Status of the $nn\Lambda$ search experiment with tritium target

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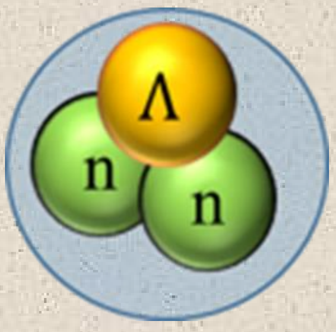
Contents

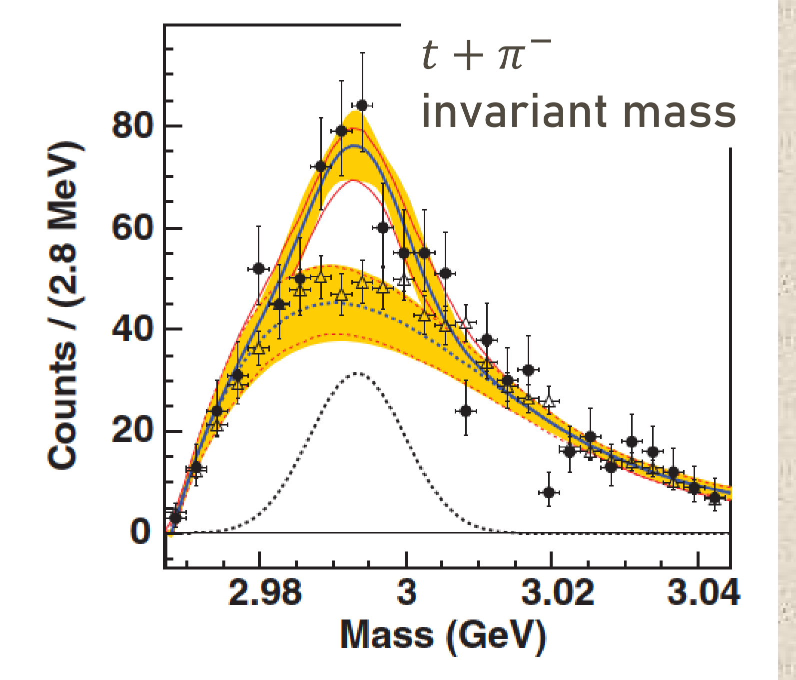
- Physics motivation ($nn\Lambda$ state problem)
- $nn\Lambda$ experiment (E12-17-003)
- Study of the Λn final state interaction
- Future Λ hypernuclear experiments

The $nn\Lambda$ state puzzle

A $nn\Lambda$ is a Λ hypernucleus with no charge.

- Thought to be unbound
- Experimental result (GSI) → Bound state?? [1]





[1]C. Rappold *et al.*, (HypHI Collaboration) Phys. Rev. C 88 041001 (2013)

Theoretical models

- Cannot reproduce with the bound $nn\Lambda$

Ref.) E. Hiyama et al., Phys. Rev. C 89, 061302 (2014).

- A resonance state may be possible

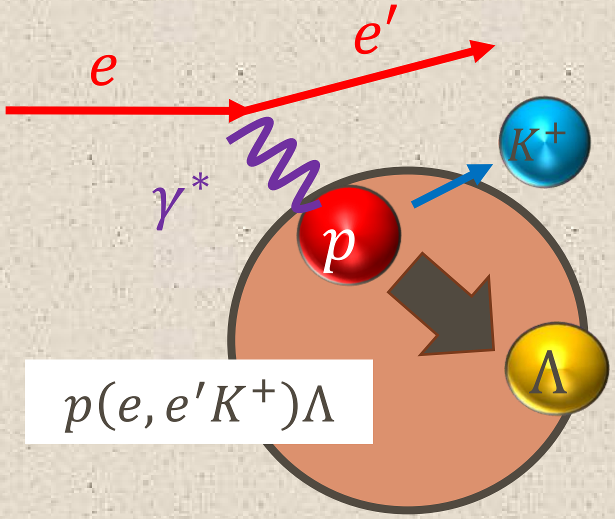
Ref.) I.R. Afnan et al., Phys. Rev. C, 92 054608 (2015).

Existence of the $nn\Lambda$ is not established at all.
Need more precise spectroscopic study
→ $(e, e'K^+)$ reaction

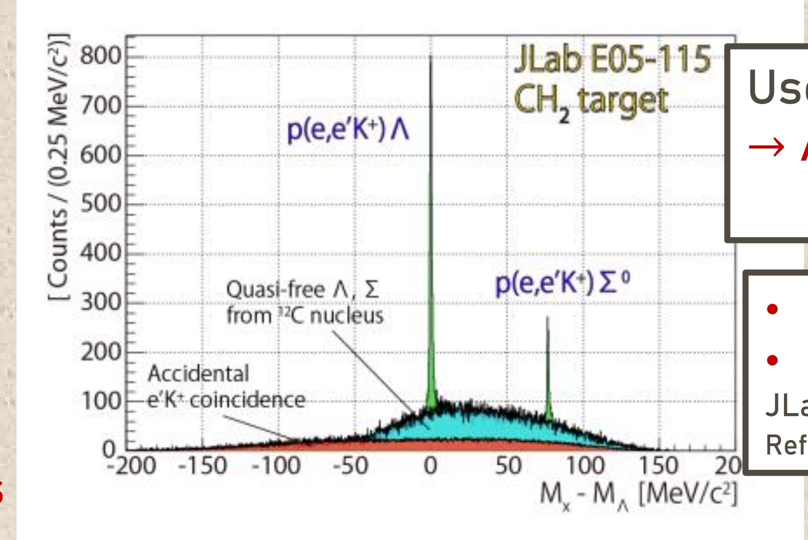
Λ hypernuclear experiment in the $(e, e'K^+)$ reaction

An experiment in the $(e, e'K^+)$ reaction enables to

- Use the primary beam (small beam energy spread : $\Delta E_e / E_e \sim 10^{-4}$)
- Measure hyperons with $p(e, e'K^+)\Lambda/\Sigma^0$ reactions



Missing masses



Used for energy calibration
→ Achievable high energy resolution and accuracy

- $M_X - M_\Lambda < 100\ \mathrm{keV}/c^2$
- resolution $\sim 1.5\ \mathrm{MeV}/c^2$ (FWHM)

JLab E05-115 Experiment (Hall C)
Ref.) T. Gogami Doctoral thesis (2014).

To search for the $nn\Lambda$ with the high energy resolution and accuracy,
we performed $nn\Lambda$ experiment in the $^3\mathrm{H}(e, e'K^+)nn\Lambda$ reaction at JLab Hall A.

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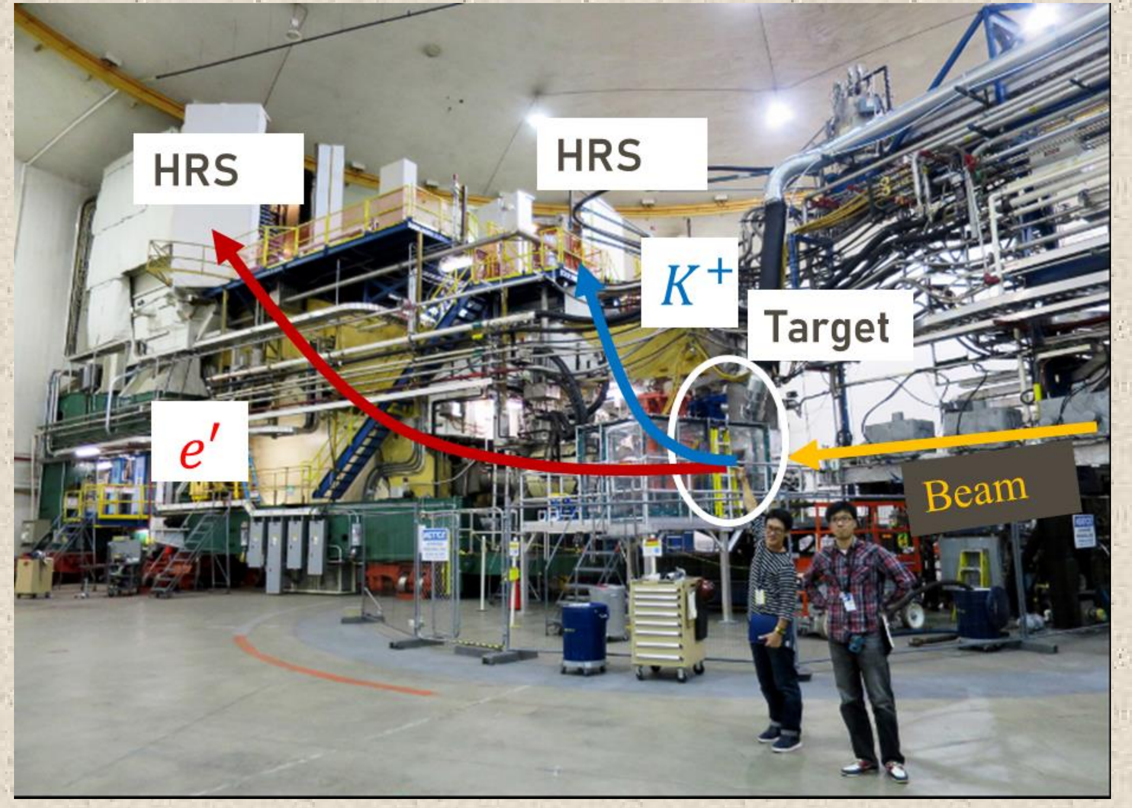
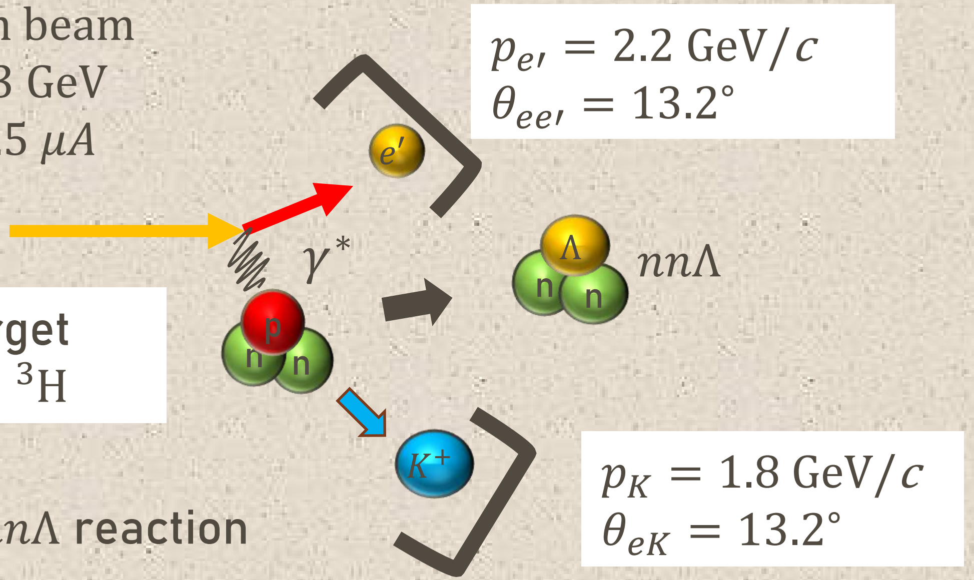
$nn\Lambda$ search experiment (E12-17-003) at Hall A

