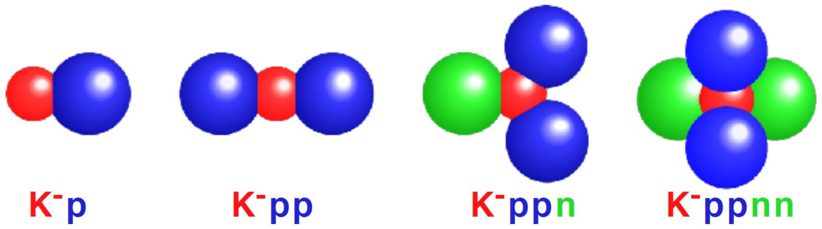
Light Kaonic Nuclei at J-PARC

– 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

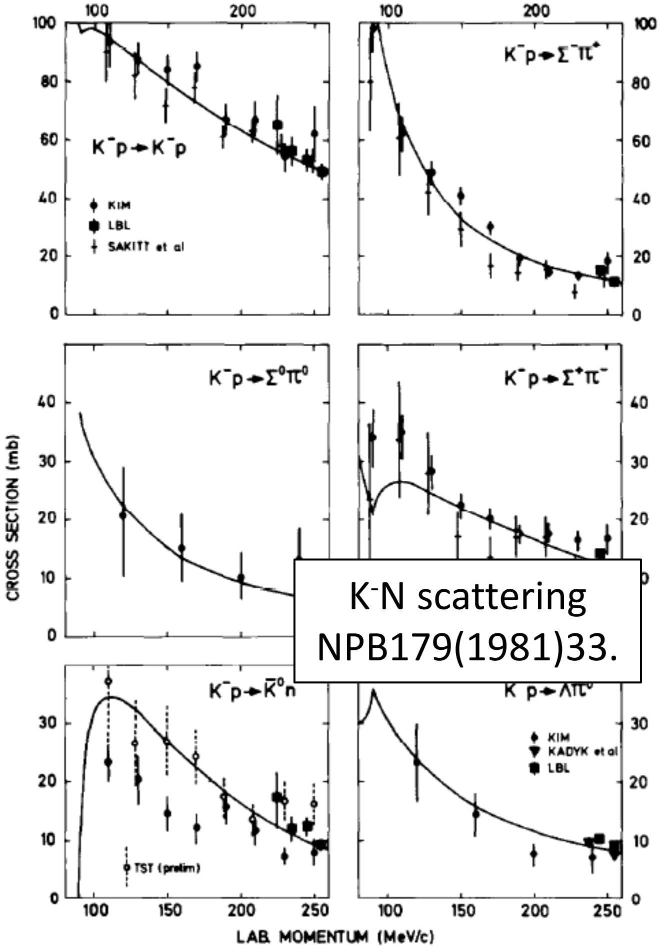
QNP 2024
8–12 Jul 2024

Physics Goal

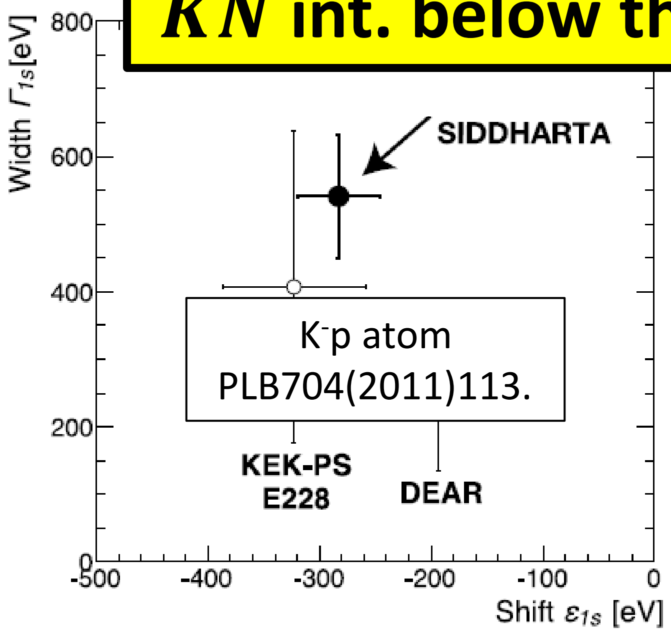
Reveal the meson properties inside nuclei via **the $\bar{K}N$ interaction**

A powerful probe to understand low energy QCD

Strongly attractive in I=0 from extensive measurements

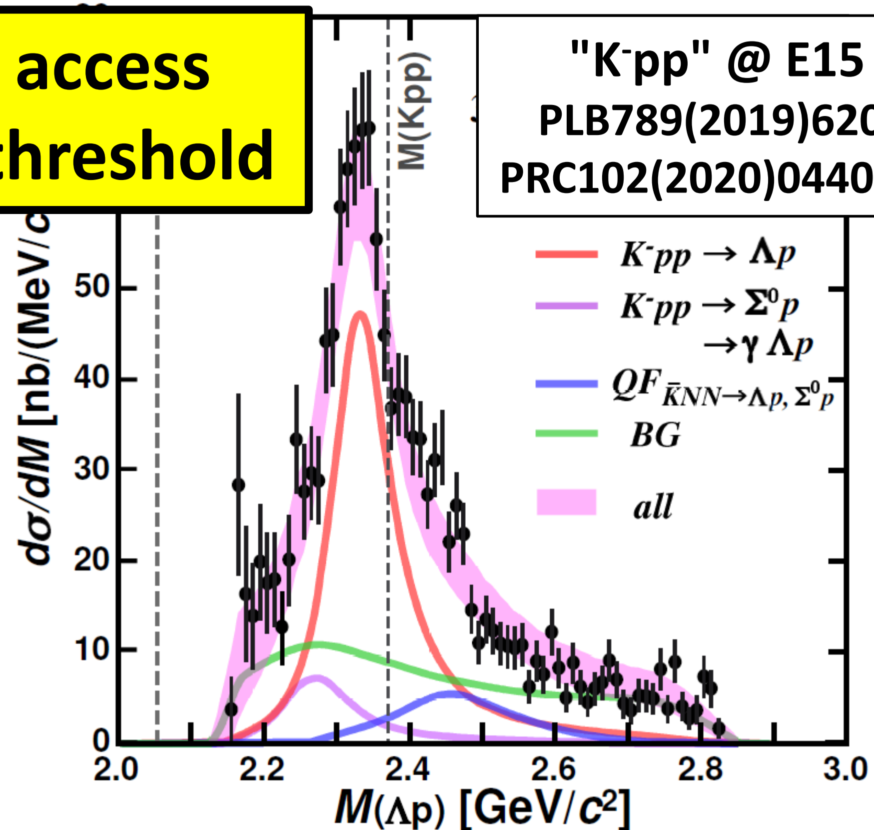


K⁻N scattering
NPB179(1981)33.



K⁻p atom
PLB704(2011)113.

Kaonic nuclei can access $\bar{K}N$ int. below the threshold

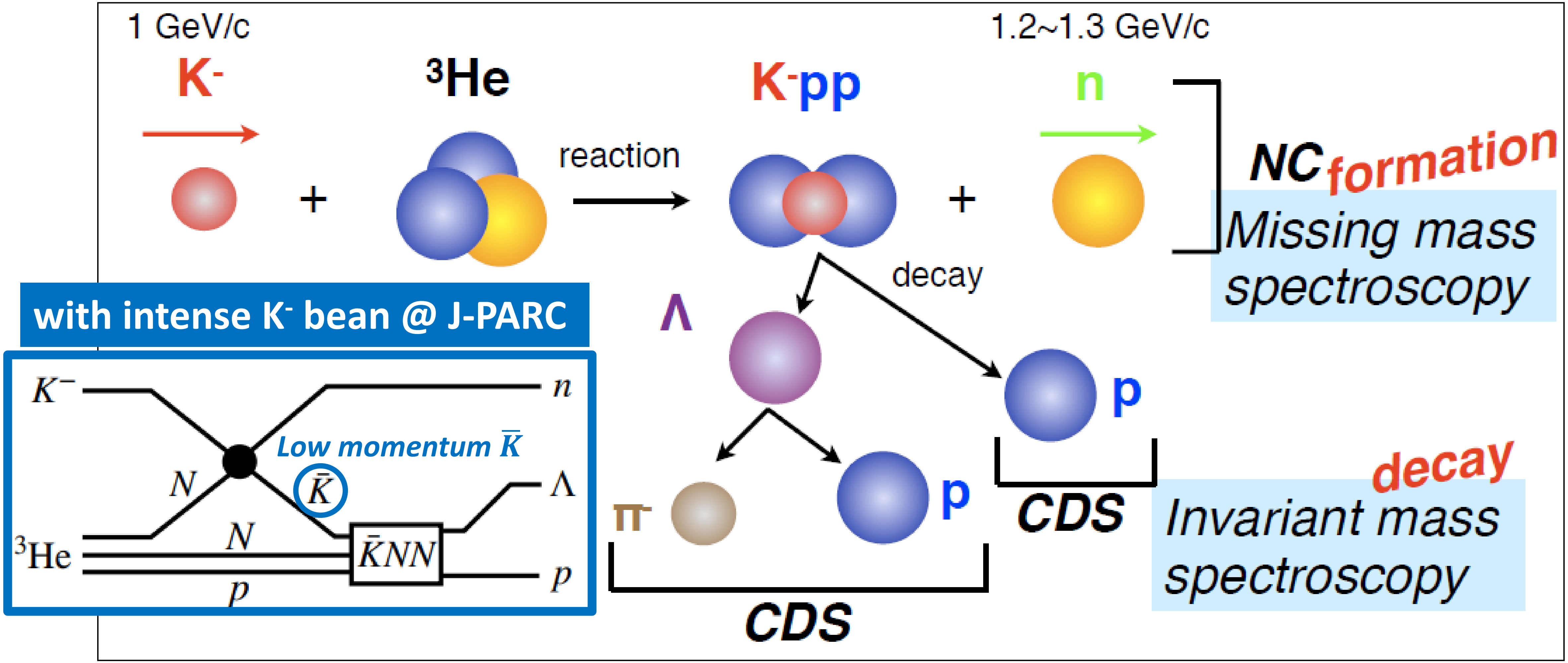


"K⁻pp" @ E15
PLB789(2019)620.
PRC102(2020)044002.

"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

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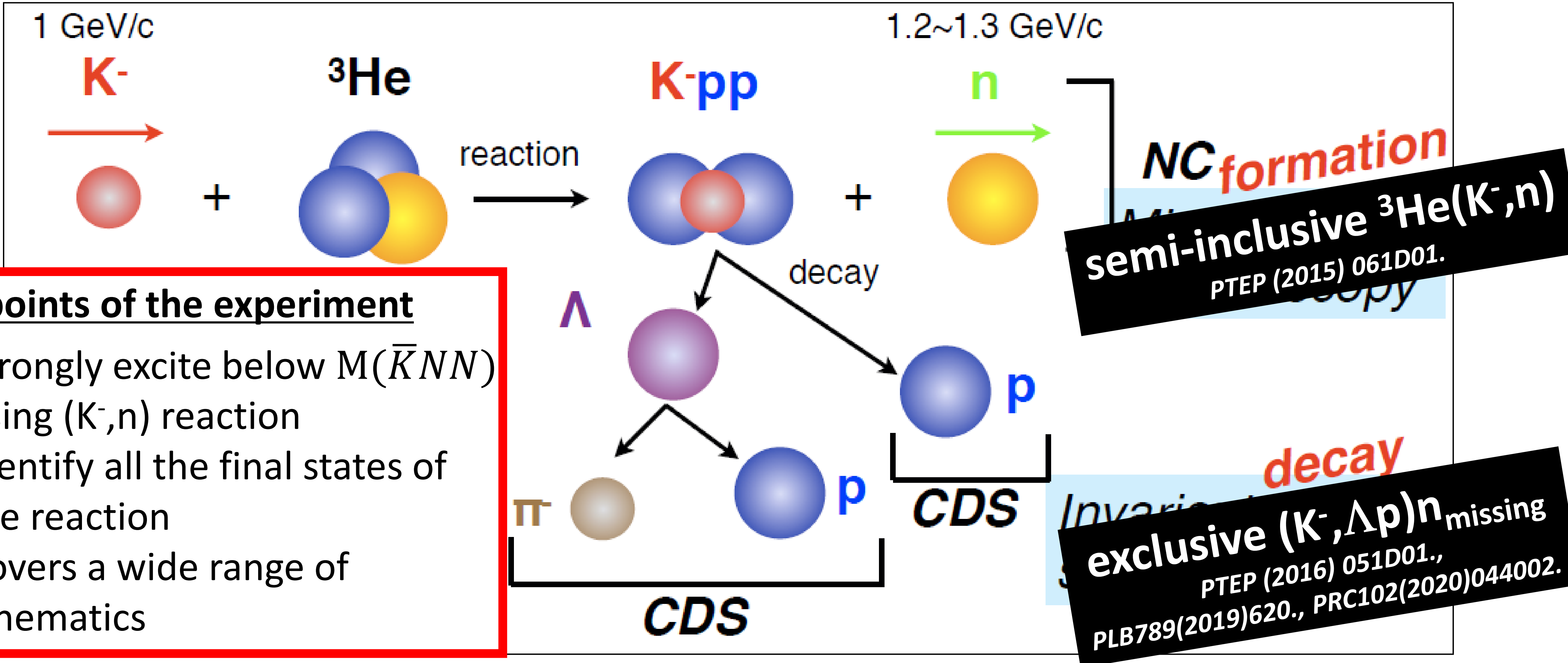


