New Frontier of Kaonic Nuclei at J-PARC

F. Sakuma, RIKEN

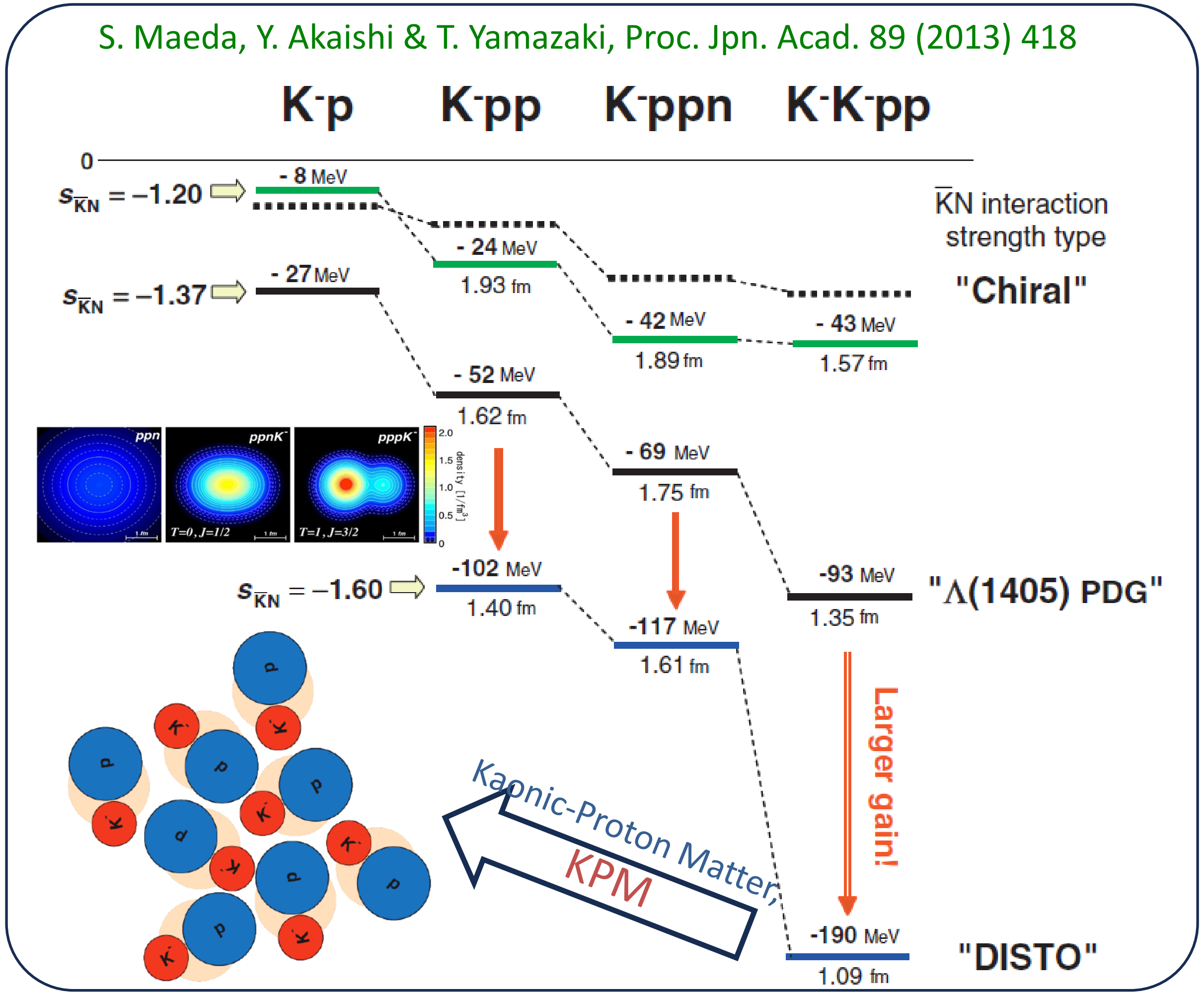
sakuma@ribf.riken.jp

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

Many Thanks, Prof. Toshimitsu Yamazaki

-- A pioneer of kaonic nuclei --

- We had many discussions on kaonic nuclei, especially on "K^-K^-pp" experiments
  - $p^{bar}+{}^3He$ / p+p reactions
- He provided many wonderful ideas
  - lead to the systematic study of kaonic nuclei
- Thank you very much for nearly 20 years of inspiration and support
  - since the beginning of my career



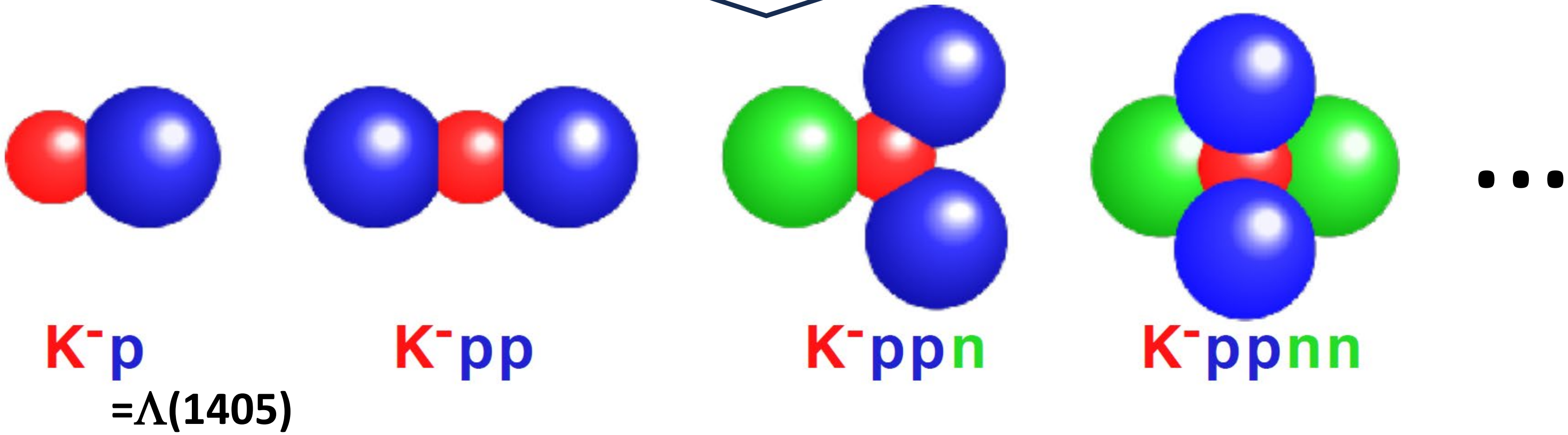
What Are "Kaonic Nuclei"?

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

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

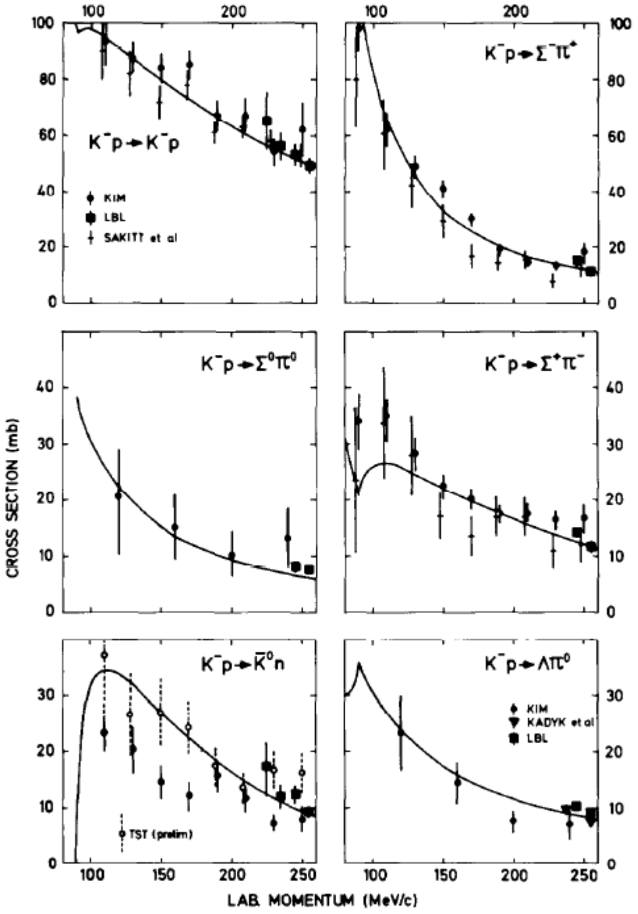
$$\bar{\mathbf{K}} = \begin{pmatrix} \bar{K}^0 \\ K^- \end{pmatrix} \begin{matrix} \bar{d}s \\ \bar{u}s \end{matrix} \quad s = -1 \qquad \mathbf{N} = \begin{pmatrix} p \\ n \end{pmatrix} \begin{matrix} uud \\ udd \end{matrix}$$

$$\mathbf{I_3} = \begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$$

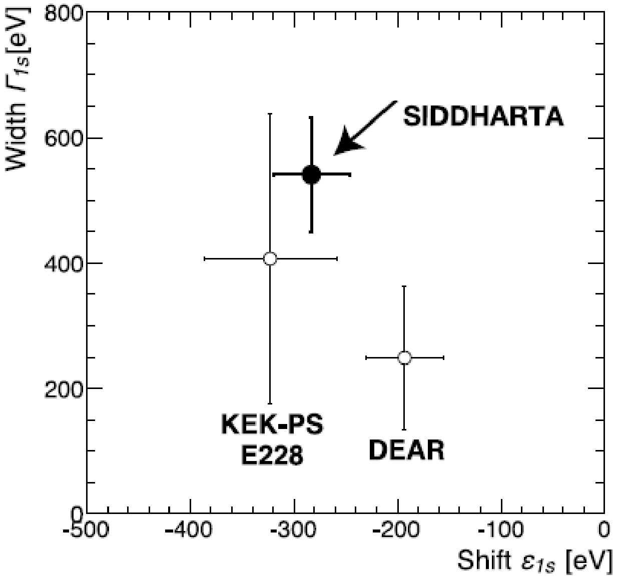


$\bar{K}N$ Interaction and Λ(1405)

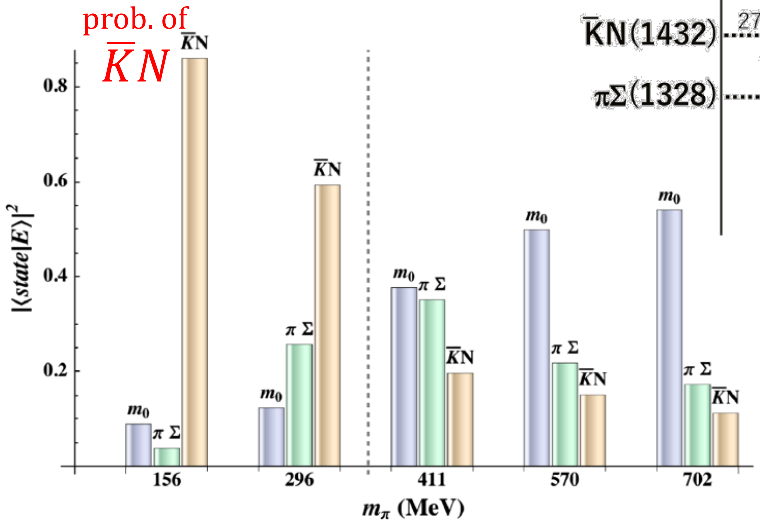
K⁻p scattering
NPB179(1981)33.

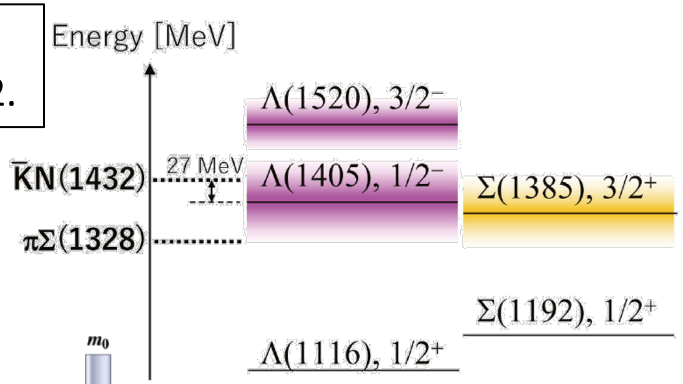


K⁻p atom
PLB704(2011)113.

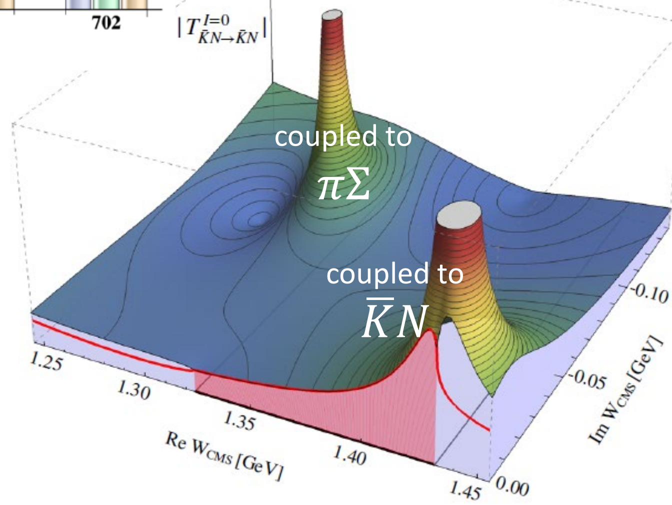


Λ(1405) in LQCD
RPL114(2015)132002.





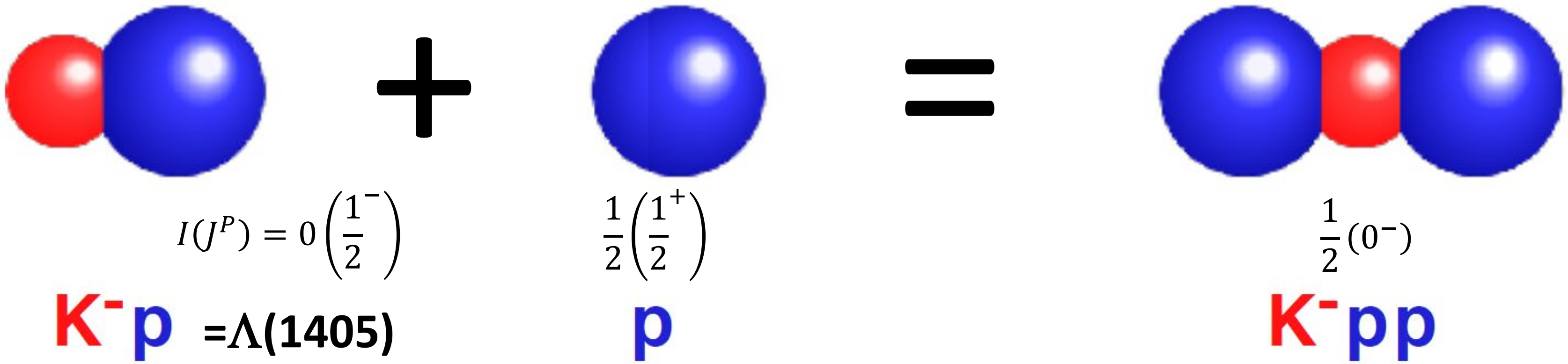
Λ(1405) in chiral
unitary model
EPJ ST230(2021)1593.



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

Λ(1405) to "Kaonic Nuclei"

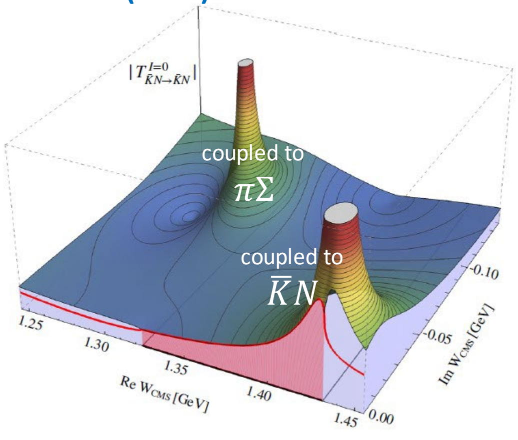
- Λ(1405) = considered as a quasi-bound state of $\bar{\mathrm{K}}$N
  → possible $\bar{\mathrm{K}}$-nucleus quasi-bound states has been widely discussed
- first idea from Y.Nogami PL7(1963)288
  - Pioneering calculation by Y.Akaishi, T.Yamazaki PRC65(2002)044005, PLB535(2002)70
  - Many calculations showing the existence of kaonic nuclei
- $\bar{\mathrm{K}}$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 $\bar{K}NN$

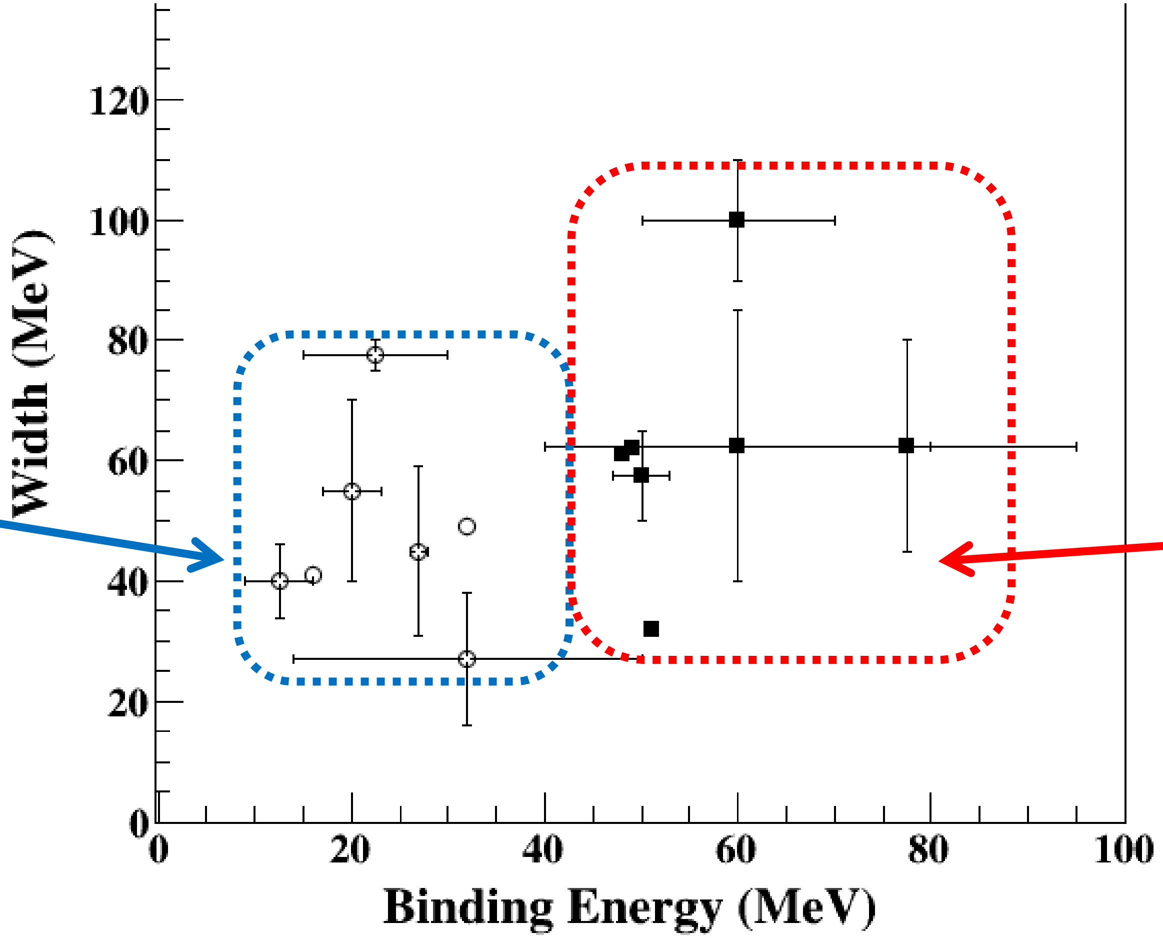
Chiral unitary model (energy dependent)

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



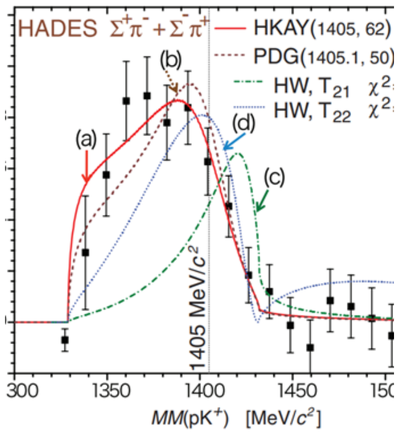
shallow $\bar{K}N$ potential

B.E. ~ 10-30 MeV



Phenomenological model (energy independent)

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



deep $\bar{K}N$ potential

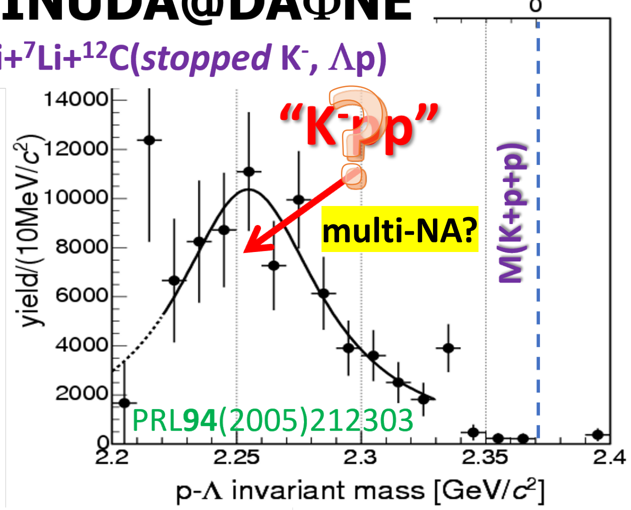
B.E. ~ 40-70 MeV

suggesting a more compact and dense system

“K⁻pp” Bound State Searches

FINUDA@DAΦNE

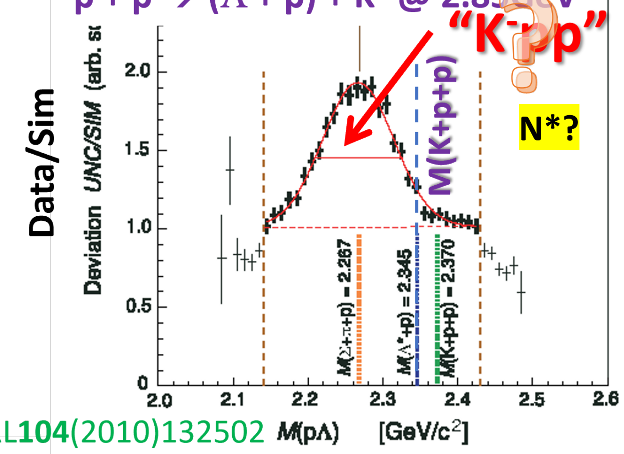
$^{6}Li+^{7}Li+^{12}C$(*stopped* K⁻, Λp)



PRL**94**(2005)212303

DISTO@SATURNE

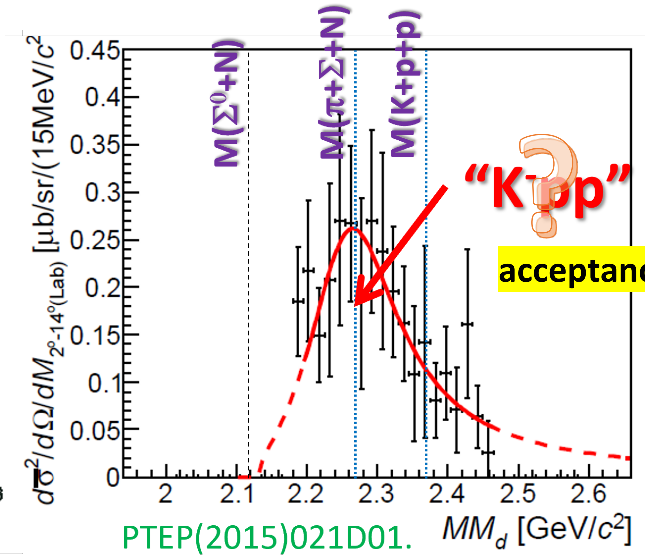
p + p → (Λ + p) + K⁺ @ 2.85GeV



PRL**104**(2010)132502

E27@J-PARC

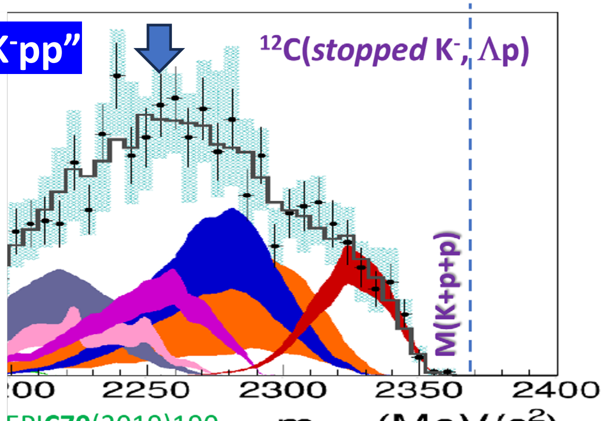
d(π⁺, K⁺)Σ⁰p @ 1.69 GeV/c



PTEP(2015)021D01.

