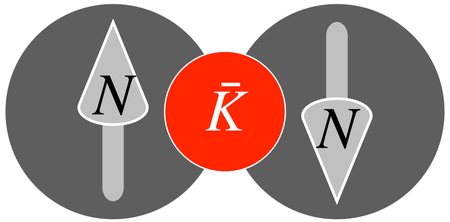
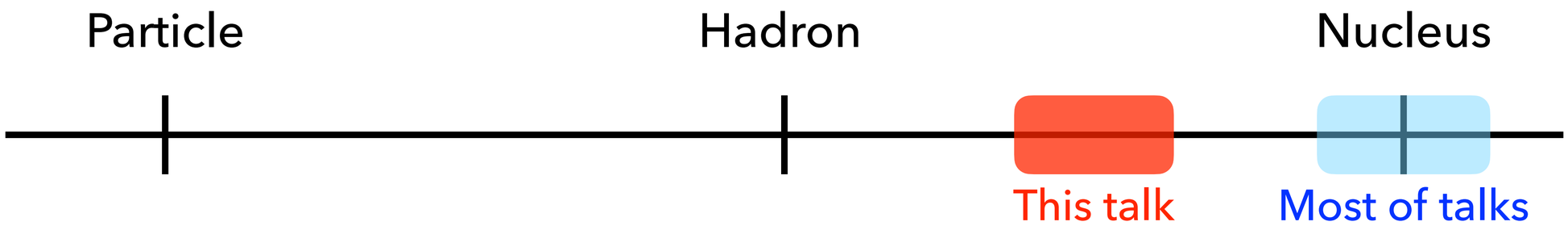
Study of of the $\bar{K}NN$ cluster at J-PARC



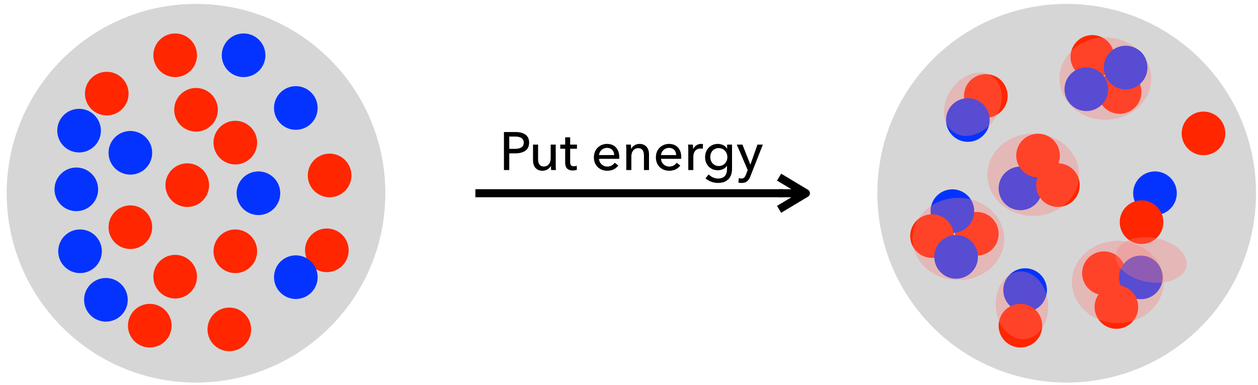
Takumi Yamaga (RIKEN)
for the J-PARC E15/E80/P89 collaboration

WNCP2023 @ Osaka Univ. (2023.11.27–29)

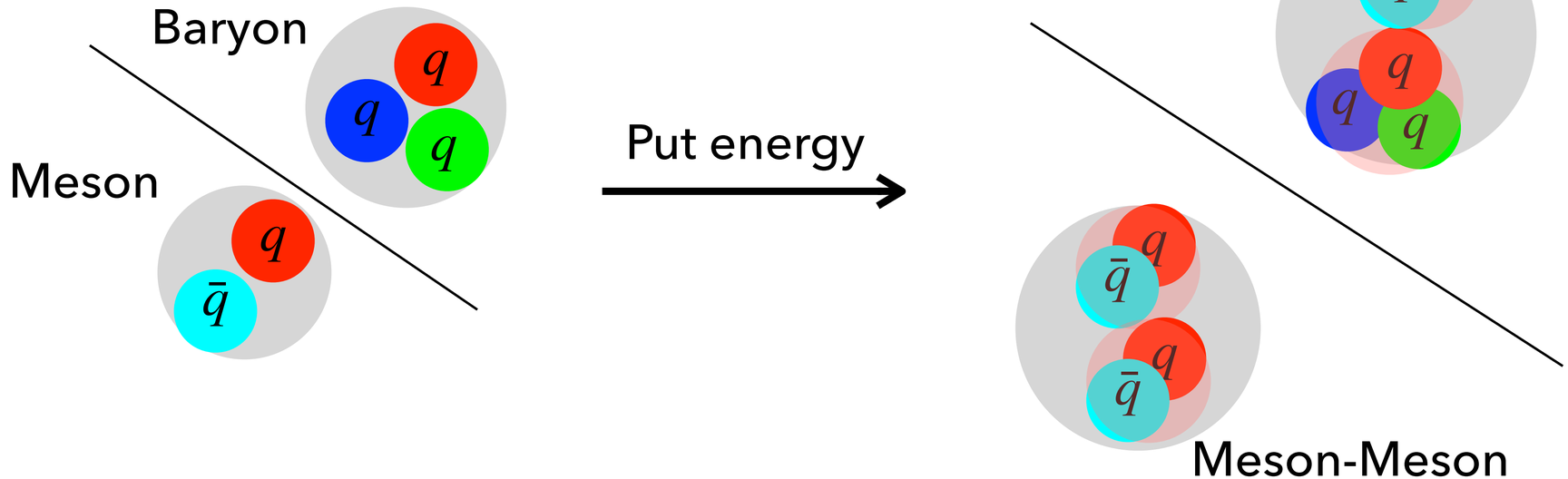

Particle
Hadron
Nucleus
This talk
Most of talks

Clustering in Nuclei / Hadrons

Nuclei



Hadrons

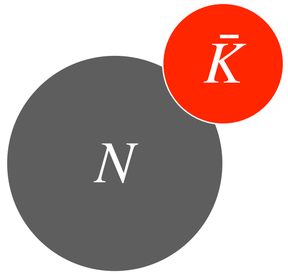


$\Lambda(1405)$

$$I(J^P) = 0\left(\frac{1}{2}^-\right)$$

R. Dalitz and S. Tuan, Ann. Phys. (N.Y.) 10, 307 (1960).

R. Dalitz, T. Wong, and G. Rajasekaran, Phys. Rev. 153,1617 (1967).

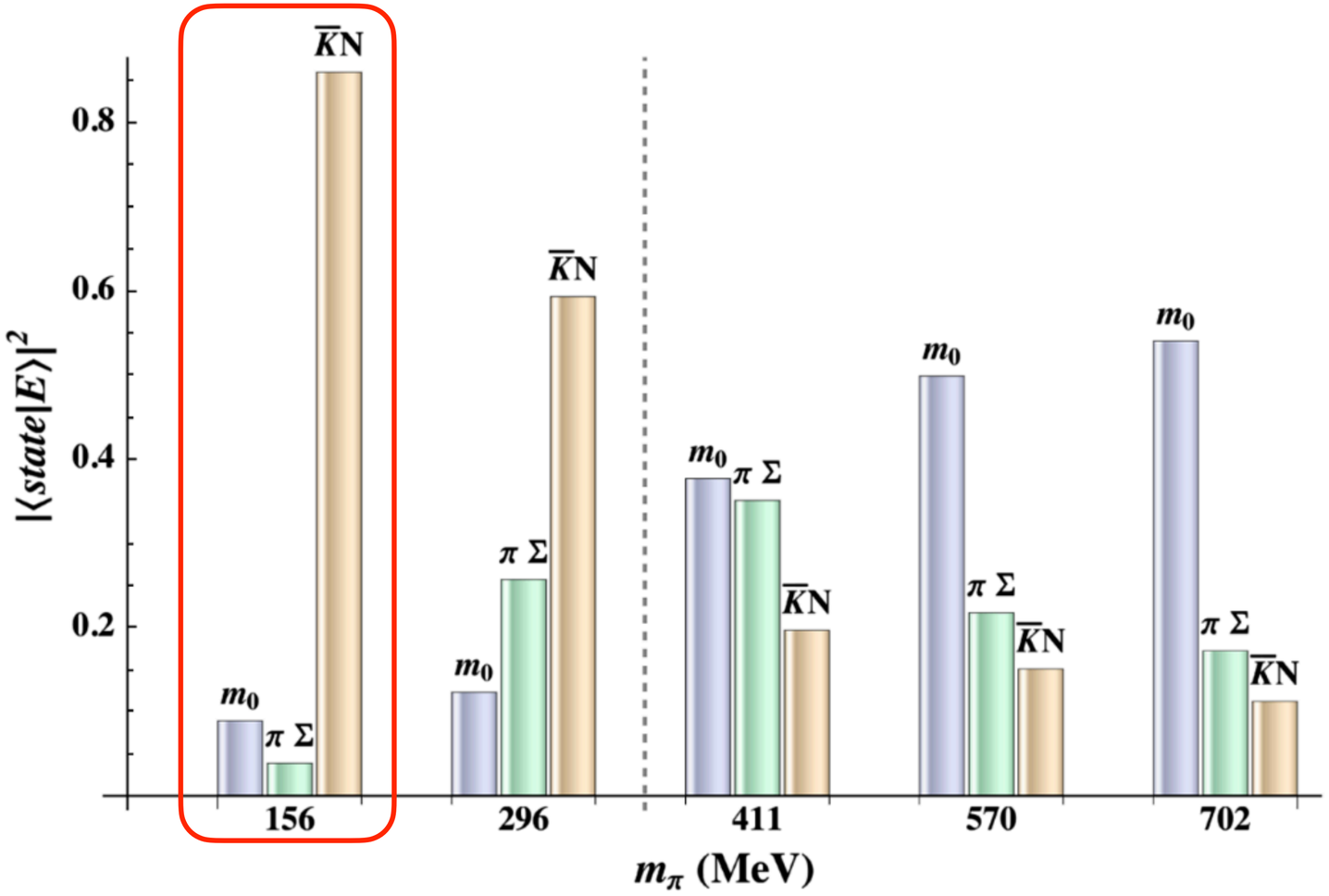


Considered to be $\bar{K}N$ cluster

$(m_{\bar{K}} + m_N \sim 1.43\ \mathrm{GeV}/c^2)$

Λ(1405)

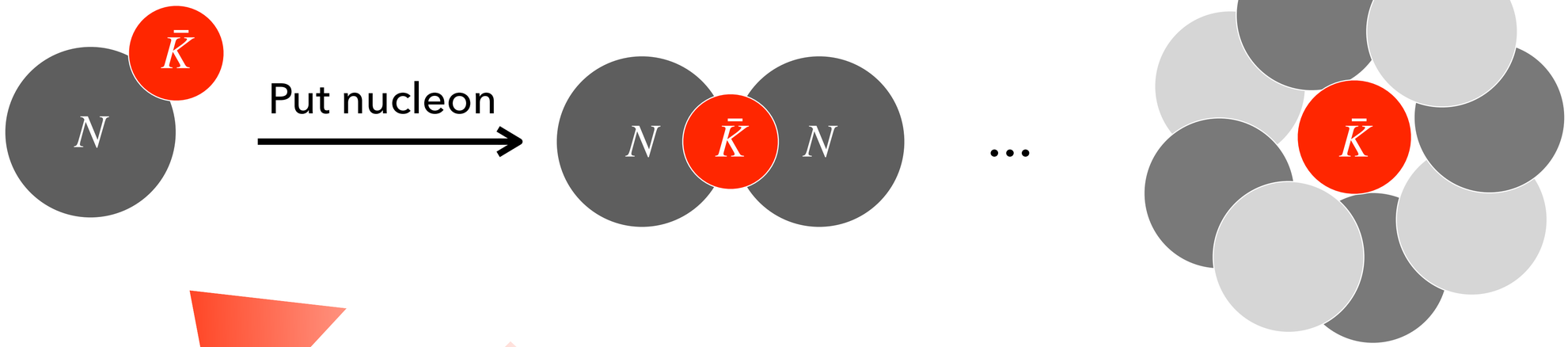
J. M. M. Hall et al., Phys. Rev. Lett. **114** (2015) 132002



How to **experimentally** determine
the internal structure of exotic hadrons?

