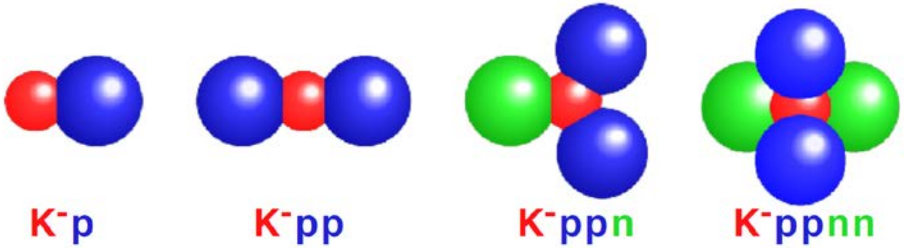
New experiment on kaonic nucleus at J-PARC

– from the $\bar{K}N$ *to* $\bar{K}NNNN$ *systems –*



F. Sakuma, RIKEN

on behalf of

the J-PARC P80 collaboration

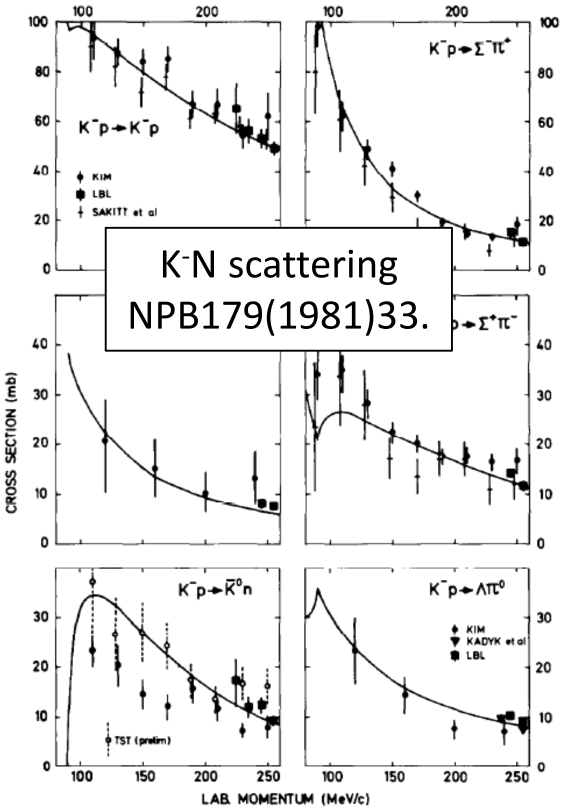
Joint THEIA-STRONG2020 and JAEA/Mainz REIMEI Web-Seminar, Dec 6, 2020

Physics Goal

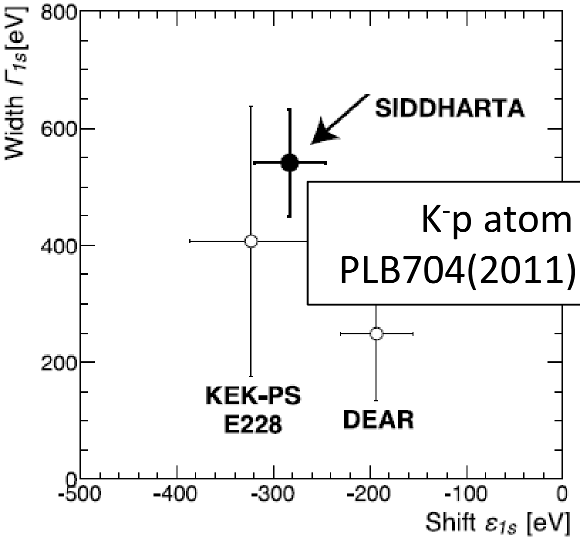
Reveal the $\bar{K}$ meson property inside nuclei via **the $\bar{K}N$ interaction**

A powerful probe to understand low energy QCD

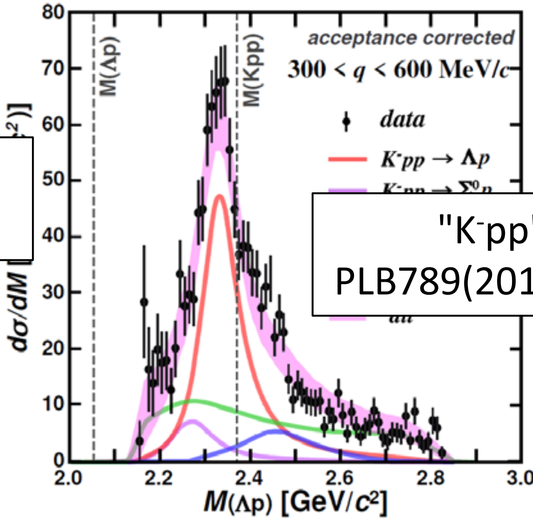
Strongly attractive in I=0 from extensive measurements **→ kaonic nuclei**



K^-N scattering
NPB179(1981)33.



K^-p atom
PLB704(2011)113.



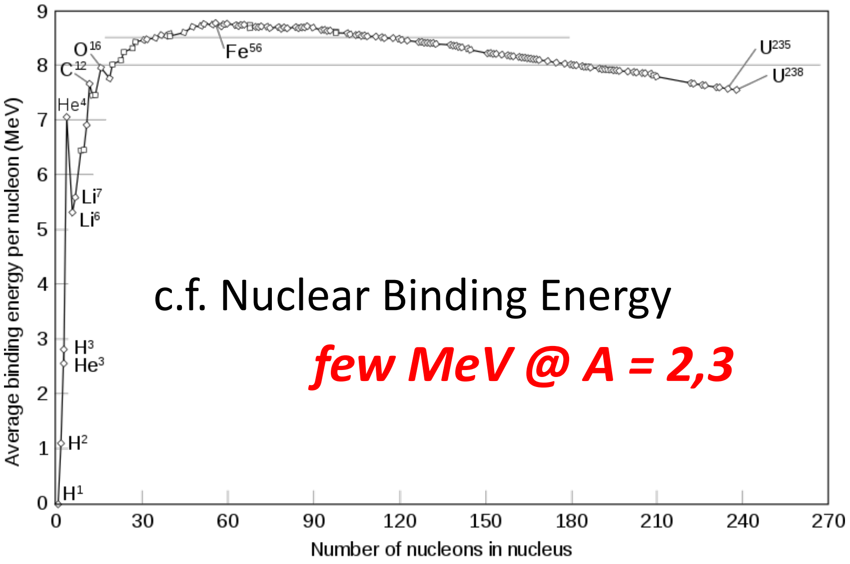
"K^-pp"
PLB789(2019)620.

Kaonic Nuclei

Predicted from **attractive $\bar{K}N$ interaction in I=0**

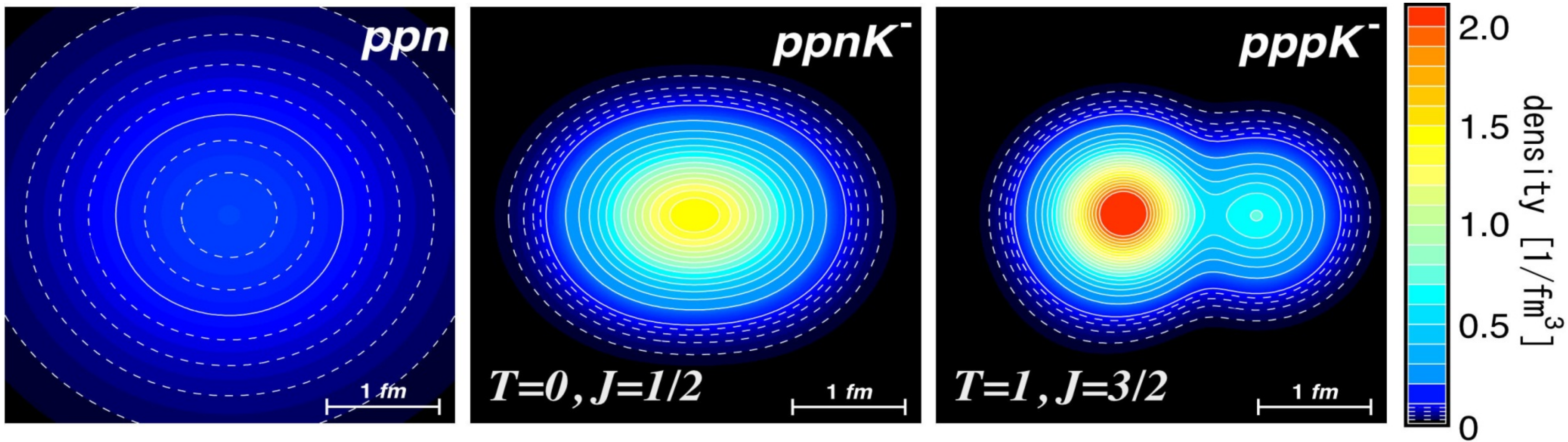
Kaonic Nuclei	Binding Energy [MeV]	Width [MeV]
$\Lambda(1405) = K^-p$	27	40
K^-pp	48	61
K^-ppp	97	13
K^-ppn	118	21

PL7(1963)288., PRC65(2002)044005., etc.



c.f. Nuclear Binding Energy

few MeV @ A = 2,3

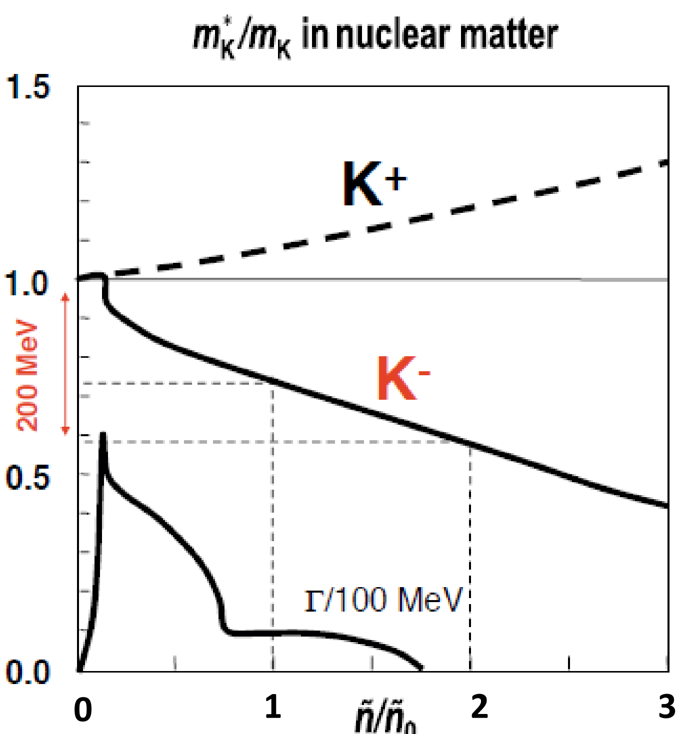


Kaonic Nuclei

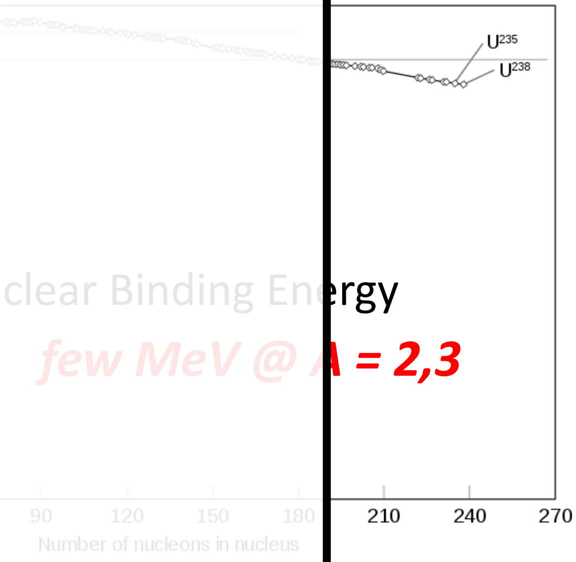
Predicted from … action in **I=0**

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

…88., PRC65(2002)044005., etc.

