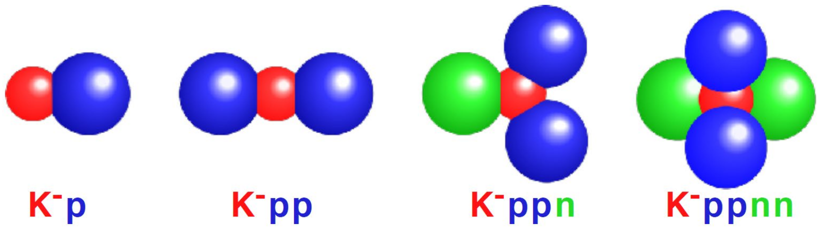
kaon-nucleus bound systems

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



F. Sakuma, RIKEN

on behalf of

the J-PARC E15/E73/T77/E80/P89 collaboration

研究会「EICで展開する新たな原子核・素粒子物理」28–30 May 2024 東京大学

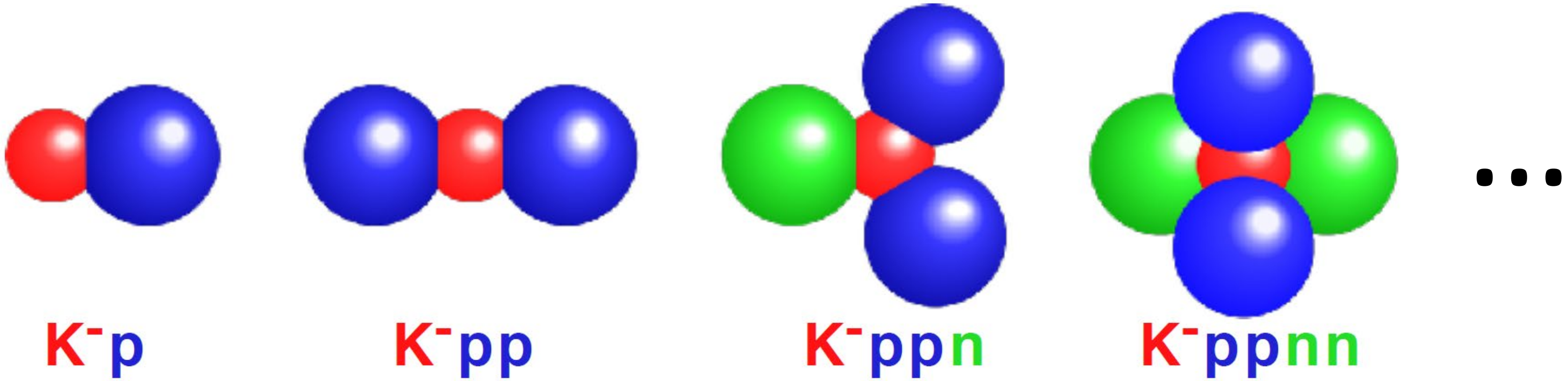
What is "Kaonic Nuclei"?

- **Kaonic nuclei = anti-kaon – nucleus bound states**
  - ✓ Predicted from attractive $\bar{\mathrm{K}}\mathrm{N}$ interaction in I=0 channel

$$\mathbf{K} = \begin{pmatrix} \mathrm{K}^+ \\ \mathrm{K}^0 \end{pmatrix} \begin{matrix} \mathrm{u\bar{s}} \\ \mathrm{d\bar{s}} \end{matrix} \quad \mathrm{s} = 1$$

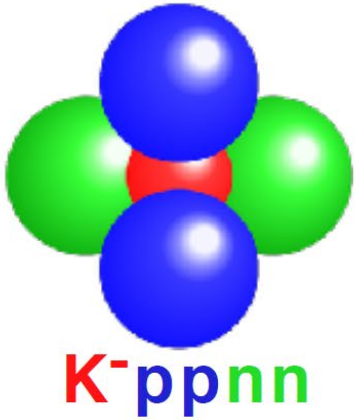
$$\bar{\mathbf{K}} = \begin{pmatrix} \bar{\mathrm{K}}^0 \\ \mathrm{K}^- \end{pmatrix} \begin{matrix} \mathrm{\bar{d}s} \\ \mathrm{\bar{u}s} \end{matrix} \quad \mathrm{s} = -1 \qquad \mathbf{N} = \begin{pmatrix} \mathrm{p} \\ \mathrm{n} \end{pmatrix} \begin{matrix} \mathrm{uud} \\ \mathrm{udd} \end{matrix}$$

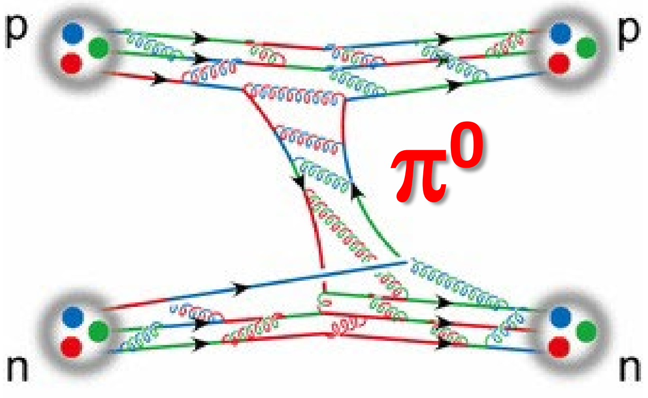
$$\mathbf{I_3} = \begin{pmatrix} +{}^1/_2 \\ -{}^1/_2 \end{pmatrix}$$



What is Interesting about "Kaonic Nuclei"?

- **Meson can be the building block of nuclei → New forms of nuclei**
  - *cf.*, "virtual" light mesons play an important role in a nucleus as "glue"

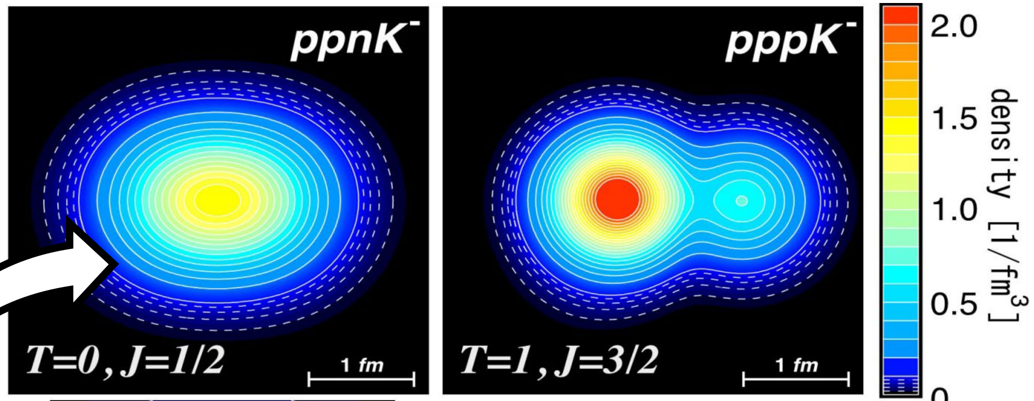


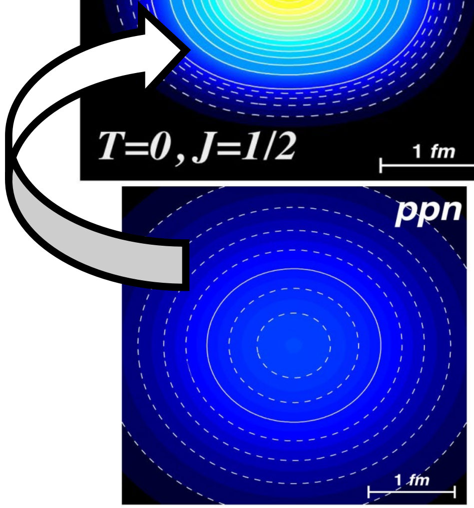


$\bar{K}$ = "real" particle

π = "virtual" particle
(Force Mediating Particle)

- **Possibility of high-density matter formation ← strongly attractive $\bar{K}$N**
  - large binding energies are expected compared to normal nuclei





e.g., antisymmetrized molecular dynamics (AMD) calculation
A. Dote et al. PRC70(2004)044313.

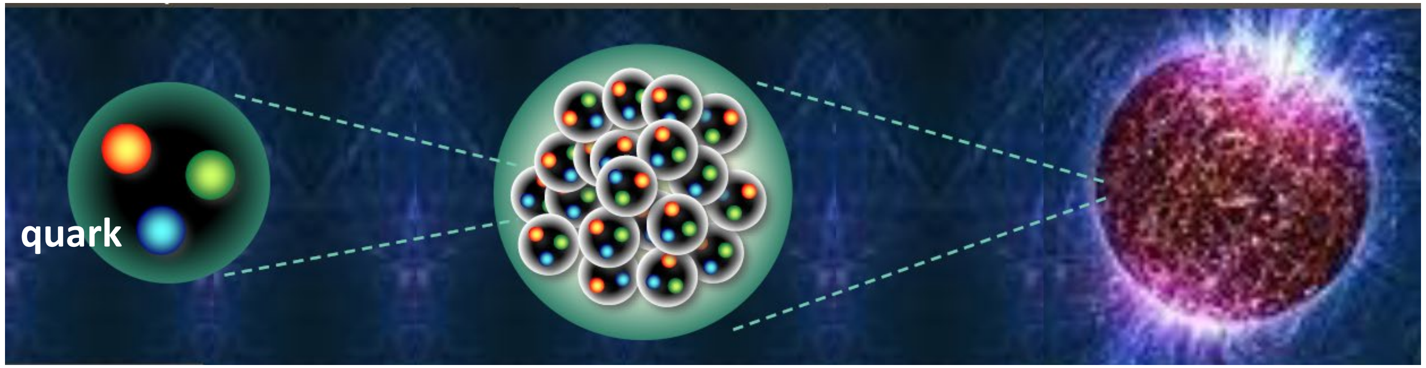
Nuclear & Hadron Physics

= Study of quantum many-body system governed by QCD

Hadron
such as proton

Nucleus

Neutron star =
"Giant nucleus"



10^{-15} m

10^{4} m

The ultimate goal:

to reveal formation and evolution of matter based on QCD, widely ranging from quarks to neutron stars

“Kaonic Nuclei” Cover Broad Subjects

through $\underline{\bar{K}N \text{ interaction}}$ in media

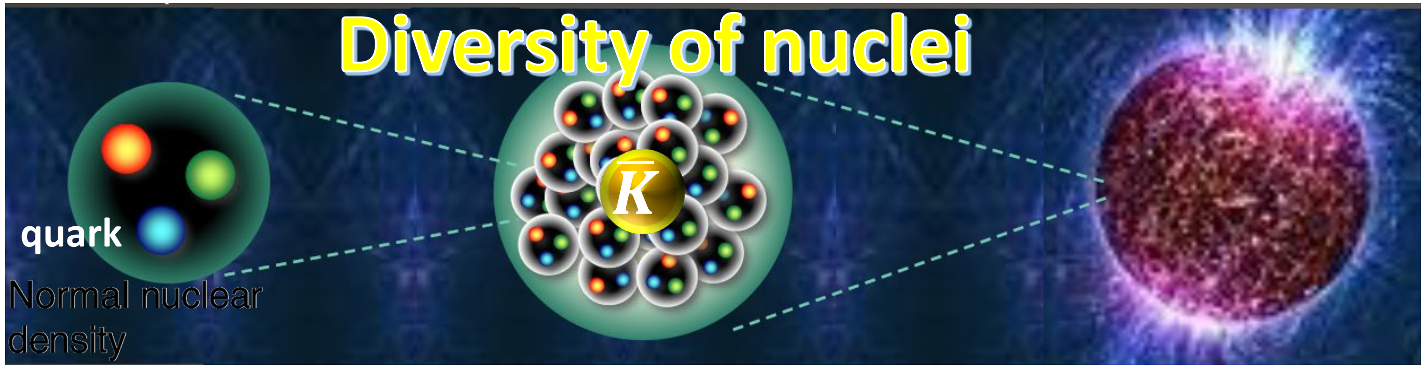
Origin of the QCD mass

Hadron such as proton

Nucleus

Neutron star = “Giant nucleus”

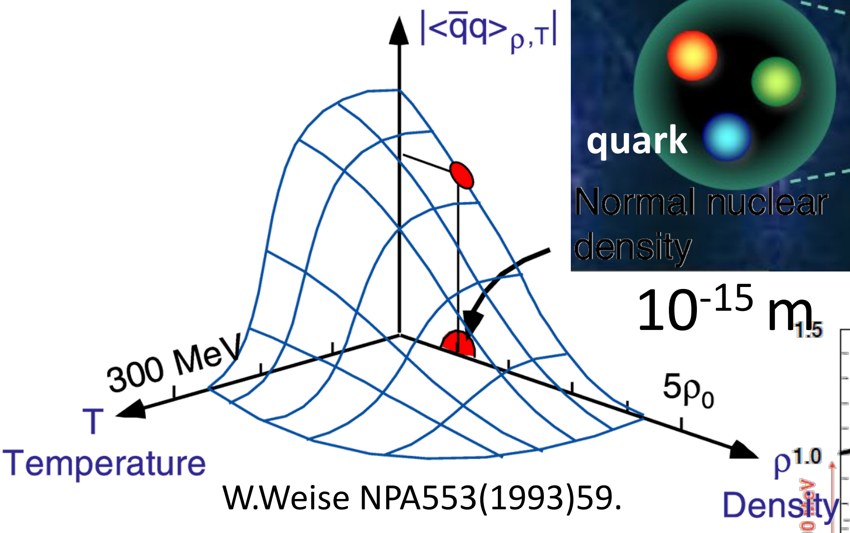
High-density nuclear matter



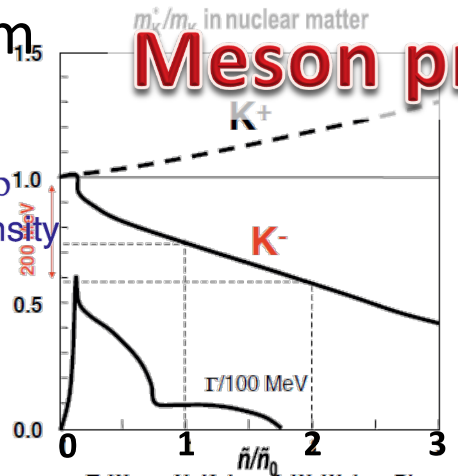
10^{-15} m

10^{4} m

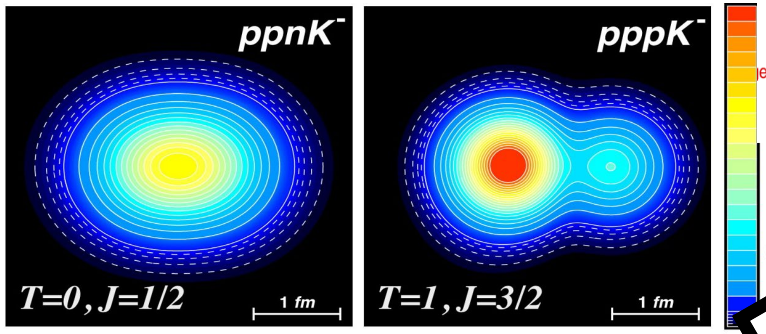
Meson properties in media

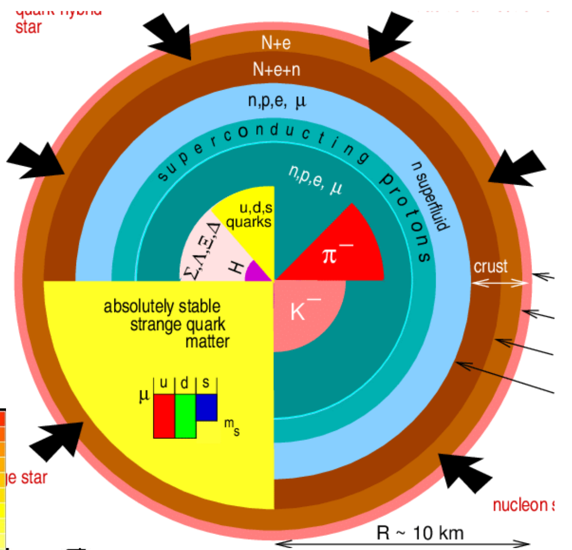


W.Weise NPA553(1993)59.