$\Lambda(1405)$

Antikaonic nuclei



Feedback to $\Lambda(1405)$

- Meson as a constituent
- Large binding energy
- Compact & Dense

$\bar{K}N$ interaction

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

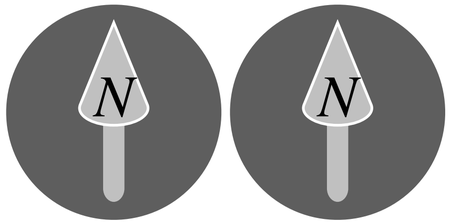
Possible to make quasi-bound state with $I_{\bar{K}N} = 0$

$\Lambda(1405)$

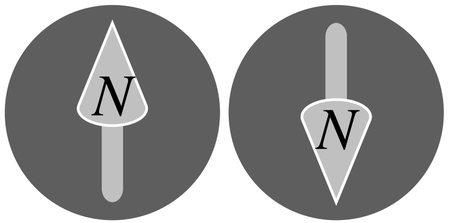
$\bar{K}$-nuclei

$\bar{K}NN$

The lightest $\bar{K}$-nucleus



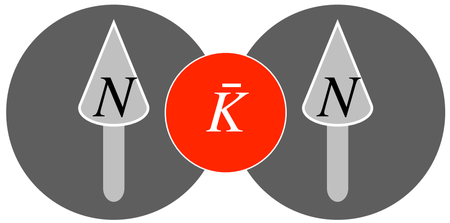
Deuteron



Unbound

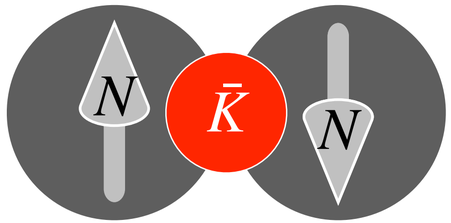
$\bar{K}NN$

The lightest $\bar{K}$-nucleus



$J^\pi = 1^-$

$$-\sqrt{\frac{1}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{3}{4}}[\bar{K}N]^{I=1}N$$



$J^\pi = 0^-$

$$\sqrt{\frac{3}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{1}{4}}[\bar{K}N]^{I=1}N$$

Ground state

$\bar{K}NN$

The lightest $\bar{K}$-nucleus

Volume 7, number 4 PHYSICS LETTERS 1 December 1963

POSSIBLE EXISTENCE OF $\bar{K}$NN BOUND STATES

Y. NOGAMI
National Research Council, Ottawa, Canada †

Received 2 November 1963

$\bar{K}NN$

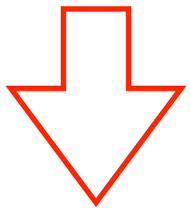
The lightest $\bar{K}$-nucleus

No theoretical study doubts the existence of $\bar{K}NN$,

but predicted BE & Γ highly depend on model.

BE = 9 – 95 MeV Γ = 16 – 110 MeV

L. Tolos & L. Fabbietti, Prog.Part.Nucl.Phys. 112 (2020) 103770



We conducted an experimental search for $\bar{K}NN$ @ J-PARC (E15 experiment)

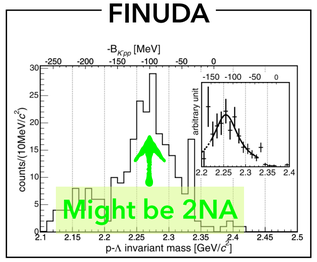
Exp. studies for $\bar{K}NN$ so far

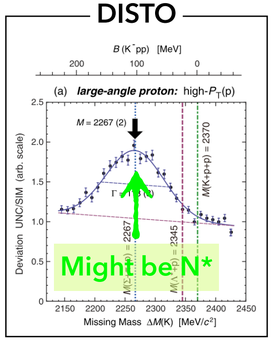
First calculation for K^-pp
PLB 535 (2002) 70

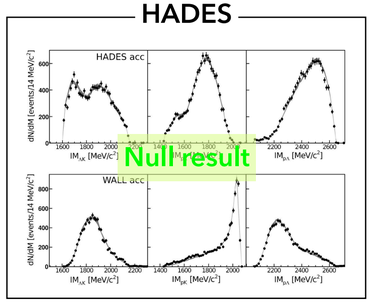
2000 — 2010 — 2020

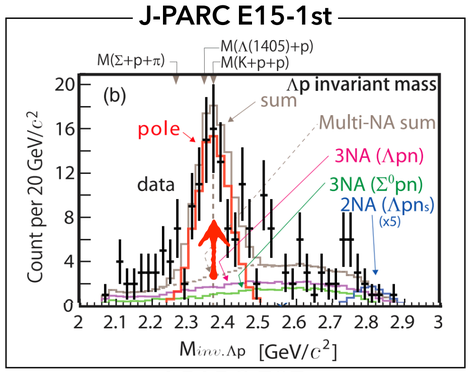
Many theoretical calculations

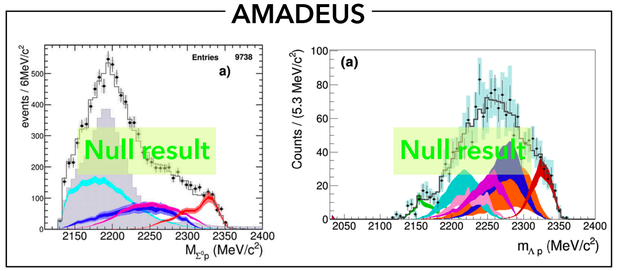
FINUDA DISTO LEPS J-PARC E15-1st J-PARC E27 AMADEUS HADES

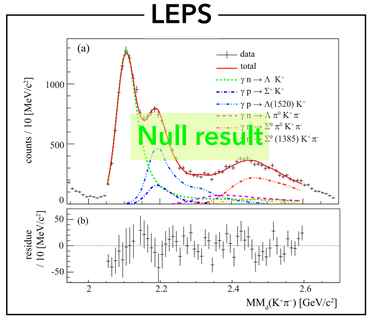


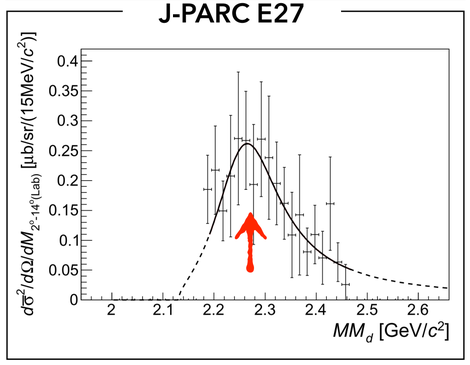








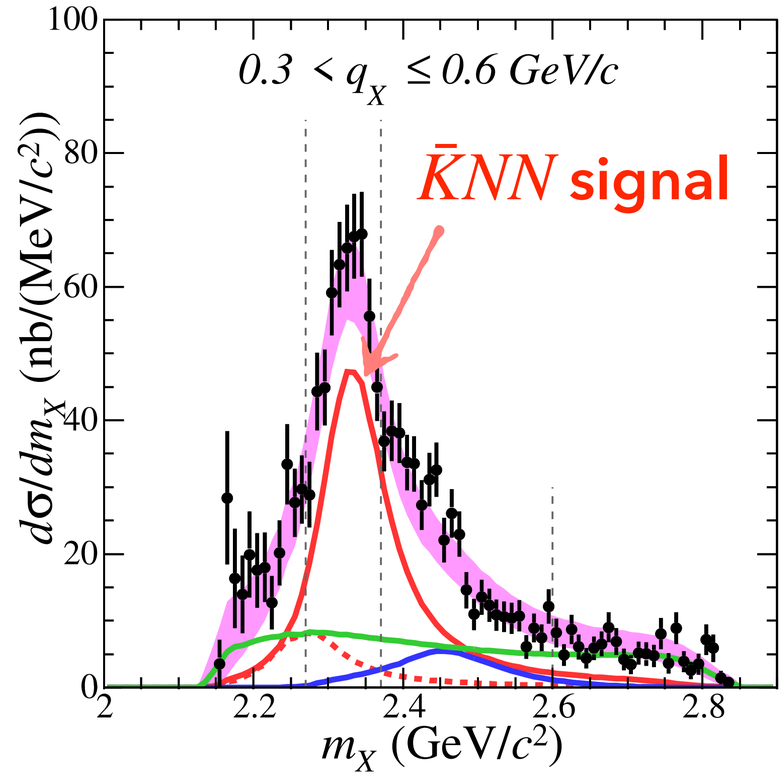




PHYSICAL REVIEW C **102**, 044002 (2020)

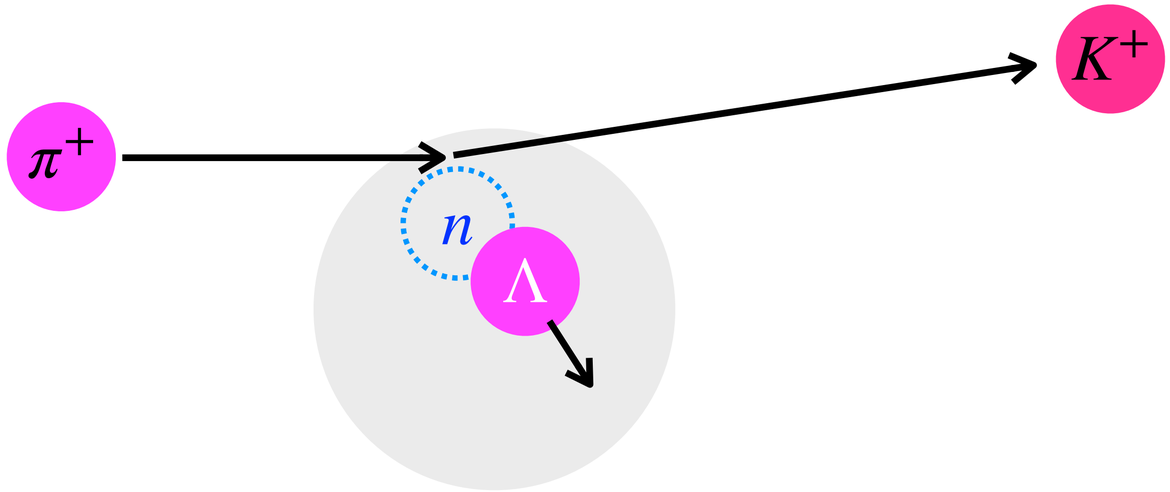
Observation of a $\bar{K}NN$ bound state in the ^{3}He(K^-, Λp)n reaction

T. Yamaga,[1,*] S. Ajimura,[2] H. Asano,[1] G. Beer,[3] H. Bhang,[4] M. Bragadireanu,[5] P. Buehler,[6] L. Busso,[7,8] M. Cargnelli,[6] S. Choi,[4] C. Curceanu,[9] S. Enomoto,[14] H. Fujioka,[15] Y. Fujiwara,[12] T. Fukuda,[13] C. Guaraldo,[9] T. Hashimoto,[20] R. S. Hayano,[12] T. Hiraiwa,[2] M. Iio,[14] M. Iliescu,[9] K. Inoue,[2] Y. Ishiguro,[11] T. Ishikawa,[12] S. Ishimoto,[14] K. Itahashi,[1] M. Iwai,[14] M. Iwasaki,[1,†] K. Kanno,[12] K. Kato,[11] Y. Kato,[1] S. Kawasaki,[10] P. Kienle,[16,‡] H. Kou,[15] Y. Ma,[1] J. Marton,[6] Y. Matsuda,[17] Y. Mizoi,[13] O. Morra,[7] T. Nagae,[11] H. Noumi,[2,14] H. Ohnishi,[22] S. Okada,[23] H. Outa,[1] K. Piscicchia,[24,9] Y. Sada,[22] A. Sakaguchi,[10] F. Sakuma,[1] M. Sato,[14] A. Scordo,[9] M. Sekimoto,[14] H. Shi,[6] K. Shirotori,[2] D. Sirghi,[9,5] F. Sirghi,[9,5] S. Suzuki,[14] T. Suzuki,[12] K. Tanida,[20] H. Tatsuno,[21] M. Tokuda,[15] D. Tomono,[2] A. Toyoda,[14] K. Tsukada,[18] O. Vazquez Doce,[9,16] E. Widmann,[6] T. Yamazaki,[12,1] H. Yim,[19] Q. Zhang,[1] and J. Zmeskal[6]
(J-PARC E15 Collaboration)



