Experimental study of $\bar{K}NN$ and future $\bar{K}$-nuclei experiments at J-PARC

Takumi Yamaga (RIKEN)
for the J-PARC E15 collaboration

QNP2022 (2022.9.5 – 9.9)

$\bar{K}N$ interaction

$I_{\bar{K}N} = 0$	$\frac{1}{\sqrt{2}}\left(-K^- p + \bar{K}^0 n\right)$	Strong attractive
$I_{\bar{K}N} = 1$	$\bar{K}^0 p$ $\frac{1}{\sqrt{2}}\left(K^- p + \bar{K}^0 n\right)$ $K^- n$	attractive

Possible to make quasi-bound states with $I_{\bar{K}N} = 0$

$\Lambda(1405)$

$\bar{K}$-nuclei

$\bar{K}NN$

The lightest $\bar{K}$-nucleus

$(\bar{K}[NN]^{I=0})^{I=1/2}$	$(\bar{K}[NN]^{I=1})^{I=1/2}$	$(\bar{K}[NN]^{I=1})^{I=3/2}$
$J^\pi = 1^-$	$J^\pi = 0^-$	$J^\pi = 0^-$
$-\sqrt{\frac{1}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{3}{4}}[\bar{K}N]^{I=1}N$	$\sqrt{\frac{3}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{1}{4}}[\bar{K}N]^{I=1}N$	$[\bar{K}N]^{I=1}N$

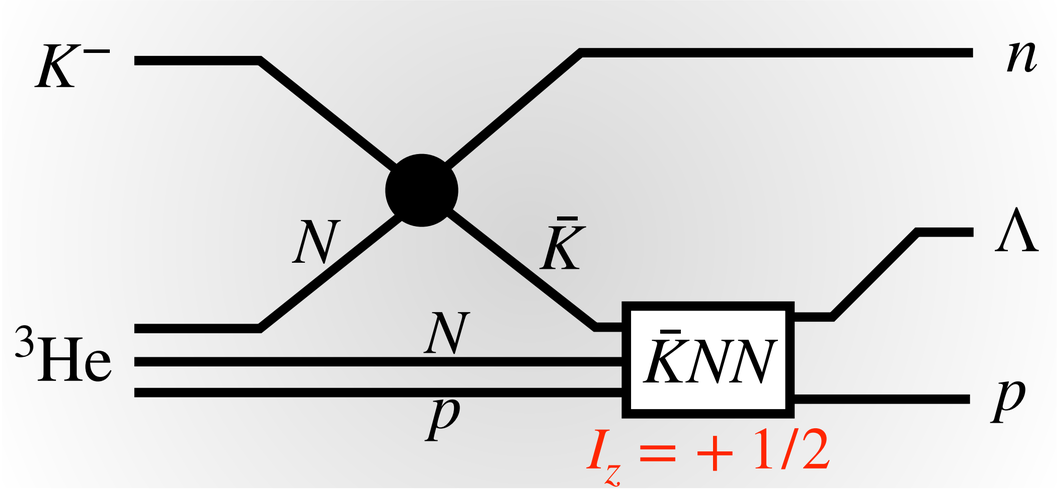
Should be the ground state

$I_z = +1/2$ K^-pp - $\bar{K}^0pn$ → We observed signal in J-PARC E15

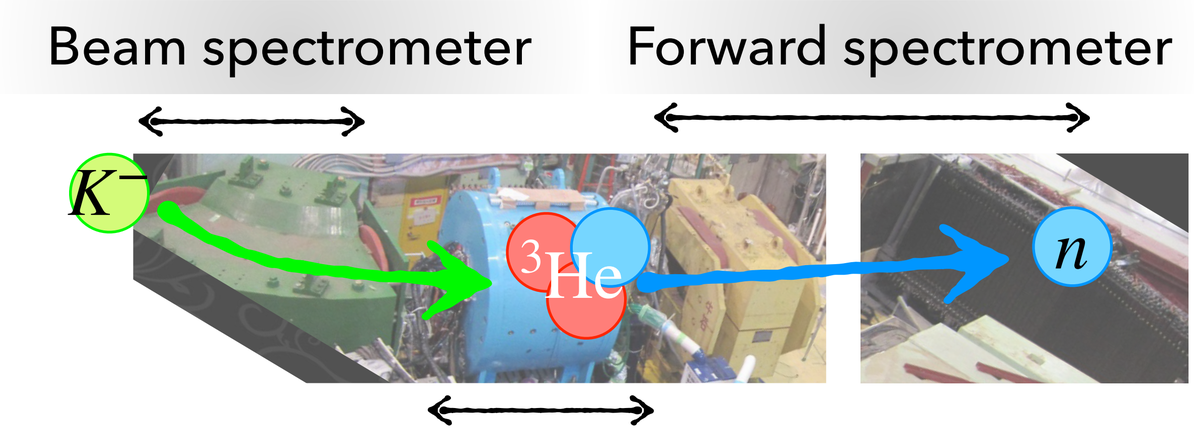
$I_z = -1/2$ K^-pn - $\bar{K}^0nn$

J-PARC E15

Production reaction



Detector system



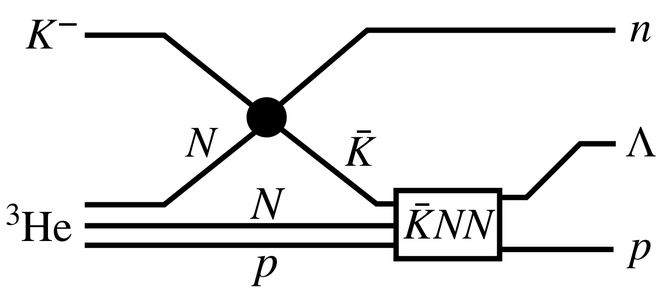
Exclusive invariant-mass spectroscopy

To select Λpn final state

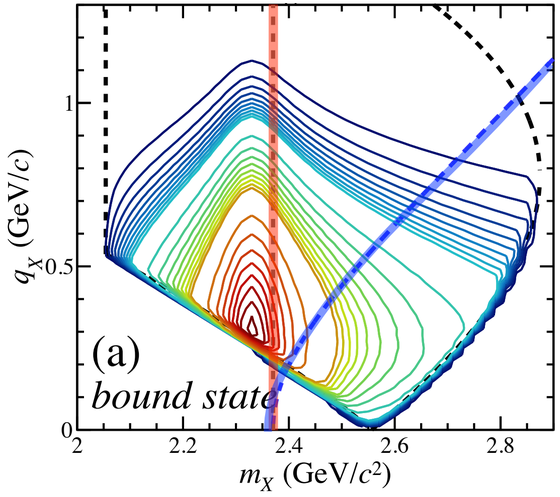
To measure Λp invariant-mass & momentum transfer

