Study of Λn FSI with Λ quasi-free productions on the $^{3}\mathrm{H}(e, e'K^{+})X$ reaction at JLab

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  - Study of the Λn interaction from $nn\Lambda$ system
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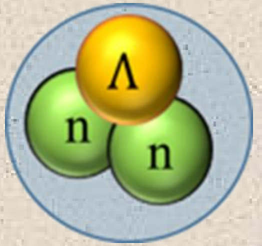
  - $^{3}\mathrm{H}(\mathrm{e},\mathrm{e}'\mathrm{K}^{+})\mathrm{X}$ missing mass spectrum
  - Λn final state interaction
- Summary

Study of the Λn interaction from the $nn\Lambda$ system

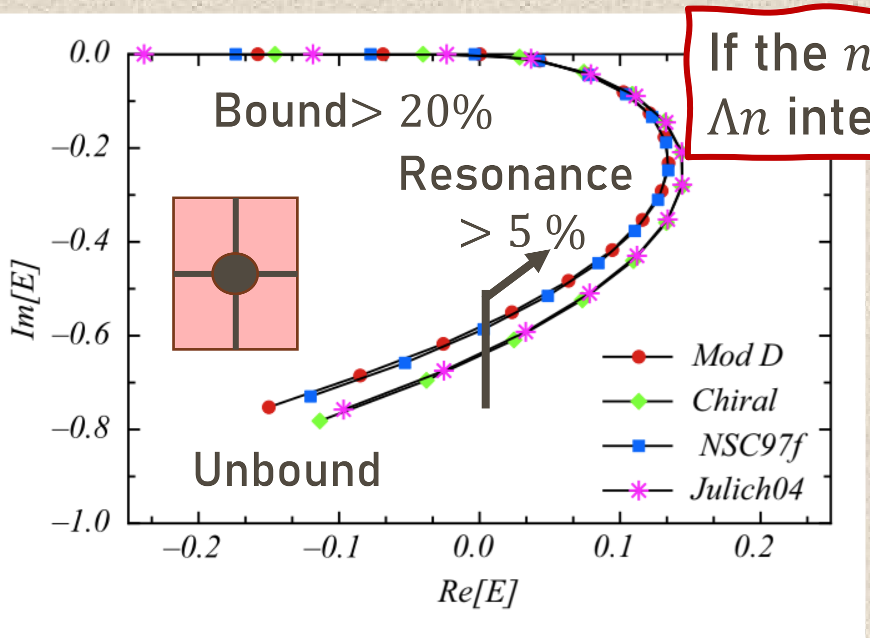


$nn\Lambda$ is pure Λ- n system→ It is good system to study the Λn interaction

The existence of the $nn\Lambda$ is not established ($nn\Lambda$ state puzzle).

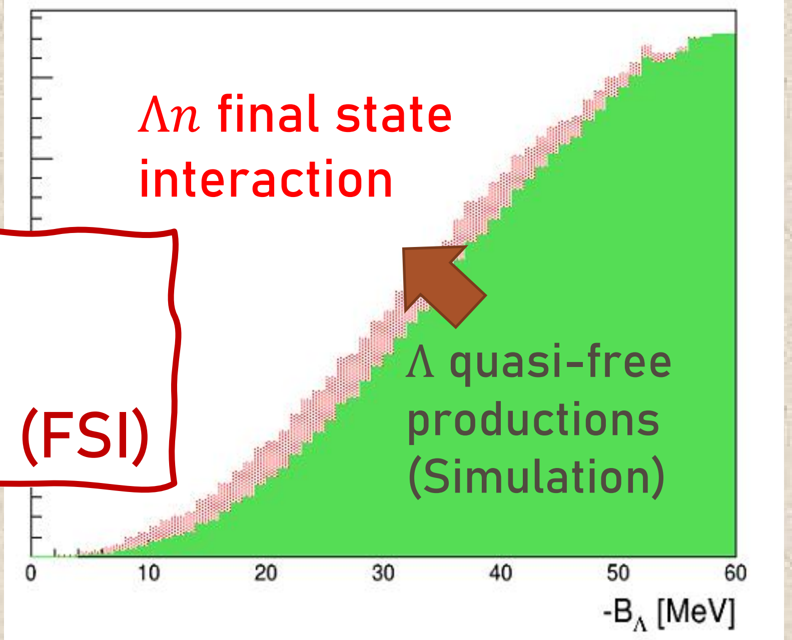
- Experimental data(GSI) → Bound state was reported. C. Rappold *et al.,* (HypHI Collaboration) Phys. Rev. C 88 041001 (2013)
- Theoretical calculation → Unbound or Resonance

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

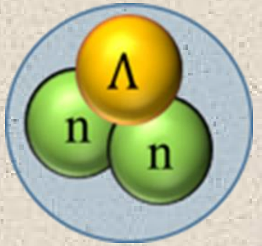


If the $nn\Lambda$ peak is observed,
Λn interaction can be constrained from it.