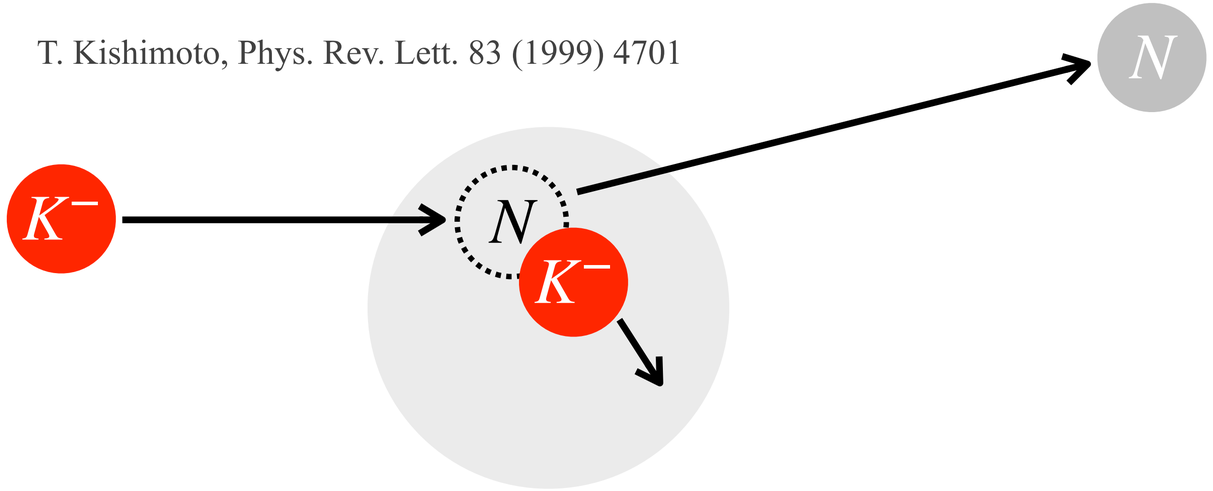
Production of $\bar{K}$-nuclei

Λ hypernuclei



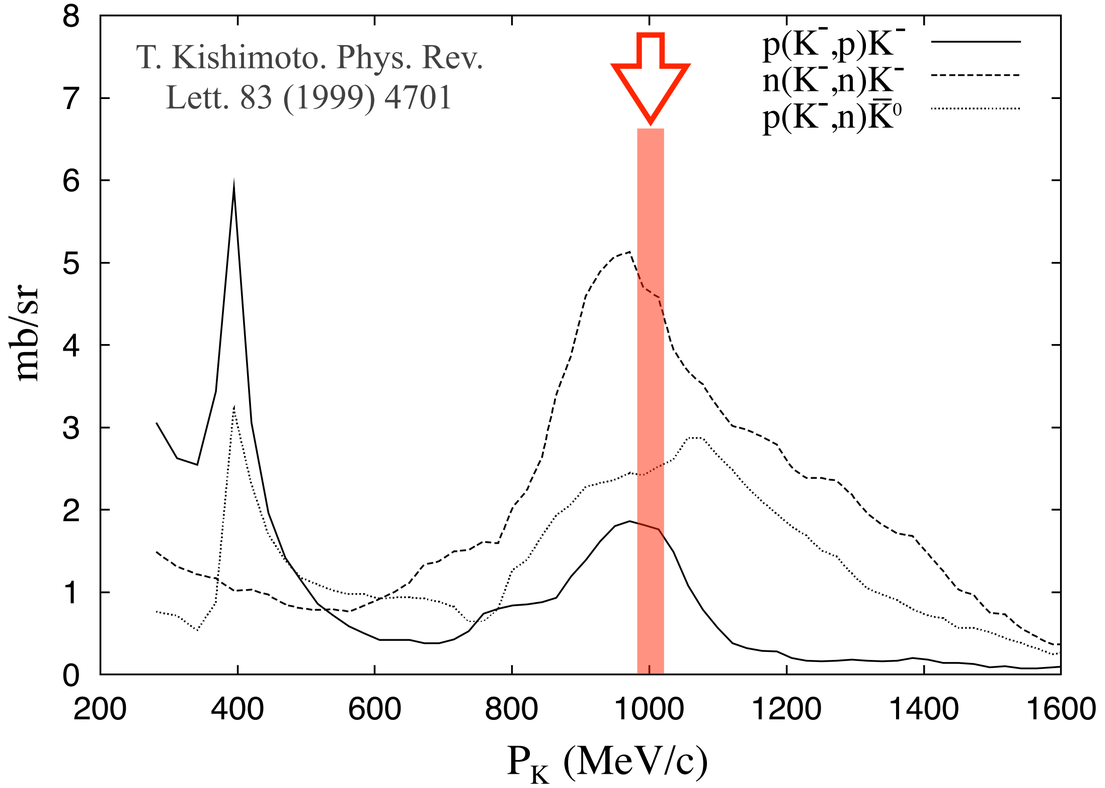
$\bar{K}$ nuclei

T. Kishimoto, Phys. Rev. Lett. 83 (1999) 4701



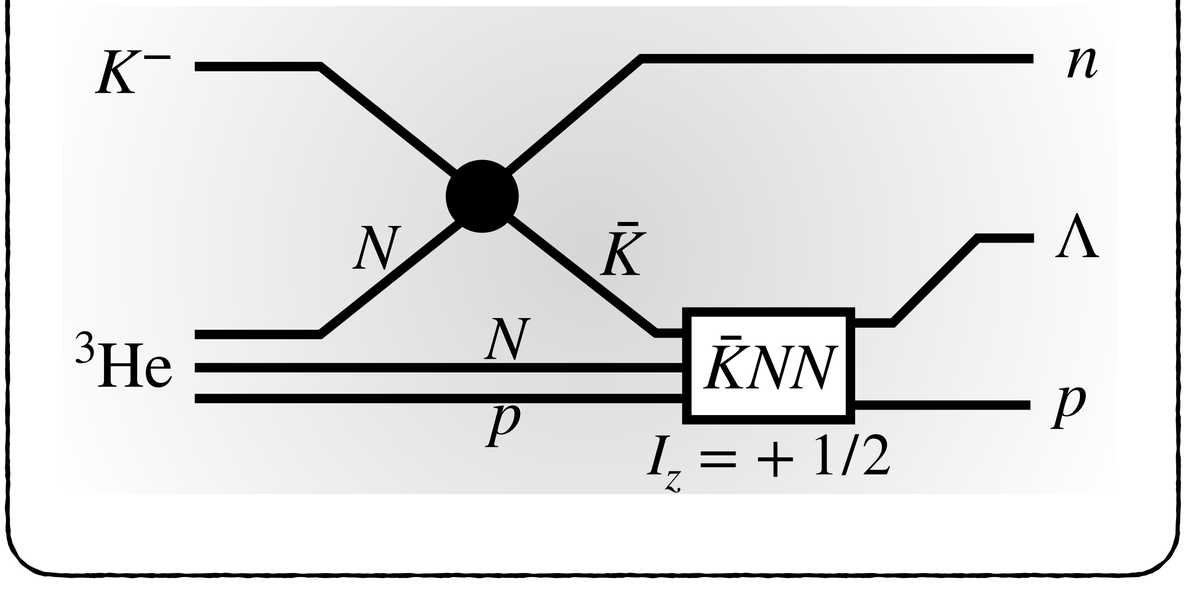
Production of $\bar{K}$-nuclei

(K^-, N) elementary cross sections @ $\theta_N = 0°$

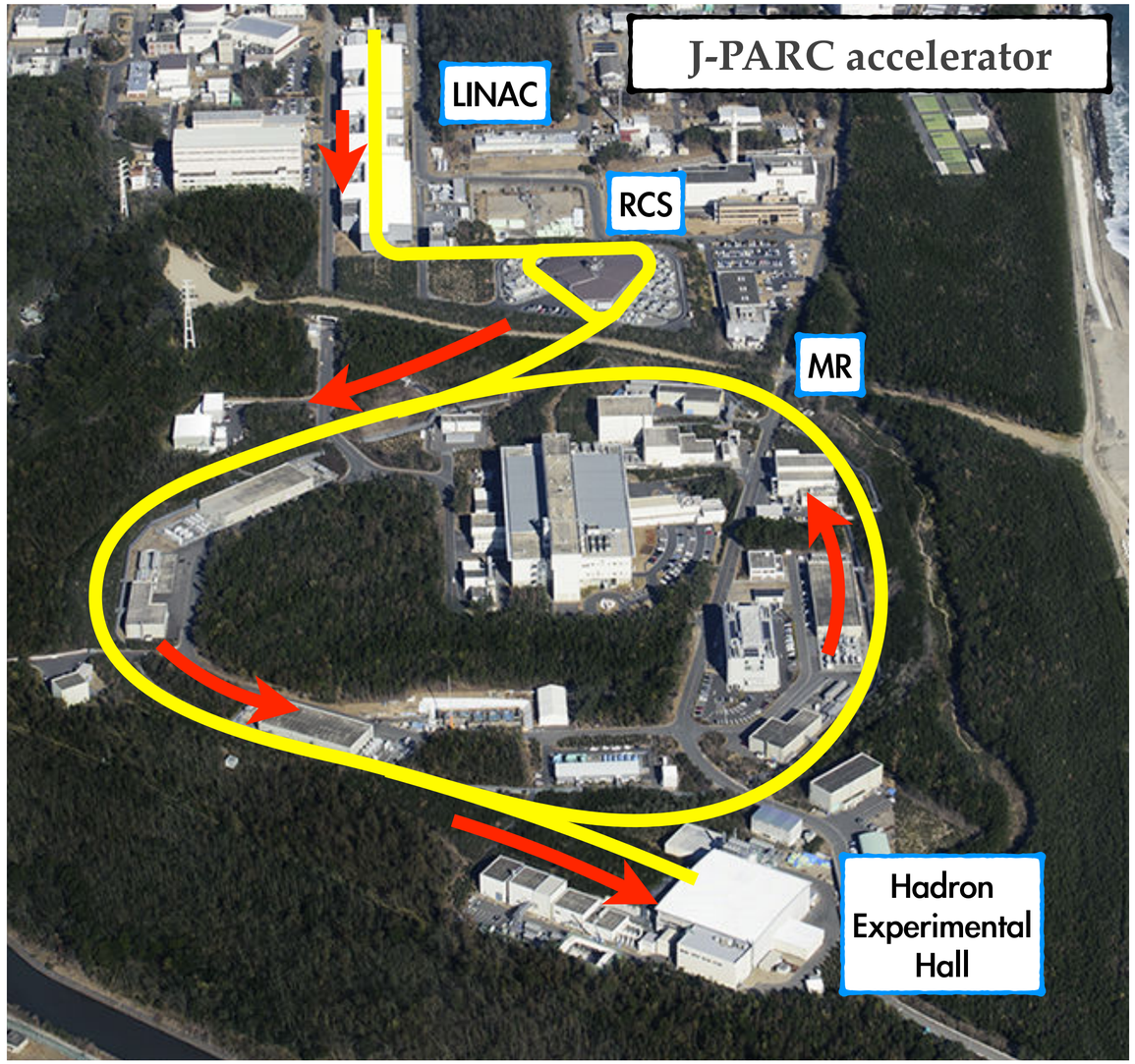


J-PARC E15

Production reaction

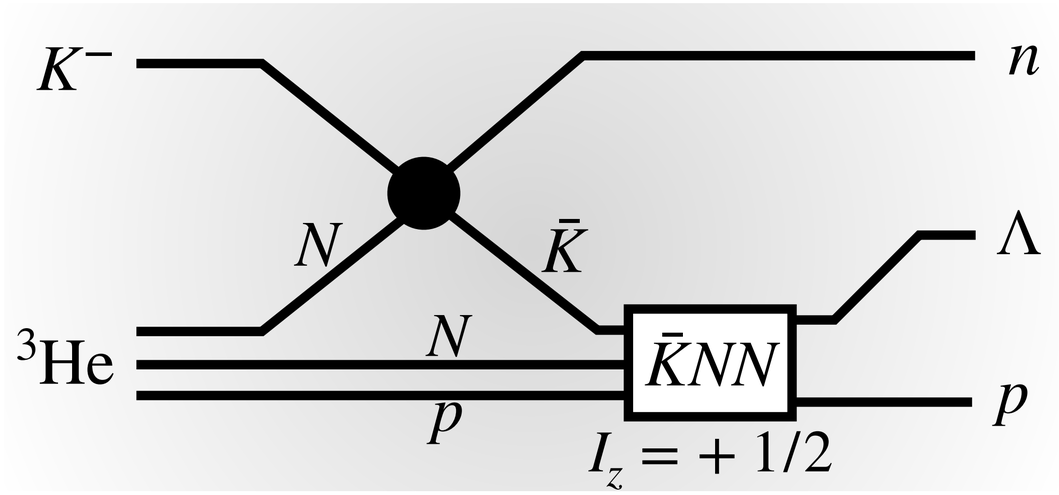


J-PARC E15

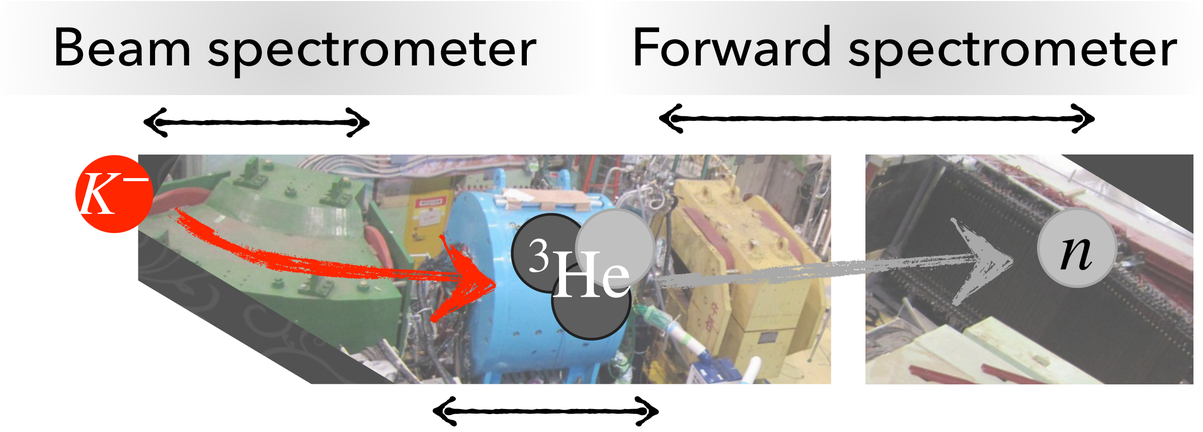


J-PARC E15