Key points of the experiment

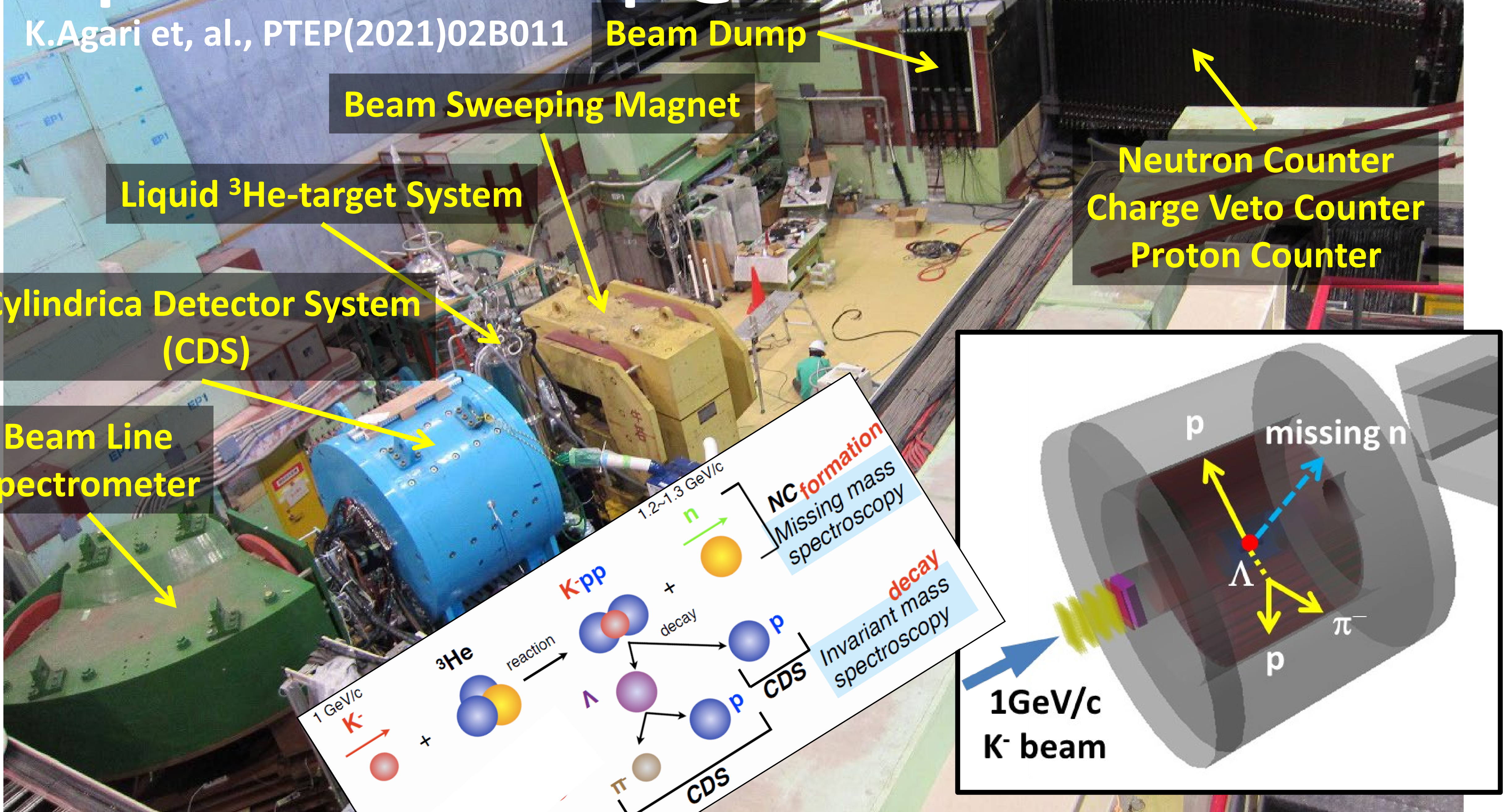
① Strongly excite below $\mathrm{M}(\bar{K}NN)$ using (K$^-$,n) reaction

② Identify all the final states of the reaction

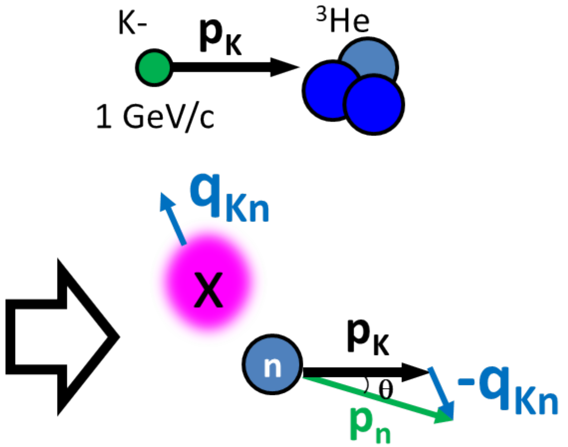
③ Covers a wide range of kinematics

Experimental Setup @ K1.8BR

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



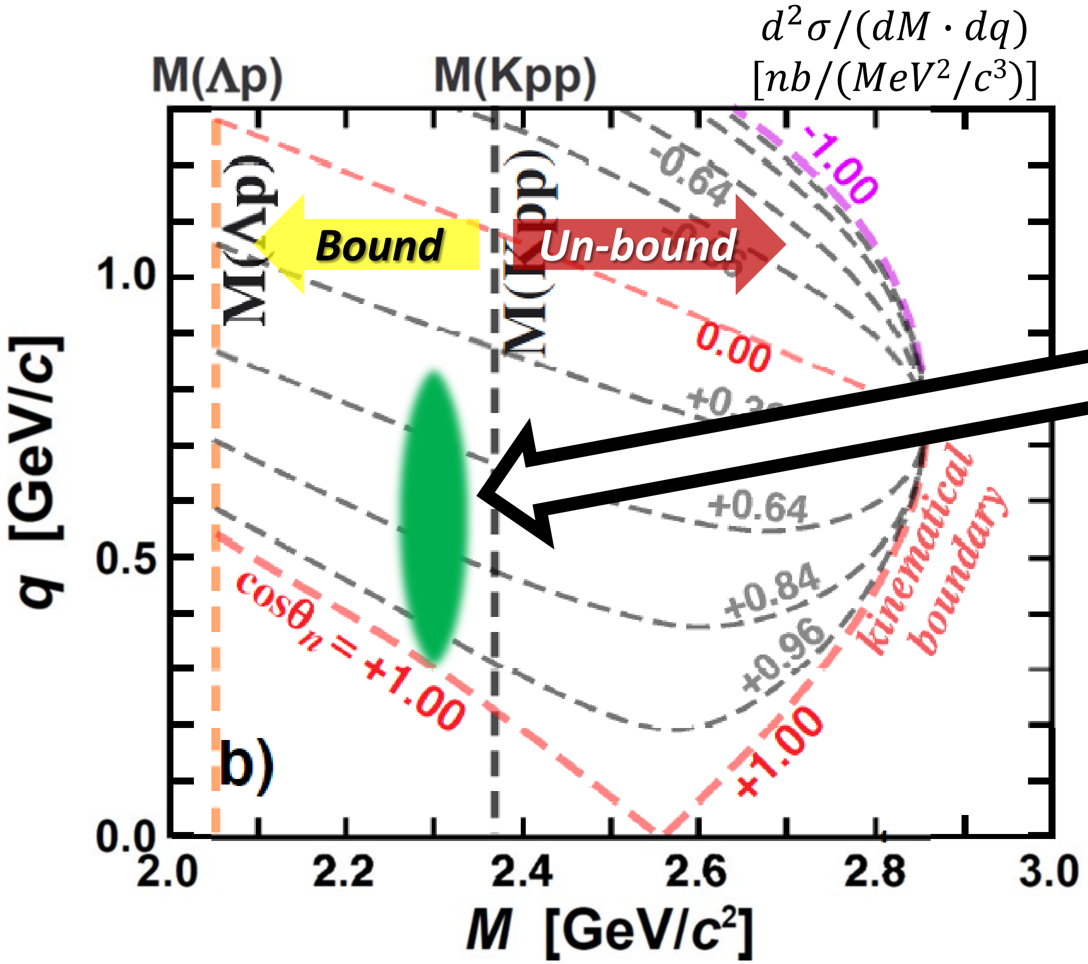
“K⁻pp” Search w/ Momentum Transfer Analysis