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



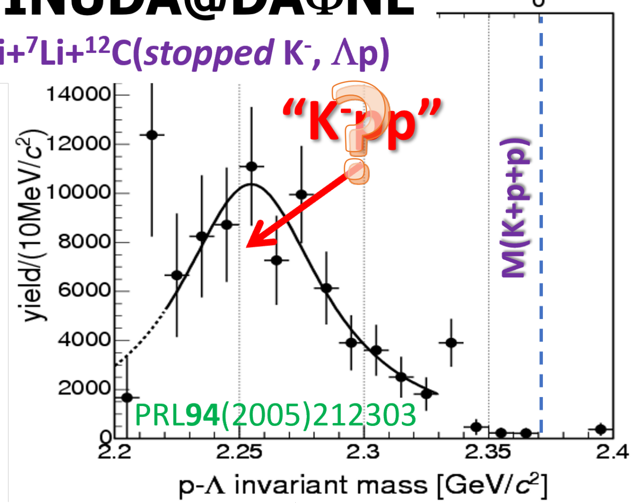


F. Weber, PPNP 54(2005)193.

“K⁻pp” Bound State Searches - History

FINUDA@DAΦNE

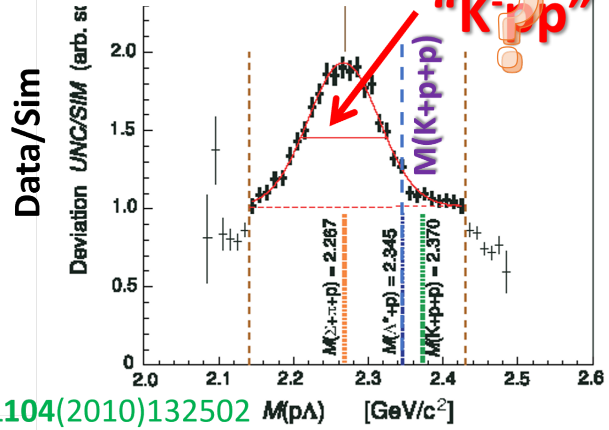
^{6}Li+^{7}Li+^{12}C(*stopped* K$^-$, Λp)



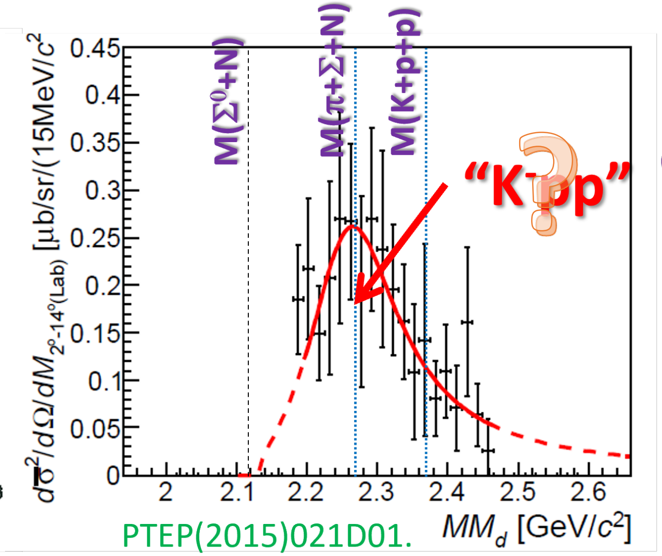
PRL**94**(2005)212303

DISTO@SATURNE

p + p → (Λ + p) + K$^+$ @ 2.85GeV



PRL**104**(2010)132502



PTEP(2015)021D01.

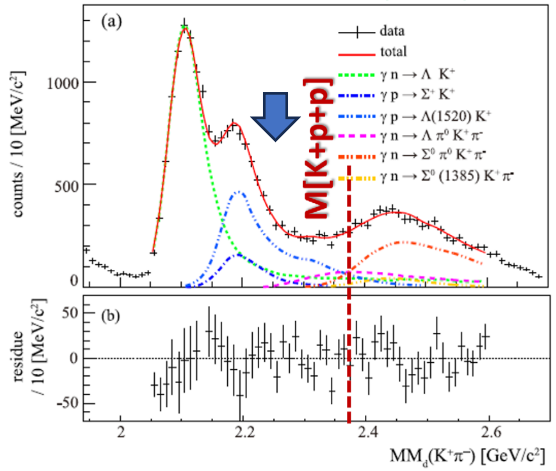
E27@J-PARC

d(π$^+$, K$^+$)Σ^{0}p @ 1.69 GeV/c

LEPS@SPring-8

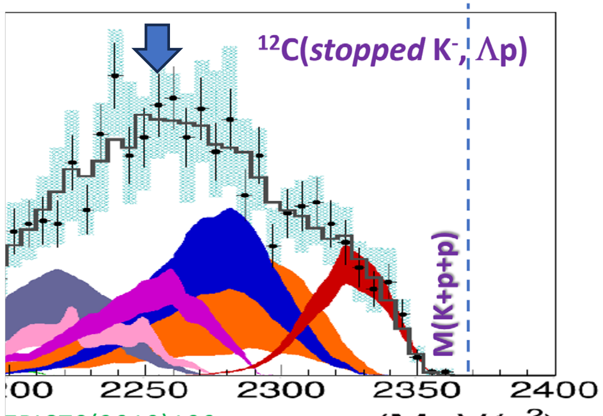
d(γ, K$^+$π$^-$)X @ 1.3-2.4 GeV/c

PLB728(2014)616.



AMADEUS@DAΦNE

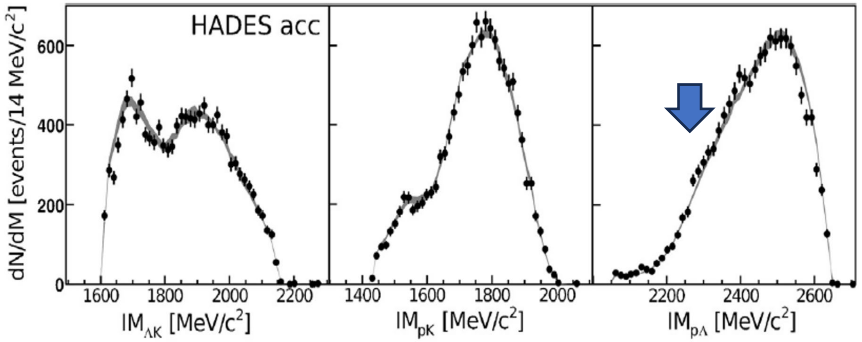
^{12}C(*stopped* K$^-$, Λp)



EPJ**C79**(2019)190

HADES@GSI PL**B742**(2015)242

p + p → (Λ + p) + K$^+$ @ 3.5GeV

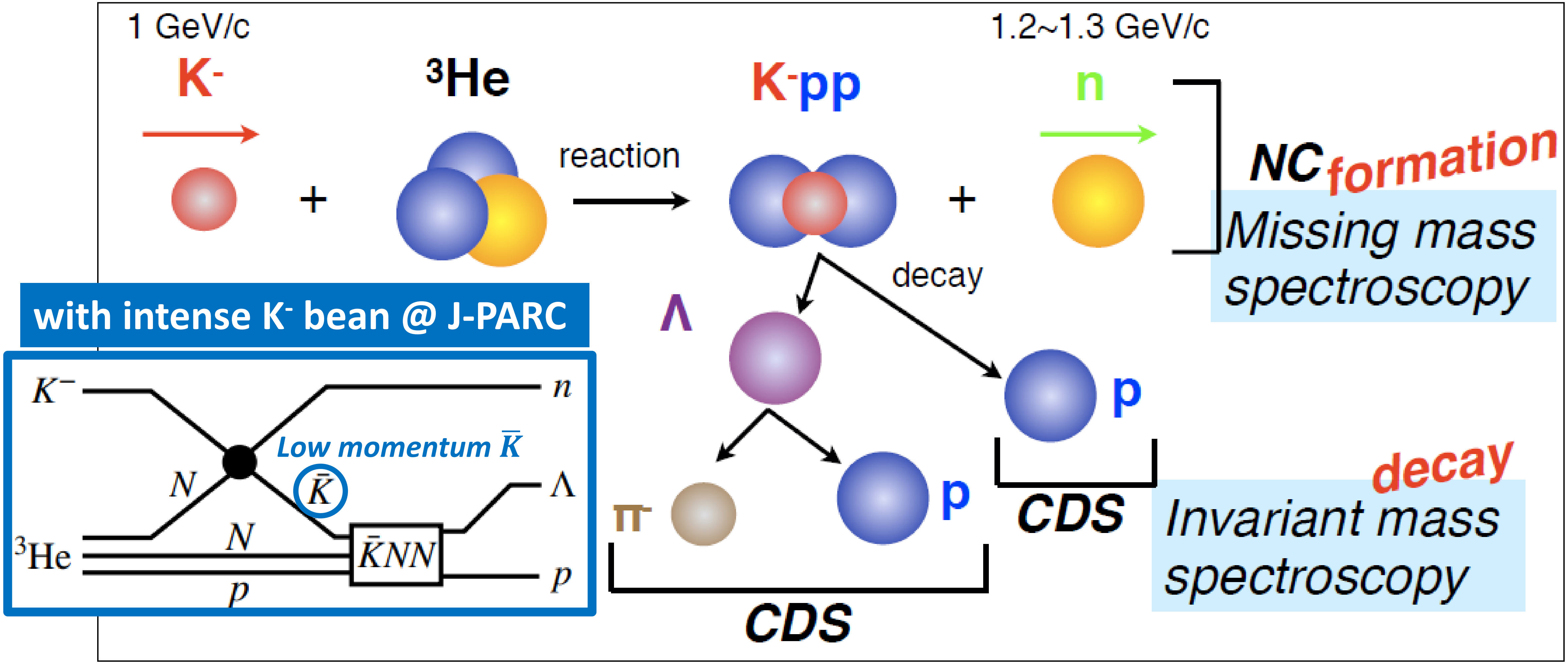


- Despite of many “K-pp” searches, NO conclusive results
  - ➢Complex reactions & difficult to understand background

"K⁻pp" Search @ J-PARC E15

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

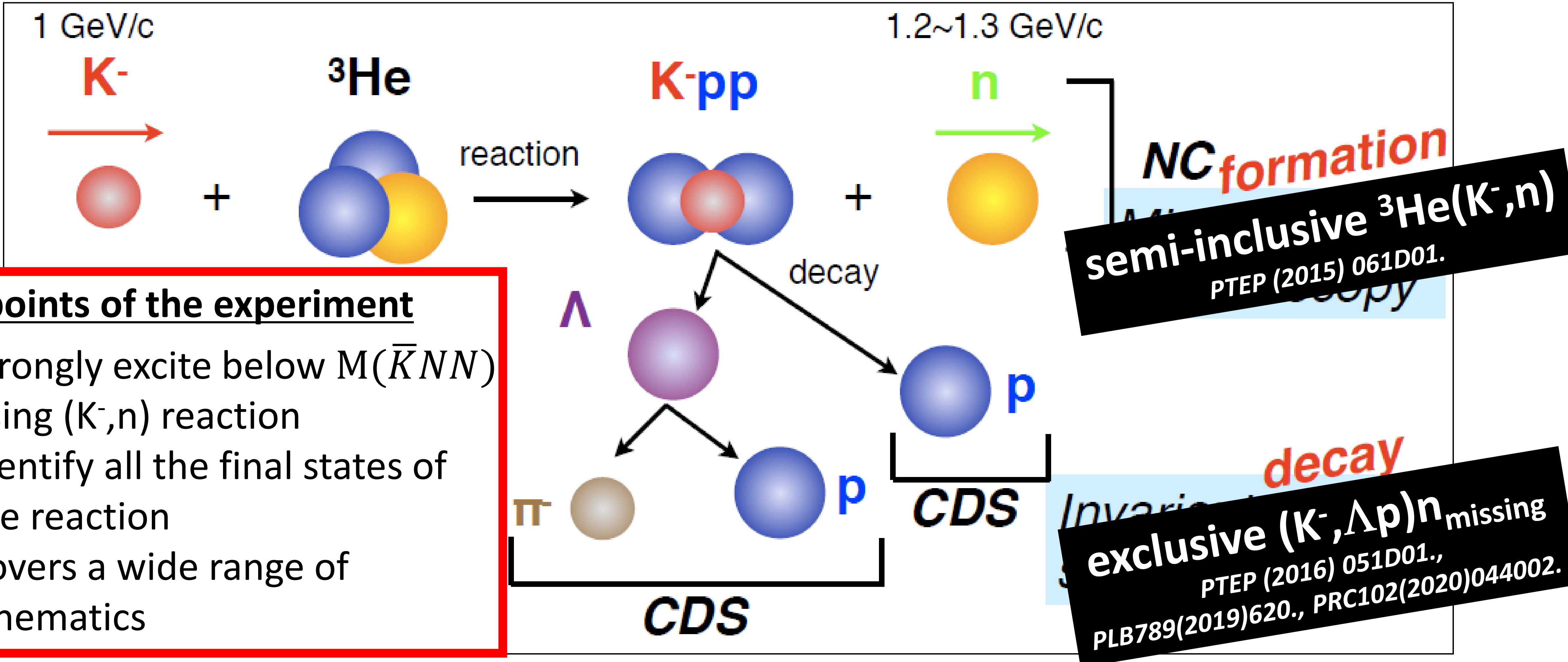
multi-NA and Y decays can be discriminated kinematically



"K$^-$pp" Search @ J-PARC E15

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

multi-NA and Y decays can be discriminated kinematically



Key points of the experiment

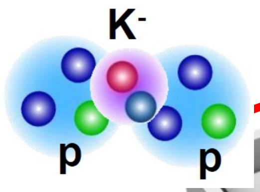
① Strongly excite below $\mathrm{M}(\bar{K}NN)$ using (K$^-$,n) reaction