AMADEUS@DAΦNE

^{12}C(*stopped* K⁻, Λp)

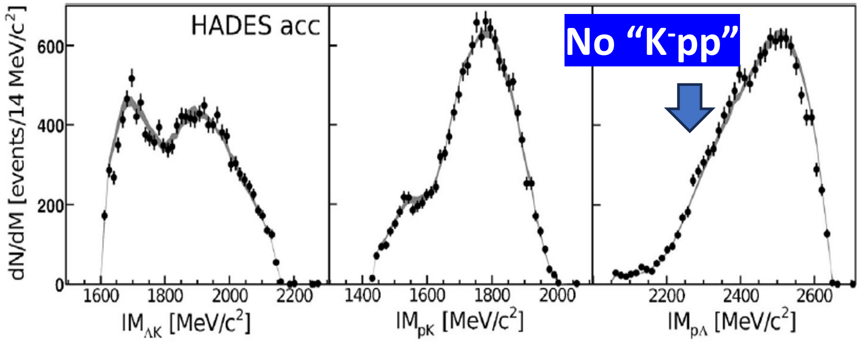


EPJC**79**(2019)190

HADES@GSI

PLB**742**(2015)242

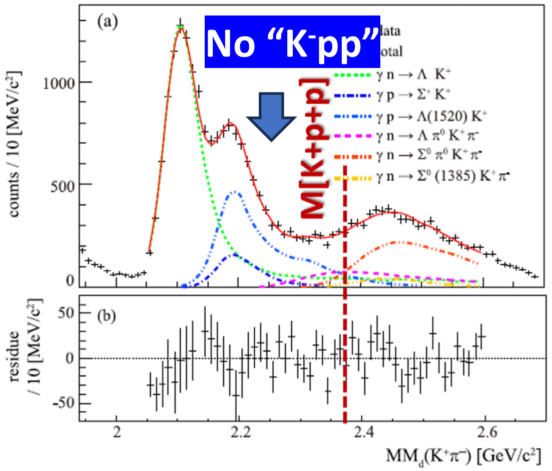
p + p → (Λ + p) + K⁺ @ 3.5GeV



LEPS@SPring-8

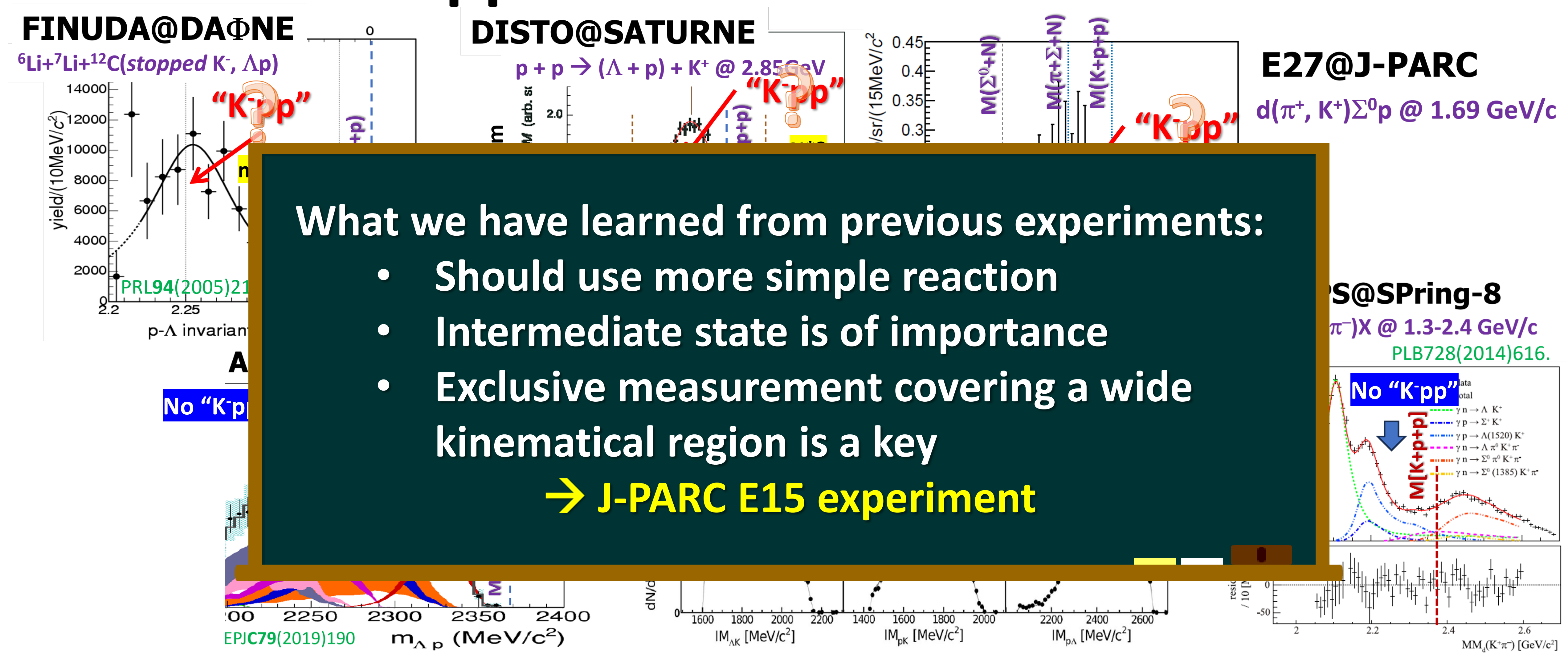
d(γ, K⁺π⁻)X @ 1.3-2.4 GeV/c

PLB728(2014)616.



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

"K⁻pp" Bound State Searches



What we have learned from previous experiments:

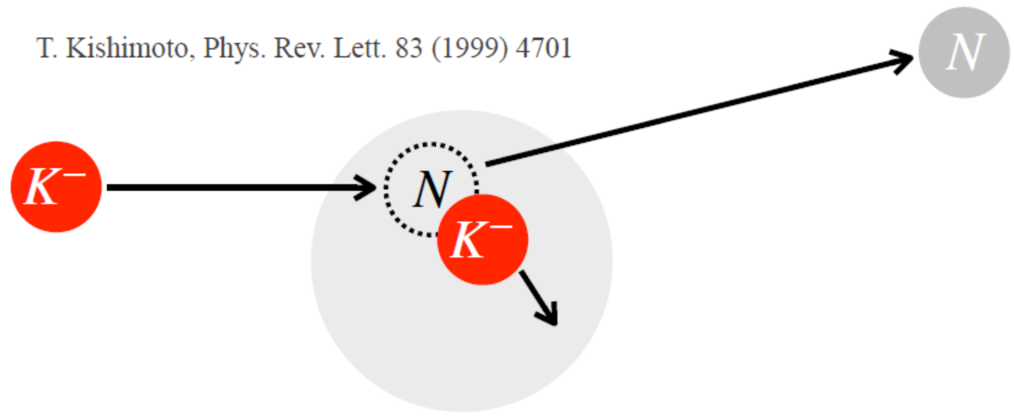
- Should use more simple reaction
- Intermediate state is of importance
- Exclusive measurement covering a wide kinematical region is a key

→ J-PARC E15 experiment

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

Experimental Searches at J-PARC

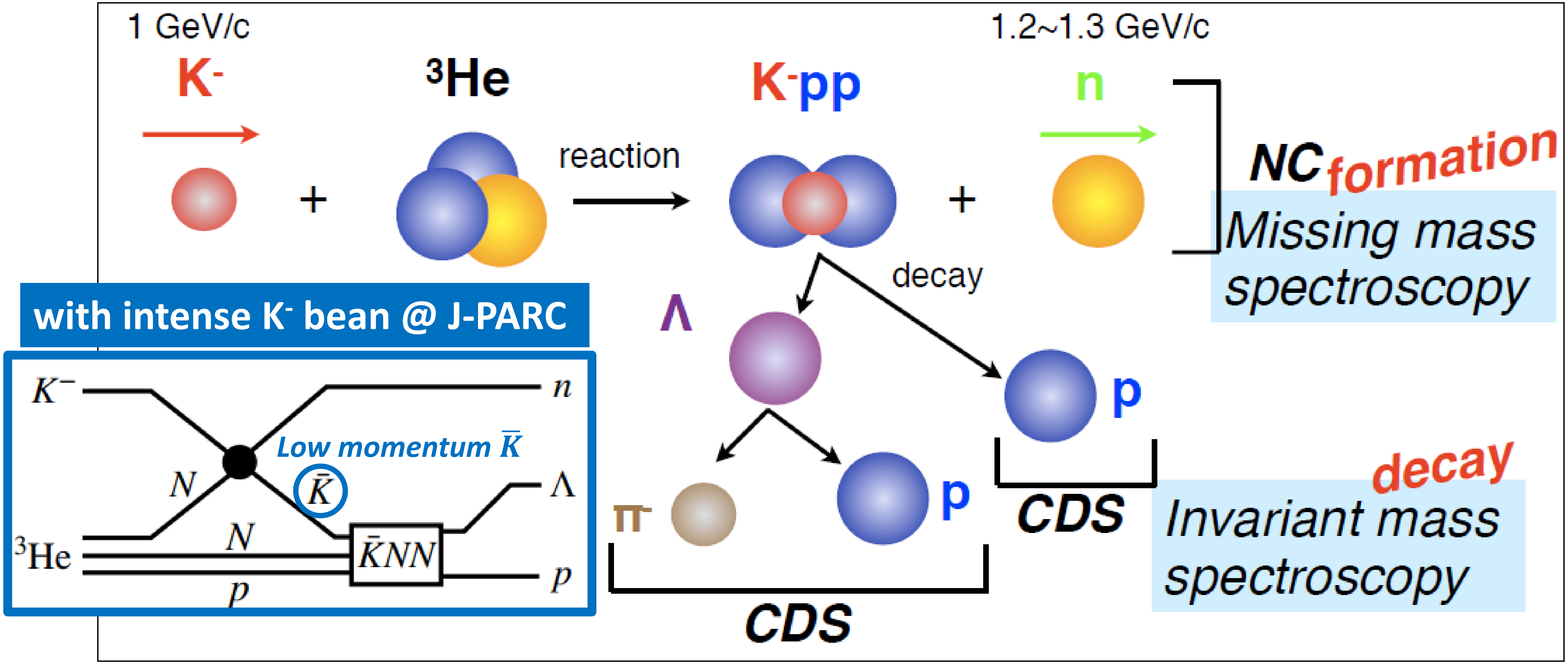
– via in-flight (K-,n) reactions –



“K⁻pp” Search @ J-PARC E15

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

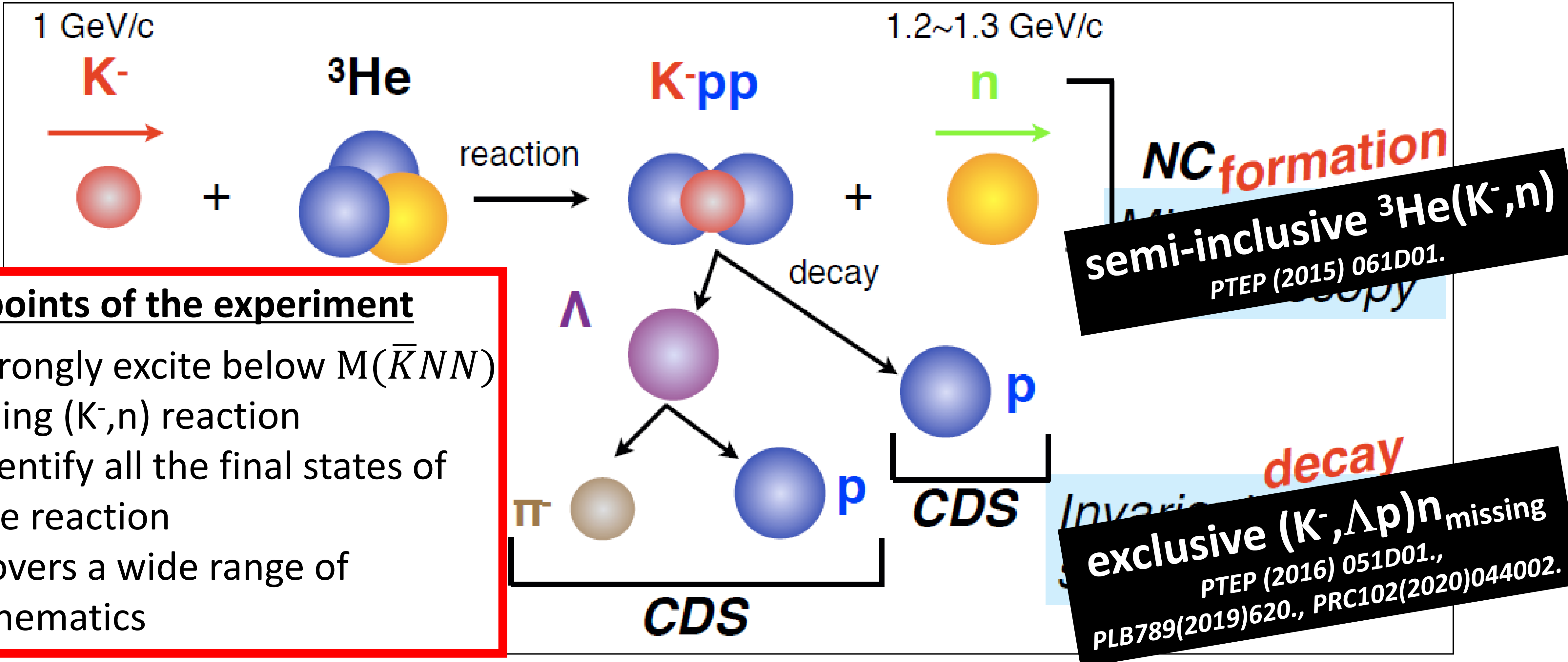
multi-NA and Y decays can be discriminated kinematically



“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

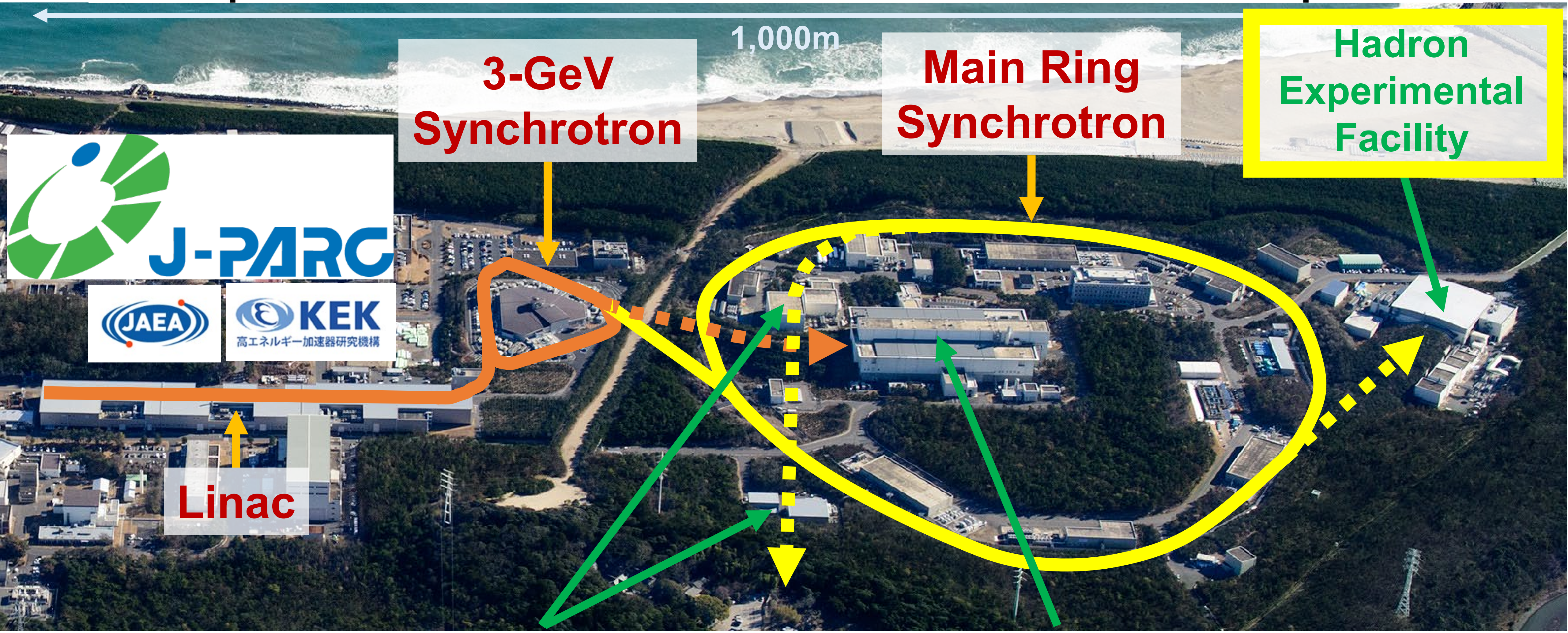


Key points of the experiment

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

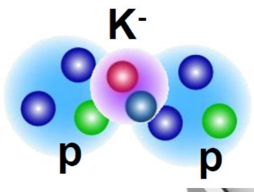
J-PARC

Japan Proton Accelerator Research Complex

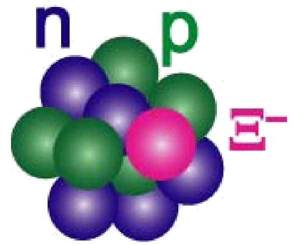


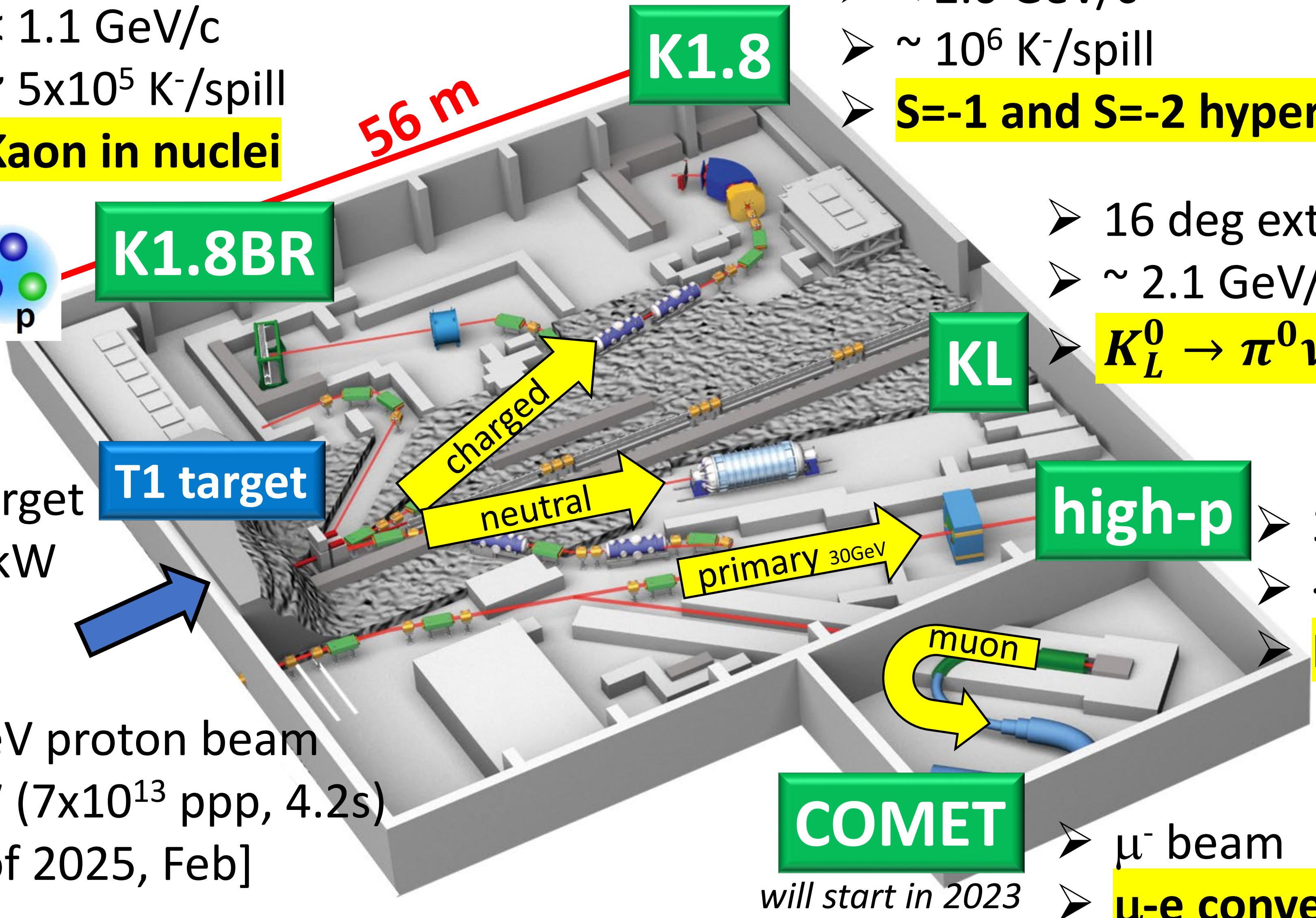
Hadron Experimental Facility (HEF)

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

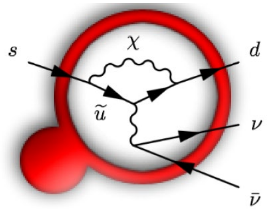


- < 2.0 GeV/c
- ~ 10^6 K^-/spill
- **S=-1 and S=-2 hypernuclei**





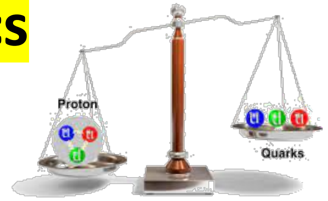
- 16 deg extraction
- ~ 2.1 GeV/c ~ 10^7 K^0_L/spill
- $K_L^0 \to \pi^0 \nu \bar{\nu}$



- Au Target
- < 95 kW

launched in 2020

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

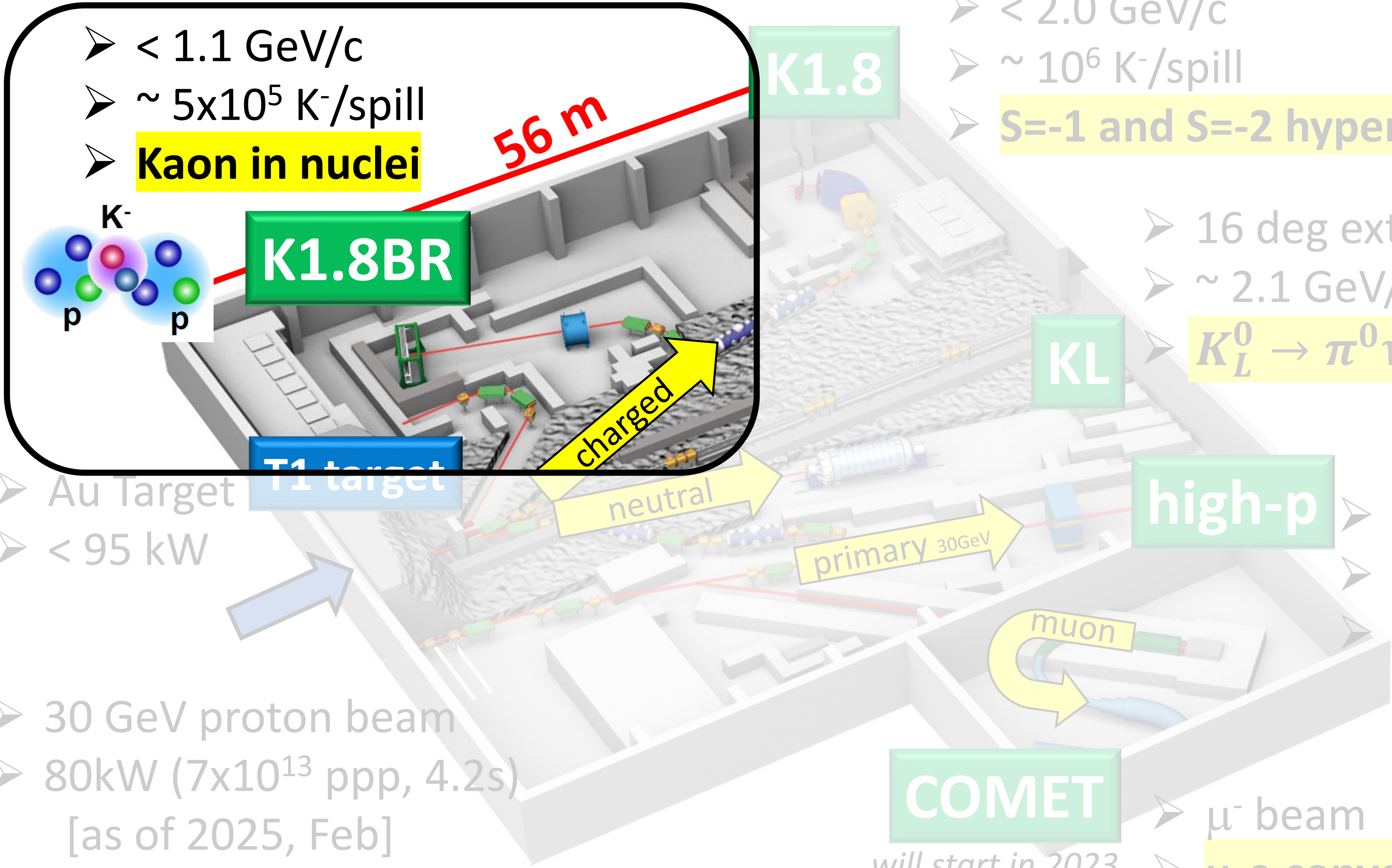


- 30 GeV proton beam
- 80kW (7×10^{13} ppp, 4.2s)
  [as of 2025, Feb]

will start in 2023

- μ^- beam
- **μ-e conversion**

Hadron Experimental Facility (HEF)



