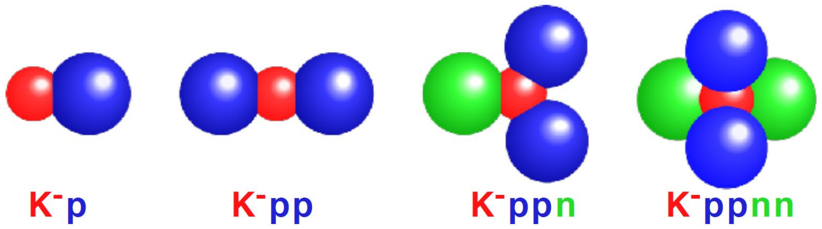
New Kaonic Nuclei Project at J-PARC

– 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

ECT*, THEIA2024, May 13-17, 2024

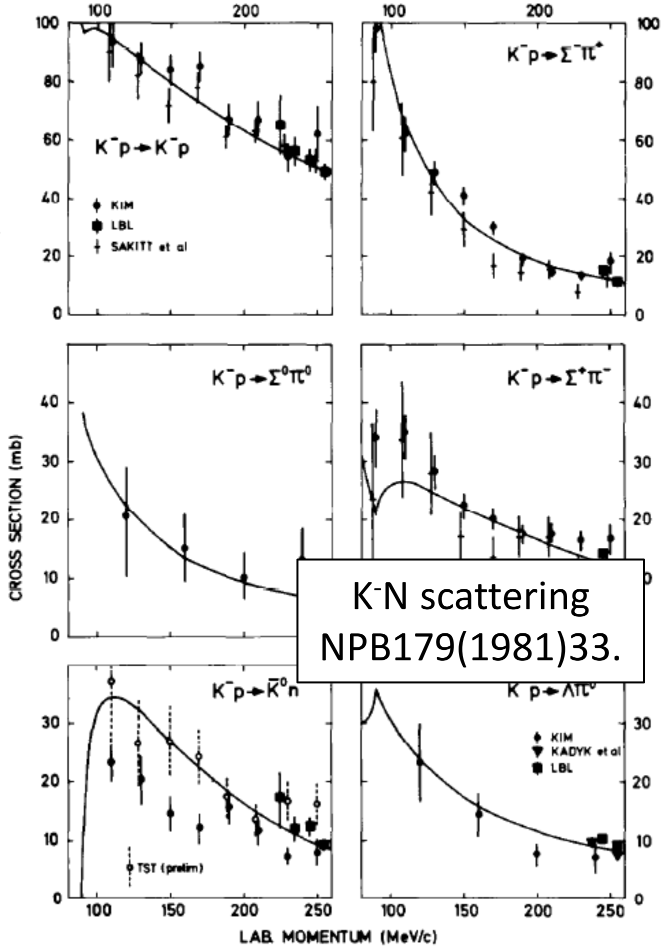
Physics Goal

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

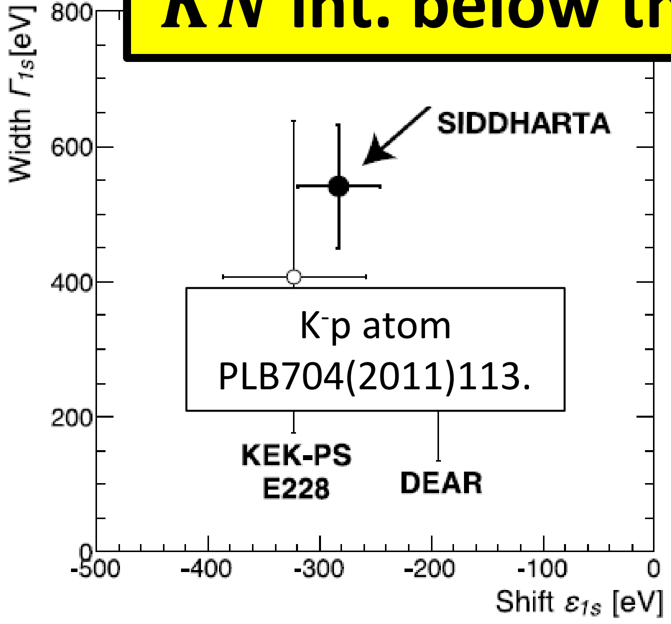
A powerful probe to understand low energy QCD

Strongly attractive in I=0 from extensive measurements

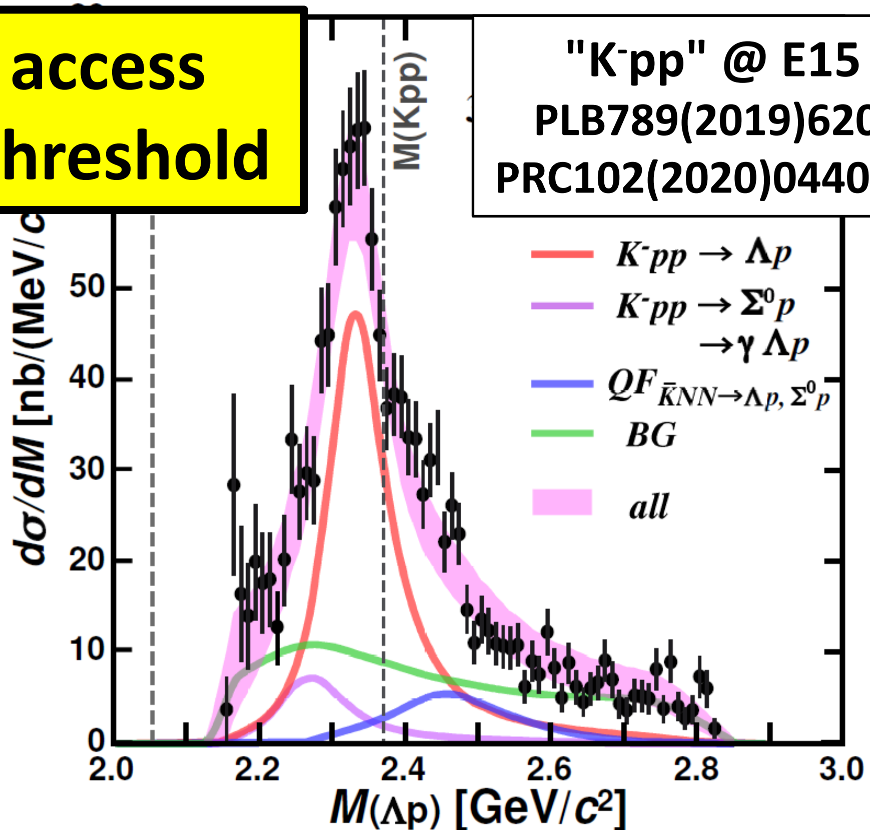
Kaonic nuclei can access $\bar{K}N$ int. below the threshold



K⁻N scattering
NPB179(1981)33.



K⁻p atom
PLB704(2011)113.

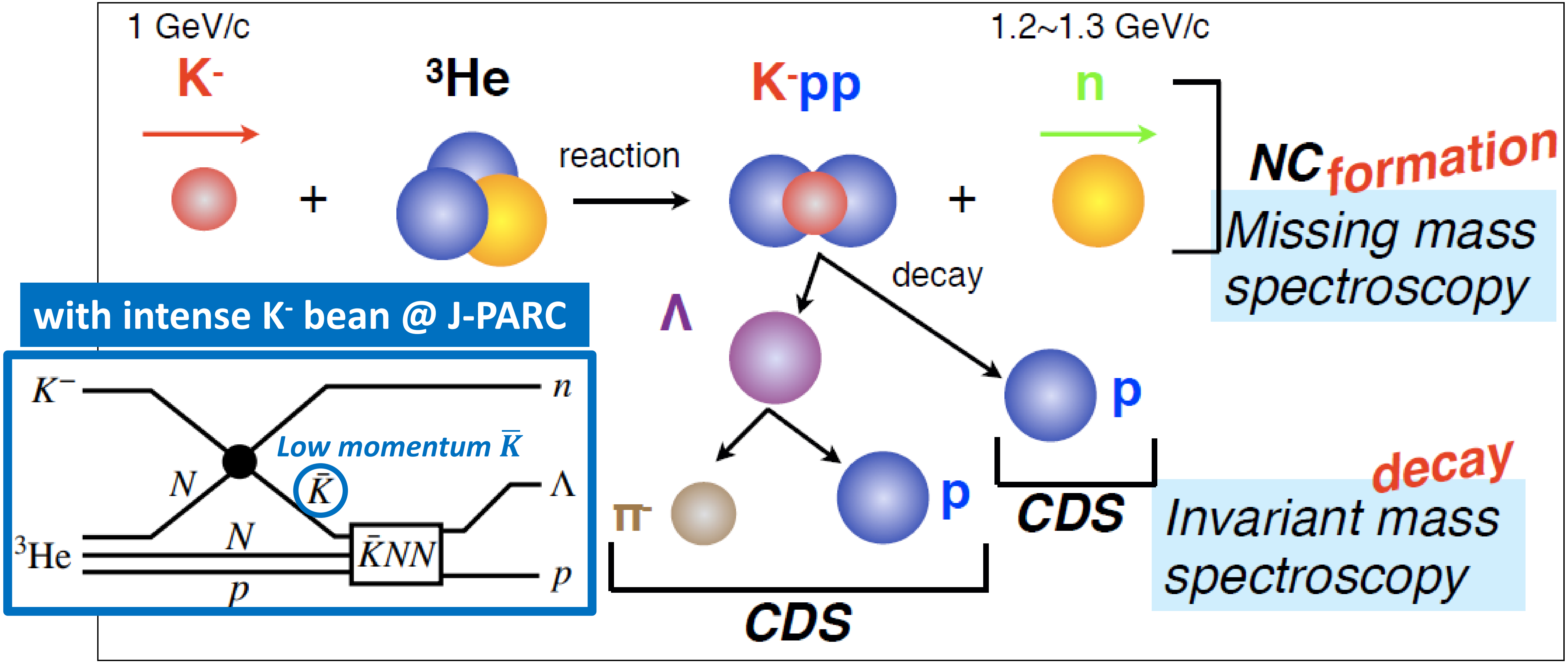


"K⁻pp" @ E15
PLB789(2019)620.
PRC102(2020)044002.

"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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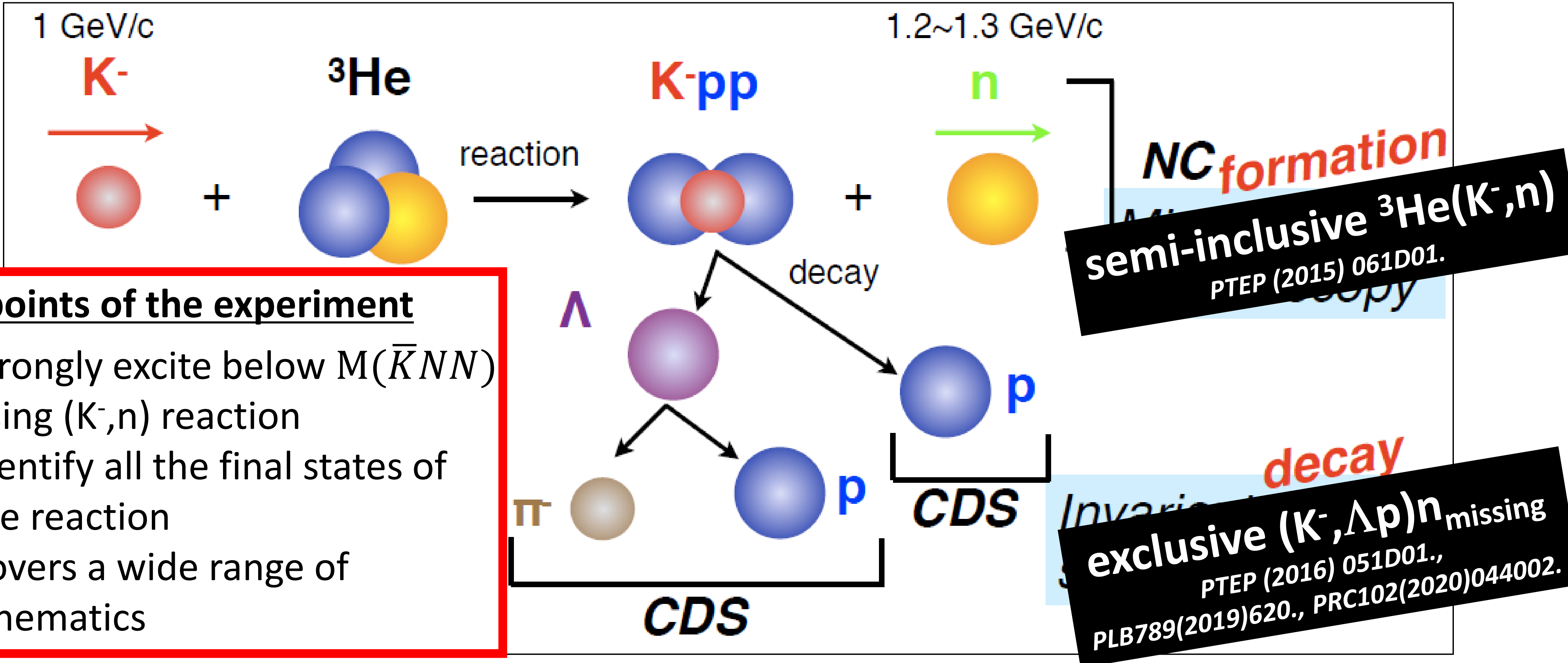
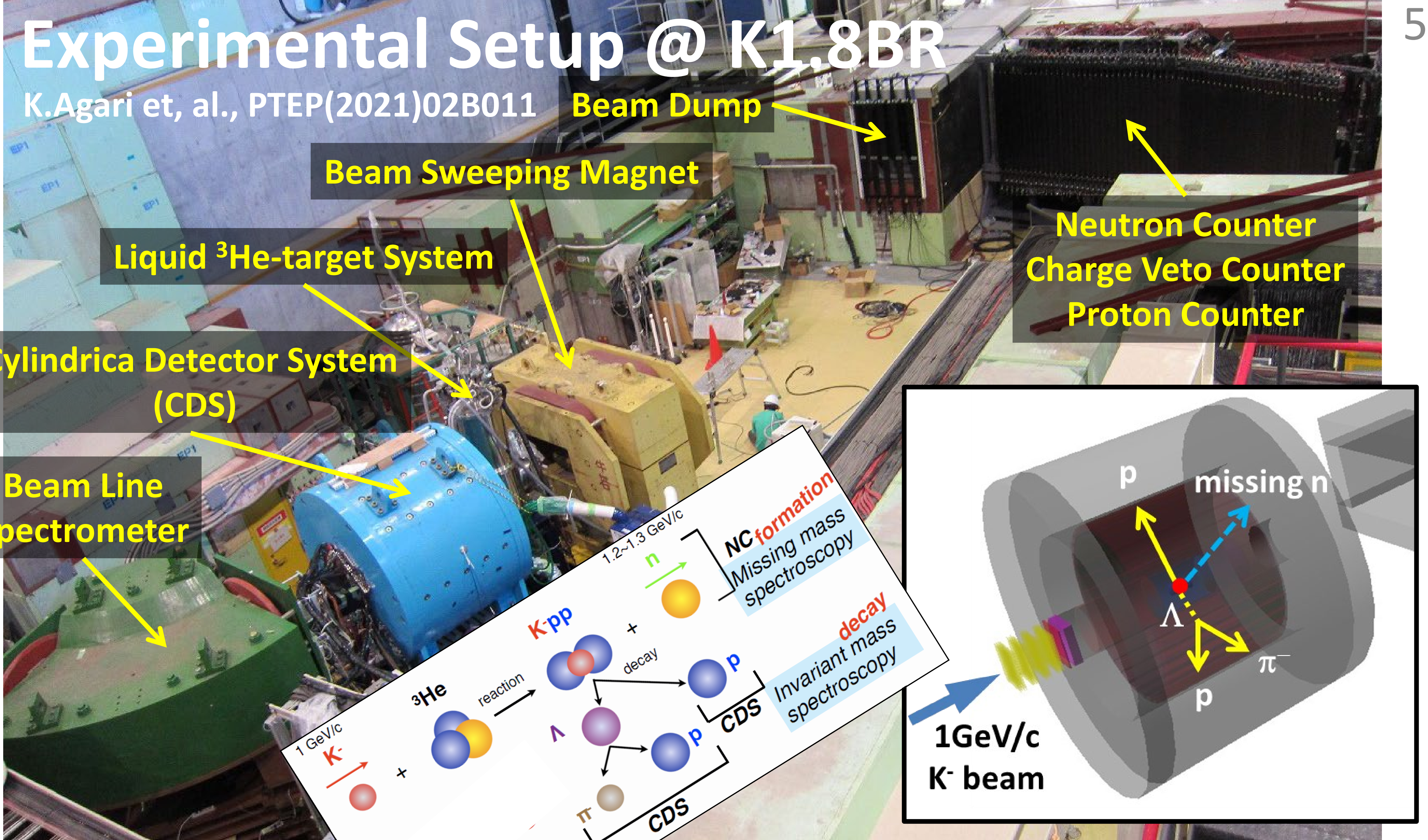


Key points of the experiment

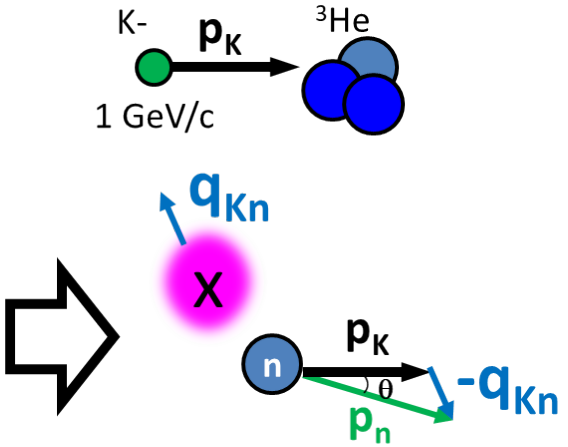
1. Strongly excite below $\mathrm{M}(\bar{K}NN)$ using (K^-,n) reaction
2. Identify all the final states of the reaction
3. Covers a wide range of kinematics

Experimental Setup @ K1.8BR

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



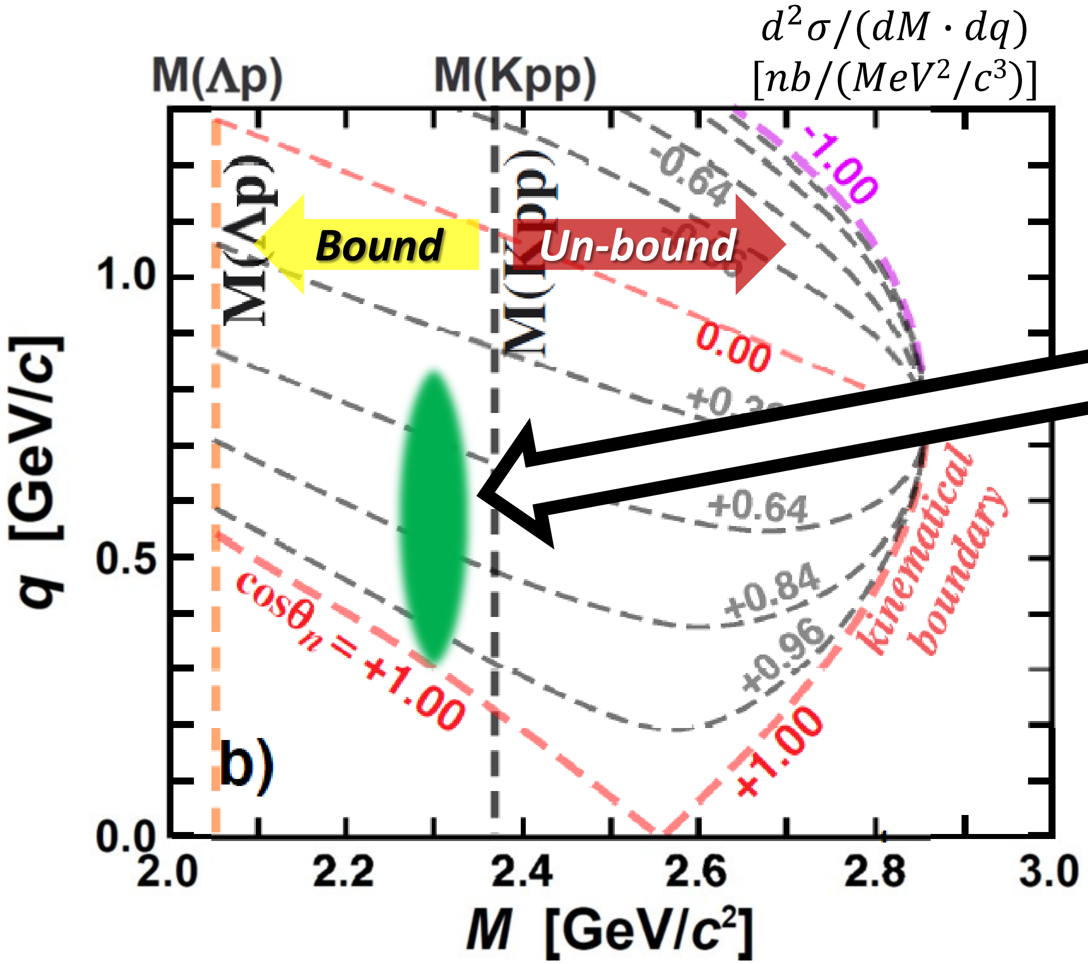
"K⁻pp" Search w/ Momentum Transfer Analysis



