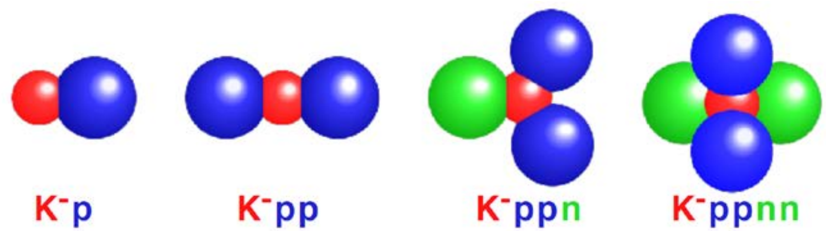
Systematic Investigation of the Light Kaonic Nuclei

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



Request for stage-1 approval of "the $\bar{K}NNN$ search"

F. Sakuma, RIKEN

on behalf of

the J-PARC P80 collaboration

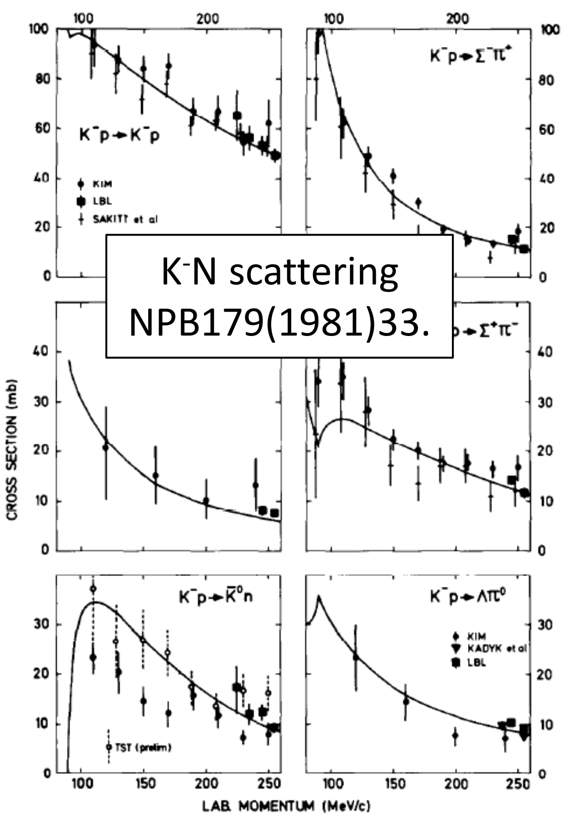
31th J-PARC PAC meeting, Jan 20-22, 2021

Physics Goal

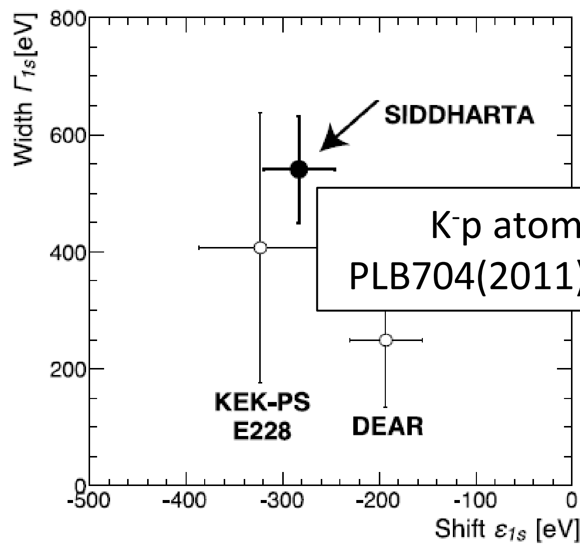
Reveal the meson properties inside nuclei
via **the $\bar{K}N$ interaction**

A powerful probe to understand low energy QCD

Strongly attractive in I=0 from extensive measurem**→ Kaonic Nuclei**

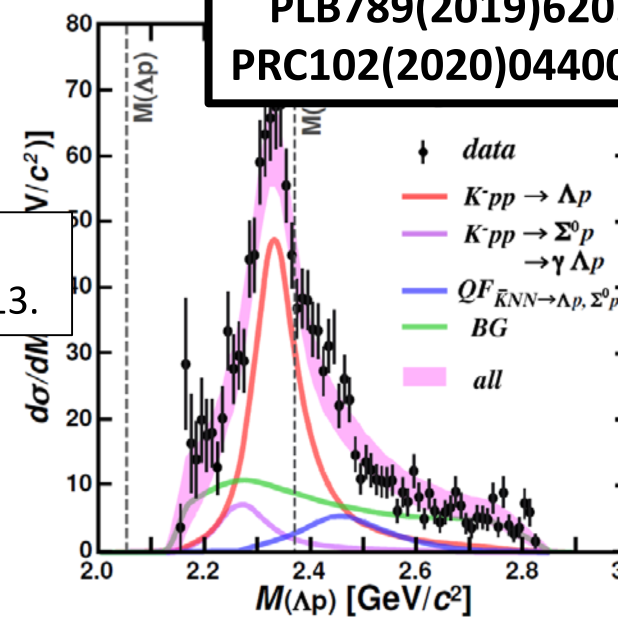


K⁻N scattering
NPB179(1981)33.



K⁻p atom
PLB704(2011)113.

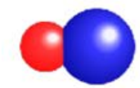
"K⁻pp" @ E15
PLB789(2019)620.
PRC102(2020)044002.



Need Further Investigations

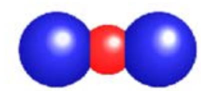
to establish the kaonic nuclei

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



K^-p

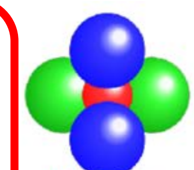
- **Further details of the $\bar{K}NN$**
  - Spin and parity of the "K^-pp"?
  - Really compact and dense system?



K^-pp

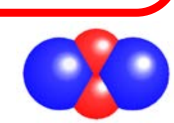
- **More heavier kaonic nuclei?**
  - Mass number dependence?

K^-ppn

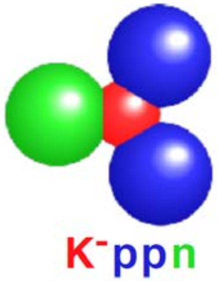


K^-ppnn

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



K^-K^-pp



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

via ^{4}He(1 GeV/c K^-, n) reaction

<u>Goals of the proposed experiment:</u>

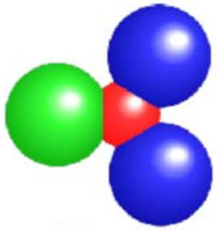
① Observe the K^-ppn state via 2-body Λd decay

- 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

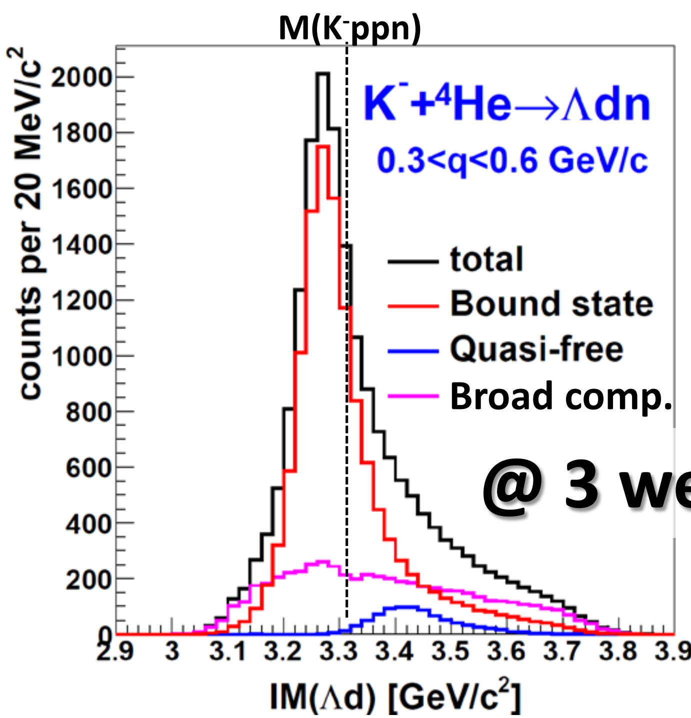
- **Feasibility study of polarization measurement**
  - *e.g.*, by installing a prototype module of a polarimeter



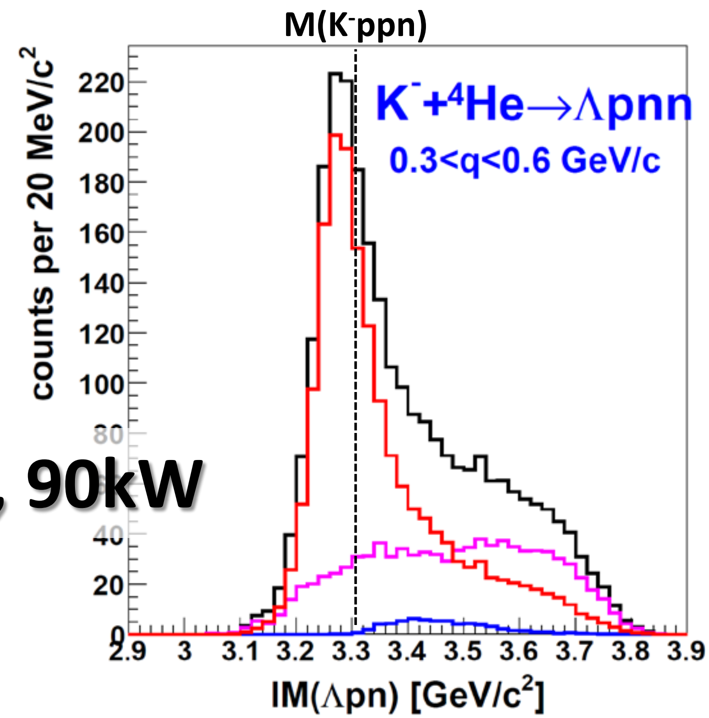
K^-ppn

Expected Spectra of K^-+^4He

① $K^-+^4He \rightarrow \Lambda d+n$



② $K^-+^4He \rightarrow \Lambda pn+n$



@ 3 weeks, 90kW

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

Answers to the 30th PAC Minutes

We have recieved 4 comments from the 30th PAC:

1. *Collaboration with theoretical groups*
2. *Relation between the proposed experiment and E15*
3. *P80 collaboration*
4. *Beamline upgrade*

Answer to the 30th PAC Minutes (1)

1. The PAC would like to encourage the collaboration to work with theoretical groups to provide more detailed studies of signals and backgrounds, including differential cross sections for processes involving the formation of Σ* hyperons.