K1.8BR
- < 1.1 GeV/c
- ~ 5x10^5 K$^-$/spill
- **Kaon in nuclei**

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

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

high-p

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

COMET

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

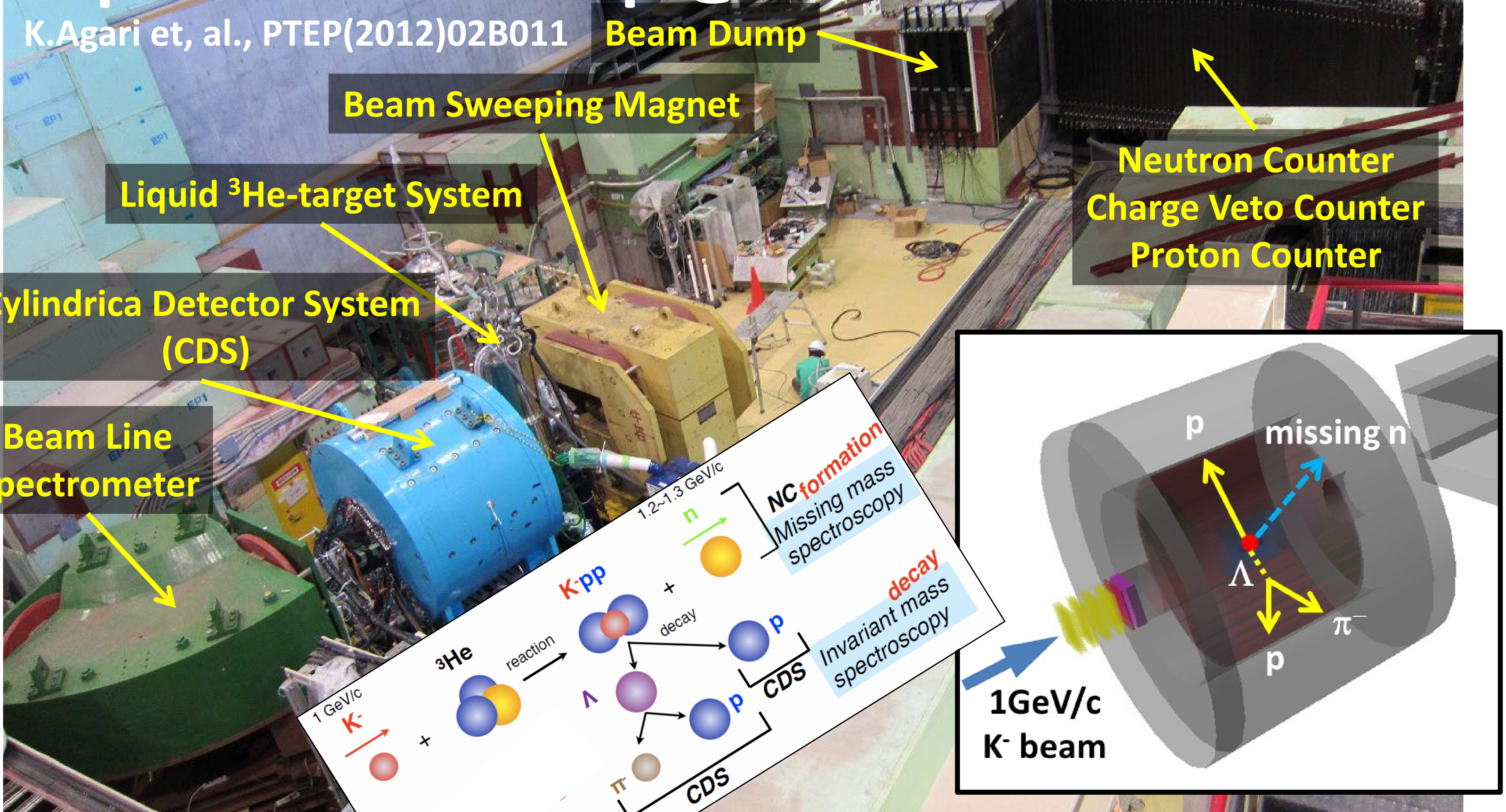
T1 target
- Au Target
- < 95 kW

- 30 GeV proton beam
- 80kW (7x10^{13} ppp, 4.2s)

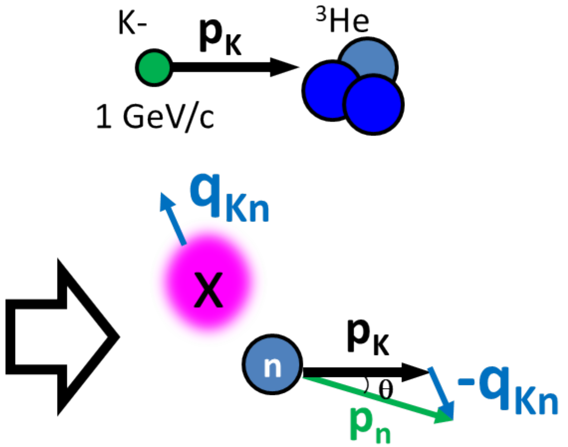
  [as of 2025, Feb]

Experimental Setup @ K1.8BR

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



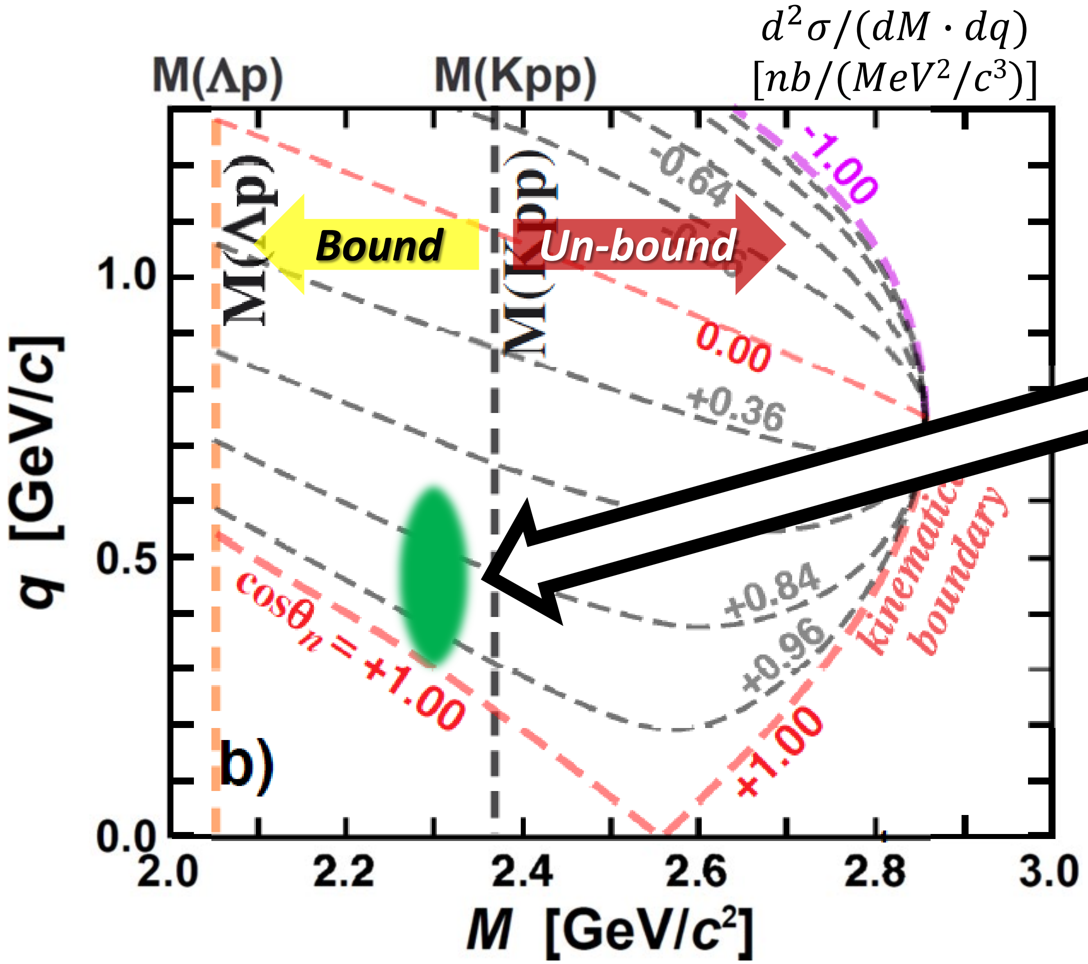
"K^-pp" Search w/ Momentum Transfer Analysis



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

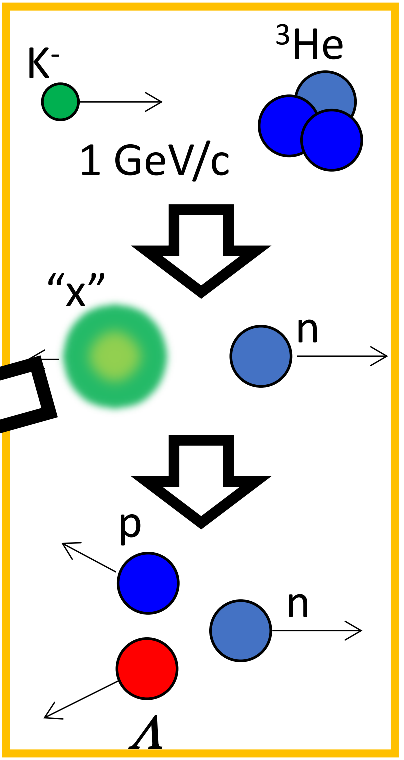
✓ M(Λp) vs. *q*

✓ give a clear information on reaction processes



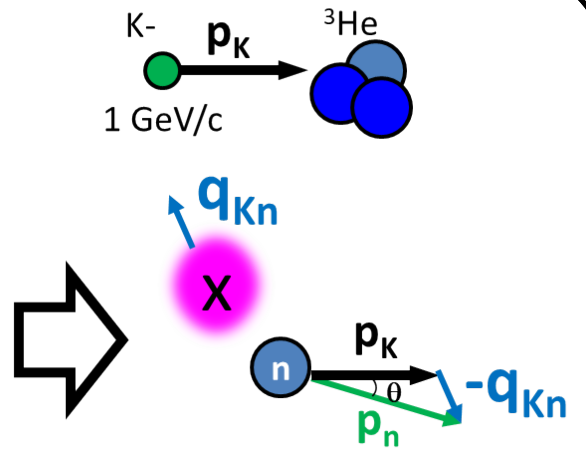
q *: (K^-,n) momentum transfer*

M *: Λp invariant mass*



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

“K⁻pp” Search w/ Momentum Transfer Analysis

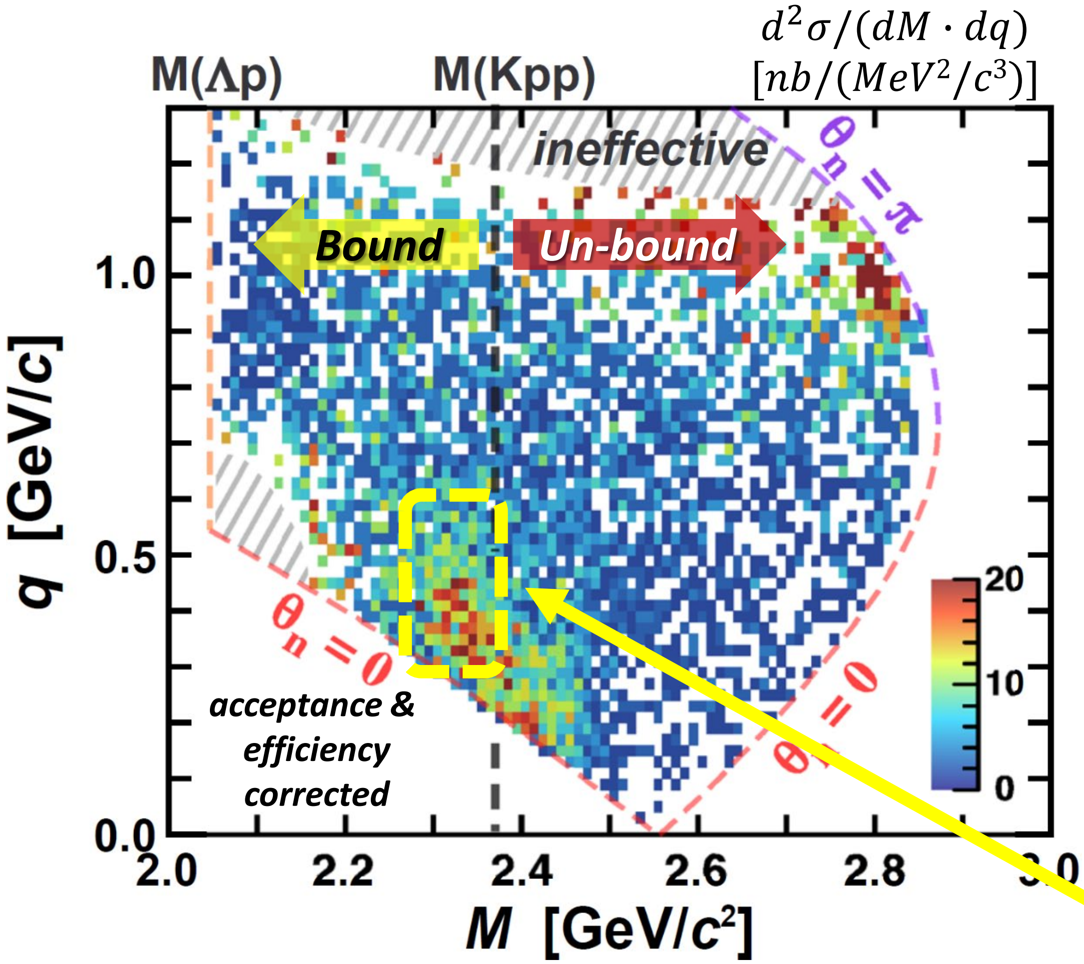


- **Momentum transfer analysis using the (K^-,n) reaction**

✓ M(Λp) vs. q

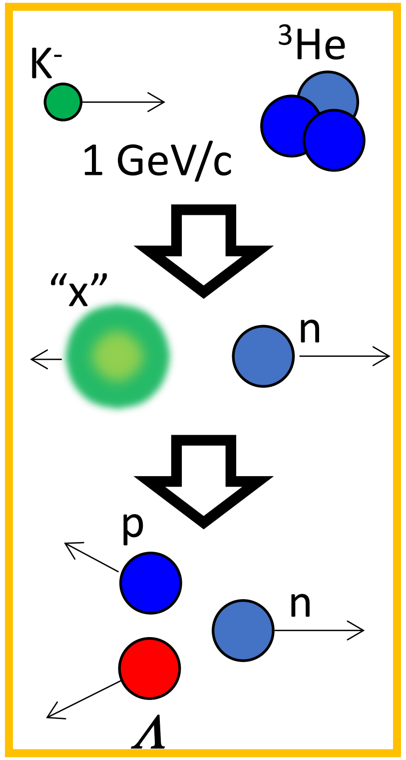
✓ give a clear information on reaction processes

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



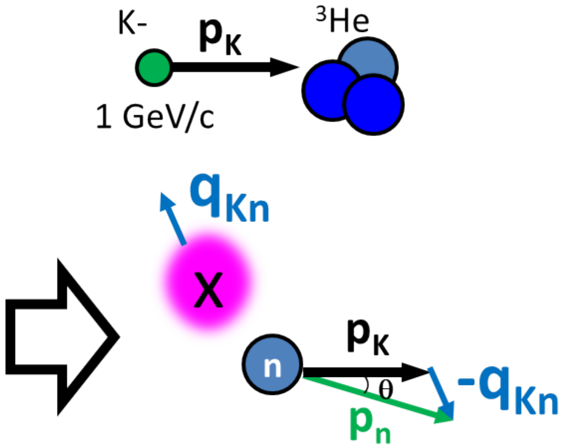
q : (K^-,n) momentum transfer

M : Λp invariant mass



A peak structure independent of q = A bound state exists

"K⁻pp" Search w/ Momentum Transfer Analysis

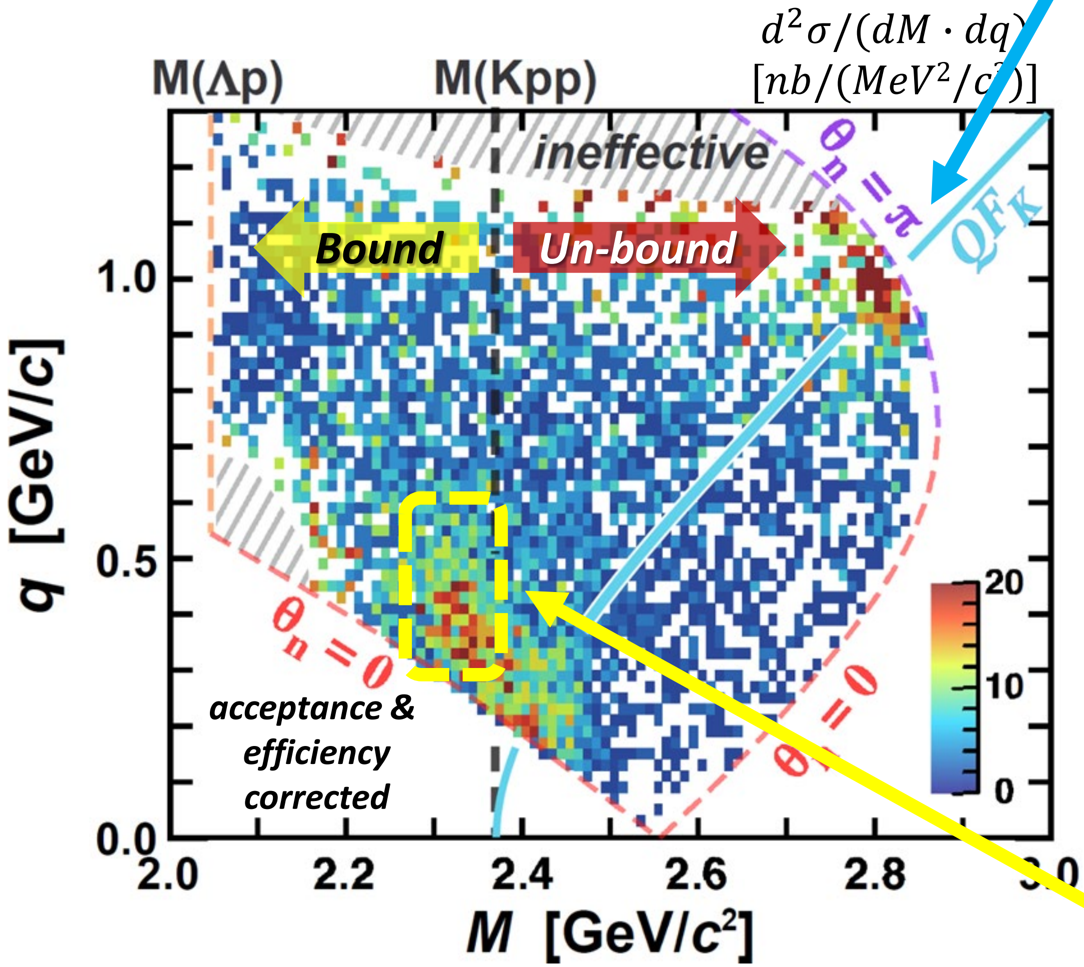


- **Momentum transfer analysis using the (K⁻,n) reaction**

✓ M(Λp) vs. *q*

✓ give a clear information on reaction processes

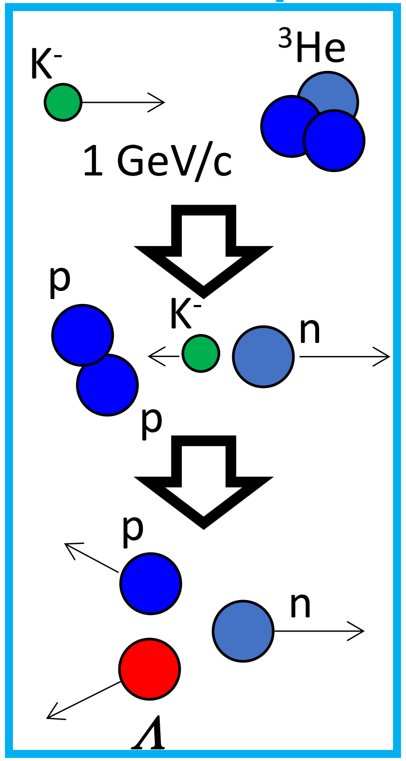
PLB789(2019)620., PRC102(2020)044002.



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

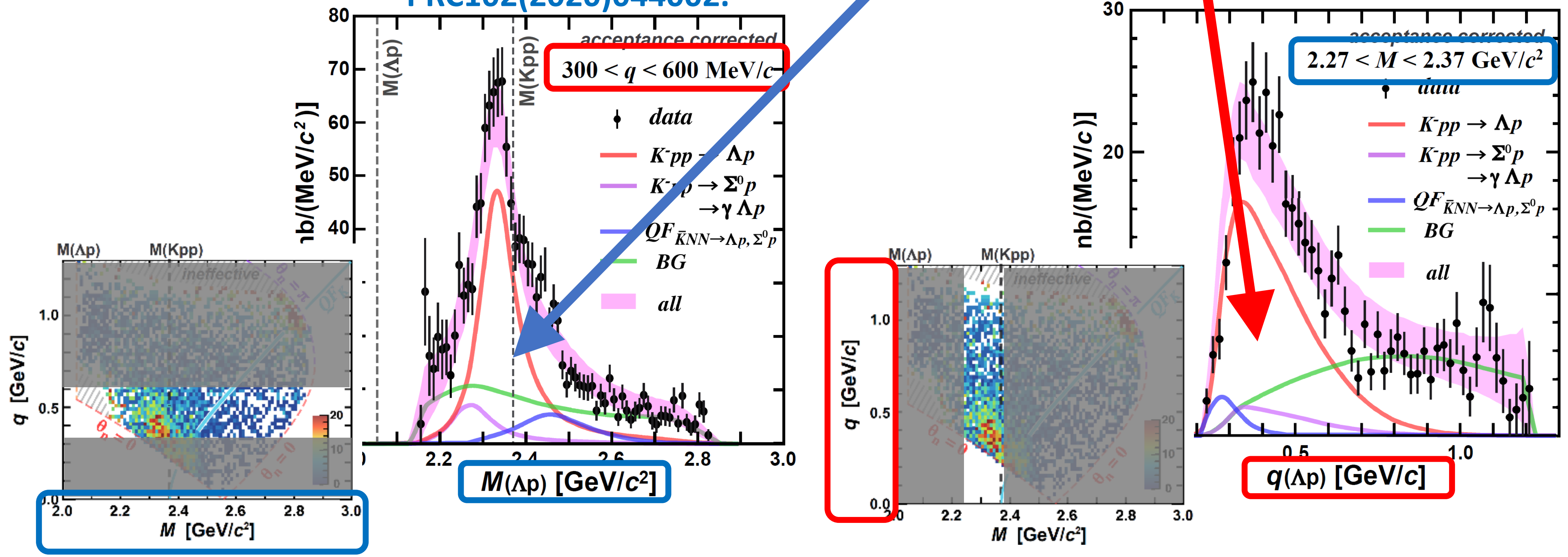
Energy term (BW type) from time integral

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* = Suggesting a compact system

Q_{kpp} ~ 400 MeV

Form factor

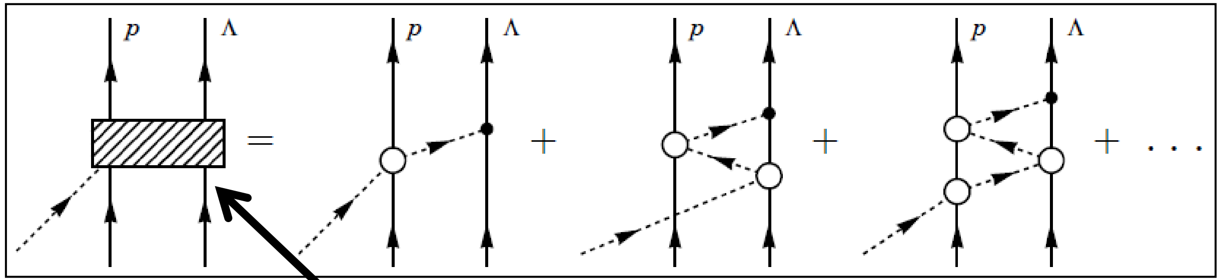
A Theoretical Interpretation

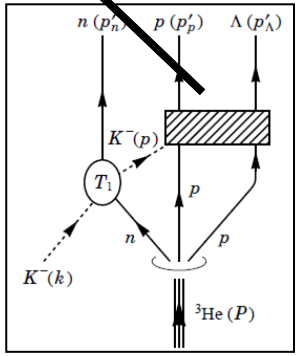
A calculation based on chiral unitary approach
reproduces the data well using the $\bar{K}NN$ bound state

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]

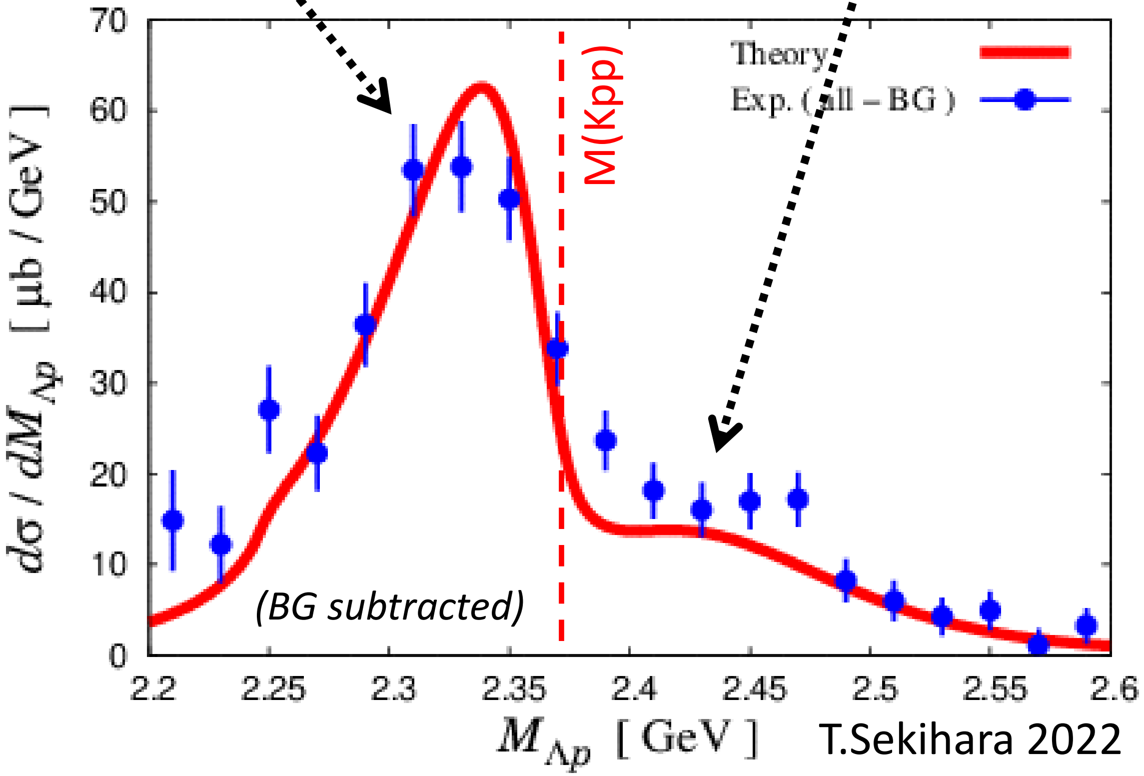




Theoretical investigations are indispensable!

