Antikaon-Nuclear Bound States at J-PARC

F. Sakuma, RIKEN

on behalf of the J-PARC E15/E80/P89 collaboration

61st International Winter Meeting on Nuclear Physics

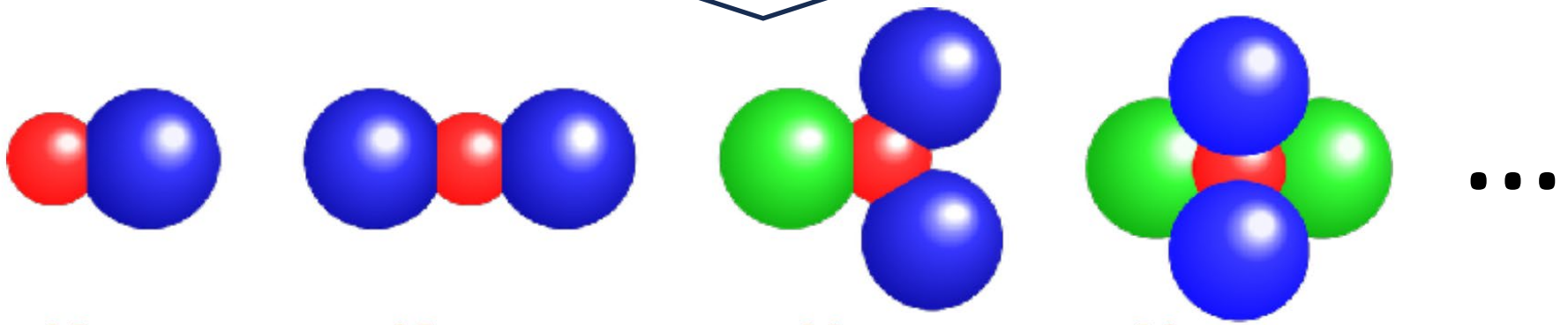
27 - 31 January 2025

Bormio, Italy

What Are "Kaonic Nuclei"?

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

$$\mathbf{K} = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix} \begin{matrix} u\bar{s} \\ d\bar{s} \end{matrix} \quad s = 1 \qquad \mathbf{\bar{K}} = \begin{pmatrix} \bar{K}^0 \\ K^- \end{pmatrix} \begin{matrix} \bar{d}s \\ \bar{u}s \end{matrix} \quad s = -1 \qquad \mathbf{N} = \begin{pmatrix} p \\ n \end{pmatrix} \begin{matrix} uud \\ udd \end{matrix} \qquad \mathbf{I_3} = \begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$$

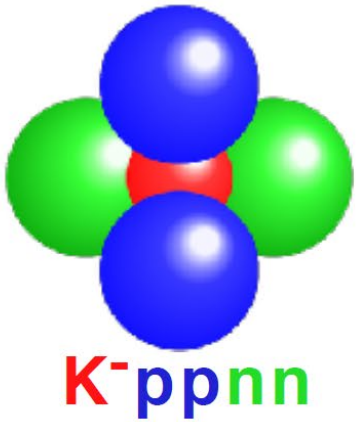


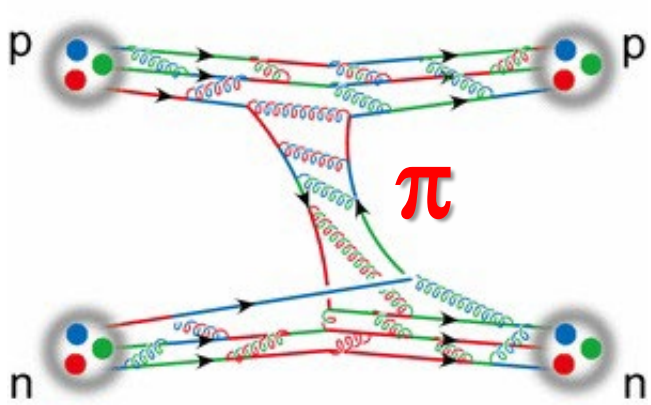
=Λ(1405)

What Is Interesting about “Kaonic Nuclei”?

① **Meson can be the building block of nuclei → New forms of nuclei**

- Exploring the diversity of nuclei



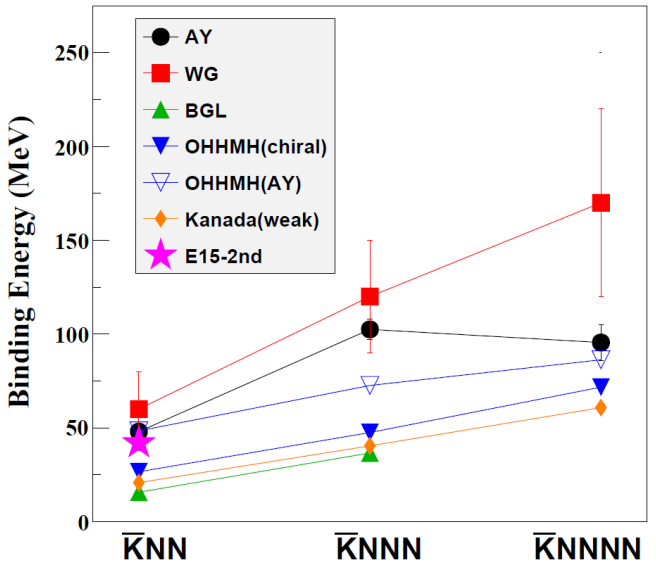


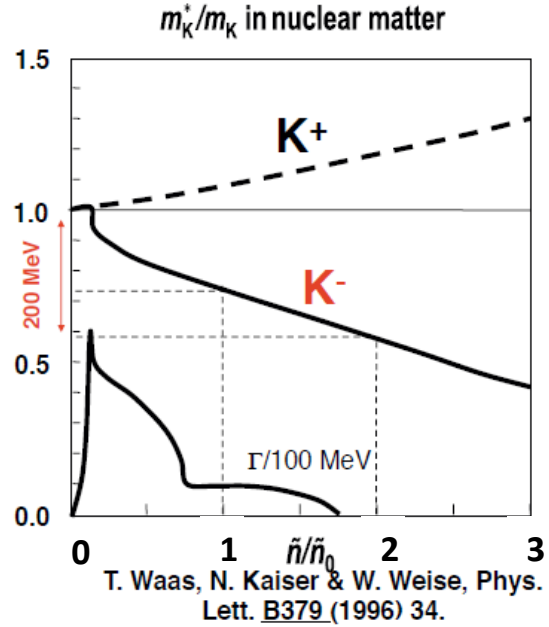
$\overline{K}$ = “real” particle

π = “virtual” particle (Force Mediating Particle)

② **Large binding energies are expected ← strongly attractive $\overline{K}N$**

- Possibility of high-density matter formation

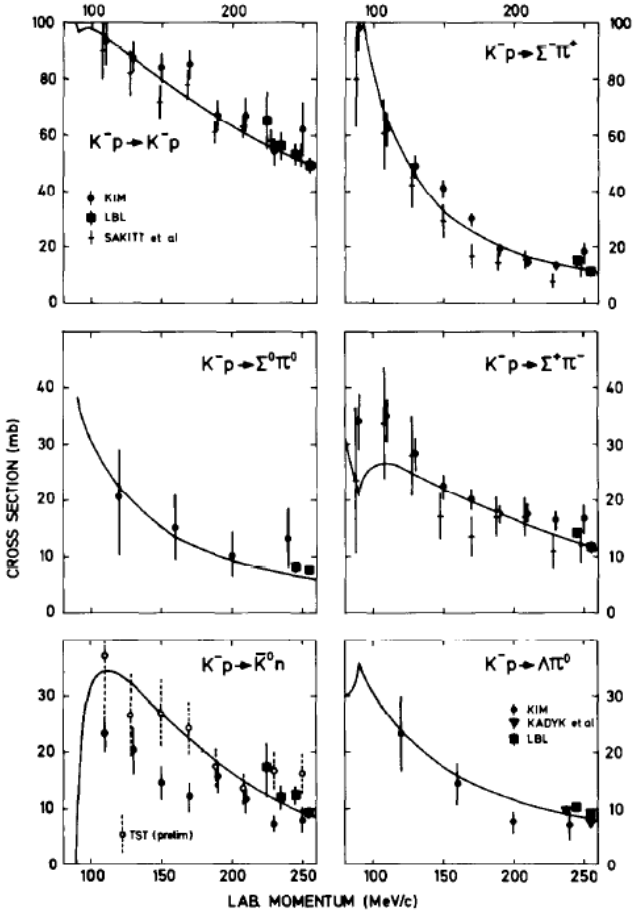




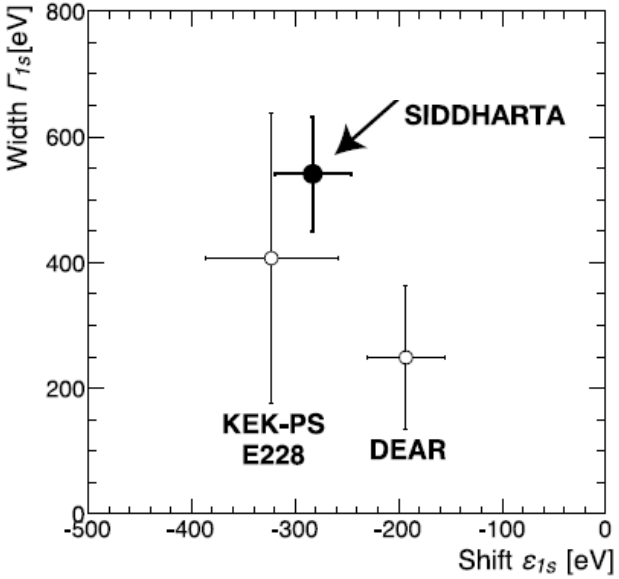
can be a probe to study changes in meson properties inside nuclear media

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

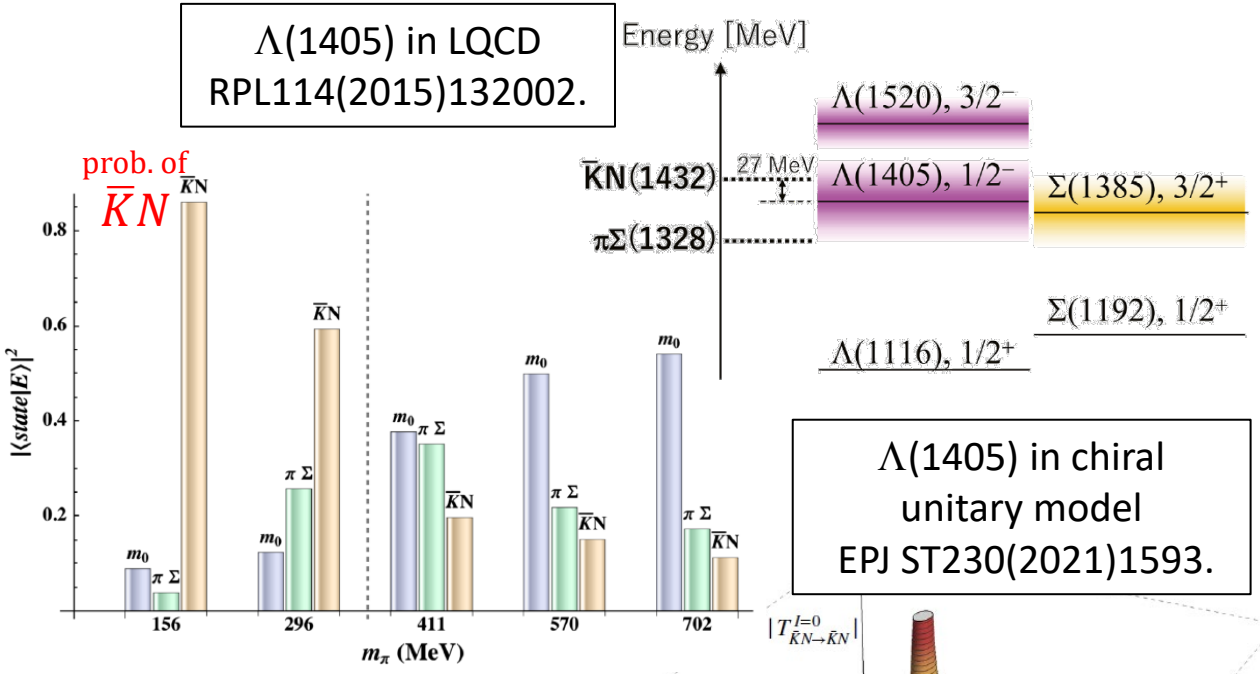
K⁻p scattering
NPB179(1981)33.



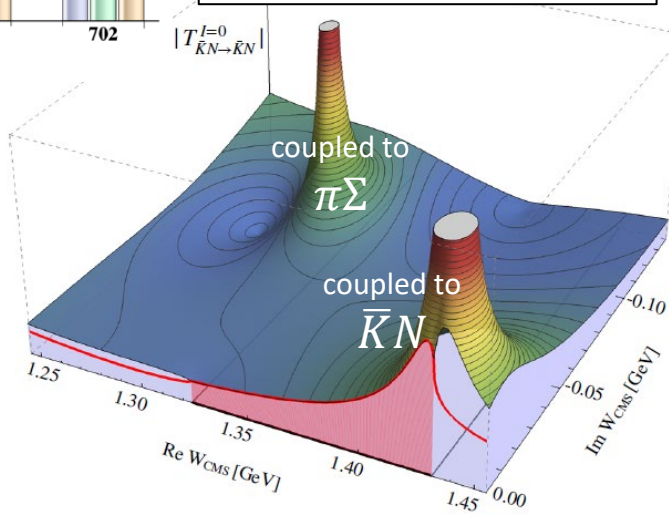
K⁻p atom
PLB704(2011)113.



$\Lambda(1405)$ in LQCD
RPL114(2015)132002.



$\Lambda(1405)$ in chiral unitary model
EPJ ST230(2021)1593.

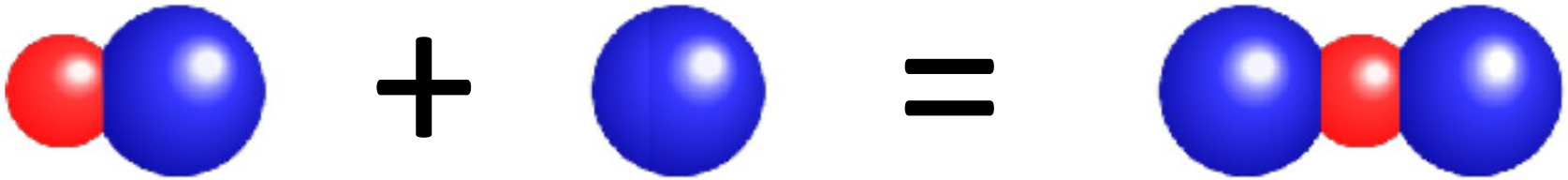


- ✓ strongly attractive $\bar{K}N$ int. in I=0
- ✓ $\Lambda(1405)$ = quasi-bound state of $\bar{K}N$

Extension to “Kaonic Nuclei”

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

  → possible $\bar{K}$-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
- $\bar{K}NN$ system : the simplest $\bar{K}$-nucleus system
  - Many experimental searches at J-PARC,DAFNE,GSI,CERN,etc. in 21st century

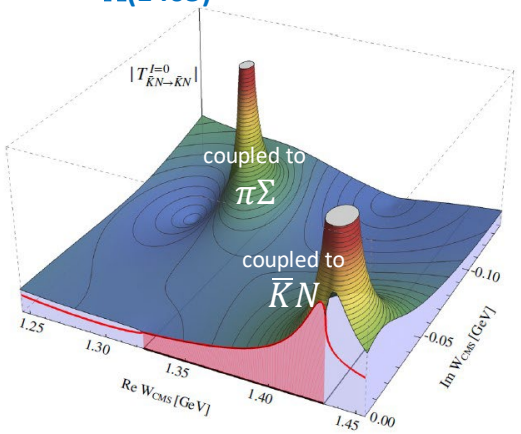


Theoretical Calculations of $\bar{K}NN$

Chiral unitary model (energy dependent)

