Kaonic nuclei: progress and prospects at J-PARC

F. Sakuma, RIKEN
sakuma@ribf.riken.jp

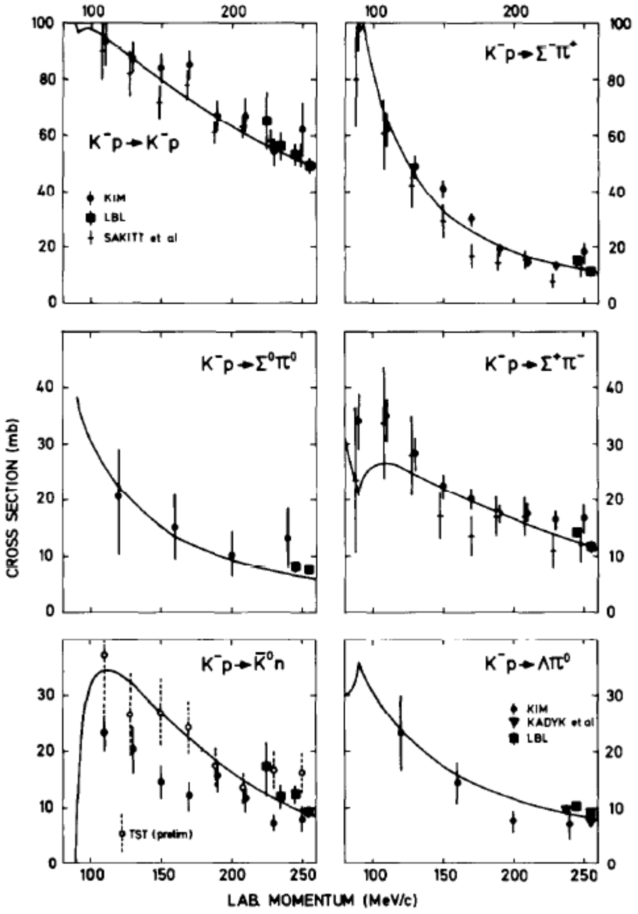
on behalf of the J-PARC E15/E31/E73/E80/E89 collaboration

Workshop on Fundamental Physics with Exotic Atoms

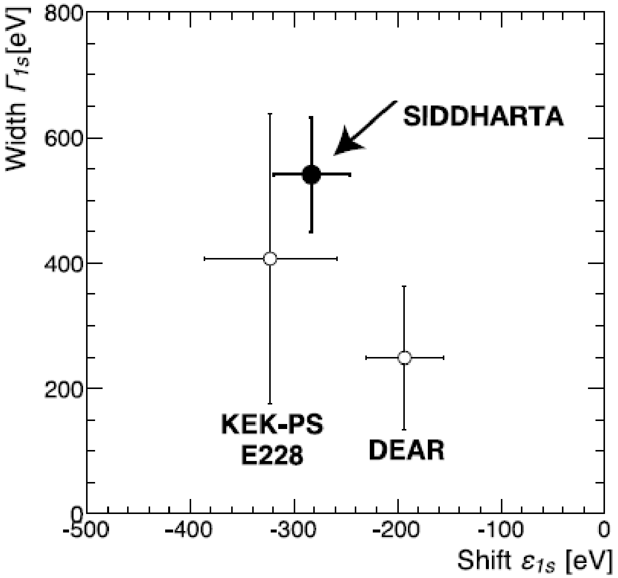
23–25 Jun 2025,
INFN-LNF, Frascati

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

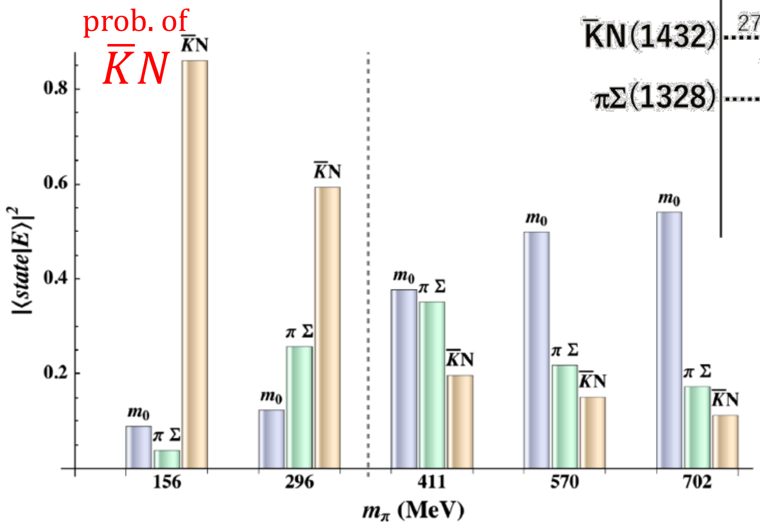
K⁻p scattering
NPB179(1981)33.

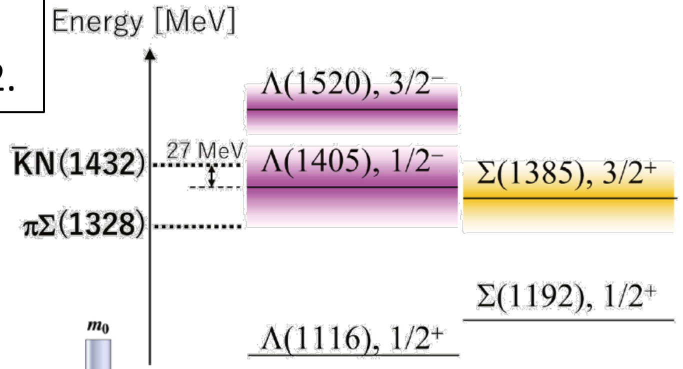


K⁻p atom
PLB704(2011)113.

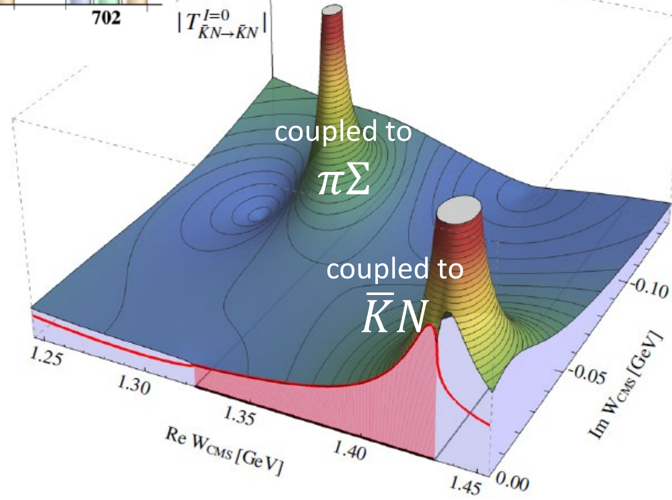


$\Lambda(1405)$ in LQCD
RPL114(2015)132002.





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

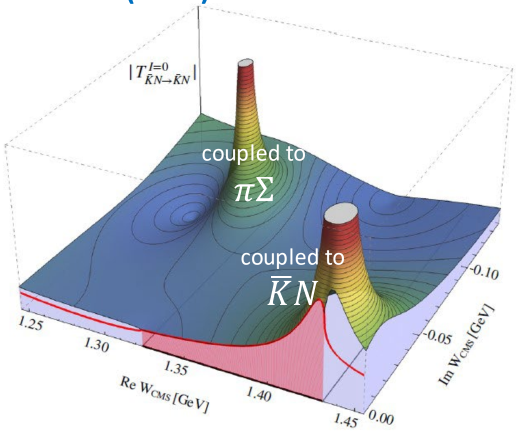


✓**strongly attractive $\bar{K}N$ int. in I=0**

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

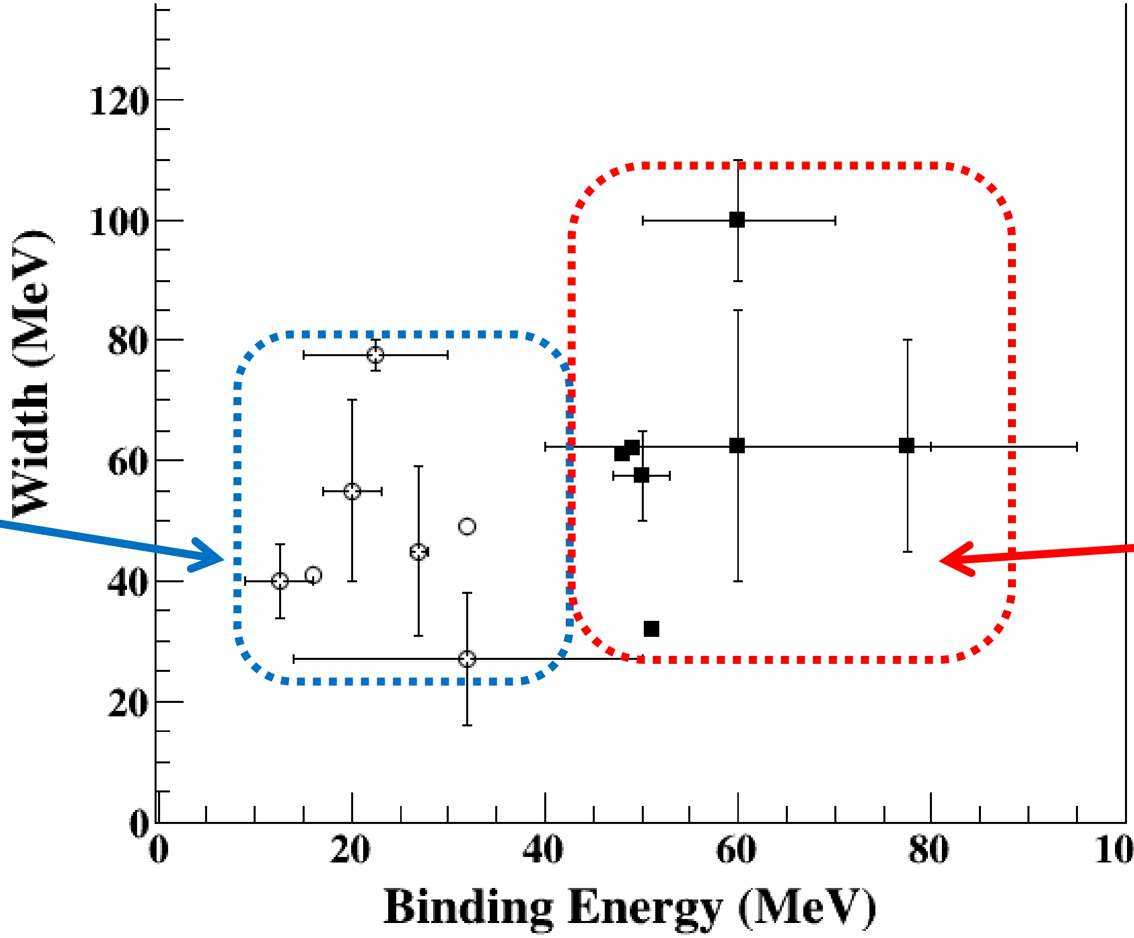
Theoretical Calculations of $\bar{\mathrm{K}}$NN

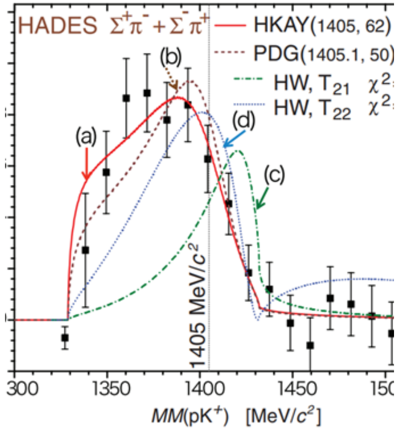
Chiral unitary model (energy dependent)	Phenomenological model (energy independent)
$M_{\Lambda(1405)}$~1420, double pole	$M_{\Lambda(1405)}$~1405, single pole



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

B.E. ~ 10-30 MeV





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

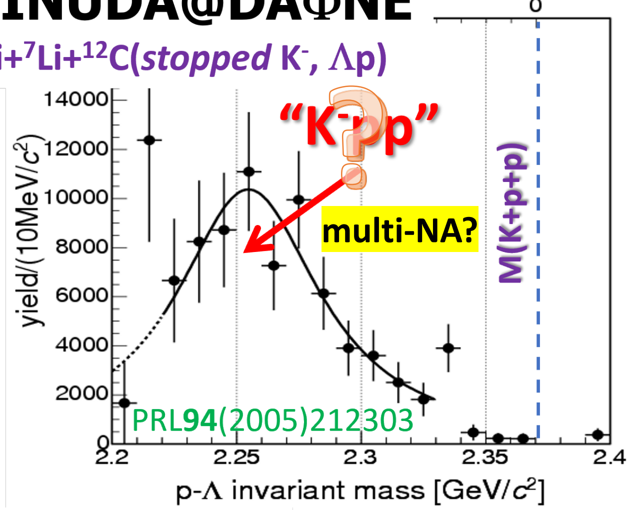
B.E. ~ 40-70 MeV

suggesting a more compact and dense system

“K^-pp” Bound State Searches

FINUDA@DAΦNE

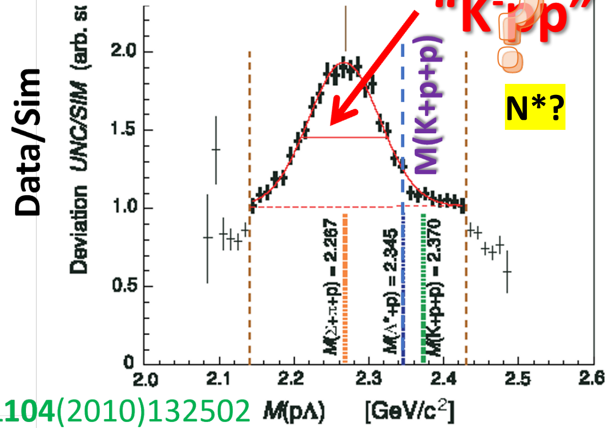
$^6Li+^7Li+^{12}C$(*stopped* K^-, Λp)



PRL**94**(2005)212303

DISTO@SATURNE

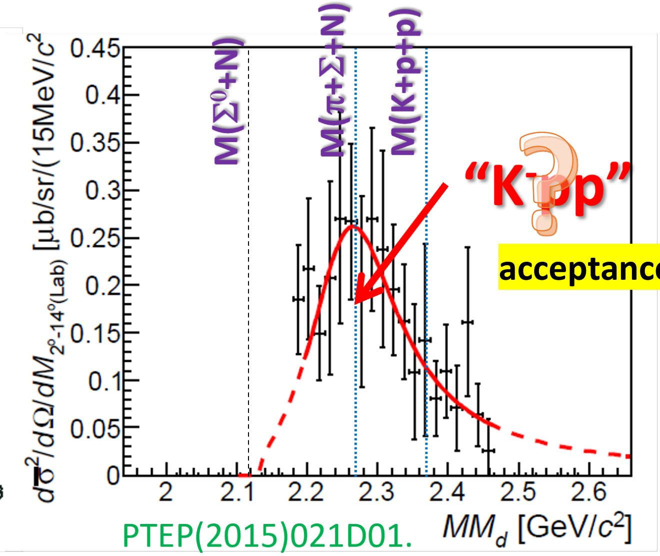
p + p → (Λ + p) + K⁺ @ 2.85GeV



PRL**104**(2010)132502

E27@J-PARC

d(π^+, K^+)Σ^0p @ 1.69 GeV/c

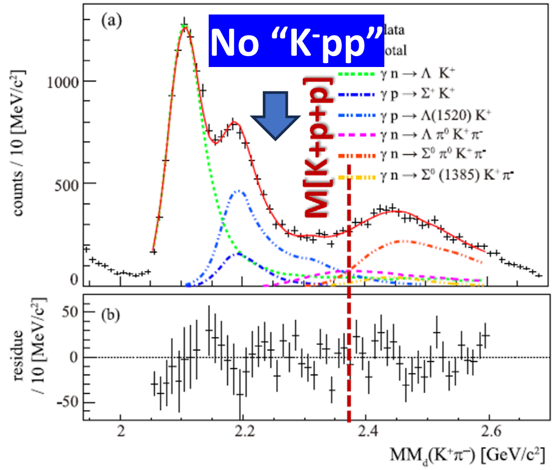


PTEP(2015)021D01.

LEPS@SPring-8

d(γ, $K^+\pi^-$)X @ 1.3-2.4 GeV/c

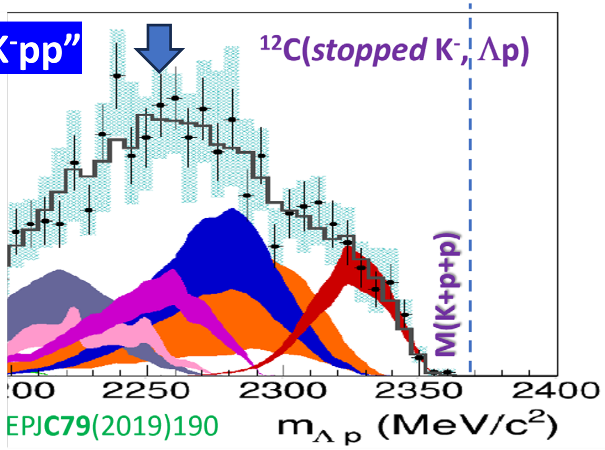
PLB728(2014)616.



AMADEUS@DAΦNE

No “K^-pp”

^{12}C(*stopped* K^-, Λp)

