Summary of the K^-pp bound-state observation in E15 and future prospects

F. Sakuma, RIKEN

on behalf of the J-PARC E15/E80 collaborations

EXA2021

INTERNATIONAL CONFERENCE ON EXOTIC ATOMS AND RELATED TOPICS (EXA 2021),

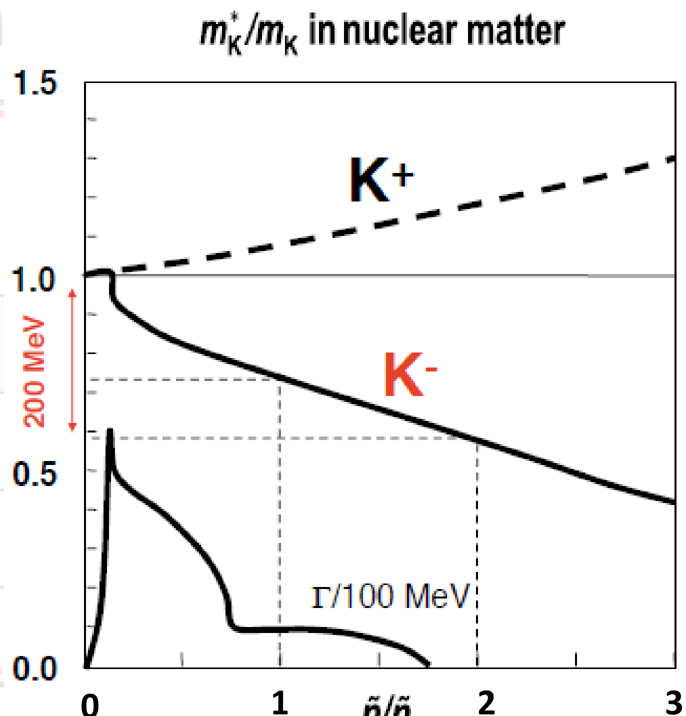
September 13-17, 2021, Online

Kaonic Nuclei

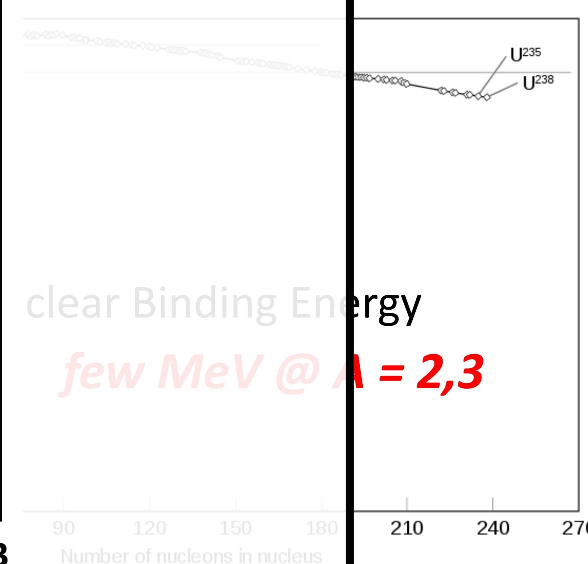
Predicted from ... action in I=0

88., PRC65(2002)044005., etc.

Kaonic Nuclei		Binding Energy [MeV]
Λ(1405) =	K⁻p	27
K⁻pp		48
K⁻ppp		97
K⁻ppn		118

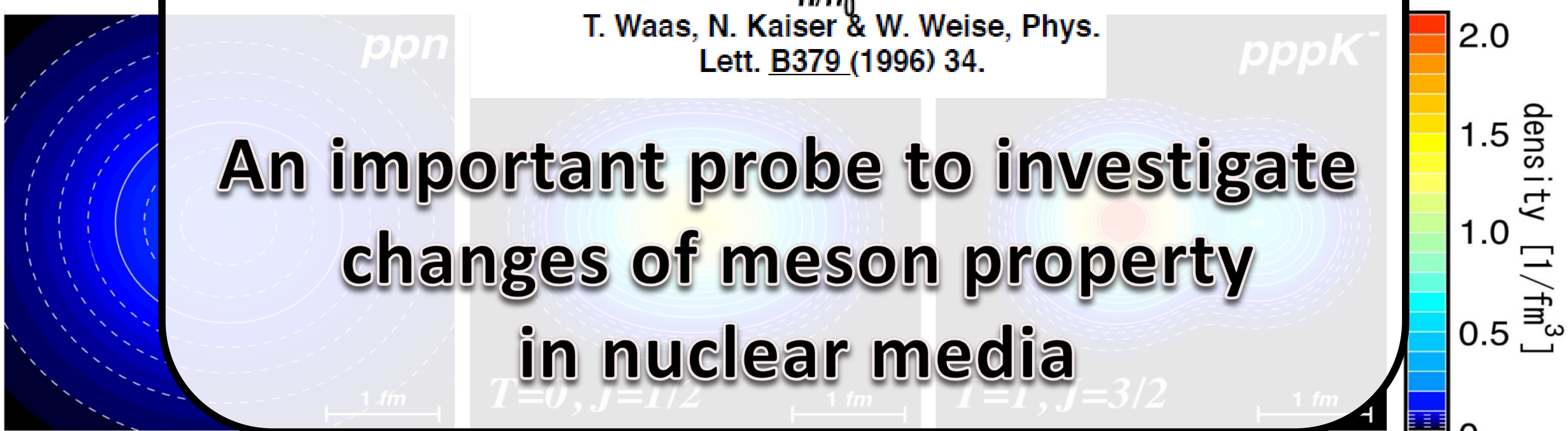


T. Waas, N. Kaiser & W. Weise, Phys. Lett. B379 (1996) 34.

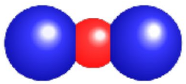


clear Binding Energy

few MeV @ A = 2,3



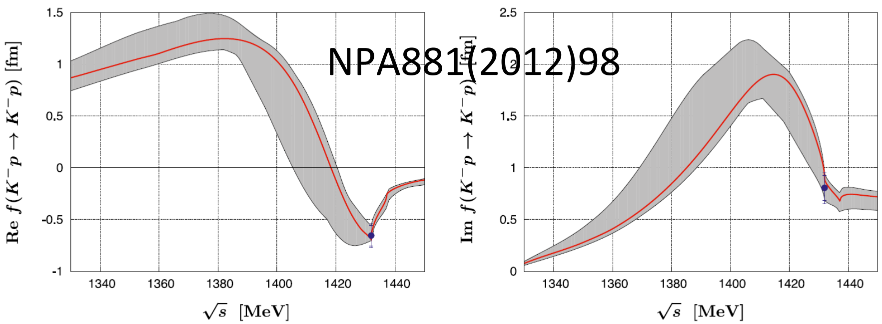
An important probe to investigate changes of meson property in nuclear media

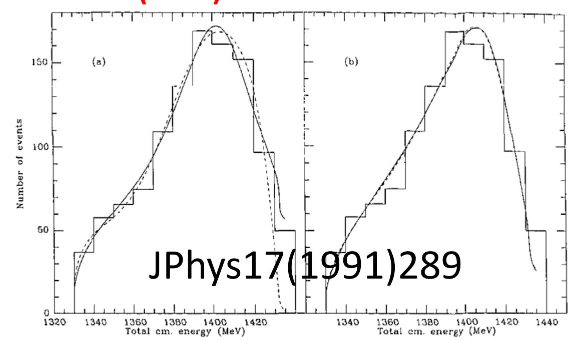


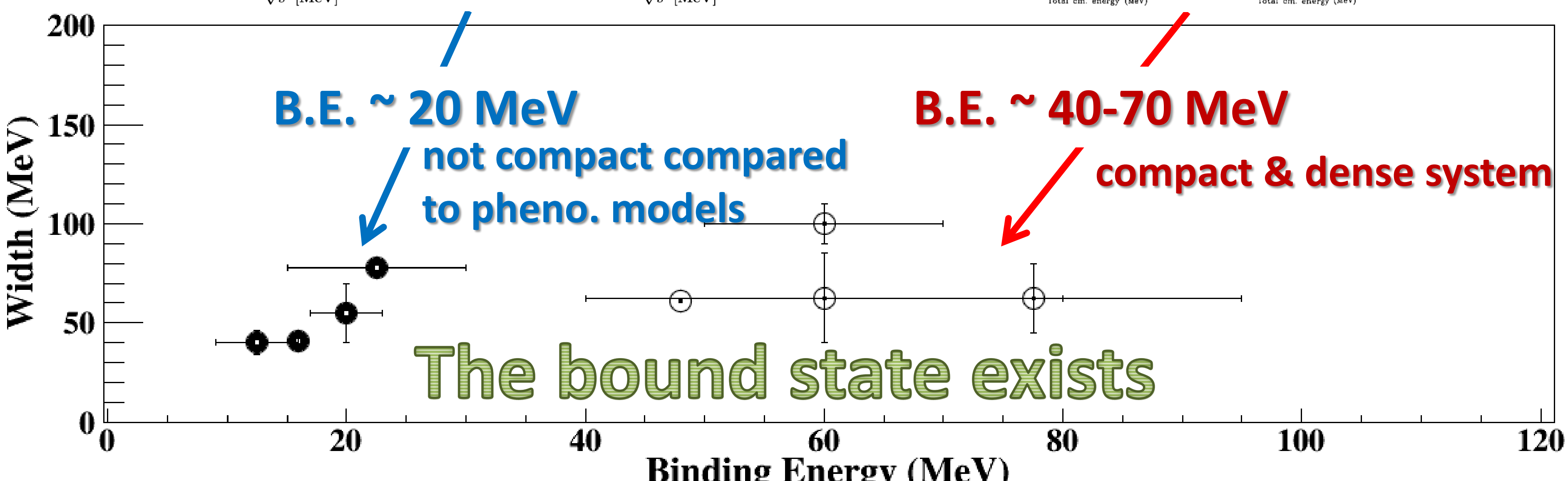
Theoretical Calculations on "K^-pp"

The simplest kaonic nuclei, $\bar{K}NN$ (J^P=0-, I=1/2)

$\bar{K}N$ int.	Chiral SU(3) (energy dependent)	Phenomenological (energy independent)
	$M_{\Lambda(1405)}$~1420, double pole	$M_{\Lambda(1405)}$~1405, single pole





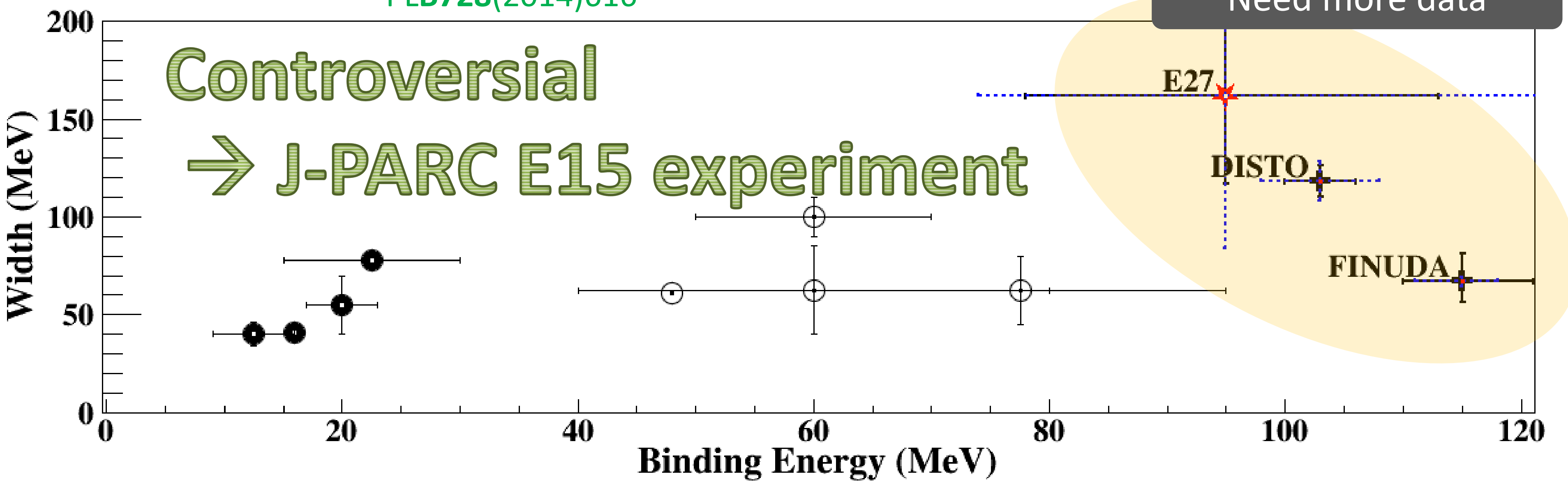


Experimental Situation "before E15"

