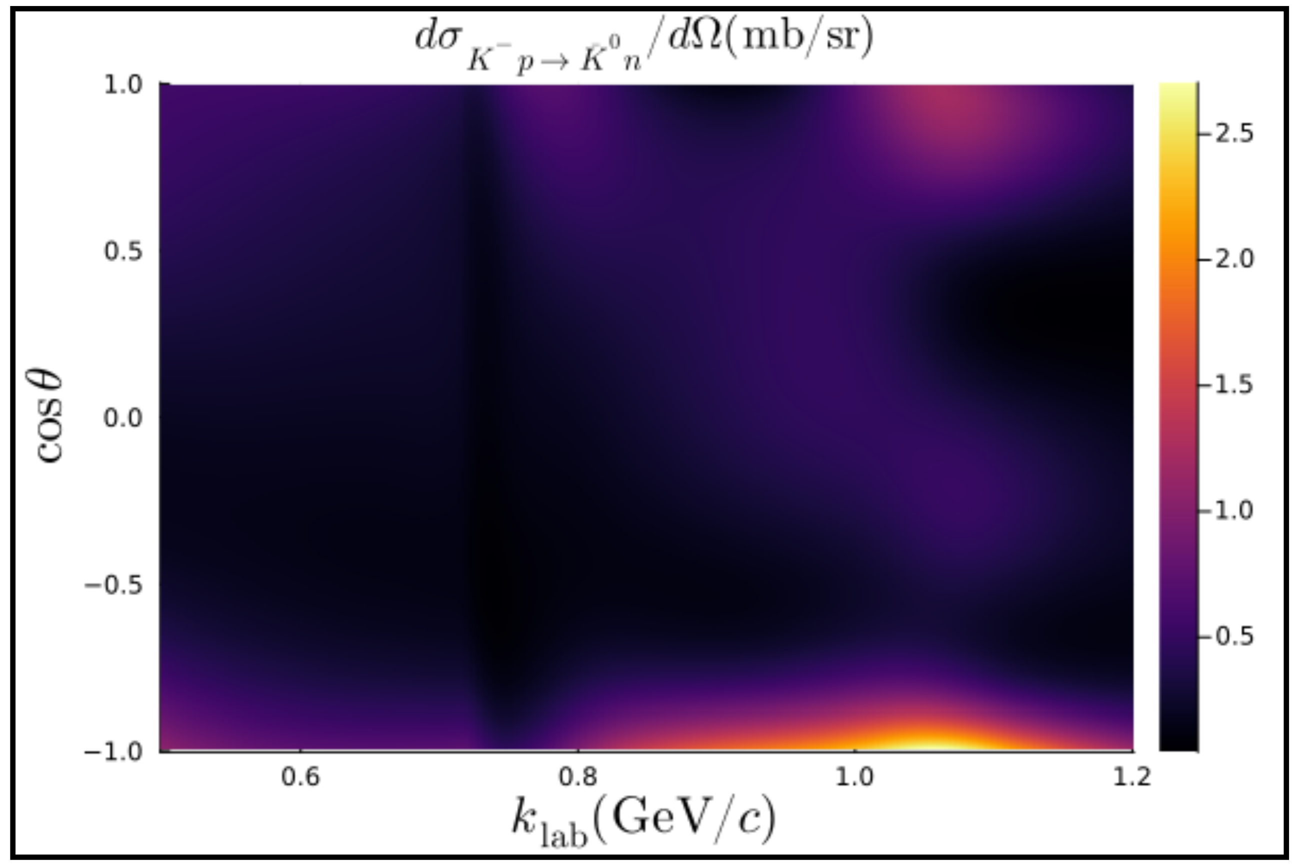
- ■ **two-body amplitude T_1 ($\bar{K}N \to \bar{K}N,\ k_{\mathrm{lab}} = 1.0\,\mathrm{GeV}$) × $\bar{K}$ propagator**

