JLab Hall A Winter Collaboration Meeting, Feb 10—11, 2022 (Online)

# Search for the nnΛ state

Kyoto University, Japan

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Feb 10, 2022

GRADUATE SCHOOL OF SCIENCE
FACULTY OF SCIENCE
KYOTO UNIVERSITY

科研費 KAKENHI

SPIRITS
SUPPORTING PROGRAM FOR INTERACTION-BASED INITIATIVE TEAM STUDIES

PTEP Progress of Theoretical and Experimental Physics
JPS The Physical Society of Japan

# The cross-section measurement for the $^3$H($e$, $e'K^+$)$nn\Lambda$ reaction

K N Suzuki ✉, T Gogami, B Pandey, K Itabashi, S Nagao, K Okuyama, S N Nakamura, L Tang, D Abrams, T Akiyama, D Androic, K Aniol, C Ayerbe Gayoso, J Bane, S Barcus, J Barrow, V Bellini, H Bhatt, D Bhetuwal, D Biswas, A Camsonne, J Castellanos, J-P Chen, J Chen, S Covrig, D Chrisman, R Cruz-Torres, R Das, E Fuchey, K Gnanvo, F Garibaldi, T Gautam, J Gomez, P Gueye, T J Hague, O Hansen, W Henry, F Hauenstein, D W Higinbotham, C E Hyde, M Kaneta, C Keppel, T Kutz, N Lashley-Colthirst, S Li, H Liu, J Mammei, P Markowitz, R E McClellan, F Meddi, D Meekins, R Michaels, M Mihovilovič, A Moyer, D Nguyen, M Nycz, V Owen, C Palatchi, S Park, T Petkovic, S Premathilake, P E Reimer, J Reinhold, S Riordan, V Rodriguez, C Samanta, S N Santiesteban, B Sawatzky, S Širca, K Slifer, T Su, Y Tian, Y Toyama, K Uehara, G M Urciuoli, D Votaw, J Williamson, B Wojtsekhowski, S A Wood, B Yale, Z Ye, J Zhang, X Zheng

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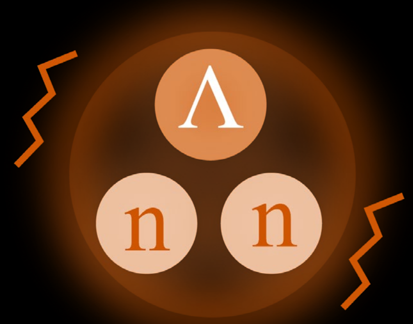
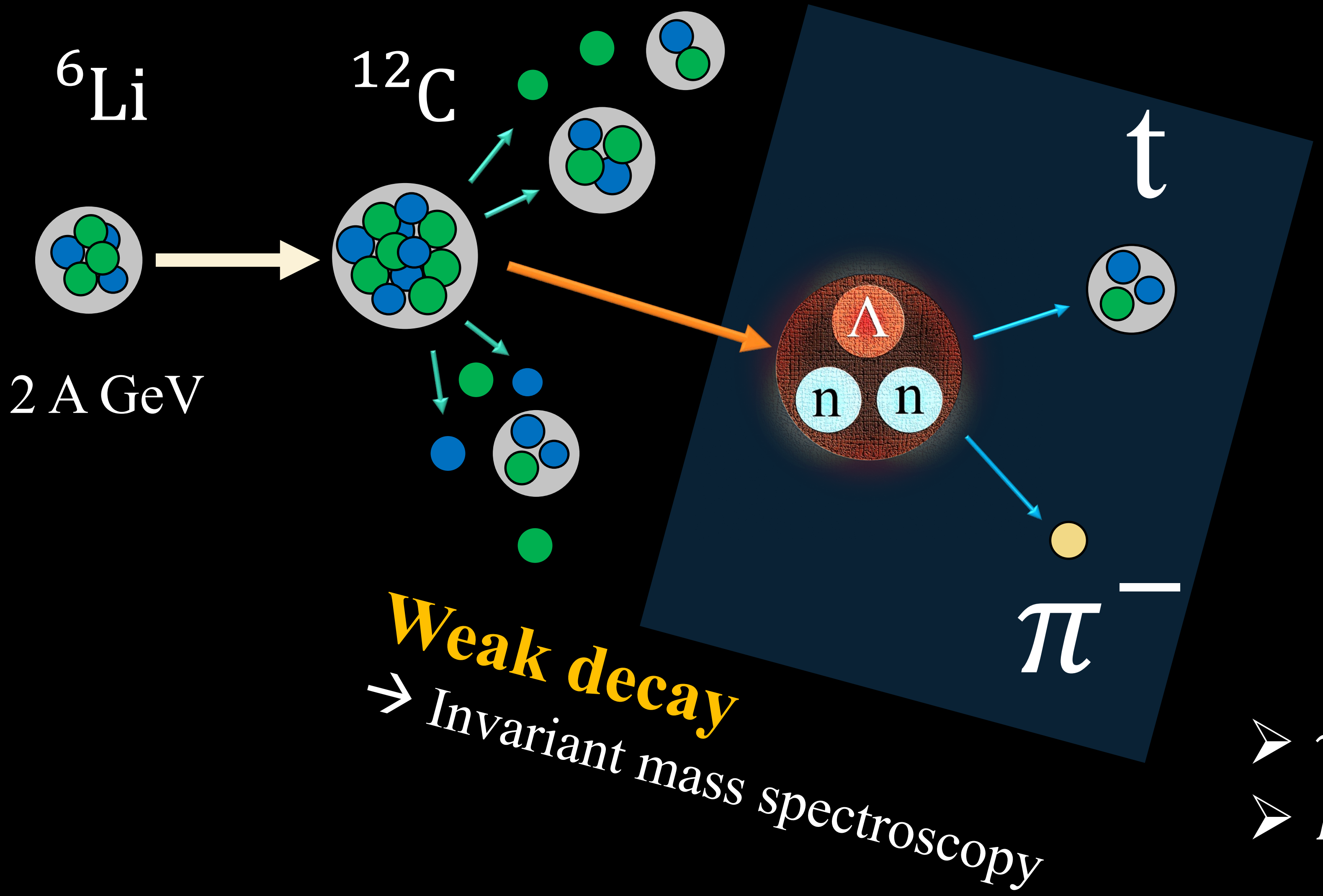
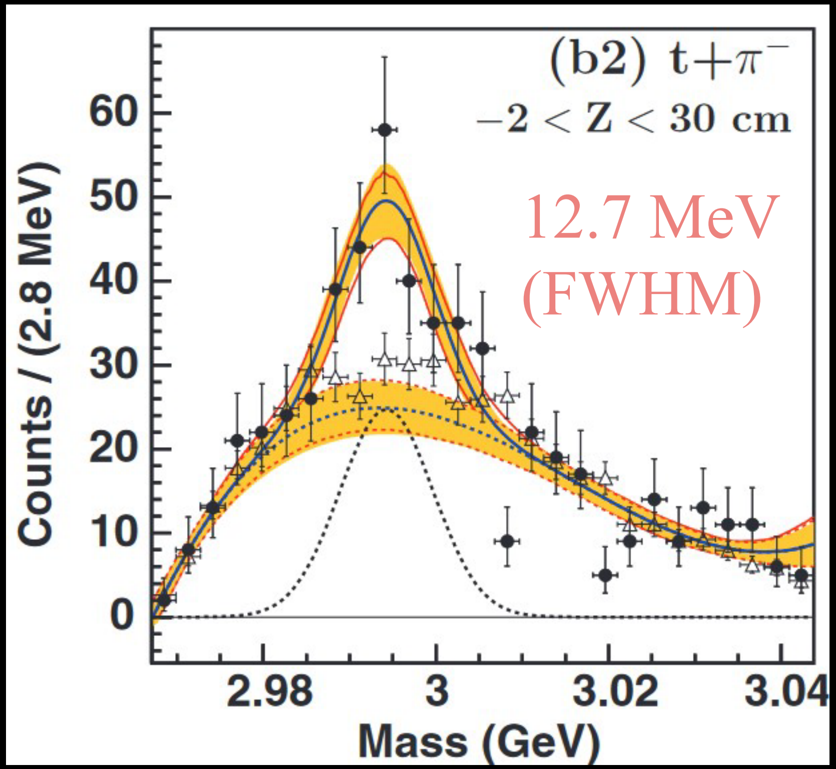