② Identify all the final states of the reaction

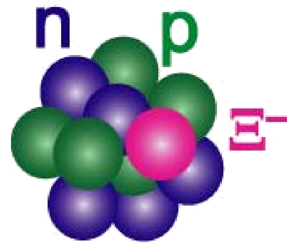
③ Covers a wide range of kinematics

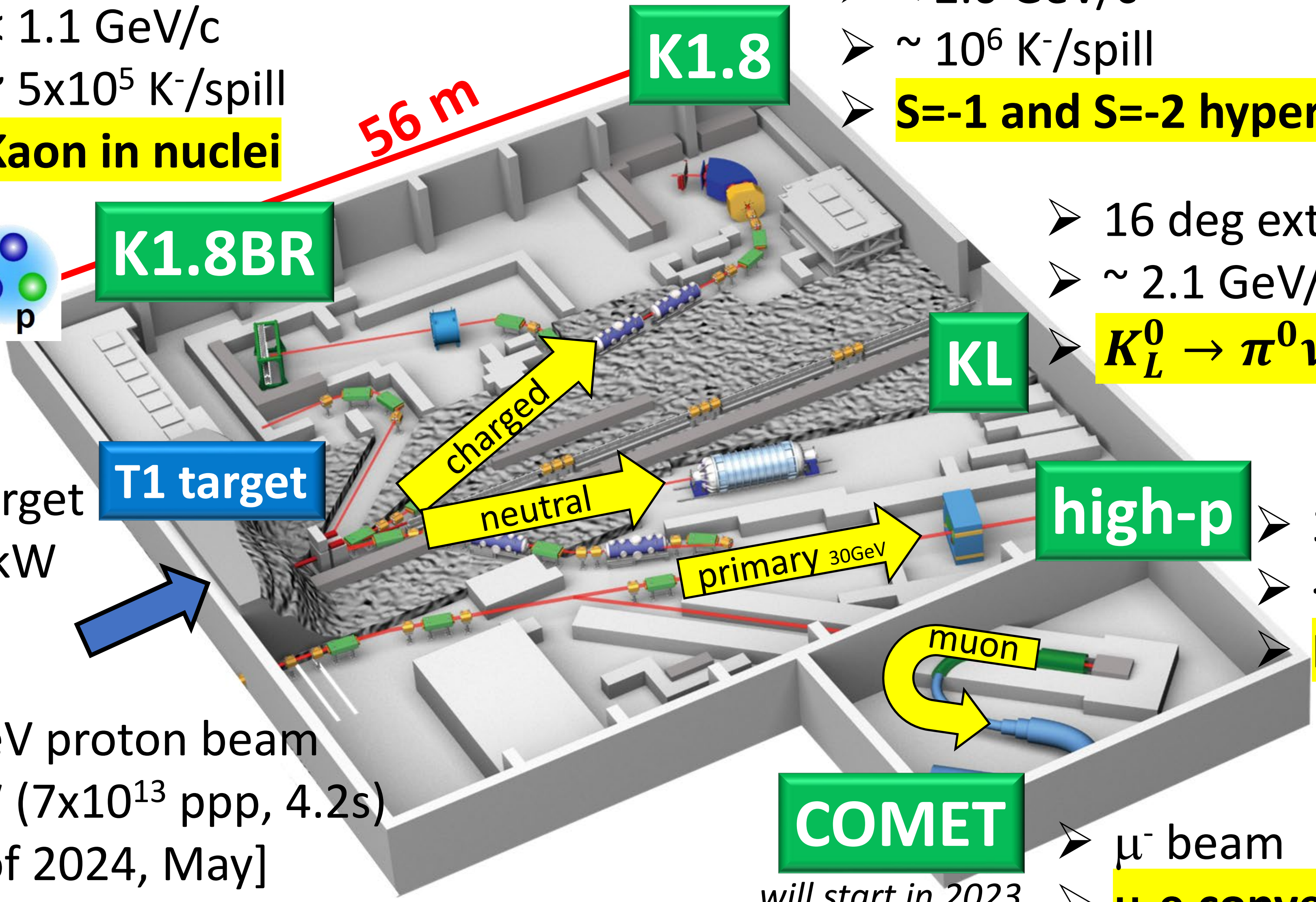
Hadron Experimental Facility (HEF)

- < 1.1 GeV/c
- ~ 5x10^5 K$^-$/spill
- **Kaon in nuclei**

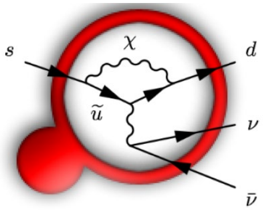


- < 2.0 GeV/c
- ~ 10^6 K$^-$/spill
- **S=-1 and S=-2 hypernuclei**





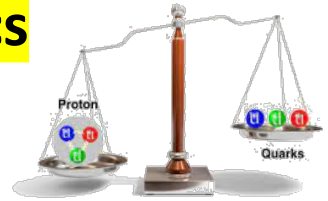
- 16 deg extraction
- ~ 2.1 GeV/c ~ 10^7 K^0_L/spill
- $K_L^0 \to \pi^0 \nu \bar{\nu}$



- Au Target
- < 95 kW

launched in 2020

- 30 GeV proton ~ 10^{10}
- < 31 GeV/c unsepa. π ~ 10^7
- **Hadron physics**

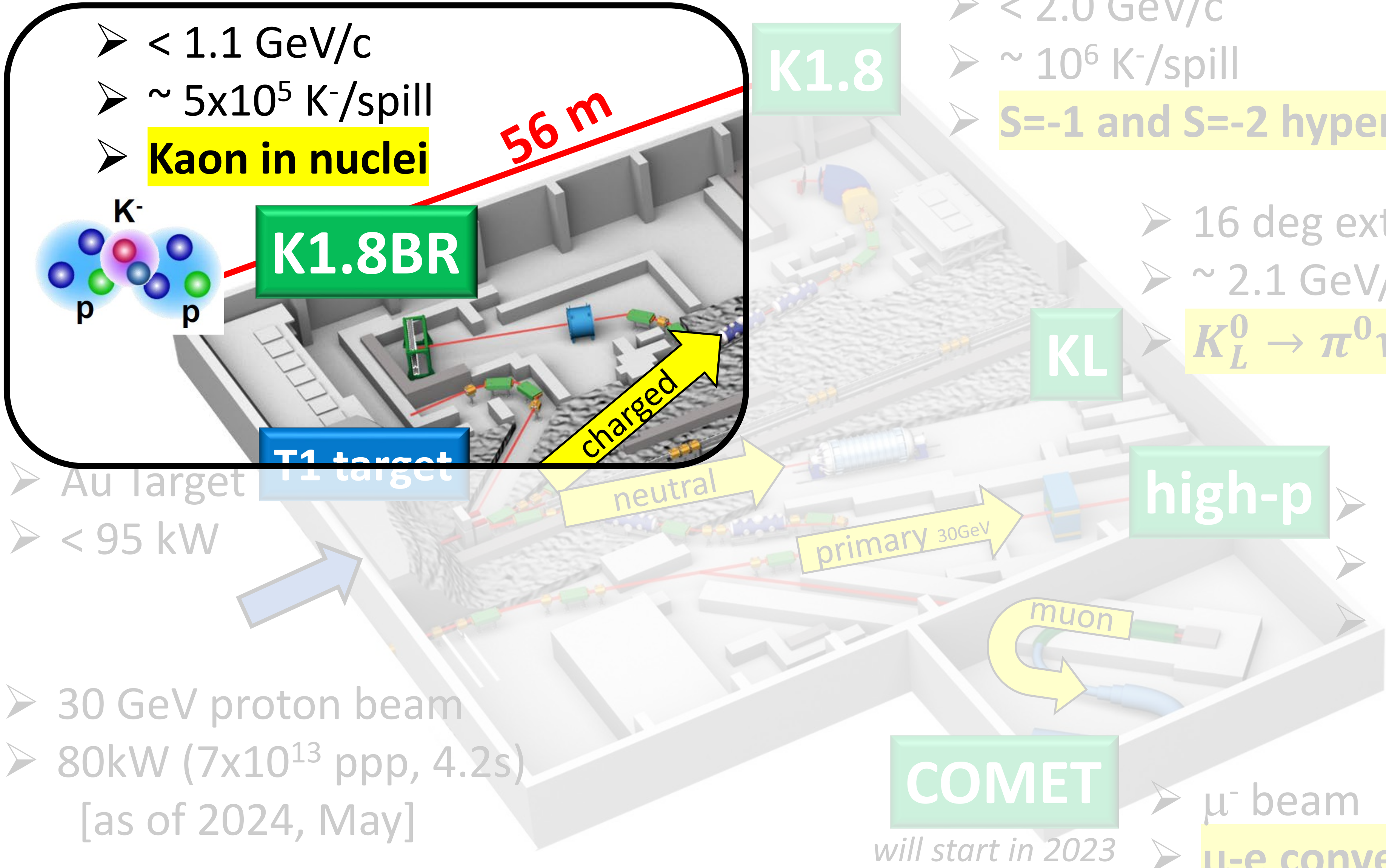


- 30 GeV proton beam
- 80kW (7x10^{13} ppp, 4.2s)
  [as of 2024, May]

will start in 2023

- μ$^-$ beam
- **μ-e conversion**

Hadron Experimental Facility (HEF)



K1.8BR
- < 1.1 GeV/c
- ~ 5×10^{5} K^-/spill
- **Kaon in nuclei**

K1.8
- < 2.0 GeV/c
- ~ 10^{6} K^-/spill
- **S=-1 and S=-2 hypernuclei**

KL
- 16 deg extraction
- ~ 2.1 GeV/c ~ 10^{7} K^0_L/spill
- $K_L^0 \to \pi^0 \nu \bar{\nu}$

high-p

launched in 2020
- 30 GeV proton ~ 10^{10}
- < 31 GeV/c unsepa. π ~ 10^{7}
- **Hadron physics**

COMET

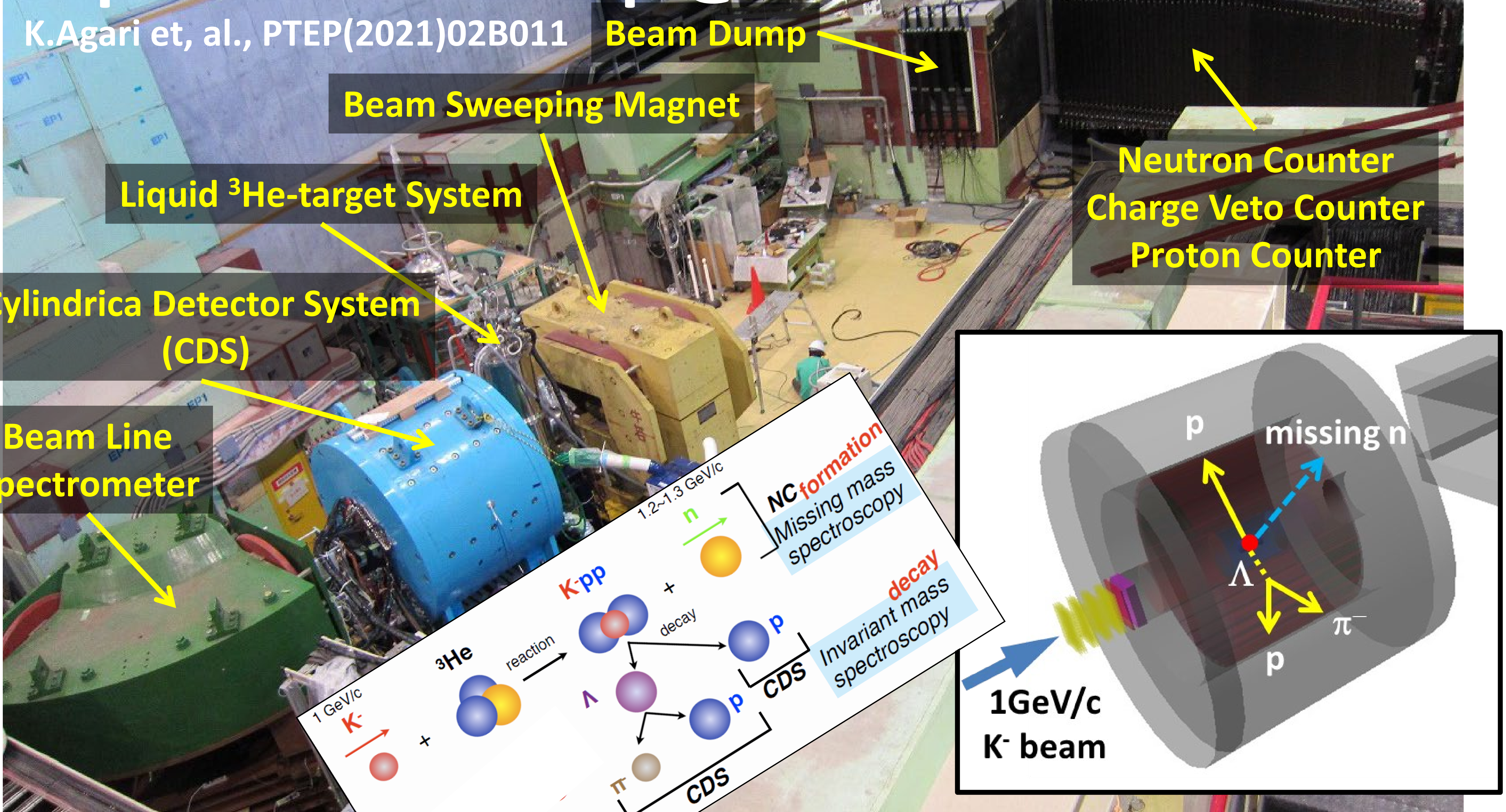
will start in 2023
- μ^- beam
- **μ-e conversion**

T1 target
- Au Target
- < 95 kW

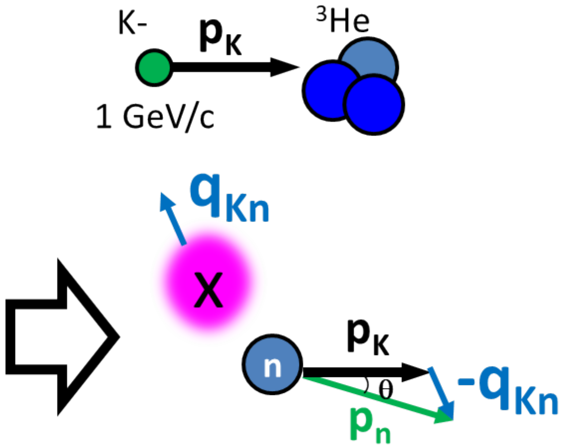
- 30 GeV proton beam
- 80kW (7×10^{13} ppp, 4.2s)
  [as of 2024, May]

Experimental Setup @ K1.8BR

K.Agari et, al., PTEP(2021)02B011



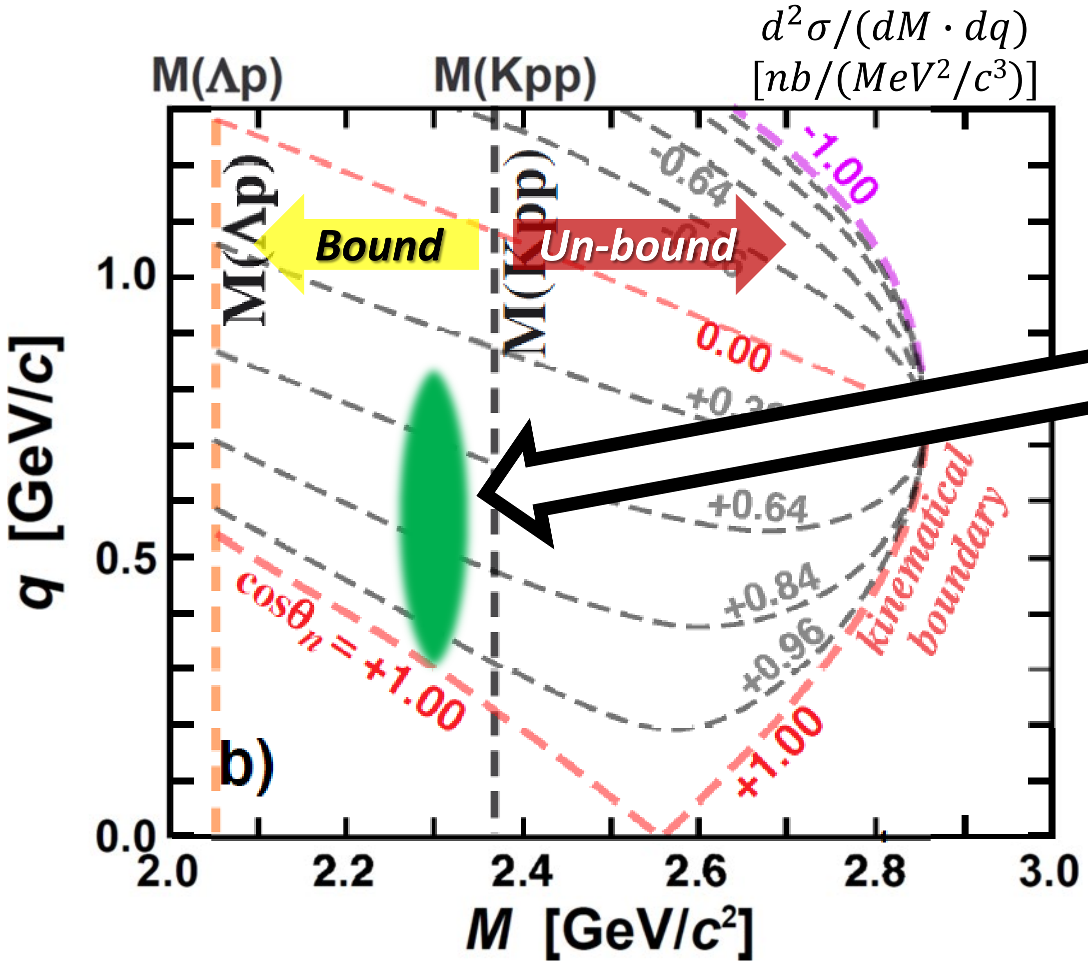
“K⁻pp” Search w/ Momentum Transfer Analysis