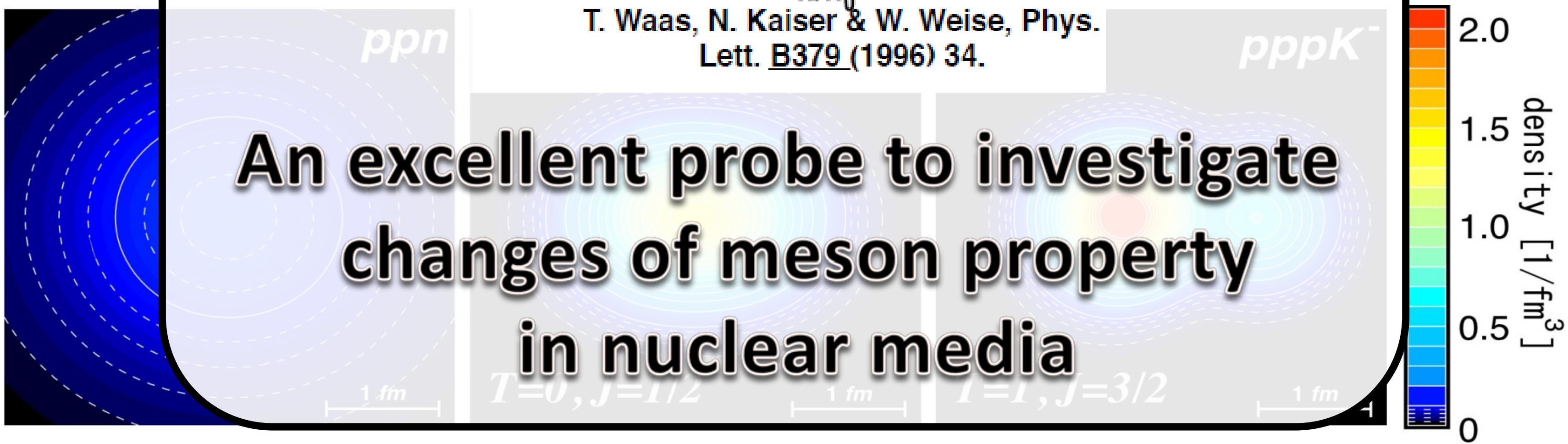


T. Waas, N. Kaiser & W. Weise, Phys. Lett. B379 (1996) 34.



…clear Binding Energy

few MeV @ A = 2,3



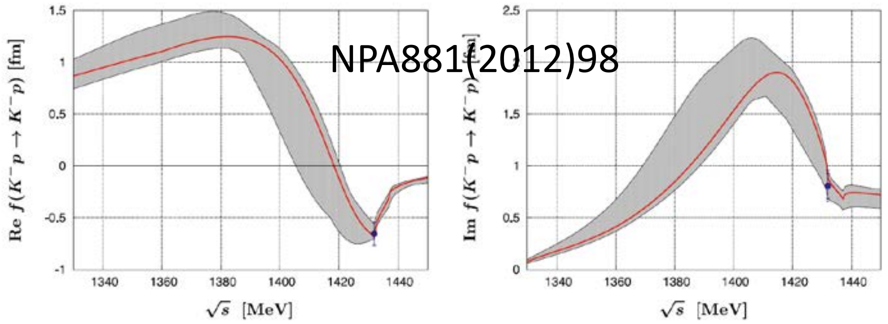
An excellent probe to investigate changes of meson property in nuclear media

Are Kaonic Nuclei Really Compact?

In the case of the $\bar{K}NN$ system ($J^P=0^-$)

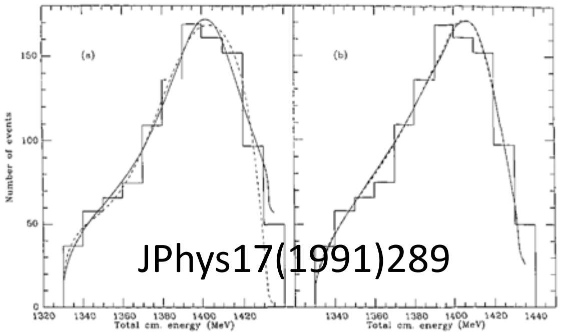
$K^{bar}N$ int.	Chiral SU(3) (energy dependent)	Phenomenological (energy independent)