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

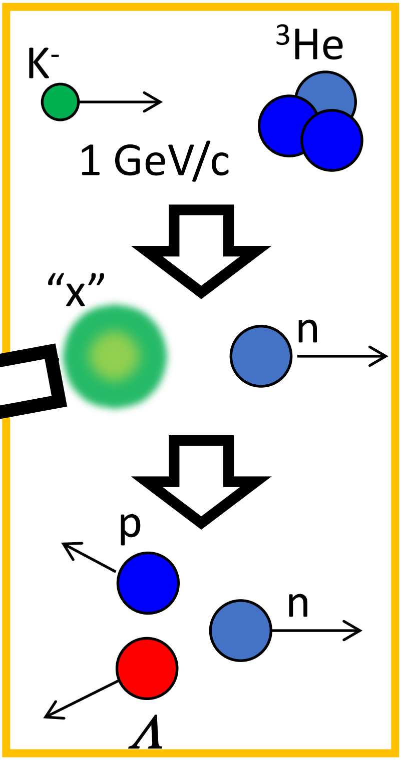
✓ M(Λp) vs. q

✓ give a clear information on reaction processes



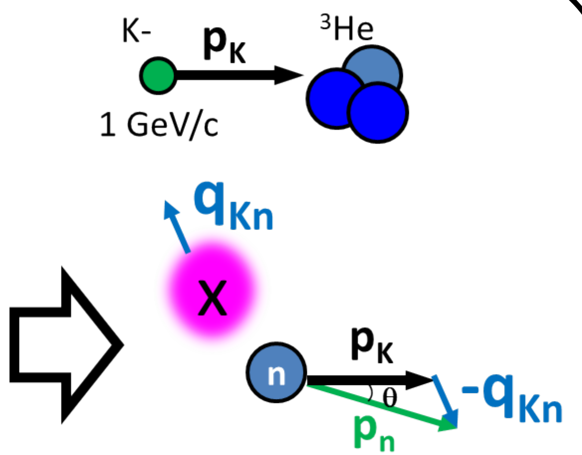
q *: (K⁻,n) momentum transfer*

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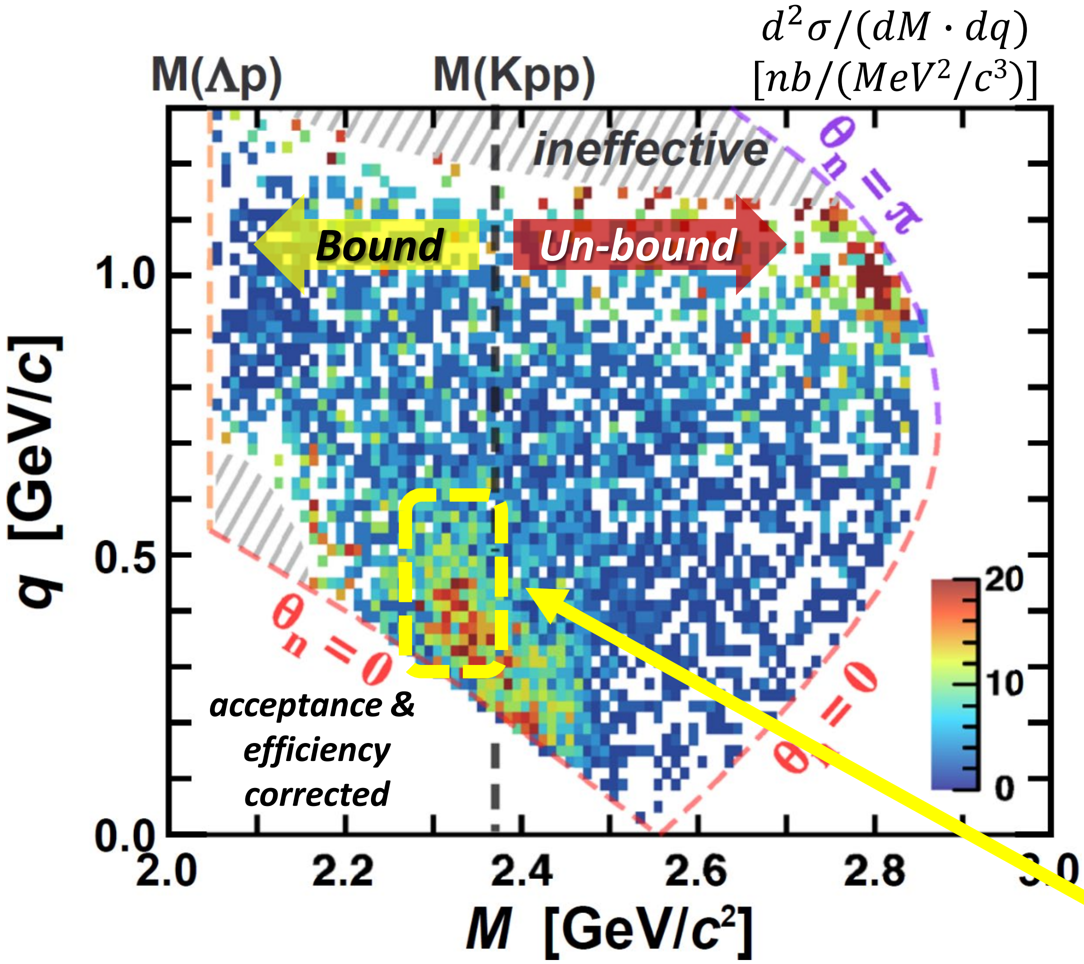
PLB789(2019)620., PRC102(2020)044002.



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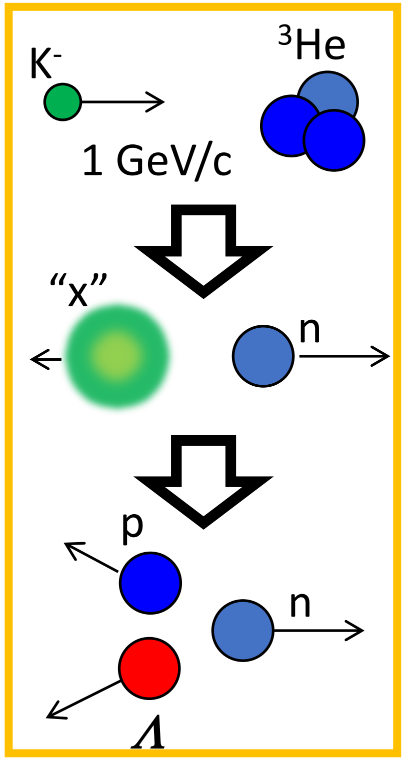
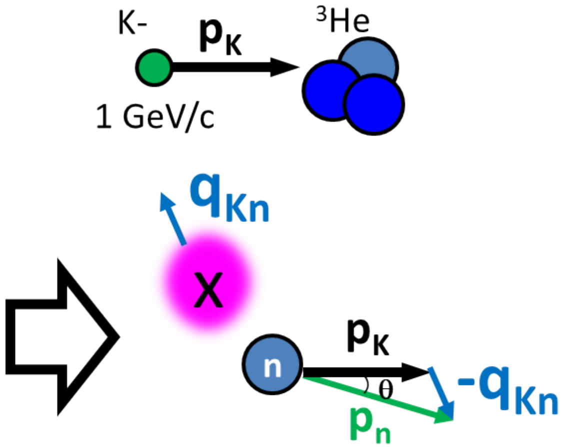


A peak structure independent of q = A bound state exists

"K⁻pp" Search w/ Momentum Transfer Analysis



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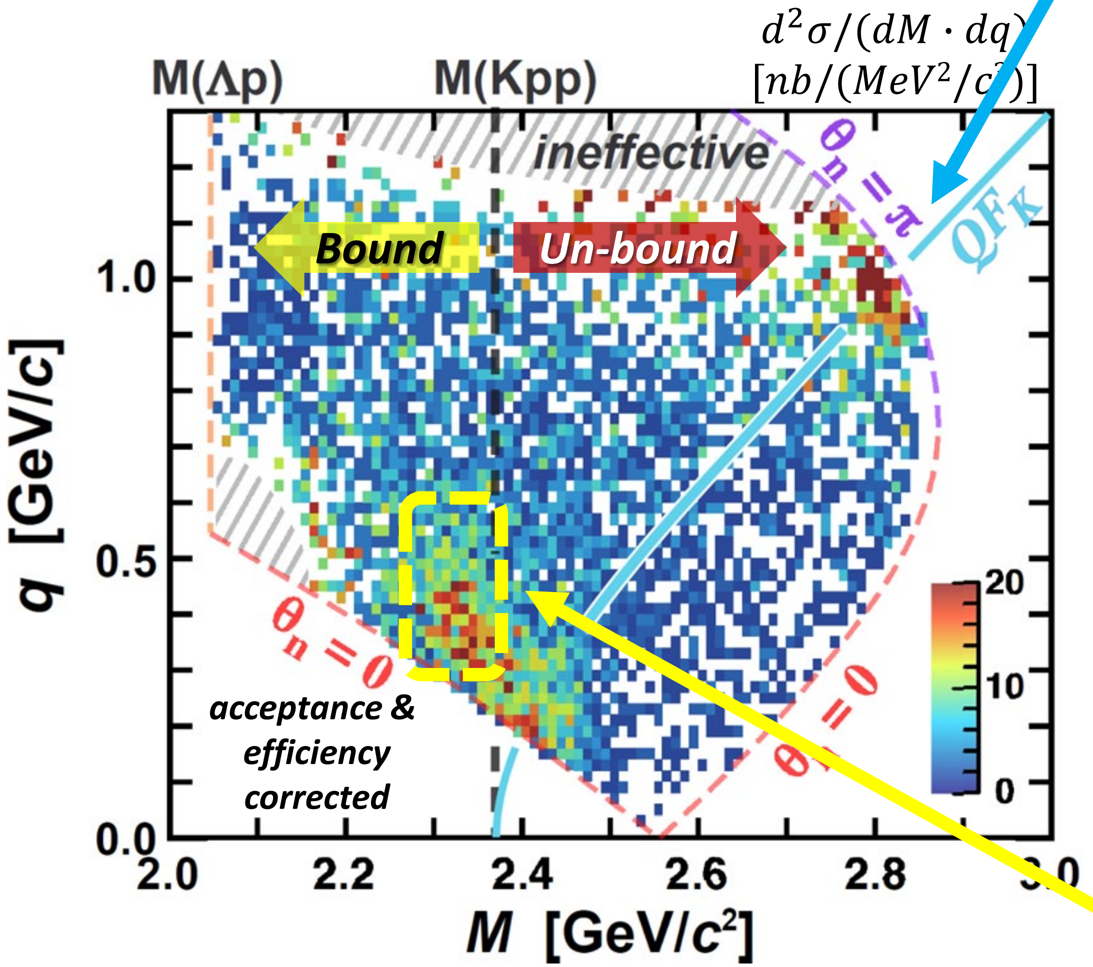
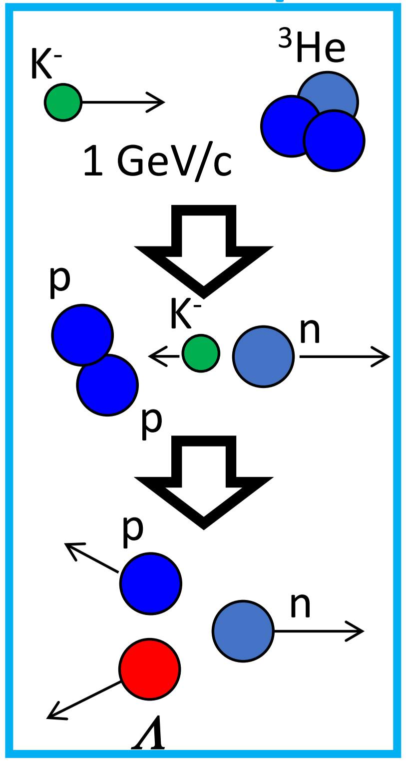
PLB789(2019)620., PRC102(2020)044002.



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

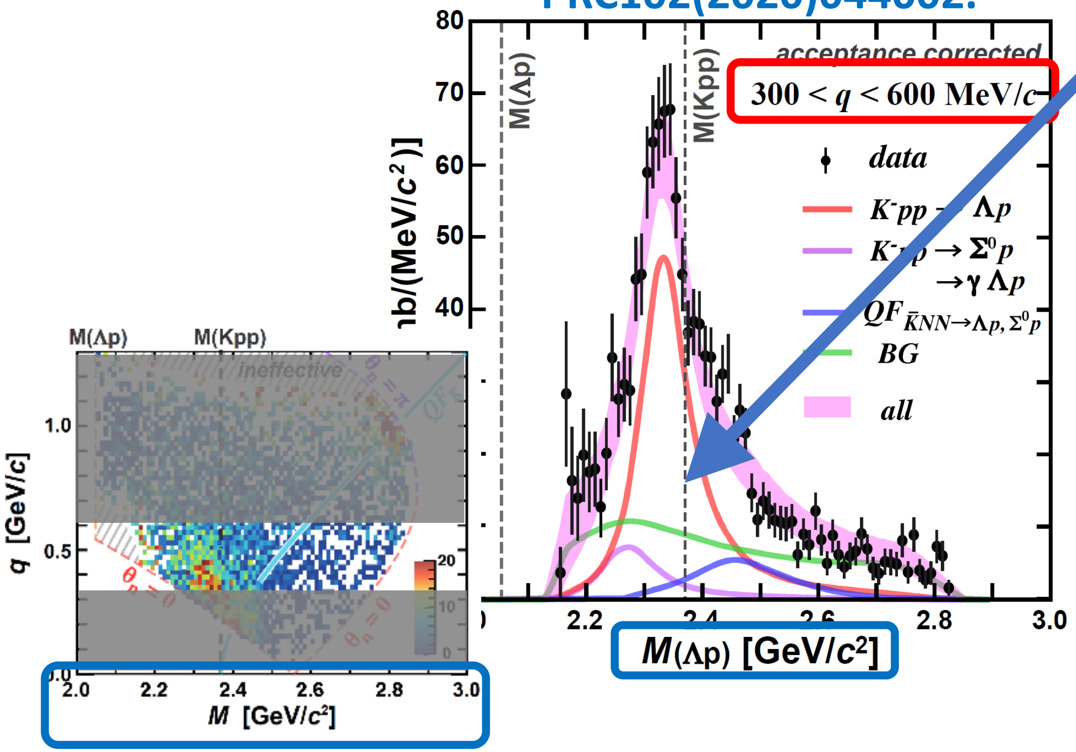
Energy term (BW type) from time integral

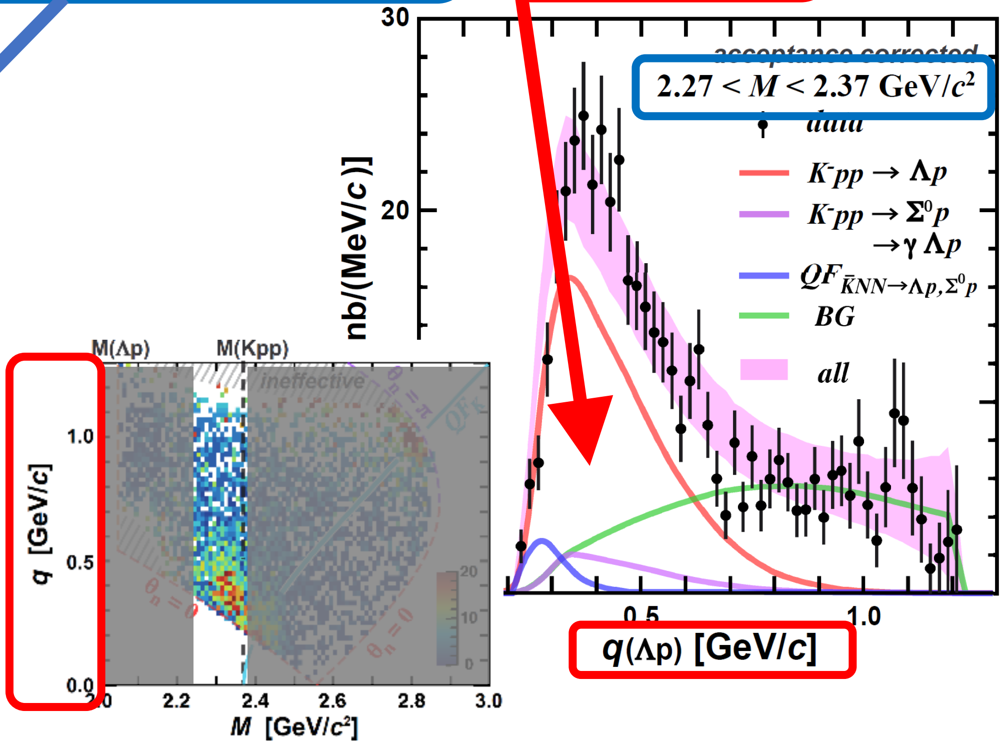
Momentum term from spatial integral

Plane Wave Impulse Approximation

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

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

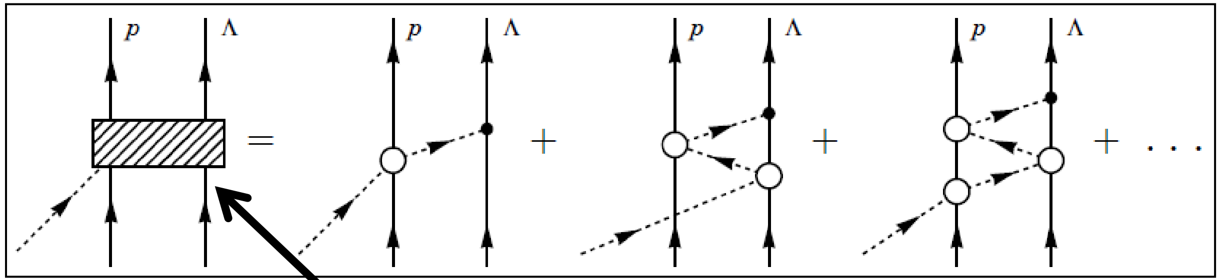
A Theoretical Interpretation

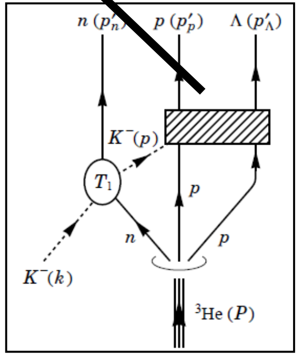
A calculation based on chiral unitary approach
reproduces the data well using the $\bar{K}NN$ bound state

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

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

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

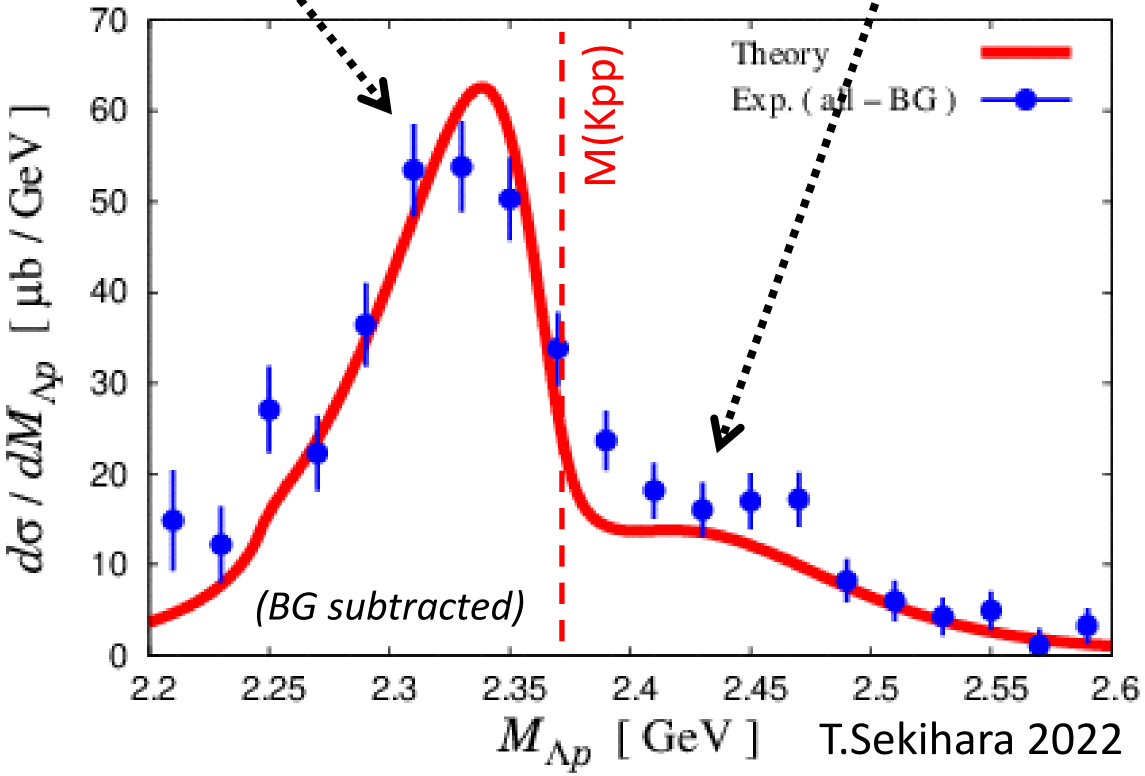




Theoretical investigations are indispensable!