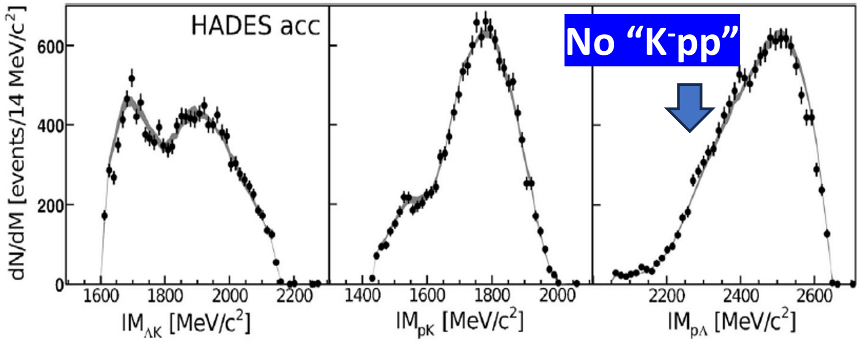


EPJC**79**(2019)190

HADES@GSI

PLB**742**(2015)242

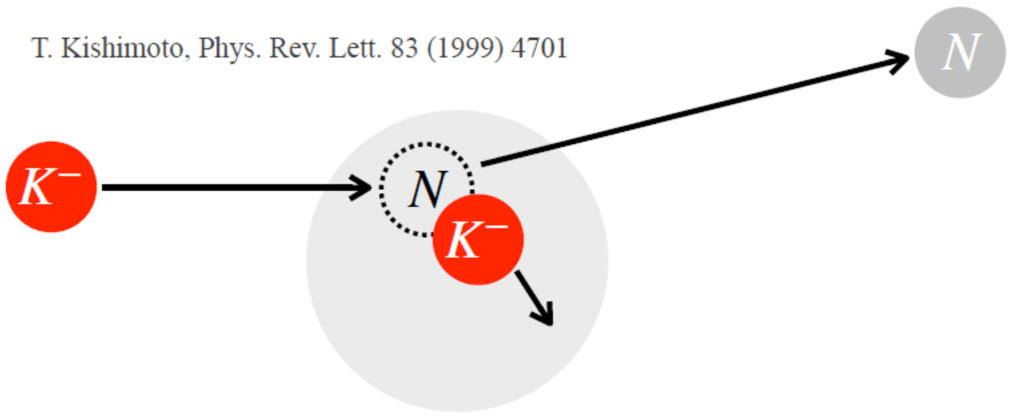
p + p → (Λ + p) + K⁺ @ 3.5GeV



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

Experimental Investigations at J-PARC

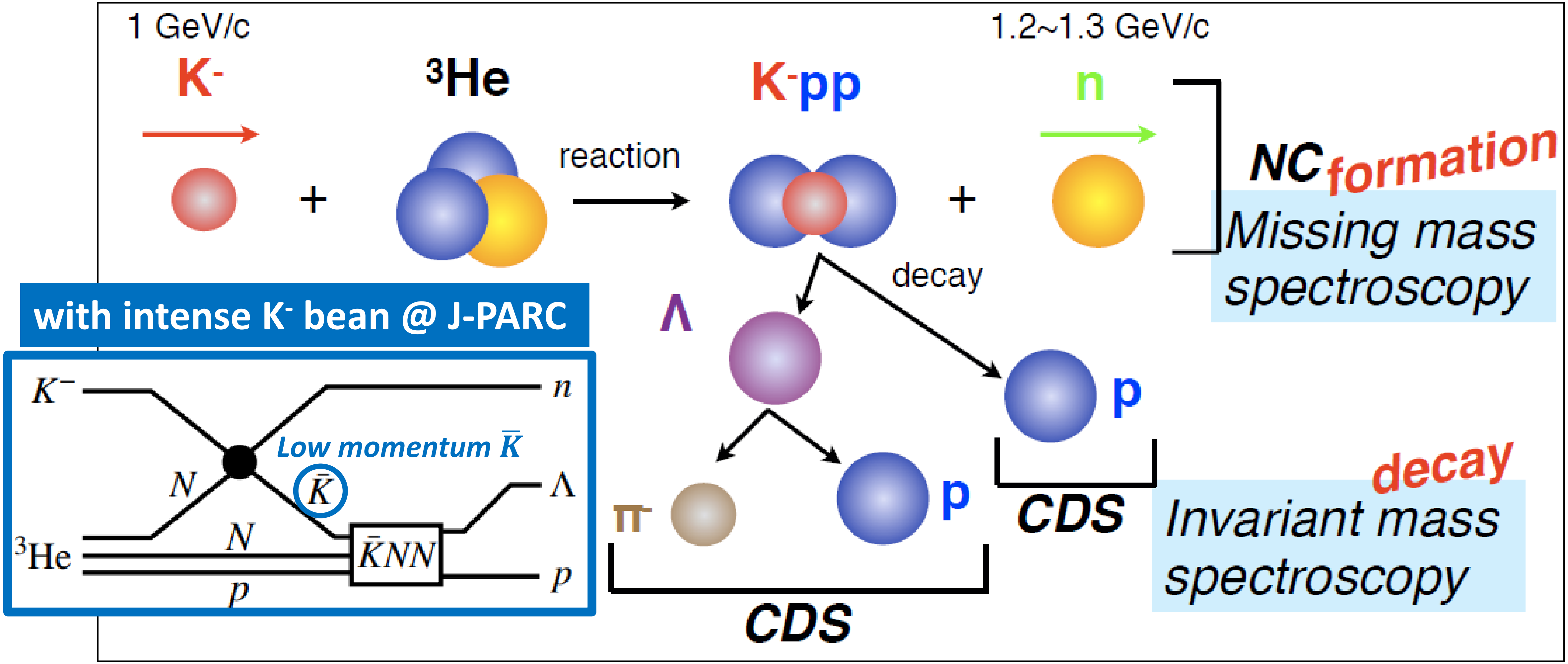
– via in-flight (K-,n) reactions –



"K⁻pp" Search @ J-PARC E15

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

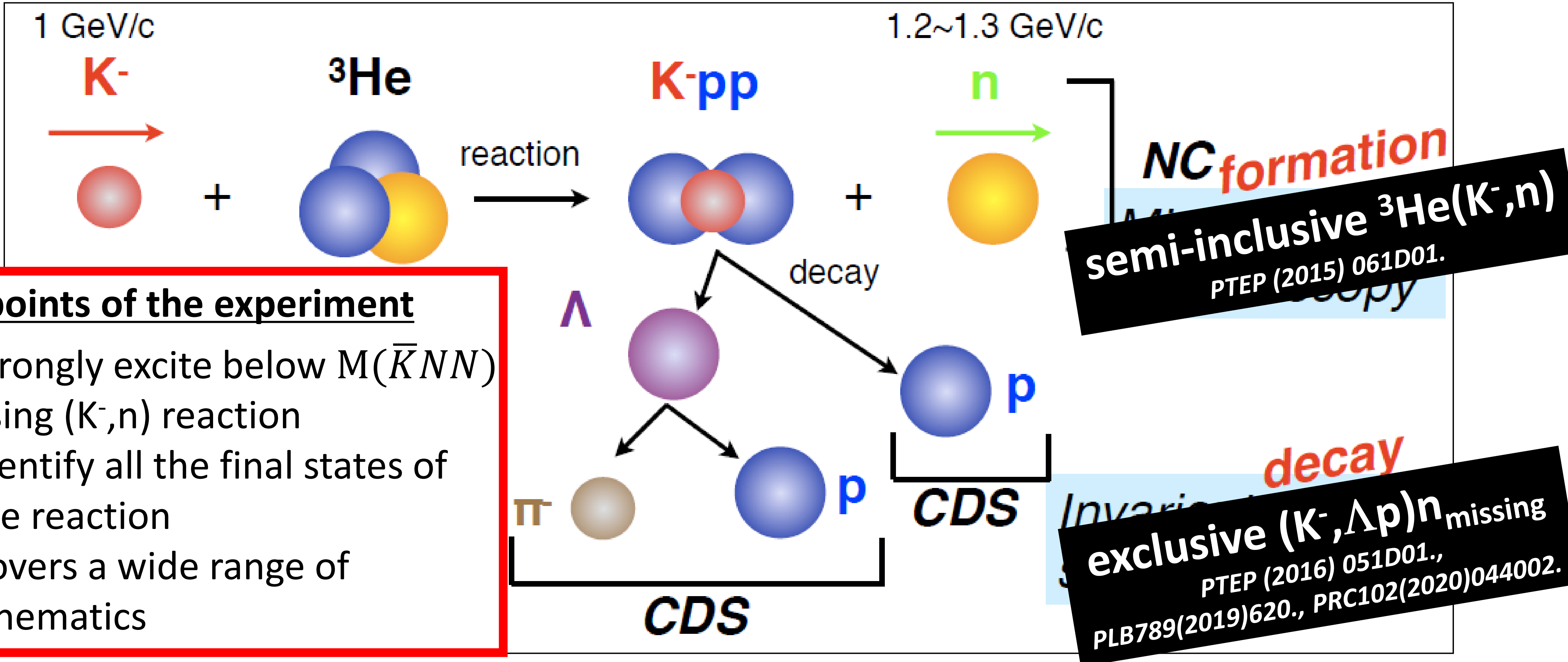
multi-NA and Y decays can be discriminated kinematically



“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

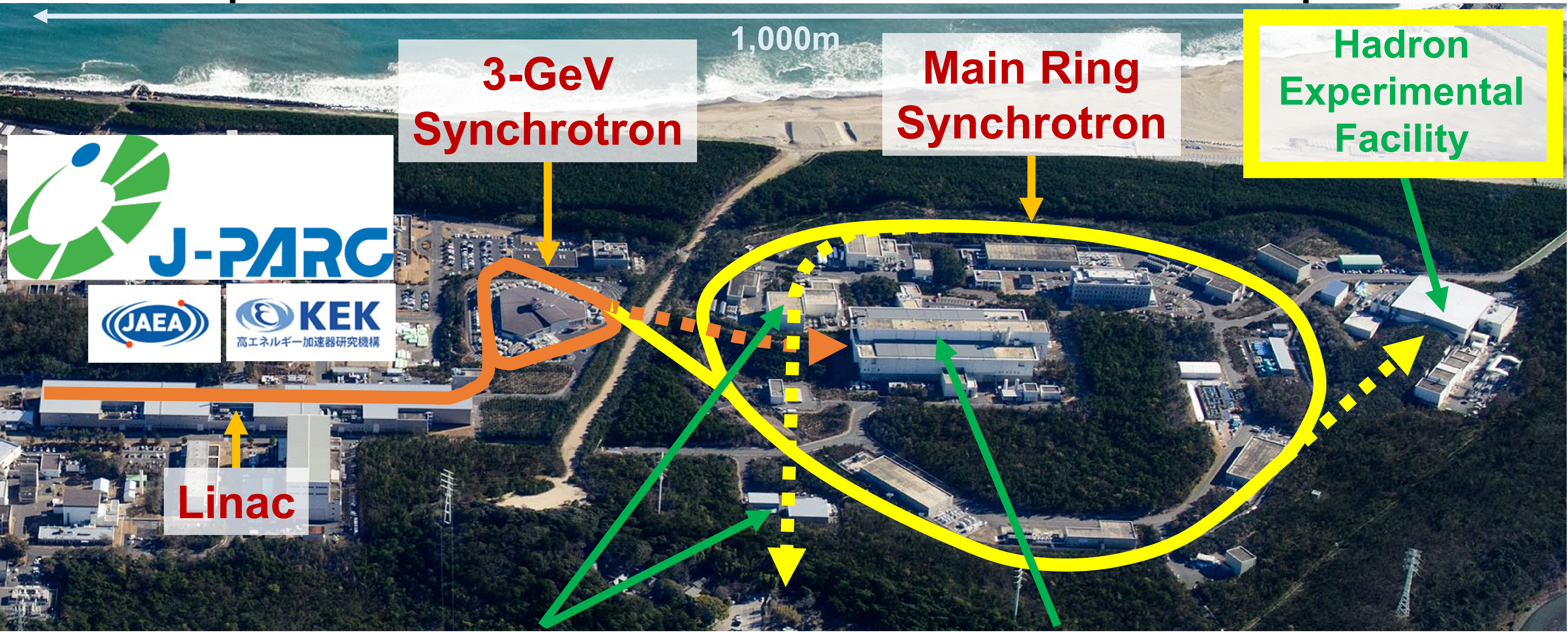
① Strongly excite below $\mathrm{M}(\bar{K}NN)$ using (K$^-$,n) reaction

② Identify all the final states of the reaction

③ Covers a wide range of kinematics

J-PARC

Japan Proton Accelerator Research Complex

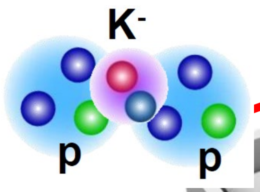


Neutrino Experimental Facility

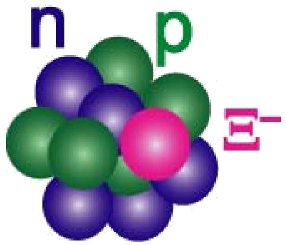
Material and Life Science Experimental Facility

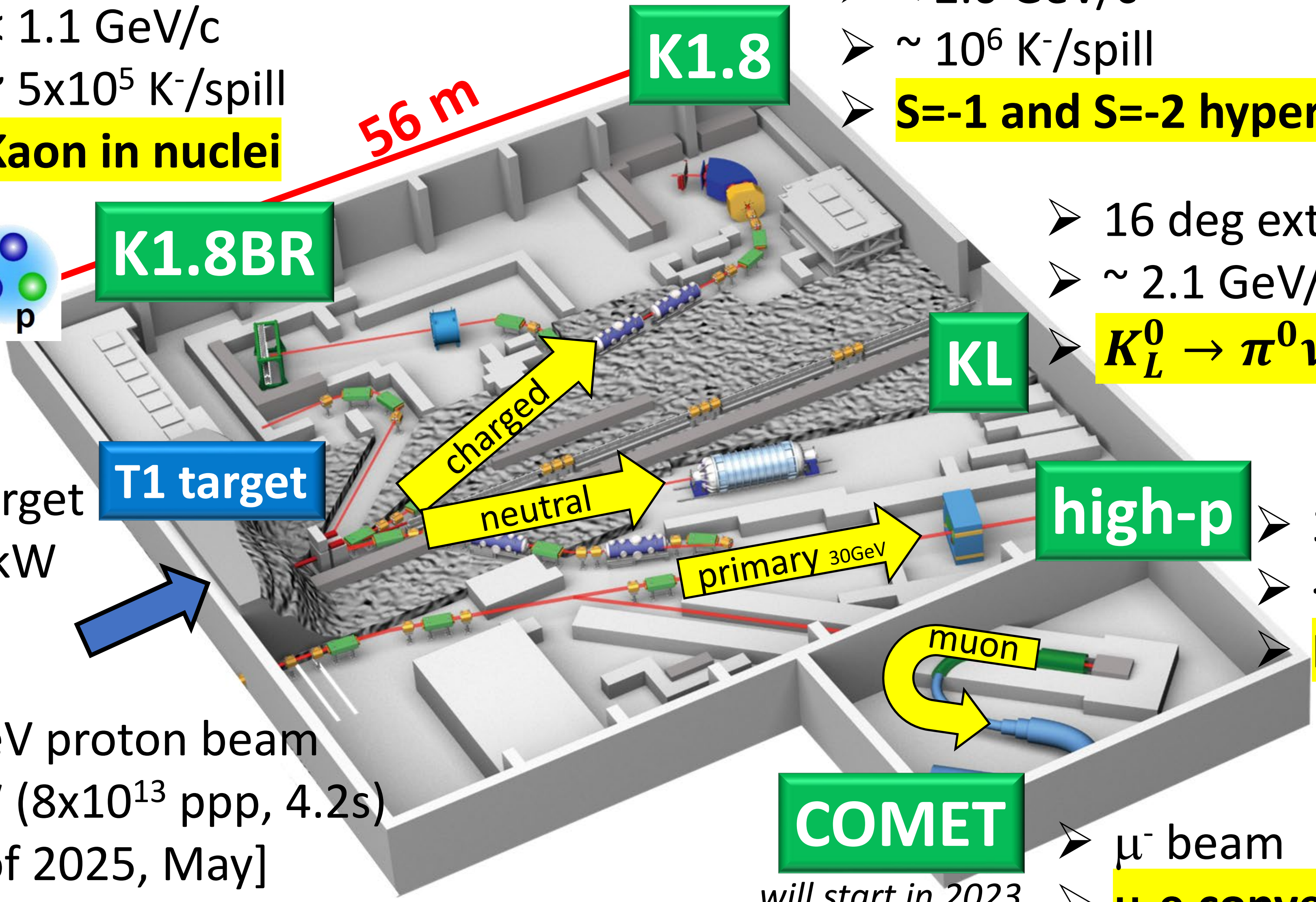
Hadron Experimental Facility (HEF)

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

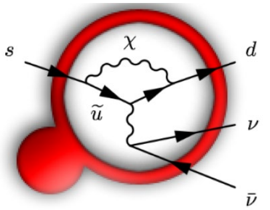


- < 2.0 GeV/c
- ~ 10^{6} K^{-}/spill
- **S=-1 and S=-2 hypernuclei**





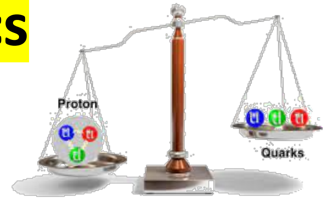
- 16 deg extraction
- ~ 2.1 GeV/c ~ 10^{7} K^{0}_{L}/spill
- $K_L^0 \to \pi^0 \nu\bar{\nu}$



- 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
- 93kW (8×10^{13} ppp, 4.2s)
  [as of 2025, May]

will start in 2023

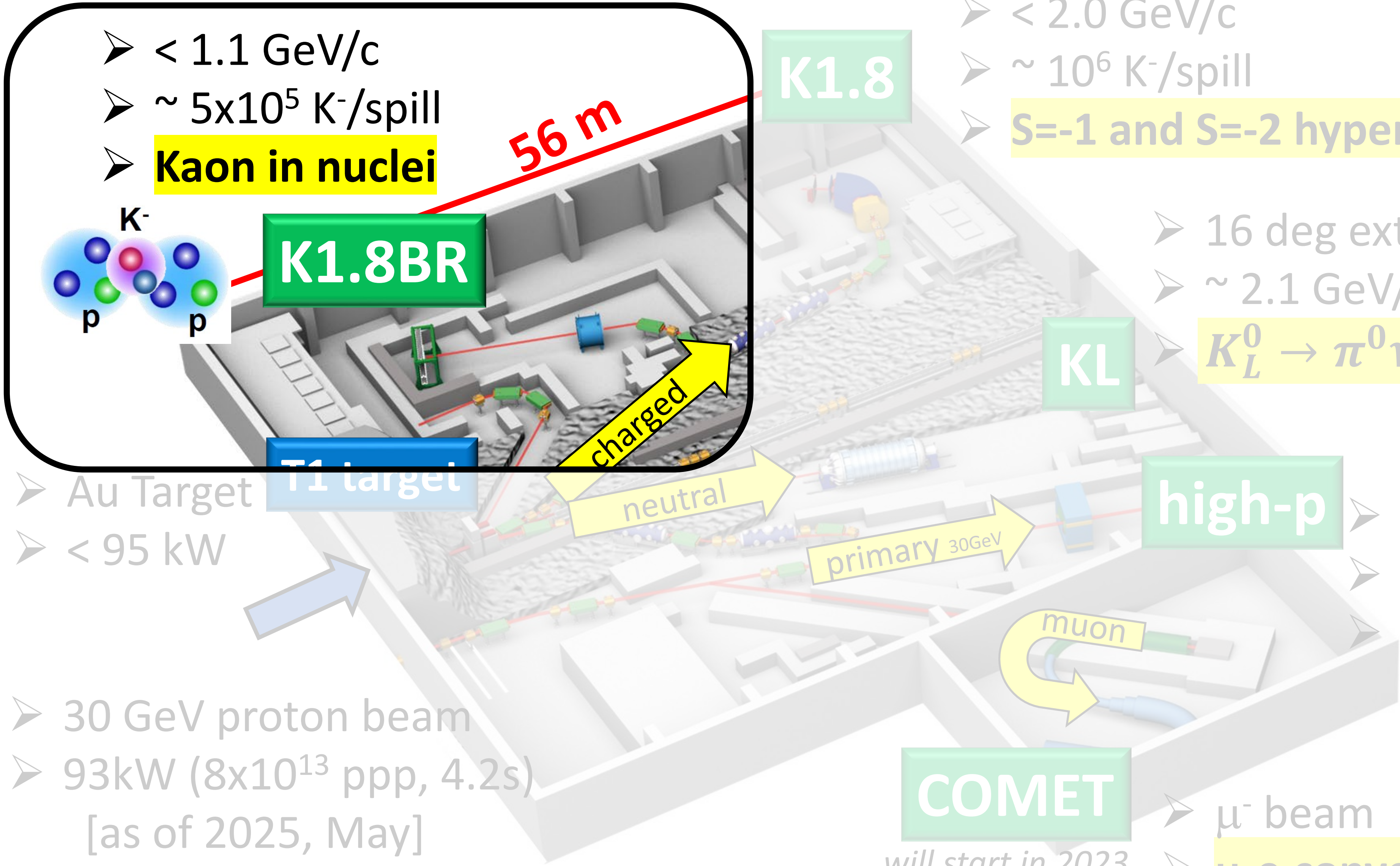
- μ^{-} beam
- **μ-e conversion**

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**

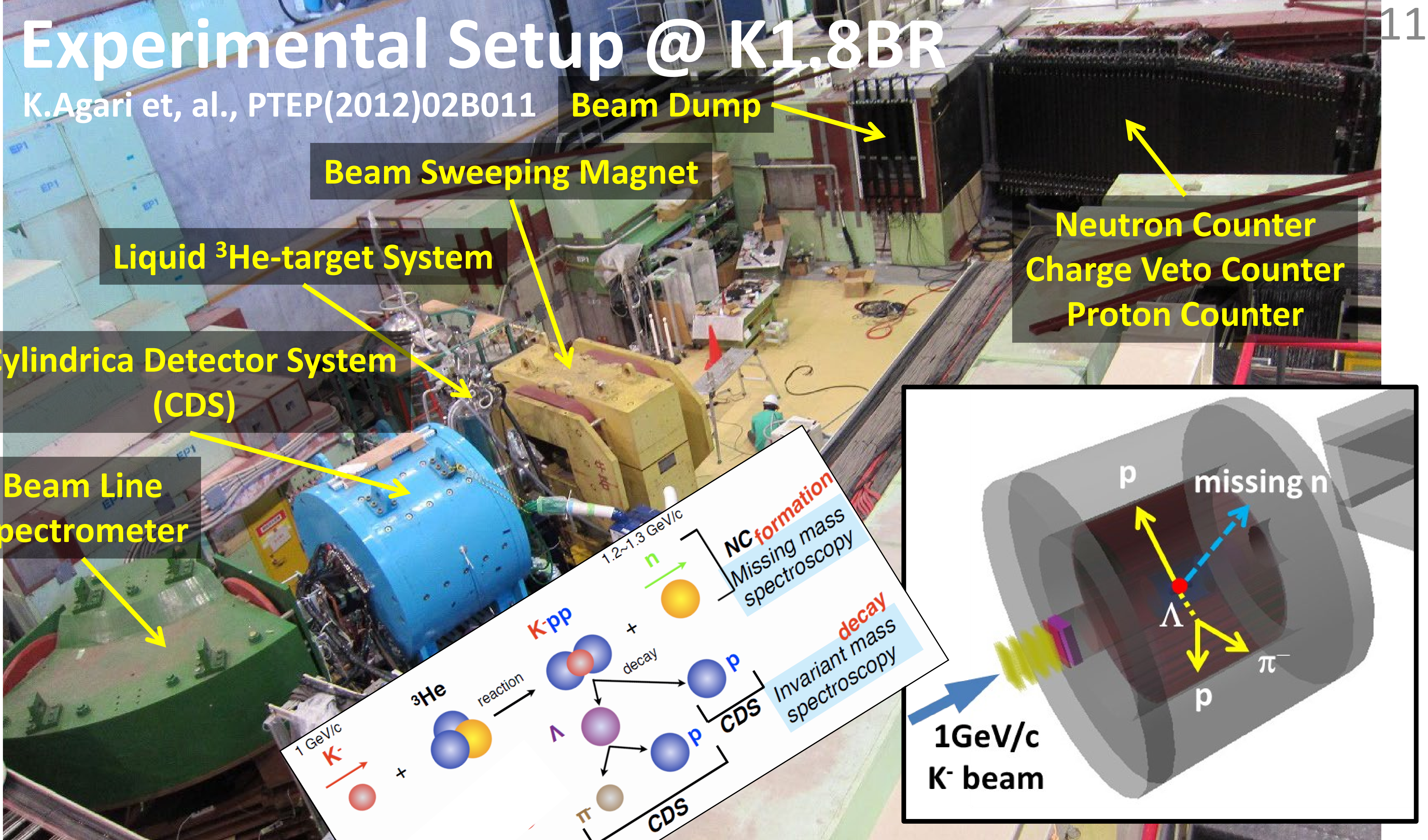
- 30 GeV proton beam
- 93kW (8×10^{13} ppp, 4.2s)
  [as of 2025, May]