The $nn\Lambda$ search experiment (E12-17-003) was performed at JLab Hall A (2018).

- Two high resolution spectrometers (HRSs) $(\Delta p/p \sim 2.0 \times 10^{-4})$
- Tritium gas target $(84.8\ \mathrm{mg/cm^2})$





$^3\mathrm{H}(e, e'K^+)nn\Lambda$ reaction

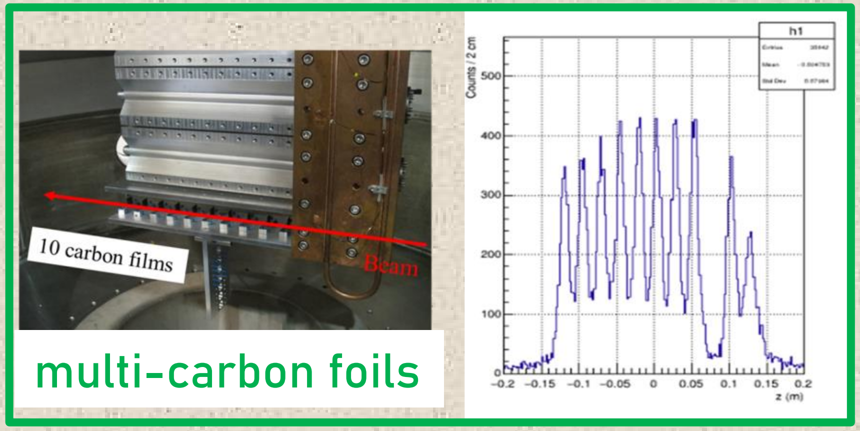
By measuring momenta of e' and K^+ with HRSs, missing mass of $nn\Lambda$ (M_X) is obtained by

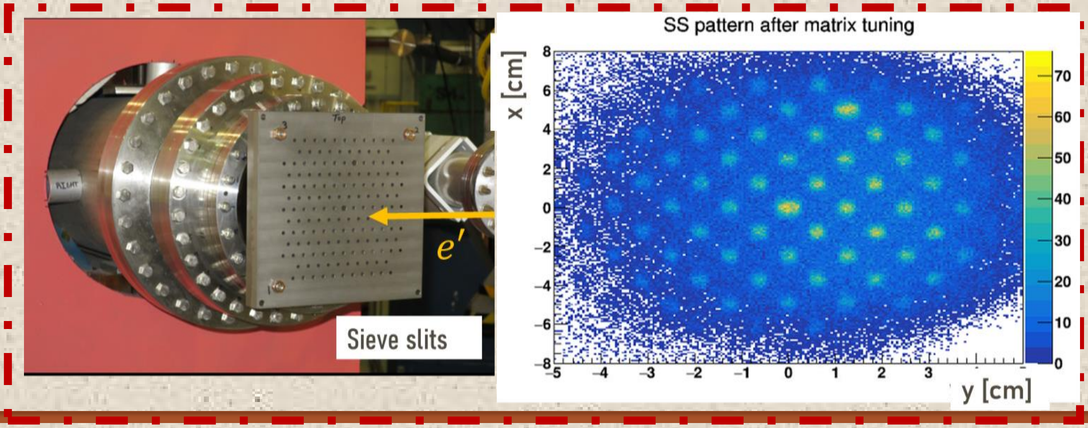
$$M_X = \sqrt{(E_e + m_T - E_{e'} - E_K)^2 - (\vec{p_e} - \vec{p_{e'}} - \vec{p_K})^2}$$

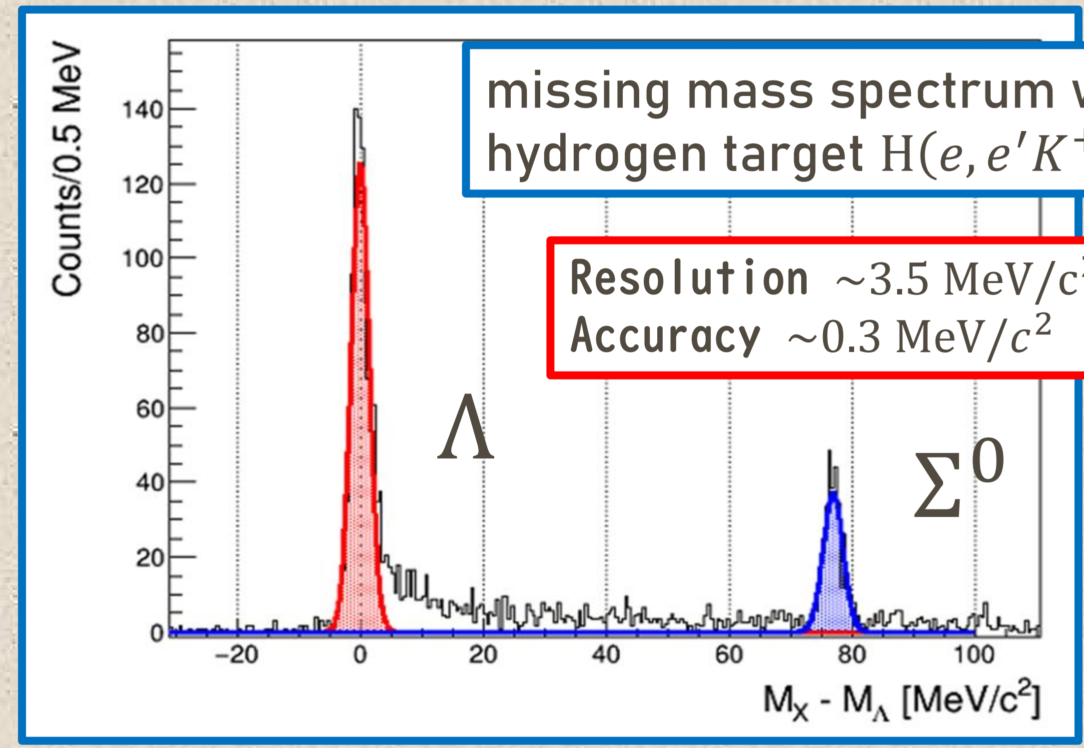
Precision of $p(e, e'K^+)\Lambda, \Sigma^0$ missing masses

This experiment required high resolution and accuracy.

→ We took calibration data for (z, θ, ϕ, p) parameters.