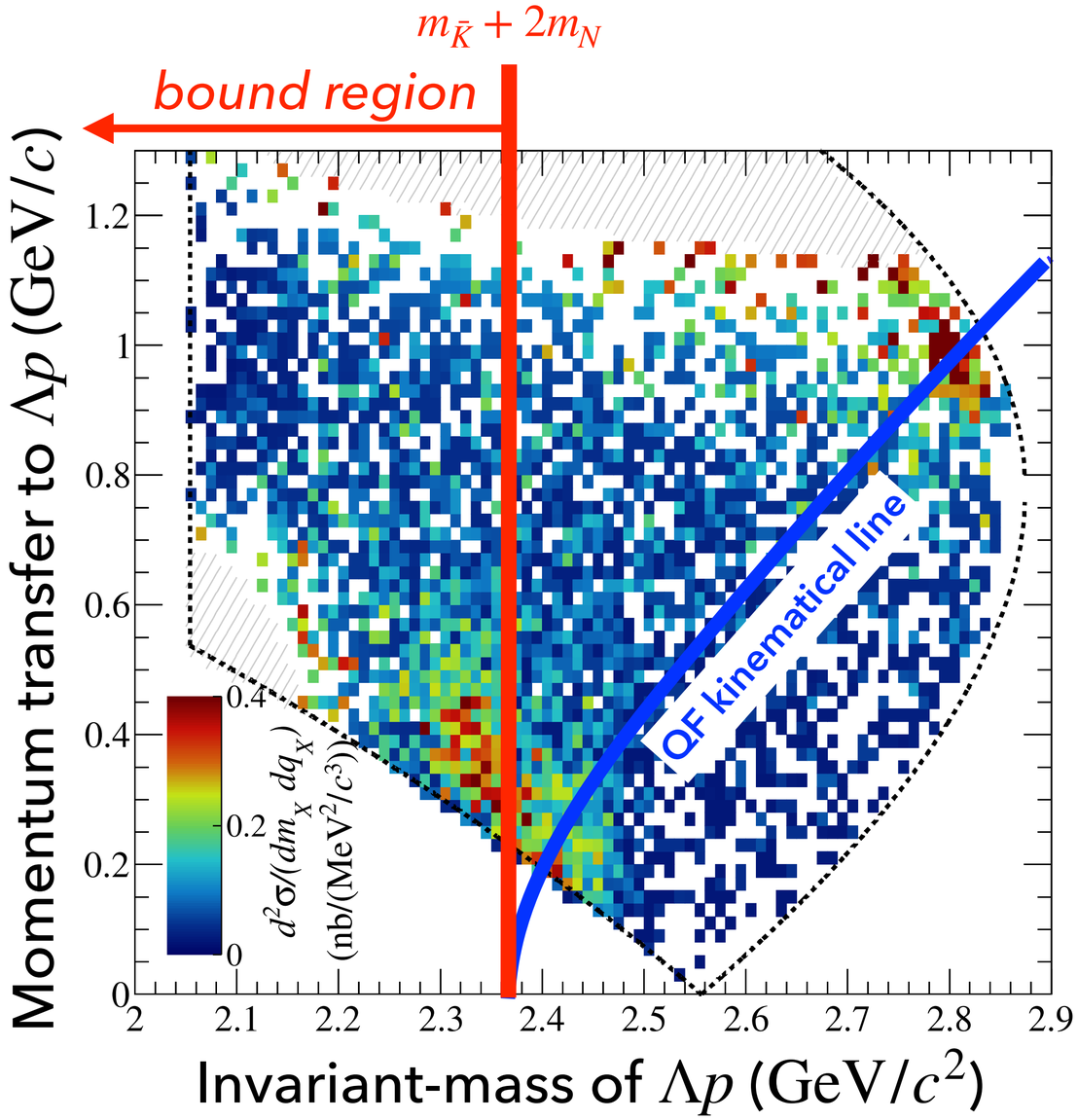
Obtained 2D distribution

$\bar{K}NN$ production

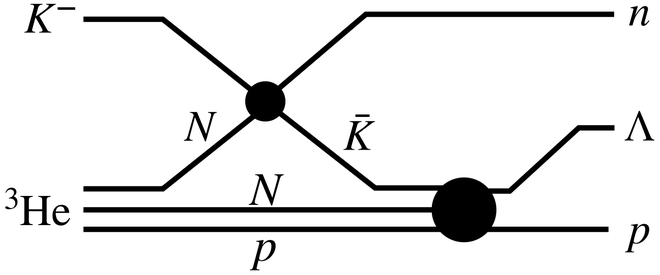


$$f_{\bar{K}NN}(m_X, q_X) = \frac{\Gamma^2/4}{(m_X - M_X)^2 + \Gamma^2/4} \times g_{K^-pp}(q_X)$$

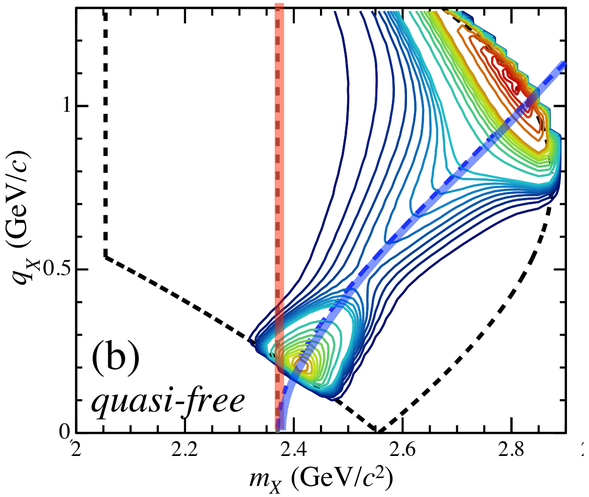




Quasi-free process with (K^-, n)

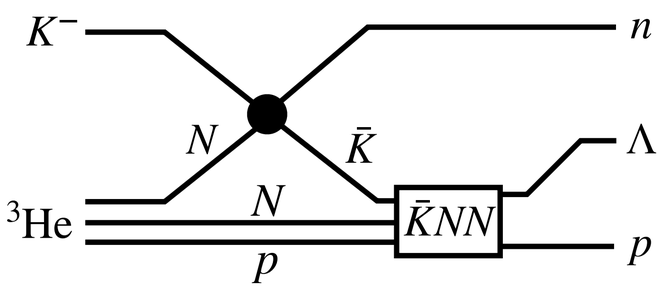


$$f_{\mathrm{QF}}(m_X, q_X) = \exp\left(-\frac{(m_X - M_F(q_X))^2}{\sigma^2(q_X)}\right) \times g_{\mathrm{QF}}(q_X)$$

