Antikaon-Nuclear Bound Systems at J-PARC

– from $\Lambda(1405)$ to $\bar{K}NNN$ and Beyond –

F. Sakuma, RIKEN

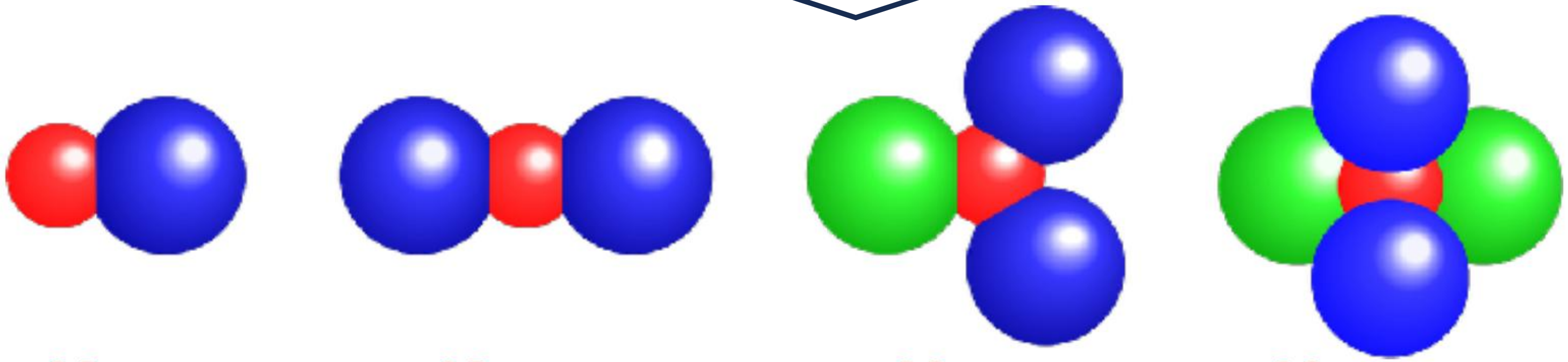
sakuma@ribf.riken.jp

on behalf of the J-PARC E15/E31/E80/E89 collaboration

"Kaonic Nuclei"

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

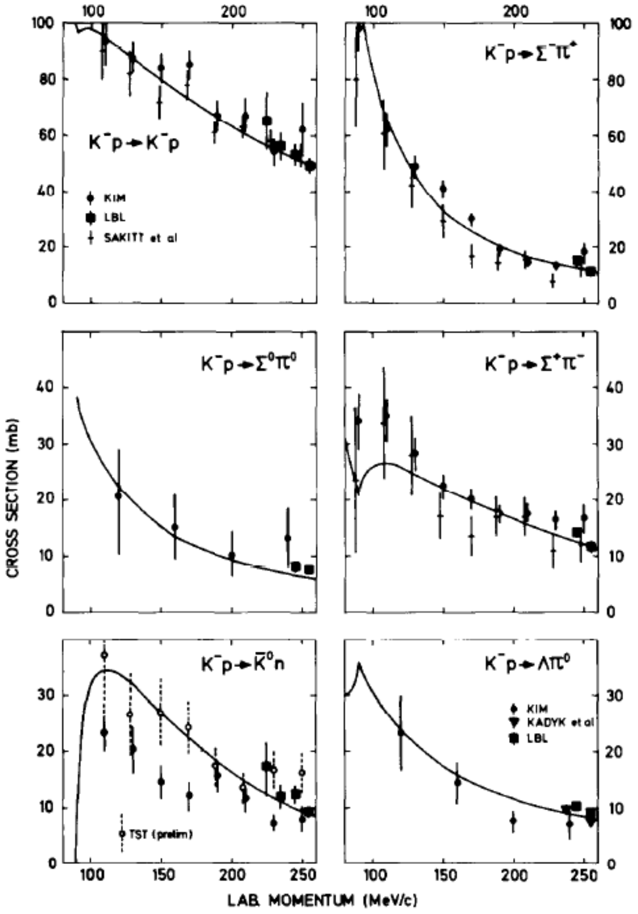
$$\mathbf{K} = \begin{pmatrix} \mathrm{K}^+ \\ \mathrm{K}^0 \end{pmatrix} \begin{matrix} \mathrm{u}\bar{\mathrm{s}} \\ \mathrm{d}\bar{\mathrm{s}} \end{matrix} \quad \mathrm{s} = 1 \qquad \bar{\mathbf{K}} = \begin{pmatrix} \bar{\mathrm{K}}^0 \\ \mathrm{K}^- \end{pmatrix} \begin{matrix} \bar{\mathrm{d}}\mathrm{s} \\ \bar{\mathrm{u}}\mathrm{s} \end{matrix} \quad \mathrm{s} = -1 \qquad \mathbf{N} = \begin{pmatrix} \mathrm{p} \\ \mathrm{n} \end{pmatrix} \begin{matrix} \mathrm{uud} \\ \mathrm{udd} \end{matrix} \qquad \mathbf{I_3} = \begin{pmatrix} +{}^1/_2 \\ -{}^1/_2 \end{pmatrix}$$



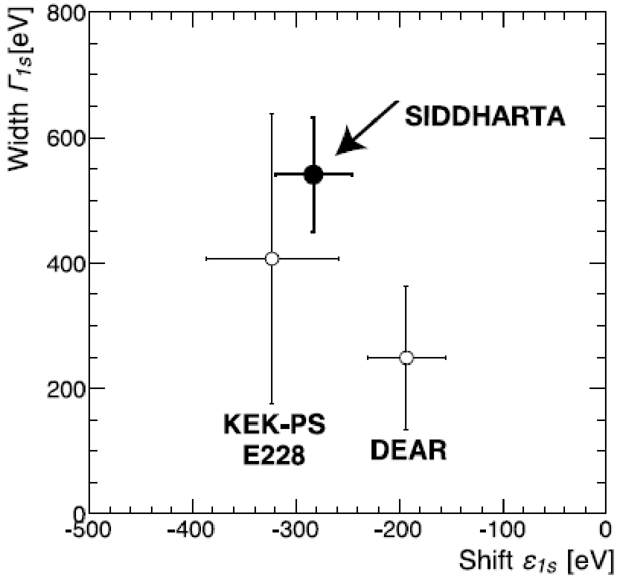
$\mathrm{K^-p}$ $=\Lambda(1405)$ $\mathrm{K^-pp}$ $\mathrm{K^-ppn}$ $\mathrm{K^-ppnn}$ …

$\bar{\mathrm{K}}$N Interaction and Λ(1405)

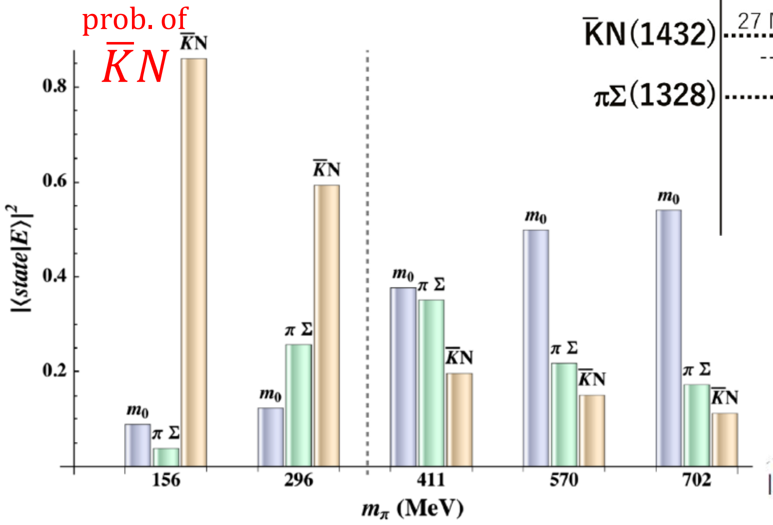
K⁻p scattering
NPB179(1981)33.

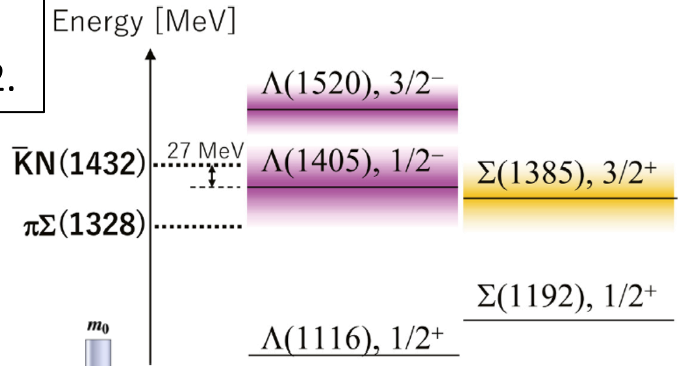


K⁻p atom
PLB704(2011)113.

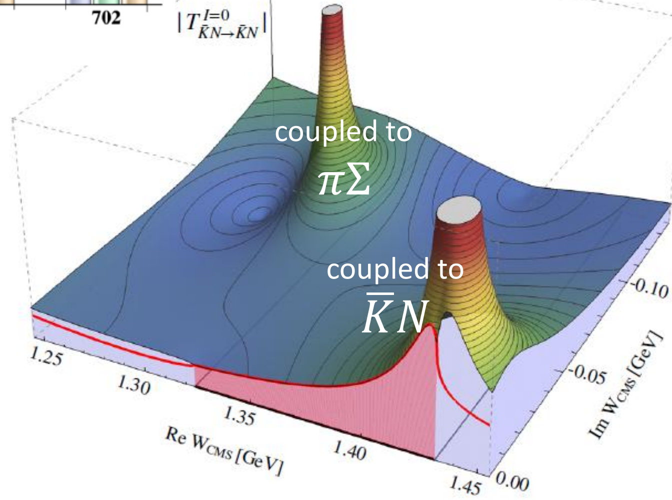


Λ(1405) in LQCD
RPL114(2015)132002.





Λ(1405) in chiral
unitary model
EPJ ST230(2021)1593.



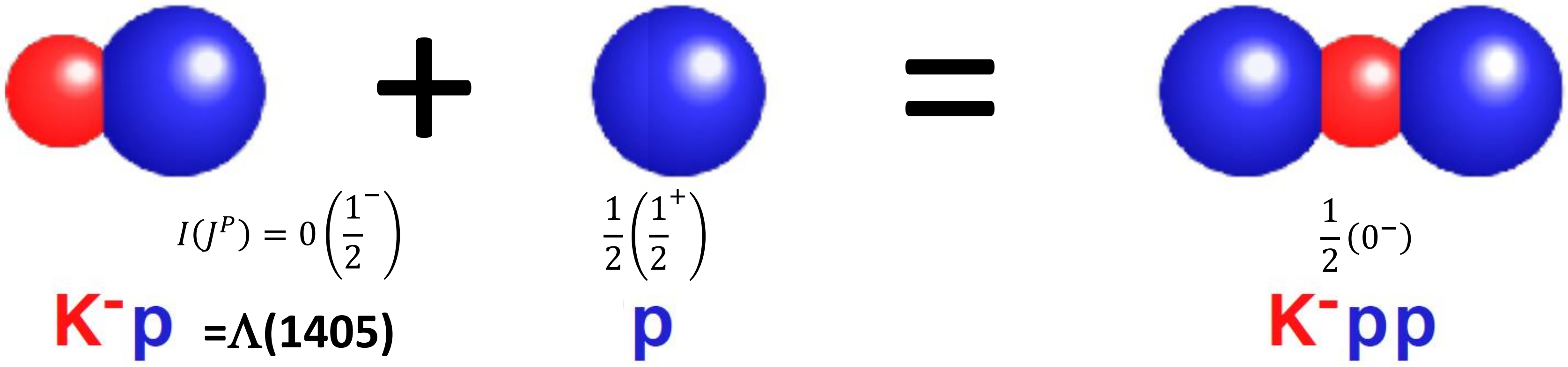
✓**strongly attractive $\bar{\mathrm{K}}$N int. in I=0**

✓**Λ(1405) = quasi-bound state of $\bar{\mathrm{K}}$N**

Λ(1405) to "Kaonic Nuclei"

- Λ(1405) = considered as a quasi-bound state of $\bar{\mathrm{K}}\mathrm{N}$

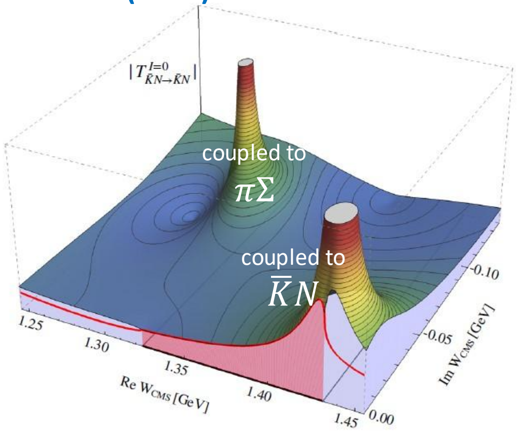
  → possible $\bar{\mathrm{K}}$-nucleus quasi-bound states has been widely discussed
- first idea from Y.Nogami PL7(1963)288
  - Pioneering calculation by Y.Akaishi, T.Yamazaki PRC65(2002)044005, PLB535(2002)70
  - Many calculations showing the existence of kaonic nuclei
- $\bar{\mathrm{K}}\mathrm{NN}$ system : the simplest $\bar{\mathrm{K}}$-nucleus system, so called "K$^-$pp"
  - It has attracted interest from both theory and experiment.



Theoretical Calculations of $\bar{\mathrm{K}}$NN

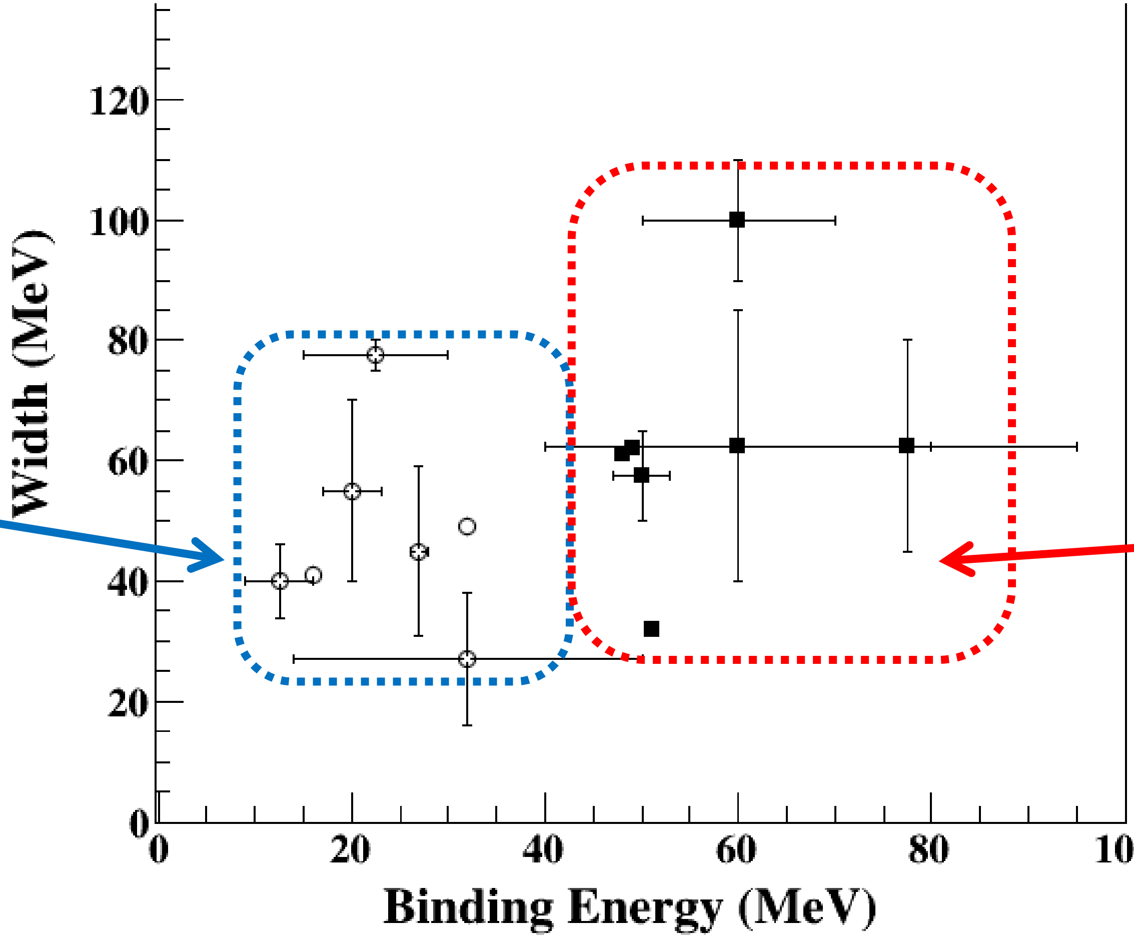
Chiral unitary model (energy dependent)

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



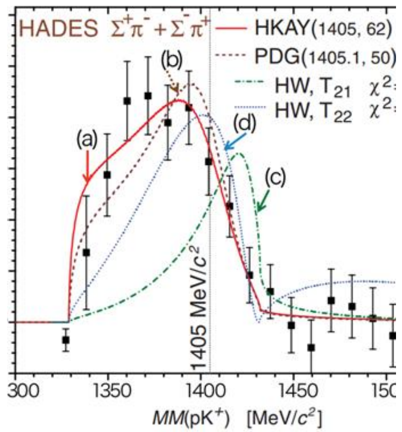
shallow $\bar{\mathrm{K}}$N potential

B.E. ~ 10-40 MeV



Phenomenological model (energy independent)