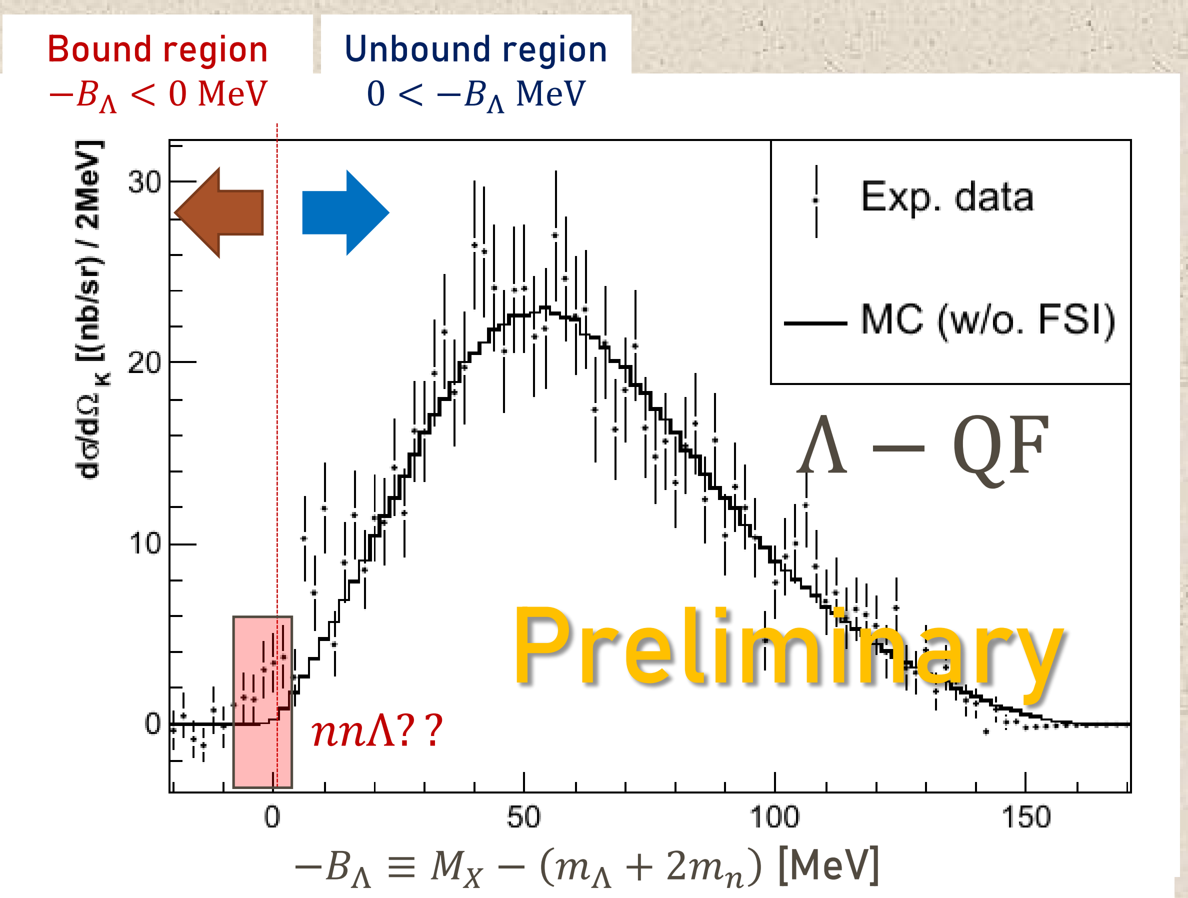


missing mass spectrum with hydrogen target $\mathrm{H}(e, e'K^+)\Lambda/\Sigma^0$

Resolution $\sim 3.5\ \mathrm{MeV}/c^2$ (FWHM)
Accuracy $\sim 0.3\ \mathrm{MeV}/c^2$

$^3\mathrm{H}(e, e'K^+)X$ missing mass spectrum

Cross section of missing mass in the $^3\mathrm{H}(e, e'K^+)X$ reaction (after mass calibration)



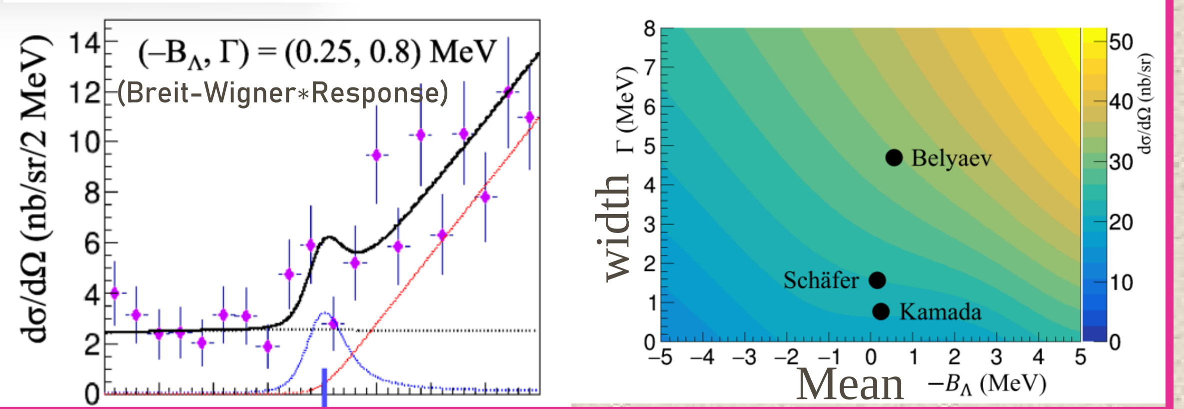
*1 : JLab Hall A/C standard Monte Carlo Simulation Including fermi momentum, kaon decay, radiative correlations

Comparing with SIMC *1, there is a structure around the $nn\Lambda$ mass threshold $(-B_\Lambda \sim 0\ \mathrm{MeV})$

- Excess events (cannot be explained by SIMC)
- Not enough peak significance

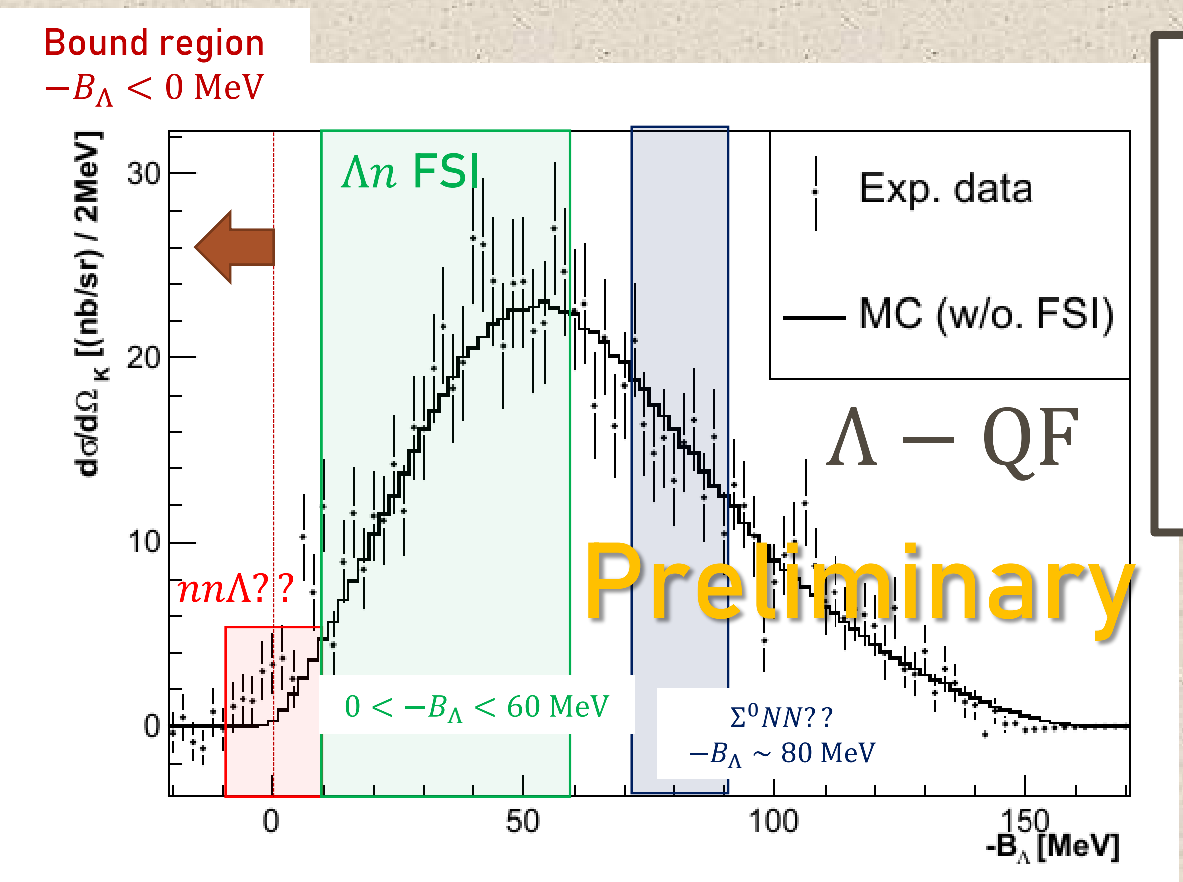
Upper limit study of $nn\Lambda$ (Published)

K.N. Suzuki *et al.,* PTEP 2022, 013D01



$^3\mathrm{H}(e,e'K^+)X$ missing mass spectrum

Our group studies three physics from the $^3\mathrm{H}(e,e'K^+)X$ missing mass.



1. Upper limit study of $nn\Lambda$
   K. N. Suzuki et al., Prog. of Theo. and Exp. Phys, 2022, 013D01 (2022).
2. Λnn and ΣNN resonance
   B. Pandey et al., Phys. Rev. C 105, L051001 (2022).
3. $\boldsymbol{\Lambda}\mathbf{n}$ final state interaction

Published two papers!
→ I will discuss about the Λn FSI.