Negative results		***Positive results***	
AMADEUS@DAΦNE $^{12}C(K^-_{stopped}, \Lambda p)$ — EPJ**C79**(2019)190	⟷	**FINUDA@DAΦNE** — PRL**94**(2005)212303 $^{6}Li/^{7}Li/^{12}C(K^-_{stopped}, \Lambda p)$	Multi-NA processes?
HADES@GSI $p + p \rightarrow (\Lambda + p) + K^+$ @ 3.5GeV — PL**B742**(2015)242	⟷	**DISTO@SATURNE** — PRL**104**(2010)132502 $p + p \rightarrow (\Lambda + p) + K^+$ @ 2.85GeV	Intermediate $N^* \rightarrow pK^+$?
LEPS@SPring-8 $d(\gamma, \pi^- K^+)X$ @ 1.5-2.4 GeV — PL**B728**(2014)616	⟷	**E27@J-PARC** — PTEP(2015)021D01. $d(\pi^+, K^+)\Sigma^0 p$ @ 1.69 GeV/c	Need more data

Controversial

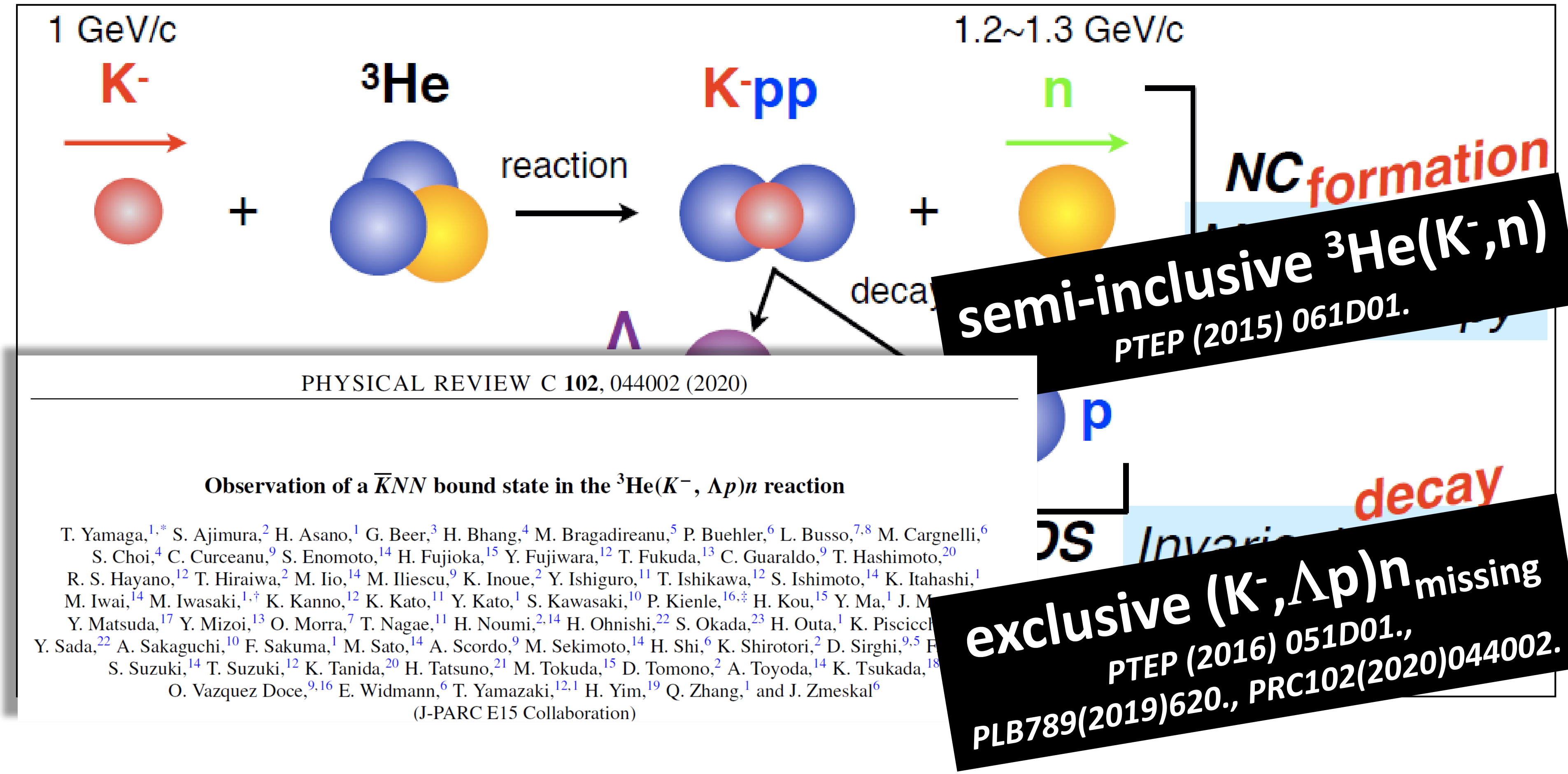
→ J-PARC E15 experiment



J-PARC E15 Experiment

- ^{3}He(*in-flight* K$^-$,n) reaction @ 1.0 GeV/c

2NΛ and Y decays can be discriminated kinematically

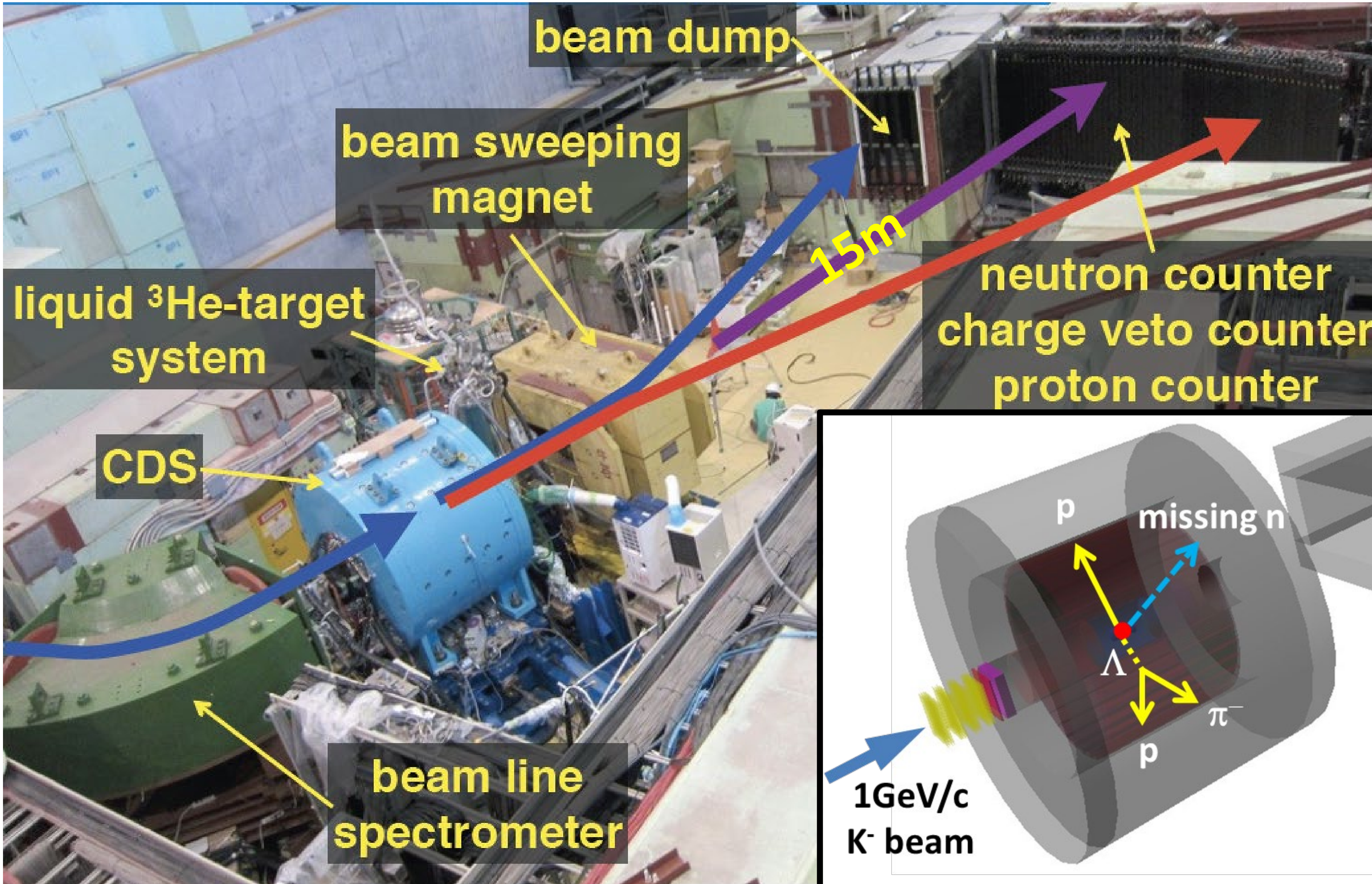


PHYSICAL REVIEW C **102**, 044002 (2020)

Observation of a $\overline{K}NN$ 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. M
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. Piscicch
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
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)