$M_{\Lambda(1405)}$~1420, double pole

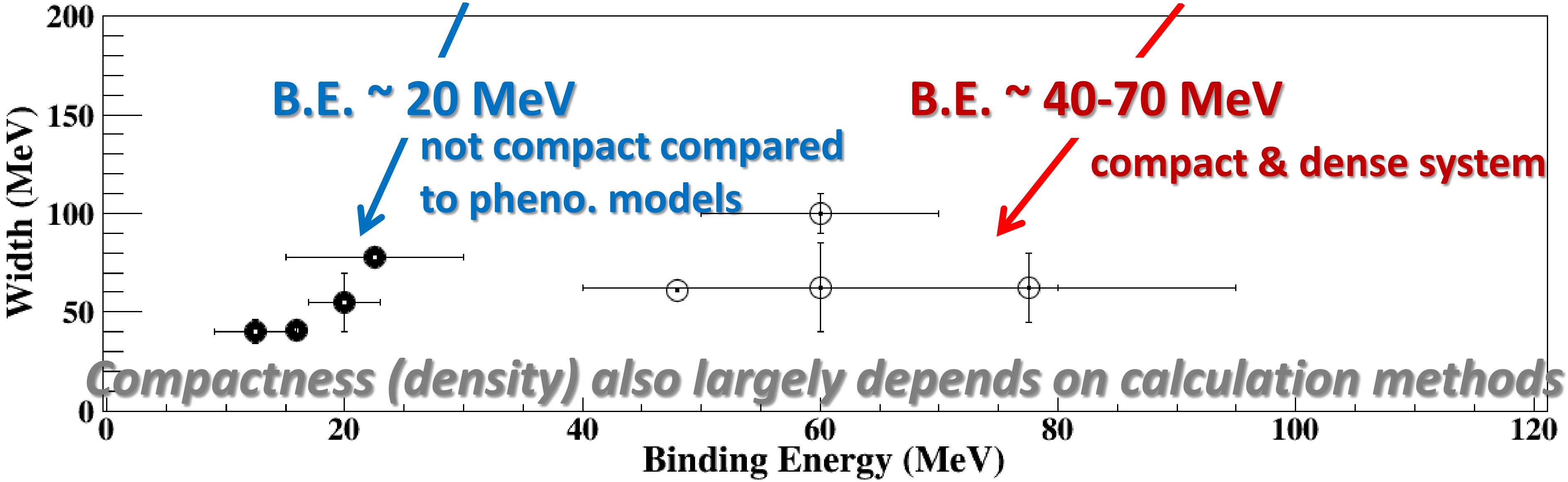


NPA881(2012)98

$M_{\Lambda(1405)}$~1405, single pole



JPhys17(1991)289



B.E. ~ 20 MeV

not compact compared to pheno. models

B.E. ~ 40-70 MeV

compact & dense system

Compactness (density) also largely depends on calculation methods

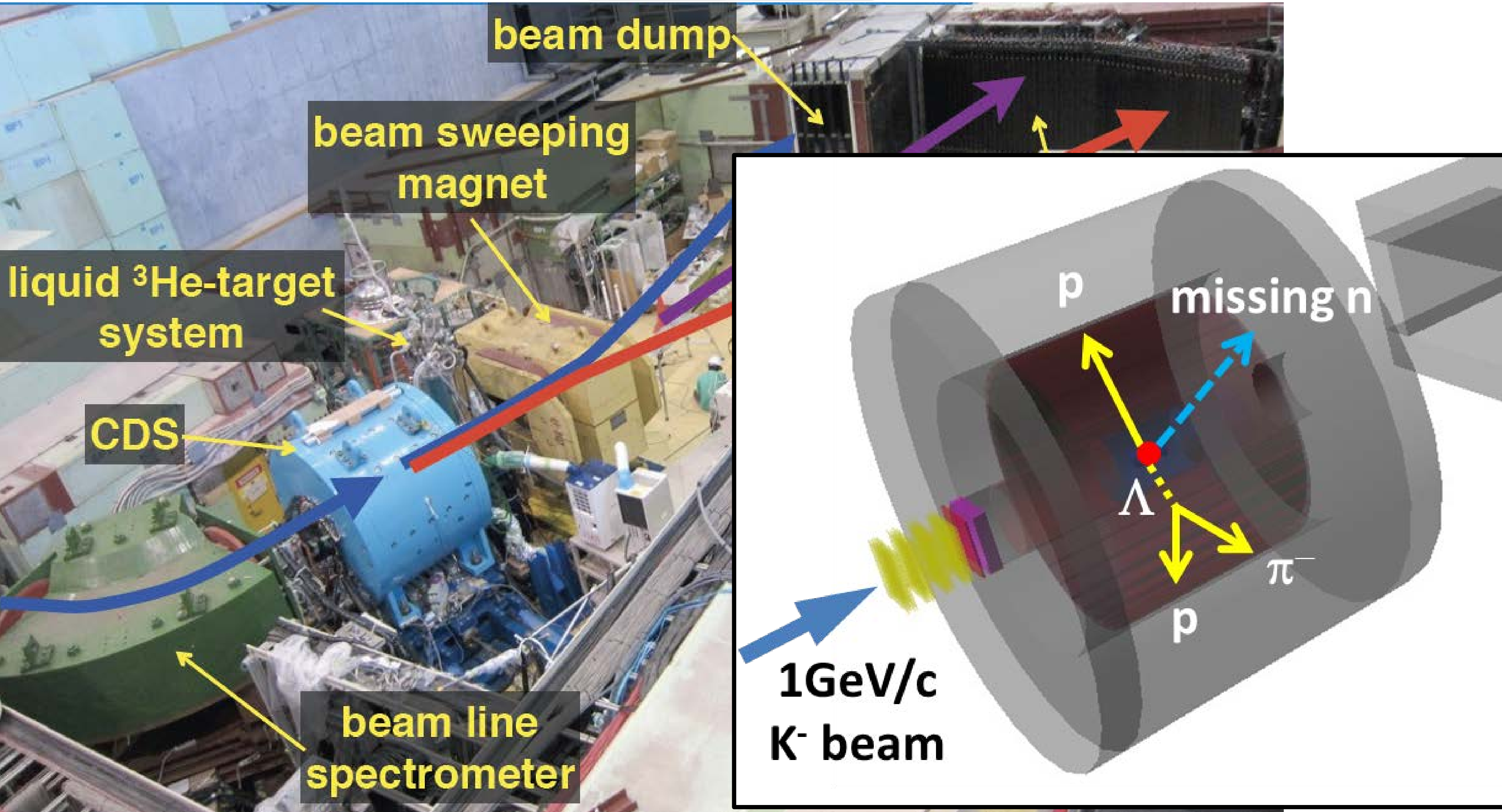
J-PARC E15 Experiment

-- brief review --

J-PARC E15 Experiment

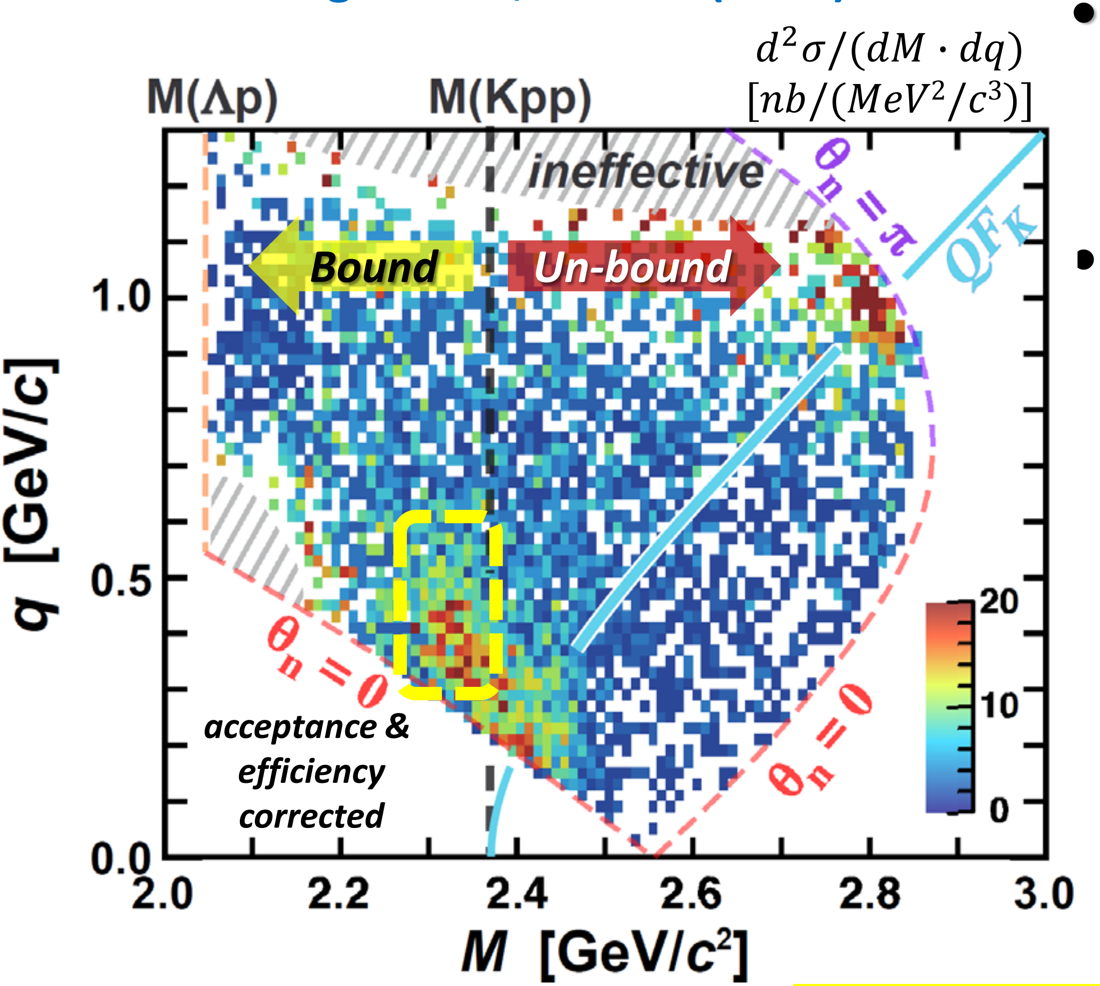
- Experimental Search for the $\bar{K}NN$ -

- We measured the **$^3He(K^-,\Lambda p)n$** reaction



(K^-,n) Momentum Transfer Analysis

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
- **QF followed by 2NA** shows Λpn FS can be generated from 2-step processes via (K^-,n)
  - ✓q-dependent

→ quite important to understand the production mechanism of the “K^-pp” bound state

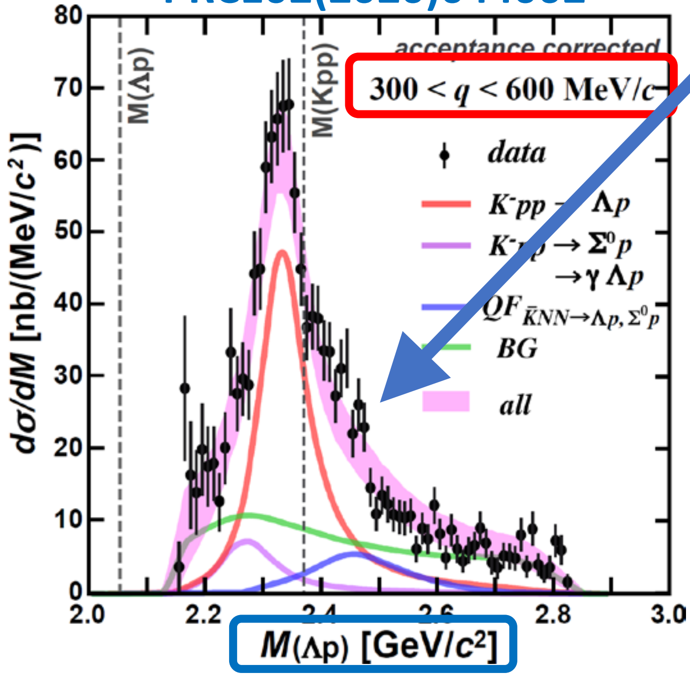
2D analysis in (M,q) is essential

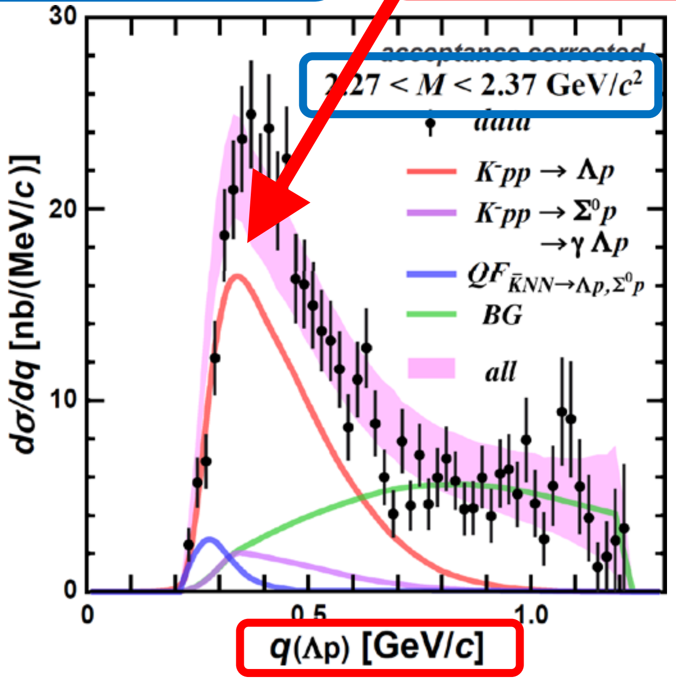
“K⁻pp” Bound State

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*

The results suggest the “K⁻pp” is quite compact

Size of “K$^-$pp”

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

B_{Kpp} ~ 40 MeV
→ *large binding energy*

Q_{kpp} ~ 400 MeV
→ *wide momentum transfer*

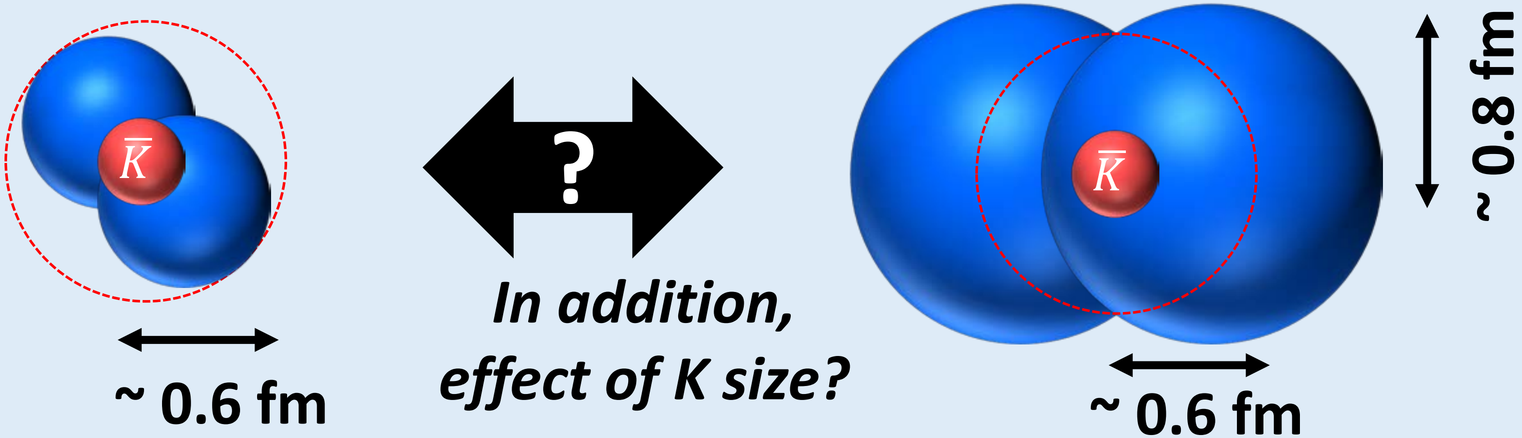
suggest the “K$^-$pp” is quite compact (R_{Kpp} ~ 0.6 fm)

→ Need more realistic theoretical calculations

Still an open question ($\bar{K}N$ = strong force)

Radius of “K$^-$pp”

Interaction range of “K$^-$”



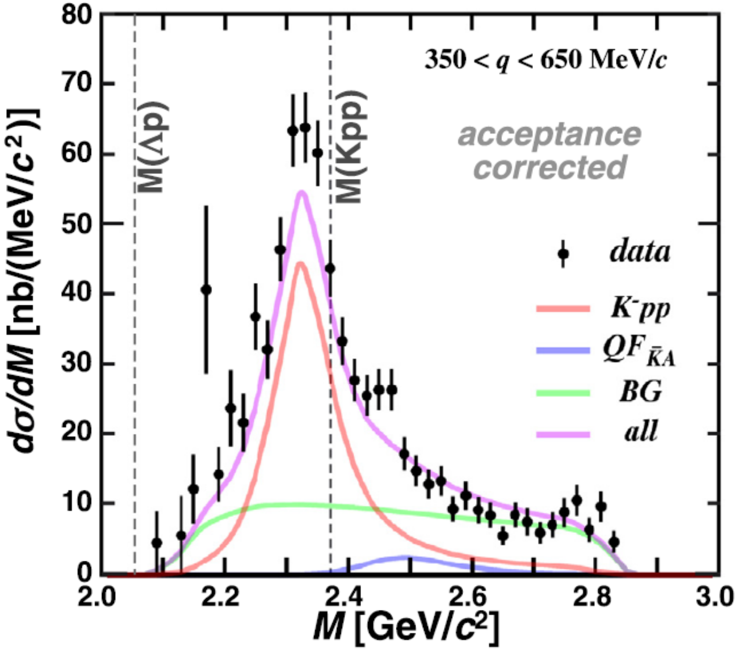
In addition, effect of K size?