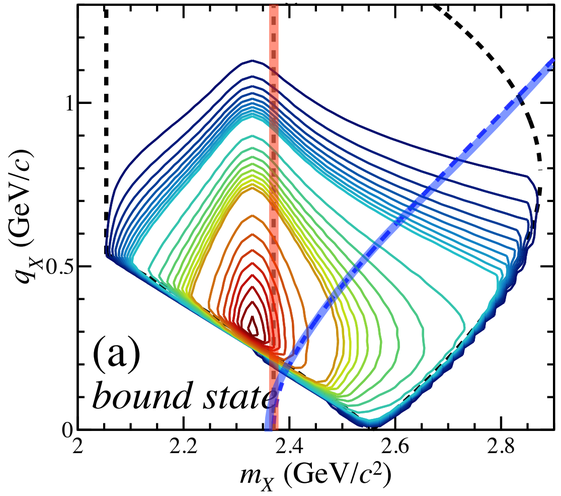


Model functions

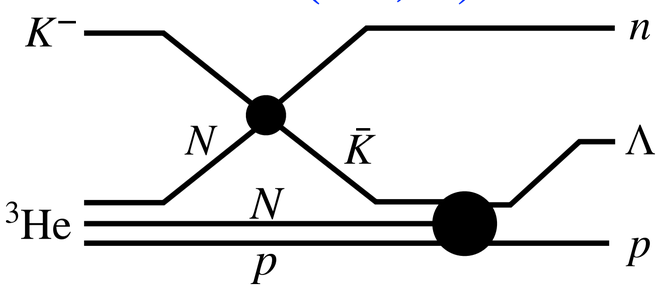
$\bar{K}NN$ production



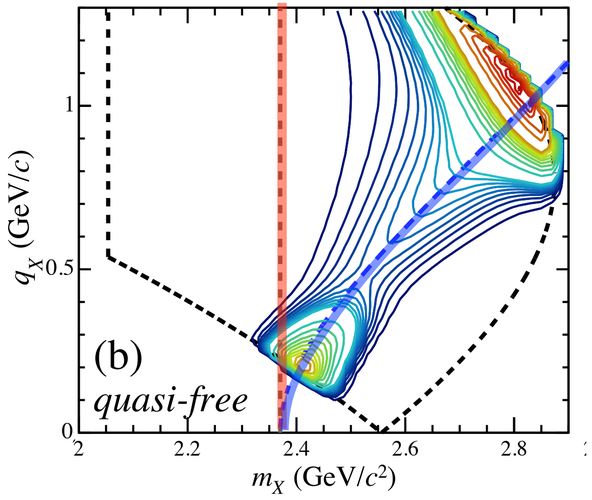
$$f_{\bar{K}NN}(m_X, q_X) = \frac{\Gamma^2/4}{(m_X - M_X)^2 + \Gamma^2/4} \times g_{K^-pp}(q_X)$$



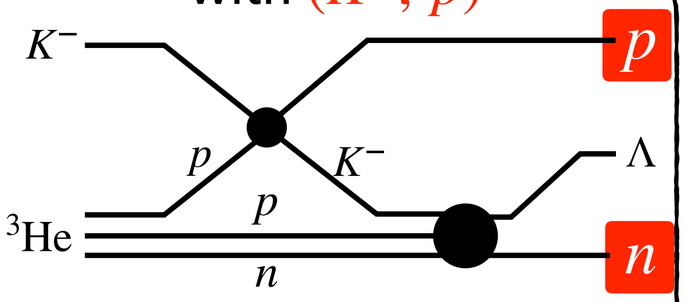
Quasi-free process with (K^-, n)



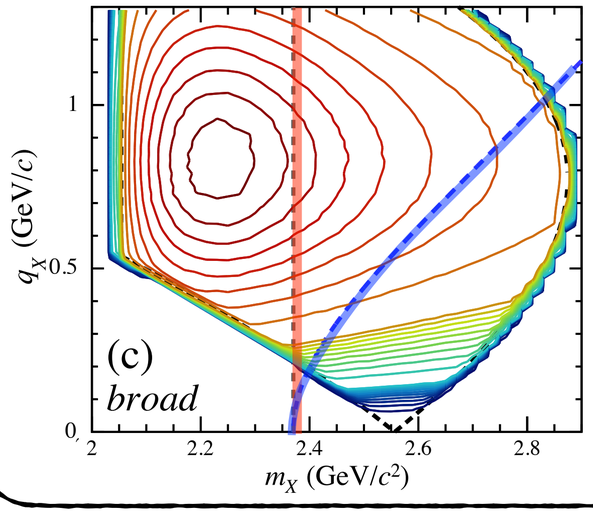
$$f_{\mathrm{QF}}(m_X, q_X) = \exp\left(-\frac{(m_X - M_F(q_X))^2}{\sigma^2(q_X)}\right) \times g_{\mathrm{QF}}(q_X)$$



Quasi-free process with (K^-, p)