Kbar NN bound state

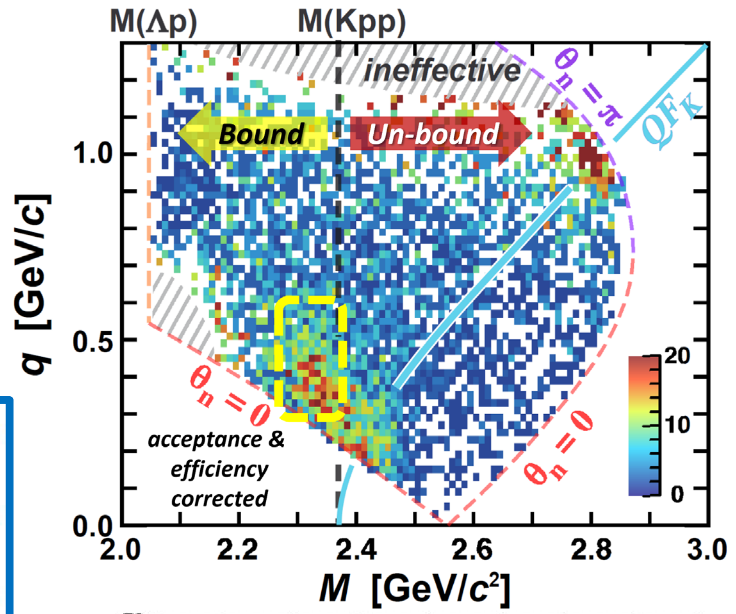
Quasi-free K- scattering (+2NA absorption)

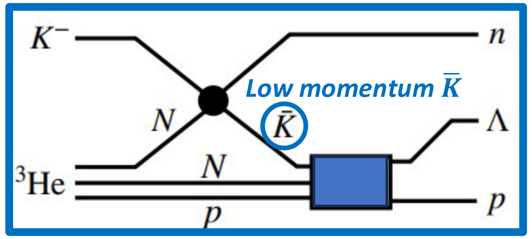


What We Observed at E15 [Discussion]

✓**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

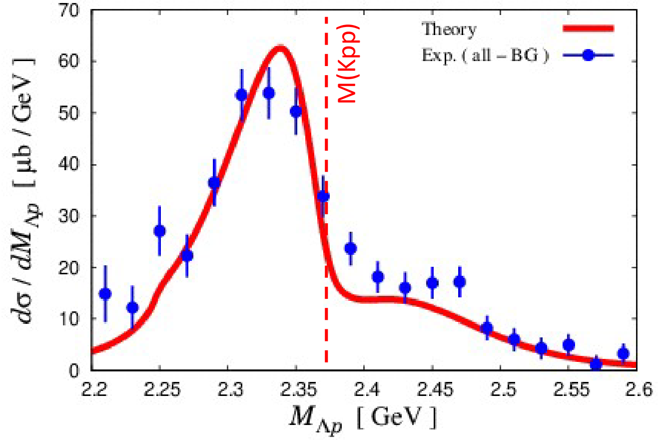




✓**Evidence of quasi-free K^- scattering**

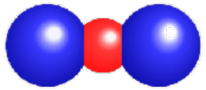
- ➢An intermediate state of $\bar{K}$ exists during the reaction

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



Observed bound state = "K-pp" bound state

→ Suggests possibility of being in a compact system

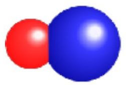


K^-pp

Need Further Investigations

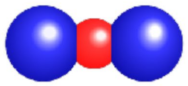
to establish the kaonic nuclei

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



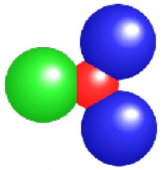
K^-p

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

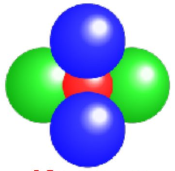


K^-pp

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

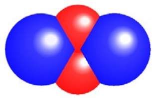


K^-ppn



K^-ppnn

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



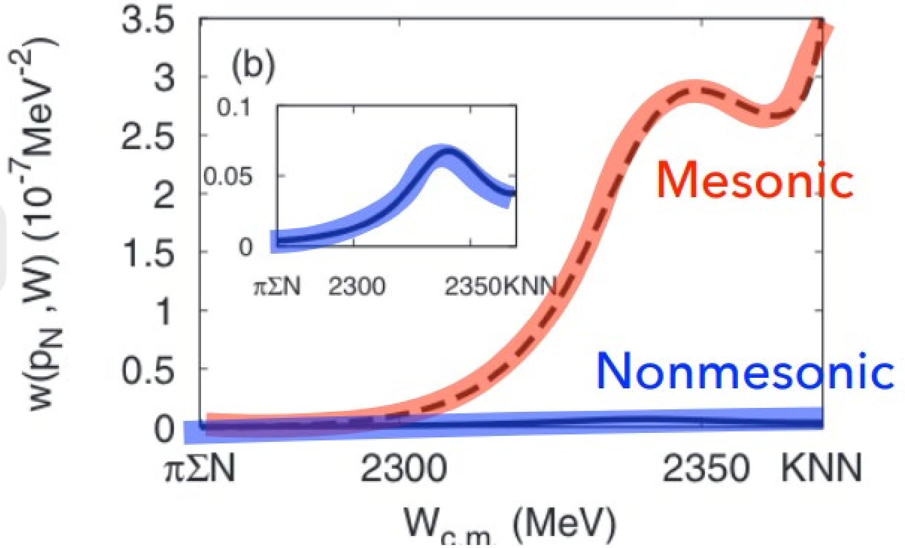
K^-K^-pp

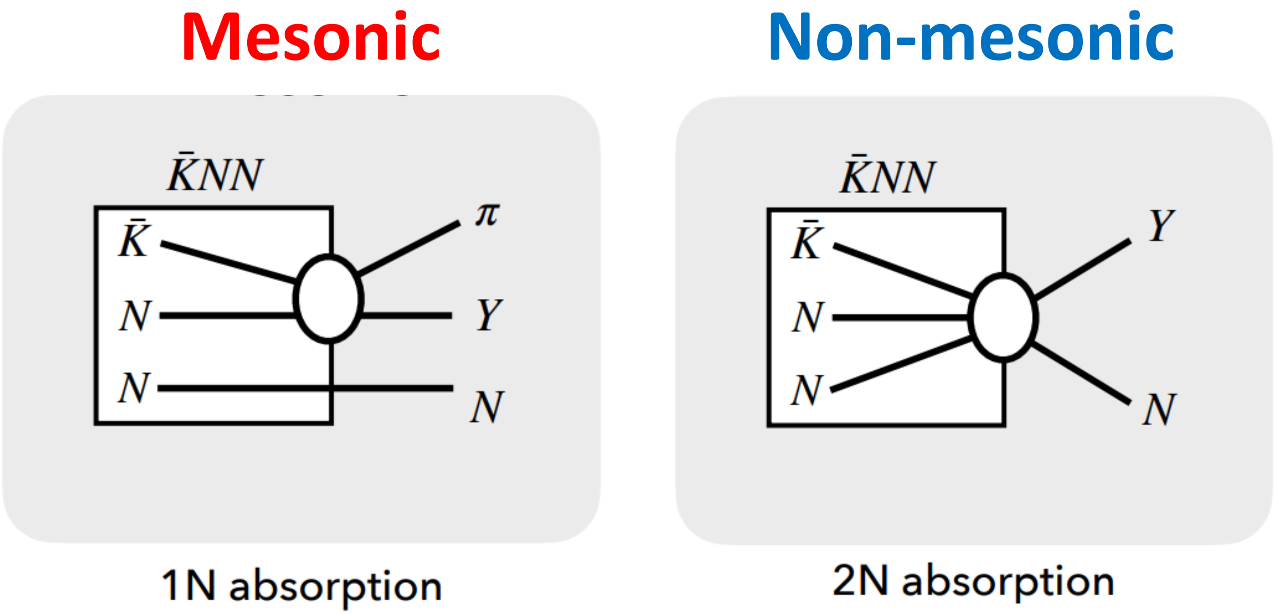
Mesonic Decay Modes of $\bar{K}NN$

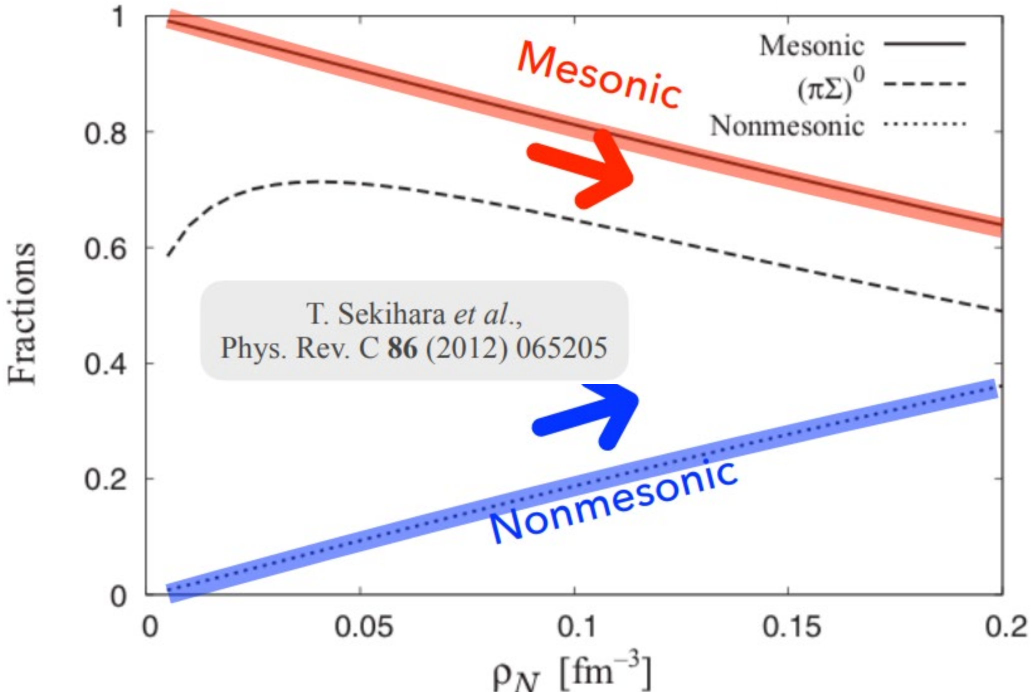
- Mesonic decays will give us further information on $\bar{K}NN$
  - ✓ internal structure
  - ✓ $\bar{K}N$ interaction below the threshold

$\Gamma_{YN} \ll \Gamma_{\pi YN}$

S. Ohnishi, et al., Phys. Rev. C 88 (2013) 025204.





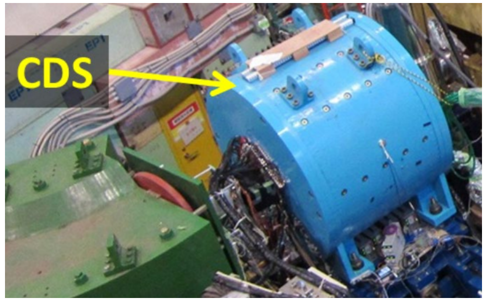


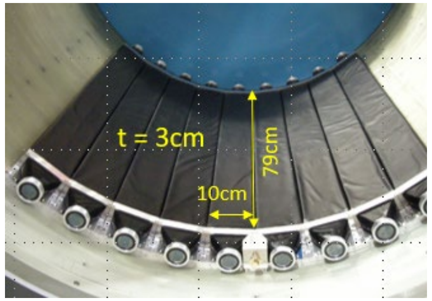
T. Sekihara *et al.*, Phys. Rev. C **86** (2012) 065205

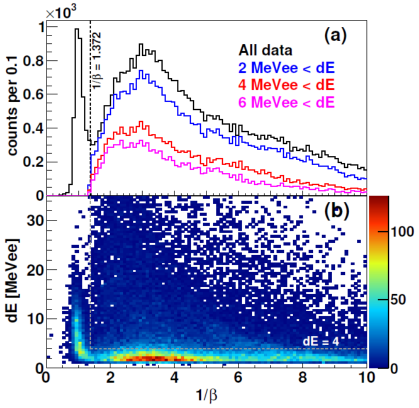
T.Yamaga et.al., arXiv:2404.01773 [nucl-ex]

Mesonic Decay Analysis with the E15 Data

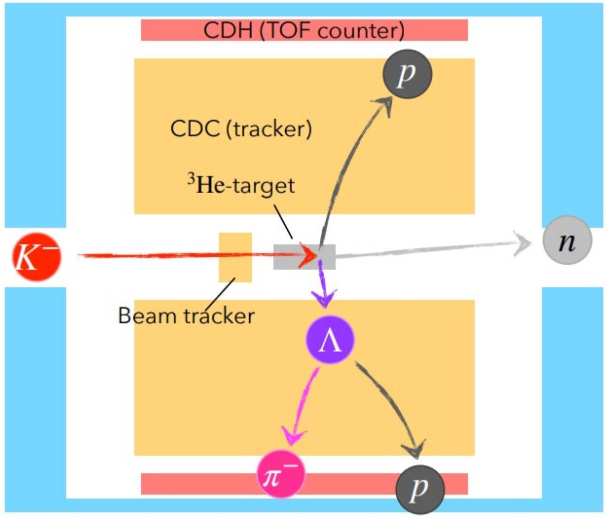
- with neutron detection using a thin scintillation counter array (CDH)
  - ☹ small efficiency (3~9%)
  - ☹ BG from the inner wall of the magnet

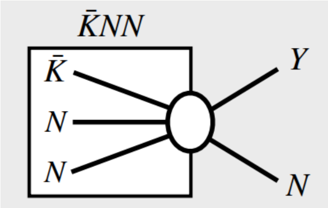




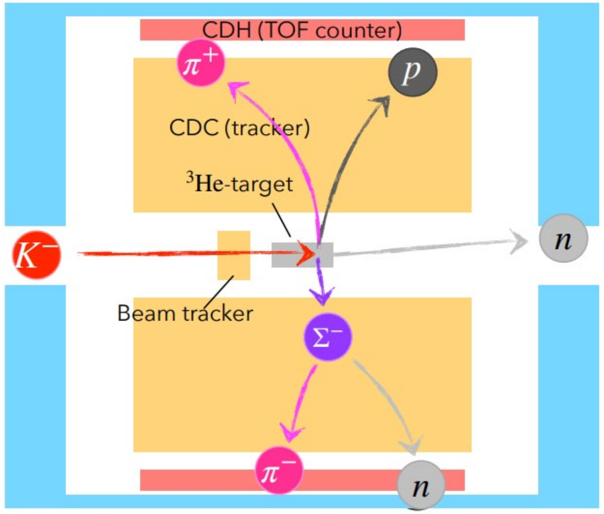


$"K^-pp" \to \Lambda p$

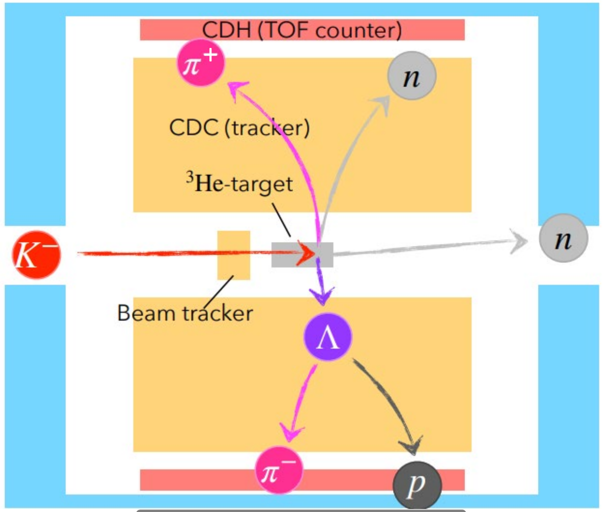




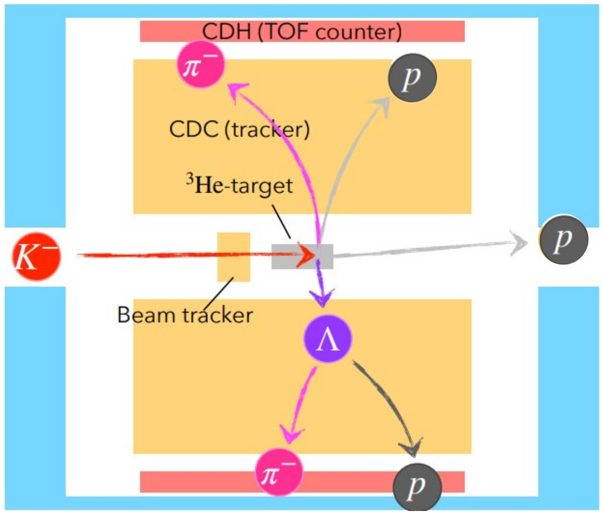
$"K^-pp" \to \pi^{\pm}\Sigma^{\mp}p$

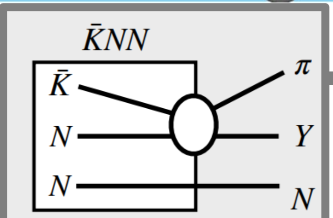


$"K^-pp" \to \pi^+\Lambda n$



$"\bar{K}^0nn" \to \pi^-\Lambda p$





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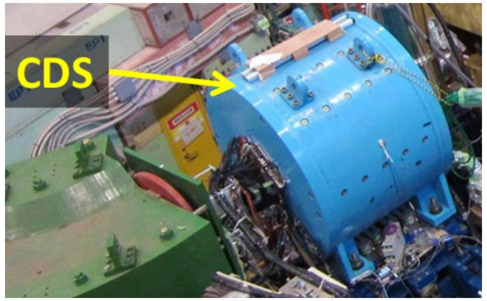
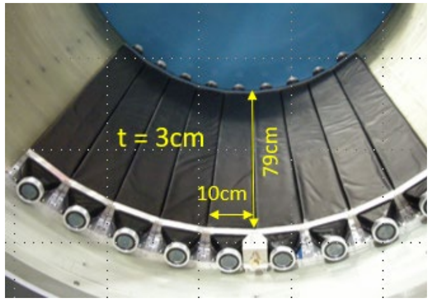
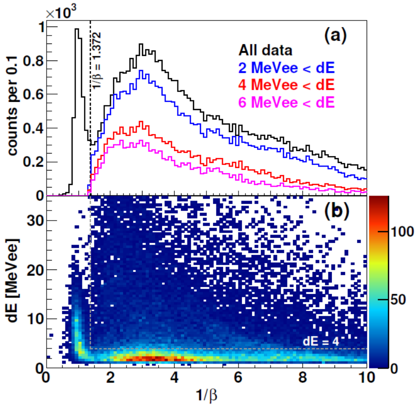
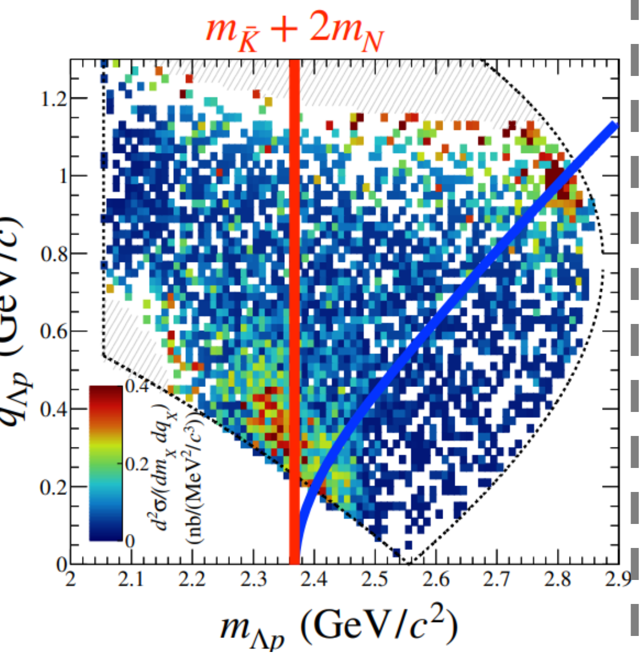