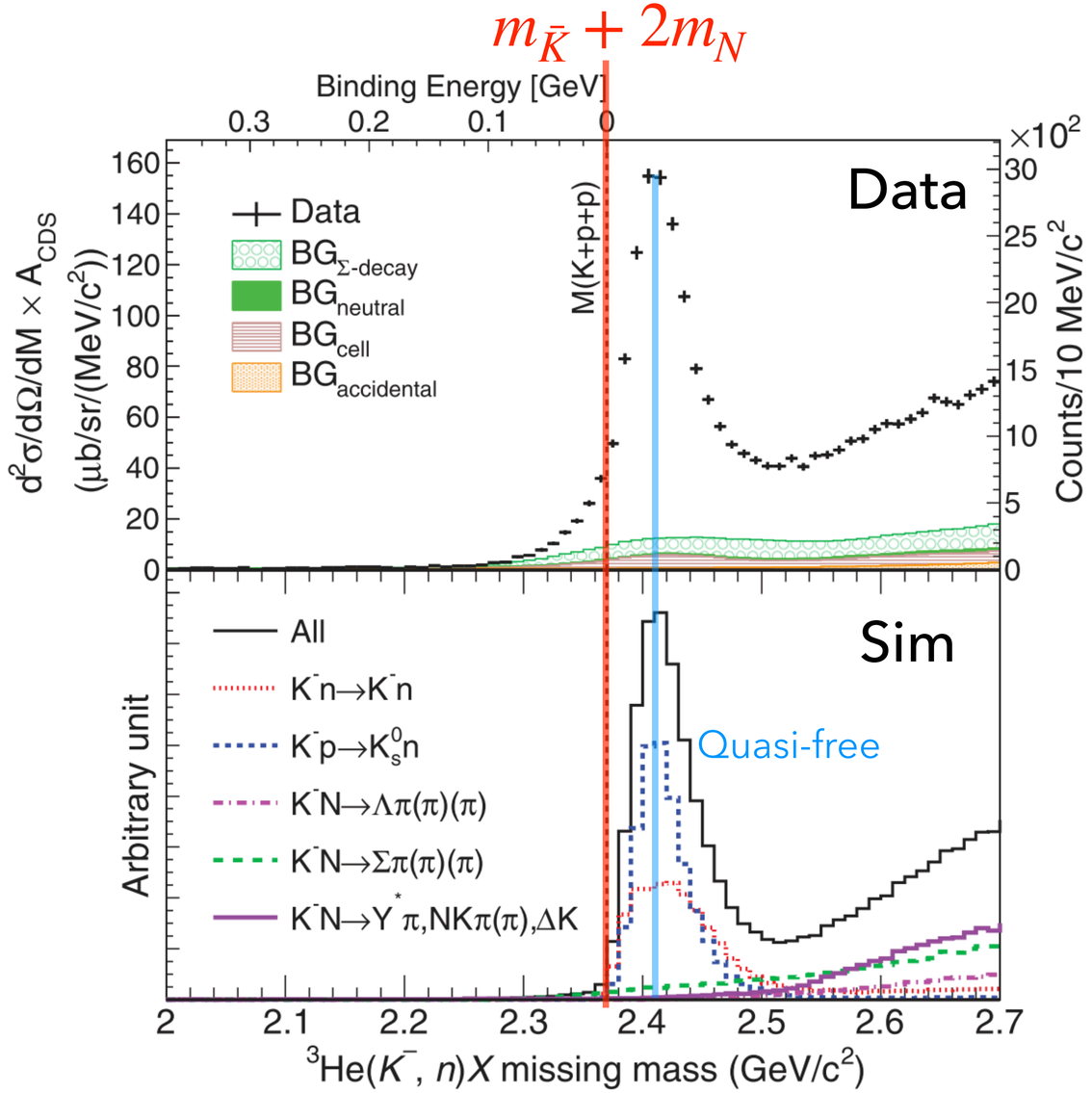
Production reaction



Detector system

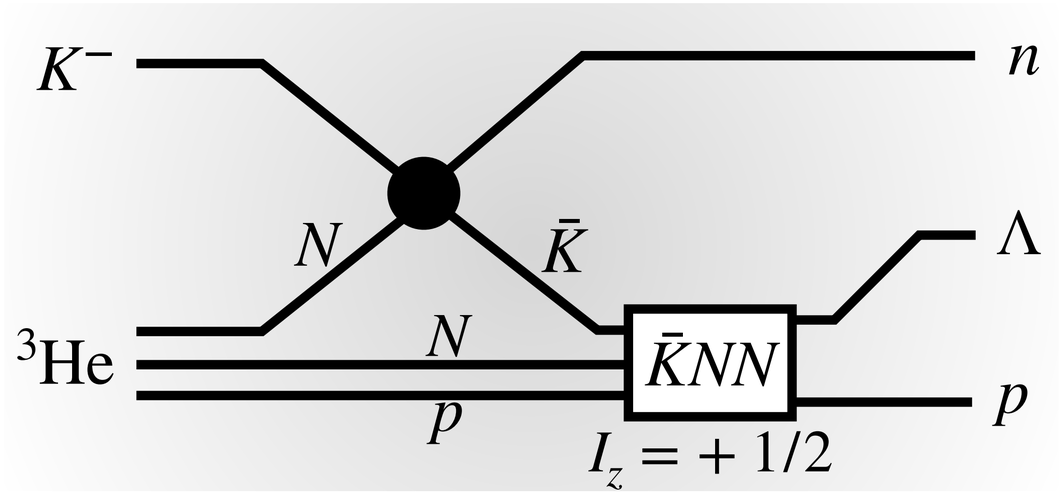


Inclusive measurement

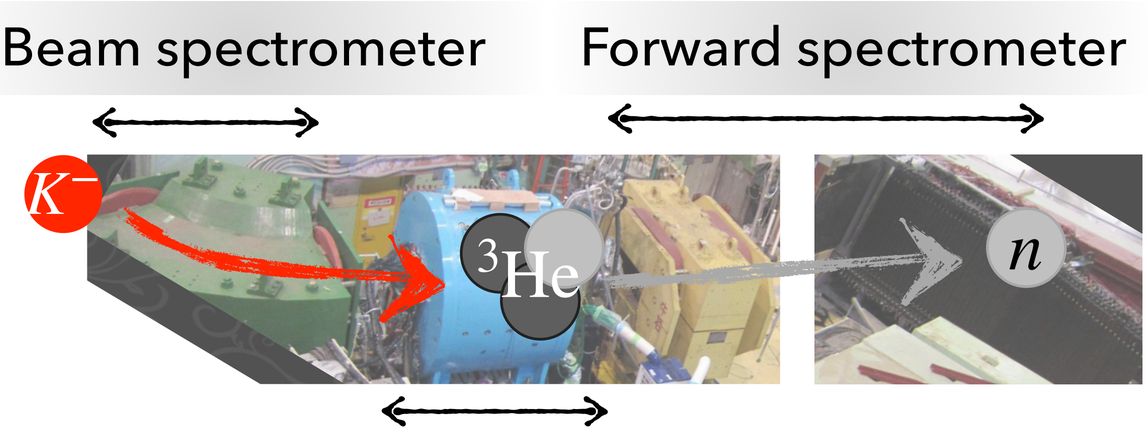


J-PARC E15

Production reaction



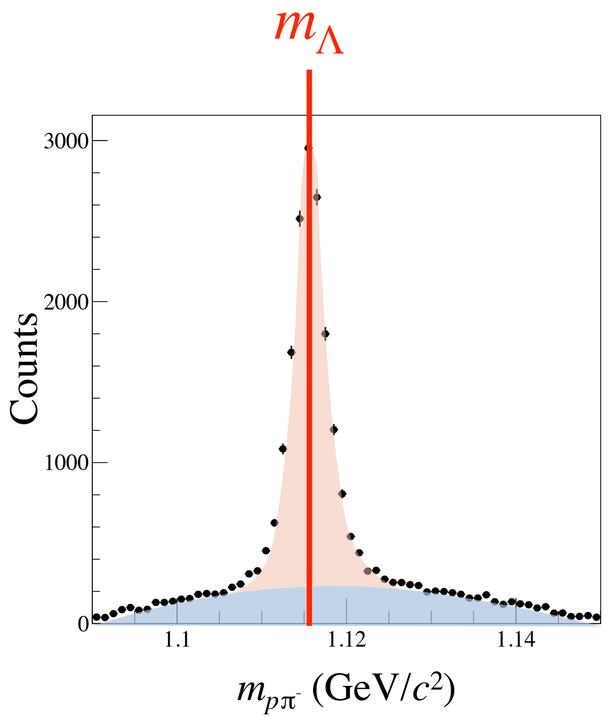
Detector system

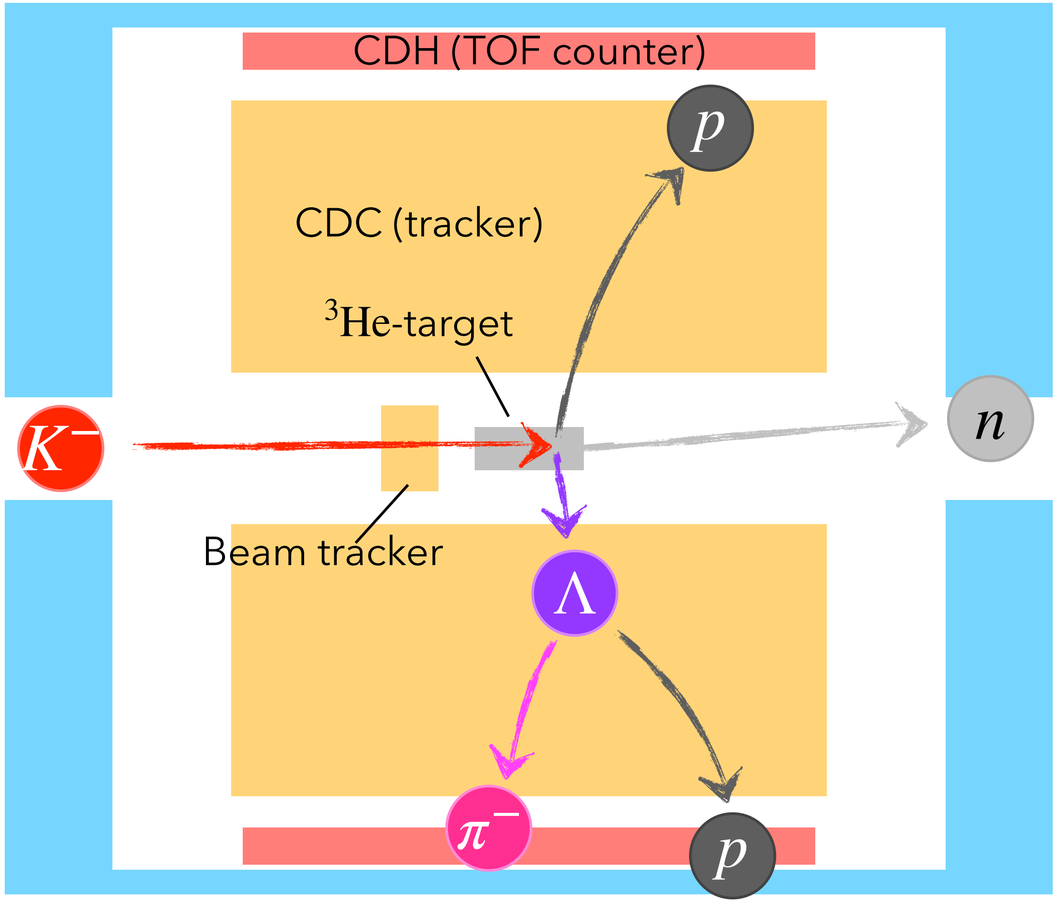


Cylindrical detector system

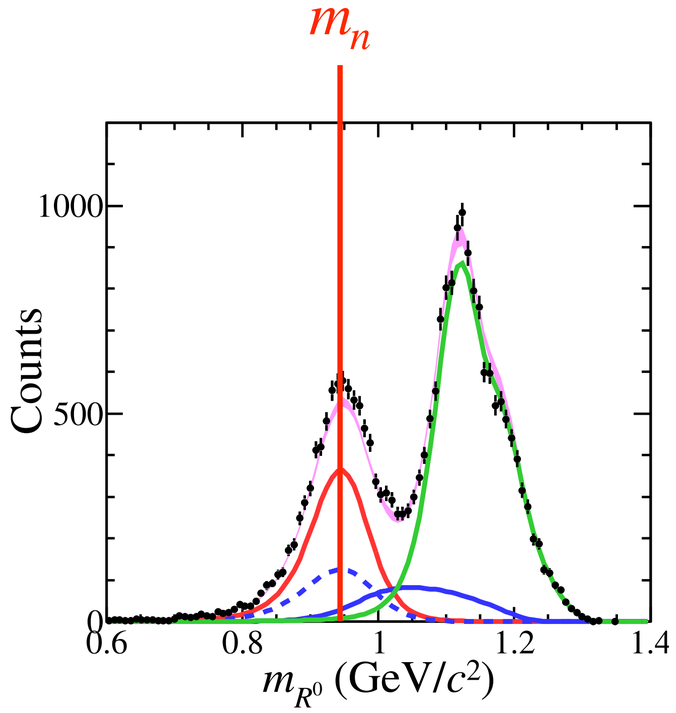
Exclusive measurement

Reconstruction of Λ



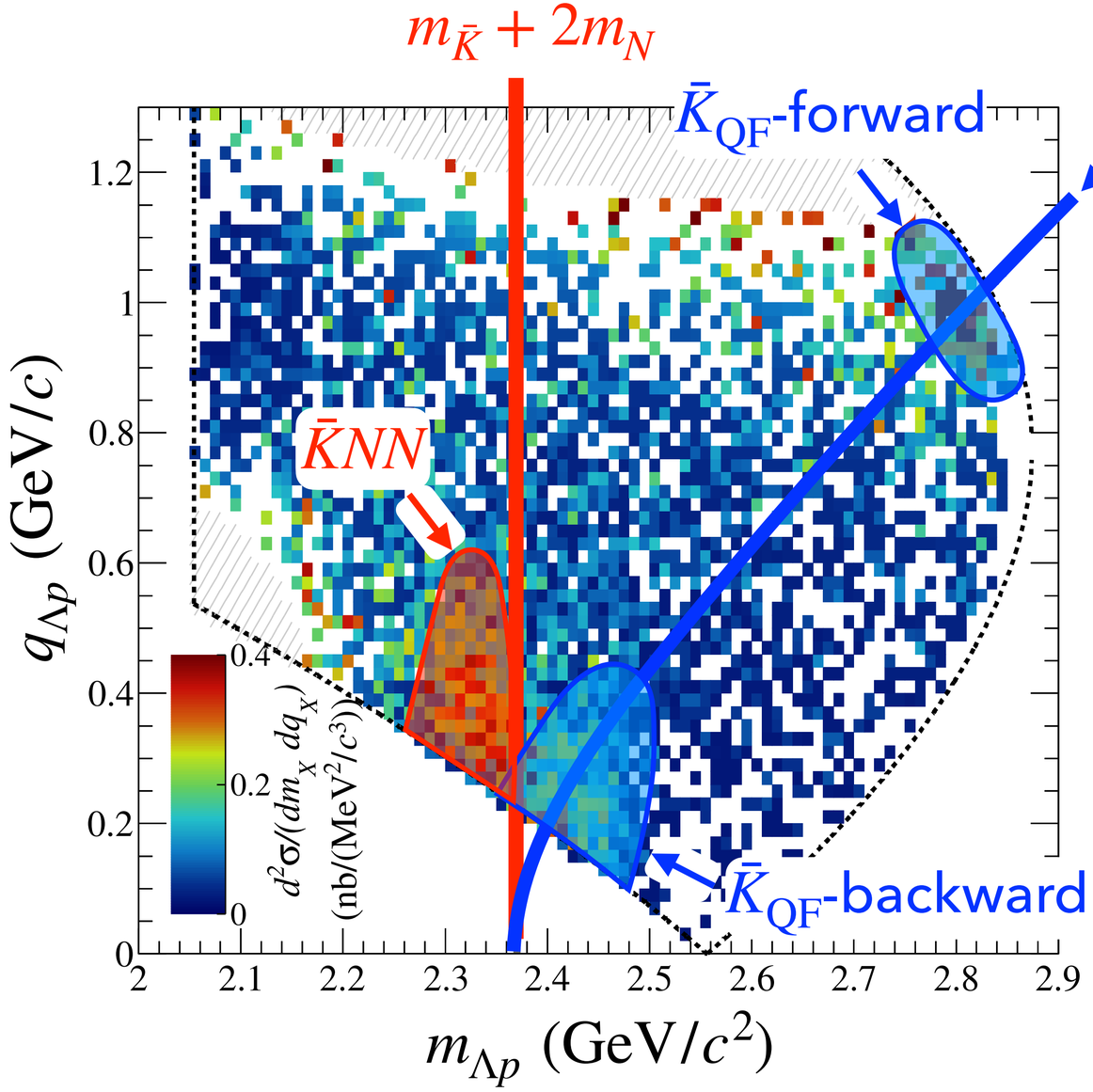


Identification of n_{miss}

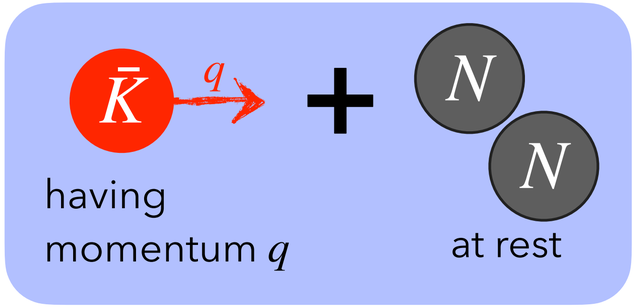