- **We have worked in collaboration with many theoreticians, since before E15 started :**
  - Structure of the kaonic nuclei - A.Dote(KEK), O.Morimatsu(KEK), D.Jido(TITECH), Y.Akaishi(Nihon U), Y.Yamaguchi (JAEA), etc.
  - Reactions of K^-+He: T.Harada(Osaka Elec. U), T.Sekihara(Kyoto Pref. U), J.Yamagaya(Kyoto Sangyo U), Y.Ikeda(Kyusyu U), etc.
  - Lattice QCD: T.Hatsuda(RIKEN), etc. NEW!
- Now we are joining monthly meeting of the J-PARC theoretical group (HD) to discuss experimental results and our future plans
- We will have a series of workshops related to “future of the kaonic-nuclei physics”, as we had workshops so far

Support letter for P80

We believe that the P80 experiment will give a great contribution to the kaonic nuclear study. A signal of a resonant state has been clearly found in the novel experiment J-PARC E15. Applying the technique developed in the E15 experiment, the P80 aims at finding a bound state of K^-ppn and further they will try to find a K^-ppnn bound state. When this experiment is accomplished successfully, data of kaonic nuclei will be completed for s-shell nuclei. As a result, we will perform *a systematic study of light kaonic nuclei; Λ(1405) (= K^-p, 2-body), K^-pp (3-body), $K^-\,{}^3$He (=K^-ppn, 4-body) and $K^-\,{}^4$He (=K^-ppnn, 5-body)*. If we can explain all experimental results of s-shell kaonic nuclei consistently, the existence of kaonic nuclei will be more reliable.

We will keep close connection with theoretical groups

\- - - - - -

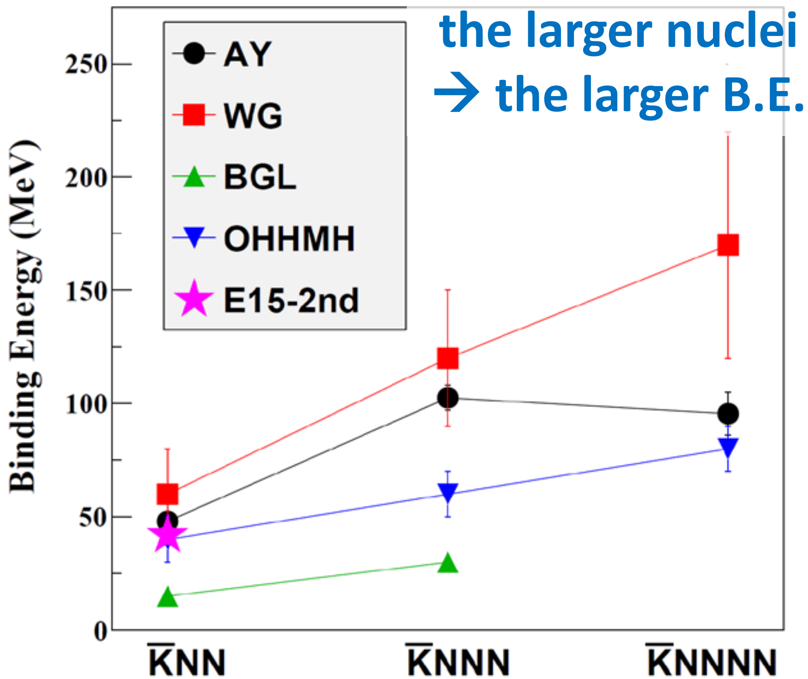
In summary, Strange Nuclear Physics section in J-PARC branch will support the P80 from theoretical side more strongly than ever.

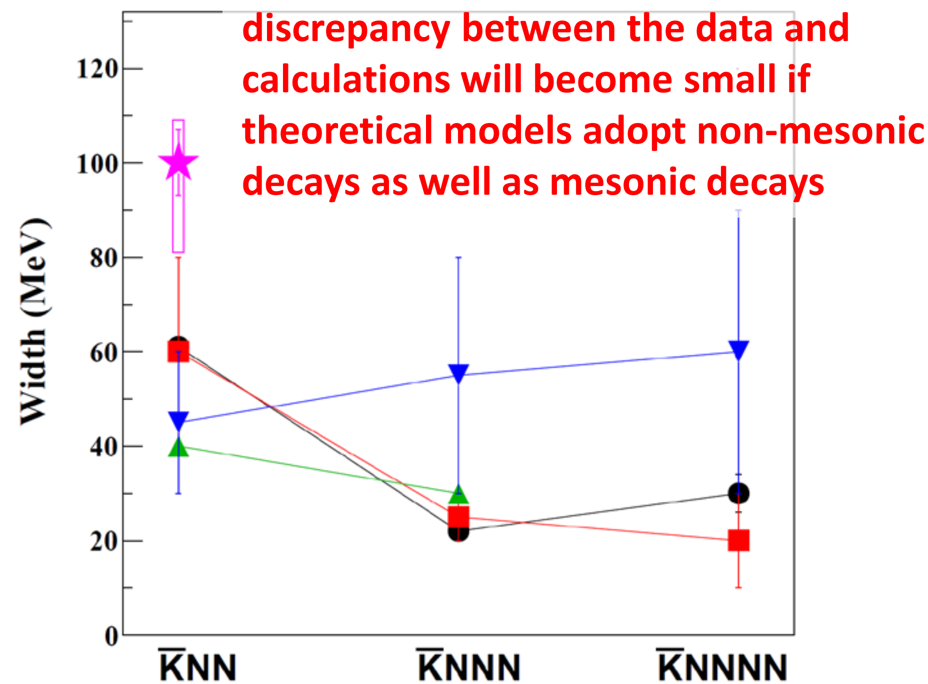
Akinobu DOTÉ (KEK) and Toru Harada (Osaka EC univ.)
on behalf of Strange Nuclear Physics section of J-PARC branch
in KEK theory center

A full version can be found in supplemental slides

Answer to the 30th PAC Minutes (2)

2. It would be helpful to have a more detailed explanation of how this proposal will improve upon the results of E15.





- Systematic measurements will provide more conclusive evidences of the kaonic nuclei

→ *Unique information on the $\bar{K}N$ interaction = density dependence*

Answer to the 30th PAC Minutes (3)

3. The PAC was concerned about the number of personnel associated with what will be a complex experiment and would like to encourage the proponents to expand the number of researchers involved.

Experiment

RIKEN
CDC, NC, Data Analysis
F.Sakuma (Spokes Person)
M.Iwasaki, H.Asano, T.Yamaga, R.Murayama, H.Outa, Y.Ma, K.Itahashi, Post.Doc., Students

JAEA
DAQ, Target, Data Analysis
T.Hashimoto, Students

Osaka-U
CDC, Data Analysis
H.Noumi, K.Shirotori, K.Inoue, Students

Tohoku-U
NC, Data Analysis
H.Ohnishi, Y.Sada, C.Yoshida, Students

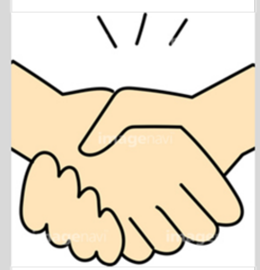
INFN-LNF
Data Analysis
C. Curceanu, M.Bazzi, A. Clozza, R.De Grande, C.Guarldo, K. Piscicchia, A. Scordo, D. Sirghi, F. Sirghi, Students

