$K^- d \to \pi \Lambda N$ reaction with in-flight kaons for studying the ΛN interaction

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Introduction

		Λp	Λn
a[fm]	(Spin) singlet	$-2.43^{+0.16}_{-0.25}$	—
	triplet	$-1.56^{+0.19}_{-0.22}$	—
r[fm]	singlet	$2.21^{+0.16}_{-0.36}$	—
	triplet	$3.7^{+0.6}_{-0.6}$	—

Experimental data[1]

- Low energy scattering amplitudes for 2-body systems are parametrized by scattering length a and effective range r.
- We want to explore the values of $a_{\Lambda n}$, $r_{\Lambda n}$ and how large is Isospin Symmetry Breaking (ISB) of the ΛN system, $a_{\Lambda n}/a_{\Lambda p}$ and $r_{\Lambda n}/r_{\Lambda p}$.

[1] A. Budzanowski *et al.* (HIRES Collaboration), Phys. Lett. B 687, 31 (2010)

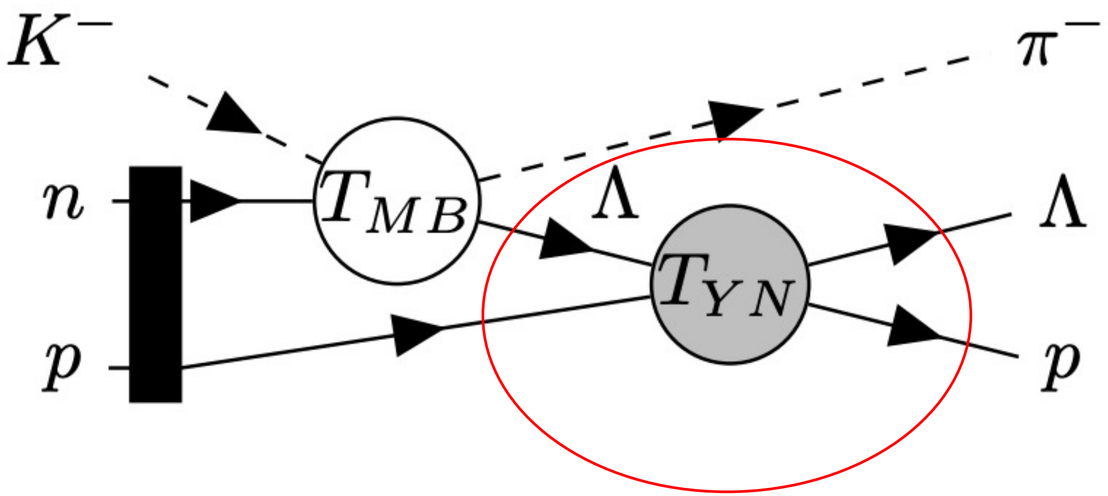
Overview of Methods

- Calculate the ΛN invariant mass spectra of $K^- d \to \pi^- \Lambda p$ and $K^- d \to \pi^0 \Lambda n$ reaction near the mass threshold.
- Incident K^- momentum is 1000 MeV/c (p-wave and spin-flip effects) (cf. our previous study[2]: zero momentum)
- When $a_{n/p} \equiv a_{\Lambda n} / a_{\Lambda p}$, $r_{n/p} \equiv r_{\Lambda n} / r_{\Lambda p}$ are used as parameters, how much does cross section ratio $\sigma_{n/p}$ vary?

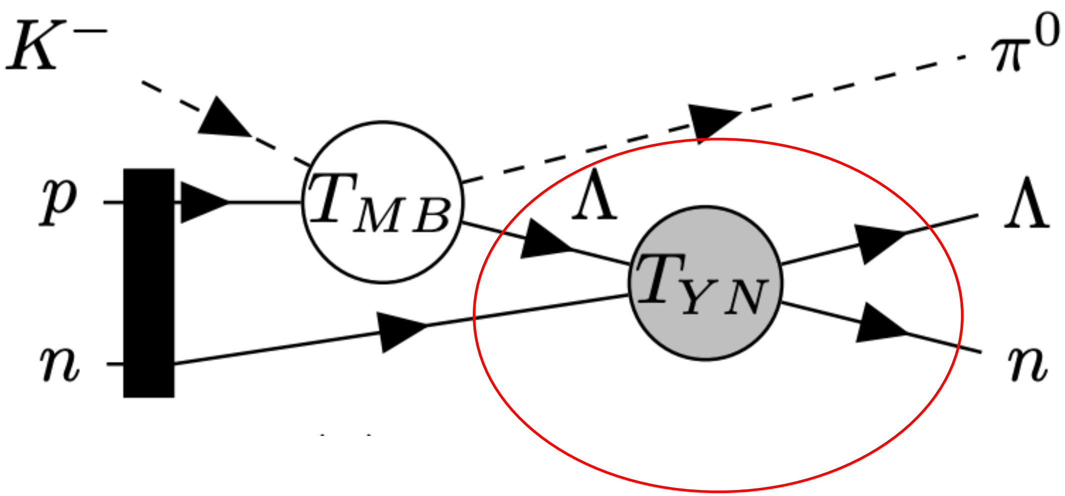
[2] Y. Iizawa, D. Jido, T. Ishikawa, Phys. Rev. C 106 045201 (2022)

Scattering processes (Foreground)

Foreground(our target) diagram for each reaction



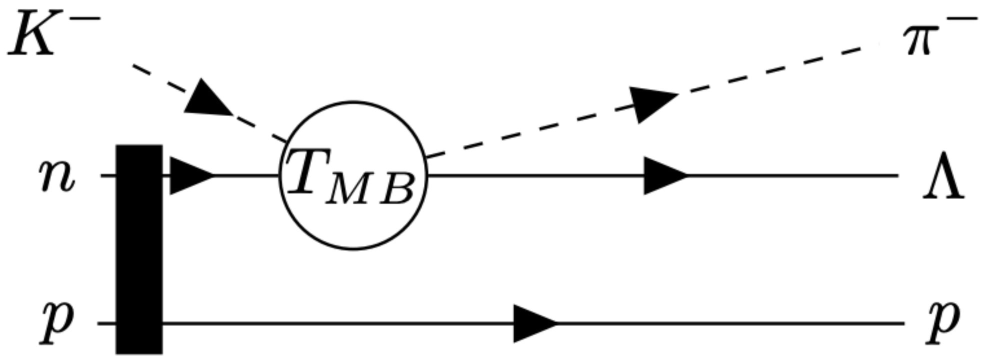
$K^- d \rightarrow \pi^- \Lambda \mathrm{p}$