Purity of the Λpn final state $\sim 80\,\%$

Exclusive measurement



Mass of



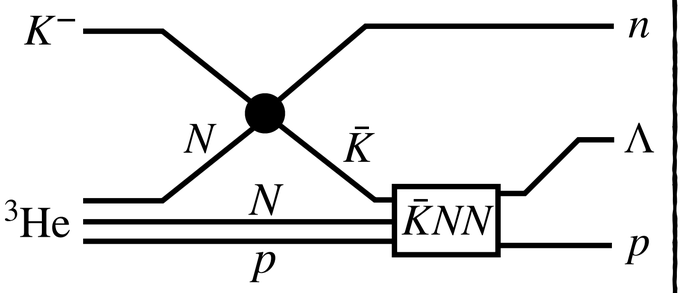
$$= \sqrt{4m_N^2 + m_{\bar{K}}^2 + 4m_N\sqrt{m_{\bar{K}}^2 + q^2}}$$

Quasi-free $\bar{K}$ absorption

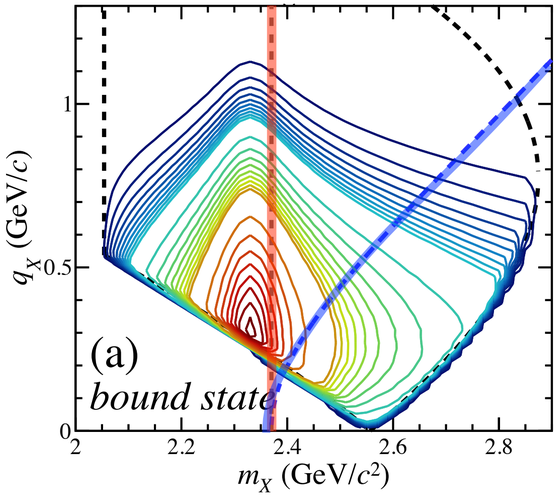
Exclusive measurement

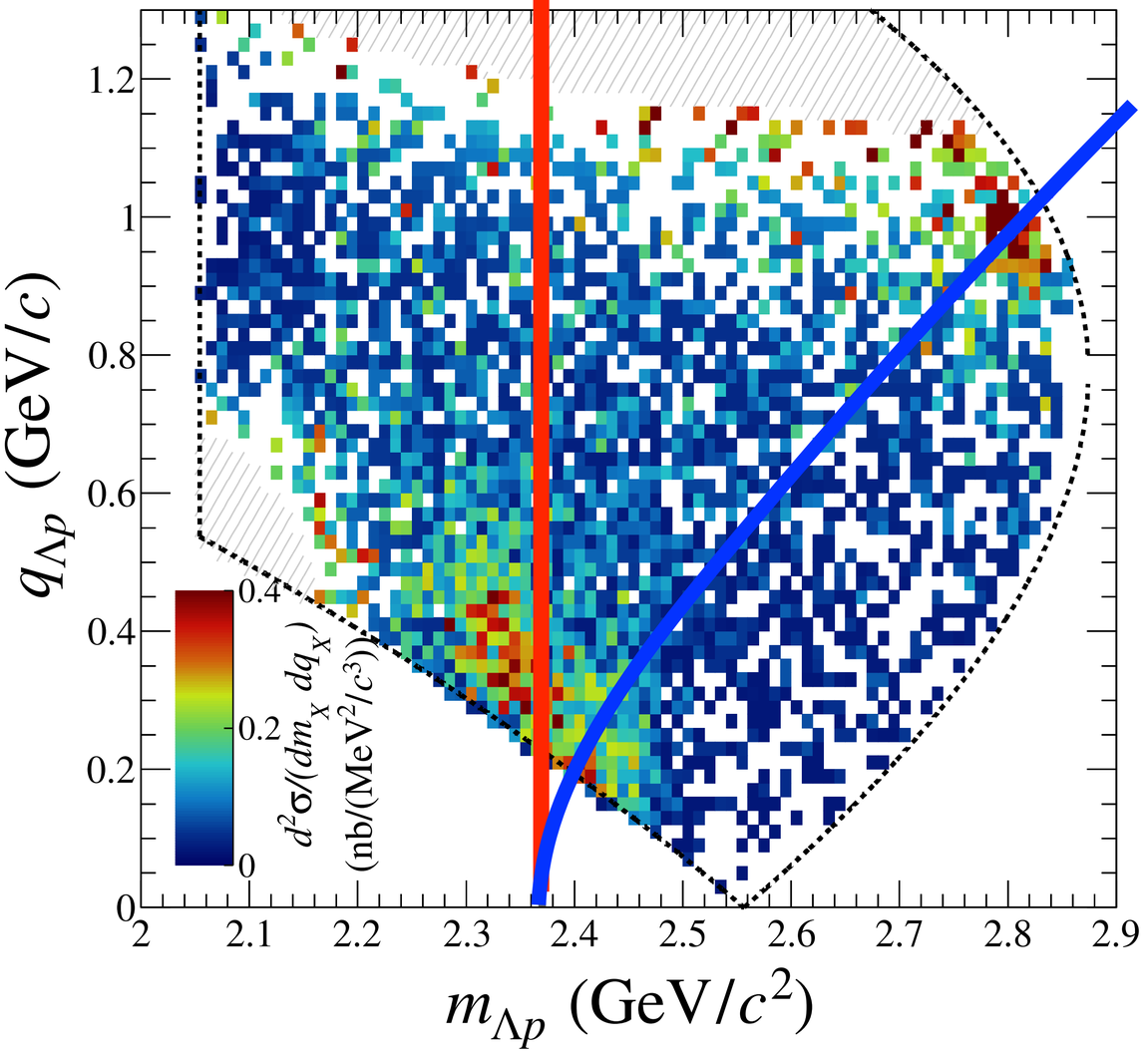
$m_{\bar{K}} + 2m_N$

$\bar{K}NN$ production

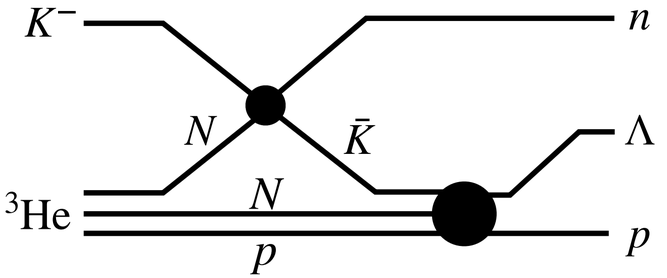


$$f_{\bar{K}NN}(m_X, q_X) = \frac{\Gamma^2/4}{(m_X - M_X)^2 + \Gamma^2/4} \times g_{K^-pp}(q_X)$$