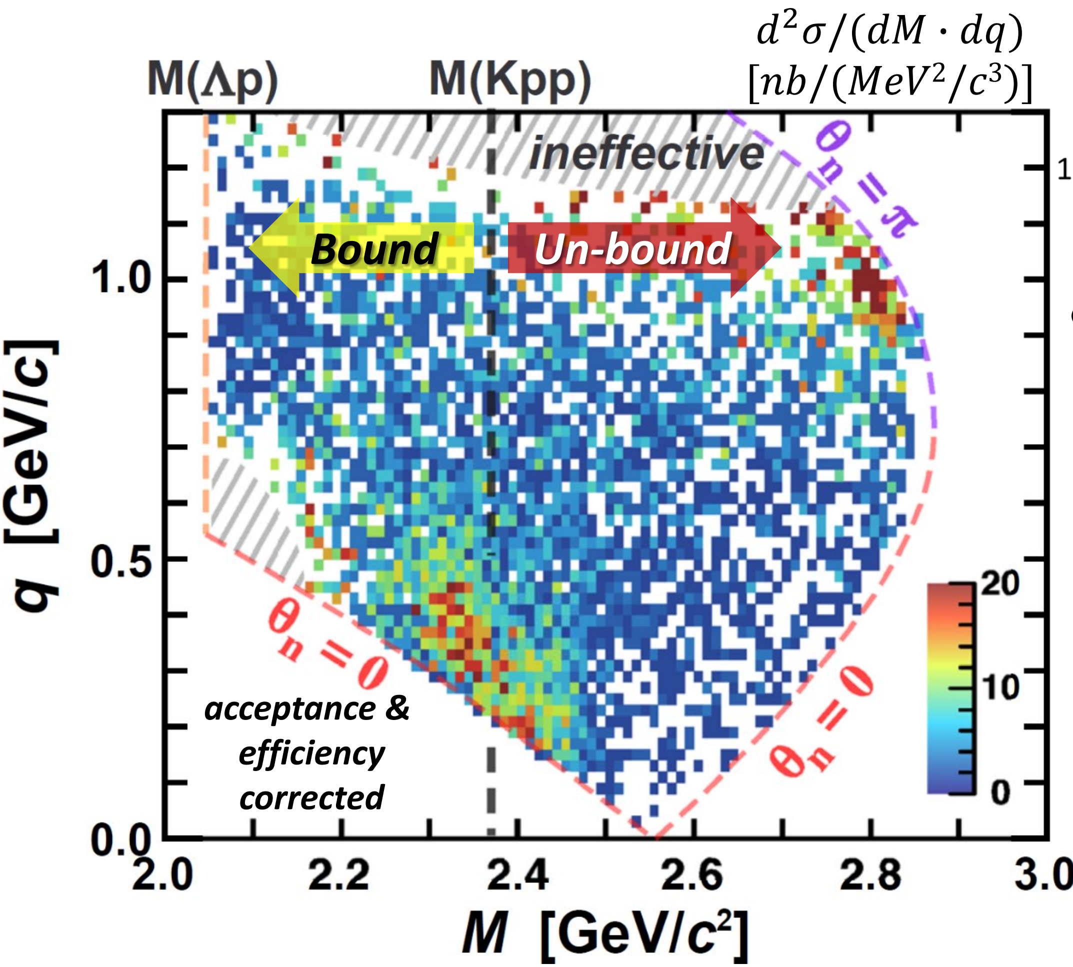
Experimental Setup @ K1.8BR

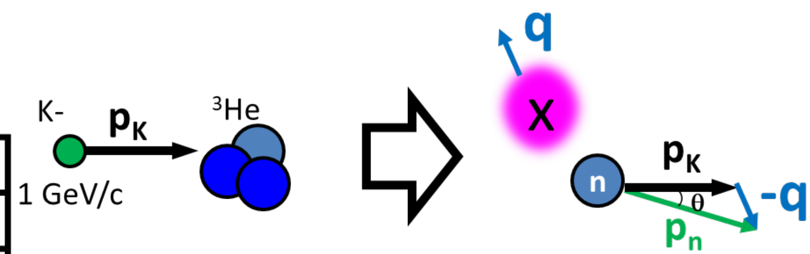


K. Agari et. al., PTEP 2012, 02B011

Exclusive $^3He(K^-,\Lambda p)n$

T.Yamaga et. al., PRC102(2020)044002.



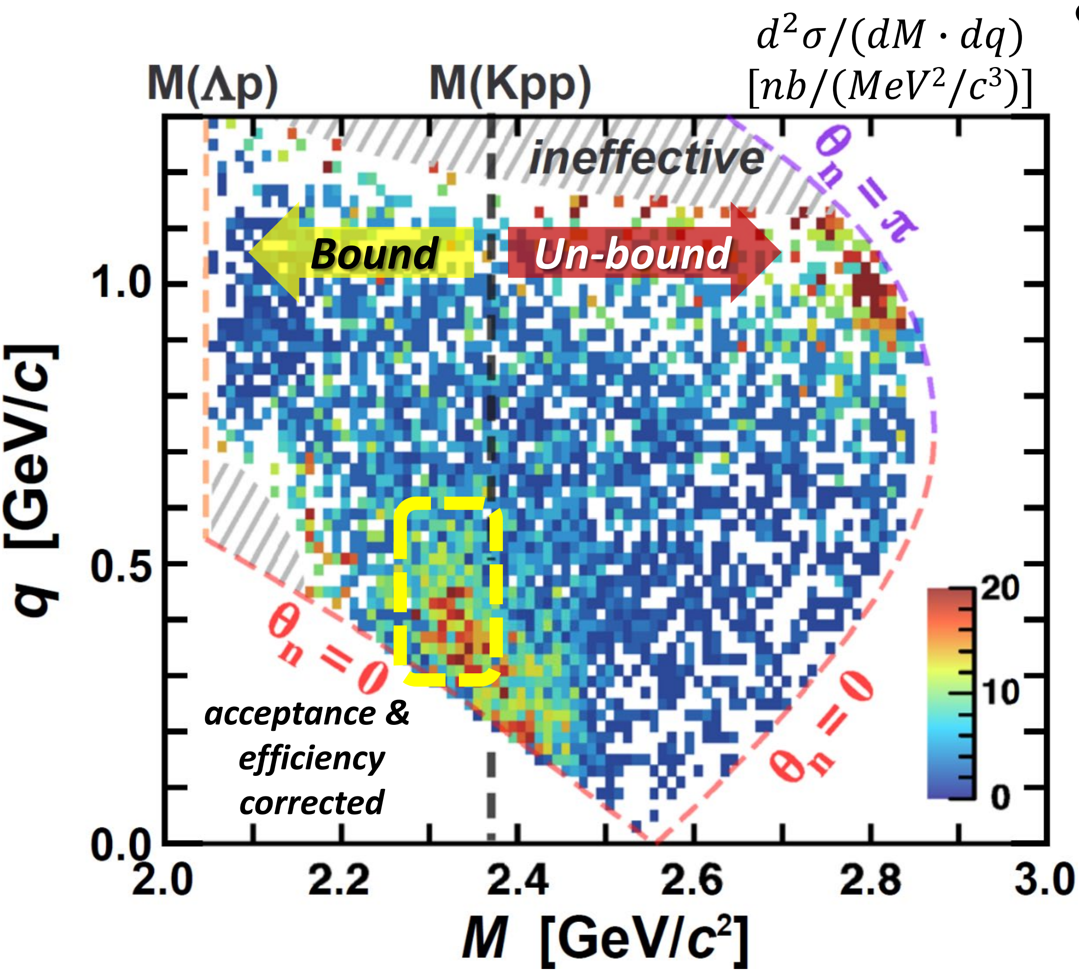


q *: momentum transfer of (K-,n)*
M *: invariant mass of Λp*

- **Momentum transfer analysis using the (K^-,n) reaction**
  - ✓M(Λp) vs. q
  - ✓give a clear information on reaction processes

Exclusive $^3He(K^-,\Lambda p)n$

T.Yamaga et. al., PRC102(2020)044002.

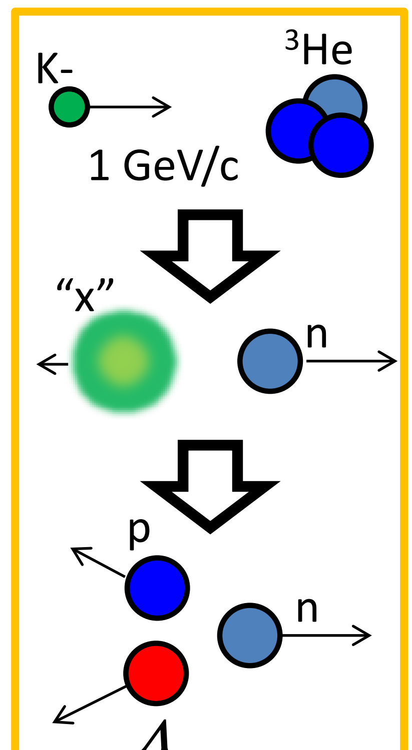


q : *momentum transfer of (K-,n)*

M : *invariant mass of Λp*

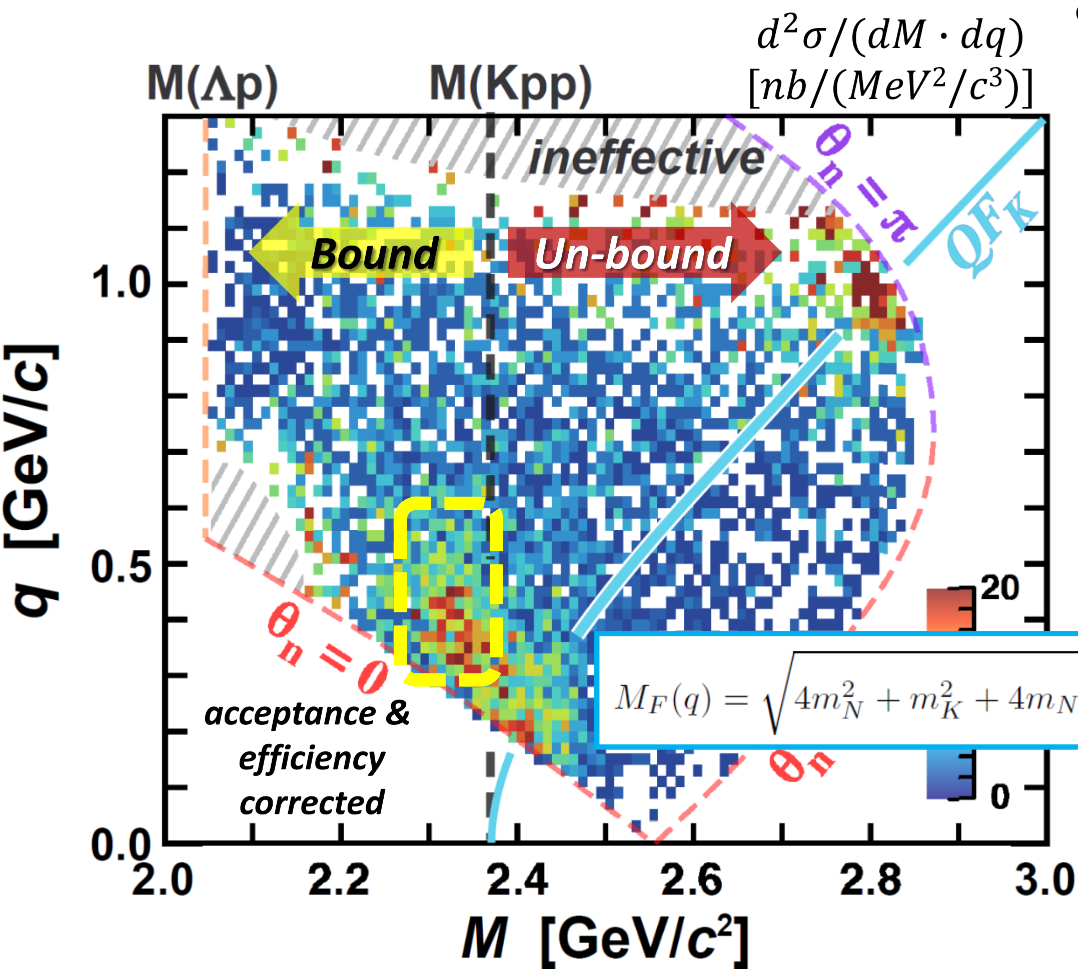
- **"K^-pp" bound state exists**

✓ q-independent



Exclusive $^3He(K^-,\Lambda p)n$

T.Yamaga et. al., PRC102(2020)044002.