- ✓ HRS-HRS @ Hall A
- ✓ Tritium target
- ✓ (e,e'$K^+$)
- ✓ Oct—Nov 2018

# nnΛ ($^{3}_{\Lambda}n$) measurement at GSI

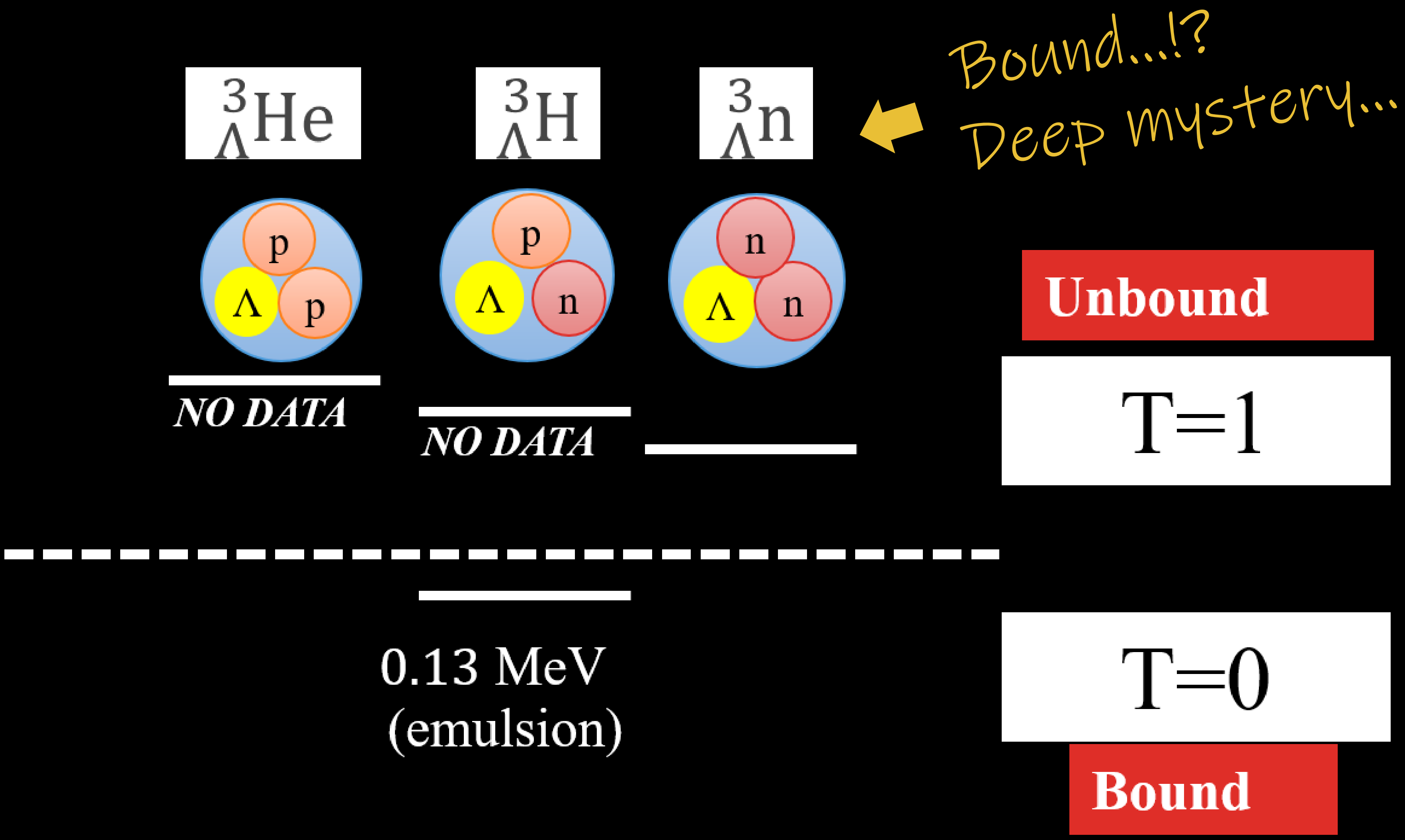



C. Rappold et al., PRC 88, 041001(R) (2013)




- $\tau = 190^{+47}_{-35}$ ps
- $B_{\Lambda} = -0.5 \pm 1.1 \pm 2.2$ MeV

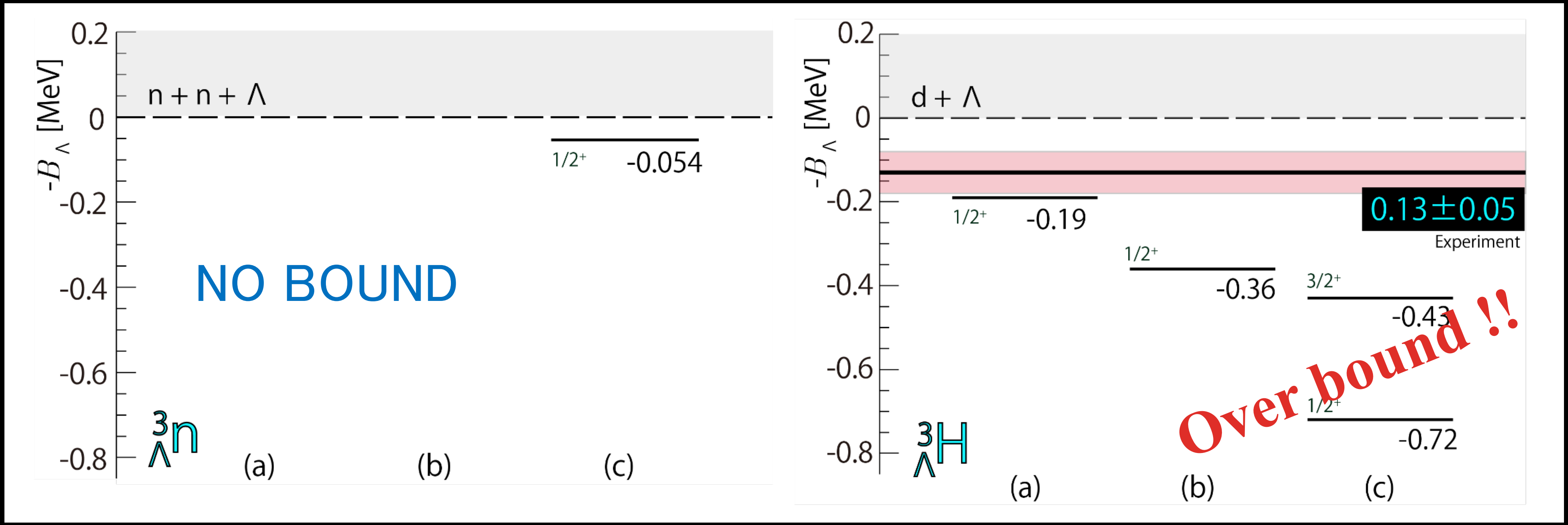
# Three-body system with Λ



# Can the $nn\Lambda$ be bound?

E. Hiyama, S. Ohnishi, B.F. Gibson, and Th. A. Rijken, Physical Review C 89, 061302(R) (2014).

AV8 ***NN*** + NSC97f ***YN*** potentials



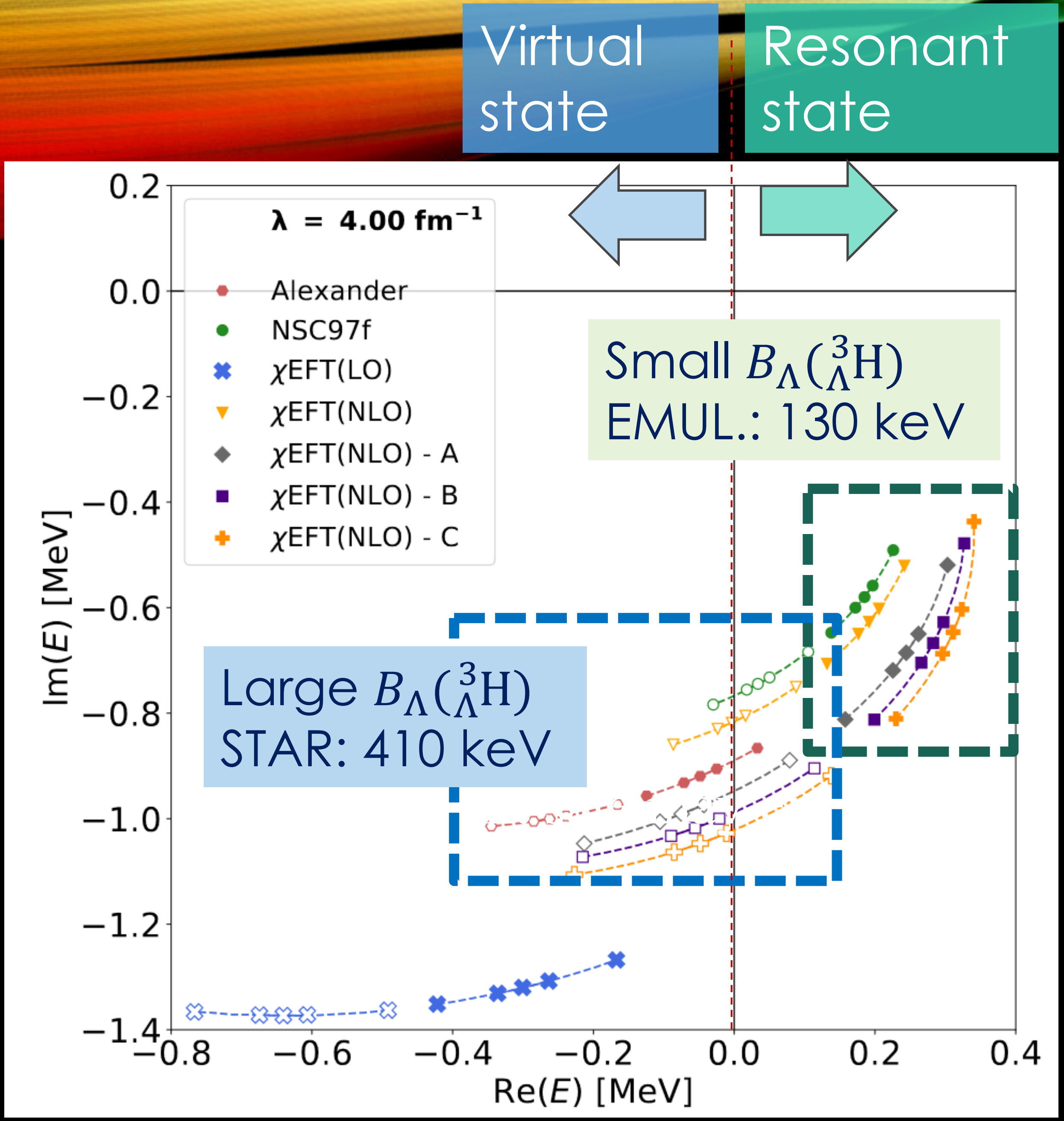

(a) $\quad {}^3V^T_{\Lambda N-\Sigma N} \times 1.0$

(b) $\quad {}^3V^T_{\Lambda N-\Sigma N} \times 1.1$

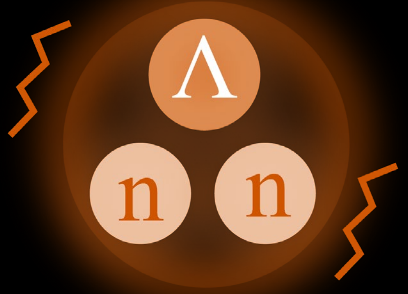
(c) $\quad {}^3V^T_{\Lambda N-\Sigma N} \times 1.2$

Tensor component of the ΛN-ΣN coupling was varied.
→ **No solution was found** to make the $nn\Lambda$ bound maintaining the consistency with the $^3_\Lambda$H ($^4_\Lambda$H, $^4_\Lambda$He) data.

# Resonant nnΛ state



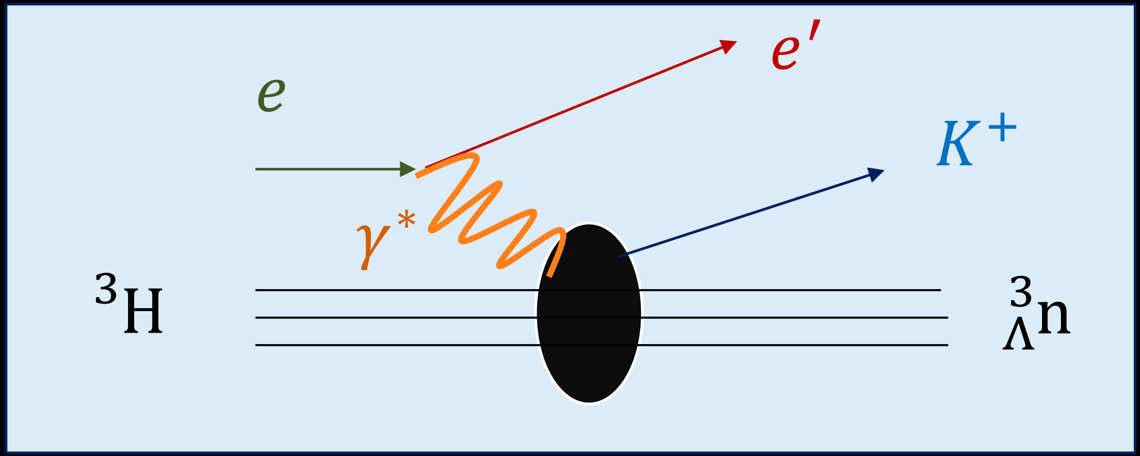

M. Schäfer et al., PRC 105, 015202 (2022)




## nnΛ

- ✓ Resonant state may exist
- ✓ Energy + width → nΛ Interaction
- ✓ Strongly related to $B_\Lambda({}^3_\Lambda\mathrm{H})$
  → E12-19-002 (HKS)