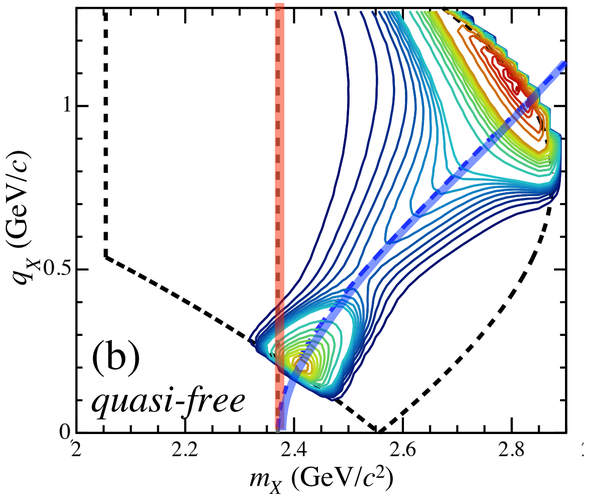




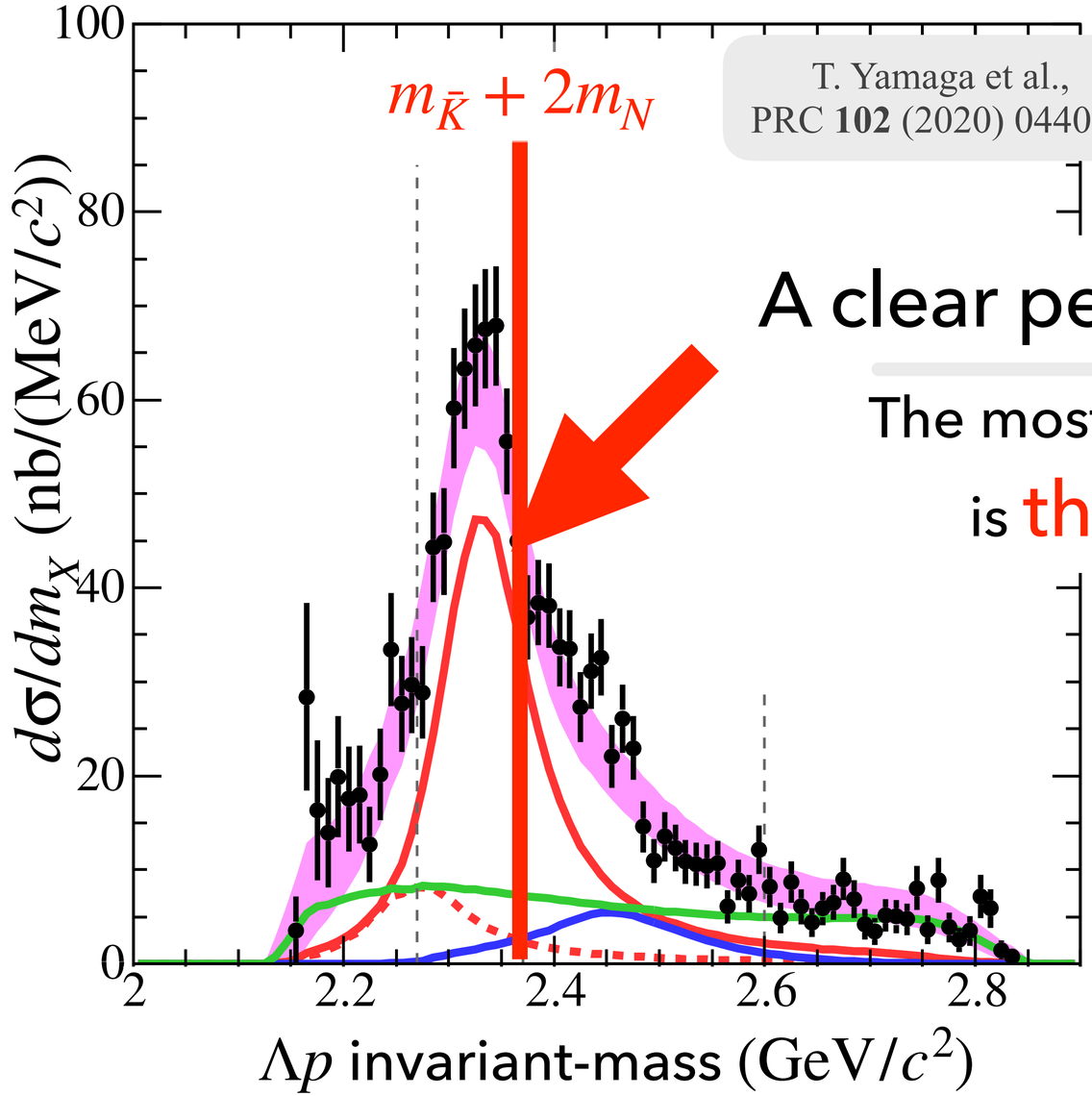
Quasi-free process with (K^-, n)



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



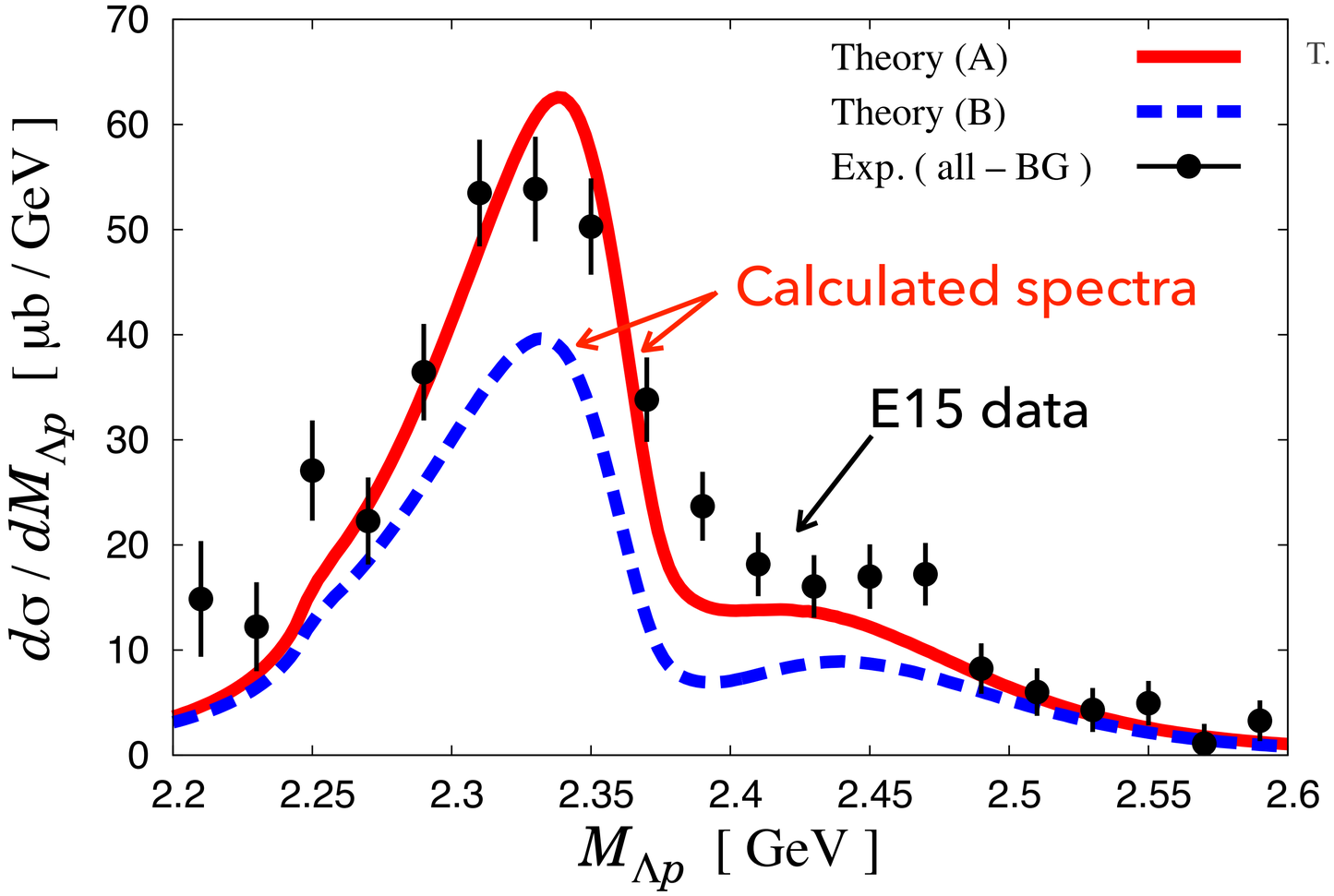
Exclusive measurement



A clear peak below $m_{\bar{K}} + 2m_N$

The most natural interpretation is the $\bar{K}NN$ signal.

Theoretical calculation



T. Sekihara, E. Oset, and A. Ramos,
JPSCP **26** (2019) 023009

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

Mass and Width of $\bar{K}NN$

	BE	Γ
J-PARC E15 PRC **102** (2020) 044002	42 ± 3 (stat.) $^{+3}_{-4}$ (syst.) MeV	100 ± 7 (stat.) $^{+19}_{-9}$ (syst.) MeV

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

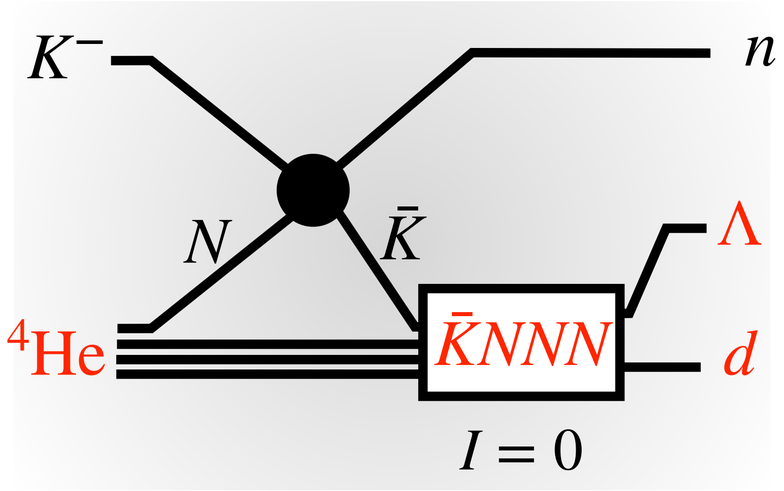
Consistent **Exp > Theor**

S. Ohnishi et al., Phys. Rev. C **95** (2017) 065202	26 – 28 MeV	31 – 59 MeV
N. Shevchenko, Few-Body Syst. **61** (2020) 27	29 – 30 MeV	46 – 47 MeV
A. Dote et al., Phys. Lett. B **784** (2018) 405	14 – 59 MeV	16 – 38 MeV