KEK
SC-Solenoid, Beamline
K.Ozawa, M.Iio, Students

SMI
Data Analysis
M.Cargnelli, J. Zmeskal, E. Widmann, Students

TITECH
Data Analysis
H.Fujioka, Students

Kyoto-U
Data Analysis
T.Nagae, Students



Theory

TITECH
Structure
D.Jido, Students

Kyoto Pref. U
Reaction
T.Sekihara, Students

Osaka Elec. U
Reaction
T.Harada, Students

KEK
Structure
A.Dote, O.Morimatsu, Students

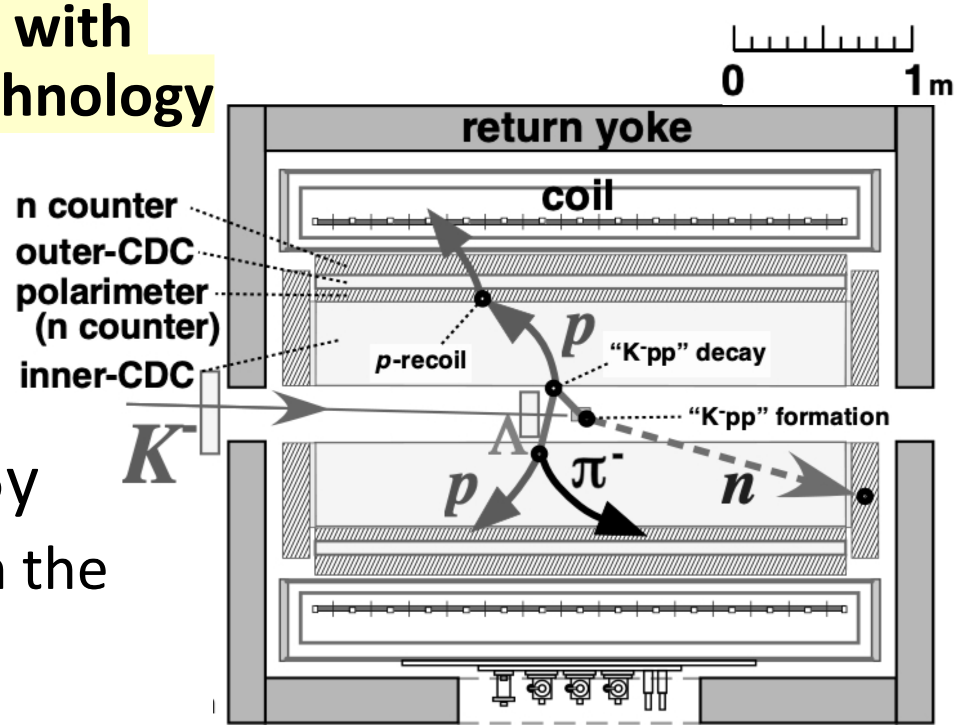
RIKEN
Lattice-QCD
T.Hatsuda, Students

We have continued to extend collaboration with other groups

Answer to the 30th PAC Minutes (3)

Spectrometer

- We are now re-designing the spectrometer to optimize both of Λdn (K-ppn search) and Λpn (J^P determination)
  - **More "simple system" to reduce cost and construction difficulties**
  - **Detectors will be constructed with matured and well studied technology**
    - ➢ SC-Solenoid/Beamline (KEK)
    - ➢ CDC (RIKEN/Osaka)
    - ➢ NC (RIKEN/Tohoku)
    - ➢ DAQ/Target (JAEA)
- Cost of construction: ~$5M/5y
  - Construction can be done with the present collaborators



Answer to the 30th PAC Minutes (3)

Schedule to complete

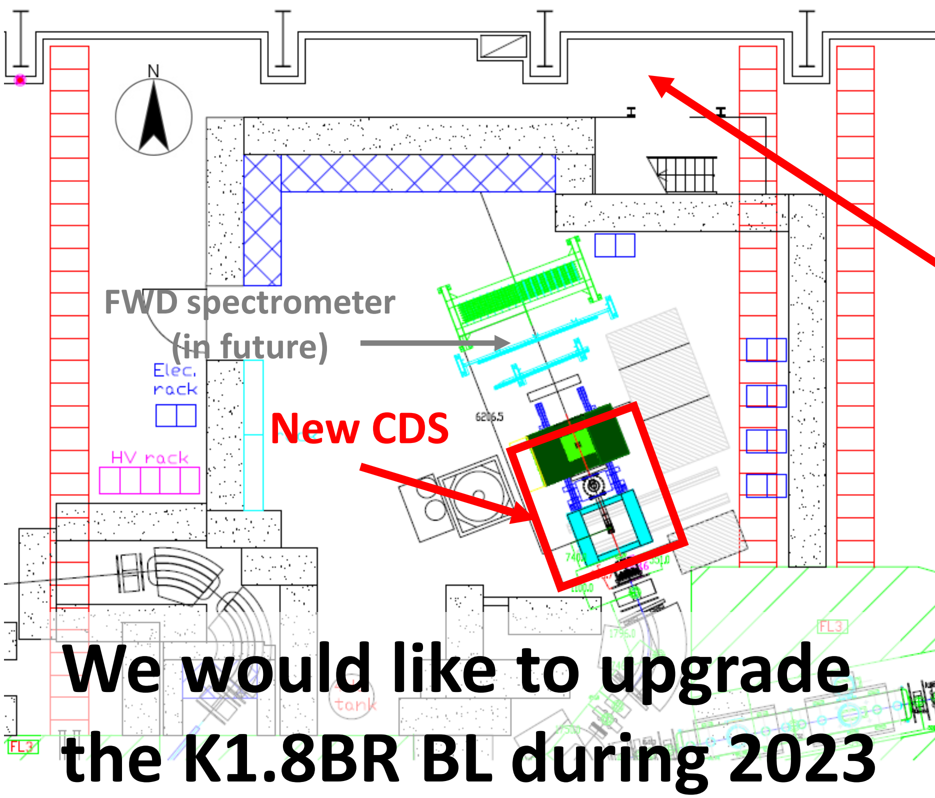
- We would like to perform the experiment **around 2024**
  - ☐ Design & construction: ~2023
  - ☐ Commissioning run followed by Physics run : 2024~

	2021				2022				2023				2024				2025~
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
SC Solenoid (KEK)	Design		Purchase (SC Wire)		Construction				Test & Commissioning								
NC (RIKEN, TOHOKU)	Design		Purchase (Scinti.)		Construction				Test & Commissioning								
Inner CDC (RIKEN, RCNP)	Design				Construction				Test & Commissioning				Integration & Commissioninng Physics Run				Analysis & Pblication
Outer CDC (RIKEN, RCNP)	Design								Construct.		Test & Commiss.						
Target (JAEA)	(Existing)																
DAQ (JAEA)	(Existing)																
Beamline (KEK)	E73(3He)				E73(3He)/E57(D2)				Upgrade				P80(4He)				E??(3He)
		↑ S2S				↑ COMET				↑ K1.8BR Upgrade							

We are now applying "Specially Promoted Research (特推)"

Answer to the 30th PAC Minutes (4)

4. It is important that the group work with laboratory management to make a serious investigation of the proposed changes to the beam line, including <u>realistic assessments of feasibility and cost</u>.



We would like to upgrade the K1.8BR BL during 2023

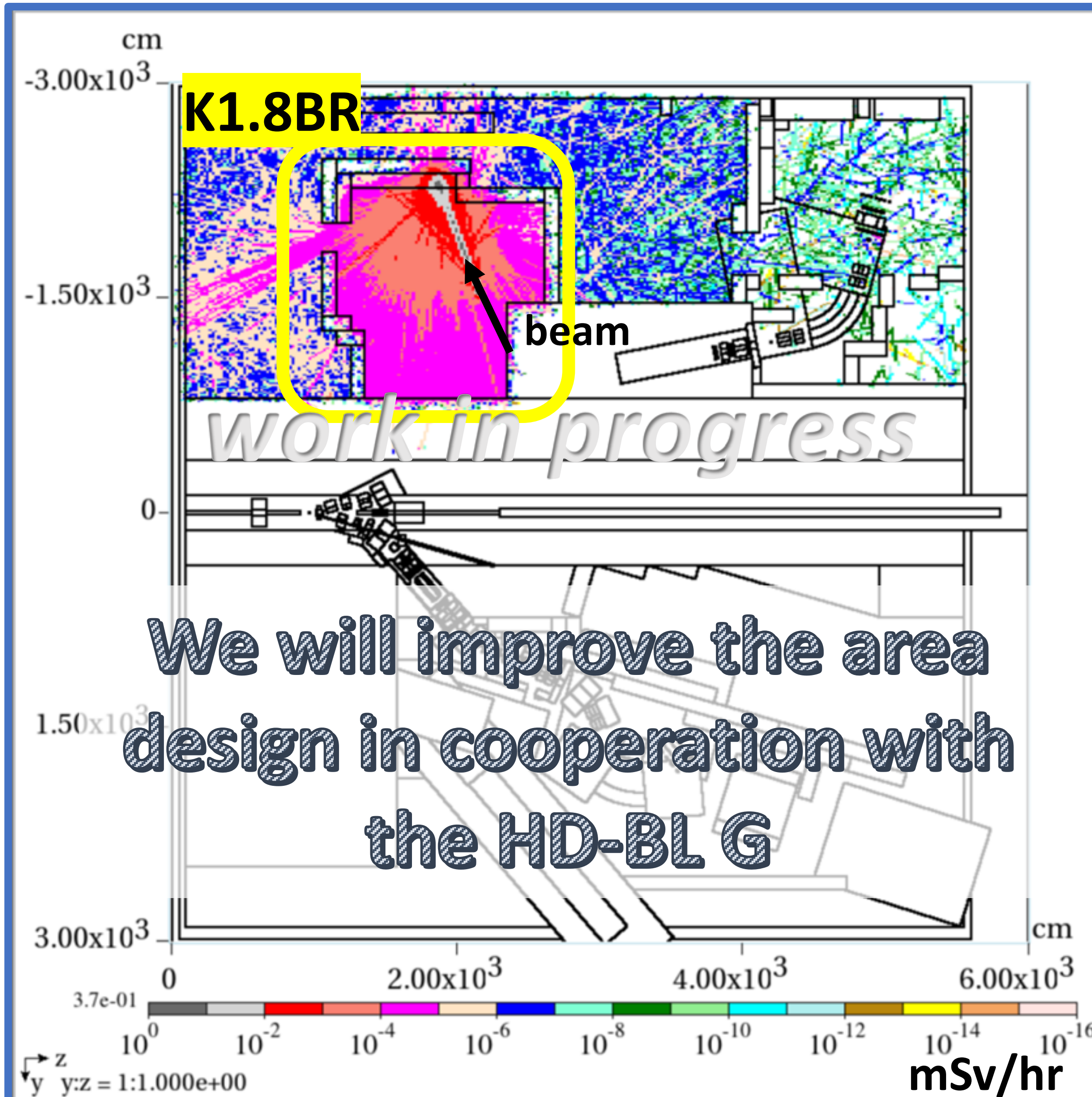
We are now working on realistic design of the area configuration in cooperation with the HD-BL G