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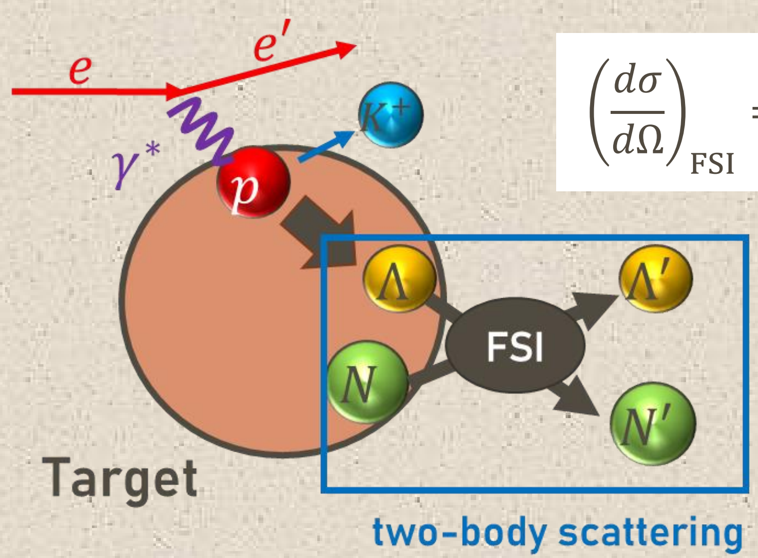
Final State Interaction (FSI)

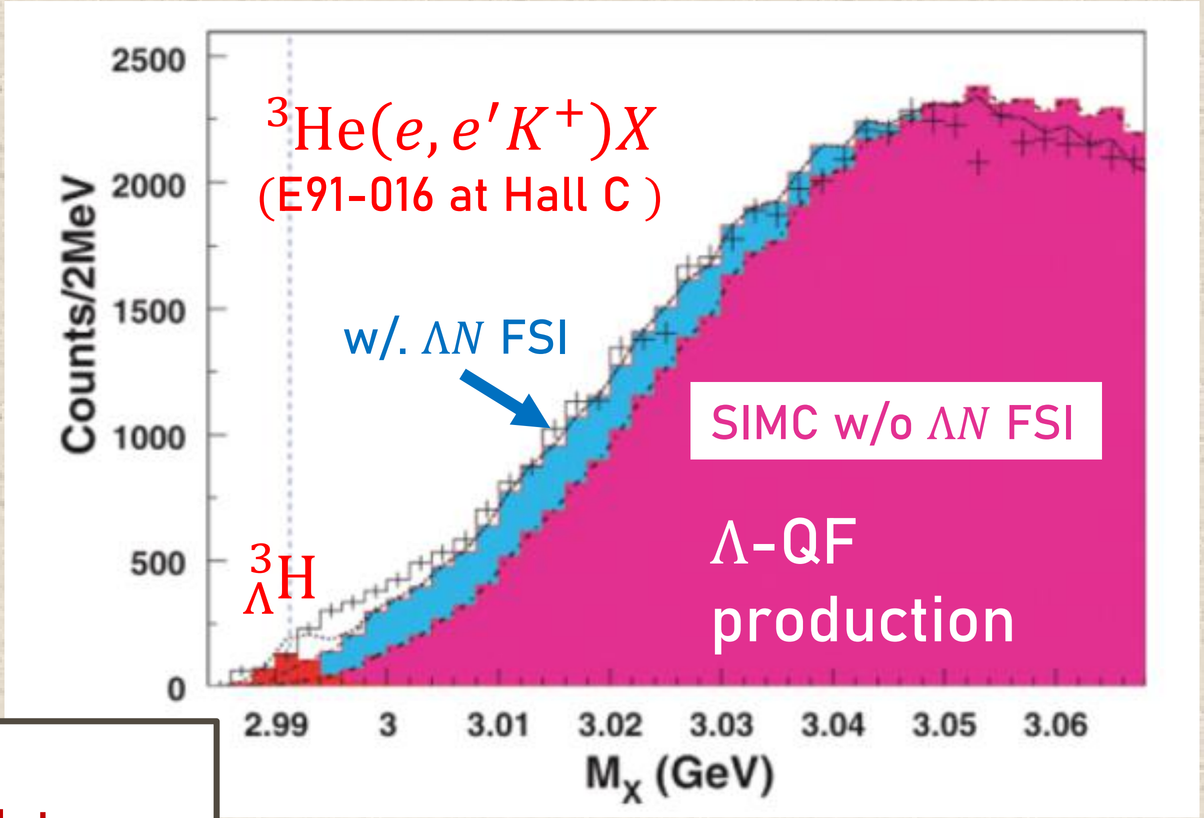
Final state interaction : Reaction between a recoil Λ and a nucleon within a target (ΛN scattering).

This effect (FSI) is known to make an enhancement $(-B_\Lambda > 0\ \mathrm{MeV})$ Ref.) Phys. Rev. C 76, 054004 (2007).

→ Better agreement with the experimental data



$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{FSI}} = \left|\frac{\psi(kr+\delta)}{\psi(kr)}\right|^2 \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{w/o\ FSI}}$$

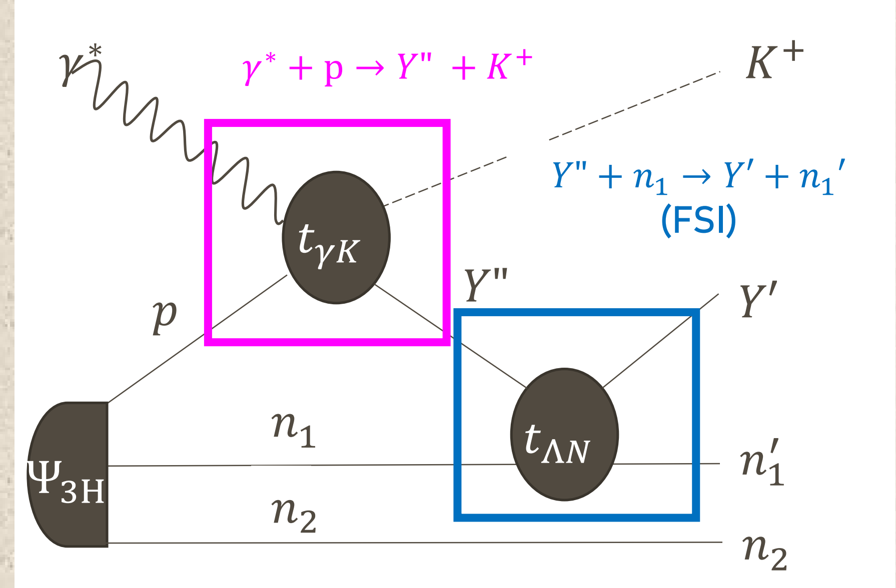


Study of the FSI from the $nn\Lambda$ system is expected to get information of the Λn interaction. No Λn scattering data.

Estimation of Λn final state interaction

FSI can be written with influence factor $I(k_{\rm rel})$ as following

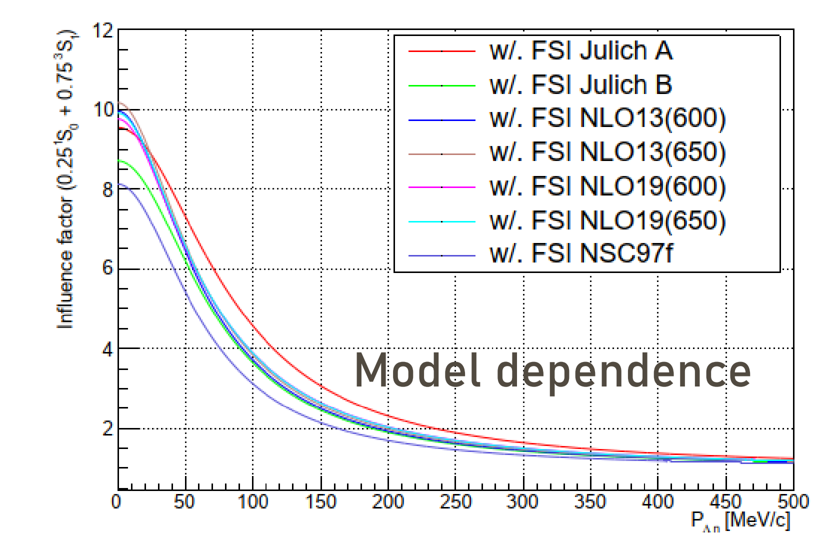
$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm FSI} = \left|\frac{\psi(kr+\delta)}{\psi(kr)}\right|^2 \left(\frac{d\sigma}{d\Omega}\right)_{\rm w/o\ FSI} = I(k_{rel})\left(\frac{d\sigma}{d\Omega}\right)_{\rm w/o\ FSI} = \frac{1}{|J_l(k_{rel})|^2}\left(\frac{d\sigma}{d\Omega}\right)_{\rm w/o\ FSI}$$