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

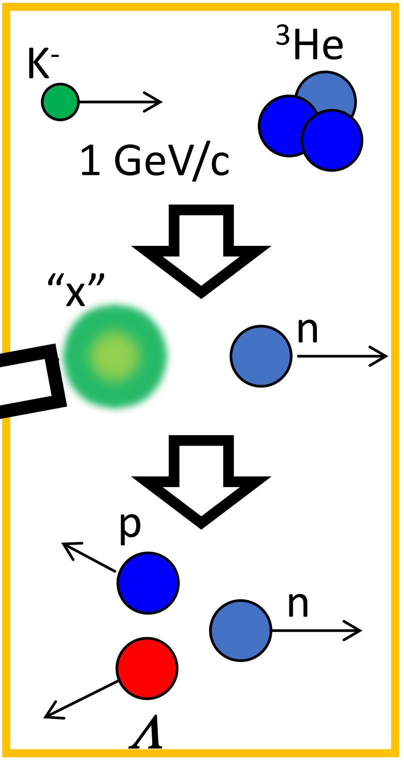
✓ M(Λp) vs. *q*

✓ give a clear information on reaction processes



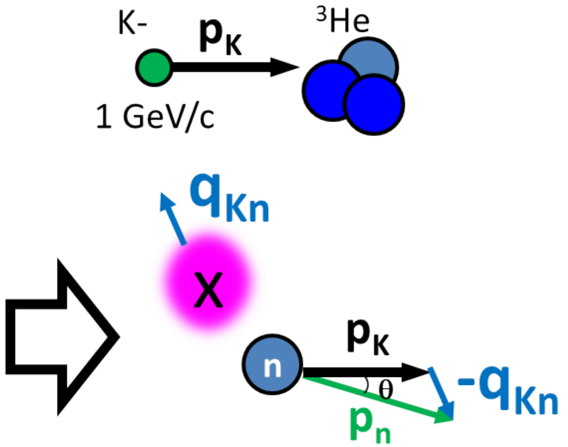
q : (K⁻,n) momentum transfer

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



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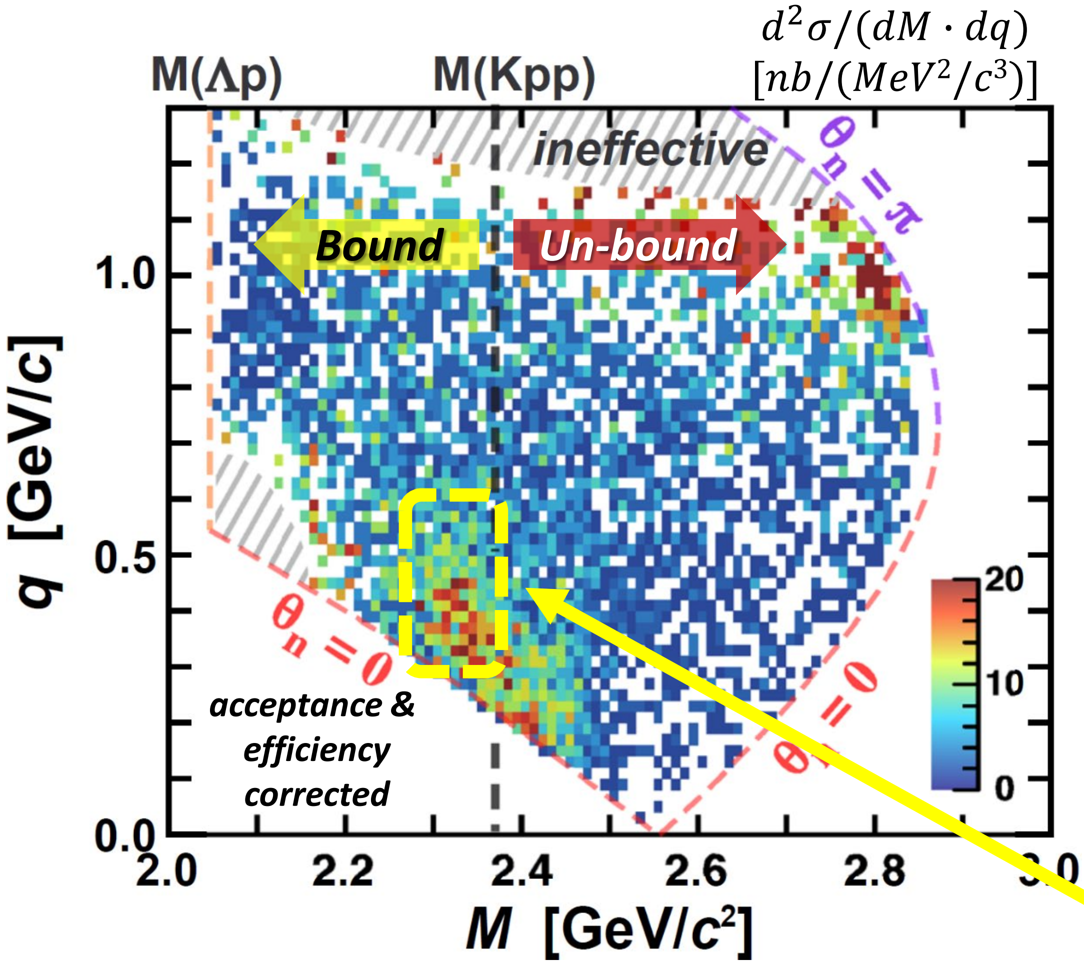
PLB789(2019)620., PRC102(2020)044002.



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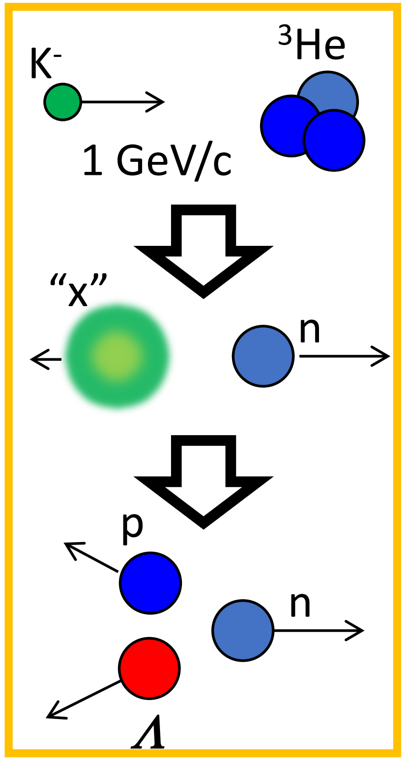
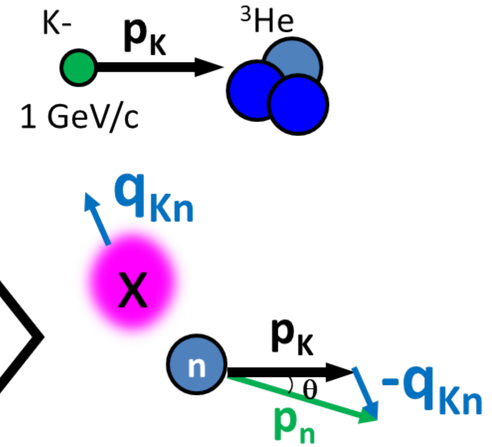


A peak structure independent of q =

A bound state exists

“K⁻pp” Search w/ Momentum Transfer Analysis



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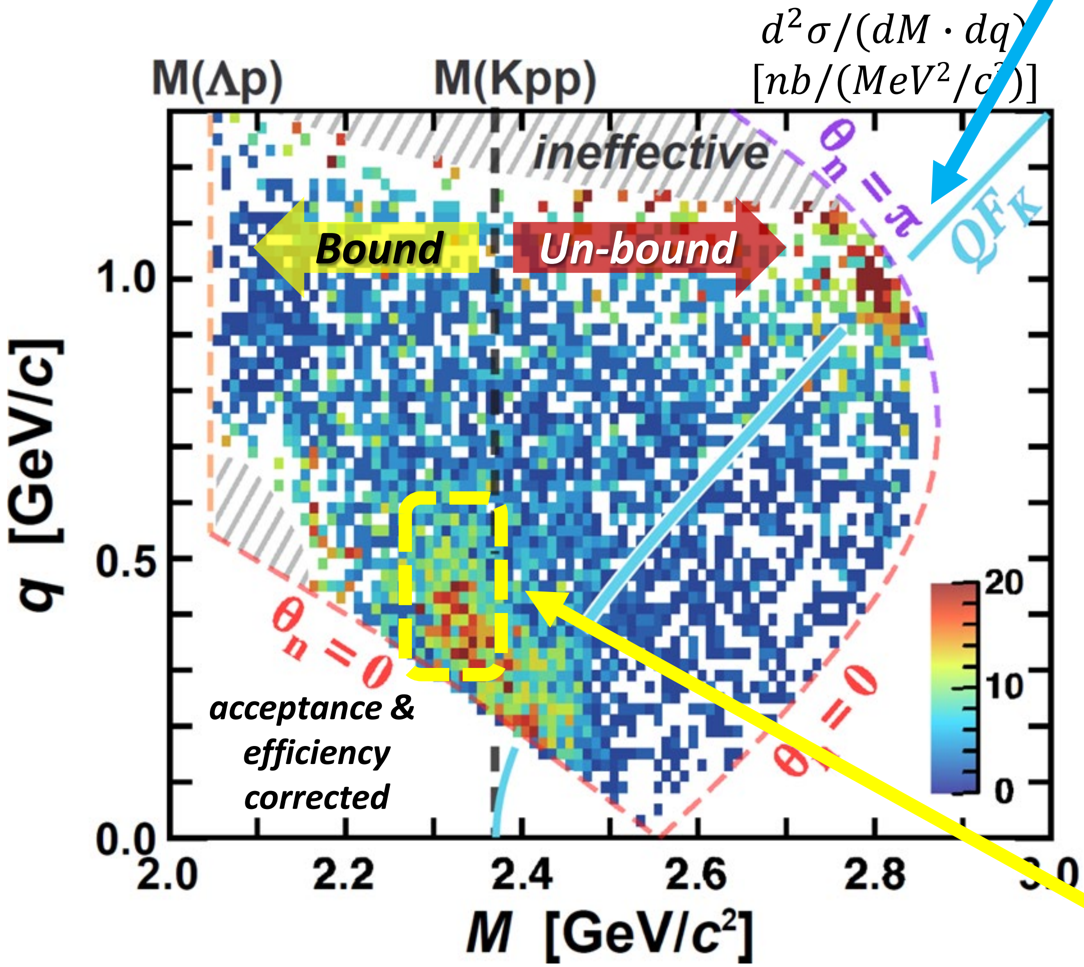
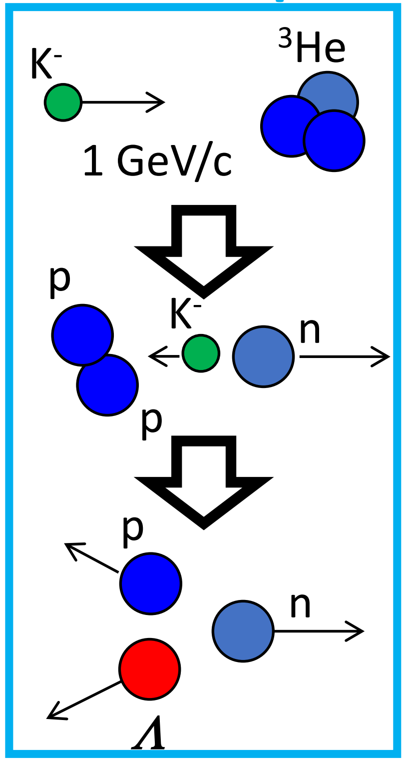
PLB789(2019)620., PRC102(2020)044002.