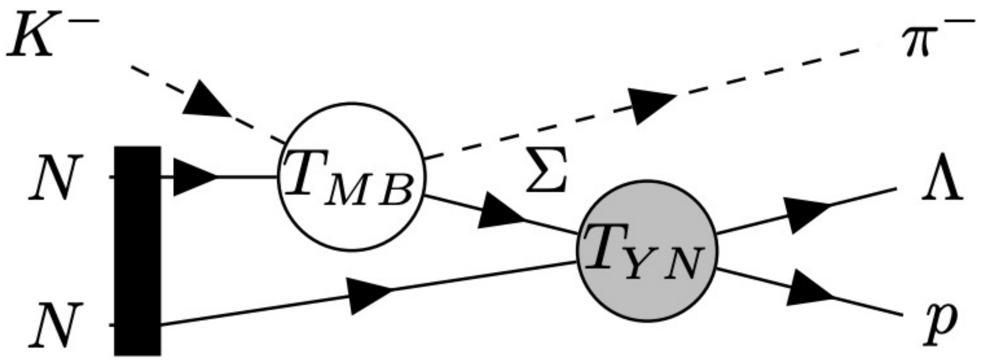
$K^- d \rightarrow \pi^0 \Lambda \mathrm{n}$

Scattering processes (Backgrounds)

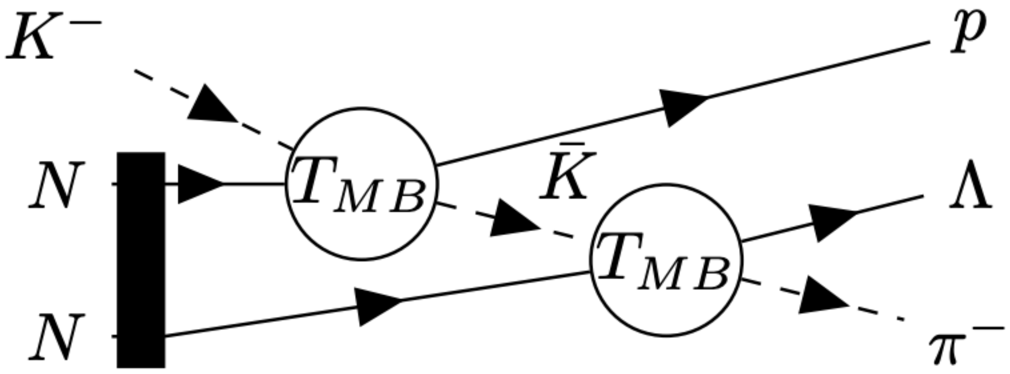
Background diagrams for the $K^- d \to \pi^- \Lambda p$ reaction



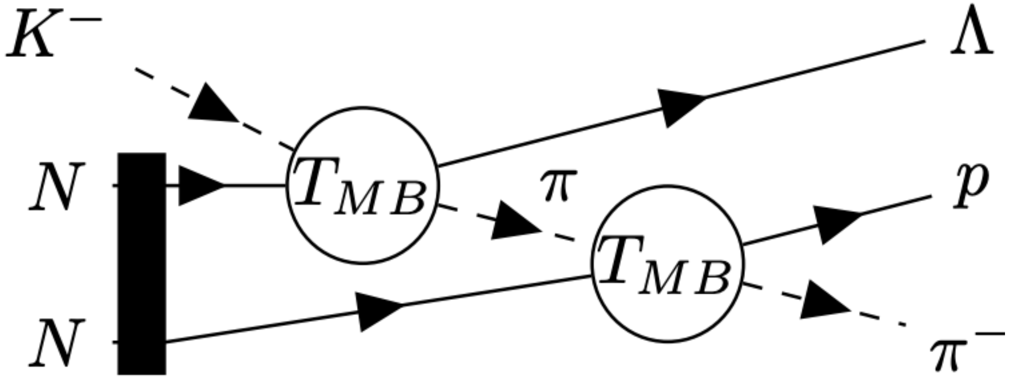
impulse



Σ exchange



$\bar{K}$ exchange



π exchange

Meson-Baryon amplitude: T_{MB}

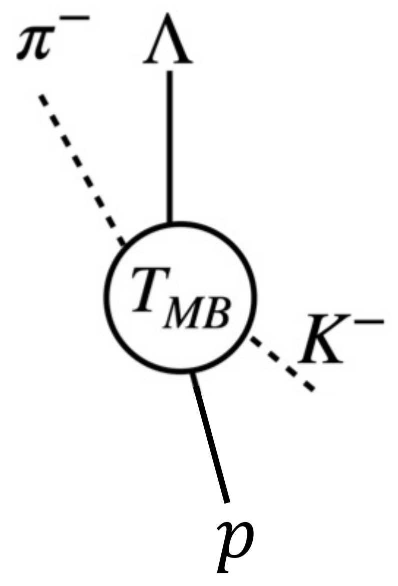
- Partial wave expansion (s-wave + p-wave)

- $\bar{K}N$ amplitudes ($\bar{K}N \to \bar{K}N, \pi Y$)

  Chiral unitary approach[3,4,5]

  (amplitudes for each isospin state)

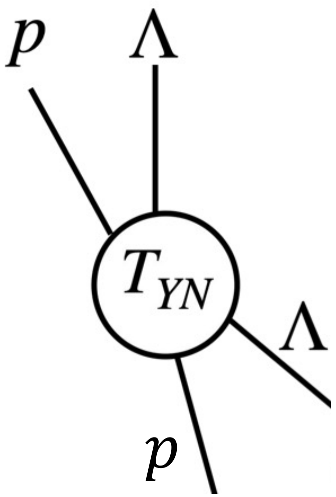
- πN amplitudes SAID data[6]



$T_{K^- p \to \pi^- \Lambda}$

[3] N. Kaiser, P. B. Siegel, and W. Weise, Nucl. Phys. A 594, 325 (1995).
[4] E. Oset, A. Ramos, Nucl. Phys. A 635, 99 (1998)
[5] D. Jido, E. Oset, A. Ramos, Phys. Rev. C 66, 055203 (2002)
[6] SAID partial-wave analysis, https://said.phys.gwu.edu/analysis/pin_analysis.html

Λ-Nucleon amplitude: $T_{\Lambda N}$



$T_{\Lambda p\to\Lambda p}$

- Near the mass threshold ($M_{\Lambda N} \sim M_\Lambda + M_N$),
  ΛN amplitudes are described by effective range expansion,

$$T_{\Lambda N\to\Lambda N} = \left(-\frac{1}{a_{\Lambda N}} + \frac{1}{2} r_{\Lambda N}\, p_\Lambda^2 - i p_\Lambda\right)^{-1}$$