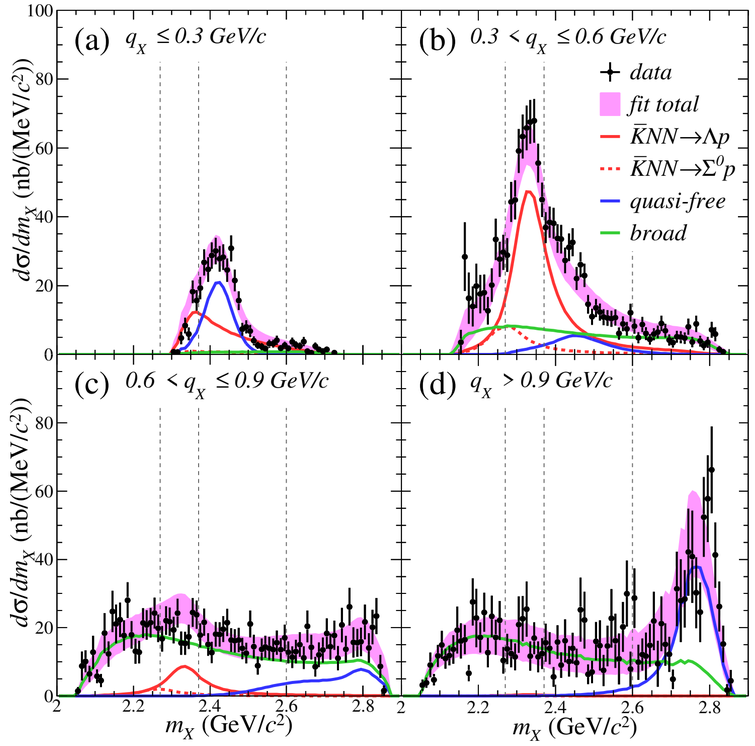


widely distributing

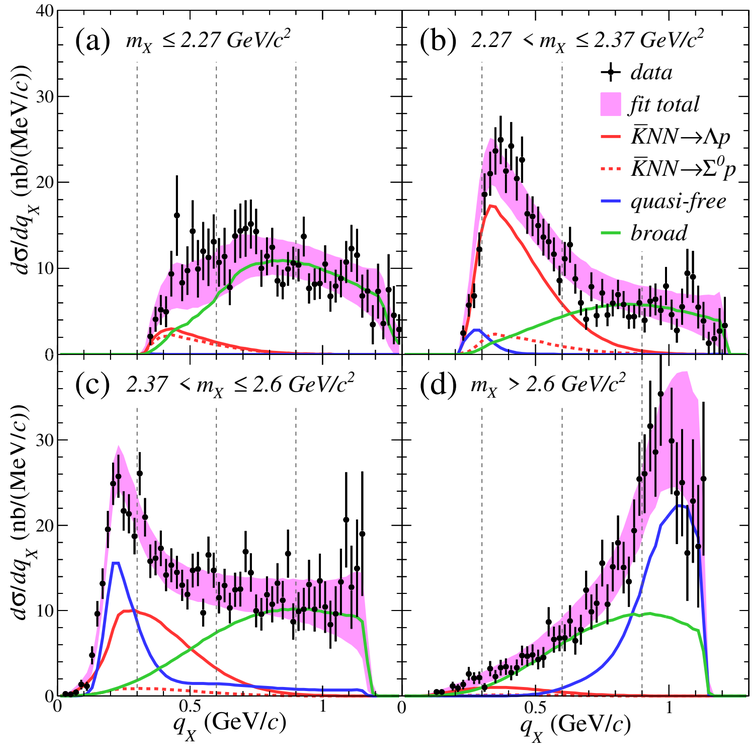


Fit result

Λp invariant-mass

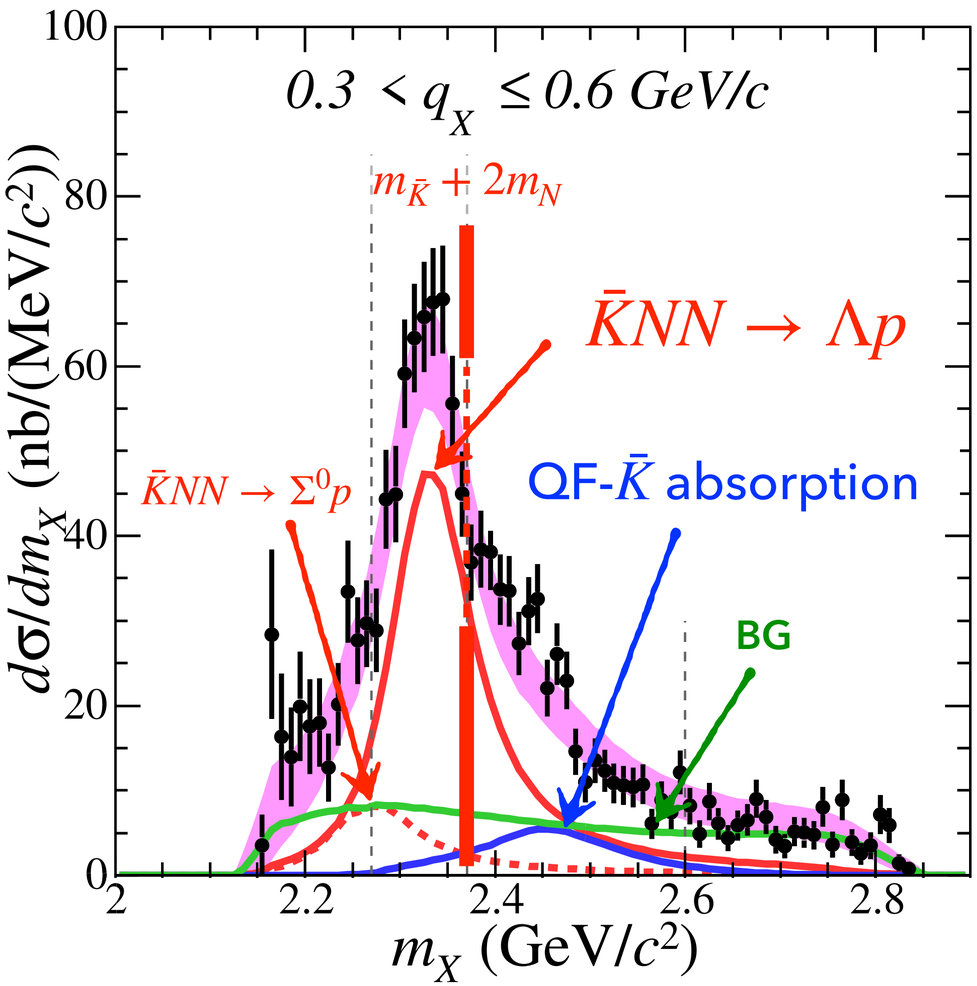


Momentum transfer to Λp



→ **Whole distributions are well reproduced.**

What we observed



The peak position does not depend on q.

➜ *It should be resonance.*

QF-$\bar{K}$ absorption process is clearly observed.

➜ *Intermediate-$\bar{K}$ exist during the reaction.*

The peak position is below the $M_{\bar{K}NN}$.

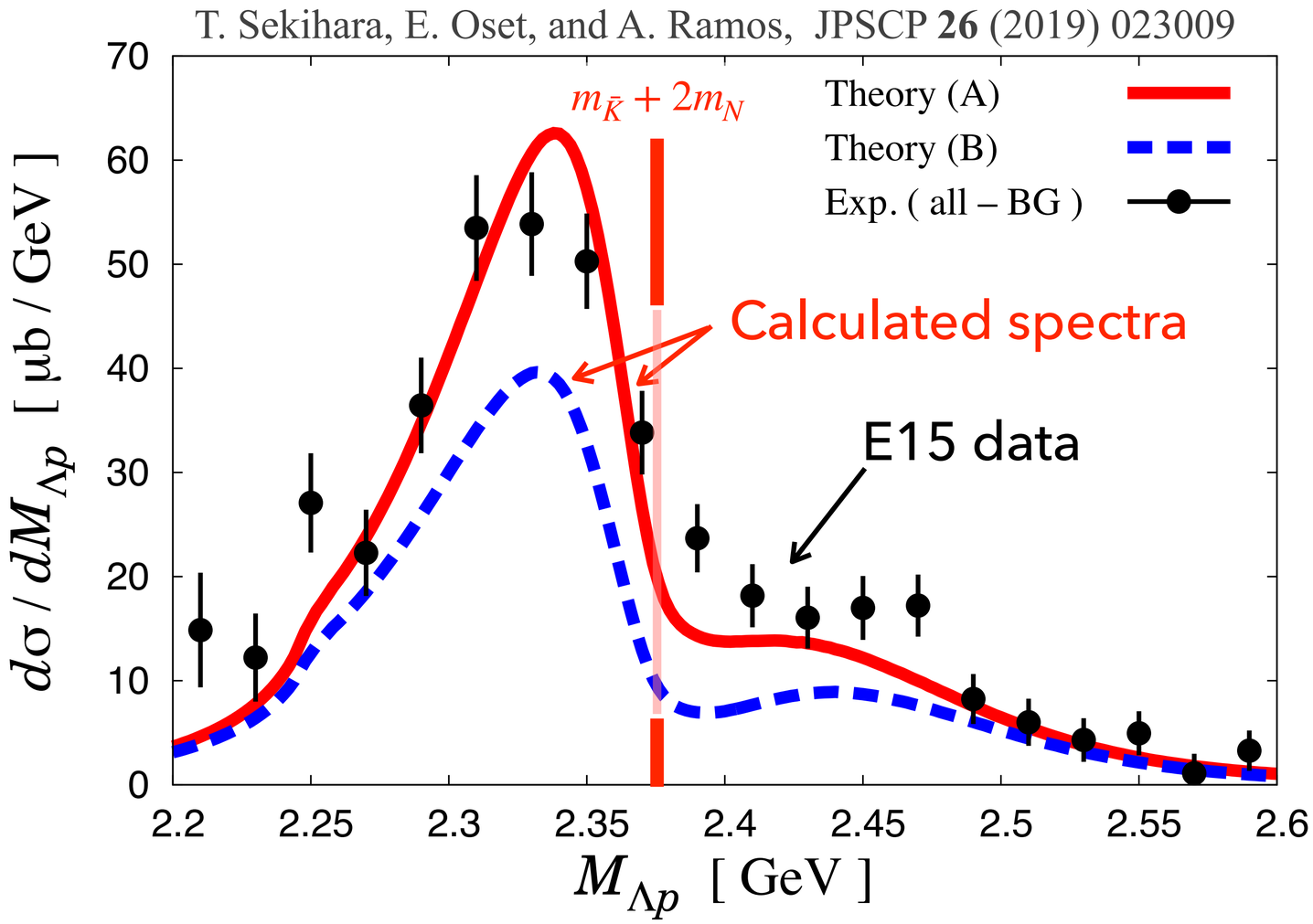
➜ *We interpreted it as $\bar{K}NN$ signal.*

$$BE = 42 \pm 3\ (\text{stat.})\ ^{+3}_{-4}\ (\text{syst.})\ \text{MeV}$$

$$\Gamma = 100 \pm 7\ (\text{stat.})\ ^{+19}_{-9}\ (\text{syst.})\ \text{MeV}$$

* obtained as peak position & width of simple Breit-Wigner

Compare to theoretical calculation



→ Theoretical calculation supports that the observed peak is $\bar{K}NN$ signal.

Remaining questions

Is the observed resonance really what we expected?

Other possibilities such as $\Sigma^* N$?