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

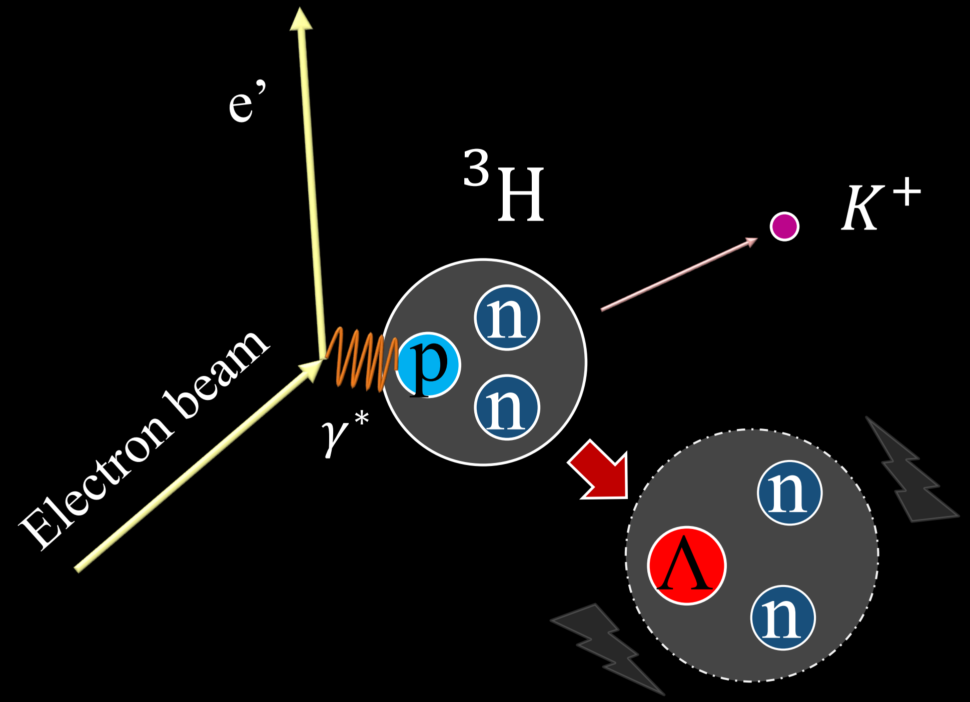


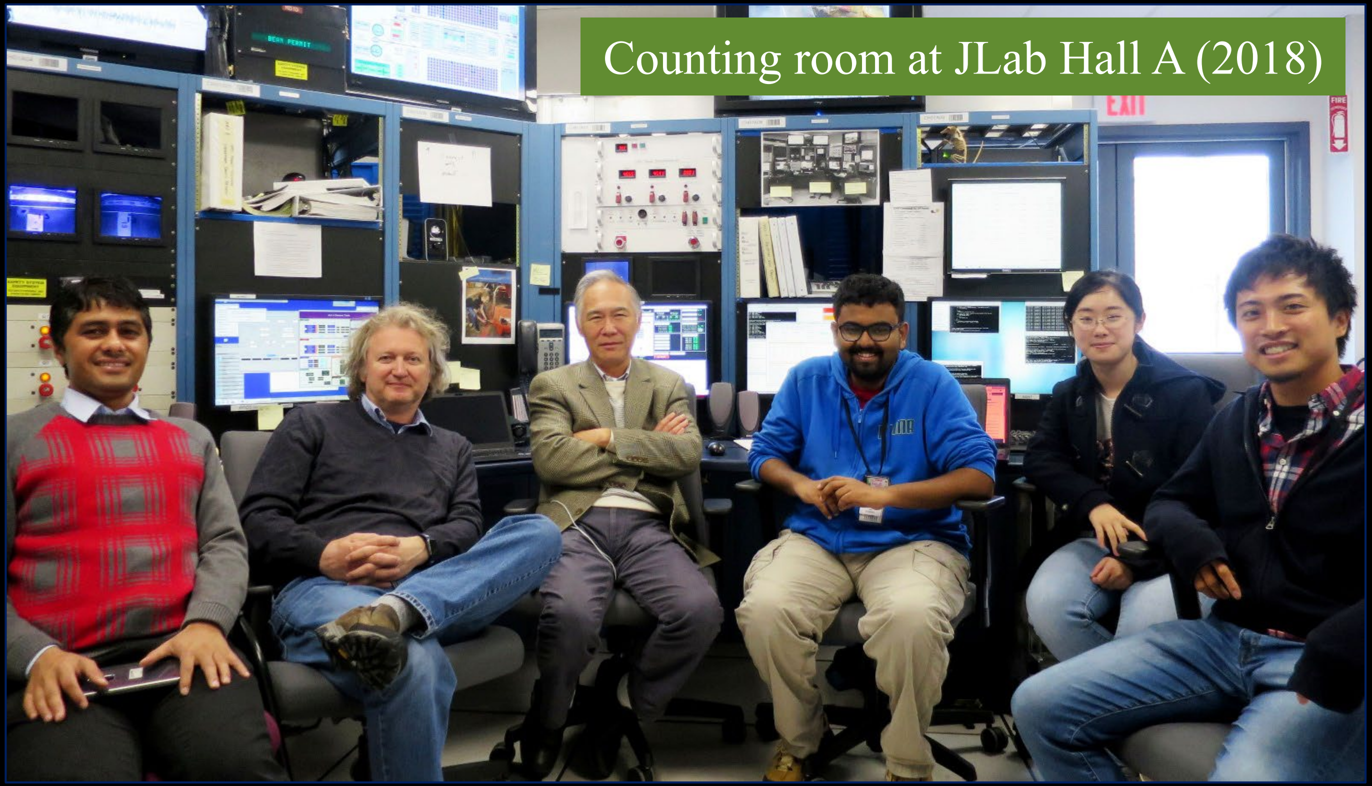

Missing-mass measurement at JLab

➔ **Sensitive to both bound and resonant states !!**

*c.f.) Invariant mass spectroscopy is sensitive to only bound state*

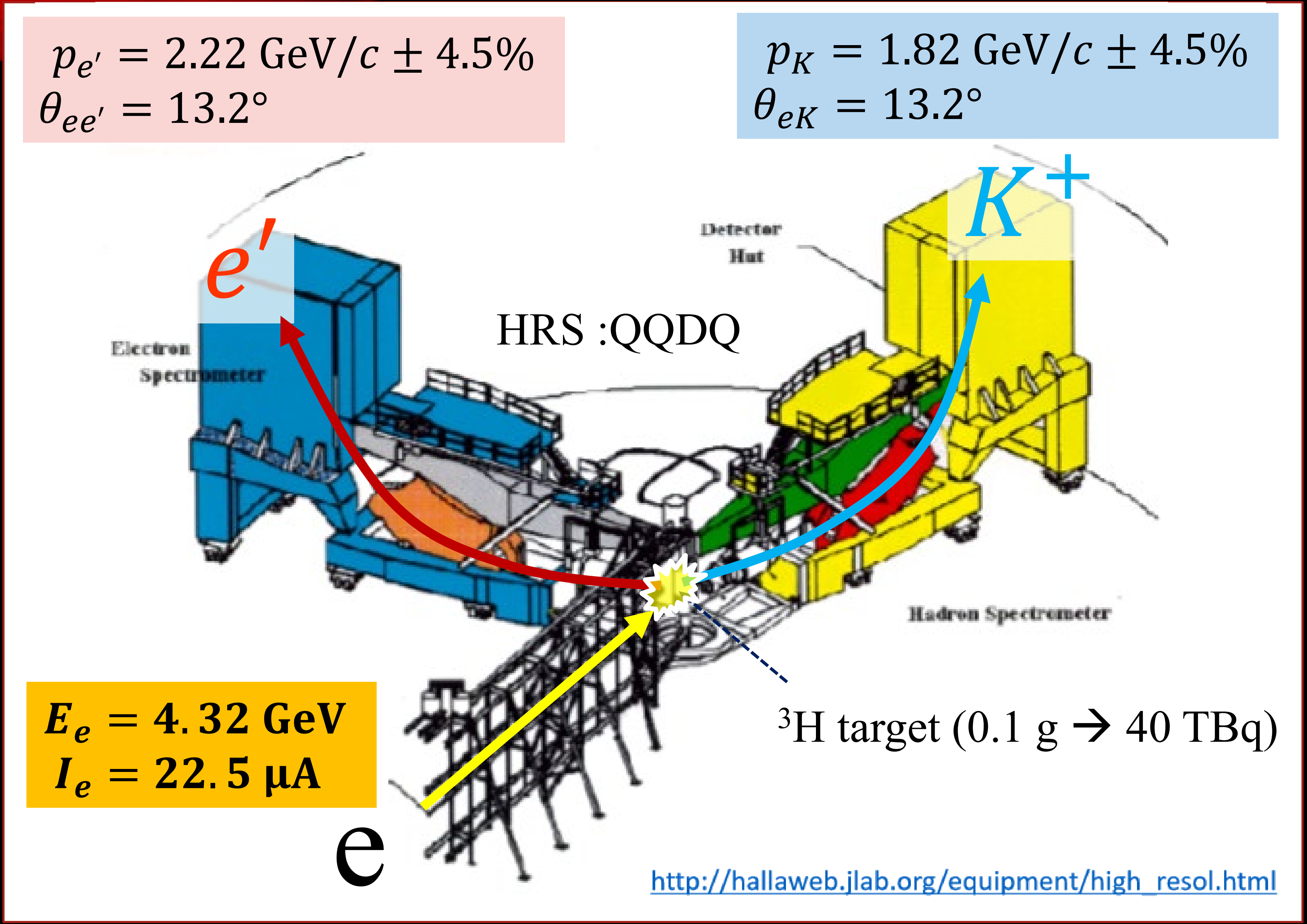
# JLab E12-17-003




**$T_2$ target, Hall A, Oct—Nov 2018**

# Experimental setup at Hall A

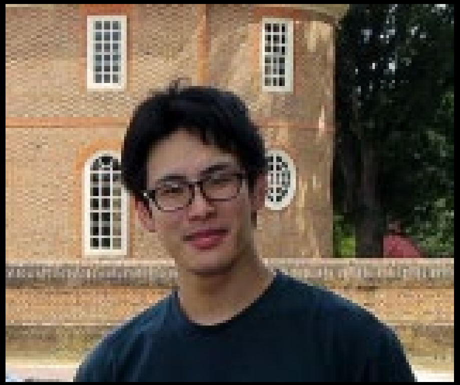



- High resolution
  - $\frac{\Delta p}{p} = 2 \times 10^{-4}$ ☺
- Long path length ☹
  - → $R_K \simeq 15\ \%$