$K^{bar}NN$ bound state

Quasi-free K^- scattering

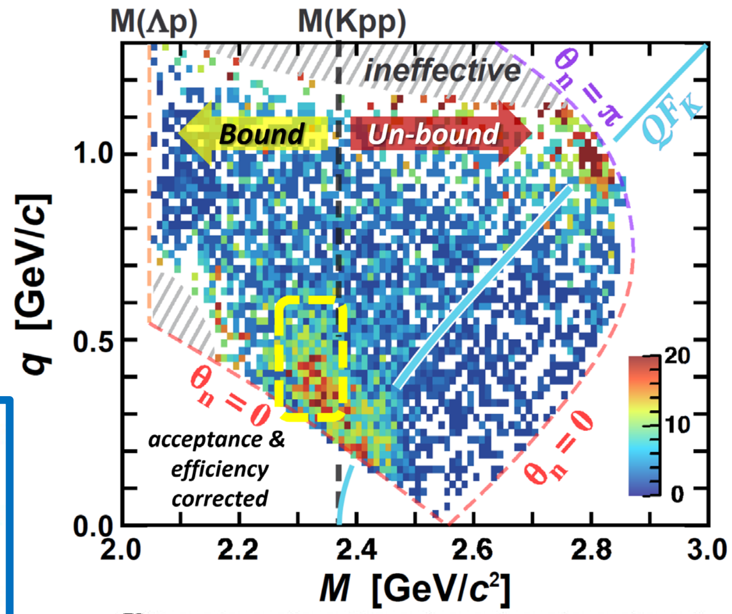


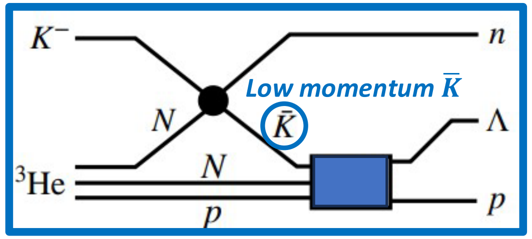
T.Sekihara 2022

What We Observed at E15?

✓**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

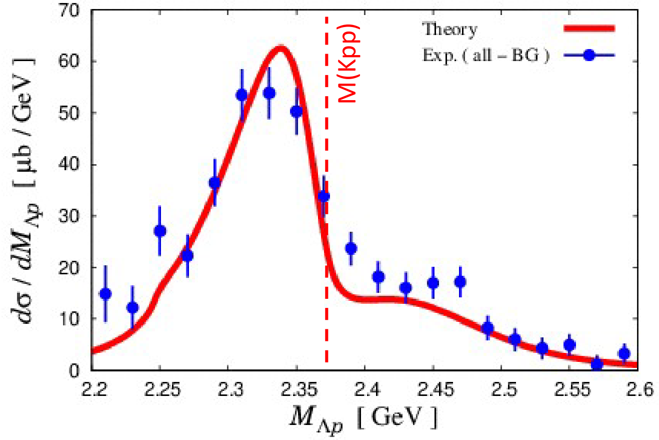




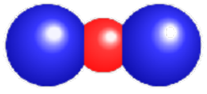
✓**Evidence of quasi-free K^- scattering**

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

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



Observed structure = "K-pp" bound state

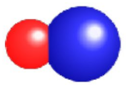


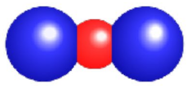
K^-pp

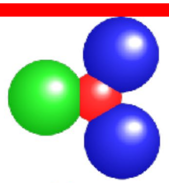
Need Further Investigations

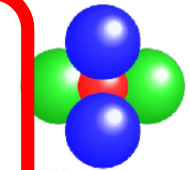
to establish the kaonic nuclei

- **Λ(1405) state**
  - $\bar{K}N$ qusi-bound state as considered?
  - Relation between $\bar{K}N$ and $\bar{K}NN$?
- **Further details of the $\bar{K}NN$**
  - Mesonic decay modes? →PRC110(2024)014002.
  - Spin and parity of the "K^-pp"?
  - Compact and dense system?
- **Heavier kaonic nuclei**
  - Mass number dependence?
- **Double kaonic nuclei**
  - Much compact and dense system?

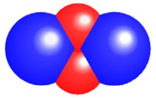

K^-p


K^-pp

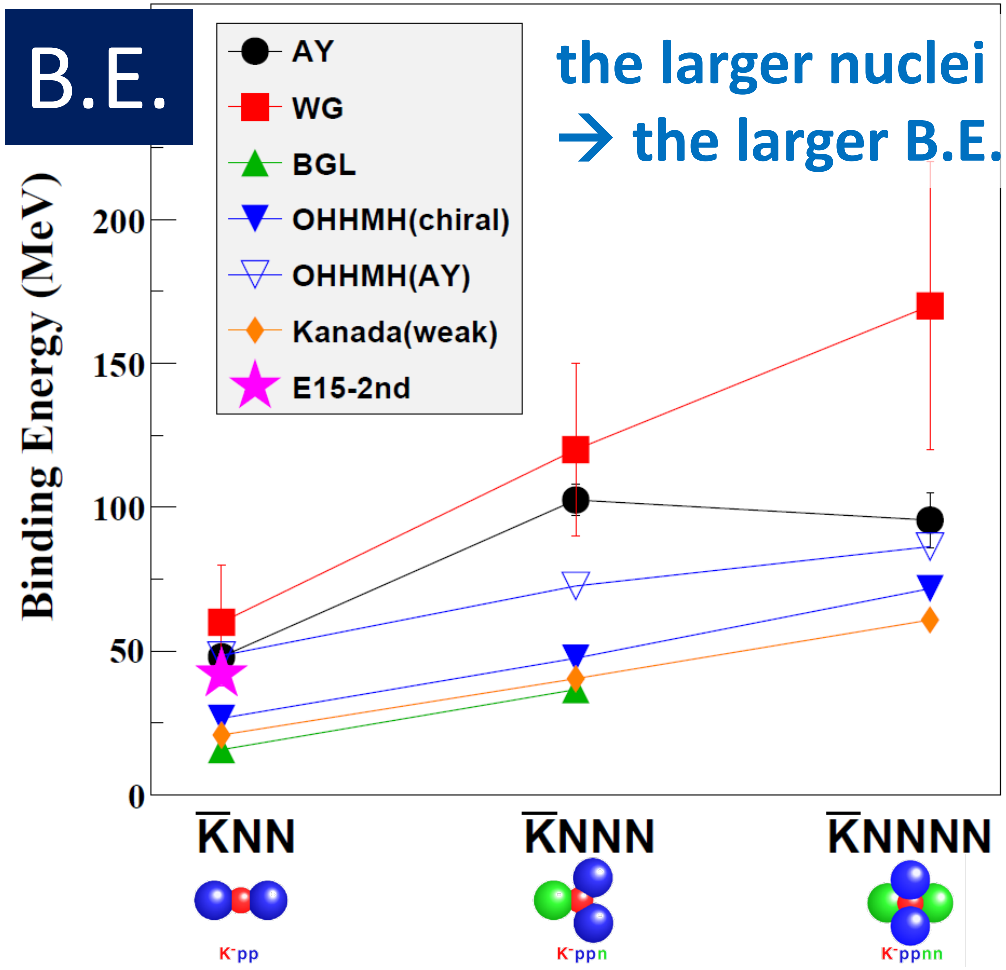

K^-ppn

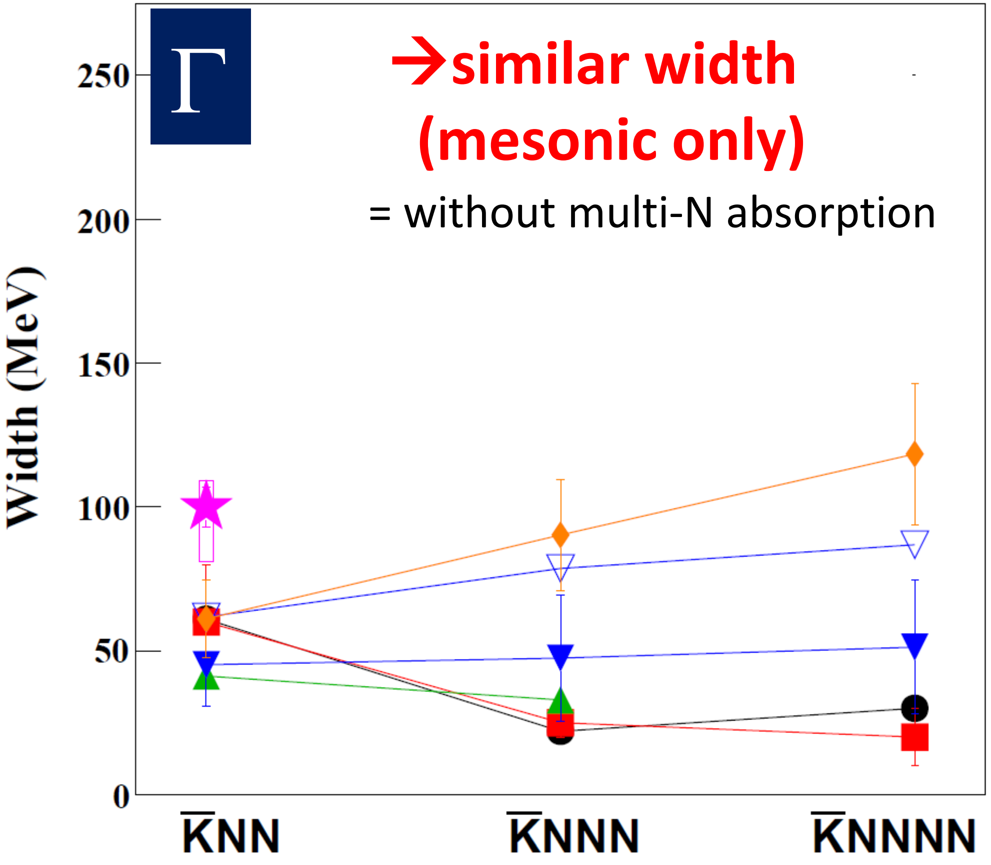

K^-ppnn

…


K^-K^-pp

Mass Number Dependence of Kaonic Nuclei



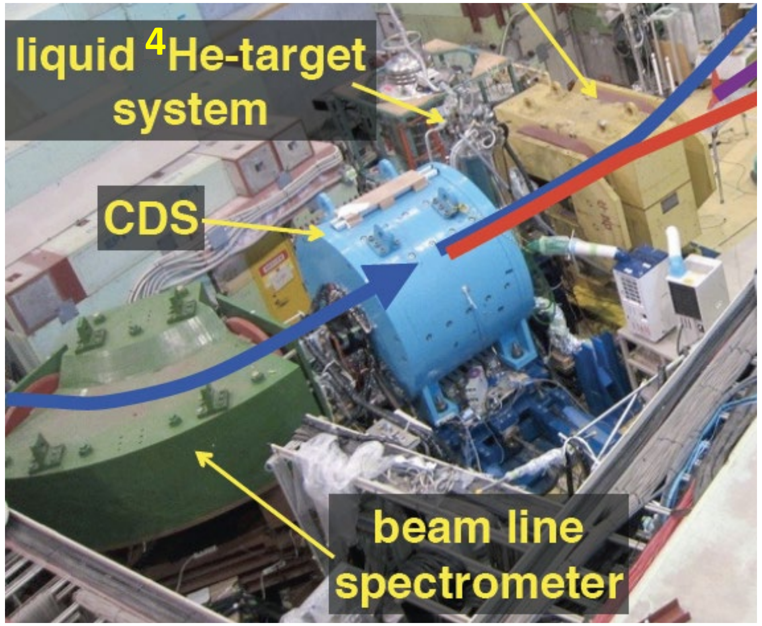


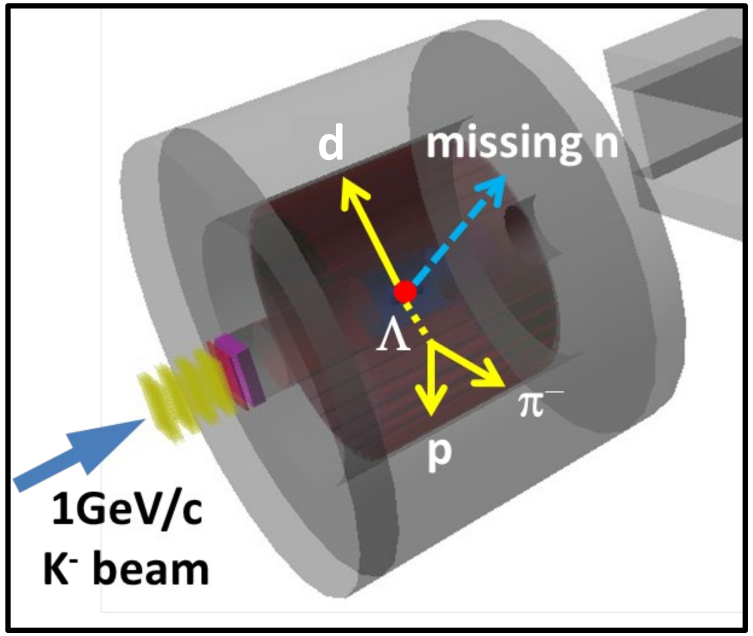
- **Systematic measurements will provide more conclusive evidence of the kaonic nuclei**

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

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

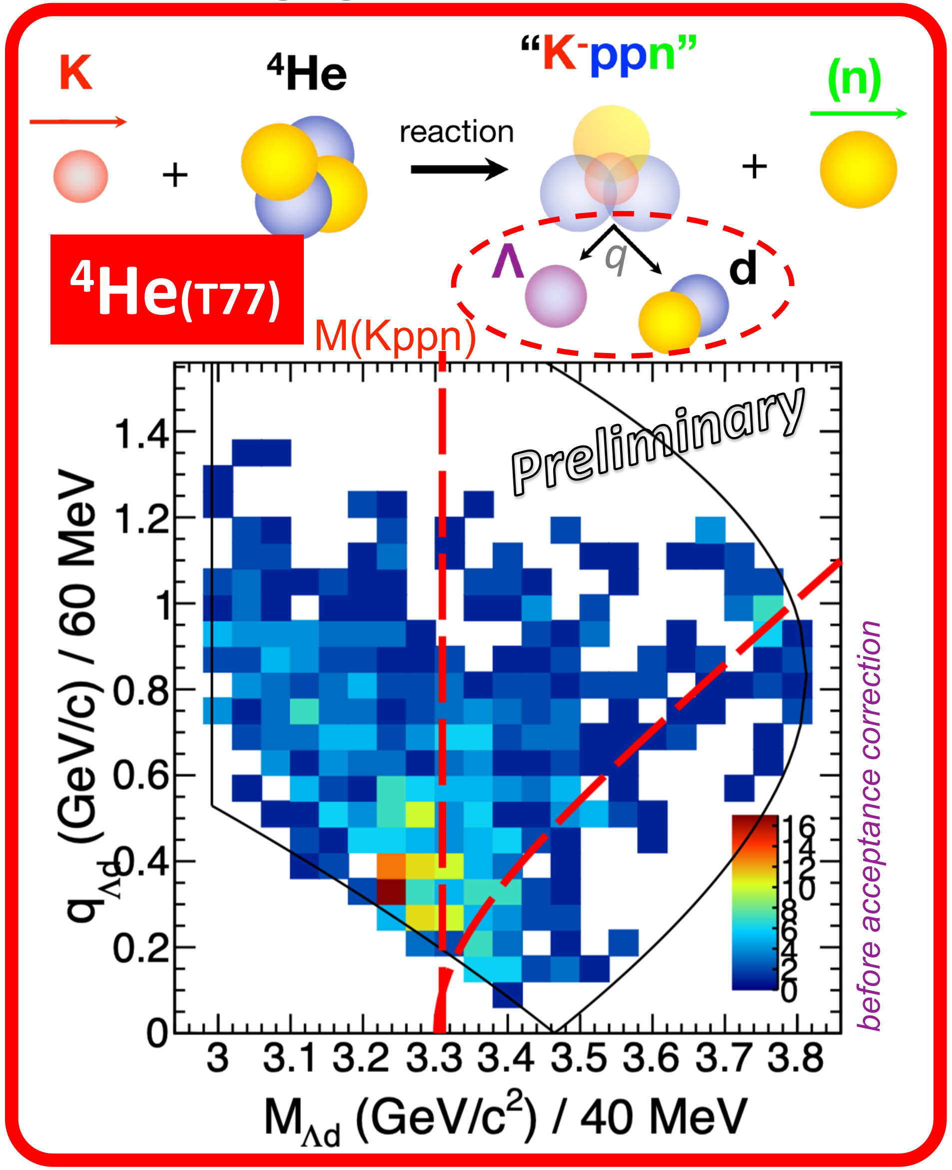
- An analysis of the **Λdn** final state with **$K^{-}{}^{4}He$** reaction at **1 GeV/c** has been conducted
  - T77: lifetime measurement of ${}^{4}_{\Lambda}H$ in 2020
- The results will be updated with a part of the E73 controlled data
  - E73: lifetime measurement of ${}^{3}_{\Lambda}H$ in 2024-25

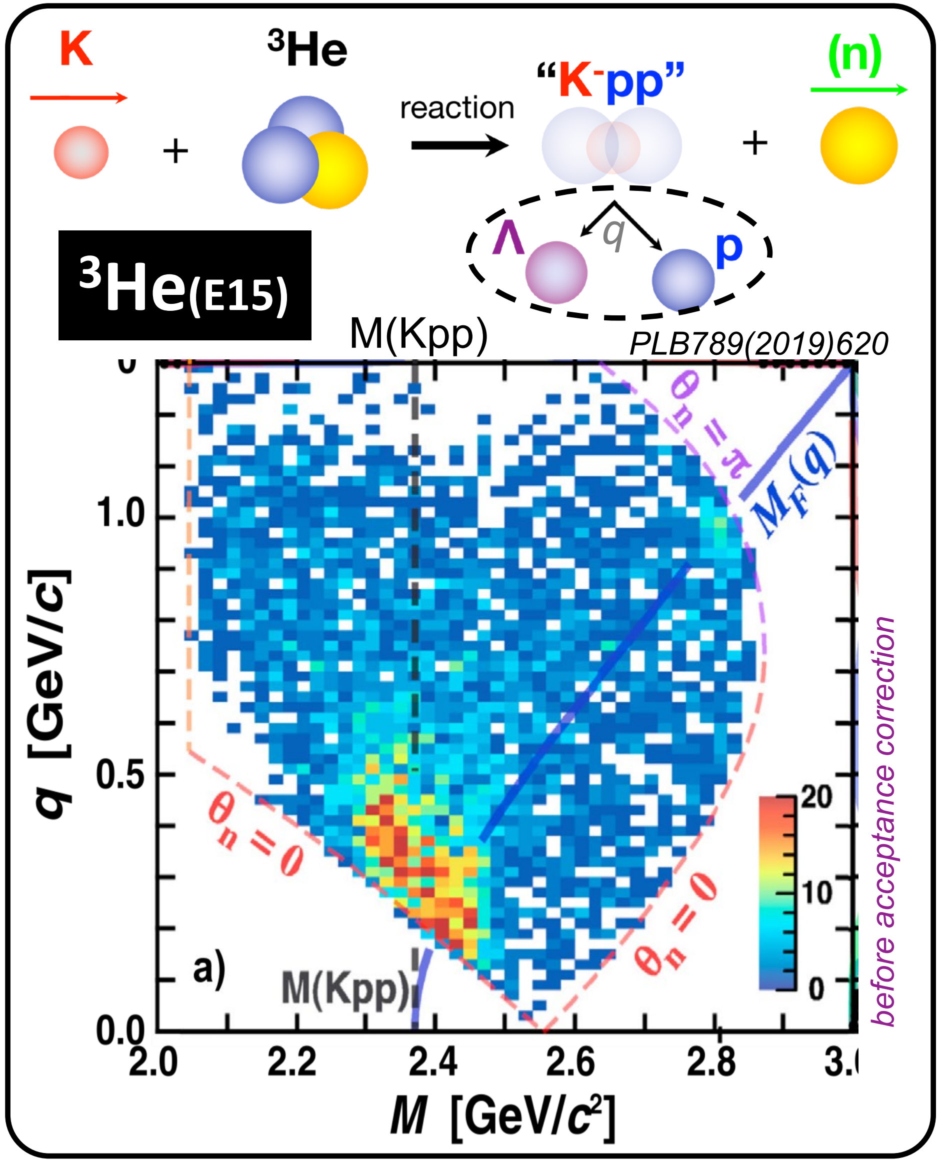




Experiment	K⁻ on target
E15 (^{3}He)	~42 x 10^{9}
T77 (^{4}He)	**~6 x 10^{9}**
E73 (^{4}He)	~12 x 10^{9}

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





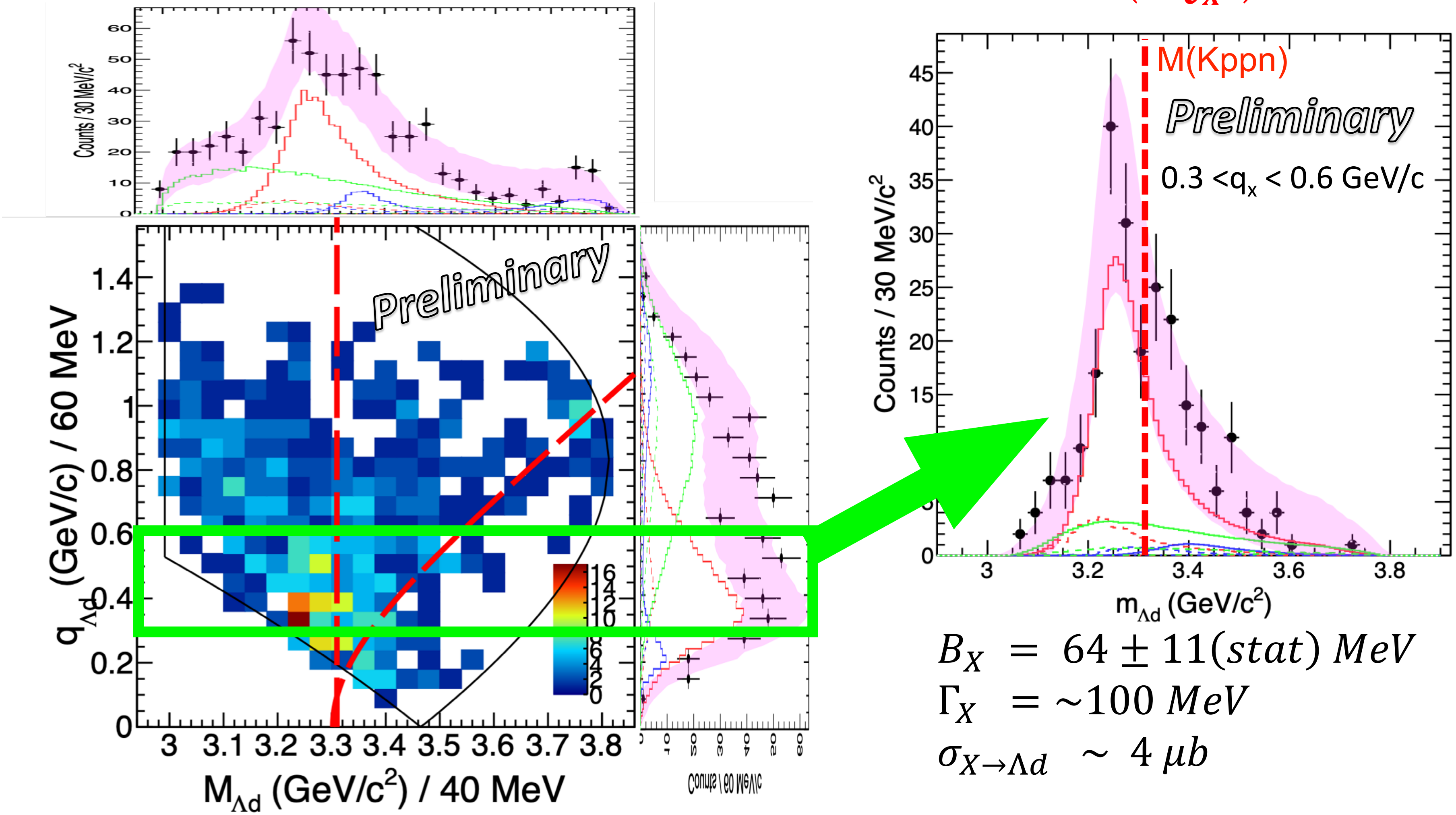
- **Two distributions are quite similar**
- structure below the threshold (**seems *q*-independent**), QF-K, BG