Shaping analysis of
Λ −QF productions
→ Effective Λn interaction (FSI)



Study of the Λn interaction from the $nn\Lambda$ system



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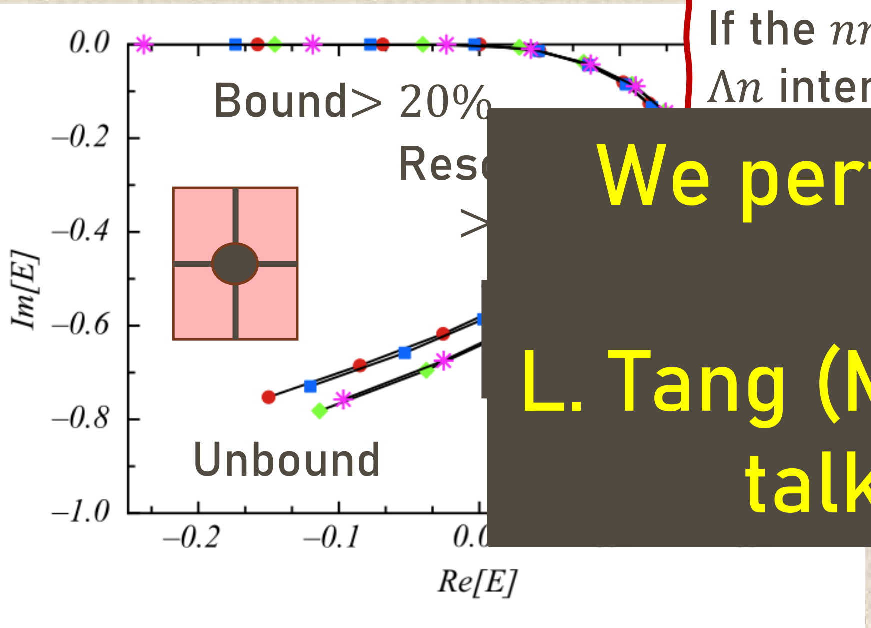

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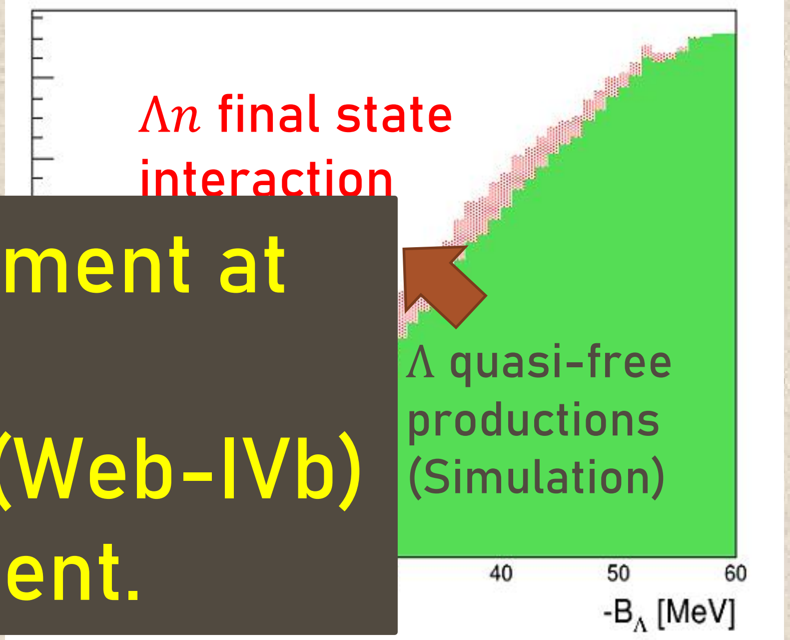
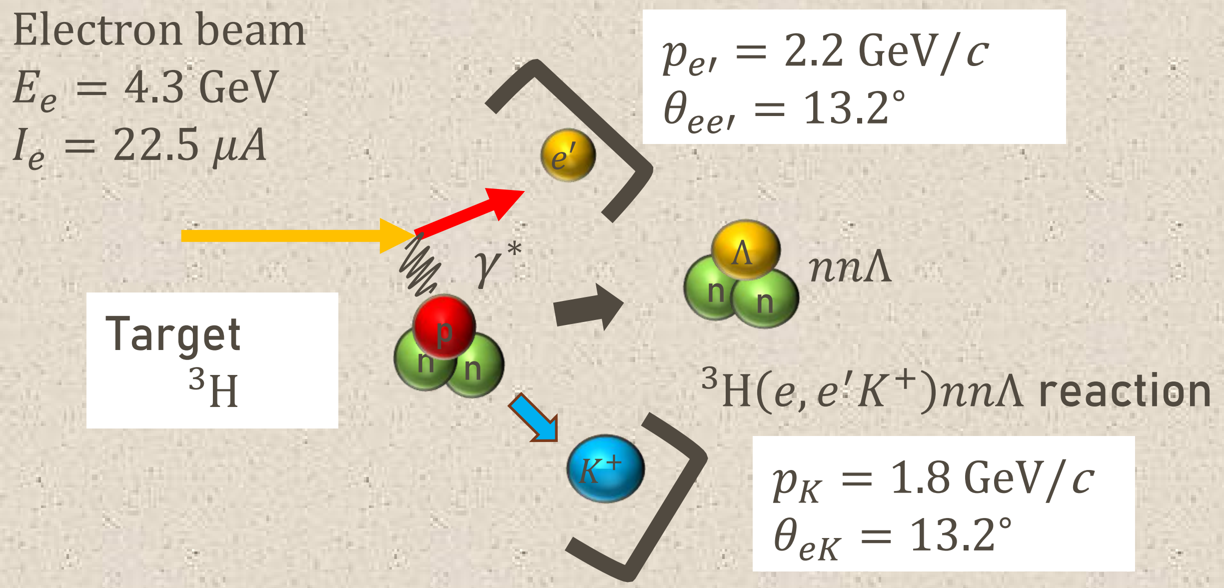