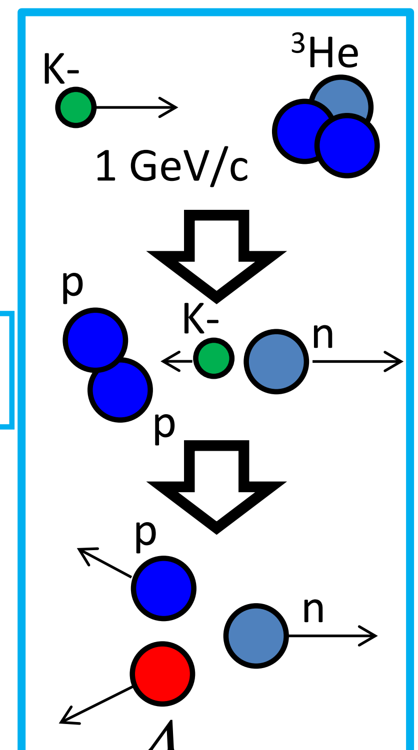


$$M_F(q) = \sqrt{4m_N^2 + m_K^2 + 4m_N\sqrt{m_K^2 + q^2}},$$

q *: momentum transfer of (K-,n)*

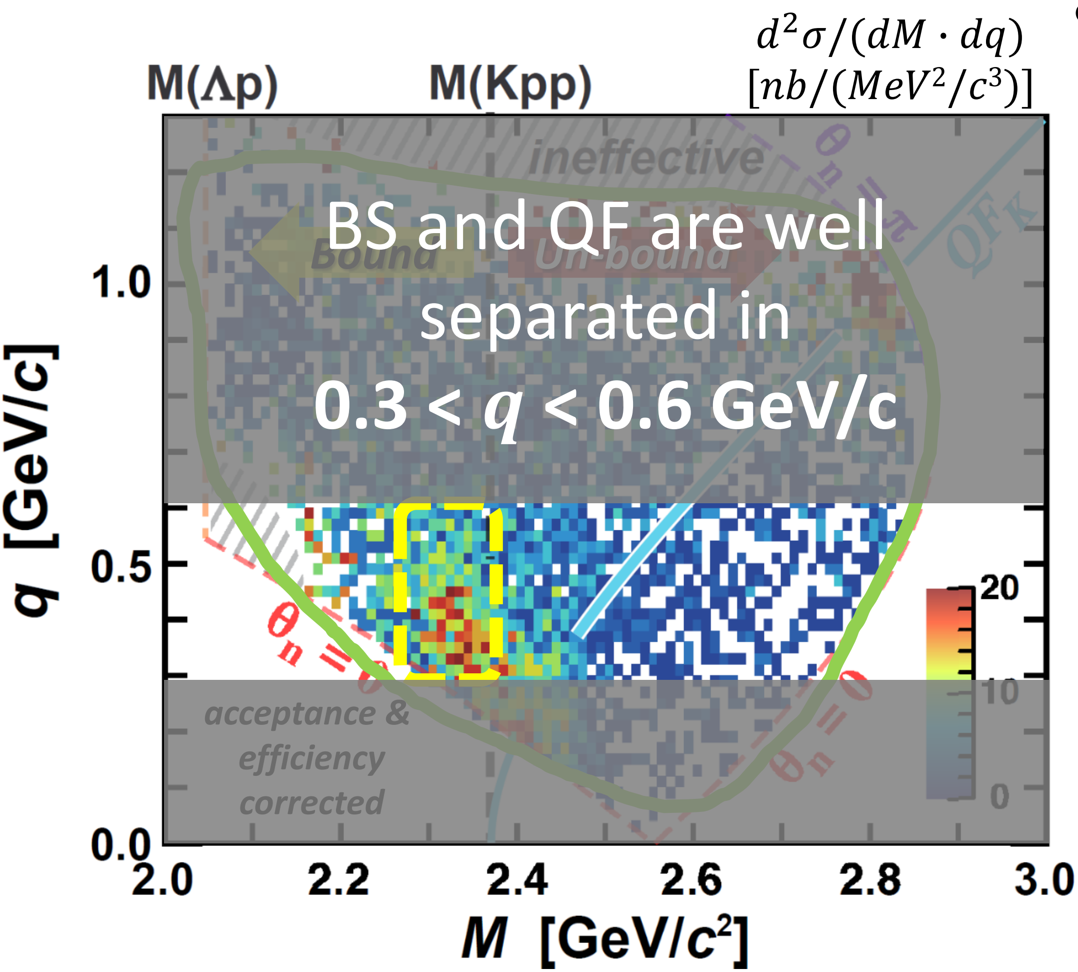
M *: invariant mass of Λp*

- **QF followed by 2NA**
  - ✓via "on-shell K^-"
  - ✓q-dependent



Exclusive $^3He(K^-,\Lambda p)n$

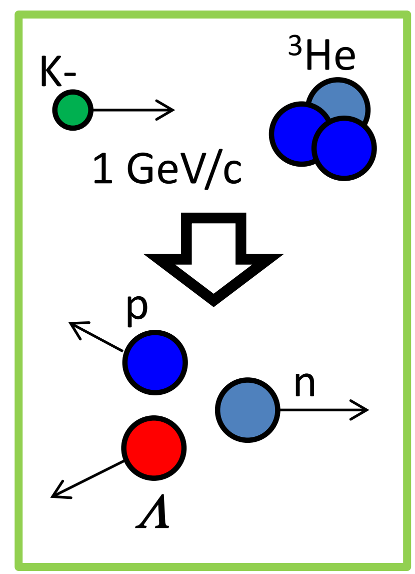
T.Yamaga et. al., PRC102(2020)044002.



q *: momentum transfer of (K-,n)*

M *: invariant mass of Λp*

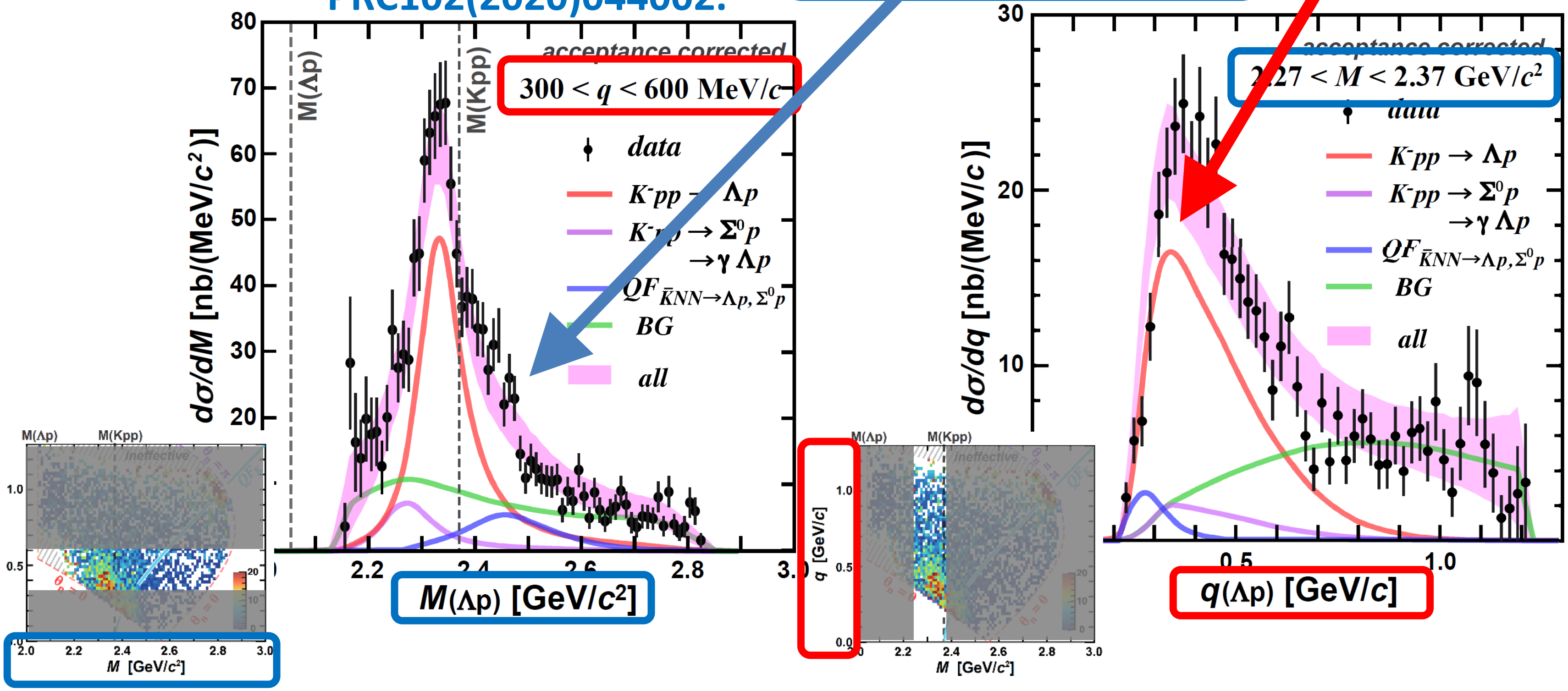
- **Broad Component**
  - ✓3NA reaction?
  - ✓Further investigations are ongoing



"K-pp" Bound State

Fit with PWIA $\sigma(M,q) \propto \rho(M,q) \times \boxed{\frac{(\Gamma_{Kpp}/2)^2}{(M-M_{Kpp})^2+(\Gamma_{Kpp}/2)^2}} \times \boxed{exp\left(-\frac{q^2}{Q_{Kpp}{}^2}\right)}$

PRC102(2020)044002.



B$_{Kpp}$ ~ 40 MeV, Γ_{Kpp} ~ 100 MeV

→ *large binding energy*

Q$_{kpp}$ ~ 400 MeV (c.f. Q_{QF} ~ 200 MeV)

→ *wide momentum transfer*

→ suggest the "K⁻pp" is quite compact

Many Questions to be Answered

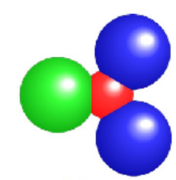
- **Further details of the $\bar{K}NN$**
  - Spin and parity of the “K⁻pp”?
  - Really compact and dense system?

K^-pp

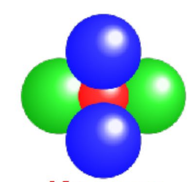
- **Λ(1405) state**
  - $\bar{K}N$ quasi-bound state as considered?
  - Size?
  - Relation between $\bar{K}N$ and $\bar{K}NN$?

K^-p

- **More heavier kaonic nuclei?**
  - Mass number dependence?



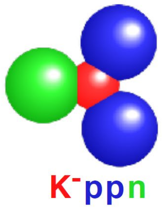
K^-ppn



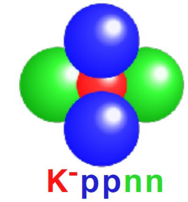
K^-ppnn

- **Double kaonic nuclei?**
  - Much compact and dense system?