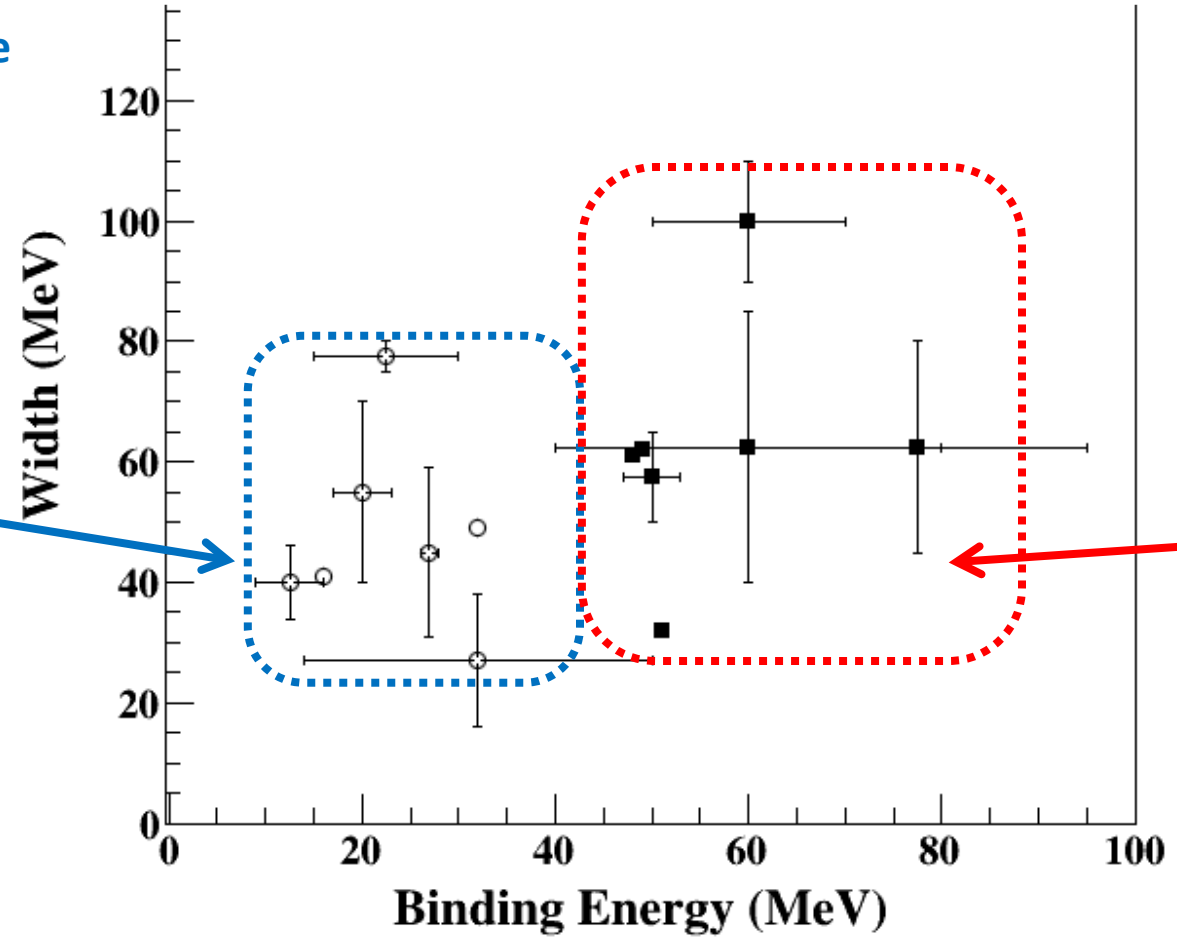
Phenomenological model (energy independent)

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

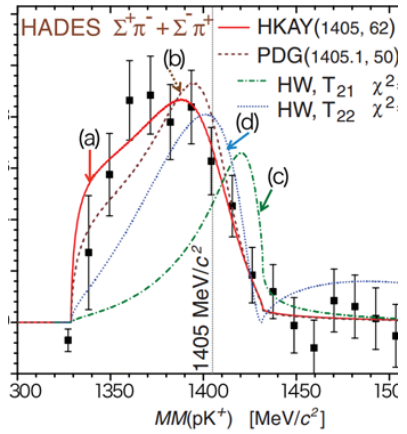


shallow $\bar{K}N$ potential

B.E. ~ 10-30 MeV



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



deep $\bar{K}N$ potential

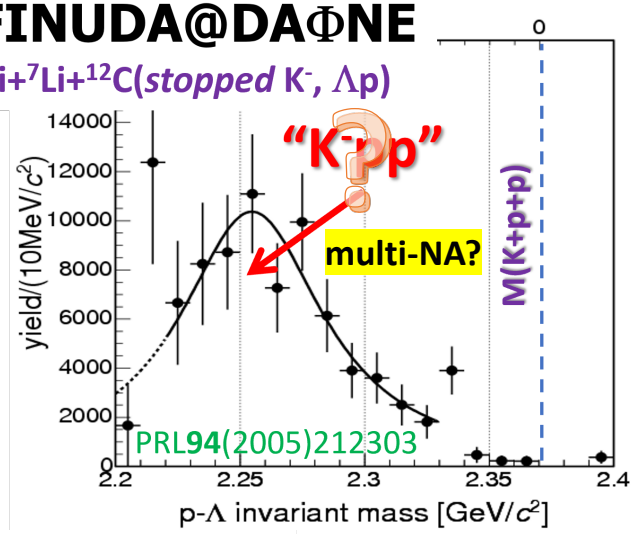
B.E. ~ 40-70 MeV

suggesting a more compact and dense system

"K⁻pp" Bound State Searches - History

FINUDA@DAΦNE

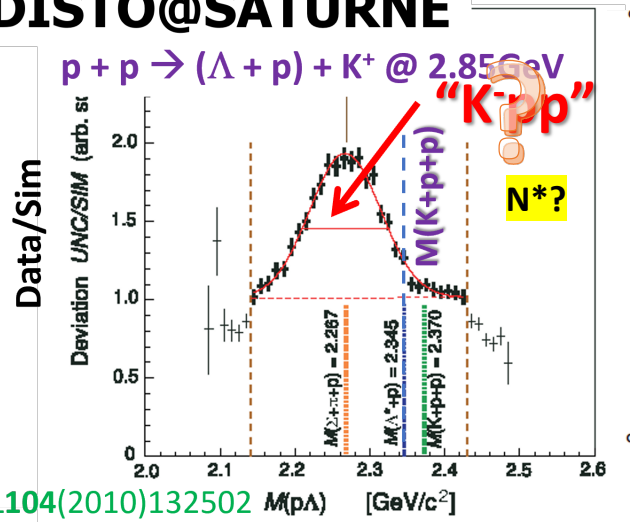
^{6}Li+^{7}Li+^{12}C(*stopped* K$^-$, Λp)



PRL**94**(2005)212303

DISTO@SATURNE

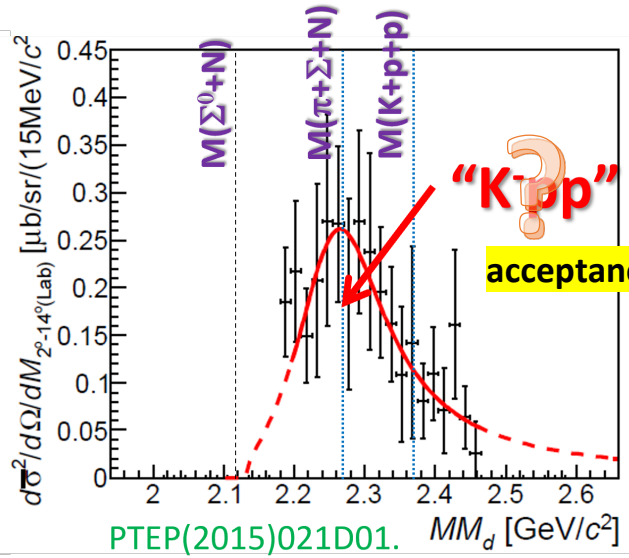
p + p → (Λ + p) + K⁺ @ 2.85GeV



PRL**104**(2010)132502

E27@J-PARC

d(π⁺, K⁺)Σ⁰p @ 1.69 GeV/c



PTEP(2015)021D01.

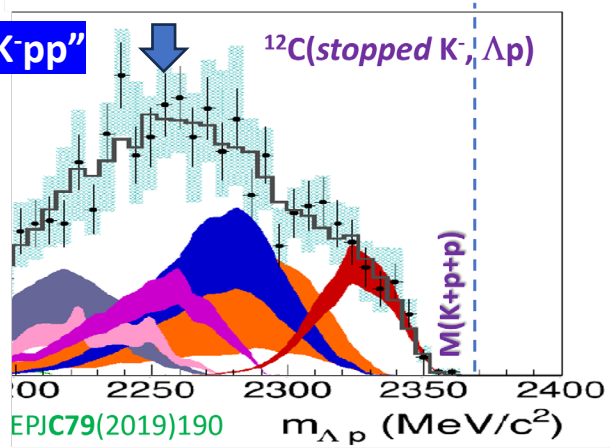
LEPS@SPring-8

d(γ, K⁺π⁻)X @ 1.3-2.4 GeV/c

PLB728(2014)616.

AMADEUS@DAΦNE

No "K⁻pp"

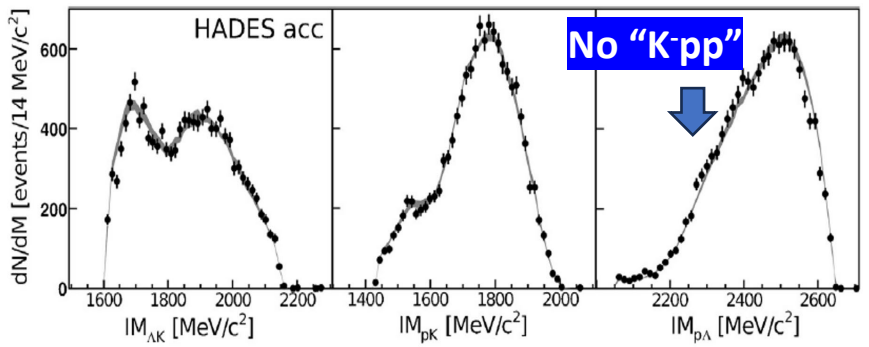


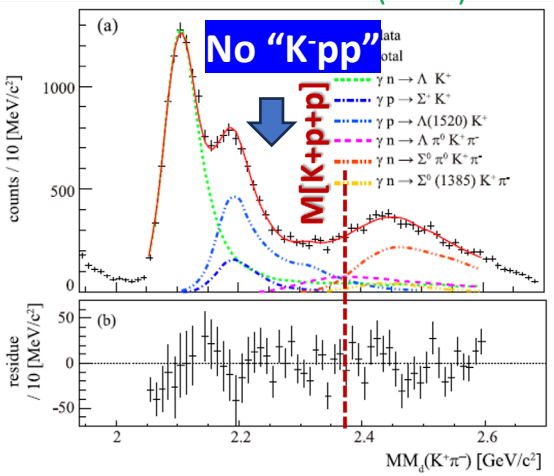
EPJ**C79**(2019)190

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" Bound State Searches - History

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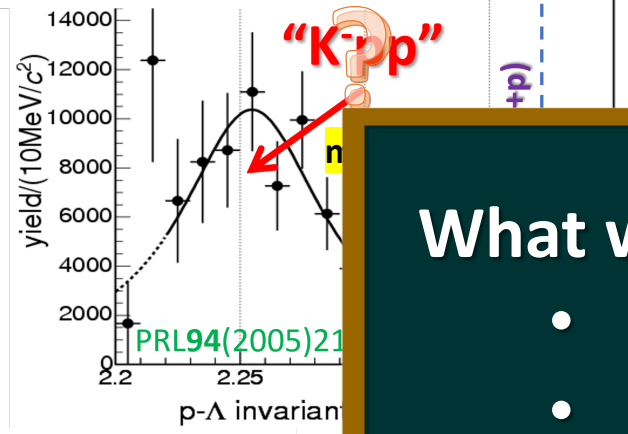
$^{6}Li+^{7}Li+^{12}C$(*stopped* K^-, Λp)



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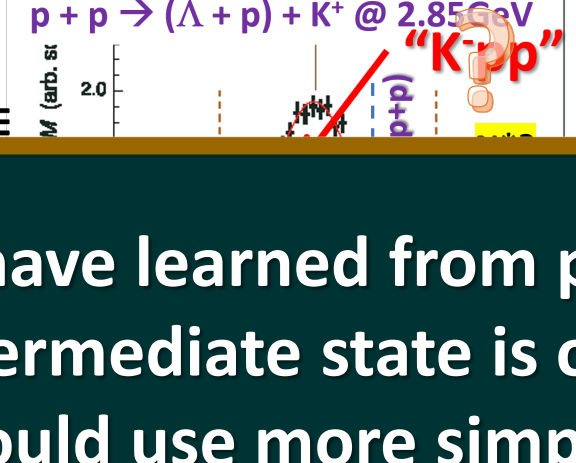
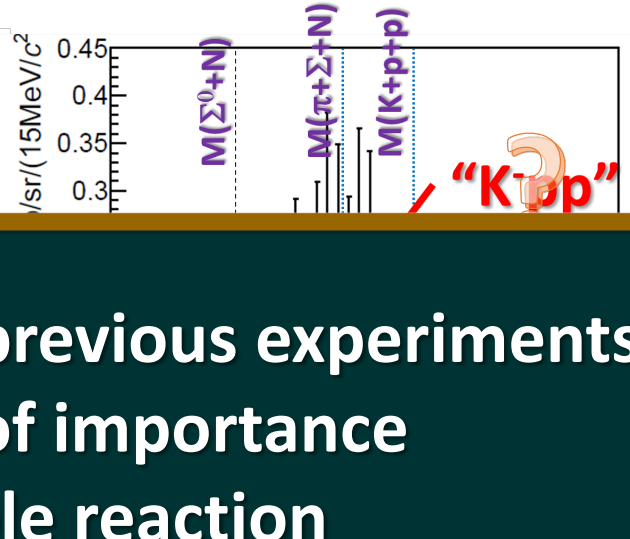


E27@J-PARC

d(π^+, K^+)Σ^0p @ 1.69 GeV/c



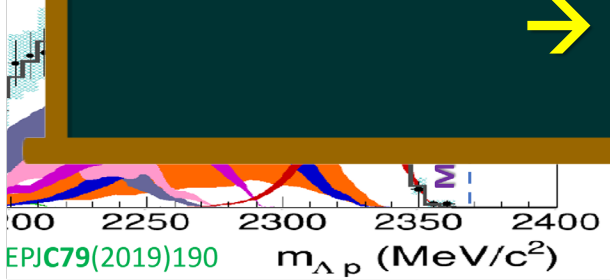
What we have learned from previous experiments:

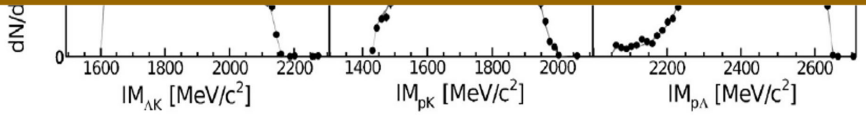
- Intermediate state is of importance
- Should use more simple reaction
- Exclusive measurement covering a wide kinematical region is a key

→ **J-PARC E15 experiment**

A

No "K⁻p

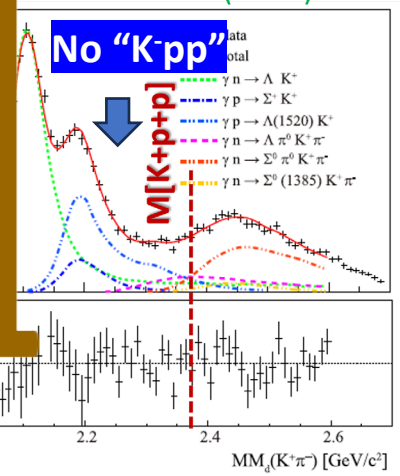




S@SPring-8

π^-)X @ 1.3-2.4 GeV/c

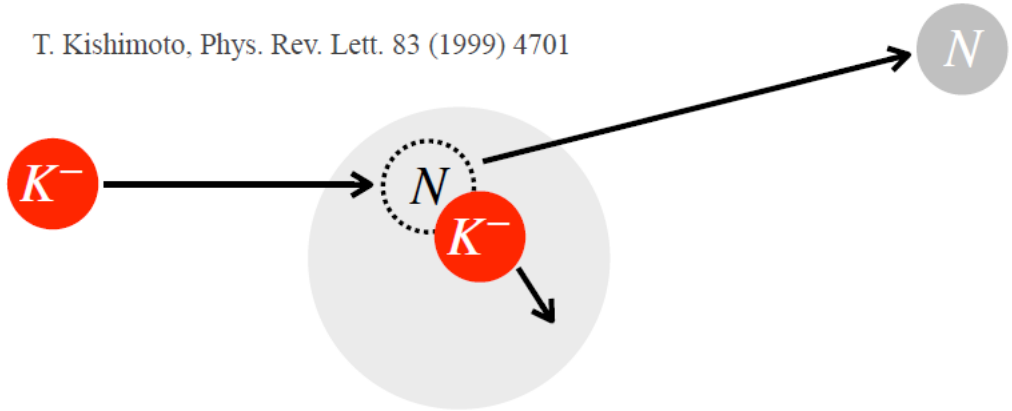
PLB728(2014)616.



