^{3}H(e, e′K^{+})X反応における Λn相互作用の研究

K. Itabashi

Contents

Experimental approach for the ΛN interaction

The ΛN interaction was known by the ΛN scattering data and the Λ hypernuclear spectroscopy.

Scattering experiment

- Major experimental method for deducing the interactions.

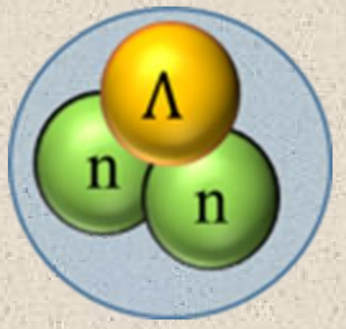
Λp scattering
→ Limited data
Λn scattering
→ No data (Not realistic)

Λ hypernuclear spectroscopy

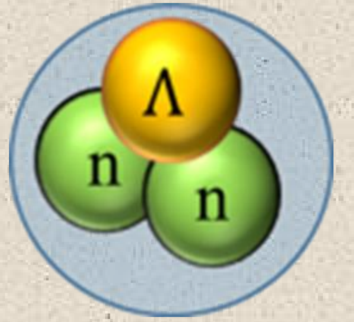
- By comparing with theoretical models

→ Understanding the effective ΛN interaction

$nn\Lambda$ is pure Λn system
→ It is good system to study the Λn interaction.

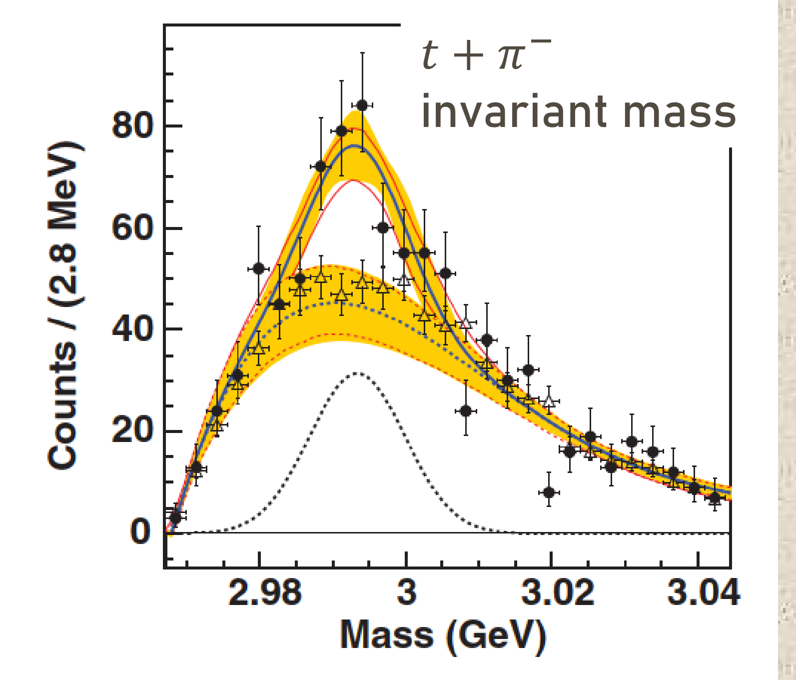


The $nn\Lambda$ state problem



Experimental suggestion

HypHI Collaboration at GSI reported structure that may be interpreted as a bound state of $nn\Lambda$ system.



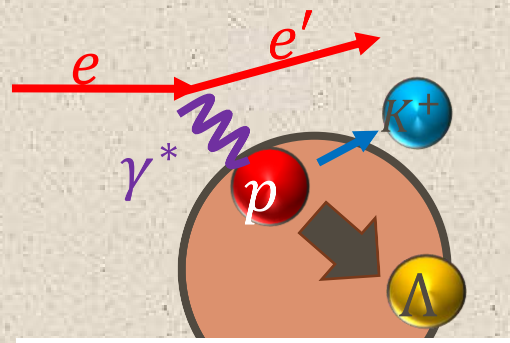
C. Rappold *et al.*, (HypHI Collaboration) Phys. Rev. C 88 041001 (2013)

Theoretical suggestion

- Theoretical calculation with Gaussian expansion method
  Ref.) E. Hiyama et al., Phys. Rev. C 89, 061302 (2014).
  Bound state of the $nn\Lambda$ is not realistic
- Faddeev calculation with S-wave separable potentials
  Ref.) I.R. Afnan et al., Phys. Rev. C, 92 054608 (2015).
  $nn\Lambda$ could be resonance state when a Λn potential is 5% deeper than Λp potential ($s > 1.05$).

Existence of the $nn\Lambda$ is not established
→ Need more precise spectroscopy measurement
We performed $nn\Lambda$ experiment at Jeffreson Lab (JLab)

High resolution spectroscopy at JLab



${}^{A}Z(e,e'K^+){}^{A}_{\Lambda}(Z-1)$

$(e,e'K^+)$ reaction

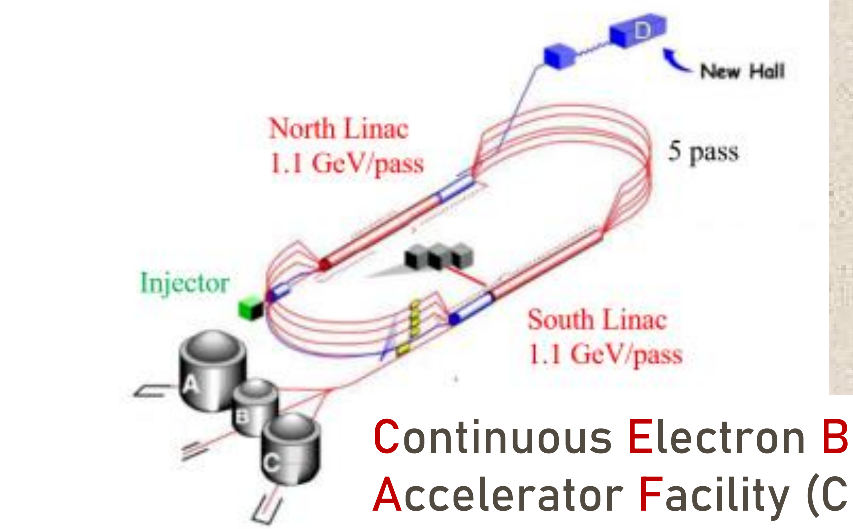
$(e \to e' + \gamma^*)$ to produce Λ in the nucleus.

The missing mass of Λ hypernuclei is

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

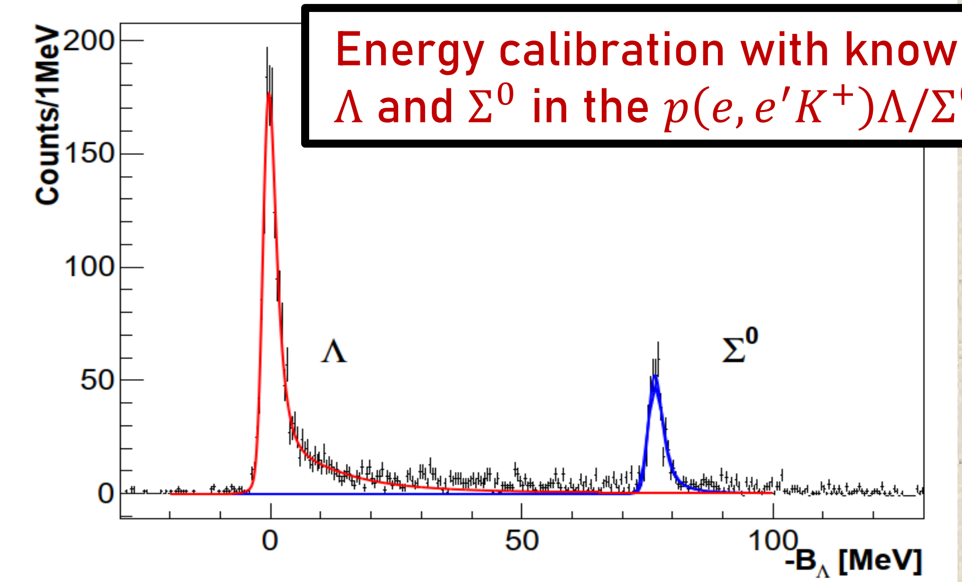
An experiment in the $(e,e'K^+)$ reaction can achievable high energy resolution (a few MeV FWHM) and precision (a few hundreds keV) due to use

Primary beam with small beam energy spread



Continuous Electron Beam Accelerator Facility (CEBAF)

Energy calibration with known mases of Λ and Σ^0 in the $p(e,e'K^+)\Lambda/\Sigma^0$ reaction

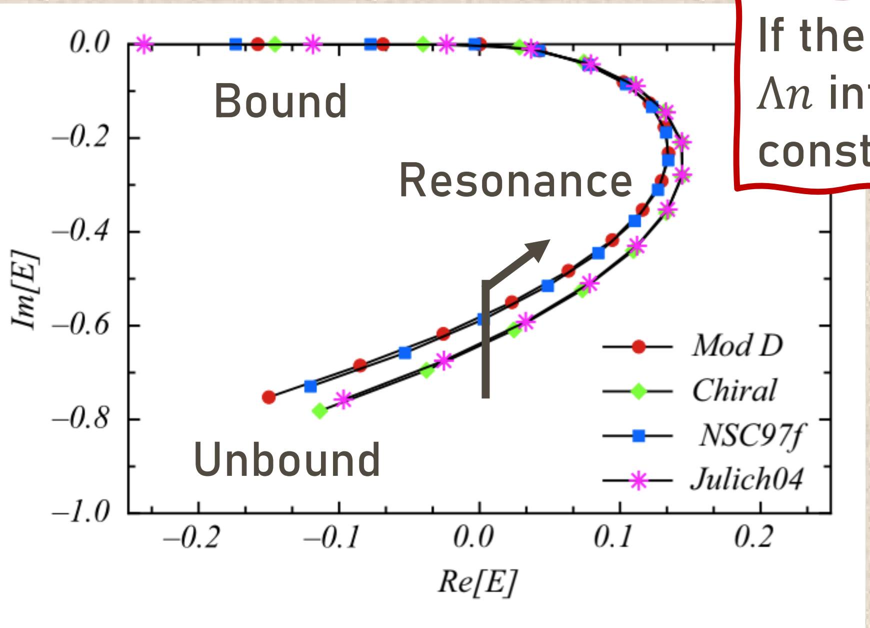


Study of the Λn interaction from $(e, e'K^+)$ reaction at JLab

There are two ways to study the Λn interaction from the $nn\Lambda$ system.

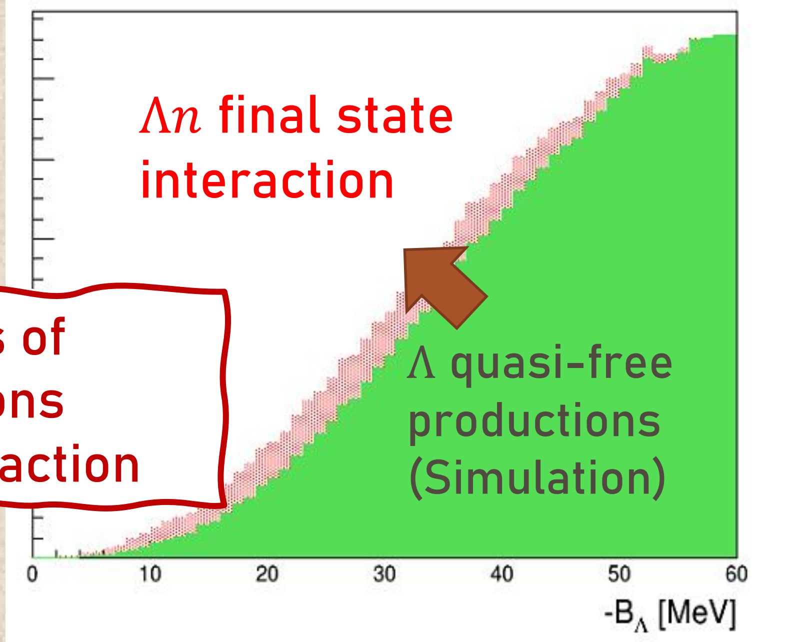
1. Analysis of $nn\Lambda$ peak (if the $nn\Lambda$ peak exists)
2. Analysis of $\Lambda - \mathrm{QF}$ distribution

Iraj R. Afnan *et al.,* Phys. Rev. C 92, 054608 (2015).



If the $nn\Lambda$ peak can be observed, Λn interaction can be constrained from the $nn\Lambda$ peak.