* Mesonic decay width only

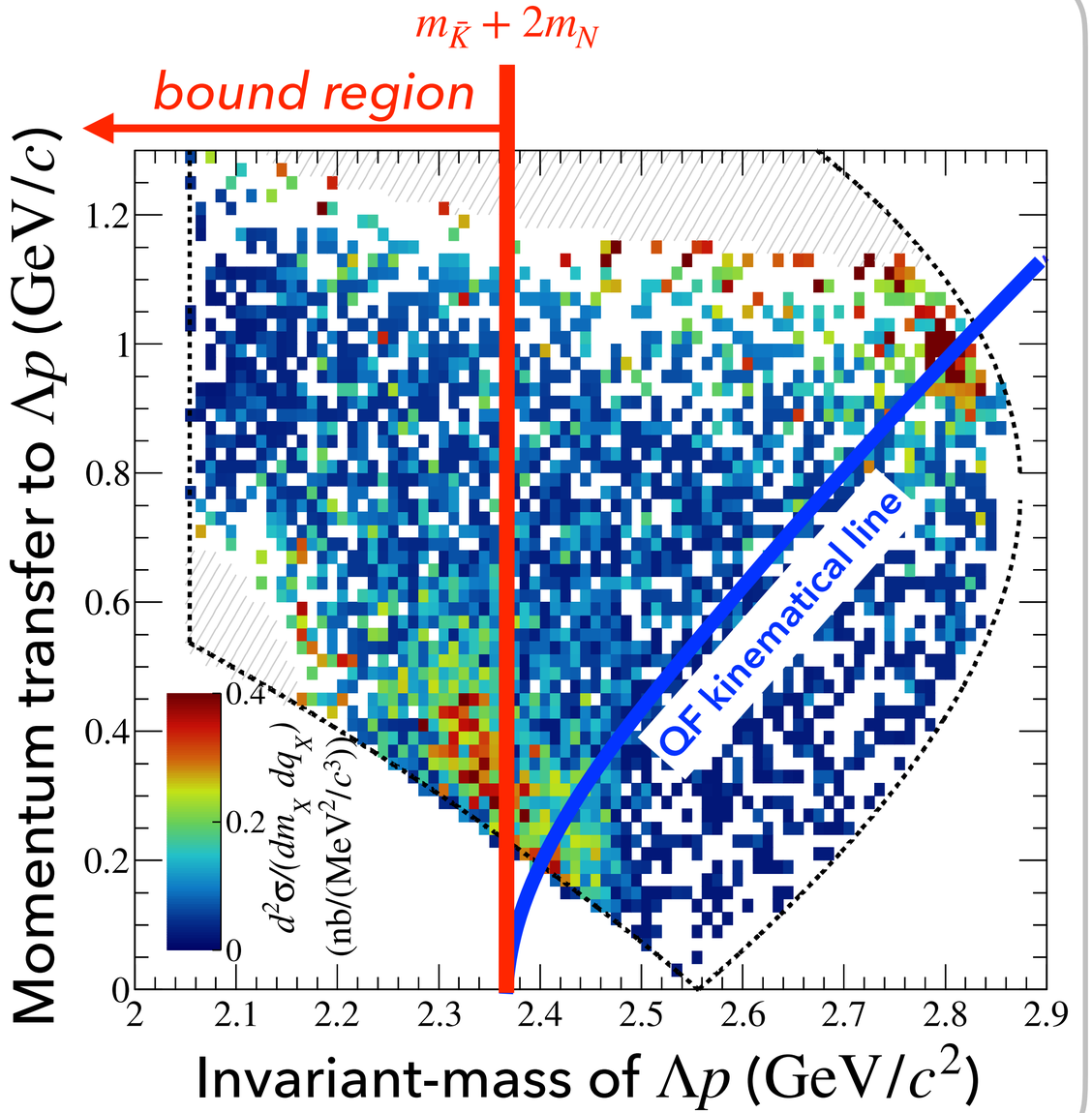
Ongoing analysis for $\bar{K}$-nuclei

$$K^- + {}^4\mathrm{He} \to \Lambda d + n$$

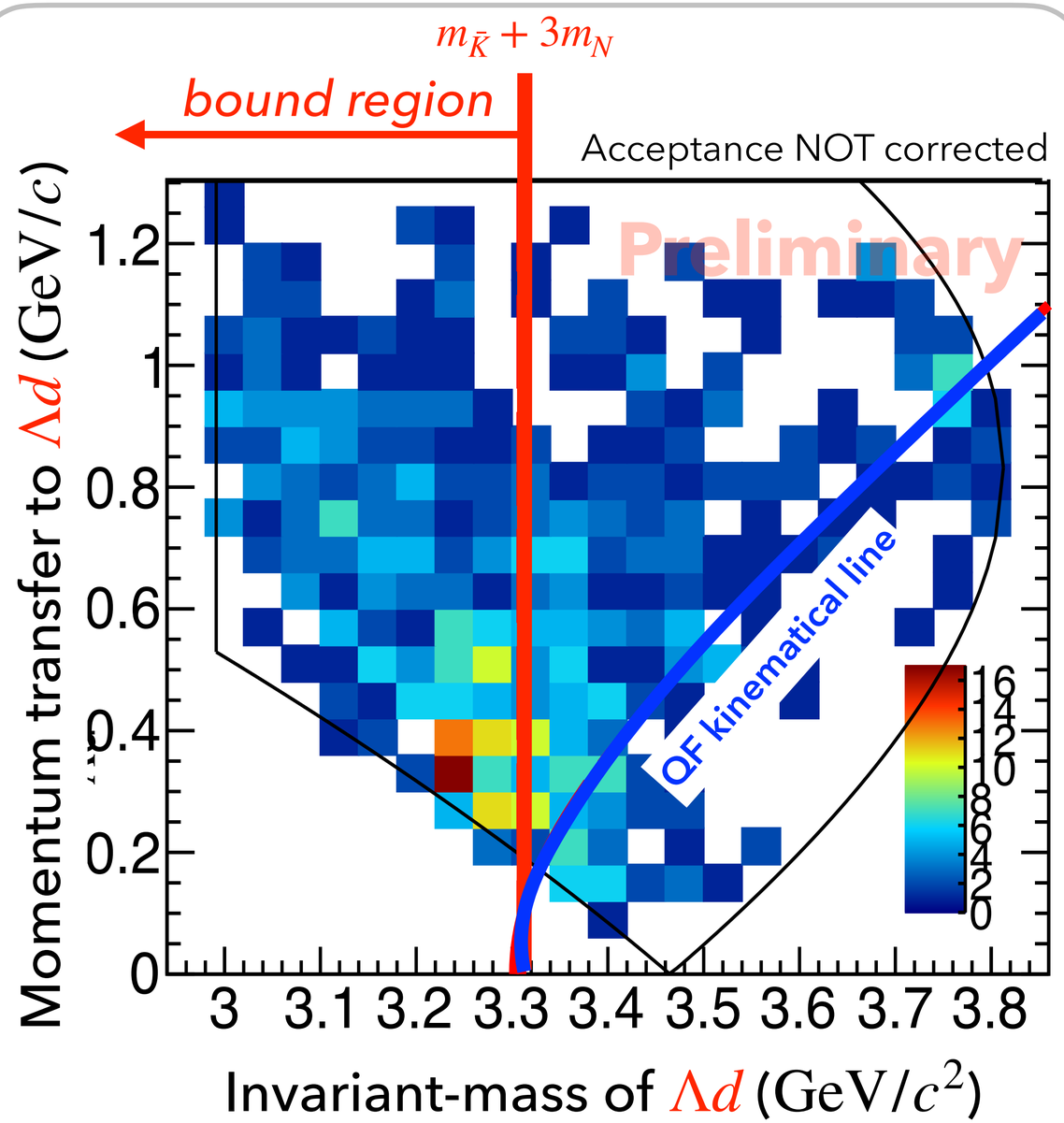


$\bar{K}NNN$ production

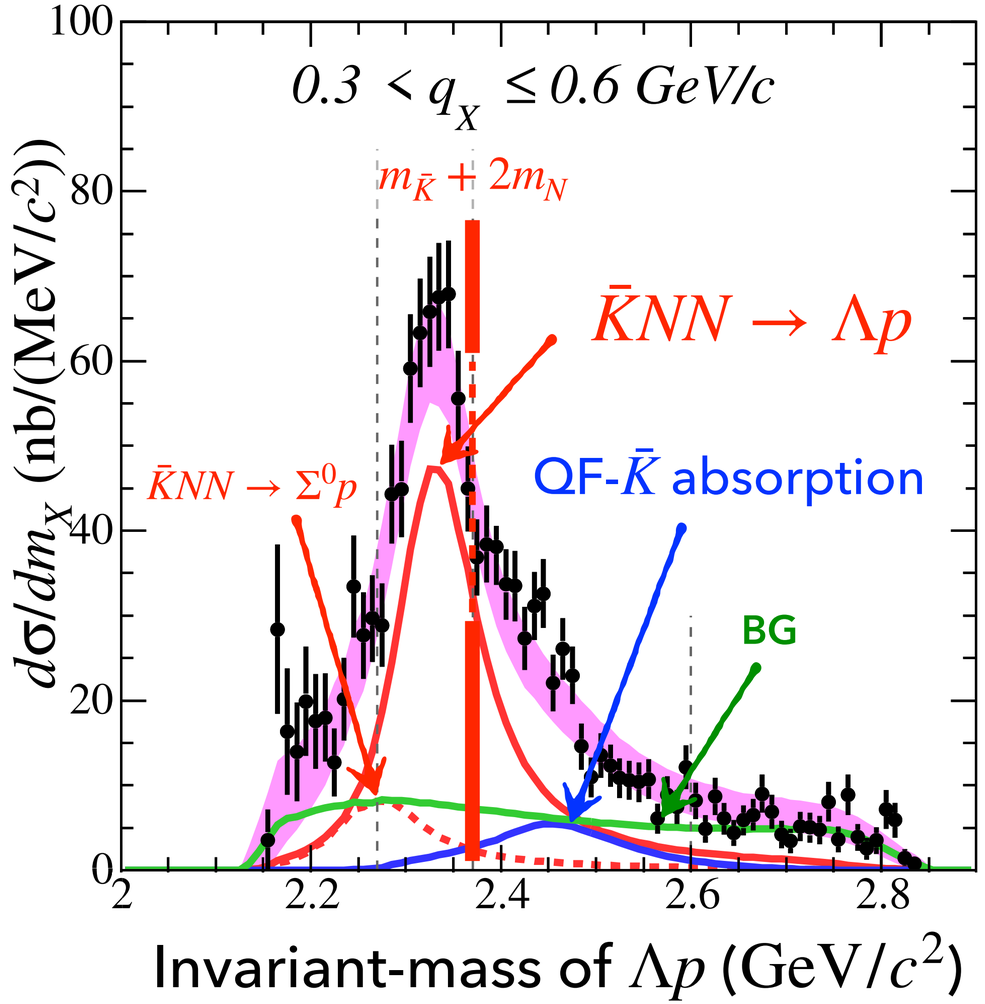
$K^- + {}^3\mathrm{He} \to \Lambda p + n$



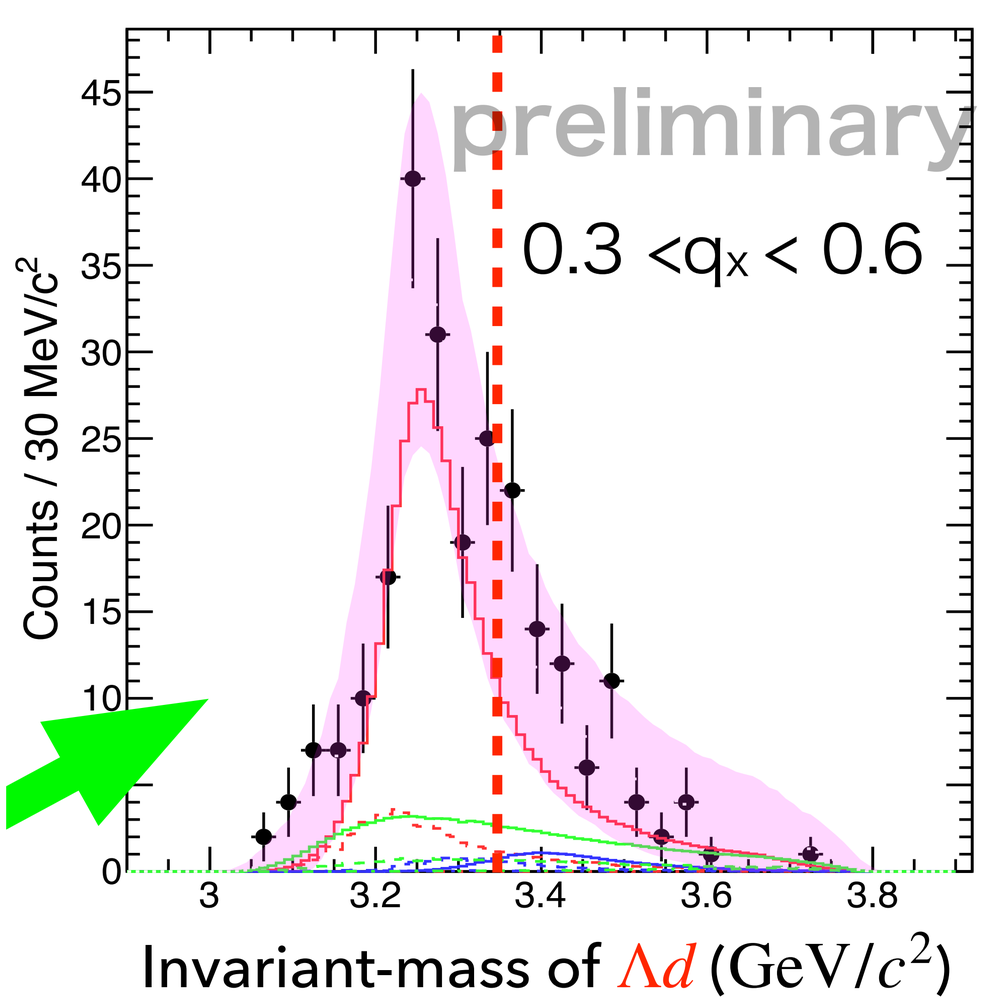
$K^- + {}^4\mathrm{He} \to \Lambda d + n$