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

Experimental Searches at J-PARC

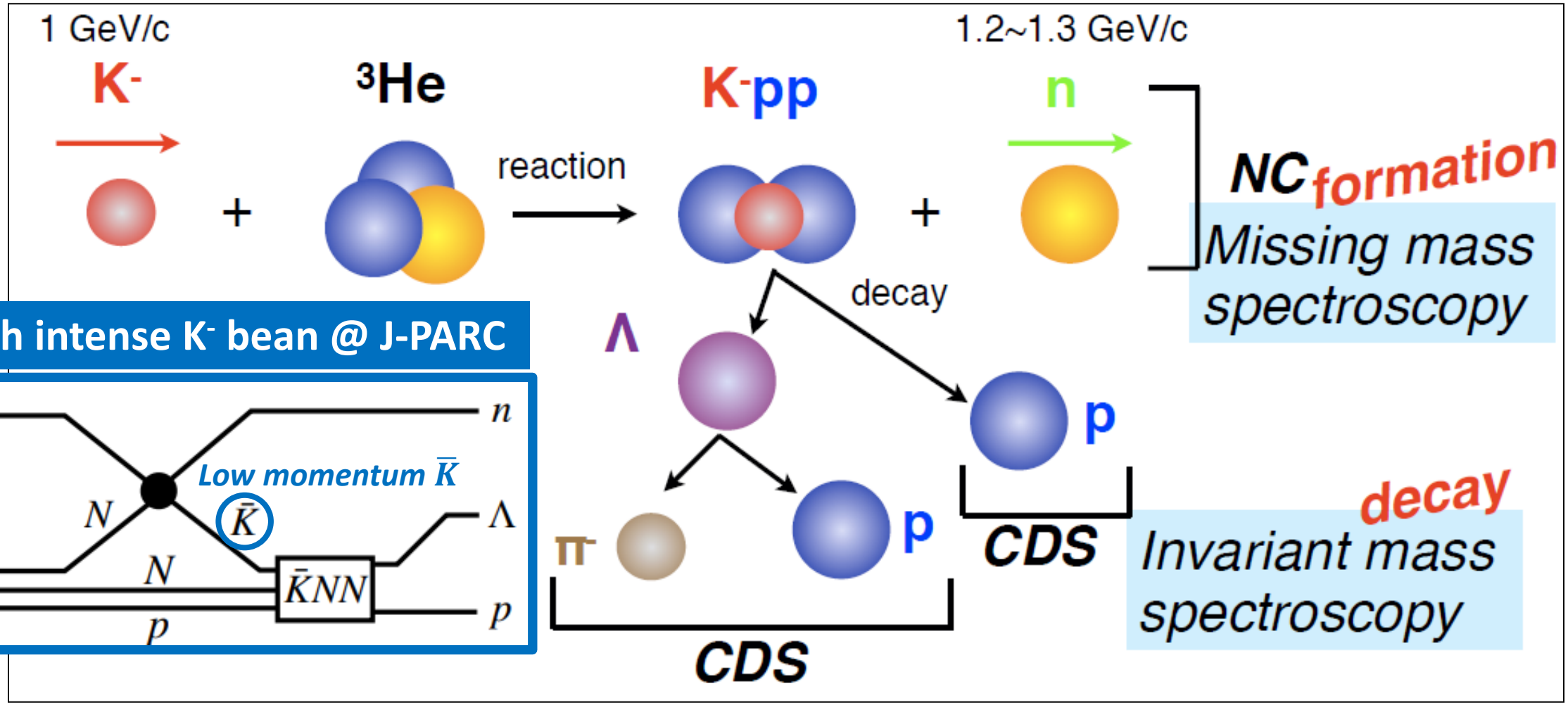
– via in-flight (K-,n) reactions –



"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

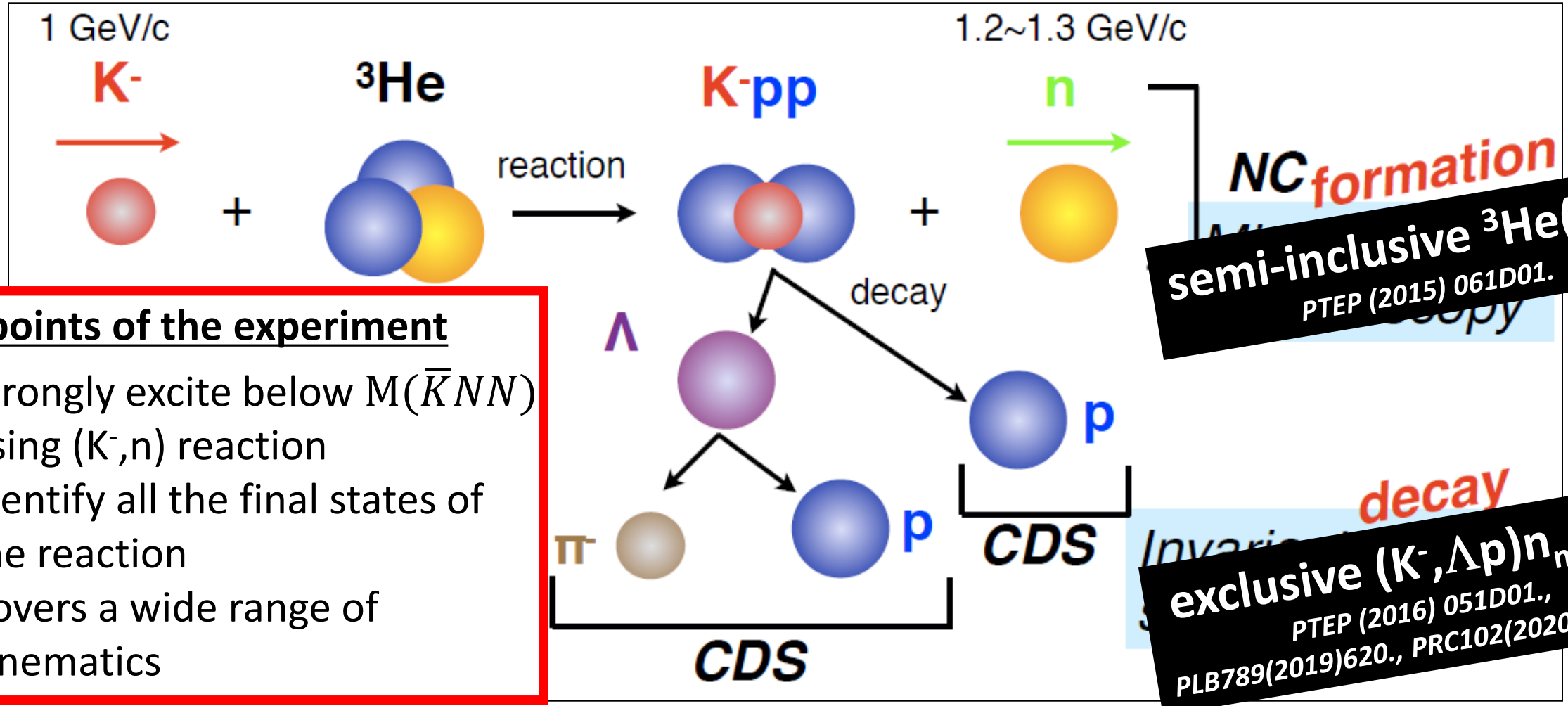


with intense K⁻ bean @ J-PARC

"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

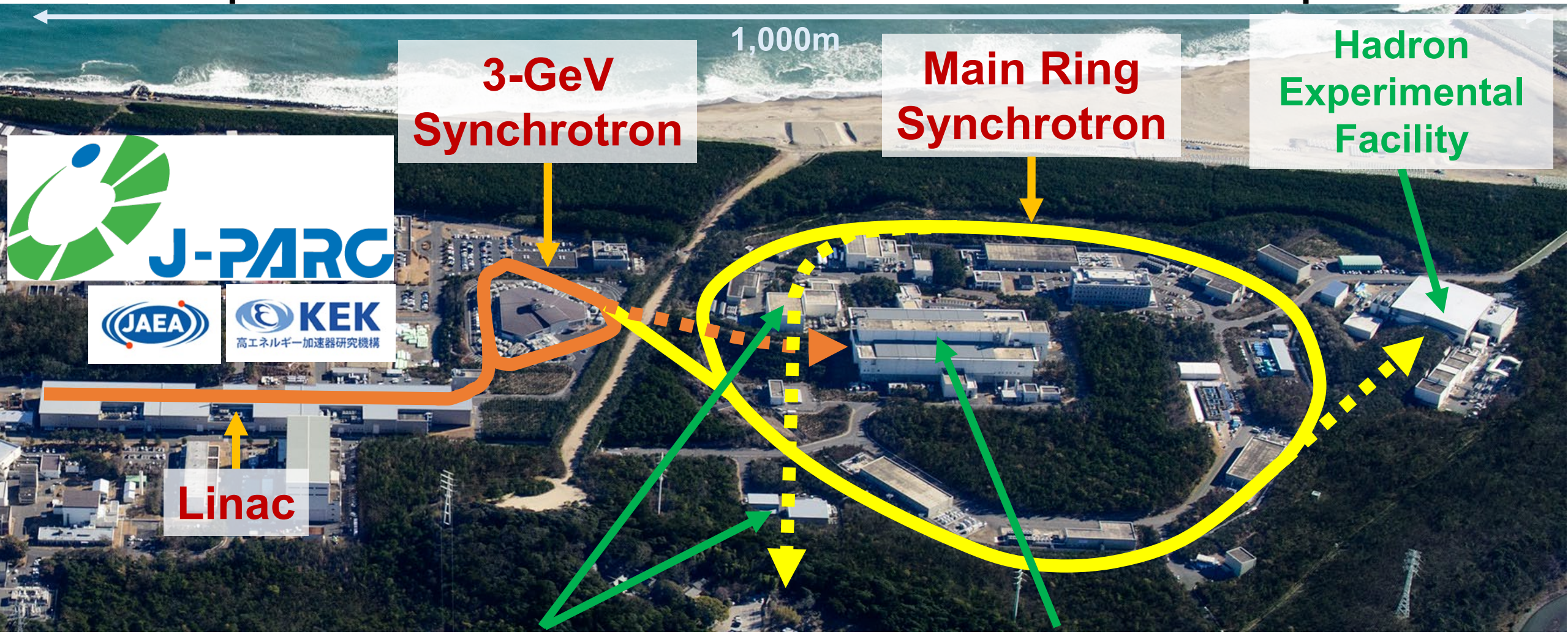
③ Covers a wide range of kinematics

semi-inclusive ^{3}He(K⁻,n)
PTEP (2015) 061D01.

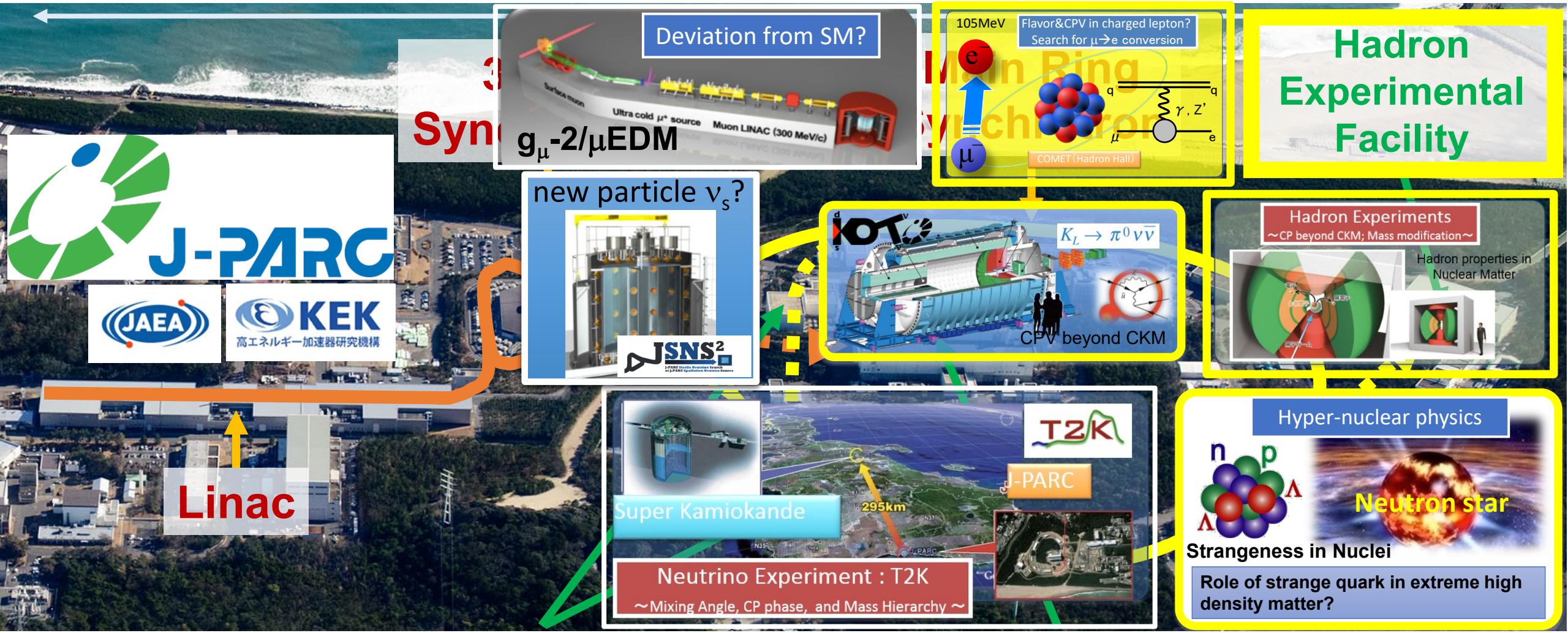
exclusive (K⁻,Λp)n$_{missing}$
PTEP (2016) 051D01.,
PLB789(2019)620., PRC102(2020)044002.

J-PARC

Japan Proton Accelerator Research Complex



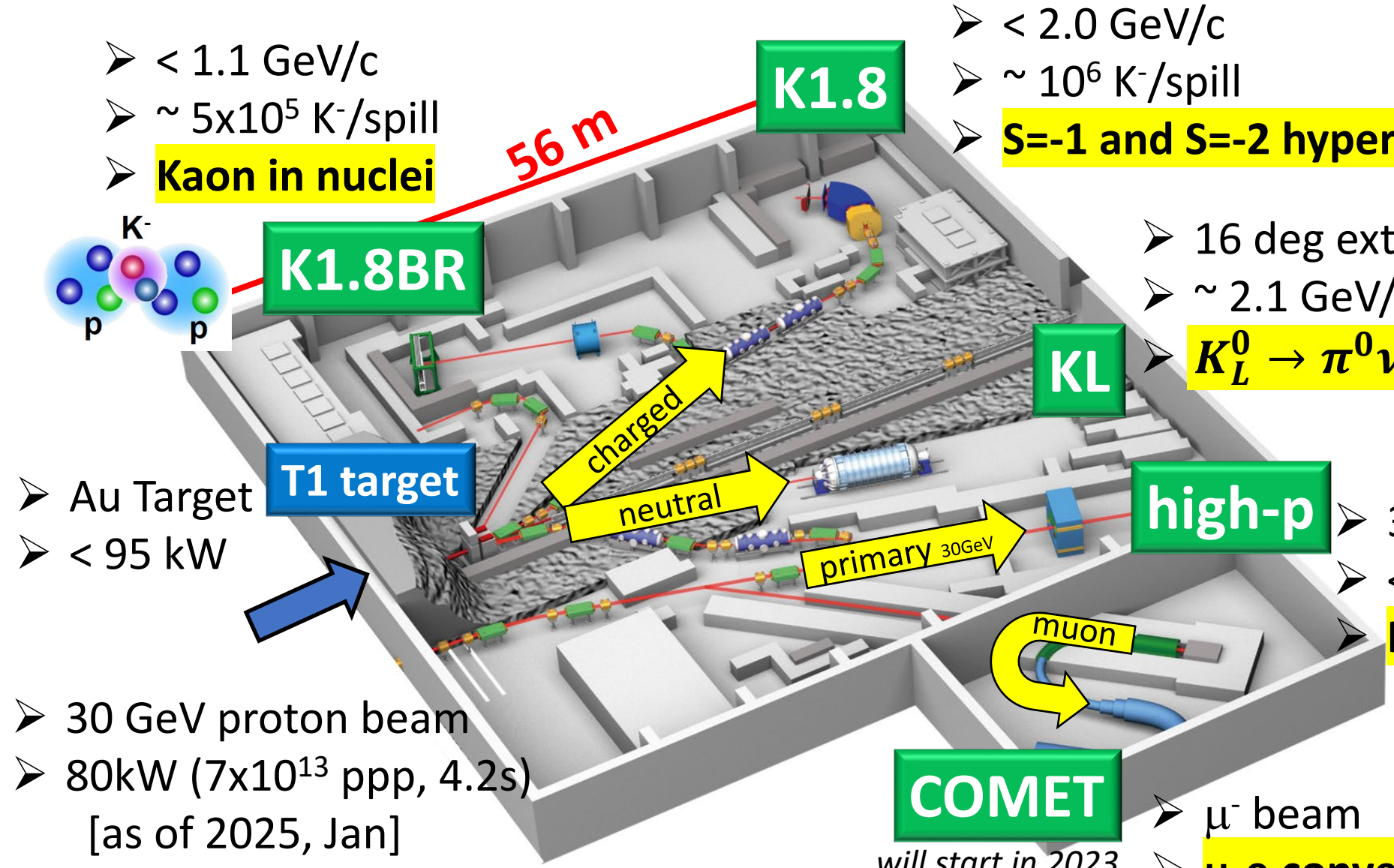
Particle and Nuclear Physics @ J-PARC



Neutrino Experimental Facility

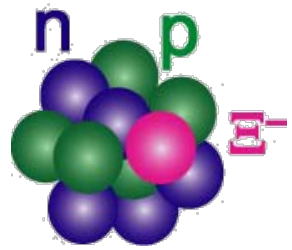
Material and Life Science Experimental Facility