Does $\bar{K}$ really keep it particle identity?

↓

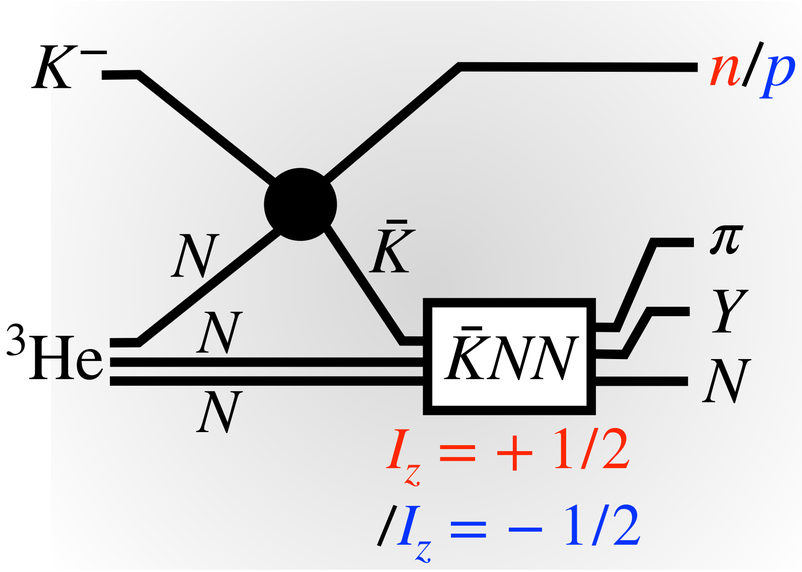
We need further systematic measurements
to answer the questions & to robustly confirm $\bar{K}$-nuclei.

Precise study for $\bar{K}NN$

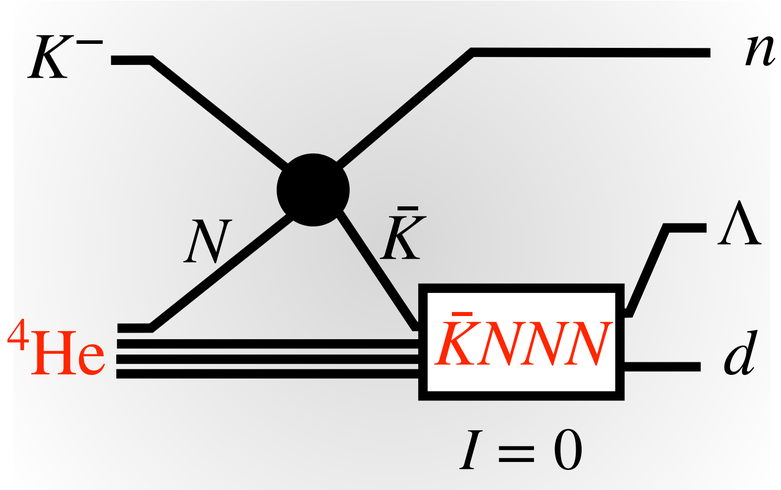
Search for heavier $\bar{K}$-nuclei

Ongoing analysis for $\bar{K}$-nuclei

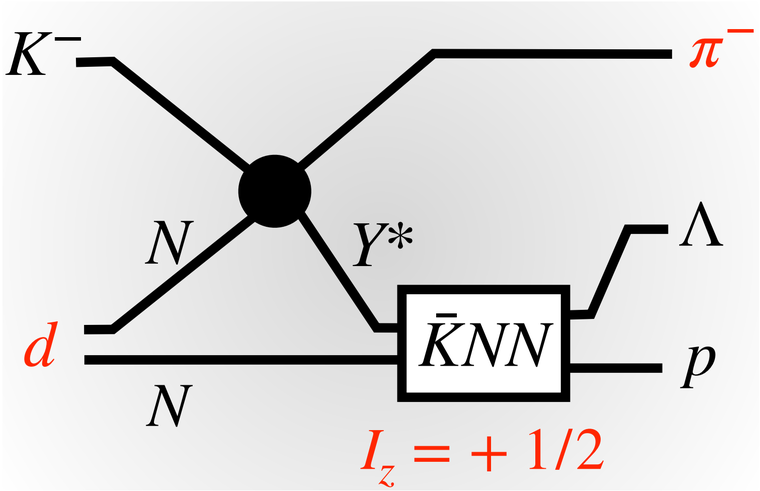
Mesonic decay of $\bar{K}NN$



$\bar{K}NNN$ production



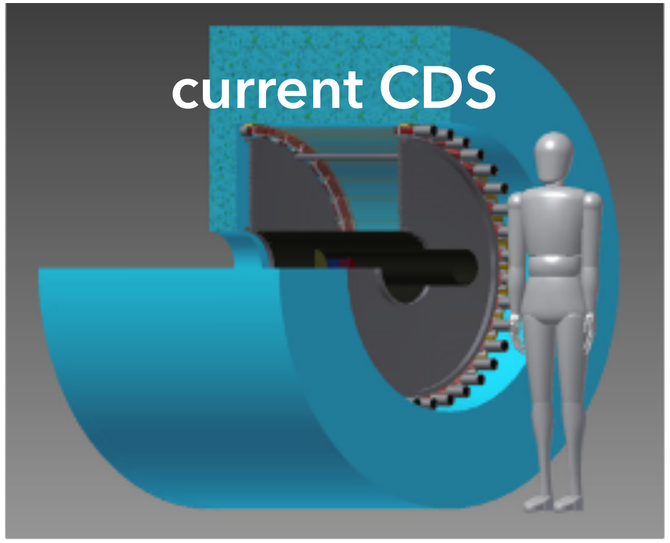
$\bar{K}NN$ production with (K^-, π^-) reaction