Shaping analysis of $\Lambda -$QF productions
→ Effective Λn interaction



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- Physics Motivation
- Experimental setup
- $^{3}\mathrm{H}(e,e'K^{+})X$ missing mass spectrum
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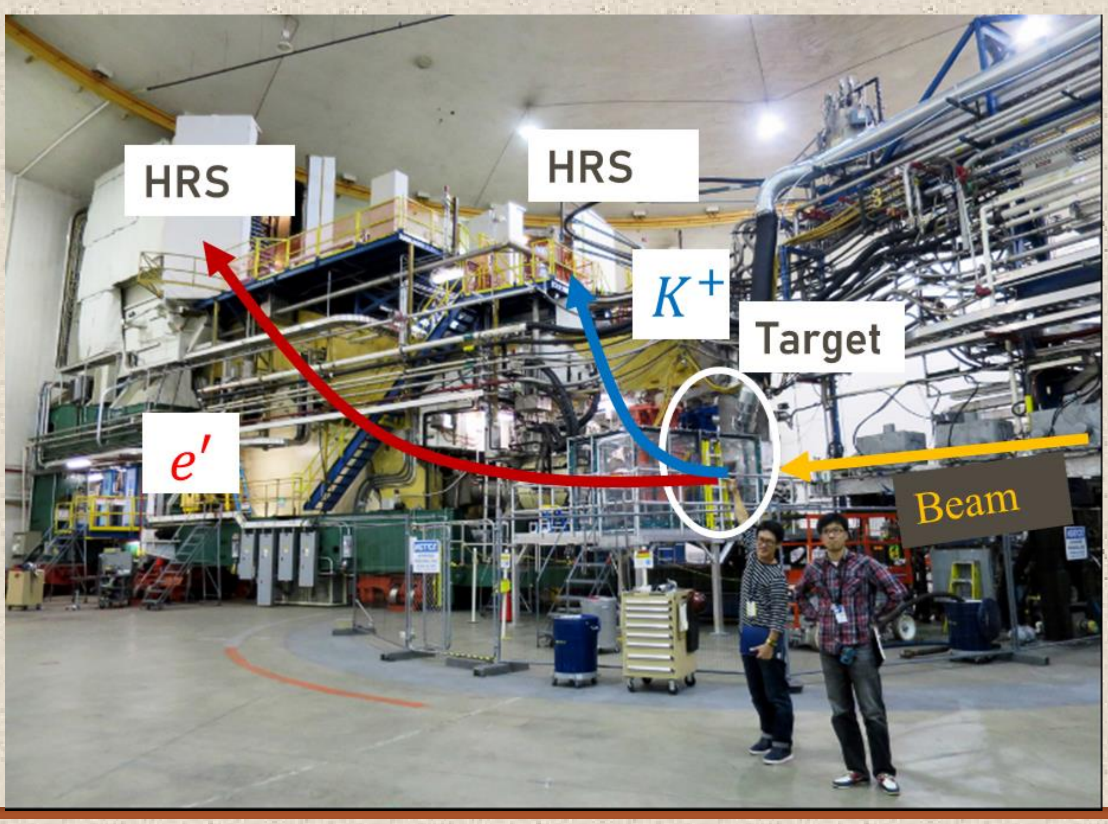
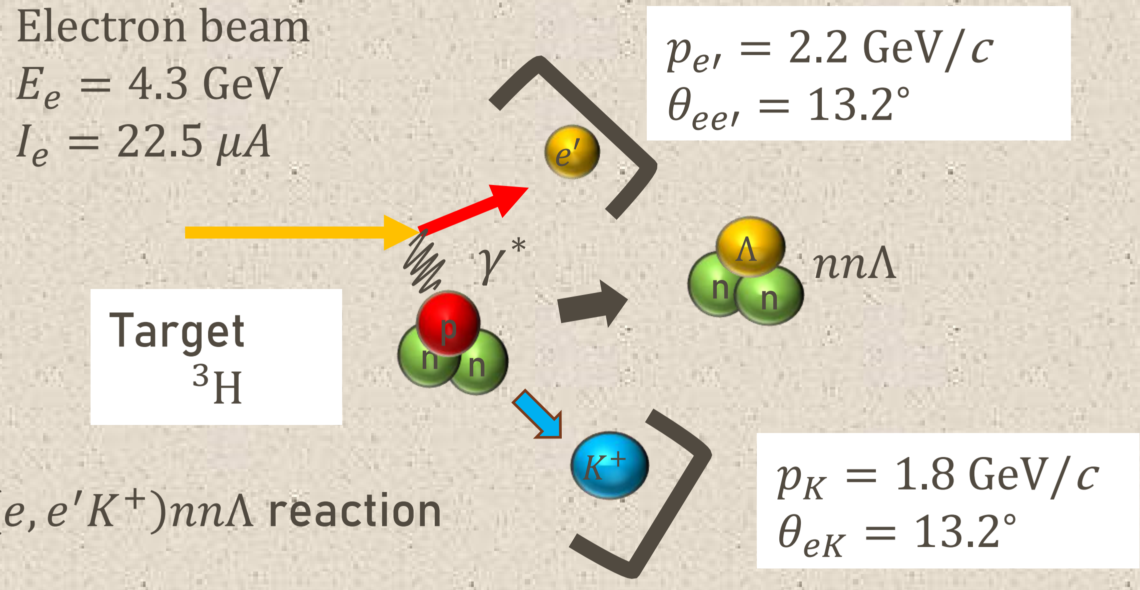
- Study of the Λn FSI in the $^{3}\mathrm{H}(e,e'K^{+})X$ reaction

$nn\Lambda$ experiment at Jefferson Lab

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 reconstructed by

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

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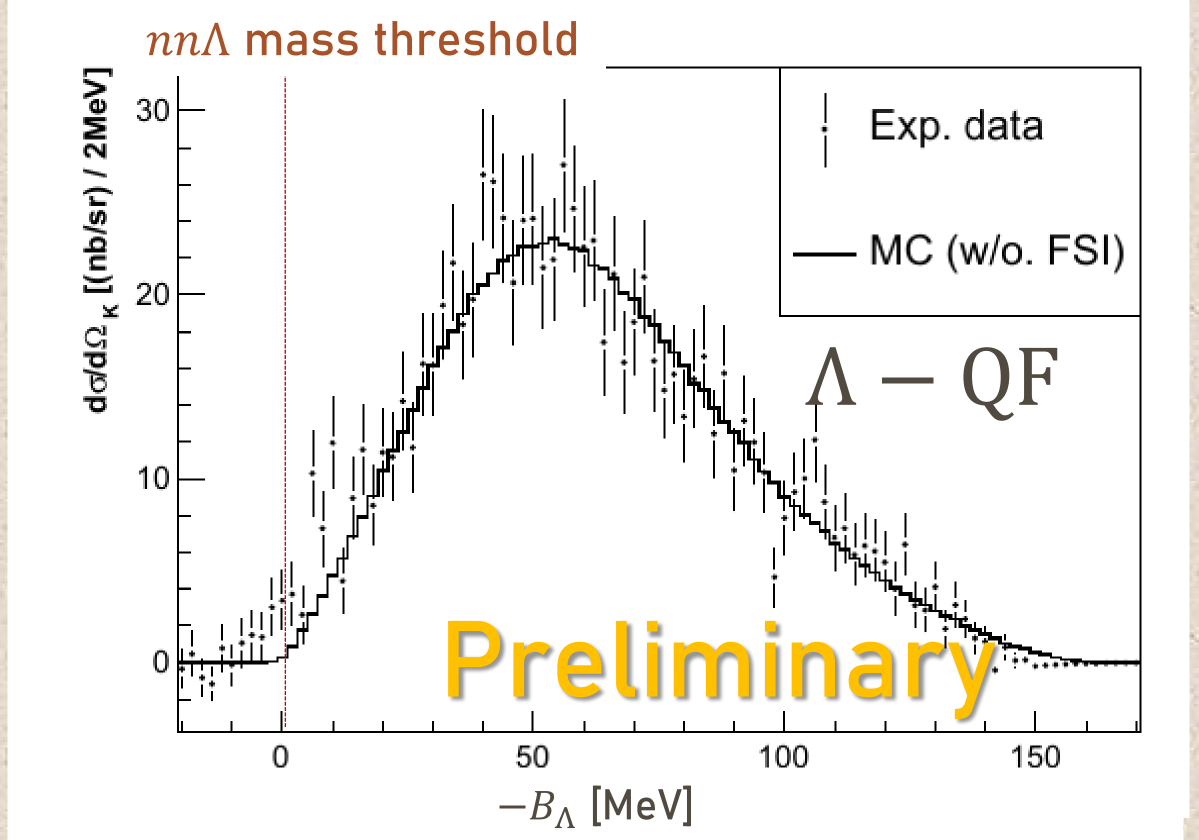
$^{3}\mathrm{H}(e,e'K^{+})X$ missing mass spectrum

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



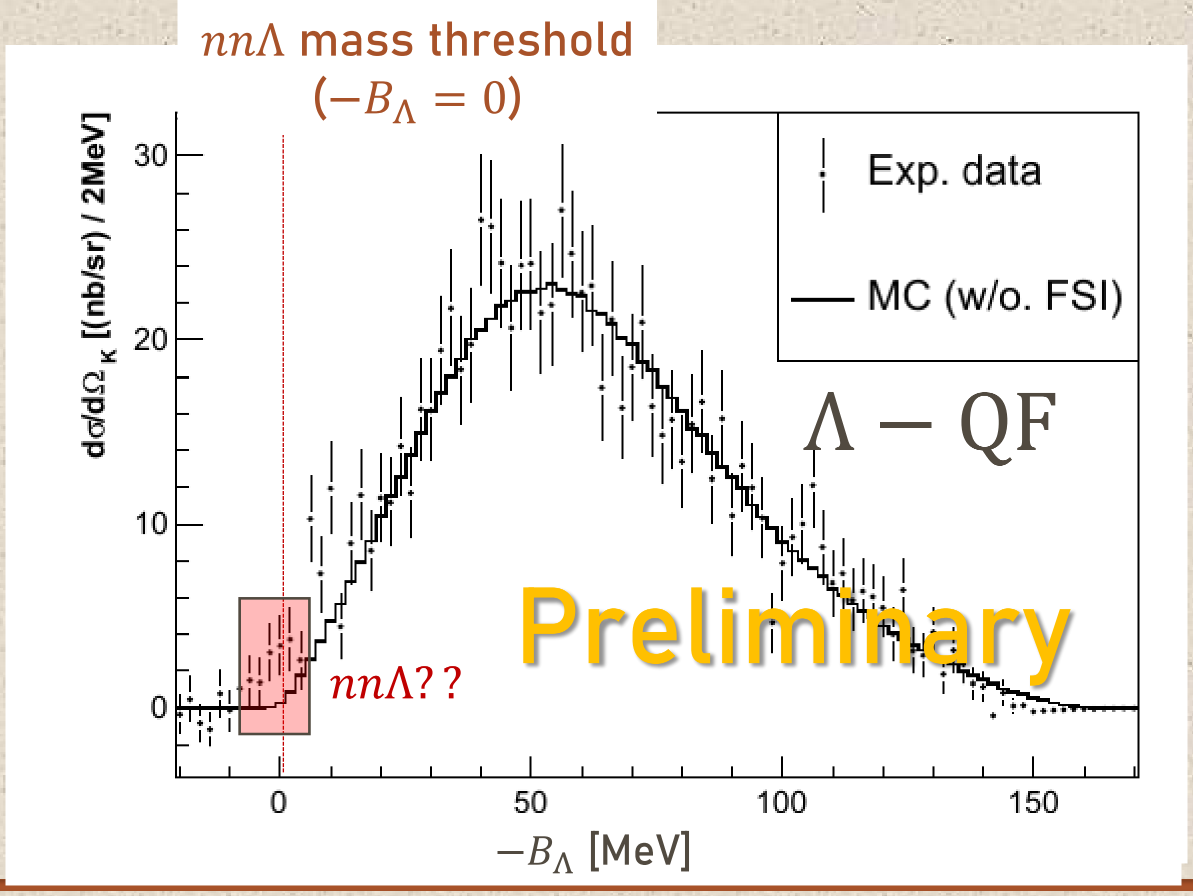
*1 : JLab Hall A/C standard Monte Carlo Simulation Including fermi momentum, kaon decay, radiative correlations

We study following physics from the $^{3}\mathrm{H}(e,e'K^{+})X$ spectrum

- Upper limit of the $nn\Lambda$ cross-section
- Spectroscopic study of the $\Sigma\mathrm{NN}$ state
- Study of the Λn final state interaction

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

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



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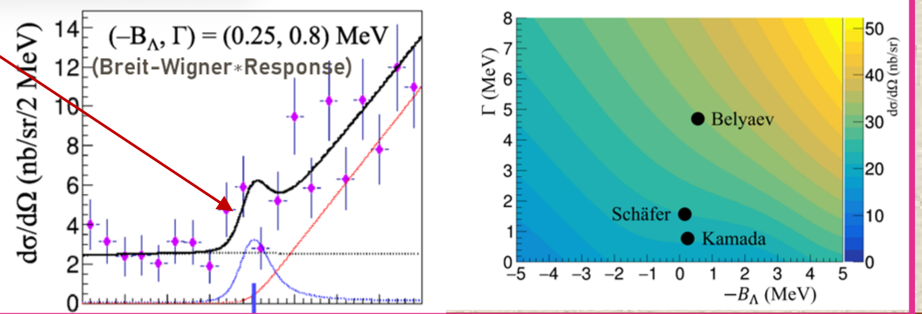
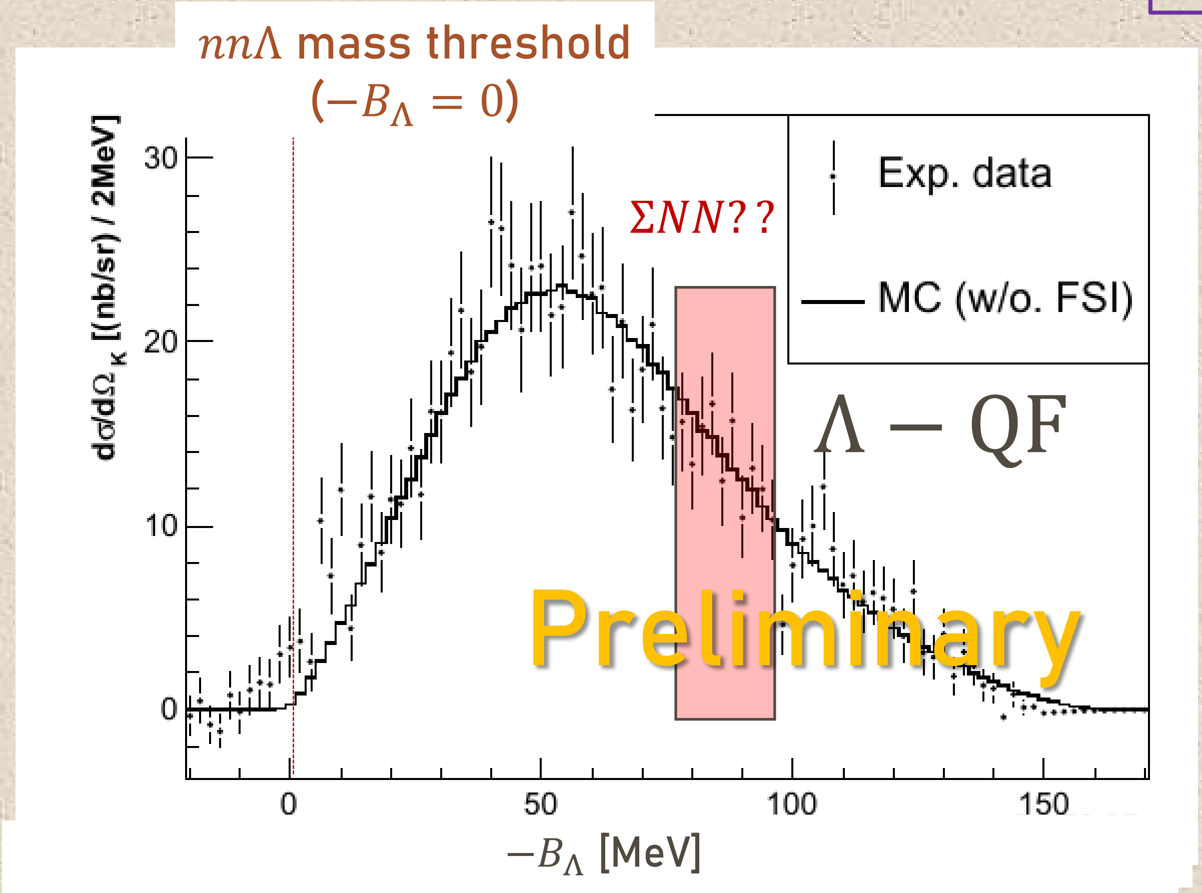
Not enough significance

Upper limit study of $nn\Lambda$ (Published)
K.N. Suzuki *et al.*, PTEP 2022, 013D01



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

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



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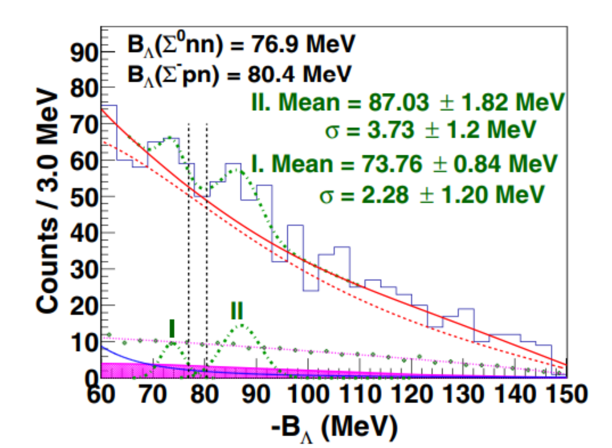

There are structure around ΣNN threshold
Study of the ΣNN state
→ Phys. Rev. C 105, L051001 (2022).