Hadron Experimental Facility (HEF)

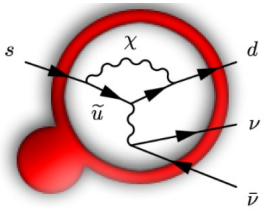


- < 1.1 GeV/c
- ~ 5x10^5 K$^-$/spill
- **Kaon in nuclei**

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



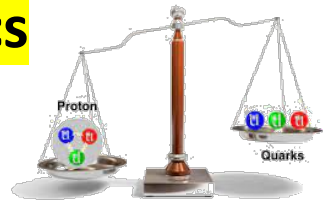
- 16 deg extraction
- ~ 2.1 GeV/c ~ 10^7 K^0_L/spill
- **$K_L^0 \to \pi^0 \nu\bar{\nu}$**



- Au Target
- < 95 kW

launched in 2020

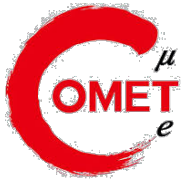
- 30 GeV proton ~ 10^{10}
- < 31 GeV/c unsepa. π ~ 10^7
- **Hadron physics**



- 30 GeV proton beam
- 80kW (7x10^{13} ppp, 4.2s)
  [as of 2025, Jan]

will start in 2023

- μ$^-$ beam
- **μ-e conversion**



Hadron Experimental Facility (HEF)

- < 1.1 GeV/c
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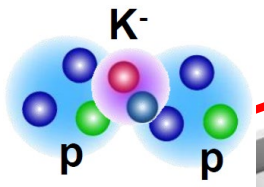

- Au Target
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- 30 GeV proton beam
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K1.8

- < 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
- $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$

high-p

launched in 2020

- 30 GeV proton ~ 10^{10}
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COMET

will start in 2023

- μ^- beam
- **μ-e conversion**

Experimental Setup @ K1.8BR

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

Beam Dump

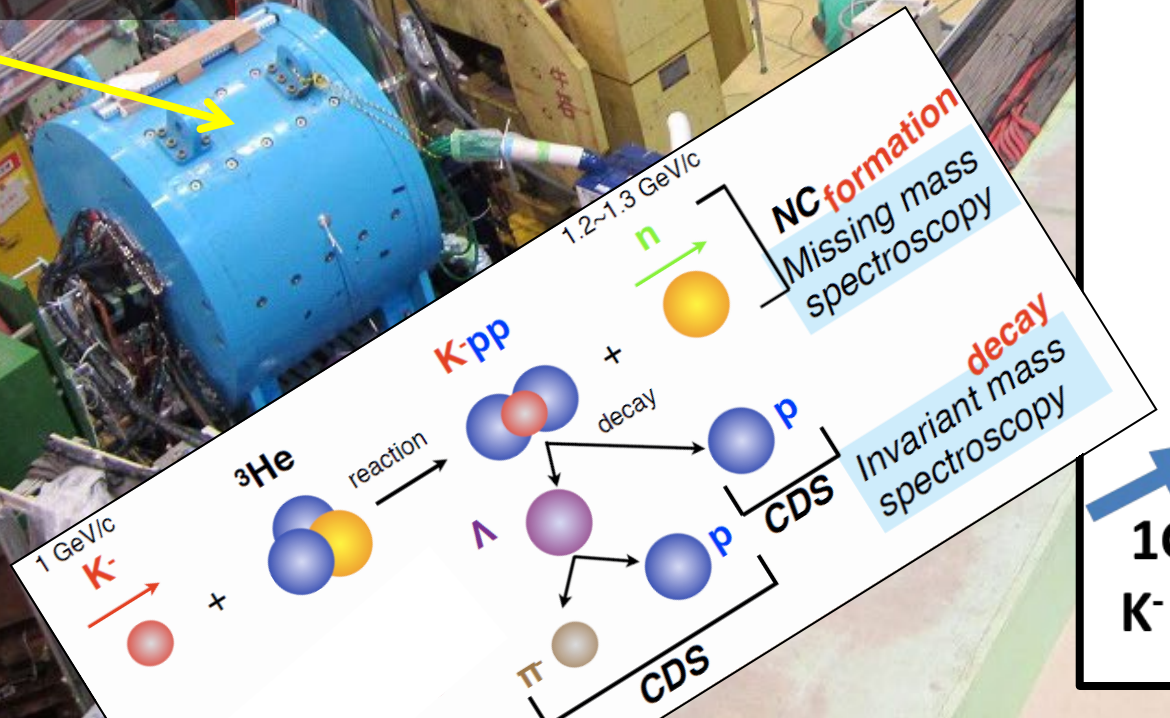
Beam Sweeping Magnet

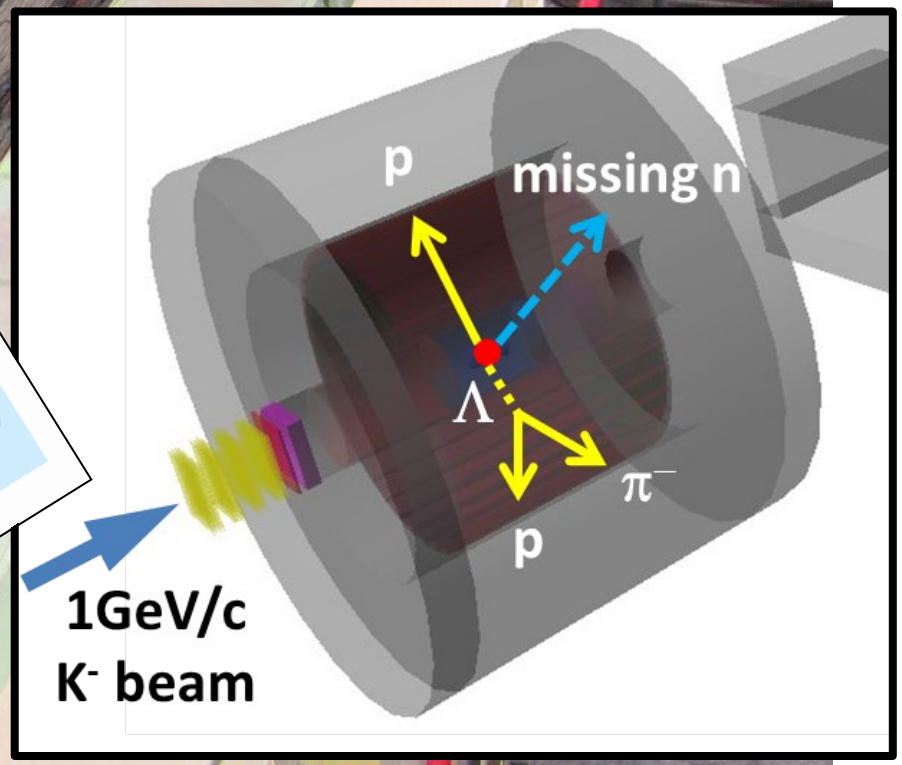
Liquid ^{3}He-target System

Cylindrica Detector System (CDS)

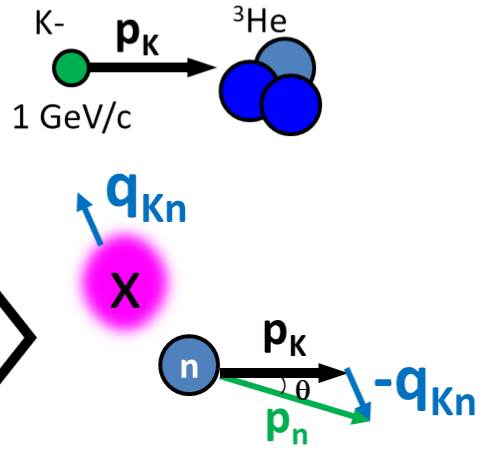
Beam Line Spectrometer

Neutron Counter
Charge Veto Counter
Proton Counter





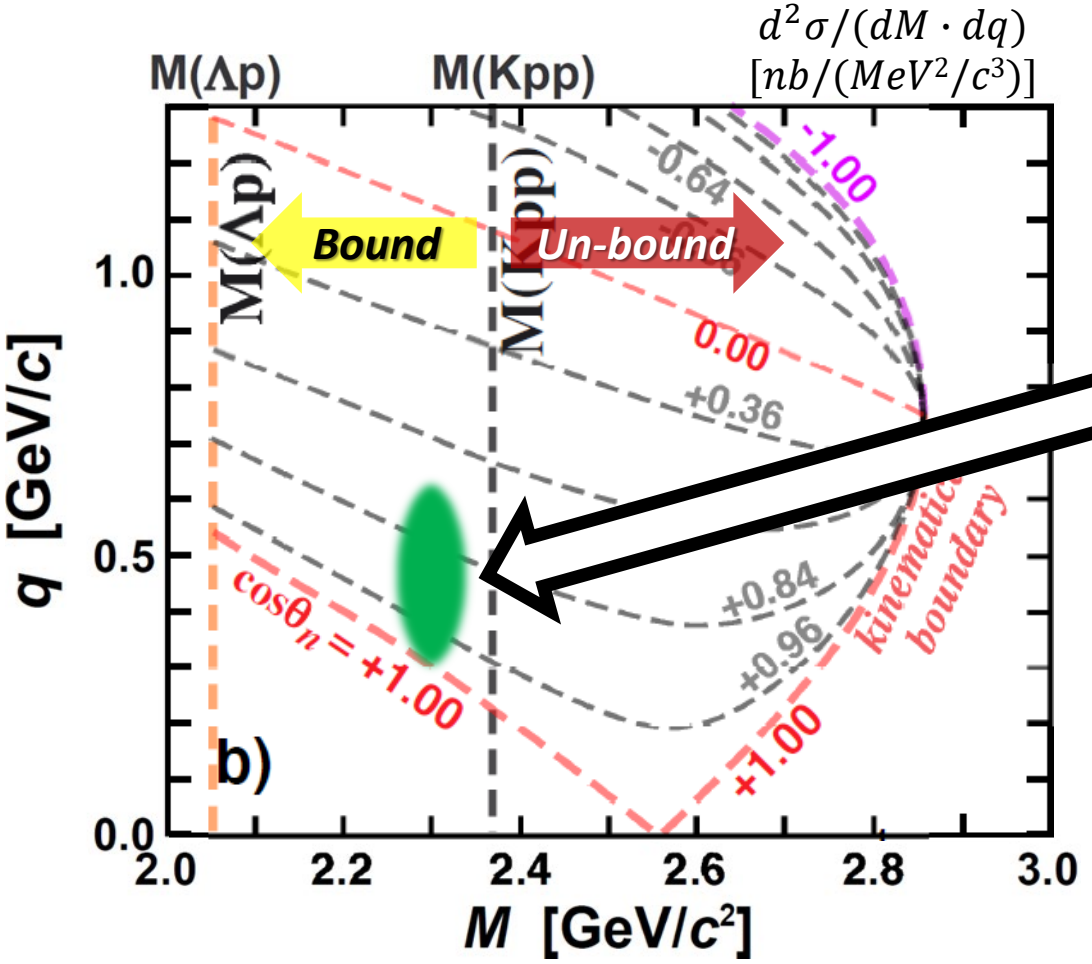
"K⁻pp" Search w/ Momentum Transfer Analysis

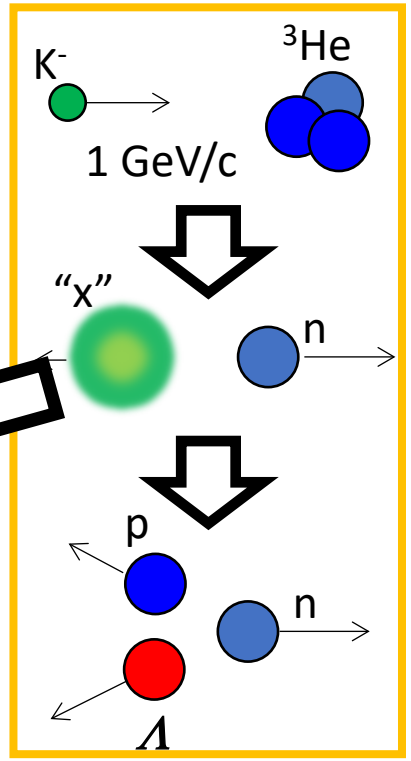


- **Momentum transfer analysis using the (K⁻,n) reaction**

✓ M(Λp) vs. q

✓ give a clear information on reaction processes



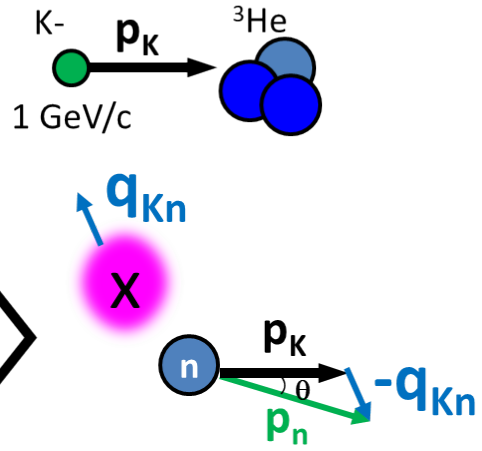


q *: (K⁻,n) momentum transfer*

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



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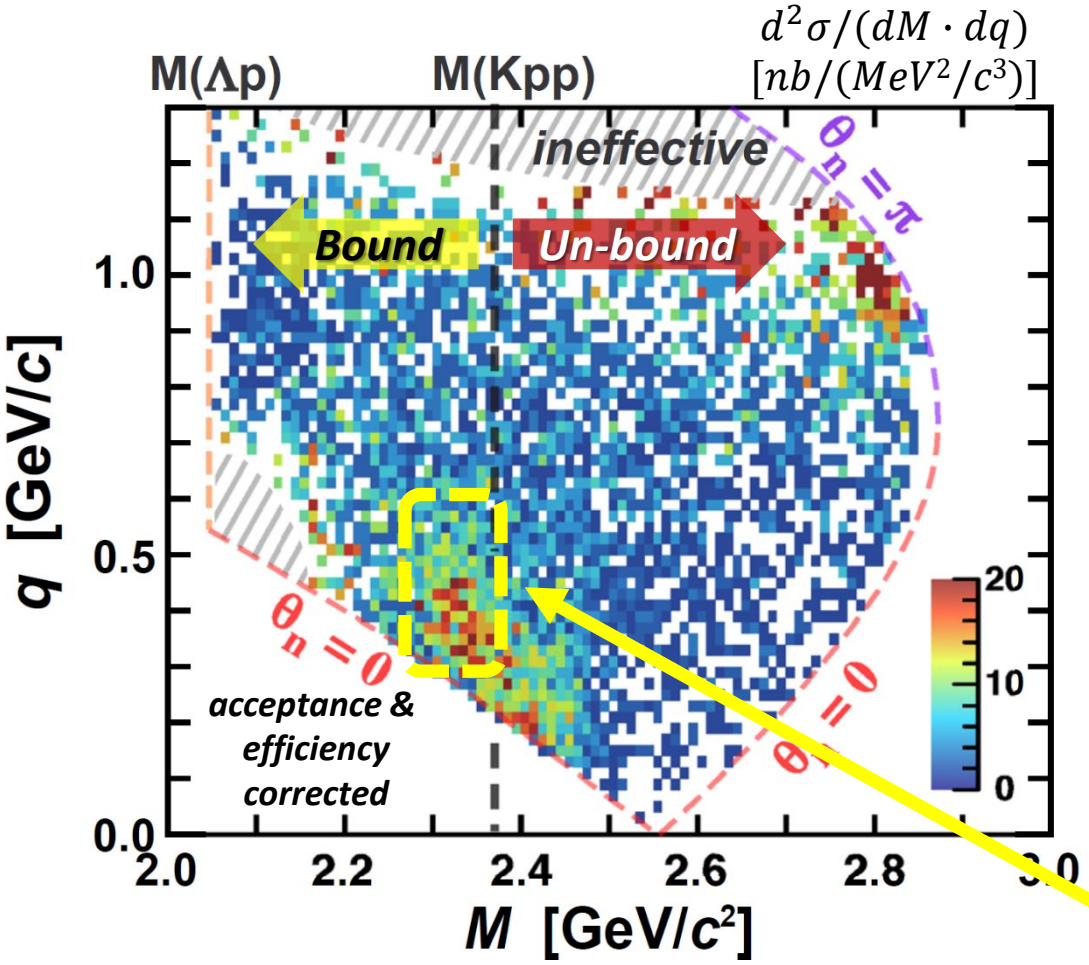
PLB789(2019)620., PRC102(2020)044002.