- **Momentum transfer analysis using the (K^-,n) reaction**

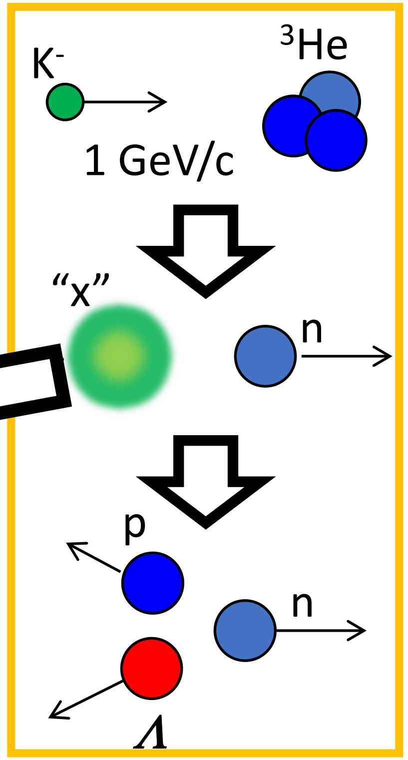
✓ M(Λp) vs. q

✓ give a clear information on reaction processes



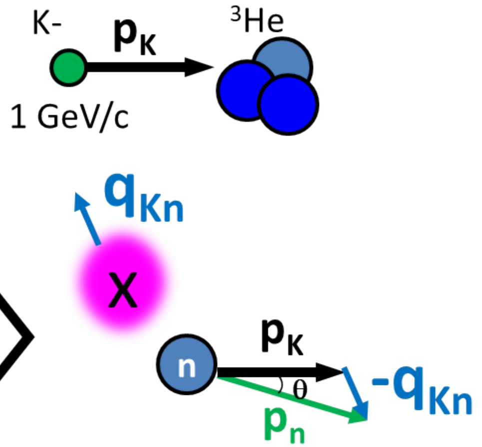
q *: (K^-,n) momentum transfer*

M *: Λp invariant mass*



If a bound state exists, there is a peak structure independent of *q* below the M(Kpp)

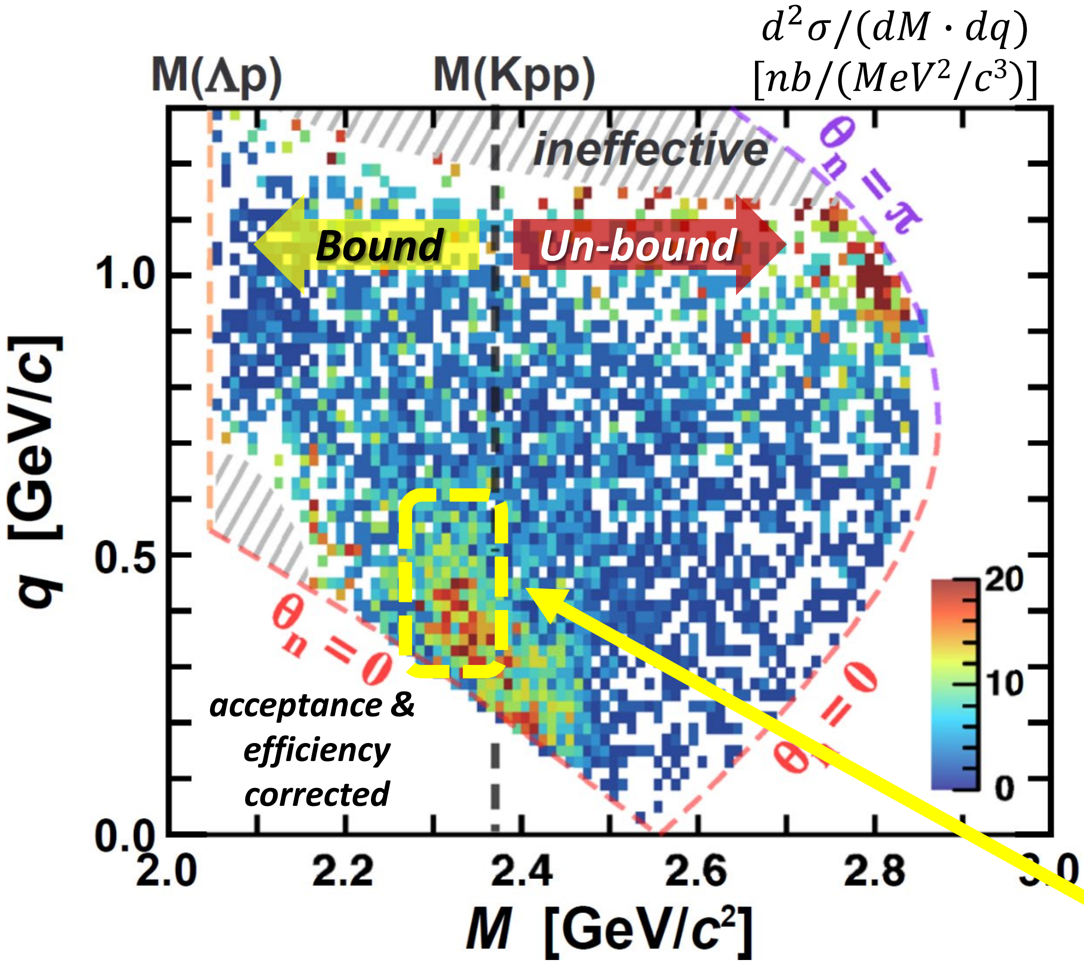
"K⁻pp" Search w/ Momentum Transfer Analysis



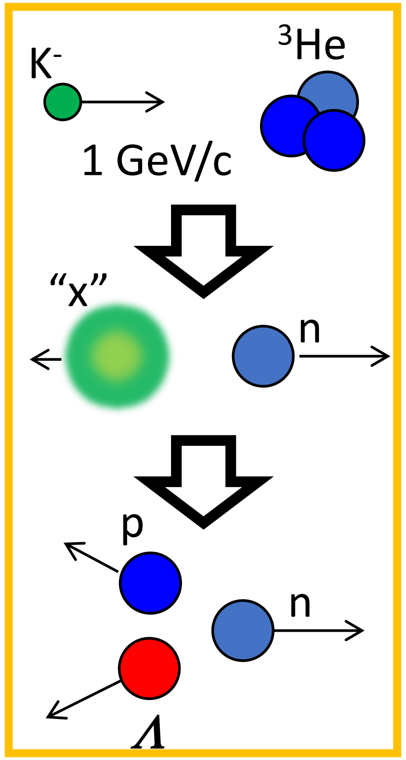
- **Momentum transfer analysis using the (K^-,n) reaction**

✓ M(Λp) vs. q
✓ give a clear information on reaction processes

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

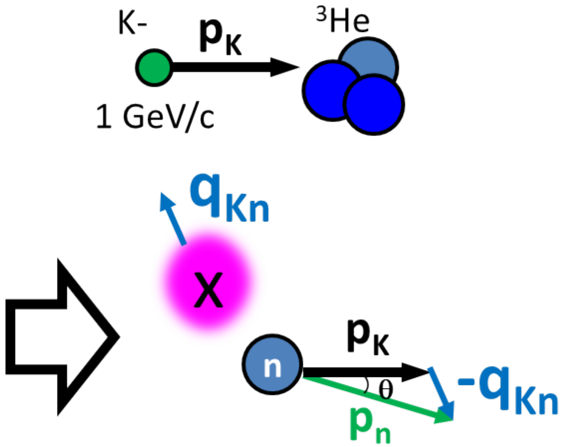


q : (K^-,n) momentum transfer
M : Λp invariant mass



A peak structure independent of q = A bound state exists

"K^-pp" Search w/ Momentum Transfer Analysis

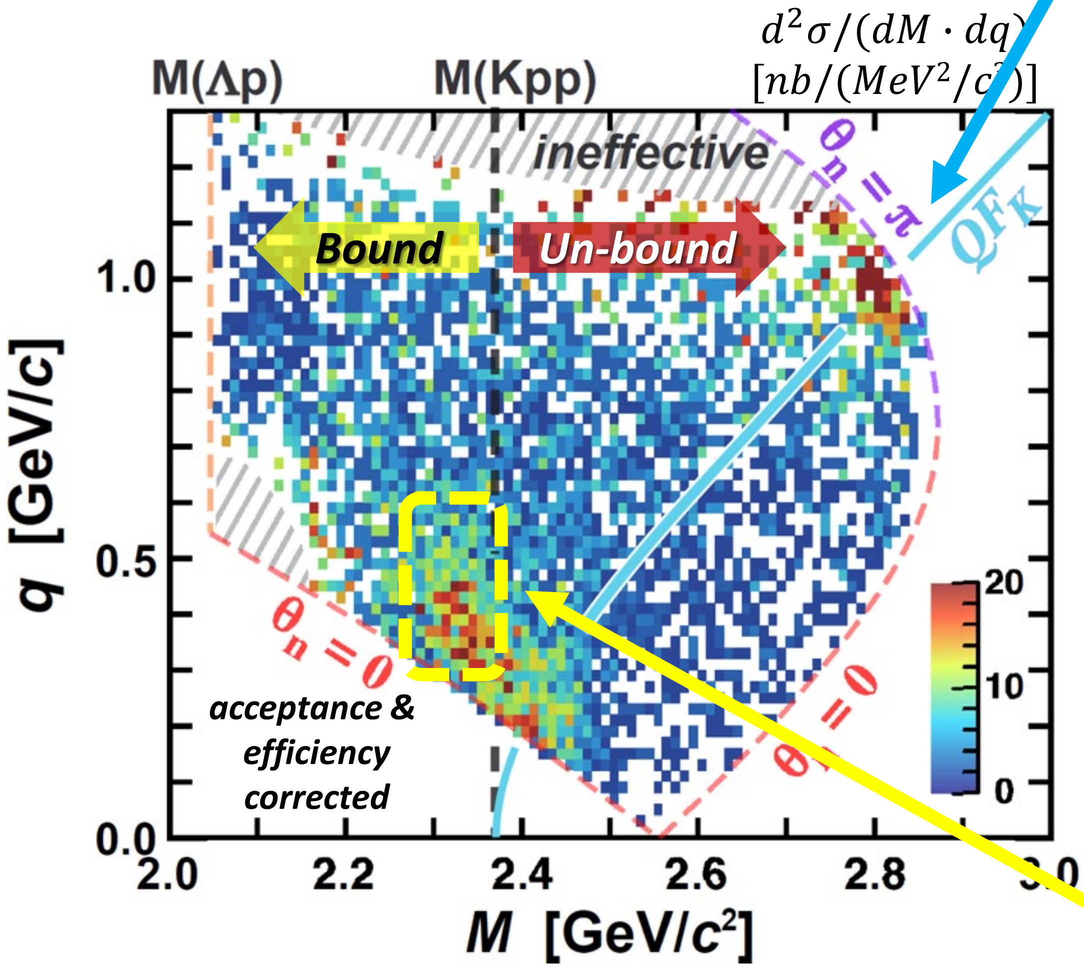


- **Momentum transfer analysis using the (K^-,n) reaction**

✓ M(Λp) vs. q

✓ give a clear information on reaction processes

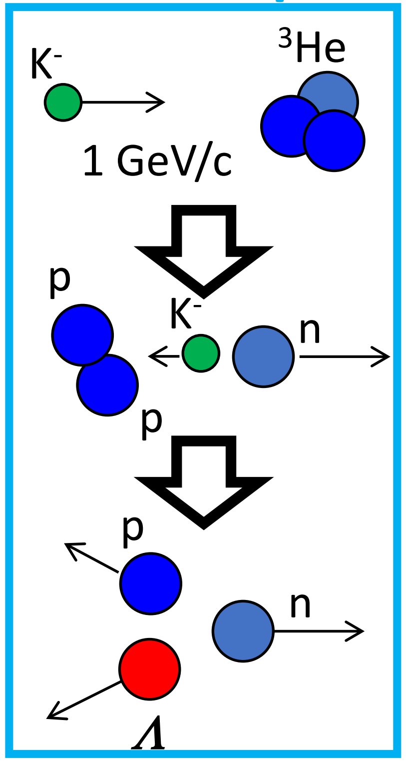
PLB789(2019)620., PRC102(2020)044002.



$\boldsymbol{q}$: (K^-,n) momentum transfer

$\boldsymbol{M}$: Λp invariant mass

Quasi-free K^- scattering (+2NA absorption)



A peak structure independent of q = A bound state exists

A PWIA-based Interpretation

Energy term (BW type) from time integral

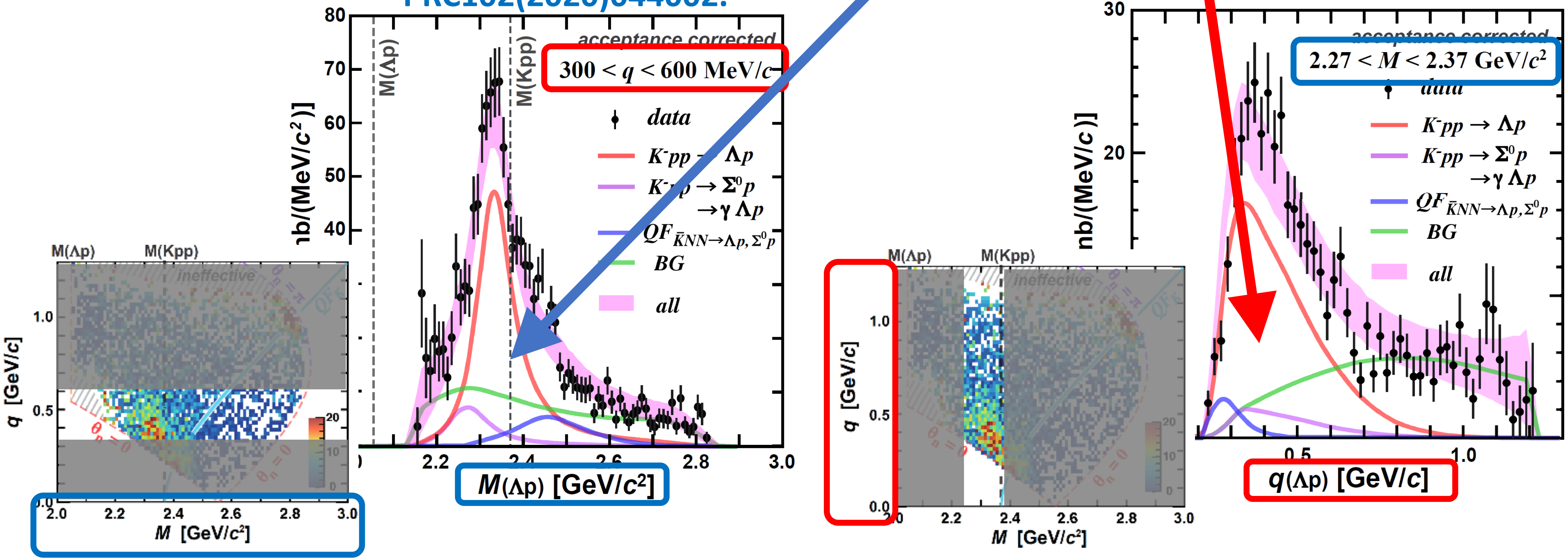
Momentum term from spatial integral

Plane Wave Impulse Approximation

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.