- **No need to largely modify north-wall side, realistically**
- Cost estimation has been started by Prof. T.Takahashi (KEK-IPNS)
- We have started shielding calculation using MARS code with the HD-BL group

Answer to the 30th PAC Minutes (4)

- Shielding calculation using MARS code is in progress
  - ➢Our member has started the calculation

(Dr. H.Asano, RIKEN)



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

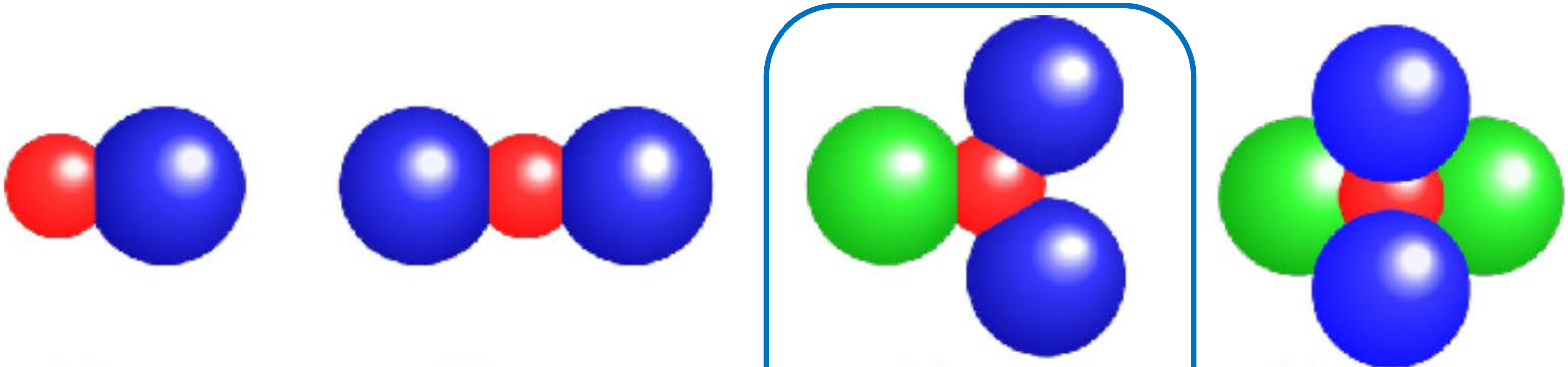
- We realize the systematic measurements with
  - ☐ a new 4π cylindrical detector system (CDS)
  - ☐ the improved K1.8BR beamline spectrometer

Stage-1 approval will greatly facilitate budget application

(conceptual design)

Thank you for your attention!

A first step of the project



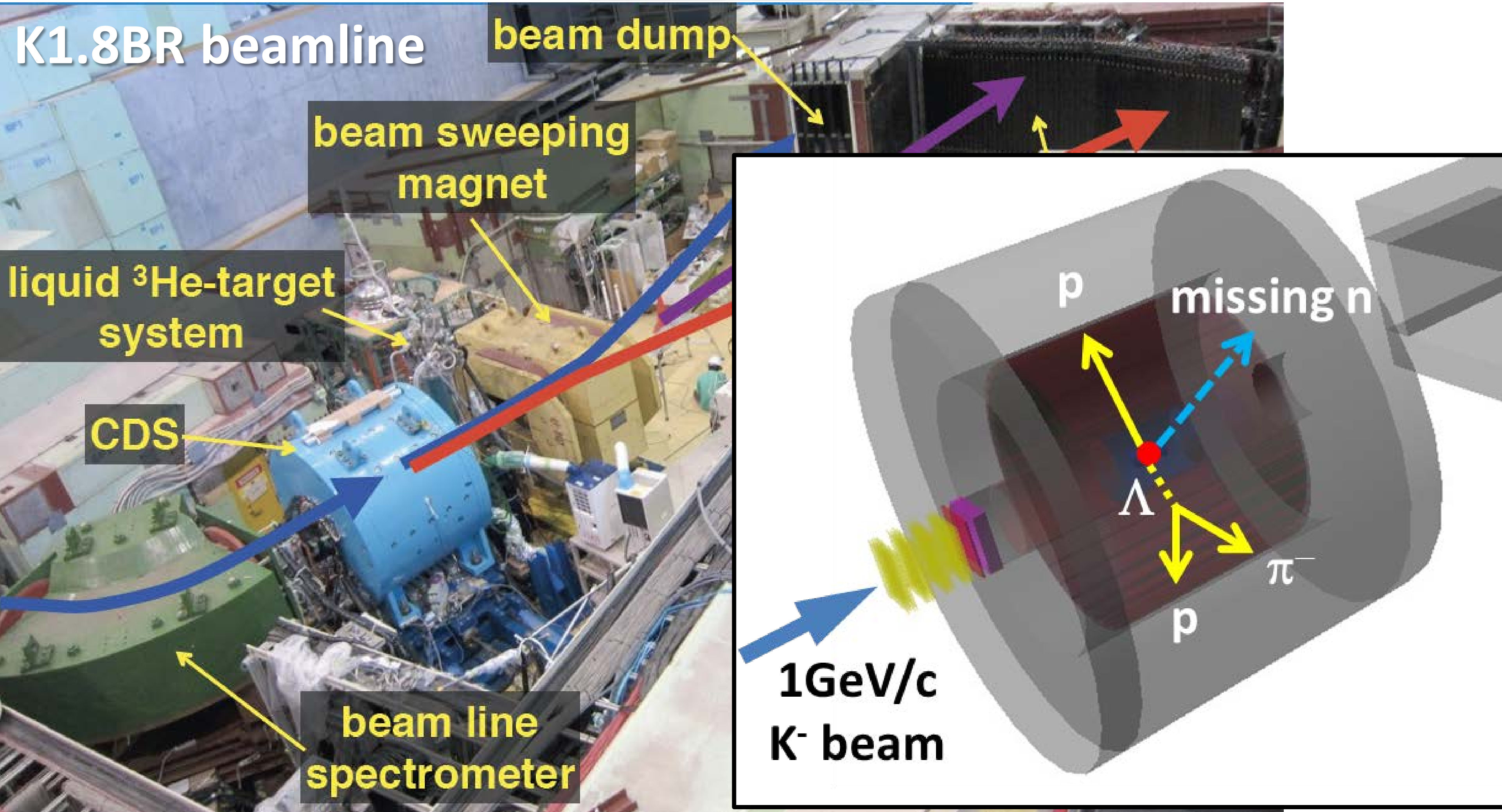
K^-p K^-pp K^-ppn K^-ppnn

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

Supplemental Slides

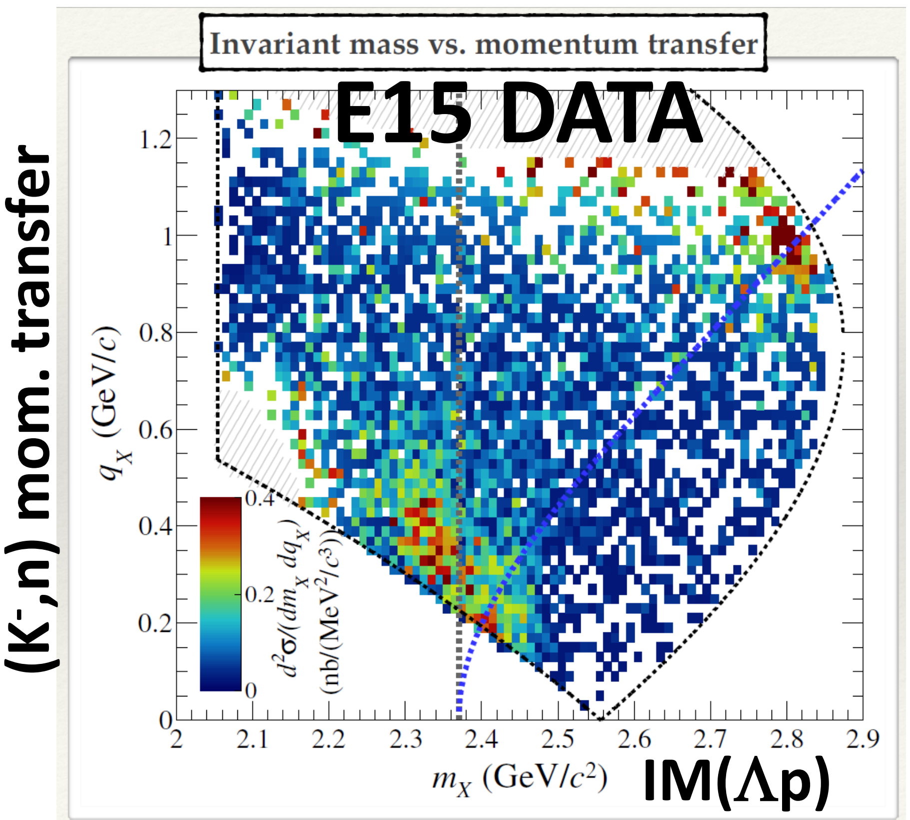
J-PARC E15 Experiment
- Experimental Search for the $\bar{K}NN$ -