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

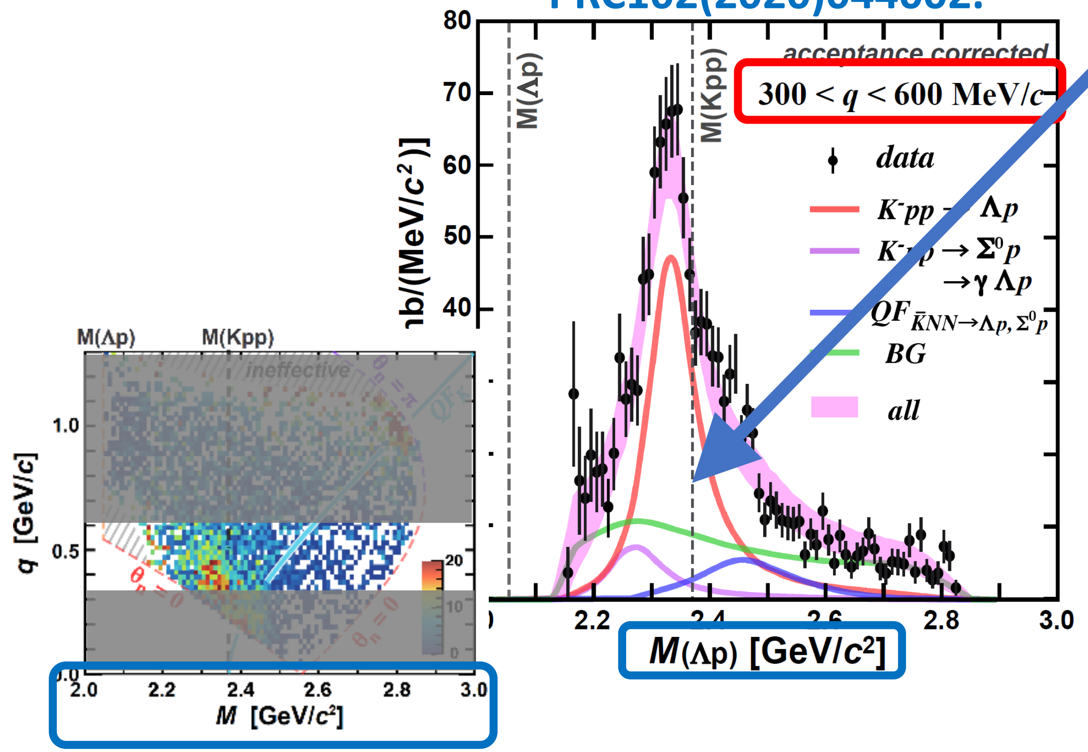
Fit with PWIA

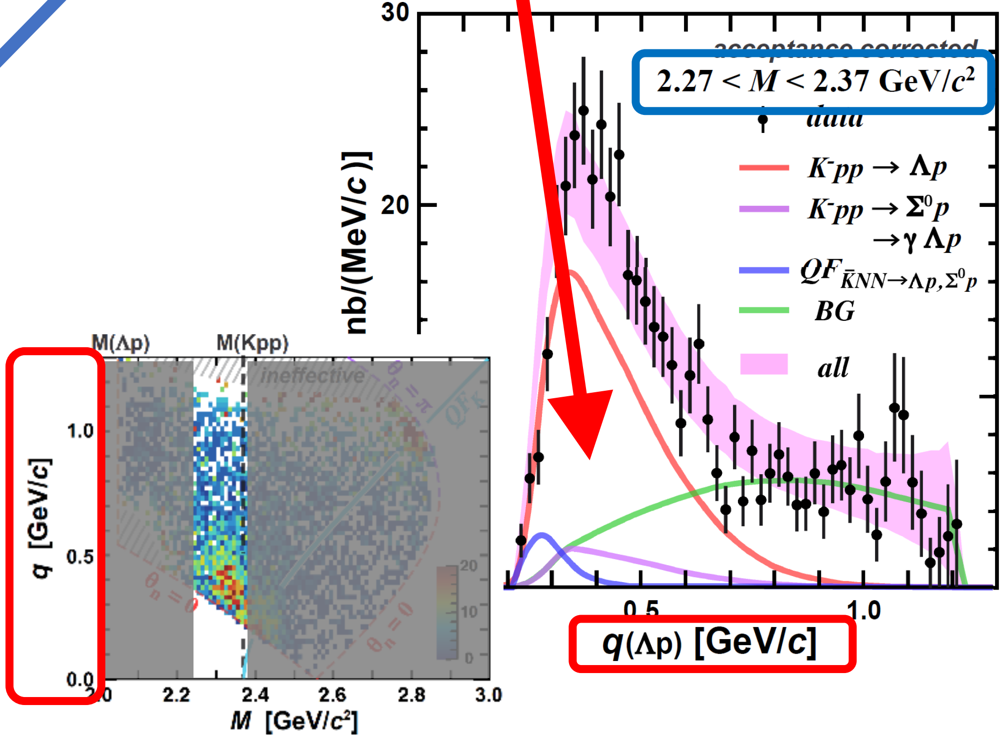
Energy term (BW type) from time integral

Momentum term from spatial integral

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

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

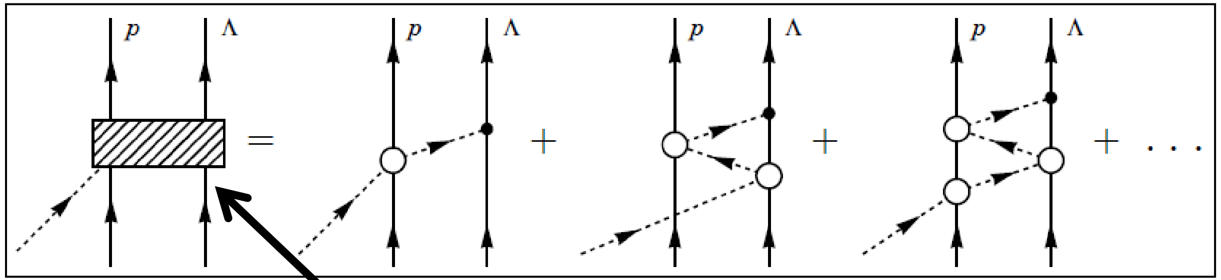
A Theoretical Interpretation

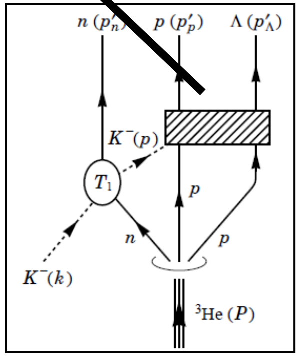
A calculation based on chiral unitary approach
reproduces the data well using the $\bar{K}NN$ bound state

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

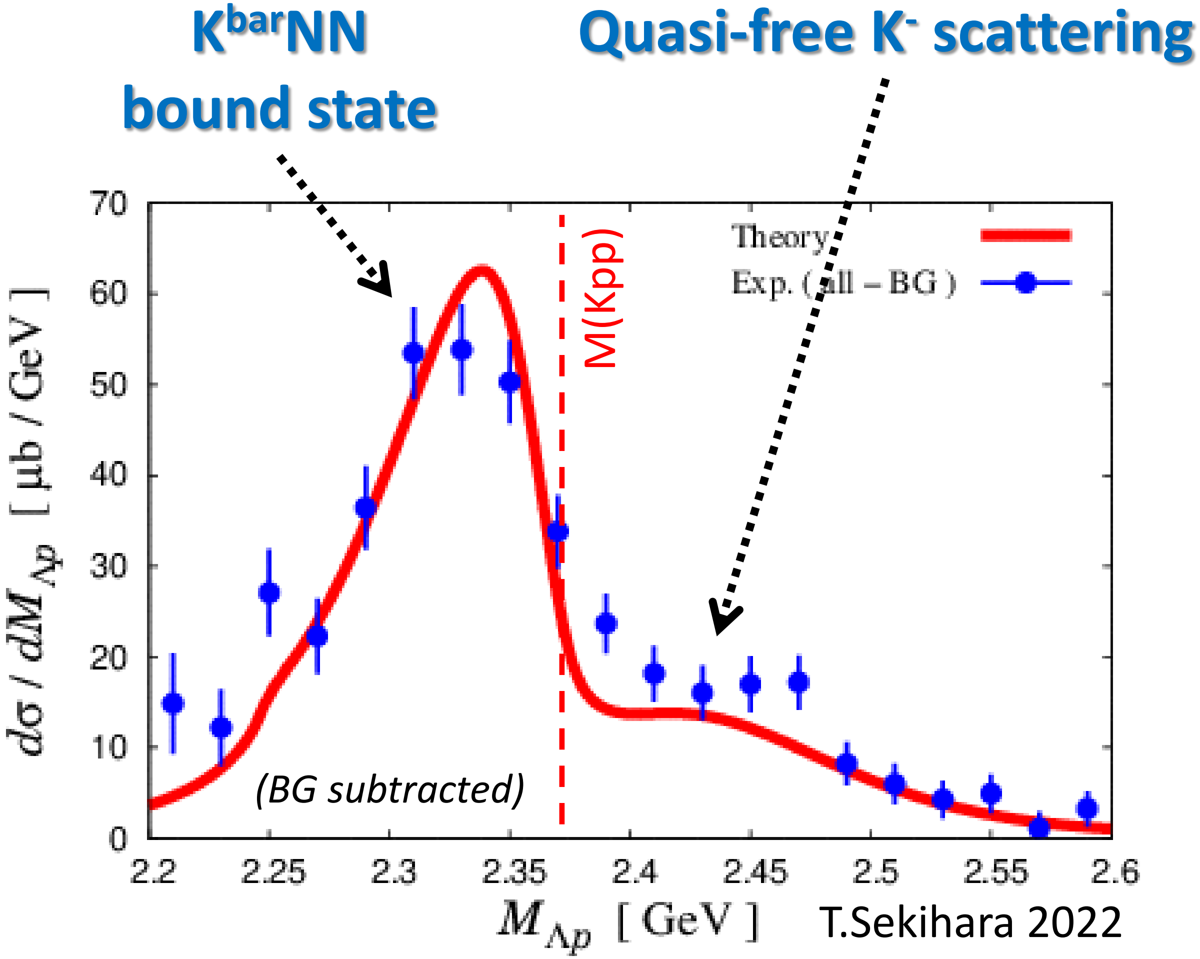
On the structure observed in the in-flight ^{3}He(K^-, Λp)n reaction at J-PARC

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





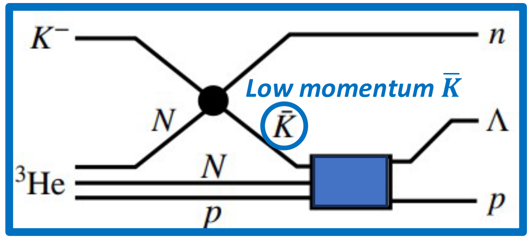
Theoretical investigations are indispensable!

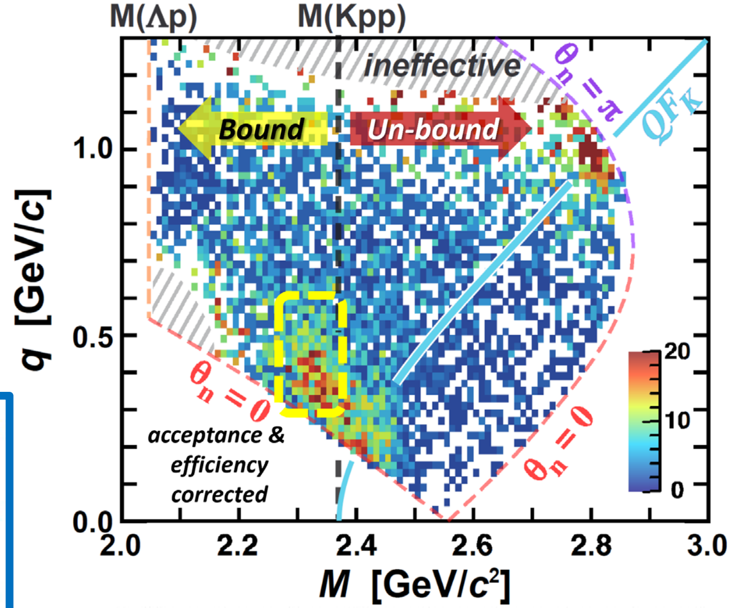


What We Observed at E15 [Discussion]

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

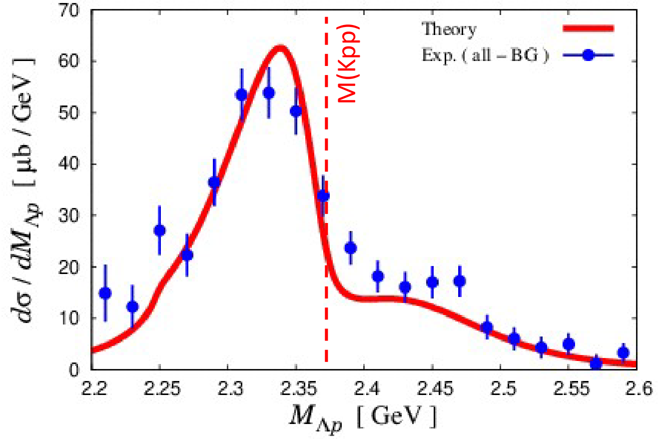
- ➢A bound state exists
- ➢~10 times the binding energy of normal light nuclei
- ➢Generated by large momentum transfer





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

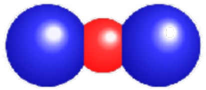
- ➢An intermediate $\bar{K}$ exists during the reaction



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

Observed bound state = "K-pp" bound state

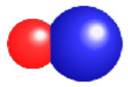
→ Suggests possibility of being in a compact system



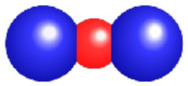
Need Further Investigations

to establish the kaonic nuclei

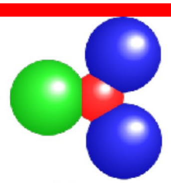
- **Λ(1405) state**
  - $\bar{K}N$ qusi-bound state as considered?
  - Relation between $\bar{K}N$ and $\bar{K}NN$?

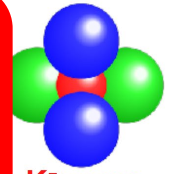


- **Further details of the $\bar{K}NN$**
  - Mesonic decay modes?
  - Spin and parity of the "K-pp"?
  - Really compact and dense system?

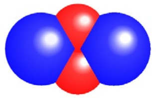


- **Heavier kaonic nuclei**
  - Mass number dependence?