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

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

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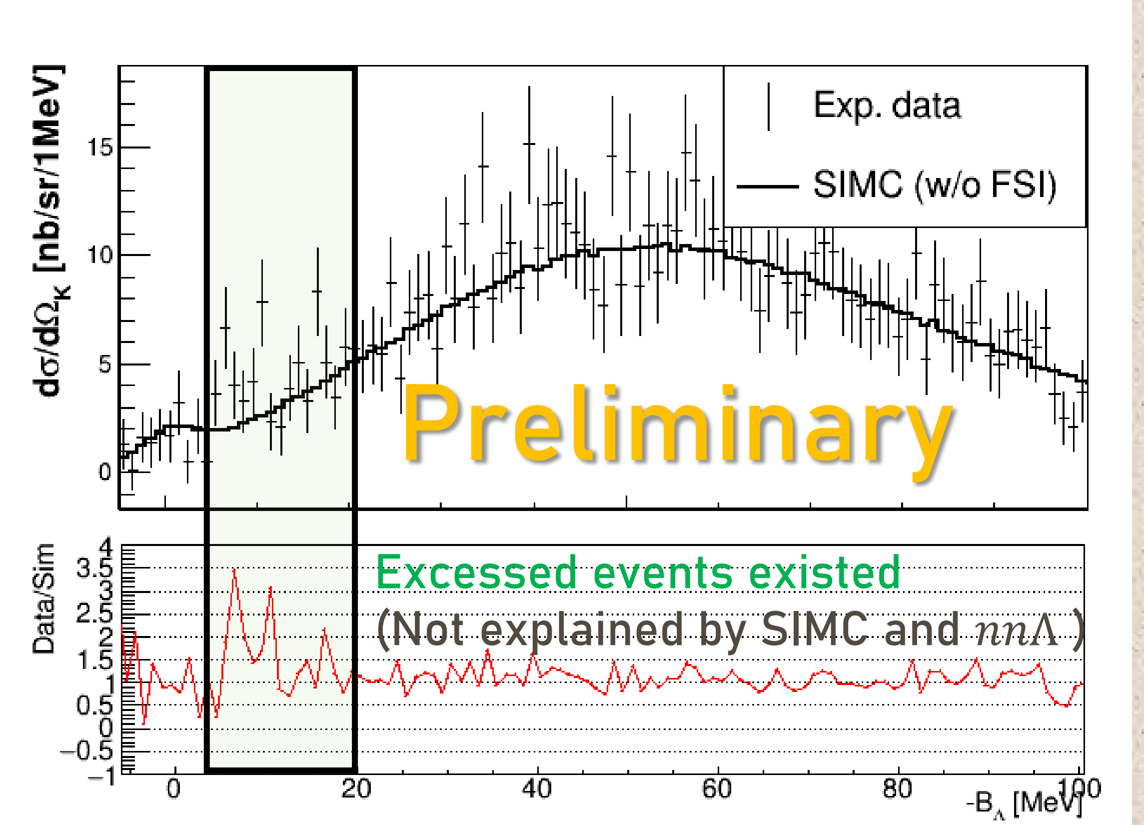
Including fermi momentum, kaon decay, radiative correlations



We study following physics from the $^{3}\mathrm{H}(e,e'K^{+})X$ spectrum

- Upper limit of the $nn\Lambda$ cross-section
- Spectroscopic study of the ΣNN state
- Study of the Λn final state interaction

Around 10 MeV region, there are excessed events even considering $nn\Lambda$ structure ($-B_{\Lambda} \sim 0$ MeV) .
→ Expected to be produced by the Λn FSI

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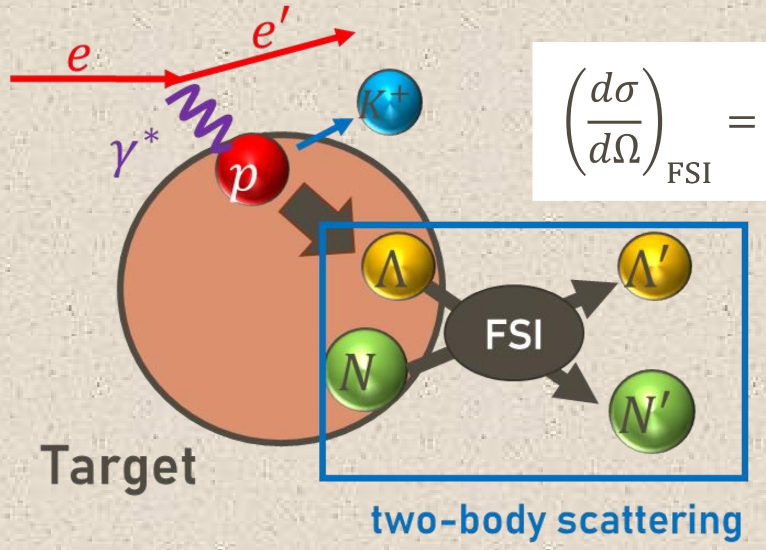
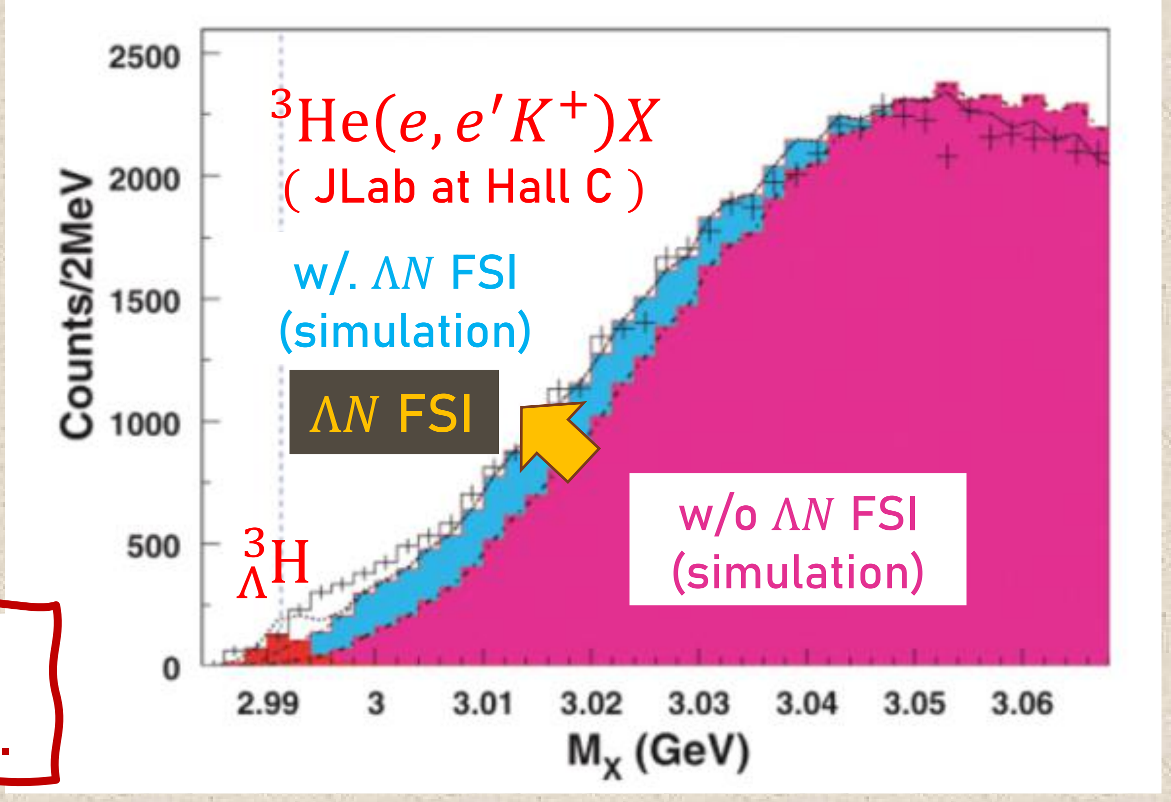
Final State Interaction (FSI)

Final state interaction (FSI) is reaction between a recoil Λ and a nucleon within a target (two-body (ΛN) scattering).



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

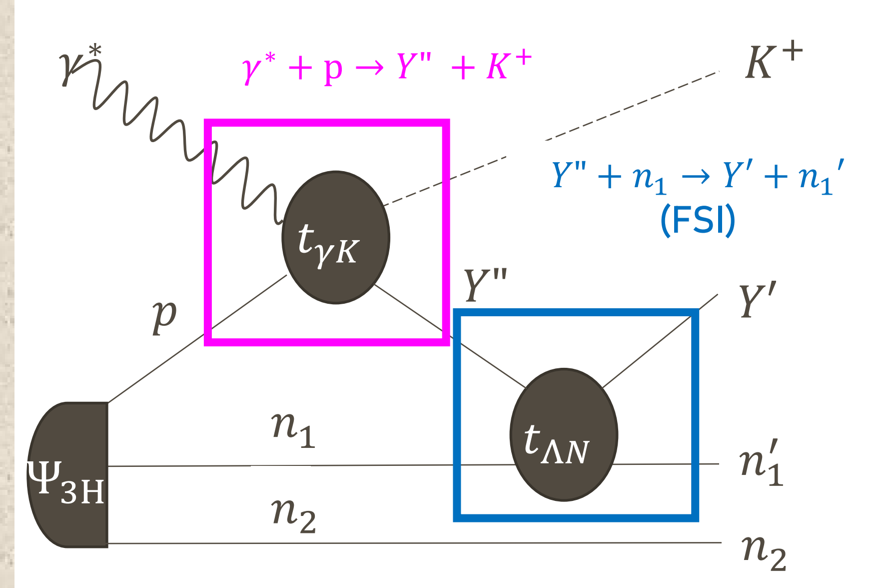


→ Λn FSI effect is expected to be appeared in the $^3\mathrm{H}(e,e'K^+)X$ missing mass spectrum.

Calculation of the Λn final state interaction

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

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

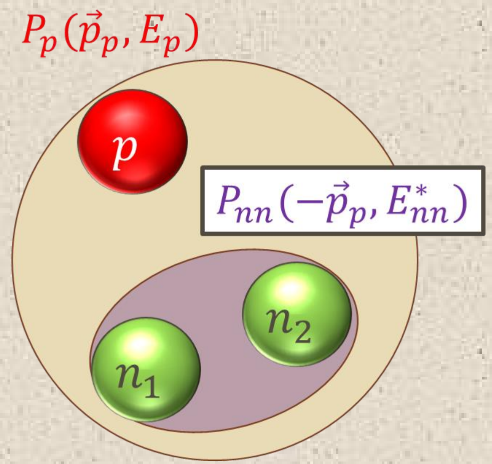


In the ERA ($k\cot\delta = -1/a + 1/2 r_e k^2$), the Jost function is written with scattering length (a) and effective range (r_e) as :

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

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

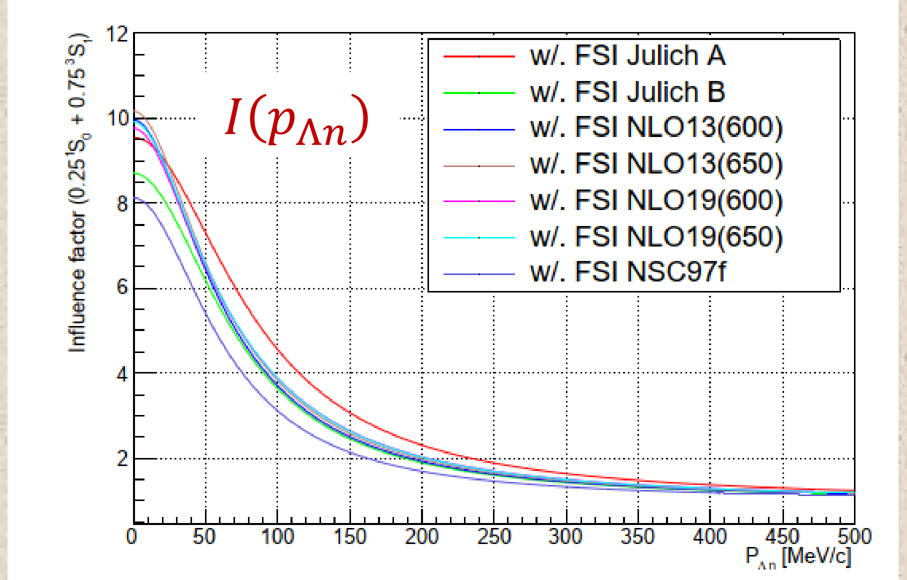
Simulation of the Λn FSI

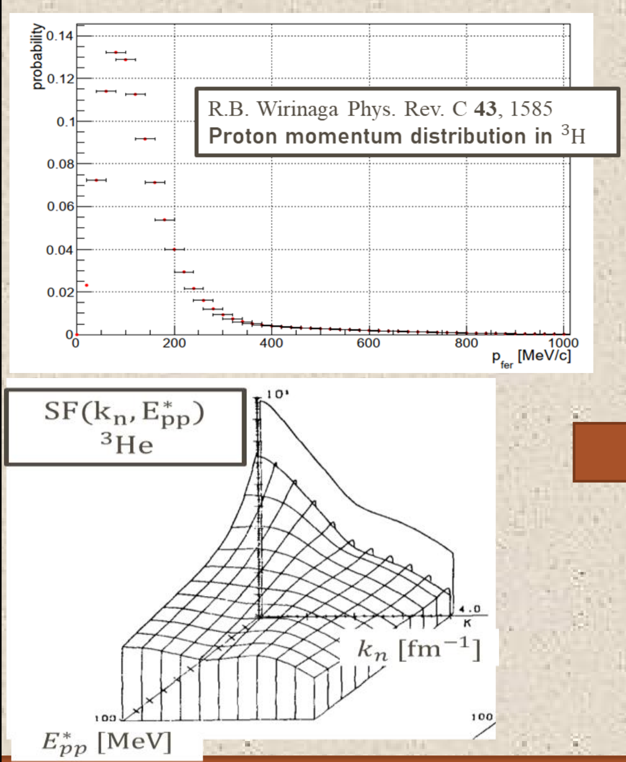


$I(p_{\Lambda n})$ is calculated with Jost function ($I(p_{\Lambda n}) = 1/|J_{l=0}(p_{\Lambda n})|^2$)