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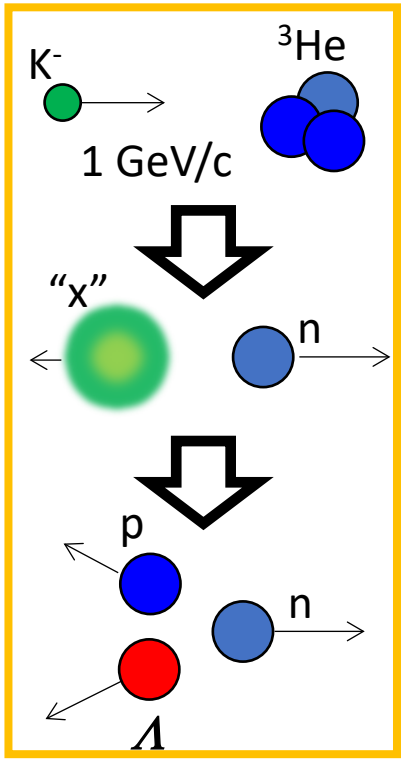
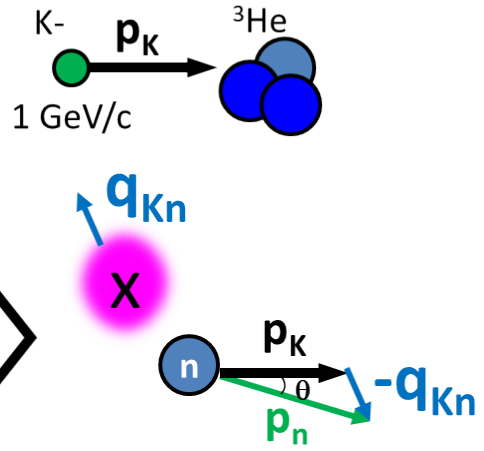
M *: Λp invariant mass*



A peak structure independent of *q* =

A bound state exists

"K⁻pp" Search w/ Momentum Transfer Analysis

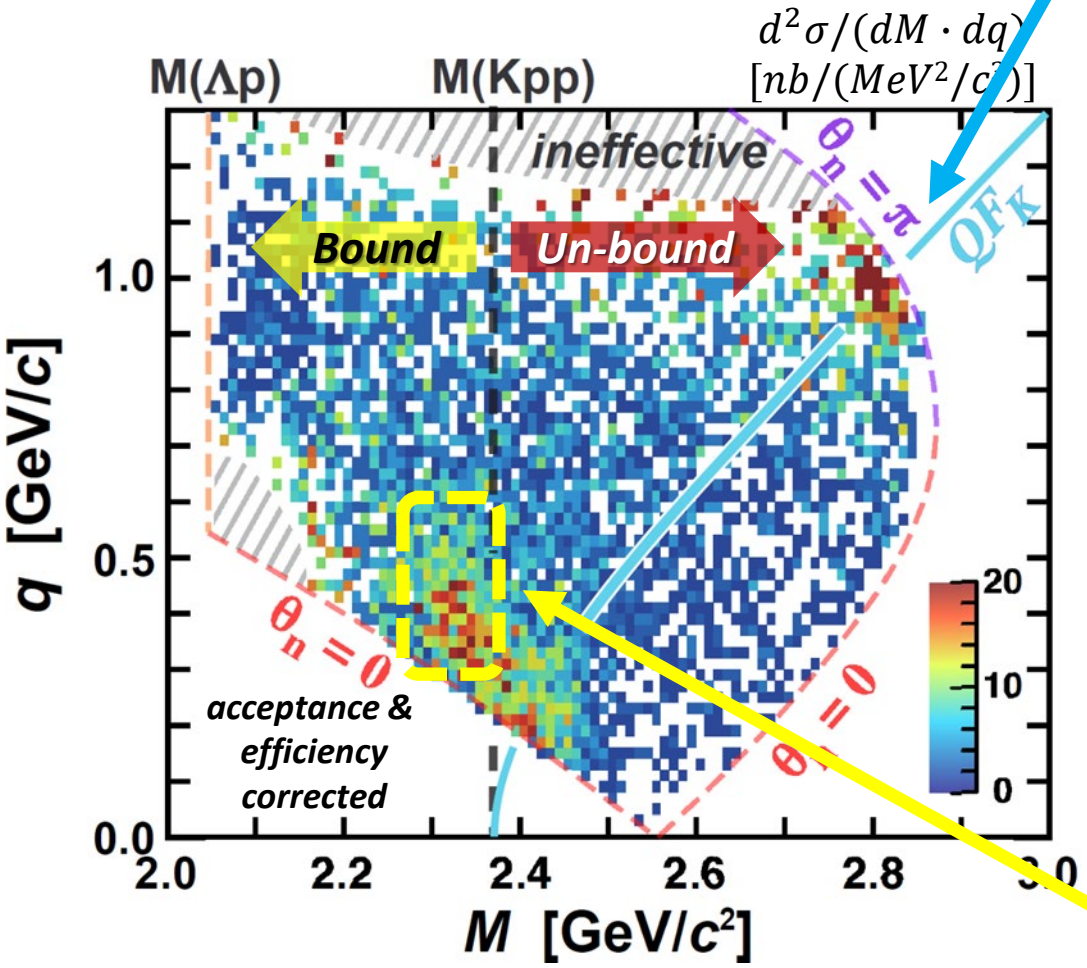


- **Momentum transfer analysis using the (K⁻,n) reaction**

✓ M(Λp) vs. q

✓ give a clear information on reaction processes

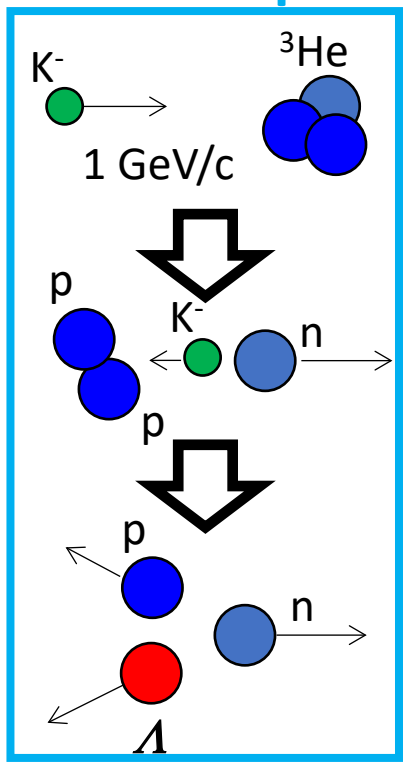
PLB789(2019)620., PRC102(2020)044002.



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

Plane Wave Impulse Approximation

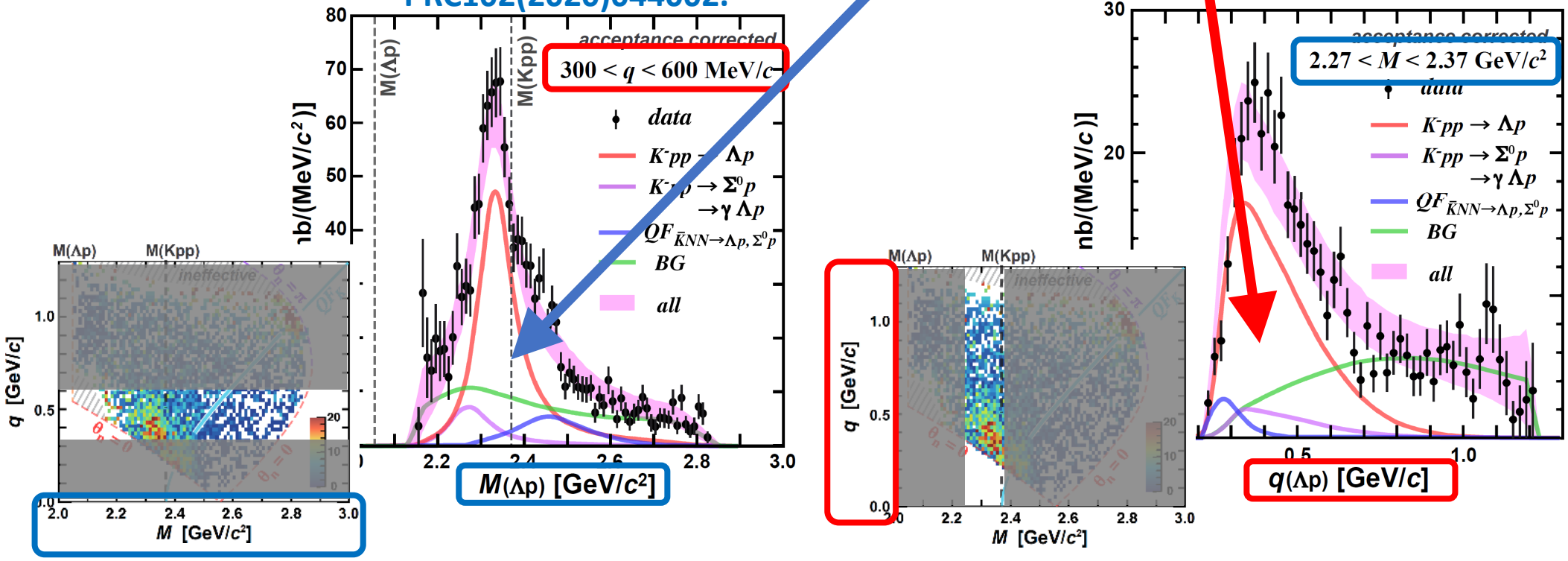
Fit with PWIA

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

Energy term (BW type) from time integral

Momentum term from spatial integral

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

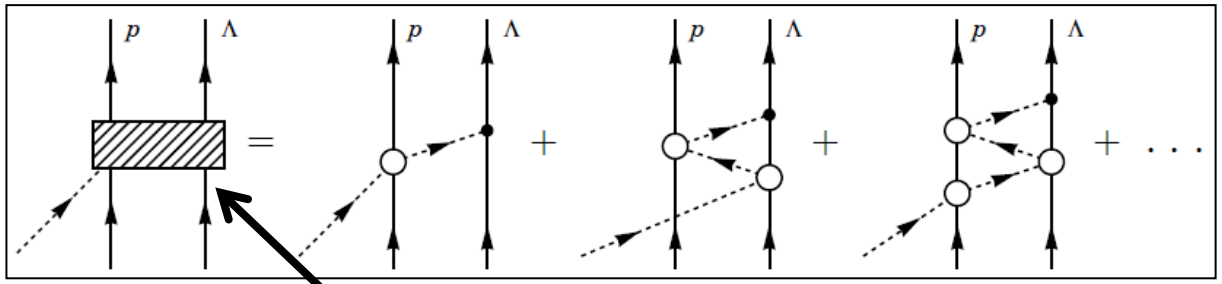
A calculation based on chiral unitary approach
reproduces the data well using the $\bar{K}NN$ bound state

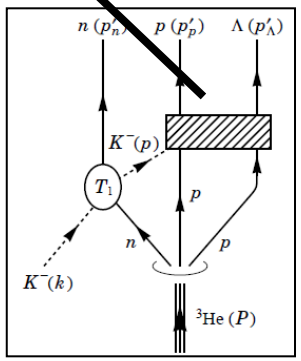
PTEP

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

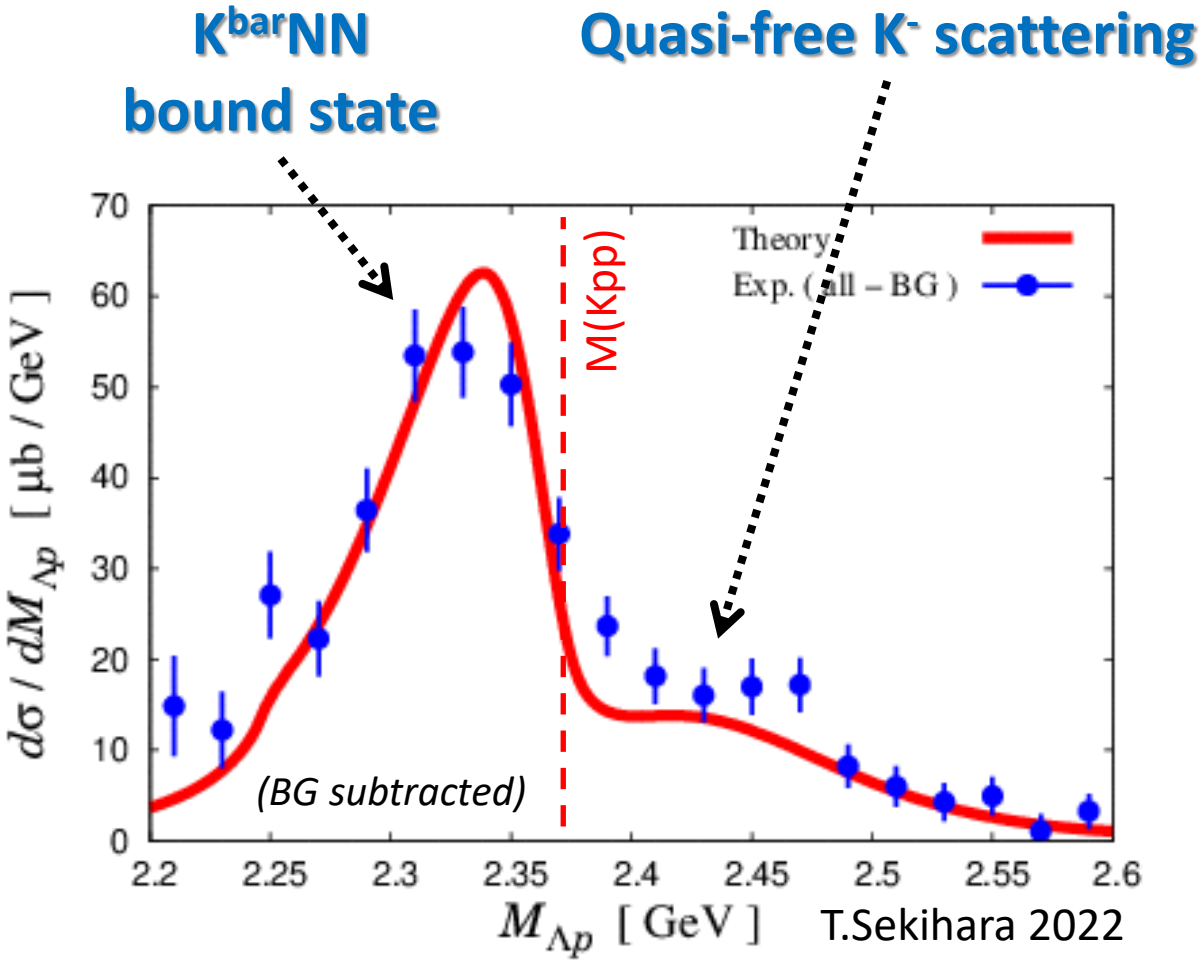
On the structure observed in the in-flight ^{3}He(K^-, Λp)n reaction at J-PARC

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





Theoretical investigations are indispensable!