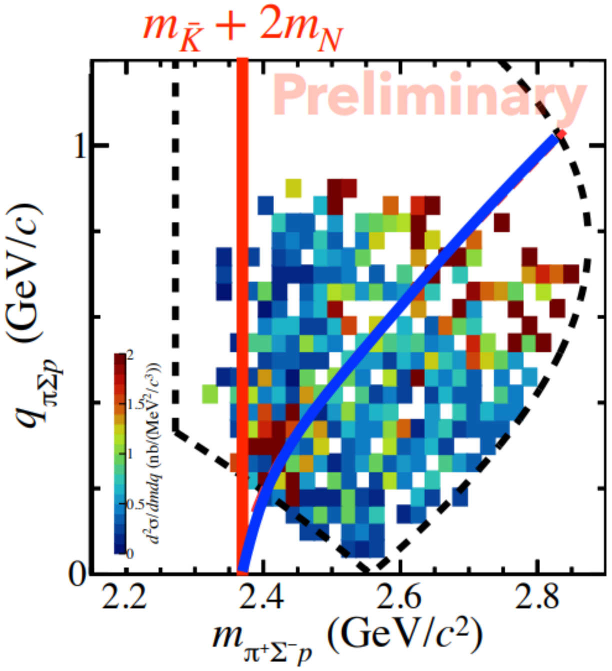




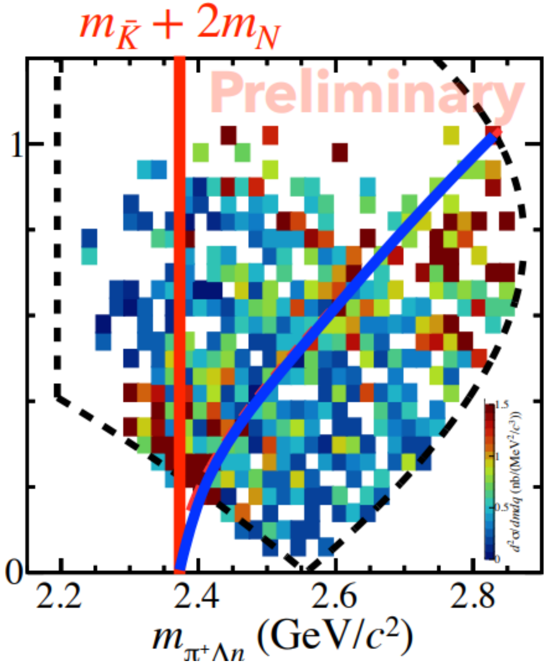
"K^-pp" → Λp



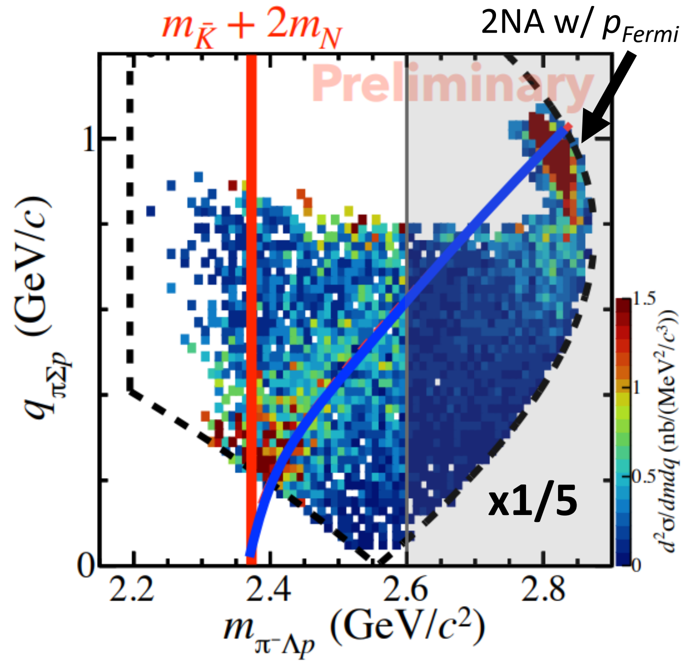
"K^-pp" → $\pi^\pm\Sigma^\mp p$



"K^-pp" → $\pi^+\Lambda n$



"$\bar{K}^0nn$" → $\pi^-\Lambda p$



Similar but not clear peak below M(KNN) due to the phase space

T.Yamaga et.al., arXiv:2404.01773 [nucl-ex]

Mesonic Decay Analysis with the E15 Data

Plane Wave Impulse Approximation

Fit with PWIA

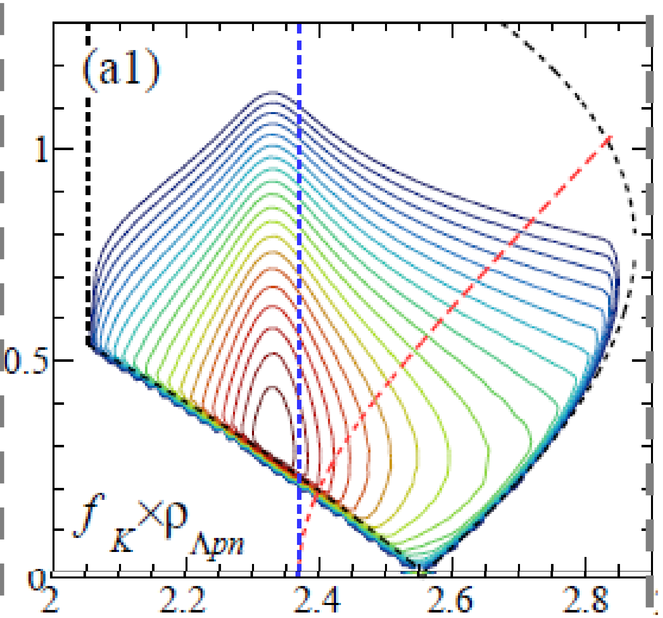
Phase space

Momentum term from spatial integral

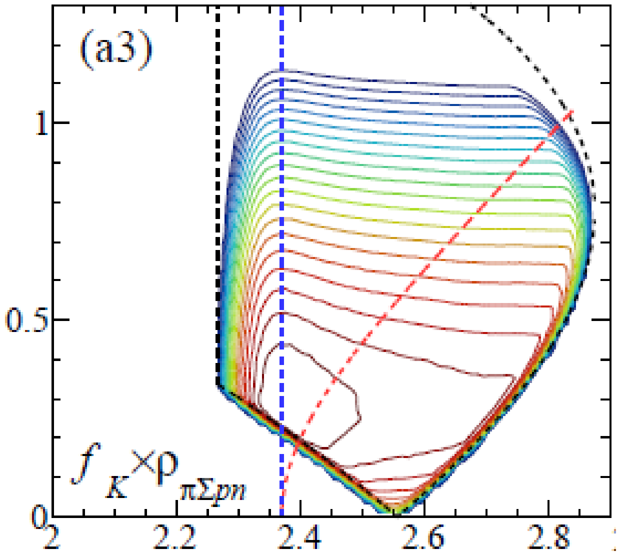
$$\sigma(M,q) \propto \rho(M,q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M-M_{Kpp})^2+(\Gamma_{Kpp}/2)^2} \times exp\left(-\frac{q^2}{{Q_{Kpp}}^2}\right)$$

Energy term (BW type) from time integral

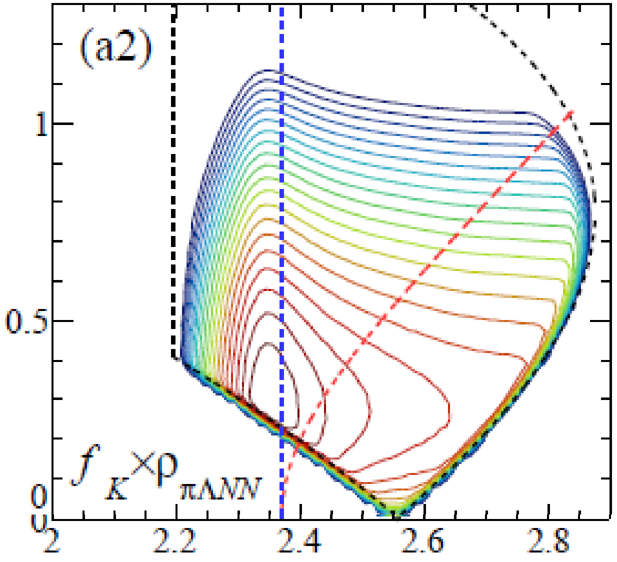
$"K^- pp" \rightarrow \Lambda p$



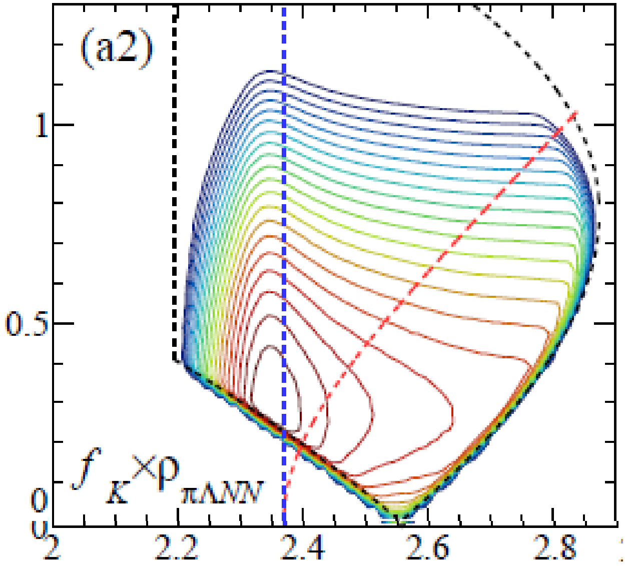
$"K^- pp" \rightarrow \pi^\pm \Sigma^\mp p$



$"K^- pp" \rightarrow \pi^+ \Lambda n$



$"\bar{K}^0 nn" \rightarrow \pi^- \Lambda p$



Employ the same model func. for KNN & QF, with each phase space

T.Yamaga et.al., arXiv:2404.01773 [nucl-ex]

Mesonic Decay Analysis with the E15 Data

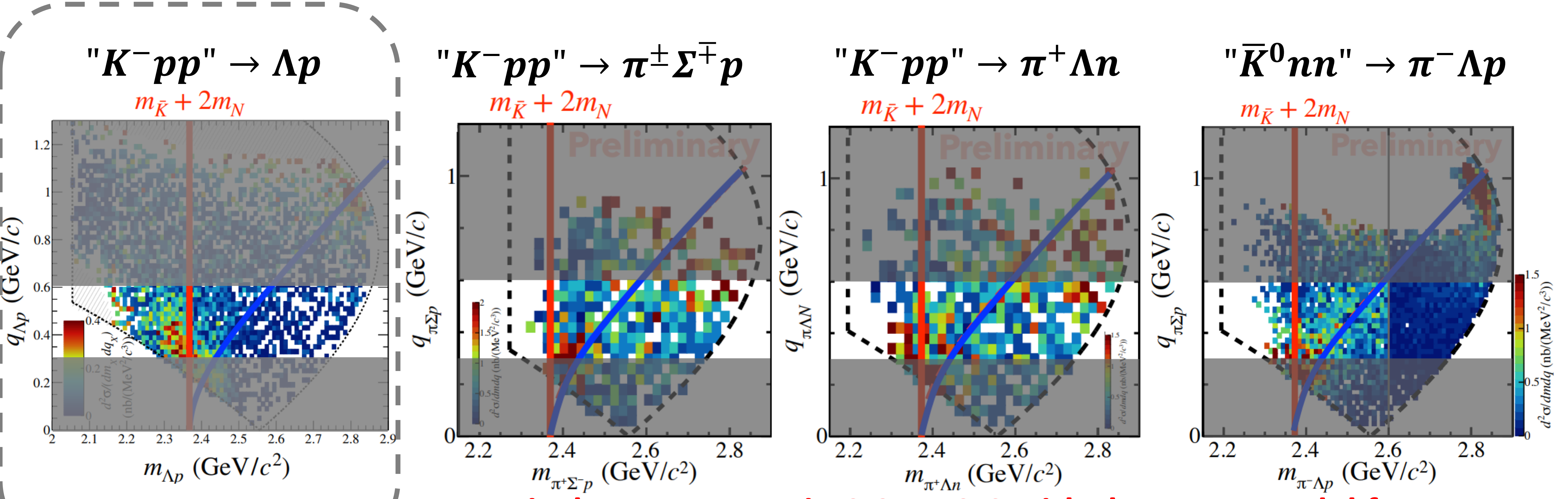
Plane Wave Impulse Approximation

Fit with PWIA

Phase space — Momentum term from spatial integral

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

Energy term (BW type) from time integral



Fit the 1D spectra in 0.3<q<0.6 with the same model func.

T.Yamaga et.al., arXiv:2404.01773 [nucl-ex]

Mesonic Decay Analysis with the E15 Data

Plane Wave Impulse Approximation

Fit with PWIA

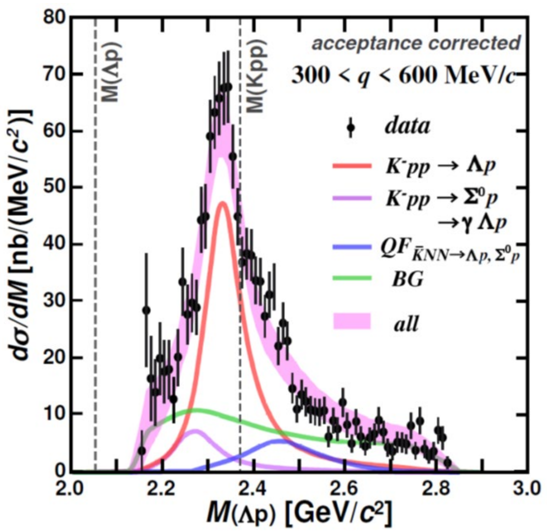
$$\sigma(M,q) \propto \rho(M,q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M-M_{Kpp})^2+(\Gamma_{Kpp}/2)^2} \times exp\left(-\frac{q^2}{{Q_{Kpp}}^2}\right)$$

Phase space

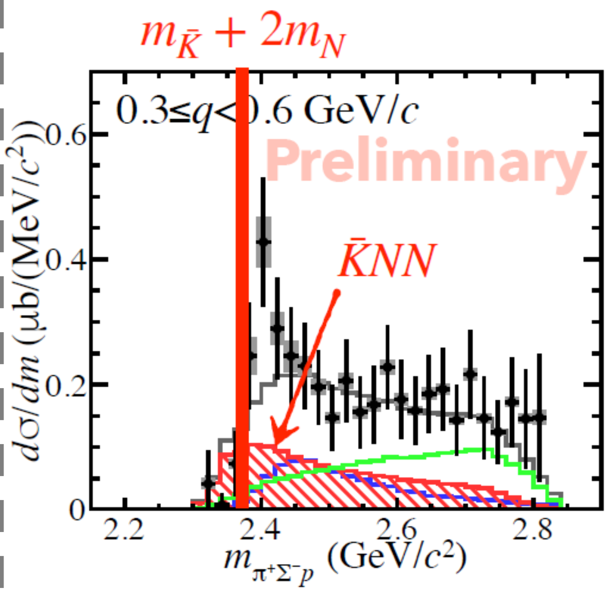
Energy term (BW type) from time integral

Momentum term from spatial integral

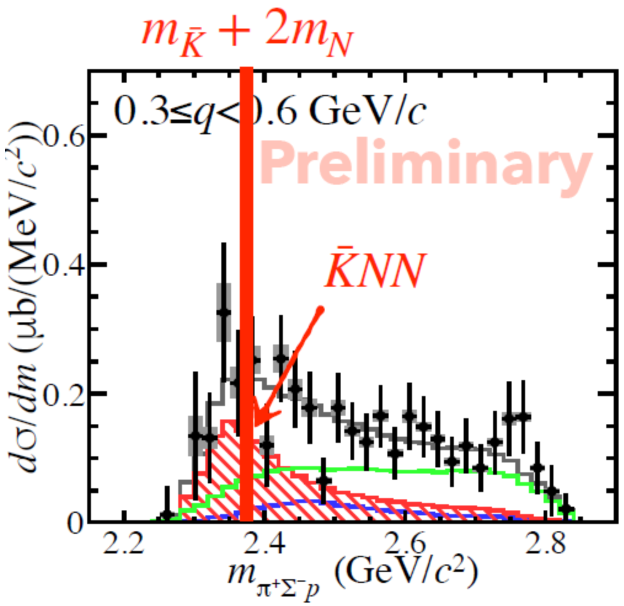
$"K^-pp" \to \Lambda p$



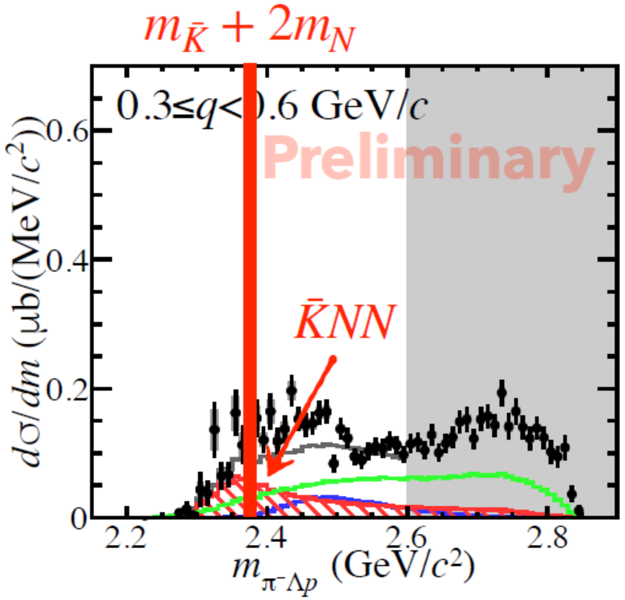
$"K^-pp" \to \pi^\pm\Sigma^\mp p$



$"K^-pp" \to \pi^+\Lambda n$



$"\bar{K}^0nn" \to \pi^-\Lambda p$



With the model func., the spectra are consistently explained.