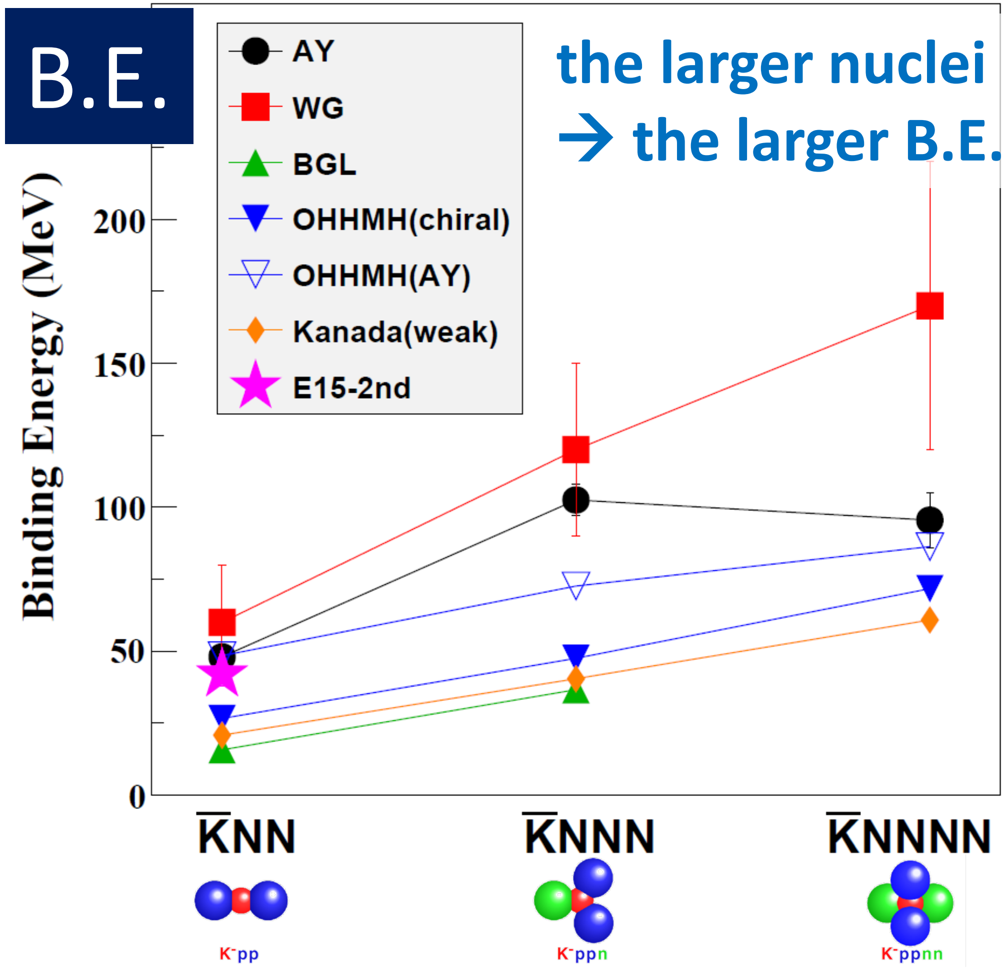


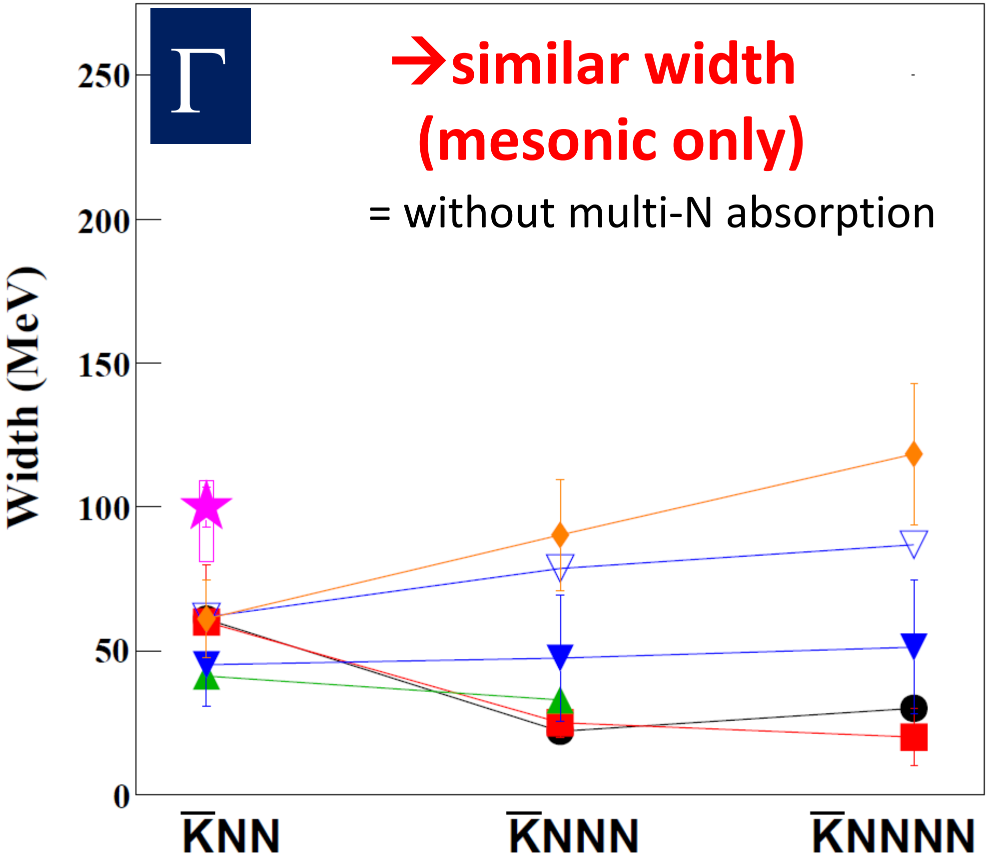


- **Double kaonic nuclei**
  - Much compact and dense system?



Mass Number Dependence of Kaonic Nuclei



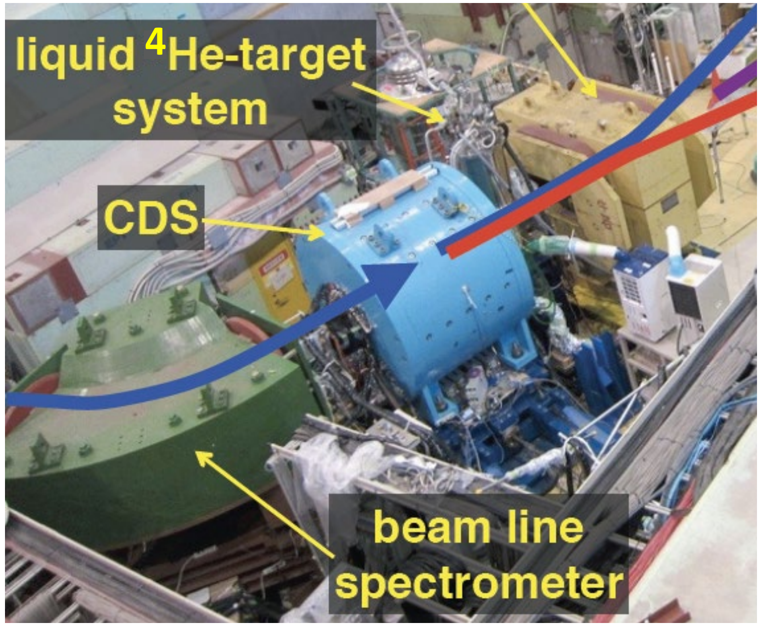


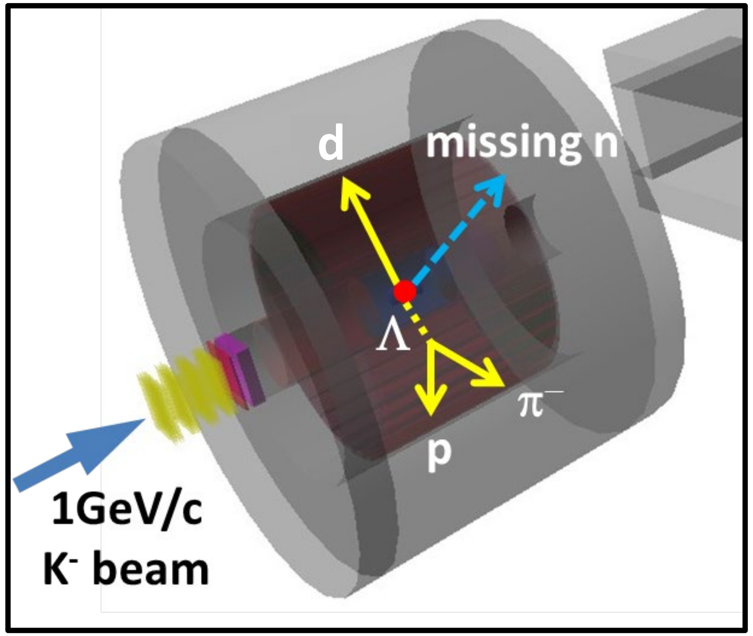
- **Systematic measurements will provide more conclusive evidence of the kaonic nuclei**

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

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

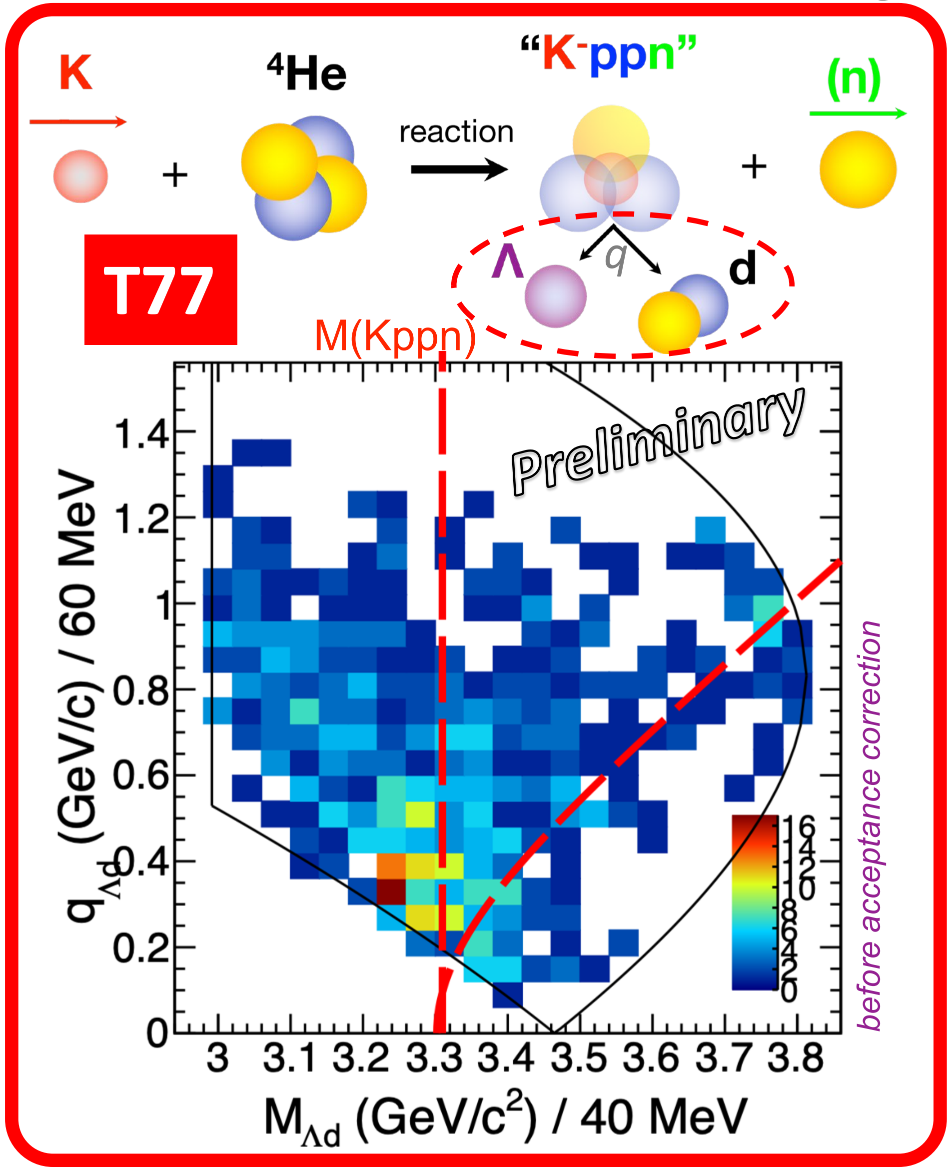
- An analysis of the **Λdn** final state with **$K^{-4}He$** reaction at **1 GeV/c** has been conducted
  - T77: lifetime measurement of $^{4}_{\Lambda}H$ in 2020
- The results will be updated with a part of the E73 controlled data
  - E73: lifetime measurement of $^{3}_{\Lambda}H$ in 2024