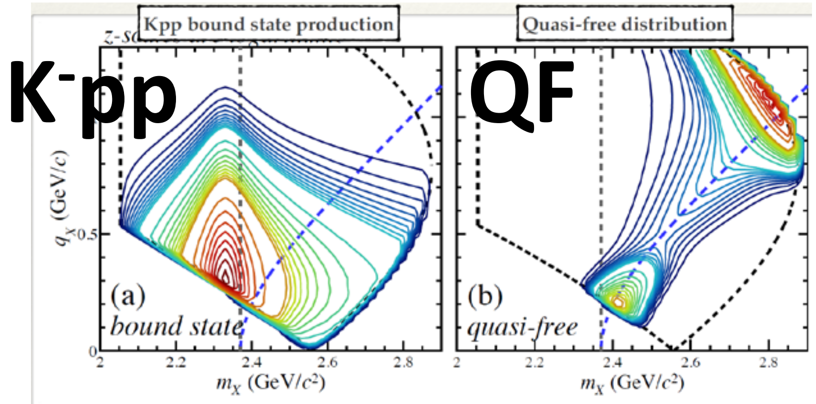
- We measured the **^{3}He(K$^-$,Λp)n** reaction

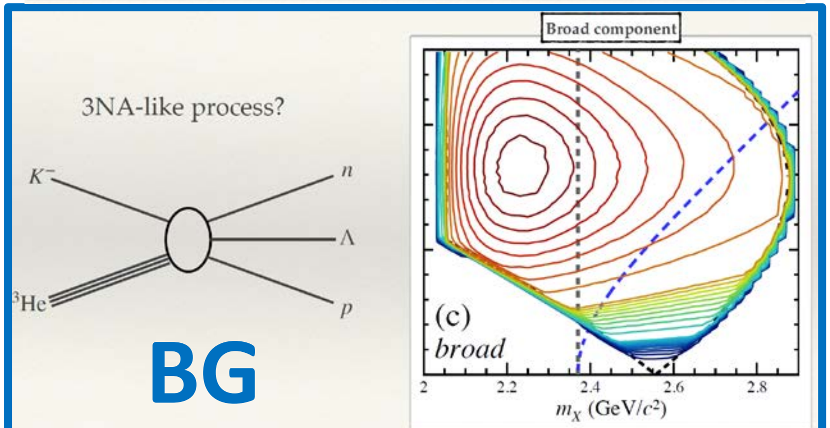


Recent progress of the E15 analysis

- In the E15 analysis so far, we assumed a point-like 3NA process for the background to explain the IM(Λp) spectrum, by parametrizing a fitting function

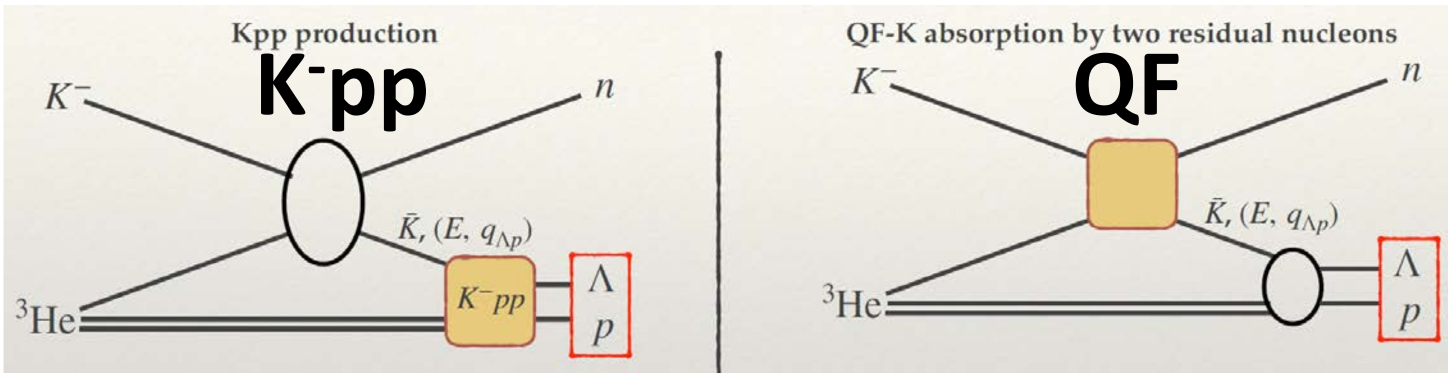




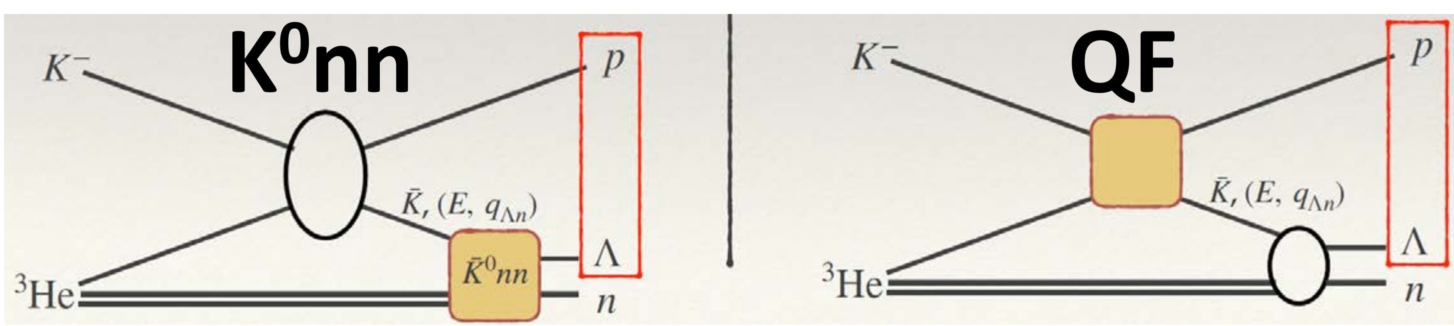


Recent progress of the E15 analysis

- For the $K^{-}pp$ and QF, we assume the following processes



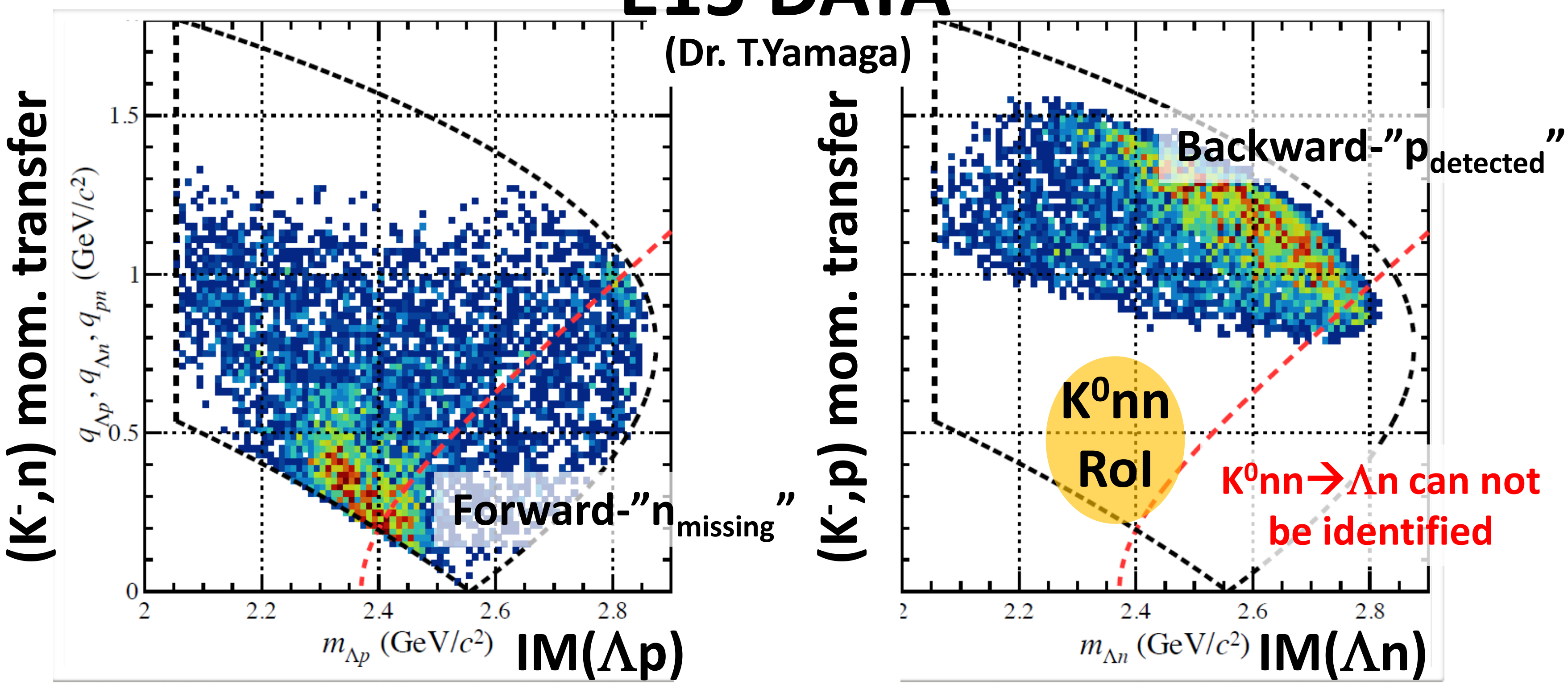
- On the other hand, “p” and “n” can be swapped in the reactions when the isospin partner of the $K^{-}pp$ (=$K^{0}nn$) is also generated