We performed the $nn\Lambda$ experiment at JLab (2018).
L. Tang (Mon-II) and B. Pandey (Web-IVb) talked about $nn\Lambda$ experiment.

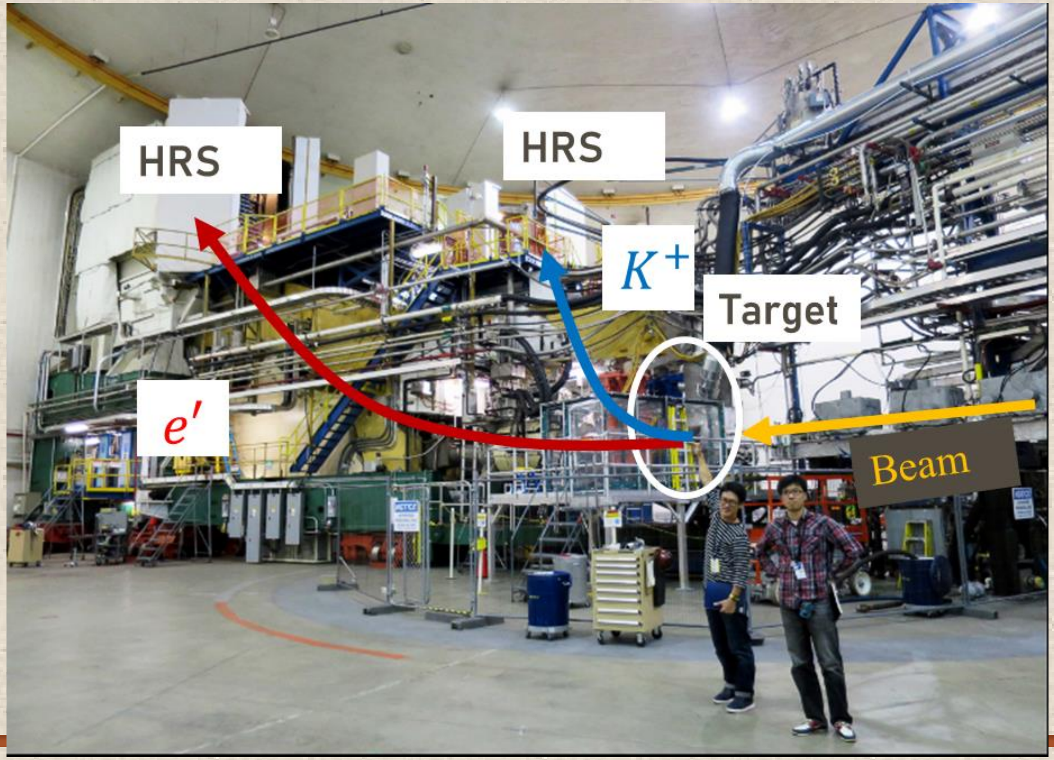
$nn\Lambda$ experiment at Jefferson Lab (E12-17-003)