Deep binding = Strong K^bar N int.

B_{Kpp}(BW) ~ 40 MeV, Γ_{Kpp}(BW) ~ 100 MeV

Binding energy   Decay width

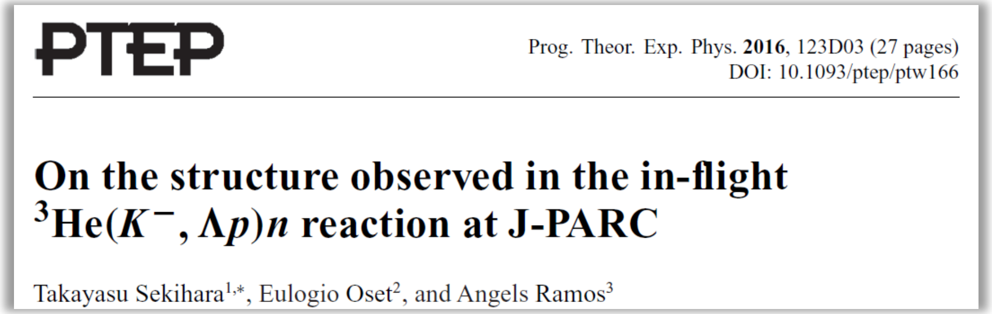
Large *Q* = Suggest a compact system

Q_{kpp} ~ 400 MeV

Form factor

A Theoretical Interpretation

A calculation based on chiral unitary approach
reproduces the data well using the $\bar{K}NN$ bound state

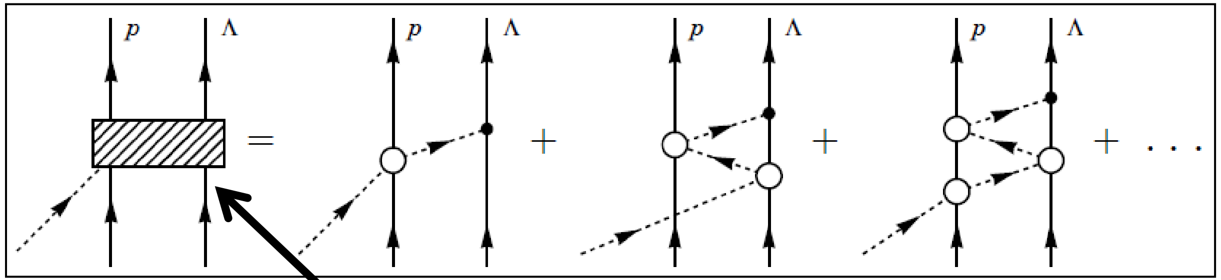


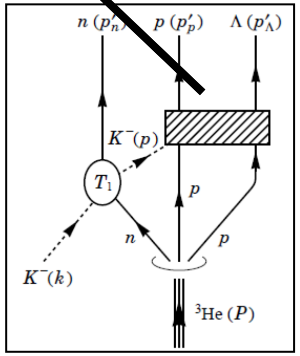
PTEP

Prog. Theor. Exp. Phys. **2016**, 123D03 (27 pages)
DOI: 10.1093/ptep/ptw166

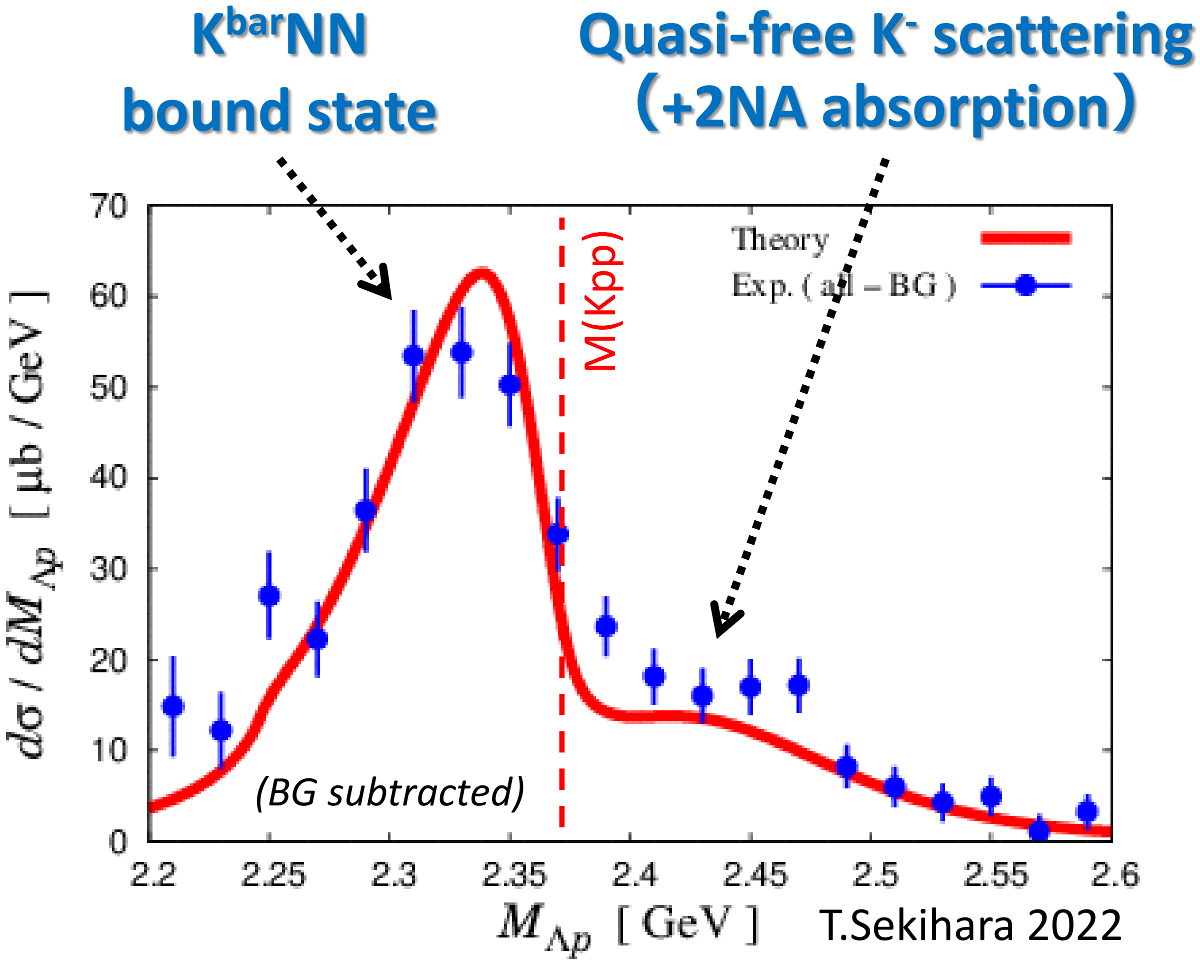
On the structure observed in the in-flight ^{3}He(K^-, Λp)n reaction at J-PARC

Takayasu Sekihara[1,*], Eulogio Oset[2], and Angels Ramos[3]





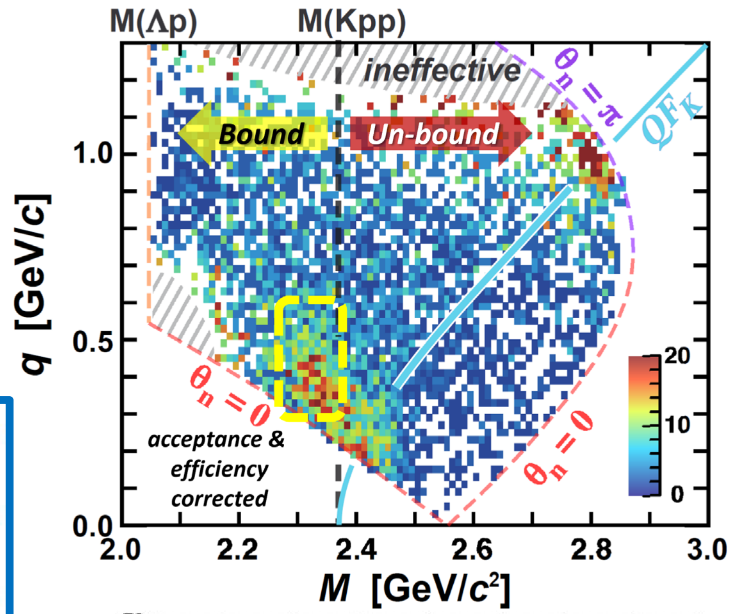
Theoretical investigations are indispensable!

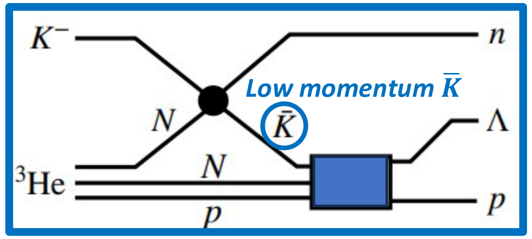


What We Observed at E15 [Discussion]

✓**A peak structure below the mass threshold M(Kpp) that does NOT depend on momentum transfer**

- ➢A bound state exists
- ➢~10 times the binding energy of normal light nuclei
- ➢Generated by large momentum transfer

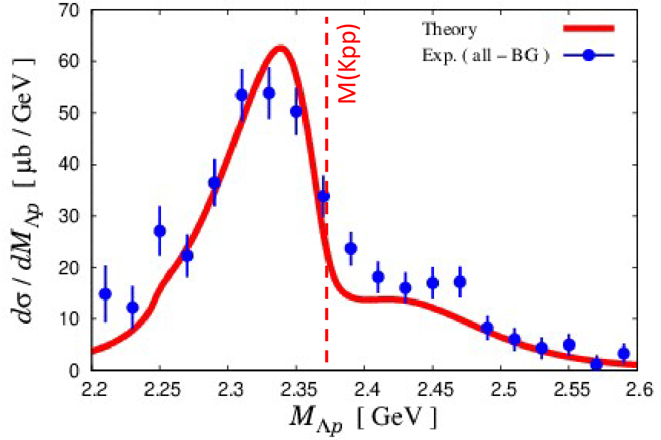




✓**Evidence of quasi-free K⁻ scattering**

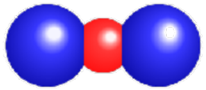
- ➢An intermediate $\bar{K}$ exists during the reaction

◆**Consistent with a theoretical calculation using "K-pp"**



Observed bound state = "K-pp" bound state

→ Suggests possibility of being in a compact system

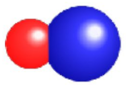


K⁻pp

Need Further Investigations

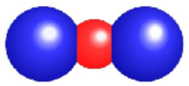
to establish the kaonic nuclei

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



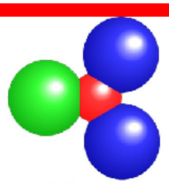
K^-p

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

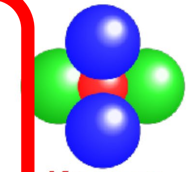


K^-pp

- **Heavier kaonic nuclei**
  - Mass number dependence?

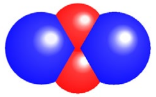


K^-ppn



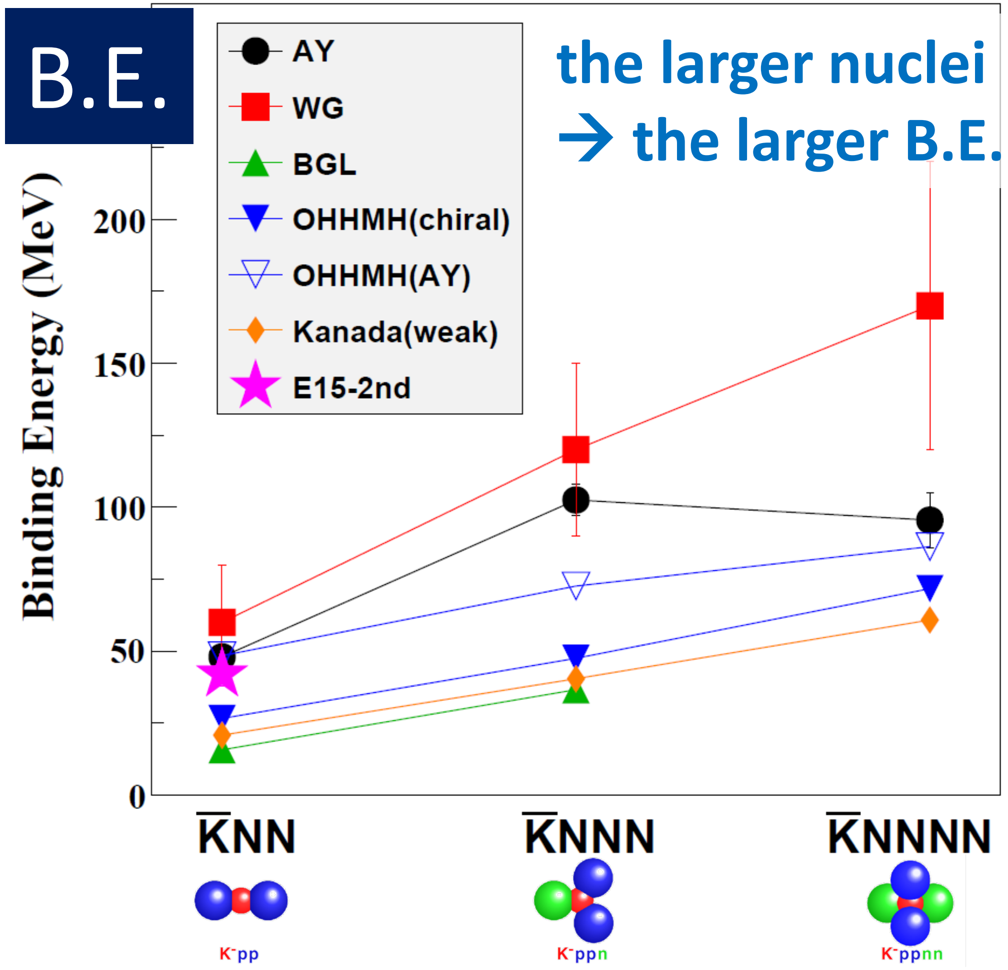
K^-ppnn

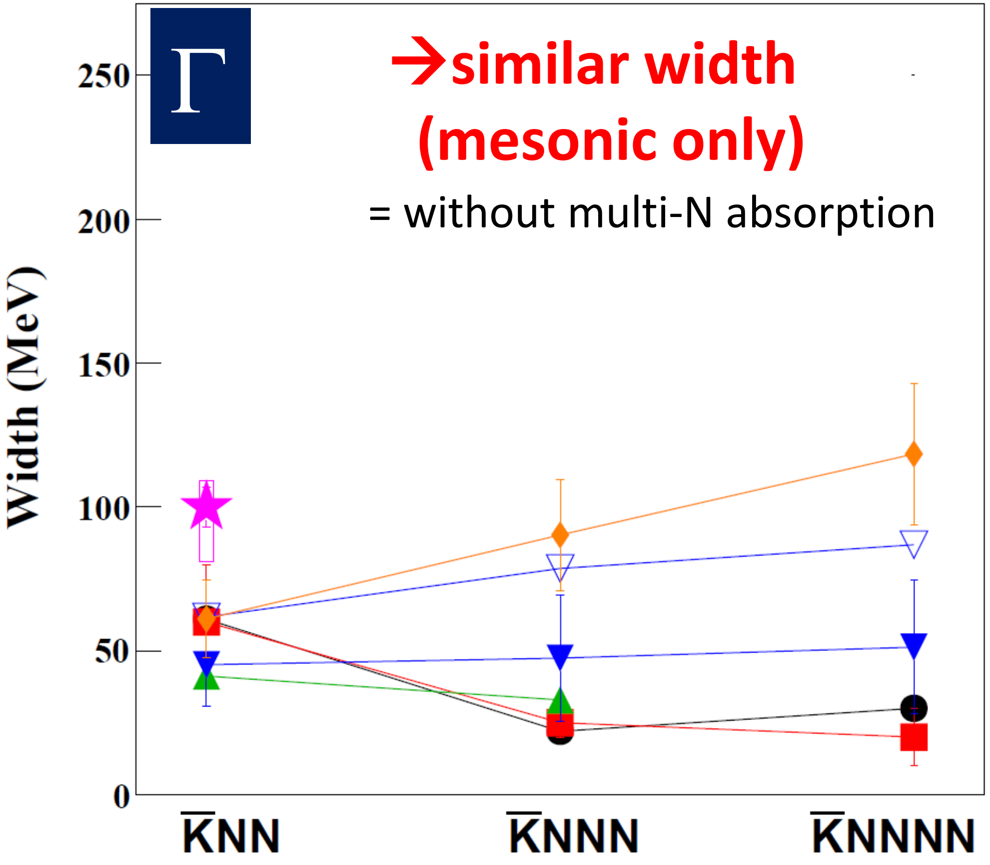
- **Double kaonic nuclei**
  - Much compact and dense system?