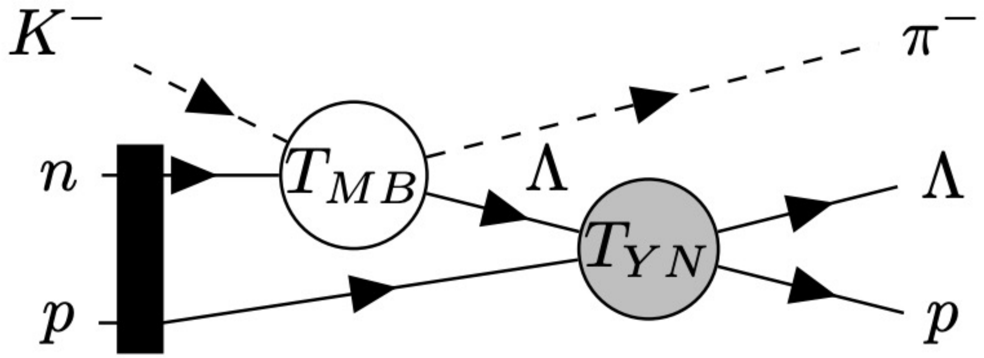
p_Λ : momentum of Λ

- Spin-singlet and spin-triplet states for the ΛN system

$$T^{singlet}_{\Lambda N\to\Lambda N} = T_{\Lambda N\to\Lambda N}(a^{singlet}, r^{singlet})$$

$$T^{triplet}_{\Lambda N\to\Lambda N} = T_{\Lambda N\to\Lambda N}(a^{triplet}, r^{triplet})$$

Spin in amplitude



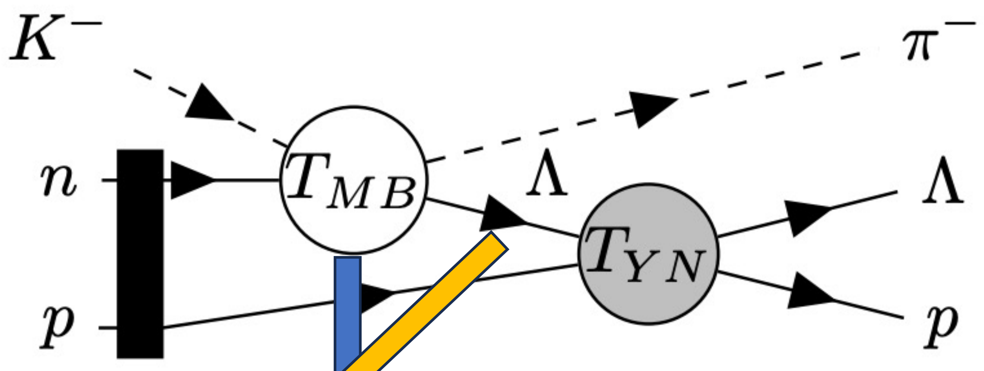
Spin part in the amplitude of the foreground

$$T_{spin} = \frac{1}{4}(3T^s_{\Lambda N} + T^t_{\Lambda N})\, T_{K^-n \to \pi^-\Lambda}\, S_d$$

$$+\frac{1}{4}(T^s_{\Lambda N} - T^t_{\Lambda N})\, \sigma_\Lambda\, T_{K^-n \to \pi^-\Lambda}\, S_d (\sigma_p)^T$$

(S_d: spin of deuteron)

Amplitude of foreground



Amplitude of the foreground

propagator

Momentum conservation

$\vec{p}_d + \vec{p}_{K^-} = \vec{q} + \vec{p}_{\pi^-}$

$$T = T_{spin} \times \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{2M_\Lambda}{q_0^2 - \vec{q} - M_\Lambda + i\epsilon} \varphi(|\vec{q} + \vec{p}_{\pi^-} - \vec{p}_{K^-}|)$$

(q: momentum of the intermediate Λ)

(φ: deuteron wave function in momentum space)

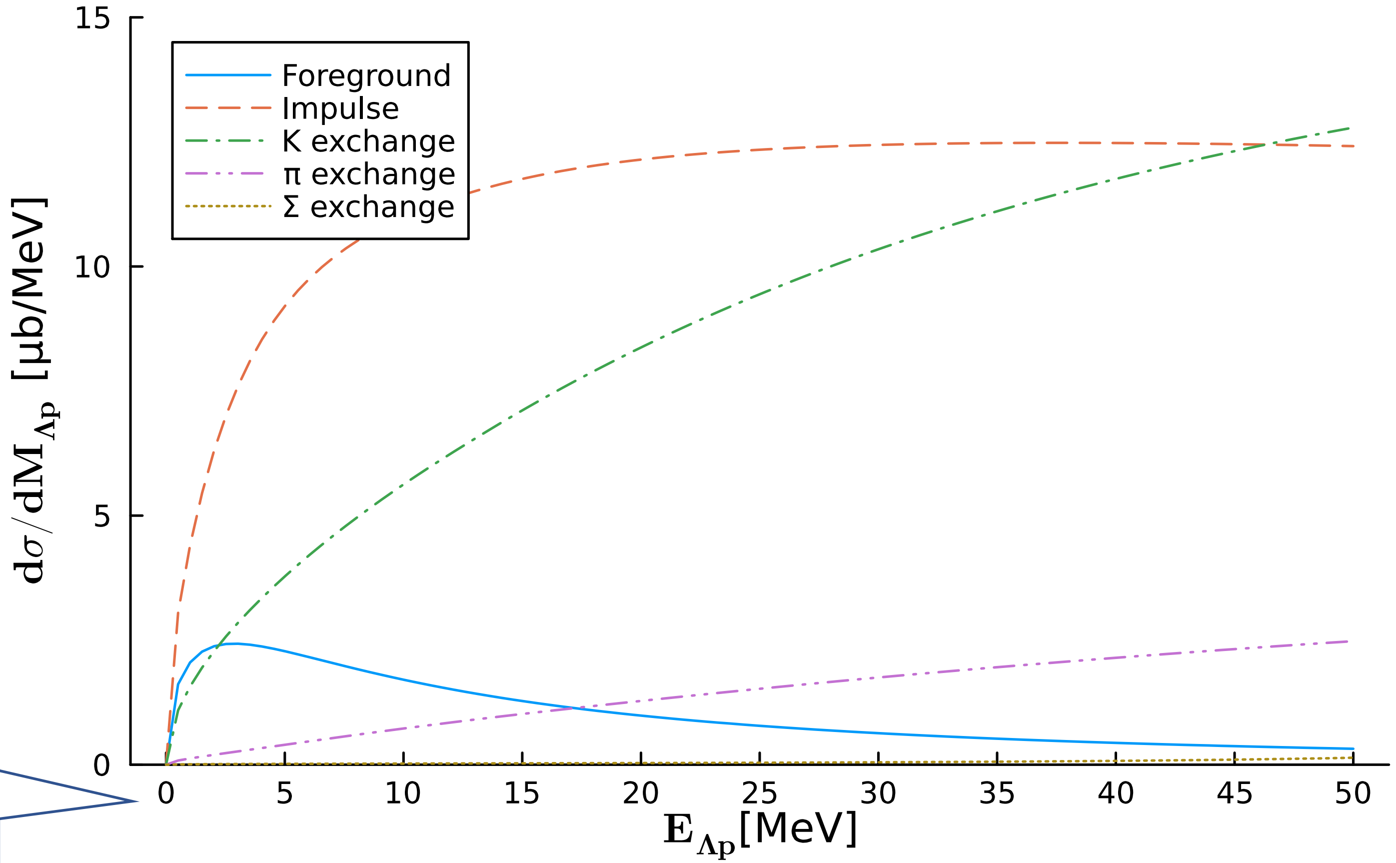
Cross section of each term ($K^- d \to \pi^- \Lambda p$)