T.Yamaga et.al., arXiv:2404.01773 [nucl-ex]

Mesonic Decay Analysis with the E15 Data

- $\Gamma_{YN} << \Gamma_{\pi YN}$: mesonic decay is dominant
- $\Gamma_{\pi\Sigma N} \sim \Gamma_{\pi\Lambda N}$: significant contribution of the $I_{KN} = 1$ as well as $I_{KN} = 0$
- $\Gamma_{\pi+\Lambda n} / \Gamma_{\pi-\Lambda p} \sim 2$: if we assume $Br_{K\text{-}pp \to \pi+\Lambda n} = Br_{K0nn \to \pi-\Lambda p} \to \sigma_{K\text{-}pp} / \sigma_{K0nn} \sim 2$

"K^-pp" $\to \Lambda p$

$\sigma^{tot}_{\bar{K}NN} \times Br\ (\mu b) =$
$9.3 \pm 0.8^{+1.4}_{-1.0}$ [all]
$5.5 \pm 0.5^{+0.8}_{-0.6}$ [<M(KNN)]

"K^-pp" $\to \Sigma^0 p$

$\sigma^{tot}_{\bar{K}NN} \times Br\ (\mu b) =$
$5.3 \pm 0.4^{+0.8}_{-0.6}$ [all]
$3.1 \pm 0.2^{+0.5}_{-0.4}$ [<M(KNN)]

"K^-pp" $\to \pi^+\Sigma^- p$

$\sigma^{tot}_{\bar{K}NN} \times Br\ (\mu b) =$
$38 \pm 3 \pm 3$ [all]
$3.2 \pm 0.2 \pm 0.2$ [<M(KNN)]

"K^-pp" $\to \pi^-\Sigma^+ p$

$\sigma^{tot}_{\bar{K}NN} \times Br\ (\mu b) =$
$110 \pm 8 \pm 8$ [all]
$9.4 \pm 0.4 \pm 0.7$ [<M(KNN)]

"K^-pp" $\to \pi^+\Lambda n$

$\sigma^{tot}_{\bar{K}NN} \times Br\ (\mu b) =$
$62 \pm 11 \pm 9$ [all]
$15.5 \pm 2.7 \pm 2.1$ [<M(KNN)]

"$\bar{K}^0 nn$" $\to \pi^-\Lambda p$

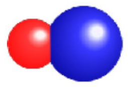
$\sigma^{tot}_{\bar{K}NN} \times Br\ (\mu b) =$
$29 \pm 3 \pm 3$ [all]
$7.2 \pm 0.6 \pm 0.7$ [<M(KNN)]

More precise measurements and theoretical investigations are needed

Need Further Investigations

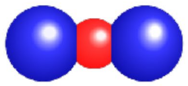
to establish the kaonic nuclei

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



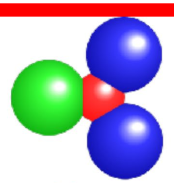
K⁻p

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

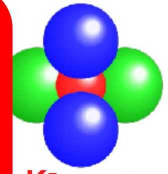


K⁻pp

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

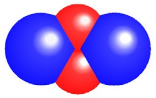


K⁻ppn



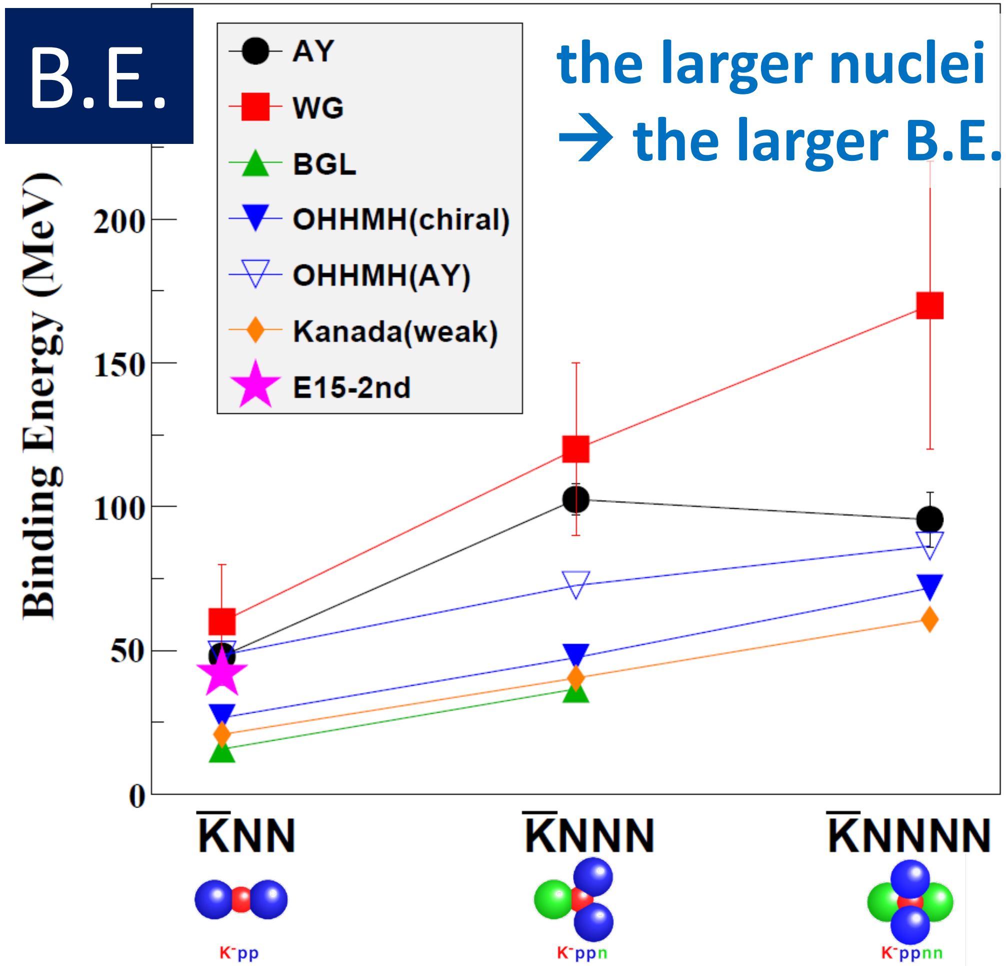
K⁻ppnn

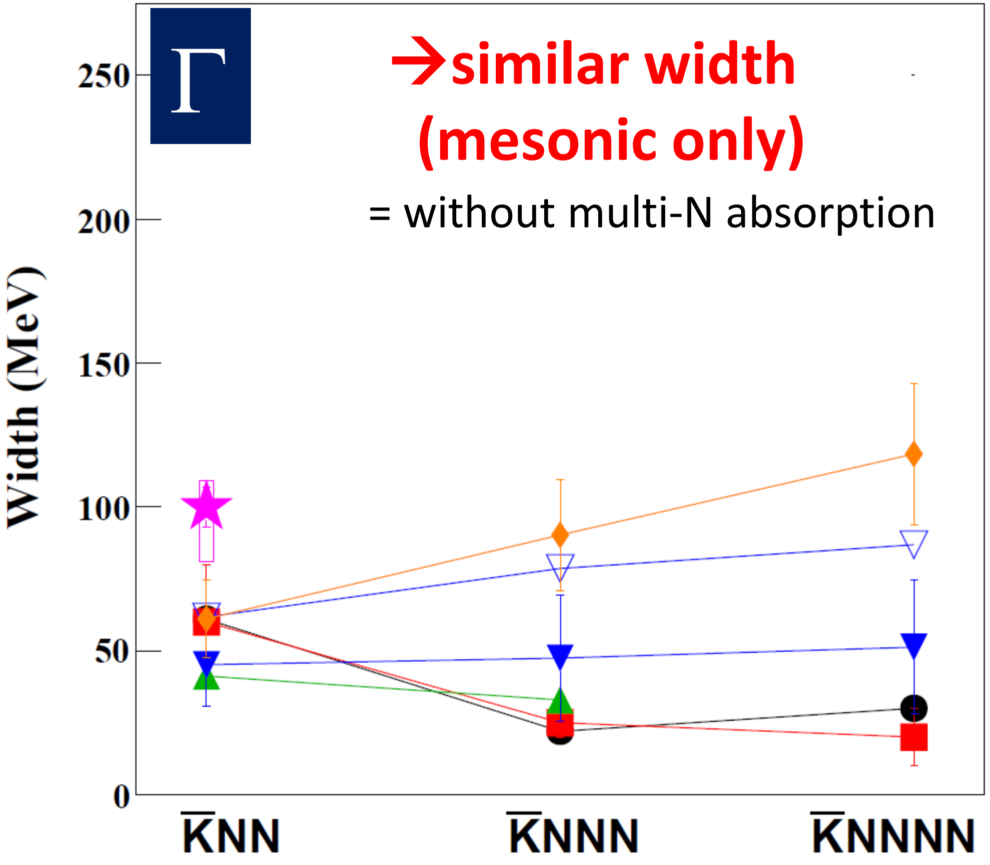
- **Double kaonic nuclei**
  - Much compact and dense system?



K⁻K⁻pp

Mass Number Dependence of Kaonic Nuclei



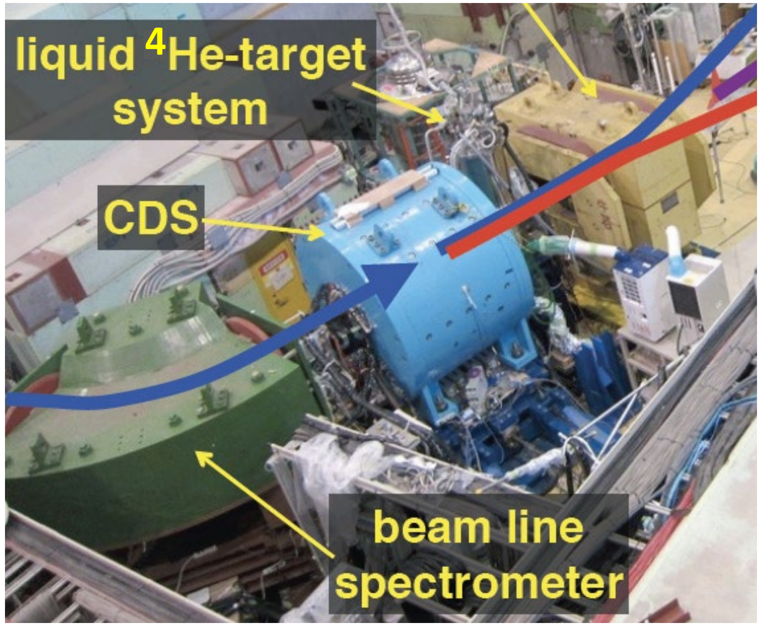


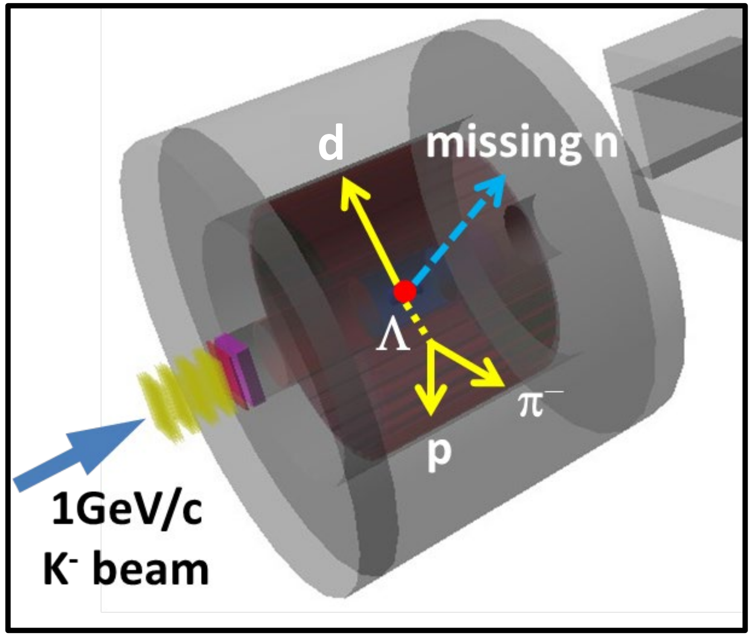
- **Systematic measurements will provide more conclusive evidence of the kaonic nuclei**

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

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

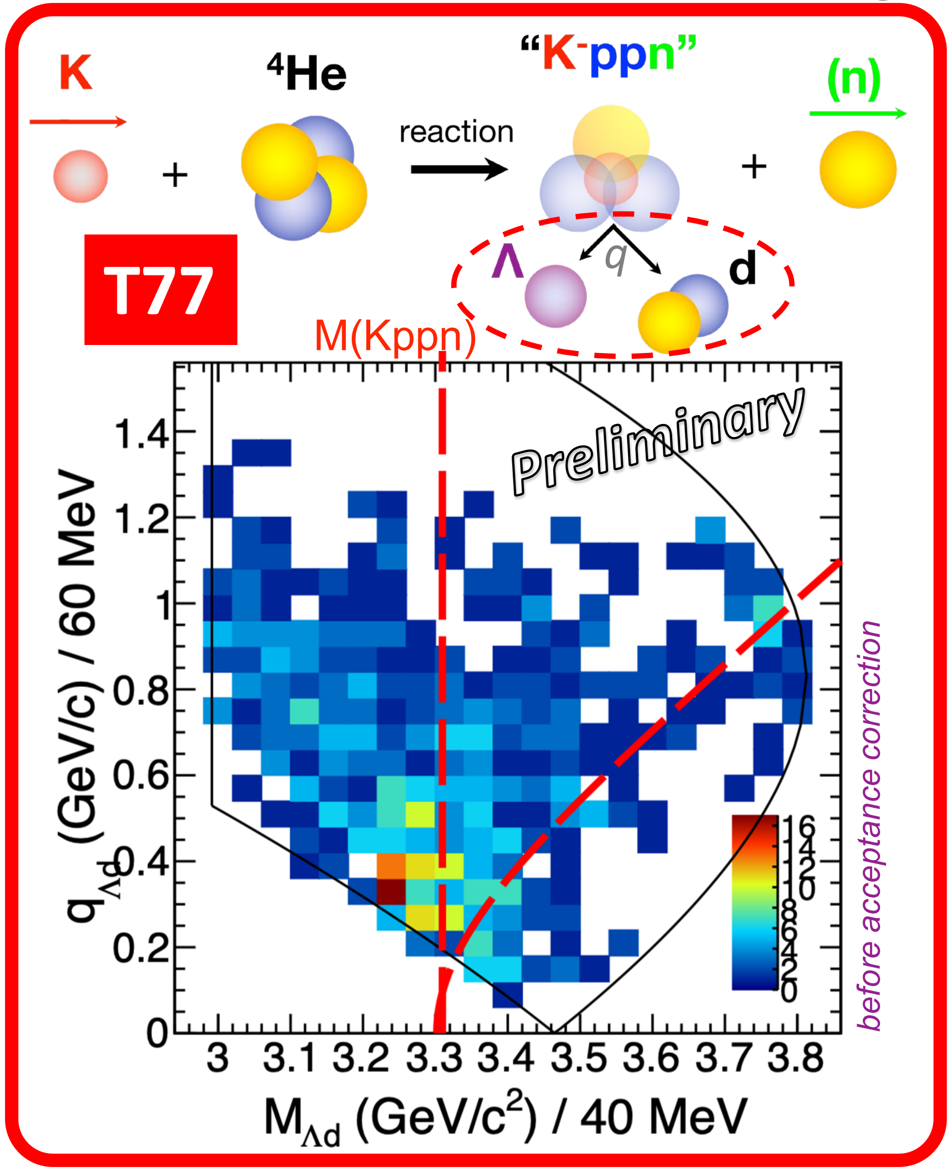
- An analysis of the **Λdn** final state with **K^{-4}He** reaction at **1 GeV/c** has been conducted
  - T77: lifetime measurement of $^4_\Lambda H$ in 2020
- The results will be updated with a part of the E73 controlled data
  - E73: lifetime measurement of $^3_\Lambda H$ in 2024 (***now in beam time!***)

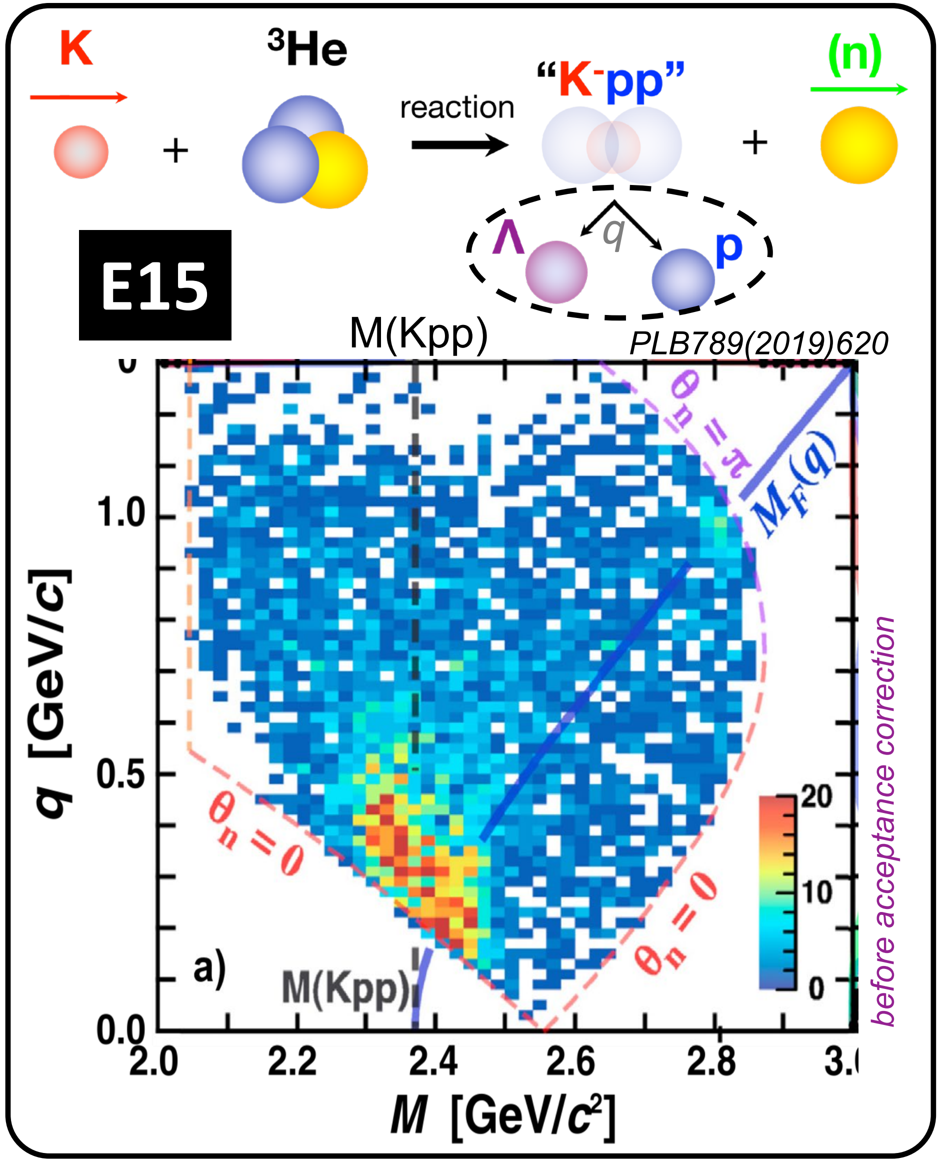




Experiment	K^- on target
E15 (^{3}He)	~42 x 10^9
T77 (^{4}He)	~6 x 10^9
E73 (^{4}He)	~6 x 10^9