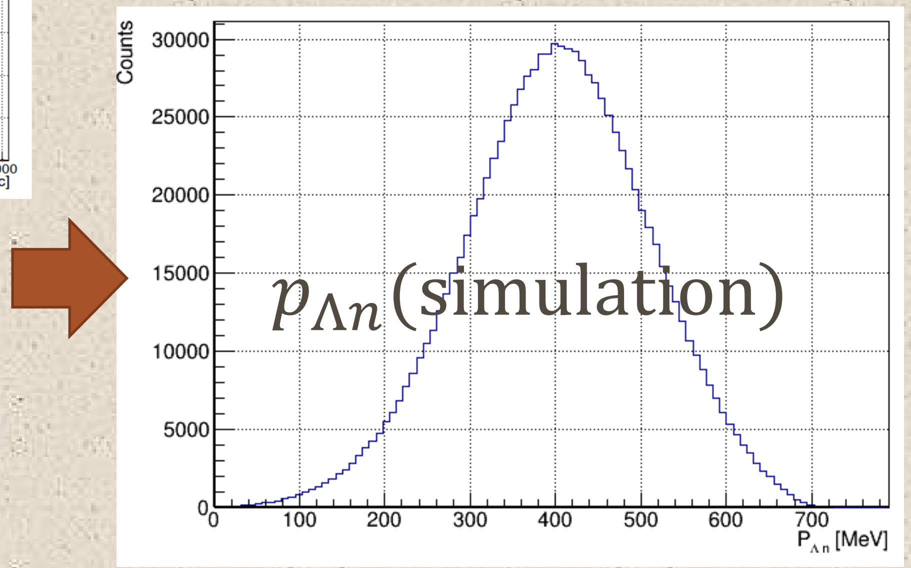
$$J_{l=0}(p_{rel}, r_e, a) = \frac{p_{\rm rel} - i\beta}{p_{\rm rel} - i\alpha},\ \frac{1}{2} r_e (\alpha - \beta) = 1,\ \frac{1}{2} r_e \alpha\beta = -\frac{1}{a}$$

$I(p_{\Lambda n})$ calculation





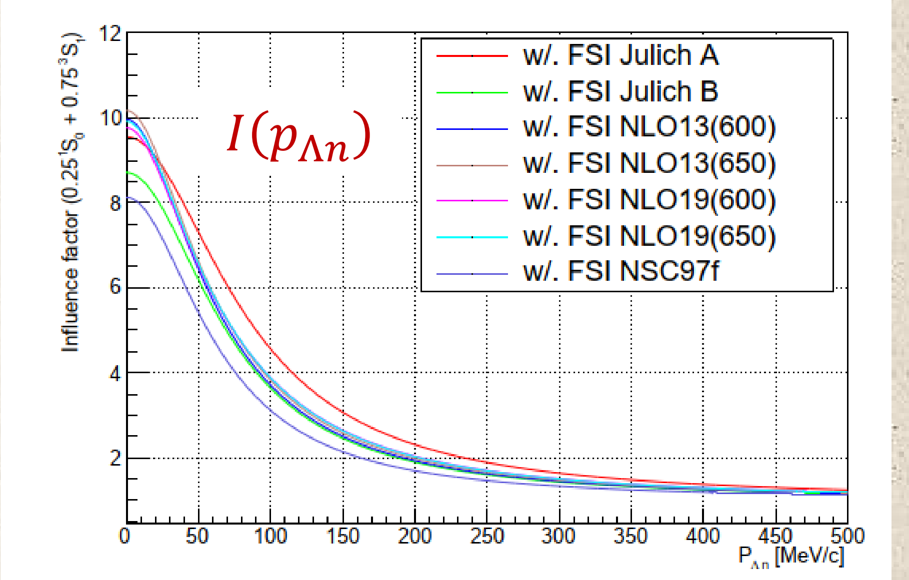
$p_{\Lambda n}$ Simulation



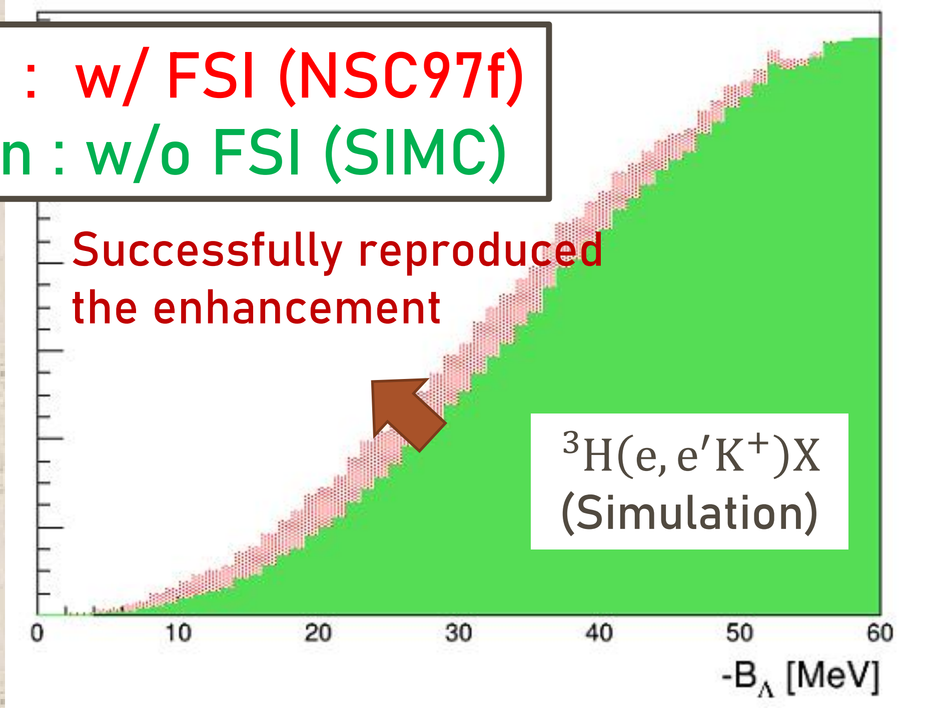
Missing mass spectrum including Λn FSI by SIMC

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

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



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



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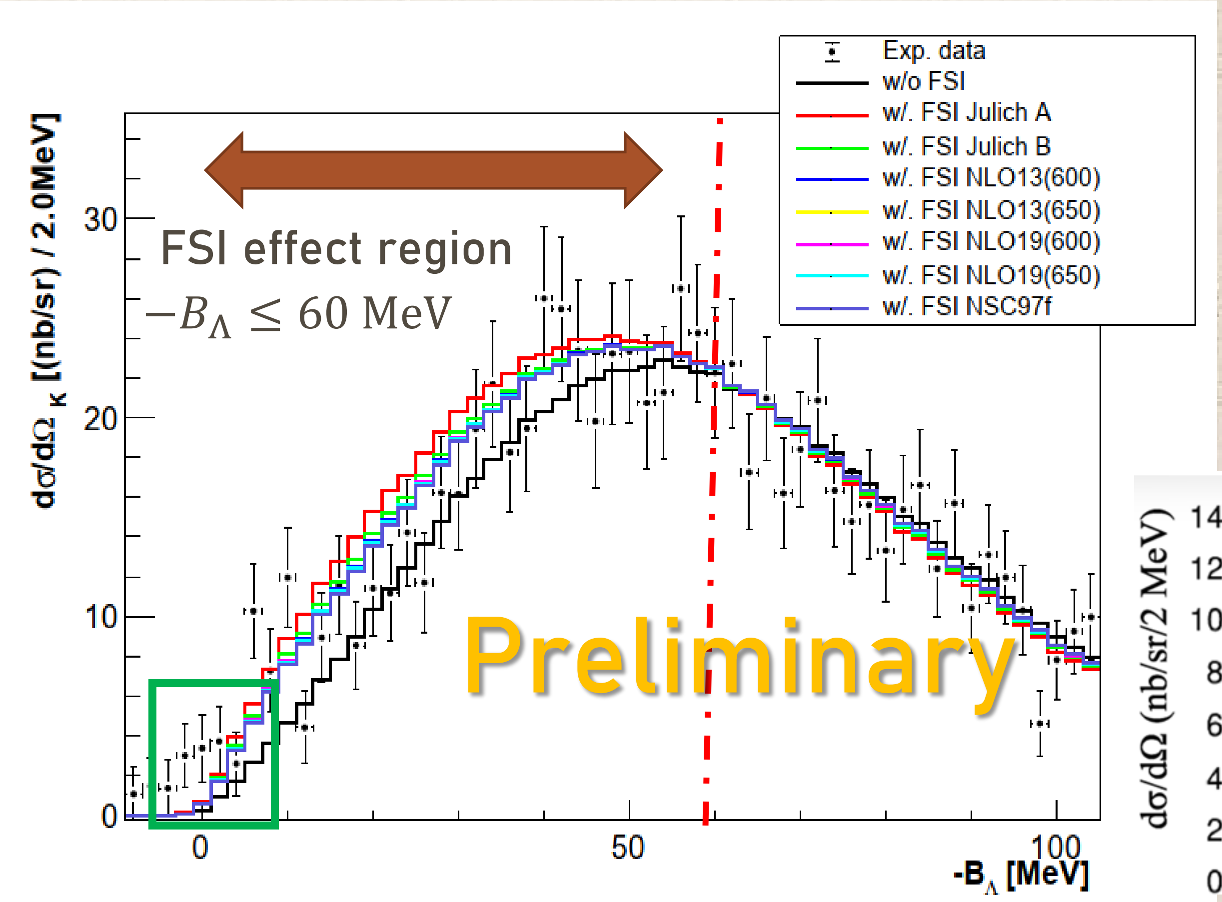
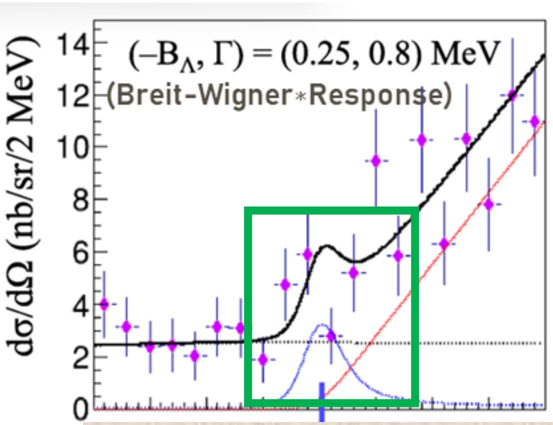
Enhancement structure in the $^3\mathrm{H}(e,e'K^+)X$ missing mass



There are two structures ($0 < -B_\Lambda < 60$ MeV)

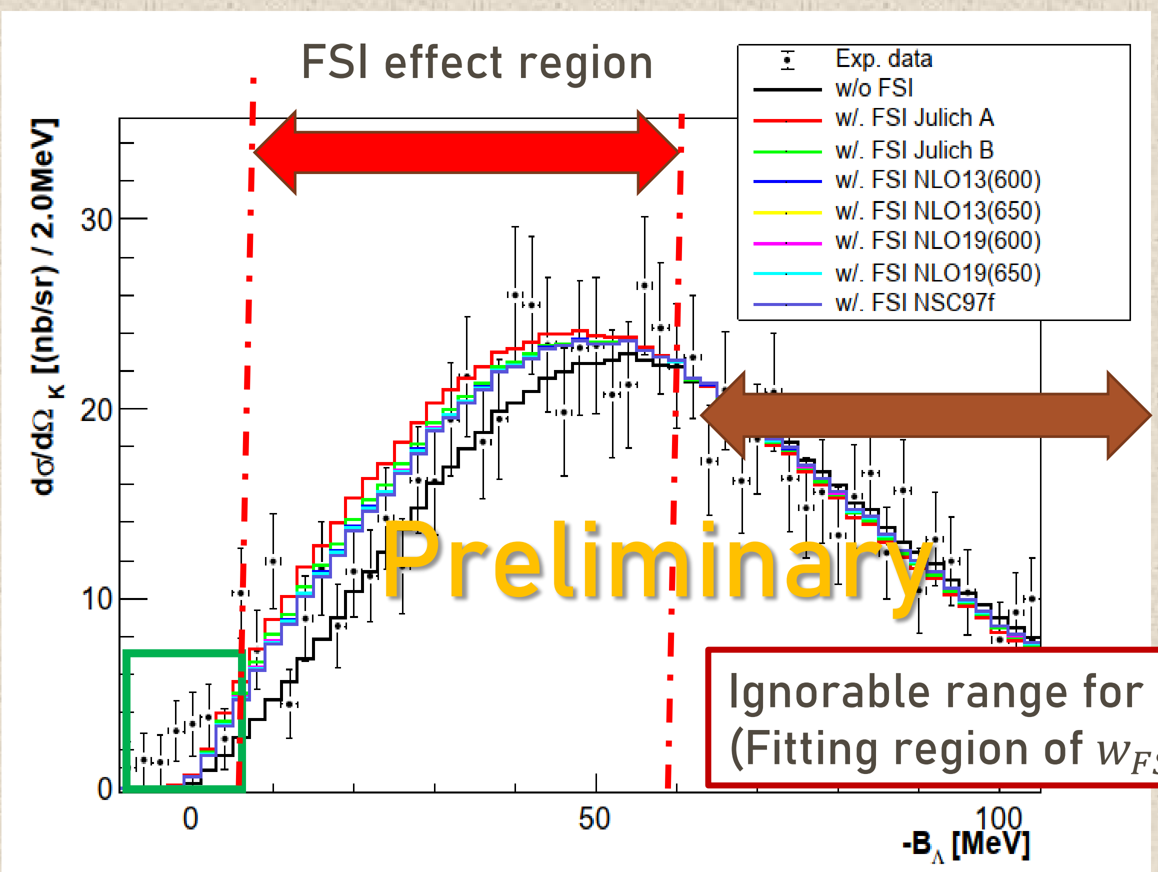
- $-B_\Lambda \sim 0$ MeV : Not reproduced by Λn FSI
- $-B_\Lambda \sim 20$ MeV : Produced by Λn FSI



The structure of $-B_\Lambda \sim 0$ MeV was reproduced by convolution integration function (f_{BW}) [*1] (Breit-Wigner ∗ Response functions)

[*1] S.N. Suzuki et al., Prog. Theor. Exp. Phys. 2022 013D01.