10/21

# ANALYSES

Independent analyses
to doublecheck (triplecheck) results



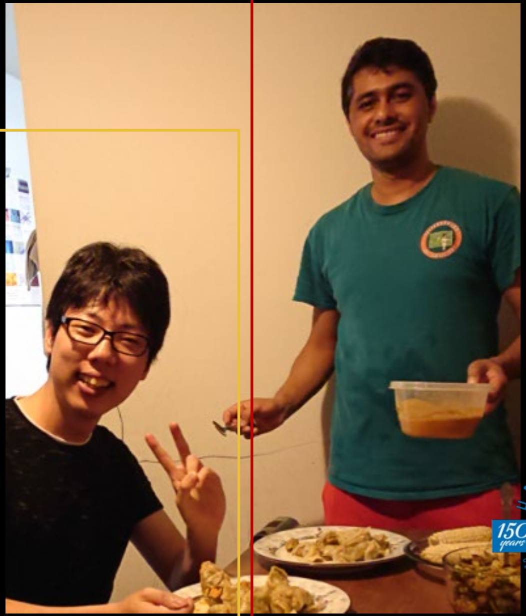
**(Dr.)** K. Itabashi
2022

K. Okuyama

東北大学

*Tohoku Univ., Japan*

E. Umezaki



**(Dr.)** K.N. Suzuki
2022

*Kyoto Univ., Japan*

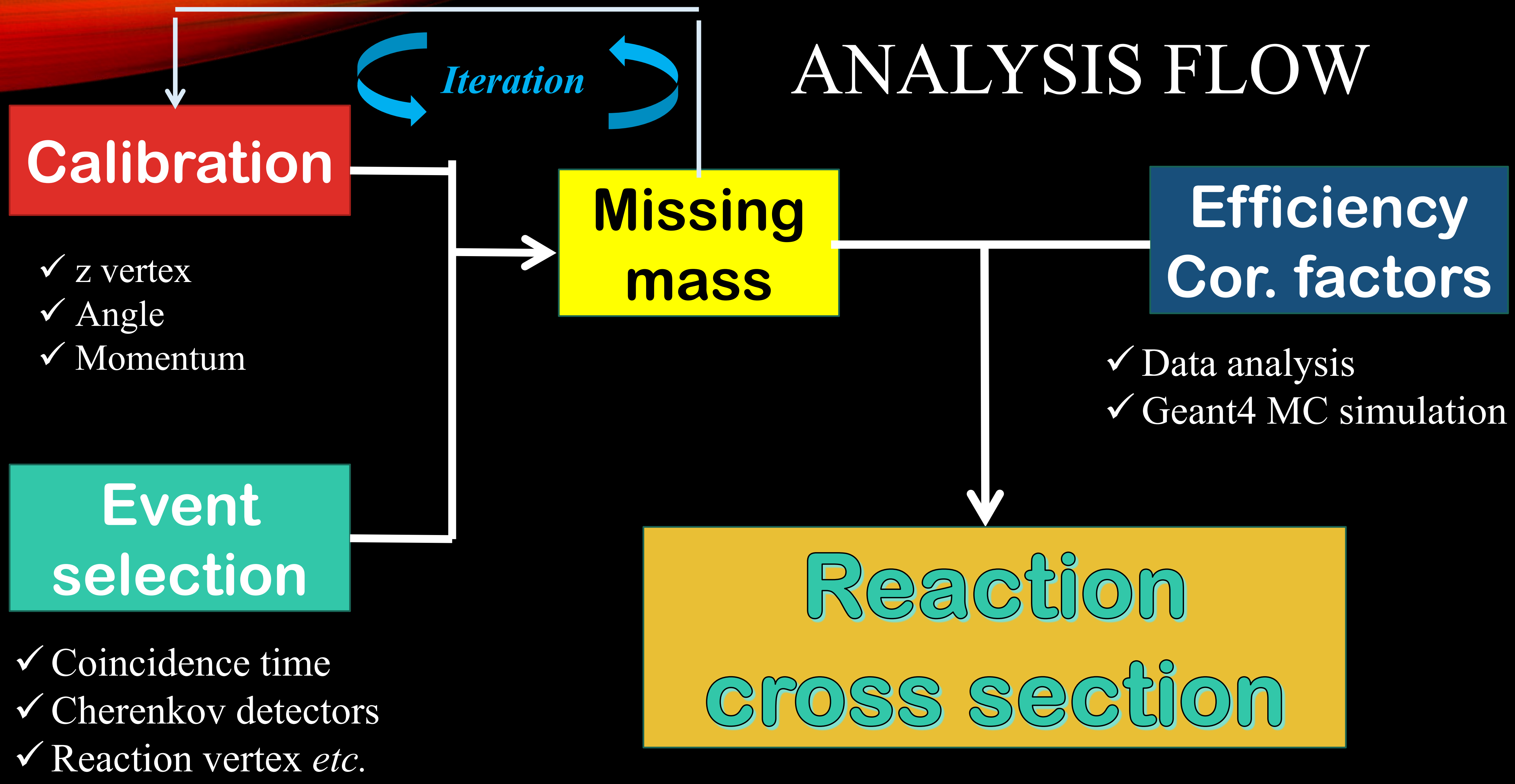
**Dr.** B. Pandey
2021

*Hampton Univ., US*

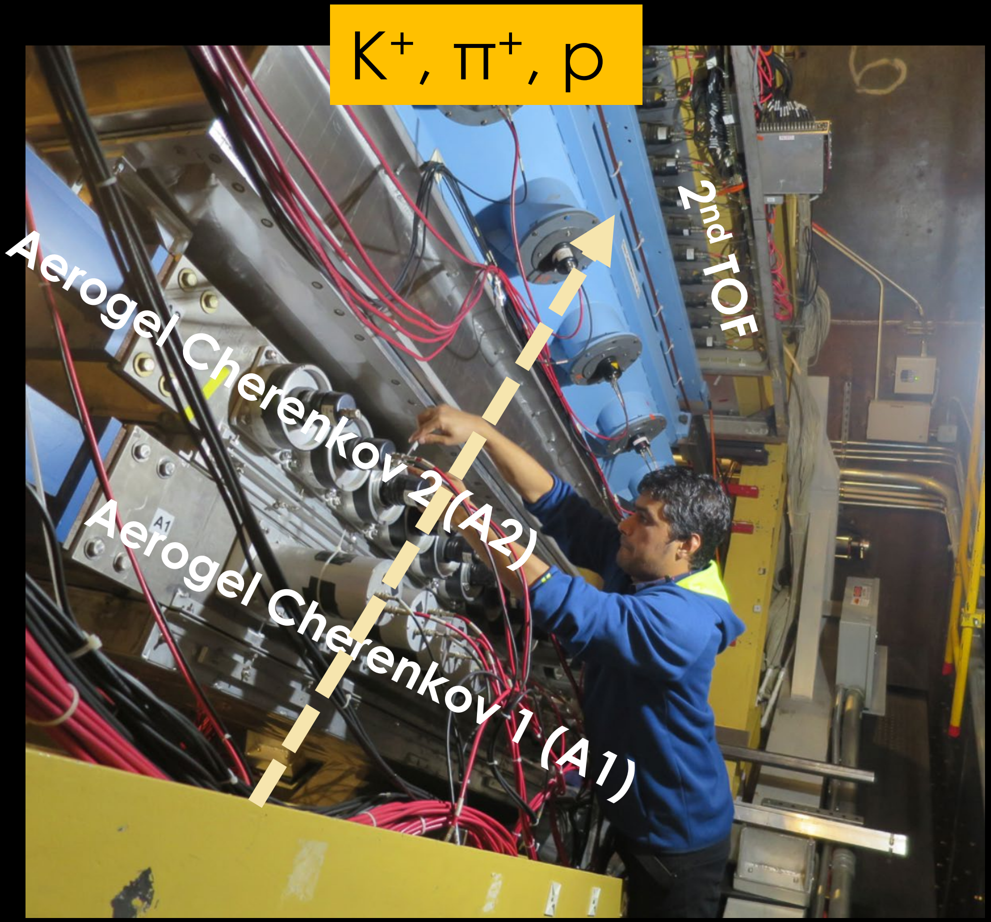
An FSI, elementary production, nnΛ search, **nnΛ production-cross section**, etc.

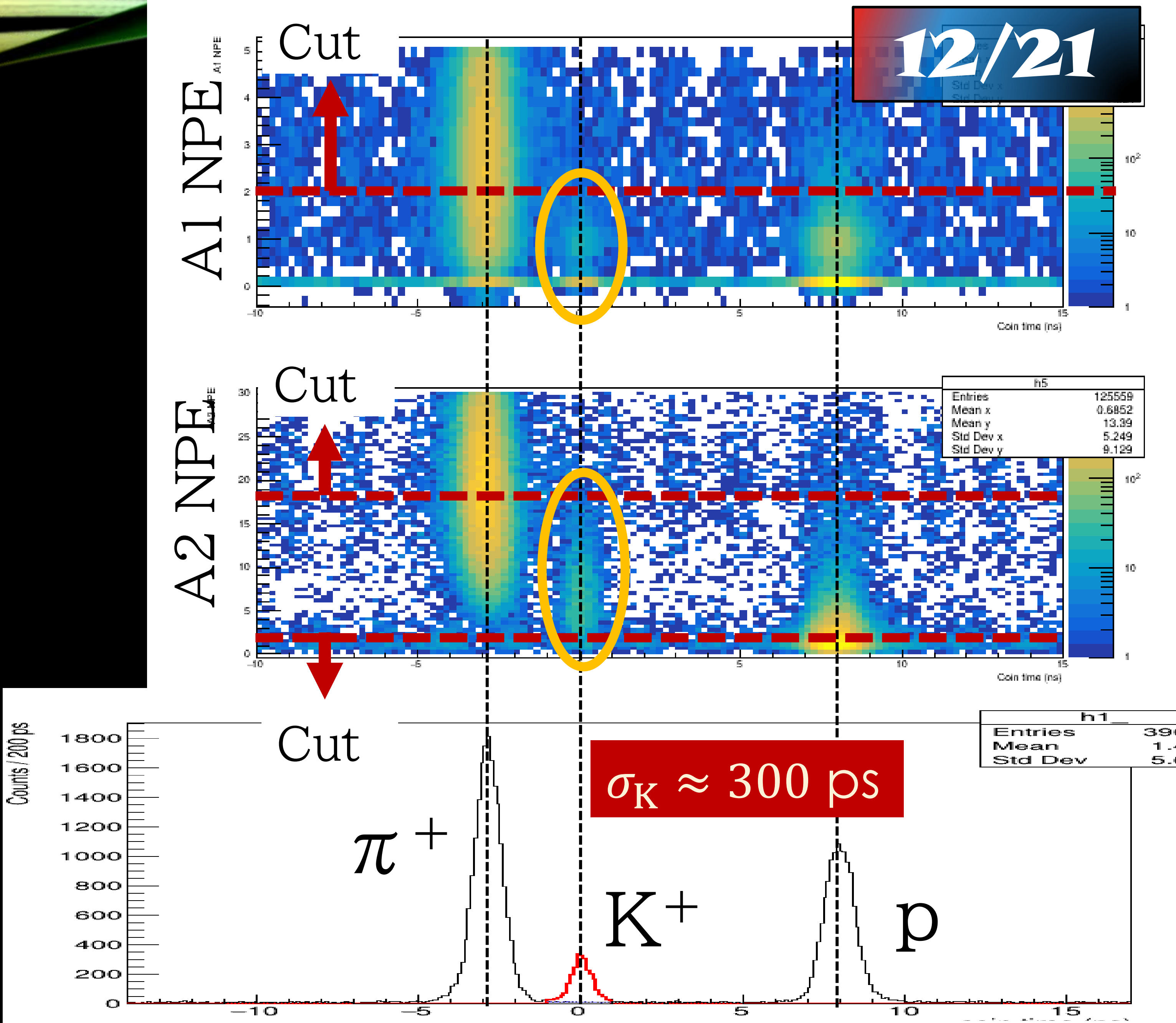
This talk → K.N. Suzuki et al. PTEP (2022)