will start in 2023

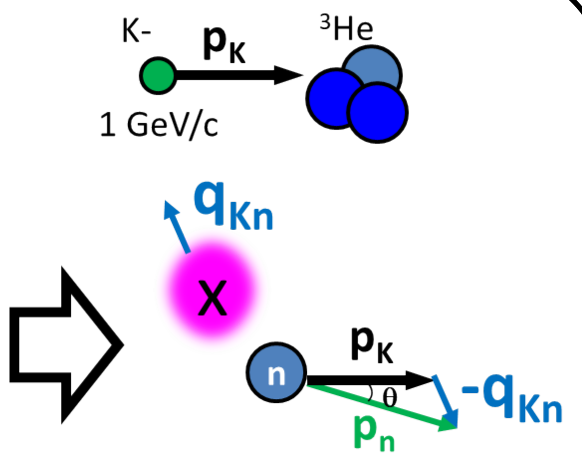
- μ^- beam
- **μ-e conversion**

Experimental Setup @ K1.8BR

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



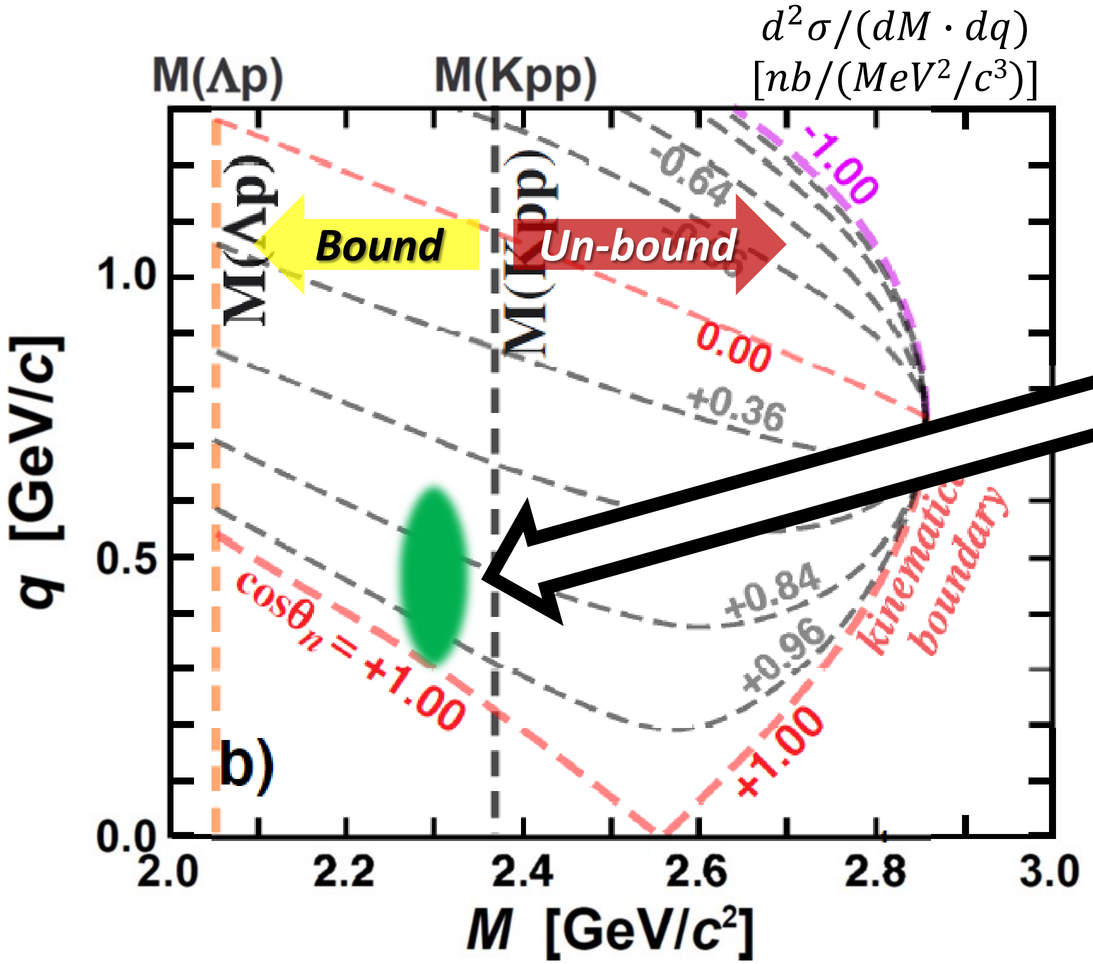
"K⁻pp" Search w/ Momentum Transfer Analysis



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

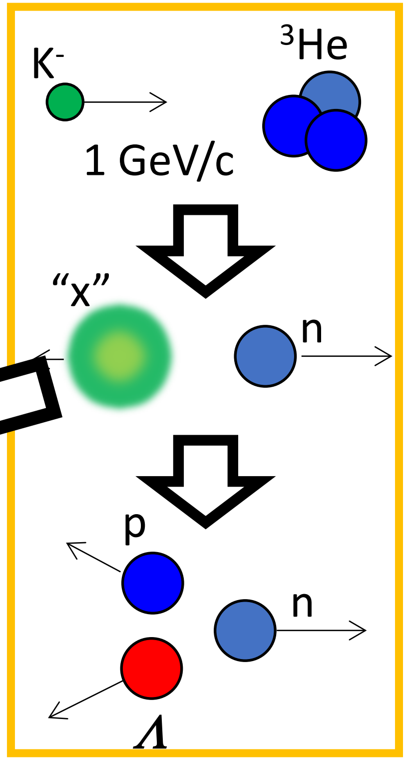
✓ M(Λp) vs. q

✓ give a clear information on reaction processes



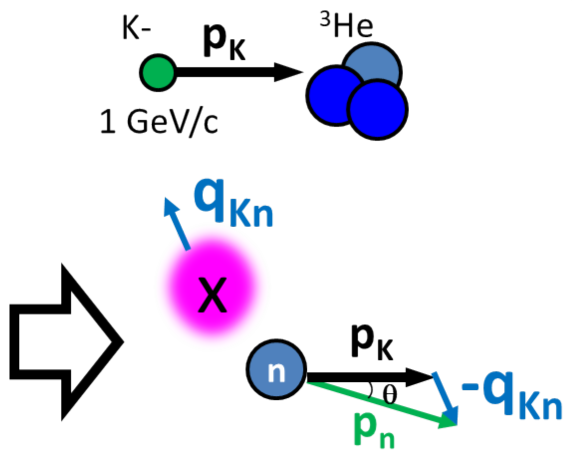
q *: (K^-,n) momentum transfer*

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

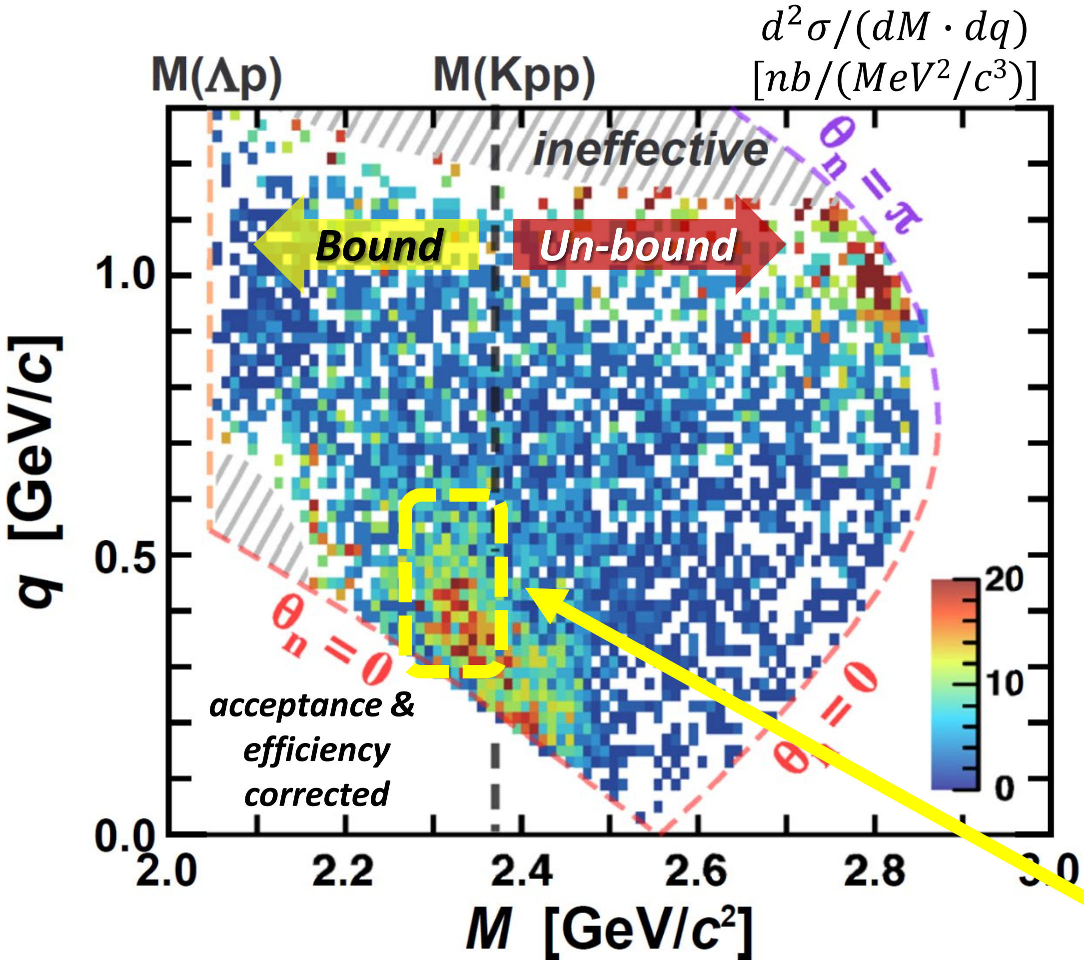


- **Momentum transfer analysis using the (K⁻,n) reaction**

✓ M(Λp) vs. q

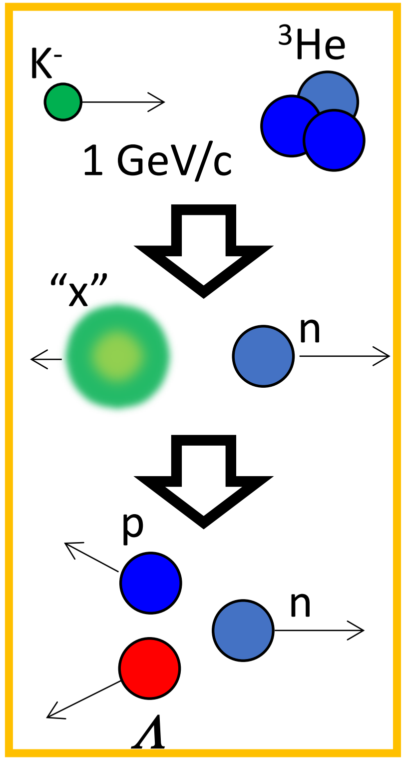
✓ give a clear information on reaction processes

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



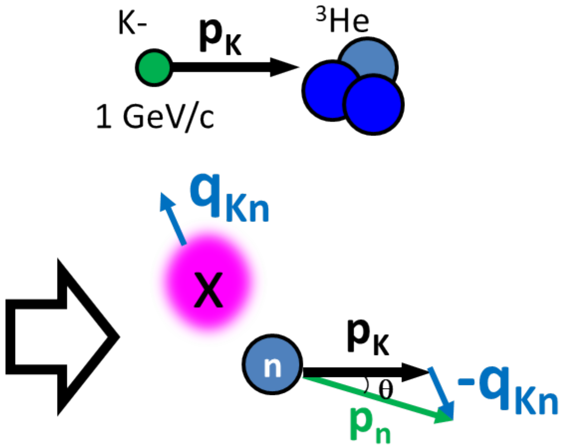
q : (K⁻,n) momentum transfer

M : Λp invariant mass



A peak structure independent of q = A bound state exists

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

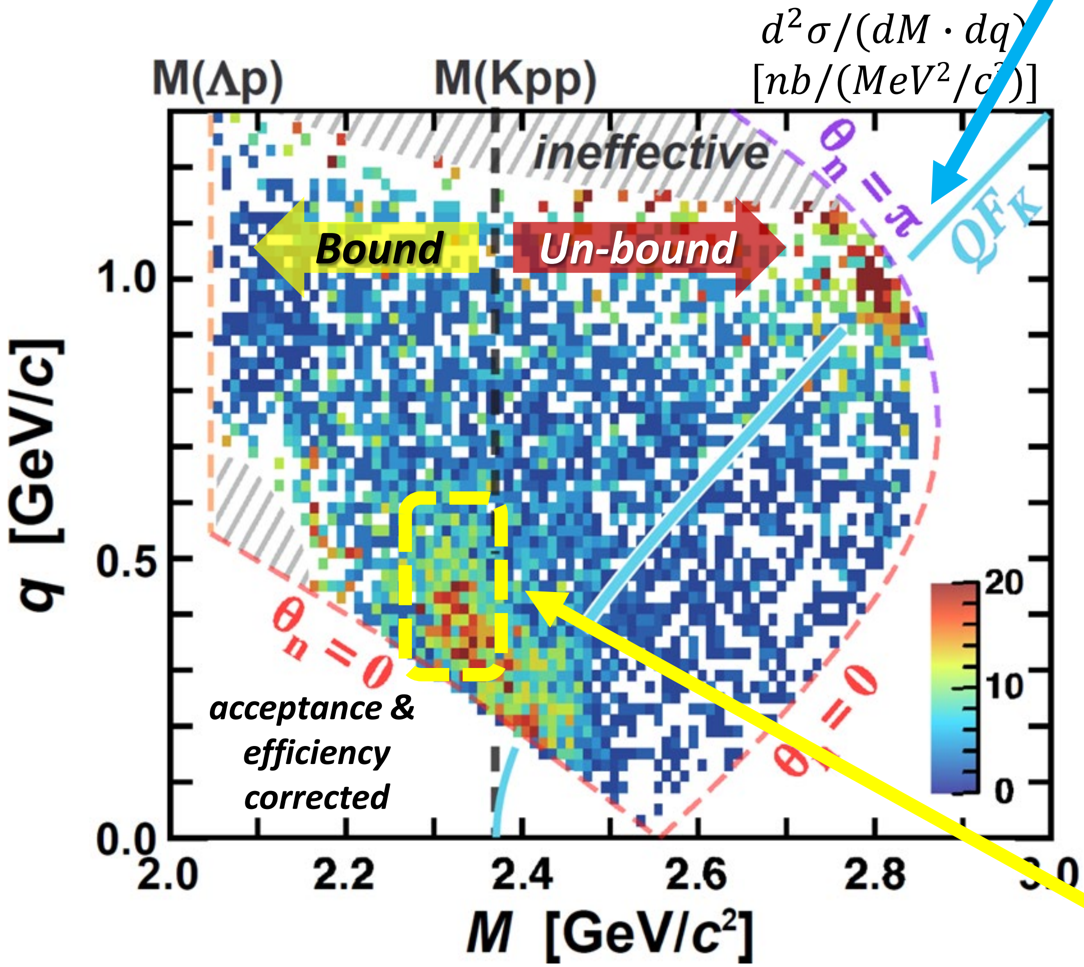


- **Momentum transfer analysis using the (K^-,n) reaction**

✓ M(Λp) vs. q

✓ give a clear information on reaction processes

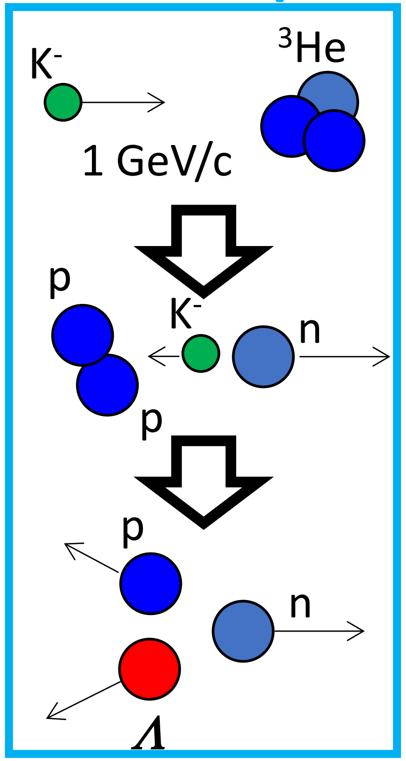
PLB789(2019)620., PRC102(2020)044002.



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

Plane Wave Impulse Approximation

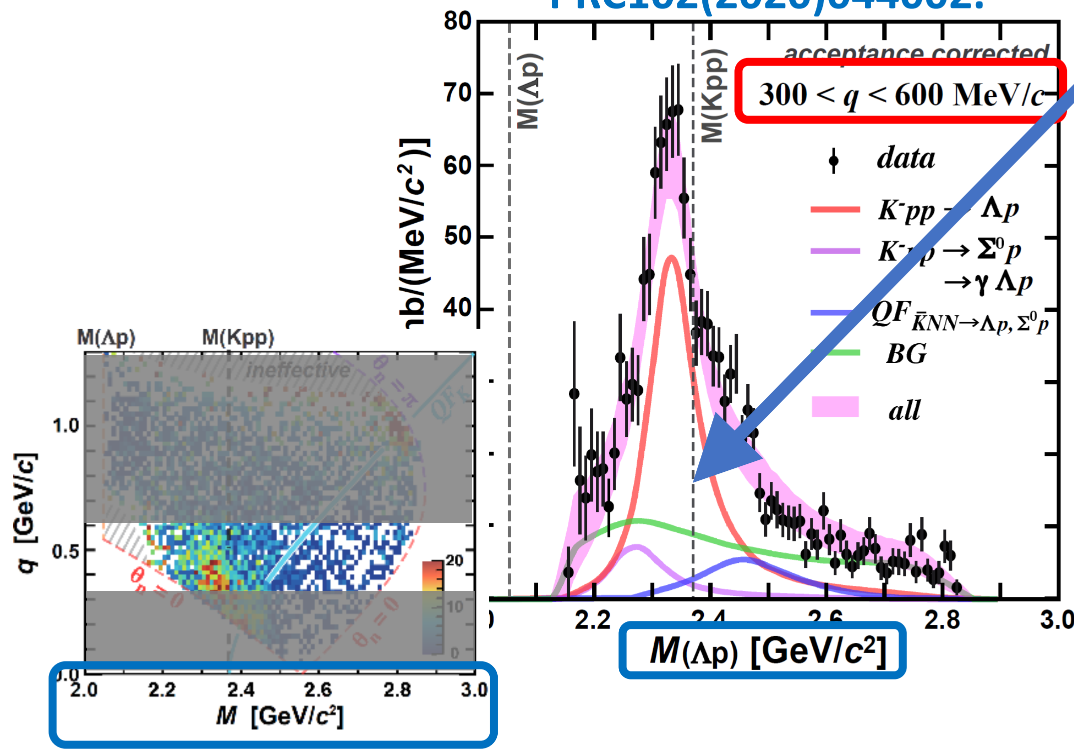
Fit with PWIA

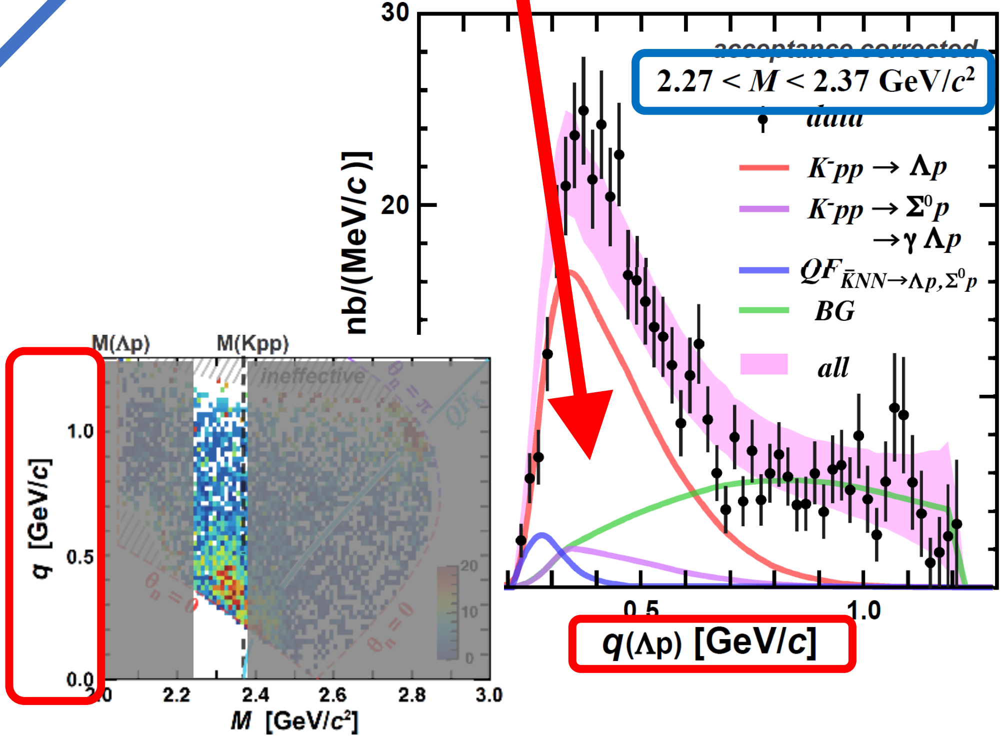
Energy term (BW type) from time integral

Momentum term from spatial integral

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

PRC102(2020)044002.





Deep binding = Strong K^{bar}N int.