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



deep $\bar{\mathrm{K}}$N potential

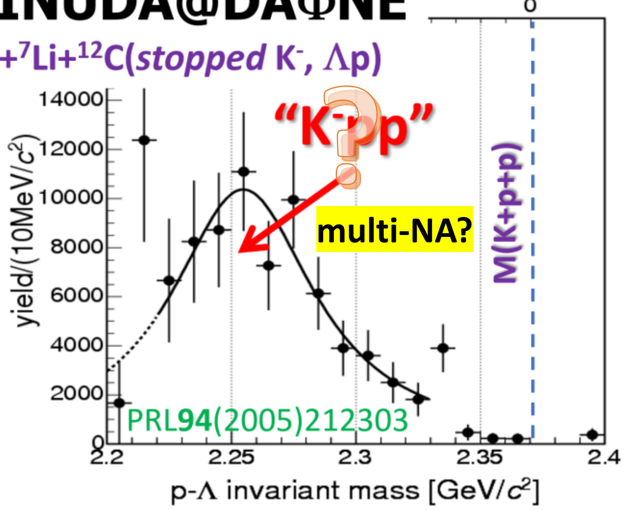
B.E. ~ 40-70 MeV

suggesting a more compact and dense system

“K^-pp” Bound State Searches

FINUDA@DAΦNE

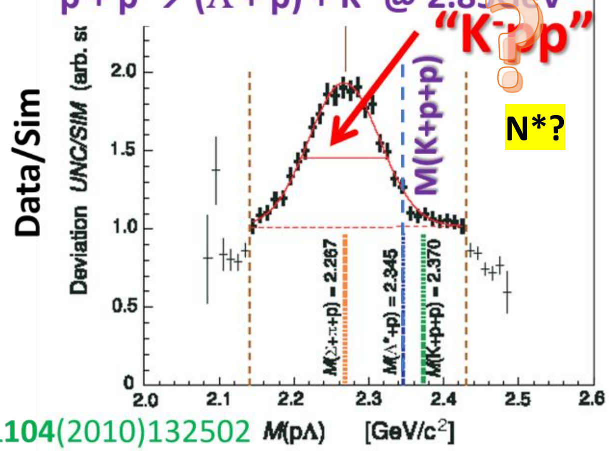
$^6Li+^7Li+^{12}C$(*stopped* K^-, Λp)



PRL**94**(2005)212303

DISTO@SATURNE

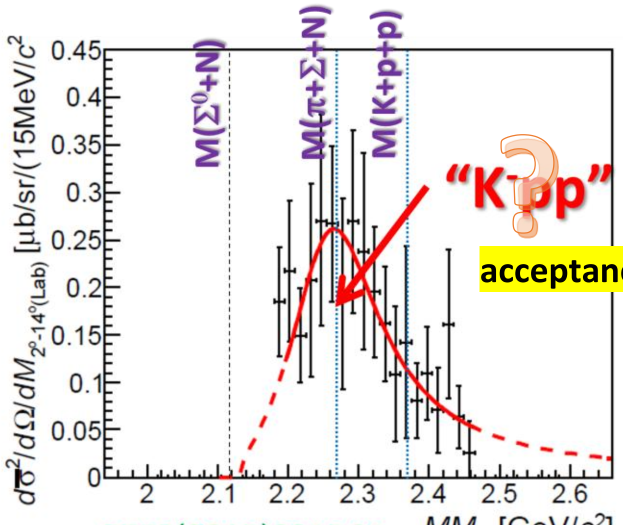
p + p → (Λ + p) + K⁺ @ 2.85GeV



PRL**104**(2010)132502

E27@J-PARC

d(π^+, K^+)Σ^0p @ 1.69 GeV/c

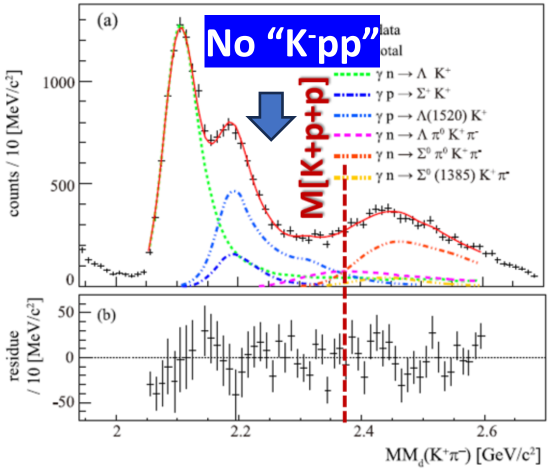


PTEP(2015)021D01.

LEPS@SPring-8

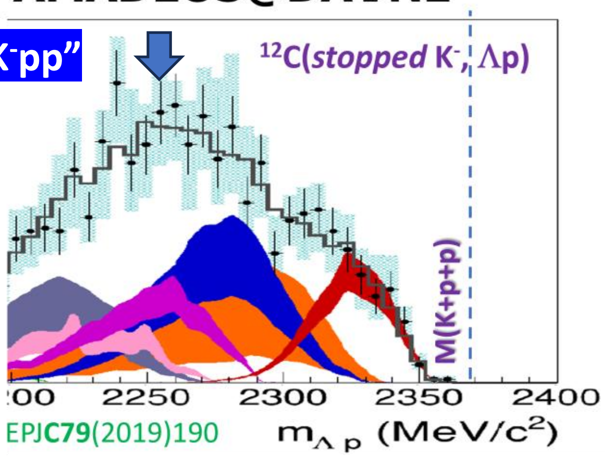
d(γ, $K^+\pi^-$)X @ 1.3-2.4 GeV/c

PLB728(2014)616.



AMADEUS@DAΦNE

^{12}C(*stopped* K^-, Λp)

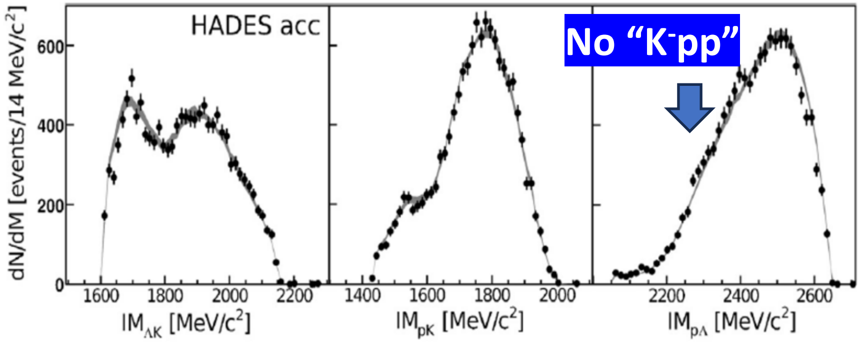


EPJC**79**(2019)190

HADES@GSI

PLB**742**(2015)242

p + p → (Λ + p) + K⁺ @ 3.5GeV

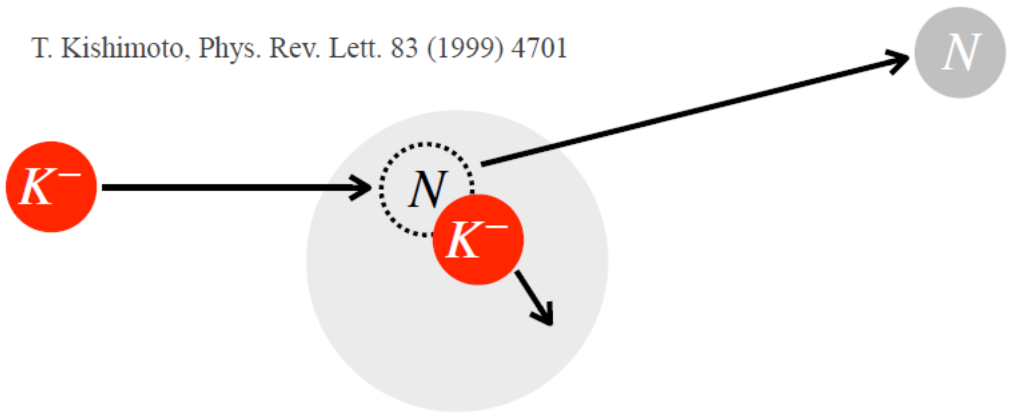


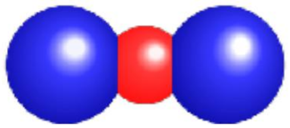
- Despite of many “K-pp” searches, NO conclusive results
  - ➢Complex reactions & difficult to understand background

Experimental Studies at J-PARC

– via in-flight (K-,n) reactions –

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

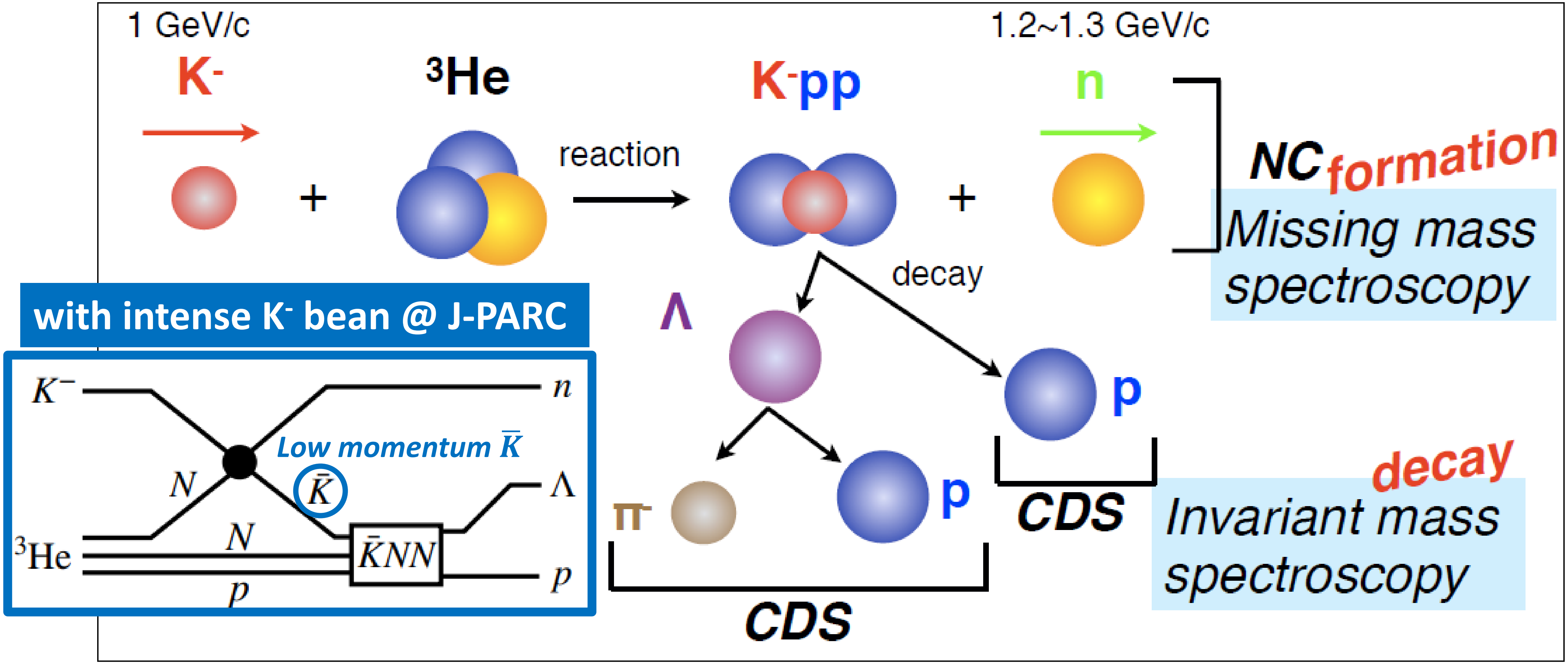


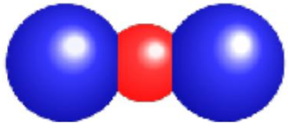


"K⁻pp" Search @ J-PARC E15

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

multi-NA and Y decays can be discriminated kinematically

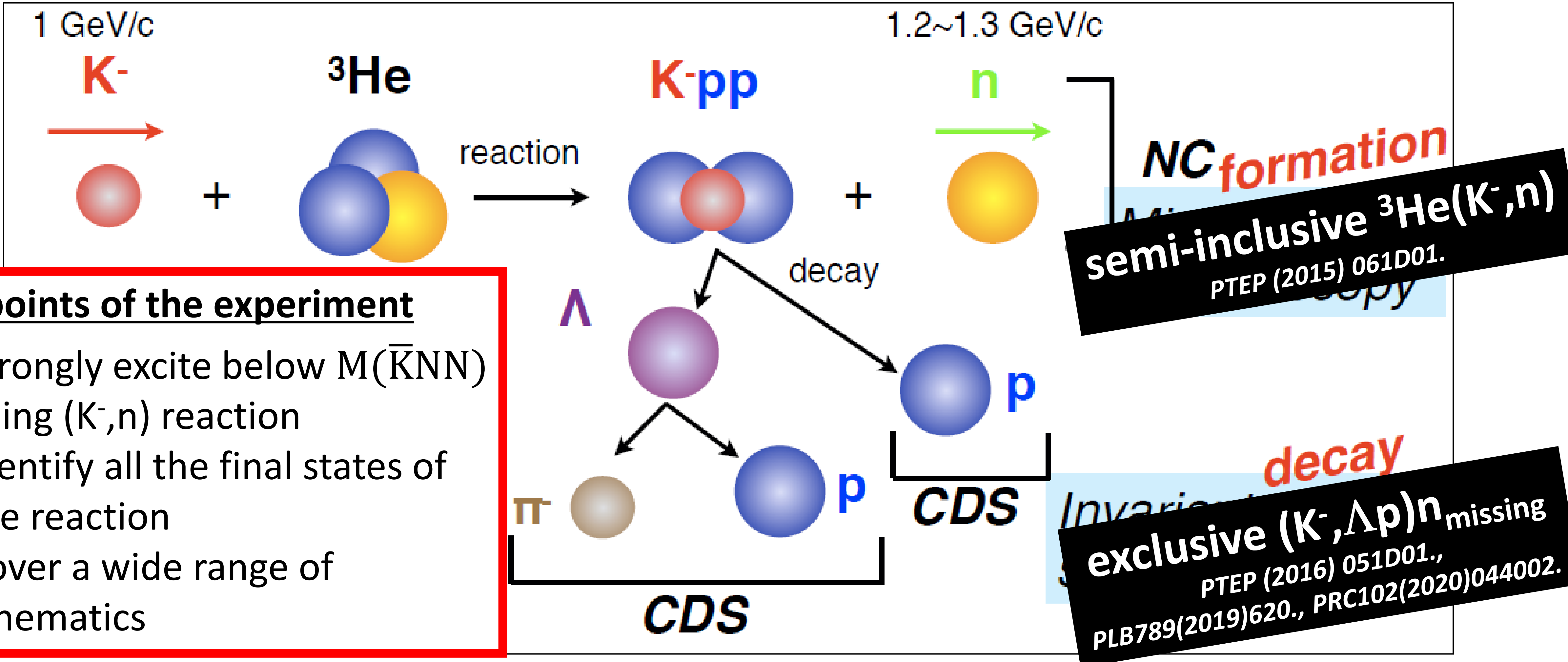




"K^-pp" Search @ J-PARC E15

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

multi-NA and Y decays can be discriminated kinematically



Key points of the experiment

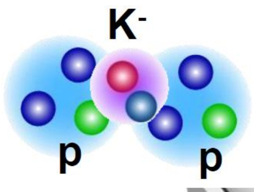
① Strongly excite below $M(\bar{K}NN)$ using (K^-,n) reaction

② Identify all the final states of the reaction

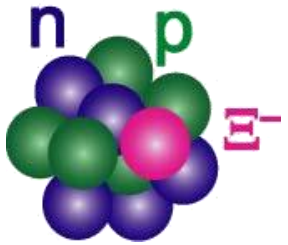
③ Cover a wide range of kinematics

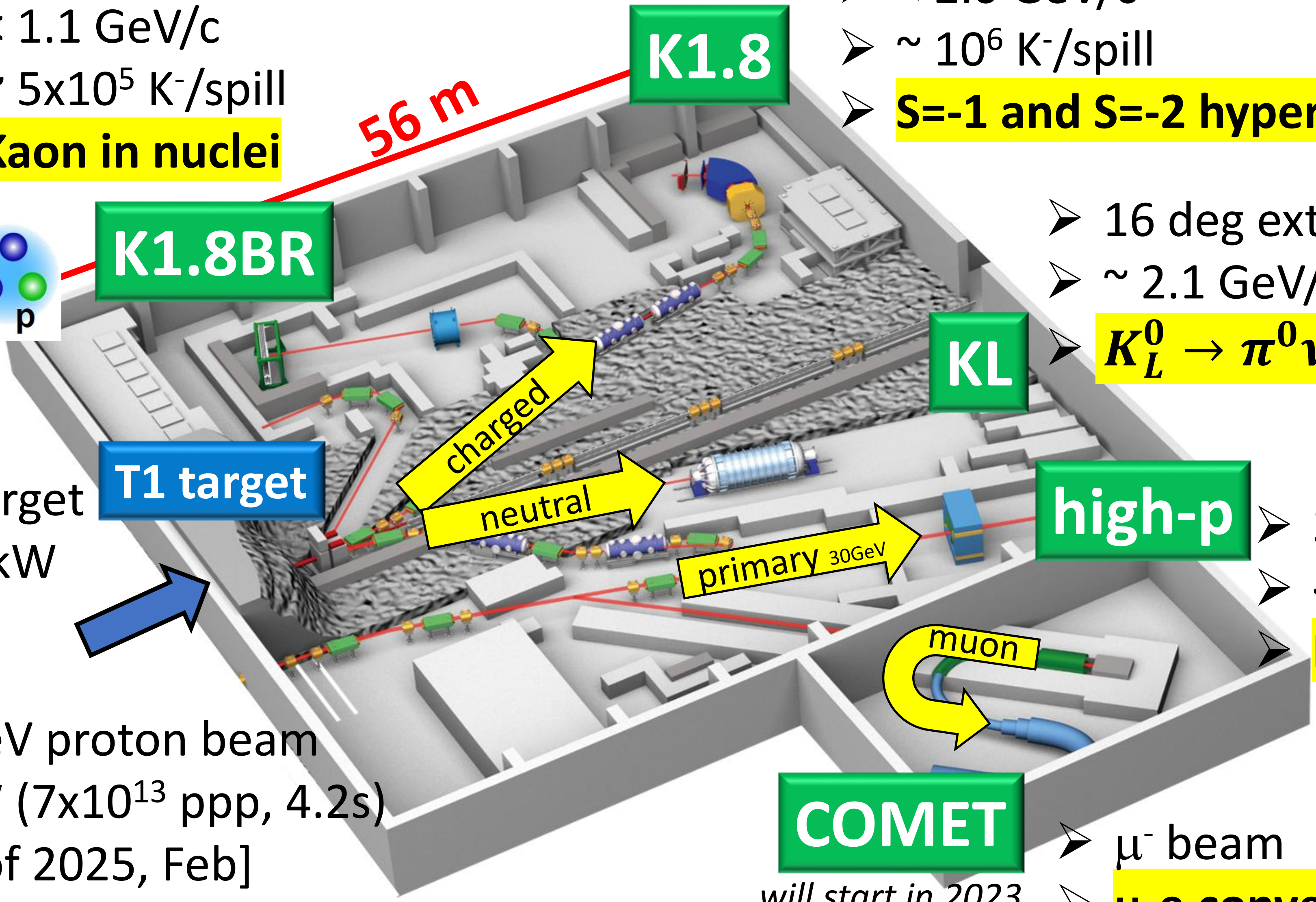
Hadron Experimental Facility (HEF)