Theoretical Progresses

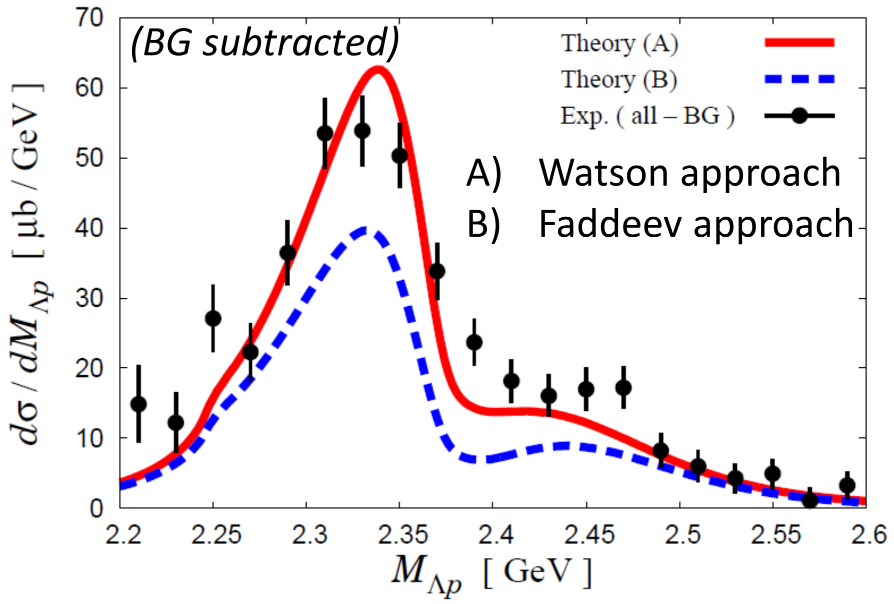
- A theoretical calculation in chiral unitary approach reproduces the mass spectrum with the $\bar{K}NN$

→ Theoretical investigations for experimental results are indispensable

PLB789(2019)620.
PRC102(2020)044002.



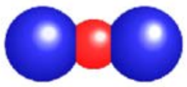
PTEP,2016(2016)123D03.
JPS Conf. Proc.26(2019)023009.



A) Watson approach
B) Faddeev approach

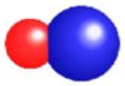
Many Questions to be Answered

- **Further details of the $\bar{K}NN$**
  - Spin and parity of the "K^-pp"?
  - Strength of $\bar{K}N$ interaction?
  - Really compact and dense system?



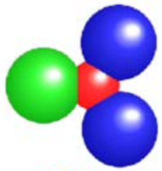
K^-pp

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



K^-p

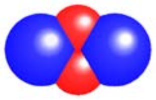
- **More heavier kaonic nuclei?**
  - Mass number dependence?



K^-ppn

K^-ppnn

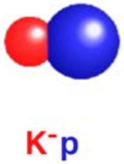
- **Double kaonic nuclei?**
  - Much compact and dense system?



K^-K^-pp

New Project

-- systematic investigation of the light kaonic nuclei --

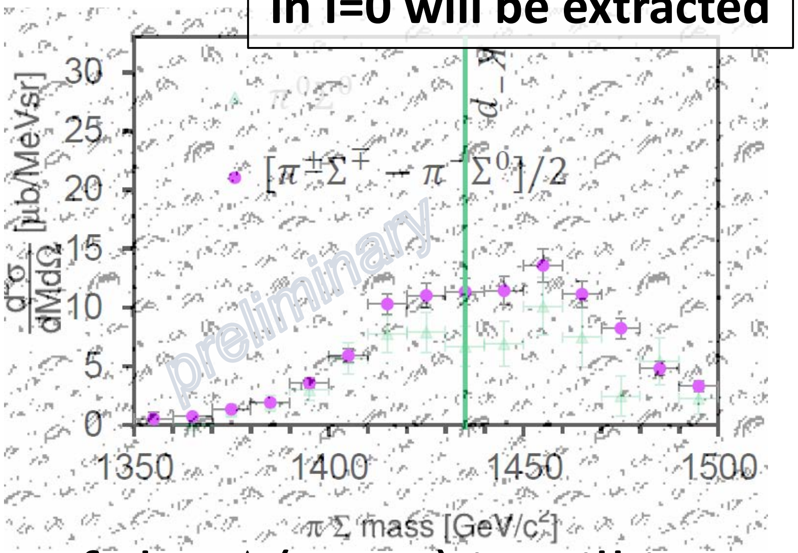


Task for $\bar{K}N$

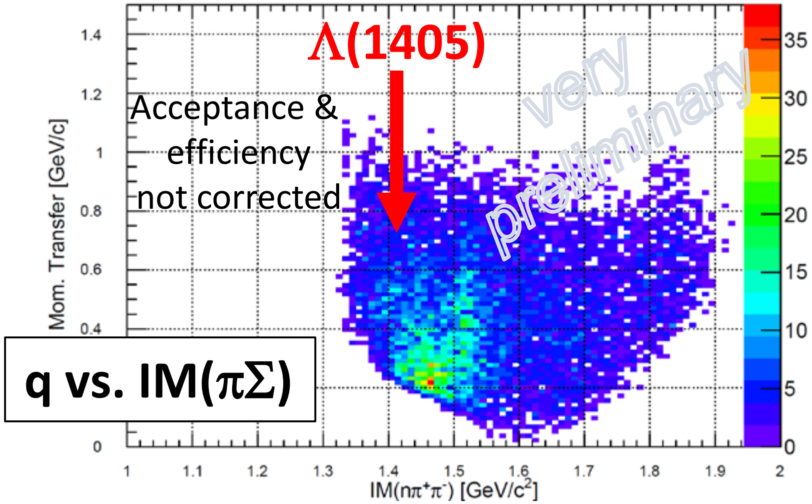
- Theoretically, $\Lambda(1405)$ is consider to be the $\bar{K}N$ quasi-free bound state
- We are now trying to determin the line shape of the $\bar{K}N \rightarrow \pi\Sigma$ channel via the (K^-,n) reaction at θ_n=0° in E31

E31 results

$\bar{K}N \rightarrow \bar{K}N$ Amplitude in I=0 will be extracted



Exploratory analysis at E31

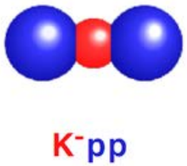


q vs. IM($\pi\Sigma$)

- Size of the $\Lambda(1405)$ is still important subject to be determined

  → Clarify the picture whether a baryonic state or a $\bar{K}N$ molcuer

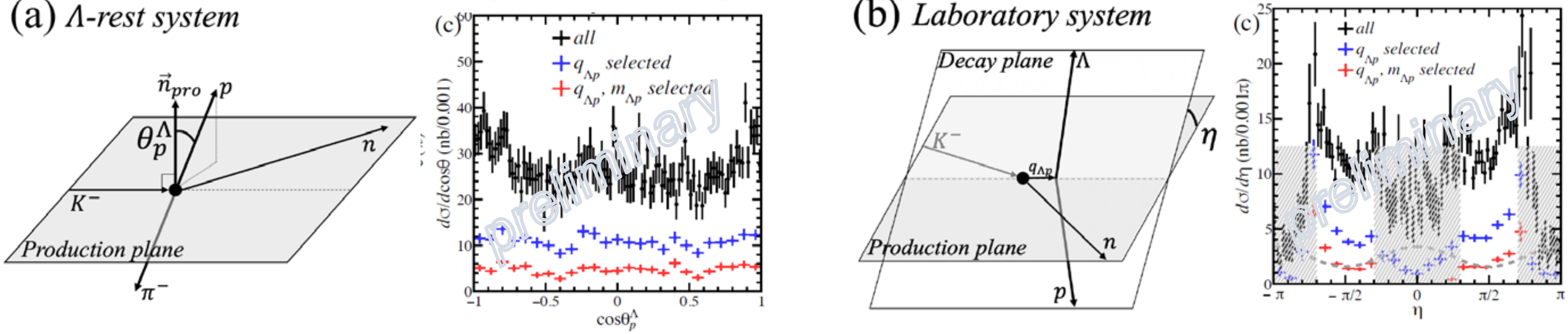
- **We deduce the $\Lambda(1405)$ size via form factor measurement in a wide range of *q***



Task for $\bar{K}NN$

- The $\bar{K}NN$ system is expected to have $J^P = 0^-$
- To determine the spin/parity, **“topological analysis of decay particles”** ***and/or*** **“direct measurement of decay particle polarization”** is essential