B_{Kpp}(BW) ~ 40 MeV, Γ_{Kpp}(BW) ~ 100 MeV

Binding energy Decay width

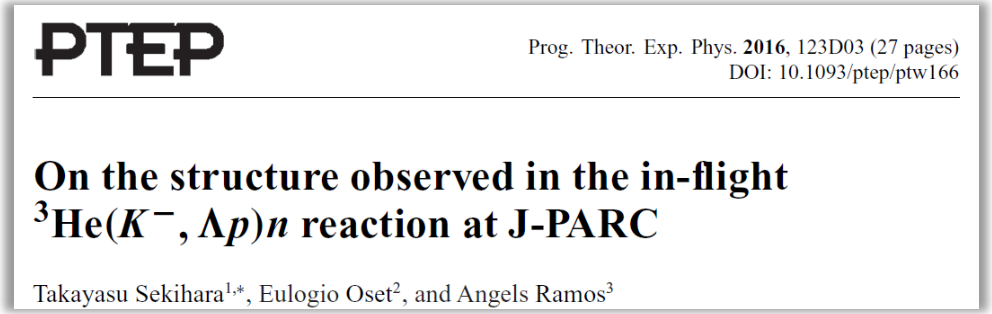
Large *Q* = Suggesting a compact system

Q_{kpp} ~ 400 MeV

Form factor

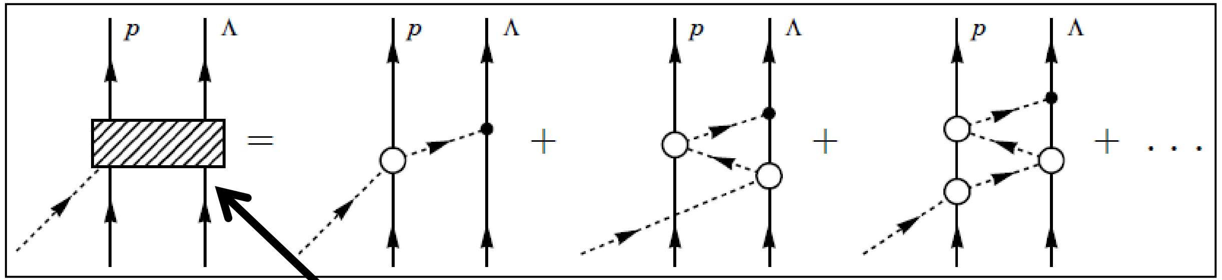
A Theoretical Interpretation

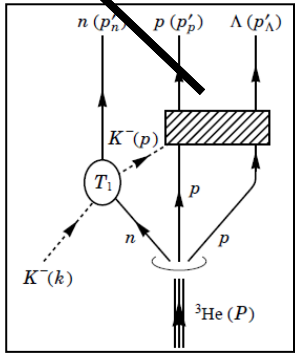
A calculation based on chiral unitary approach
reproduces the data well using the $\bar{\mathrm{K}}$NN bound state


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

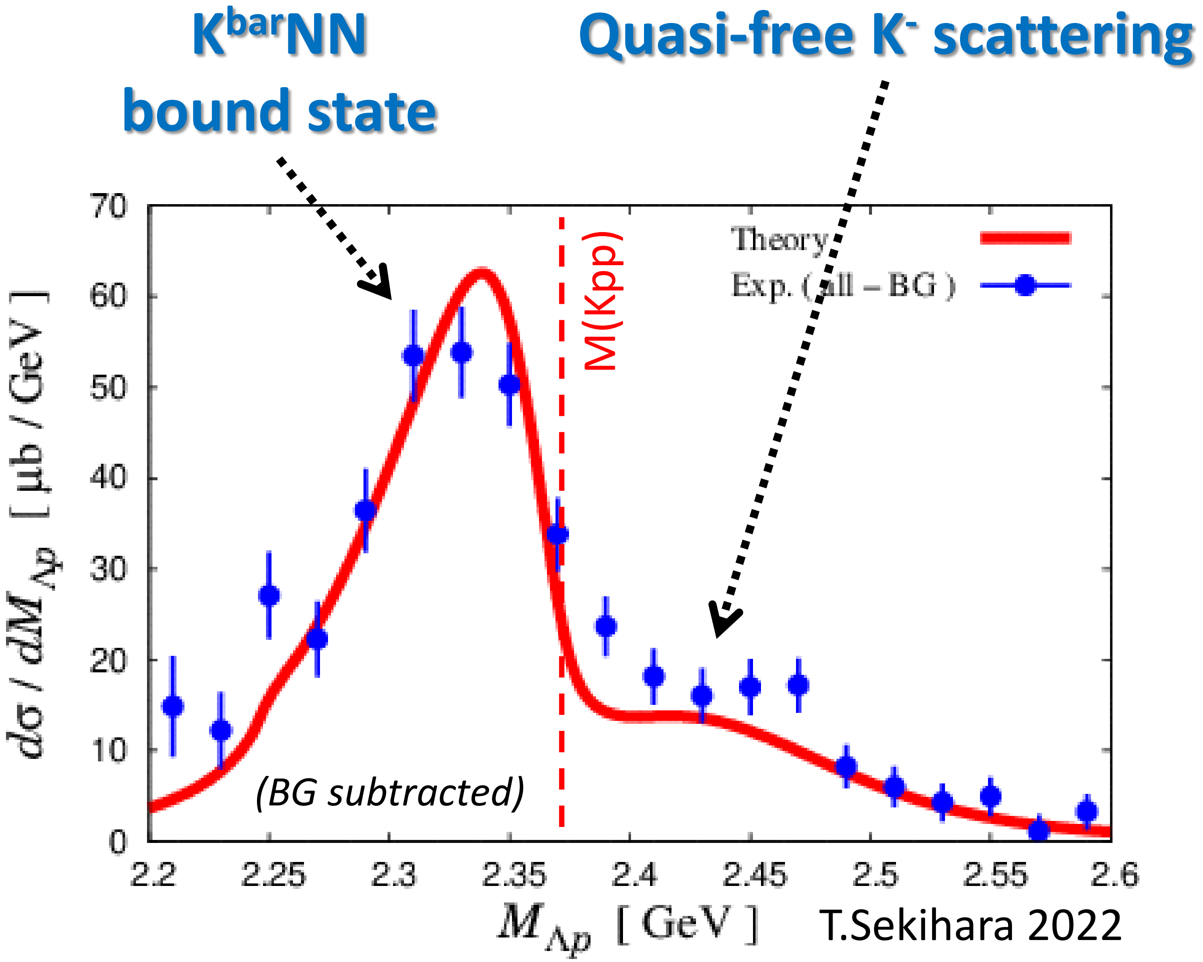
On the structure observed in the in-flight ^{3}He(K^-, Λp)n reaction at J-PARC

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





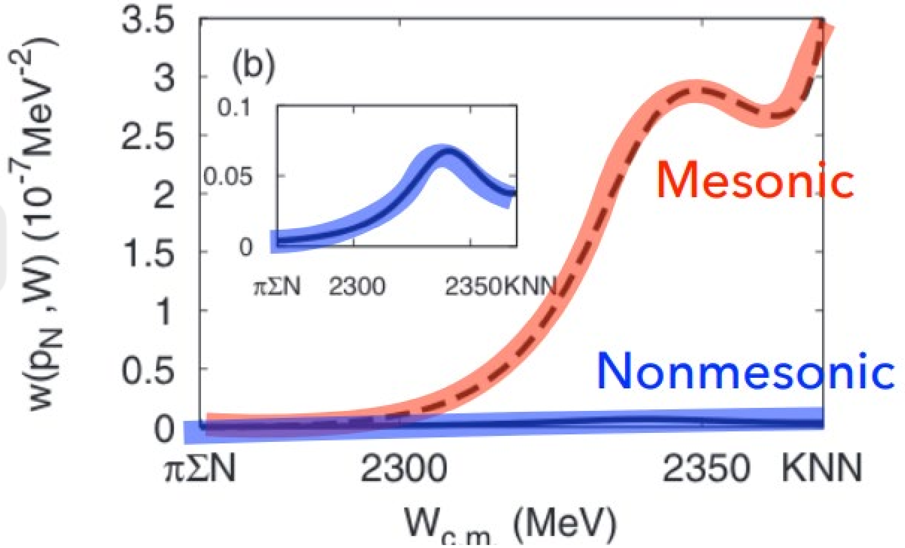
Theoretical investigations are indispensable!



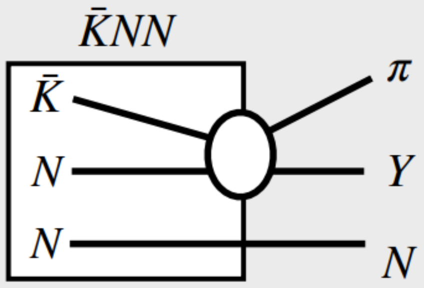
Mesonic Decay Modes of $\bar{K}NN$

- 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.

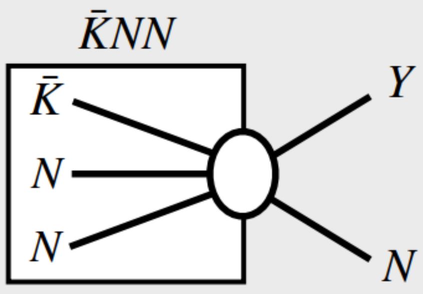


Mesonic

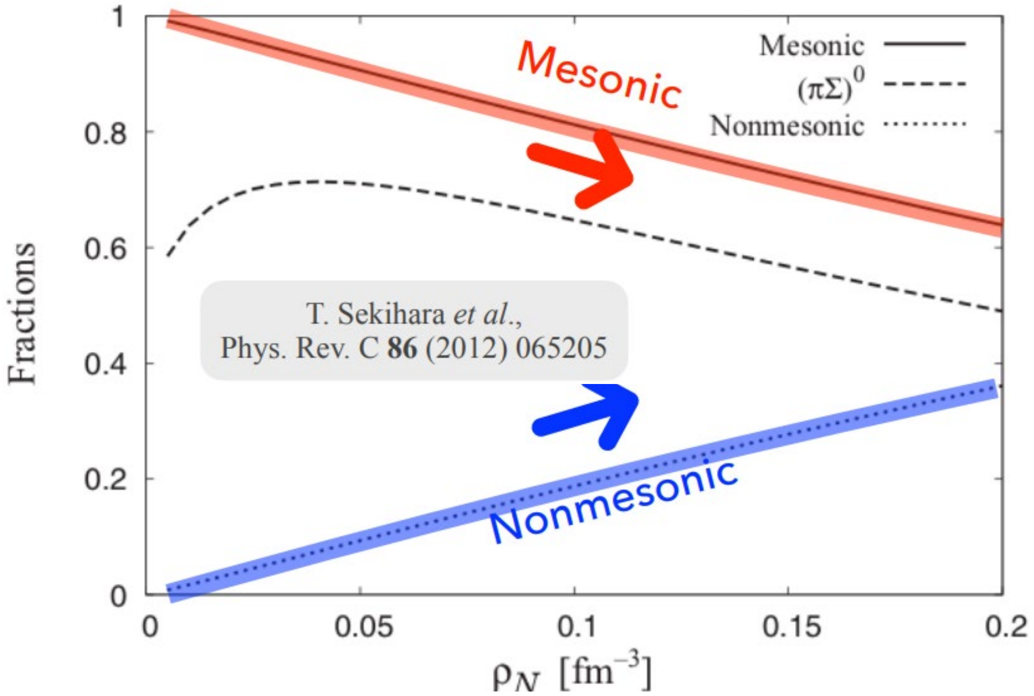


1N absorption

Non-mesonic



2N absorption

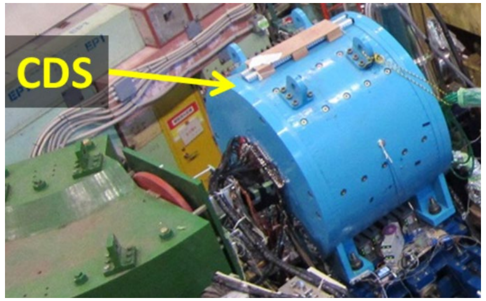


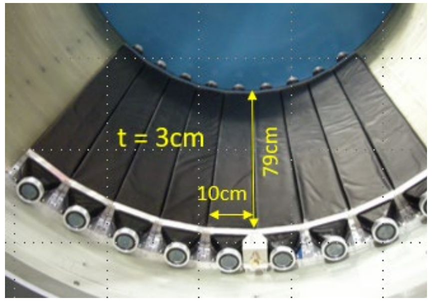
T. Sekihara *et al.*, Phys. Rev. C **86** (2012) 065205

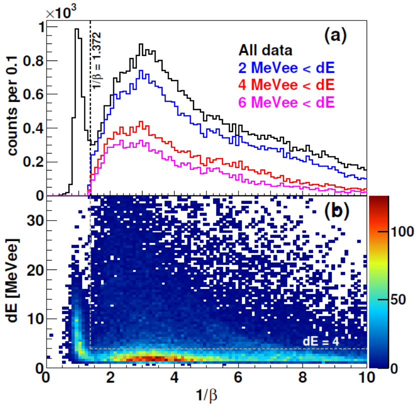
PRC110(2024) 014002.

πYN Mesonic Decay Analysis

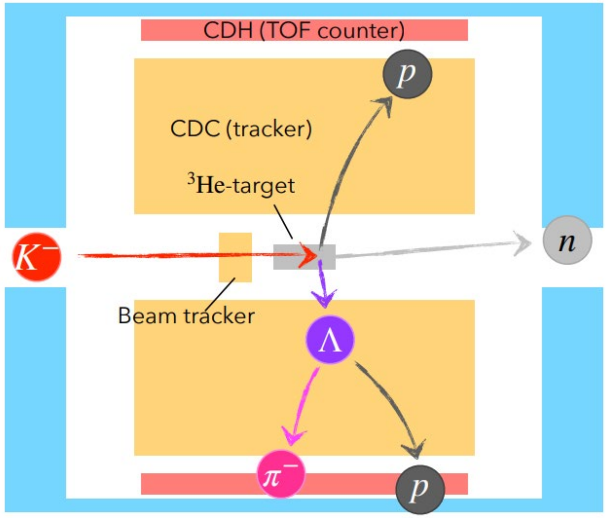
- with neutron detection using a thin scintillation counter array (CDH)
  - ☹ small efficiency (3~9%)
  - ☹ BG from the inner wall of the magnet

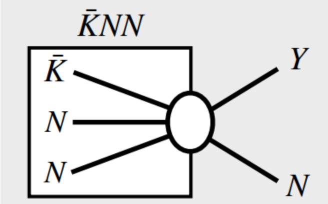




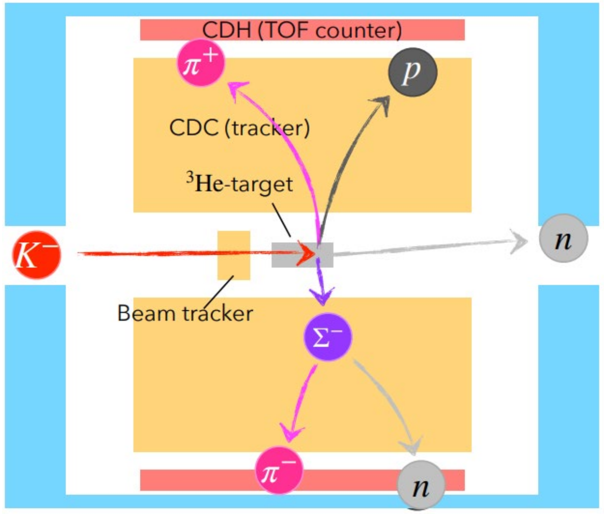


$"K^-pp" \to \Lambda p$

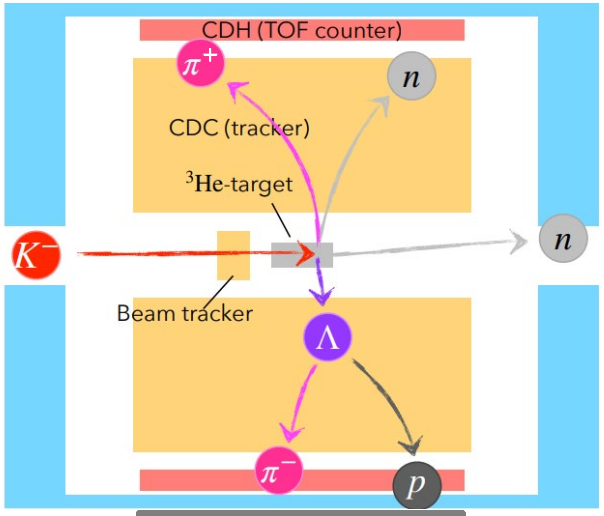




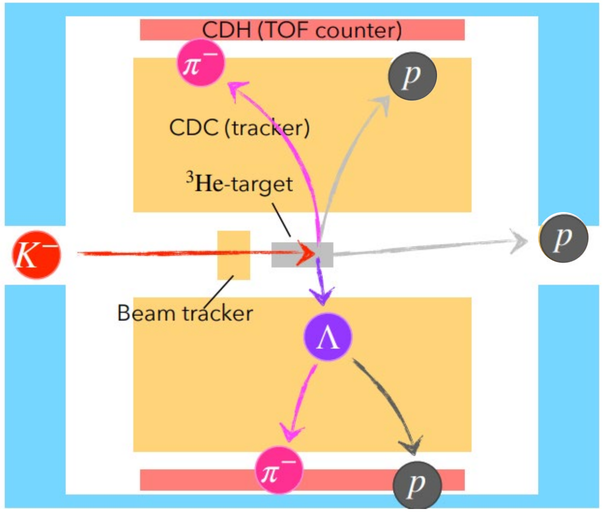
$"K^-pp" \to \pi^\pm\Sigma^\mp p$

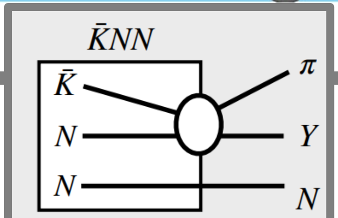


$"K^-pp" \to \pi^+\Lambda n$



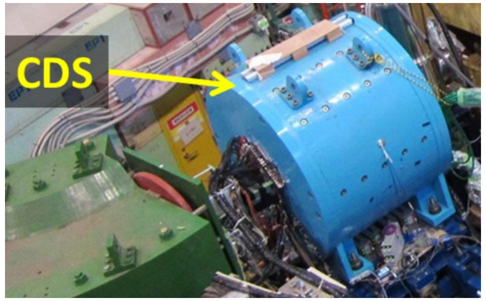
$"\bar{K}^0nn" \to \pi^-\Lambda p$

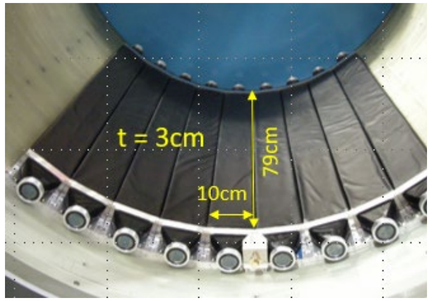


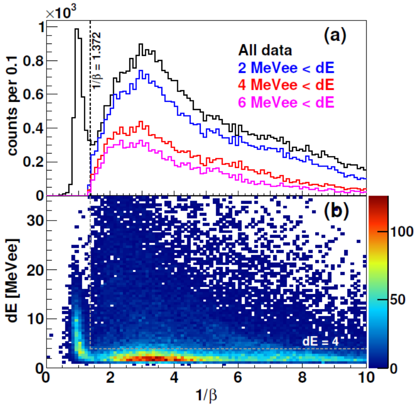


πYN Mesonic Decay Analysis

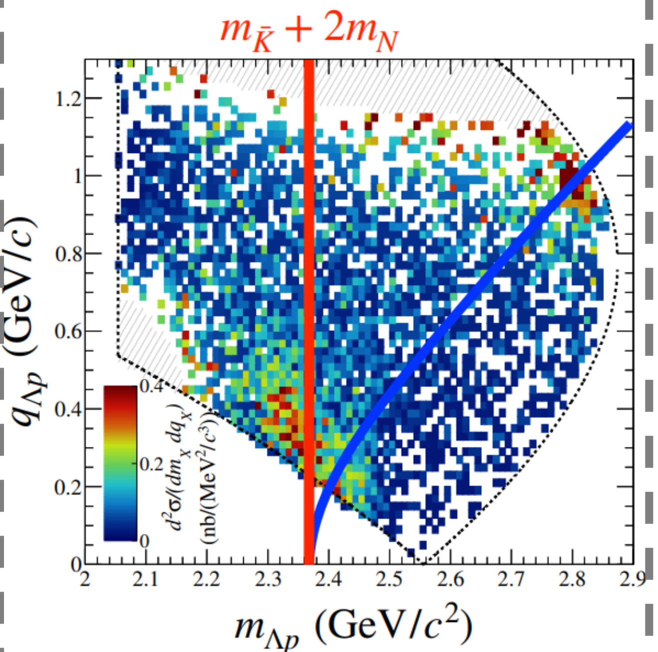
- with neutron detection using a thin scintillation counter array (CDH)
  - ☹ small efficiency (3~9%)
  - ☹ BG from the inner wall of the magnet