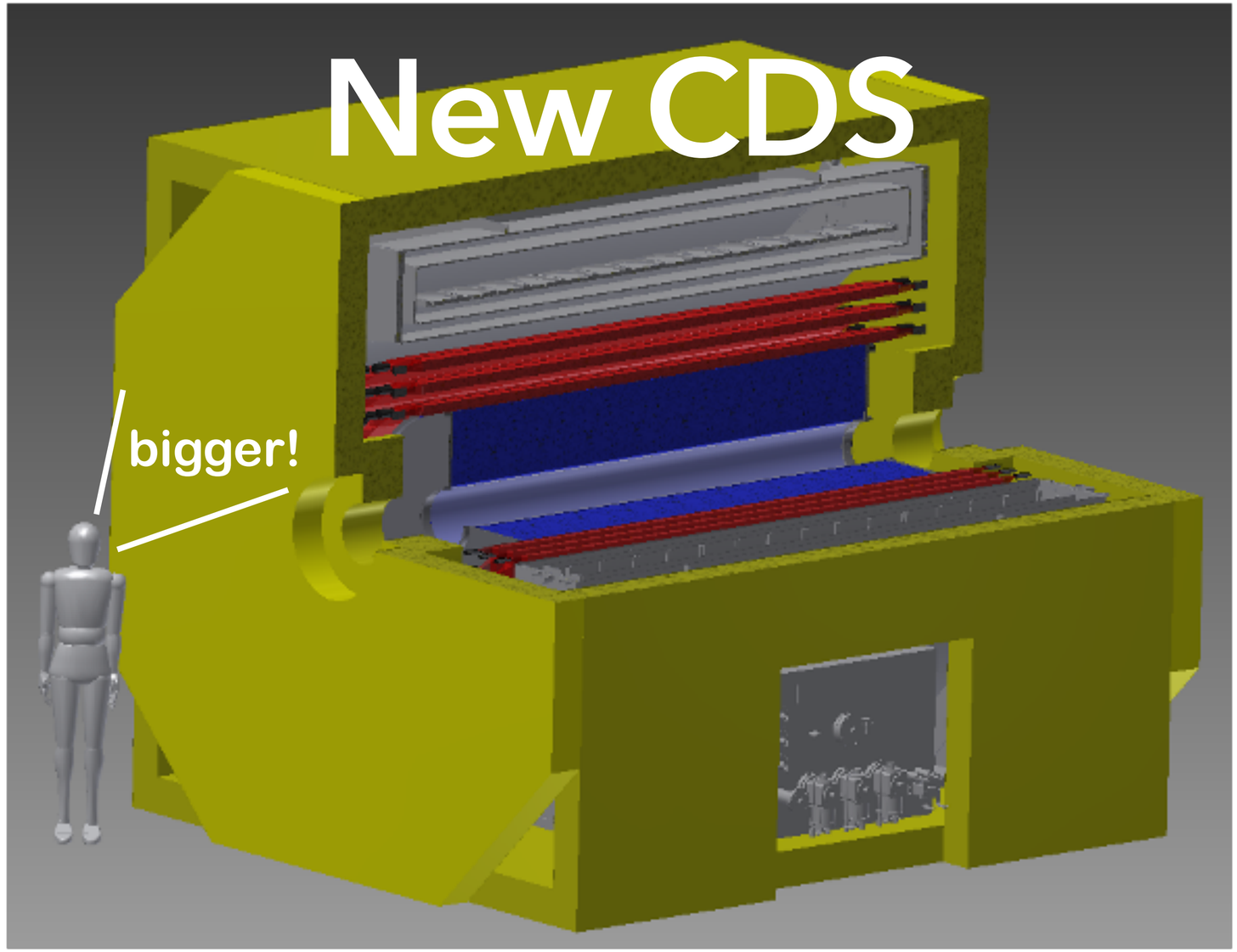


→ *Talked by R. Murayama*

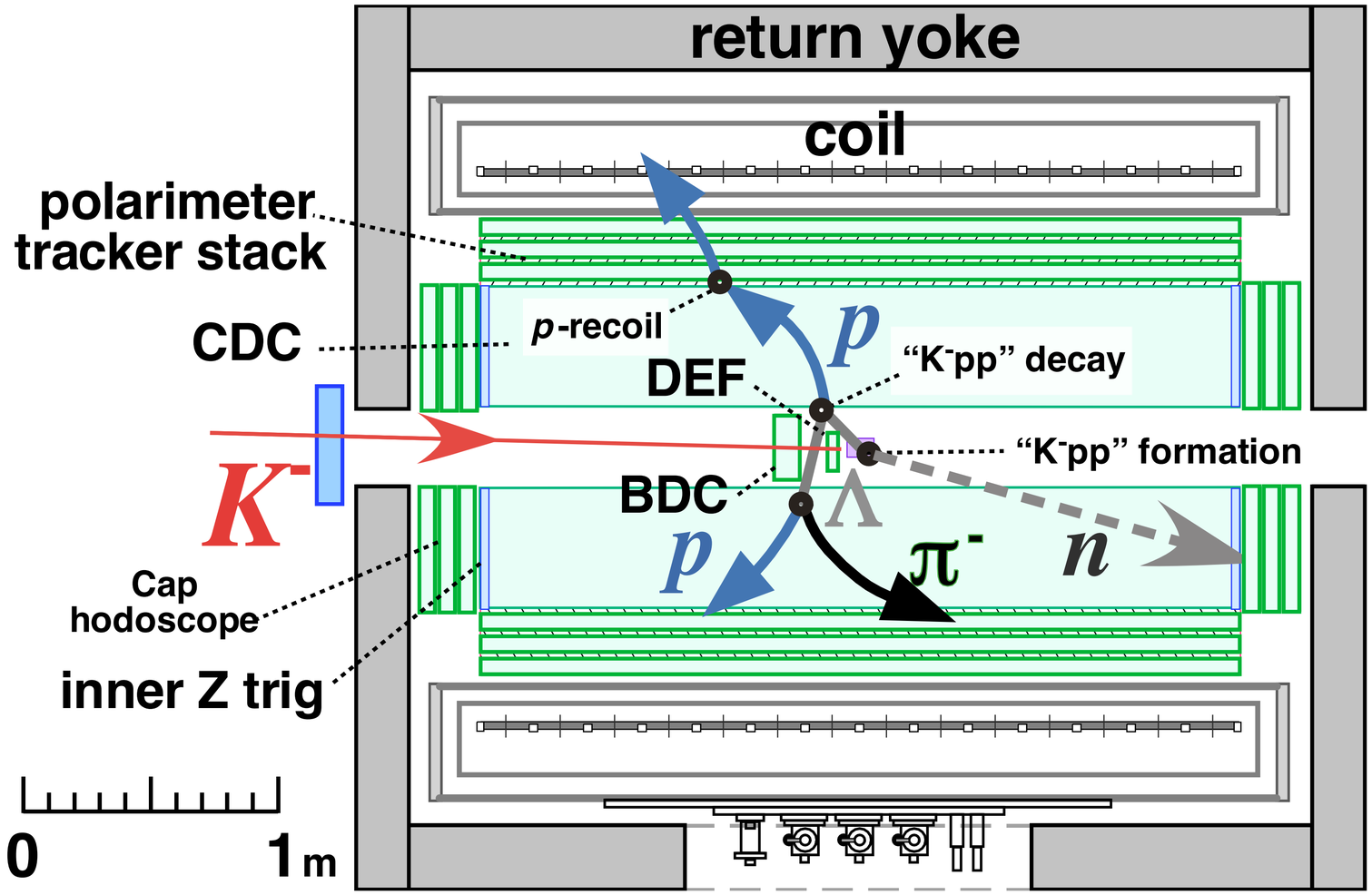
→ New results are coming soon.

Future experiments





Conceptual design of new CDS



>90% solid angle coverage

Neutron detection capability

Sensitivity for proton polarization

Construction has been started (Completed in 2025)

Programs for $\bar{K}$-nuclei

Lighter system

$\Lambda(1405)$

with wider q-region

$d(K^-, n)$ reaction

$\pi^{\pm}\Sigma^{\mp}$ decay

&

$\pi^0\Sigma^0$ decay as well

$\bar{K}NN$ system

J^{π} determination

To confirm the existence more robustly

Measuring $d\sigma/dq$ & $\alpha_{\Lambda p}$

Search for $(\bar{K}NN)^{I_z=-1/2}$

Isospin partner of observed $\bar{K}NN$

$\bar{K}NN \to \Lambda n$ decay

Decay branch

Non-mesonic	Mesonic
Λp, $\Sigma^0 p$, $\Sigma^+ n$	$\pi\Lambda N$, $\pi\Sigma N$

Heavier system

$\bar{K}NNN$ system

Door to heavier system

$^4\mathrm{He}(K^-, N)$ reaction

$K^-ppn - \bar{K}^0pnn$ (I=0)

$\bar{K}NNNN$ system

Expected large B.E. & high density

$^6\mathrm{Li}(K^-, d)$ reaction

K^--α $\bar{K}^0$-α

Determination of J^π for $\bar{K}NN$

Internal configuration & J^π

$(\bar{K}[NN]^{I=0})^{I=1/2}$	$(\bar{K}[NN]^{I=1})^{I=1/2}$	$(\Sigma^* N)^{I=1/2}$
$J^\pi = 1^-$	$J^\pi = 0^-$	$J^\pi = 2^+$
$-\sqrt{\frac{1}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{3}{4}}[\bar{K}N]^{I=1}N$	$\sqrt{\frac{3}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{1}{4}}[\bar{K}N]^{I=1}N$	–

↓

Possible internal configurations have different J^π.