- Cross section of the reaction

$$\frac{d\sigma}{dM_{\Lambda N}} = (kinetic\ term) \times \int |T|^2 dV$$

T: scattering amplitude
dV: phase space of the reaction

Λp threshold ($M_\Lambda + M_p$)



Angular restriction of Pion (background reduction①)

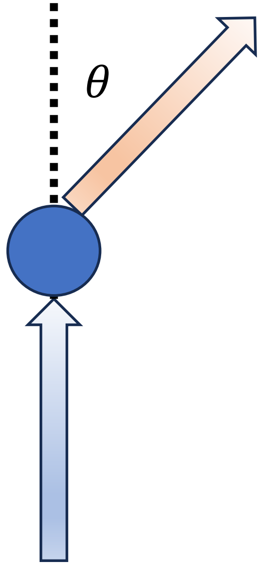
We restrict pion angle to the forward direction ($\cos\theta \geq 0.9$).

1. Reduction of background processes

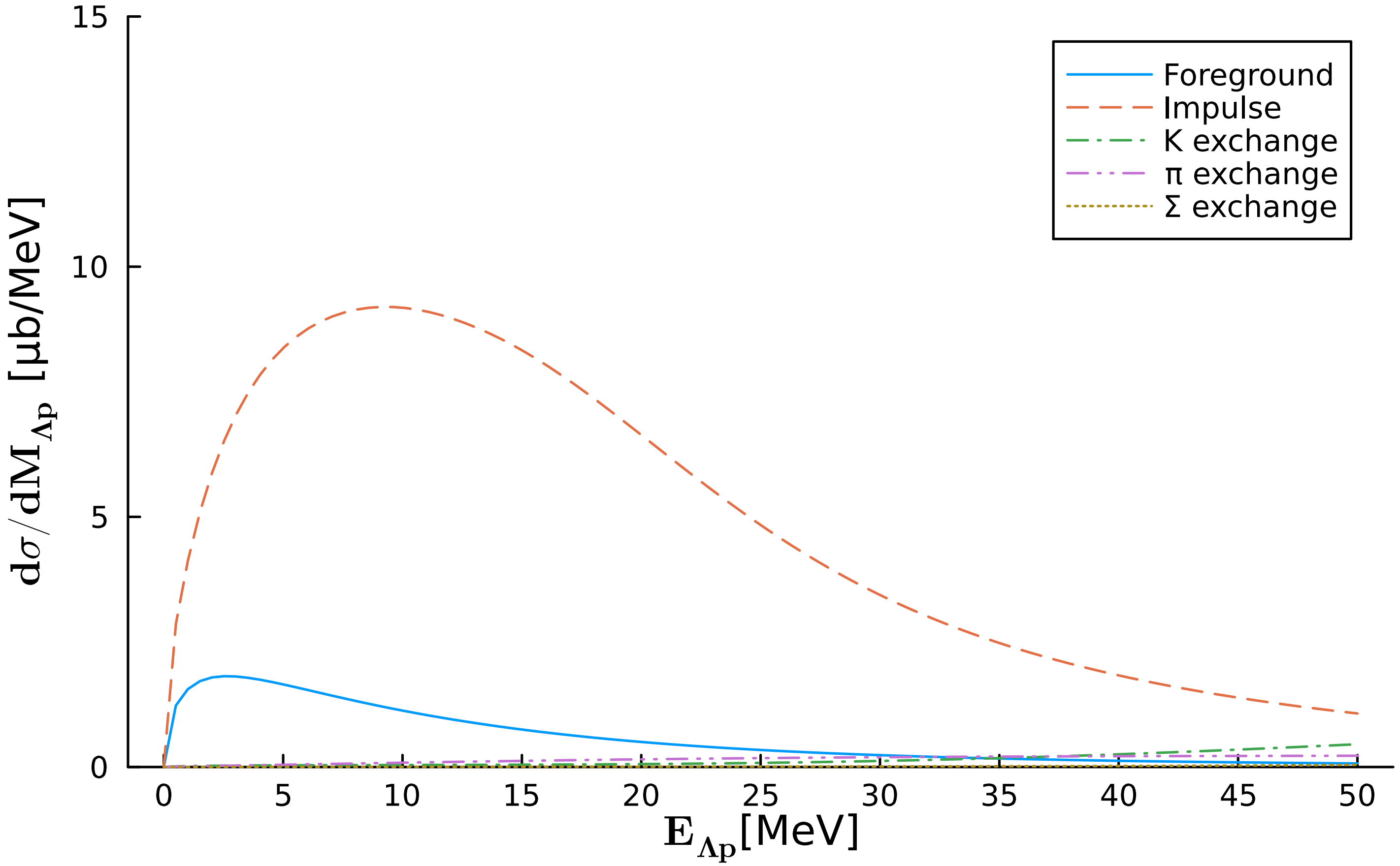
2. Separation of parameters (spin selection rule)

   4 parameters $a^s_{n/p}, r^s_{n/p}, a^t_{n/p}, r^t_{n/p}$

   Results become dependent solely on $a^t_{n/p}, r^t_{n/p}$ (triplet)