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

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

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

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

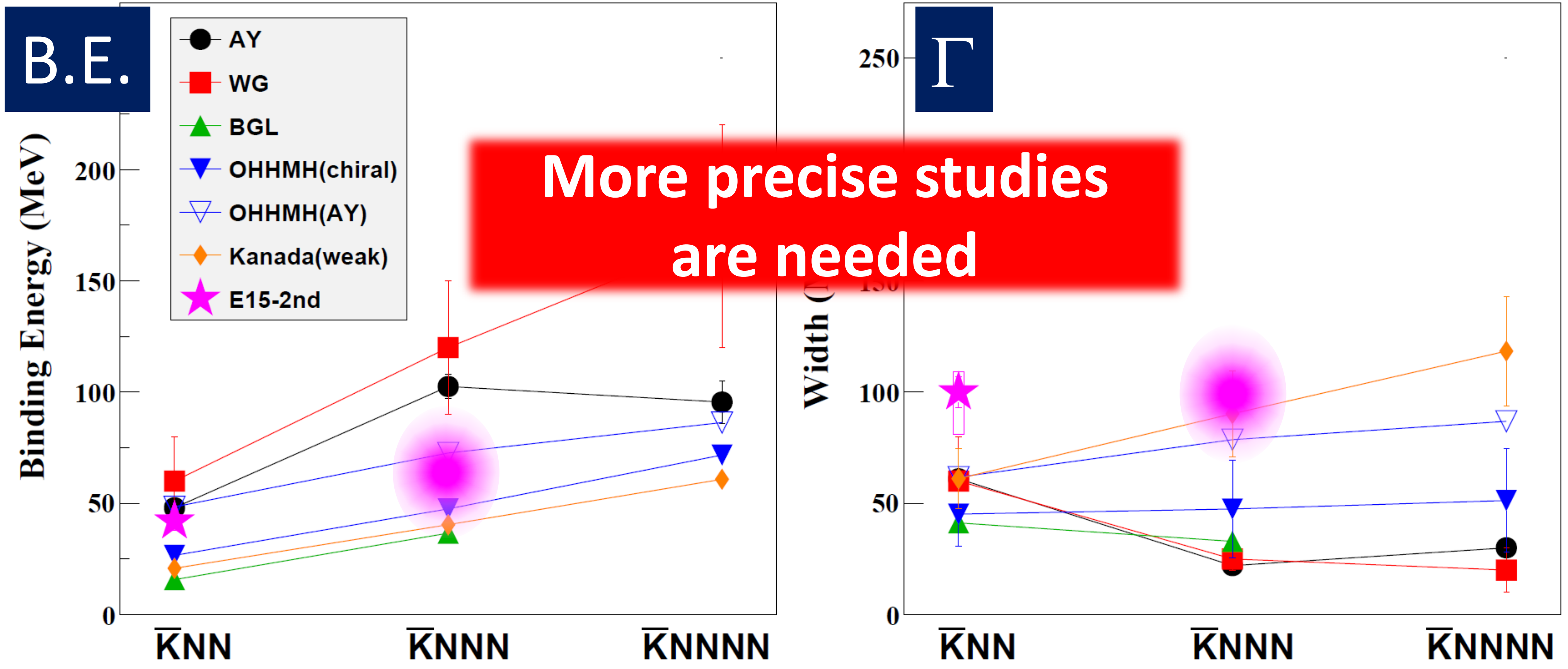


$B_X = 64 \pm 11(stat)\ MeV$

$\Gamma_X = \sim 100\ MeV$

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

If the Observed Structure Is "K⁻ppn",

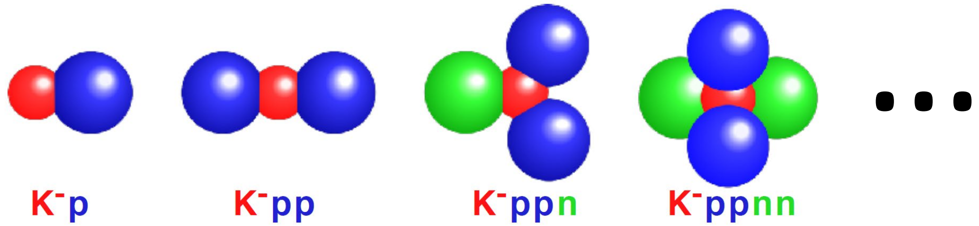


- The binding energy is comparable with some theoretical predictions
- The width is larger than theoretical predictions

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

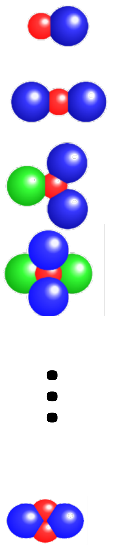
– from the $\bar{K}N$ to $\bar{K}NNNN$ systems and more –



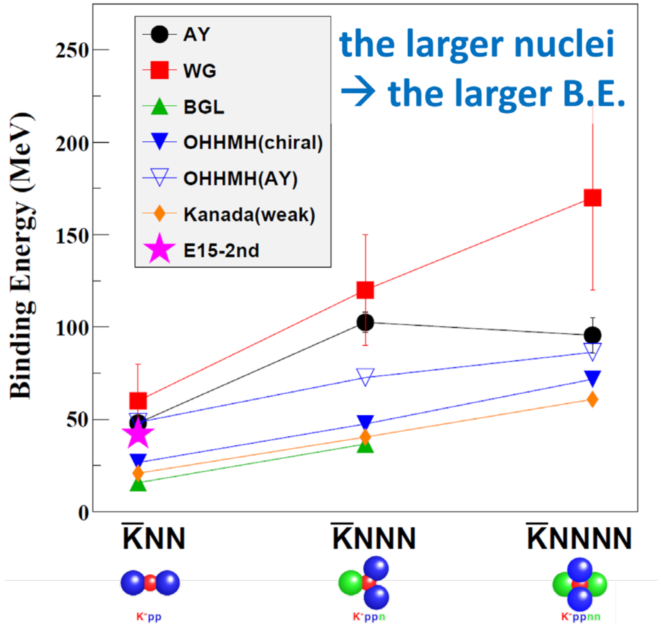
Systematic investigation of the light kaonic nuclei

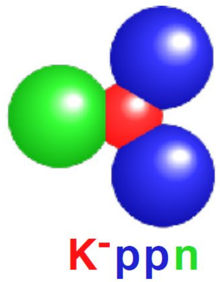
- Systematic measurement will be promoted at J-PARC
  - mass number dependence
    - binding energy, branching ratio, *q* dependence, ..
  - spin/parity determination

➢ Extract internal structure with theoretical investigations



	Reaction	Key Decay Mode
$\bar{K}N$	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)	$\Lambda\alpha n/\Lambda ddn$
$\bar{K}\bar{K}NN$	$\bar{p}$ + ^{3}He	$\Lambda\Lambda$



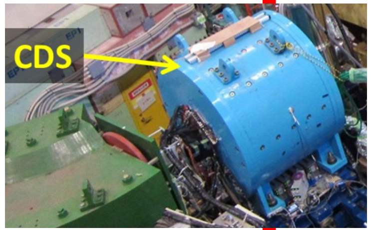


$\bar{K}NNN$ @ E80

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

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

- "K-ppn"→Λd 2-body decay

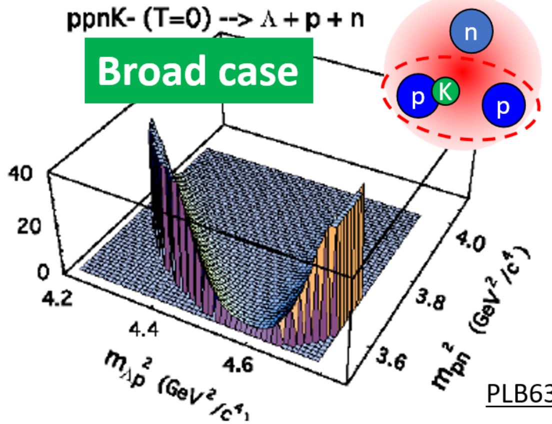


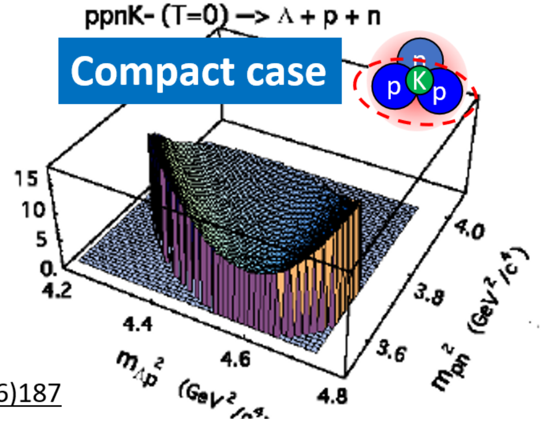
② **Study the multi-particle decay mode of $\bar{K}NNN$ toward understanding its internal structure**

- "K-ppn"→Λpn 3-body decay

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

Utilize Dalitz plots → Differences in distribution

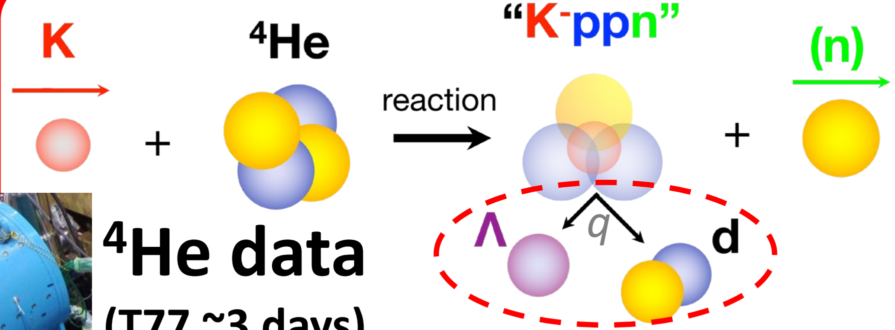




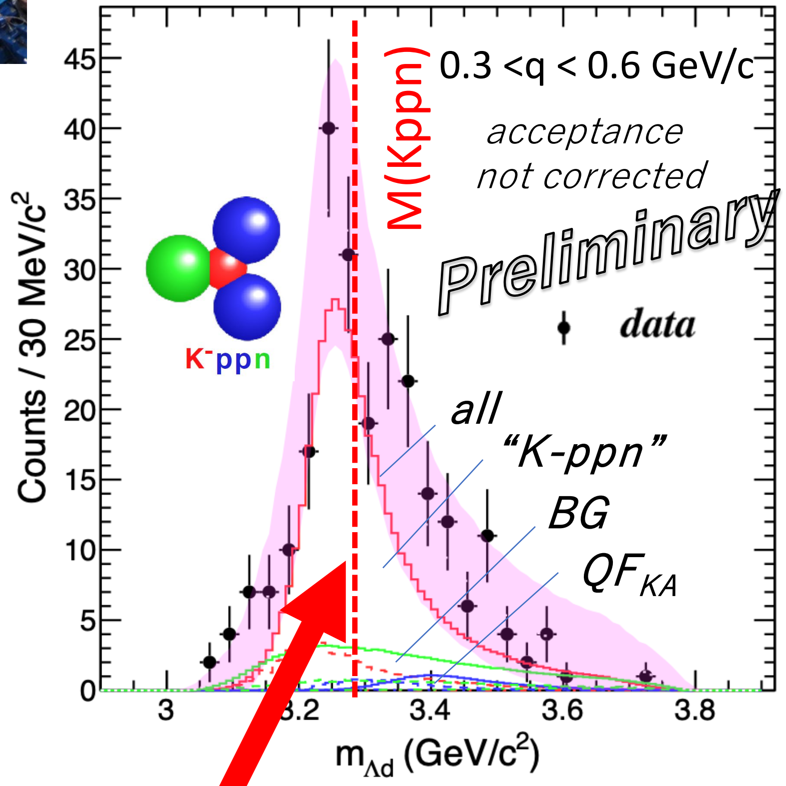
PLB632(2006)187

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

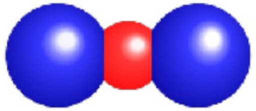
Widely distributed in the plane
- All particles have a momentum larger than the Fermi momentum



^{4}He 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

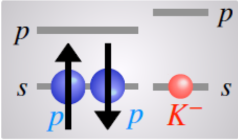
② Determine the spin/parity of $\bar{K}NN$

- spin-spin correlation measurement of "K⁻pp"→Λp

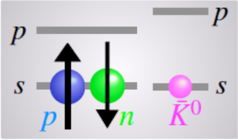
There are two possible configurations for the $\bar{K}NN$ ground state.

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

$J^P = 0^-$



+

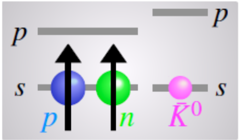


$$\frac{|I_{\bar{K}N}=0|^2}{|I_{\bar{K}N}=1|^2} = \frac{3}{1}$$

Deeper bound expected

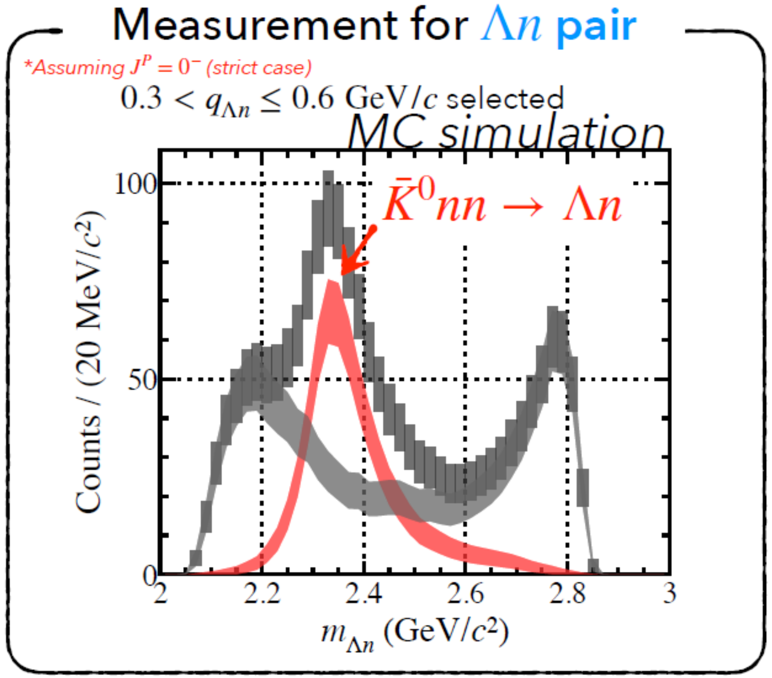
" $(NN)_{(I.asym \times S.sym)} \otimes \bar{K}$ "

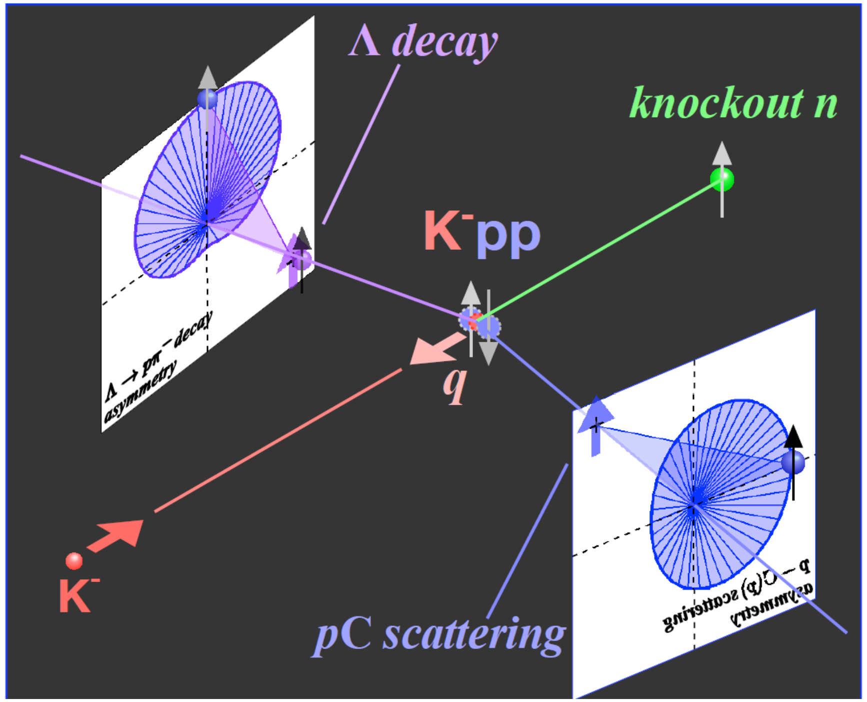
$J^P = 1^-$



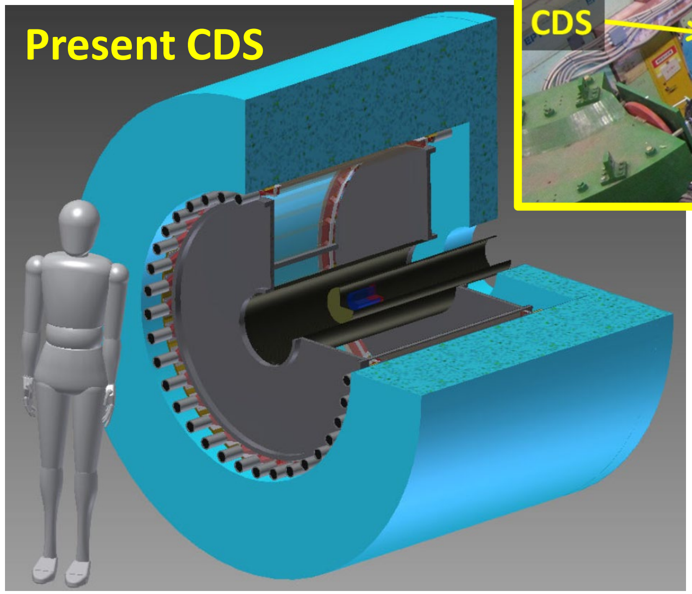
$$\frac{|I_{\bar{K}N}=0|^2}{|I_{\bar{K}N}=1|^2} = \frac{1}{3}$$

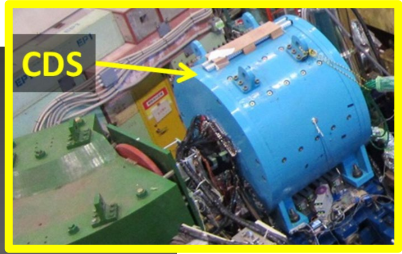
Shallower bound expected





New Cylindrical Detector System (CDS)





✓**Solid angle:** **x1.6** (59% → 93%)

✓**Neutron eff.:** **x7** (3% → 12%x1.6)

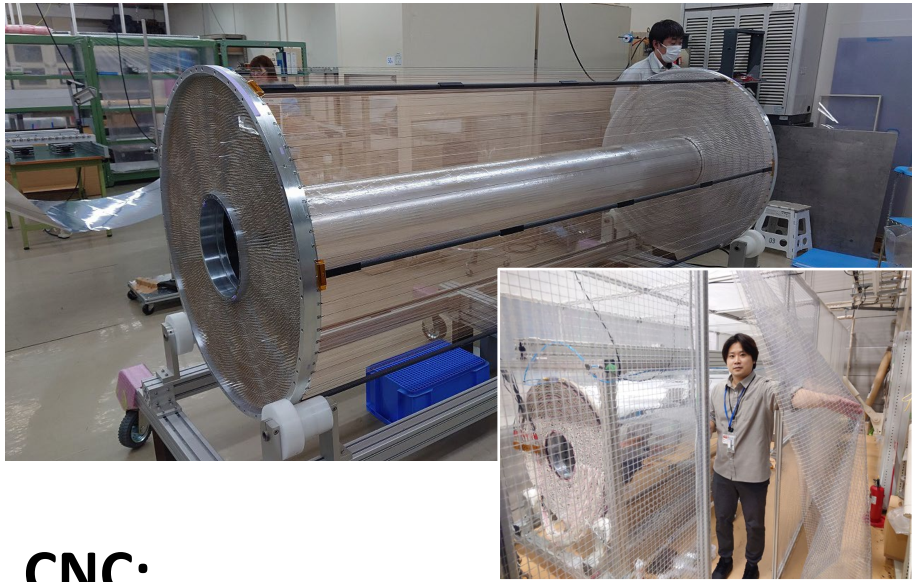
+ forward TOF counter
+ proton polarimeter (in future)

Construction Status of the CDS

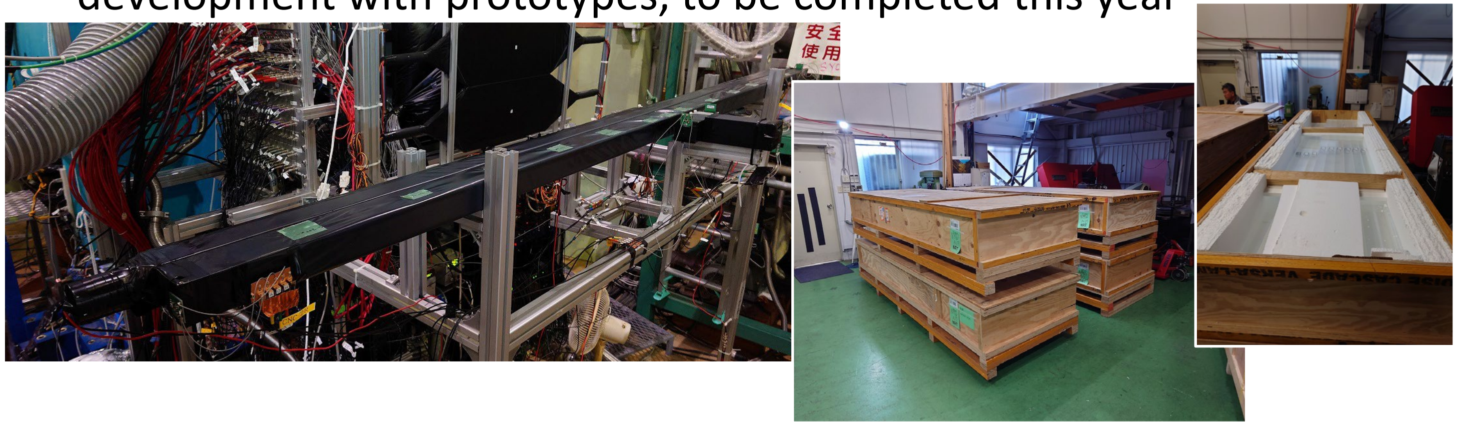
Return York:
completed

SC Solenoid:
completed

CDC:
completed, in commissioning



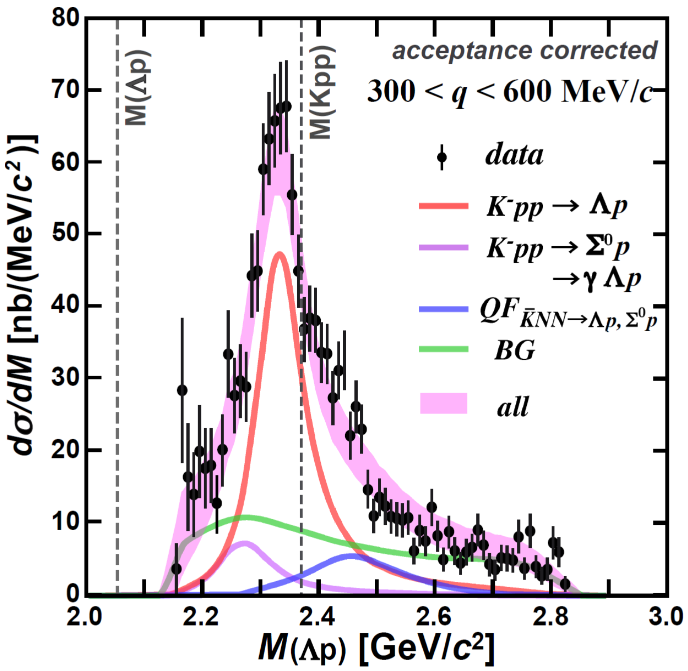
CNC:
development with prototypes, to be completed this year