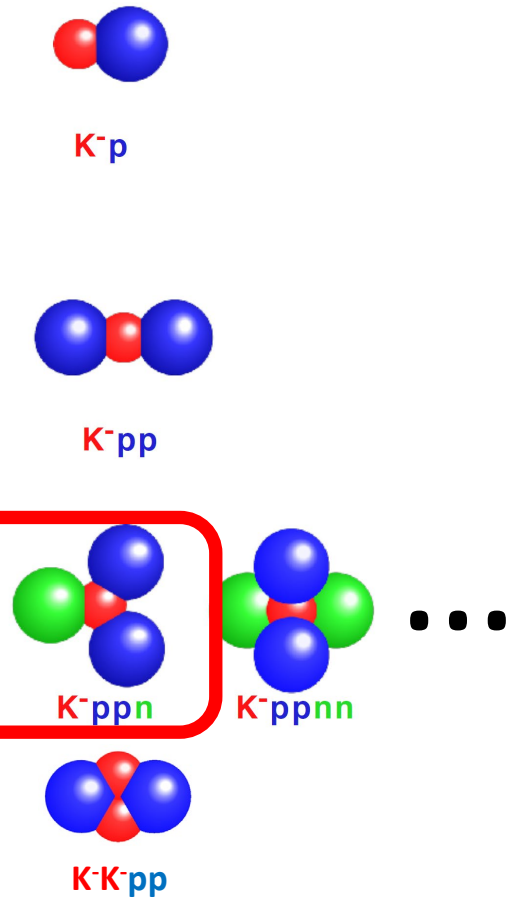


T.Sekihara 2022

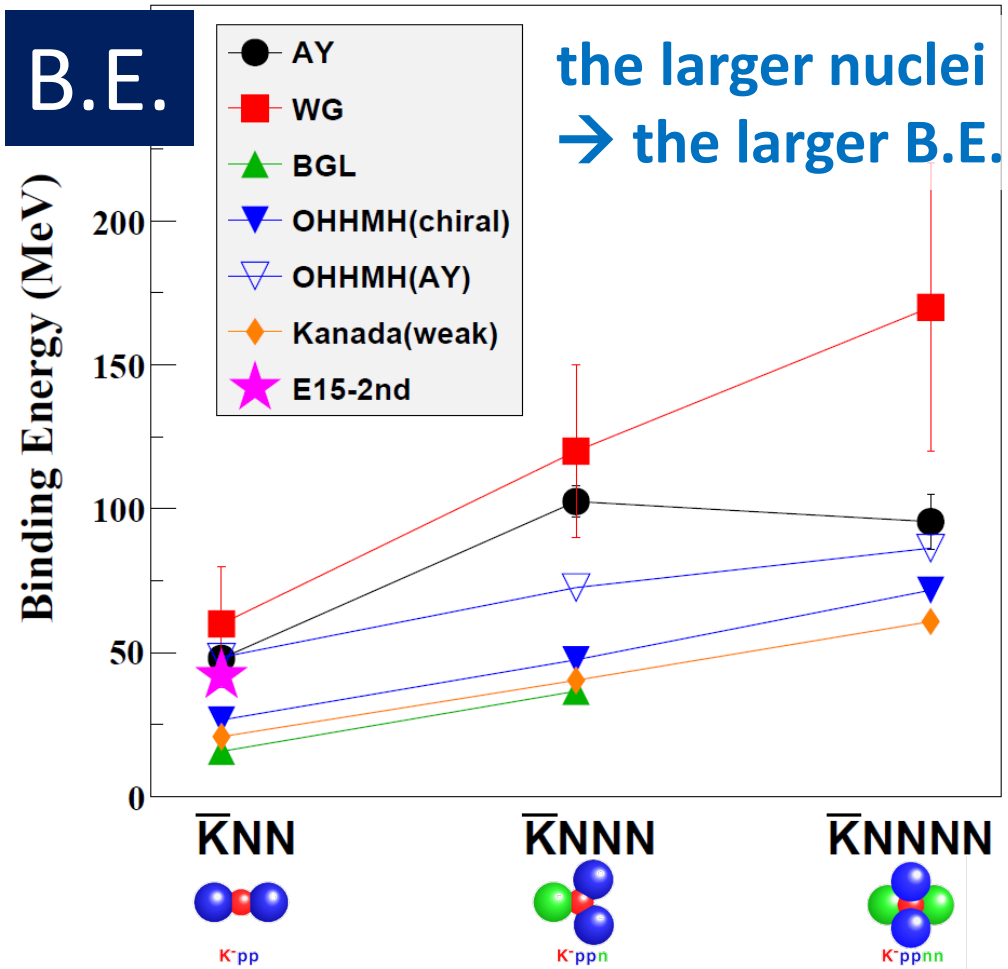
Need Further Investigations

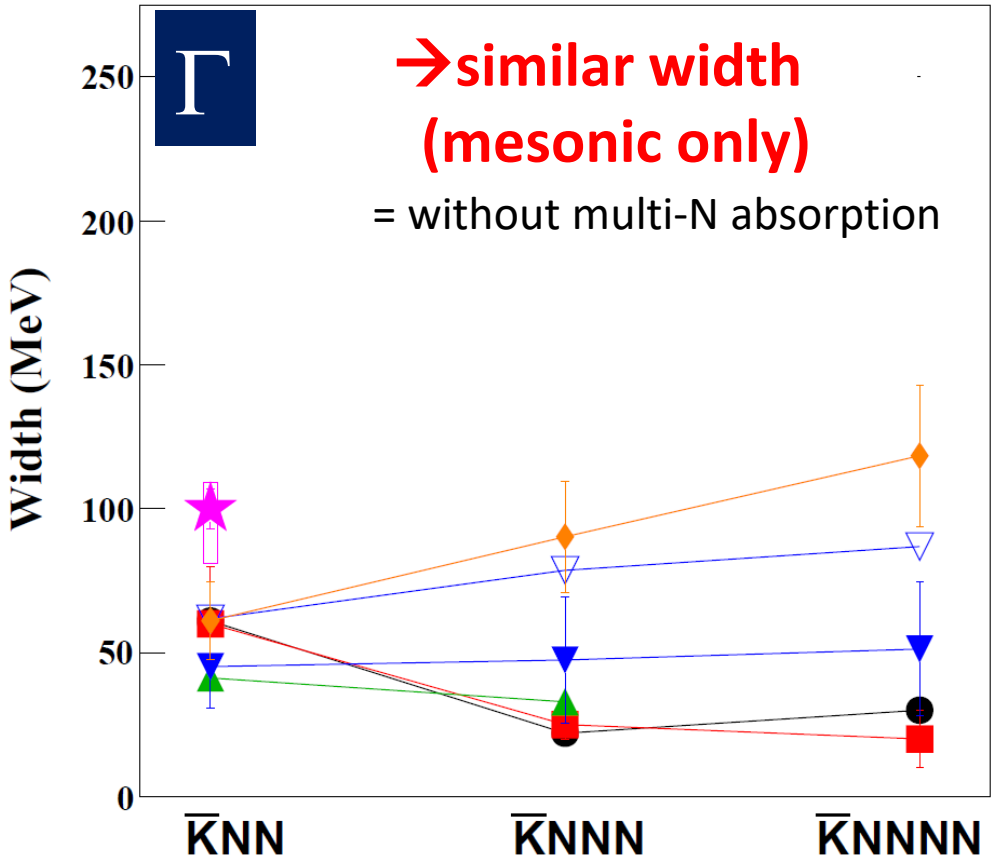
to establish the kaonic nuclei

- **$\Lambda(1405)$ state**
  - $\bar{K}N$ qusi-bound state as considered?
  - Relation between $\bar{K}N$ and $\bar{K}NN$?
- **Further details of the $\bar{K}NN$**
  - Mesonic decay modes?
  - Spin and parity of the "K^-pp"?
  - Really compact and dense system?
- **Heavier kaonic nuclei**
  - Mass number dependence?
- **Double kaonic nuclei**
  - Much compact and dense system?



Mass Number Dependence of Kaonic Nuclei



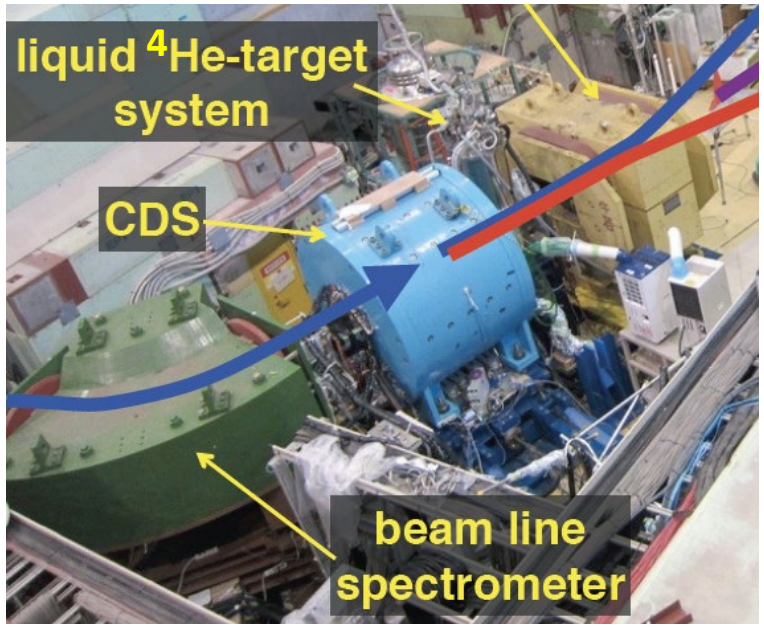


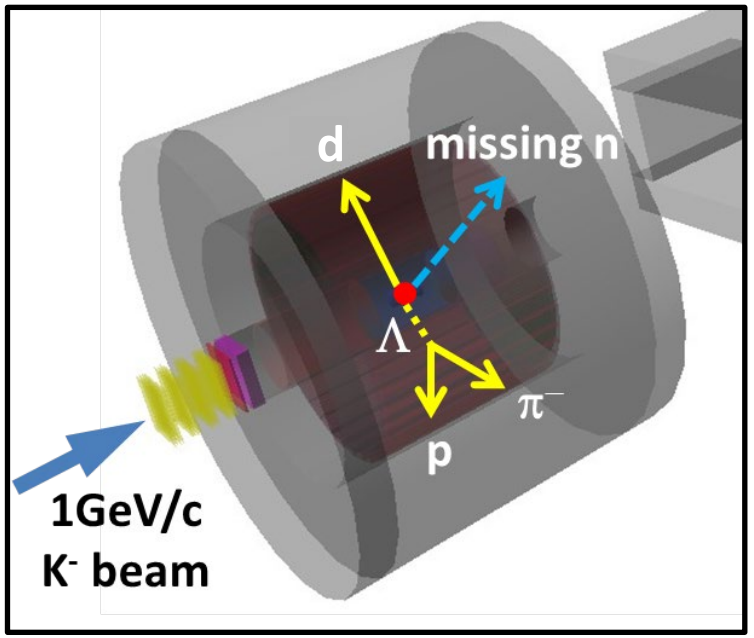
- **Systematic measurements will provide more conclusive evidence of the kaonic nuclei**

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

"K⁻ppn" Search with K⁻⁴He → Λdn

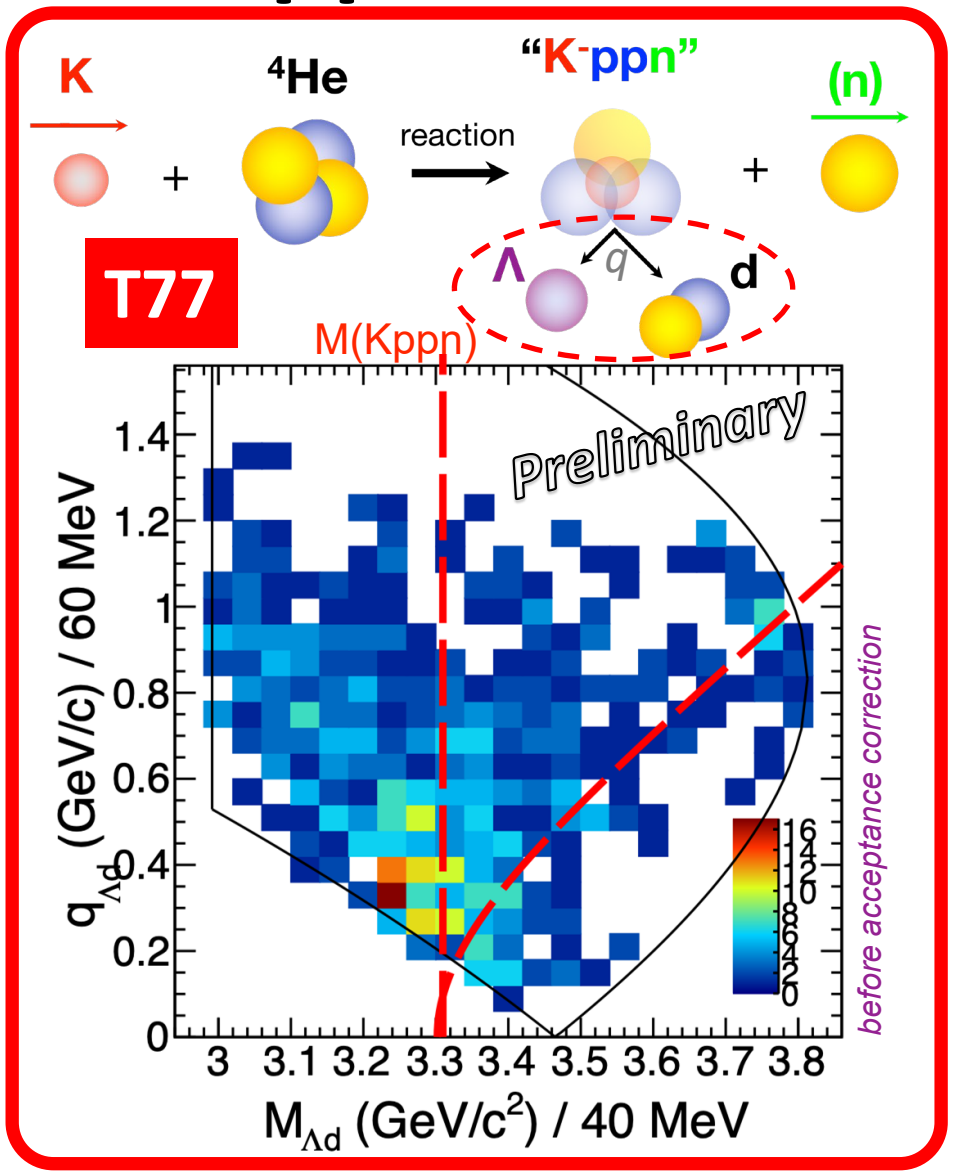
- An analysis of the **Λdn** final state with **K⁻⁴He** reaction at **1 GeV/c** has been conducted
  - T77: lifetime measurement of ${}^{4}_{\Lambda}$H in 2020
- The results will be updated with a part of the E73 controlled data
  - E73: lifetime measurement of ${}^{3}_{\Lambda}$H in 2024-25

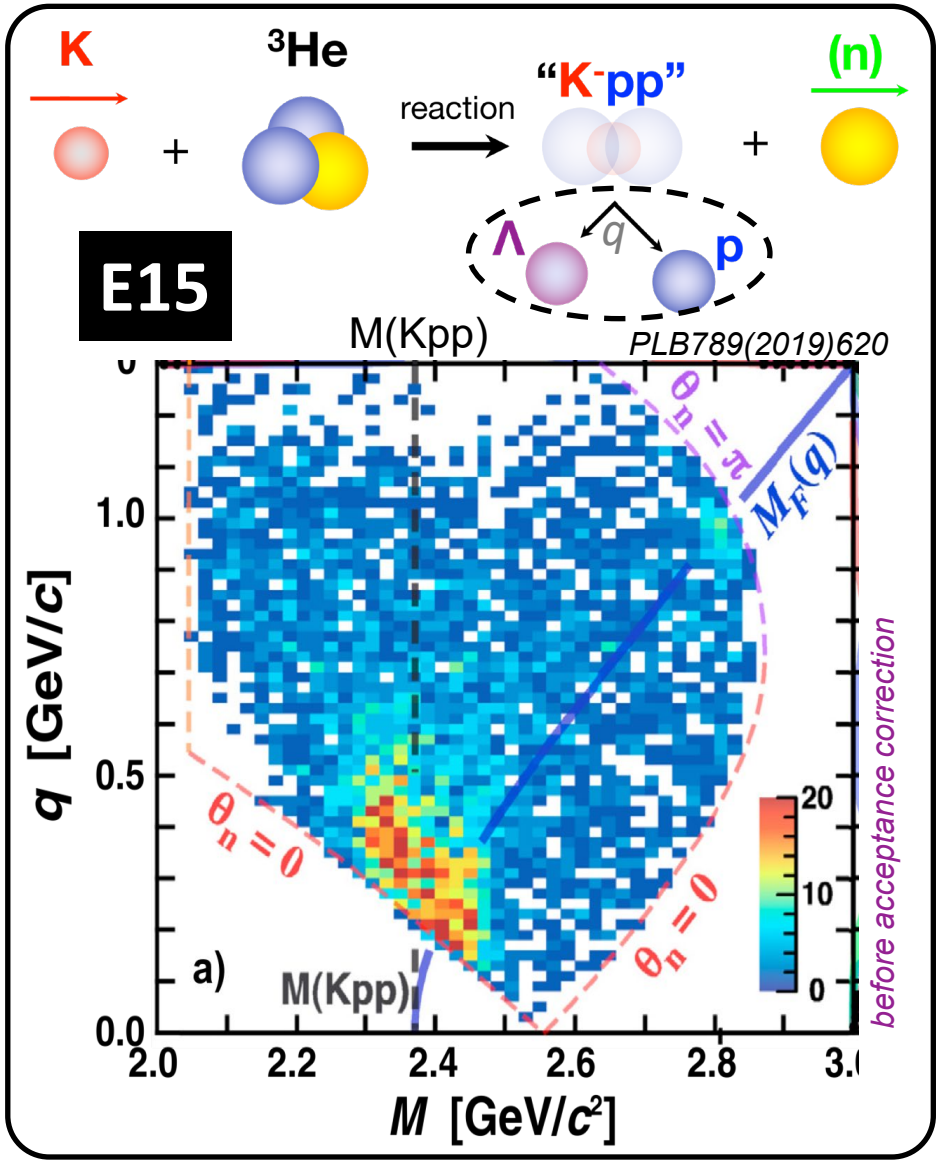




Experiment	K⁻ on target
E15 (³He)	~42 x 10⁹
T77 (⁴He)	~6 x 10⁹
E73 (⁴He)	~6 x 10⁹