Reduction of meson exchange (background reduction①)



Restriction
Forward pion,
$\cos\theta \geq 0.9$

$$\frac{d\sigma}{dM_{\Lambda N}} = (kinetic)\times\int_{\cos\theta\geq 0.9} |T|^2\, dV$$

Reduction of backgrounds (K, π exchange)

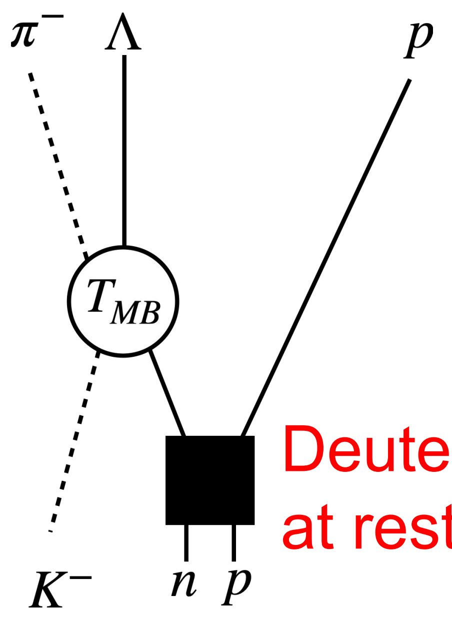
Momentum restriction of Nucleon
(background reduction②)

- We pick up events where nucleon momentum is large.

$$p_{Nucleon} \geq 150 \text{ MeV/c}$$

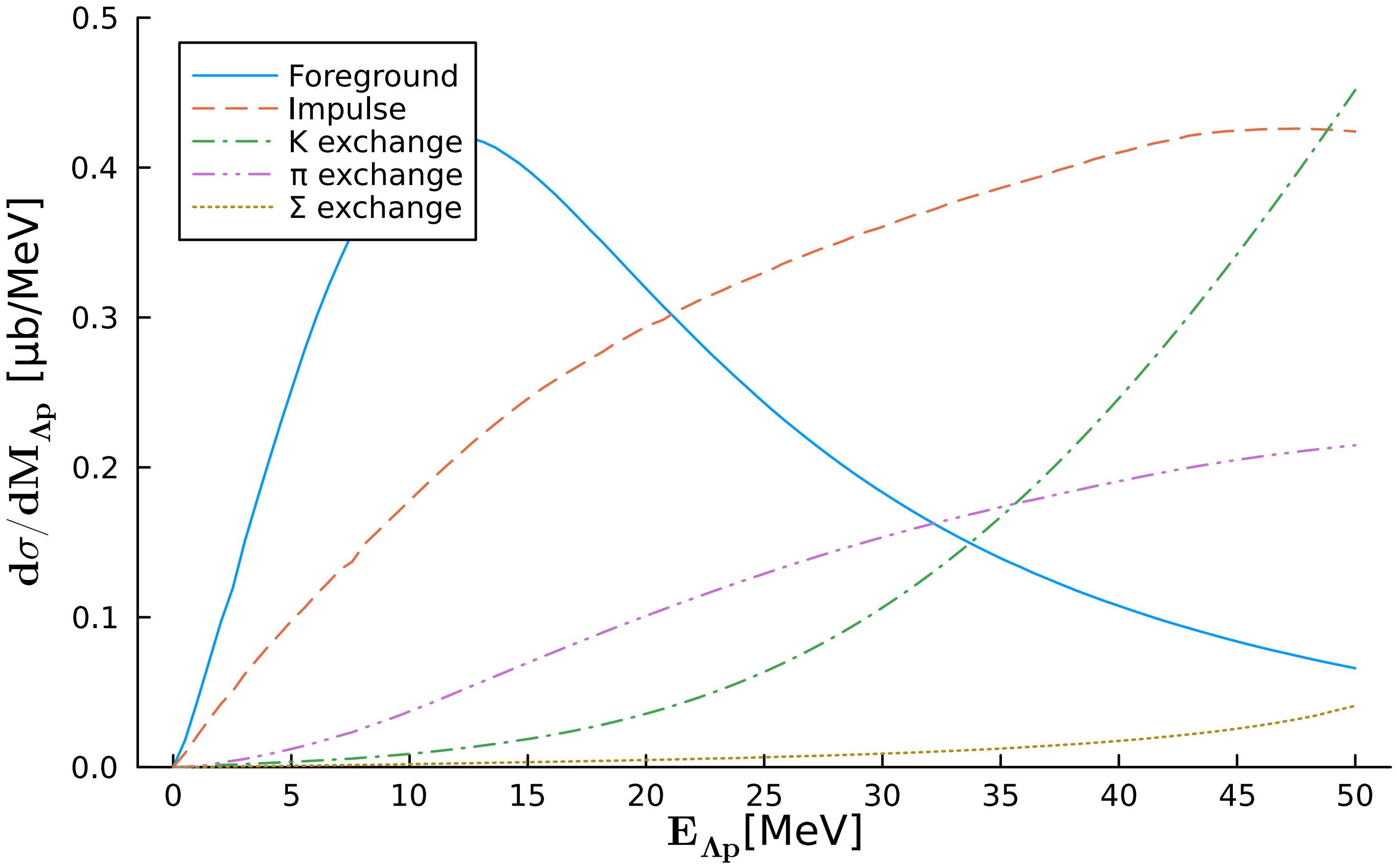
- Impulse diagram will be reduced by this nucleon momentum selection.

impulse



Deuteron at rest

Reduction of impulse (background reduction②)



Reduction of background (impulse)

Restriction
①Pion angle,
$\cos\theta \geq 0.9$
②Nucleon momentum,
$p_N \geq 150\text{MeV/c}$