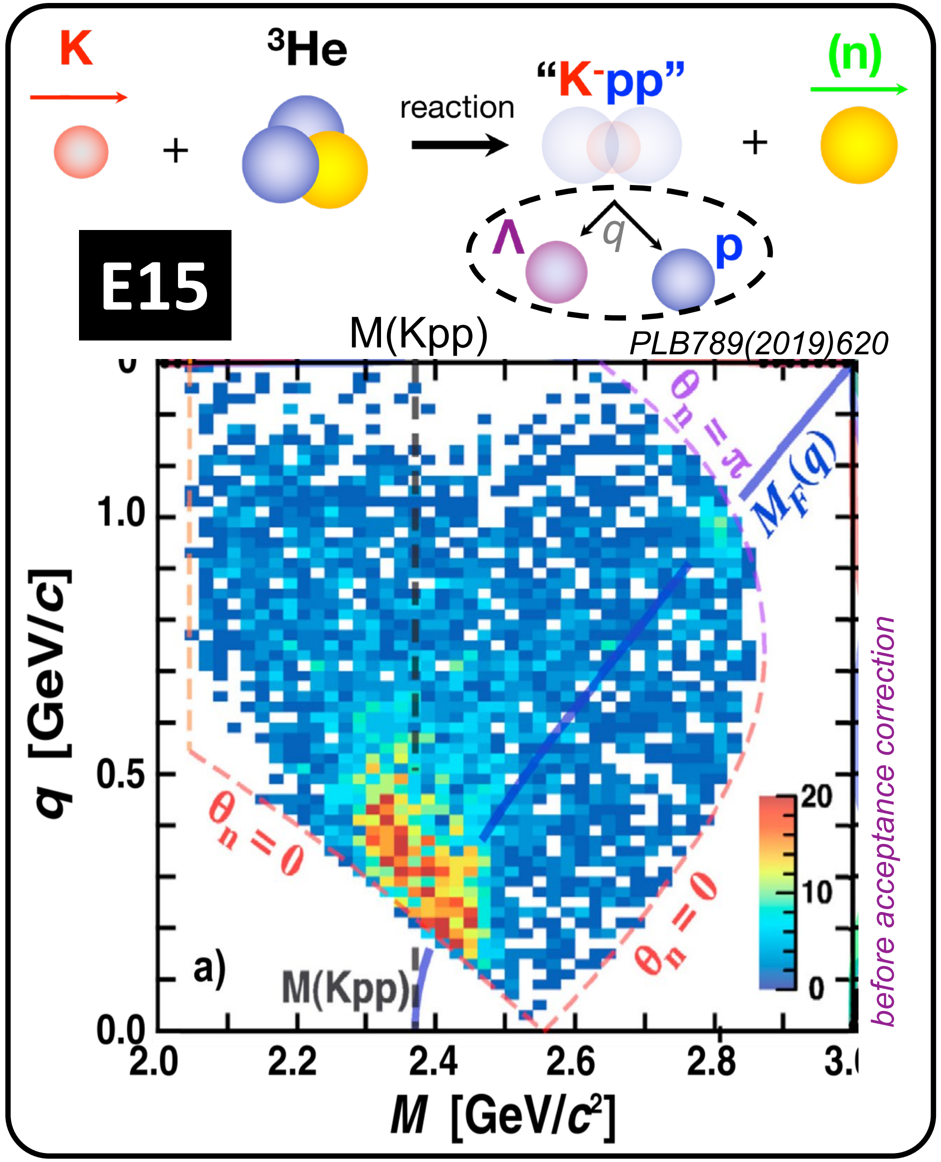




Experiment	K^- on target
E15 (^{3}He)	~42 x 10^9
T77 (^{4}He)	~6 x 10^9
E73 (^{4}He)	~6 x 10^9

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





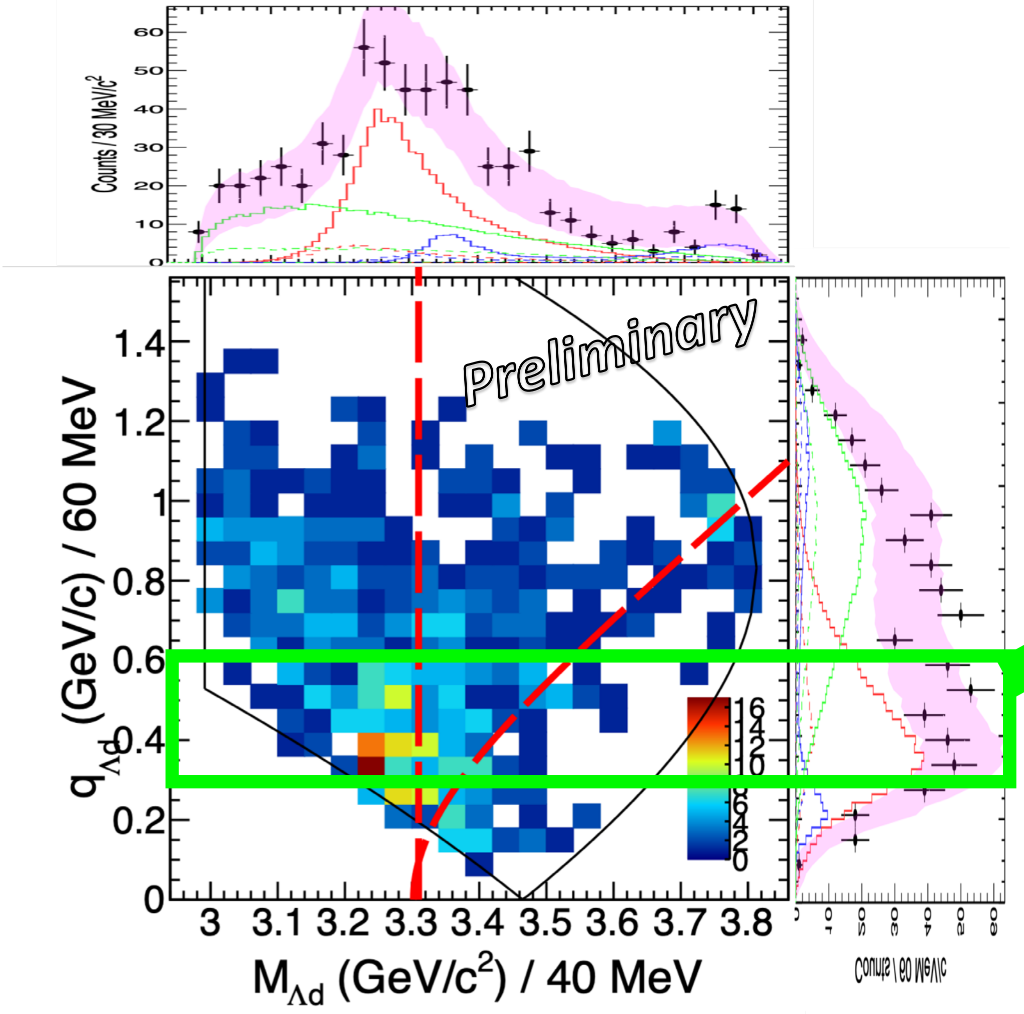
- **Two distributions are quite similar**
- structure below the threshold (**seems *q*-independent**), QF-K, BG

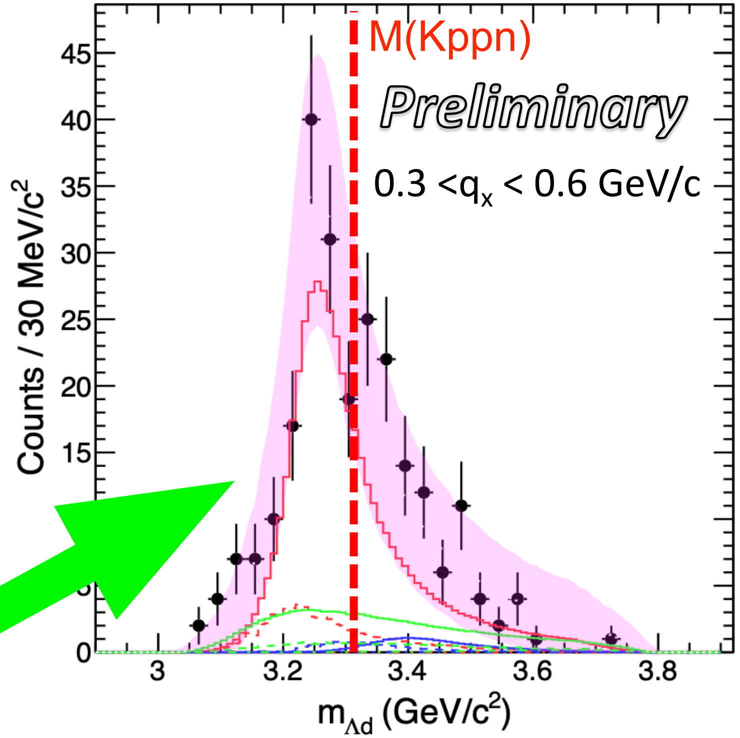
$K^- {}^4He \rightarrow \Lambda dn$ Analysis with the T77 Data

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

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

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





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

$\Gamma_X = \sim 100\ MeV$

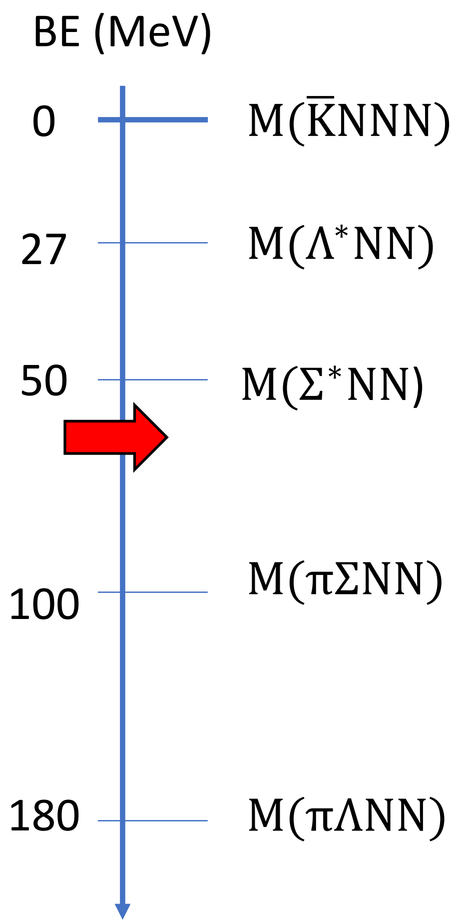
$\sigma_{X \to \Lambda d} \sim 4\ \mu b$

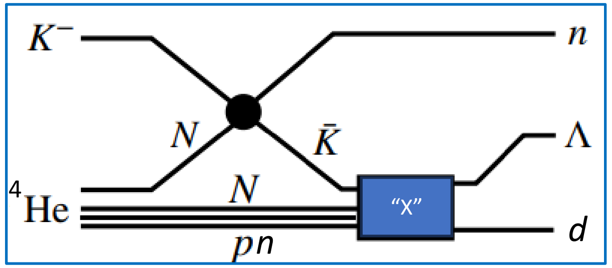
$K^-{}^4He \rightarrow \Lambda dn$ Analysis with the T77 Data

What is the observed structure? [Discussion]

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

2. <u>**"X"="K^-ppn" with $J_{"X"}$ = 1/2** would be likely, considering the isospin and spin combination in S-wave interaction</u>
   - **$J_{"X"}$ = 1/2:** ^4He 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