How to determine J^P

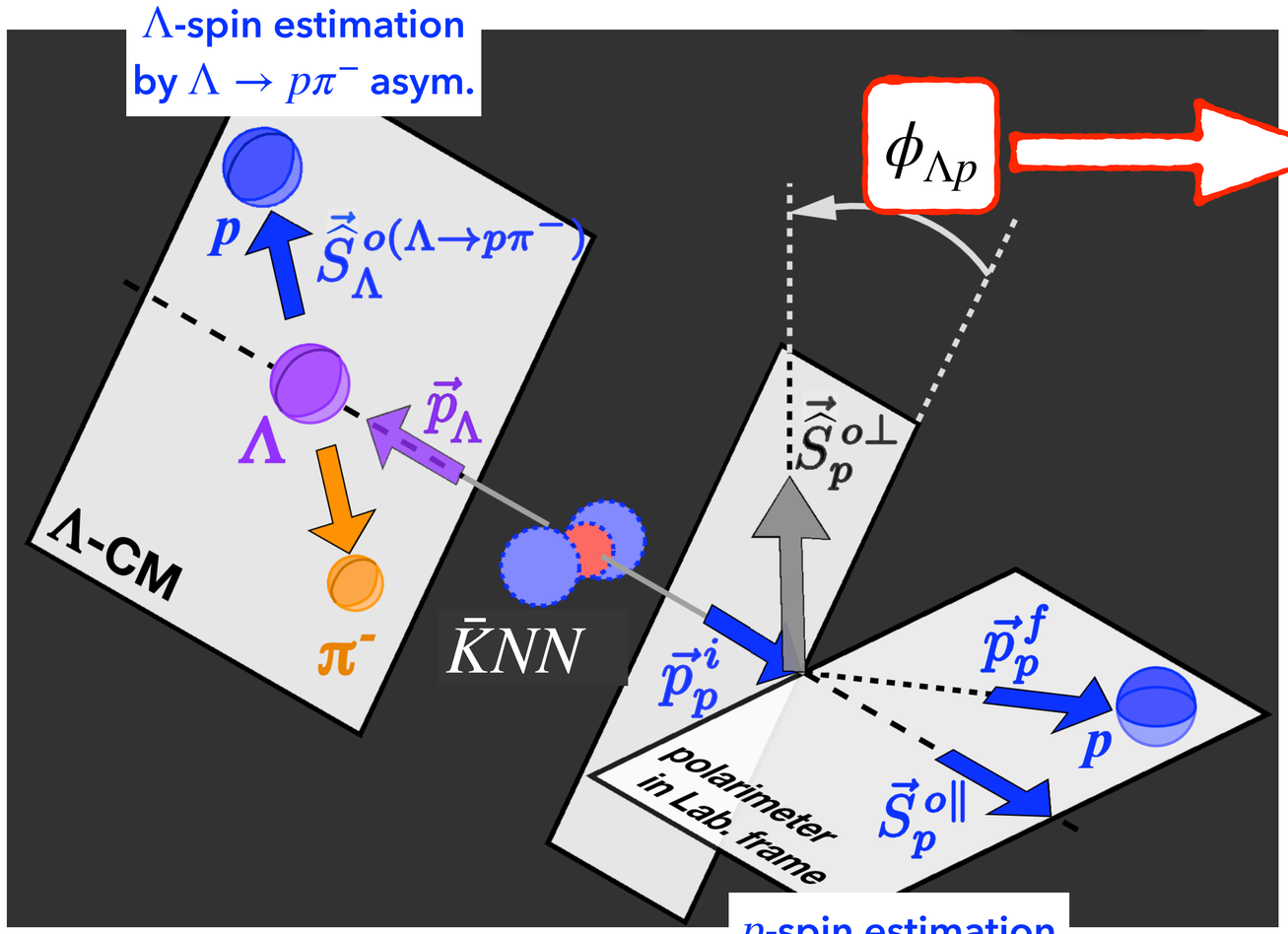
$(\bar{K}[NN]^{I=0})^{I=1/2}$	$(\bar{K}[NN]^{I=1})^{I=1/2}$	$(\Sigma^* N)^{I=1/2}$
$J^\pi = 1^-$	$J^\pi = 0^-$	$J^\pi = 2^+$
$[L_{\Lambda p} = 1]$	$[L_{\Lambda p} = 1]$	$[L_{\Lambda p} = 2]$
$\otimes$	$\otimes$	$\otimes$
$\frac{2}{3}[S_{\Lambda p} = 1] + \frac{1}{3}[S_{\Lambda p} = 0]$	$[S_{\Lambda p} = 1]$	$\frac{1}{2}[S_{\Lambda p} = 1] + \frac{1}{2}[S_{\Lambda p} = 0]$
$\Downarrow$	Spin alignment $\alpha_{\Lambda p}$ $\Downarrow$	$\Downarrow$
$\alpha_{\Lambda p} = +1/3$	$\alpha_{\Lambda p} = +1$	$\alpha_{\Lambda p} = \pm 0$

$\downarrow$

Three different internal configurations can be distinguished by $\alpha_{\Lambda p}$.

Measurement of $\alpha_{\Lambda p}$

– Spin alignment measurement by $\Lambda \to p\pi^-$ & p-C scattering –



Spin-spin correlation on ϕ-asymmetry

$$N(\phi_{\Lambda p}) = N_0 \cdot (1 + r^{(J^P)} \cdot \alpha_{\Lambda p} \cos\phi_{\Lambda p})$$

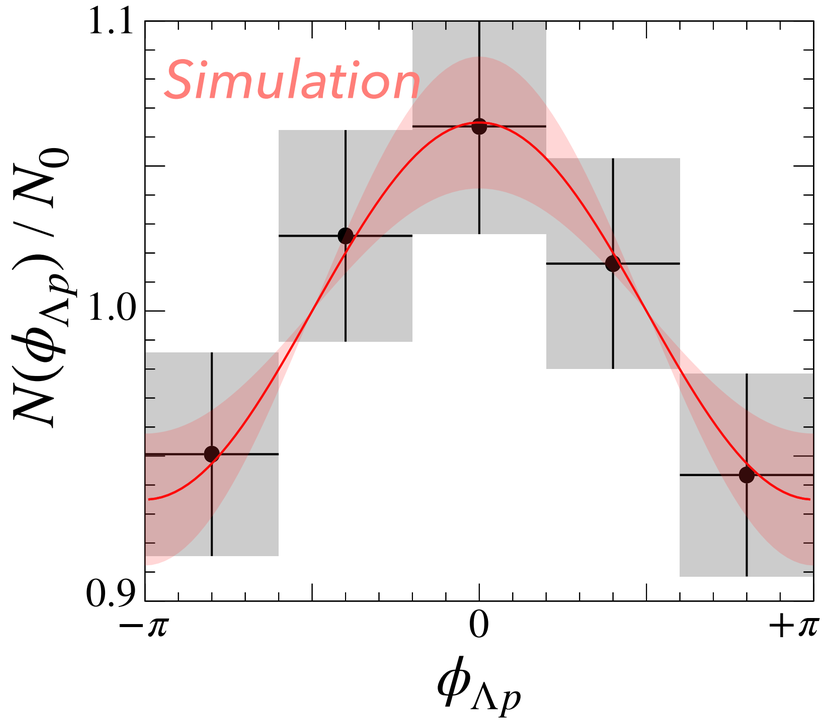
$r^{(J^P)}$: asymmetry reduction factor defined by;