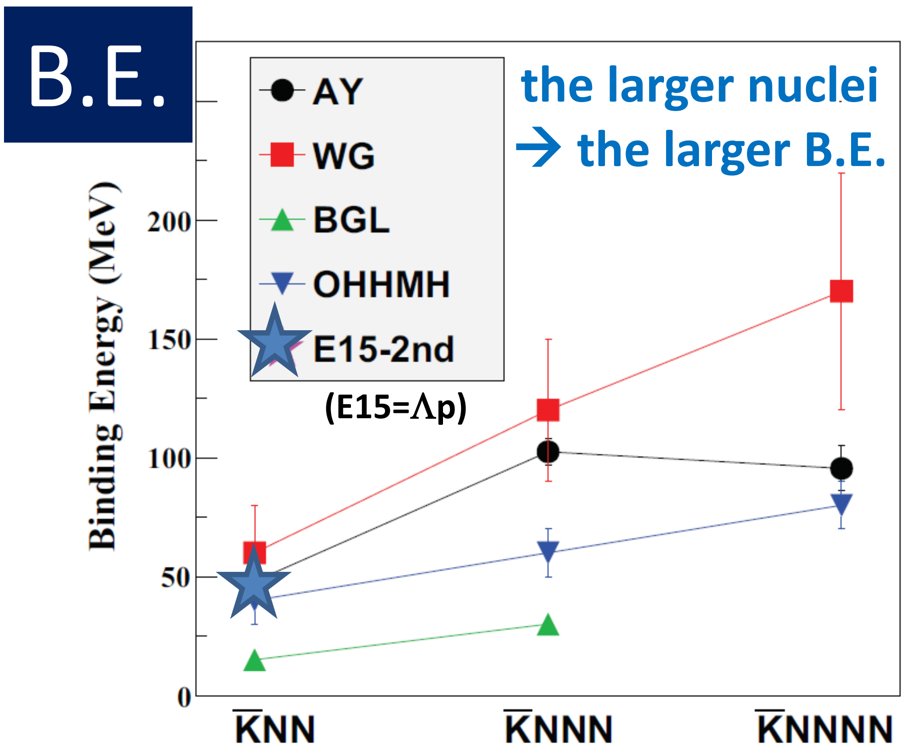
K^-K^-pp

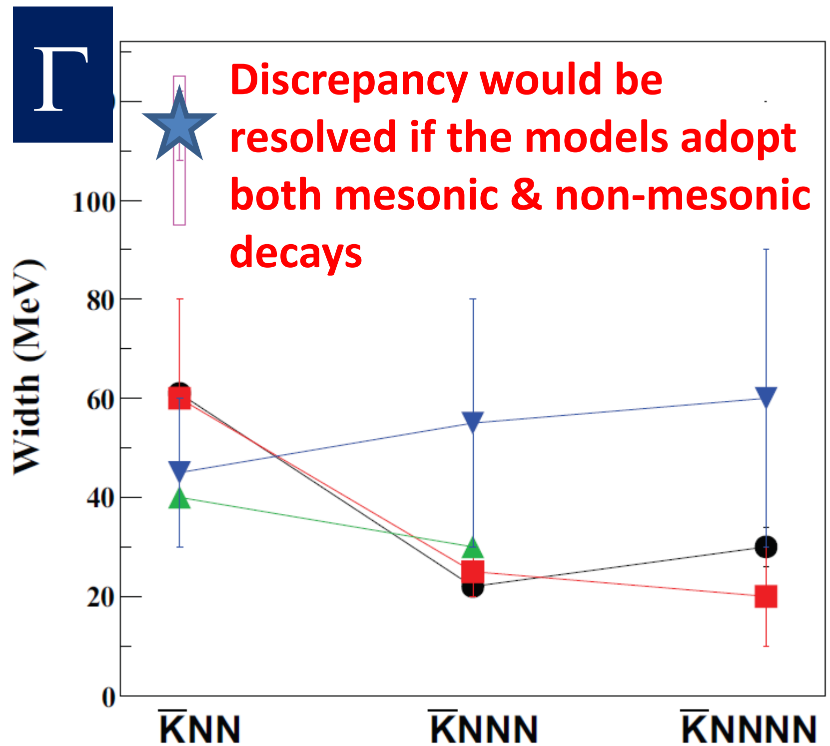


$\bar{K}NNN$ and $\bar{K}NNNN$



- More heavier system must be explored to provide more conclusive evidence of the kaonic nuclei



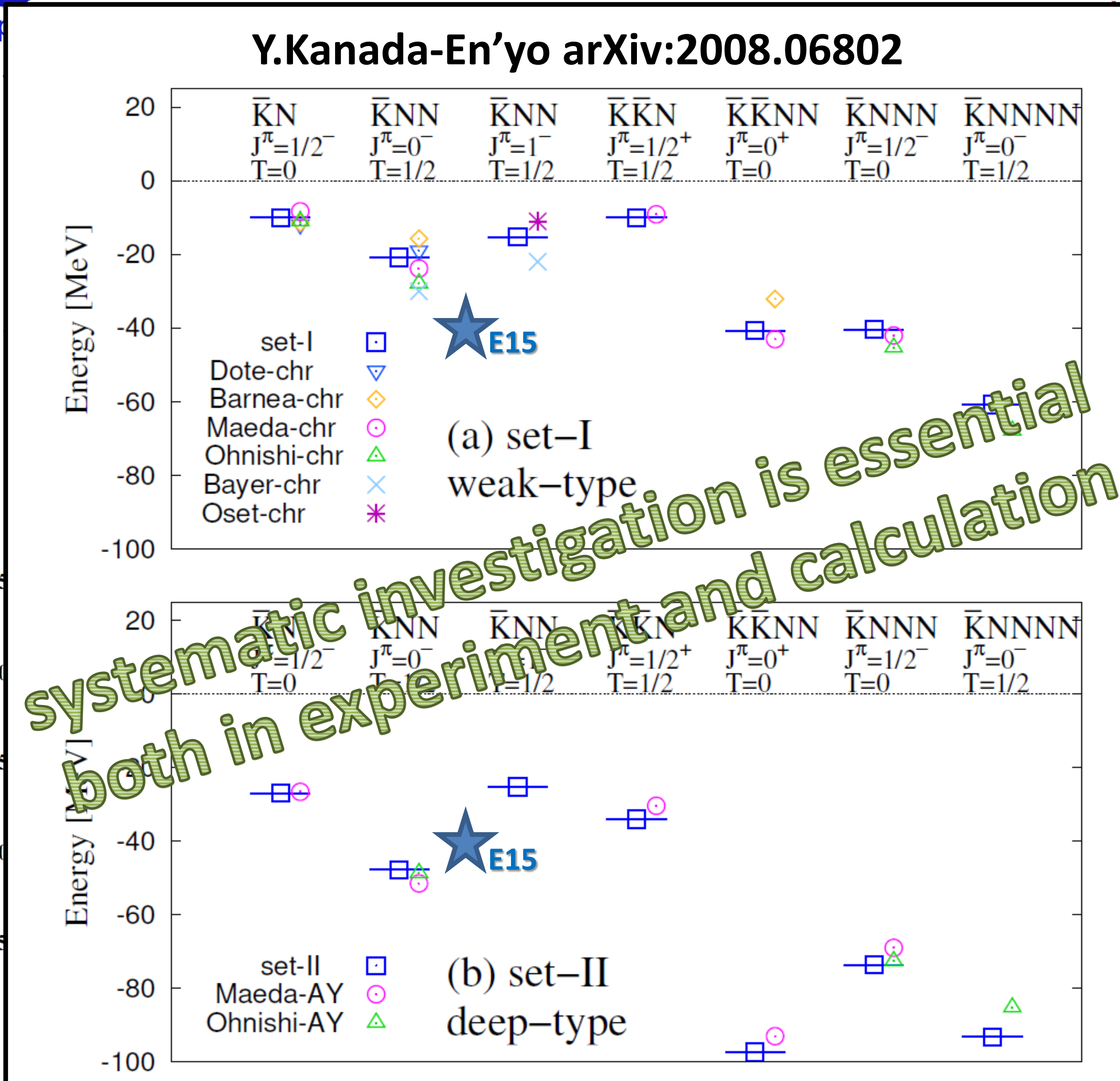


➢ The $\bar{K}NNNN$ system is expected to be the most compact system due to an α particle configuration

$\bar{K}NNN$ and $\bar{K}NNNN$

K⁻pp ... ppnn

- Be ... ust be ...
  - ✓ ... l to be ... e



systematic investigation is essential both in experiment and calculation

Binding Energy (MeV)

if ... onic

NNNN

New Project @ J-PARC

-- systematic investigation of the light kaonic nuclei --

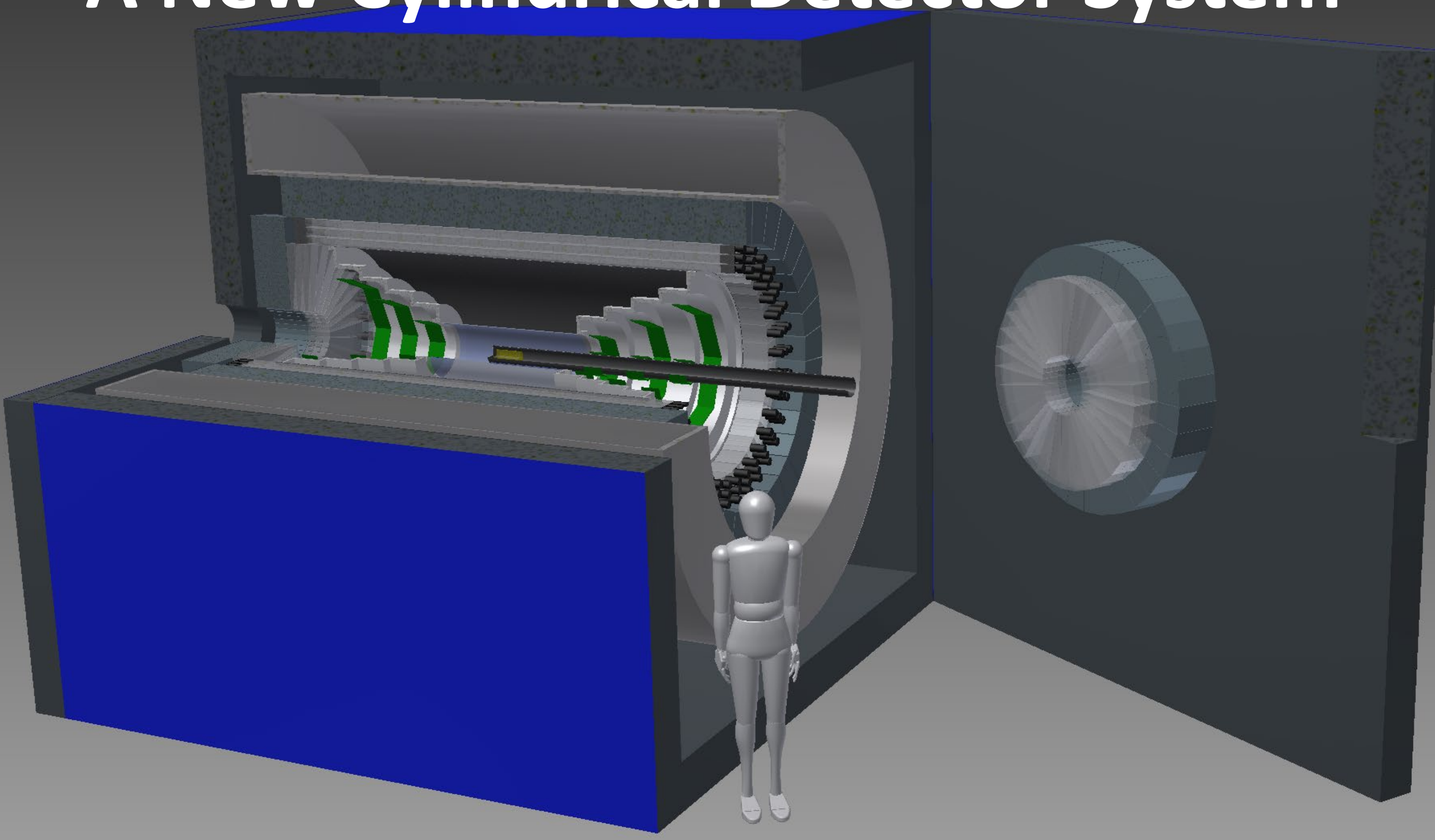
Strategy of the New Project

- for systematic study from the $\bar{K}N$ to $\bar{K}NNNN$ systems -

	Reaction	Decays	Key
$\bar{K}N$	$d(K^-,n)$	$\pi^{\pm 0}\Sigma^{\mp 0}$	F-factor → n/γ identification
$\bar{K}NN$	$^3He(K^-,N)$	$\Lambda p/\Lambda n$	J^P → polarimeter
$\bar{K}NNN$	$^4He(K^-,N)$	$\Lambda d/\Lambda pn$	large acceptance ← **A first step**
$\bar{K}NNNN$	*$^6Li(K^-,d)$*	$\Lambda t/\Lambda dn/\Lambda pnn$	*many body decay*
$\bar{K}\bar{K}NN$	*$\bar{p}$ + ^3He*	$\Lambda\Lambda$	*$\bar{p}$ beam yield*