Recent progress of the E15 analysis

- IM(Λp) and IM(Λn)
  - Acceptances are quite different between the "Λp" and "Λn"
  - In IM(Λn), a forward going proton is out of the acceptance

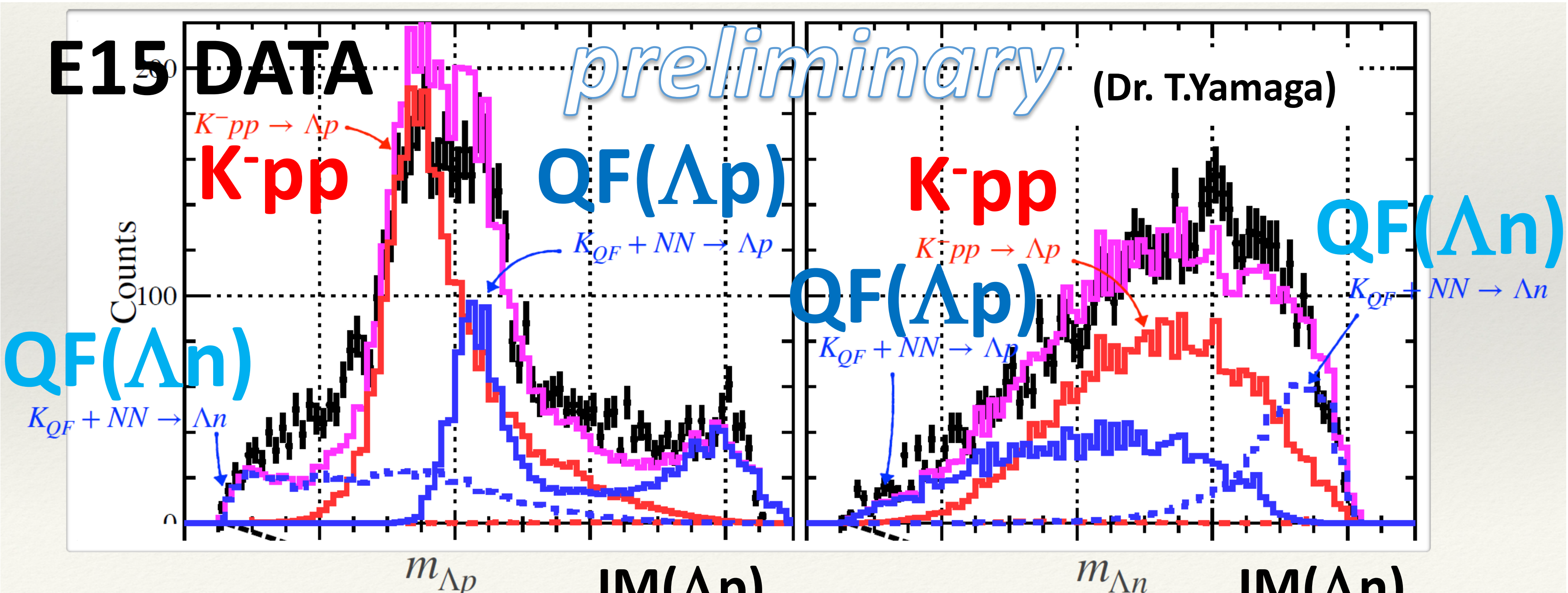
E15 DATA



Recent progress of the E15 analysis

- Both of IM(Λp) and IM(Λn) can be reproduced by the "signal" and "QFs"
  - Eye fit results → further analysis is on going

need further data with the new 4π spectrometer



(all mom. transfer region selected)

Σ*N bound state? Other possibilities?

Σ(1385) 3/2$^+$ $I(J^P) = 1(\frac{3}{2}^+)$

Σ(1385) DECAY MODES	Fraction (Γ_i/Γ)
$\Lambda\pi$	(87.0 ±1.5) %
$\Sigma\pi$	(11.7 ±1.5) %

- Σ* coupling through K^{bar}-N channel (P-wave) would be weak
  - ✓A.Cieply et al., PRC84(2011)045206, etc.
- Naively, Σ*N system with $1^+/2^+$ state (S-wave) could not be bound, because corresponding ΔN system (non-strangeness sector) is considered to be no-bound or quite-weakly bound
  - ✓R. D. Mota et al., PRC59(1999)46, etc.

need J^P determination with a polarimeter

- The $K^{bar}NN$ state (I=1/2, $J^P=0^-$) is calculated with a $K^{bar}NN$-πΣN-πΛN coupled channel system, where the πΛN coupling is expected to be small
- The $K^{bar}NN$ state with $J^P=1^-$ (K^{bar}-d like configuration) is expected to not be bound, or have small B.E.
  - ✓ S.Ohnishi et al., PRC95(2017)065202, etc.

Σ*N bound state? Other possibilities?

- One theoretical possibility is a "πΛN-πΣN dibaryon"

Nuclear Physics A 897 (2013) 167–178

Relativistic three-body calculations of a $Y = 1$, $I = \frac{3}{2}$, $J^P = 2^+$ $\pi\Lambda N$–$\pi\Sigma N$ dibaryon

H. Garcilazo [a], A. Gal [b,*]

- Calculated πΛN resonance with **Σ*N-ΔΣ** configuration is:
  - I=1/2, $J^P=2^+$: **E = -10-i52 MeV**
  - I=3/2, $J^P=2^+$: **E = -120-i2.6 MeV** with respect to M(K^{bar}NN)

- The obtained K^-pp parameter at E15 is **E=-40-i50 MeV**
- Therefore, the "observed K-pp structure" would be different from the "πΛN-πΣN dibaryon"

Strategy of the New Project

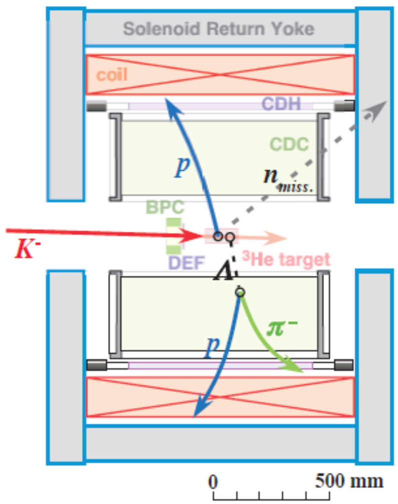
- for systematic study from the $\bar{K}N$ to $\bar{K}NNNN$ systems -

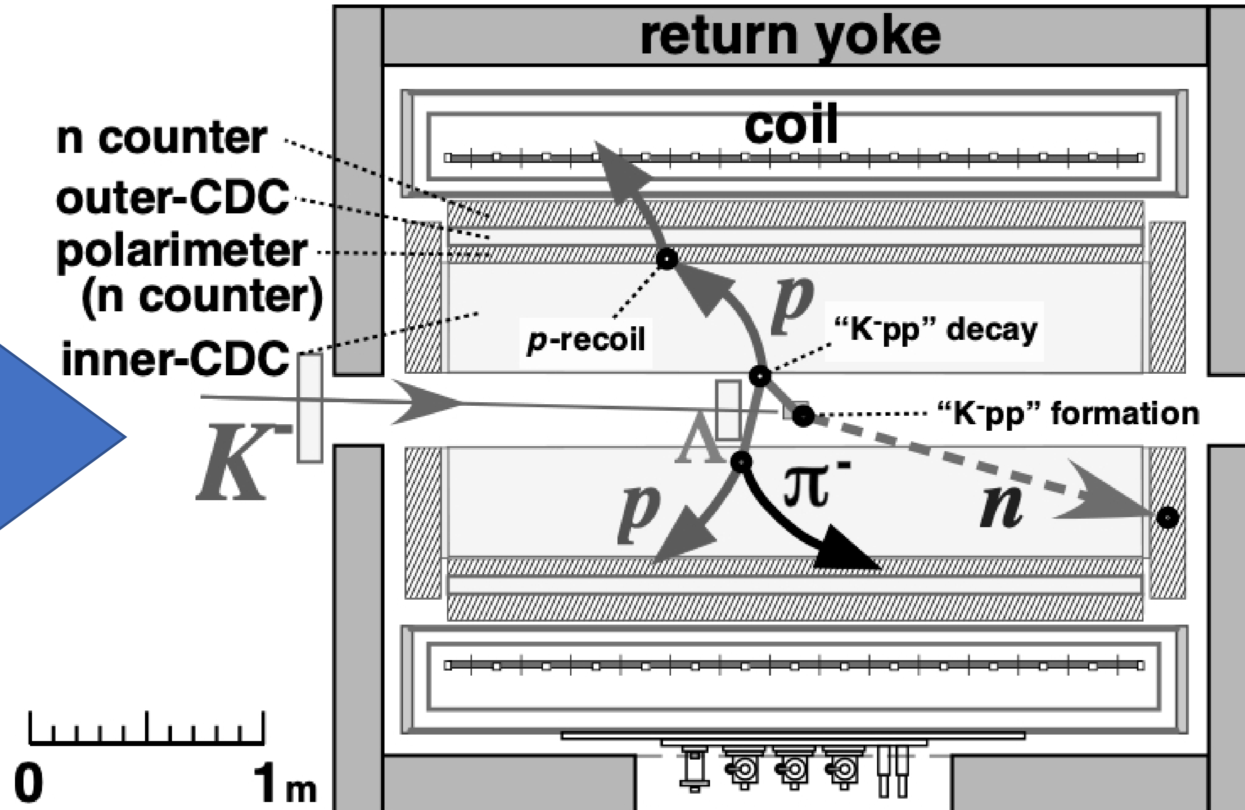
	Reaction	Decays	Key
$\bar{K}N$	d(K$^-$,n)	$\pi^{\pm 0}\Sigma^{\mp 0}$	n/γ identification
$\bar{K}NN$	^{3}He(K$^-$,N)	Λp/Λn	polarimete← **Feasibility study**
$\bar{K}NNN$	^{4}He(K$^-$,N)	Λd/Λpn	large acce← **A first step**
$\bar{K}NNNN$	*^{6}Li(K$^-$,d)*	*Λt/Λdn/Λpnn*	*many body*← **Feasibility study**
$\bar{K}\bar{K}NN$	*$\bar{p}$ + ^{3}He*	*$\Lambda\Lambda$*	*$\bar{p}$ beam yield*