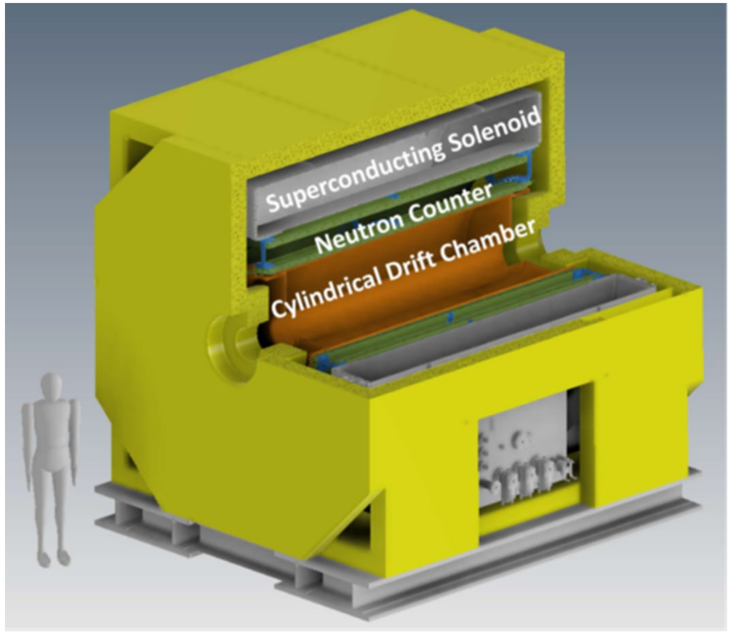


The experiment will be ready in early 2027

Summary

- 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 x3 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

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

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

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

M. Iio, S. Ishimoto, Y. Makida, H. Ohhata, M. Oonaka, K. Ozawa, K. Sasaki, [illegible], S. S[illegible]ki, T. [illegible], M. [illegible]ida
High Energy Accelerator Research Organization (KEK), I[illegible]aki, 305-0801, Japan

T. [illegible]agae
Depart[illegible] [illegible]ics, K[illegible], K[illegible], Japan

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

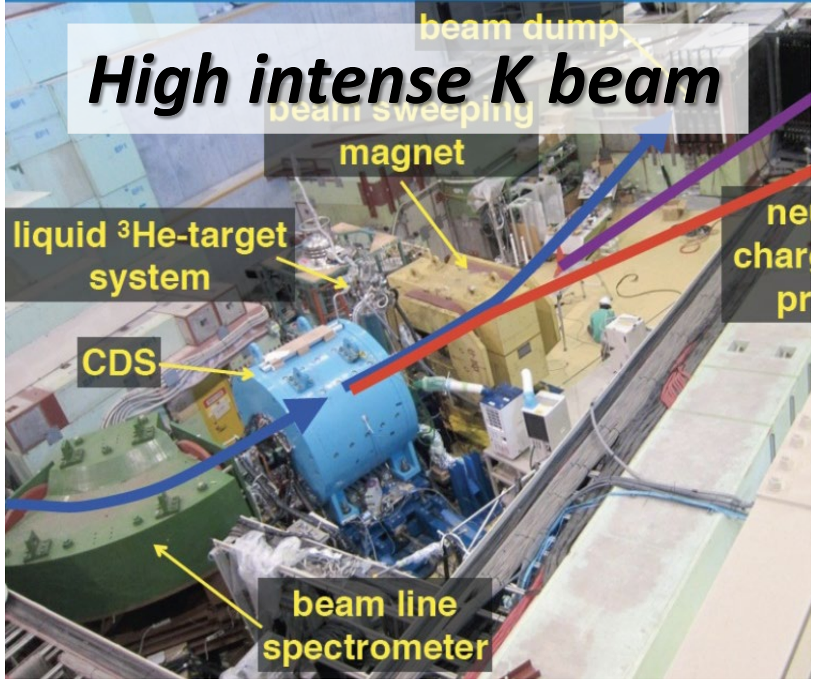
S. Okada
Chubu University, Aichi, 487-0027, Japan

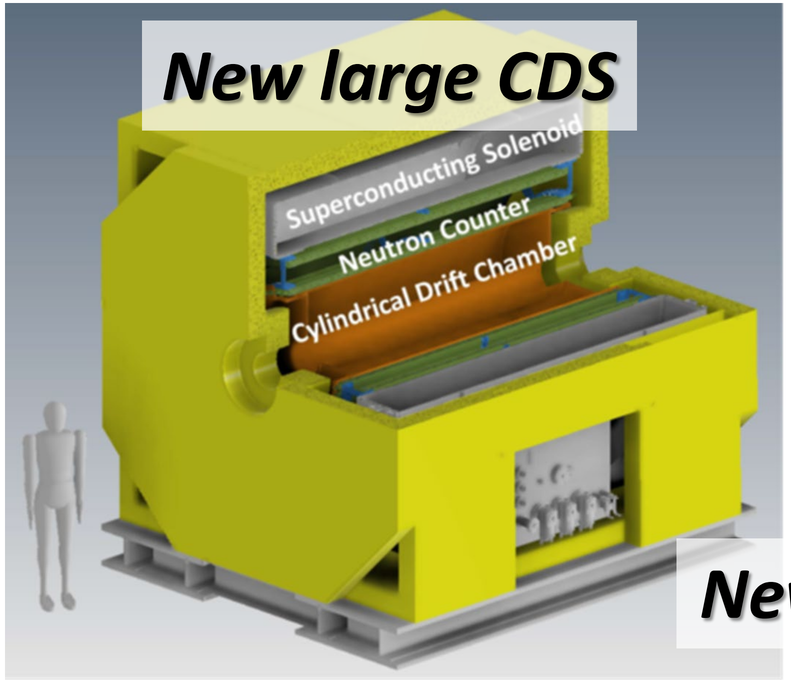
M. Bazzi, A. Clozza, C. Curceanu, C. Guaraldo, M. Iliescu, S. Manti, A. Scordo, F. Sgaramella, D. Sirghi, F. Sirghi
Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy

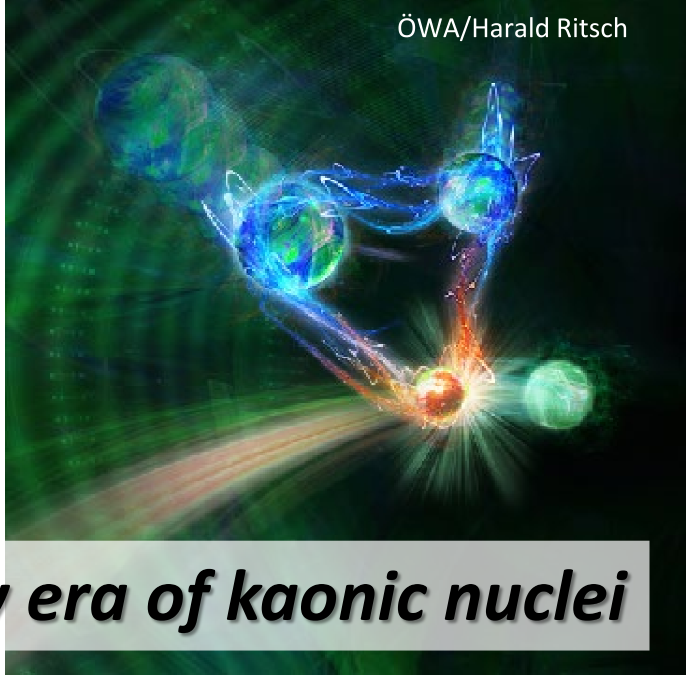
P. Buehler, E. Widmann, J. Zmeskal
Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria

We're looking for new collaborators!

RIKEN
TOHOKU
KEK
RCNP
JAEA
Tokyo Tech
INFN Istituto Nazionale di Fisica Nucleare

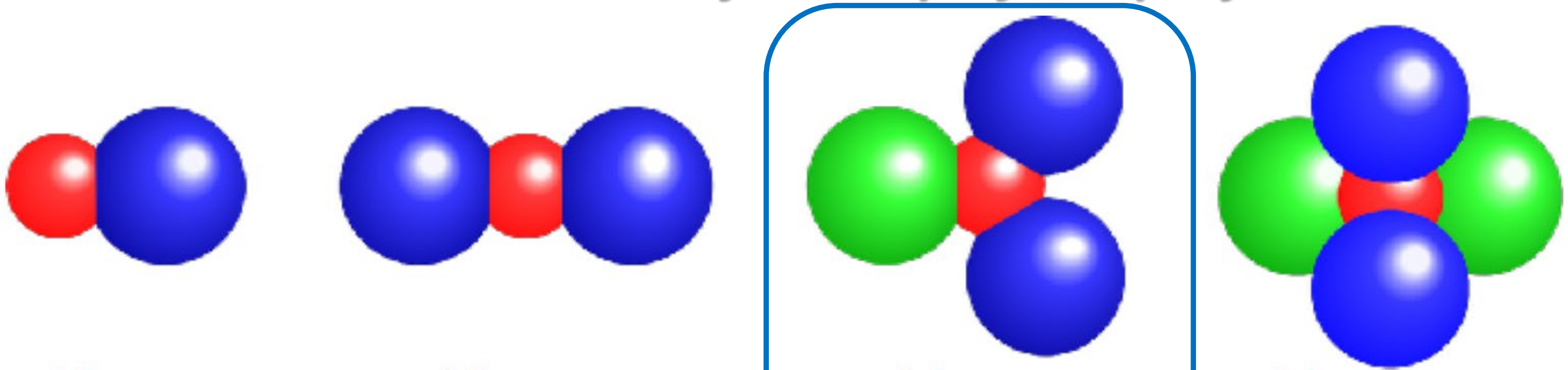






Thank you for your attention!

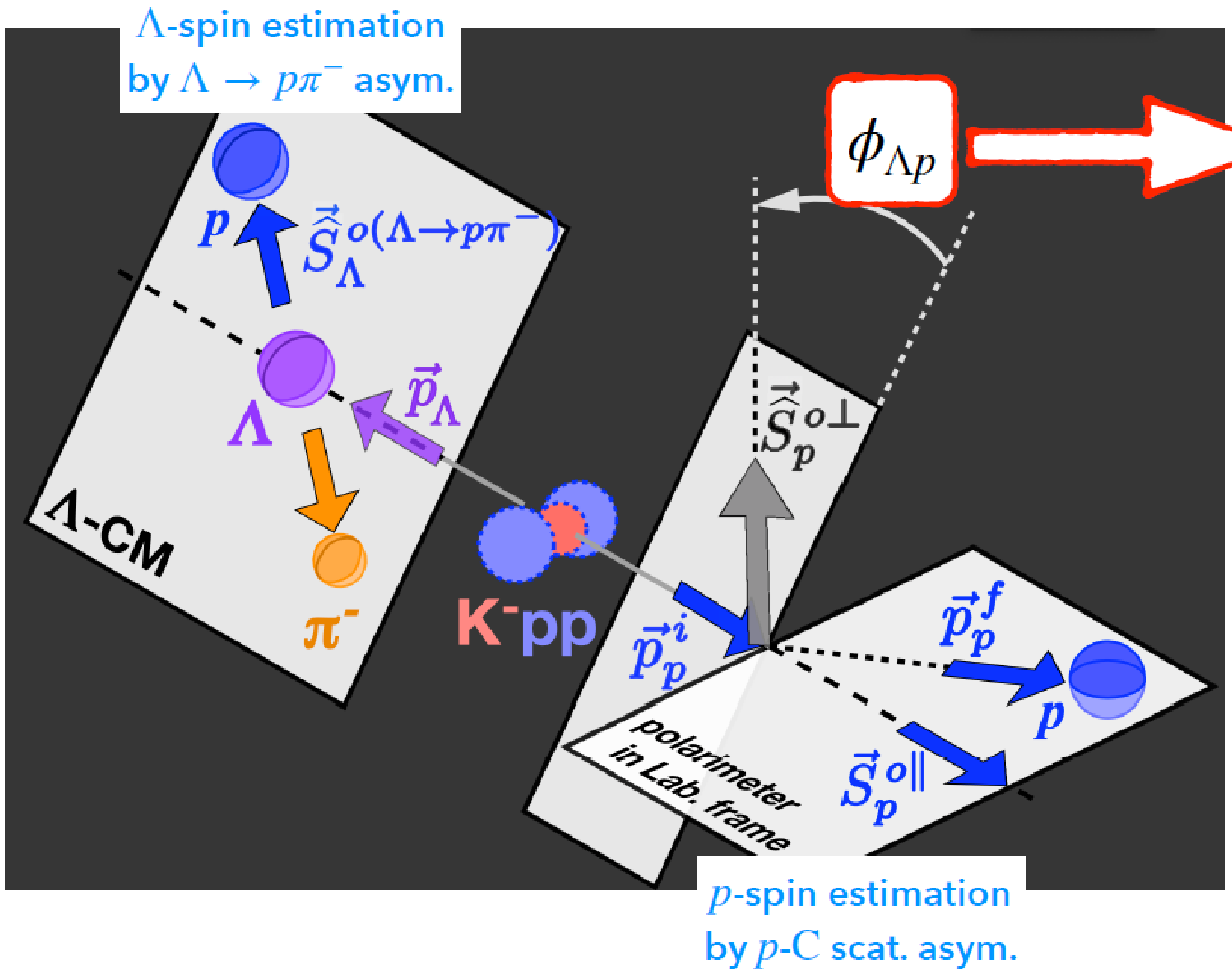
A first step of the project



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

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

How to measure the spin-spin correlation



Spin-spin correlation on ϕ-asymmetry

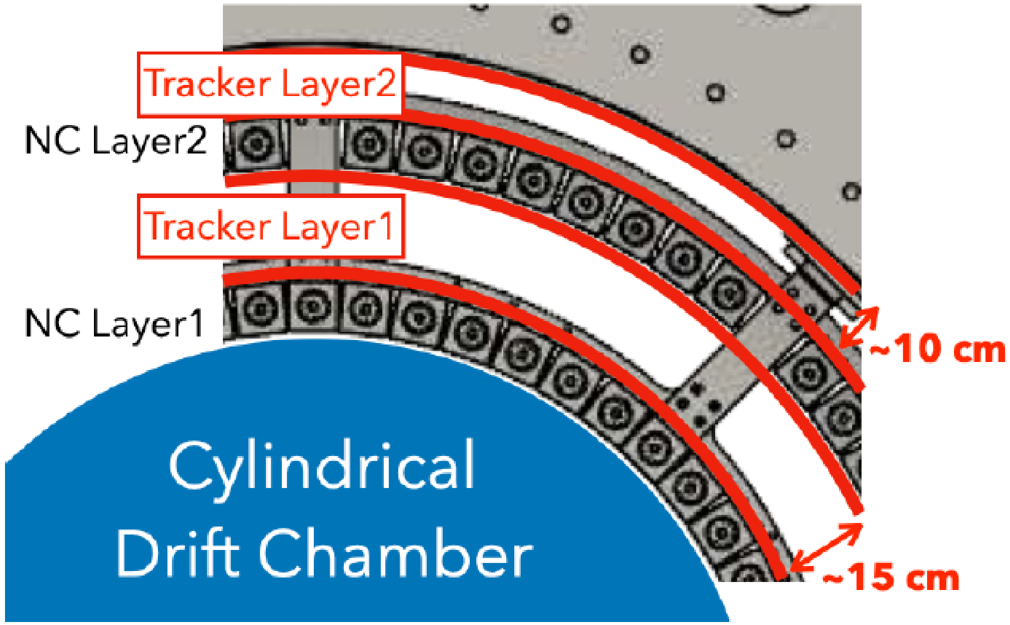
$$N(\phi_{\Lambda p}) = N_0 \cdot (1 + r^{(J^P)} \cdot \alpha_{\Lambda p} \cos \phi_{\Lambda p})$$

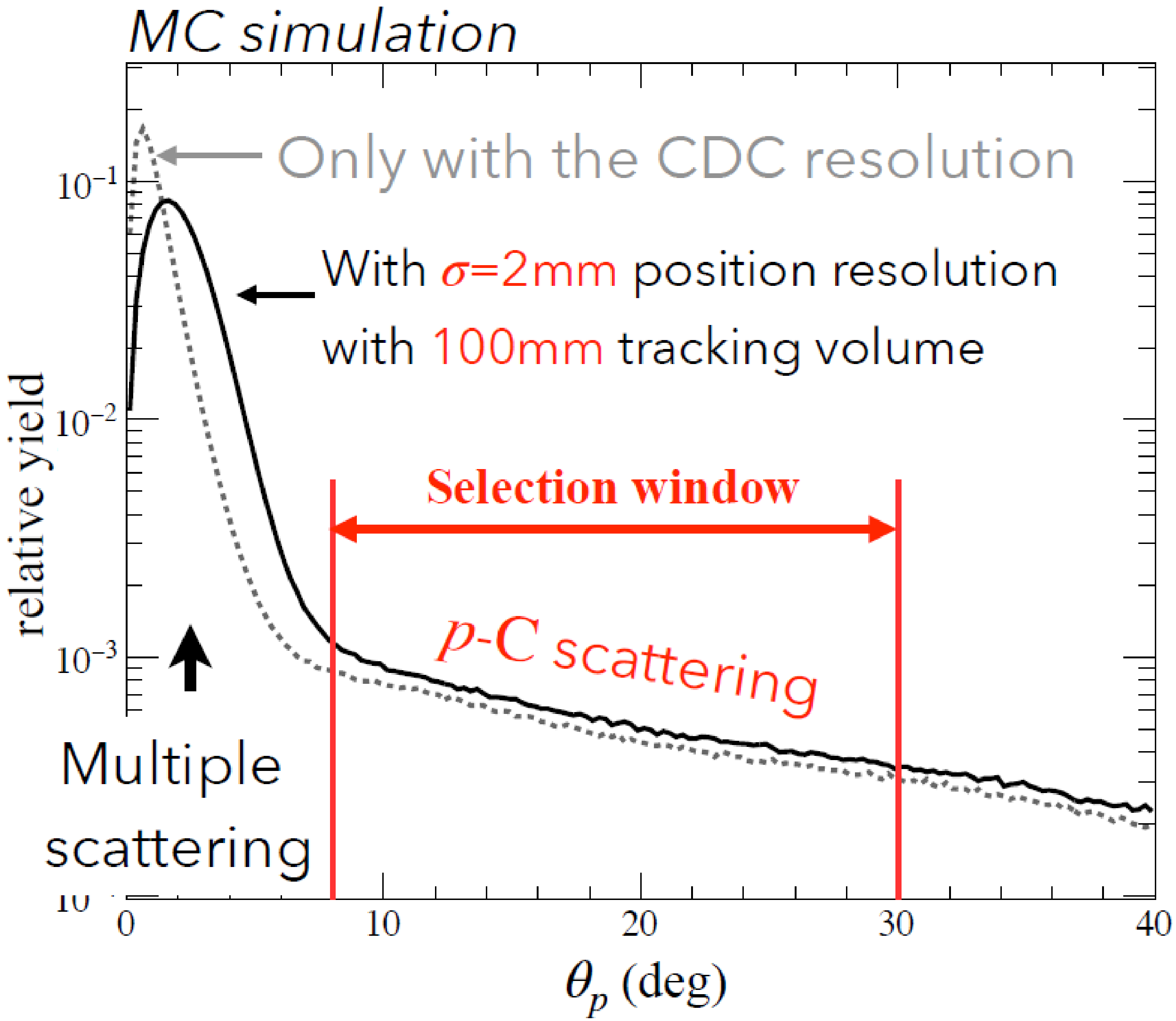
$r^{(J^P)}$: asymmetry reduction factor defined by;

- α_- : Λ asym. parameter
- A_{pC} : Analyzing power
- $f_{\vec{S}_\Lambda}$: Spin distribution
- B : Magnetic field
- $B_{\bar{K}}$: Binding energy
- q : Momentum transfer

We can deduce $\alpha_{\Lambda p}$ from $\phi_{\Lambda p}$-distribution.

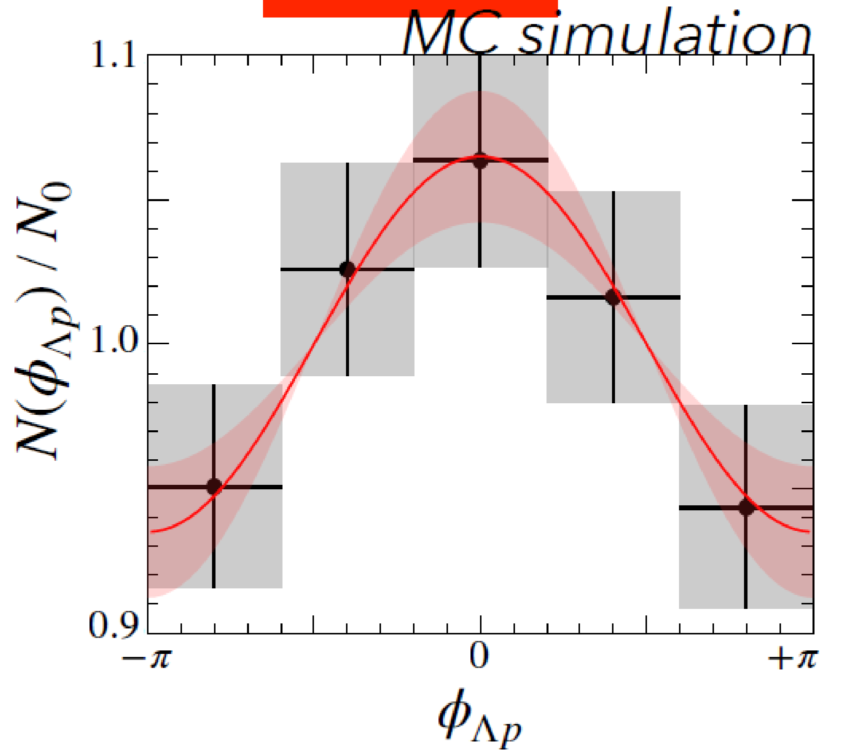
Necessary Position Resolution for the Tracker

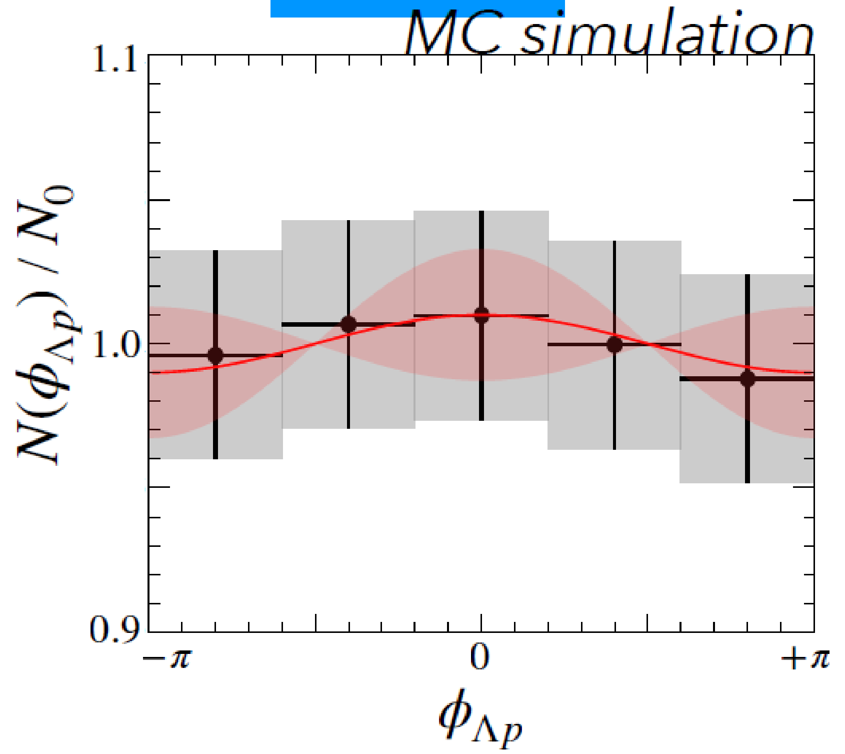




Expected spectra for $\alpha_{\Lambda p}$ measurment

8 weeks $\otimes$ 90 kW



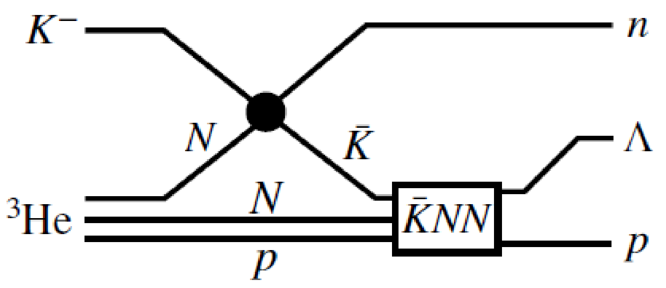


We would exclude $J^P = 1^-$ with **95%** confidence level.