# ANALYSIS FLOW



# $K^+$ identification



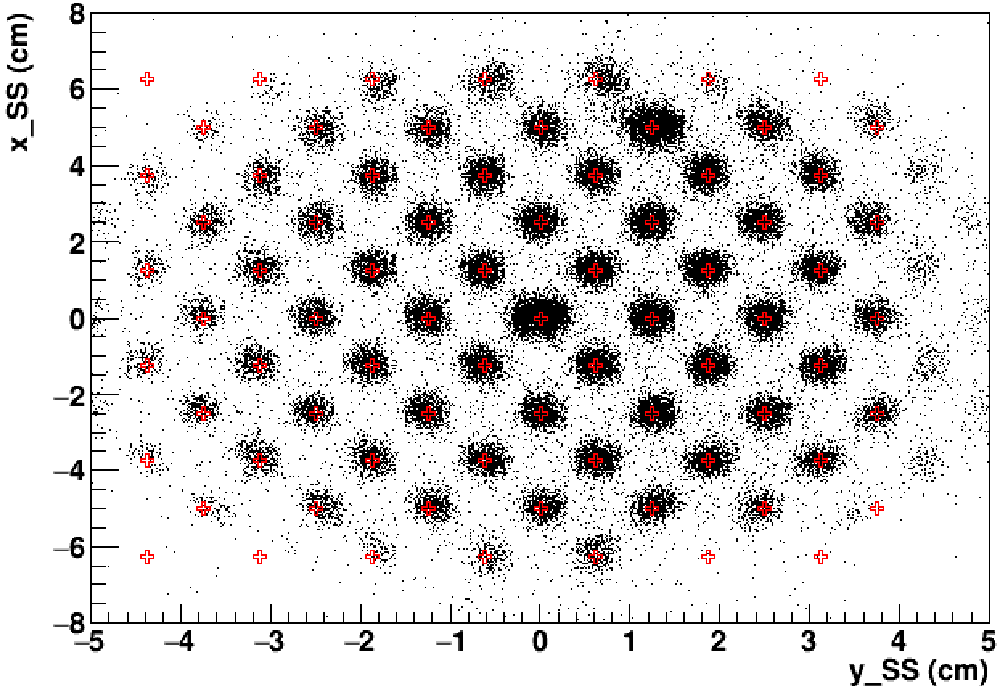




Timing consistency between L and R assuming $m_K$ → Coin time (ns)

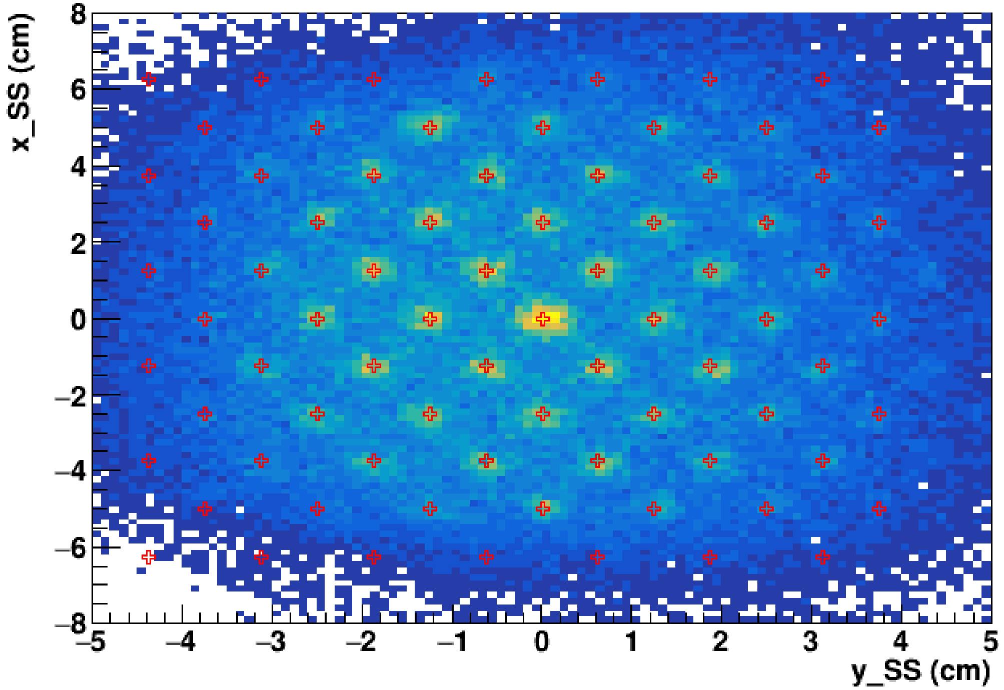
# Angle calibration by using sieve slits

The $4^{th}$ order polynomial

Sieve slit pattern (LHRS)

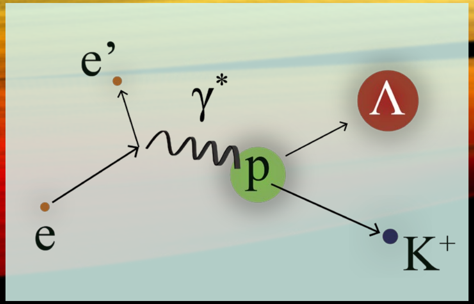



Sieve slit pattern (RHRS)



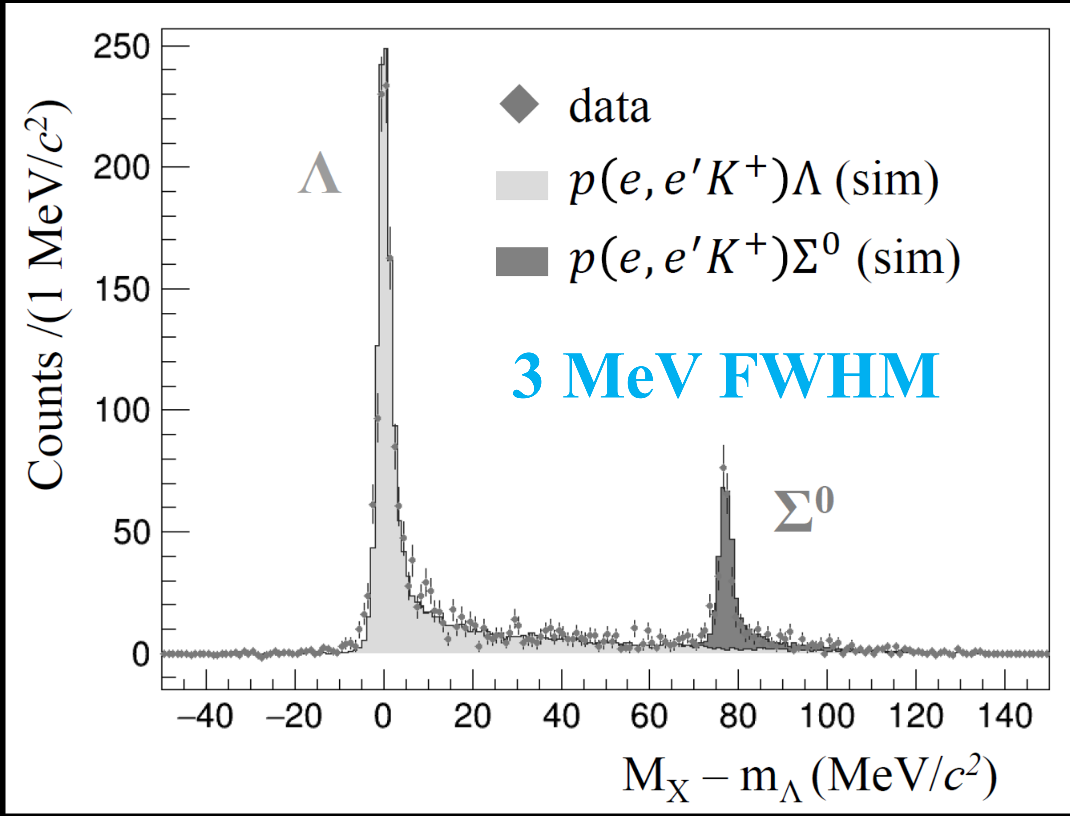

*e'*

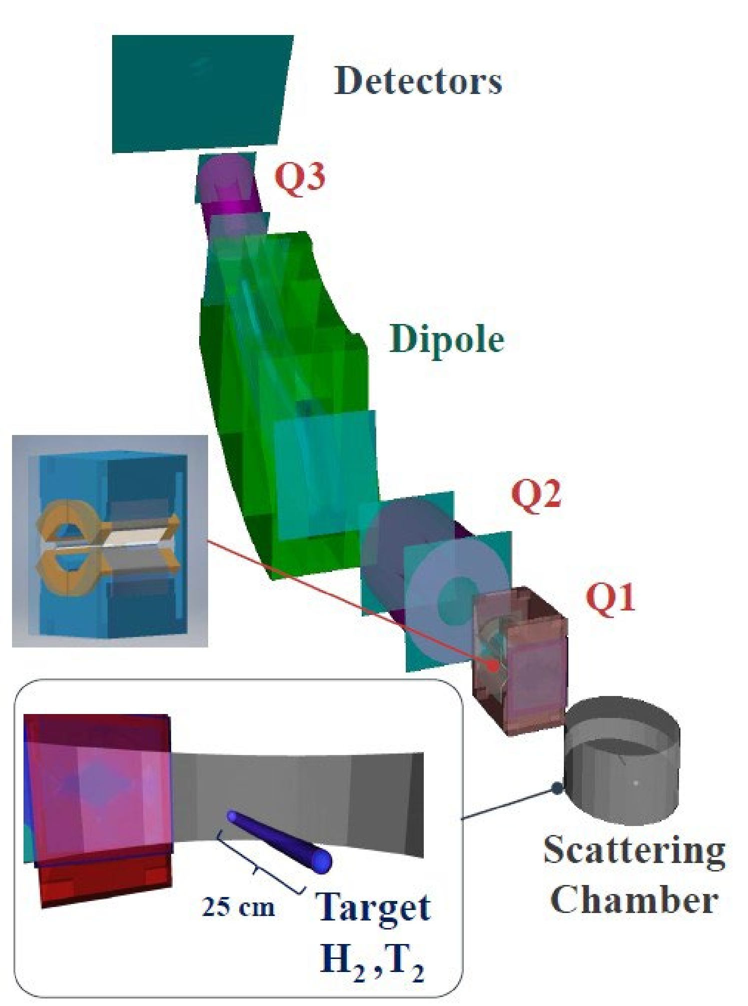
Hadrons




# Energy calibration by Λ and Σ

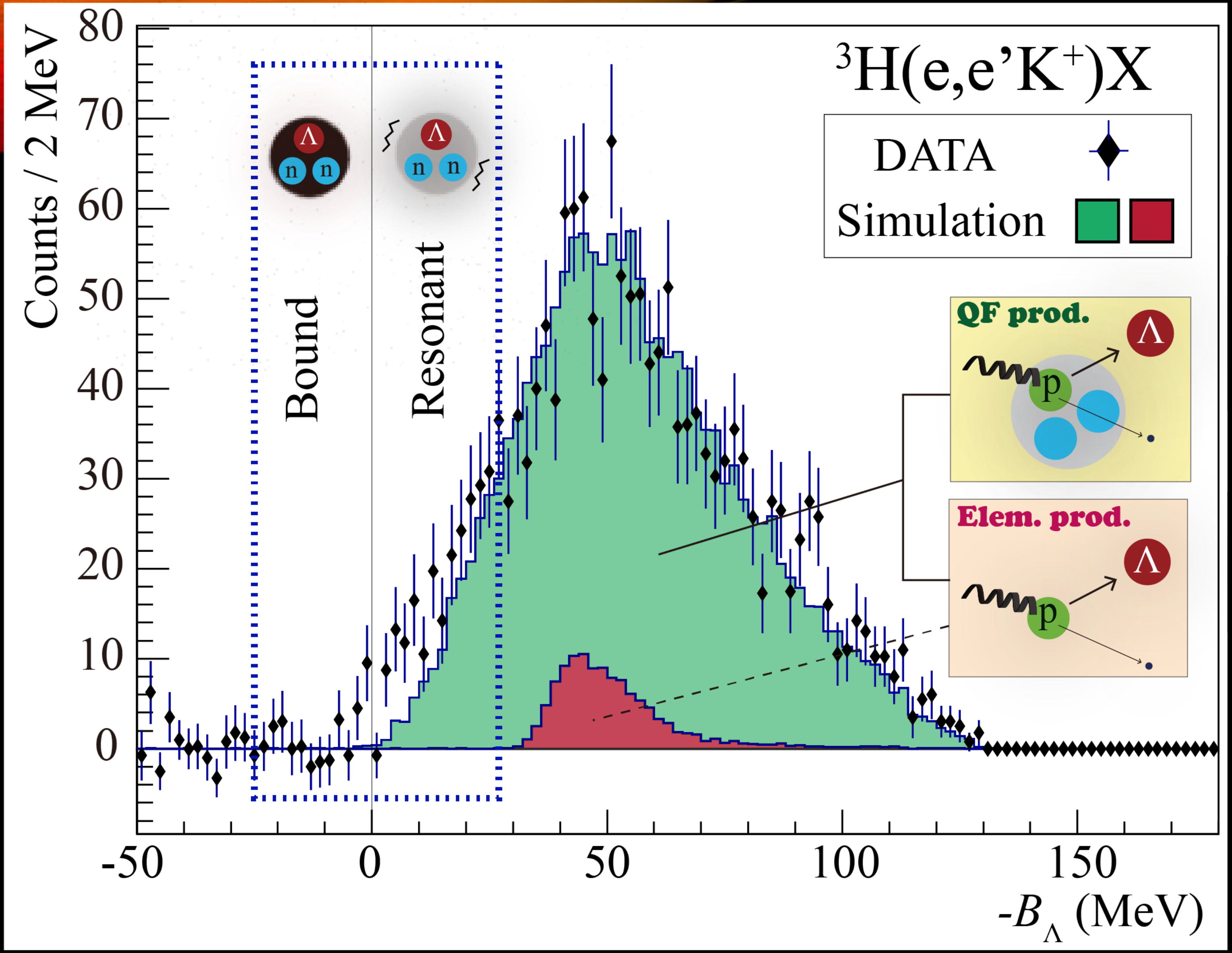
Fig from K.N. Suzuki's Ph.D. thesis (2022)