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

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%)

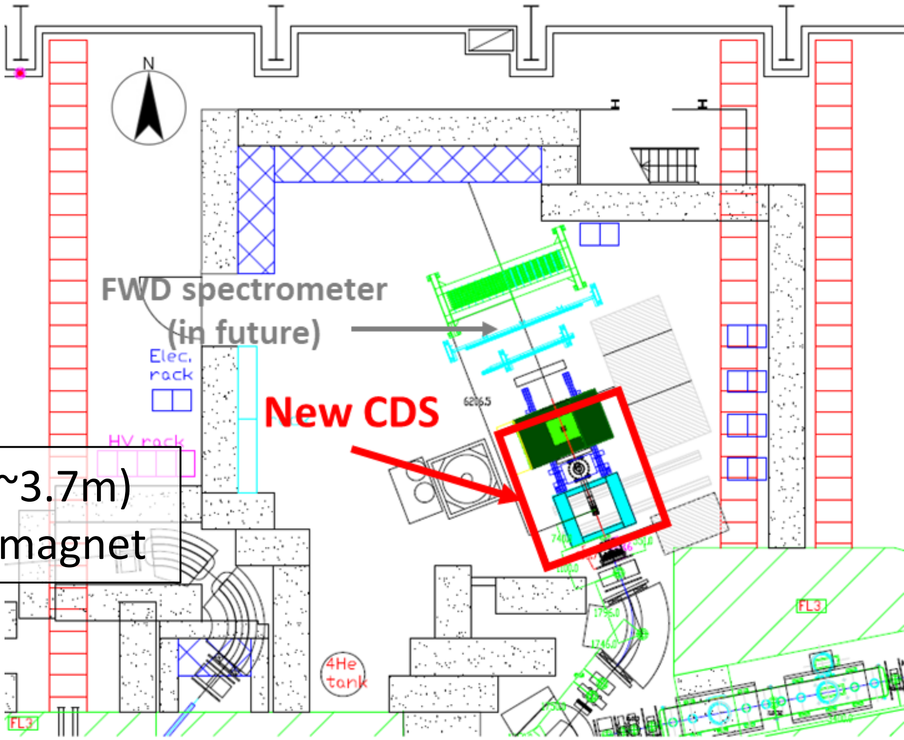
Neutron detection capability: ~x10

(~1.5x15%)

Improvement of Kaon Intensity

K1.8BR beamline

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 $\bar{K}NNN$

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

- 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^-) (%)
$K^-He^4 \to \Sigma^+\pi^- H^3$	9.3±2.3
$\to \Sigma^+\pi^- dn$	1.9±0.7
$\to \Sigma^+\pi^- pnn$	1.6±0.6
$\to \Sigma^+\pi^0\ nnn$	3.2±1.0
$\to \Sigma^+\ \ nnn$	1.0±0.4
Total $\Sigma^+ = (17.0\pm2.7)\%$	
$K^-He^4 \to \Sigma^-\pi^+ H^3$	4.2±1.2
$\to \Sigma^-\pi^+ dn$	1.6±0.6
$\to \Sigma^-\pi^+ pnn$	1.4±0.5
$\to \Sigma^-\pi^0\ He^3$	1.0±0.5
$\to \Sigma^-\pi^0\ pd$	1.0±0.5
$\to \Sigma^-\pi^0\ ppn$	1.0±0.4
$\to \Sigma^-\ \ pd$	1.6±0.6
$\to \Sigma^-\ \ ppn$	2.0±0.7
Total $\Sigma^- = (13.8\pm1.8)\%$	
$K^-He^4 \to \pi^-\Lambda\ He^3$	11.2±2.7
$\to \pi^-\Lambda\ pd$	10.9±2.6
$\to \pi^-\Lambda\ ppn$	9.5±2.4
$\to \pi^-\Sigma^0\ He^3$	0.9±0.6
$\to \pi^-\Sigma^0\ (pd, ppn)$	0.3±0.3
$\to \pi^0\Lambda\ (\Sigma^0)(pnn)$	22.5±4.2
$\to \Lambda\ (\Sigma^0)\ \ (pnn)$	11.7±2.4
$\to \pi^+\Lambda\ (\Sigma^0) nnn$	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 2024
    - 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^-+^4He

@ 3 weeks, 90kW

B_{Kppn} ~ 40 MeV

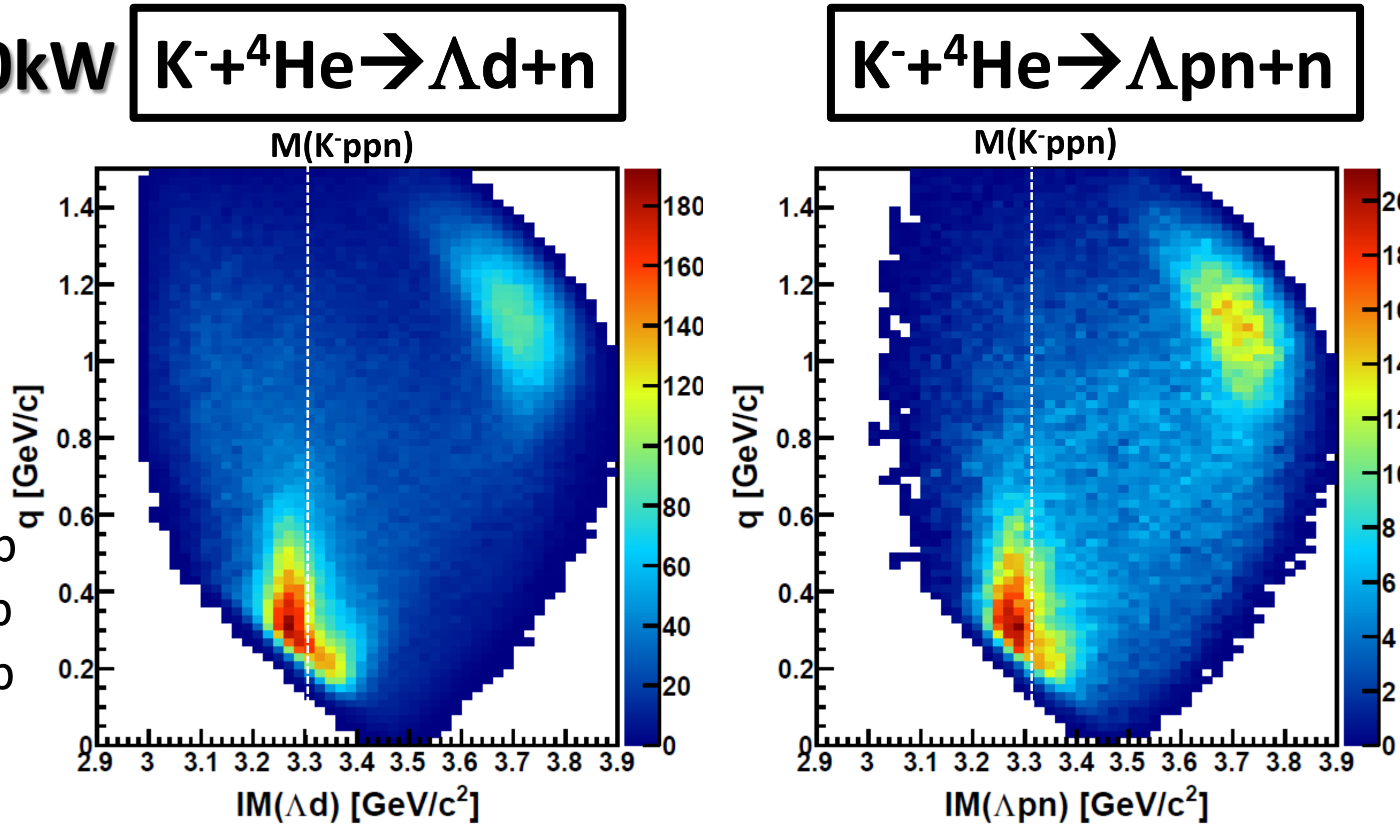
Γ_{Kppn} ~ 100 MeV

Q_{kppn} ~ 400 MeV/c

$\sigma(K^-ppn)$*Br ~ 10 μb

σ(QF) ~ 10 μb

σ(BG) ~ 20 μb



- Similar parameters obtained with the $K^-+^3He \rightarrow \Lambda pn$ (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