- < 1.1 GeV/c
- ~ 5×10^5 K^-/spill
- **Kaon in nuclei**

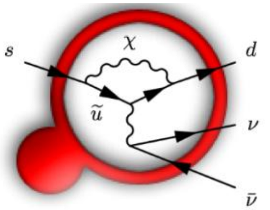


- < 2.0 GeV/c
- ~ 10^6 K^-/spill
- **S=-1 and S=-2 hypernuclei**





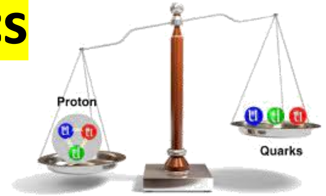
- 16 deg extraction
- ~ 2.1 GeV/c ~ 10^7 K^0_L/spill
- $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$



- 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 (7×10^{13} ppp, 4.2s)

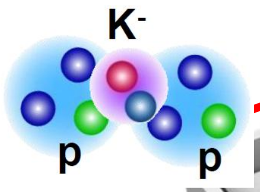
  [as of 2025, Feb]

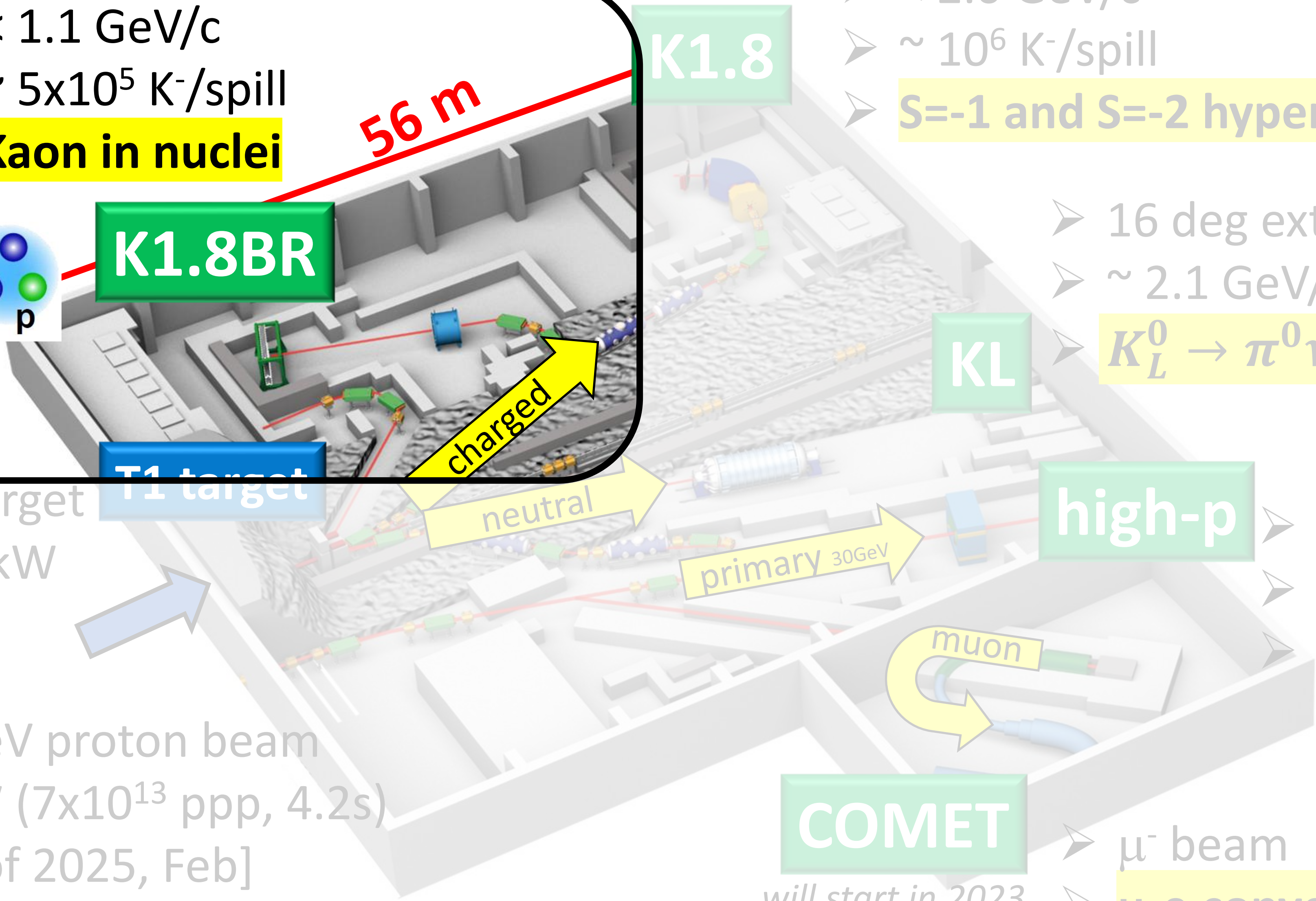
will start in 2023

- μ^- beam
- **μ-e conversion**

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
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- $K_L^0 \to \pi^0 \nu \bar{\nu}$

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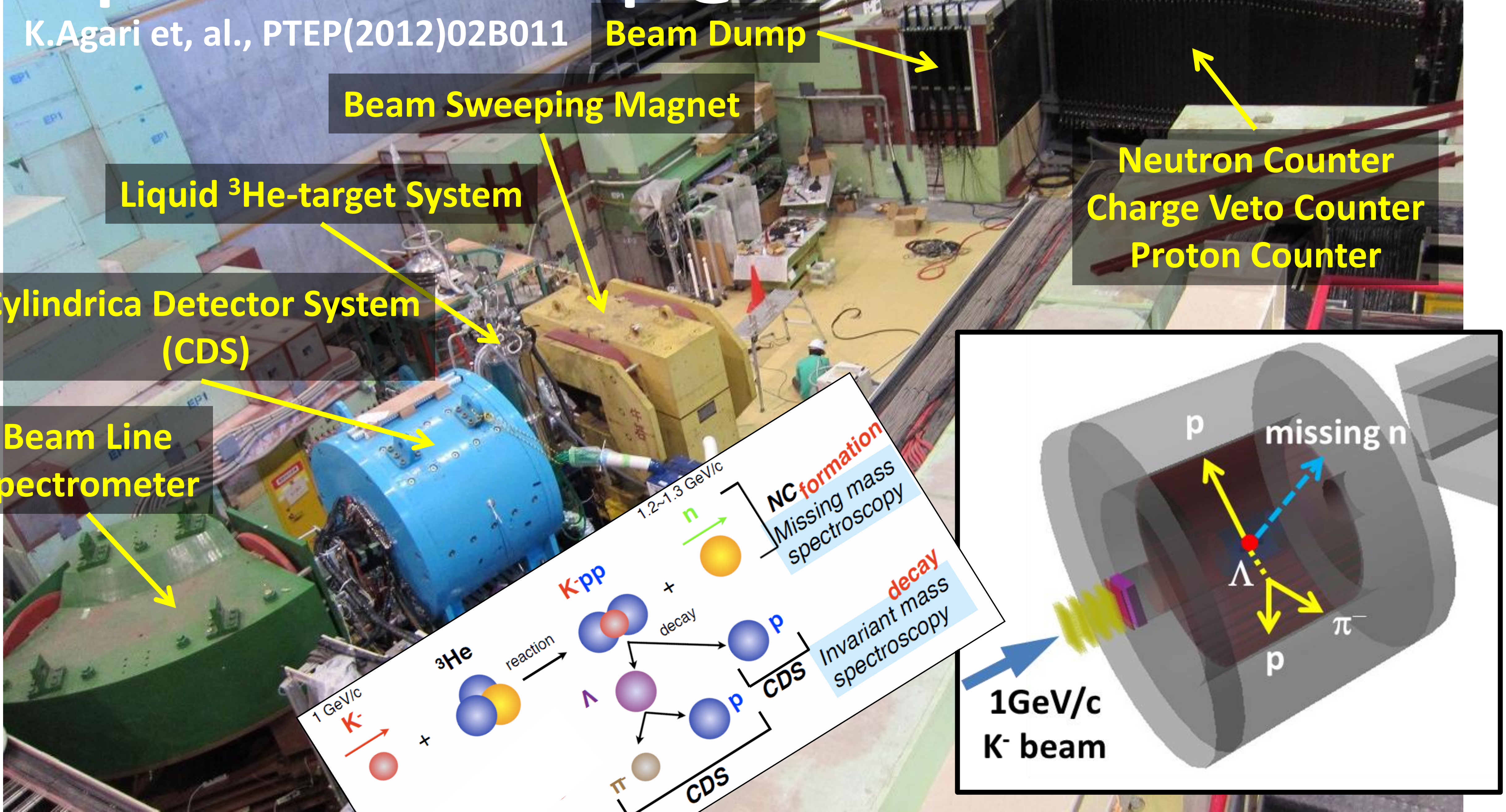
  [as of 2025, Feb]

will start in 2023

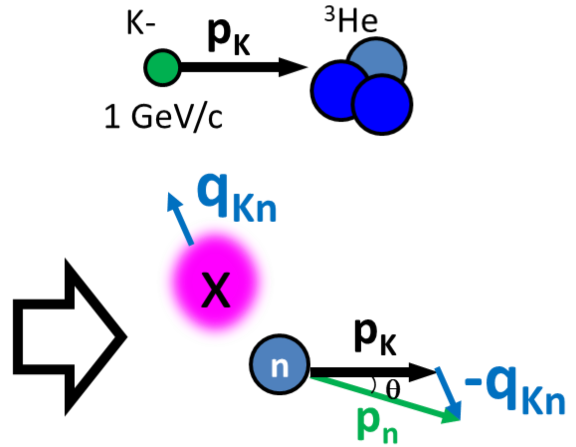
- μ$^-$ beam
- μ-e conversion

Experimental Setup @ K1.8BR

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

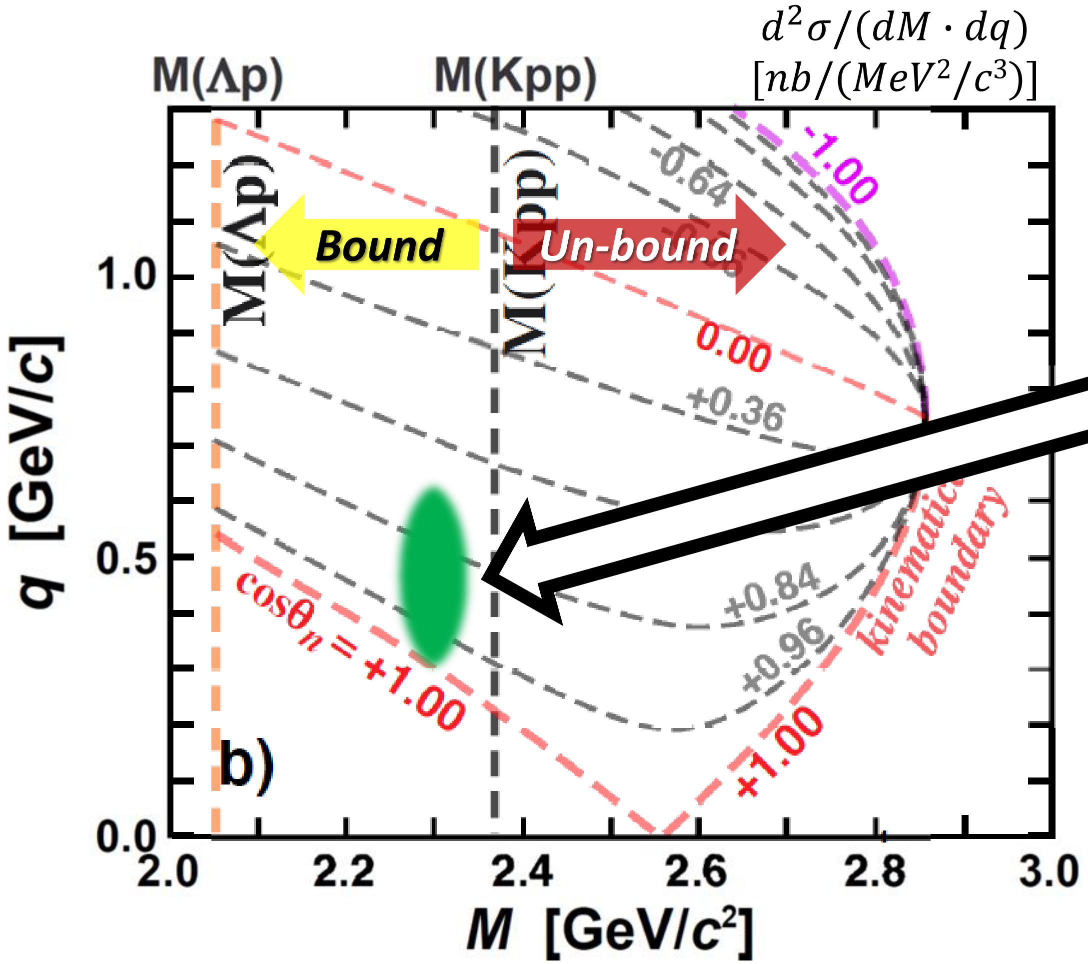


“K⁻pp” Search w/ Momentum Transfer Analysis

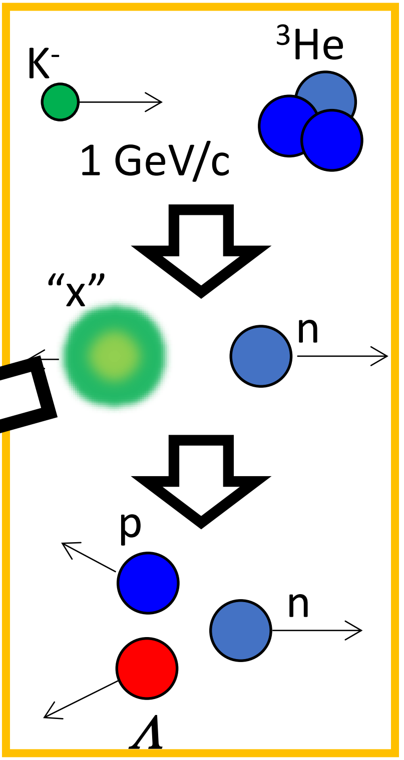


- **Momentum transfer analysis using the (K⁻,n) reaction**

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

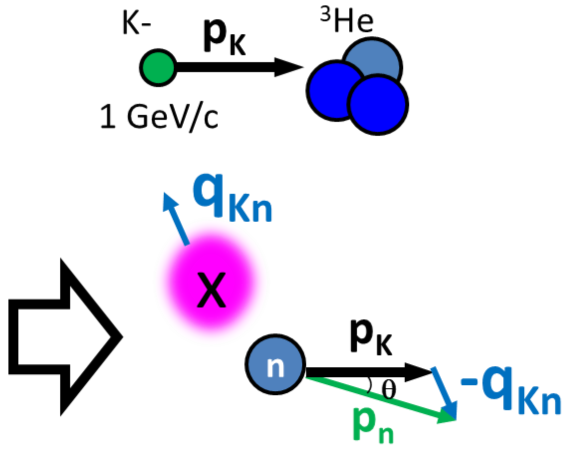


$\boldsymbol{q}$: (K⁻,n) momentum transfer
$\boldsymbol{M}$: Λp invariant mass



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

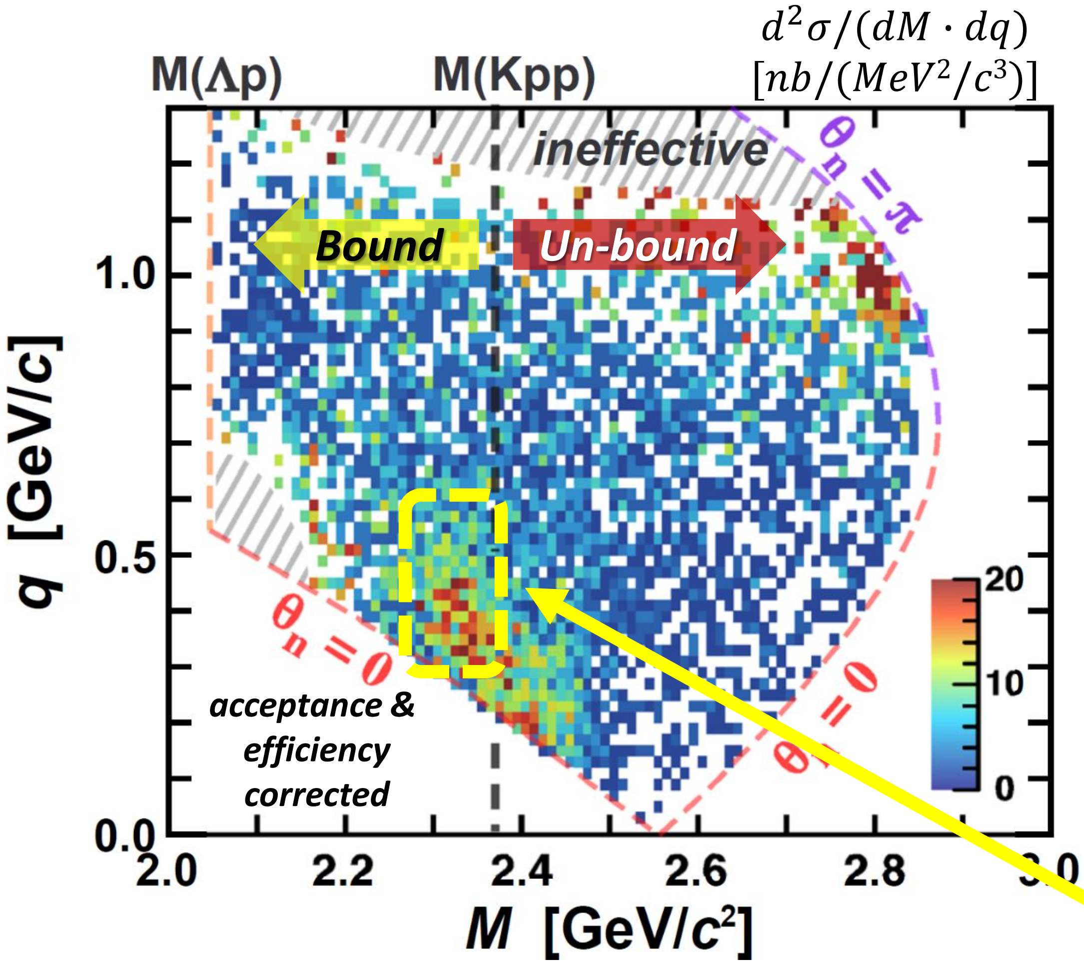
"K⁻pp" Search w/ Momentum Transfer Analysis