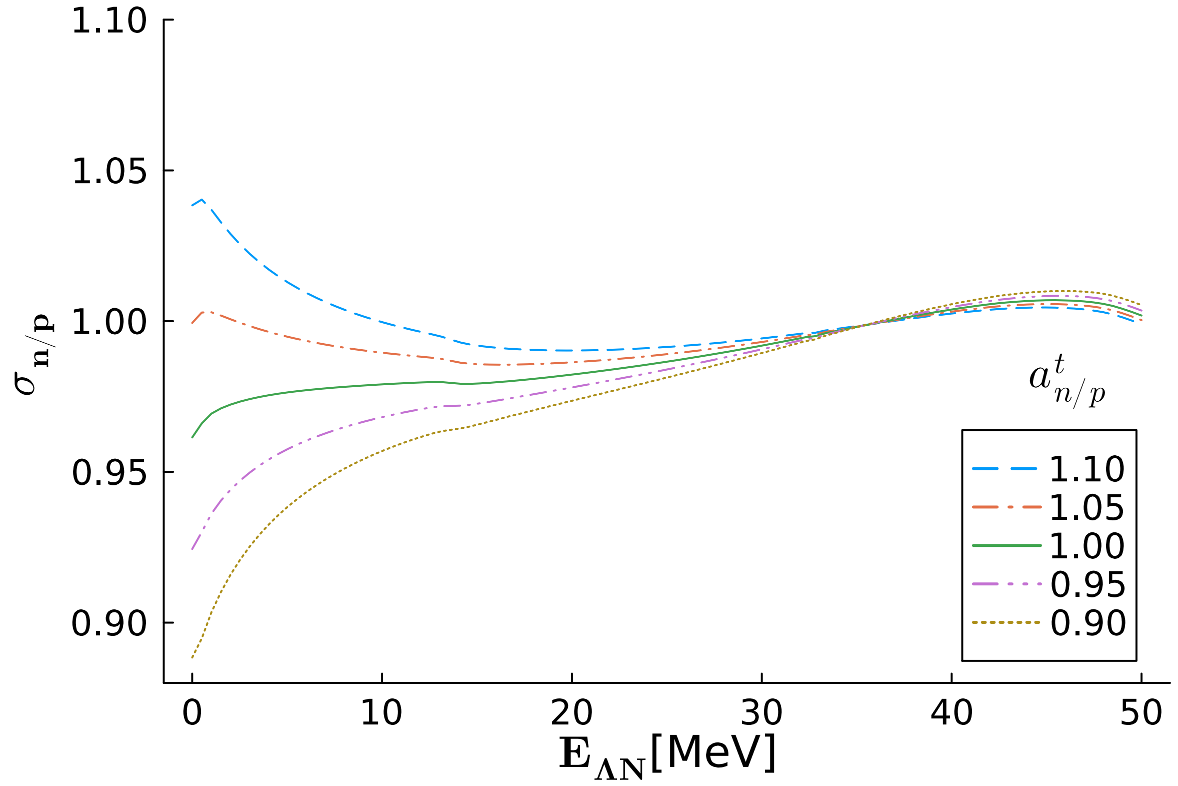
Cross section ratio

- If isospin symmetry were exact,
  the ratio of scattering cross section would satisfy

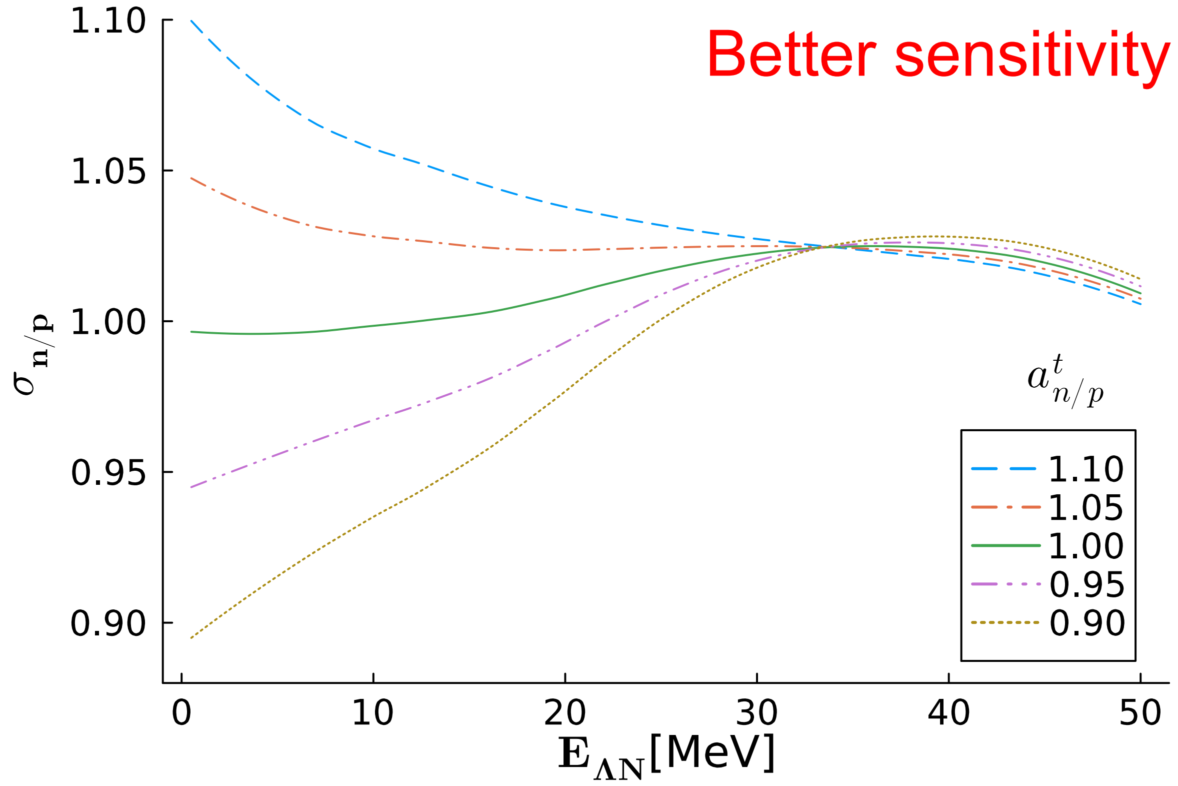
$$\sigma_{n/p} \equiv 2 \times \frac{\sigma_{\pi^0 \Lambda n}}{\sigma_{\pi^- \Lambda p}} = 1$$

- Deviation from exact ratio(=1) and numerical result
  reflects the ISB of the ΛN system.