In the ERA ($k\cot\delta = -1/a + 1/2 r_e k^2$), the Jost function is written with scattering length (a) and effective range (r_e) as :

$$J_{l=0}(k_{rel}) = \frac{k_{\rm rel} - i\beta}{k_{\rm rel} - i\alpha}$$

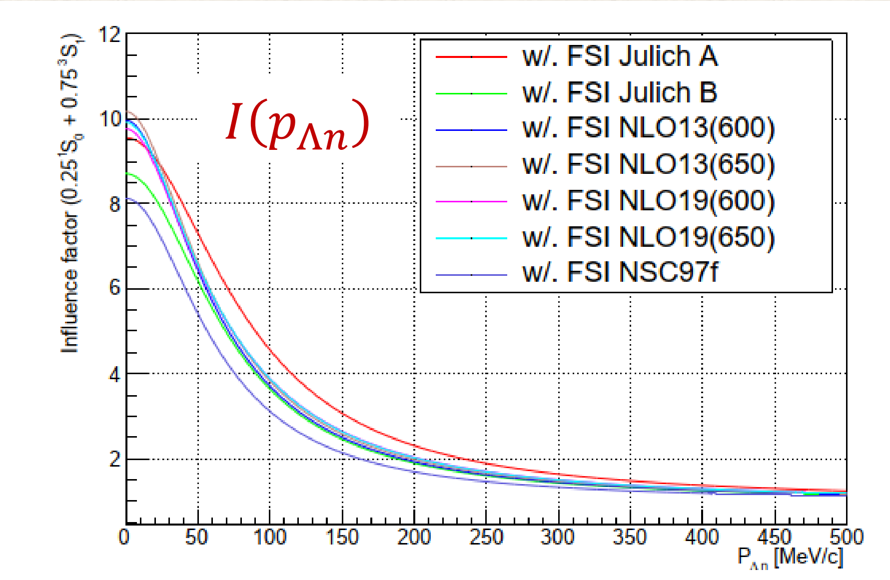
$$\frac{1}{2} r_e(\alpha - \beta) = 1,\ \frac{1}{2} r_e \alpha\beta = -\frac{1}{a}$$



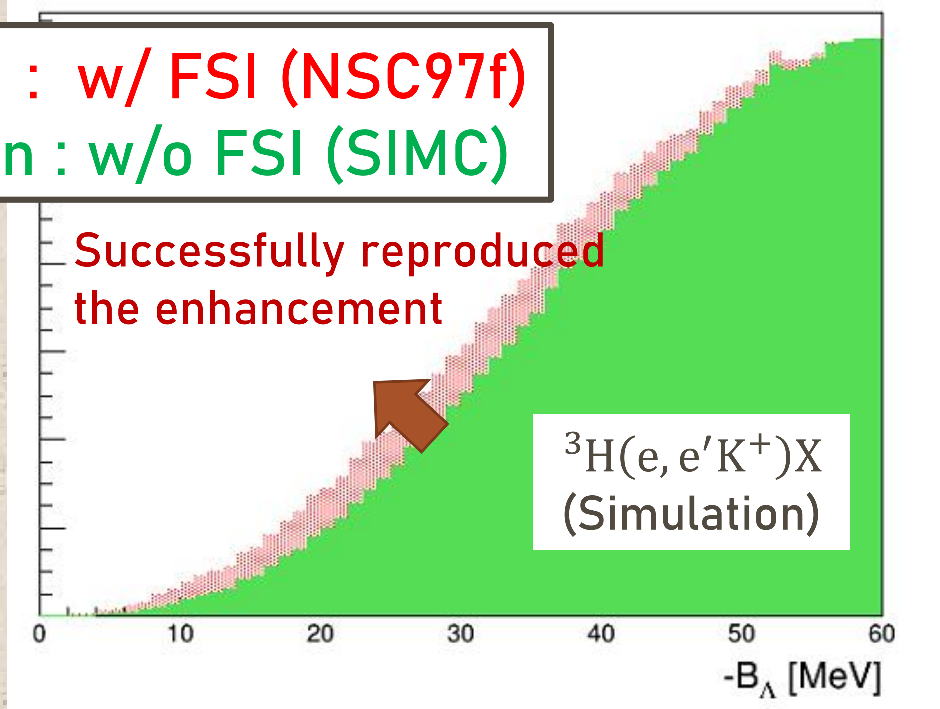
Missing mass spectrum including Λn FSI by SIMC

Missing mass with Λn FSI is $\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{FSI}} = I(k_{rel})\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{w/o\ FSI}}$

- $\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{w/o\ FSI}}$: Given by SIMC (w/o FSI)
- $I(k_{rel})$: Calculated by Jost function



Calculating $\vec{p}_{\Lambda n}$ and $I(\vec{p}_{\Lambda n})$ each event



Missing mass spectra with Λn FSI

The structure $(-B_\Lambda \sim 0\ \mathrm{MeV})$: Assuming resonance state of $nn\Lambda$ $(\Gamma, -B_\Lambda) = (4.7, 0.55)\ \mathrm{MeV}$

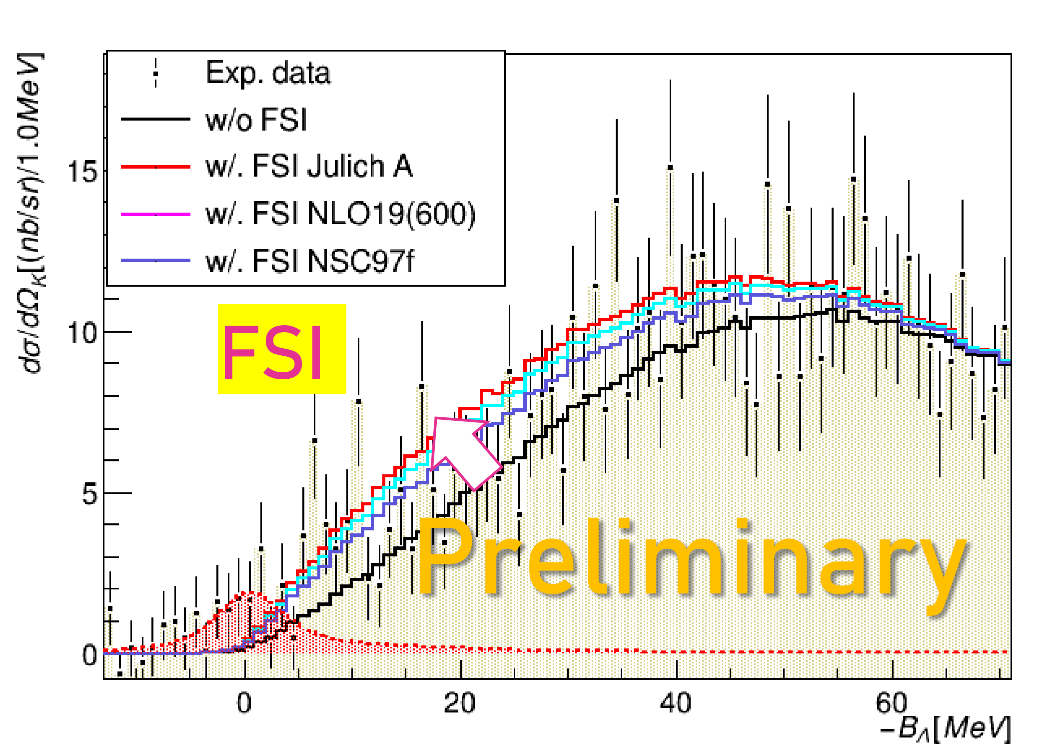
SIMC spectra including Λn FSI and $nn\Lambda$ were scaled by chi-square fitting $(0 \le -B_\Lambda \le 60\ \mathrm{MeV})$

$$\chi^2 = \sum_i \frac{\left(y^i_{\mathrm{data}} - w_{FSI} \cdot y^i_{\mathrm{FSI}} - w_{nn\Lambda} \cdot y^i_{nn\Lambda}\right)^2}{\sigma^i_{\mathrm{data}}}$$

$(w_{FSI}, w_{nn\Lambda}$ are scaling factors)

Missing mass spectra with FSI :

- Succeeded in reproducing enhancement structure $(0 \le -B_\Lambda \le 60\ \mathrm{MeV})$
- Better agreement with the experimental data



Search for the best Λn potential parameters

Λn FSI : calculated by Jost function with the (a, r) potential parameters

→ Study of the (a, r)-dependence of χ^2 (Search for the best (a, r) parameters)