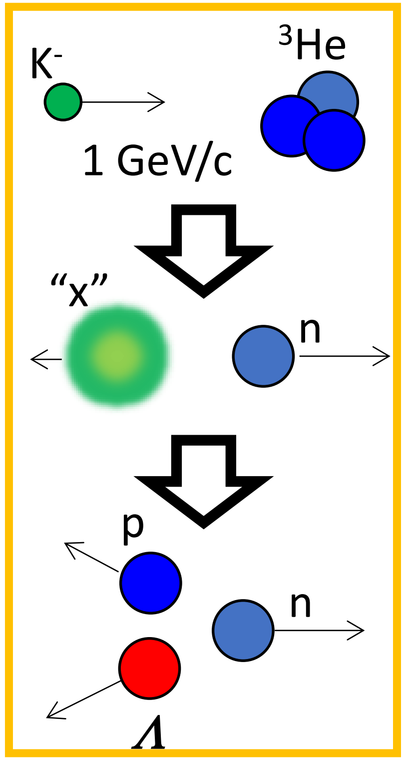
- **Momentum transfer analysis using the (K^-,n) reaction**

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

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

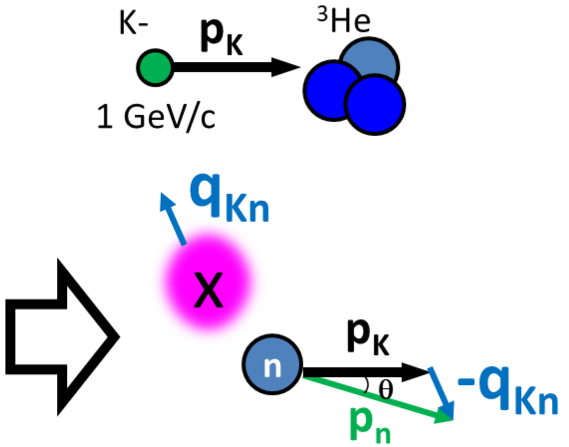


q *: (K^-,n) momentum transfer*
M *: Λp invariant mass*



A peak structure **independent of q** **=**
A bound state exists

“K⁻pp” Search w/ Momentum Transfer Analysis

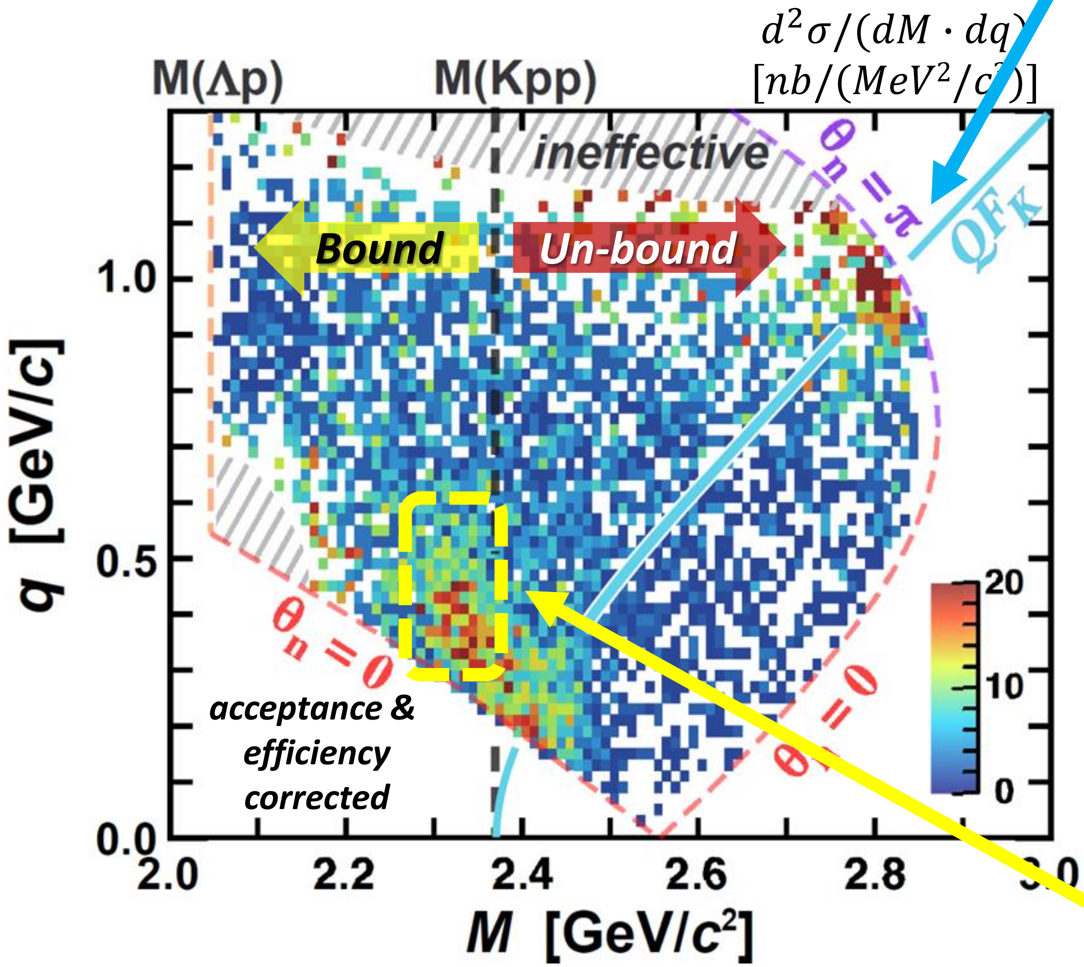


- **Momentum transfer analysis using the (K^-,n) reaction**

✓ M(Λp) vs. q

✓ give a clear information on reaction processes

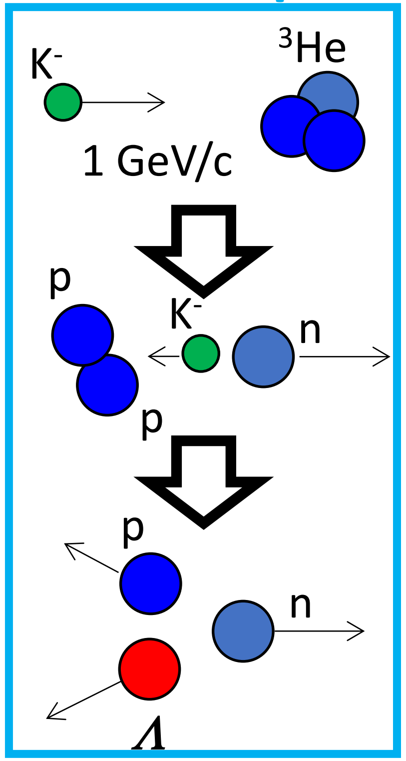
PLB789(2019)620., PRC102(2020)044002.



q : (K^-,n) momentum transfer

M : Λp invariant mass

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



A peak structure independent of q = A bound state exists

A PWIA-based Interpretation

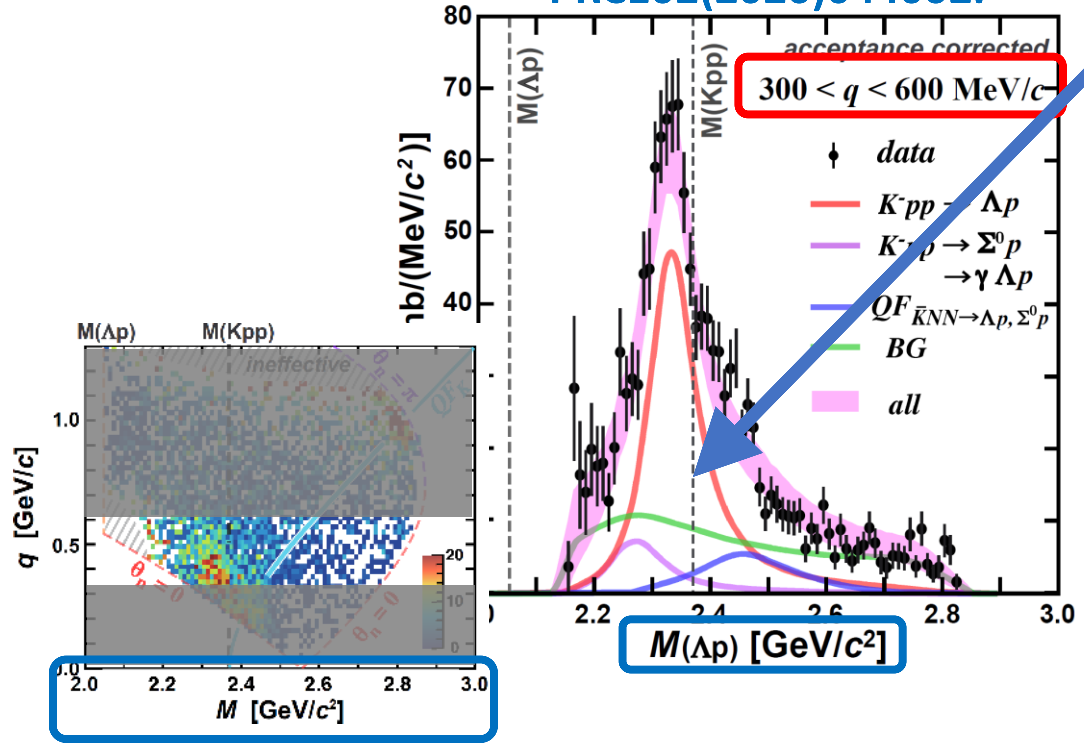
Energy term (BW type) from time integral

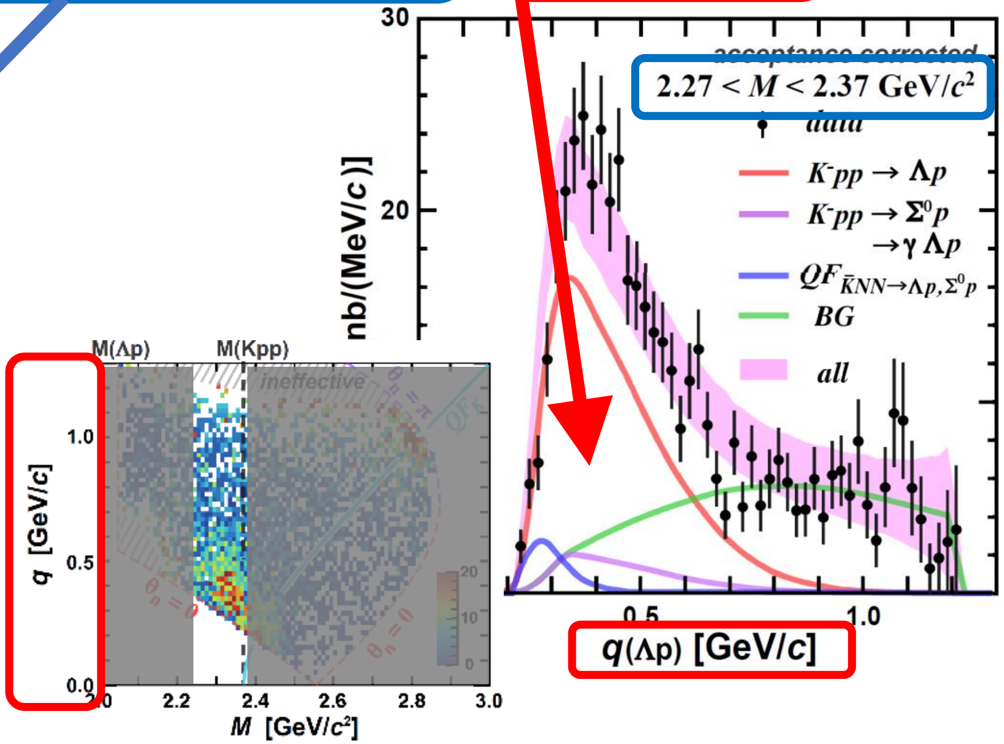
Momentum term from spatial integral

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

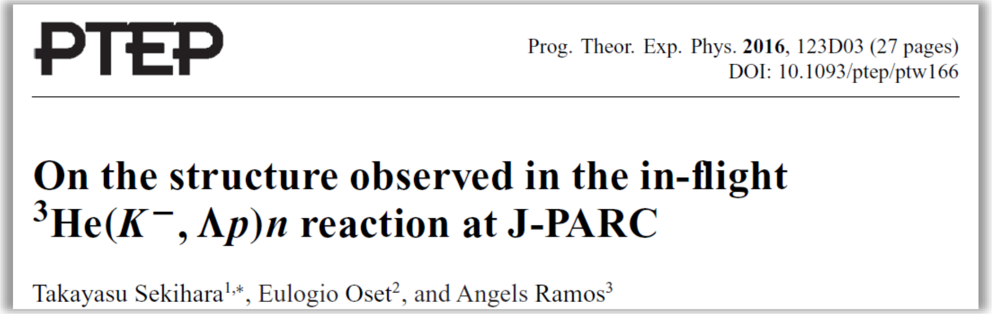
Large *Q* = Suggesting a compact system

Q_{kpp} ~ 400 MeV

Form factor

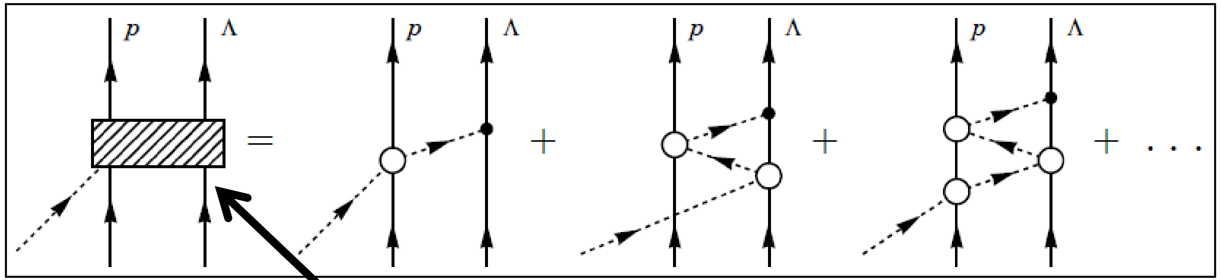
A Theoretical Interpretation

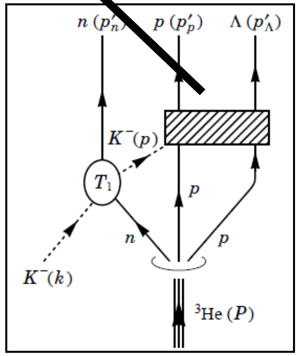
A calling based on chiral unitary approach
reproduces the data well using the $\bar{\mathrm{K}}$NN bound state


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

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

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

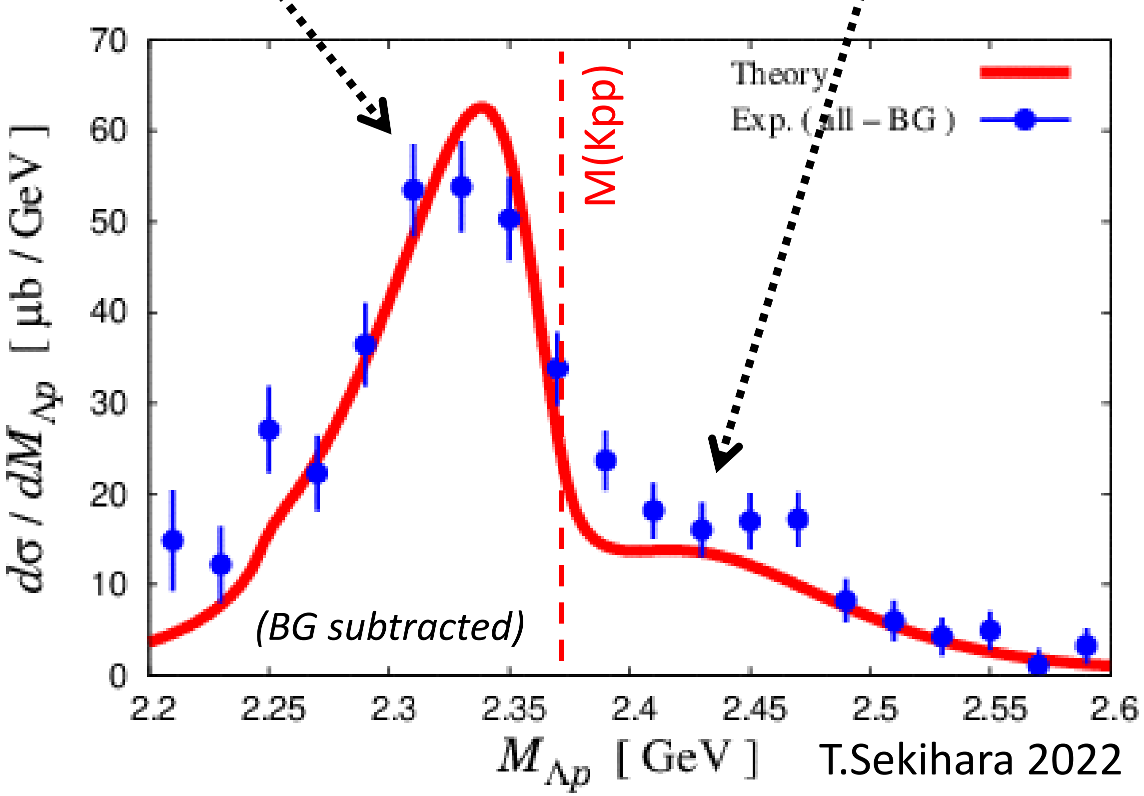




Theoretical investigations are indispensable!