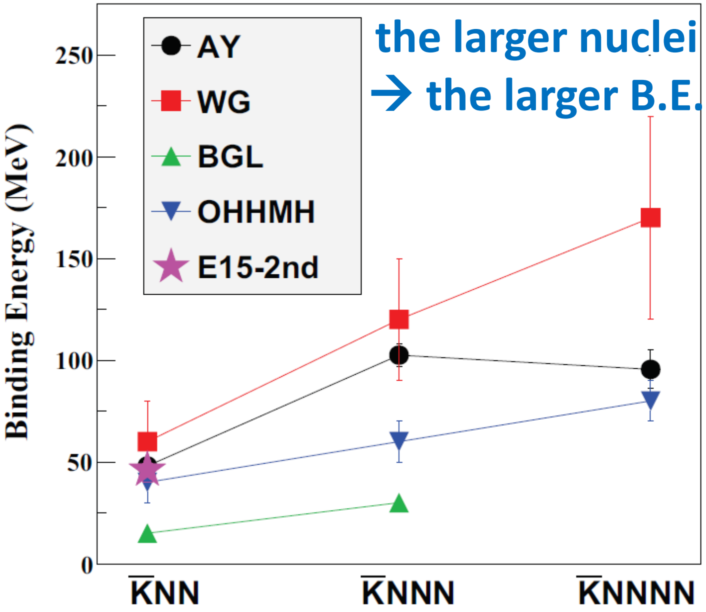
Exploratory analysis at E15



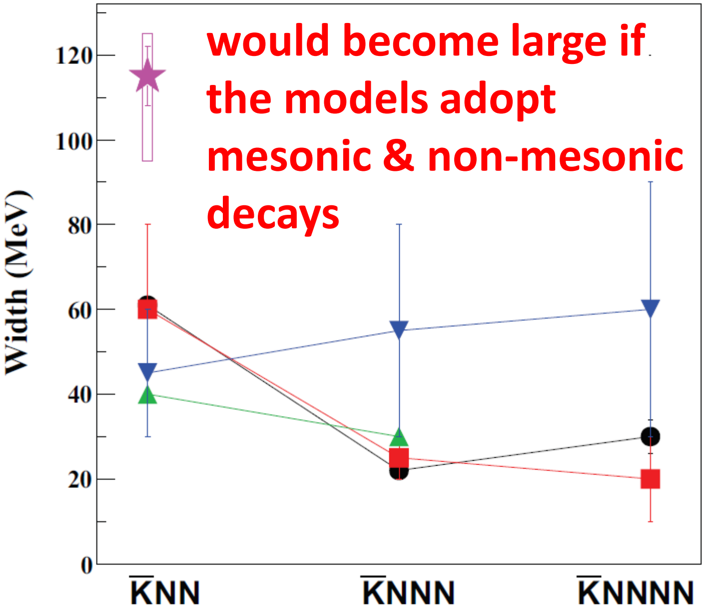
- **We determine the spin/parity of the system via its Λp decay**
  - by introducing a polarimeter composed of a hodoscope and a tracker
- **We precisely deduce the system size**
  - with more statistical data in corporation with theoretical analyses

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

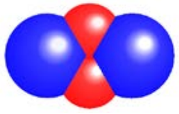
- Beyond the $\bar{K}NN$, more heavier system must be explored to establish the kaonic nuclei
  - ✓In particular, the $\bar{K}NNNN$ system is expected to be the most compact system due to an α particle configuration
- **We reveal the mass number dependence of the binding energy, decay width, and system size**



the larger nuclei
→ the larger B.E.

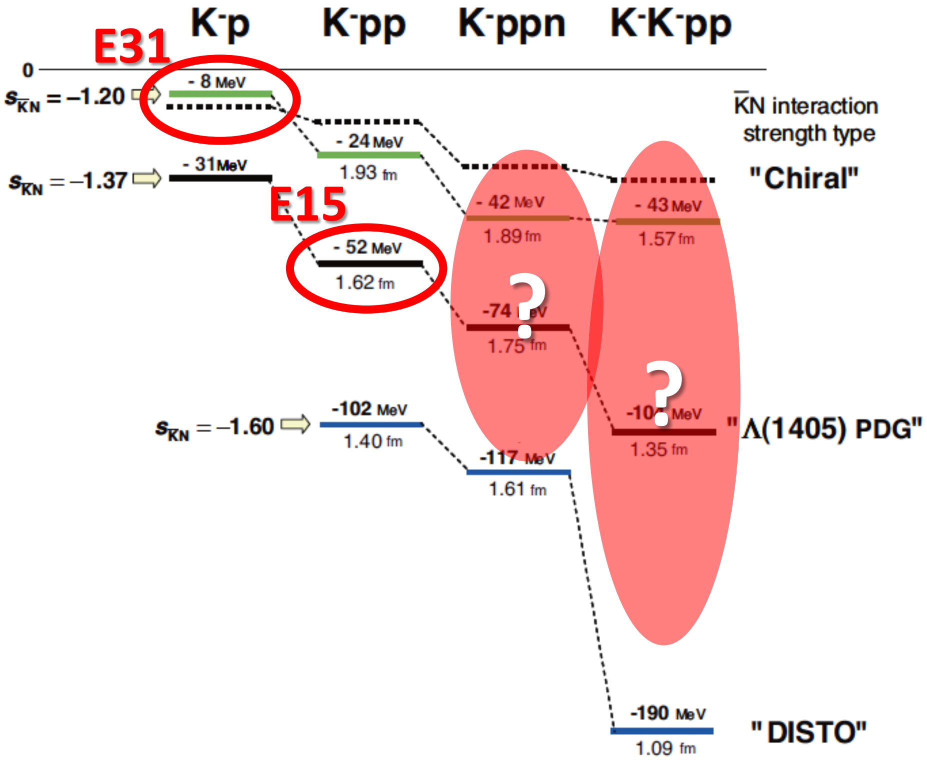


would become large if the models adopt mesonic & non-mesonic decays



Toward $\bar{K}\bar{K}NN$

- **We also wish to access the S = −2 kaonic nuclei such as the theoretically predicted “K⁻K⁻pp” state**
  - ✓LoI was submitted ($\bar{p}\ {}^{3}\mathrm{He}$ annialation)
  - ✓A good probe to the $\bar{K}N$ int.



Proc. Jpn. Acad., **B89** (2013) 418.

- The $\bar{K}\bar{K}NN$ system could give us a chance to access much higher density than the S = −1 kaonic nuclei

The $\bar{K}\bar{K}NN$ production cross section would be quite small
→roughly 1/1000 of that of the $\bar{K}NN$

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)	$\pi^{\pm0}\Sigma^{\mp0}$	n/γ identification	
$\bar{K}NN$	^{3}He(K$^-$,N)	$\Lambda p/\Lambda n$	polarimeter	**← Feasibility study**
$\bar{K}NNN$	^{4}He(K$^-$,N)	$\Lambda d/\Lambda pn$	large acceptance	**← A first step**
$\bar{K}NNNN$	*^{6}Li(K$^-$,d)*	*$\Lambda t/\Lambda dn/\Lambda pnn$*	*many body decay*	**← Feasibility study**
$\bar{K}\bar{K}NN$	*$\bar{p}$ + ^{3}He*	*$\Lambda\Lambda$*	*$\bar{p}$ beam yield*	

*We take a **step-by-step** approach*

- To realize the systematic measurements, we utilize
  - ☐ **a large acceptance spectrometer**
    - detect/identify all particles to specify the reaction
  - ☐ **high-intensity kaon beam**
    - more K$^-$ yield than the existing beamline

J-PARC P80 Experiment

-- $\bar{K}NNN$ *search via* $K^{-}+{}^{4}He$ *reactions --*

“K$^-$ppn” Candidates so far

- A few candidates have been reported in ***inclusive*** measurements

◆**E471/E549@KEK** ← **NULL results**

  - ^{4}He(stopped-K$^-$,p/n)X

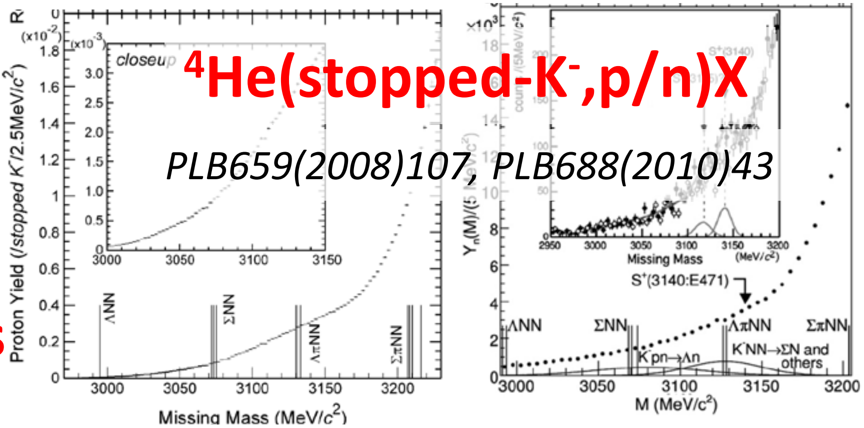
◆**FINUDA@DAΦNE** ← **Observed?**

  - Li/C(stopped-K$^-$,Λd)

◆**FOPI@GSI** ← **Observed?**

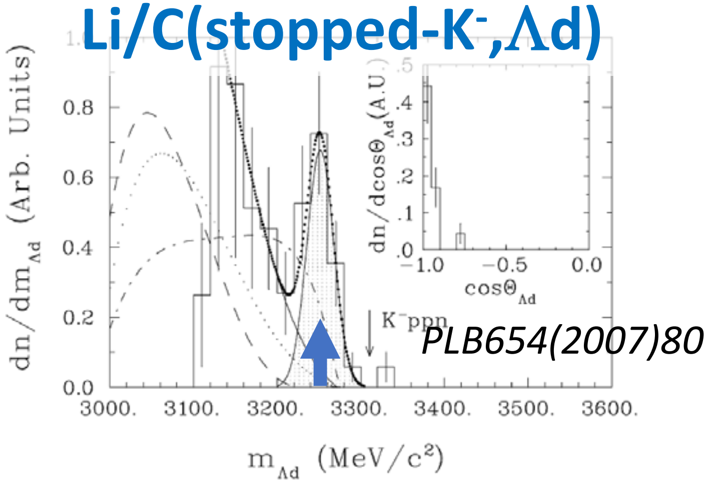
  - Λd in Ni+Ni

- **Exclusive measurement using a simple reaction (in-flight & light nuclei) is crucial**



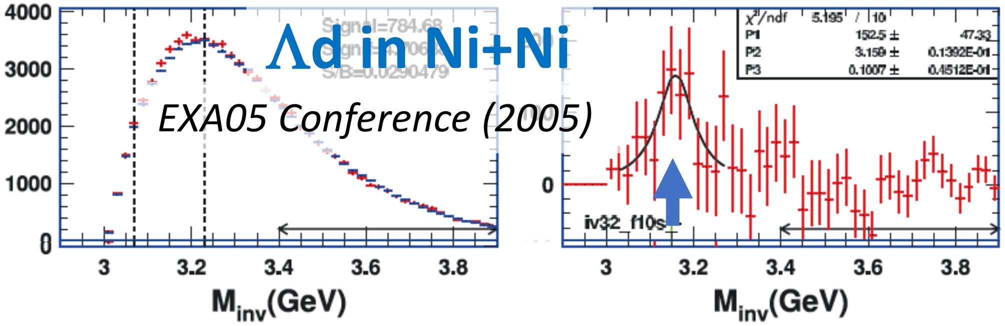
^{4}He(stopped-K$^-$,p/n)X

PLB659(2008)107, PLB688(2010)43



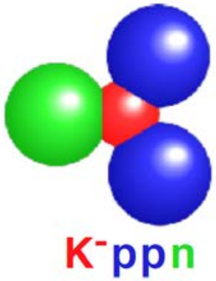
Li/C(stopped-K$^-$,Λd)

PLB654(2007)80



Λd in Ni+Ni

EXA05 Conference (2005)