Chi-square fitting



Ignorable range for FSI
(Fitting region of w_{FSI})

MC with FSI spectra was scaled as

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{FSI}} = w_{\mathrm{FSI}} \cdot \mathrm{I}(k_{\mathrm{rel}}) \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{w/o\ FSI}} + w_{BW} f_{BW}$$

(w_{FSI}, w_{BW} are scaling factor)

Fixed parameters : $(-B_{\Lambda}, \Gamma) = (0.55, 4.7)$ MeV *1

*1 V.B. Belyaev et al., Nucl. Phys. A, 803, 210226 (2008).

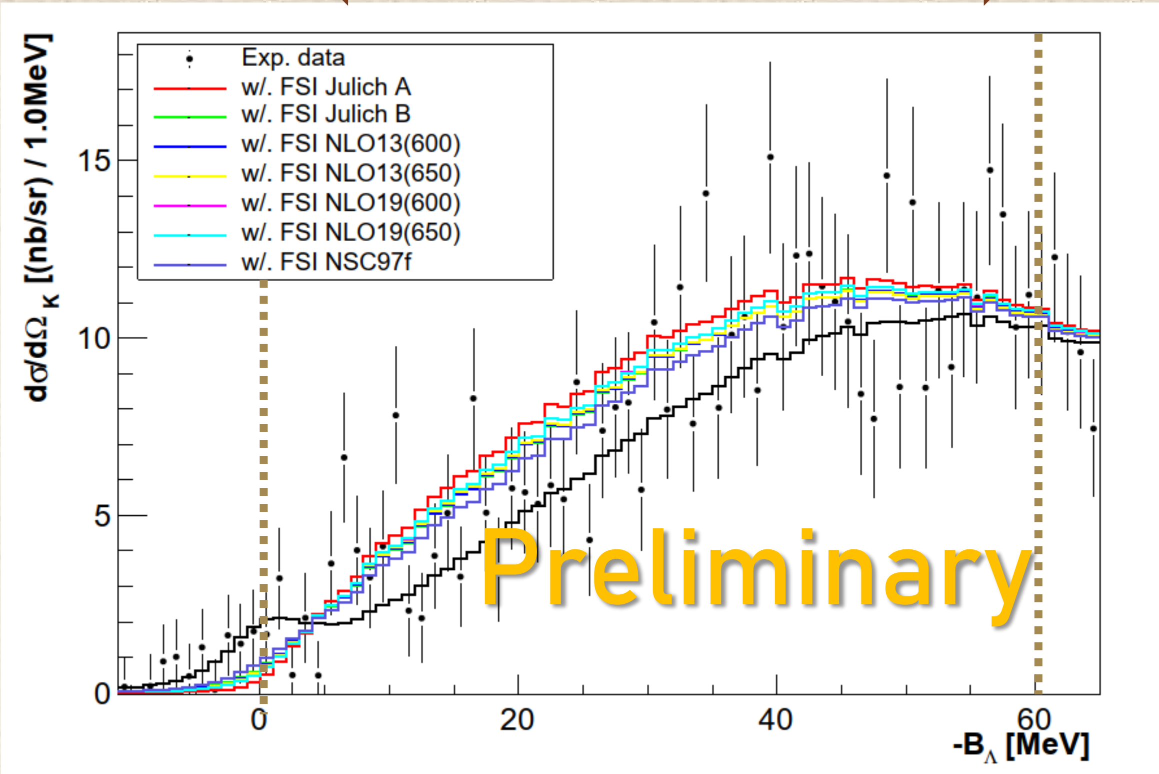
w_{BW} and w_{FSI} were given by chi-square fitting with ranges of

w_{BW} : $(-B_{\Lambda} \sim 0 \text{ MeV})$

w_{FSI} : $(60 \leq -B_{\Lambda} \leq 140 \text{ MeV})$

Fitting results of the SIMC spectra with Λn FSI

$0 \leq -B_\Lambda \leq 60$ MeV



SIMC spectra with Λn FSI were scaled in the region above 60 MeV (FSI ignorable range).

The goodness of fit of the SIMC spectra in each Λn potential model was evaluated by chi-squares with a range of $0 \leq -B_\Lambda \leq 60$ MeV .

Λn Potential	Reduced chi-square (χ^2/ndf)	$-B_\Lambda \sim 0$ MeV structure [nb/sr]
w/o FSI (w/o nnL peak)	1.24	0.0
w/o FSI	1.09	23.0
Jülich A	1.40	1.1
Jülich B	1.15	5.5
NSC97f	1.05	8.0
NLO13(600)	1.16	5.1
NLO13(650)	1.17	4.7
NLO19(600)	1.22	4.0
NLO19(650)	1.22	4.0

Preliminary

Contents

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)

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

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

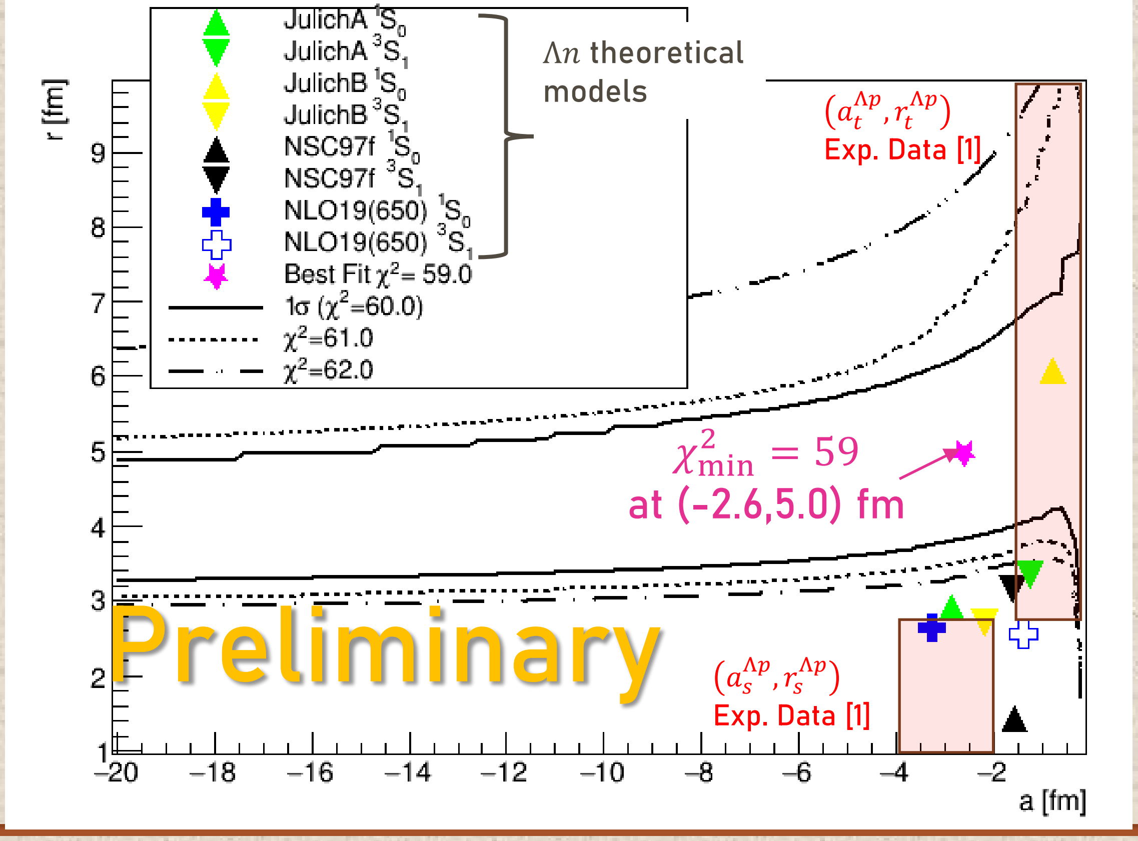
$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{FSI}} = \left(\left|\frac{1}{\mathrm{J}\,(\mathrm{k_{rel}})}\right|^2\right)\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{w/o\ FSI}}$$

Minimum chi-square $\chi^2_{\min}$ is 59 at $(\bar{a}, \bar{r}) = (-2.6, 5.0)$ fm.

Black solid line is the contour line at $\chi^2_{\min} + 1$.

→ It indicates statistical err.

Assuming $\bar{a} = -2.6$ fm
(Preliminary) $3.8 < \bar{r} < 5.3$ fm



Summary

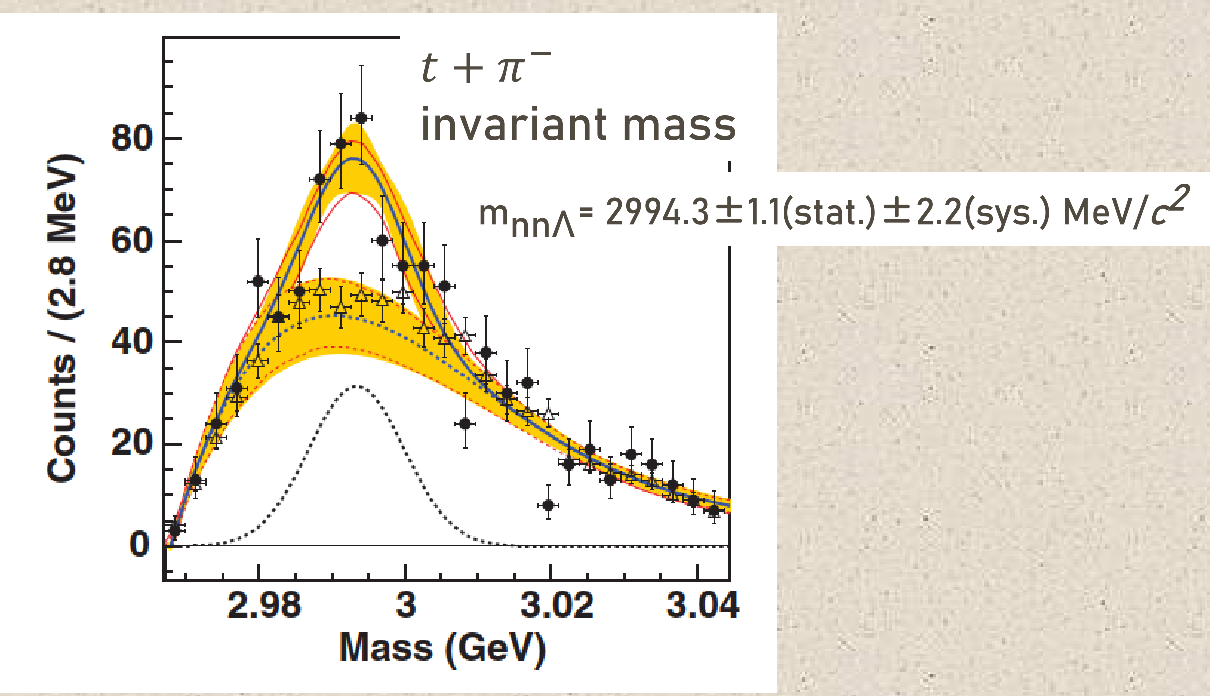
- ΛN final state interaction can be studied by the shaping analysis of the Λ −QF distribution.
- Λn FSI was investigated from the Λ −QF productions in the $^{3}\mathrm{H}(e,e'K^{+})X$ reaction.
- Using the Jost function, the potential parameters of Λn potentials (a,r) were successful to be restricted by the chi-square fitting.
- Assuming $\bar{a} = -2.6$ fm (Preliminary) $\bar{r} = 5.0^{+1.3}_{-1.2}$ (stat.) fm

BackUp

$nn\Lambda$ Experiment at JLab

$nn\Lambda$ production reaction

Reaction	Target	Resolution
$(\pi^+, K^+), (K^-, \pi^-)$	nnn	
Heavy ion	some	△
$(e, e'K^+)$	$^3\mathrm{H}$	○



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

- GSI measured invariant mass and lifetime of $t + \pi^-$ in $^6\mathrm{Li} + {}^{12}\mathrm{C}$ reaction at 2A GeV

  Not enough peak significance of $nn\Lambda$ and enough mass resolution to study Λn interaction

[1] T. Gogami , Doctoral thesis (2014).