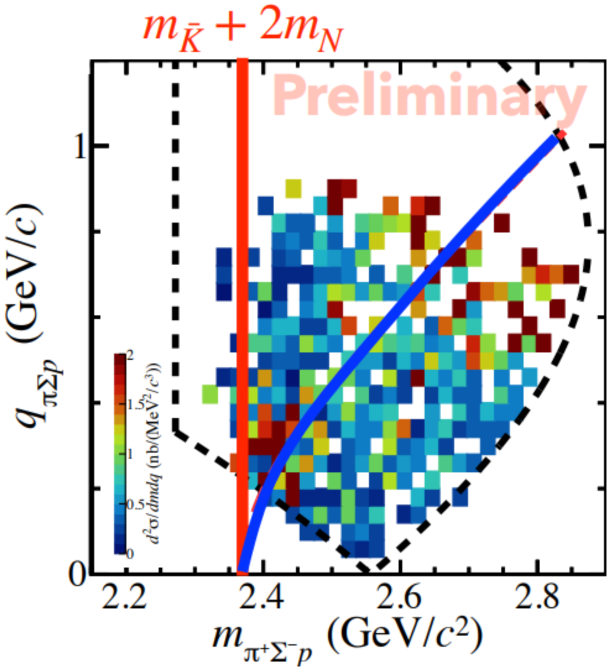




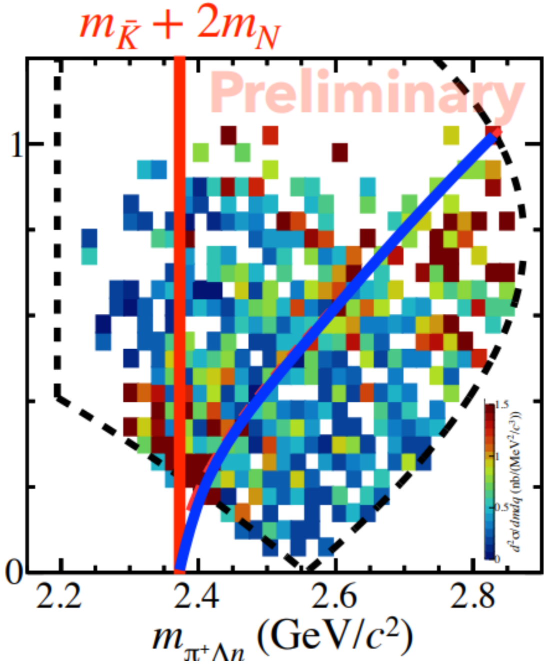
"K^-pp" $\to \Lambda p$



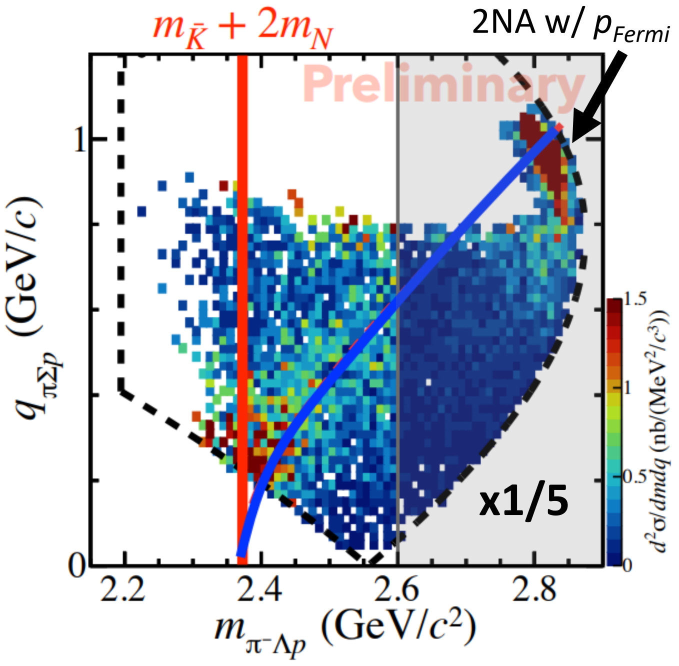
"K^-pp" $\to \pi^\pm \Sigma^\mp p$



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



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



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

πYN Mesonic Decay Analysis

Plane Wave Impulse Approximation

Fit with PWIA

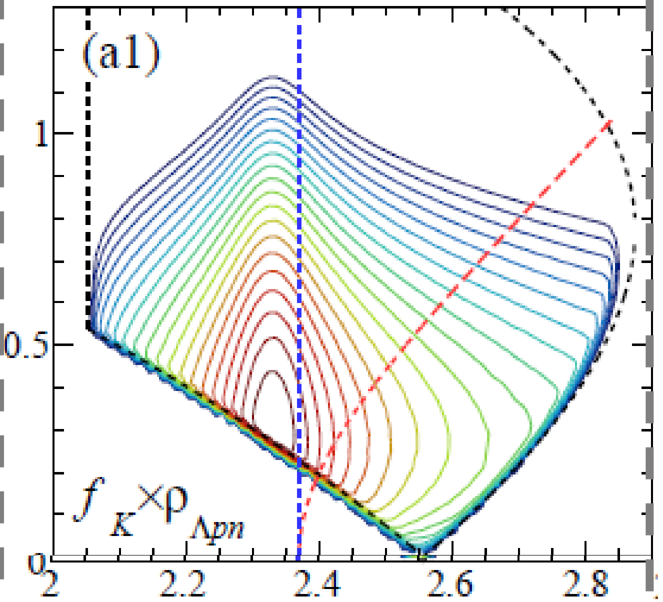
Phase space

Momentum term from spatial integral

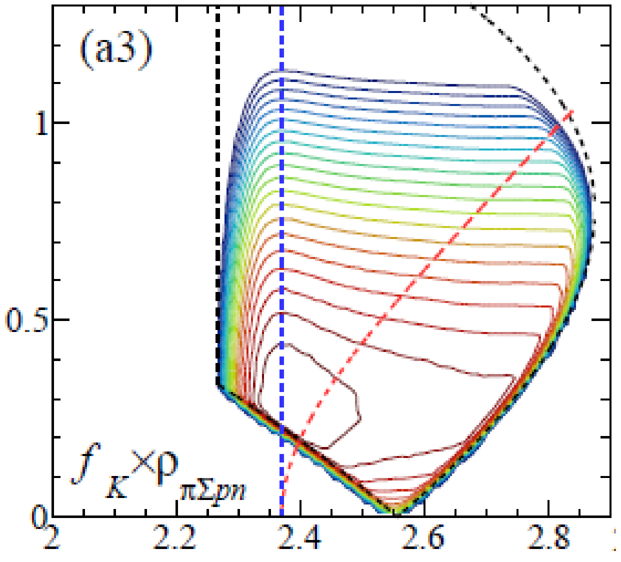
$$\sigma(M,q) \propto \boxed{\rho(M,q)} \times \boxed{\frac{(\Gamma_{Kpp}/2)^2}{(M-M_{Kpp})^2+(\Gamma_{Kpp}/2)^2}} \times \boxed{exp\left(-\frac{q^2}{Q_{Kpp}{}^2}\right)}$$

Energy term (BW type) from time integral

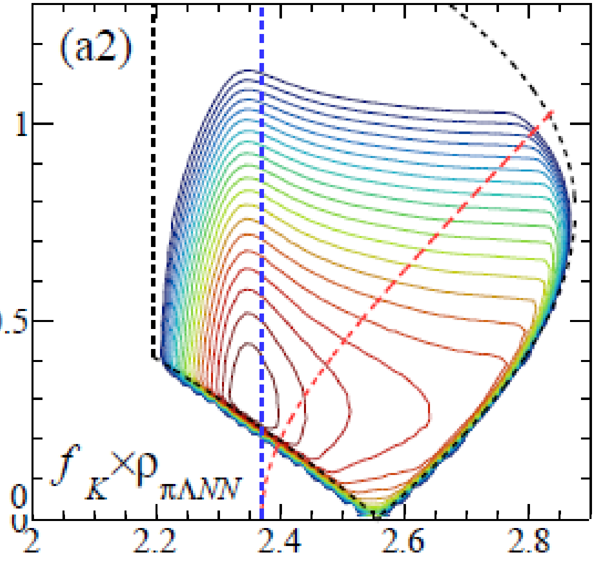
"K^-pp" → Λp



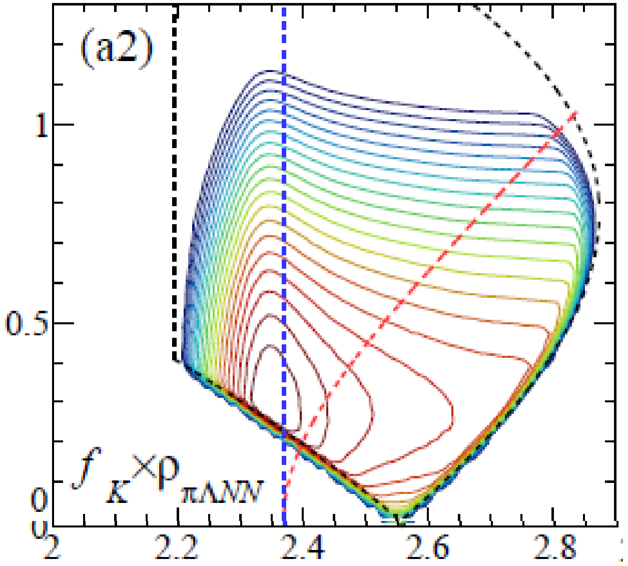
"K^-pp" → $\pi^\pm \Sigma^\mp p$



"K^-pp" → $\pi^+ \Lambda n$



"$\bar{K}^0 nn$" → $\pi^- \Lambda p$



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

PRC110(2024) 014002.

πYN Mesonic Decay Analysis

Plane Wave Impulse Approximation

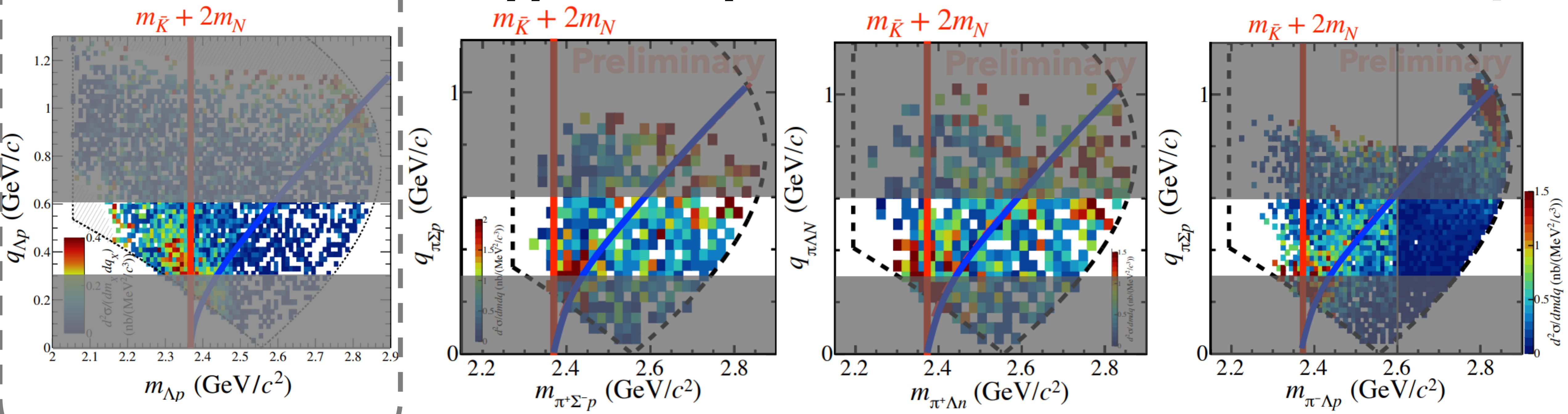
Fit with PWIA

Phase space — Momentum term from spatial integral

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

Energy term (BW type) from time integral

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



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

PRC110(2024) 014002.

πYN Mesonic Decay Analysis

Plane Wave Impulse Approximation

Fit with PWIA

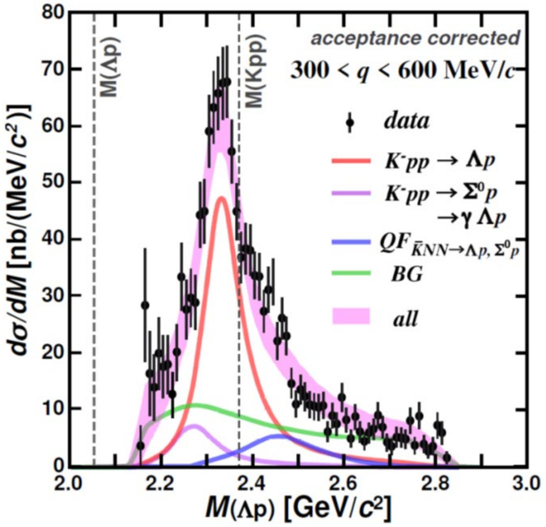
Phase space

Momentum term from spatial integral

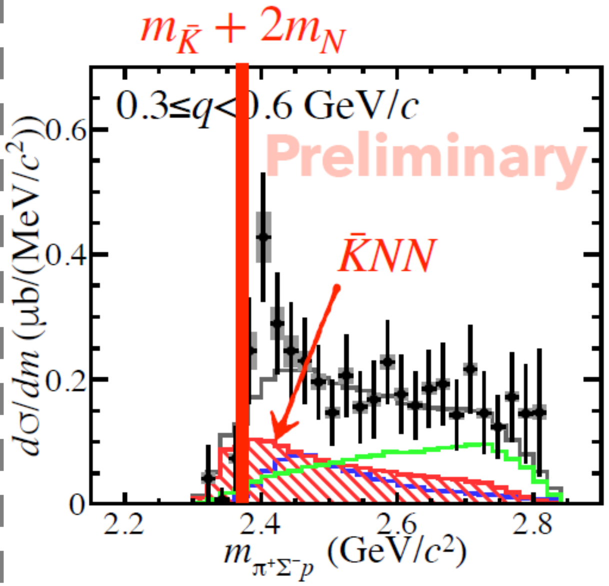
$$\sigma(M,q) \propto \boxed{\rho(M,q)} \times \boxed{\frac{(\Gamma_{Kpp}/2)^2}{(M-M_{Kpp})^2+(\Gamma_{Kpp}/2)^2}} \times \boxed{exp\left(-\frac{q^2}{{Q_{Kpp}}^2}\right)}$$

Energy term (BW type) from time integral

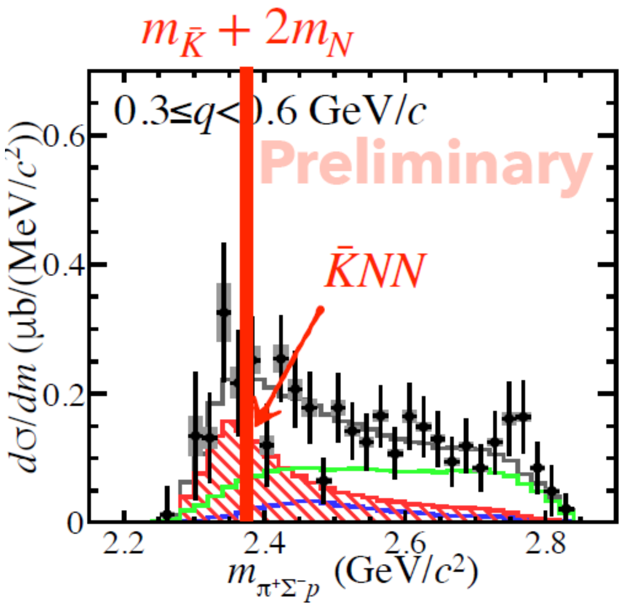
$"K^-pp" \rightarrow \Lambda p$



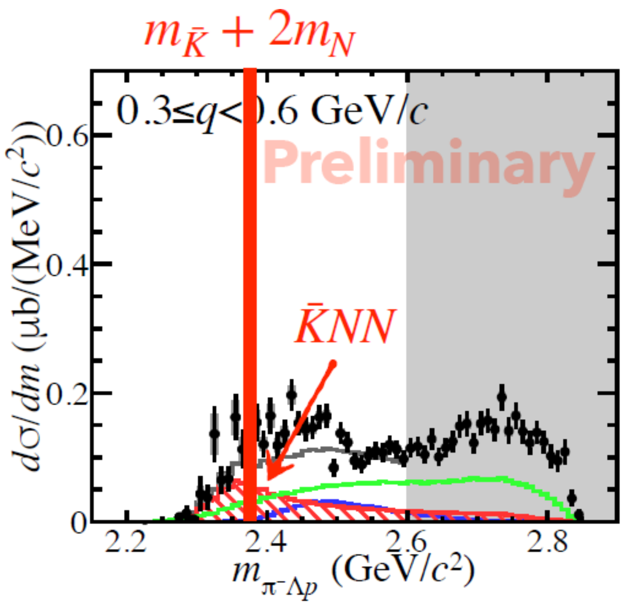
$"K^-pp" \rightarrow \pi^\pm\Sigma^\mp p$



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



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



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

PRC110(2024) 014002.

πYN Mesonic Decay Analysis

- $\Gamma_{YN} << \Gamma_{\pi YN}$: 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 $Br_{K\text{-}pp\rightarrow\pi+\Lambda n} = Br_{K0nn\rightarrow\pi-\Lambda p} \rightarrow \sigma_{K\text{-}pp} / \sigma_{K0nn} \sim 2$

"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)]

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

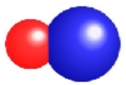
$\sigma^{tot}_{\bar{K}NN} \times Br\ (\mu b) =$
$29 \pm 3 \pm 3$ [all]
$7.2 \pm 0.6 \pm 0.7$ [<M(KNN)]

More precise measurements and theoretical investigations are needed

Need Further Investigations

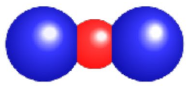
to establish the kaonic nuclei

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



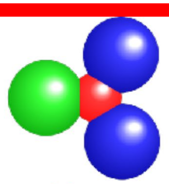
K^-p

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

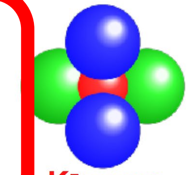


K^-pp

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



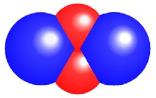
K^-ppn



K^-ppnn

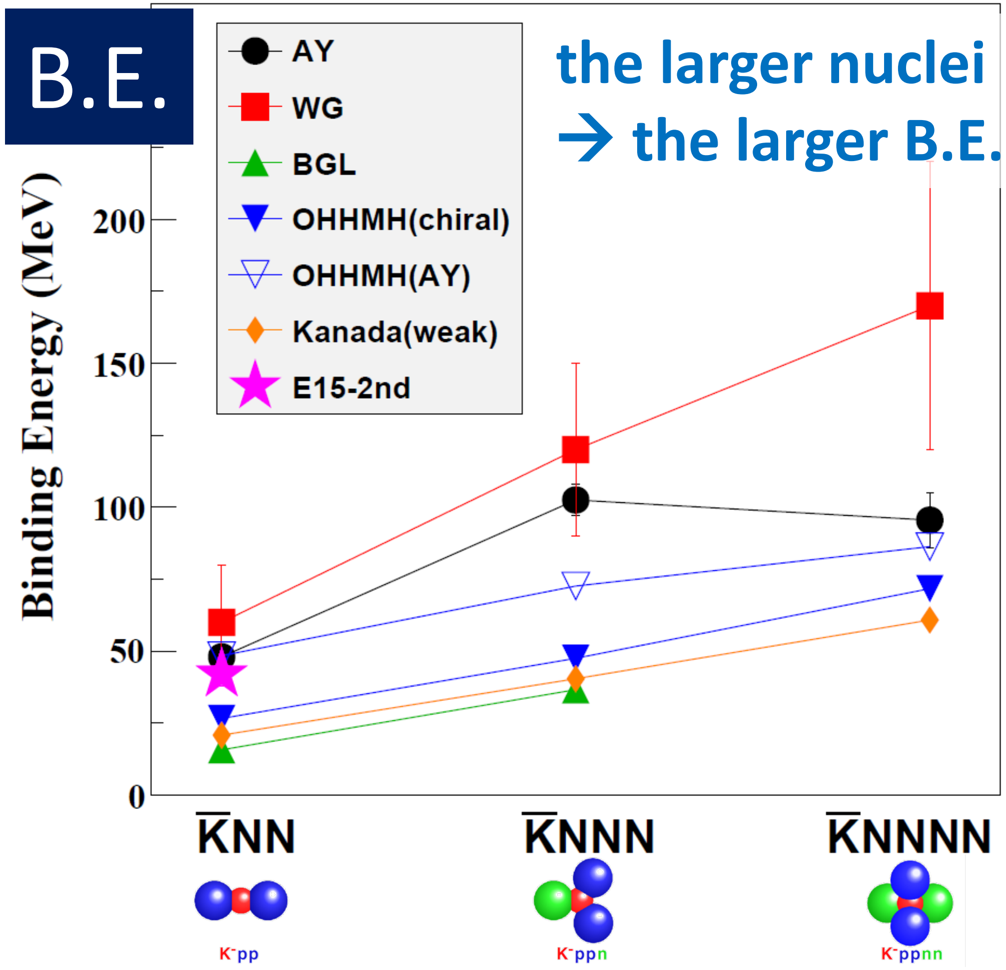
…

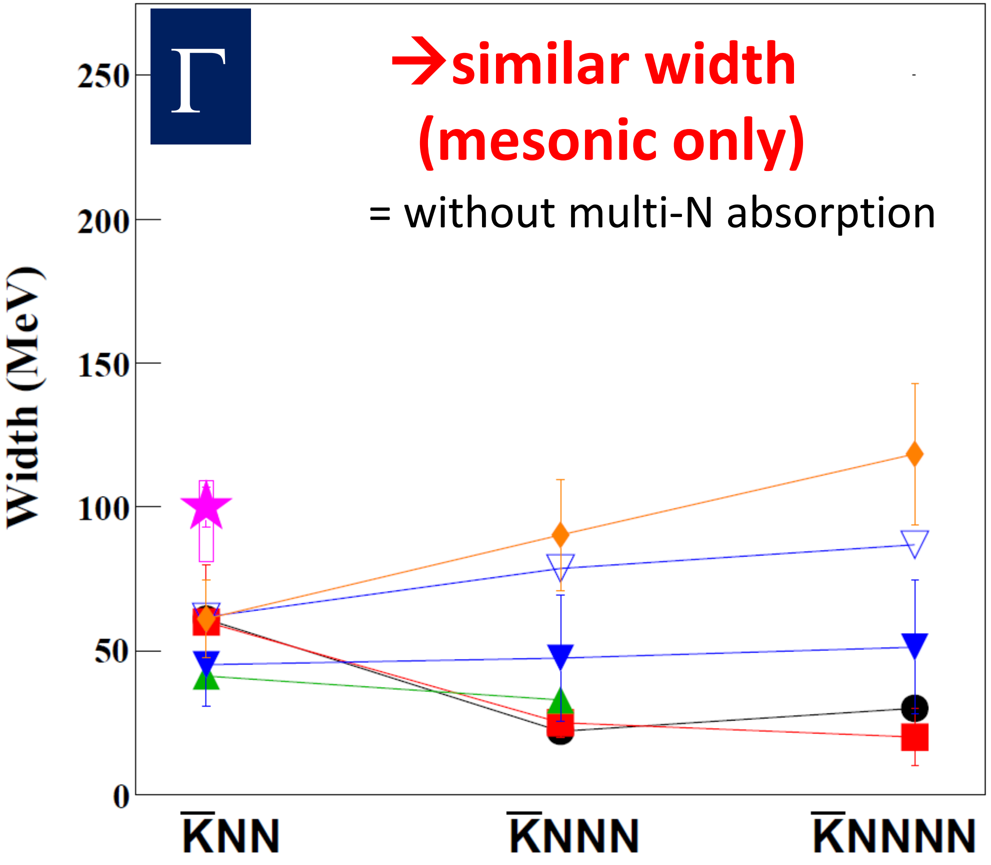
- **Double kaonic nuclei**
  - Much compact and dense system?