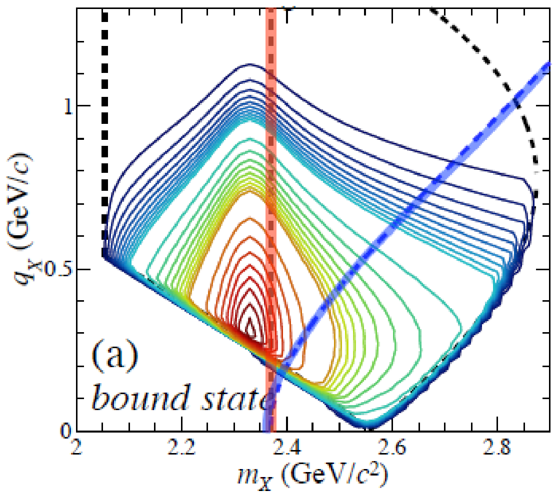
Takumi Yamaga (RIKEN)
for the J-PARC E15/E80/P89 collaboration
WNCP2023 @ Osaka Univ. (2023.11.27–29)

Exclusive measurement

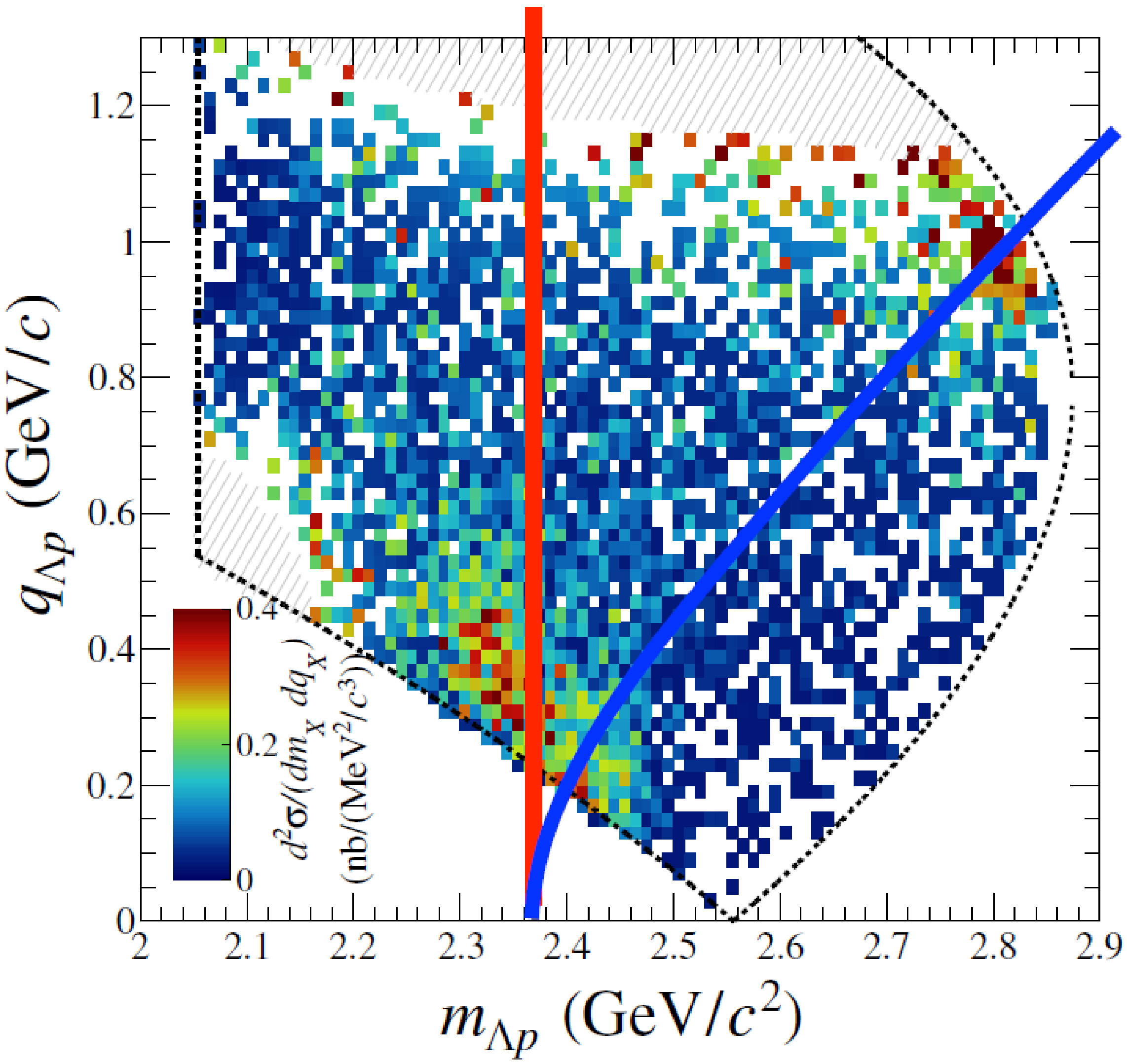
$\bar{K}NN$ production



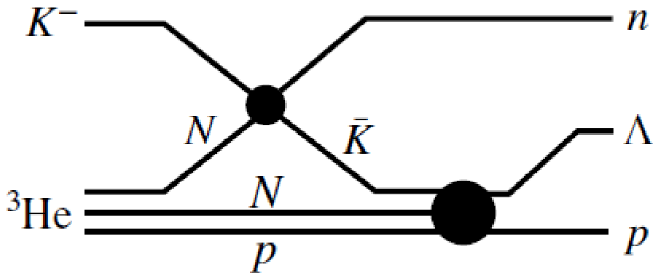
$$f_{\bar{K}NN}(m_X, q_X) = \frac{\Gamma^2/4}{(m_X - M_X)^2 + \Gamma^2/4} \times g_{K^-pp}(q_X)$$



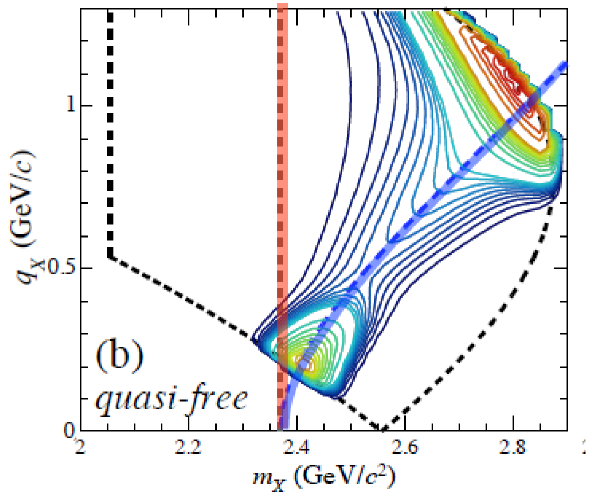
$m_{\bar{K}} + 2m_N$



Quasi-free process with (K^-, n)



$$f_{QF}(m_X, q_X) = \exp\left(-\frac{(m_X - M_F(q_X))^2}{\sigma^2(q_X)}\right) \times g_{QF}(q_X)$$

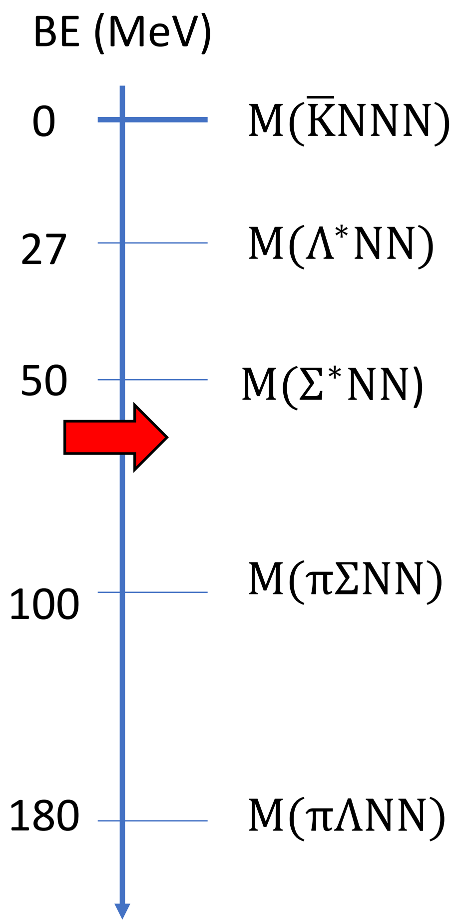


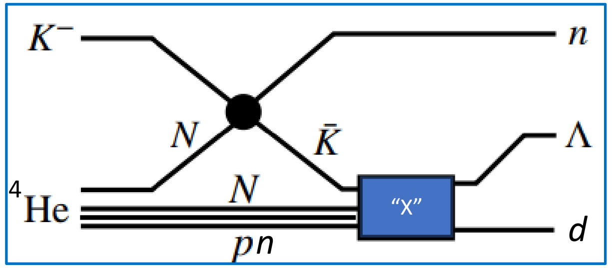
K^{-} ^{4}He → Λdn Analysis with the T77 Data

What is the observed structure?

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$^-$), ^{3}He = 1/2(1/2$^+$) , ^{4}He = 0(0$^+$)

2. <u>**“X”=“K^-ppn” with $J_{“X”}$ = 1/2** would be likely</u>
   - **$J_{“X”}$ = 1/2:**
     - ➢ ^{4}He initial state is I(J) = 0(0), and remaining “NNN” would be I(J) = 1/2(1/2)
     - ➢ low-momentum intermediate $\bar{K}$ would react with “NNN” in S-wave
   - **Exclusion of “X”=“Y*(I=1)NN”**:
     - ➢ “NN” is I(J) = 1(0)
     - ➢ “Y*(I=1)NN”→Λd decay would be suppressed
       - ✓ spin/isospin flip is needed to reconfigure “NN” into “d” [I(J) = 0(1)]
       - ✓ Λpn decay would be dominant for “Y*(I=1)NN”



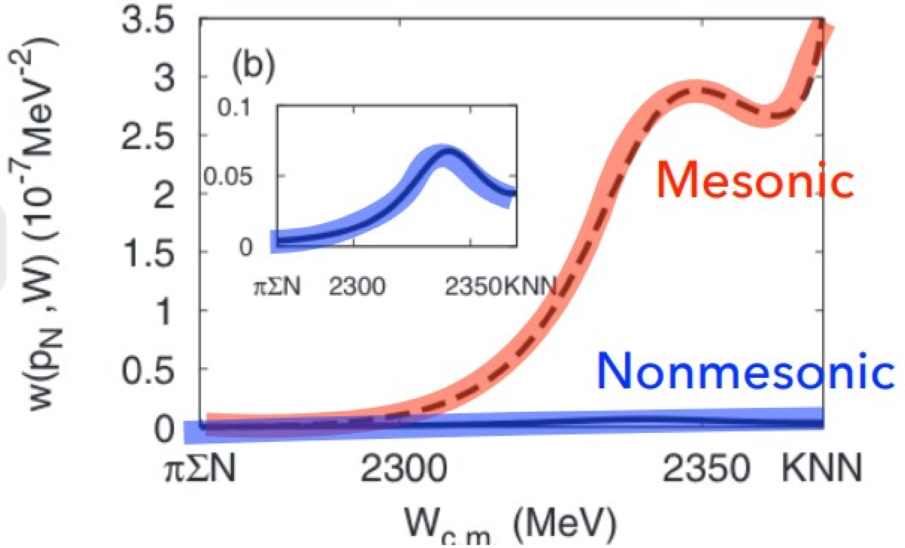


Mesonic Decay Modes of $\bar{K}NN$

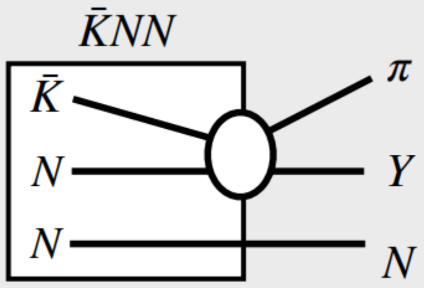
- Mesonic decays will give us further information on $\bar{K}NN$
  - ✓ internal structure
  - ✓ $\bar{K}N$ interaction below the threshold

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

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

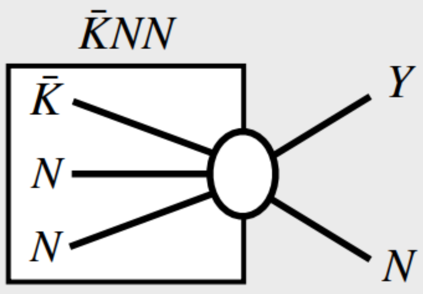


Mesonic

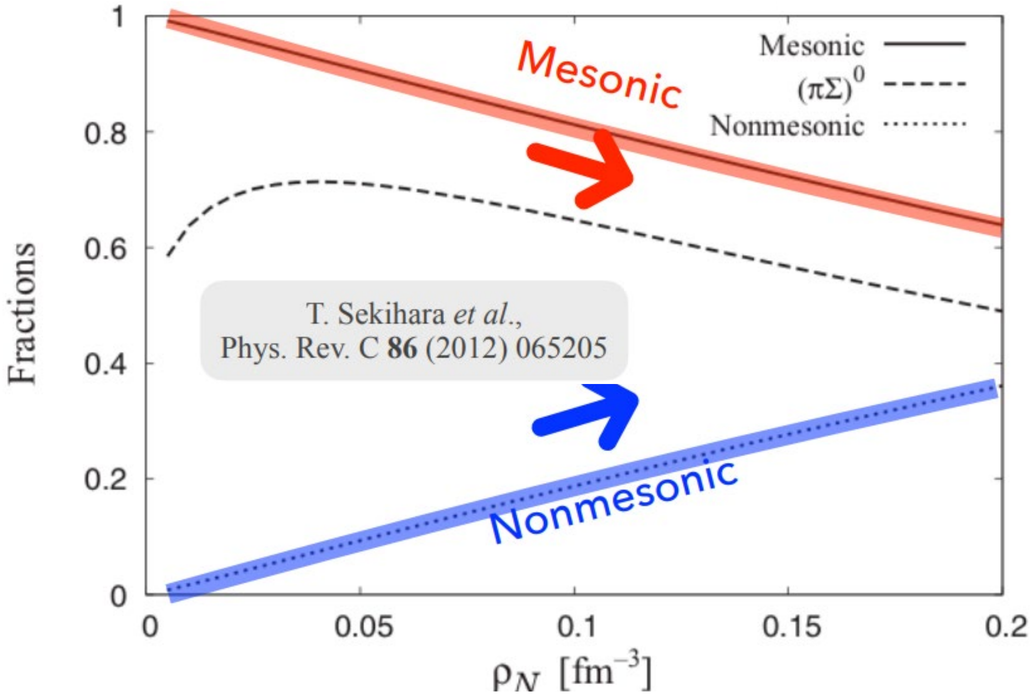


1N absorption

Non-mesonic



2N absorption

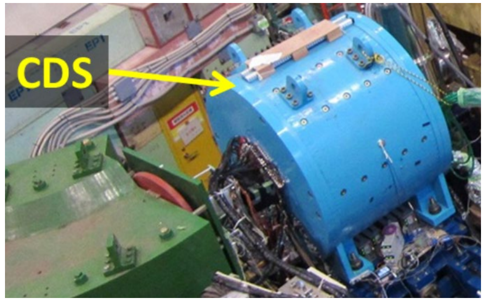


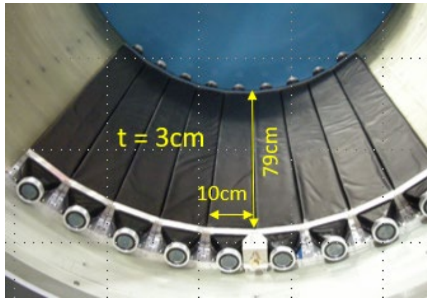
T. Sekihara *et al.*, Phys. Rev. C **86** (2012) 065205

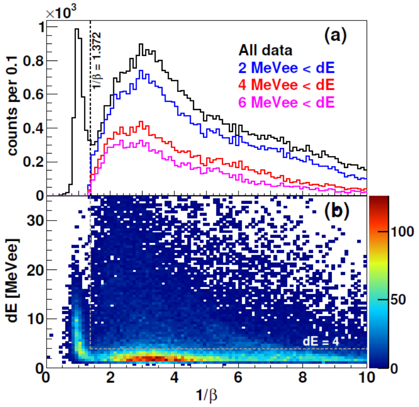
T.Yamaga et.al., arXiv:2404.01773 [nucl-ex]

Mesonic Decay Analysis with the E15 Data

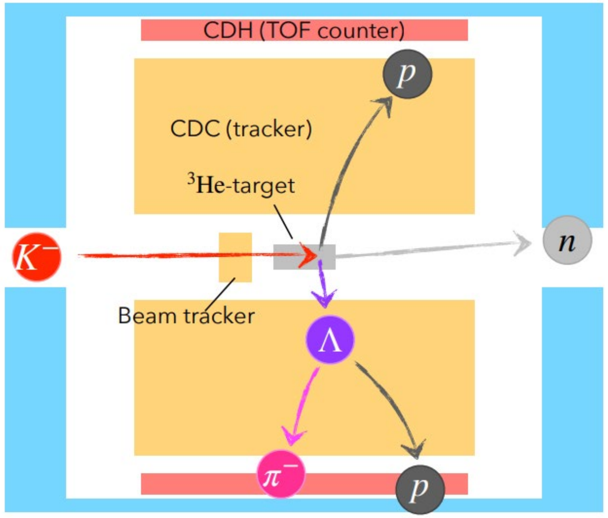
- with neutron detection using a thin scintillation counter array (CDH)
  - ☹ small efficiency (3~9%)
  - ☹ BG from the inner wall of the magnet

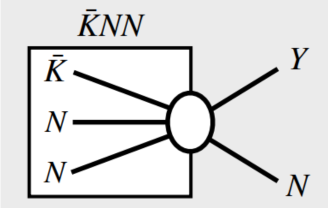




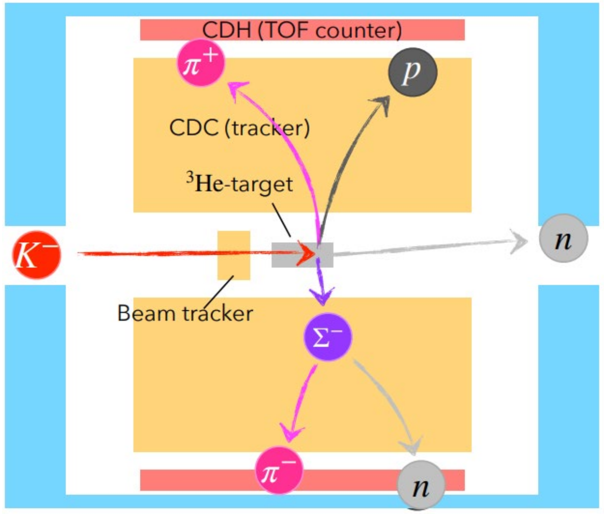


"K^-pp" → Λp

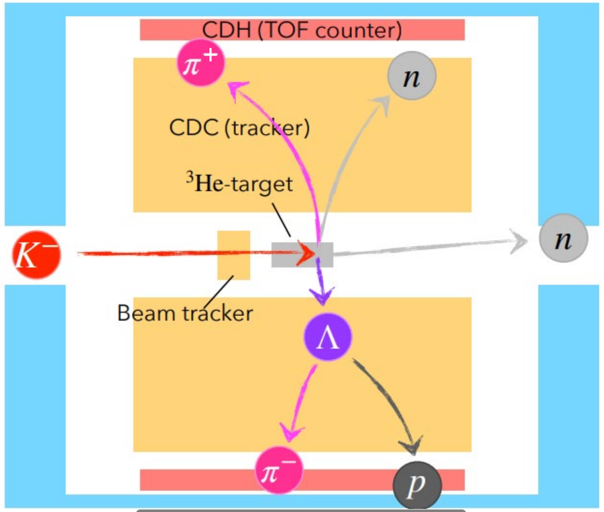




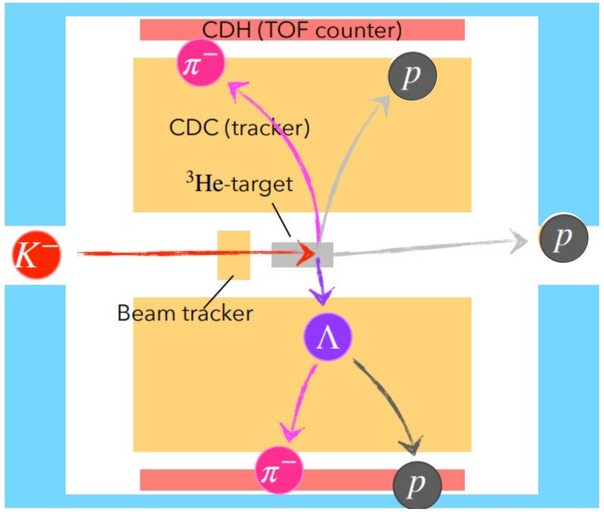
"K^-pp" → $\pi^\pm\Sigma^\mp p$

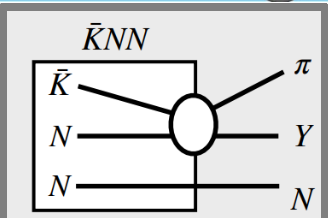


"K^-pp" → $\pi^+\Lambda n$



"$\bar{K}^0nn$" → $\pi^-\Lambda p$

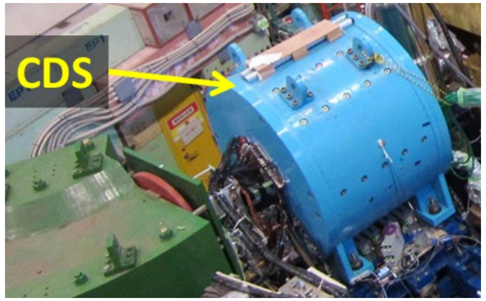


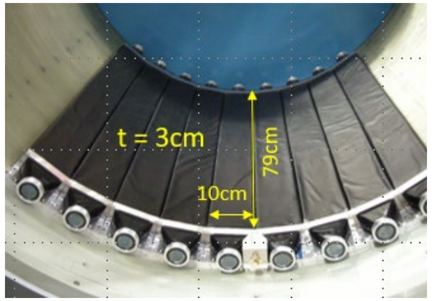


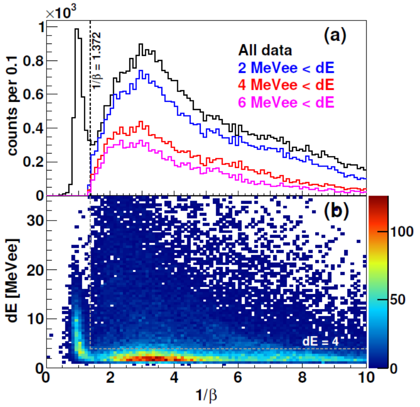
T.Yamaga et.al., arXiv:2404.01773 [nucl-ex]