K^-K^-pp

Mass Number Dependence of Kaonic Nuclei



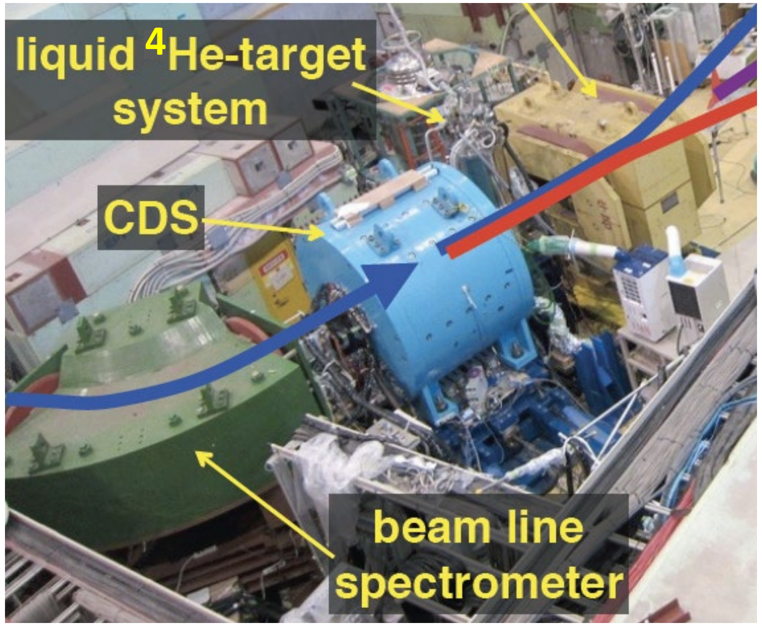


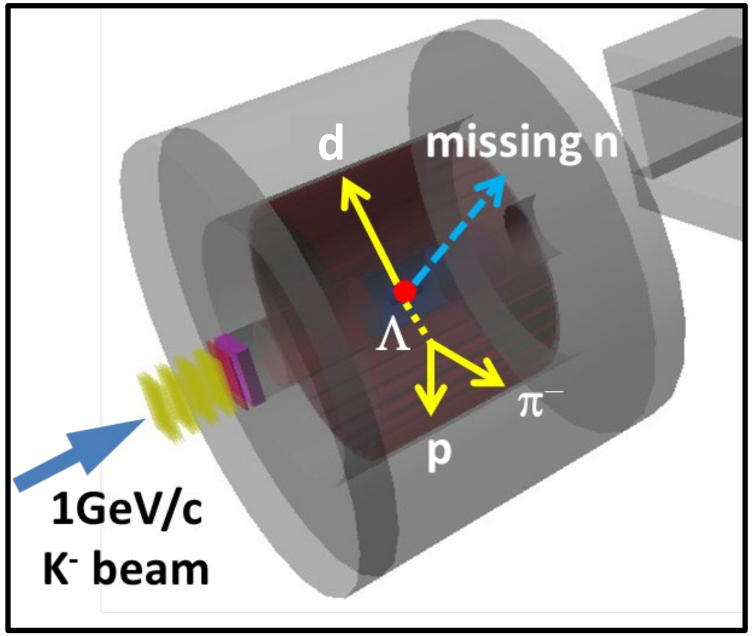
- **Systematic measurements will provide more conclusive evidence of the kaonic nuclei**

AY: PRC65(2002)044005, PLB535(2002)70.
WG: PRC79(2009)014001.
BGL: PLB712(2012)132.
OHHMH: PRC95(2017)065202.
Kanada: EPJA57(2021)185.

K^{-} ^{4}He → Λdn Analysis with the T77 Data

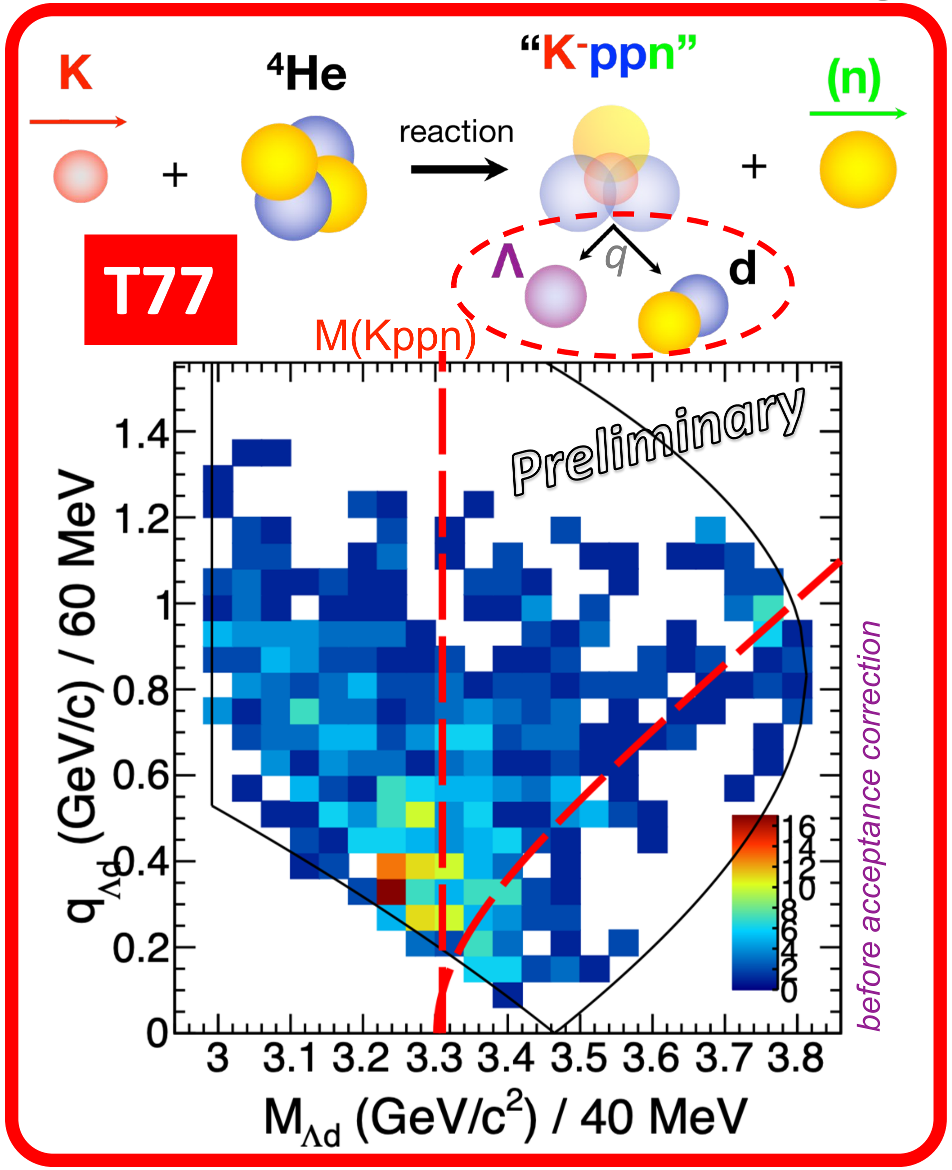
- An analysis of the **Λdn** final state with **K^{-} ^{4}He** reaction at **1 GeV/c** has been conducted
  - T77: lifetime measurement of $^4_\Lambda$H in 2020
- The results will be updated with a part of the E73 controlled data
  - E73: lifetime measurement of $^3_\Lambda$H in 2024 (***now in beam time!***)

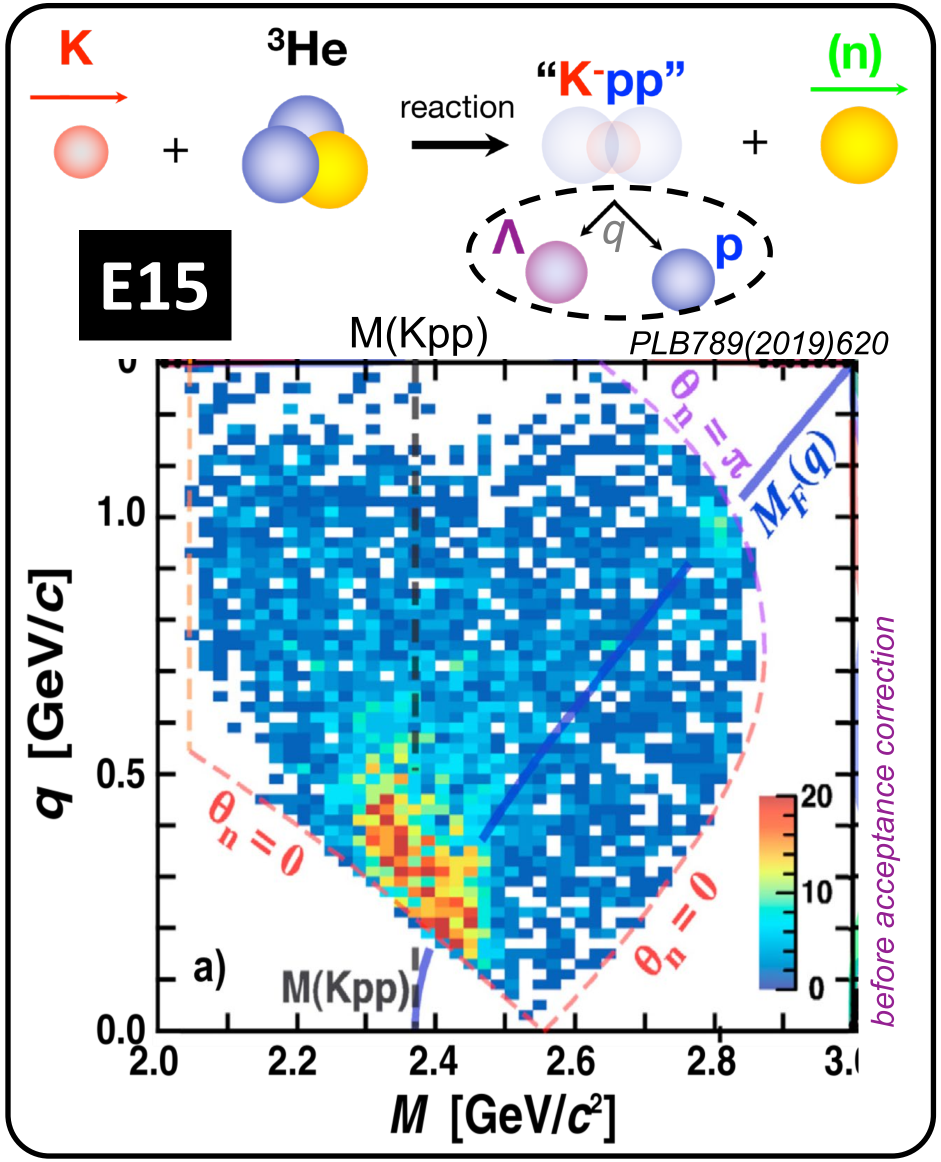




Experiment	K^- on target
T77 (^{4}He)	~6 x 10^9
E73 (^{4}He)	~6 x 10^9
E15 (^{3}He)	~42 x 10^9

$K^{-4}He \rightarrow \Lambda dn$ Analysis with the T77 Data





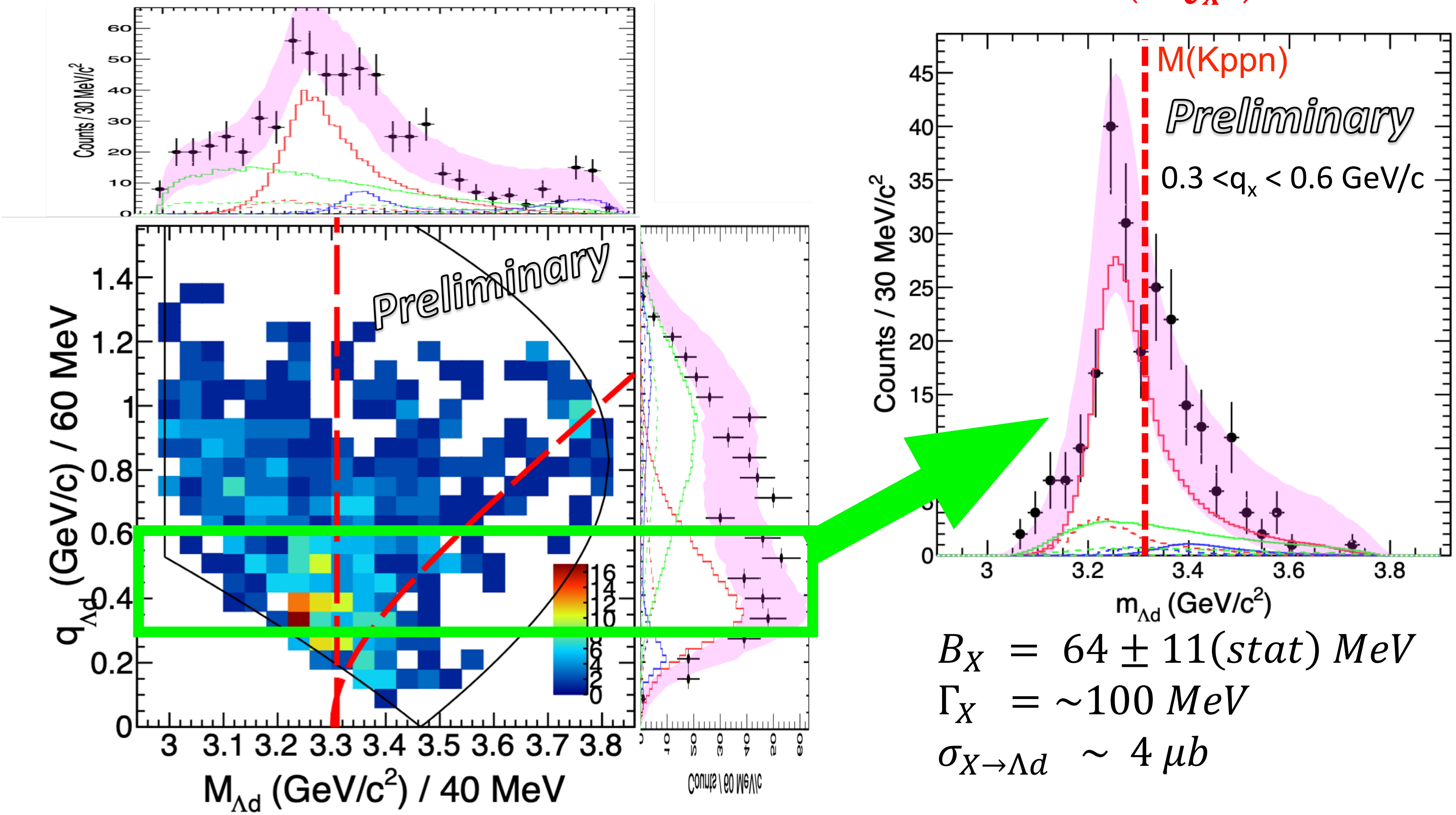
- **Two distributions are quite similar**
- structure below the threshold (**seems *q*-independent**), QF-K, BG