K^bar NN bound state

Quasi-free K⁻ scattering

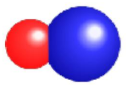


T.Sekihara 2022

Further Investigations

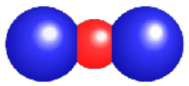
to establish the existence of kaonic nuclei

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



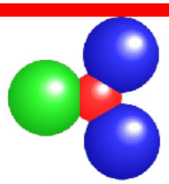
K^-p

- **Further details of the $\bar{K}NN$**
  - Mesonic decay modes? →PRC110(2024)014002.
  - Spin and parity of the "K^-pp"?
  - Compact and dense system?

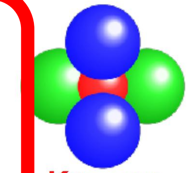


K^-pp

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



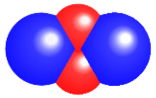
K^-ppn



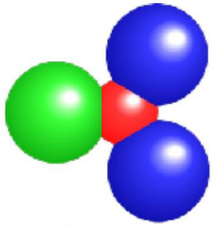
K^-ppnn

…

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



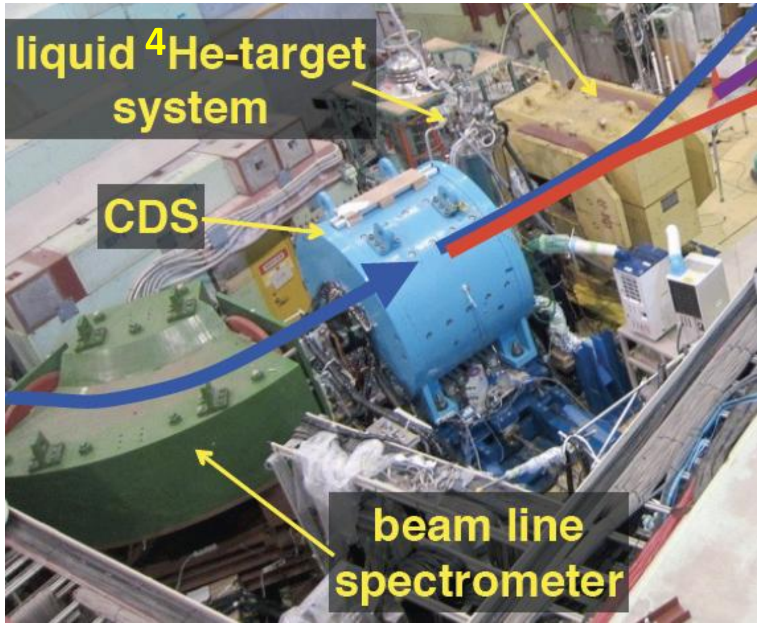
K^-K^-pp

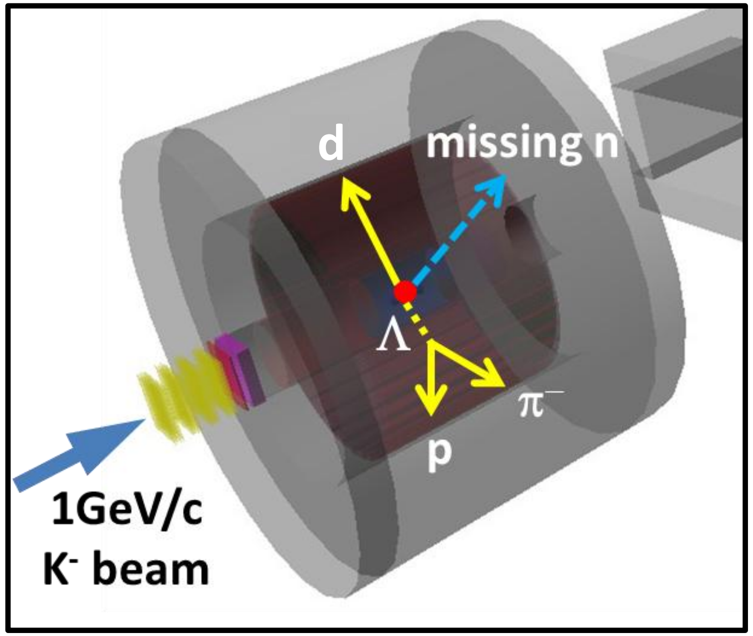


K^-ppn

"K^-ppn" Search with $K^-{}^4He \to \Lambda dn$

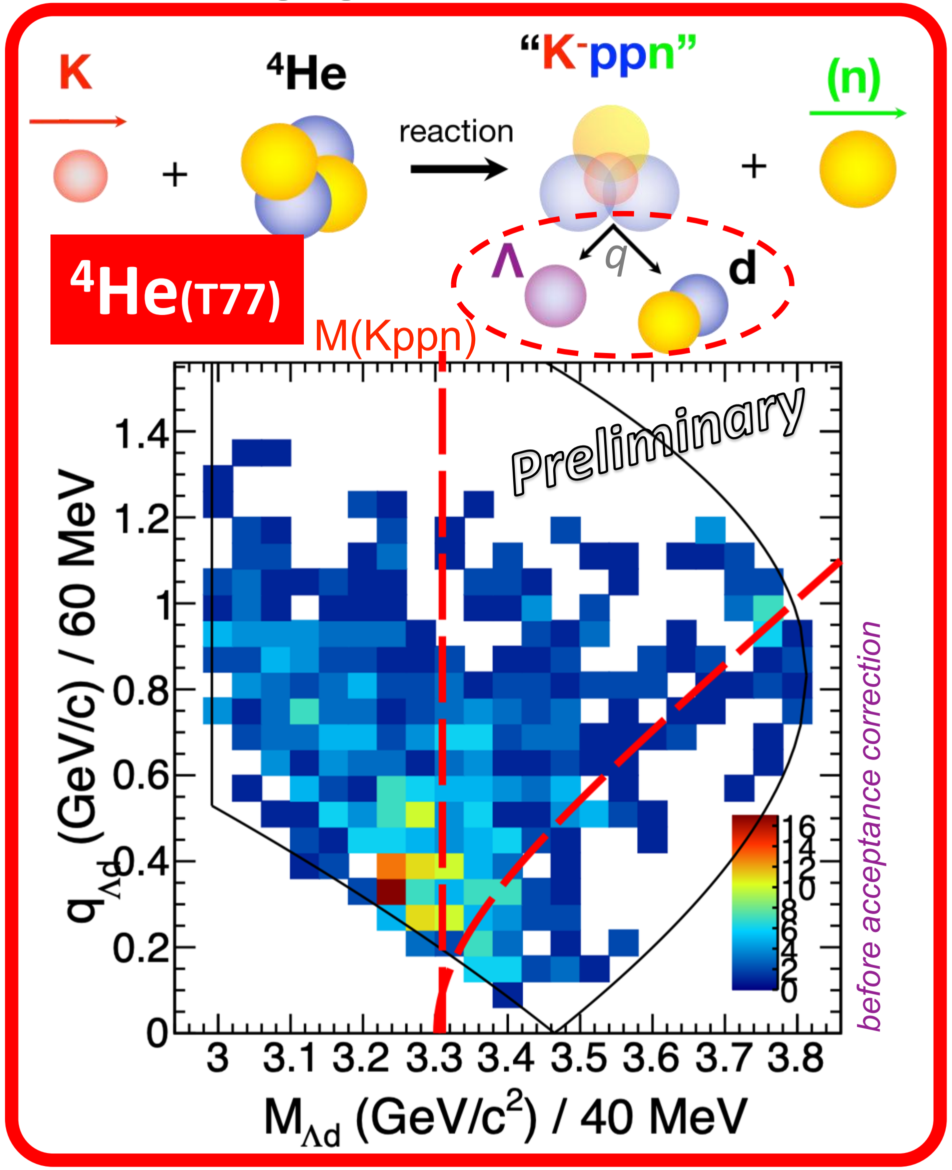
- An analysis of the **Λdn** final state with **$K^-{}^4He$** reaction at **1 GeV/c** has been conducted
  - T77: lifetime measurement of $^4_\Lambda H$ in 2020
- The results will be updated with a part of the E73 controlled data
  - E73: lifetime measurement of $^3_\Lambda H$ in 2024-25

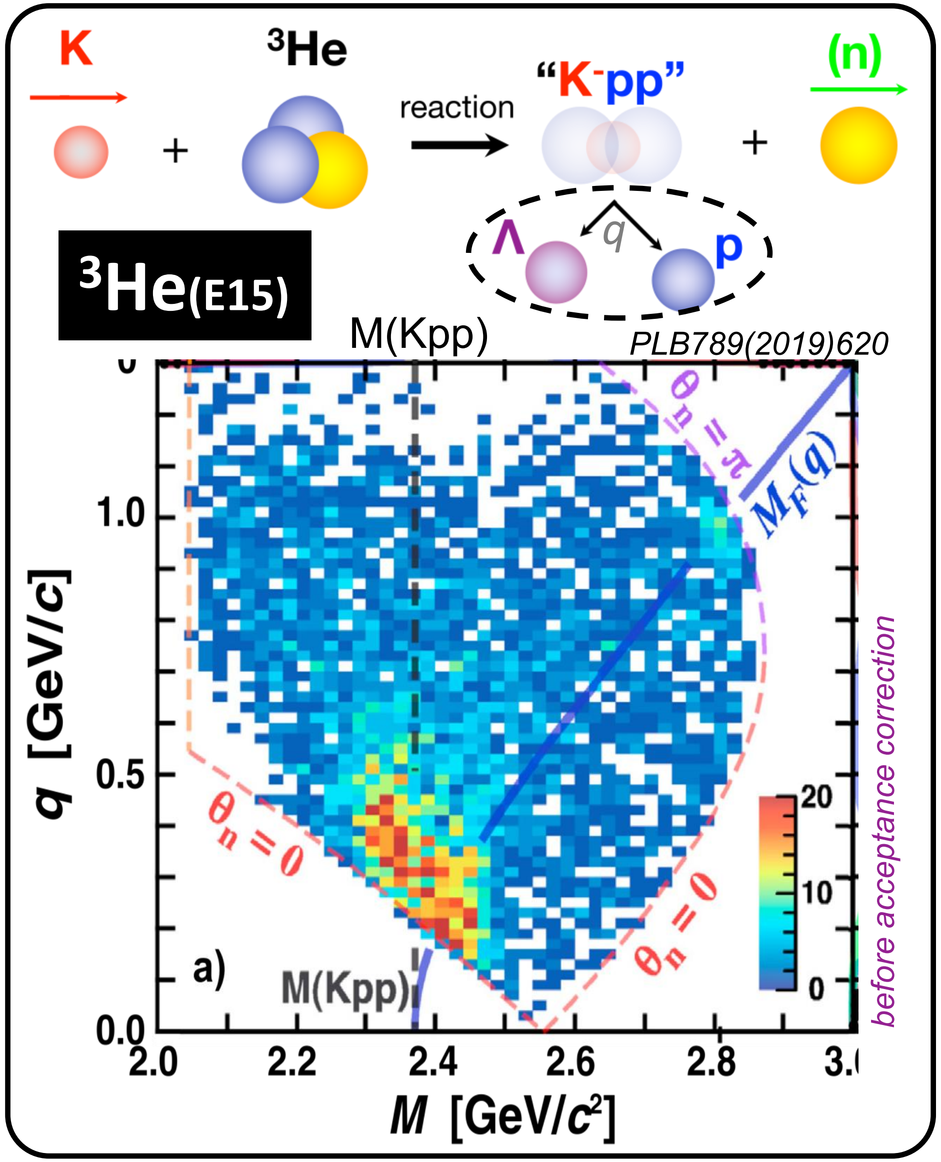




Experiment	K^- on target
E15 (^{3}He)	~42 x 10^9
T77 (^{4}He)	**~6 x 10^9**
E73 (^{4}He)	~12 x 10^9

“K⁻ppn” Search with $K^{-4}He \rightarrow \Lambda dn$





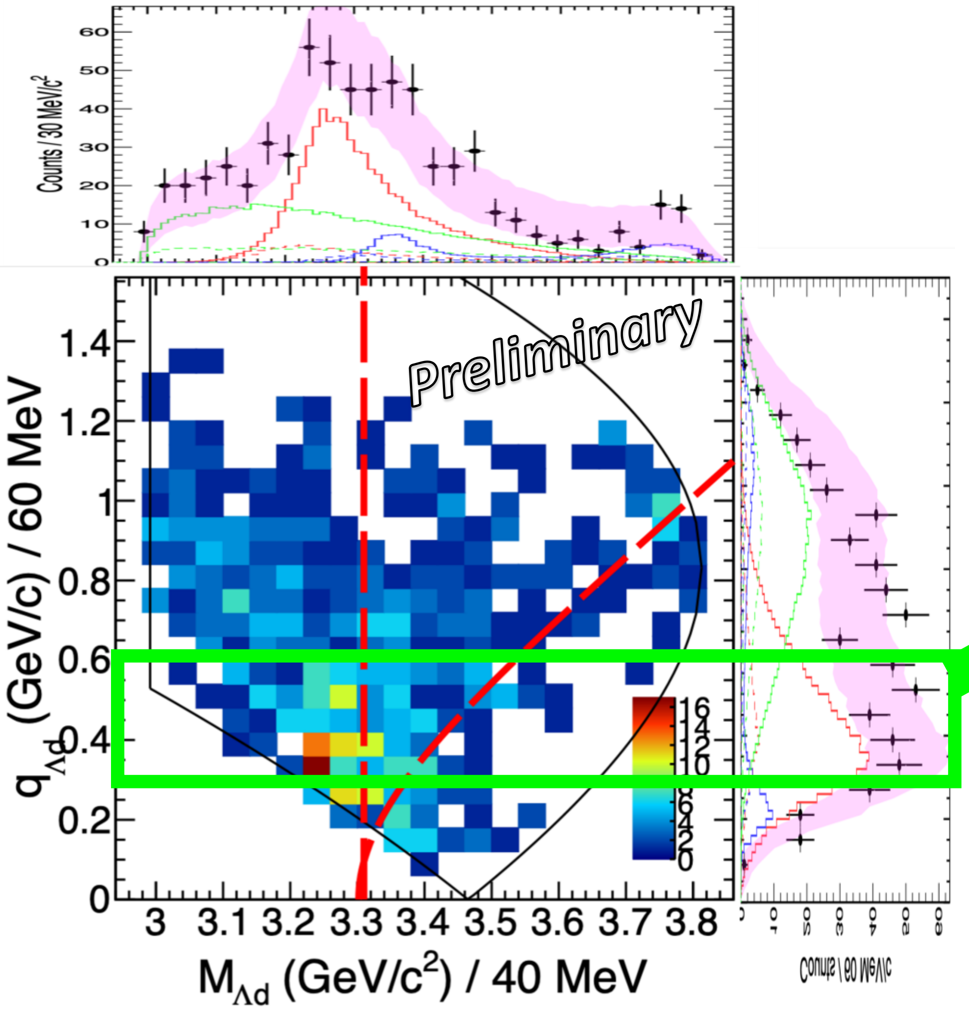
- **Two distributions are quite similar**
- structure below the threshold (**seems *q*-independent**), QF-K, BG

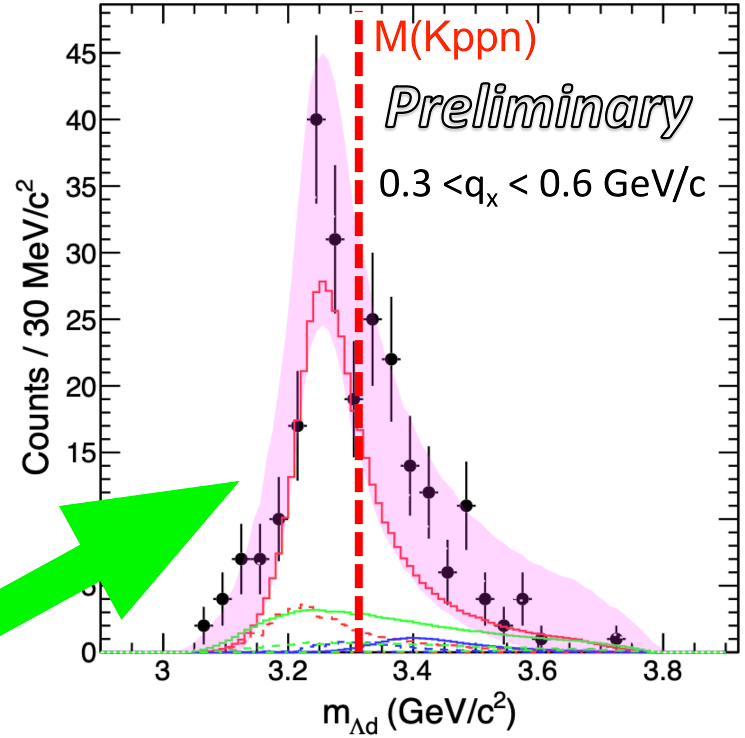
"K⁻ppn" Search with $K^{-}\,{}^4He \rightarrow \Lambda dn$

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

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

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





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

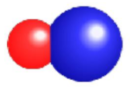
$\Gamma_X \;=\; \sim 100\; MeV$

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

Further Investigations

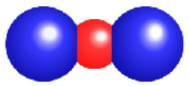
to establish the existence of kaonic nuclei

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



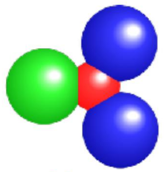
K⁻p

- **Further details of the $\bar{K}NN$**
  - Mesonic decay modes? →PRC110(2024)014002.
  - Spin and parity of the "K⁻pp"?
  - Compact and dense system?