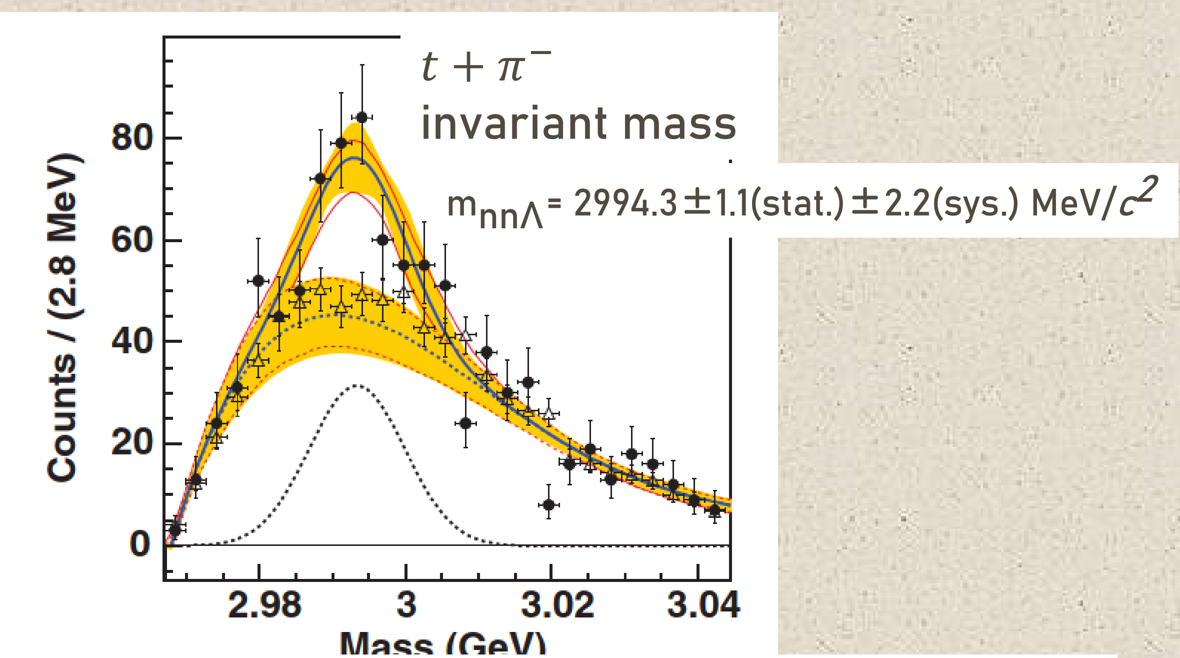
- $(e, e'K^+)$ reaction enable to achieve high resolution $(-B_\Lambda \sim 0.5\ \mathrm{MeV\ \ in\ FWHM})$ [1]

  Need radioactive material of $^3\mathrm{H}$ for the target

$nn\Lambda$ Experiment at JLab

$nn\Lambda$ production reaction

Reaction	Target	Resolution
$(\pi^+, K^+), (K^-, \pi^-)$	nnn	
Heavy ion	some	△
$(e, e'K^+)$	$^3\mathrm{H}$	○



Jefferson Lab (JLab) meets the requirements
- High quality electron beam accelerator (CEBAF)
- Able to handle tritium target (Tritium Campaign 2017-2018)

- $(e, e'K^+)$ reaction enable to achieve high resolution ($-B_\Lambda \sim 0.5$ MeV in FWHM) [1]

Need radioactive material of $^3\mathrm{H}$ for the target

Calculation of the Λ momentum (p_Λ)

Λ momentum ($\vec{p}_\Lambda$) :

$$\vec{p}_\Lambda = \vec{p}_p + \vec{p}_{\gamma^*} - \vec{p}_K$$

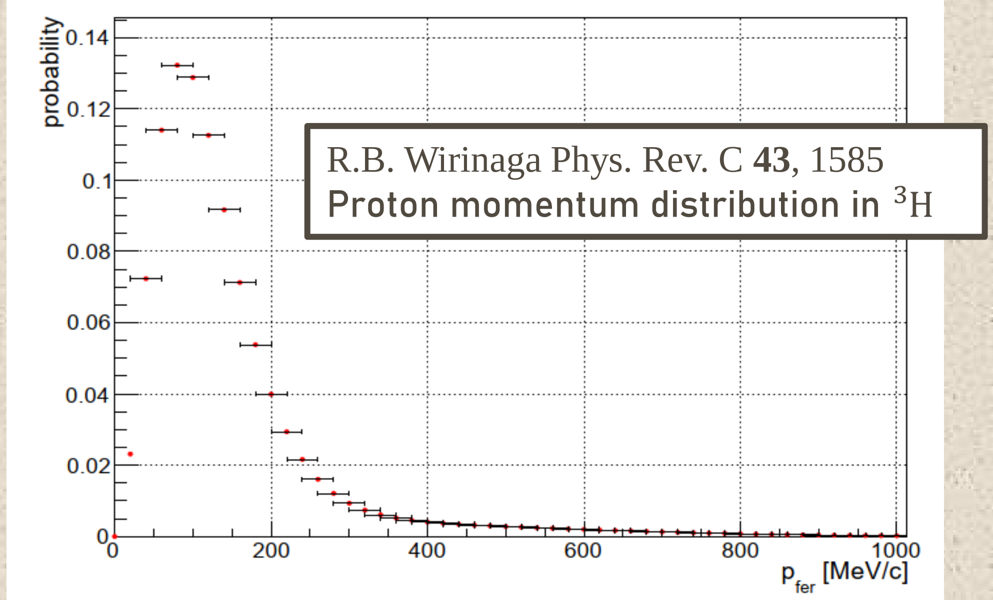
Measured values

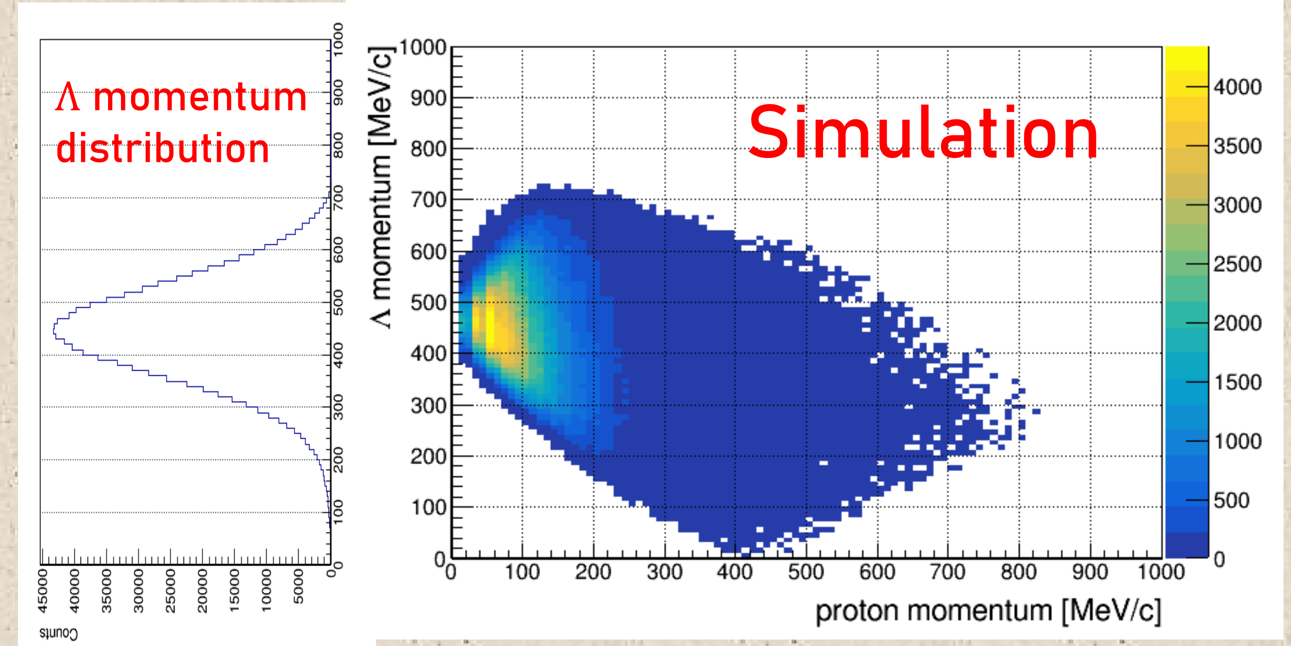
$\vec{p}_K = 1800 \pm 80\ \mathrm{MeV}/c$

$\vec{p}_{\gamma^*} = 2100 \pm 100\ \mathrm{MeV}/c$

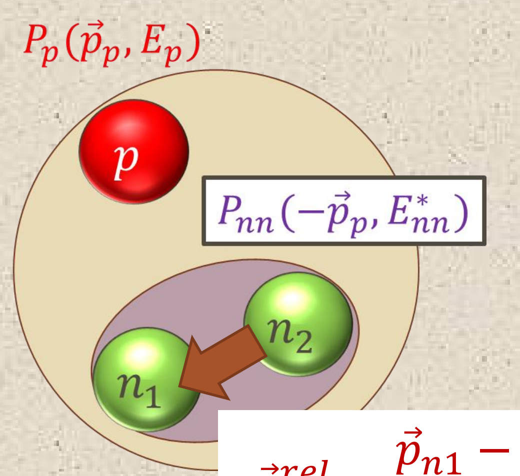
$|\vec{p}_p|$ was given by Fermi momentum probability.

$(\theta_p,\ \phi_p)$ was generated by a spherical uniform distribution.





Estimation of each neutron momentum ($\vec{p}_n$)



$$\vec{p}^{rel}_{nn} = \frac{\vec{p}_{n1} - \vec{p}_{n2}}{2}$$

Stopped target (^{3}H)→ $\vec{p}_p + \vec{p}_{n1} + \vec{p}_{n2} = 0$

with nn relative momentum $\vec{p}^{\mathrm{rel}}_{nn}$, a neutron momentum $\left(\vec{p}_{n1(n2)}\right)$ were

$$\vec{p}_{n1(n2)} = -\frac{1}{2}\vec{p}_p + \vec{p}^{rel}_{nn}$$

$$\left|\vec{p}_{n1(n2)}\right| = \sqrt{\left|\vec{p}^{rel}_{nn}\right|^2 + \frac{\left|\vec{p}_p\right|^2}{4} \mp \left|\vec{p}_p\right|\left|\vec{p}^{rel}_{nn}\right|\cos\theta}$$

unknown

θ: spherical uniform, $\vec{p}_p$: Fermi momentum

Each neutron momentum cannot be determined.

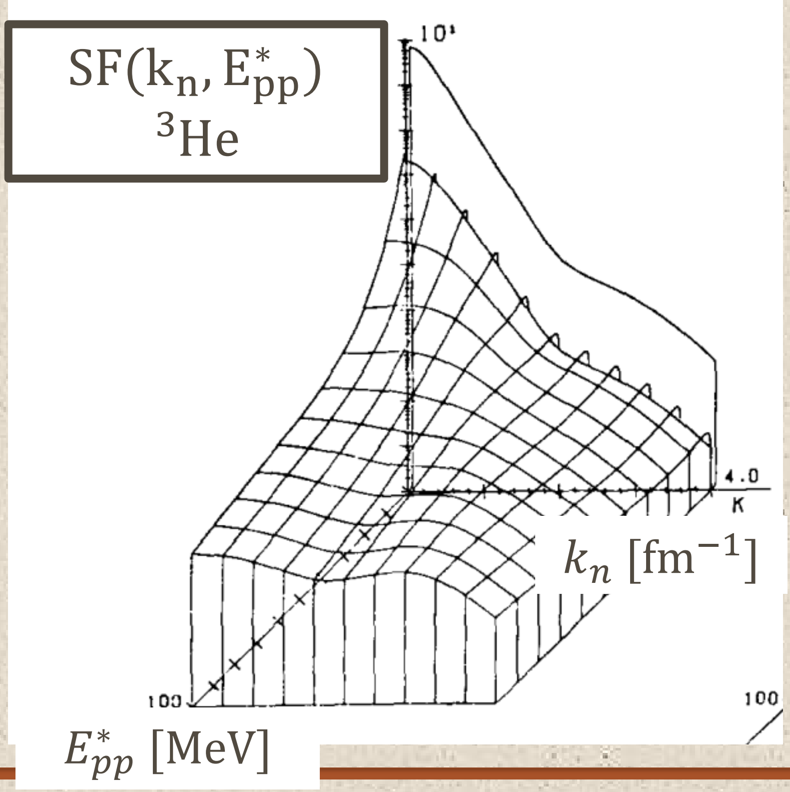
→ $\vec{p}^{rel}_{nn}$ is given by ^{3}H spectral function (SF)

Spectral functions of three body system

One of the nucleon momentum in ^{3}H is given by spectral function (SF)

However, spectral function of ^{3}H could not reproduced

→ Using SF of ^{3}He assuming charge symmetry



The relative momentum was written by the excited energy of residual system

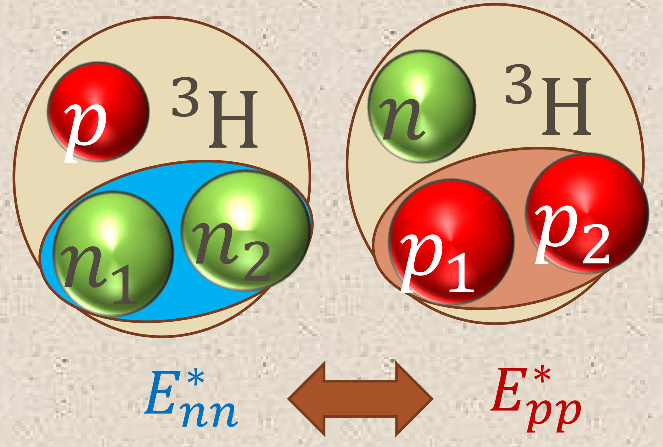
$$E^*_{pp} = \frac{\left|\vec{p}^{\,rel}_{pp}\right|^2}{2\mu} = \frac{\left|\vec{p}^{\,rel}_{pp}\right|^2}{m_p}$$

The proton momentum in ^{3}He

$$\left|\vec{p}^{\,3He}_{p}\right| = \sqrt{m_p E^*_{pp} + \frac{|\vec{p}_n|^2}{4} \mp |\vec{p}_n|(m_p E^*_{pp})\cos\theta}$$

$$\left|\vec{p}^{\,3H}_{n}\right| = \sqrt{m_n E^*_{pp} + \frac{\left|\vec{p}_p\right|^2}{4} \mp \left|\vec{p}_p\right|(m_n E^*_{pp})\cos\theta}$$

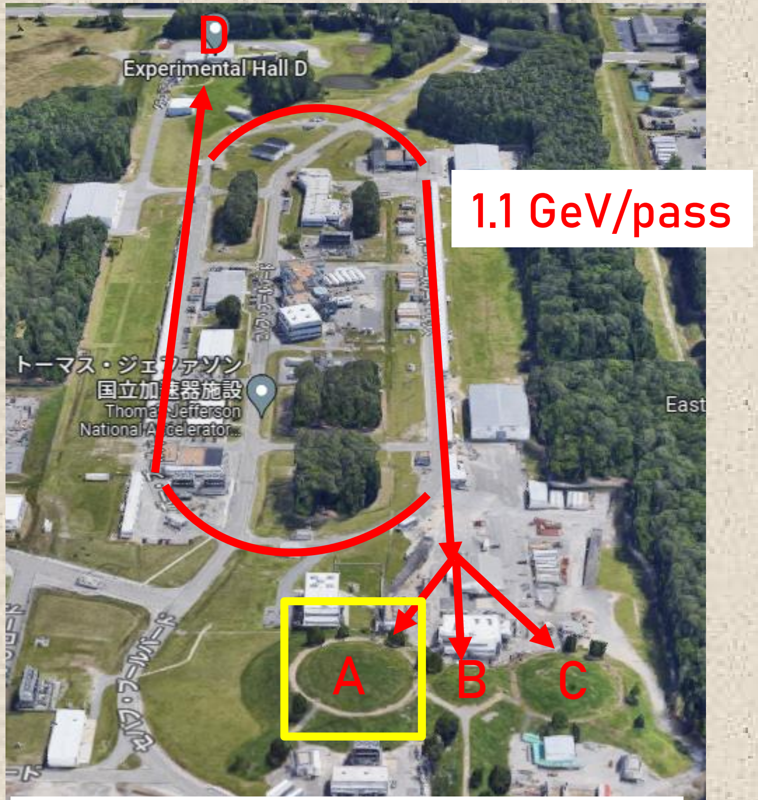
Mirror system



Assuming charge symmetry

$$E^*_{nn} = E^*_{pp}$$

Jefferson Lab (JLab)



Continuous Electron Beam Accelerator Facility (CEBAF)

Jefferson Lab (JLab) has continuous electron beam accelerator facility (CEBAF) which provides us high current and quality electron beam.