$K^{-4}He \rightarrow \Lambda dn$ Analysis with the T77 Data

2D fit on the (M,q) space with similar shapes to E15:

Breit-Wigner wtih Gaus. form factor (PWIA), QF-K^-, and Broad BG

$$\sigma(M,q) \propto \rho(M,q) \times \frac{(\Gamma_X/2)^2}{(M-M_X)^2+(\Gamma_X/2)^2} \times exp\left(-\frac{q^2}{{Q_X}^2}\right)$$



$B_X = 64 \pm 11(stat)\ MeV$

$\Gamma_X = \sim 100\ MeV$

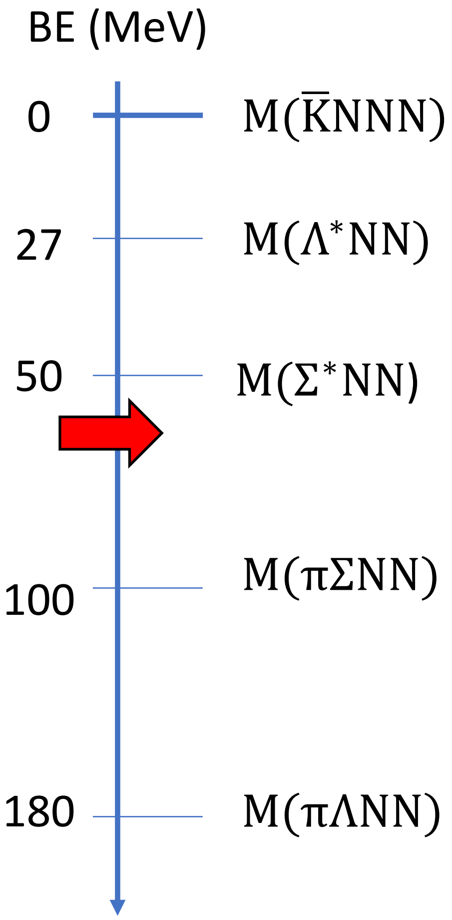
$\sigma_{X\rightarrow\Lambda d} \sim 4\ \mu b$

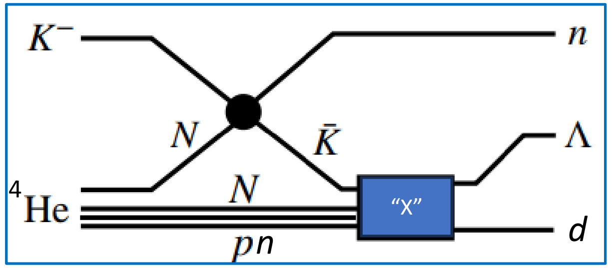
K^{-4}He → Λdn Analysis with the T77 Data

What is the observed structure? [Discussion]

1. "X"→Λd decay mode is unique evidence of **$I_{„X"} = 0$**
   - I(J^P) : Λ = 0(1/2$^+$), d = 0(1$^+$), K^- = 1/2(0$^-$), ^{3}He = 1/2(1/2$^+$) , ^{4}He = 0(0$^+$)

2. **"X"="K^-ppn" with $J_{„X"}$ = 1/2** would be likely, considering the isospin and spin combination in S-wave interaction
   - **$J_{„X"}$ = 1/2:** ^{4}He initial state is I(J) = 0(0) and low-momentum intermediate $\bar{K}$ would react with remaining NNN [I(J) = 1/2(1/2)] in S-wave
   - **Exclusion of Y*(I=1)NN**: probability of "X"→Λd decay would be suppressed because spin/isospin flip is needed to reconfigure NN [I(J) = 1(0)] into deuteron [I(J) = 0(1)]
     - ➢ Λpn decay would be dominant

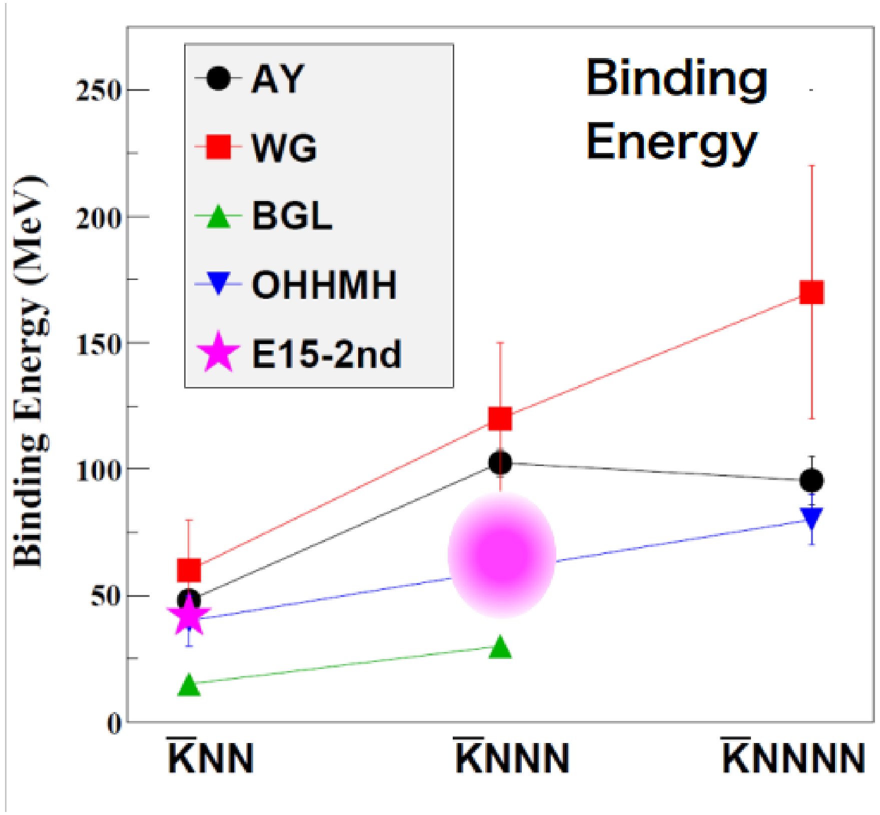


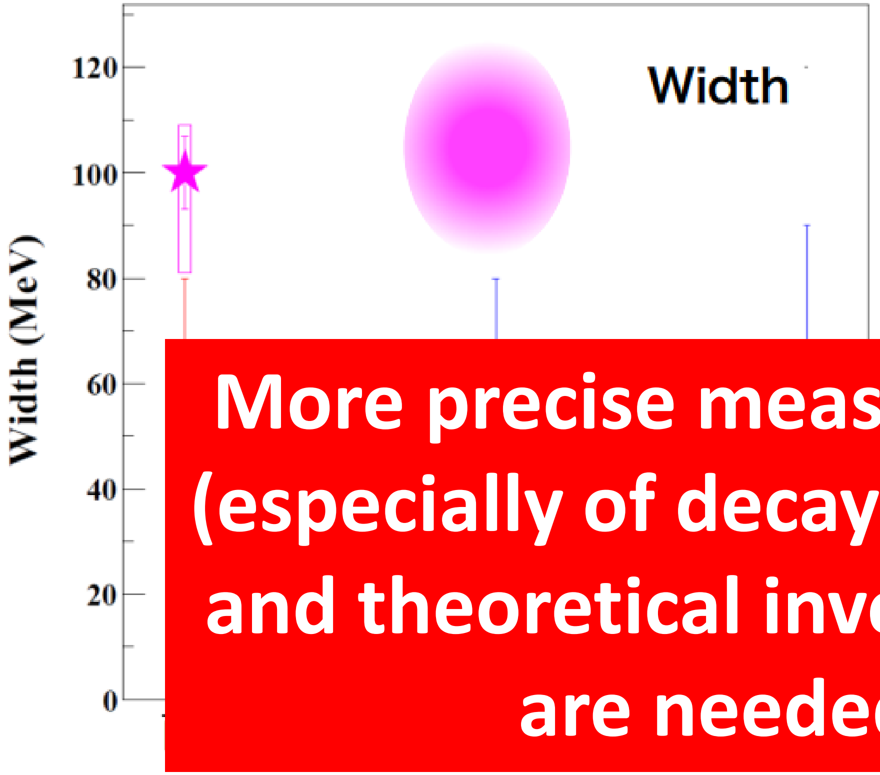


$K^{-4}He \rightarrow \Lambda dn$ Analysis with the T77 Data

What is the observed structure? [Discussion]

If “X” is “$K^{-}ppn$”



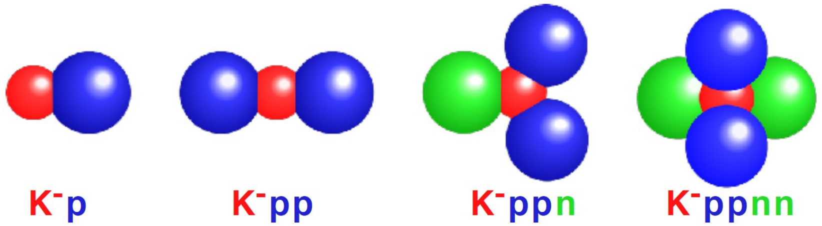


More precise measurements (especially of decay branches) and theoretical investigations are needed

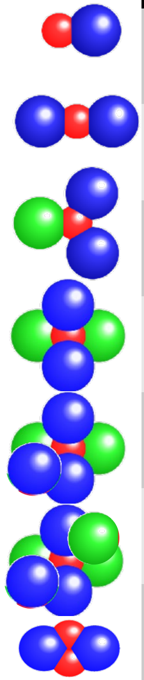
- The binding energy is compatible with some theoretical predictions
- The width is larger than theoretical predictions

New Kaonic Nuclei Project at J-PARC

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

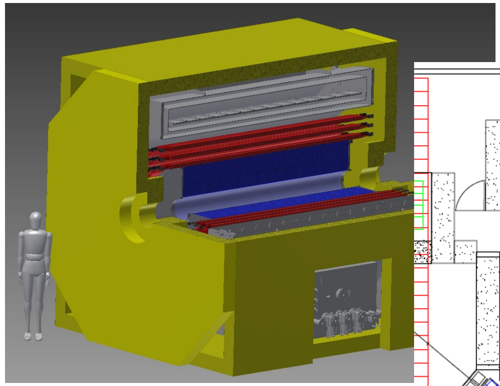


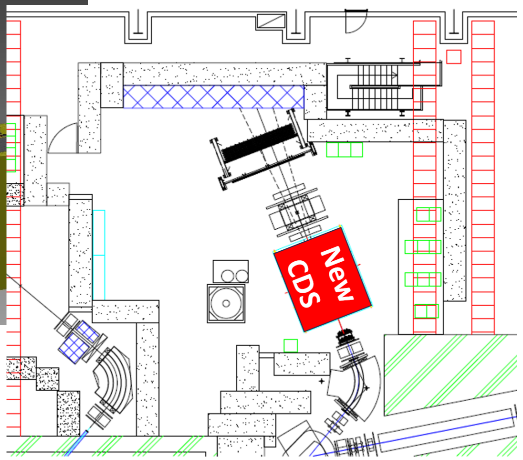
Strategy



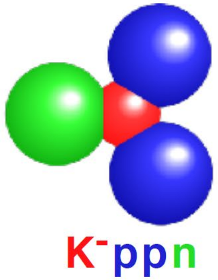
	Reaction	Decays	Key	Experiment
$\bar{K}N$	d(K$^-$,n)	$\pi^{\pm 0}\Sigma^{\mp 0}$	n/γ identification	Future
$\bar{K}NN$	^{3}He(K$^-$,N)	Λp/Λn	polarimeter	P89
$\bar{K}NNN$	^{4}He(K$^-$,N)	Λd/Λpn	large acceptance	E80 ← **A first step**
$\bar{K}NNNN$	^{6}Li(K$^-$,d)	Λt/Λdn	many body decay	Future
$\bar{K}NNNNN$	^{6}Li(K$^-$,N)	$\Lambda\alpha$/Λdd/Λdpn	many body decay	Future
$\bar{K}NNNNNN$	^{7}Li(K$^-$,N)	$\Lambda\alpha$n/Λddn	many body decay	Future
$\bar{K}\bar{K}NN$	*$\bar{p}$ + ^{3}He*	*$\Lambda\Lambda$*	*$\bar{p}$ beam yield*	*Future (LoI)*

- 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** **← improved K1.8BR**
    - more K$^-$ yield than the existing beamline



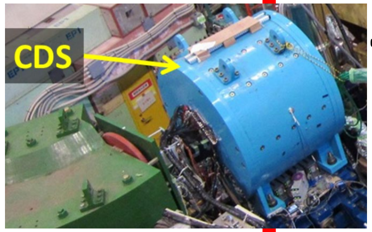


We take a step-by-step approach



$\bar{K}NNN$ @ E80

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



① **Establish the existence of $\bar{K}NNN$**

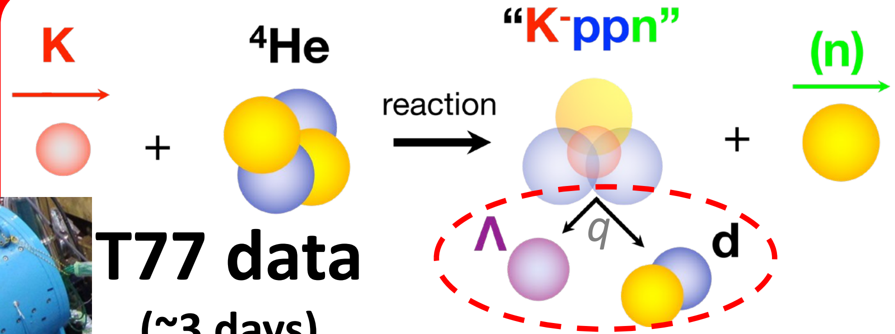
- "K-ppn"→Λd 2-body decay

② **Study the multi-particle decay mode of $\bar{K}NNN$ toward understanding its internal structure**