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

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



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



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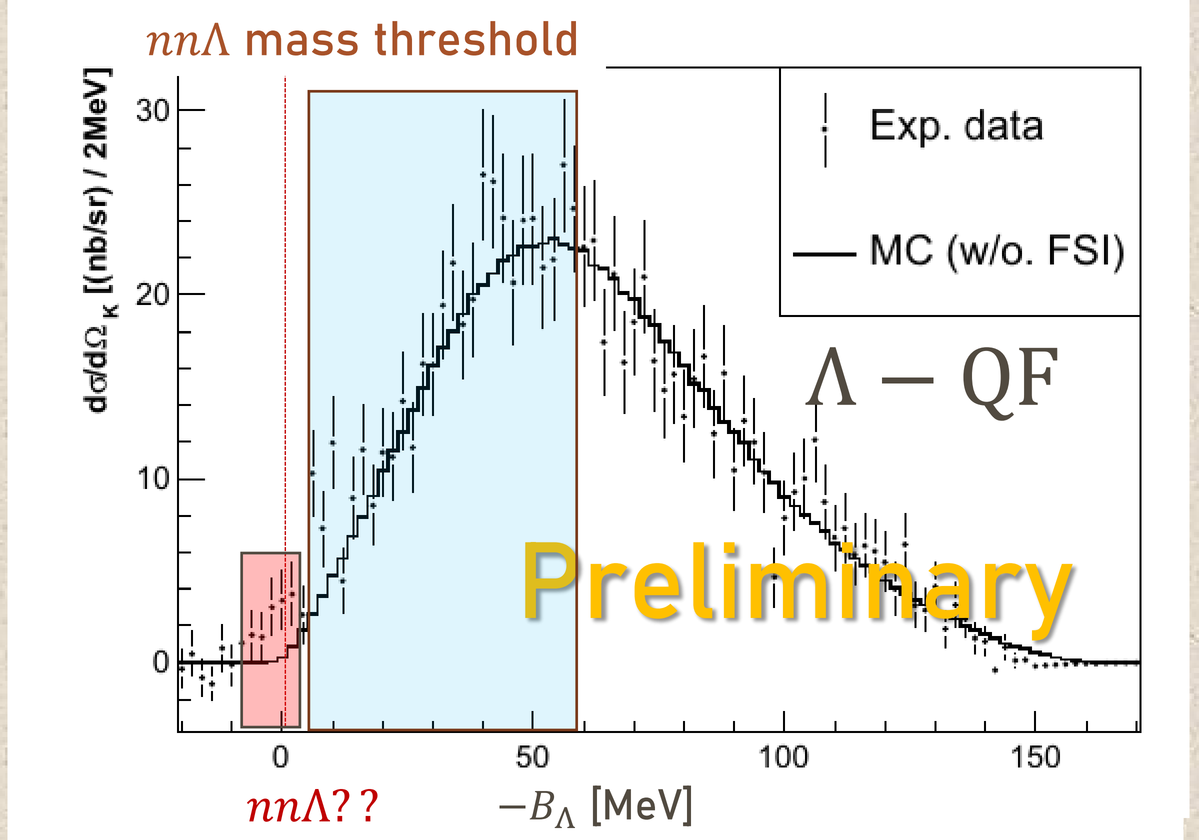
$^3\mathrm{H}(e,e'K^+)X$ missing mass spectrum

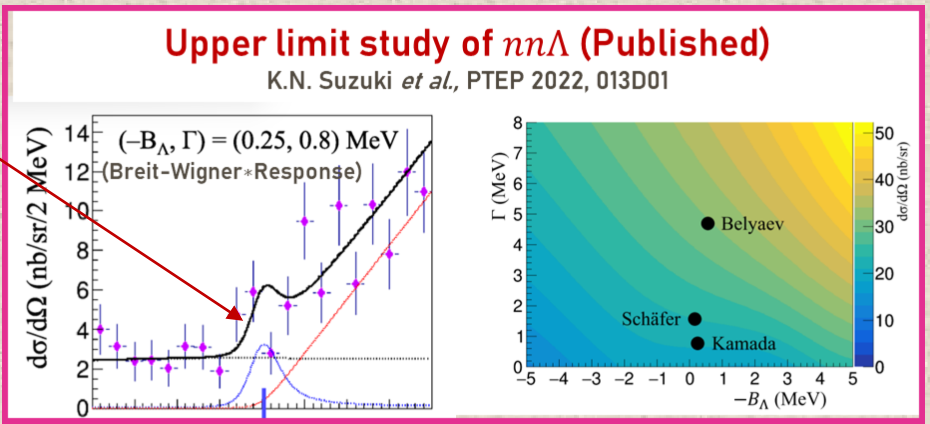
Cross section of missing mass in the $^3\mathrm{H}(e,e'K^+)X$ reaction