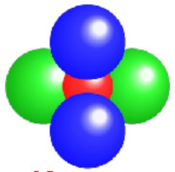


K⁻pp

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



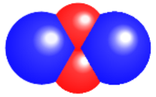
K⁻ppn



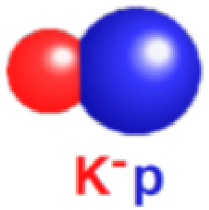
K⁻ppnn

…

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



K⁻K⁻pp

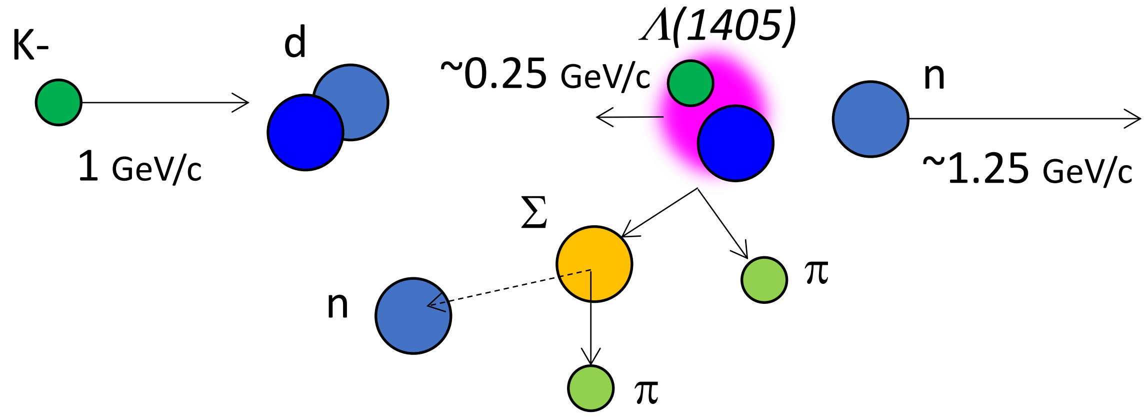


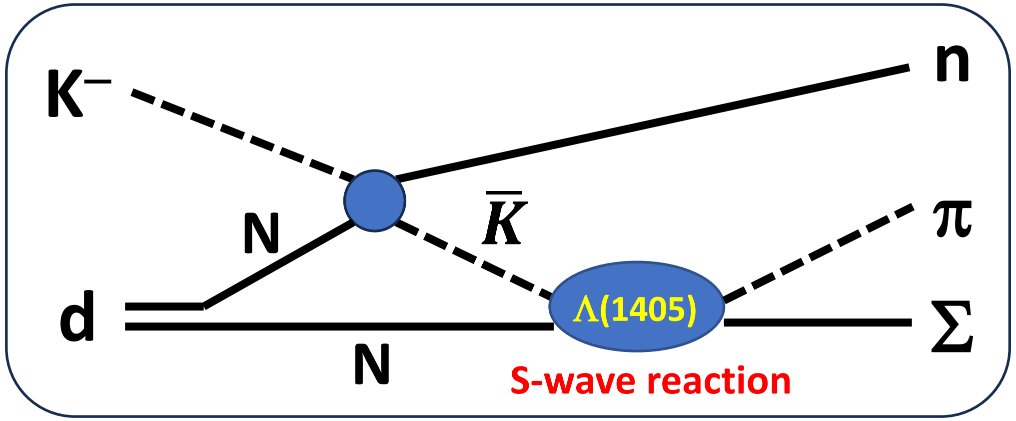
Λ(1405) Line Shape @ J-PARC E31

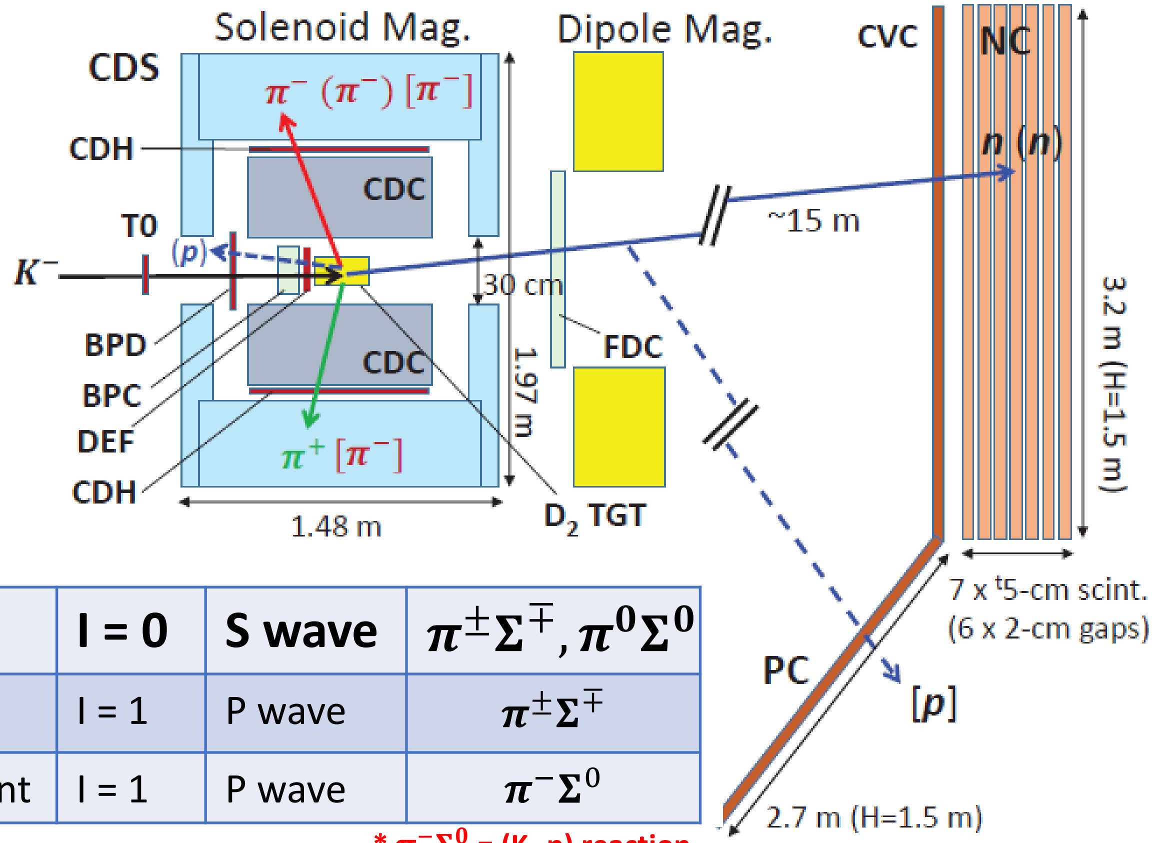
PLB837(2023)137637.

KEY POINTS

- $d(K^-,n)\pi\Sigma$ reaction at θ_n~0 degree
  ➔ enhance **S-wave $\bar{K}N \to \pi\Sigma$ reaction**





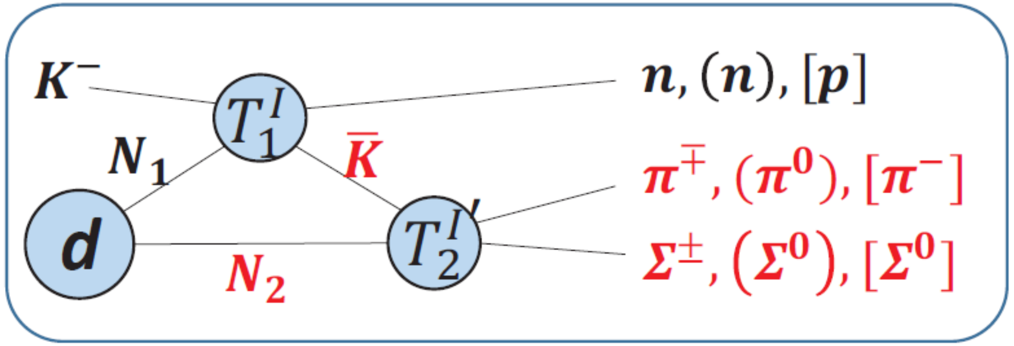


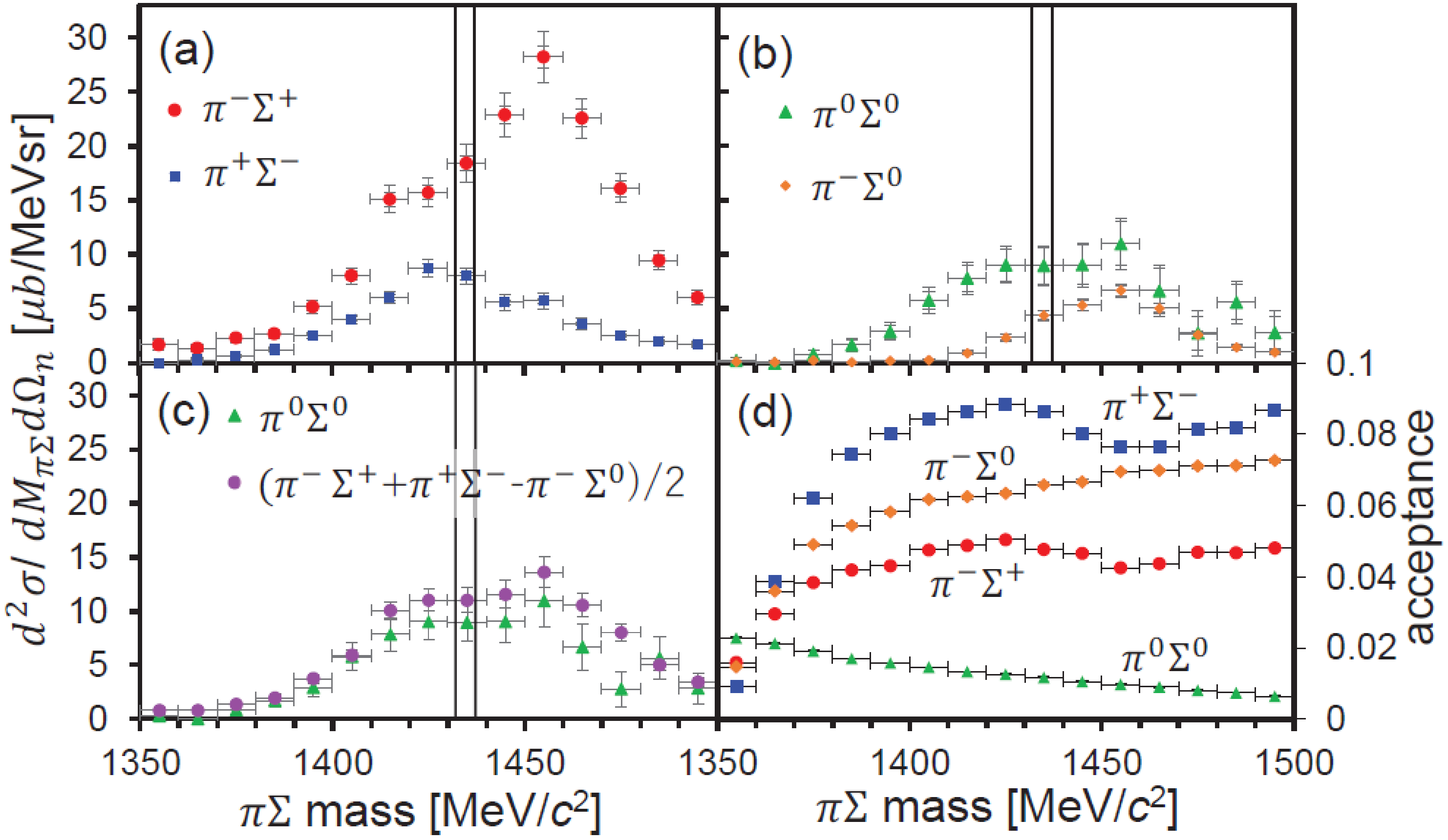
Λ(1405)	I = 0	S wave	$\pi^{\pm}\Sigma^{\mp},\pi^0\Sigma^0$
Σ(1385)	I = 1	P wave	$\pi^{\pm}\Sigma^{\mp}$
Non-resonant	I = 1	P wave	$\pi^{-}\Sigma^{0}$

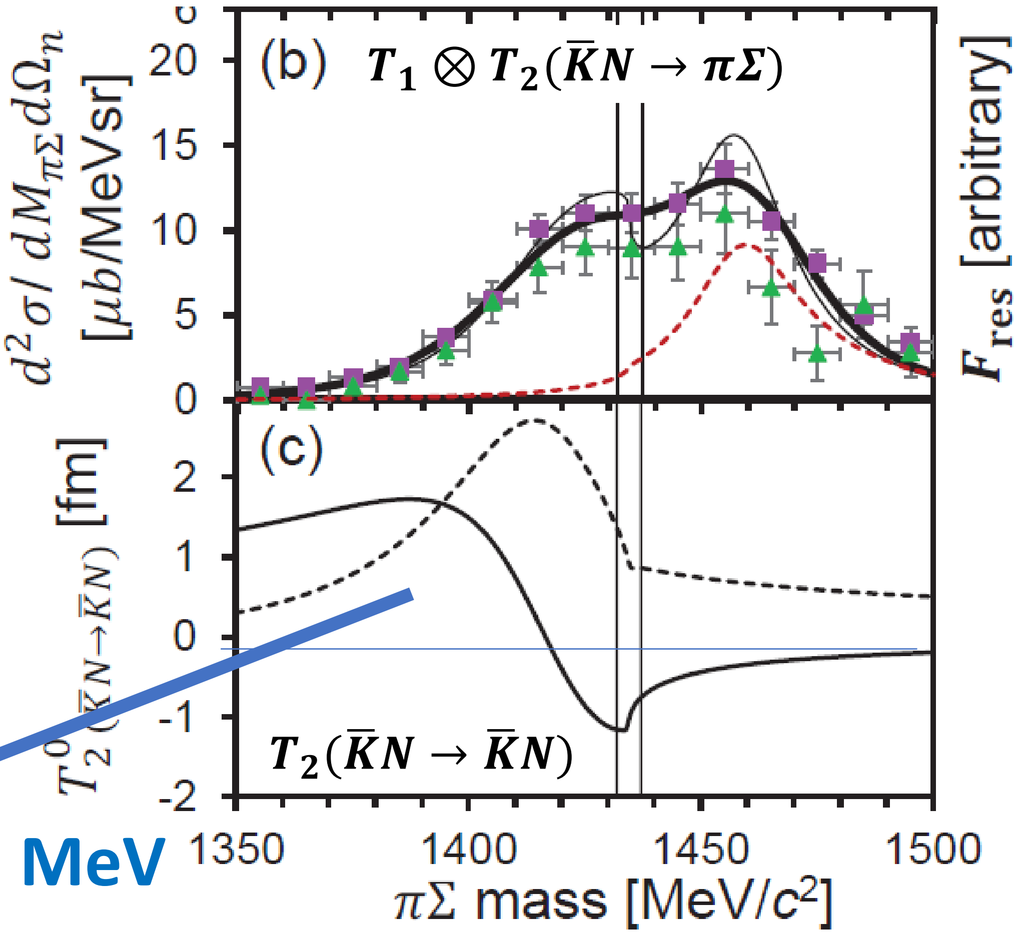
* $\pi^-\Sigma^0$ = (K-,p) reaction

Λ(1405) Line Shape @ J-PARC E31

PLB837(2023)137637.





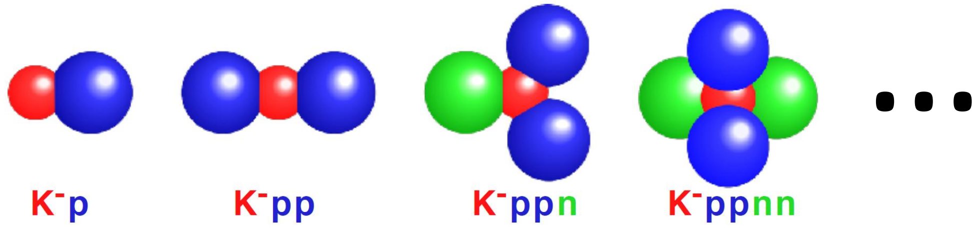


Λ(1405) pole : $1417.7^{+6.0+1.1}_{-7.4-1.0} - i\,26.1^{+6.0+1.7}_{-7.9-2.0}$ MeV

* In this fit, the second pole is located outside the physical region.