A First Step: Search for $\bar{K}NNN$

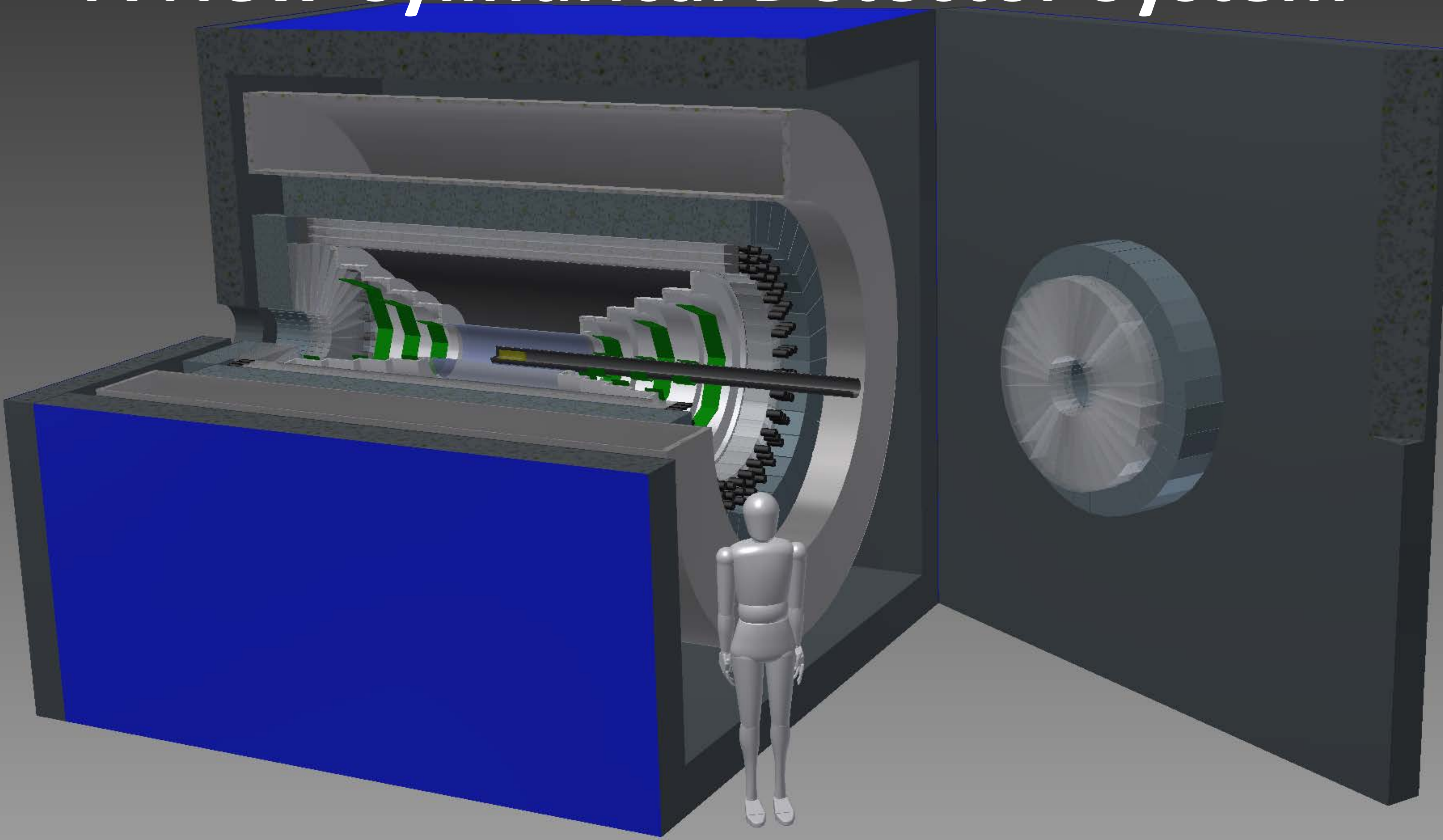
Goals of the proposed experiment:

① **Observe the K$^-$ppn state via 2-body Λd decay**
- Establish the existence of the kaonic nuclei

② **Reconstruct the K$^-$ppn state via 3-body Λpn decay**
- As a feasibility study to access heavier system

- **Feasibility study of the polarization measurement**
  - *e.g.*, by installing a prototype module of the polarimeter

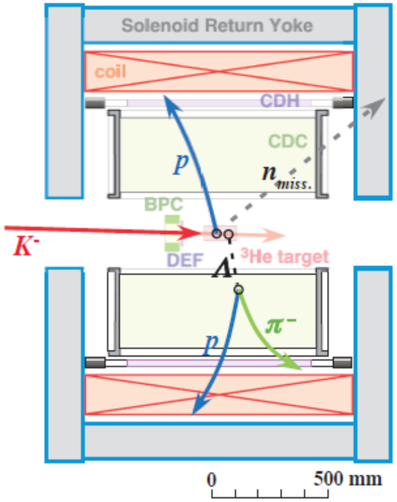
A New Cylindrical Detector System

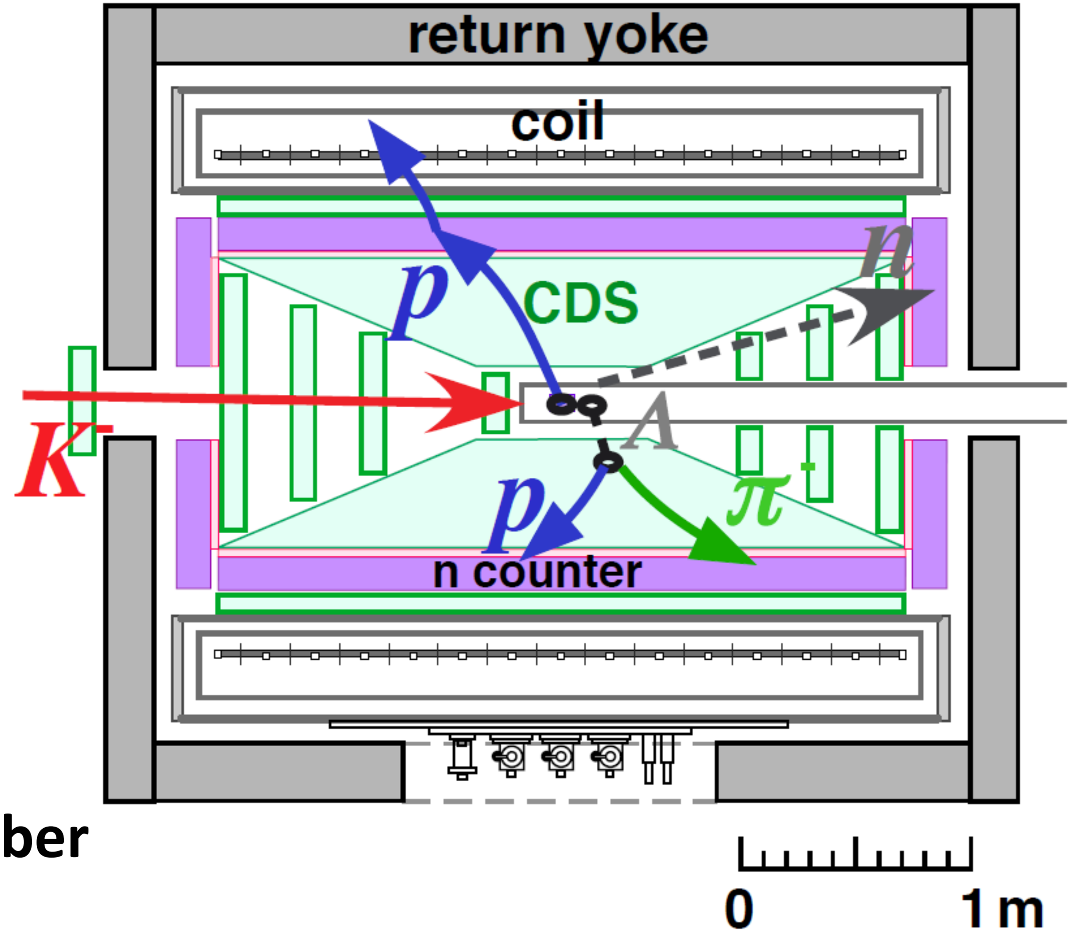


A new 4π spectrometer with n/γ detection capability

A New Cylindrical Detector System

present setup





- **SC Solenoid Magnet**
- **Cylindrical Drift Chamber**
- **Neutron Counter**
- FWD/BWD Drift Chambers
- Vertex Fiber Tracker
- Electromagnetic Calorimeter (constructed in 2nd-stage)

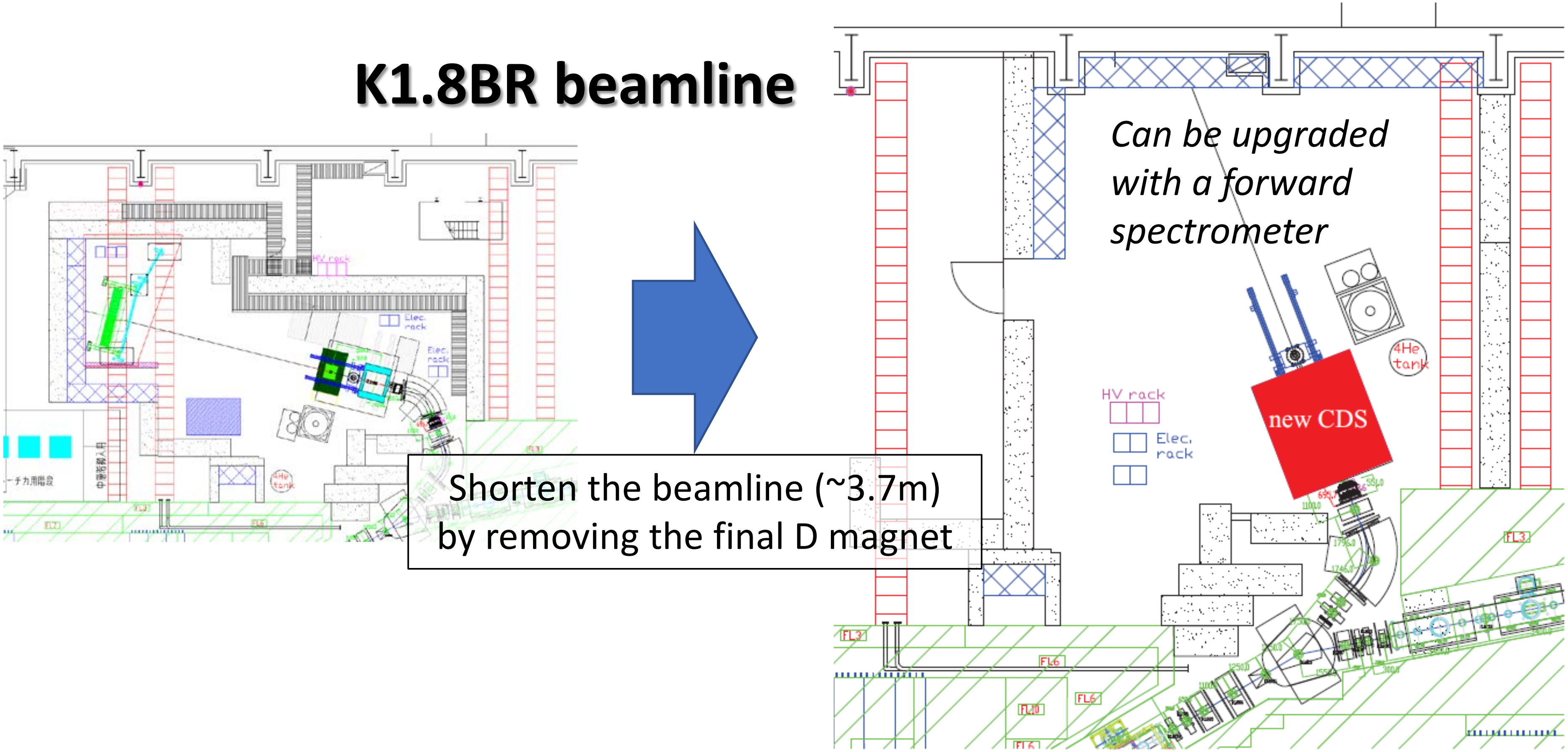
Solid angle: ~x1.5 (~90%)