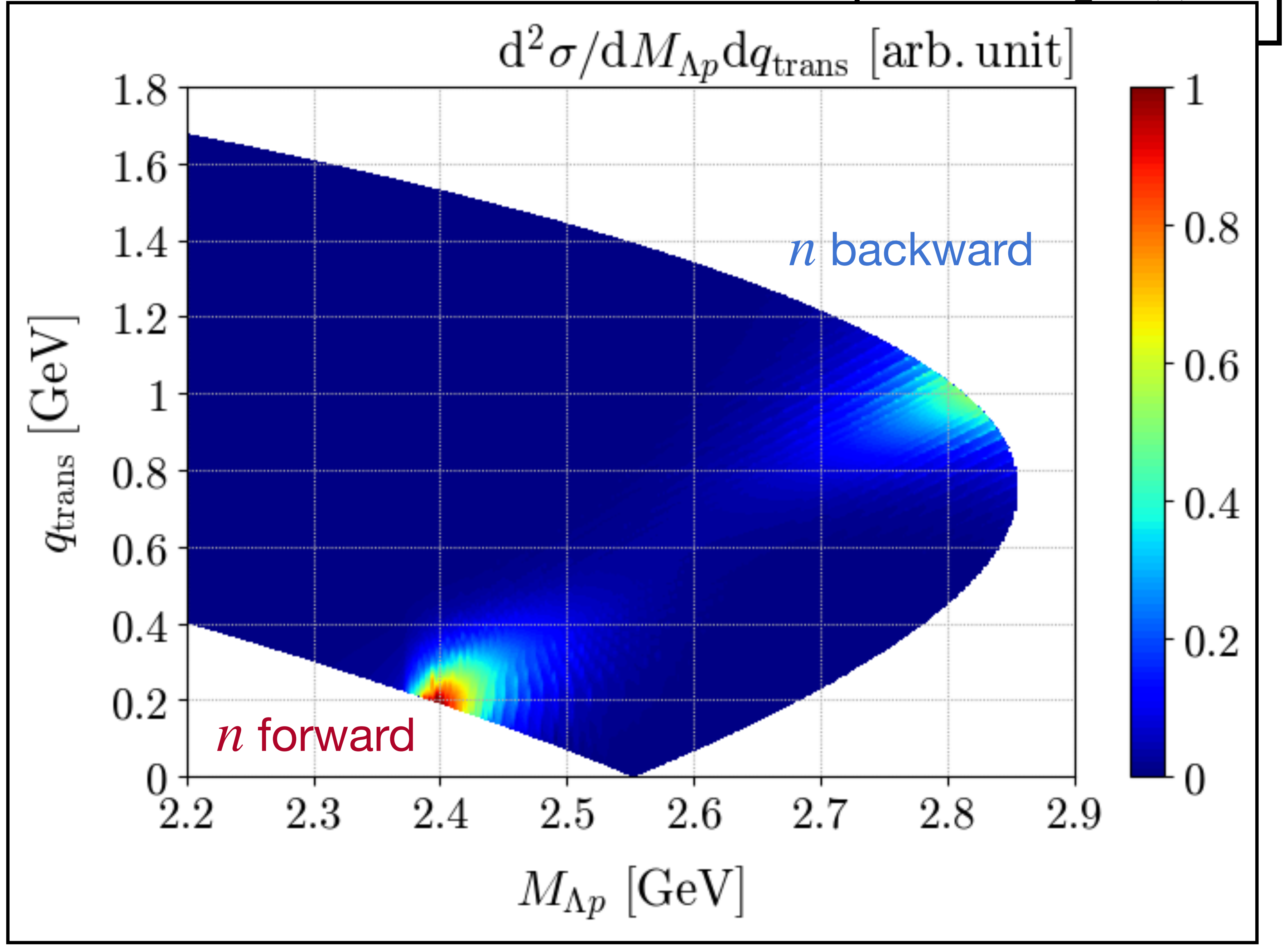
☐ **Inclusion Kamano amplitude T_{Kamano} into $\bar{K}$ propagator**

- considering the final state n

$$T = \int \frac{d^3 p_\lambda}{(2\pi)^3} \frac{w^{\nu}(p_\lambda) T_{\mathrm{Kamano}}}{(q^0_{\mathrm{ex}})^2 - \boldsymbol{q}^2_{\mathrm{ex}} - m^2_{\bar{K}} + i\varepsilon}$$