Cross section ratio



Restriction
Pion angle, $\cos\theta \geq 0.9$



Restriction
①Pion angle, $\cos\theta \geq 0.9$
②Nucleon momentum, $p_N \geq 150$ MeV/c

Summary

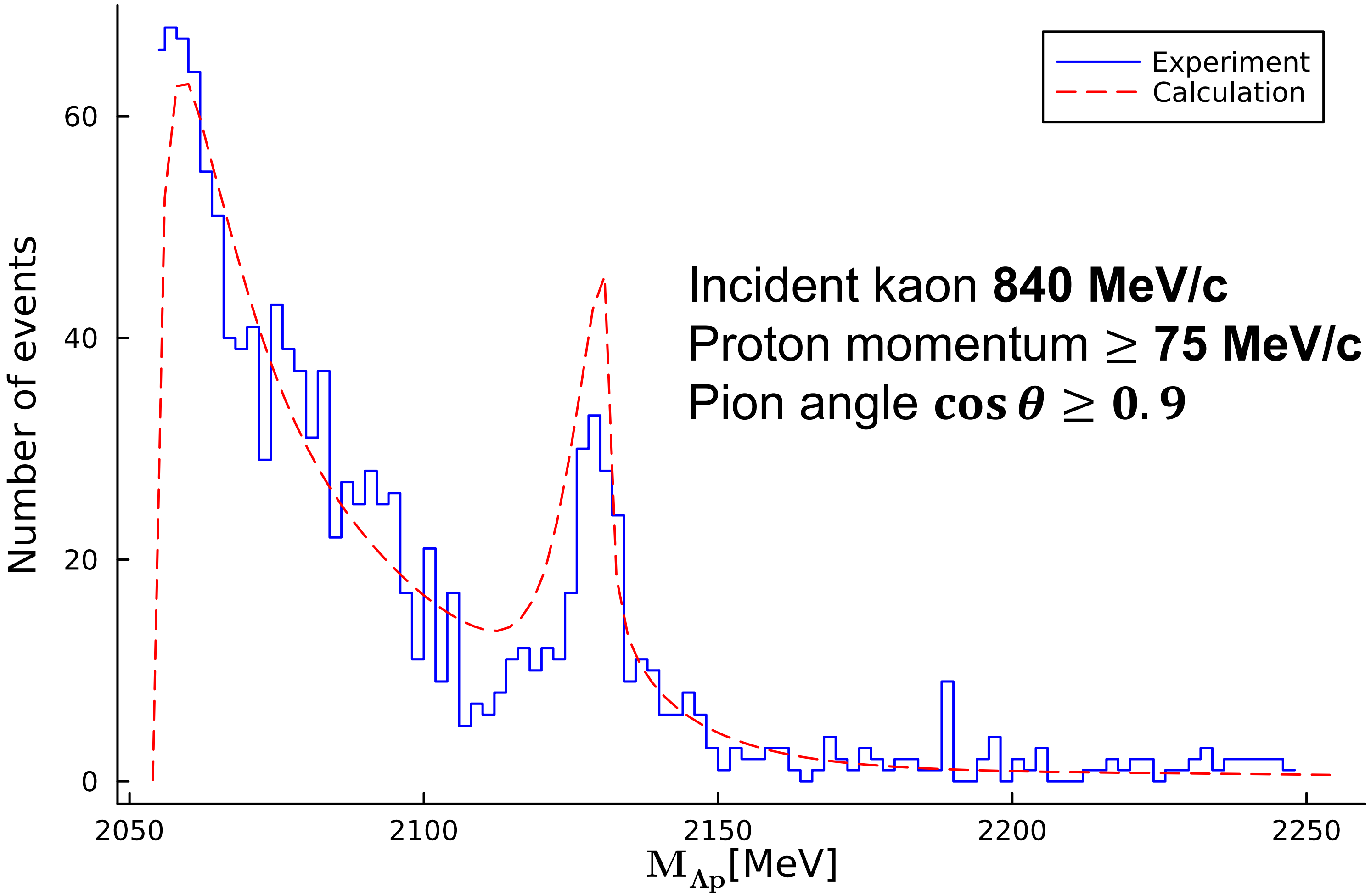
- We calculated scattering cross section when incident K^- have momenta (p-wave and spin-flip effects).

- Angular restriction of pion, $\cos\theta \geq 0.9$ momentum restriction for nucleon, $p_N \geq 150$ MeV/c → Reduction of backgrounds

- ISB of cross section ratio $\sigma_{n/p}$ varys $\sim 10\%$ if ISB of $a_{n/p}$ and $r_{n/p}$ are $\sim 10\%$.