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





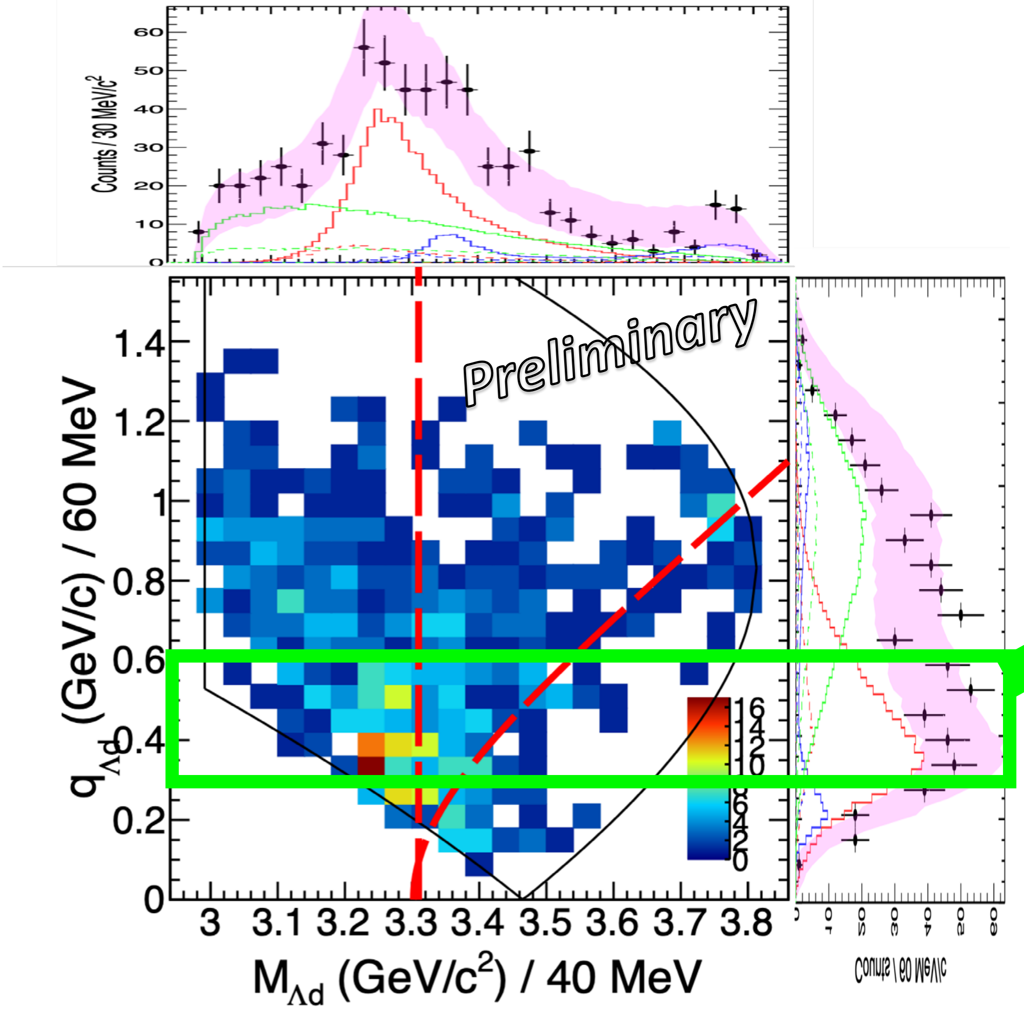
- **Two distributions are quite similar**
- structure below the threshold (**seems *q*-independent**), QF-K, BG

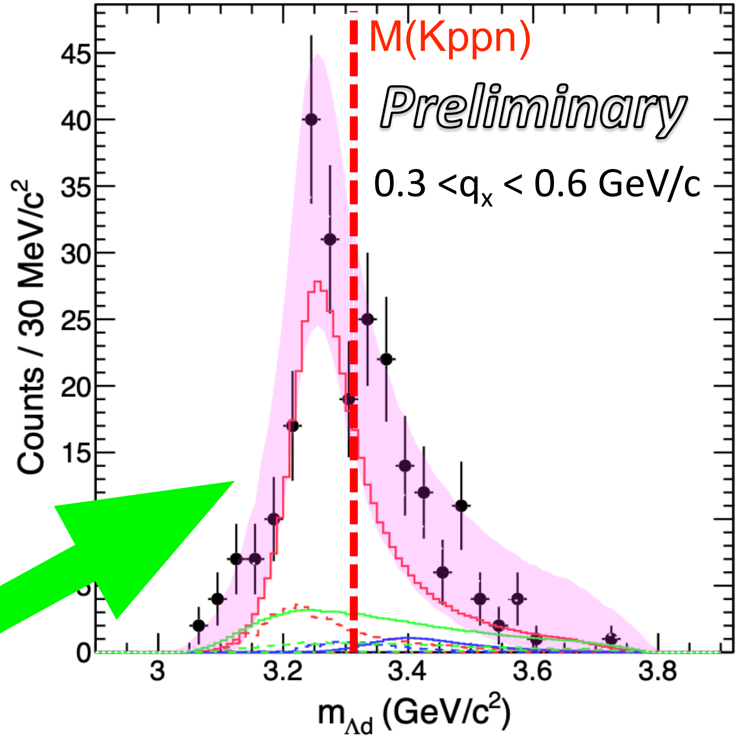
$K^{-4}He \rightarrow \Lambda dn$ Analysis with the T77 Data

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

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

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





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

$\Gamma_X = \sim 100\ MeV$

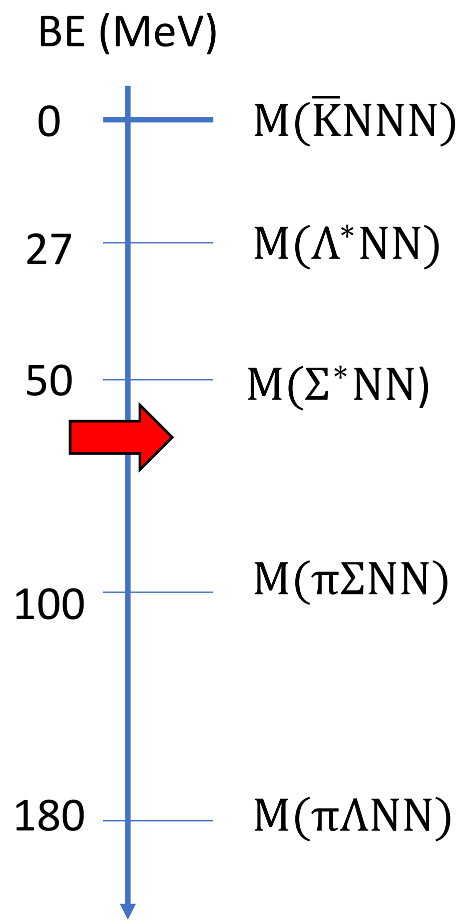
$\sigma_{X \to \Lambda d} \sim 4\ \mu b$

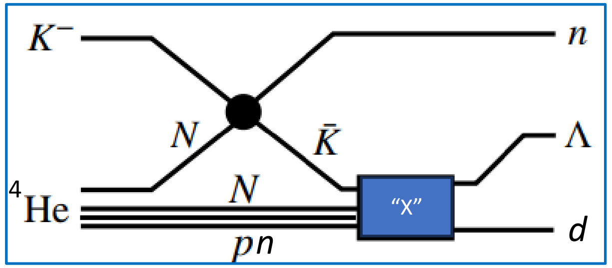
$K^{-4}He \rightarrow \Lambda dn$ Analysis with the T77 Data

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

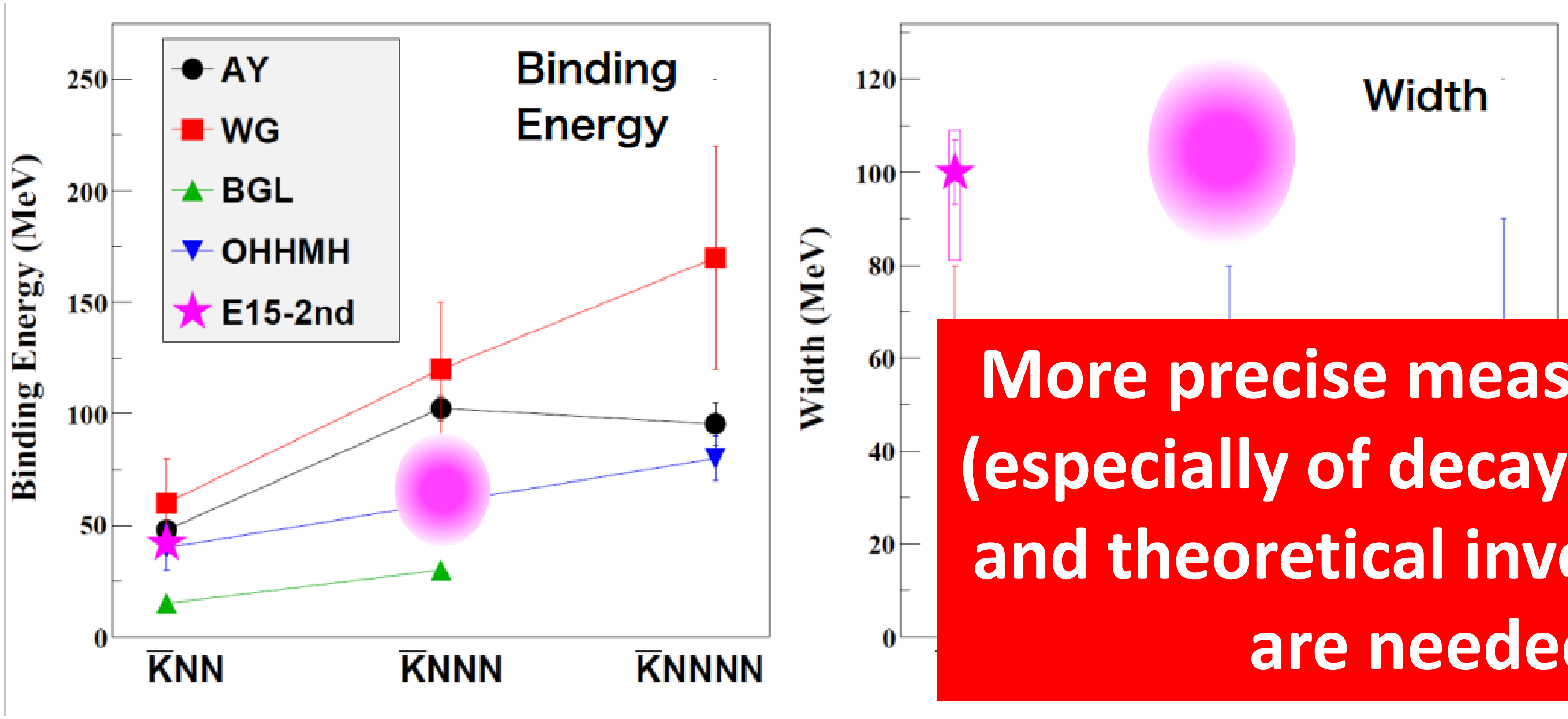




$K^{-4}He \rightarrow \Lambda dn$ Analysis with the T77 Data

What is the observed structure? [Discussion]

If "X" is "K⁻ppn"

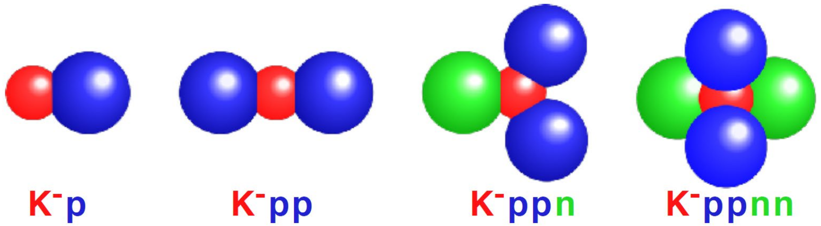


More precise measurements (especially of decay branches) and theoretical investigations are needed

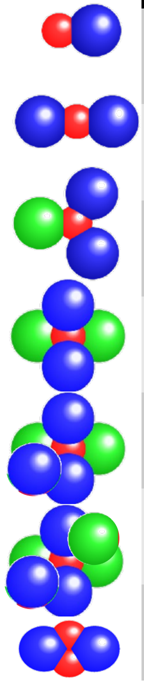
- The binding energy is compatible with some theoretical predictions
- The width is larger than theoretical predictions

New Kaonic Nuclei Project at J-PARC

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

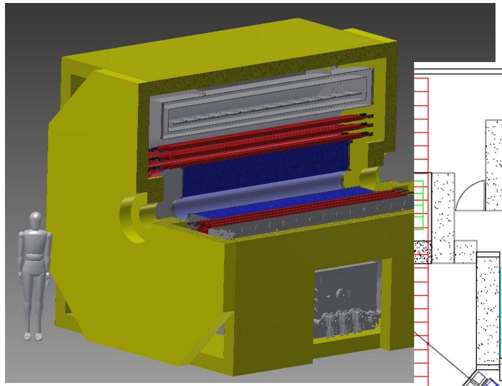


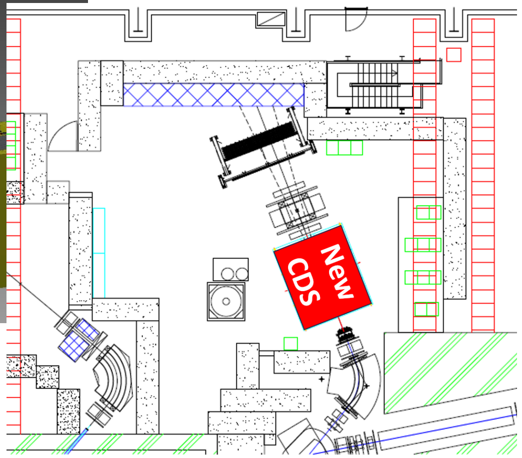
Strategy



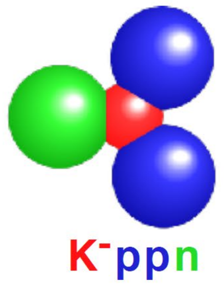
	Reaction	Decays	Key	Experiment
$\bar{K}N$	d(K$^-$,n)	$\pi^{\pm 0}\Sigma^{\mp 0}$	n/γ identification	Future
$\bar{K}NN$	^{3}He(K$^-$,N)	Λp/Λn	polarimeter	P89
$\bar{K}NNN$	^{4}He(K$^-$,N)	Λd/Λpn	large acceptance	E80 ← **A first step**
$\bar{K}NNNN$	^{6}Li(K$^-$,d)	Λt/Λdn	many body decay	Future
$\bar{K}NNNNN$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



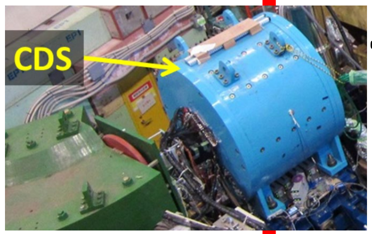


We take a step-by-step approach



$\bar{K}NNN$ @ E80

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



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

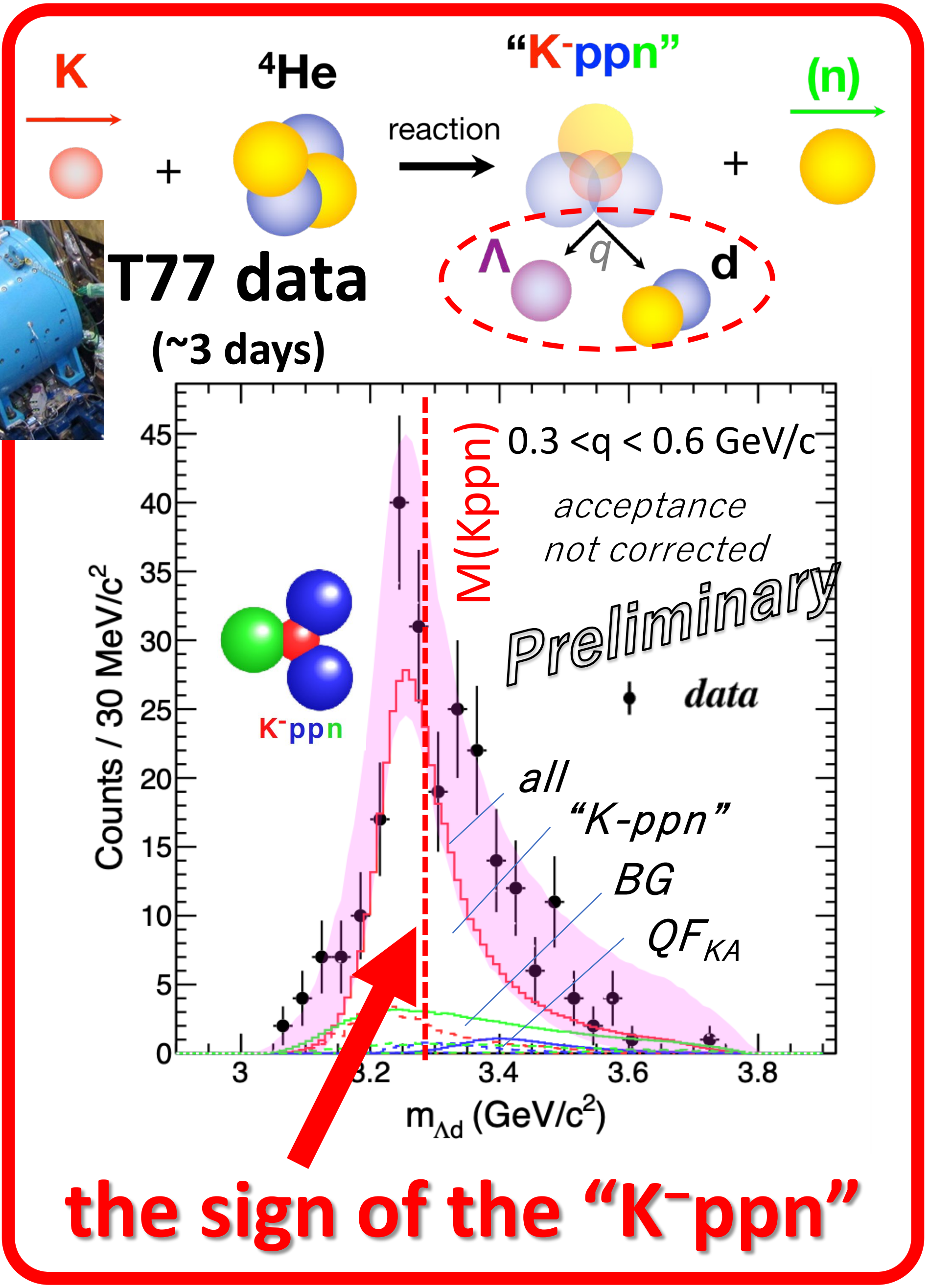
- "K-ppn"→Λd 2-body decay

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

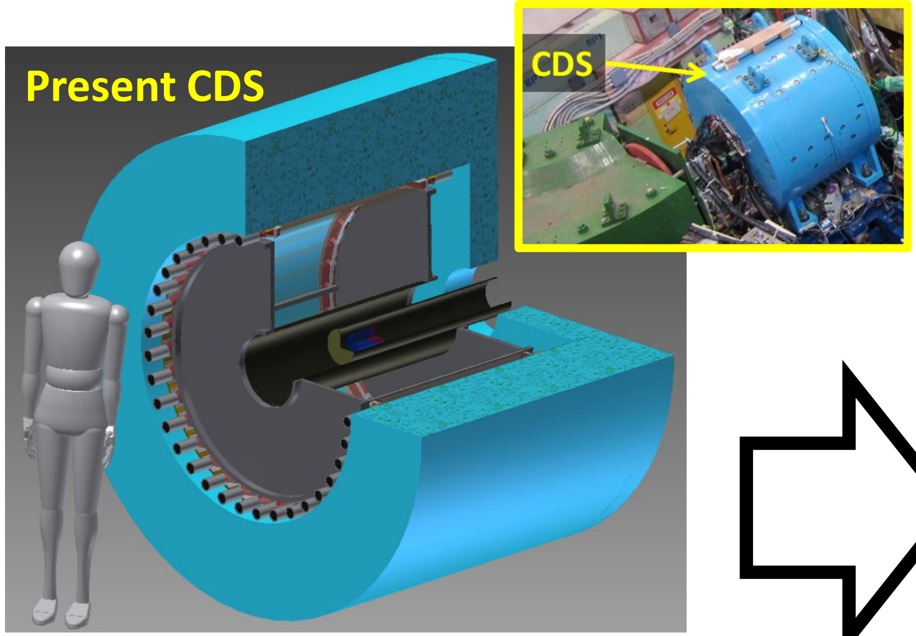
- "K-ppn"→Λpn 3-body decay

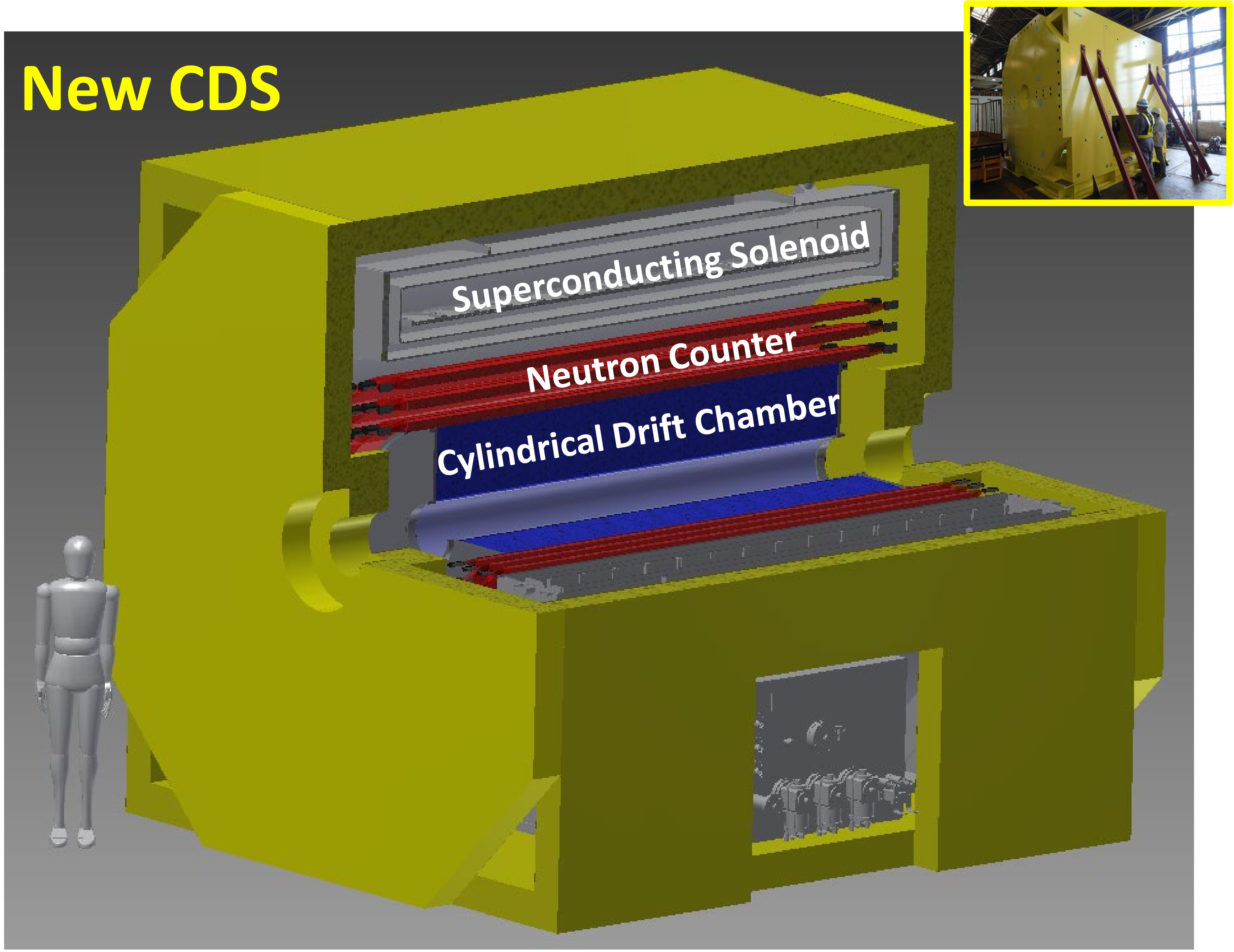
- **Feasibility study of spin-spin correlation measurement for P89**
  - *e.g.*, installing a prototype module of a polarimeter