K^-K^-pp

Mass Number Dependence of Kaonic Nuclei



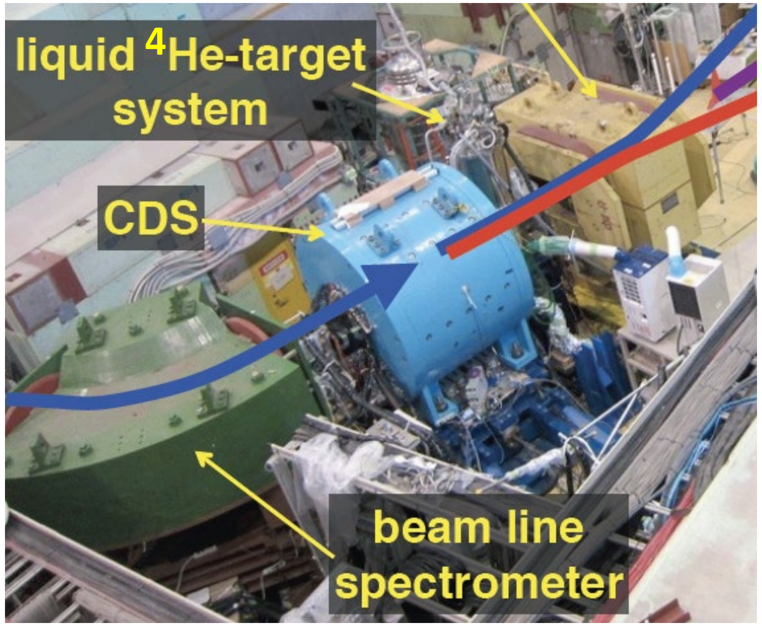


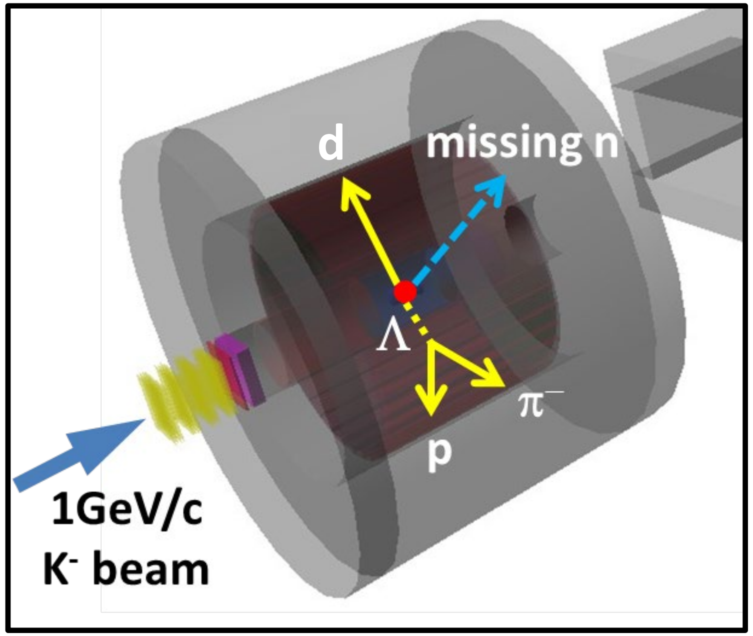
- **Systematic measurements will provide more conclusive evidence of the kaonic nuclei**

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 $K^{-4}He \to \Lambda dn$

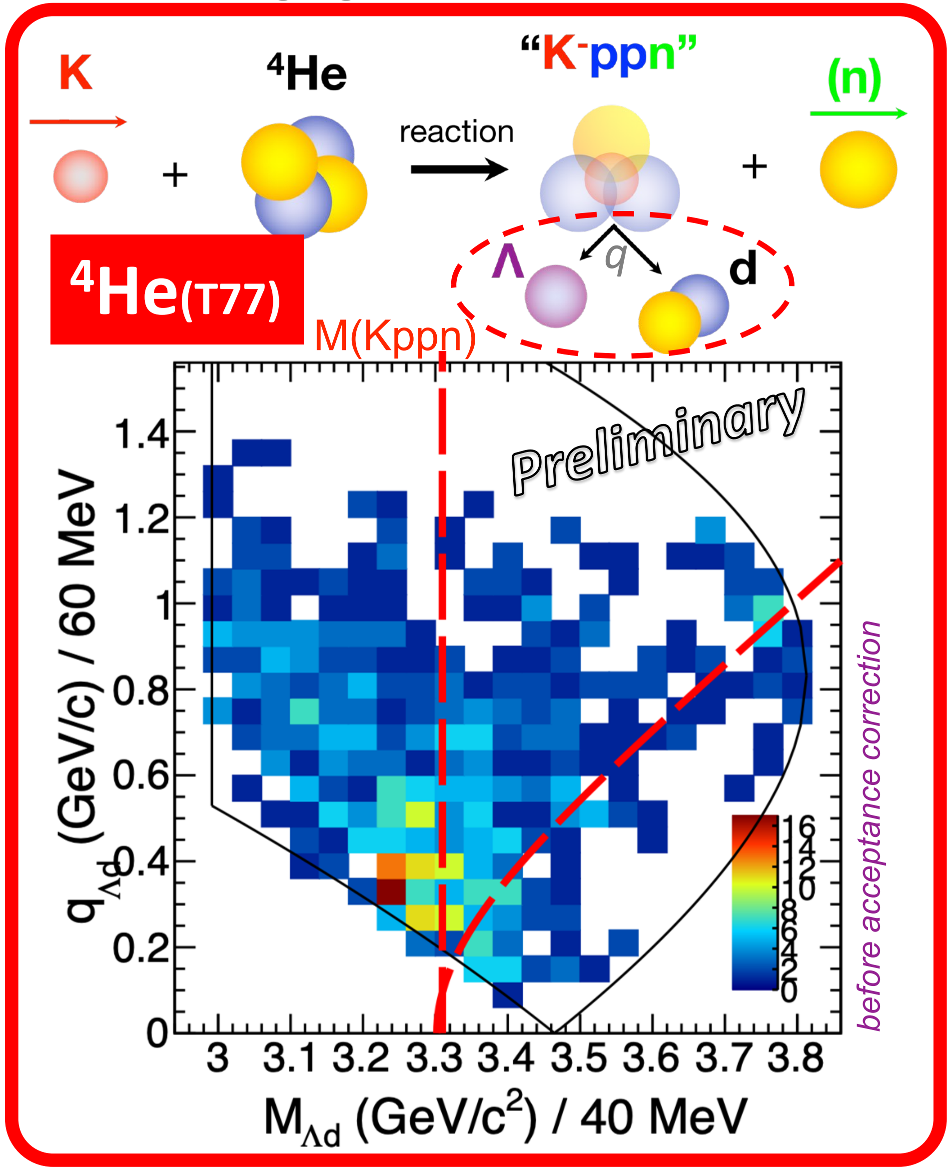
- An analysis of the **Λdn** final state with **$K^{-4}He$** reaction at **1 GeV/c** has been conducted
  - T77: lifetime measurement of $^{4}_{\Lambda}H$ in 2020
- The results will be updated with a part of the E73 controlled data
  - E73: lifetime measurement of $^{3}_{\Lambda}H$ in 2024-25

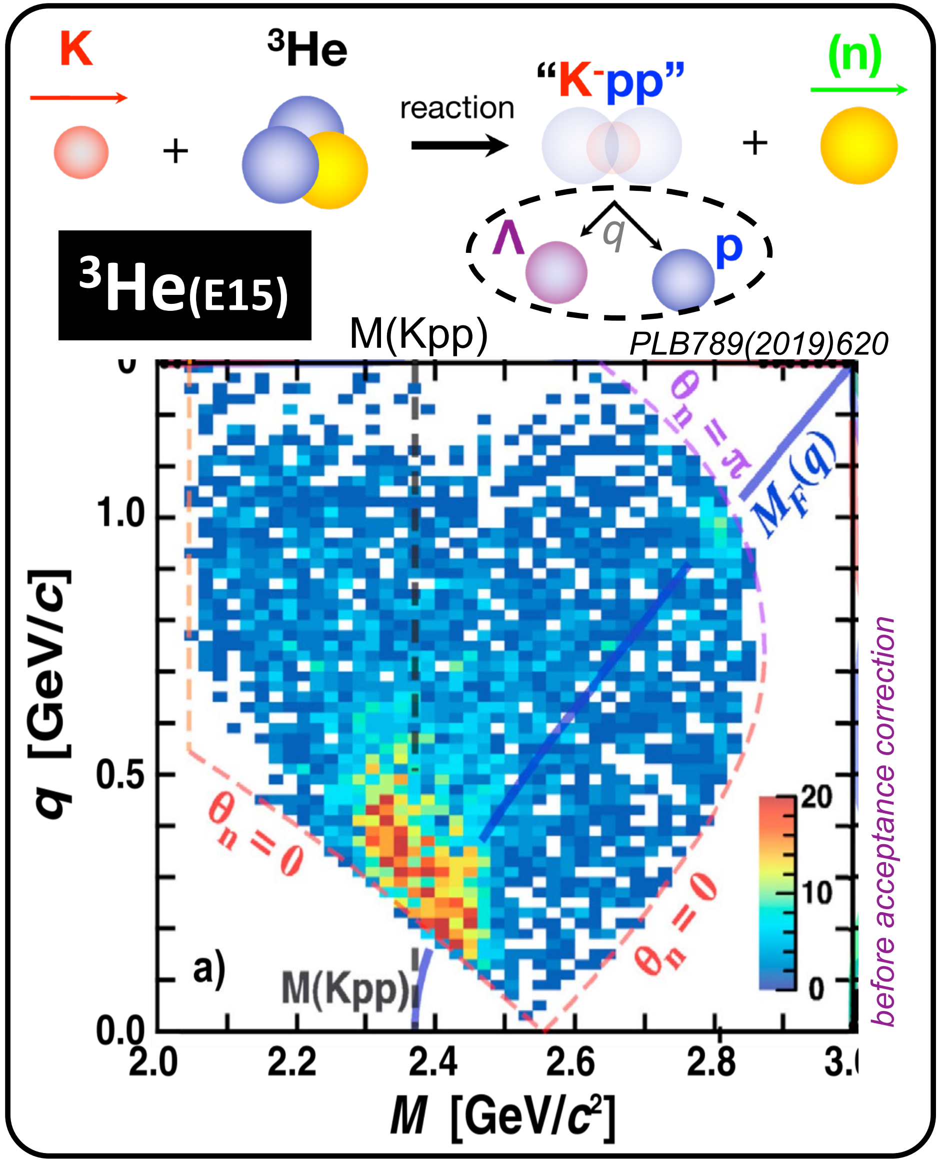




Experiment	K⁻ on target
E15 (^{3}He)	~42 x 10^{9}
T77 (^{4}He)	**~6 x 10^{9}**
E73 (^{4}He)	~12 x 10^{9}

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





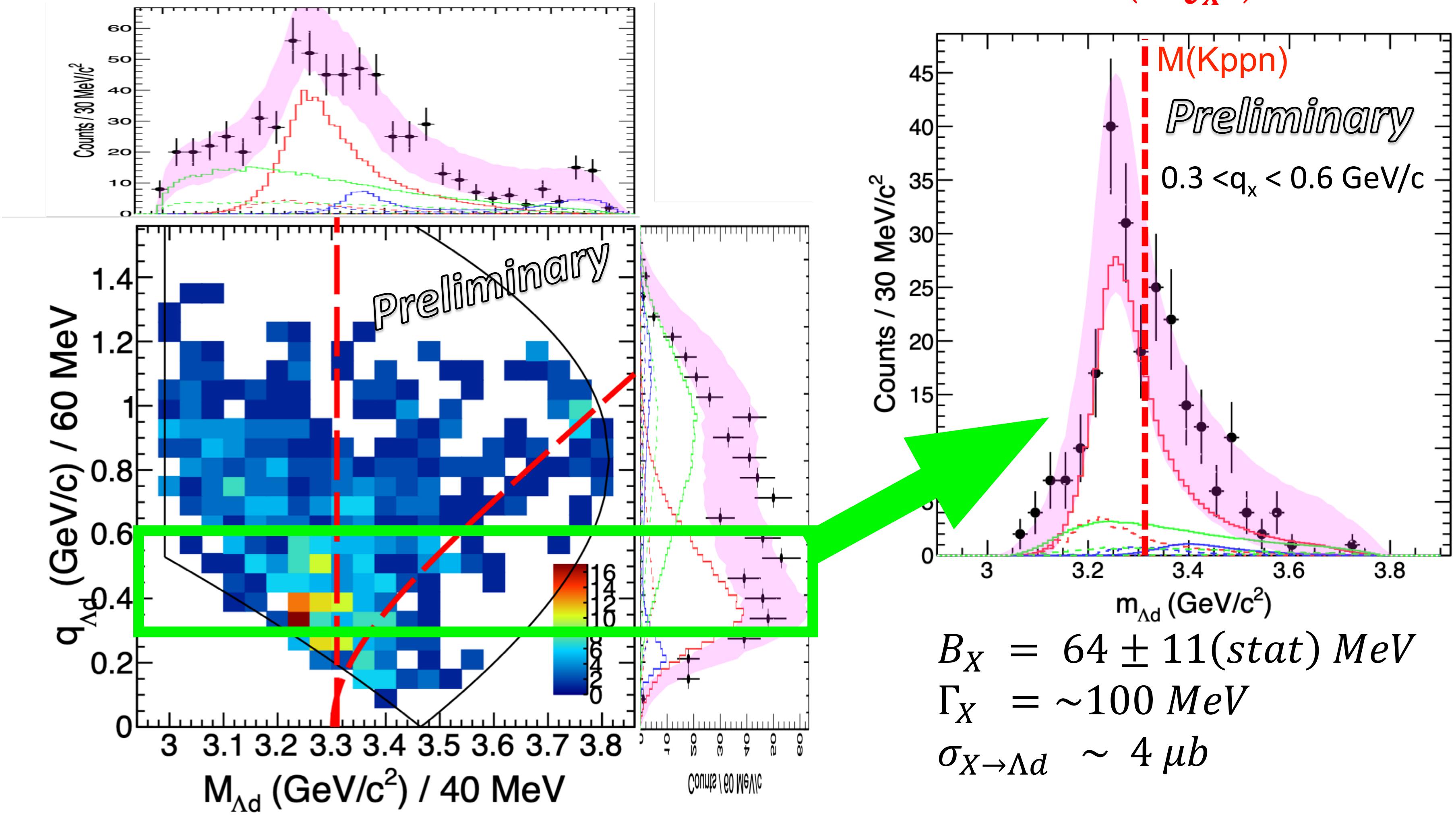
- **Two distributions are quite similar**
- structure below the threshold (**seems *q*-independent**), QF-K, BG

"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

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

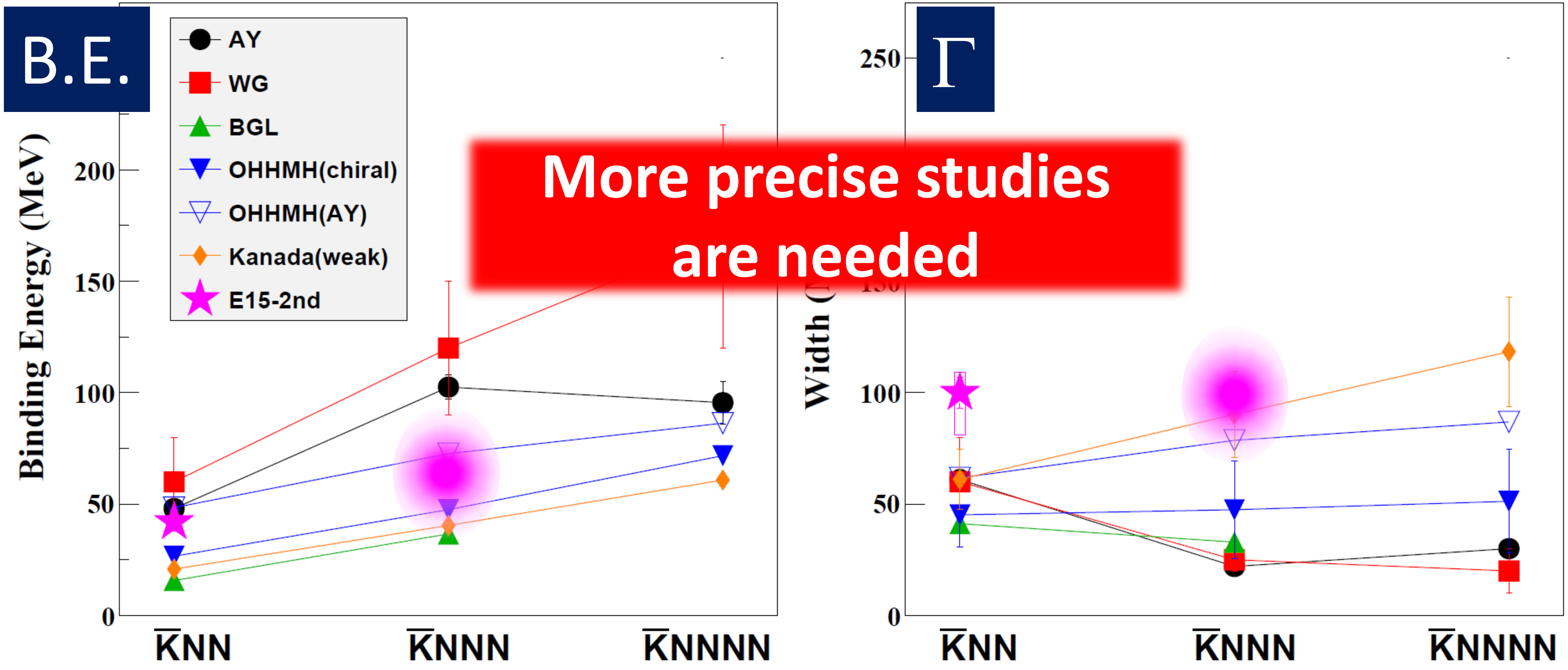


$B_X \ = \ 64 \pm 11(stat)\ MeV$

$\Gamma_X \ = \sim 100\ MeV$

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

If the Observed Structure Is "K⁻ppn",



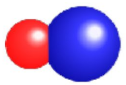
- The binding energy is comparable with some theoretical predictions
- The width is larger than theoretical predictions

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

Need Further Investigations

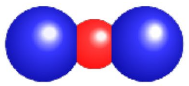
to establish the kaonic nuclei

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



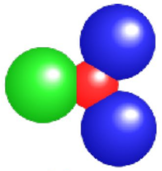
K^-p

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

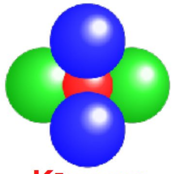


K^-pp

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



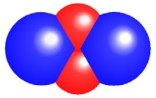
K^-ppn



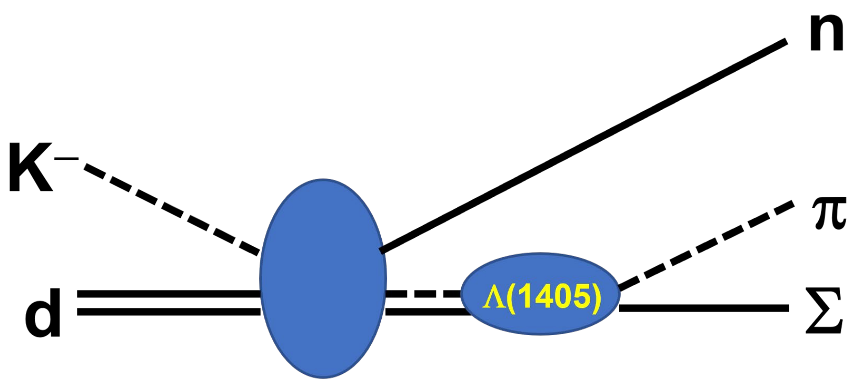
K^-ppnn

…

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



K^-K^-pp

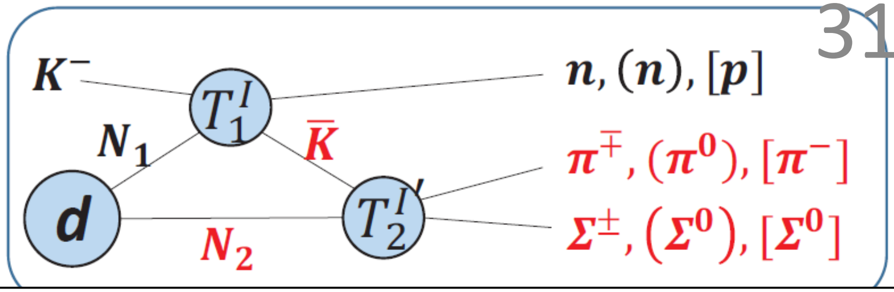


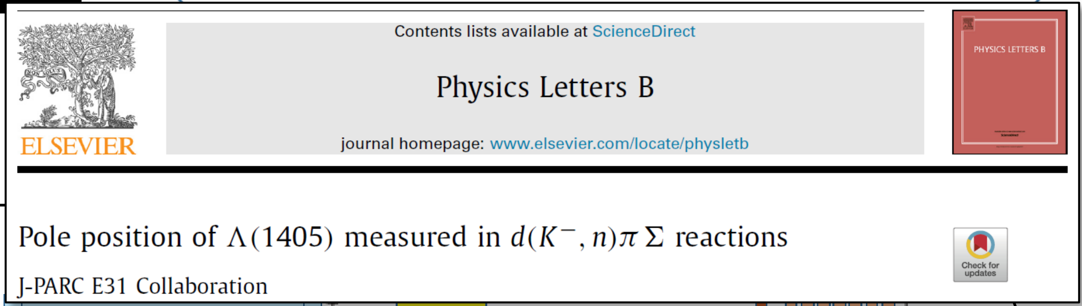
J-PARC E31

$K^-d \rightarrow n\Sigma^{\pm}\pi^{\mp}/\Sigma^0\pi^0$

@ θ_n=0

PLB837(2023)137637.




Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

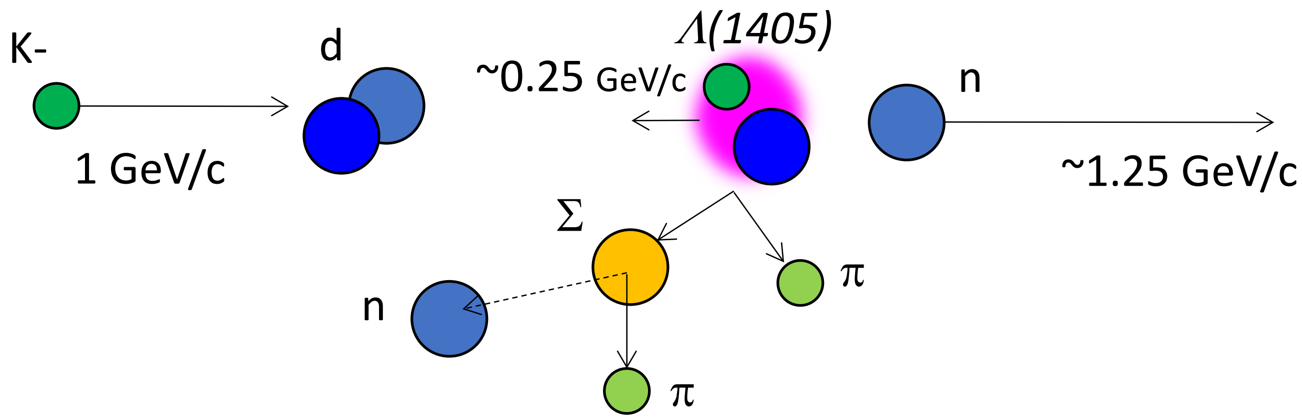
ELSEVIER

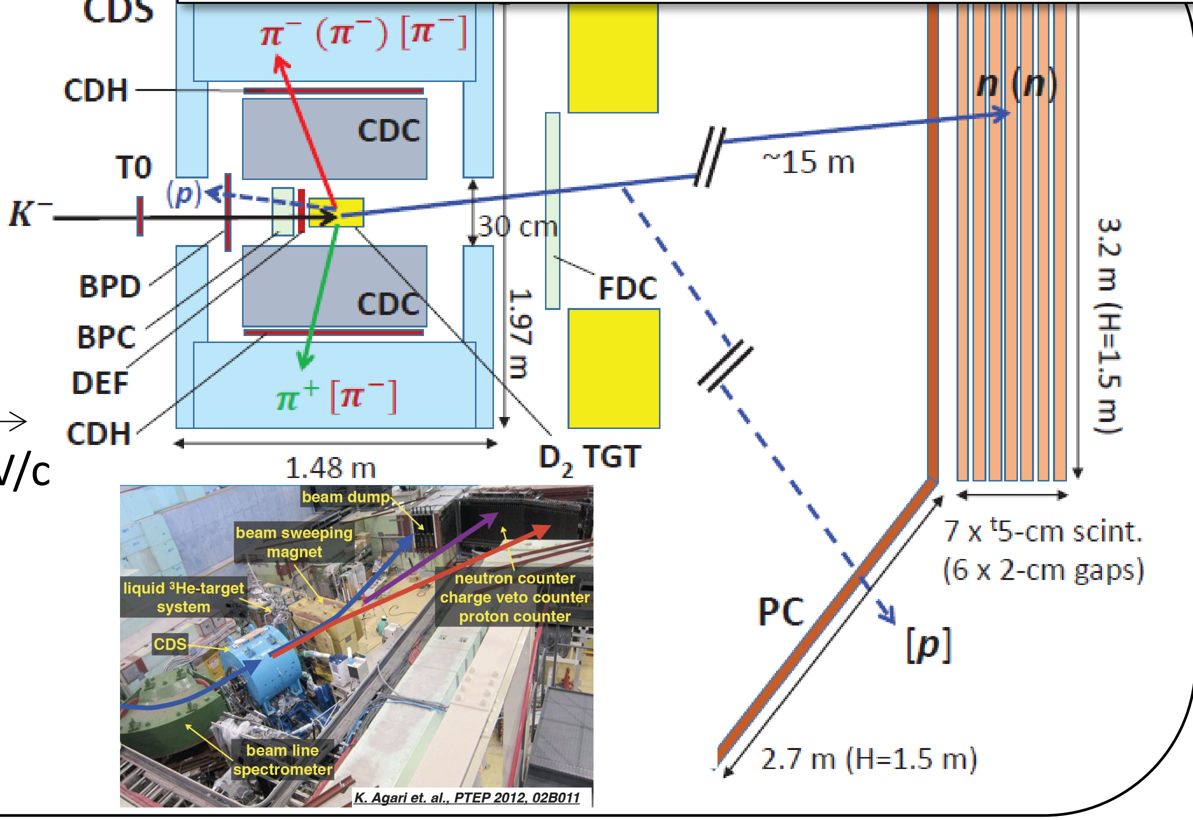
Pole position of $\Lambda(1405)$ measured in $d(K^-, n)\pi\Sigma$ reactions

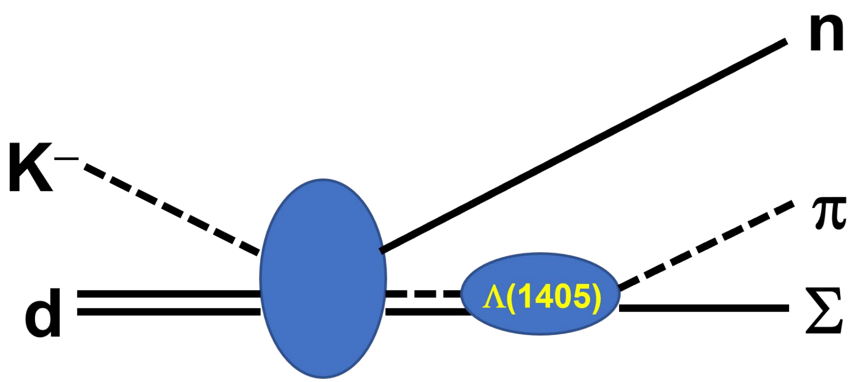
J-PARC E31 Collaboration

- $d(K^-,n)\pi\Sigma$ reaction at θ_n~0 degree

➔ enhance **S-wave $K^{bar}N \rightarrow \pi\Sigma$ reaction**





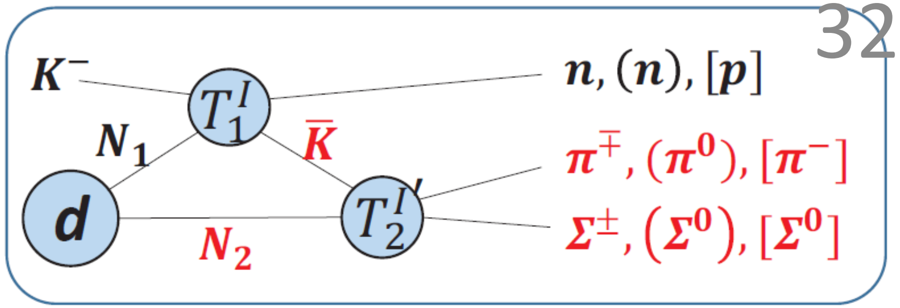


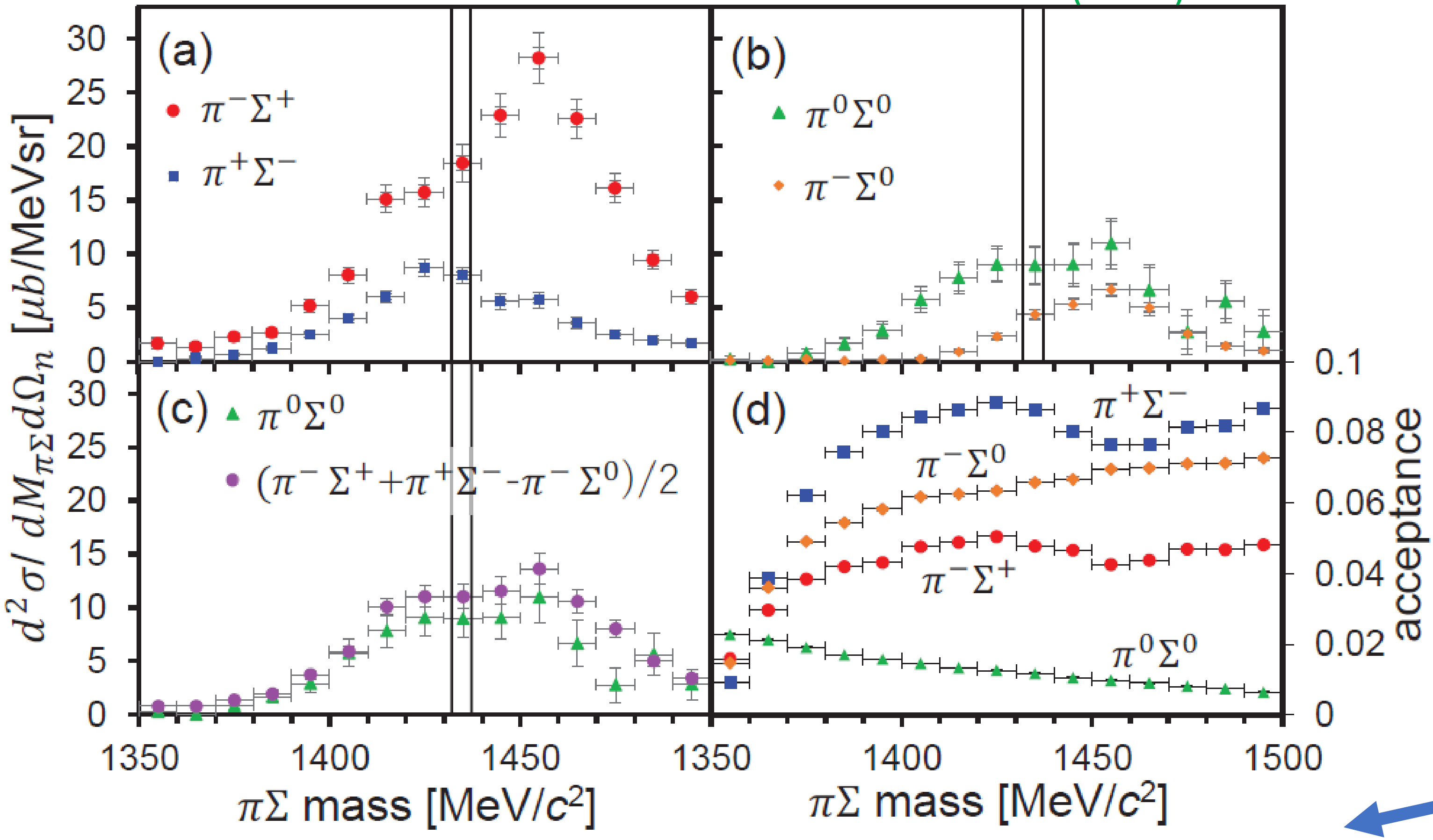
J-PARC E31

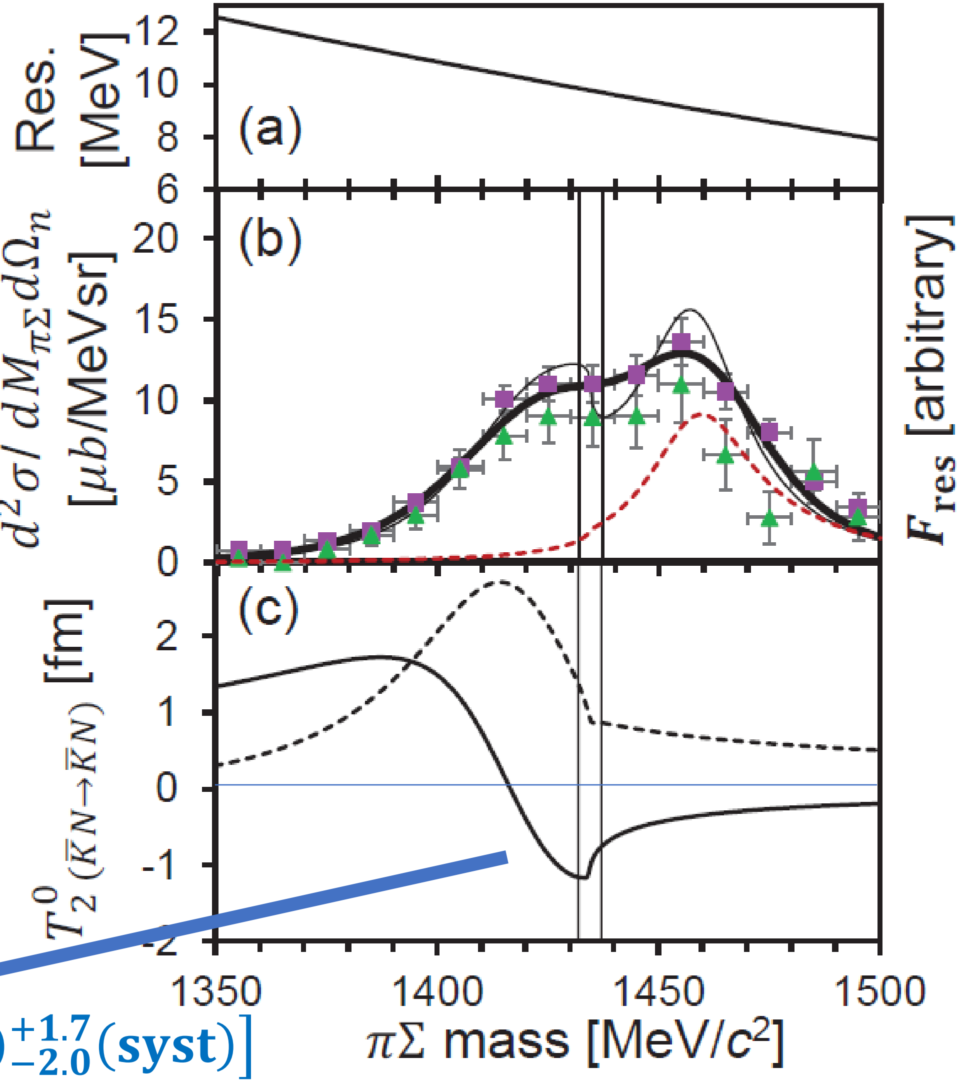
$K^-d \rightarrow n\Sigma^{\pm}\pi^{\mp}/\Sigma^0\pi^0$

@ $\theta_n = 0$

PLB837(2023)137637.



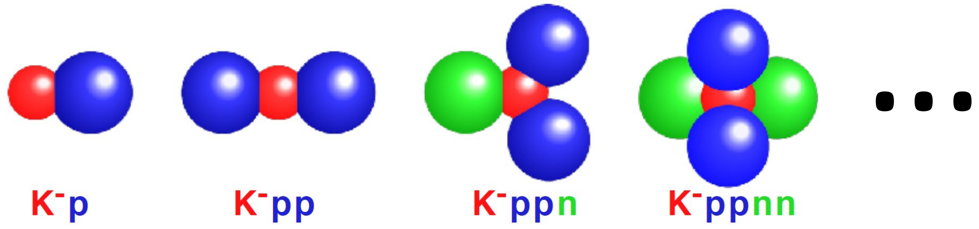




$\Lambda(1405)$ pole : $1417.7^{+6.0}_{-7.4}(\mathrm{fit})^{+1.1}_{-1.0}(\mathrm{syst}) - i\left[26.1^{+6.0}_{-7.9}(\mathrm{fit})^{+1.7}_{-2.0}(\mathrm{syst})\right]$

New Kaonic Nuclei Project at J-PARC

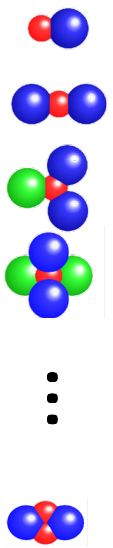
– from the $\bar{K}N$ to $\bar{K}NNNN$ systems and more –



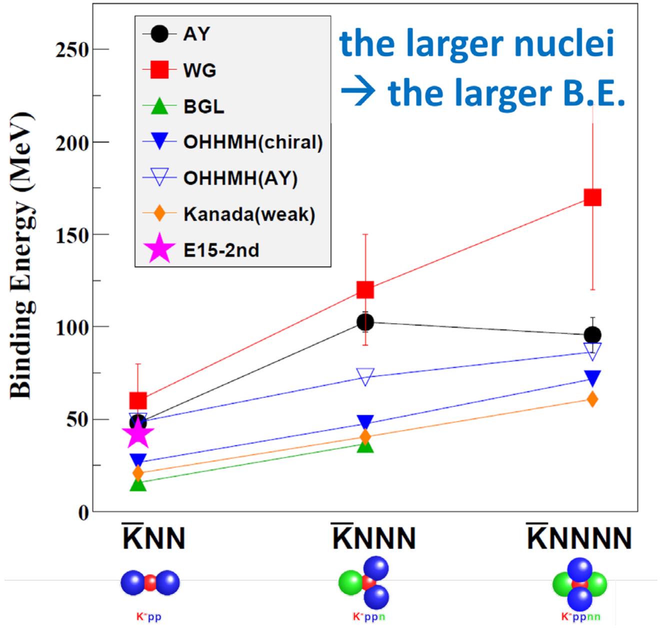
Systematic investigation of the light kaonic nuclei

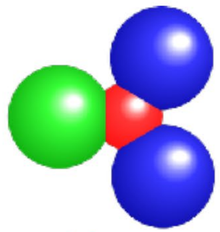
- Systematic measurement will be promoted at J-PARC
  - mass number dependence
    - binding energy, branching ratio, *q* dependence, ..
  - spin/parity determination

➢ 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	$\Lambda\Lambda$



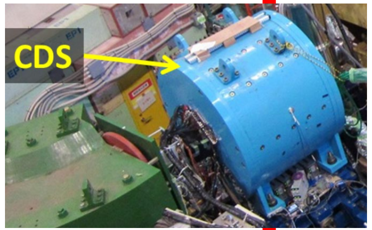


$\bar{K}NNN$ @ E80

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

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

- "K-ppn"→Λd 2-body decay

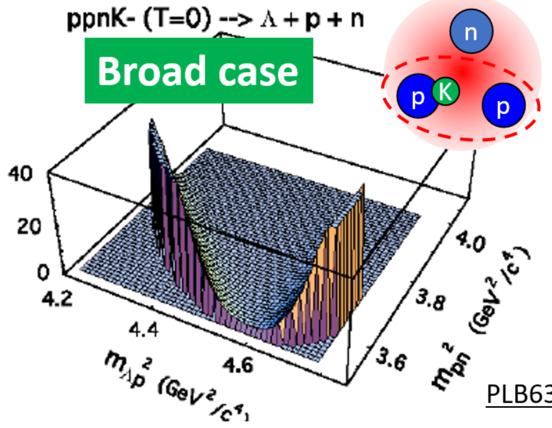


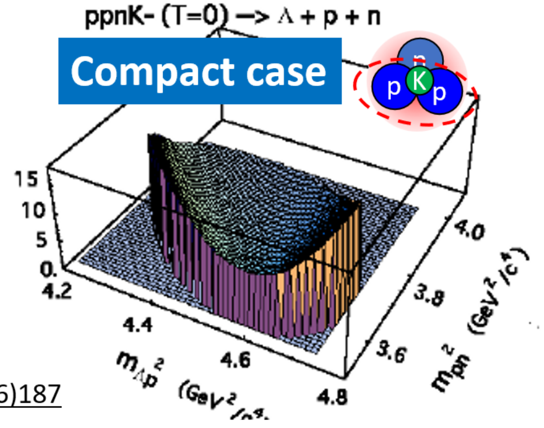
② **Study the multi-particle decay mode of $\bar{K}NNN$ toward understanding its internal structure**