Additional slides

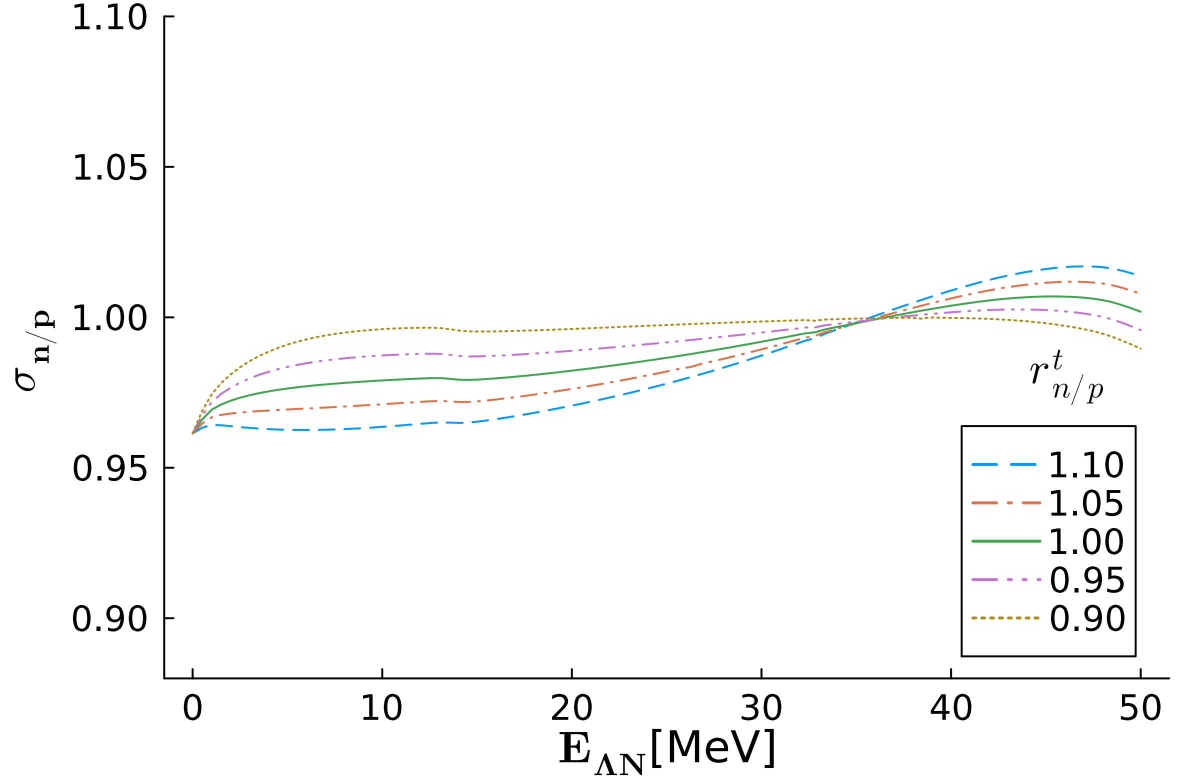
Comparison with an old experiment



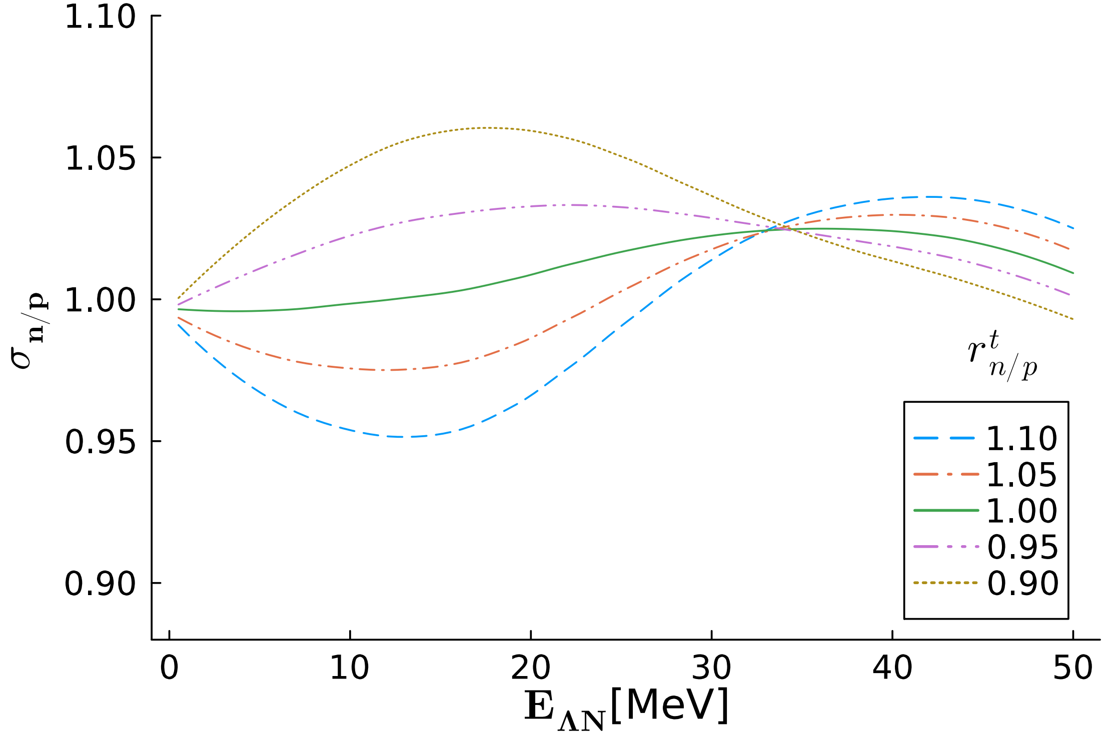
- $K^- d \to \pi^- \Lambda p$ reaction
- An experimental data is by reference [A1]
- The parameter of Σ exchange term $a^t_{\Sigma N} = 1.68 - 2.35i$ [A2]

[A1] O. Braun, et al, Nuclear Physics B 124, 45 (1977).
[A2] T. A. Rijken, V. G. J. Stoks, and Y. Yamamoto, Phys. Rev. C 59, 21 (1999).

Cross section ratio (effective range)



Restriction
Pion angle, $\cos\theta \geq 0.9$



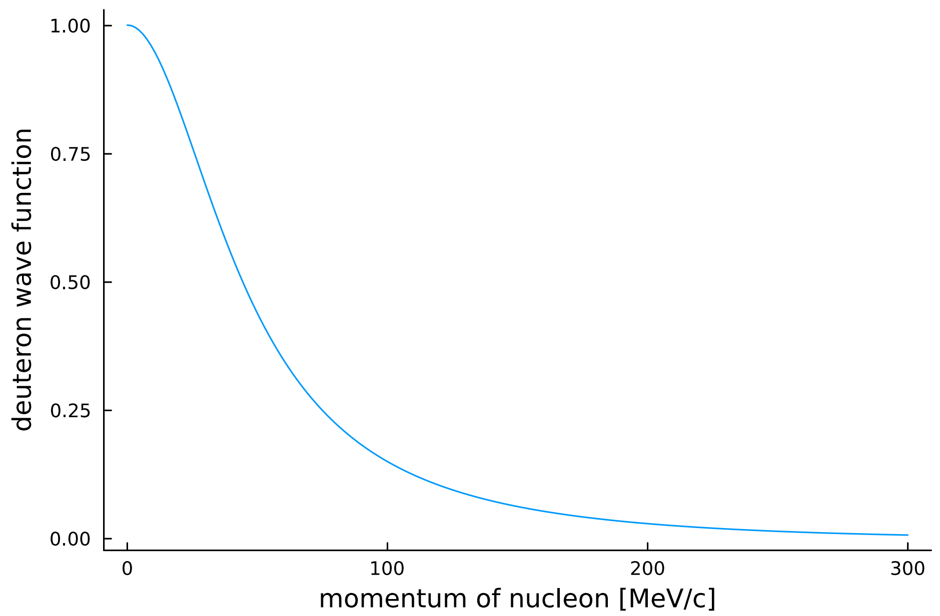
Restriction
①Pion angle, $\cos\theta \geq 0.9$
②Nucleon momentum, $p_N \geq 150\text{MeV}$

Deuteron wave-function

- We employ deuteron wave-function, CD-Bonn potential[A3] $\varphi(p)$ (p denotes momentum of nucleon in deuteron).

- The scale of amplitudes are mainly determined by $\varphi(p)$.

- From momentum conservation, p varies for each diagram.



[A3] R. Machleidt, Phys. Rev. C 63, 024001 (2001).

Calculation of Σ exchange diagram

- We use effective range expansion for Σ exchange in the same way as Λ exchange.
- $a_{\Sigma N\to\Lambda N}$, $r_{\Sigma N\to\Lambda N}$ are calculated by unitarization (by P) of ΣN and ΛN doublet state.

$$T = (V^{-1} + P)^{-1}$$

$$T = \begin{pmatrix} T_{\Lambda N\to\Lambda N}(a,r) & T_{\Lambda N\to\Sigma N}(a,r) \\ T_{\Sigma N\to\Lambda N}(a,r) & T_{\Sigma N\to\Sigma N}(a,r) \end{pmatrix}$$