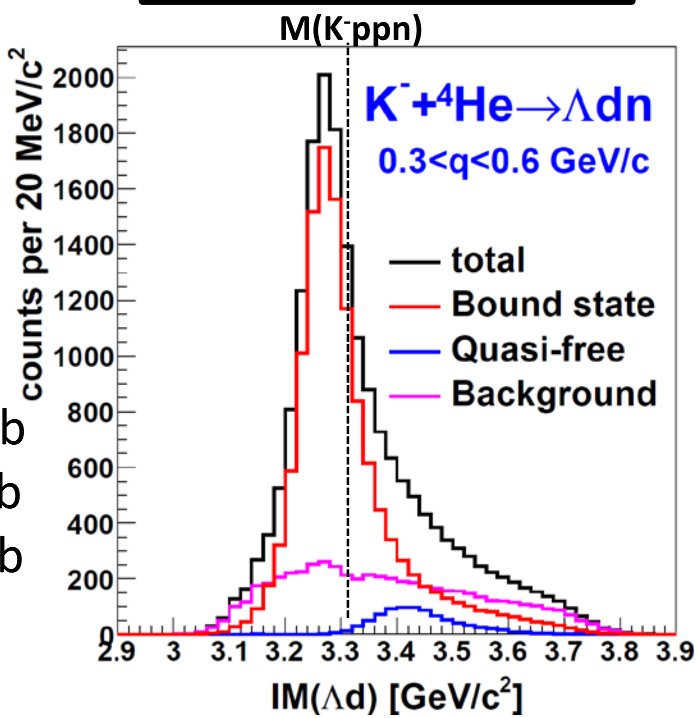
Q_{kppn} ~ 400 MeV/c

$\sigma(K^{-}ppn)$*Br ~ 10 μb

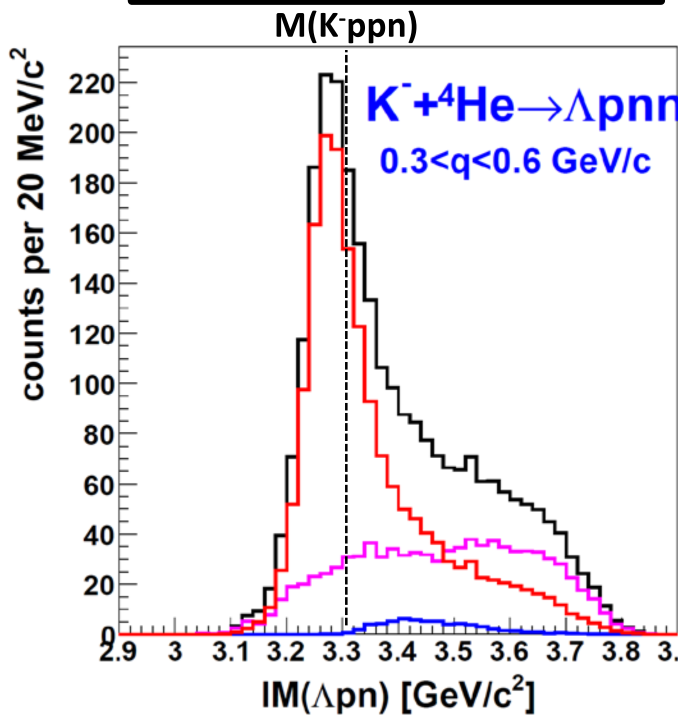
σ(QF) ~ 10 μb

σ(BG) ~ 20 μb

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



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



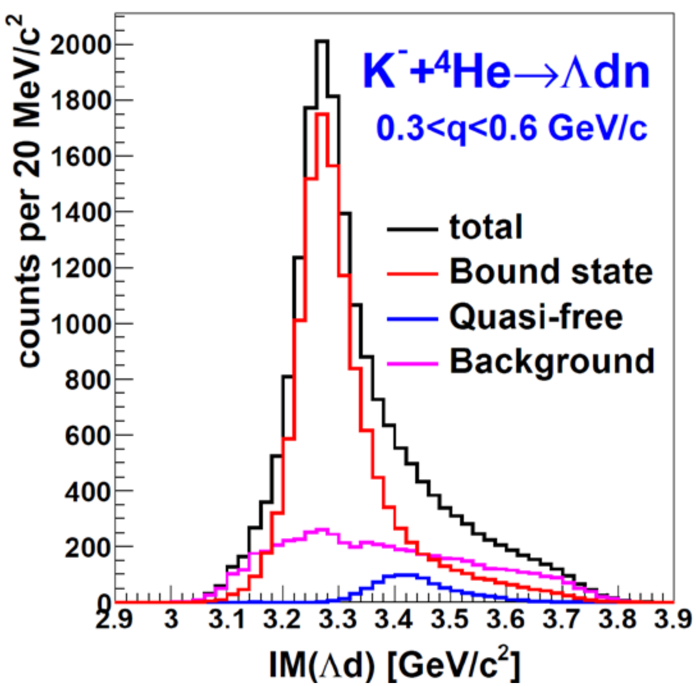
- The signals can be enhanced by selecting 0.3 < q < 0.6 GeV/c
- **The K^{-}ppn signal will be observed if the $\sigma(K^{-}ppn)$*Br is more than ~ μb**

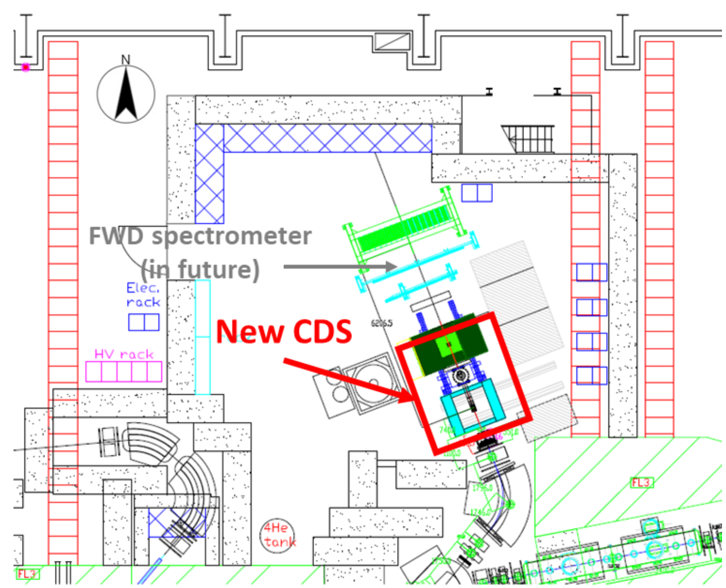
Requests to PAC

1. stage-1 approval of **"the $\bar{K}NNN$ search via ^{4}He(K$^-$,N) reactions"**

2. Endorse of **"the K1.8BR beamline upgrade"**

   We would like to perform the upgrade during the long shutdown in 2023





Collaboration of the New Project

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Support letter for P80

We believe that the P80 experiment will give a great contribution to the kaonic nuclear study. A signal of a resonant state has been clearly found in the novel experiment J-PARC E15. Applying the technique developed in the E15 experiment, the P80 aims at finding a bound state of K^-ppn and further they will try to find a K^-ppnn bound state. When this experiment is accomplished successfully, data of kaonic nuclei will be completed for s-shell nuclei. As a result, we will perform *a systematic study of light kaonic nuclei; Λ(1405) (=*K^-p*, 2-body),* K^-pp *(3-body),* K^--^3He *(=*K^-ppn*, 4-body) and* K^--^4He *(=*K^-ppnn*, 5-body)*. If we can explain all experimental results of s-shell kaonic nuclei consistently, the existence of kaonic nuclei will be more reliable.

Precise experimental data of kaonic nuclei could shed light to the long-standing problems in hadron physics, such as "partial restoration of the chiral symmetry in dense matter" and "kaon condensation in neutron star", because K^{bar} meson involved in kaonic nuclei is a Nambu-Goldstone boson associated with the chiral-symmetry breaking. We will achieve deeper understanding of the chiral dynamics and furthermore the QCD, which is the fundamental theory for hadron physics. Therefore, we believe that the P80 experiment will give a great impact to us.

In KEK theory center, there is a J-PARC branch to support J-PARC experiments from theoretical side. The Strange Nuclear Physics section in the branch has very often held meetings to consult with experimentalists studying hypernuclei and kaonic nuclei. This year, we are planning to reinforce our activity: Monthly meeting, Open discussion with many researchers, and Organizing workshops.

We will keep close connection with members of P80, and help resolving their problems at each time. As often pointed out, there are still few theoretical researchers who are experts of reaction study, which is directly connected to the analysis of experimental results. We will make efforts to find such theorists through J-PARC branch activities and involve them to our research field. On the other hand, the recent progress of Lattice QCD study is remarkable. We will ask Lattice QCD people to collaborate with us.

In summary, Strange Nuclear Physics section in J-PARC branch will support the P80 from theoretical side more strongly than ever.

Akinobu DOTÉ (KEK) and Toru Harada (Osaka EC univ.)
on behalf of Strange Nuclear Physics section of J-PARC branch
in KEK theory center

Spectrometer [Plan B]

- **Reuse and modify the existing solenoid magnet**
  - Small CDC + vertex detector + neutron counter
  - Forward/backward particle ID w/ TOF
- Easily constructed, and cost can be reduced to ~$1M

Acceptance & efficiency:
charged particle: proposed spectrometer x ~0.7
neutron: proposed spectrometer x ~0.3