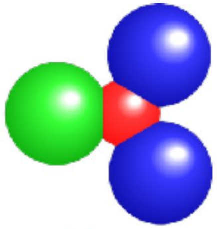
- To realize the systematic measurements, we need
  - ☐ **a large acceptance spectrometer** **← new CDS**
    - detect/identify all particles to specify the reaction
  - ☐ **high-intensity kaon beam** **← modified K1.8BR**
    - more K^- yield than the existing beamline
- *We take a **step-by-step** approach*

A New Cylindrical Detector System



A new 4π spectrometer with n/γ detection capability

Expected $\bar{K}NNN$ in K$^-$+^{4}He



K$^-$ppn

B_{Kppn} ~ 40 MeV

Γ_{Kppn} ~ 100 MeV

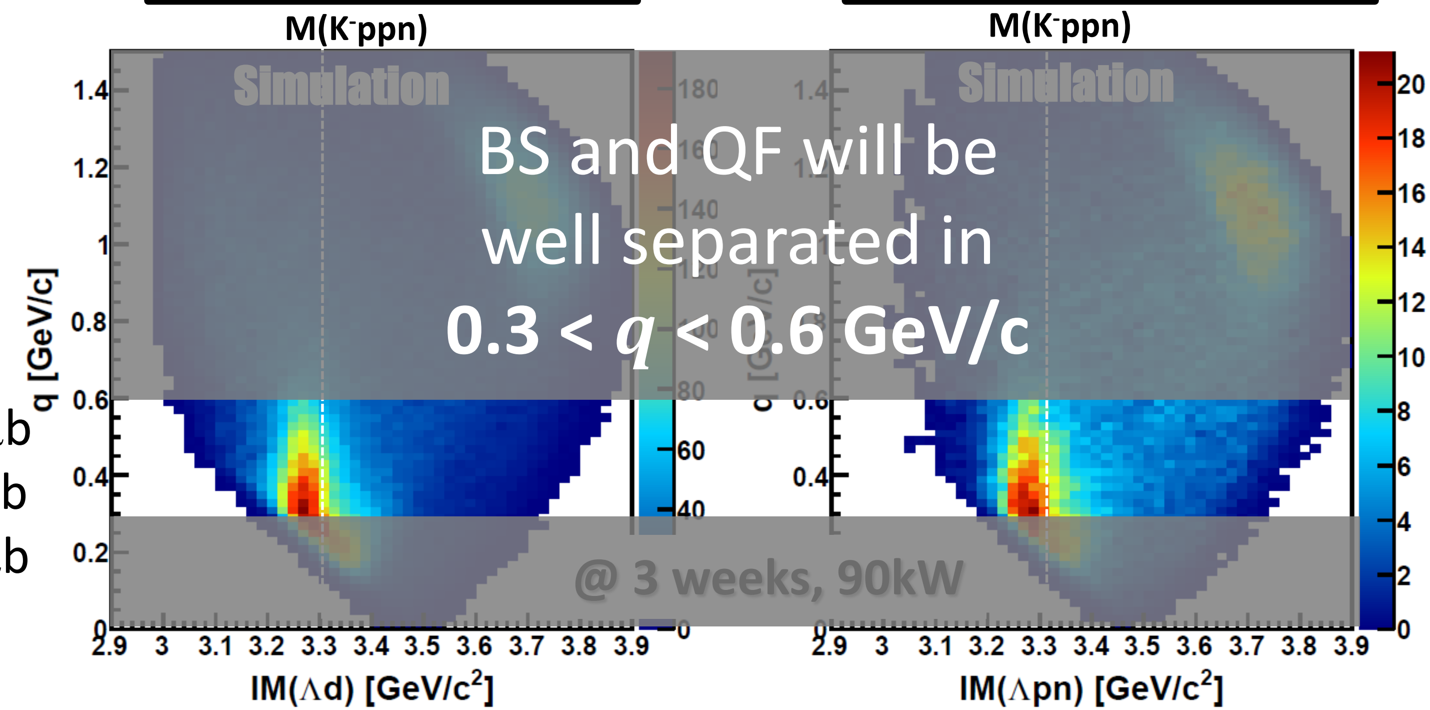
Q_{kppn} ~ 400 MeV/c

σ(K$^-$ppn)*Br ~ 10 μb

σ(QF) ~ 10 μb

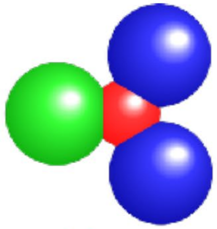
σ(BG) ~ 20 μb

K$^-$+^{4}He→Λd+n | **K$^-$+^{4}He→Λpn+n**



BS and QF will be well separated in **0.3 < q < 0.6 GeV/c**

- Similar parameters obtained with the K$^-$+^{3}He→Λpn (PRC102(2020)044002.) are adopted to K$^-$ppn/QF/BG shapes
- **"K$^-$ppn" signal [<u>q-independent</u>] will be seen clearly**

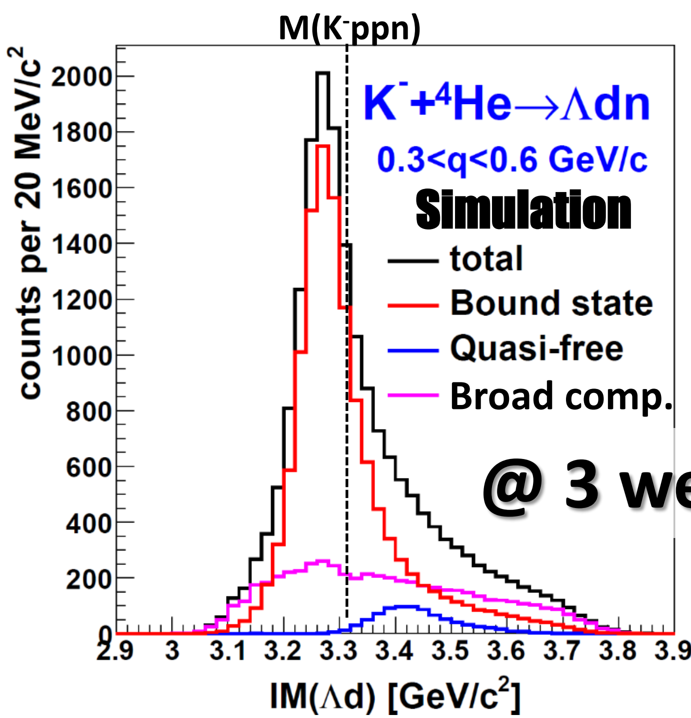


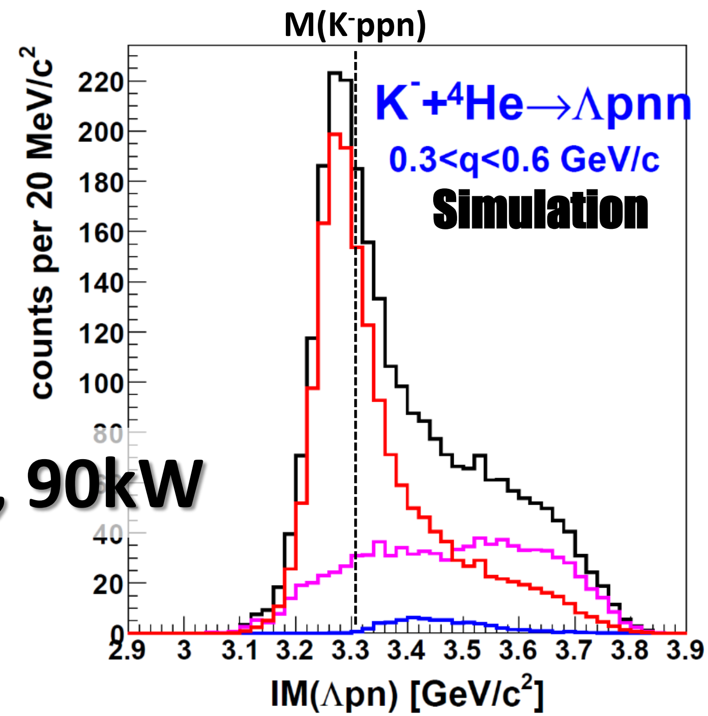
K$^-$ppn

Expected $\bar{K}NNN$ in K$^-$+^{4}He

K$^-$+^{4}He→Λd+n

K$^-$+^{4}He→Λpn+n





@ 3 weeks, 90kW

- Assumption: similar parameters obtained at E15
- **Mass-number dependence of the kaonic nuclei will be provided for the first time.**

Summary

- **We observed the "K^-pp" bound state in $^3He(K^-,\Lambda p)n$**

J-PARC E15 ✓ PLB789(2019)620., PRC102(2020)044002.

- **As the next step, the new project has been launched to reveal the properties of the light kaonic nuclei from the $\bar{K}N$ to $\bar{K}NNNN$**
  - ➢ a powerful probe to understand low energy QCD
  - ➢ the best approach to cold & high-density nuclear matter

- We take a step-by-step approach:

J-PARC E80 – **a $\bar{K}NNN$ search via $^4He(K^-,N)$ reactions as the first step**

J-PARC P89 – a spin/parity measurement of the $\bar{K}NN$ as the second step

– experimental challenges of $\bar{K}N$, $\bar{K}NNNN$, and $\bar{K}\bar{K}NN$ will also be followed

J-PARC E15 Collaboration

S. Ajimura[a], H. Asano[n], G. Beer[b], C. Berucci[f], H. Bhang[c], M. Bragadireanu[e], P. Buehler[f], L. Busso[g,h], M. Cargnelli[f], S. Choi[c], C. Curceanu[d], S. Enomoto[o], H. Fujioka[m], Y. Fujiwara[k], T. Fukuda[l], C. Guaraldo[d], T. Hashimoto[u], R. S. Hayano[k], T. Hiraiwa[a], M. Iio[o], M. Iliescu[d], K. Inoue[a], Y. Ishiguro[j], T. Ishikawa[k], S. Ishimoto[o], K. Itahashi[n], M. Iwai[o], M. Iwasaki[m,n*], K. Kanno[k], K. Kato[j], Y. Kato[n], S. Kawasaki[i], P. Kienle[†p], H. Kou[m], Y. Ma[n], J. Marton[f], Y. Matsuda[q], Y. Mizoi[l], O. Morra[g], T. Nagae[j$], H. Noumi[a], H. Ohnishi[w], S. Okada[n], H. Outa[n], K. Piscicchia[d], Y. Sada[a], A. Sakaguchi[i], F. Sakuma[n], M. Sato[o], A. Scordo[d], M. Sekimoto[o], H. Shi[d], K. Shirotori[a], D. Sirghi[d,e], F. Sirghi[d,e], K. Suzuki[f], S. Suzuki[o], T. Suzuki[k], K. Tanida[u], H. Tatsuno[v], M. Tokuda[m], D. Tomono[a], A. Toyoda[o], K. Tsukada[r], O. Vazquez Doce[d,p], E. Widmann[f], T. Yamaga[n], T. Yamazaki[k,n], H. Yim[t], Q. Zhang[n], and J. Zmeskal[f]