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

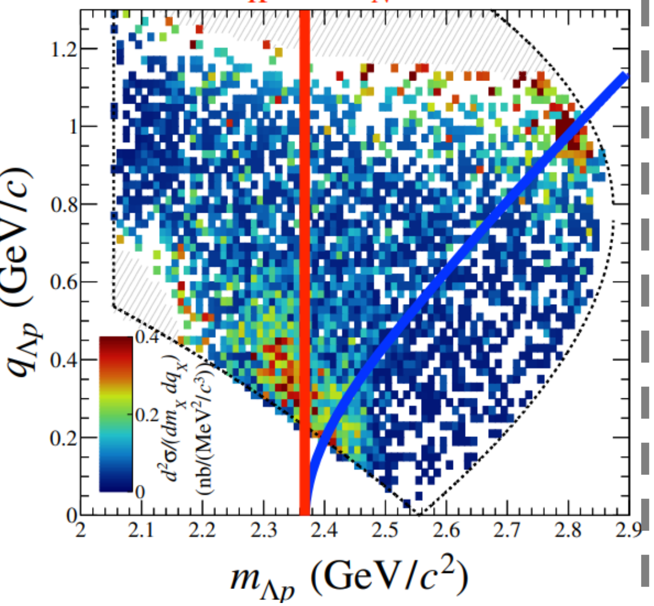






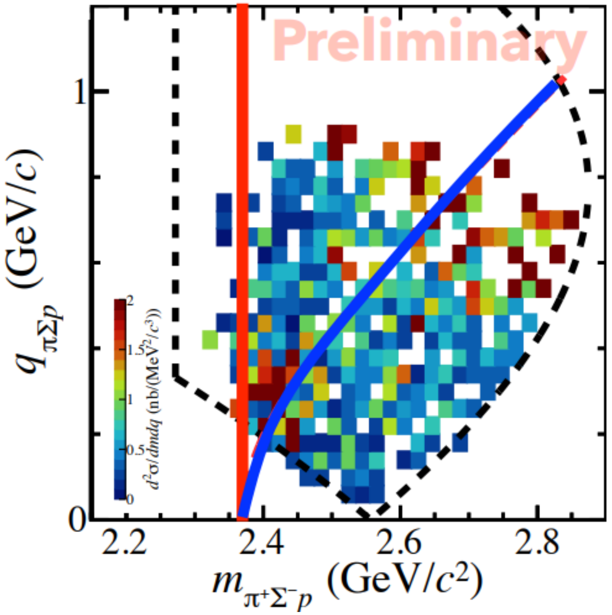
"K^-pp" → Λp

$m_{\bar{K}} + 2m_N$



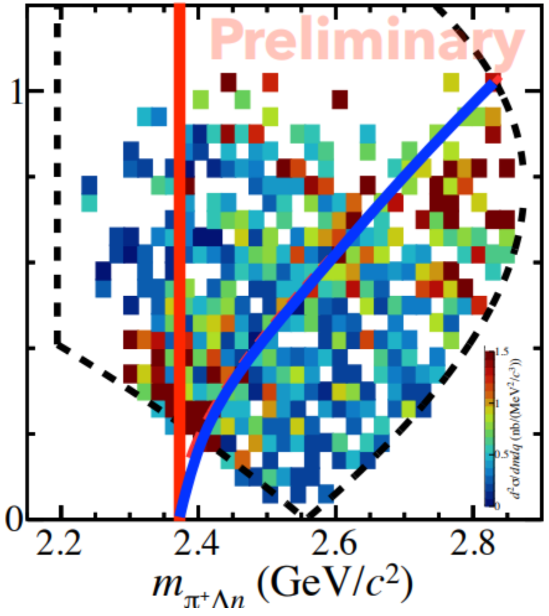
"K^-pp" → $\pi^{\pm}\Sigma^{\mp}p$

$m_{\bar{K}} + 2m_N$



"K^-pp" → $\pi^+\Lambda n$

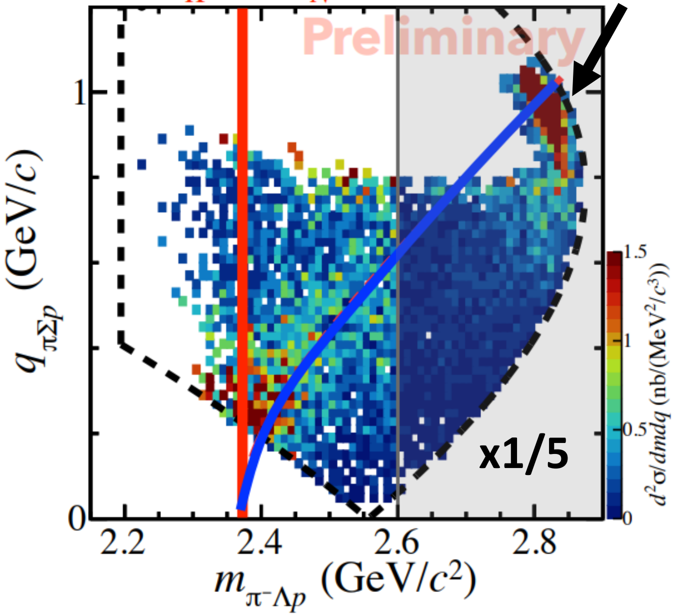
$m_{\bar{K}} + 2m_N$



"$\bar{K}^0nn$" → $\pi^-\Lambda p$

$m_{\bar{K}} + 2m_N$

2NA w/ p_{Fermi}



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

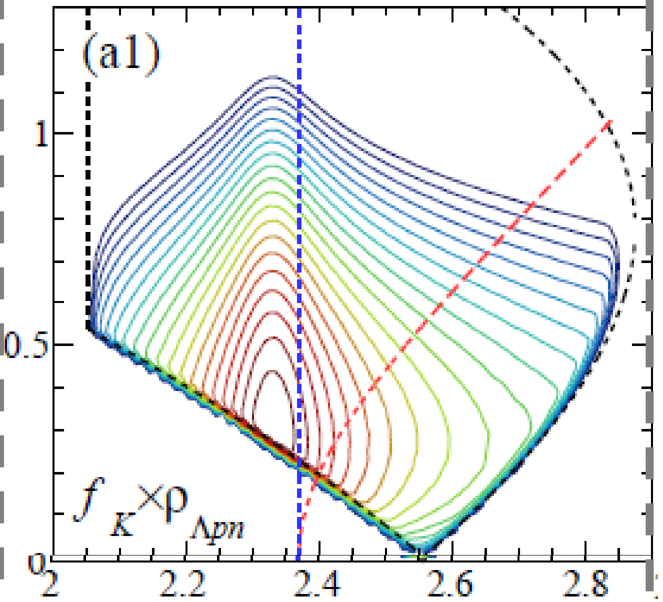
Phase space

Momentum term from spatial integral

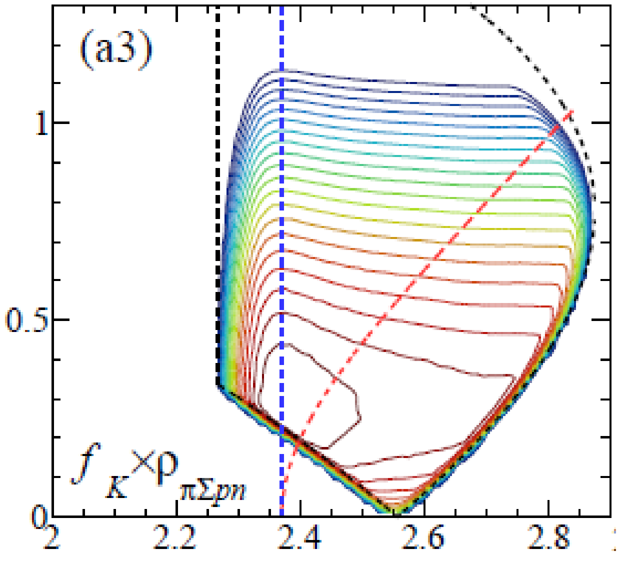
$$\sigma(M,q) \propto \rho(M,q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2} \times exp\left(-\frac{q^2}{{Q_{Kpp}}^2}\right)$$

Energy term (BW type) from time integral

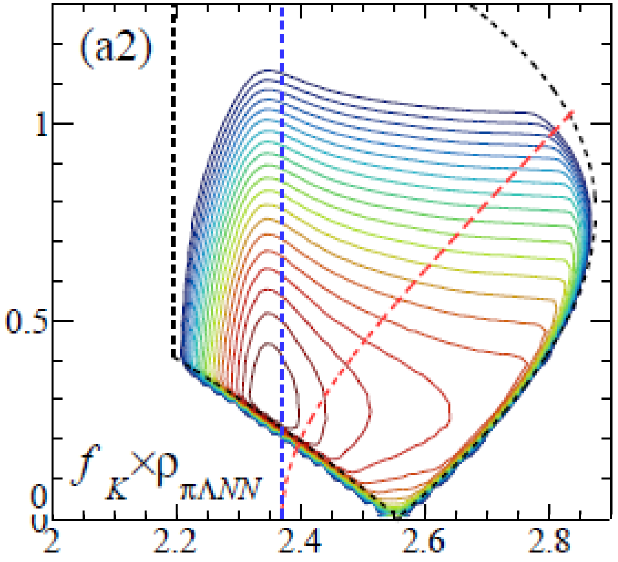
$"K^-pp" \rightarrow \Lambda p$



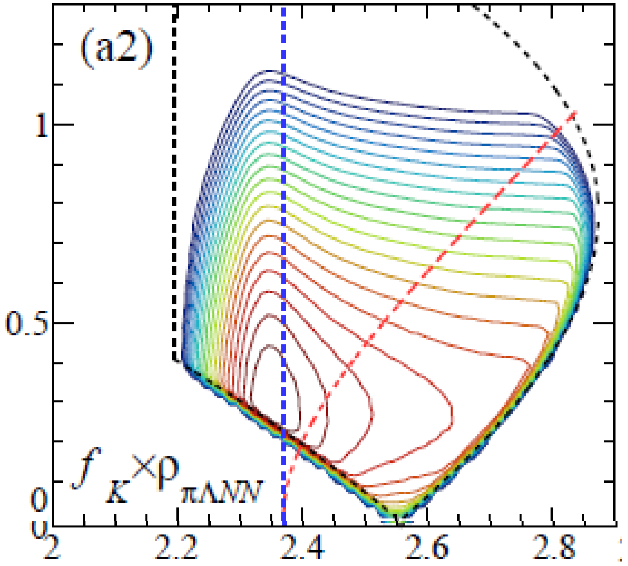
$"K^-pp" \rightarrow \pi^\pm \Sigma^\mp p$



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



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



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

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

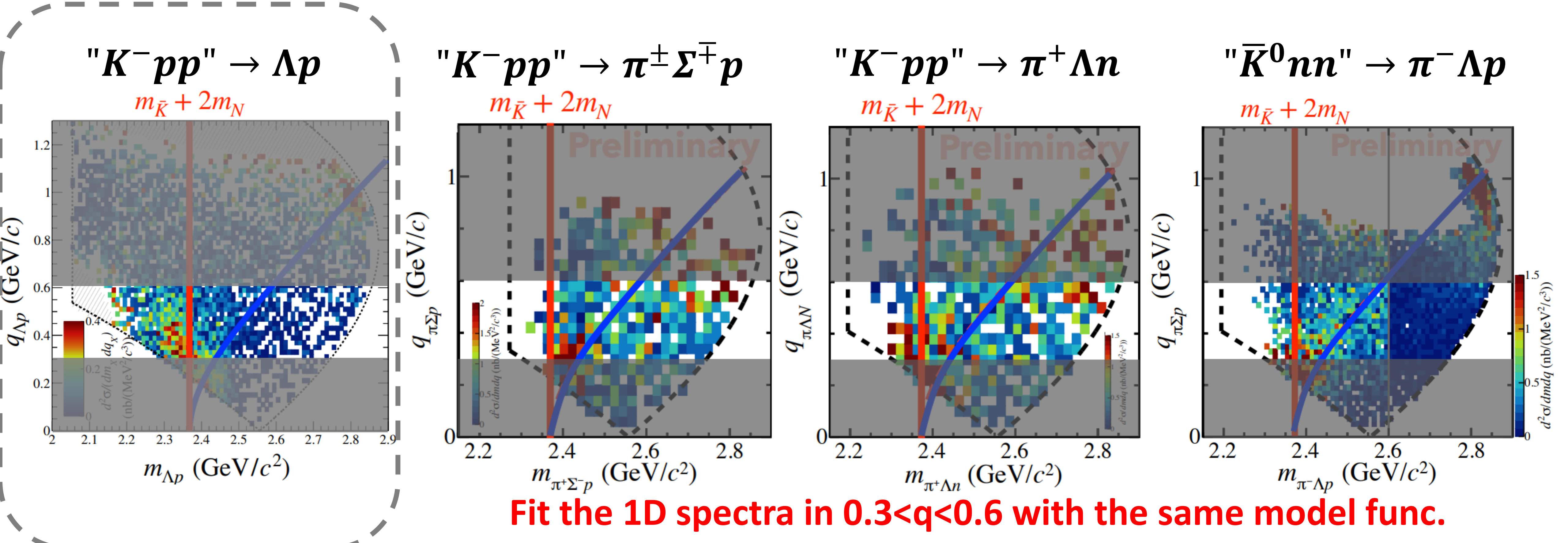
Mesonic Decay Analysis with the E15 Data

Plane Wave Impulse Approximation

Fit with PWIA

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

- Phase space: $\rho(M,q)$
- Energy term (BW type) from time integral
- Momentum term from spatial 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

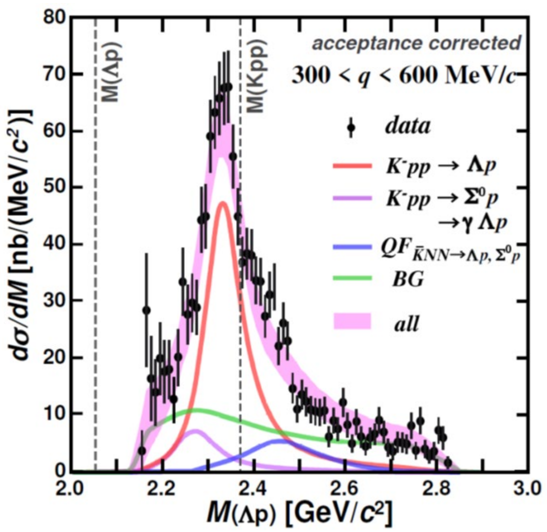
Fit with PWIA

Phase space — Momentum term from spatial integral

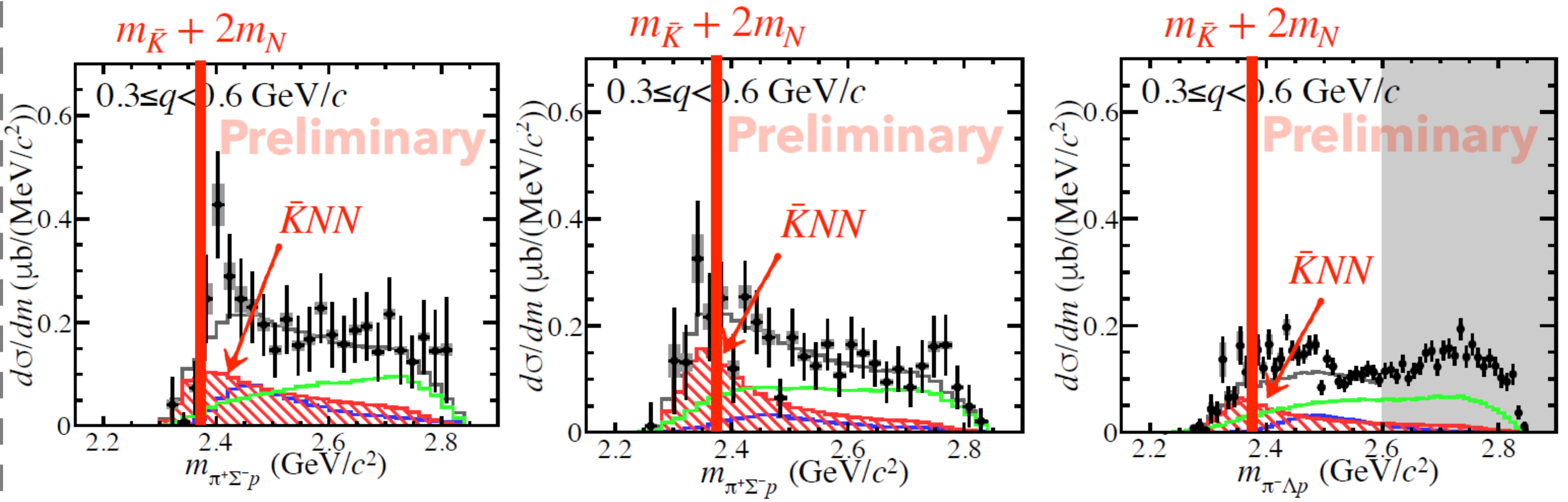
$$\sigma(M,q) \propto \rho(M,q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2} \times exp\left(-\frac{q^2}{Q_{Kpp}{}^2}\right)$$

Energy term (BW type) from time integral

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



$"K^- pp" \to \pi^\pm \Sigma^\mp p$ — $"K^- pp" \to \pi^+ \Lambda n$ — $"\bar{K}^0 nn" \to \pi^- \Lambda p$



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 $Br_{K\text{-}pp\to\pi+\Lambda n} = Br_{K0nn\to\pi-\Lambda p}$ → $\sigma_{K\text{-}pp} / \sigma_{K0nn} \sim 2$

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

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

$"K^{-}pp" \rightarrow \Sigma^{0}p$

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

$"K^{-}pp" \rightarrow \pi^{+}\Sigma^{-}p$

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

$"K^{-}pp" \rightarrow \pi^{-}\Sigma^{+}p$

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

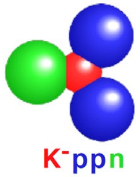
$"K^{-}pp" \rightarrow \pi^{+}\Lambda n$

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

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

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

More precise measurements and theoretical investigations are needed

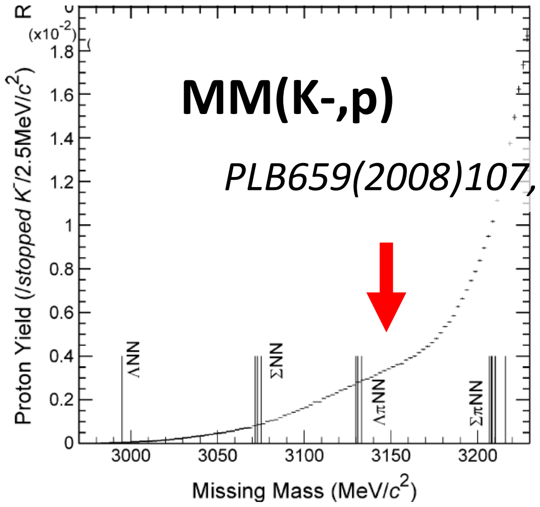


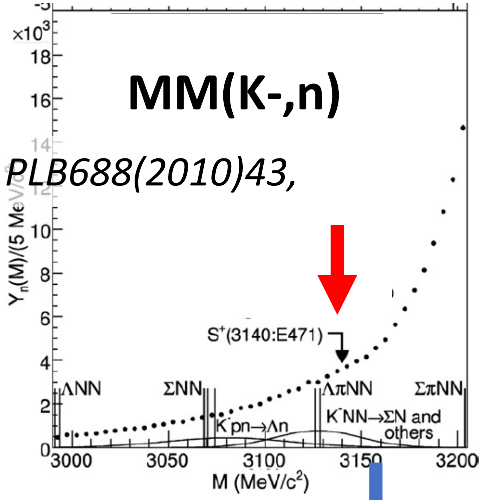
$\bar{K}$NNN Searches so far

E471/E549@KEK

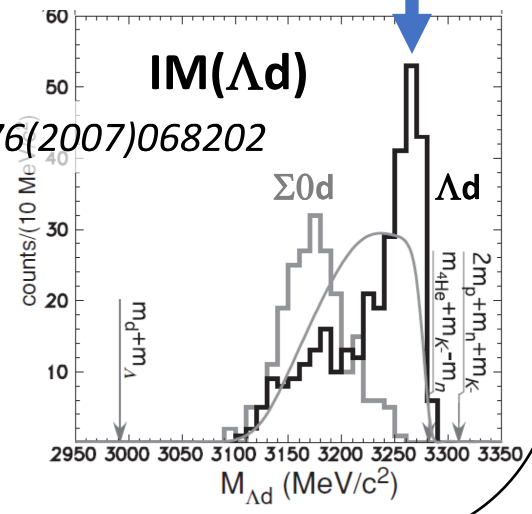
^{4}He(stopped-K^{-},p/n/Yd)

PLB659(2008)107, PLB688(2010)43,



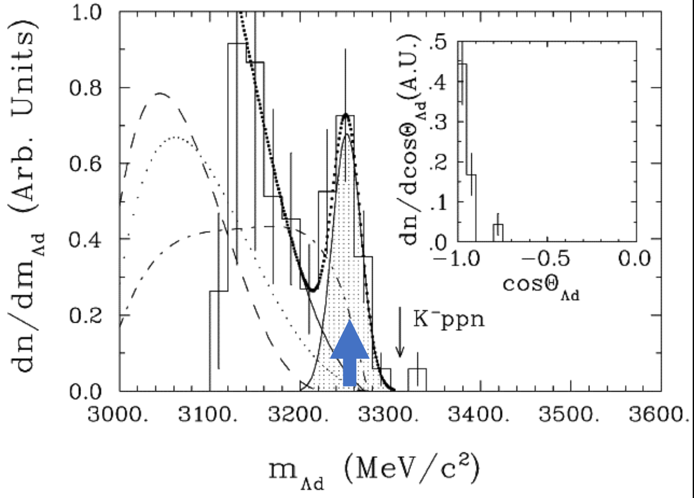


PRC76(2007)068202



FINUDA@DAΦNE

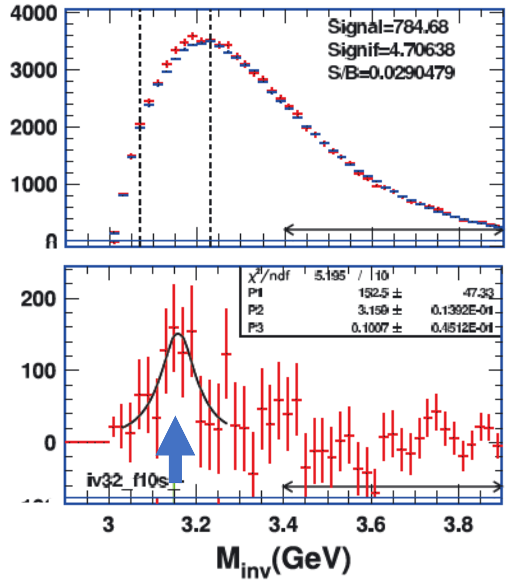
Li/C(stopped-K^{-},Λd)



PLB654(2007)80

FOPI@GSI

Λd in Ni+Ni

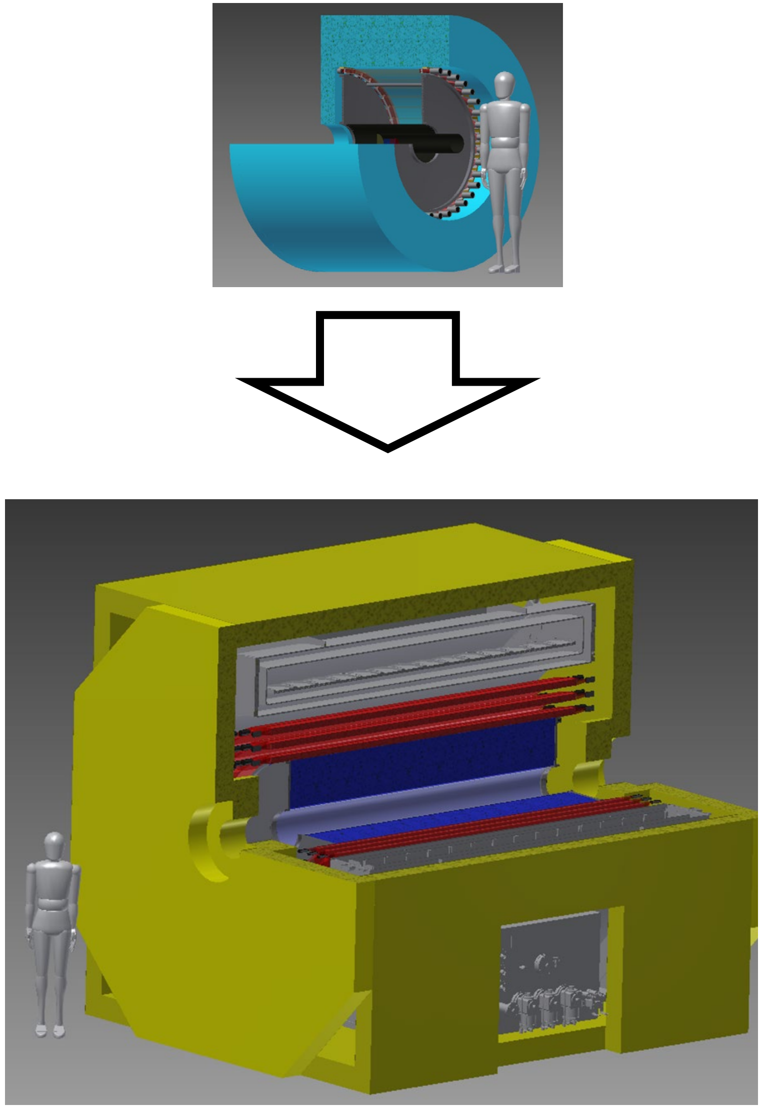


EXA05 Conference (2005)

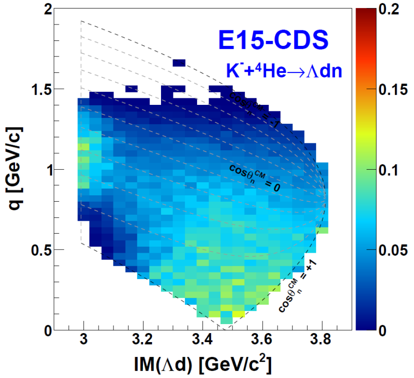
No conclusive results.

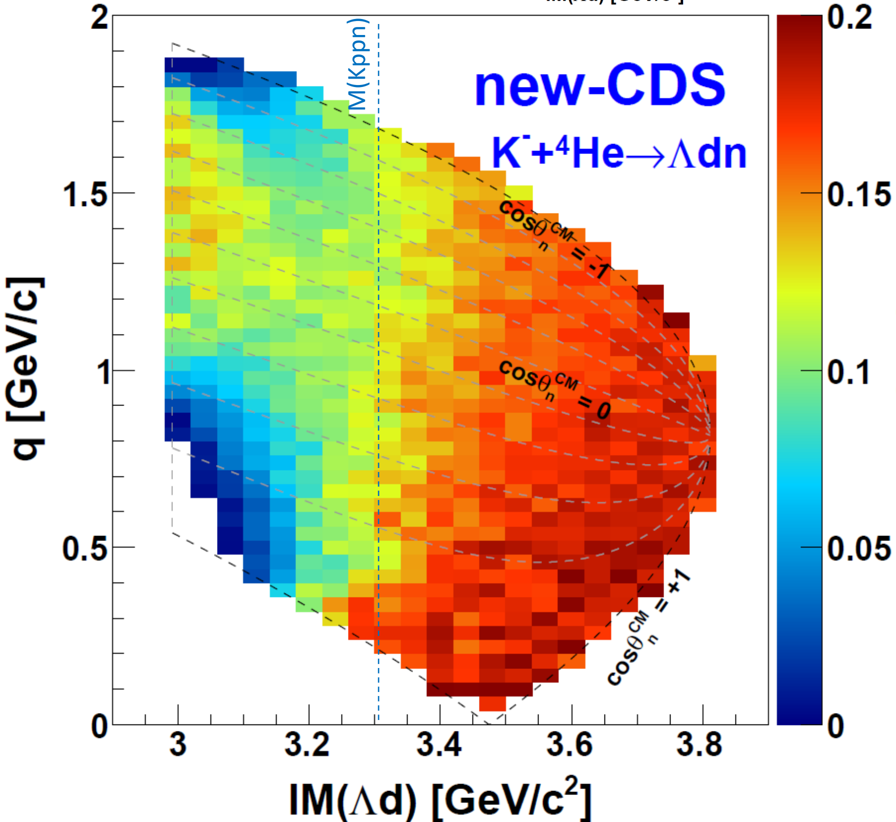
multi-N absorption in stopped-K reaction makes interpretation difficult

Acceptance for $K^{-4}He$ reaction



Λd in CDS





Λpn in CDS