Neutron detection capability: ~x10

(~1.5x15%)

Improvement of Kaon Intensity

K1.8BR beamline



Can be upgraded with a forward spectrometer

Shorten the beamline (~3.7m) by removing the final D magnet

- **We propose a new configuration of the beamline**
  - K- yield is expected to increase by **~ 1.4 times @ 1.0 GeV/c**

Expected Yield of $\bar{K}NNN$

$$\begin{aligned} N &= \sigma \times N_{beam} \times N_{target} \times \epsilon, \\ \epsilon &= \epsilon_{DAQ} \times \epsilon_{trigger} \times \epsilon_{beam} \times \epsilon_{fiducial} \times \Omega_{CDS} \times \epsilon_{CDS}, \end{aligned}$$

- We assume the K$^-$ppn cross section of

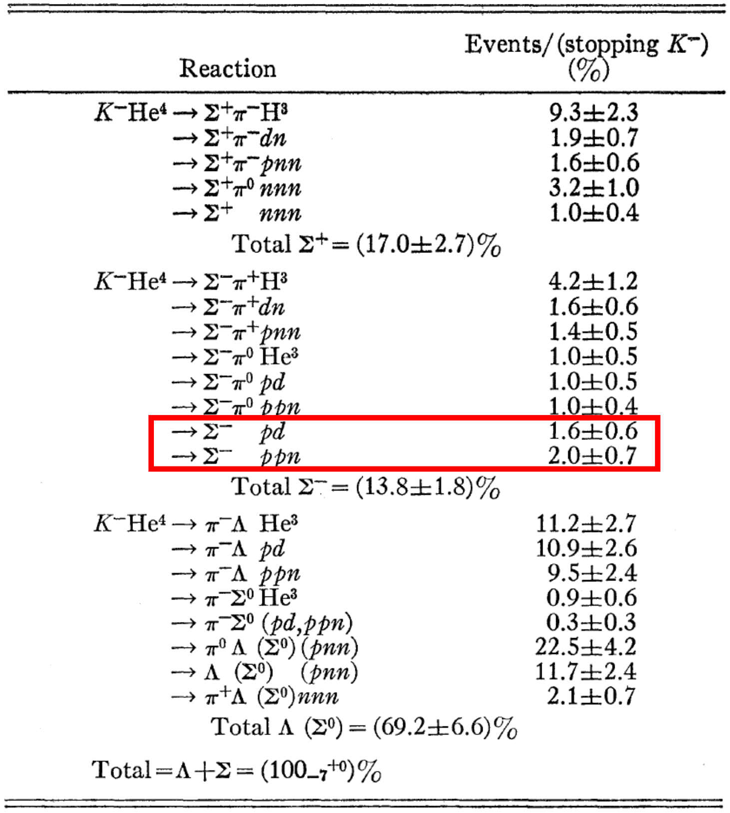
$$\boldsymbol{\sigma(K^-ppn) \cdot Br(\Lambda d) \sim 10\ \mu b}$$
$$\boldsymbol{\sigma(K^-ppn) \cdot Br(\Lambda pn) \sim 10\ \mu b}$$

◆ The same CS of “K-pp”→Λp in E15

◆ *As for Λd decay, we refer to the absorption of stopped K$^-$ on ^{4}He*

→decay fraction to Σ$^-$pd : Σ$^-$ppn ~ 1 : 1

absorption of stopped K$^-$ on ^{4}He



Reaction	Events/(stopping K^-) (%)
$K^-\mathrm{He}^4 \rightarrow \Sigma^+\pi^-\mathrm{H}^3$	9.3±2.3
$\rightarrow \Sigma^+\pi^- dn$	1.9±0.7
$\rightarrow \Sigma^+\pi^- pnn$	1.6±0.6
$\rightarrow \Sigma^+\pi^0\ nnn$	3.2±1.0
$\rightarrow \Sigma^+\quad nnn$	1.0±0.4
Total $\Sigma^+ = (17.0\pm2.7)\%$	
$K^-\mathrm{He}^4 \rightarrow \Sigma^-\pi^+\mathrm{H}^3$	4.2±1.2
$\rightarrow \Sigma^-\pi^+ dn$	1.6±0.6
$\rightarrow \Sigma^-\pi^+ pnn$	1.4±0.5
$\rightarrow \Sigma^-\pi^0\ \mathrm{He}^3$	1.0±0.5
$\rightarrow \Sigma^-\pi^0\ pd$	1.0±0.5
$\rightarrow \Sigma^-\pi^0\ ppn$	1.0±0.4
$\rightarrow \Sigma^-\quad pd$	1.6±0.6
$\rightarrow \Sigma^-\quad ppn$	2.0±0.7
Total $\Sigma^- = (13.8\pm1.8)\%$	
$K^-\mathrm{He}^4 \rightarrow \pi^-\Lambda\ \mathrm{He}^3$	11.2±2.7
$\rightarrow \pi^-\Lambda\ pd$	10.9±2.6
$\rightarrow \pi^-\Lambda\ ppn$	9.5±2.4
$\rightarrow \pi^-\Sigma^0\ \mathrm{He}^3$	0.9±0.6
$\rightarrow \pi^-\Sigma^0\ (pd, ppn)$	0.3±0.3
$\rightarrow \pi^0\Lambda\ (\Sigma^0)\ (pnn)$	22.5±4.2
$\rightarrow \Lambda\ (\Sigma^0)\quad (pnn)$	11.7±2.4
$\rightarrow \pi^+\Lambda\ (\Sigma^0) nnn$	2.1±0.7
Total $\Lambda\ (\Sigma^0) = (69.2\pm6.6)\%$	
Total $= \Lambda + \Sigma = (100_{-7}^{+0})\%$	

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Expected Yield of $\bar{K}NNN$

$$
\begin{aligned}
N &= \sigma \times N_{beam} \times N_{target} \times \epsilon, \\
\epsilon &= \epsilon_{DAQ} \times \epsilon_{trigger} \times \epsilon_{beam} \times \epsilon_{fiducial} \times \Omega_{CDS} \times \epsilon_{CDS},
\end{aligned}
$$

- N_{beam} = **100 G** K- on target
  - under the MR beam power of **90 kW** with **5.2 s** repetition cycle. around 2023
    - 3.2 x 10^5 K- on target / spill @ 1.0 GeV/c
  - **3 weeks** data taking (90% up-time)

- **N(K^-ppn→Λd) ~ 2 x 10^4**
- **N(K^-ppn→Λpn) ~ 3 x 10^3**
  - c.f. 1.7 x 10^3 "K^-pp"→Λp accumulated in E15-2nd (40 G K^-)

	Λd / Λpn
σ(K^-ppn)*Br	10 μb
N(K^- on target)	100 G
N(target)	2.65 x 10^{23}
ε(DAQ)	0.9
ε(trigger)	0.93
ε(beam)	0.55
Ω(CDC)	0.27 / 0.077
ε(CDC)	0.6 / 0.3
N(K^-ppn)	19 k / 2.8 k