New Kaonic Nuclei Project at J-PARC

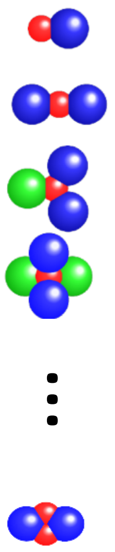
– from the $\bar{K}N$ to $\bar{K}NNNN$ systems and beyond –



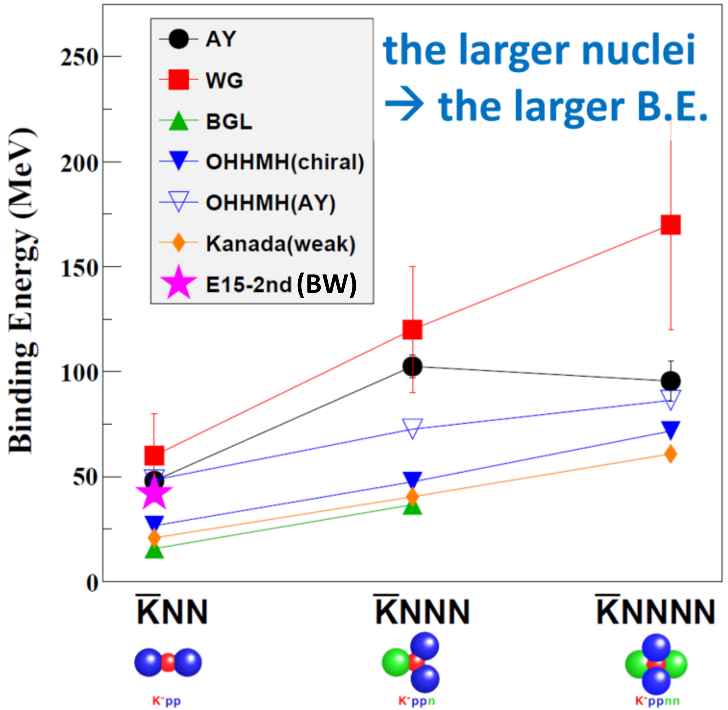
Systematic investigation of the light kaonic nuclei

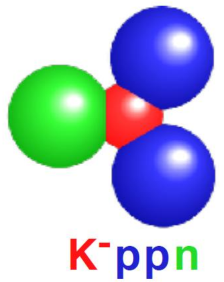
- ●Promote systematic measurement at J-PARC
  - mass number dependence
    - binding energy, branching ratio, *q* dependence, ..
  - spin/parity determination

➢Extract internal structure with theoretical investigations



	Reaction	Key Decay Mode
$\bar{K}N$	d(K$^-$,n)	$\pi^{\pm0}\Sigma^{\mp0}$
$\bar{K}NN$	^{3}He(K$^-$,N)	$\Lambda p/\Lambda n$
$\bar{K}NNN$	^{4}He(K$^-$,N)	$\Lambda d/\Lambda pn$
$\bar{K}NNNN$	^{6}Li(K$^-$,d)	$\Lambda t/\Lambda dn$
$\bar{K}NNNNN$	^{6}Li(K$^-$,N)	$\Lambda\alpha/\Lambda dd/\Lambda dpn$
$\bar{K}NNNNNN$	^{7}Li(K$^-$,N)	$\Lambda\alpha n/\Lambda ddn$
$\bar{K}\bar{K}NN$	$\bar{p}$ + ^{3}He	$\Lambda\Lambda$



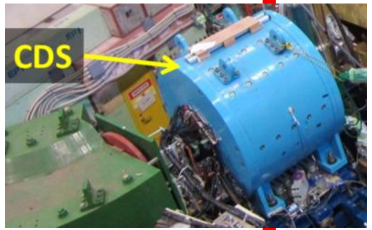


$\bar{K}NNN$ @ E80

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

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

- "K-ppn"→Λd 2-body decay

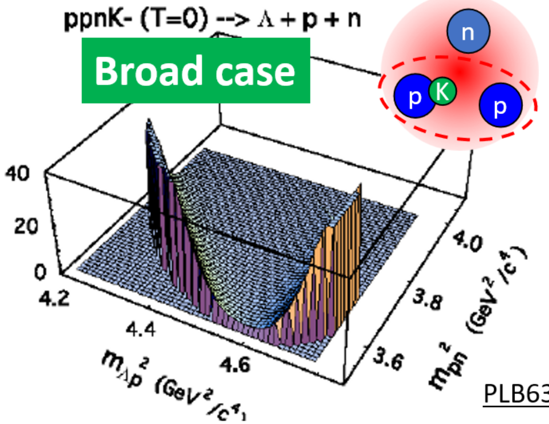


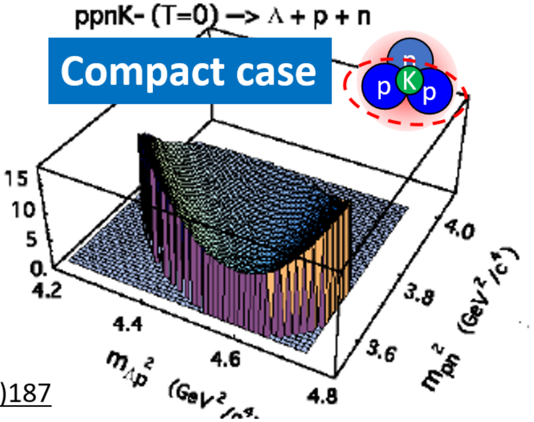
② Study the multi-particle decay mode of $\bar{K}NNN$ toward understanding its internal structure

- "K-ppn"→Λpn 3-body decay

Paul Kienle [a,b], Yoshinori Akaishi [c,d], Toshimitsu Yamazaki [d,e,*]

Utilize Dalitz plots → Differences in distribution

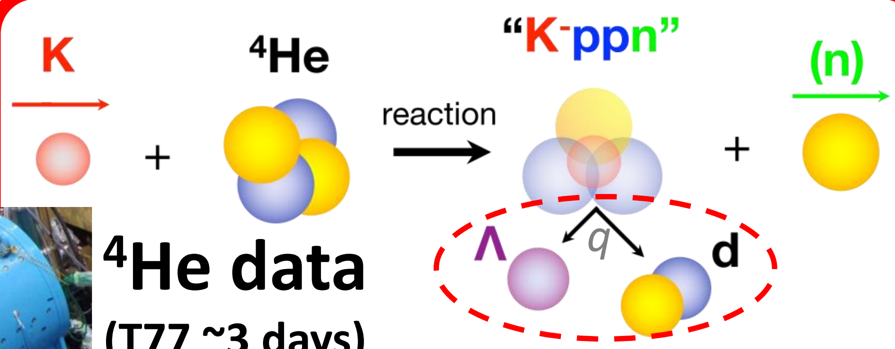




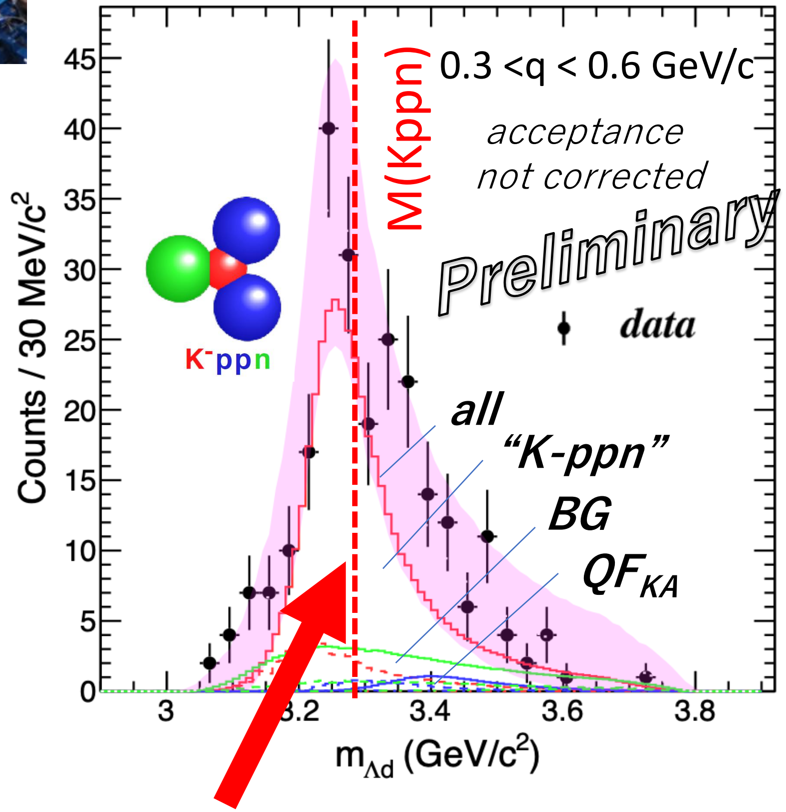
PLB632(2006)187

Distributed in parts of the plane
- 1 nucleon has the Fermi momentum

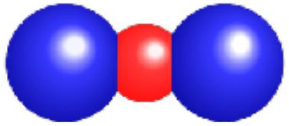
Widely distributed in the plane
- All particles have a momentum larger than the Fermi momentum



⁴He data
(T77 ~3 days)



the sign of the "K⁻ppn"



K$^-$pp

$\bar{K}$NN @ E89

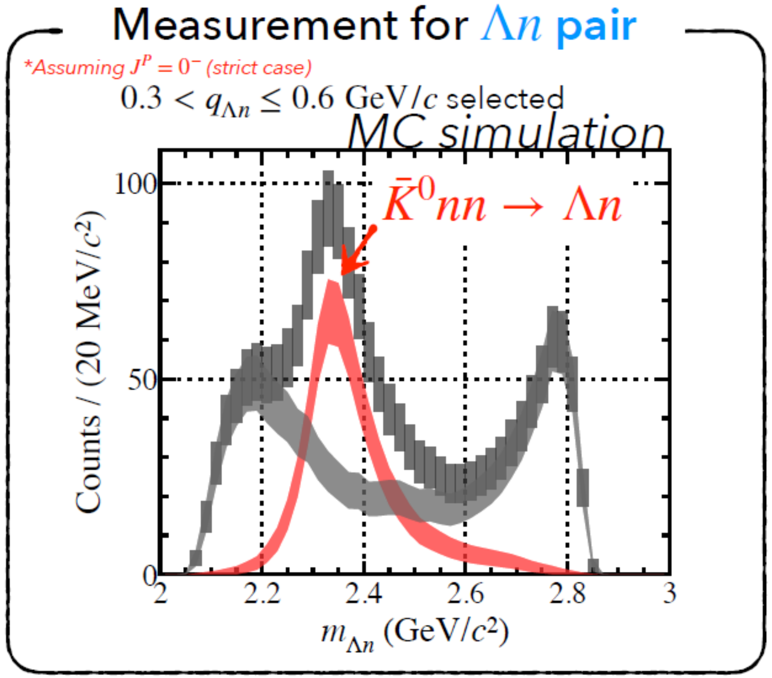
via ^{3}He(1 GeV/c K$^-$, n) reaction

① Search for "$\bar{K}^0$nn", isospin partner of "K$^-$pp"

- "$\bar{K}^0$nn"→Λn/Σ$^-$p

② Determine the spin/parity of $\bar{K}$NN

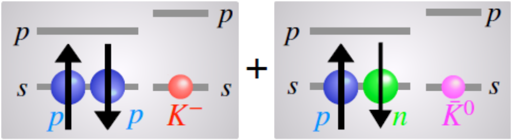
- spin-spin correlation measurement of "K$^-$pp"→Λp



There are two possible configurations for the $\bar{K}NN$ ground state.

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

$J^P = 0^-$

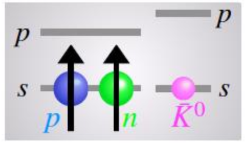


$$\frac{|I_{\bar{K}N} = 0|^2}{|I_{\bar{K}N} = 1|^2} = \frac{3}{1}$$

Deeper bound expected

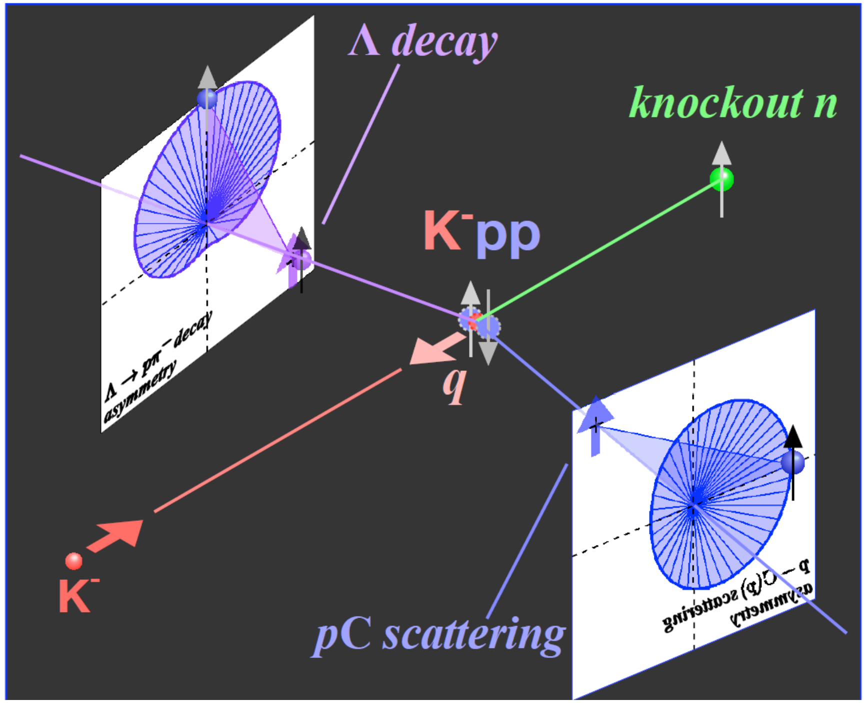
" $(NN)_{(I.asym \times S.sym)} \otimes \bar{K}$ "

$J^P = 1^-$

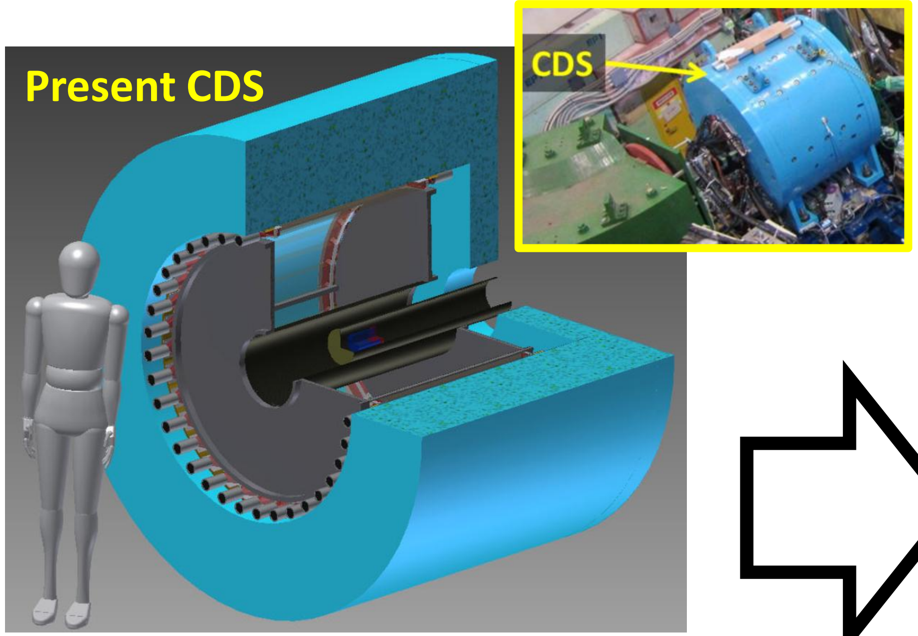


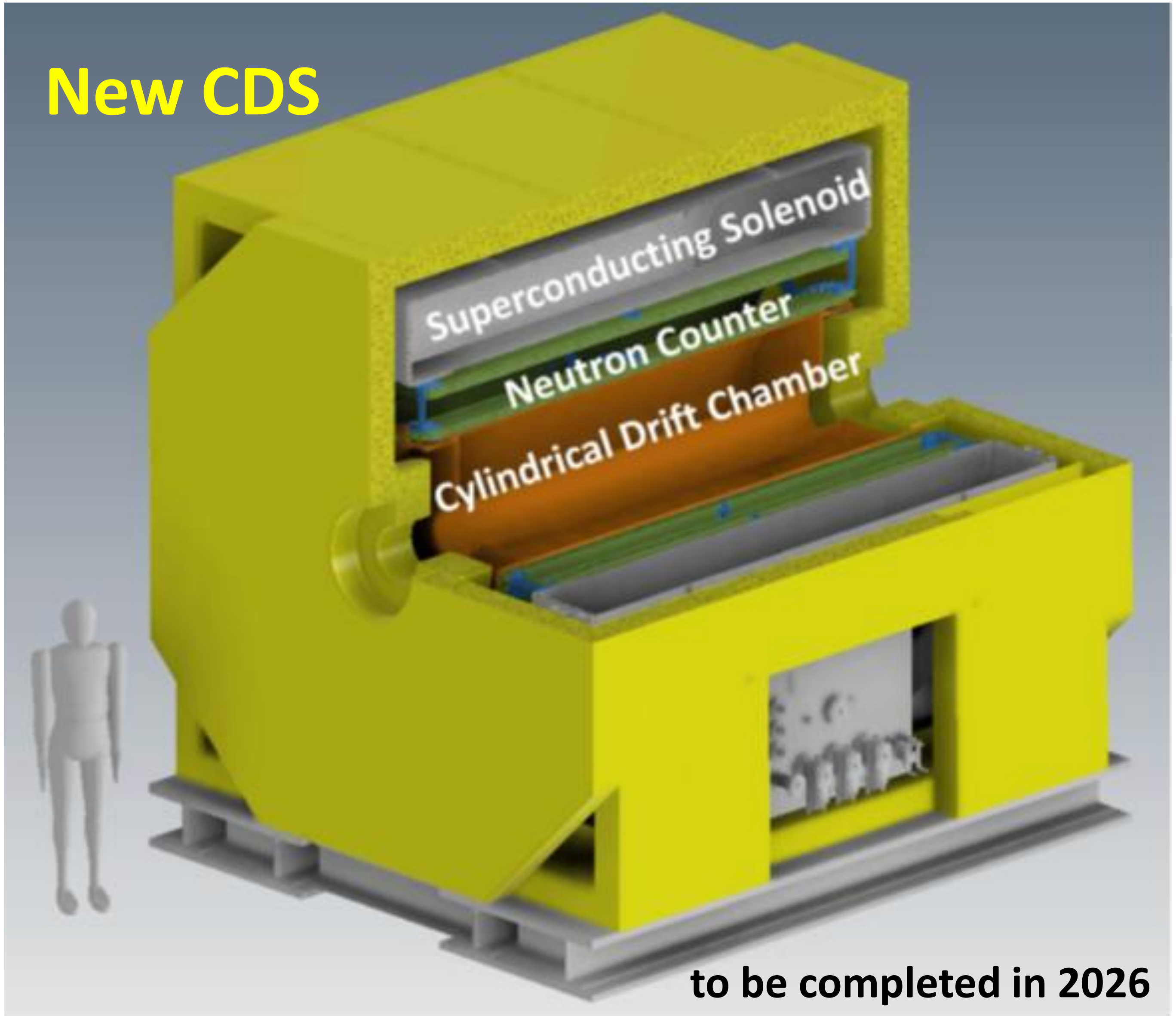
$$\frac{|I_{\bar{K}N} = 0|^2}{|I_{\bar{K}N} = 1|^2} = \frac{1}{3}$$