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



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

Not enough significance

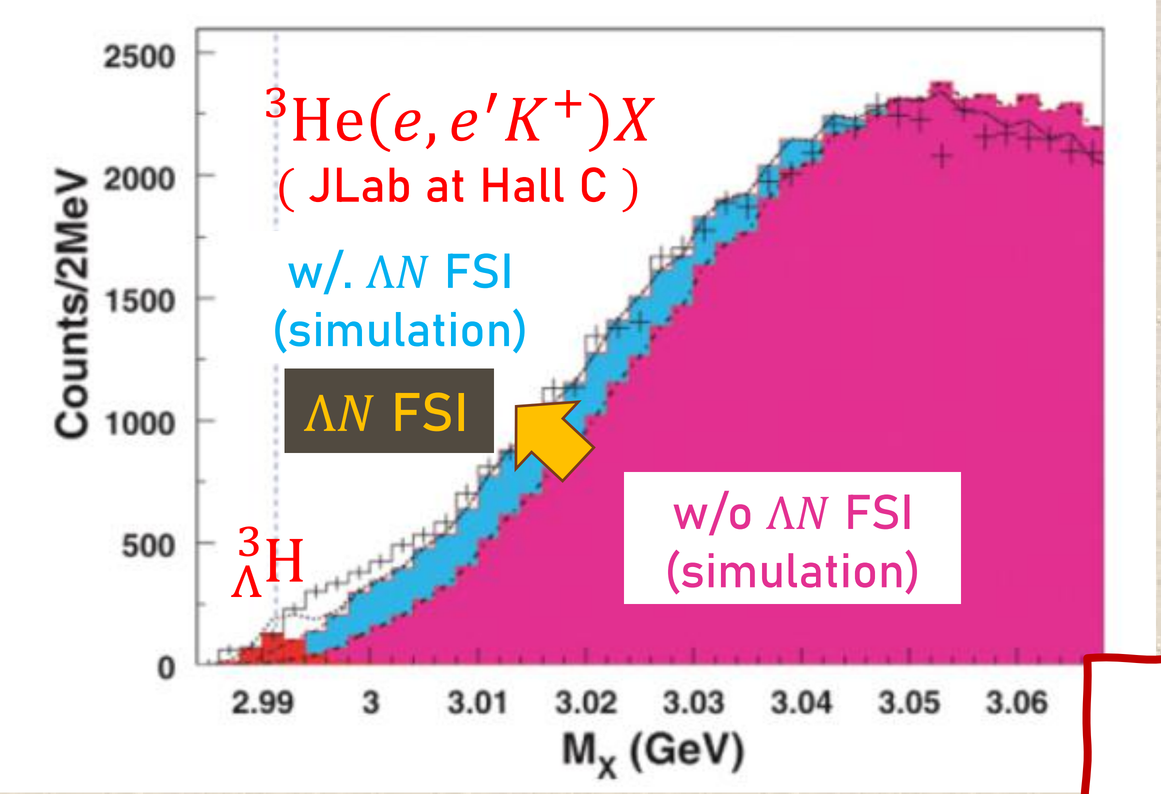


- $10 < -B_\Lambda < 60$ MeV

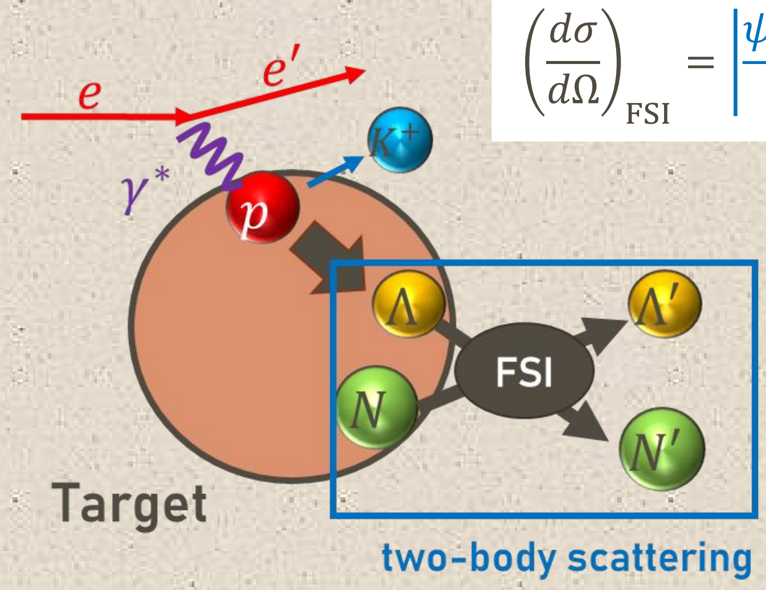
Due to Λn final state interaction (Λn FSI)

Final State Interaction (FSI)