**** improved from E15***

Expected Spectrum of K^{-}+^{4}He

@ 3 weeks, 90kW

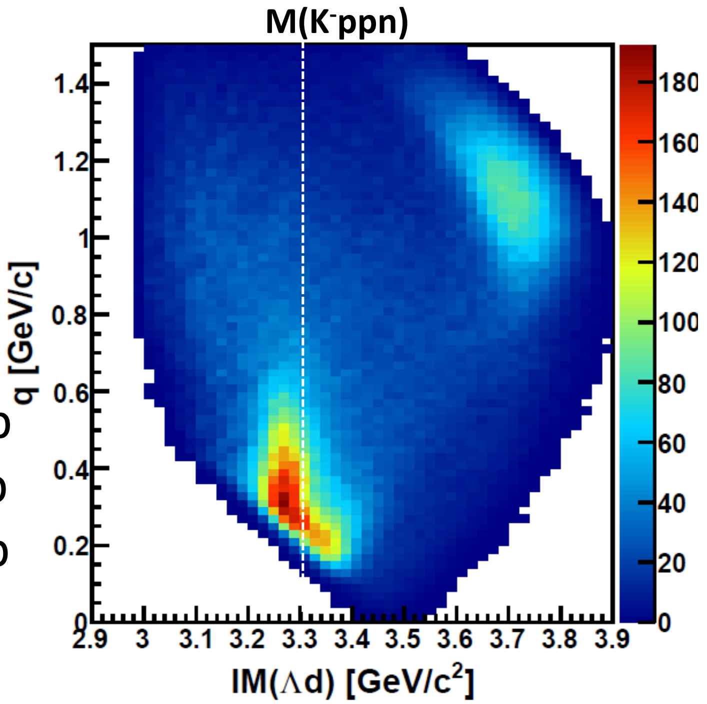
B_{Kppn} ~ 40 MeV

Γ_{Kppn} ~ 100 MeV

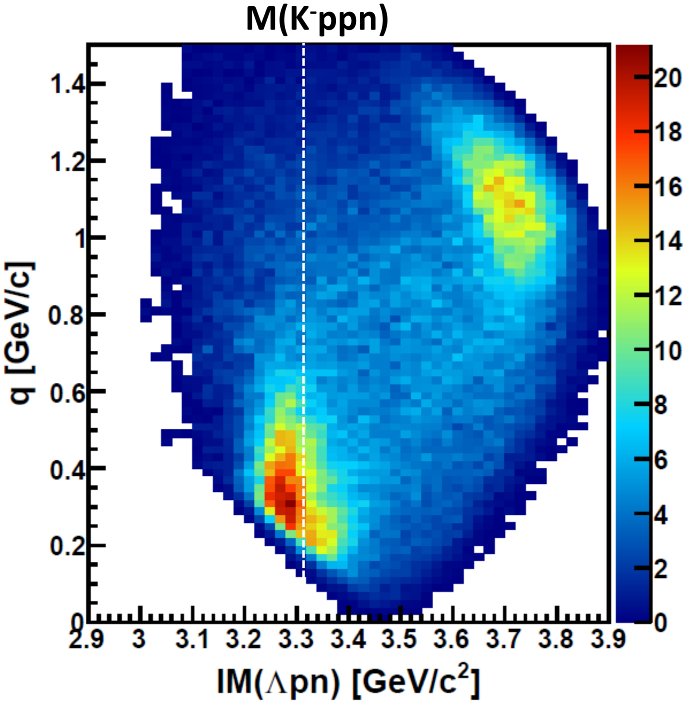
Q_{kppn} ~ 400 MeV/c

$\sigma(K^{-}ppn)$*Br ~ 10 μb
σ(QF) ~ 10 μb
σ(BG) ~ 20 μb

K^{-}+^{4}He→Λd+n



K^{-}+^{4}He→Λpn+n



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

Expected Spectrum of $K^{-}+^{4}He$

@ 3 weeks, 90kW

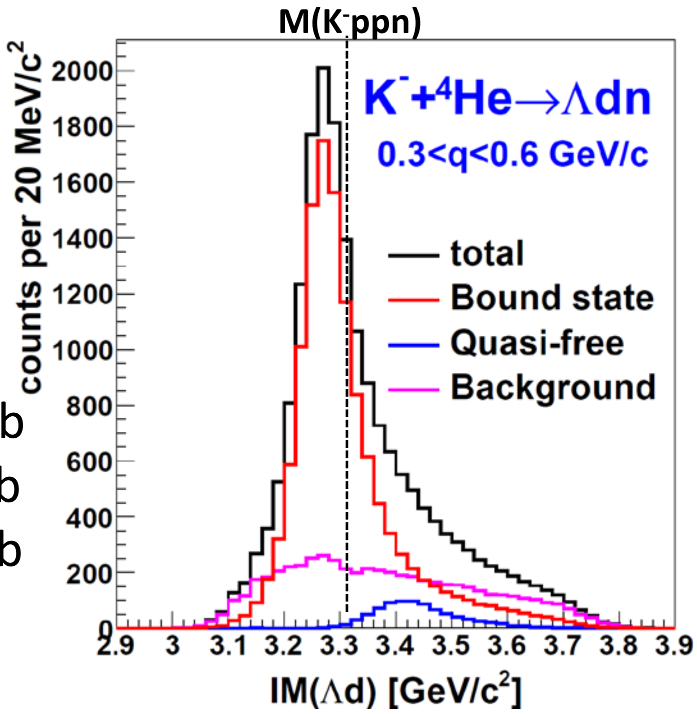
B_{Kppn} ~ 40 MeV

Γ_{Kppn} ~ 100 MeV

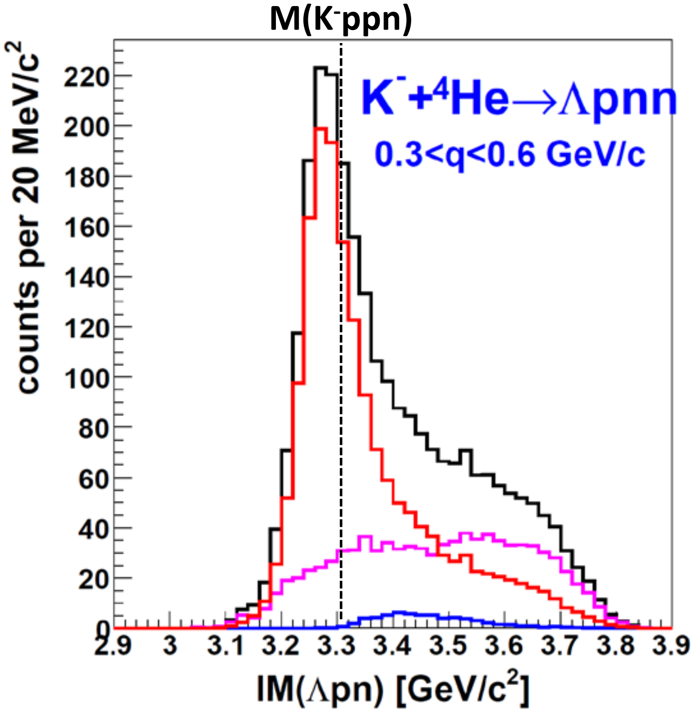
Q_{kppn} ~ 400 MeV/c

$\sigma(K^{-}ppn)$*Br ~ 10 μb
σ(QF) ~ 10 μb
σ(BG) ~ 20 μb

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



$K^{-}+^{4}He \rightarrow \Lambda pn+n$

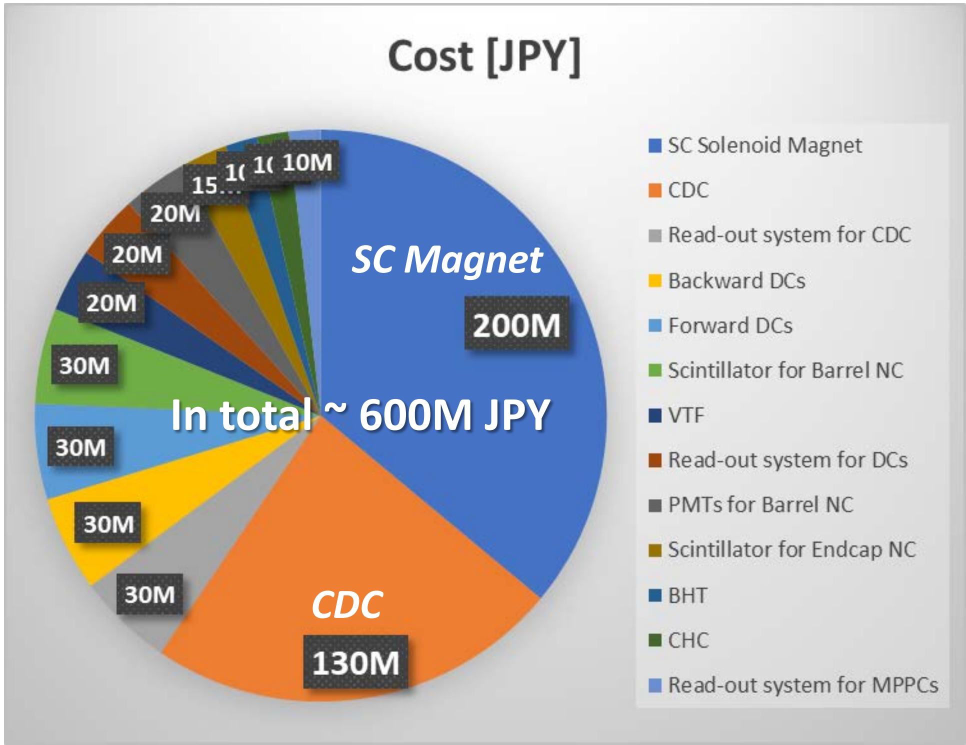


- The signals can be enhanced by selecting 0.3 < q < 0.6 GeV/c
- **The $K^{-}ppn$ signal will be observed if the $\sigma(K^{-}ppn)$*Br is more than ~ μb**

Schedule & Cost

- We would like to preform the proposed experiment **around 2023**
  - ☐ Design & construction: ~2022
  - ☐ Commissioning run : 2023
  - ☐ Performance run followed by Physics run : 2023~

- Most of the construction cost will be covered by “MEXT Grant-In-Aid” and “RIKEN internal budget”
  - ✓ We are now applying “Specially Promoted Research (特推)”



Summary of the New Project

- **The new project aims 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:
  - **a $\bar{K}NNN$ search via 4He(K-,N) reactions as a first step**
  - followed by a spin/parity measurement of the $\bar{K}NN$, soon
  - experimental challenges of $\bar{K}N$, $\bar{K}NNNN$, and $\bar{K}\bar{K}NN$ will also be followed

- We realize the systematic measurements with
  - ☐ a new 4π cylindrical detector system (CDS)
  - ☐ the improved K1.8BR beamline spectrometer

Collaboration of the New Project

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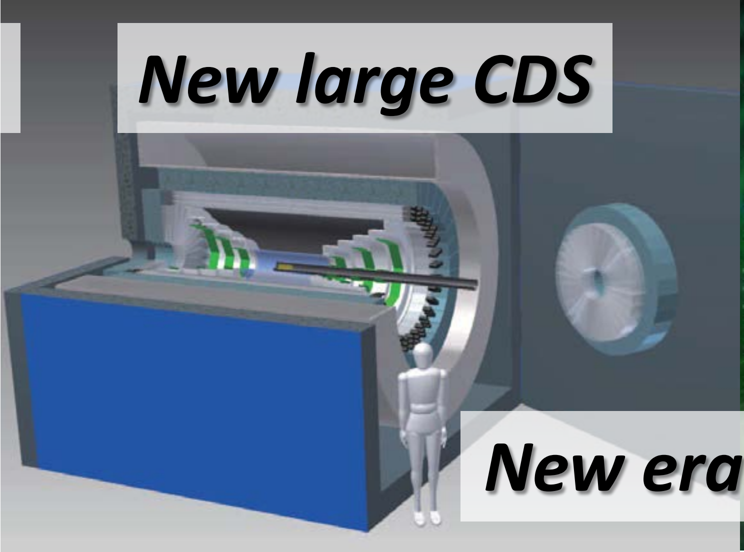
We're looking for new collaborators!

High intense K beam



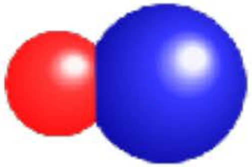
New large CDS

ÖWA/Harald Ritsch

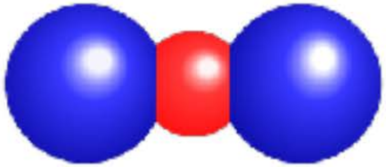
New era of kaonic nuclei

Thank you for your attention!

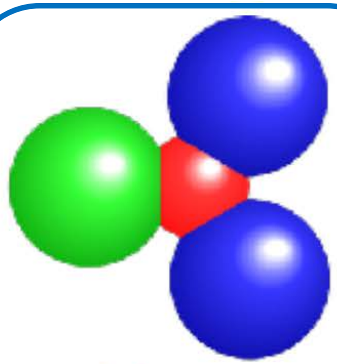
A first step of the project



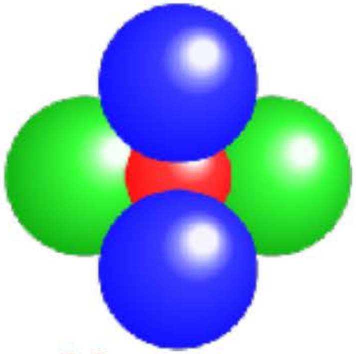
K^-p



K^-pp



K^-ppn



K^-ppnn

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