α_- : Λ asym. parameter	B : Magnetic field
A_{pC} : Analyzing power	$B_{\bar{K}}$: Binding energy
$f_{\vec{S}_\Lambda}$: Spin distribution	q : Momentum transfer

Expected $\phi_{\Lambda p}$ distributions

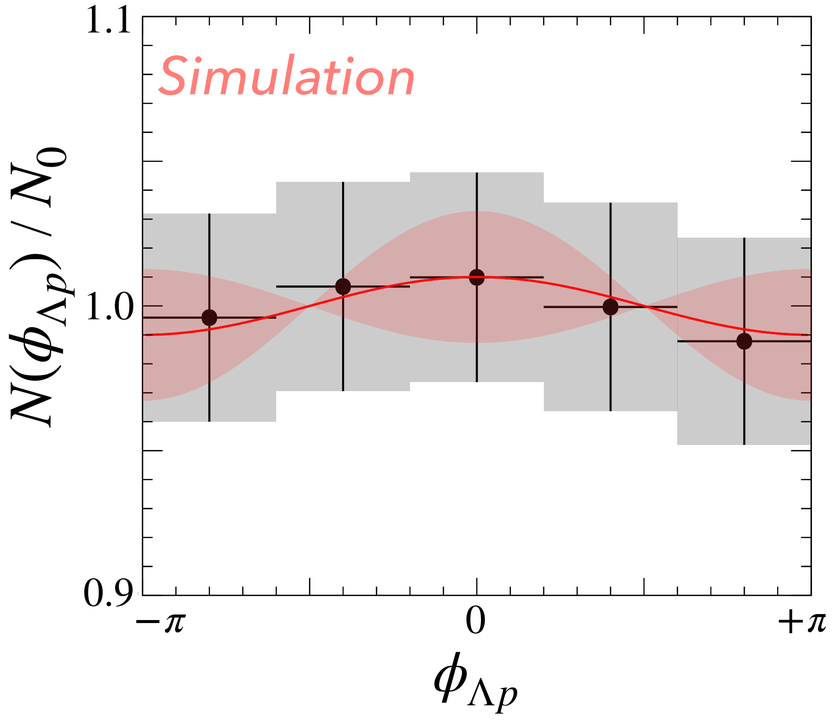
$(\bar{K}[NN]^{I=1})^{I=1/2} : J^{\pi} = 0^{-}$

→ $\alpha_{\Lambda p} = +1$



$(\bar{K}[NN]^{I=0})^{I=1/2} : J^{\pi} = 1^{-}$

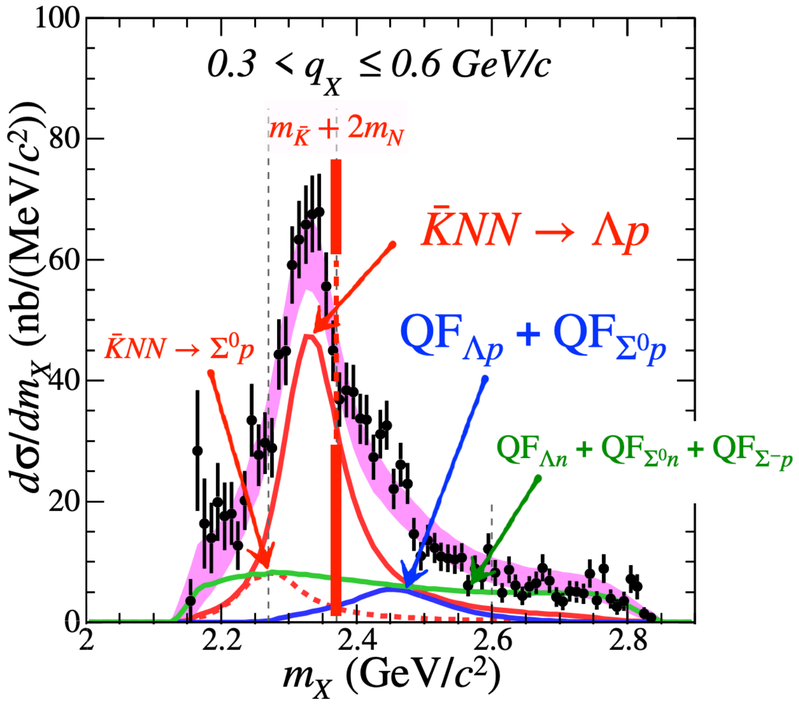
→ $\alpha_{\Lambda p} = +1/3$



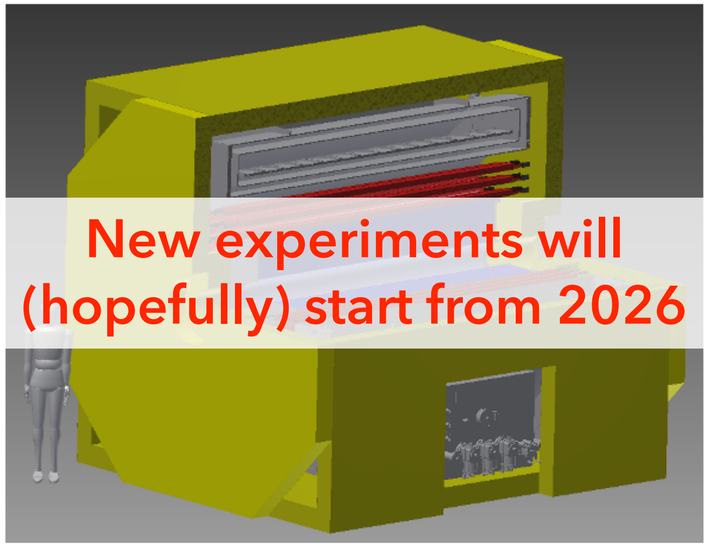
→ $\phi_{\Lambda p}$ measurement has a sensitivity to distinguish J^{π}.

Summary

We observed the first clear signal of $\bar{K}NN$ in J-PARC E15



We would like to robustly confirm the existence of $\bar{K}$-nuclei
&
clarify their internal structure



Are you interested in? Join us!

Thank you for your attention!

= Collaboration =

Experimentalists

RIKEN: H. Asano, K. Itahashi, M. Iwasaki, Y. Ma, R. Murayama, H. Outa, F. Sakuma, T. Yamaga

JAEA: T. Hashimoto, K. Tanida

TOHOKU: H. Ohnishi, Y. Sada, C. Yoshida

OSAKA UNIVERSITY: T. Akaishi

KYOTO UNIVERSITY: T. Nagae

RCNP: K. Inoue, S. Kawasaki, H. Noumi, K. Shirotori

INFN Istituto Nazionale di Fisica Nucleare: M. Bazzi, A. Clozza, C. Curceanu, C. Guaraldo, M. Iliescu, M. Miliucci, A. Scordo, D. Sirghi, F. Sirghi

Tokyo Tech: H. Fujioka

KEK: M. Iio, S. Ishimoto, K. Ozawa, S. Suzuki

SMI: J. Marton, H. Shi, M. Tuechler, E. Widmann, J. Zmeskal

Theorists

Tokyo Tech: D. Jido

KPU: T. Sekihara