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



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

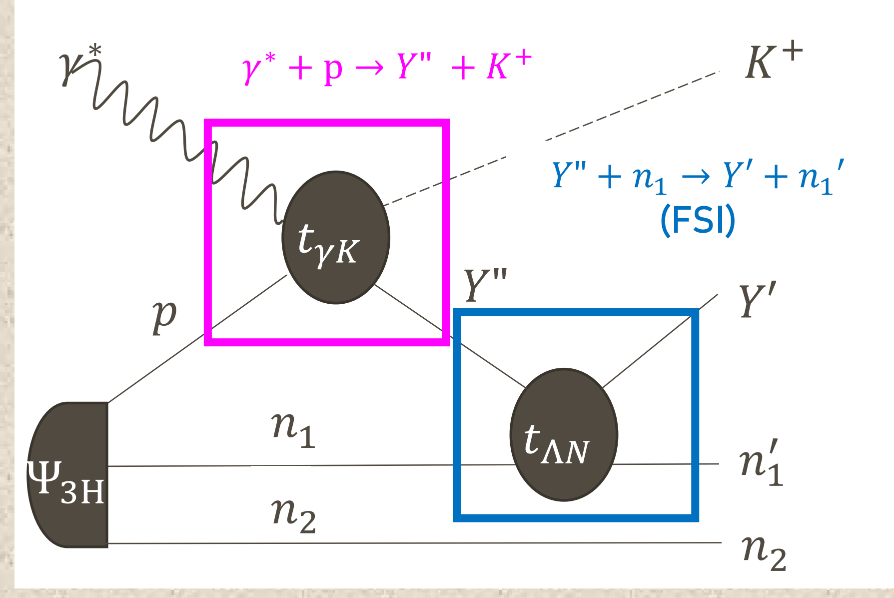


→ Can derive the Λn FSI from the $^3\mathrm{H}(e,e'K^+)X$ missing mass spectrum.

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

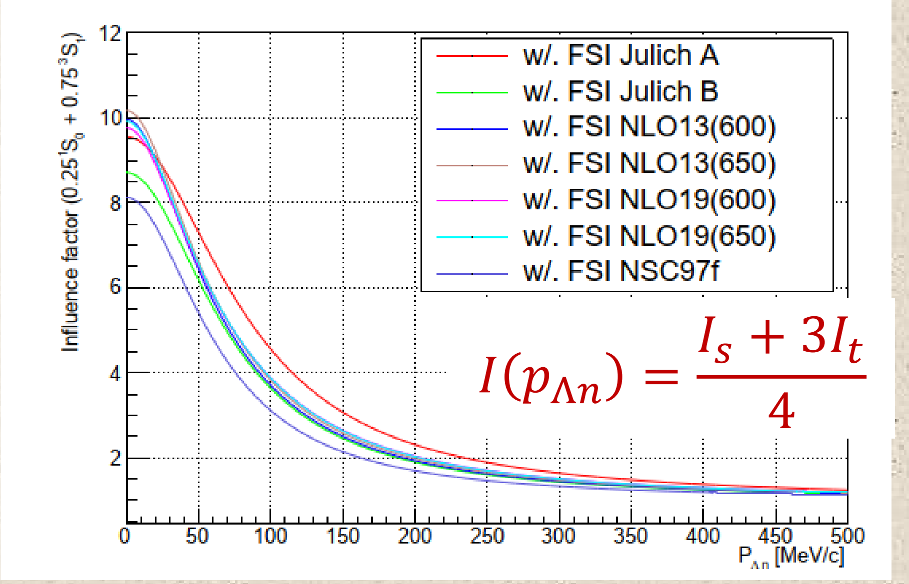
$$J_{l=0}(k_{rel}) = \frac{k_{\mathrm{rel}} - i\beta}{k_{\mathrm{rel}} - i\alpha}$$

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

Missing mass spectrum including Λn FSI by SIMC

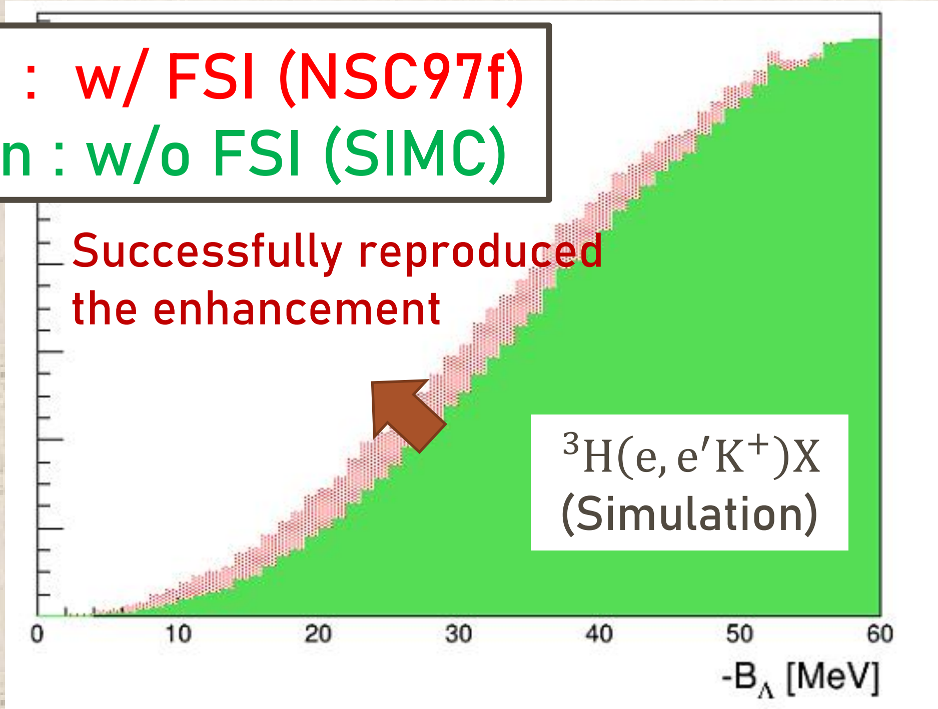
Missing mass with Λn FSI is written as $\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{FSI}} = I(k_{rel})\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{w/o\ FSI}}$