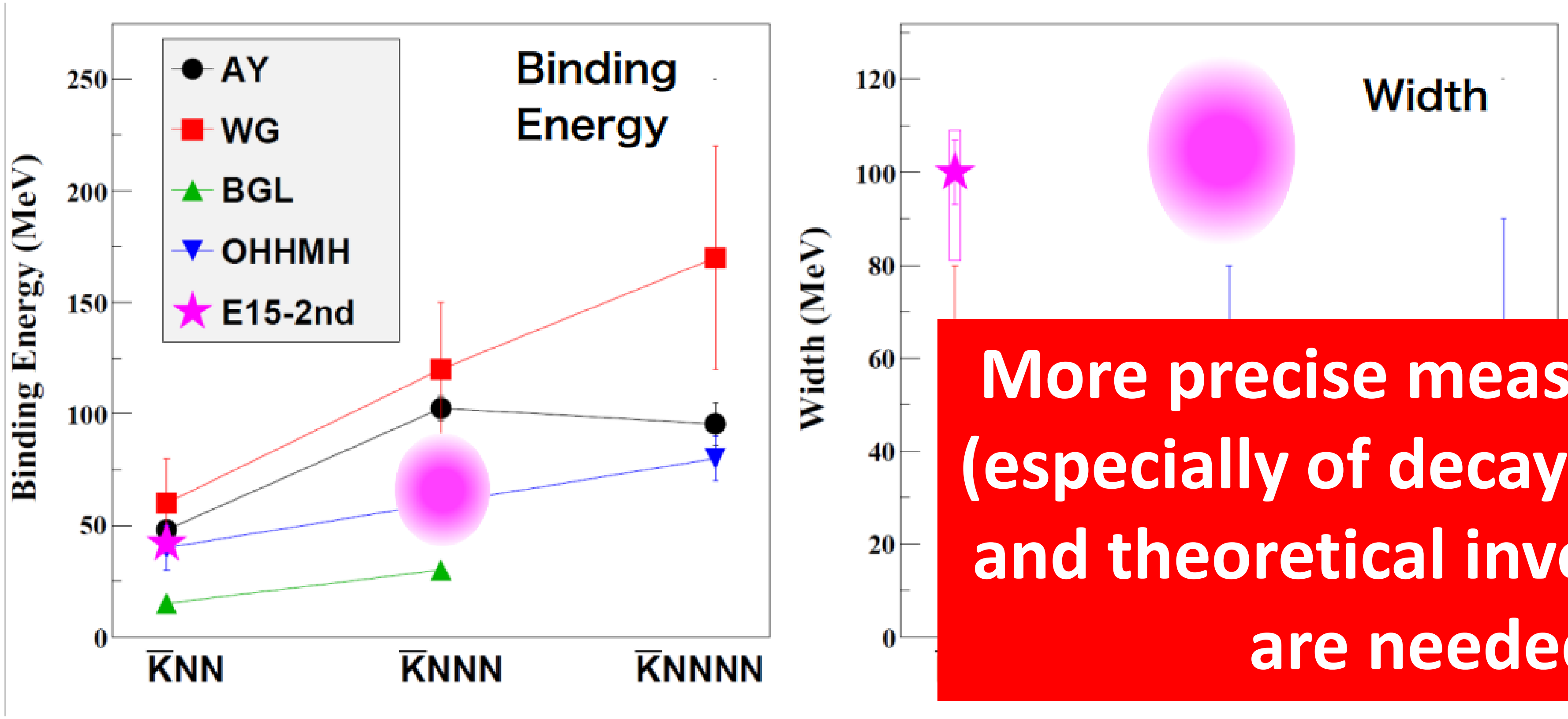




$K^{-4}He \rightarrow \Lambda dn$ Analysis with the T77 Data

What is the observed structure? [Discussion]

If "X" is "K^-ppn"

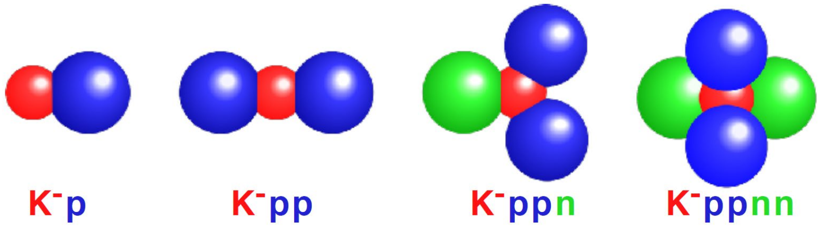


More precise measurements (especially of decay branches) and theoretical investigations are needed

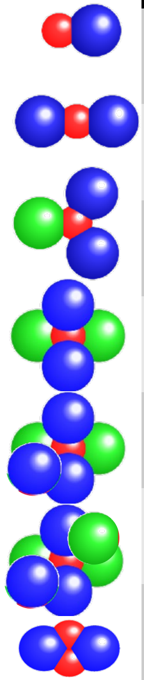
- The binding energy is compatible with some theoretical predictions
- The width is larger than theoretical predictions

New Kaonic Nuclei Project at J-PARC

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

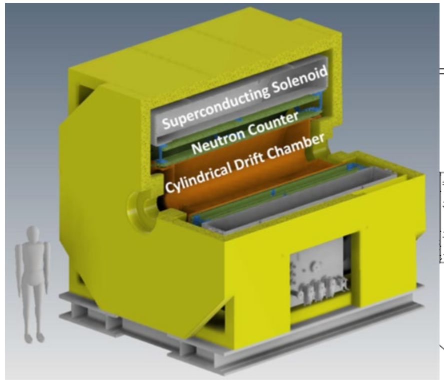


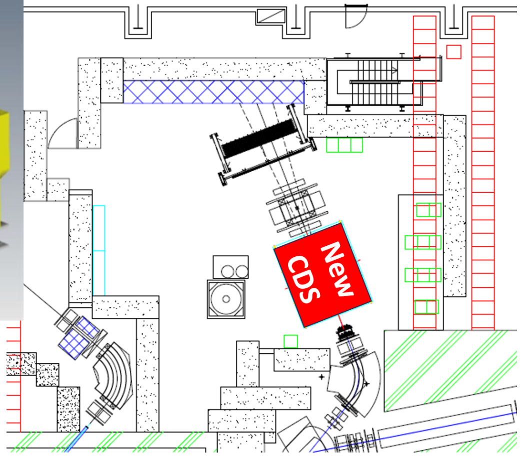
Strategy



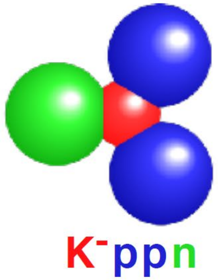
	Reaction	Decays	Key	Experiment
$\bar{K}N$	d(K$^-$,n)	$\pi^{\pm0}\Sigma^{\mp0}$	n/γ identification	Future
$\bar{K}NN$	^{3}He(K$^-$,N)	Λp/Λn	polarimeter	P89
$\bar{K}NNN$	^{4}He(K$^-$,N)	Λd/Λpn	large acceptance	E80 ← **A first step**
$\bar{K}NNNN$	^{6}Li(K$^-$,d)	Λt/Λdn	many body decay	Future
$\bar{K}NNNNN$	^{6}Li(K$^-$,N)	Λα/Λdd/Λdpn	many body decay	Future
$\bar{K}NNNNNN$	^{7}Li(K$^-$,N)	Λαn/Λddn	many body decay	Future
$\bar{K}\bar{K}NN$	*$\bar{p}$ + ^{3}He*	*ΛΛ*	*$\bar{p}$ 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



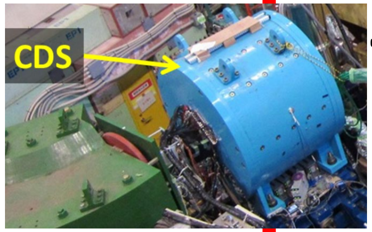


We take a step-by-step approach



$\bar{K}NNN$ @ E80

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



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

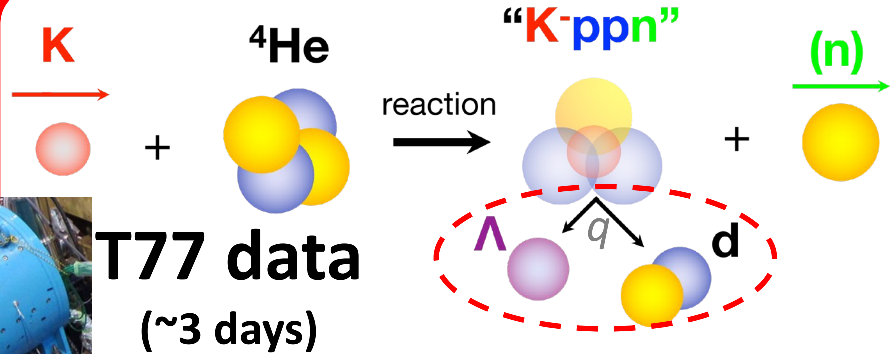
- "K-ppn"→Λd 2-body decay

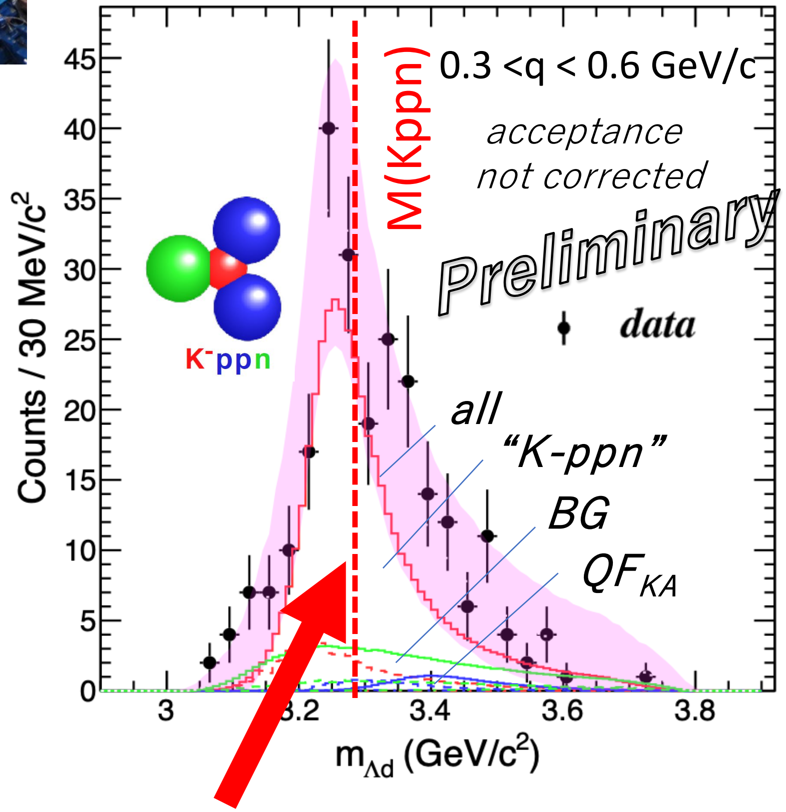
② Study the multi-particle decay mode of $\bar{K}NNN$ toward understanding its internal structure

- "K-ppn"→Λpn 3-body decay

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

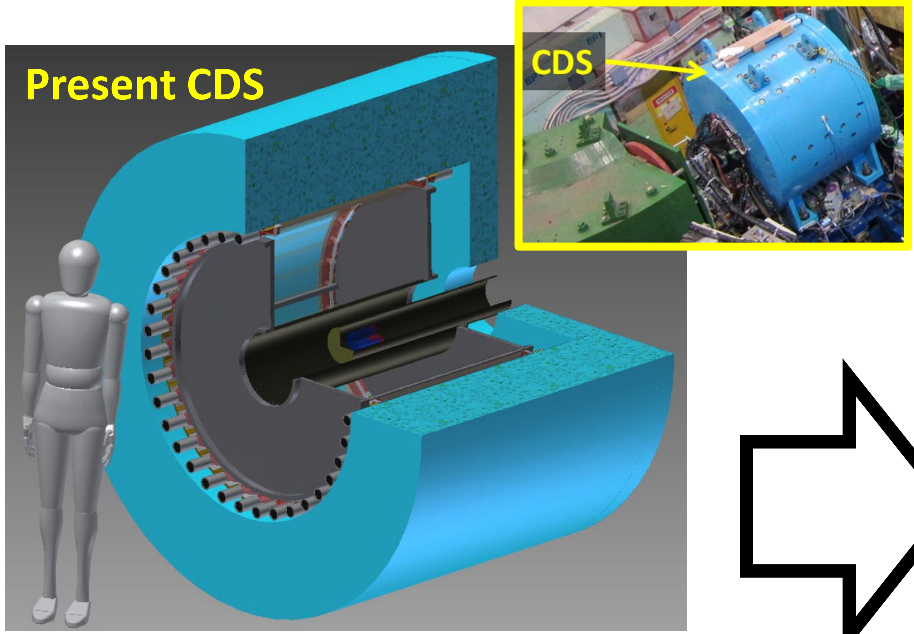
Beam intensity	90kW
Beam time	1+1+3 weeks





the sign of the "K⁻ppn"