(a) Research Center for Nuclear Physics (RCNP), Osaka University, Osaka, 567-0047, Japan
(b) Department of Physics and Astronomy, University of Victoria, Victoria BC V8W 3P6, Canada
(c) Department of Physics, Seoul National University, Seoul, 151-742, South Korea
(d) Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy
(e) National Institute of Physics and Nuclear Engineering - IFIN HH, Romania
(f) Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria
(g) INFN Sezione di Torino, Torino, Italy
(h) Dipartimento di Fisica Generale, Universita' di Torino, Torino, Italy
(i) Department of Physics, Osaka University, Osaka, 560-0043, Japan
(j) Department of Physics, Kyoto University, Kyoto, 606-8502, Japan
(k) Department of Physics, The University of Tokyo, Tokyo, 113-0033, Japan
(l) Laboratory of Physics, Osaka Electro-Communication University, Osaka, 572-8530, Japan
(m) Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551, Japan
(n) RIKEN Nishina Center, RIKEN, Wako, 351-0198, Japan
(o) High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan
(p) Technische Universität München, D-85748, Garching, Germany
(q) Graduate School of Arts and Sciences, The University of Tokyo, Tokyo, 153-8902, Japan
(r) Department of Physics, Tohoku University, Sendai, 980-8578, Japan
(s) Excellence Cluster Universe, Technische Universität München, D-85748, Garching, Germany
(t) Korea Institute of Radiological and Medical Sciences (KIRAMS), Seoul, 139-706, South Korea
(u) ASRC, Japan Atomic Energy Agency, Ibaraki 319-1195, Japan
(v) Department of Chemical Physics, Lund University, Lund, 221 00, Sweden
(w) Research Center for Electron Photon Science (ELPH), Tohoku University, Sendai, 982-0826, Japan

J-PARC E80 Collaboration

H. Asano K. Itahashi, M. Iwasaki, Y. Ma, R. Murayama, H. Outa, F. Sakuma*, T. Yamaga
RIKEN Cluster for Pioneering Research, RIKEN, Saitama, 351-0198, Japan

K. Inoue, S. Kawasaki, H. Noumi, K. Shirotori
Research Center for Nuclear Physics (RCNP), Osaka University, Osaka, 567-0047, Japan

H. Ohnishi, Y. Sada, C. Yoshida
Research Center for Electron Photon Science (ELPH), Tohoku University, Sendai, 982-0826, Japan

We're looking for new collaborators!

T. [illegible]
Japan Atomic Energy Agency (JAEA), [illegible] 119[illegible], Japan

M. Iio, S. Ishimoto, K. Ozawa, S. Suzuki
High [illegible] (KEK), [illegible], Japan

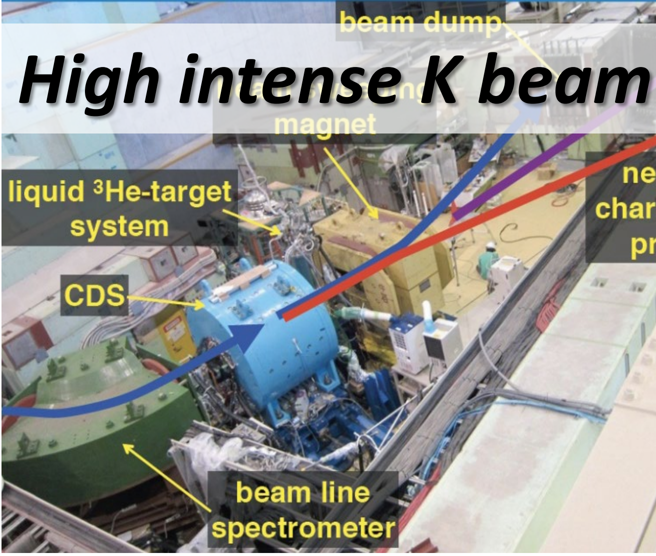
T. Akaishi
Department of Physics, Osaka University, Osaka, 560-0043, Japan

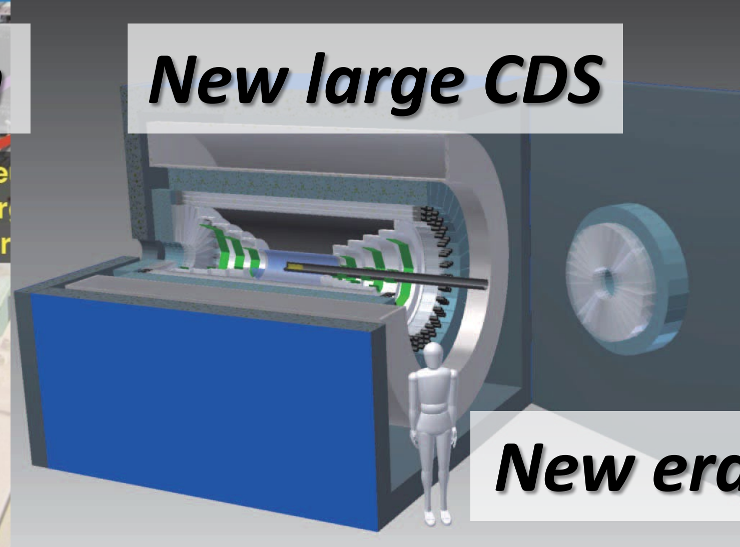
T. Nagae
Department of Physics, Kyoto University, Kyoto, 606-8502, Japan

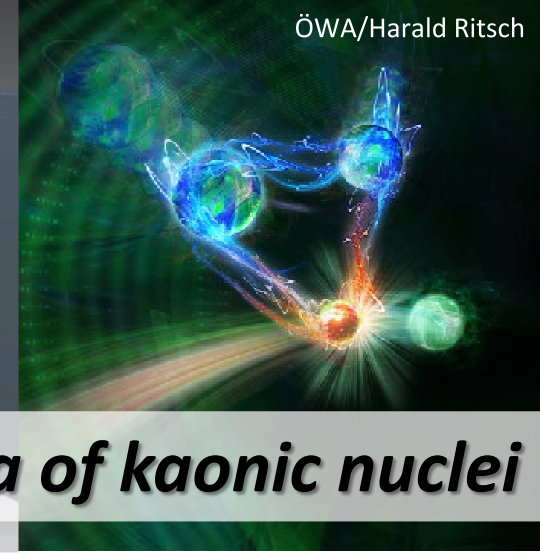
H. Fujioka
Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551, Japan

M. Bazzi, A. Clozza, C. Curceanu, C. Guaraldo, M. Iliescu, M. Miliucci, A. Scordo, D. Sirghi, F. Sirghi
Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy

P. Buehler, M. Simon, E. Widmann, J. Zmeskal
Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria

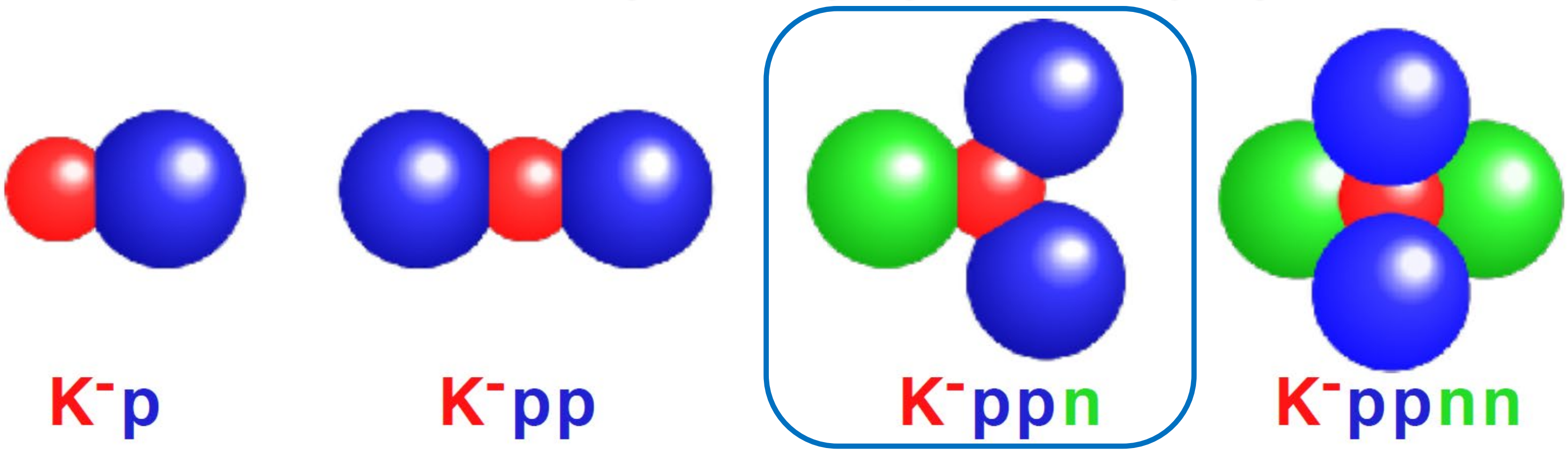






Thank you for your attention!

A first step of the new project



via in-flight $^4He(K^-,N)$

Investigation of fundamental properties of the $\bar{K}NN$ state

J-PARC P89

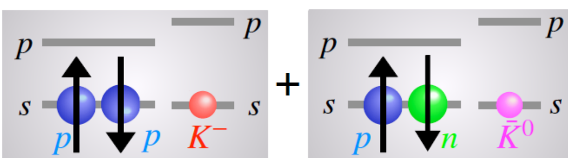
J-PARC P89

Internal structure & spin-parity

There are two possible J^P as for the $\bar{K}NN$ ground state.

$$" (NN)_{(I.sym \times S.asym)} \otimes \bar{K} "$$

$J^P = 0^-$

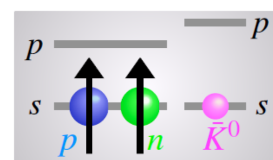


$$\frac{|I_{\bar{K}N} = 0|}{|I_{\bar{K}N} = 1|} = \frac{3}{1}$$

Deeper bound expected

$$" (NN)_{(I.asym \times S.sym)} \otimes \bar{K} "$$

$J^P = 1^-$



$$\frac{|I_{\bar{K}N} = 0|}{|I_{\bar{K}N} = 1|} = \frac{1}{3}$$

Shallower bound expected

* *Positive parity state should be higher excited state if exist.*

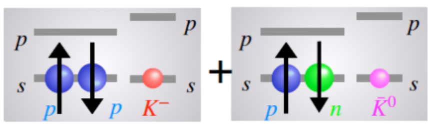
T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

J-PARC P89

How to determine J^P

– Λp spin-spin correlation ($\alpha_{\Lambda p}$) in $K^- pp \to \Lambda p$ decay –