HRS Geant4 simulation

- Calibration with well known masses
- Geant4 simulation is consistent with data




- *Simulation w/o FSI*
- *w/ acceptance cut*

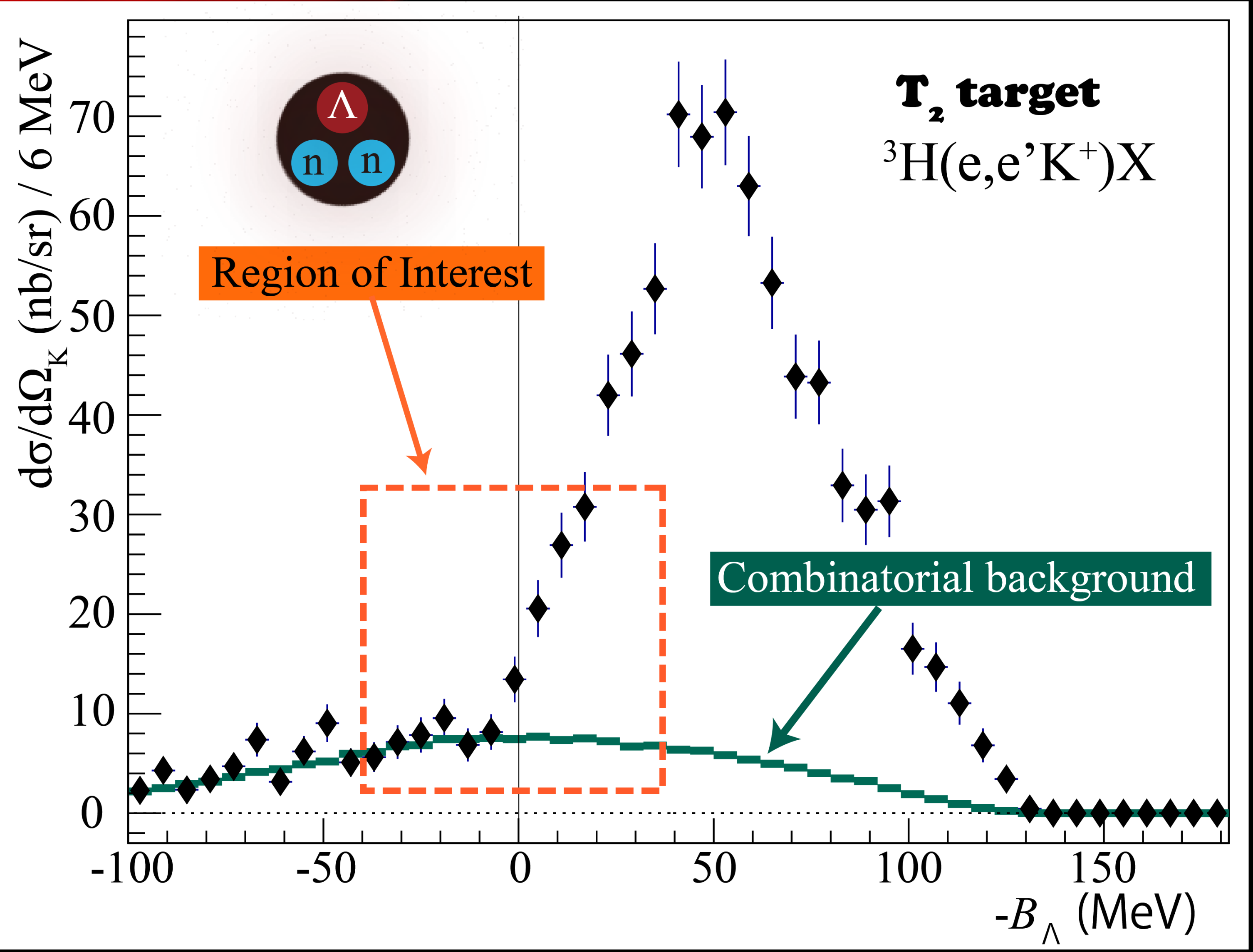
# $^3\mathrm{H}(e, e'K^+)X$

Binding energy:
$B_\Lambda = (2M_n + M_\Lambda) - M_x$

- ✓ Overall structure is **understandable**
- ✓ **FSI** may need to be taken into account for the threshold region

# Cross section spectrum






**Unbinned maximum likelihood fit**

**($-20 < B_\Lambda < 20$ MeV)**

**Probability density function (PDF):**

1. Response function (RF)
   - Geant4 simulation
2. Decay width
   - Breit Wigner

Next page

3. QF shape ($-B_\Lambda > 0$)
   - Unknown
     → Linear function ⊗ RF
4. Combinatorial background
   - Data → the 4$^{th}$ order polynomial