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



New Cylindrical Detector System (CDS)





✓**Solid angle: x1.6** (59% → 93%)
✓**Neutron eff.: x8** (3% → 15%x1.6)

Superconducting Solenoid Magnet

- Same design as "the detector solenoid magnet" for COMET-I

being constructed in cooperation with the J-PARC Cryogenics Section

- 3.3m x 3.3m x 3.9m, ~108t in total
- Max. field of 1.0T @ center
  - 189A – 10V
- NbTi/Cu SC wire, 98km in total
- **Conduction-cooling with GM*3**
- Semi-active quench-back system
- **Will be completed in FY2024**

SHI FA-50
(air cooling)

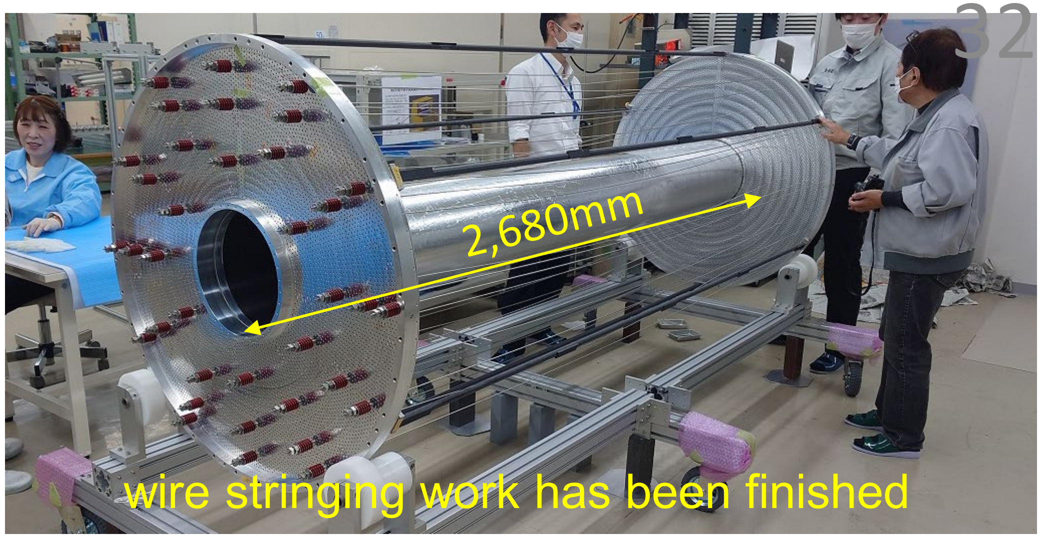
SHI RDE-418D4

Completed in FY2023

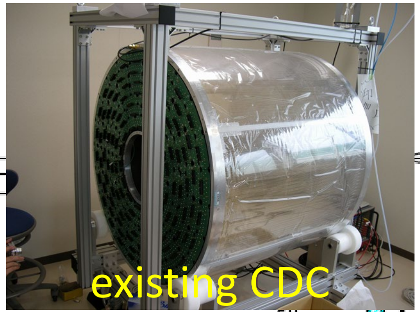
Completed in FY2022

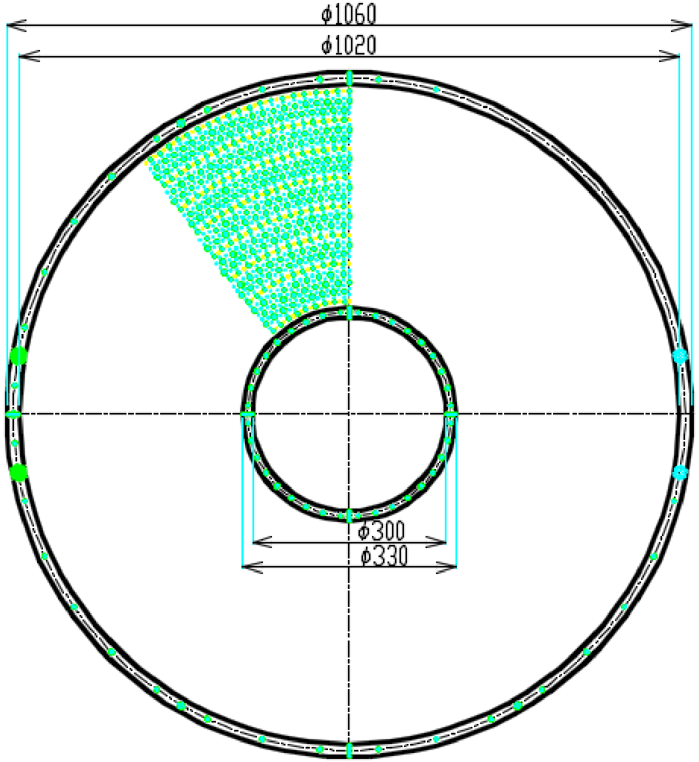
Cylindrical Drift Chamber

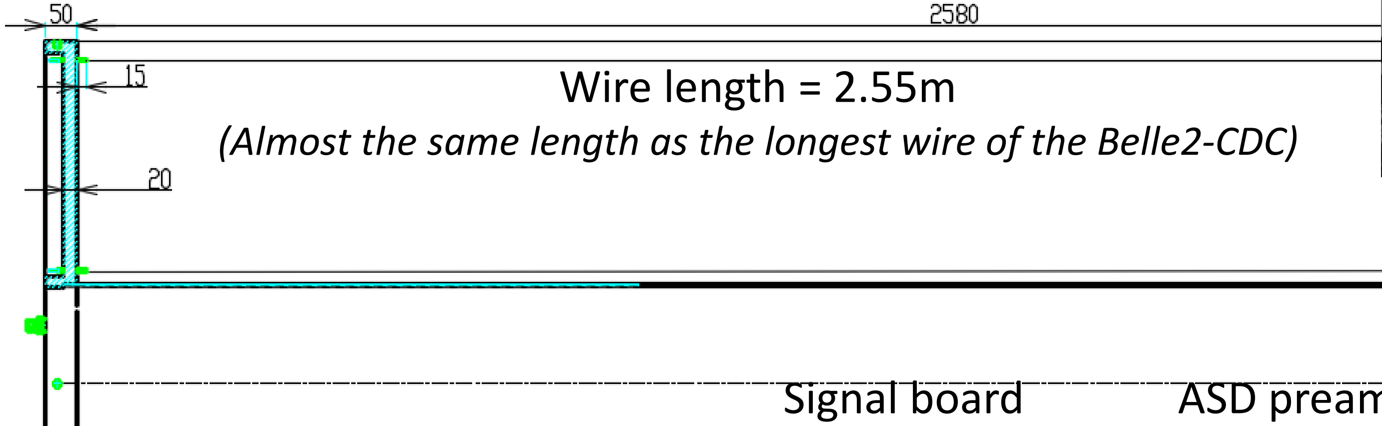
- The same design of the present end-cap
  - New CDC is 3 times the length of the existing CDC

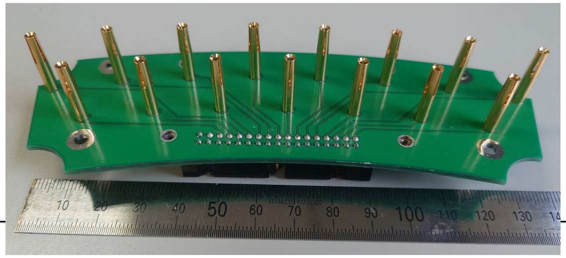


Will be completed next month, and commissioning starts



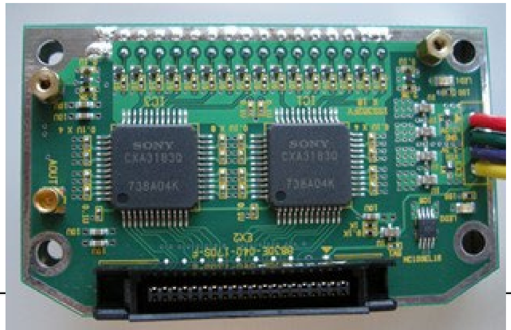






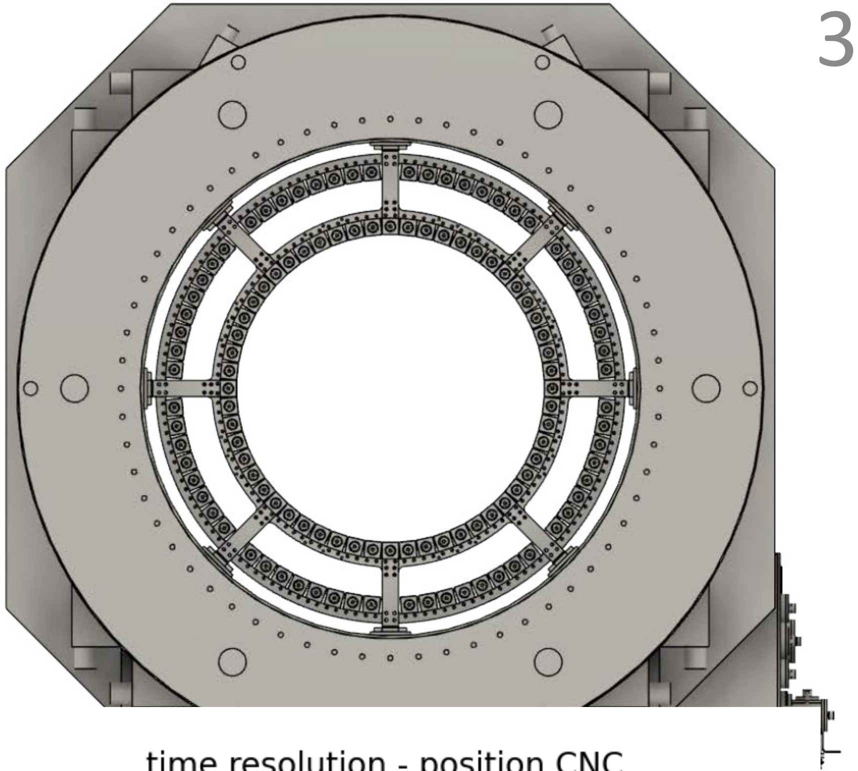
Signal board

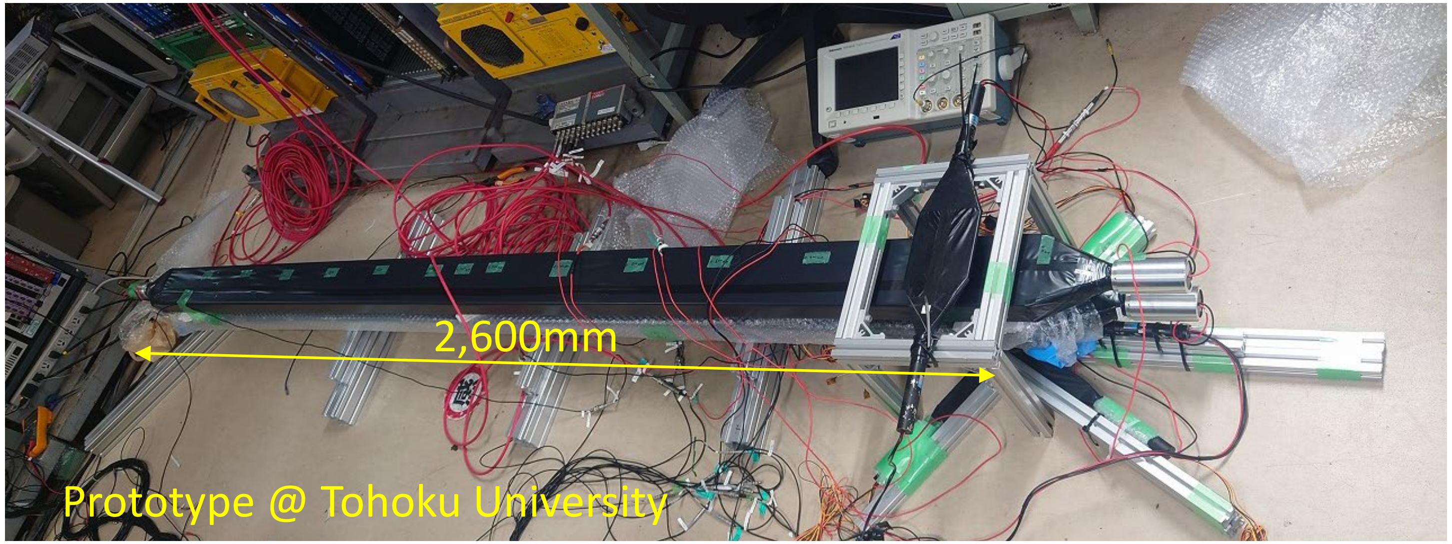
ASD preamplifier board

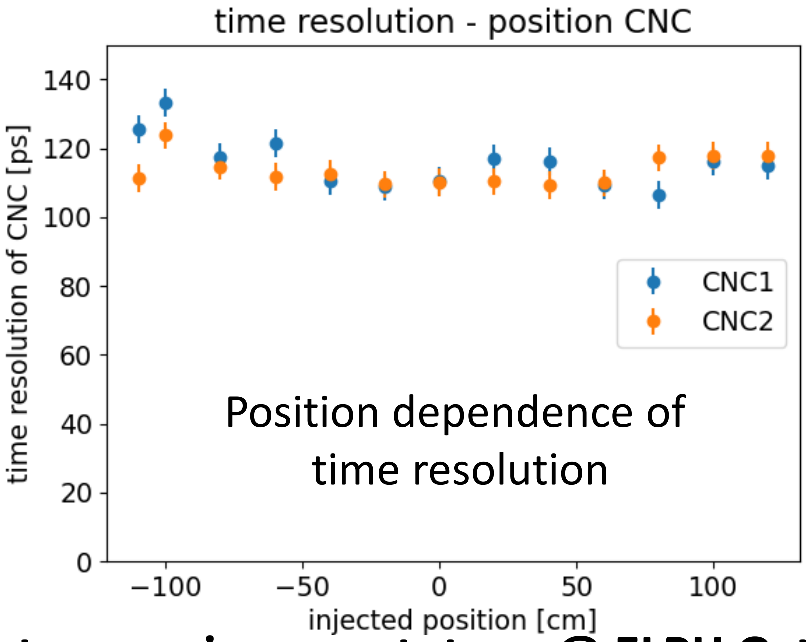


Neutron Counter

- scintillator array: 2 layers, 12cm thickness
- ELJEN EJ-200: (T)60mm, (W)60mm, (L)3,000mm
- 1.5-inch FM-PMT [H8409(R7761)]
  & MPPC array [S13361-6050AE-04]
- Neutron detection efficiency of 12~36%
- **Design work is on going**
- **Will be fabricated in FY2024**







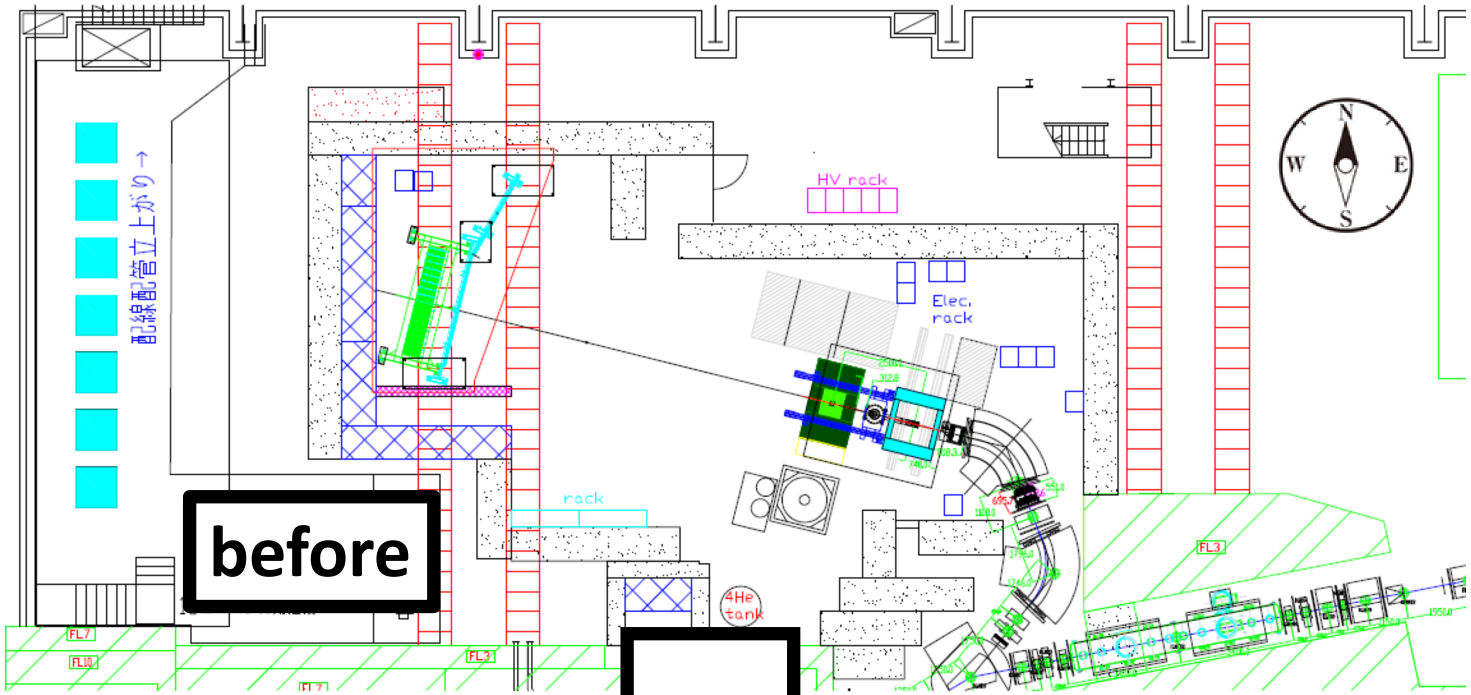
Test exp. using a prototype @ ELPH Oct.2023