$J^P = 0^-$



To make negative parity from Λp

$L_{\Lambda p} = 1$

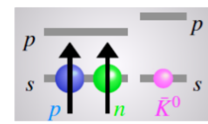
To be $J = 0$

$S_{\Lambda p} = 1$

$\alpha_{\Lambda p} = +1$

Spin parallel

$J^P = 1^-$



To make negative parity from Λp

$L_{\Lambda p} = 1$

To be $J = 1$

$BR = 1/3$ $S_{\Lambda p} = 0$ + $S_{\Lambda p} = 1$ $BR = 2/3$

$\alpha_{\Lambda p} = -1$ + $\alpha_{\Lambda p} = +1$

Spin anti-parallel | Spin parallel

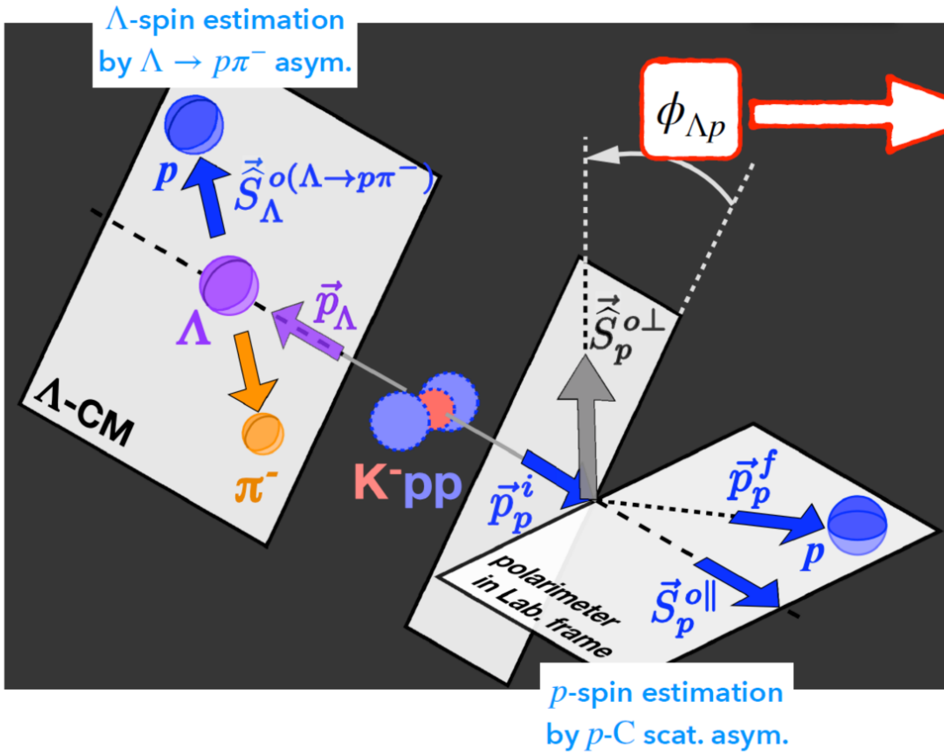
We can deduce J^P from $\alpha_{\Lambda p}$ measurement.

T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

J-PARC P89

How to measure spin-spin correlation

– 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;

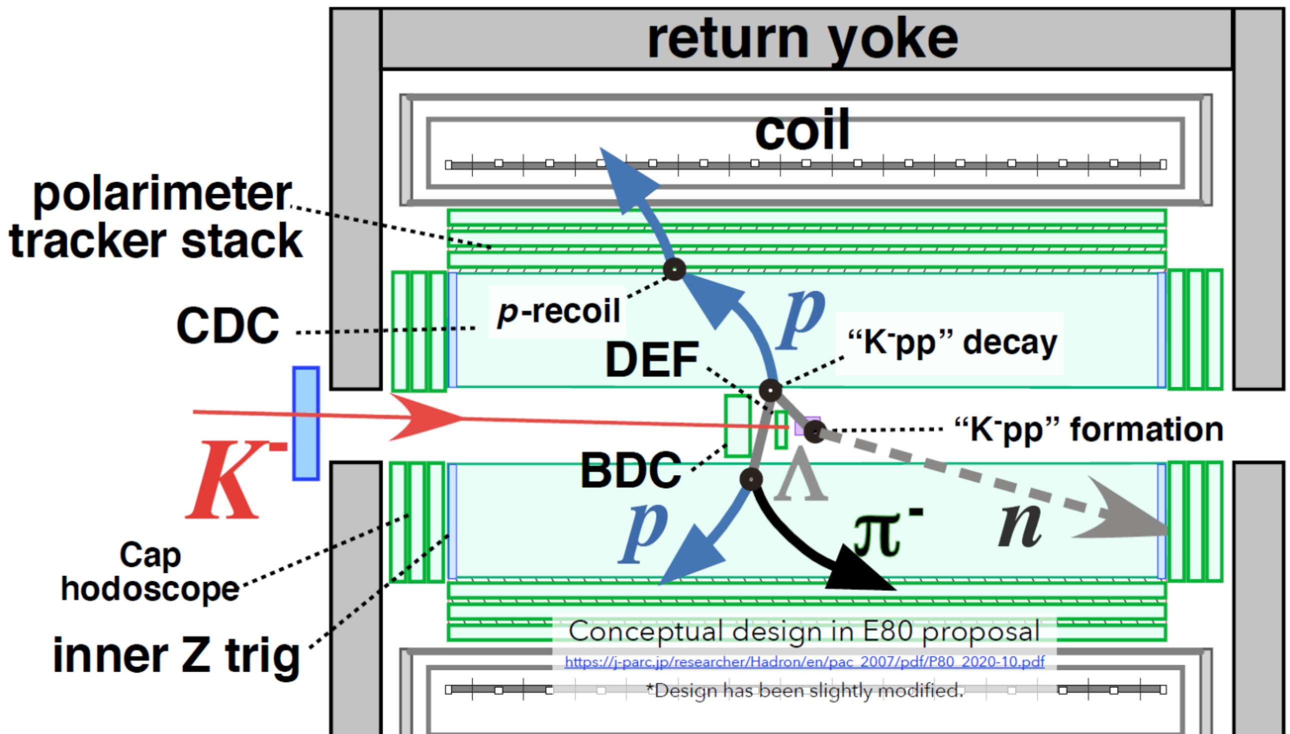
- α_- : Λ asym. parameter
- A_{pC} : Analyzing power
- $f_{\vec{S}_\Lambda}$: Spin distribution
- B : Magnetic field
- $B_{\bar{K}}$: Binding energy
- q : Momentum transfer

We can observe $\alpha_{\Lambda p}$ from $\phi_{\Lambda p}$-distribution.

T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

J-PARC P89

Cylindrical detector system



$\sim 4\pi$ acceptance for charged & neutron

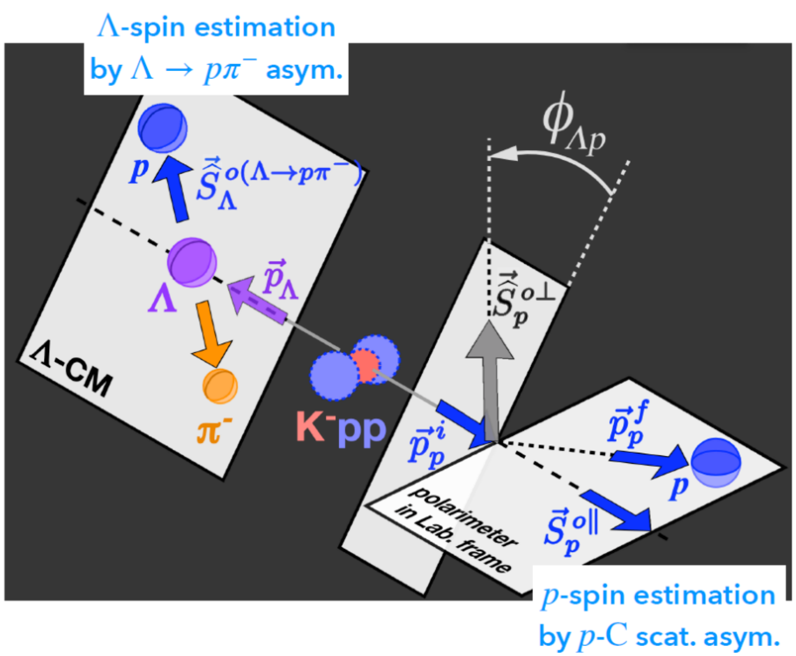
Polarimeter system for p-spin measurement

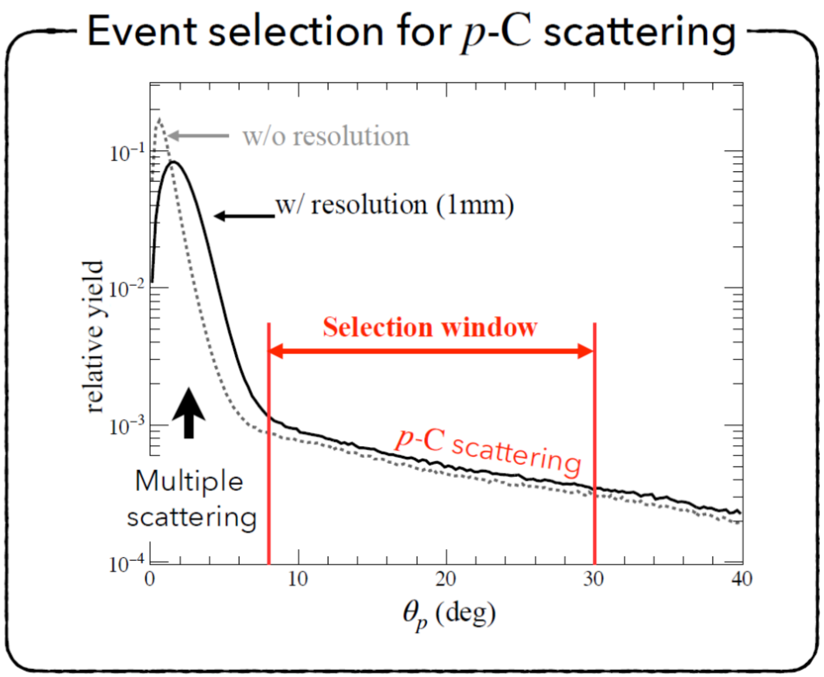
T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

J-PARC P89

Expected spectra

– To measure $\phi_{\Lambda p}$-asymmetry for J^P determination –



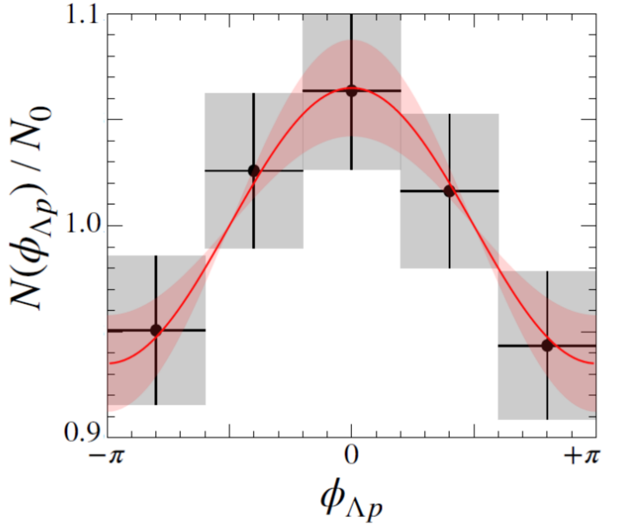


J-PARC P89

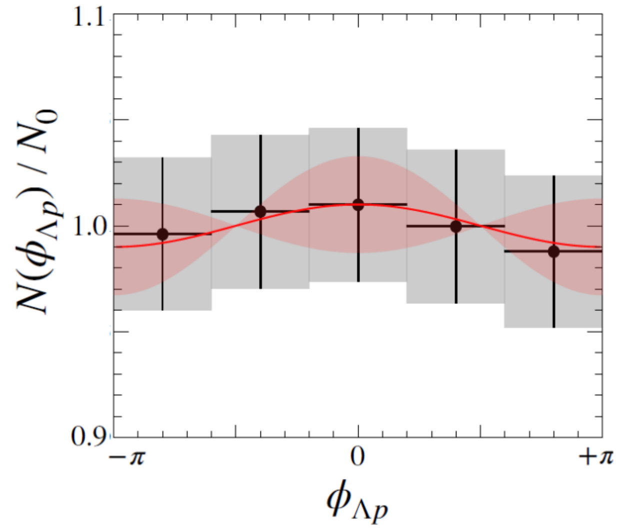
Expected spectra

– To measure $\phi_{\Lambda p}$-asymmetry for J^P determination –

$J^P = 0^-$



$J^P = 1^-$



We would exclude $J^P = 1^-$ with **95%** confidence level from **only $\phi_{\Lambda p}$-asym**.

T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/