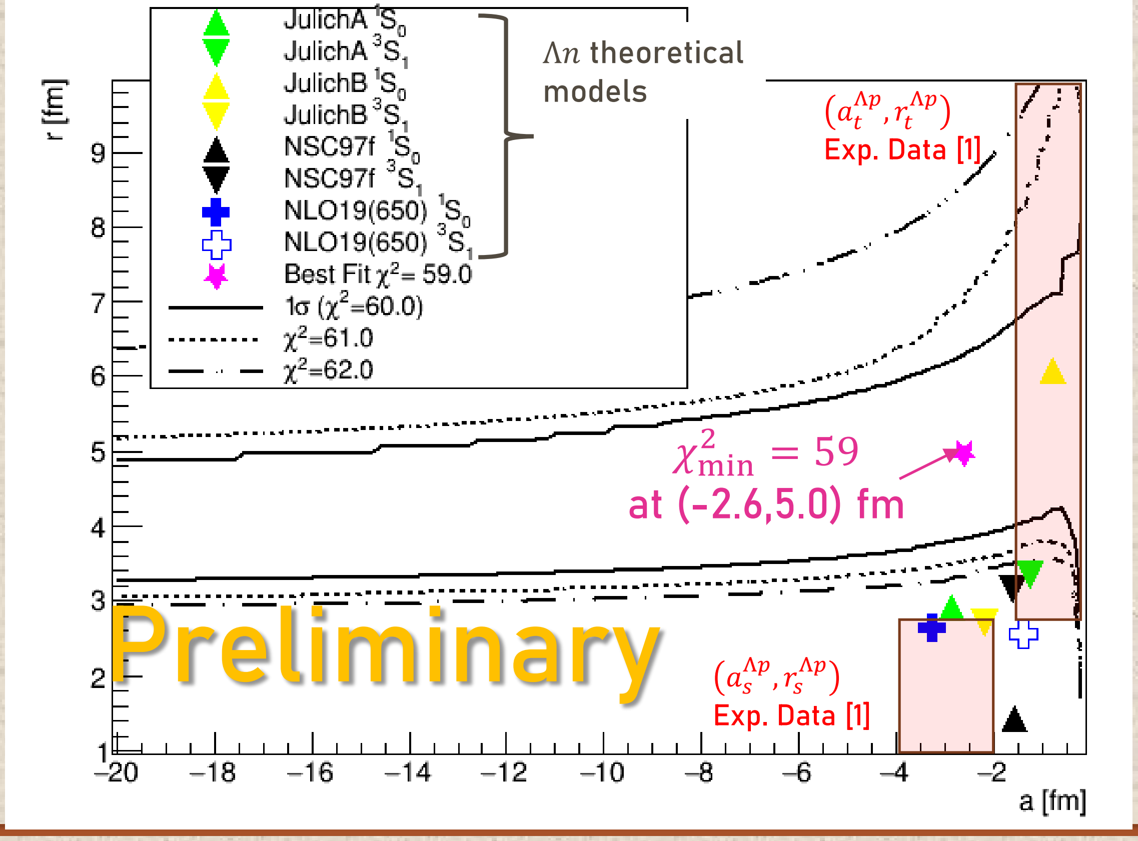
Using two parameters $(\bar{a},\ \bar{r})$: $\bar{a} \equiv a_s = a_t,\ \bar{r} \equiv r_s = r_t$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{FSI}} = \left(\left|\frac{1}{\mathrm{J}\,(\mathrm{k_{rel}})}\right|^2\right)\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{w/o\ FSI}}$$

Assuming $\bar{a} = -2.6$ fm
(Preliminary) $\bar{r} = 5.0^{+1.3}_{-1.2}$ (stat.) fm

I am going to publish this study as soon!

[1] Eur. Phys. J. A 21, 313-321 (2004).



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Future Λ hypernuclear experiment

Three other experiments were approved

- An isospin dependence study of the ΛN interaction (E12-15-008)
- High accuracy measurement of nuclear masses of ${}^{3,4}_{\Lambda}\mathrm{H}$ (E12-19-002)
- Studying Λ interactions in nuclear matter with the ${}^{208}\mathrm{Pb}(e, e'K^+){}^{208}_{\Lambda}\mathrm{Tl}$ (E12-20-013)

We are planning to perform them at Hall C at earliest occasion.
→ Preparing for these experiments

Summary

The $nn\Lambda$ experiment (E12-17-003) was performed in 2018 at JLab Hall A.

Two papers were published.

- The cross-section measurement for the $^{3}\mathrm{H}(e, e'K^{+})nn\Lambda$ reaction
  Prog. of Theo. and Exp. Phys, 2022, 013D01 (2022).
- Spectroscopic study of a possible Λnn resonance and a pair of ΣNN states
  Phys. Rev. C 105, L051001 (2022).

Study of the Λn FSI

- Assuming $\bar{a} = -2.6$ fm , (Preliminary) $\bar{r} = 5.0^{+1.3}_{-1.2}\,(\mathrm{stat.})$ fm

Future Λ hypernuclear experiments

Three experiments (PAC) were accepted (E12-15-008, E12-19-002, E12-20-013).

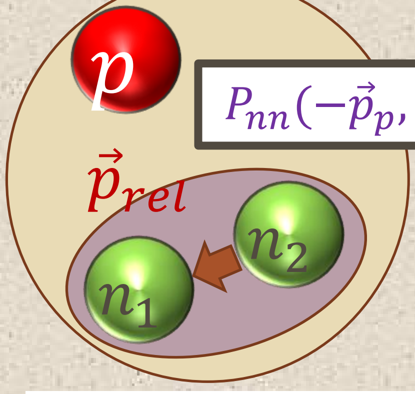
We are preparing for these experiment to be performed at Hall C.

Backup

Estimation of Λn relative momentum

Influence factor (I) is depending on Λn relative momentum $(\vec{k}_{\Lambda n} = \vec{p}_\Lambda - \vec{p}_{n1})$

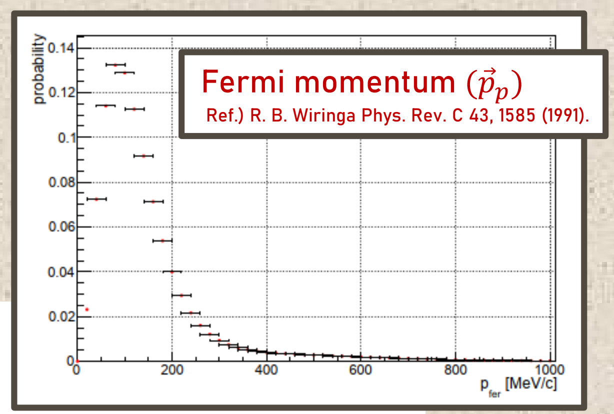
$P_p(\vec{p}_p, E_p)$



$P_{nn}(-\vec{p}_p, E^*_{nn})$

Λ momentum : $\vec{p}_\Lambda = \vec{p}_p + (\vec{p}_e - \vec{p}'_e) - \vec{p}_K$

- $\vec{p}_e$, $\vec{p}_{e'}$ and $\vec{p}_K$: observables (by CEBAF and HRSs).
- $\vec{p}_p$: Given by Fermi momentum distribution in the tritium.

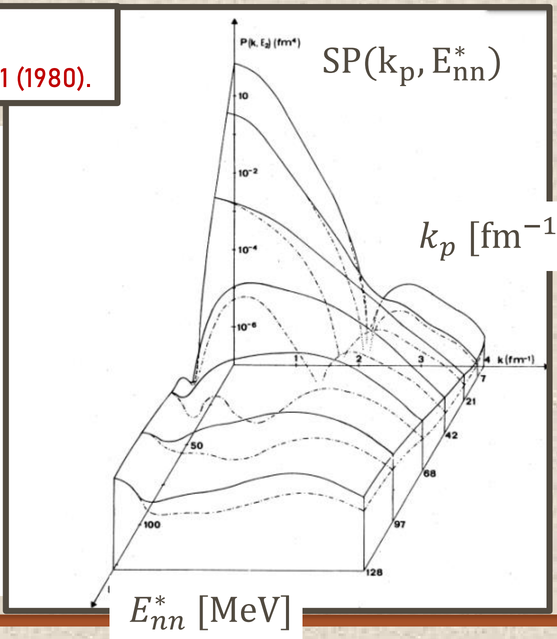


Fermi momentum $(\vec{p}_p)$

Ref.) R. B. Wiringa Phys. Rev. C 43, 1585 (1991).

Spectral function of ^{3}H

Ref.) C. Ciofi degli Atti et al., Phys. Rev. C, 21 (1980).



Neutron momentum $(\vec{p}_{n1})$: $\vec{p}_p + \vec{p}_{n1} + \vec{p}_{n2} = 0$

$$\vec{p}_{n1(n2)} = -\frac{1}{2}\vec{p}_p + \vec{p}_{rel} \quad (\vec{p}_{rel} \equiv M_n\vec{p}_{n1} - M_n\vec{p}_{n2}/2M_{2n})$$

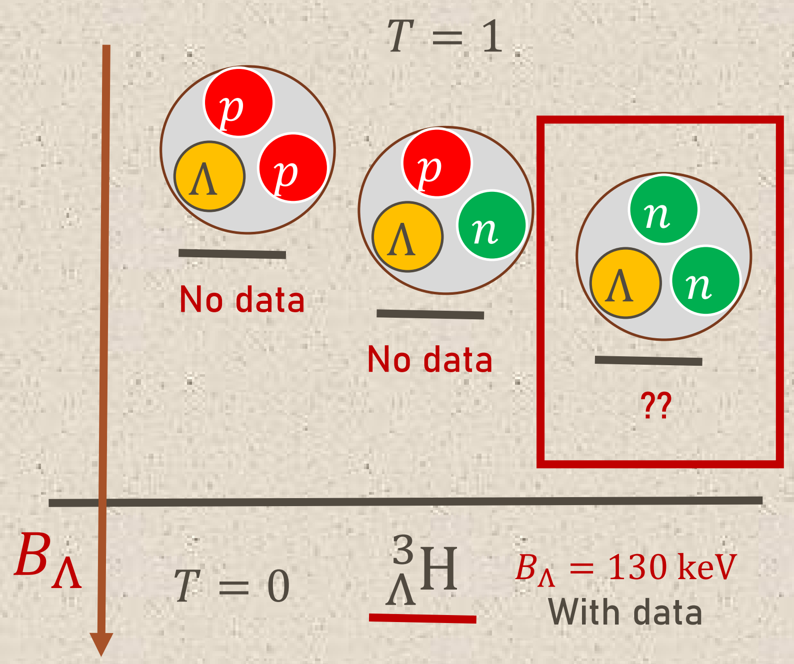
Relative momentum $(\vec{p}_{rel})$: Given from an excited energy of nn system (E^*_{nn})