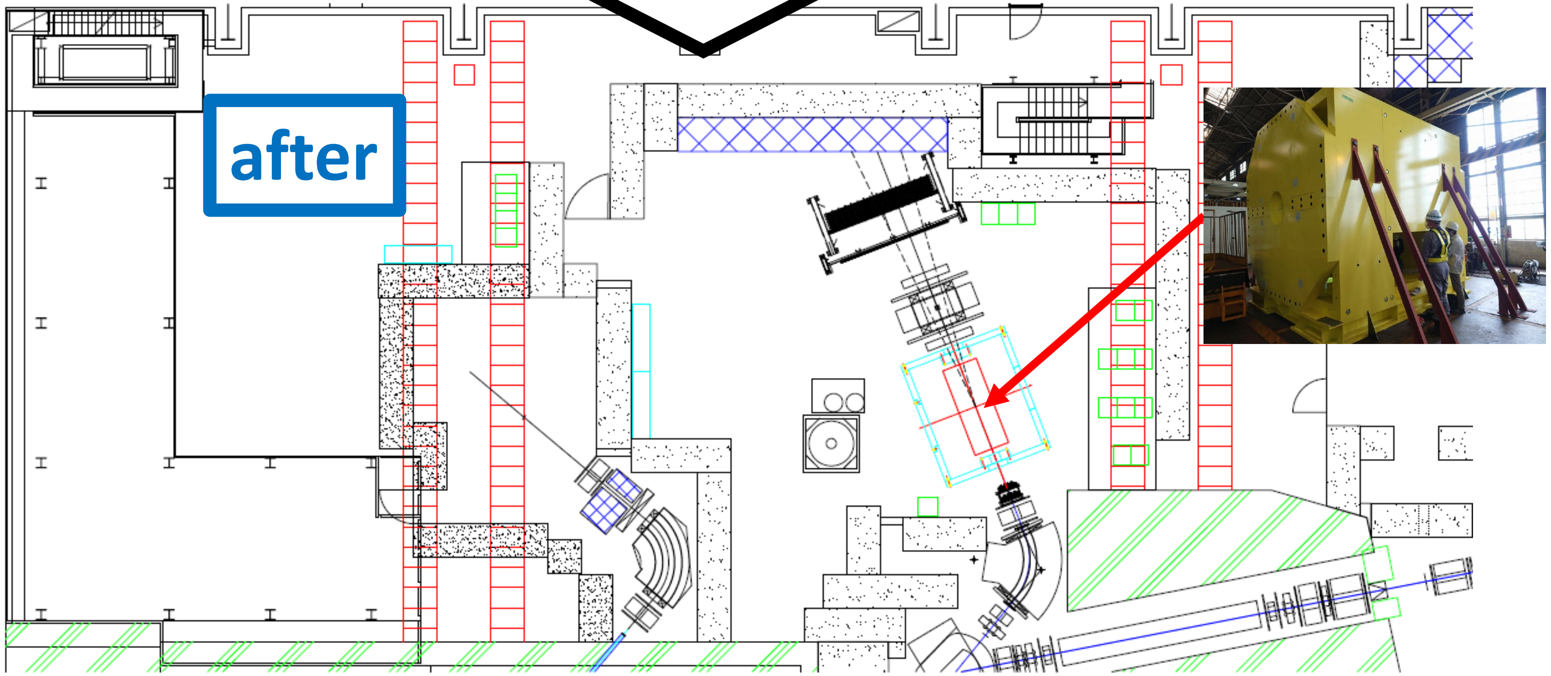
K1.8BR Upgrade

- **We have proposed a new configuration of the beam line**
  - ➢ K- yield is expected to increase by **~ 1.4 times @ 1.0 GeV/c** with π/K ~ 2

Shorten the beamline (~2.5m) by removing the final D5 magnet

Relative beam-line length (beam yield)	D5	D4
Present CDS	0 (x1)	-3.7m (x1.6)
New CDS	+1.2m (x0.9)	**-2.5m (x1.4)**





Schedule

<table>
<tr><th rowspan="2"></th><th colspan="4">FY2022</th><th colspan="4">FY2023</th><th colspan="4">FY2024</th><th colspan="4">FY2025</th><th colspan="4">FY2026</th><th colspan="4">FY2027</th></tr>
<tr><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th></tr>
<tr><td>SC Solenoid Magnet</td><td colspan="2">Design</td><td colspan="2">Purchase (SC Wire)</td><td colspan="8">Construction</td><td colspan="4">Stored at KEK</td><td>Installation</td><td colspan="3" rowspan="3">Integration, Test & Commissioning</td><td rowspan="3">Commissioning w/ Beam</td><td rowspan="3">Physics Run</td><td colspan="2" rowspan="3">Analysis & Pblication</td></tr>
<tr><td>CDC</td><td colspan="4">Design</td><td colspan="5">Construction</td><td colspan="8">Test & Commissioning</td></tr>
<tr><td>NC</td><td colspan="10">Design & R&D</td><td colspan="2">Purchase (Scinti.)</td><td>Assembly</td><td colspan="4">Test & Commissioning</td></tr>
<tr><td>K1.8BR Beam Line</td><td colspan="15">E73(CDS) -> E72(HypTPC) Experiments</td><td colspan="2">Upgrade</td><td colspan="7">E80 Experiment</td></tr>
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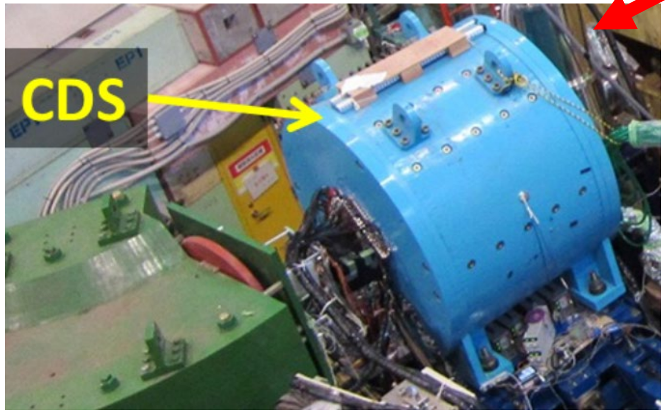
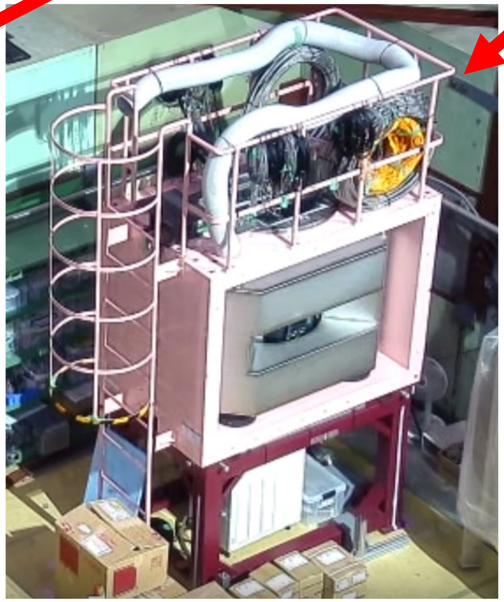
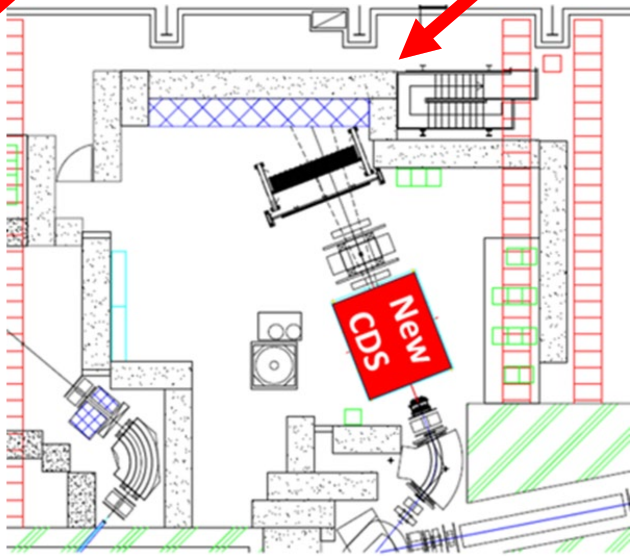
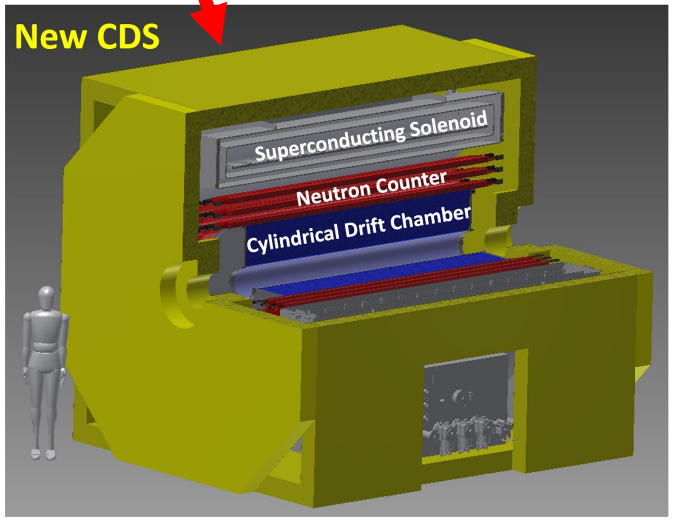


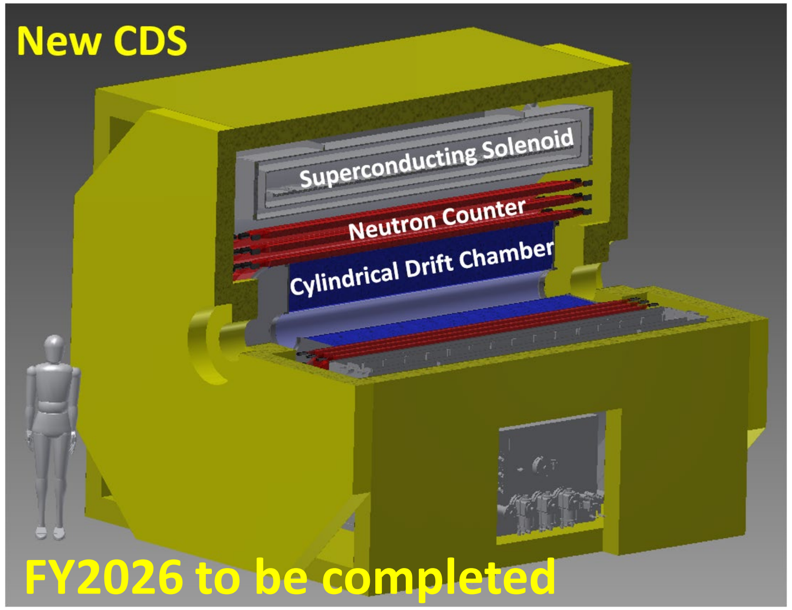


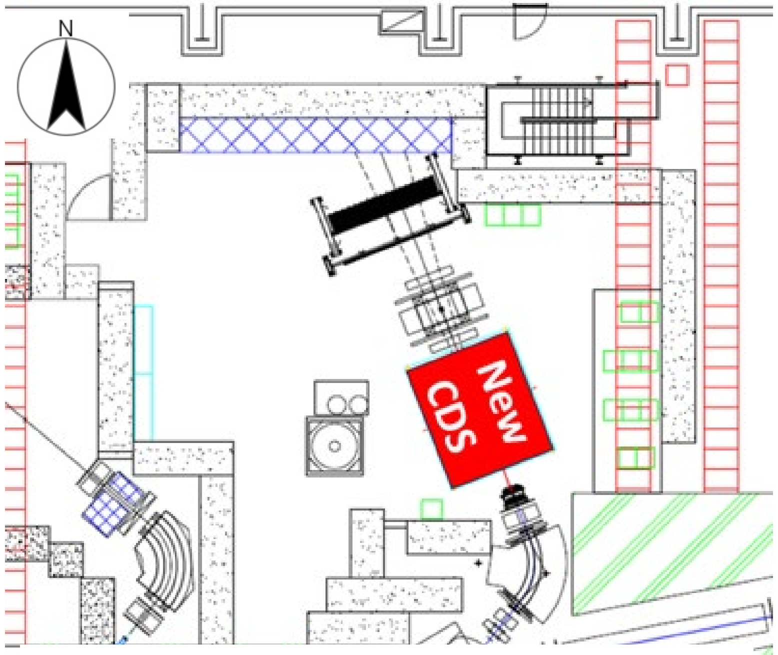




Summary

- 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 to improve kaon yield





Hope to modify around FY2025

J-PARC E80 Collaboration

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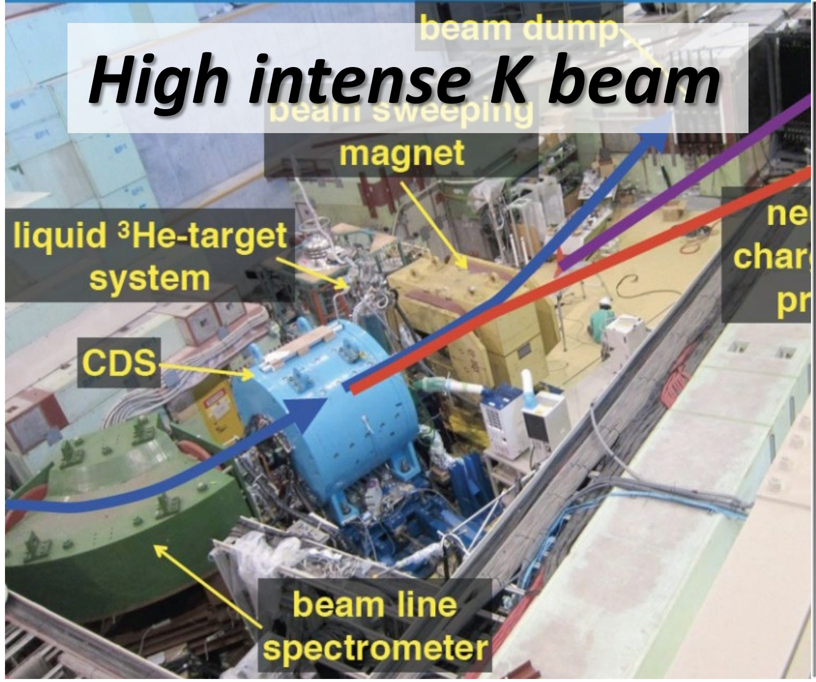
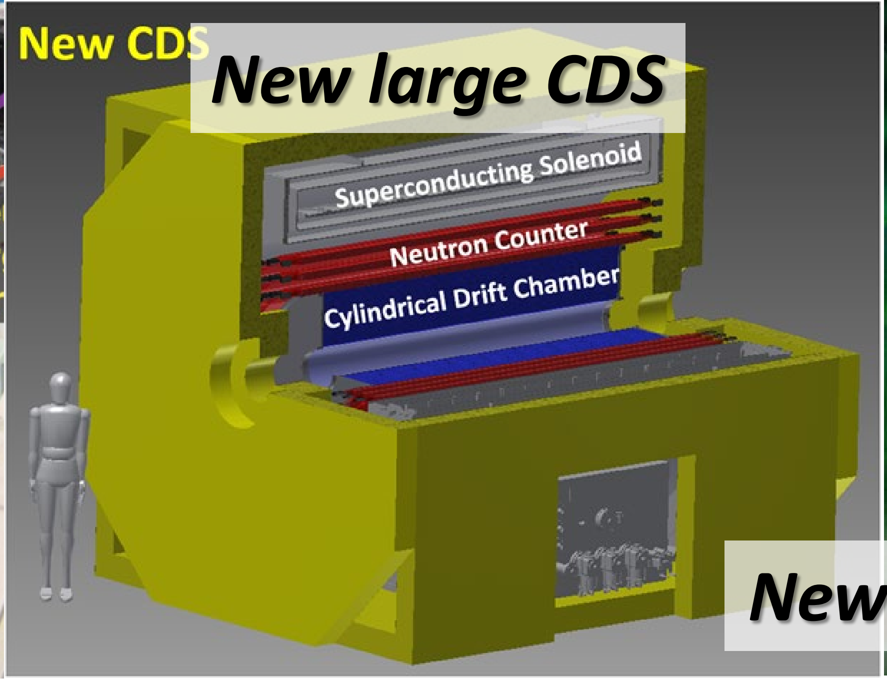
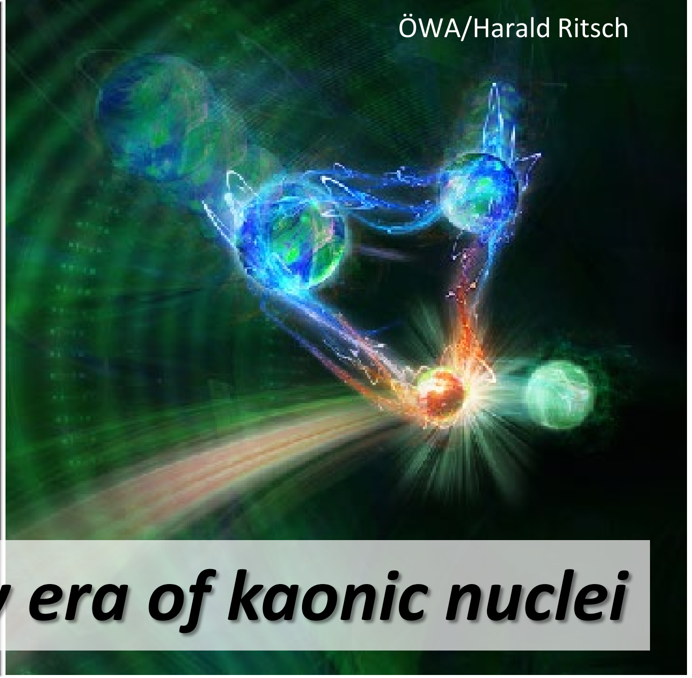
We're looking for new collaborators!

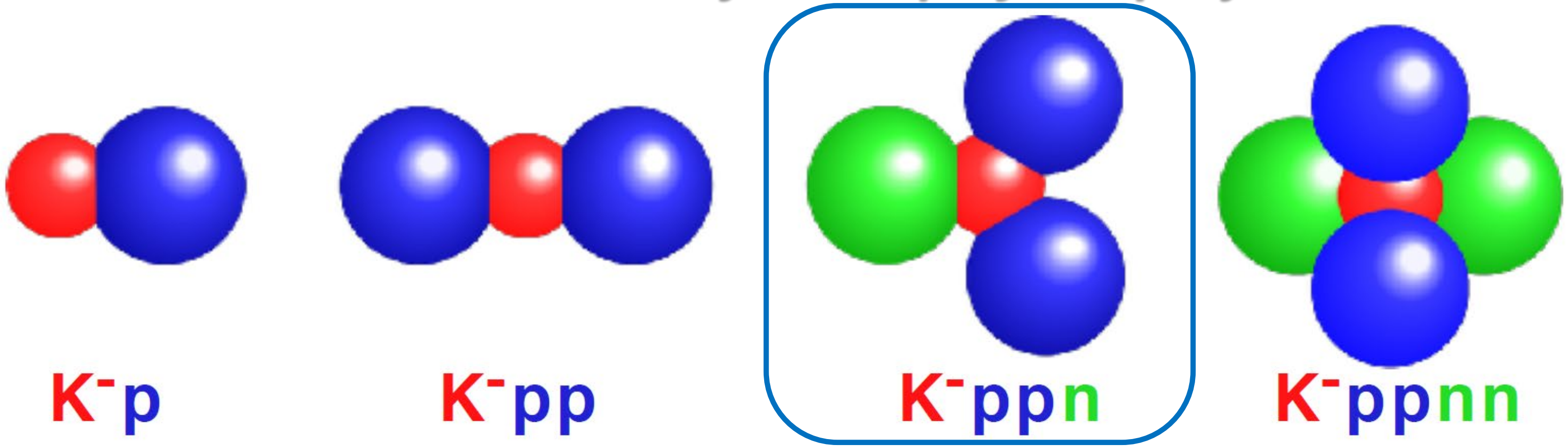






Thank you for your attention!

A first step of the project



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