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



$$I(p_{\Lambda n}) = \frac{I_s + 3I_t}{4}$$

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



χ^2 fiiting with missing mass spectrum

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

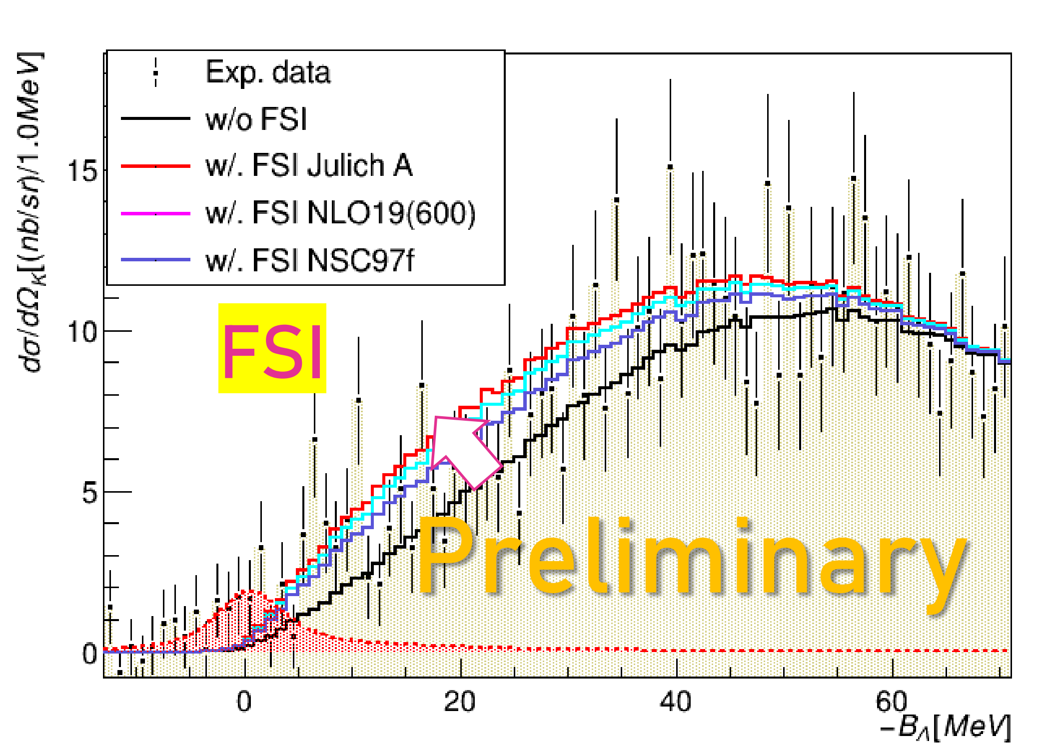
- Excess events around $nn\Lambda$ mass threshold $(-B_\Lambda \sim 0\ \mathrm{MeV})$

  → Assuming resonance state of $nn\Lambda$ $(\Gamma, -B_\Lambda) = (4.7, 0.55)\ \mathrm{MeV}$ V.B. Belyaev et al., Nucl. Phys. A, 803 (2008).

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

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

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



Missing mass spectra with FSI :

- Succeeded in reproducing enhancement structure $(0 \leq -B_\Lambda \leq 60\ \mathrm{MeV})$
- 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)