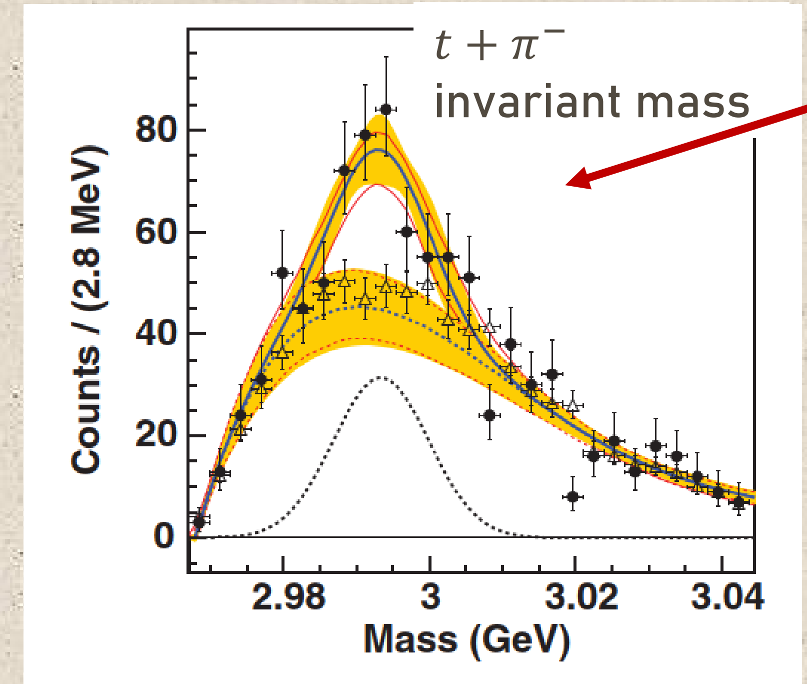
$\rightarrow$ E^*_{nn} was given by spectral function of ^{3}H

$nn\Lambda$ state problem

A $nn\Lambda$ is a Λ hypernucleus with no charge.

- Thought not to be bound
- Experimental data(GSI) → Bound state?? [1]



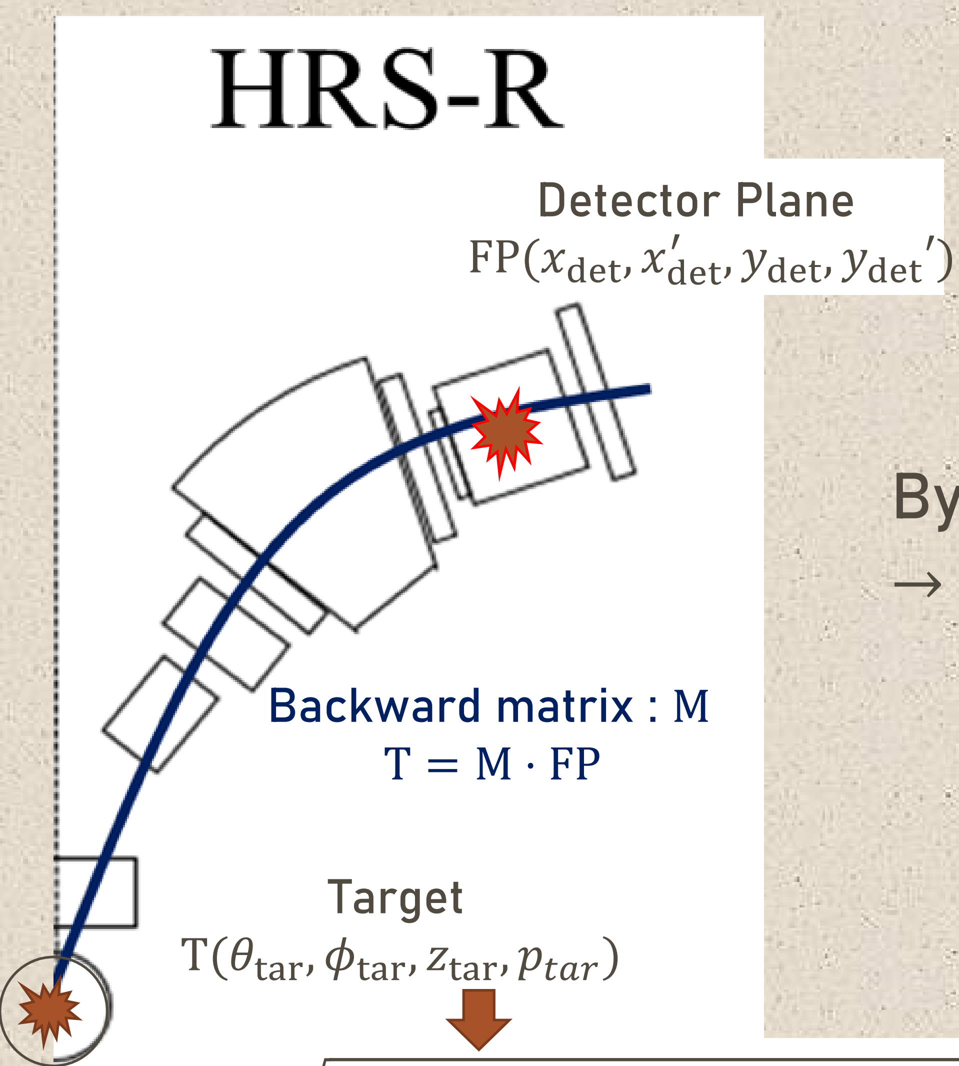


- Around $nn\Lambda$ mass threshold
- Enough lifetime
- Not enough peak significance

Bound state ??

[1] C. Rappold *et al.,* (HypHI Collaboration) Phys. Rev. C 88 041001 (2013)

Analyzing process



$$M_X = \sqrt{(E_e + m_T - E_{e'} - E_K)^2 - (\vec{p_e} - \vec{p_{e'}} - \vec{p_K})^2}$$

$\vec{p}(\theta_{tar}, \phi_{tar}, p_{tar})$ was reconstructed with backward matrix

$$\begin{pmatrix} \theta_{tar} \\ \phi_{tar} \\ z_{tar} \\ p_{tar} \end{pmatrix} = \begin{pmatrix} a_{11} & \cdots & a_{1N} \\ \vdots & \ddots & \vdots \\ a_{41} & \cdots & a_{4N} \end{pmatrix} \begin{pmatrix} x_{det} \\ y_{det} \\ \vdots \\ (x_{det})^i (y_{det})^j (x_{det}')^k (y'_{det})^l \\ \vdots \end{pmatrix}$$

By optimized matrix elements (a_{ij})

→ Achievable high mass resolution and accuracy

Calibration data for $(\theta_{tar},\ \phi_{tar},\ z_{tar},\ p_{tar})$

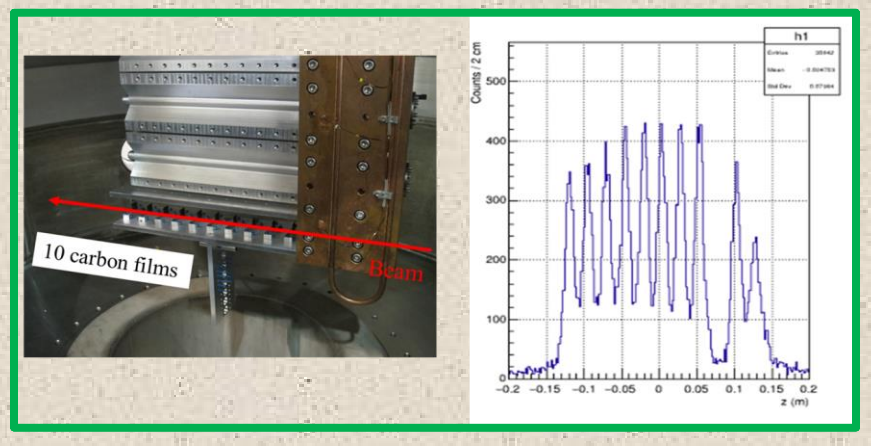
- z_{tar} : multi-carbon foils target
- θ_{tar}, ϕ_{tar} : sieve slit
- p_{tar} : hydrogen target (Λ and Σ^0 missing mass)