CEBAF Main Specifications

- Max Beam Energy : 12 GeV (6 paths)
- Max beam current : 85 μA
- Beam spread (ΔE/E): 1.8×10^{-4} (FWHM)

Missing mass spectra with Λn FSI

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

- Excess events around $nn\Lambda$ mass threshold $(-B_\Lambda \sim 0\ \mathrm{MeV})$

  → Assuming resonance state of $nn\Lambda$ $(\Gamma, -B_\Lambda) = (4.7, 0.55)\ \mathrm{MeV}$

- Including Λn FSI effects $(0 < -B_\Lambda < 60\ \mathrm{MeV})$

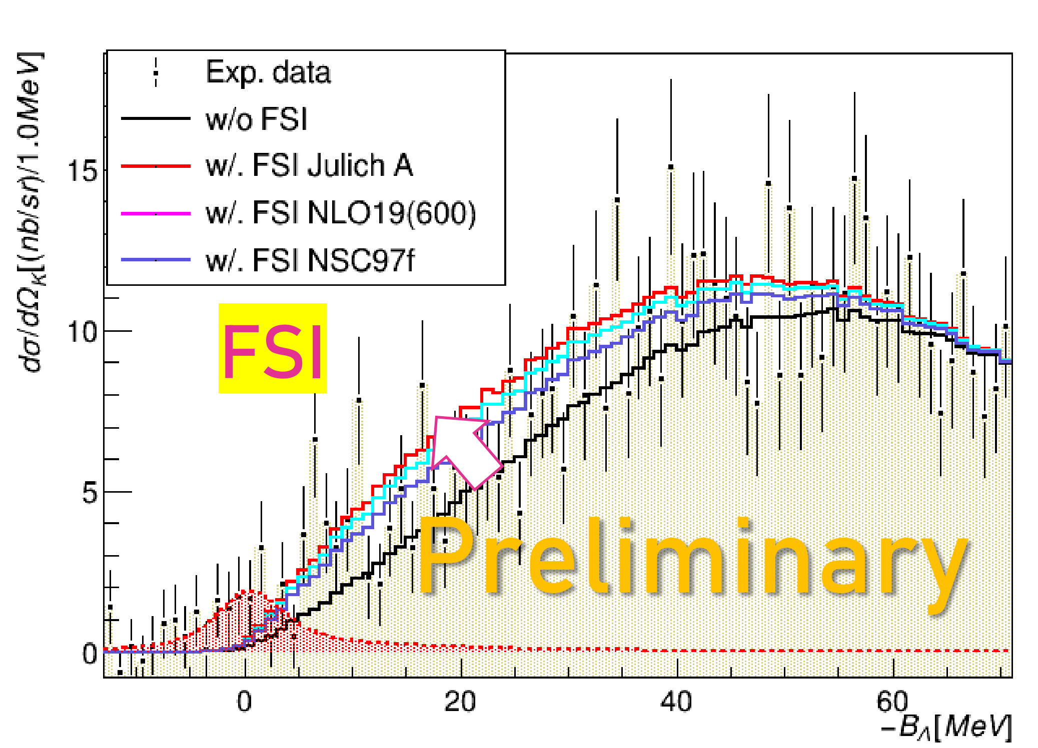
Experimental data was fitted with chi-square as

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

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

Missing mass spectra with FSI :

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



The scaling of MC spectra

The enhancement by Λn FSI

Low mass region ($-B_\Lambda < 60$ MeV) → Effective

High mass region ($-B_\Lambda > 60$ MeV) → Ignorable

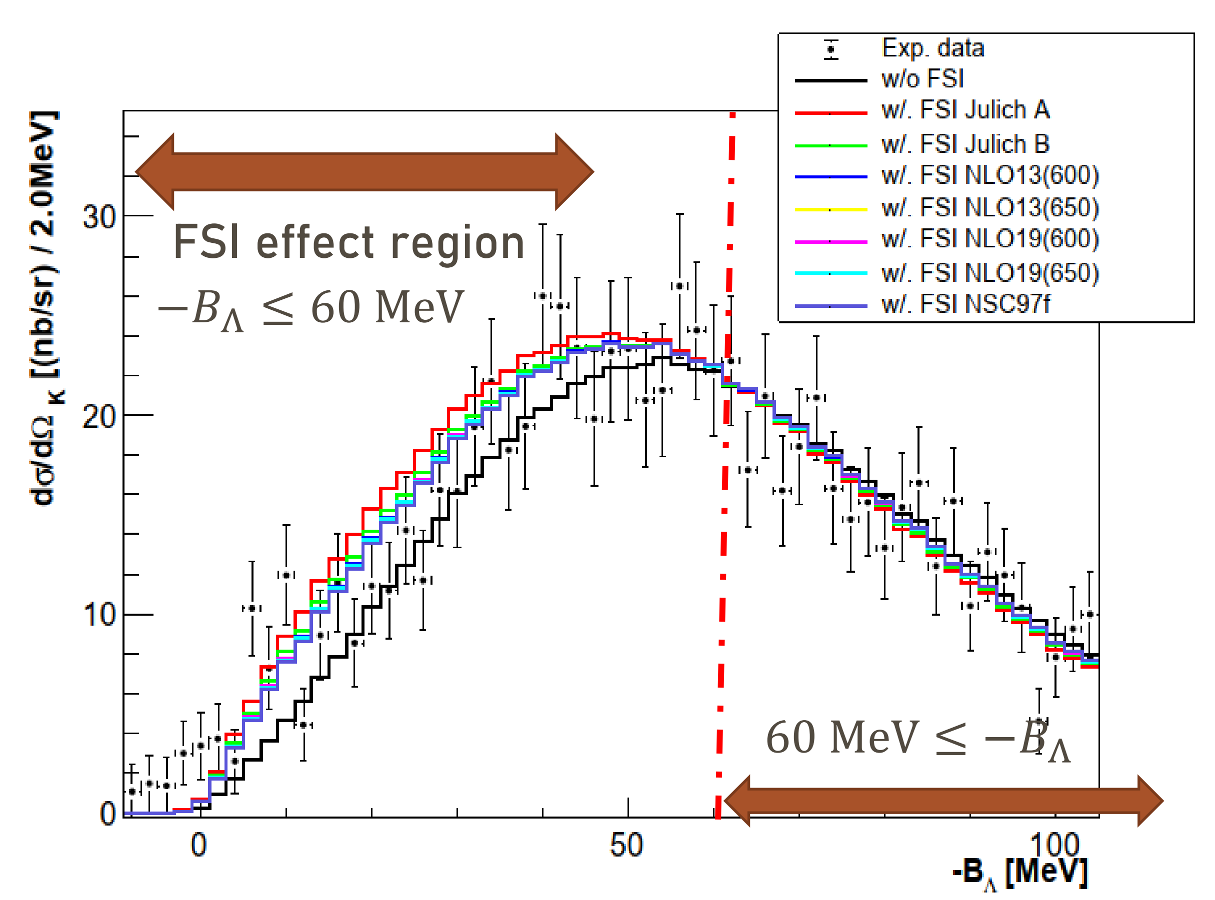
MC with FSI spectra was scaled as

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{FSI}} = f_{\mathrm{FSI}} \cdot \mathrm{I}(k_{\mathrm{rel}}) \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{w/o\ FSI}}$$

(f_{FSI} is scaling factor)

f_{FSI} was determined by the value with the smallest chi-square within ($60 \leq -B_\Lambda \leq 140$ MeV)

$$\chi^2 = \sum_i^{N_{\mathrm{bin}}} \frac{\left(y^i_{\mathrm{data}} - f_{\mathrm{FSI}} \cdot \mathrm{I}(k^i_{rel}) y^i_{\mathrm{MC}}\right)^2}{\sigma^i_{\mathrm{data}}}$$



Ignorable range for FSI
(Fitting region)

The scaling of MC spectra

With influence factor $\mathrm{I}(\mathrm{k_{rel}})$,

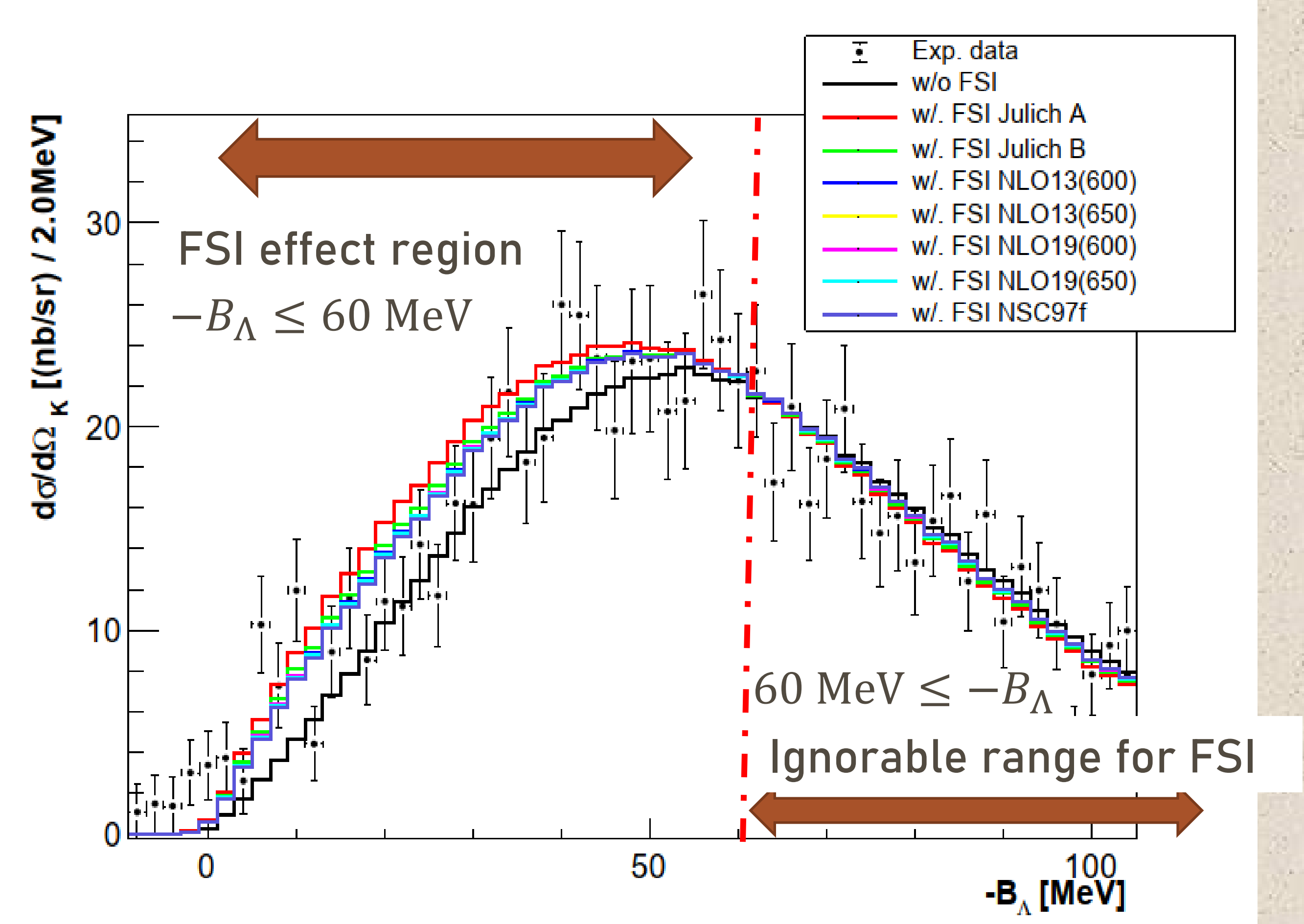
MC with FSI spectra was

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{FSI}} = f_{\mathrm{FSI}} \cdot \mathrm{I}(k_{\mathrm{rel}}) \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{w/o\ FSI}}$$

f_{FSI} is scaling factor.

f_{FSI} was determined by the value with the smallest chi-square within $(60 \leq -B_\Lambda \leq 140\ \mathrm{MeV})$