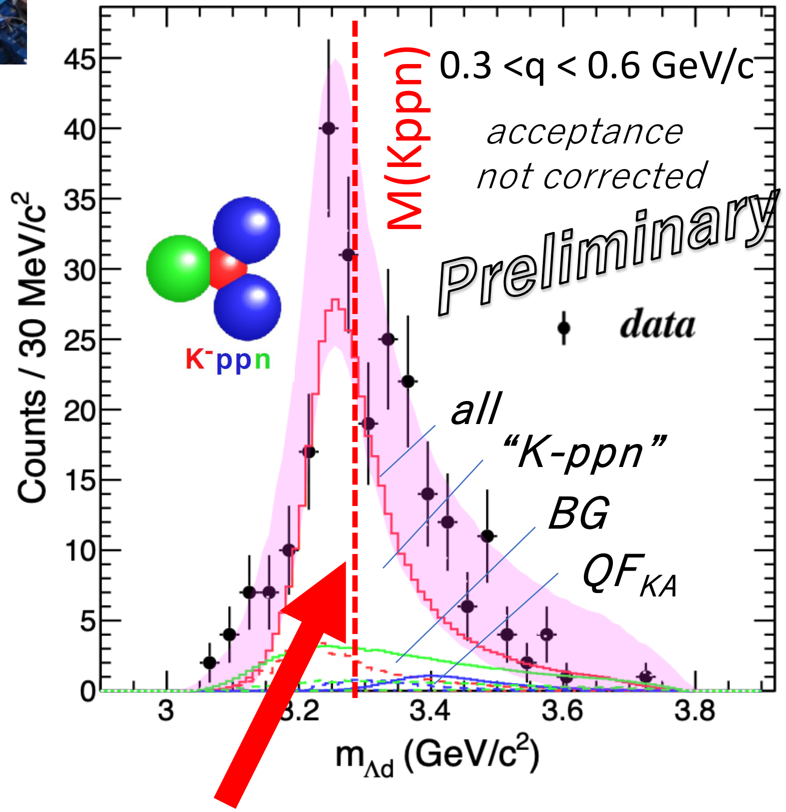
- "K-ppn"→Λpn 3-body decay

- **Feasibility study of spin-spin correlation measurement for P89**
  - *e.g.*, installing a prototype module of a polarimeter

Beam intensity	90kW
Beam time	1+1+3 weeks

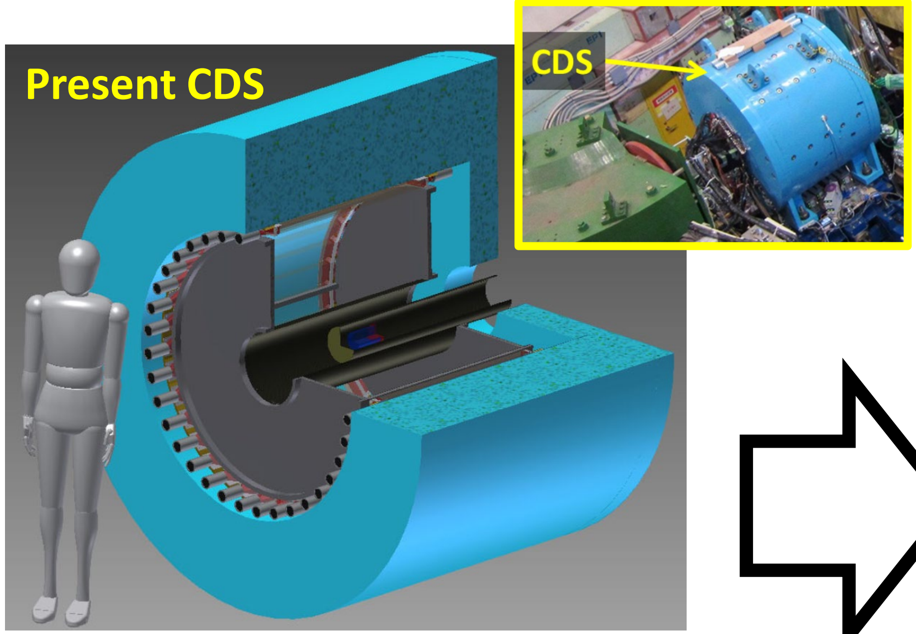


T77 data
(~3 days)



the sign of the "K⁻ppn"

New Cylindrical Detector System (CDS)

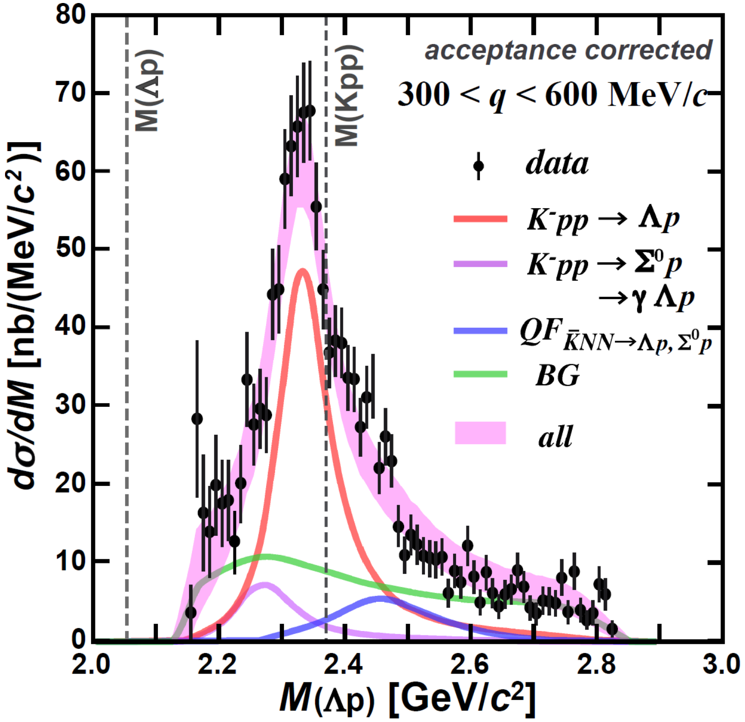


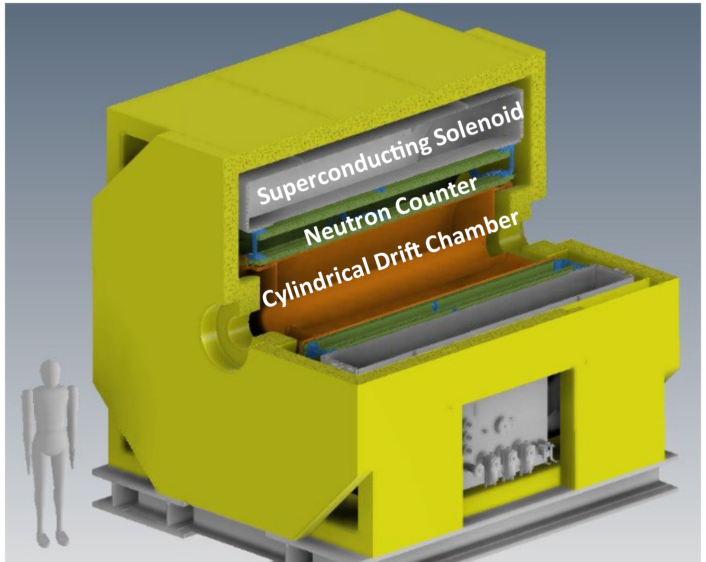
✓**Solid angle: x1.6** (59% → 93%)

✓**Neutron eff.: x6~7** (3% → 15%x1.6)

Summary

- We observed the “K^-pp” bound state in $^3He(K^-,\Lambda p)n$
  - ✓PLB789(2019)620., PRC102(2020)044002.
- We also obtained hints of mesonic decays of “K-pp”
  - ✓arXiv:2404.01773 [nucl-ex]
- We observed the sign of the “K^-ppn” in $^4He(K^-,\Lambda d)n$
  - ✓will be published soon with twice statistics
- New project has started from E80, “K^-ppn”, aiming at the systematic study of the kaonic nuclei
  - Constructing a large solenoid spectrometer
  - Modify the K1.8BR BL to improve kaon yield
  - **Data taking will start in FY2026-27**





FY2026 to be completed

J-PARC E80 Collaboration

K. Itahashi, M. Iwasaki, T. Hashimoto, Y. Ma, R. Murayama, T. Nanamura, F. Sakuma*
RIKEN, Saitama, 351-0198, Japan

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

Y. Kimura, G. Kojima, H. Ohnishi, K. Toho, M. Tsuruta
Research Center for Accelerator and Radioisotope Science (RARIS), Tohoku University, Sendai, 982-0826, Japan

M. Iio, S. Ishimoto, Y. Makida, H. Ohhata, M. Oonaka, K. Ozawa, K. Sasaki, N. Sumi, S. Suzuki, T. Yamaga, M. Yoshida
High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan

We're looking for new collaborators!

K. Tanida
Japan Atomic Energy Agency (JAEA), Ibaraki 319-1195, Japan

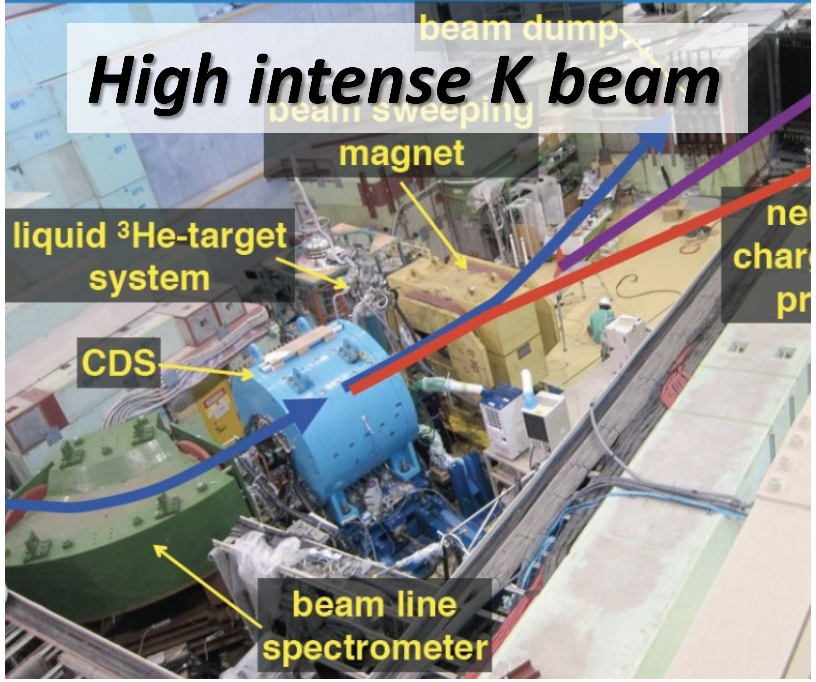
T. Nagae
Department of Physics, Kyoto University, Kyoto, 606-8502, Japan

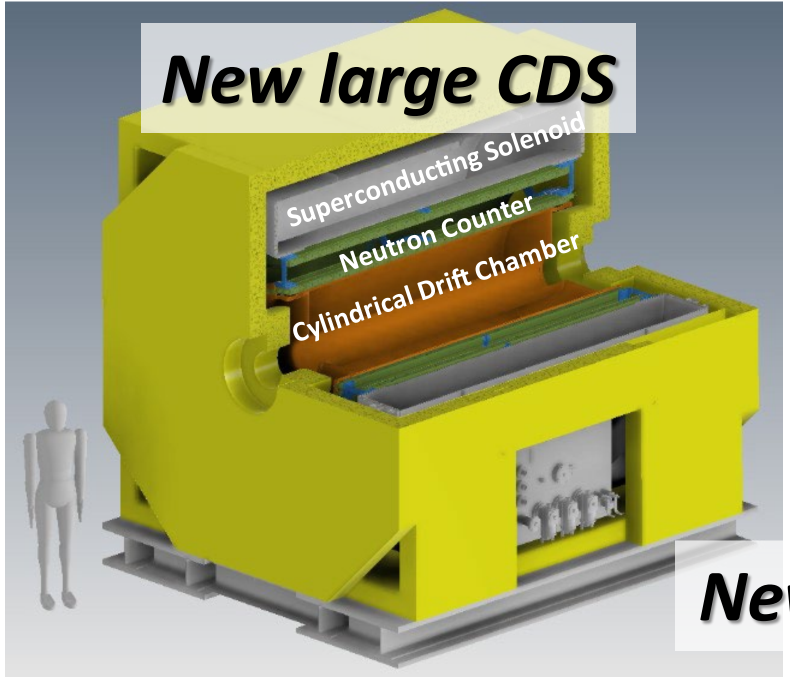
H. Fujioka
Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551, Japan

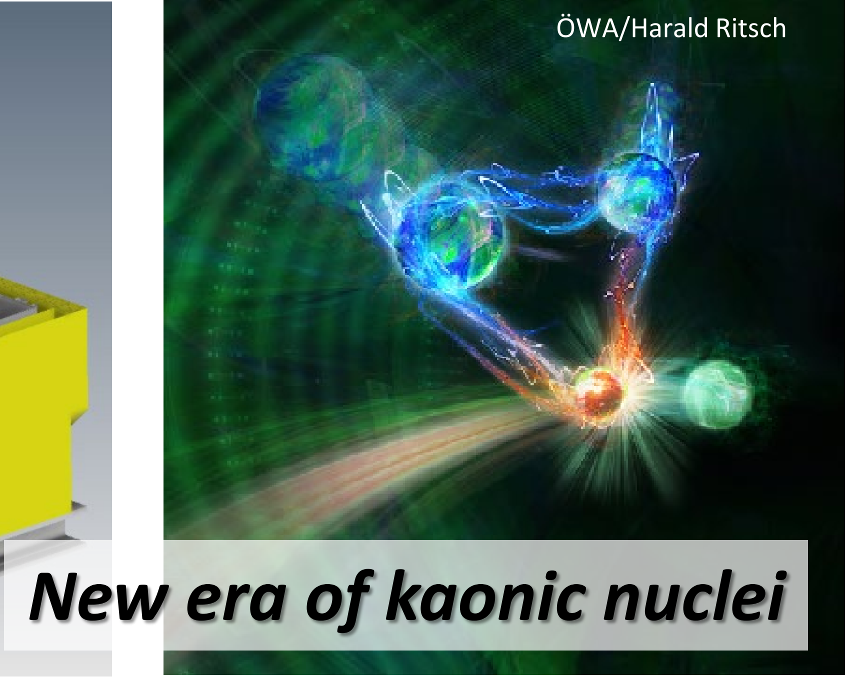
S. Okada
Chubu University, Aichi, 487-0027, Japan

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

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

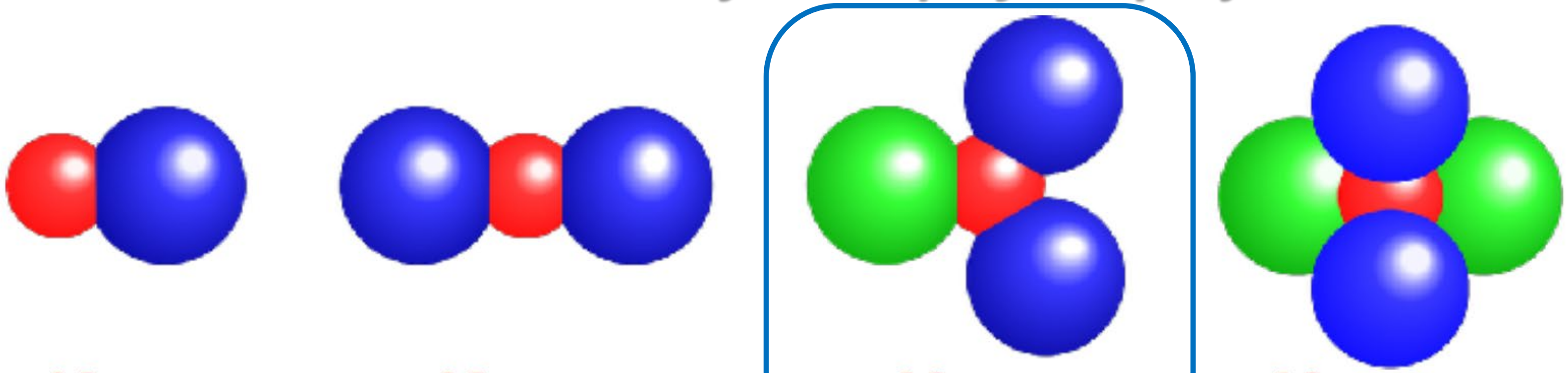






Thank you for your attention!

A first step of the project



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

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