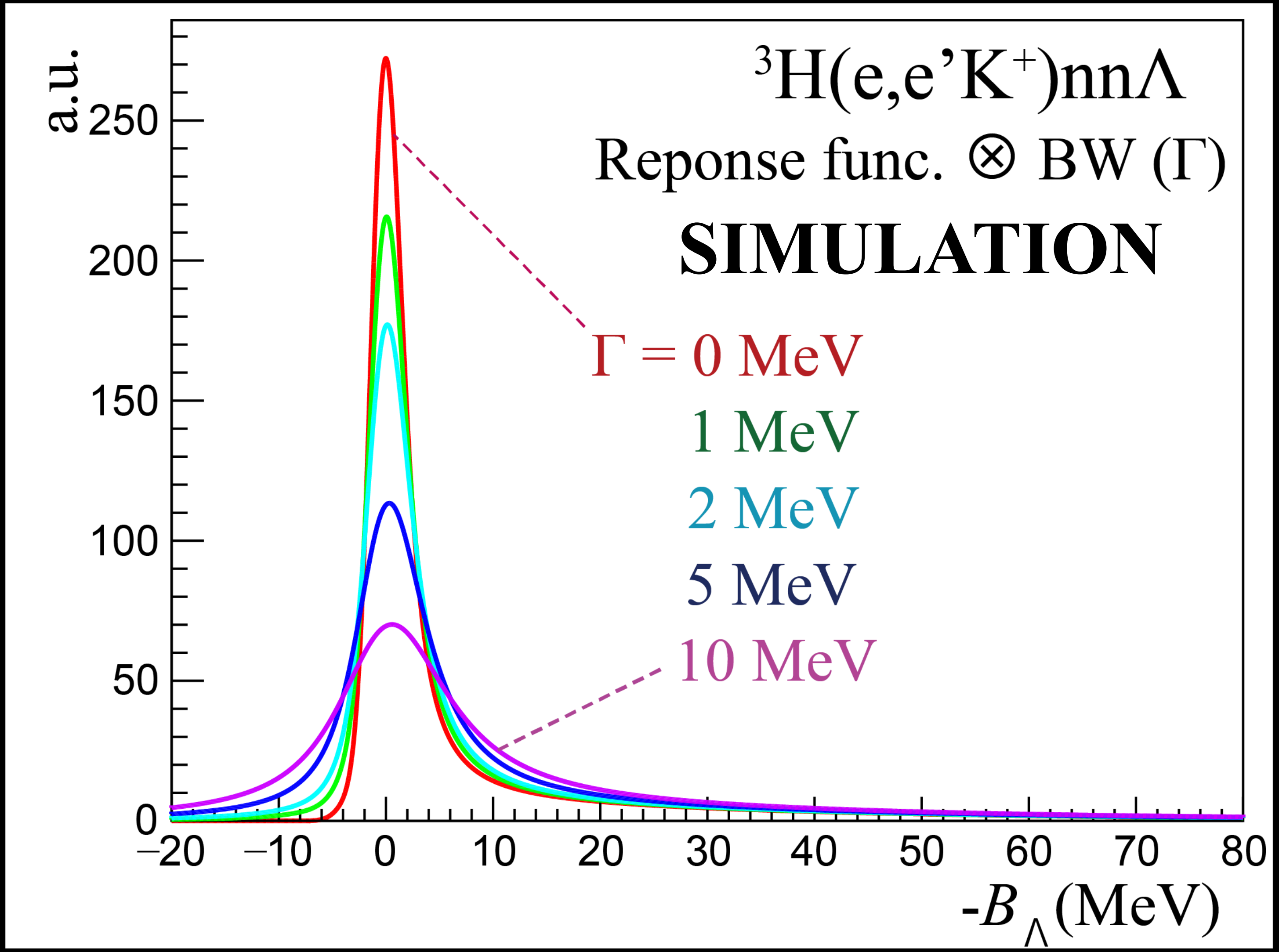
# Response function ⊗ BW

1. **Response function (RF)**

✓ Geant4 simulation

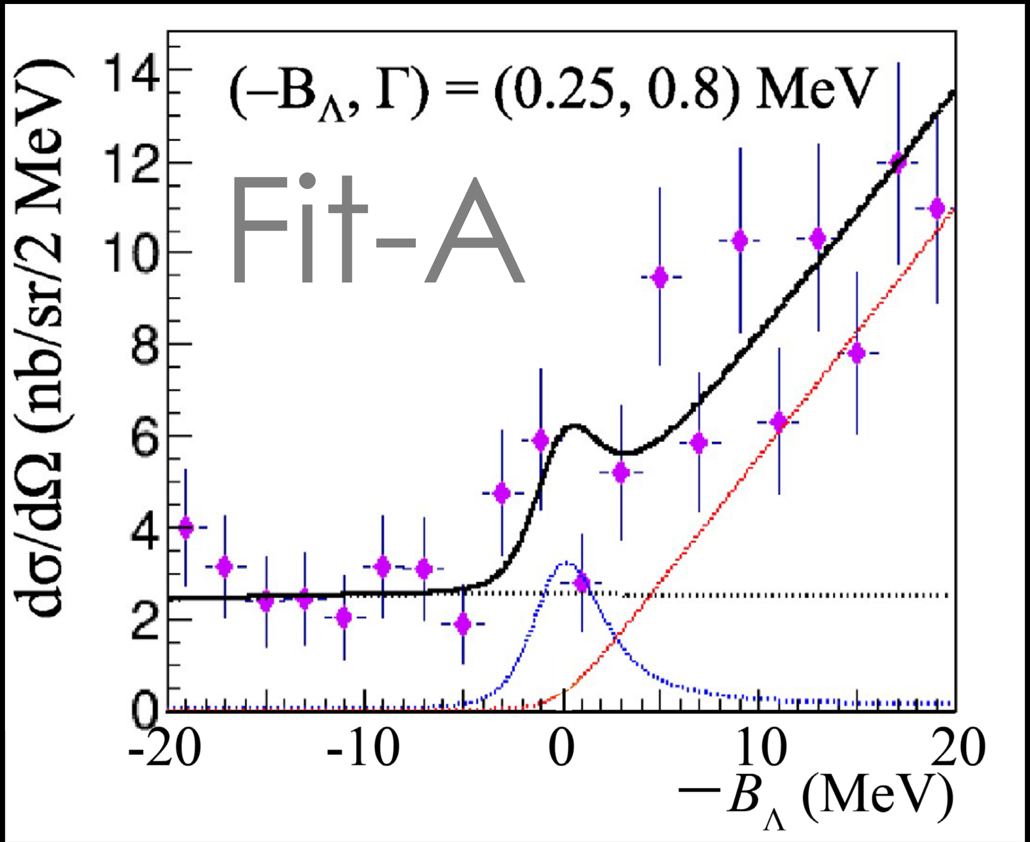
2. **Signal function**

✓ RF convoluted by Breit Wigner



# Fit result (typical cases)

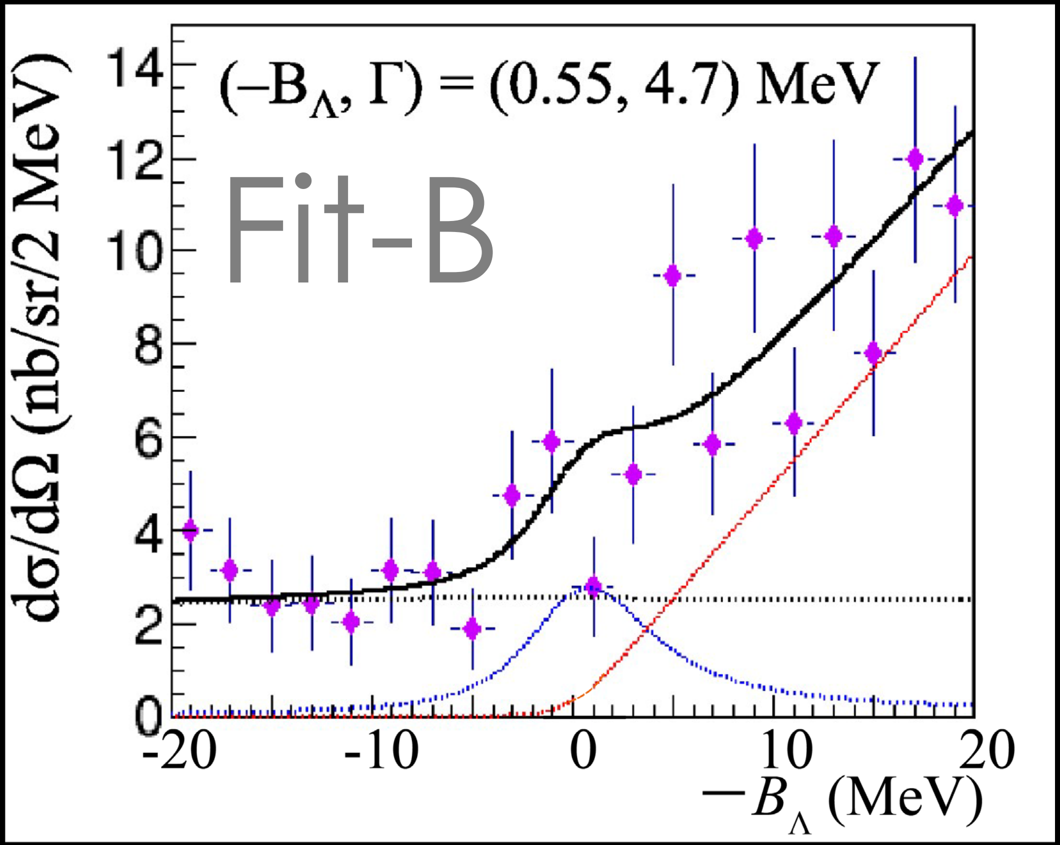
Kamada (2016): YN int. = **Nijmegen89**




$$\left(\frac{d\sigma}{d\Omega_K}\right)_{\text{Fit A}} = \mathbf{11.2} \pm 4.8\,(\text{stat.})^{+4.1}_{-2.1}\,(\text{sys.})$$

2.3 σ (only stat.)

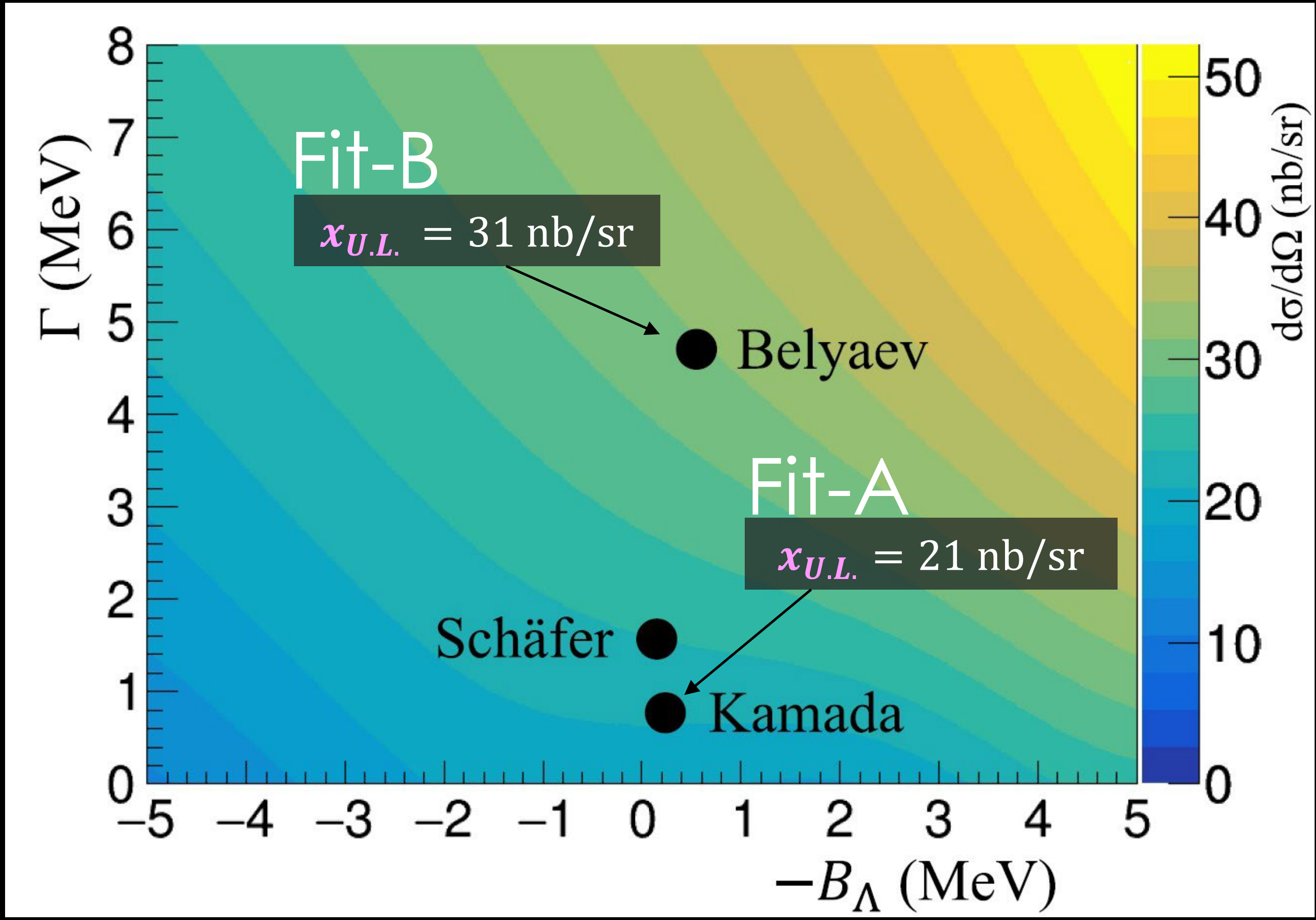
Belyaev (2008): YN int. = **Minesota**




$$\left(\frac{d\sigma}{d\Omega_K}\right)_{\text{Fit B}} = \mathbf{18.1} \pm 6.8\,(\text{stat.})^{+4.2}_{-2.9}\,(\text{sys.})$$

2.7 σ (only stat.)

# Upper limit at 90% C.L. (2-D scan)




**Upper limit** $x_{U.L.}$:

$$\frac{\int_0^{x_{U.L.}^{stat.}} g(x)dx}{\int_0^{\infty} g(x)dx} = 90\%$$

where, $g(x)$ is a Gaus.

⇩

$$x_{U.L.} = x_{U.L.}^{stat.} + sys.err.$$

Theoretical calculations to be compared with the results are awaited !!