"K⁻ppn" Search with K^{-} + ^{4}He → Λdn





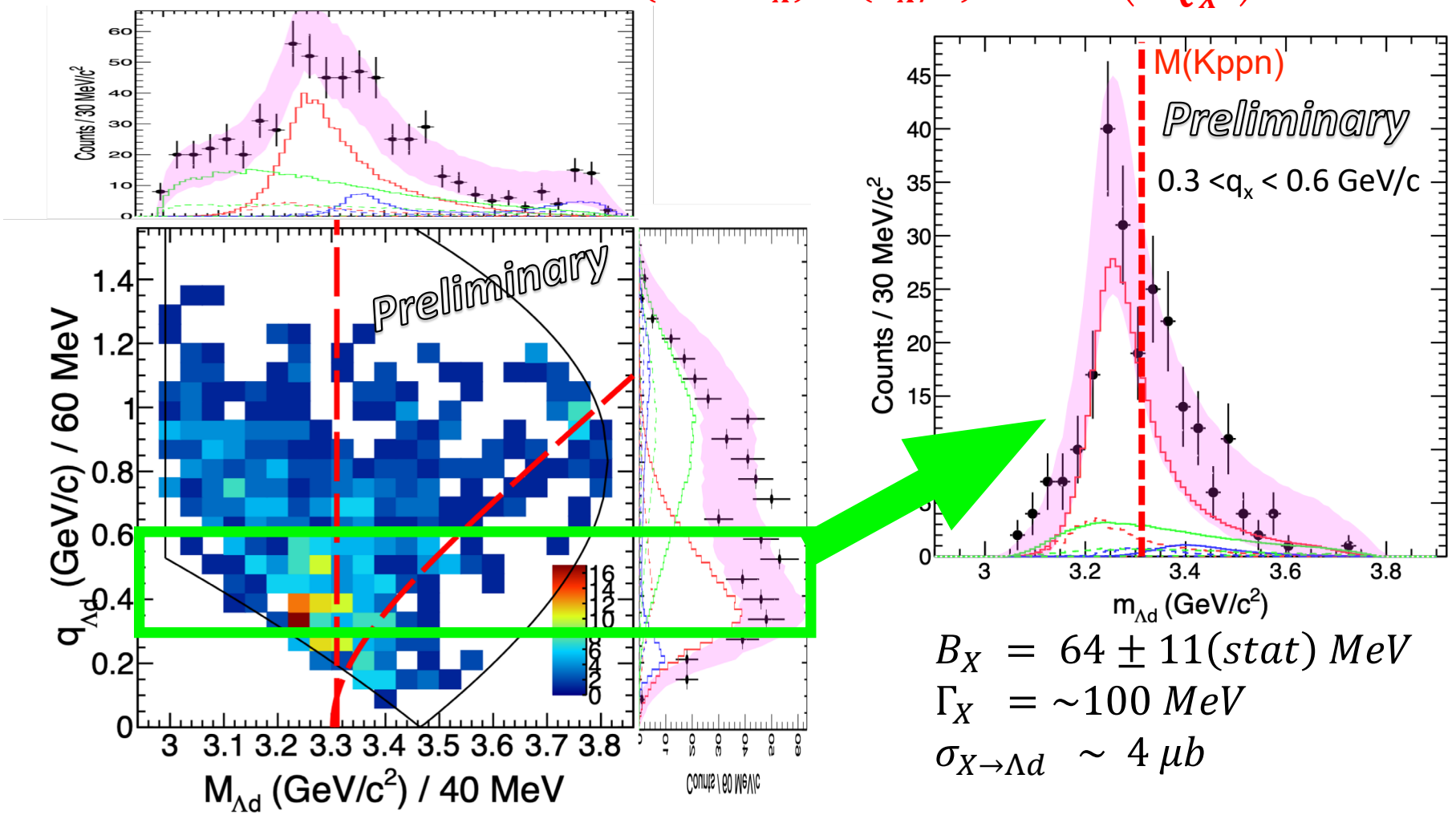
- **Two distributions are quite similar**
- structure below the threshold (**seems *q*-independent**), QF-K, BG

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

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

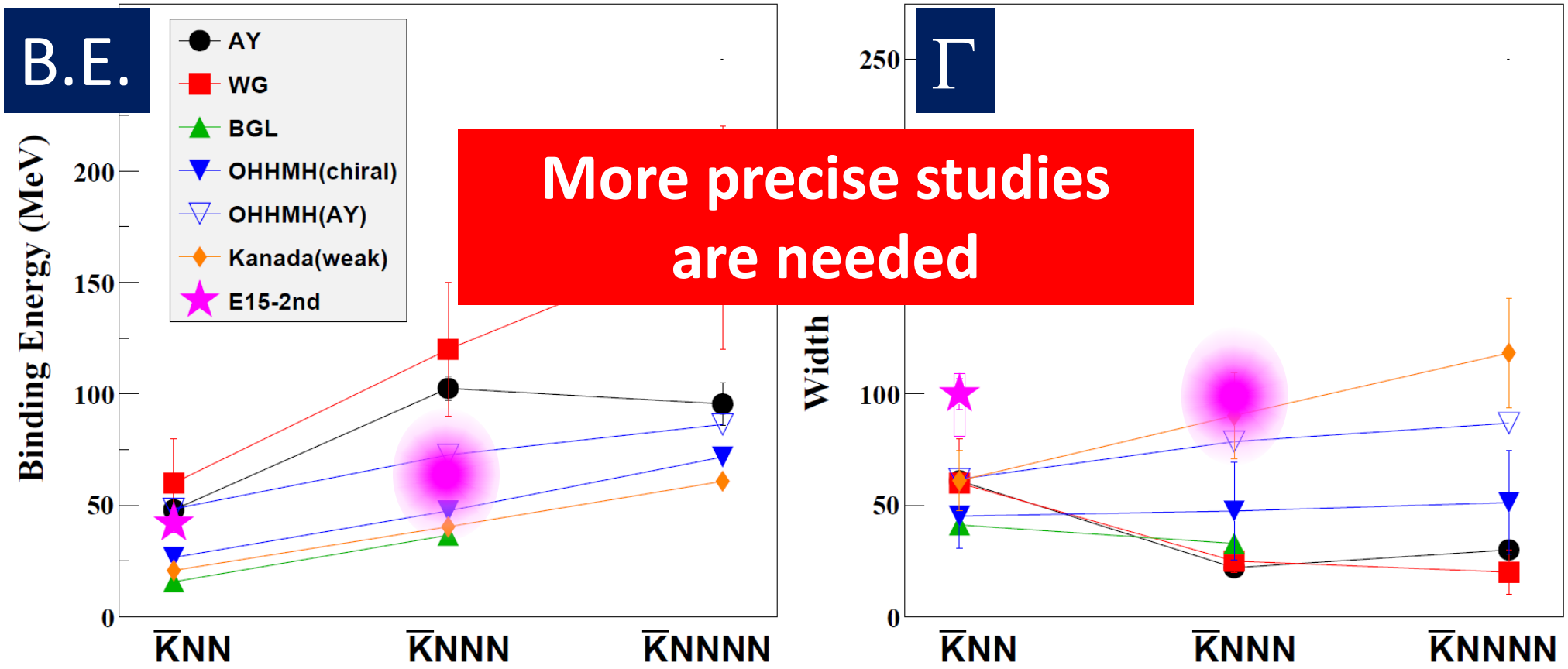
Breit-Wigner wtih Gaus. form factor (PWIA), QF-K⁻, and Broad BG

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



$$B_X = 64 \pm 11(stat)\ MeV$$
$$\Gamma_X = \sim 100\ MeV$$
$$\sigma_{X\rightarrow\Lambda d} \sim 4\ \mu b$$

If the Observed Structure Is "K⁻ppn",



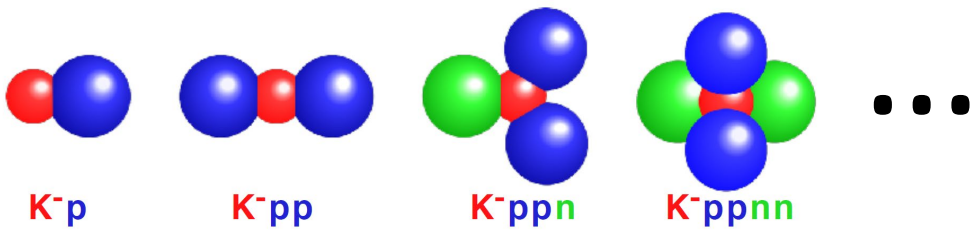
More precise studies are needed

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

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

New Kaonic Nuclei Project at J-PARC

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

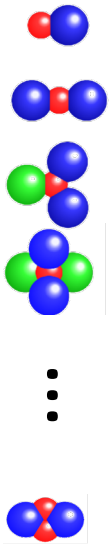


…

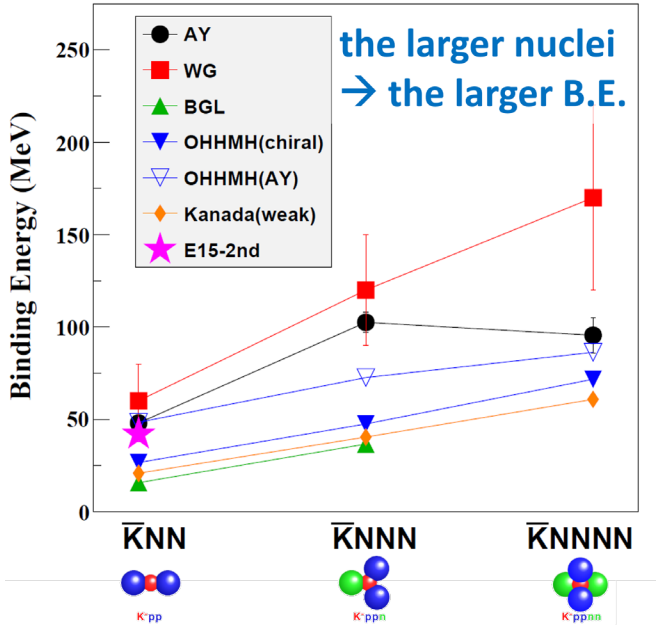
Systematic investigation of the light kaonic nuclei

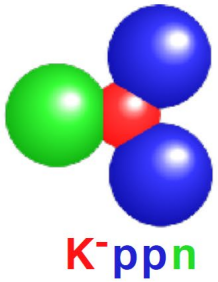
- Systematic measurement will be promoted at J-PARC
  - mass number dependence
    - binding energy, branching ratio, *q* dependence, ..
  - spin/parity determination

➢ Extract internal structure with theoretical investigations



	Reaction	Decays
$\bar{K}N$	d(K^-,n)	$\pi^{\pm 0}\Sigma^{\mp 0}$
$\bar{K}NN$	^{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)	$\Lambda\alpha n/\Lambda ddn$
$\bar{K}\bar{K}NN$	$\bar{p} + {}^3He$	$\Lambda\Lambda$



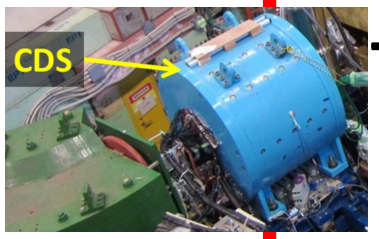


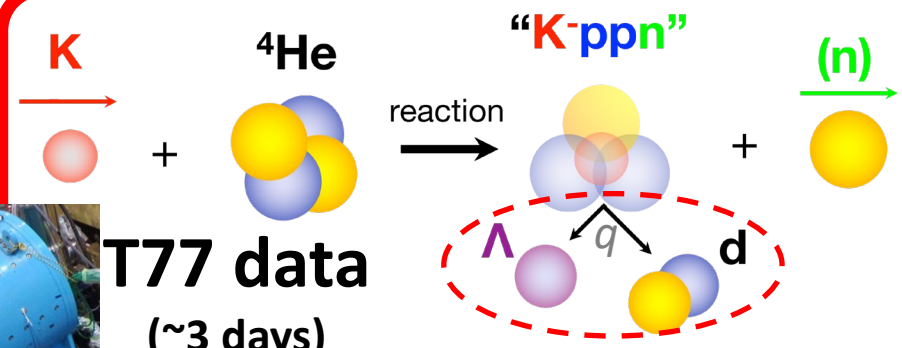
$\bar{K}NNN$ @ E80

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

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

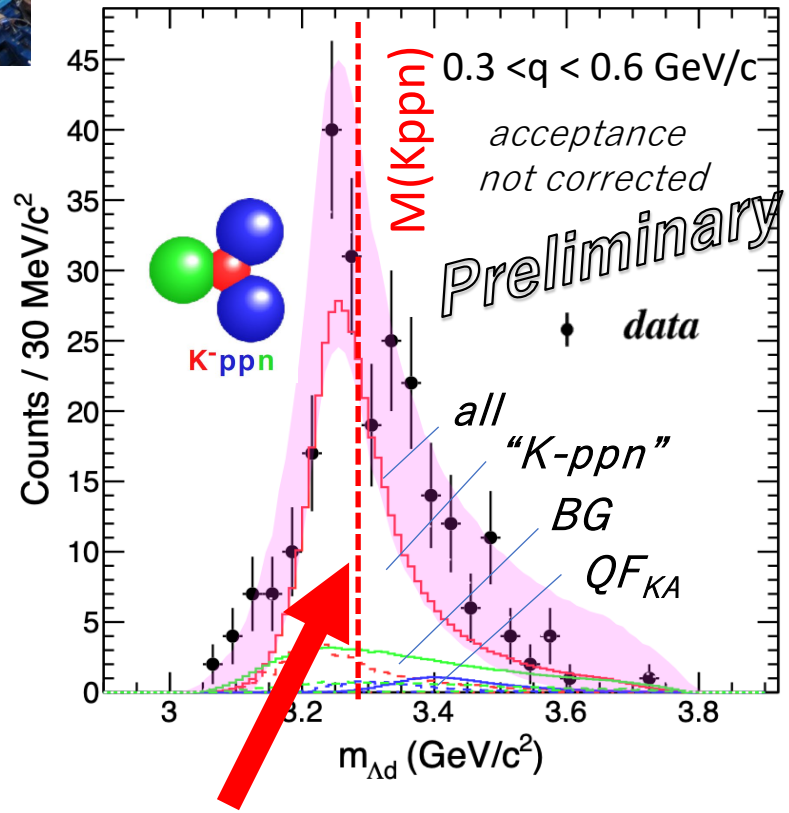
- "K-ppn"→Λd 2-body decay





T77 data

(~3 days)

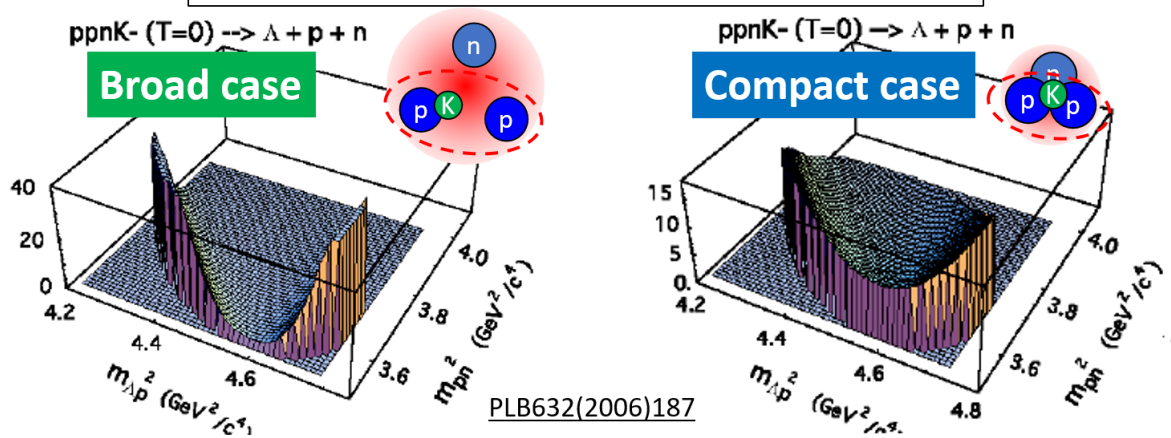


the sign of the "K⁻ppn"