New Cylindrical Detector System (CDS)

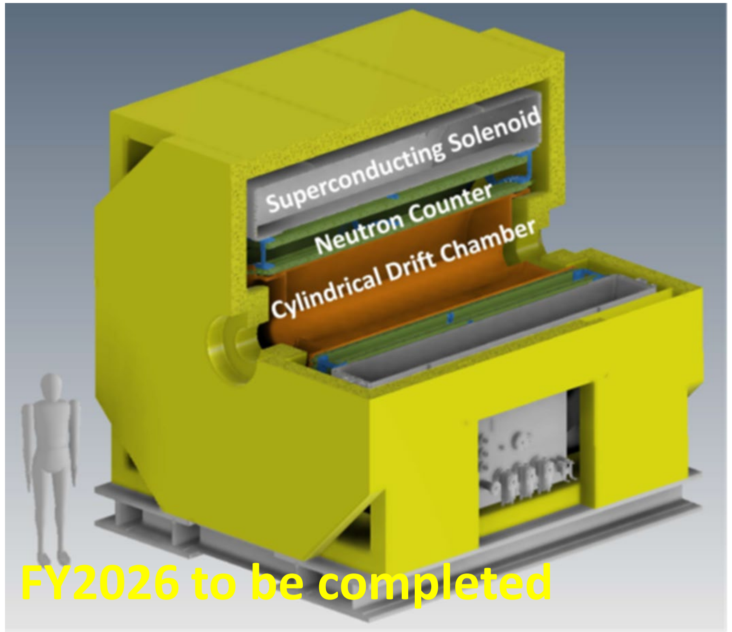


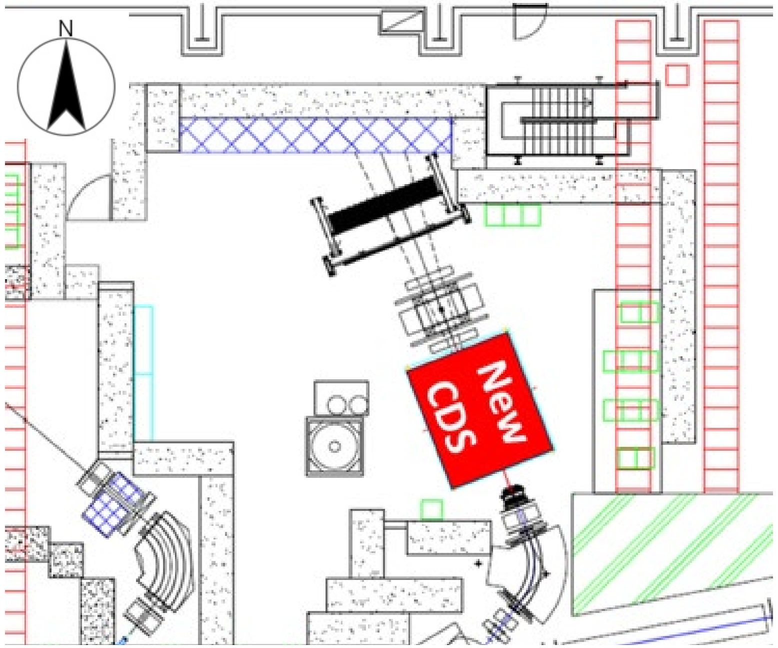
✓**Solid angle: x1.6** (59% → 93%)
✓**Neutron eff.: x7** (3% → 12%x1.6)

FY2026 to be completed

Summary

- We observed the “K⁻pp” bound state in $^{3}He(K^{-},\Lambda p)n$
  - ✓PLB789(2019)620., PRC102(2020)044002.
- **We also obtained hints of mesonic decays of “K-pp”**
  - ✓**arXiv:2404.01773 [nucl-ex] <- <u>PRC accepted</u>**
- We observed the sign of the “K⁻ppn” in $^{4}He(K^{-},\Lambda d)n$
  - ✓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 to improve kaon yield





Hope to modify around FY2025-26

J-PARC E80 Collaboration

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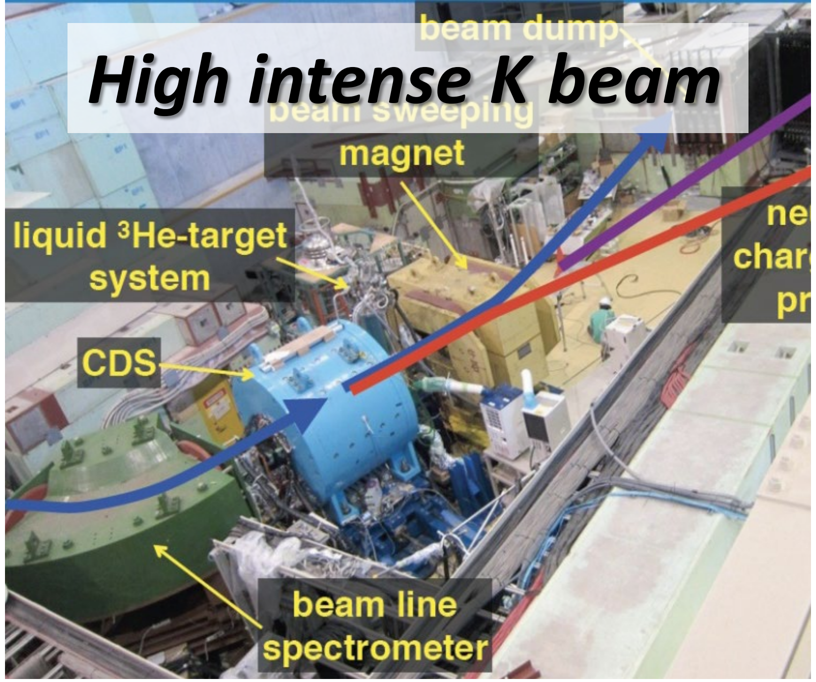
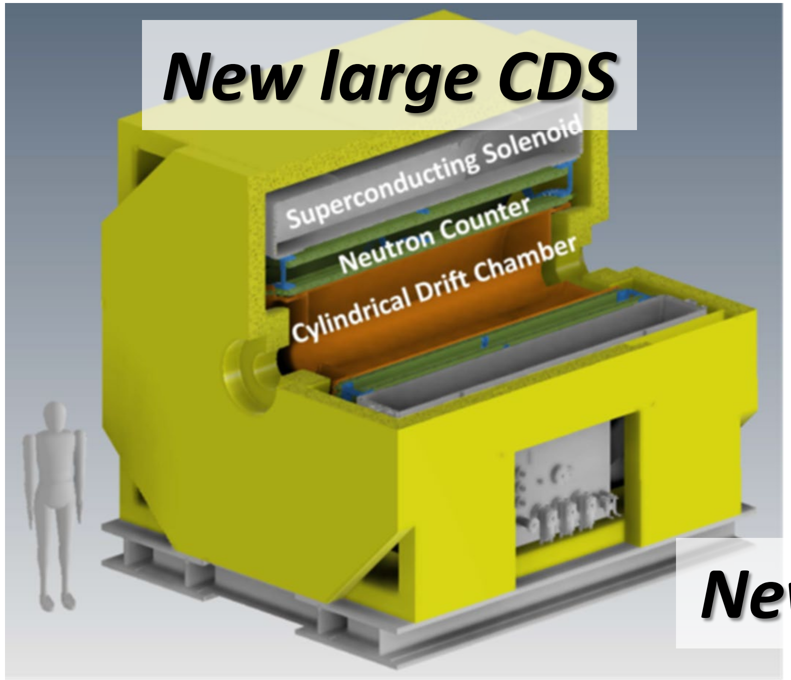
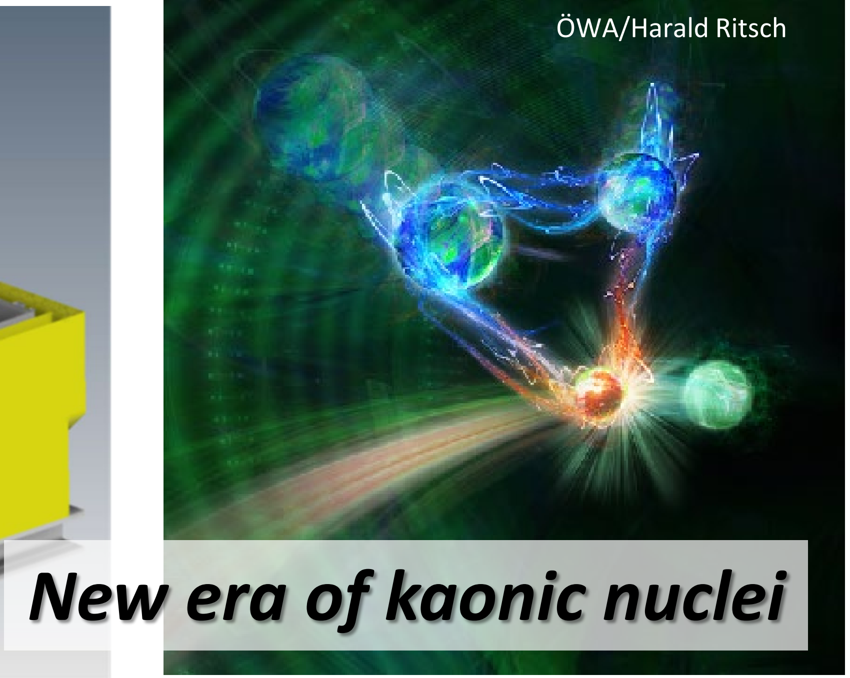
We're looking for new collaborators!

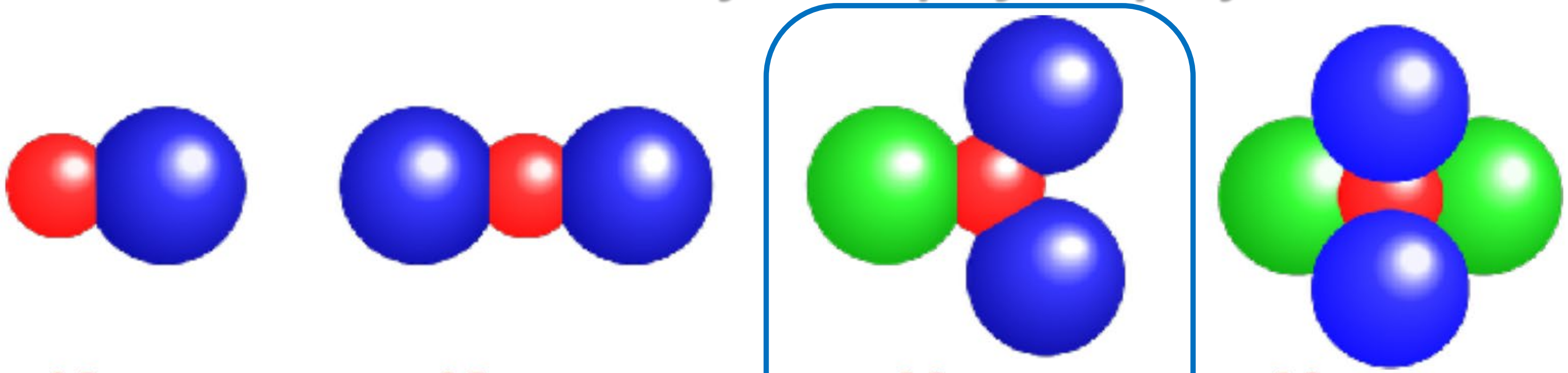






Thank you for your attention!

A first step of the project



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

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