$K^- + {}^3\mathrm{He} \to \Lambda p + n$



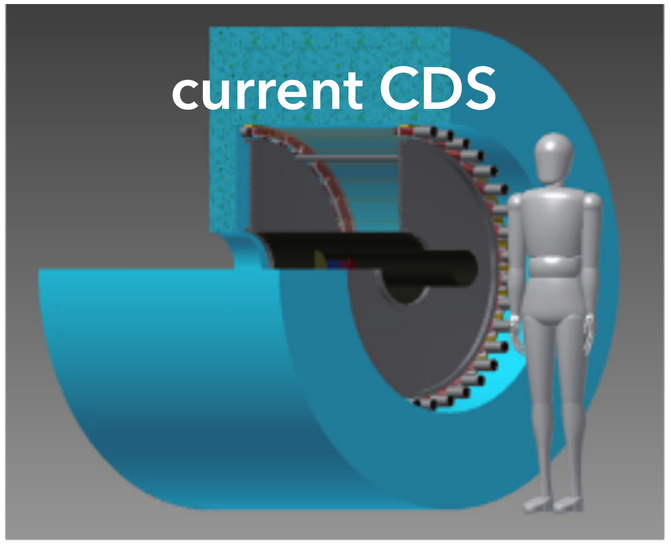
$K^- + {}^4\mathrm{He} \to \Lambda d + n$

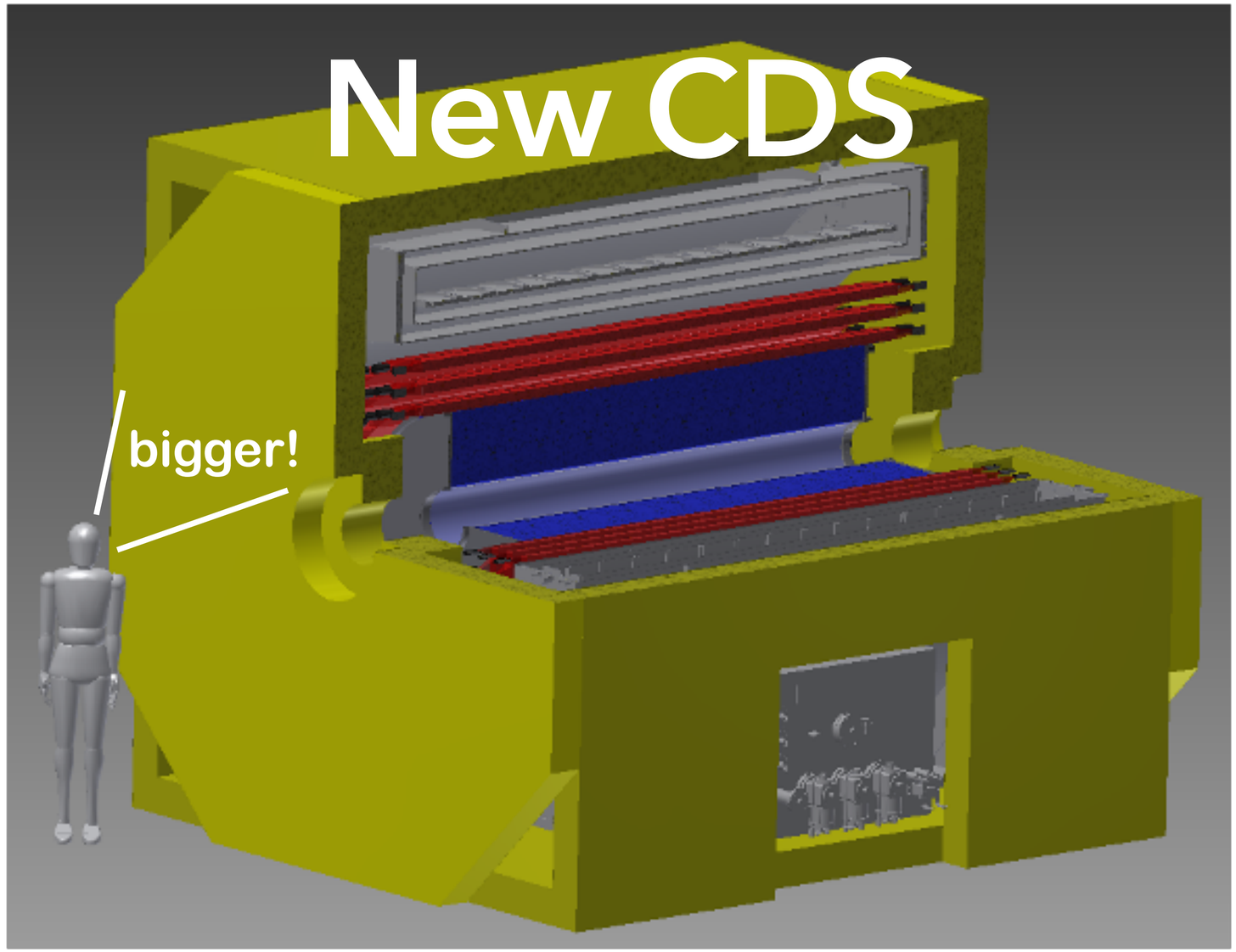


→ Peak observed in Λd invariant-mass could be signal of $\bar{K}NNN$.

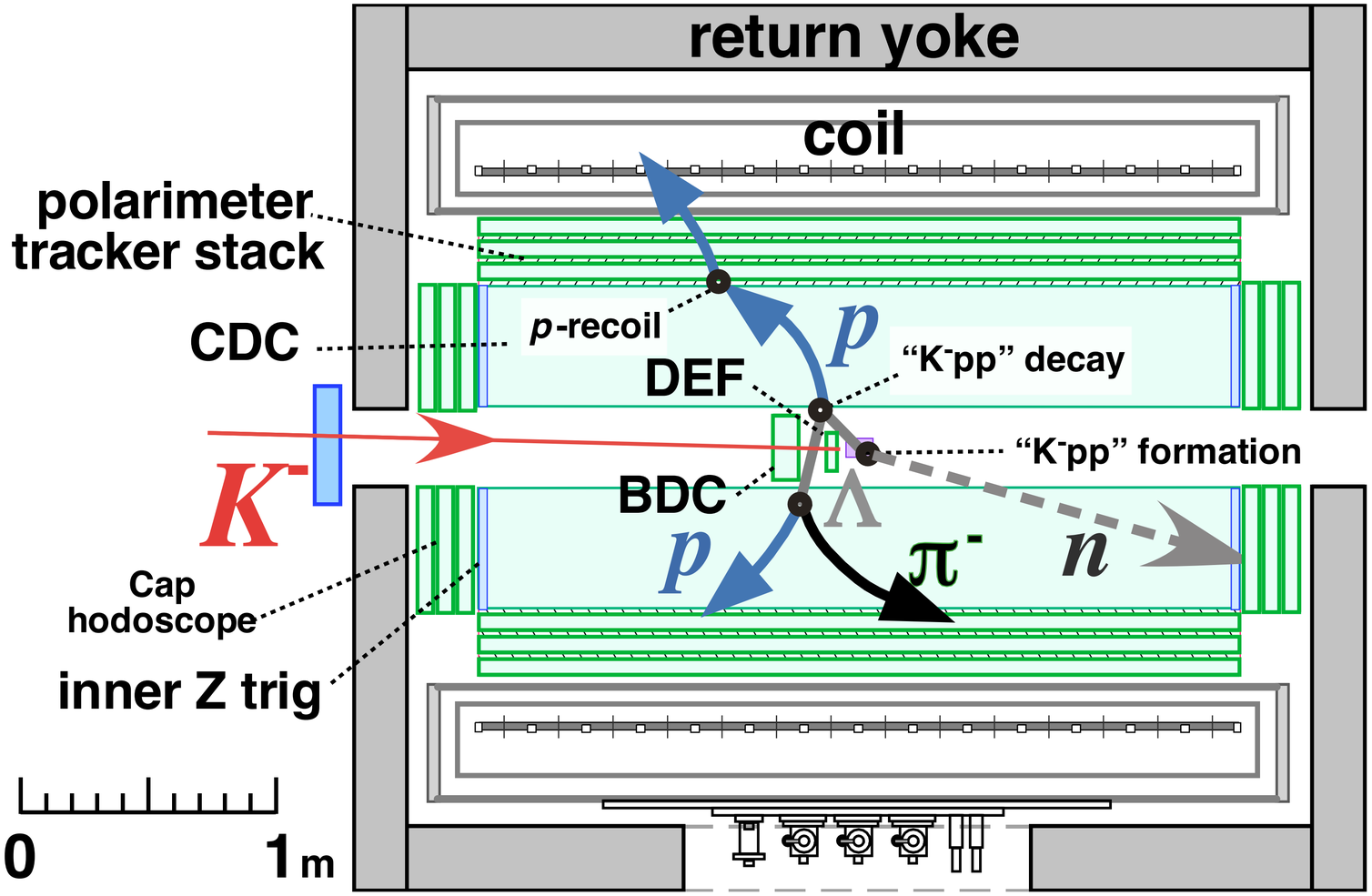
How to **experimentally** determine
the internal structure of $\bar{K}$-nuclei?

Future plan





New CDS



>90% solid angle coverage

Neutron detection capability

Sensitivity for proton polarization

Construction has been started
(Completed in 2025)


Construction has been started
(Completed in 2025)

New programs for kaonic 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^P determination

To confirm the existence more robustly

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

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

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

Collaborators

T. Yamaga,[1,*] S. Ajimura,[2] H. Asano,[1] G. Beer,[3] H. Bhang,[4] M. Bragadireanu,[5] P. Buehler,[6] L. Busso,[7,8] M. Cargnelli,[6] S. Choi,[4] C. Curceanu,[9] S. Enomoto,[14] H. Fujioka,[15] Y. Fujiwara,[12] T. Fukuda,[13] C. Guaraldo,[9] T. Hashimoto,[20] R. S. Hayano,[12] T. Hiraiwa,[2] M. Iio,[14] M. Iliescu,[9] K. Inoue,[2] Y. Ishiguro,[11] T. Ishikawa,[12] S. Ishimoto,[14] K. Itahashi,[1] M. Iwai,[14] M. Iwasaki,[1,†] K. Kanno,[12] K. Kato,[11] Y. Kato,[1] S. Kawasaki,[10] P. Kienle,[16,‡] H. Kou,[15] Y. Ma,[1] J. Marton,[6] Y. Matsuda,[17] Y. Mizoi,[13] O. Morra,[7] T. Nagae,[11] H. Noumi,[2,14] H. Ohnishi,[22] S. Okada,[23] H. Outa,[1] K. Piscicchia,[24,9] Y. Sada,[22] A. Sakaguchi,[10] F. Sakuma,[1] M. Sato,[14] A. Scordo,[9] M. Sekimoto,[14] H. Shi,[6] K. Shirotori,[2] D. Sirghi,[9,5] F. Sirghi,[9,5] S. Suzuki,[14] T. Suzuki,[12] K. Tanida,[20] H. Tatsuno,[21] M. Tokuda,[15] D. Tomono,[2] A. Toyoda,[14] K. Tsukada,[18] O. Vazquez Doce,[9,16] E. Widmann,[6] T. Yamazaki,[12,1] H. Yim,[19] Q. Zhang,[1] and J. Zmeskal[6]

(J-PARC E15 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

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

Theorists

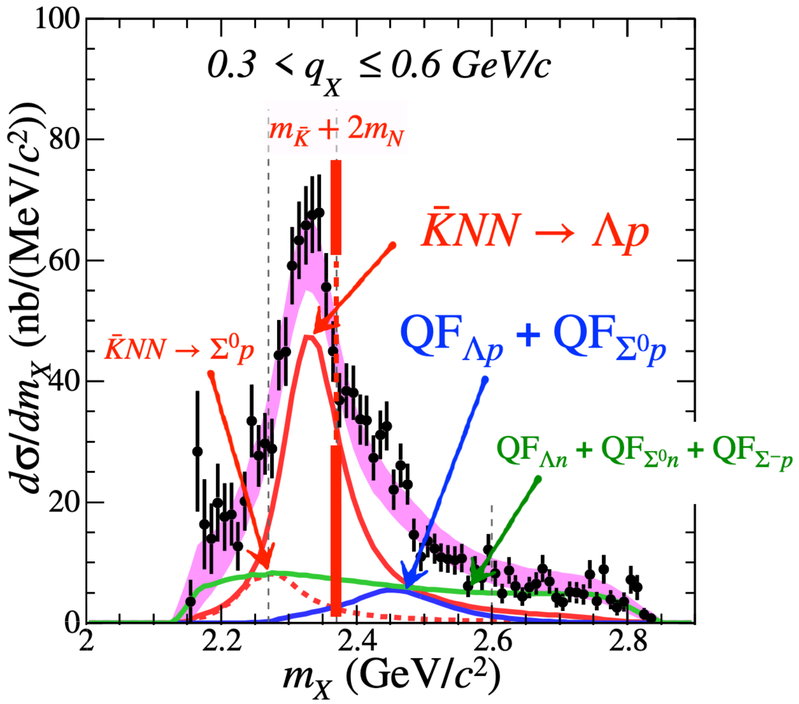
Tokyo Tech — D. Jido

KPU — T. Sekihara

Are you interested in? Join us!

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

Thank you for your attention!