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

- "K-ppn"→Λpn 3-body decay

Utilize Dalitz plots → Differences in distribution



PLB632(2006)187

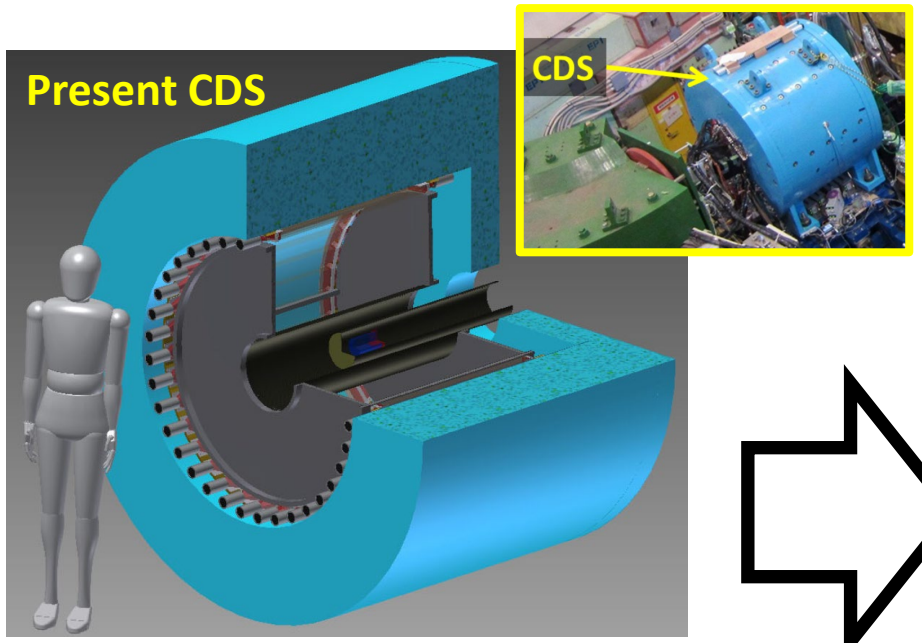
Distributed in parts of the plane

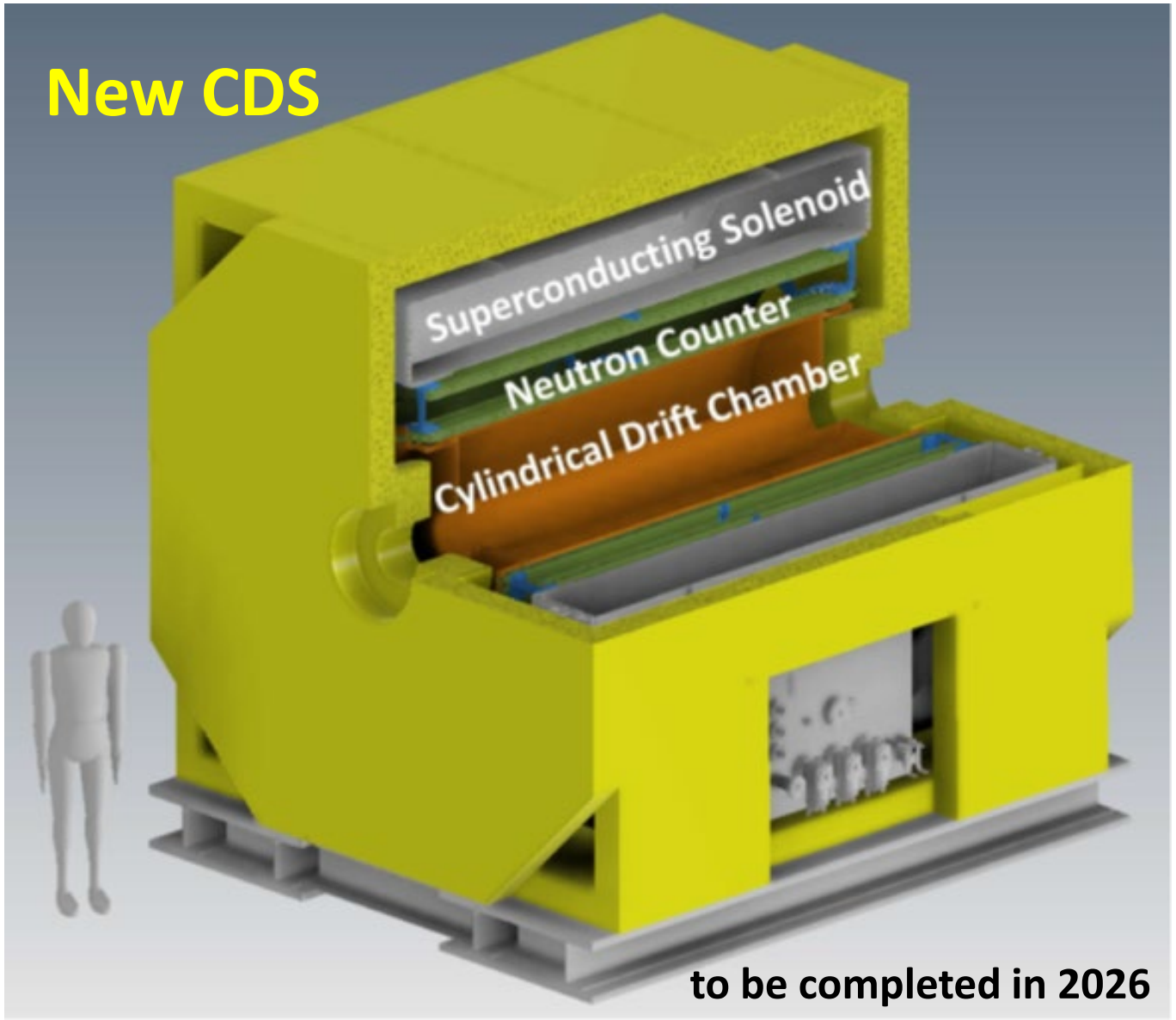
- 1 nucleon has the Fermi momentum

Widely distributed in the plane

- All particles have a momentum larger than the Fermi momentum

New Cylindrical Detector System (CDS)





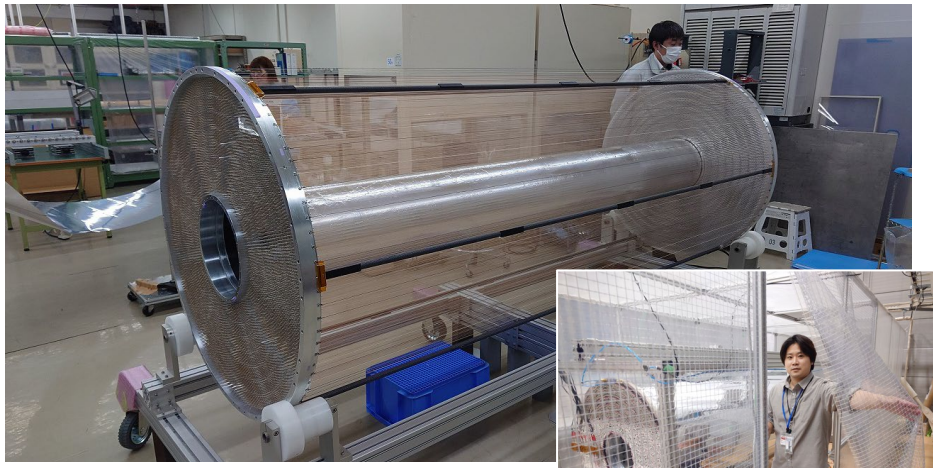
- ✓**Solid angle:** **x1.6** (59% → 93%)
- ✓**Neutron eff.:** **x7** (3% → 12%x1.6)
  + forward TOF counter
  + proton polarimeter (in future)

Construction Status of the CDS

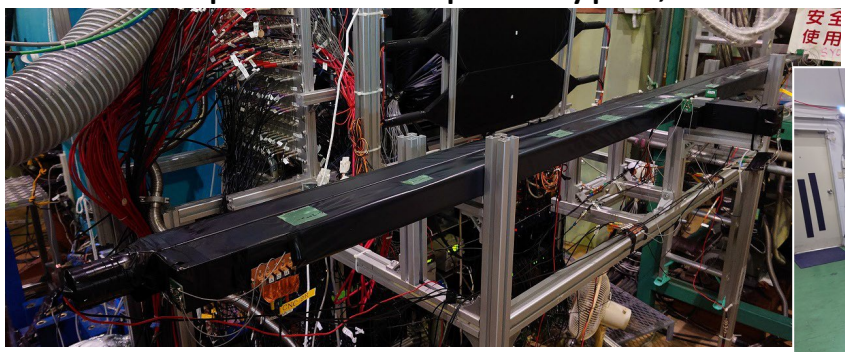
Return York:
completed

SC Solenoid:
to be completed next month

CDC:
completed, in commissioning



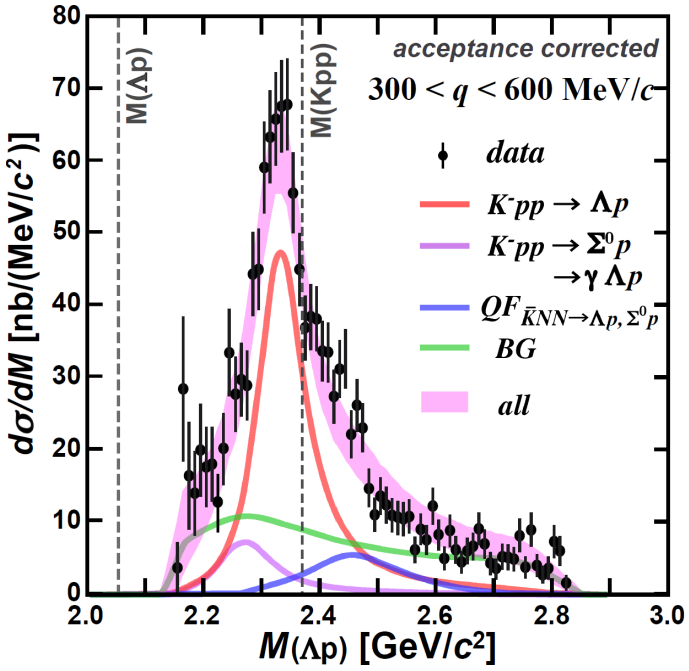
CNC:
development with prototypes, to be completed this year



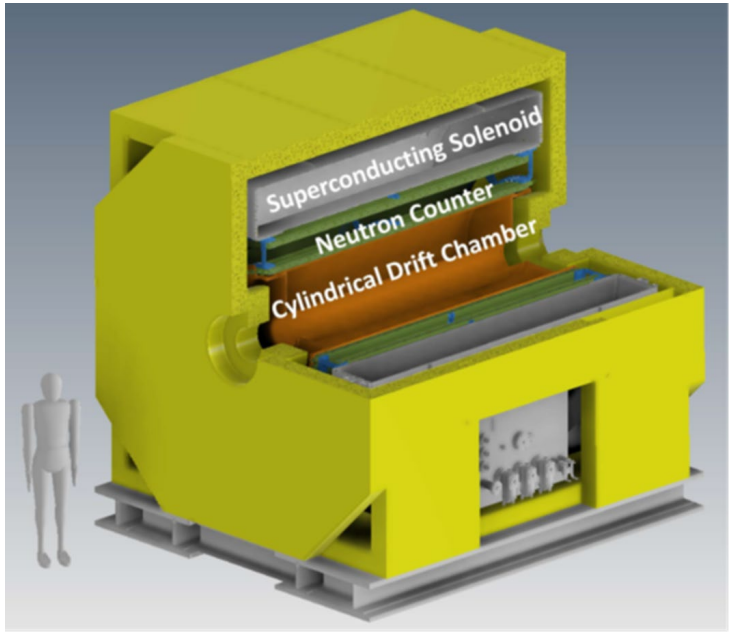
The experiment will be ready in early 2027

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"**
  - ✓**PRC110(2024)014002.**



- 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
  - will start in early 2027

J-PARC E80 Collaboration

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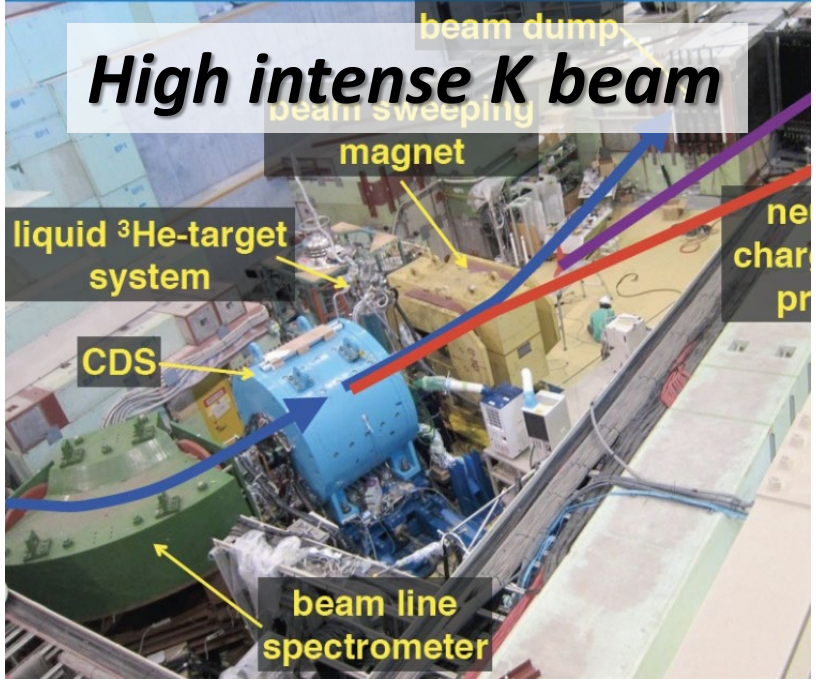
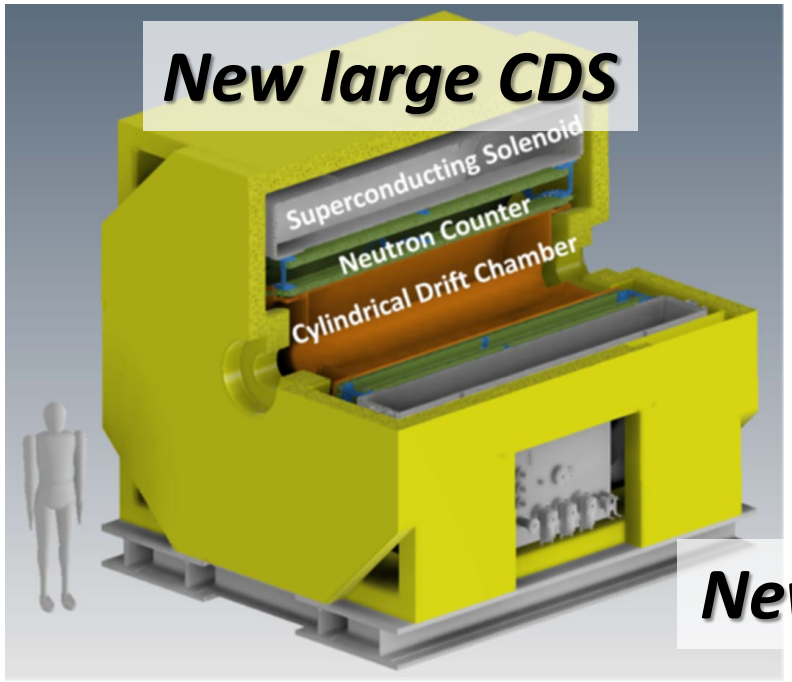
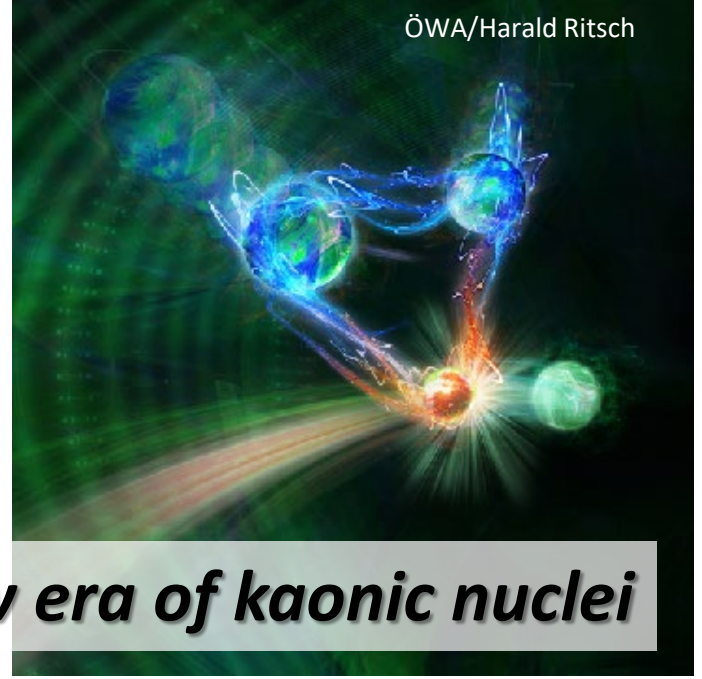
We're looking for new collaborators!



High intense K beam



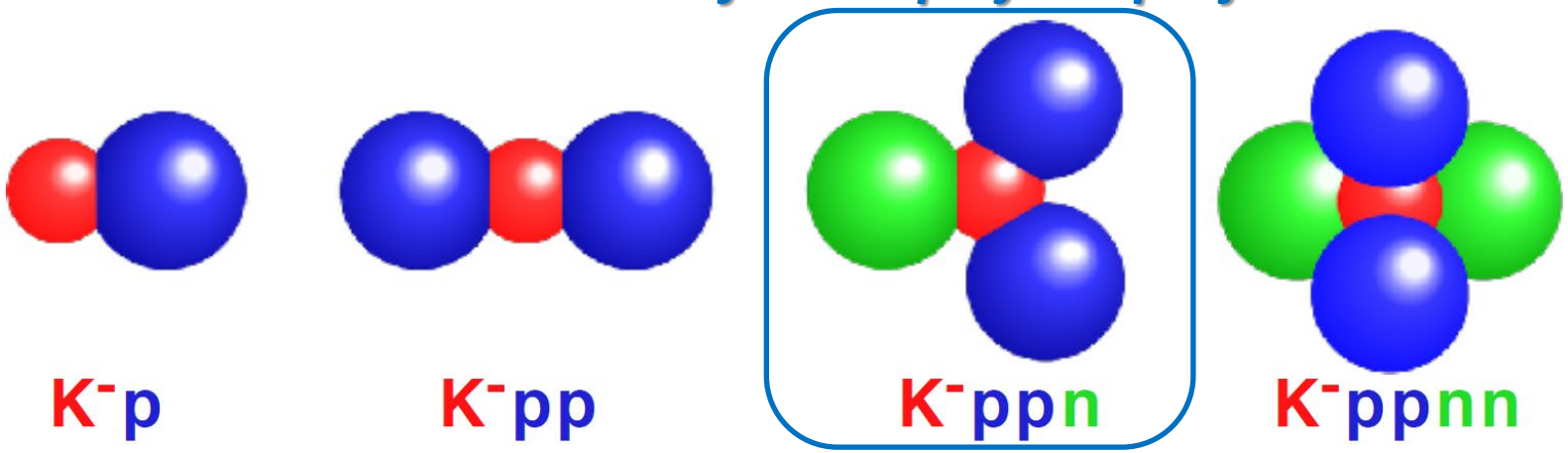
New large CDS



New era of kaonic nuclei

Thank you for your attention!

A first step of the project



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