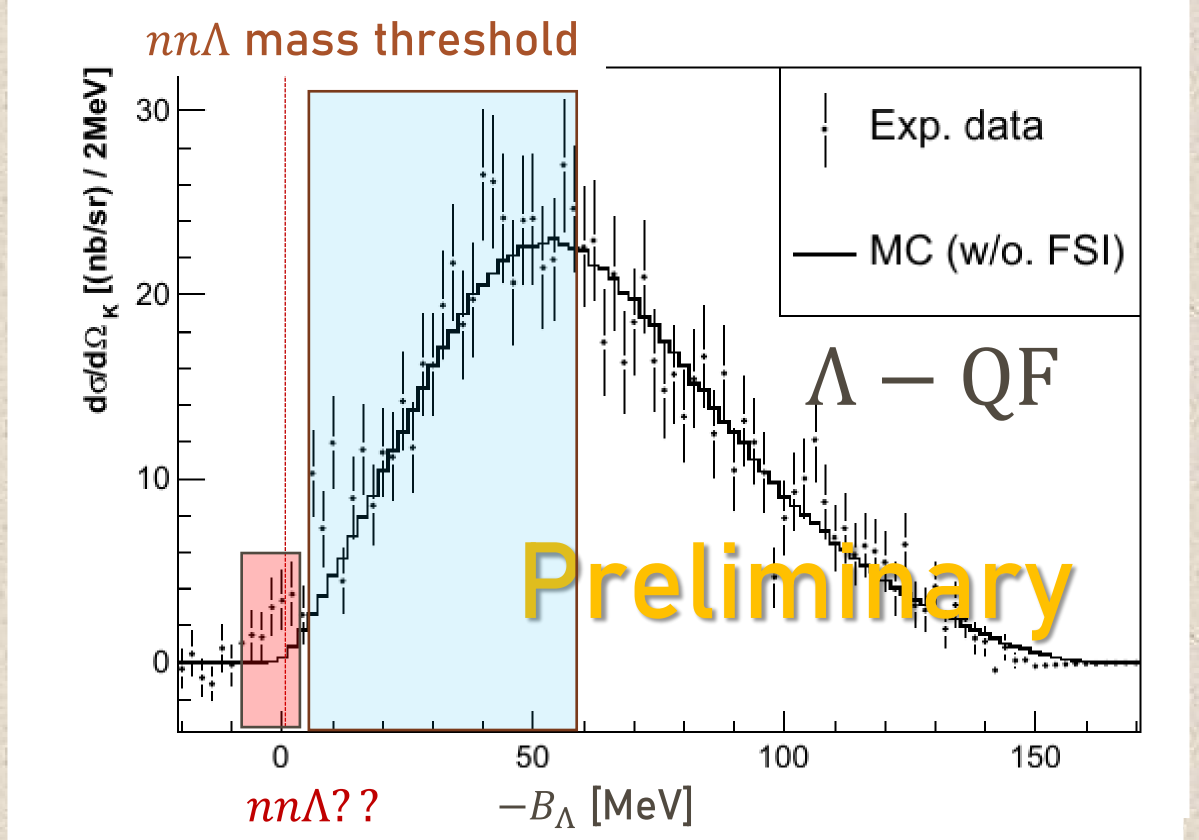
$$\chi^2 = \sum_i^{N_{\mathrm{bin}}} \frac{\left(y_{\mathrm{data}}^i - f_{\mathrm{FSI}} \cdot \mathrm{I}\left(k_{rel}^i\right) y_{\mathrm{MC}}^i\right)^2}{\sigma_{\mathrm{data}}^i}$$



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

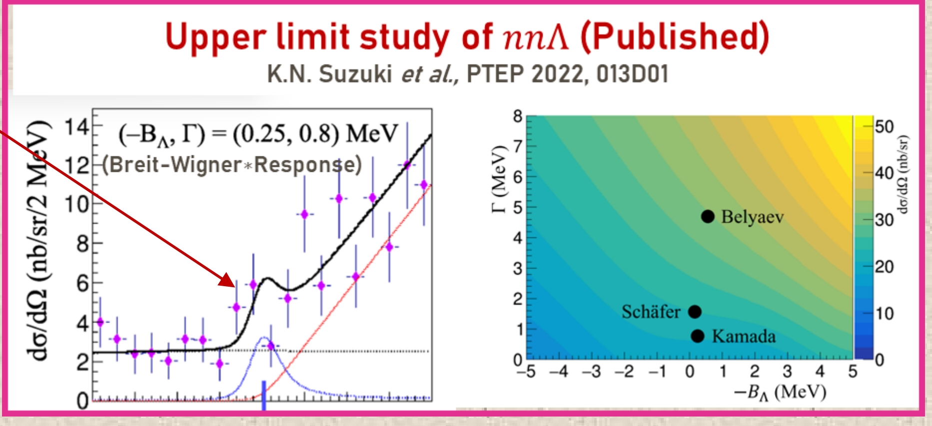
Cross section of missing mass
in the $^3\mathrm{H}(e,e'K^+)X$ reaction

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



- $B_\Lambda \sim 0$ MeV : $nn\Lambda$ resonance??

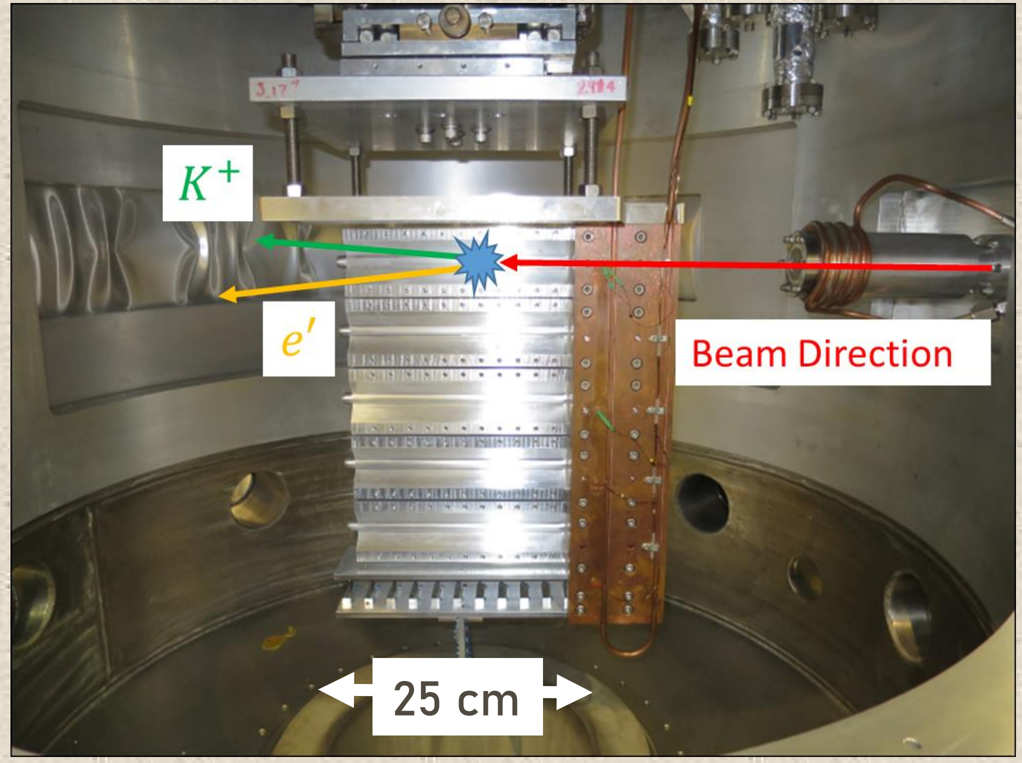
Not enough significance

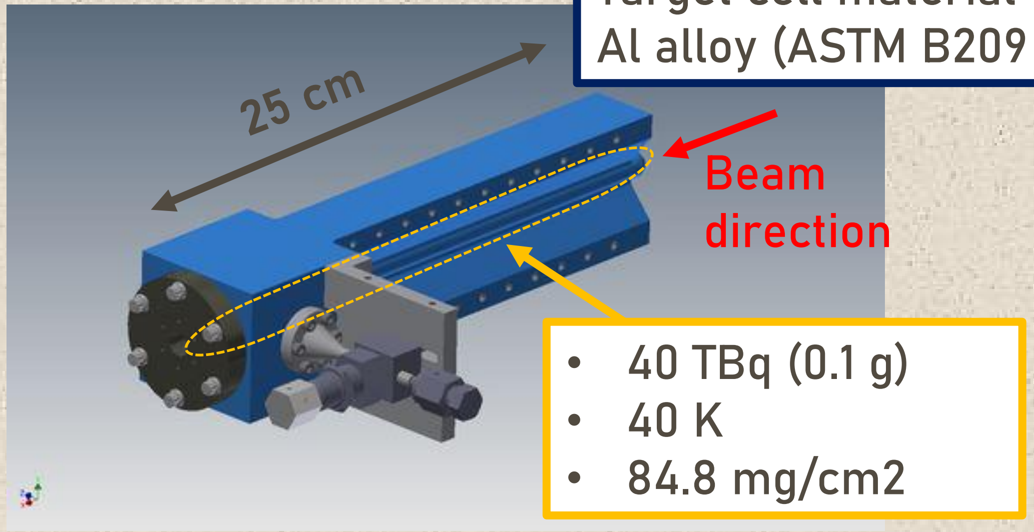


- $10 < -B_\Lambda < 60$ MeV
Due to Λn final state interaction (Λn FSI)

Target system in $nn\Lambda$ expereiment

This picture was taken in vacuum chamber





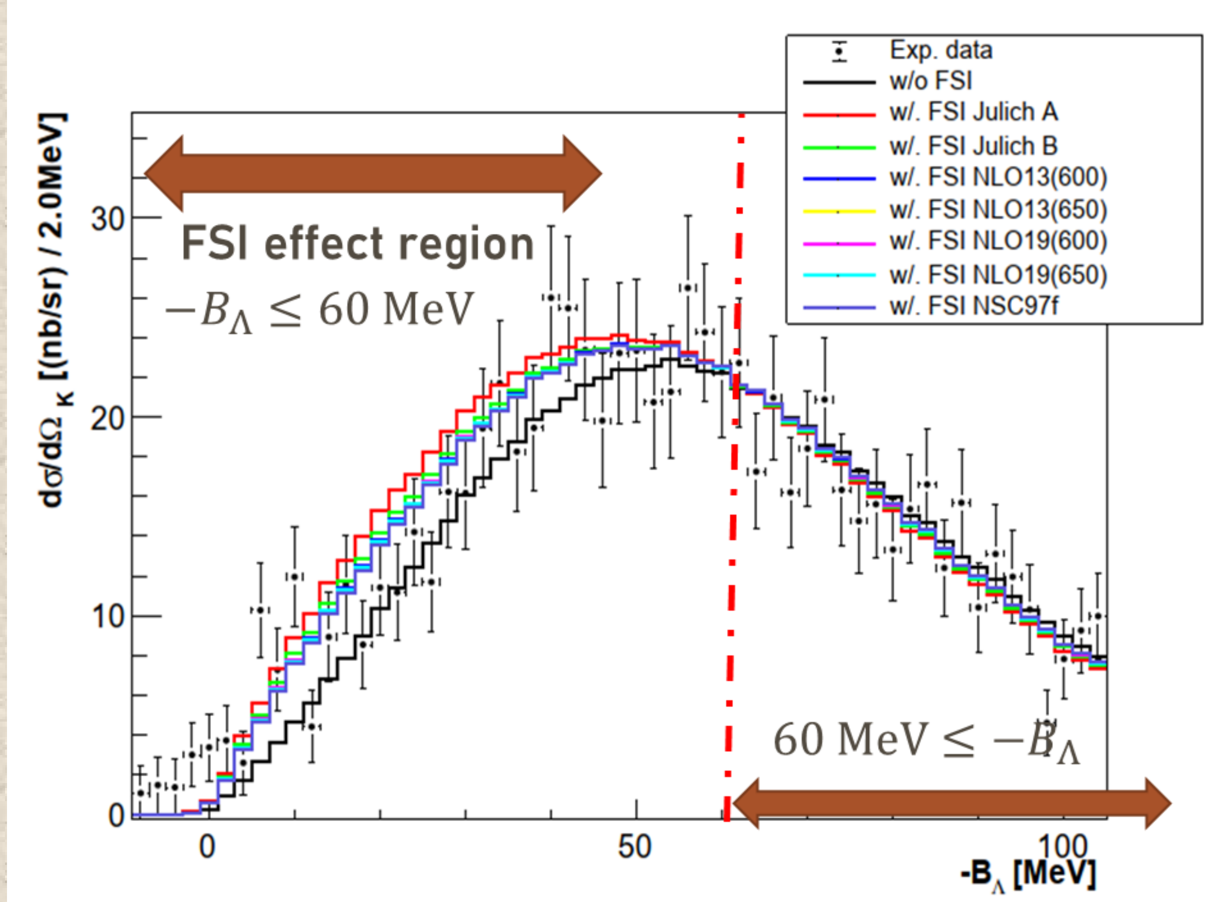
Target cell material
Al alloy (ASTM B209 AL 7075-T651)

- 40 TBq (0.1 g)
- 40 K
- 84.8 mg/cm2

https://wiki.jlab.org/jlab_tritium_target_wiki/index.php/Main_Page

Tritium decays to herium3 with half-lifetime at 12.32 ± 0.02 years $(^3\mathrm{H} \rightarrow {}^3\mathrm{He} + \mathrm{e}^- + \overline{\nu_e})$.

The scaling of MC spectra



The enhancement by Λn FSI

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$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{FSI}} = f_{\mathrm{FSI}} \cdot \mathrm{I}(k_{\mathrm{rel}}) \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{w/o\ FSI}}$$

(f_{FSI} is scaling factor)

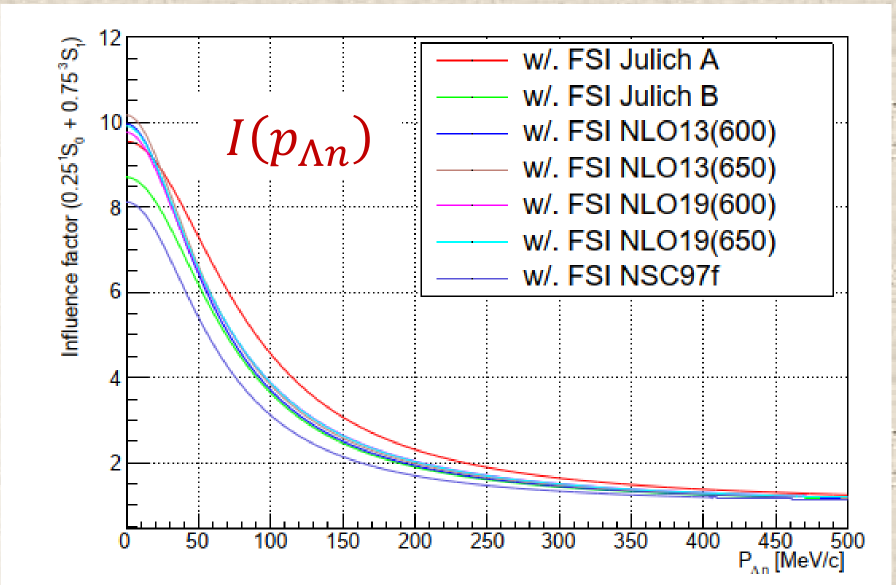
f_{FSI} was determined by the value with the smallest chi-square within ($60 \leq -B_\Lambda \leq 140$ MeV)

$$\chi^2 = \sum_i^{N_{\mathrm{bin}}} \frac{\left(y^i_{\mathrm{data}} - f_{\mathrm{FSI}} \cdot \mathrm{I}\left(k^i_{rel}\right) y^i_{\mathrm{MC}}\right)^2}{\sigma^i_{\mathrm{data}}}$$

Simulation of the Λn FSI

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

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



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