# Other analyses in progress

- Peak search
  from a count base spectrum
  *(Hampton Univ.)*

- Λn FSI
  *(Tohoku Univ.)*

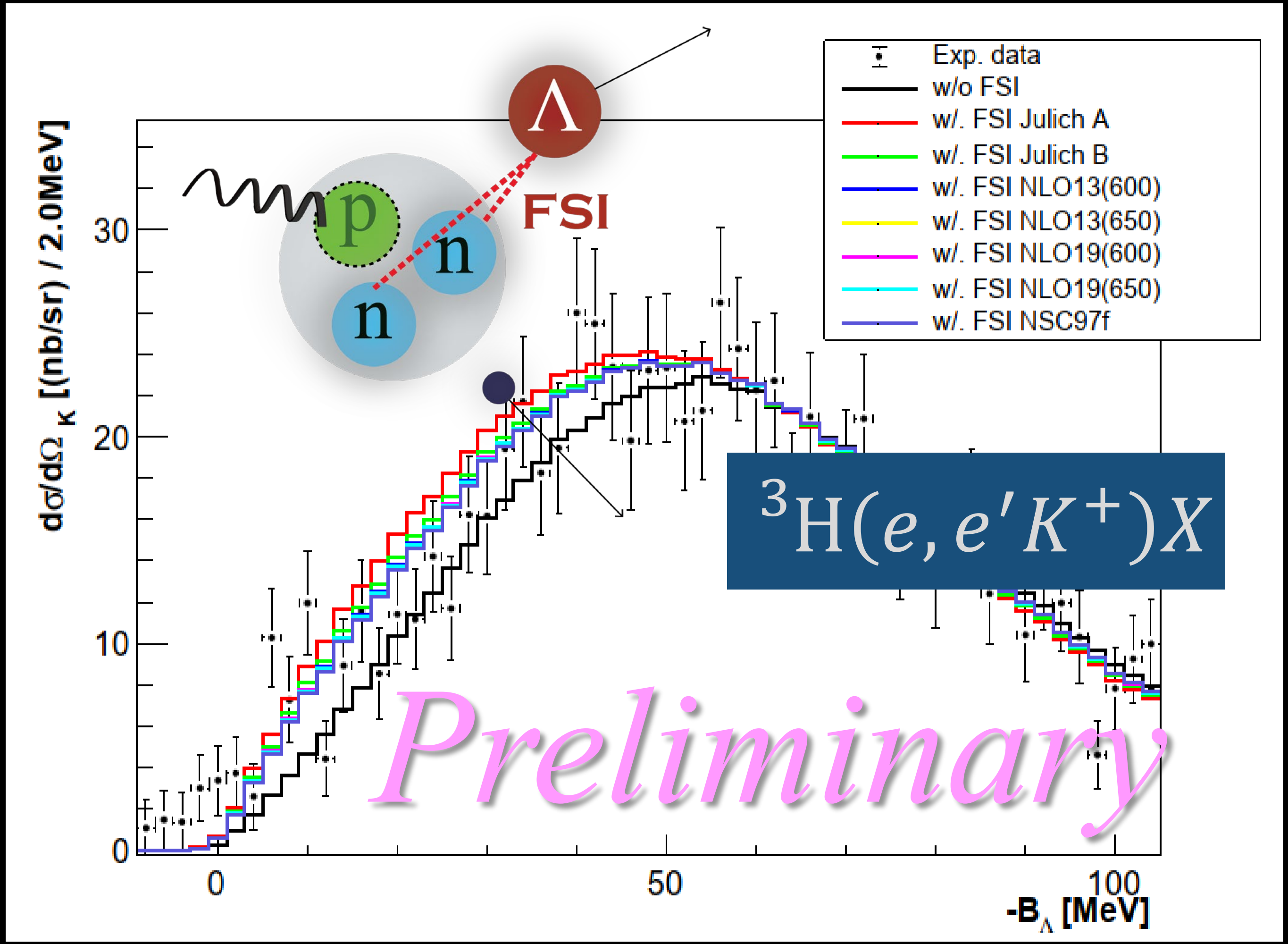
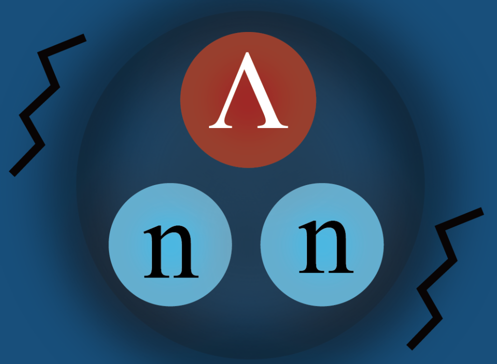



Figure from K. Itabashi (Tohoku Univ.)

# SUMMARY

## nnΛ search experiment (E12-17-003, 2018)

- The existence of nnΛ bound state is a deep mystery (theory)
- Resonant state may exist (theory)
- $^{3}$H(e,e'K$^{+}$)nnΛ @ Hall A
  - Sensitive to both bound and resonant states → **very unique**



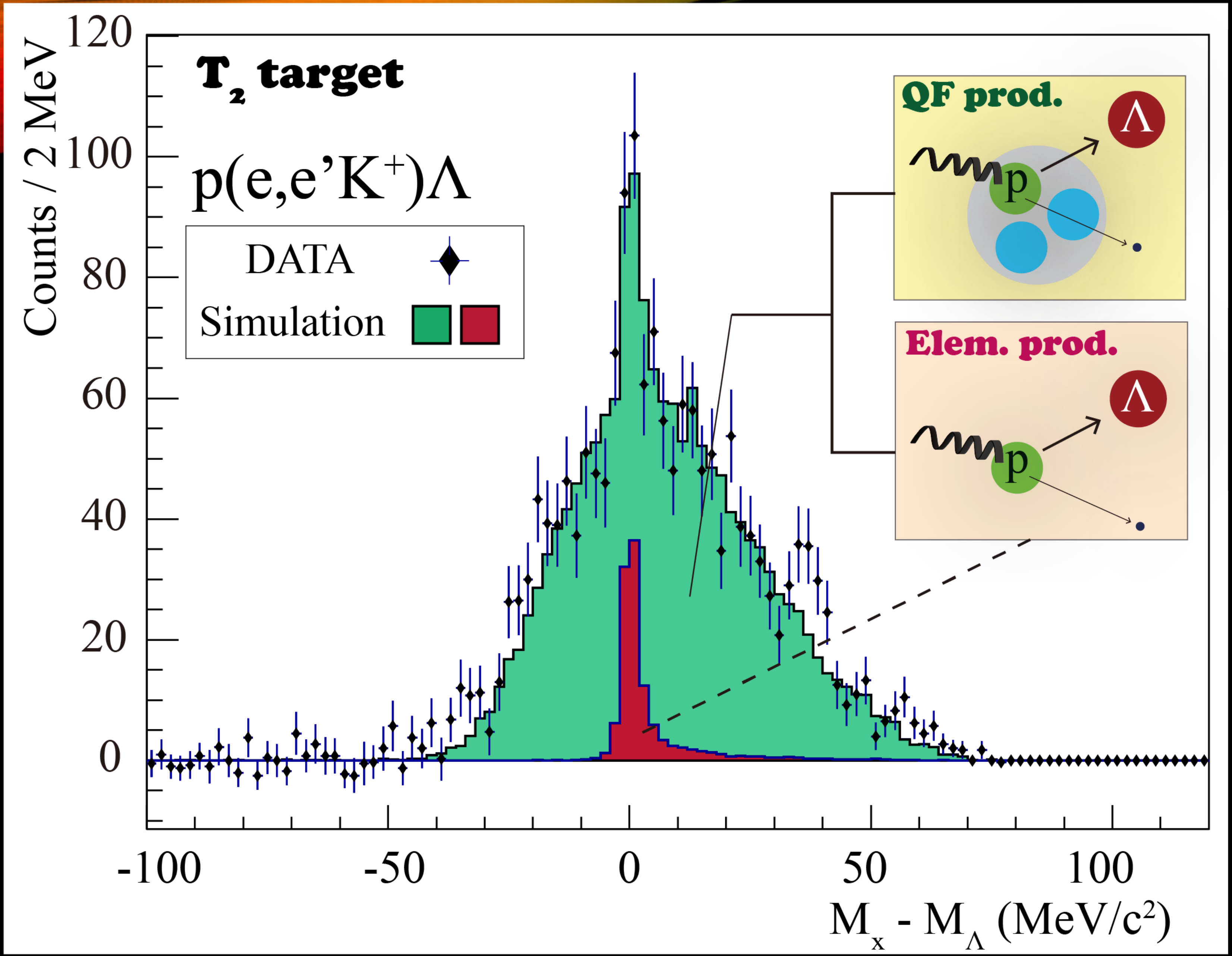

## Analyses

1. Production cross section ← **Published, and introduced today.**
   - Excess was found to be about 2.3~2.7 σ (Fit-A and B)
   - Upper limits at 90% C.L. : 21 and 31 nb/sr for Fit-A and B
2. Peak search with a count-base spectrum
3. nΛ FSI from the QF shape

*K.N. Suzuki et al., PTEP* 2022, 1, 013D01 (2022)

# THANK YOU FOR YOUR ATTENTION

# BACKUP




# $H_2$ in $T_2$ target

A few % of $H_2$ compared to $T_2$

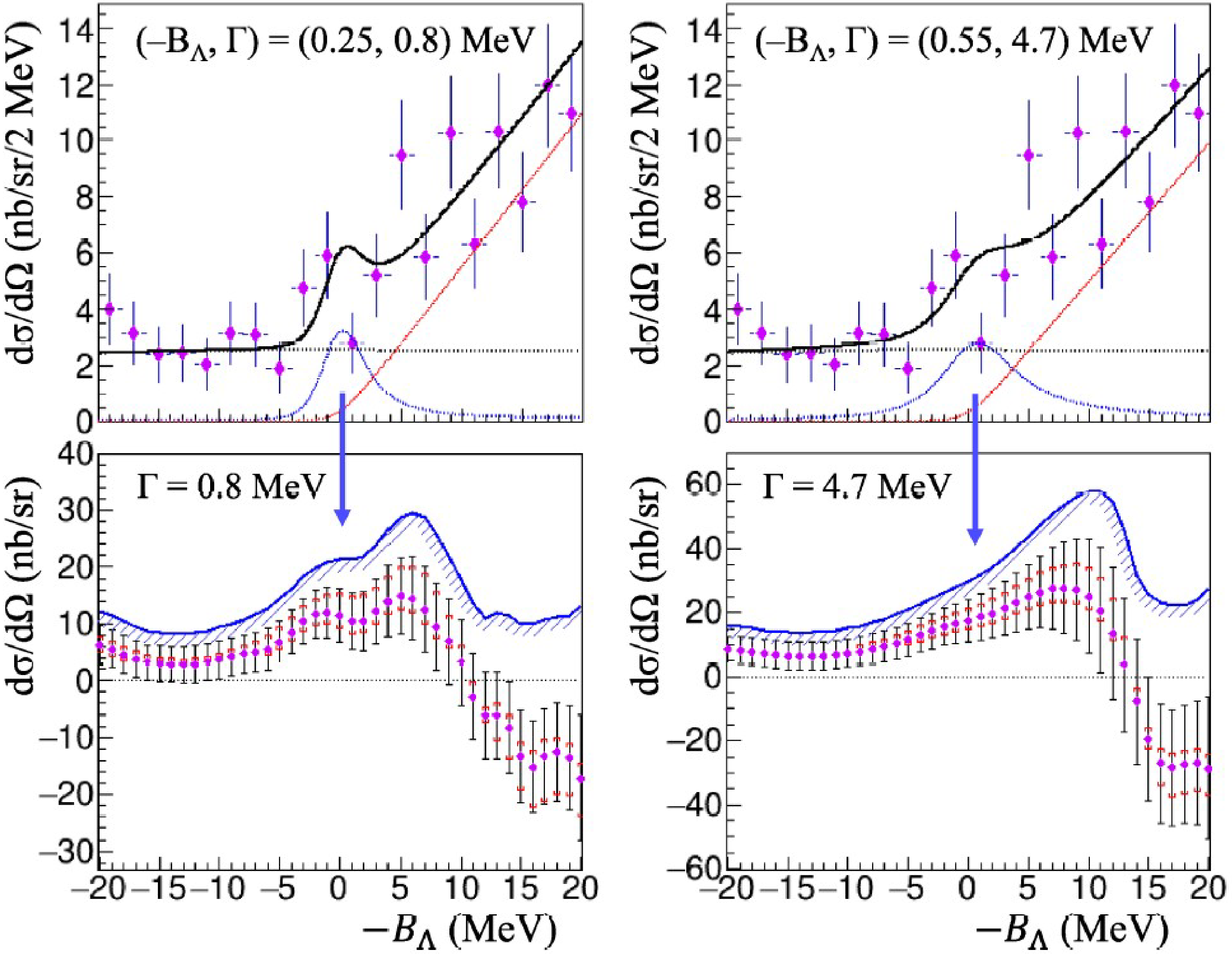



**Fig. 11.** The differential cross-section as a function of $-B_{\Lambda}$ (MeV). Spectral fits were done by assuming $(-B_{\Lambda}, \Gamma) = (0.25, 0.8)$ MeV and (0.55,4.7) MeV respectively, which are predictions adopted from Refs. [8,12]. Each panel shows the differential cross-section of exceeded events over the assumed QF distribution as a function of an assumed peak center.

# 1-D SCAN