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

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

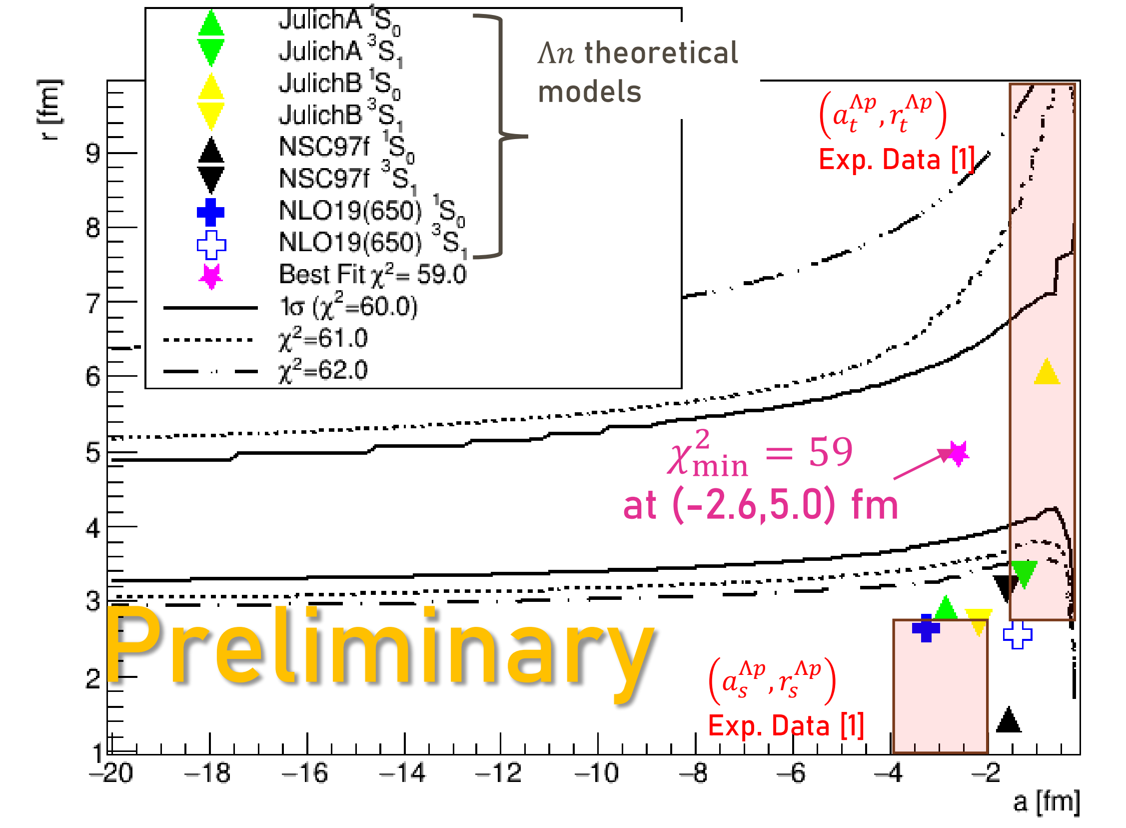
$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{FSI}} = \left(\left|\frac{1}{J\,(k_{rel})}\right|^2\right)\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{w/o\ FSI}}$$

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
$3.8 < \bar{r} < 6.3$ fm (Preliminary)

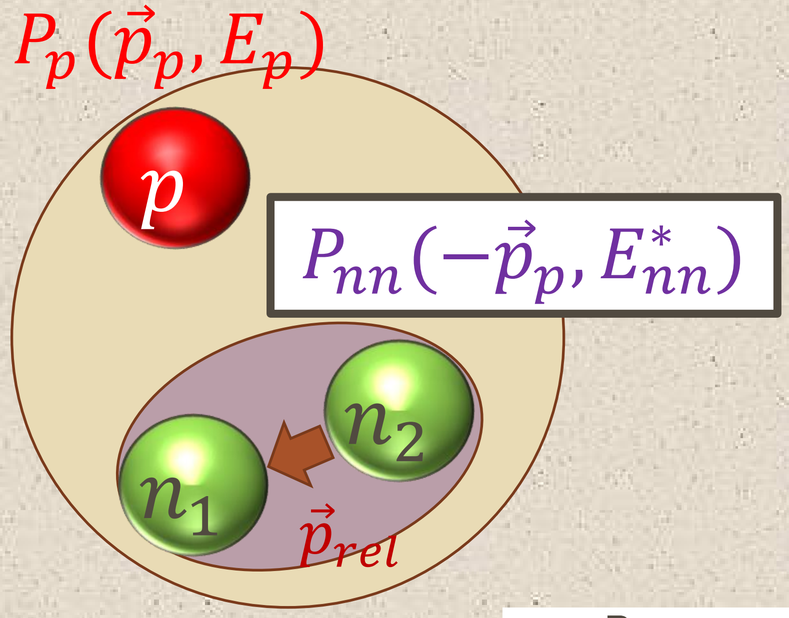


Summary

- 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, scattering length and effective range (a, r) were successfully restricted by the chi-square fitting.
- For $\bar{a} = -2.6$ fm, $3.8 < \bar{r} < 6.3$ fm (Preliminary)

Backup

Estimation for the relative Λn momentum



Λ momentum calculation

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

Neutron momentum calculation

Stopped tritium target → $\vec{p}_p + \vec{p}_{n1} + \vec{p}_{n2} = 0$

Relative momentum was defined as $\vec{p}_{rel} = \frac{M_n\vec{p}_{n1} - M_n\vec{p}_{n2}}{2M_n}$

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

- Proton momentum (p_p) : Fermi momentum distribution
  Ref.) R. B. Wiringa Phys. Rev. C 43, 1585 (1991).
- Angle between $\vec{p}_p$ and $\vec{p}_{rel}$ (θ) : Assuming spherical uniform distribution
- Relative momentum $(\vec{p}_{rel})$: Given by an excited energy of nn system (E^*_{nn})

  E^*_{nn} was estimated by spectral function of ^{3}H Ref.) C. Ciofi degli Atti et al., Phys. Rev. C, 21 (1980).

Experimental approach for the ΛN interaction

The ΛN interaction have been understood with the data for ΛN scattering and the Λ hypernuclear spectroscopy.

Scattering experiment

- Major experimental method for deducing the B-B 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 $\Lambda - n$ system
→ It is good system to study the Λn interaction.