Shallower bound expected



New Cylindrical Detector System (CDS)





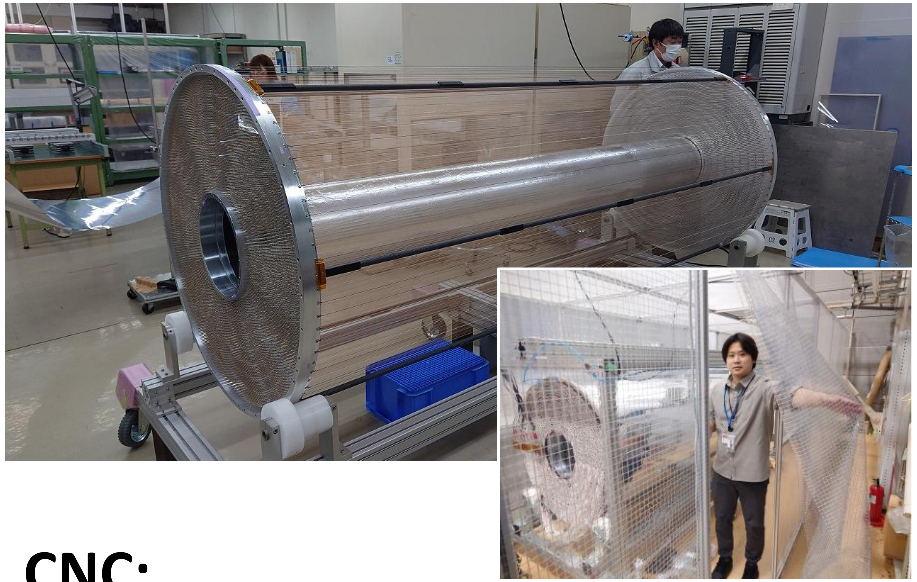
✓**Solid angle:** **x1.6** (59% → 93%)
✓**Neutron eff.:** **x7** (3% → 12%x1.6)
+ forward TOF counter
+ proton polarimeter (in future)

Construction Status of the CDS

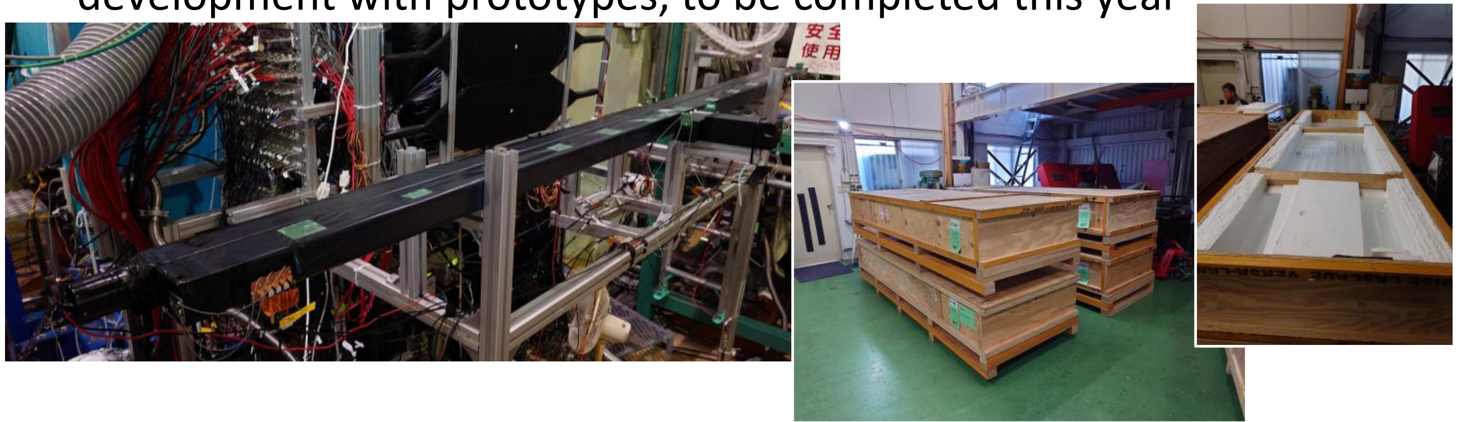
Return York:
completed

SC Solenoid:
completed

CDC:
completed, in commissioning

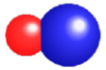


CNC:
development with prototypes, to be completed this year



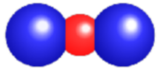
The experiment will be ready in early 2027

Summary



Λ(1405) from d(K-,n)

✓**πΣ**: PLB837(2023)137637.



"K^{-}pp" from ^{3}He(K^{-}, n)

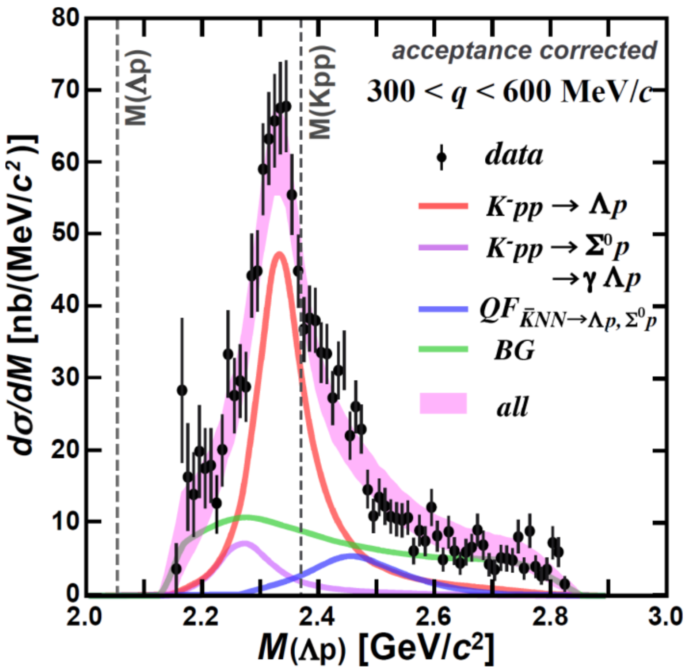
✓**Λp**: PLB789(2019)620., PRC102(2020)044002.

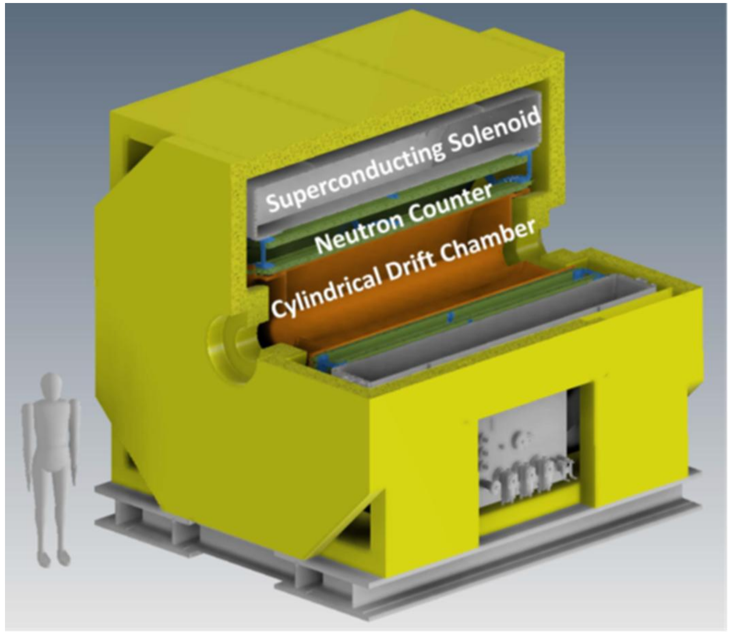
✓**πYN**: PRC110(2024)014002.

"K^{-}ppn" from ^{4}He(K^{-},n)

✓**Λd**: A hint has been observed.

- New project has started from E80, "K^{-}ppn", aiming at the systematic study of the kaonic nuclei
  - Constructing a large solenoid spectrometer
  - will start in early 2027





J-PARC E80 Collaboration

M. Ichikawa, M. Iwasaki, T. Hashimoto, R. Kino, Y. Ma, R. Murayama, F. Sakuma[1]
RIKEN, Saitama, 351-0198, Japan

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

Y. Kimura, G. Kojima, H. Ohnishi, S. Ohtaka, S. Sasaki, 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), Ibaraki, 305-0801, Japan

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

H. Fujioka
Institute of Science Tokyo, Tokyo, 152-8551, Japan

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

T. Nanamura
Tohoku University, Miyagi, 980-8578, Japan

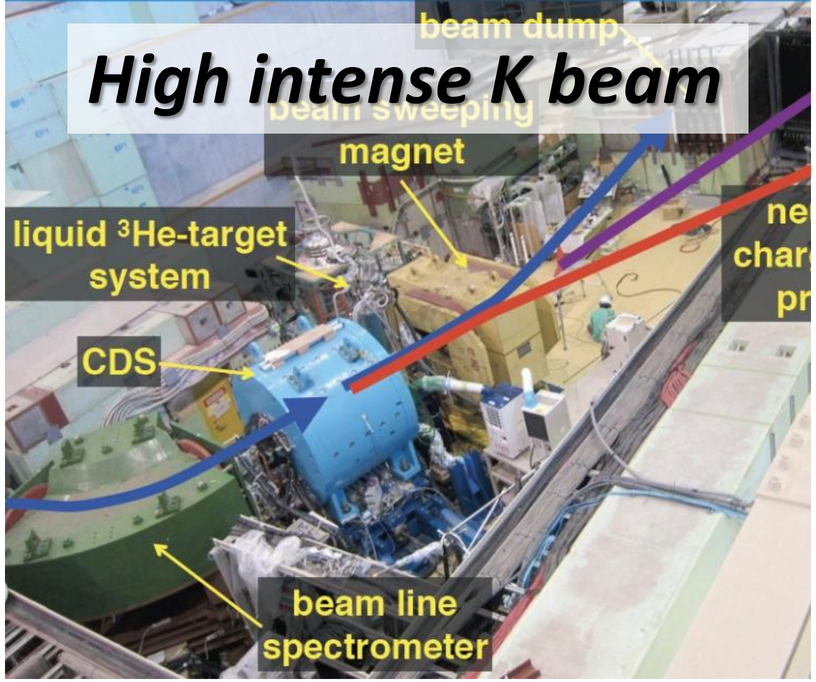
M. Fujita, S. Nagao, S.N. Nakamura, Y. Tsutsumi
The University of Tokyo, Tokyo, 113-8654, Japan

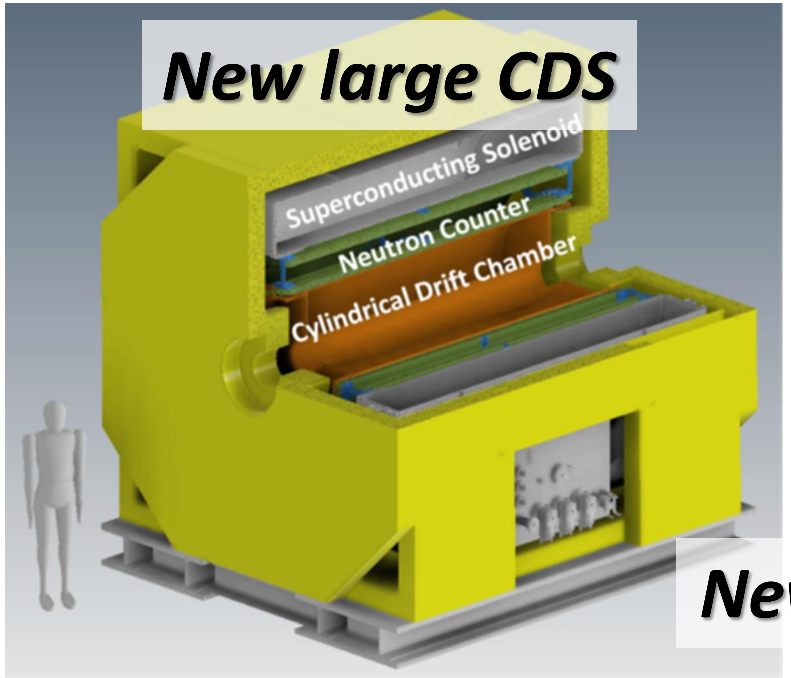
K. Itahashi
Osaka University, Osaka, 565-0871, Japan

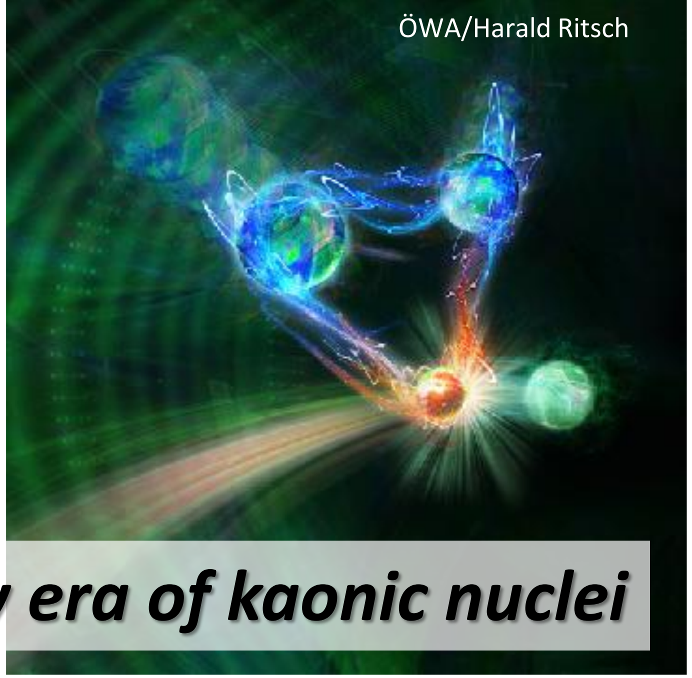
M. Bazzi, A. Clozza, C. Curceanu, M. Iliescu, S. Manti, A. Scordo, F. Sgaramella, D. Sirghi, F. Sirghi
Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy

J. Marton
Technical University Vienna, 1020 Vienna, Austria

We're looking for new collaborators!

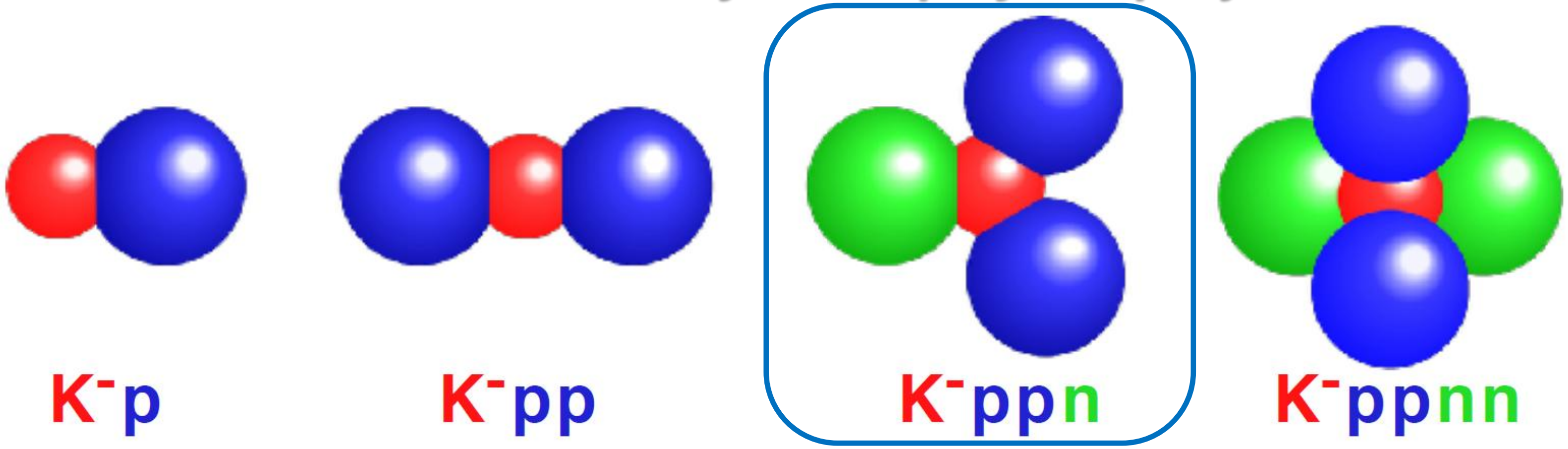






Thank you for your attention!

A first step of the project



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