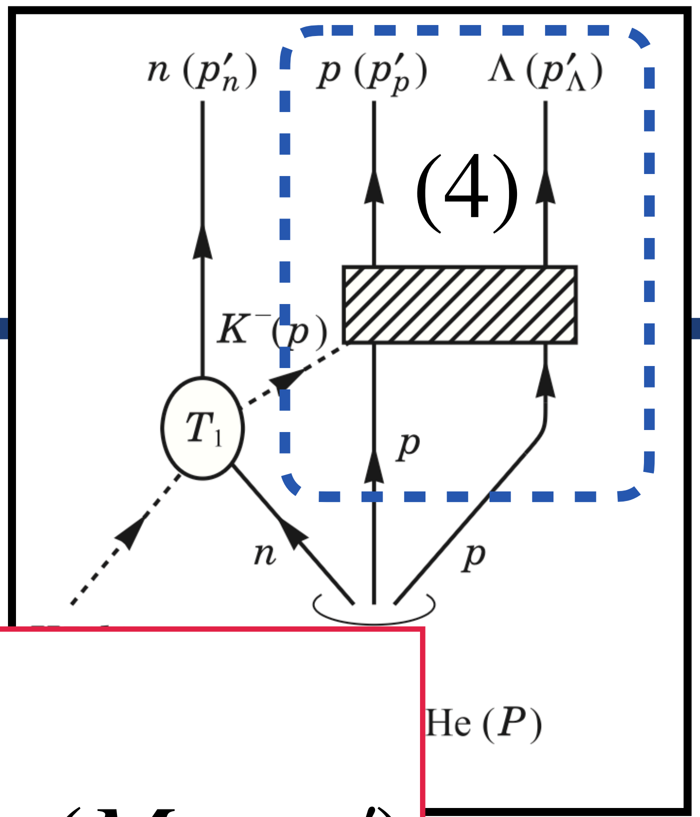


☐ **We have 2 regions**

・n forward → **Essential to generate $\bar{K}NN$ bound state**

・n backward

3. Formulation in the ${}^3\mathrm{He}(K^-, \Lambda p)n$ reaction



- $\bar{K}NN \to \Lambda N$ **scattering amplitude(** $X_{\bar{K}NN\to\Lambda N}$ **)**

☐ $\bar{K}NN \to \Lambda N$ **scattering amplitude :**

$$X_{\bar{K}NN\to\Lambda N} = \int_0^\infty \frac{dp}{2\pi^2} p^2 v^\nu(p) \int_0^\infty \frac{dp'}{2\pi^2} p'^2 X_{11}(M_{\Lambda p}, p', p) Z_{\Lambda N}(M_{\Lambda p}, p')$$

☐ **Full amplitude in overall reaction :**

$$T_{\mathrm{full}} = \int \frac{d^3 p_\lambda}{(2\pi)^3} \frac{w^\nu(p_\lambda) T_{\mathrm{Kamano}} X_{\bar{K}NN\to\Lambda N}}{(q^0_{\mathrm{ex}})^2 - \boldsymbol{q}^2_{\mathrm{ex}} - m^2_{\bar{K}} + i\varepsilon}$$

☐ **We consider the coupled channels for each spin/parity as below.**

$$\overbrace{K^- pp - \underbrace{\bar{K}^0 pn - \bar{K}^0 np}_{J^P = 1^-}}^{J^P = 0^-}$$

- It is in progress and we will calculate observables corresponding to the Exp. Data !

4. Summary and Outlook

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■ Summary

☐ Our Purpose：Determine the spin/parity and pole position of the $\bar{K}NN$ nucleus

☐ We performed spectral calculation with two-nucleon absorption in a framework of Faddeev equation.

☐ We construct a precise model for reaction calculation.

■ Outlook

☐ Perform reaction calculation.

- production cross section, pole position, …

☐ Evaluate and compare with the Exp. Data at J-PARC.

Thank you for your attention !