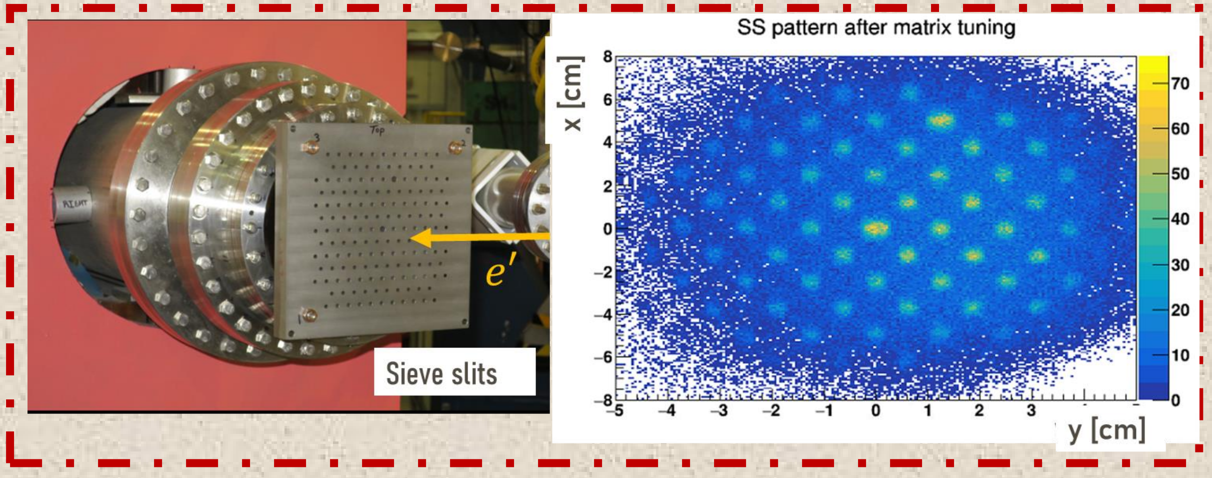
Optimization

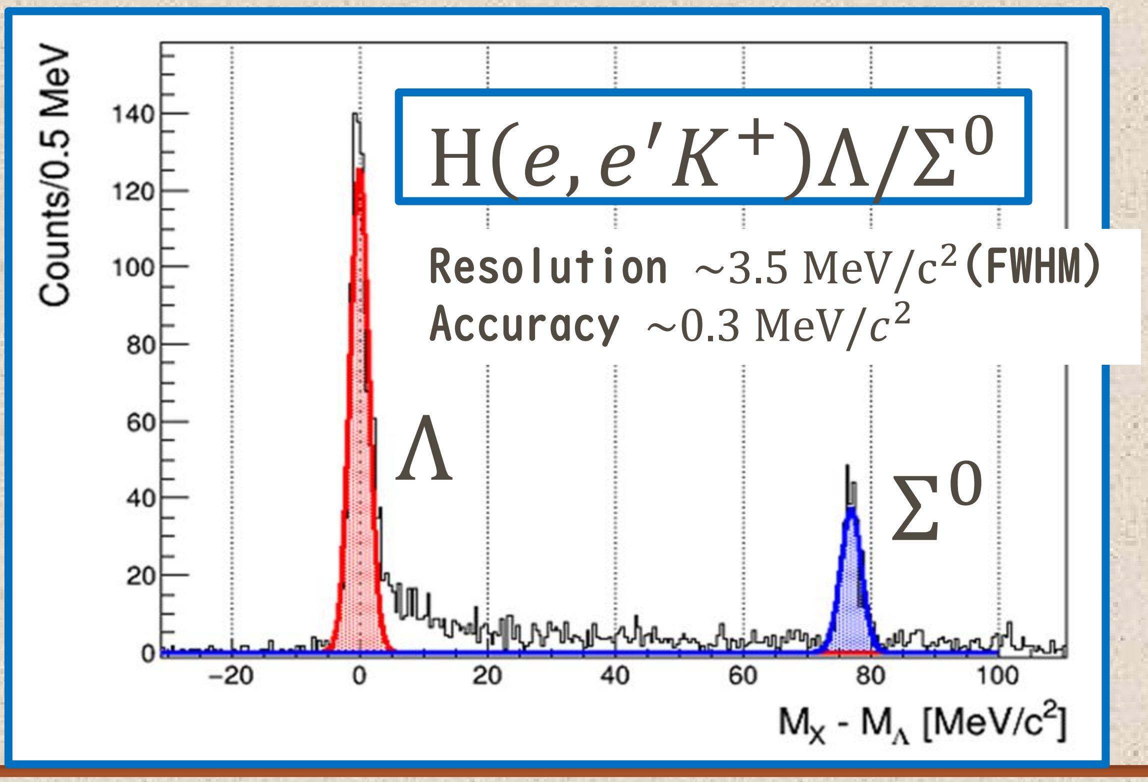
Optimization of parameters : $(\theta_{tar}, \phi_{tar}, z_{tar}, p_{tar})$

- z_{tar} : multi-carbon foils target
- θ_{tar}, ϕ_{tar} : sieve slit
- p_{tar} : hydrogen target (Λ and Σ^0 missing mass)

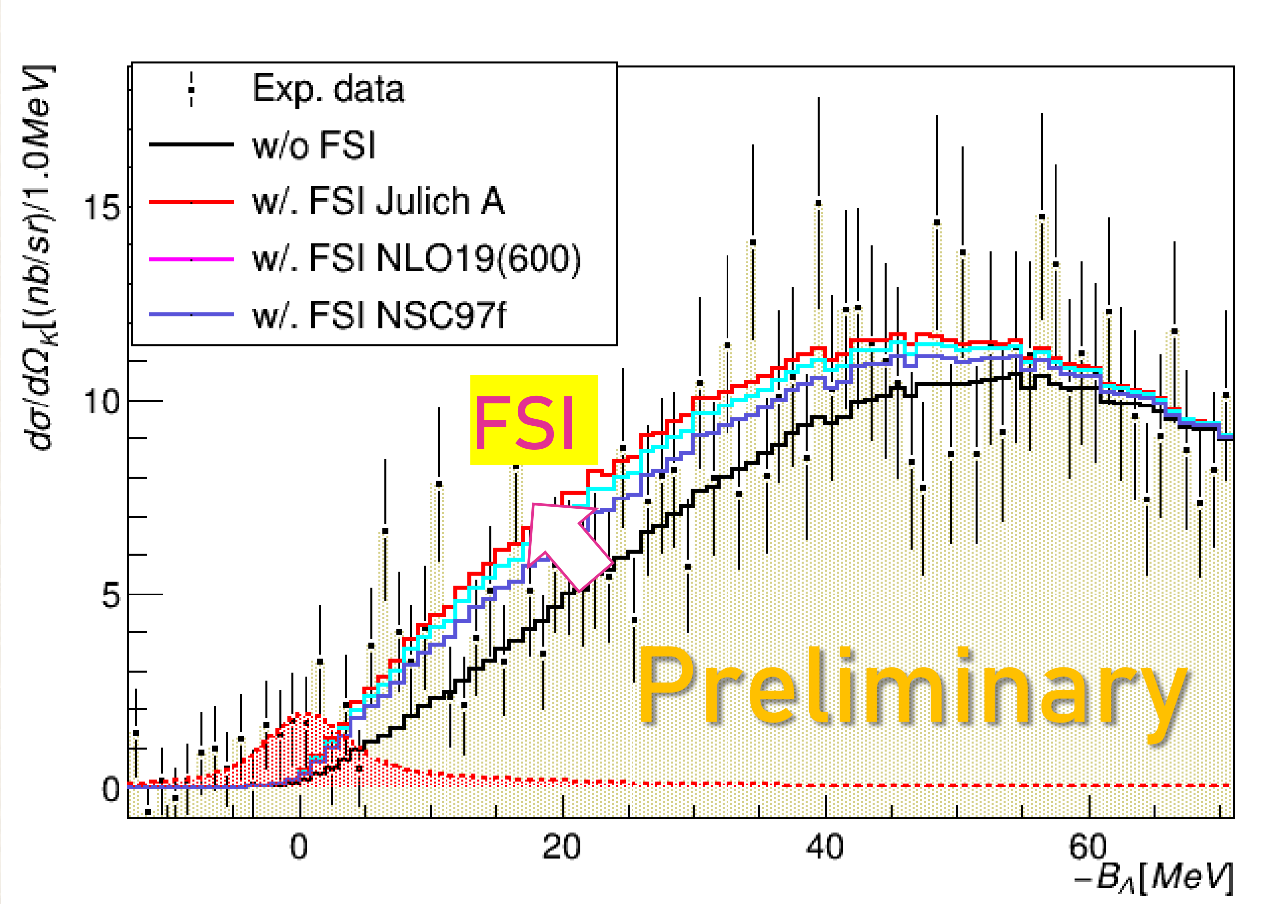
Achieved high mass resolution and accuracy







Missing mass spectra with Λn FSI



Any $\Lambda-$QF spectra with Λn FSI were fitted with

$$\chi^2 = \sum_i^{N_{\mathrm{bin}}} \frac{\left(y^i_{\mathrm{data}} - w_{FSI} \cdot y^i_{\mathrm{FSI}} - w_{nn\Lambda} \cdot y^i_{nn\Lambda}\right)^2}{\sigma^i_{\mathrm{data}}}$$

: $w_{FSI}, w_{nn\Lambda}$ are scaling factors

Missing mass spectra with FSI :

- Succeeded in producing enhancement structure ($0 \leq -B_\Lambda \leq 60$ MeV)
- Better agreement with experimental data