- "K-ppn"→Λpn 3-body decay

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

Utilize Dalitz plots → Differences in distribution





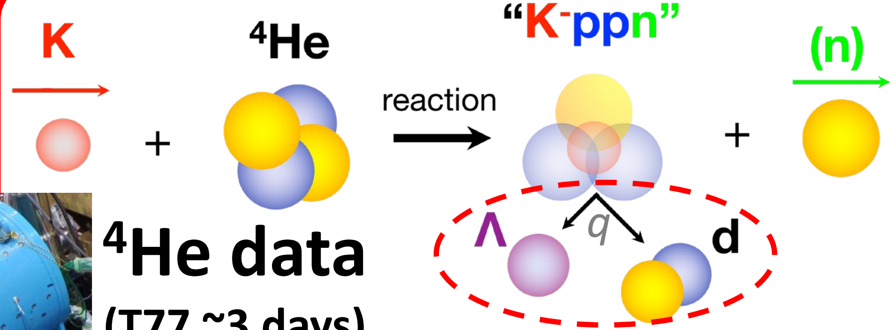
PLB632(2006)187

Distributed in parts of the plane

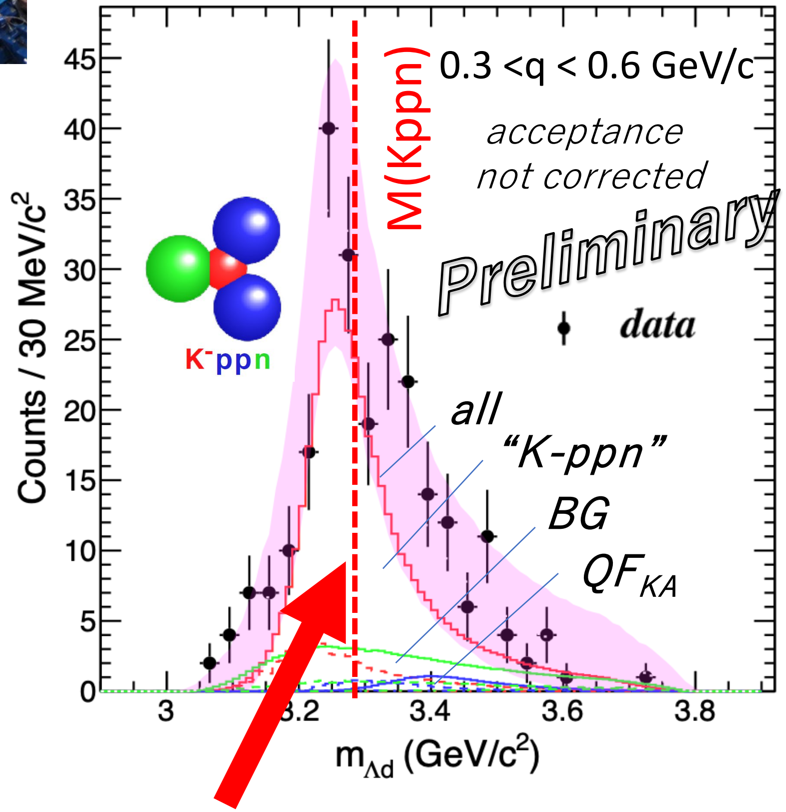
- 1 nucleon has the Fermi momentum

Widely distributed in the plane

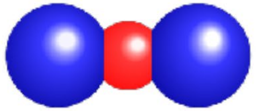
- All particles have a momentum larger than the Fermi momentum



^{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

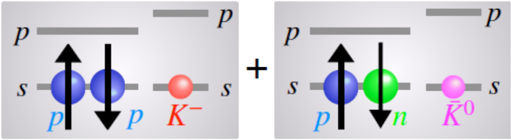
② **Determine the spin/parity of $\bar{K}NN$**

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

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

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

$J^P = 0^-$

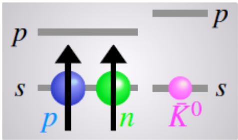


$$\frac{|I_{\bar{K}N}=0|^2}{|I_{\bar{K}N}=1|^2} = \frac{3}{1}$$

Deeper bound expected

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

$J^P = 1^-$

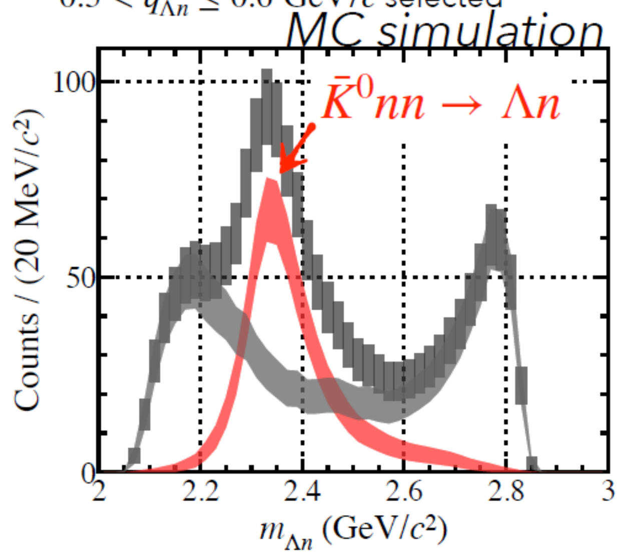


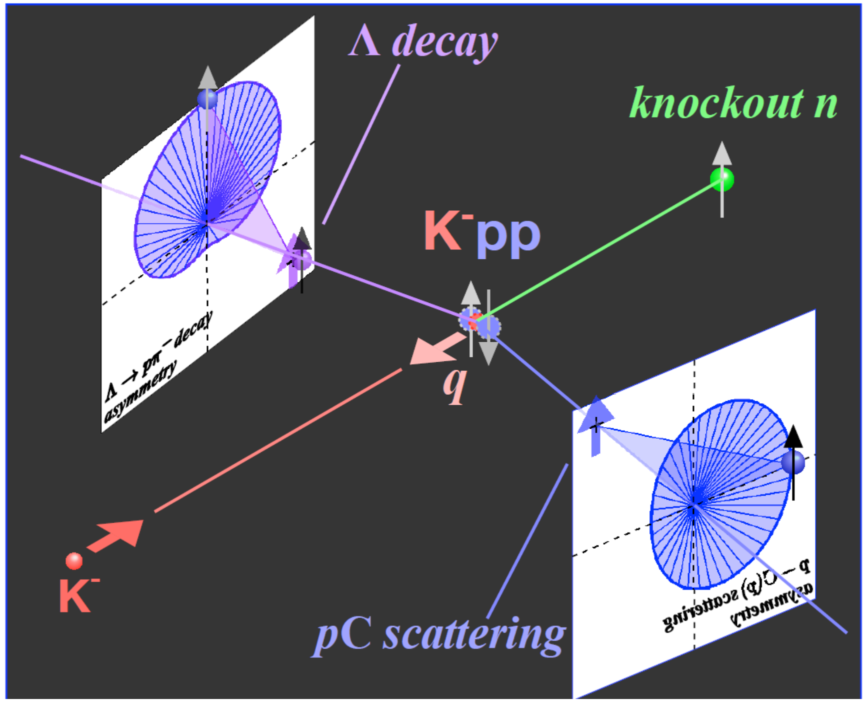
$$\frac{|I_{\bar{K}N}=0|^2}{|I_{\bar{K}N}=1|^2} = \frac{1}{3}$$

Shallower bound expected

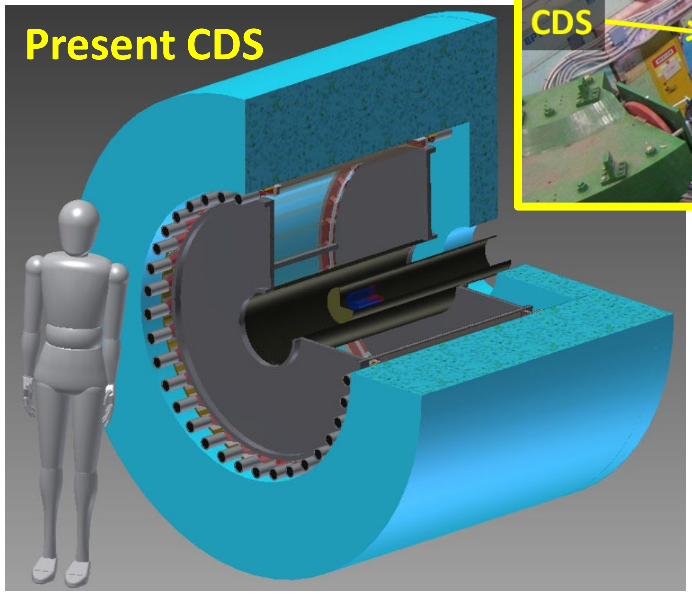
Measurement for Λn pair

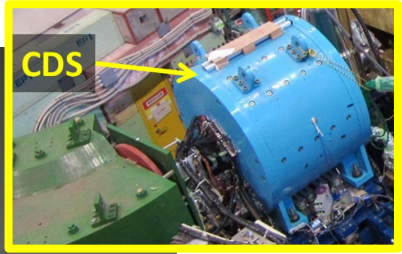
*Assuming $J^P = 0^-$ (strict case)





New Cylindrical Detector System (CDS)





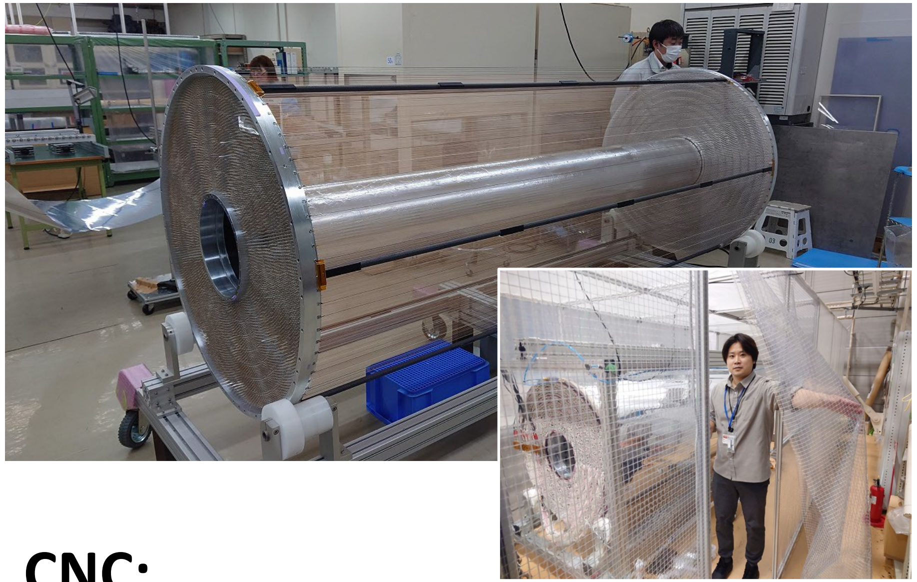
✓**Solid angle: x1.6** (59% → 93%)
✓**Neutron eff.: x7** (3% → 12%x1.6)
+ forward TOF counter
+ proton polarimeter (in future)

Construction Status of the CDS

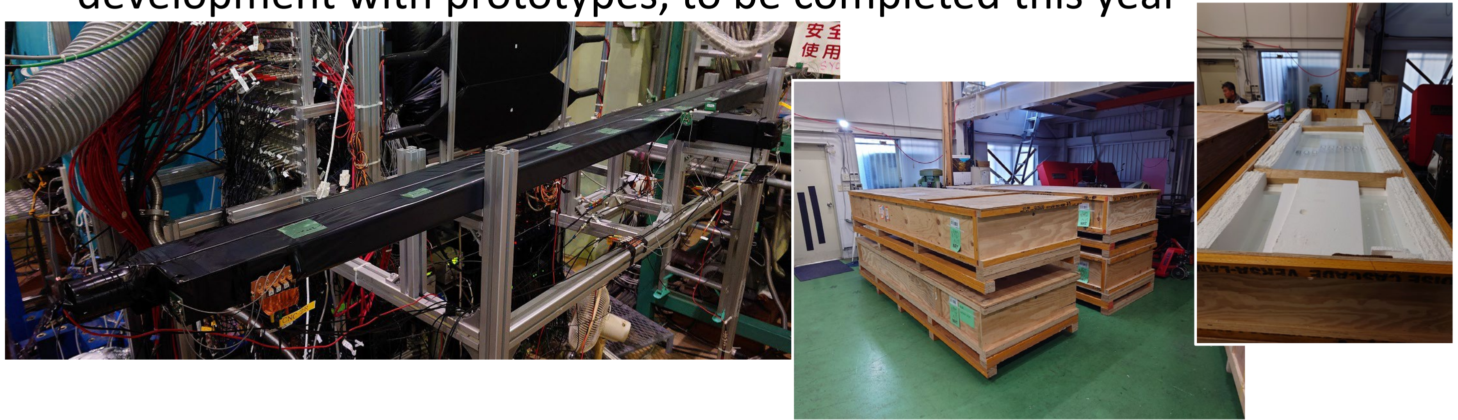
Return York:
completed

SC Solenoid:
completed

CDC:
completed, in commissioning



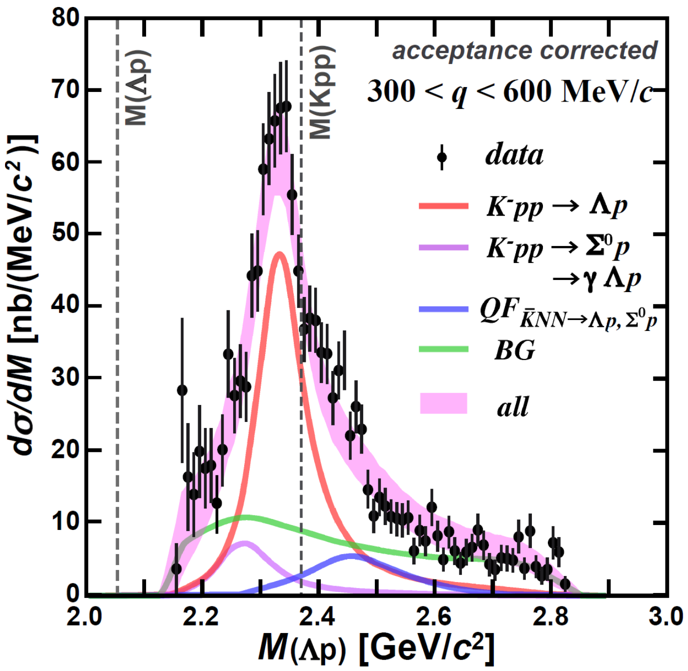
CNC:
development with prototypes, to be completed this year

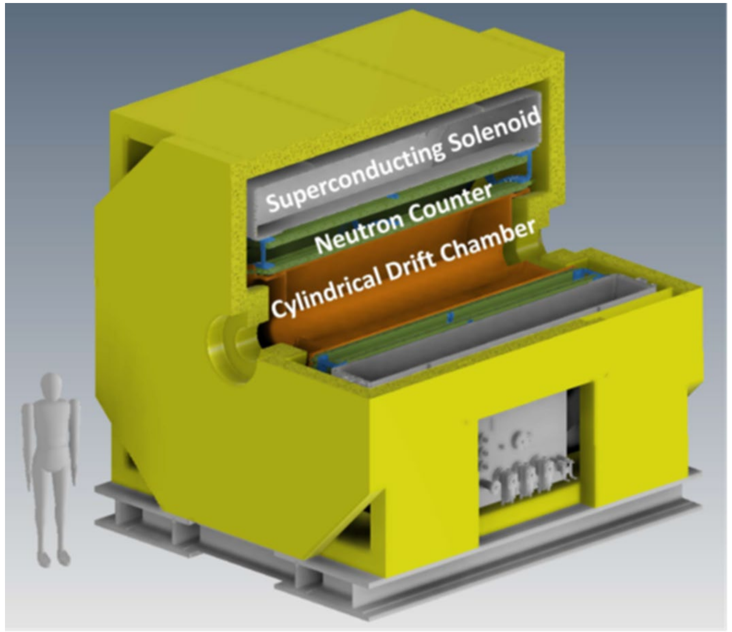


The experiment will be ready in early 2027

Summary

- We observed the "K⁻pp" bound state in ^{3}He(K$^-$,Λp)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 ^{4}He(K$^-$,Λd)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] Physics, K[illegible] University, Kyoto [illegible], Japan

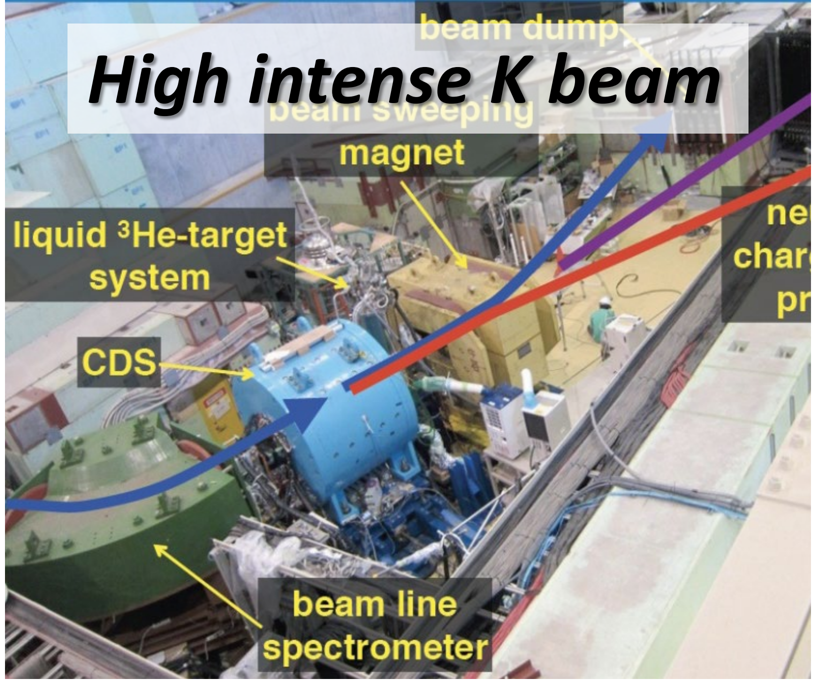
H. Fujioka
Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551, Japan

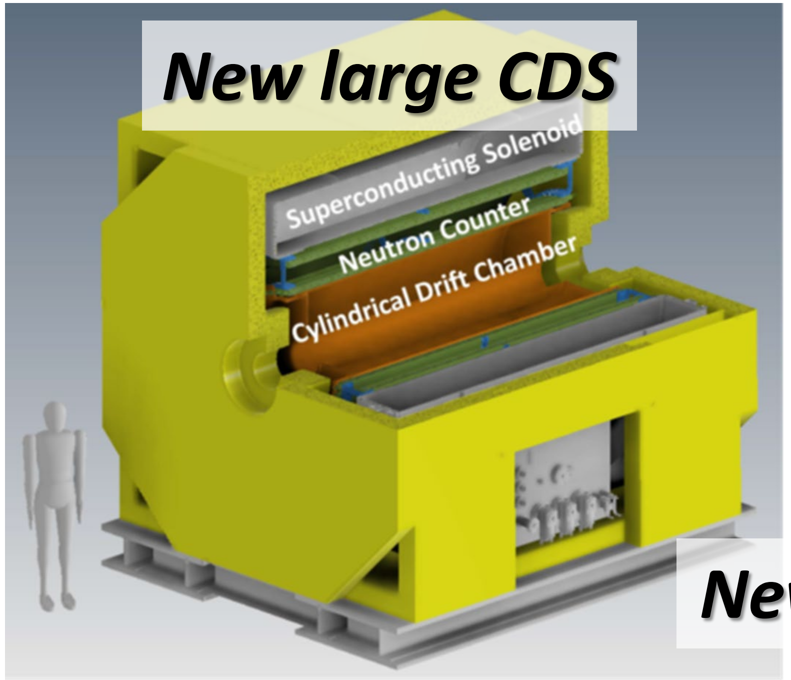
S. Okada
Chubu University, Aichi, 487-0027, Japan

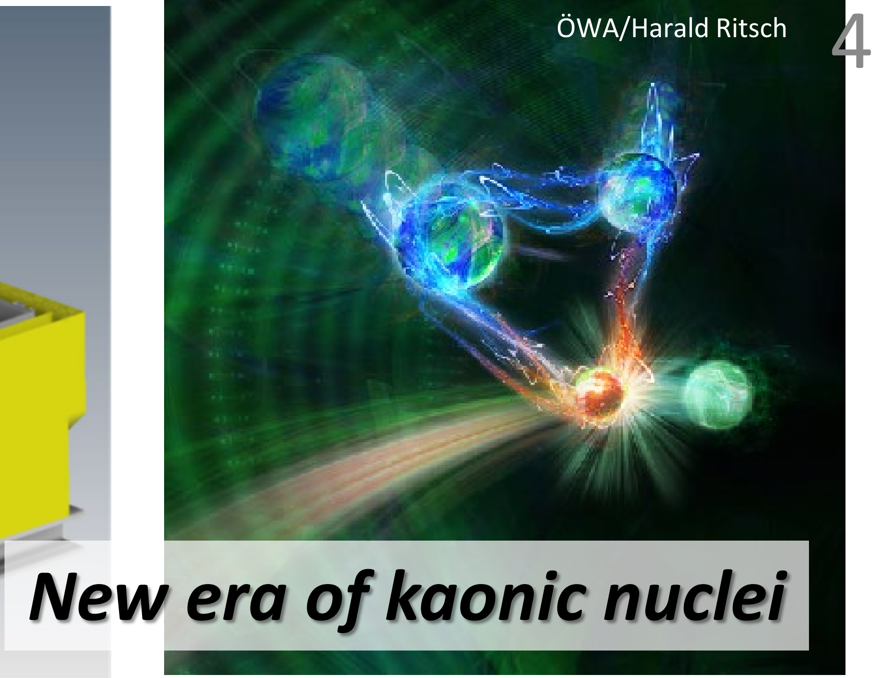
M. Bazzi, A. Clozza, C. Curceanu, C. Guaraldo, M. Iliescu, S. Manti, A. Scordo, F. Sgaramella, D. Sirghi, F. Sirghi
Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy

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

We're looking for new collaborators!

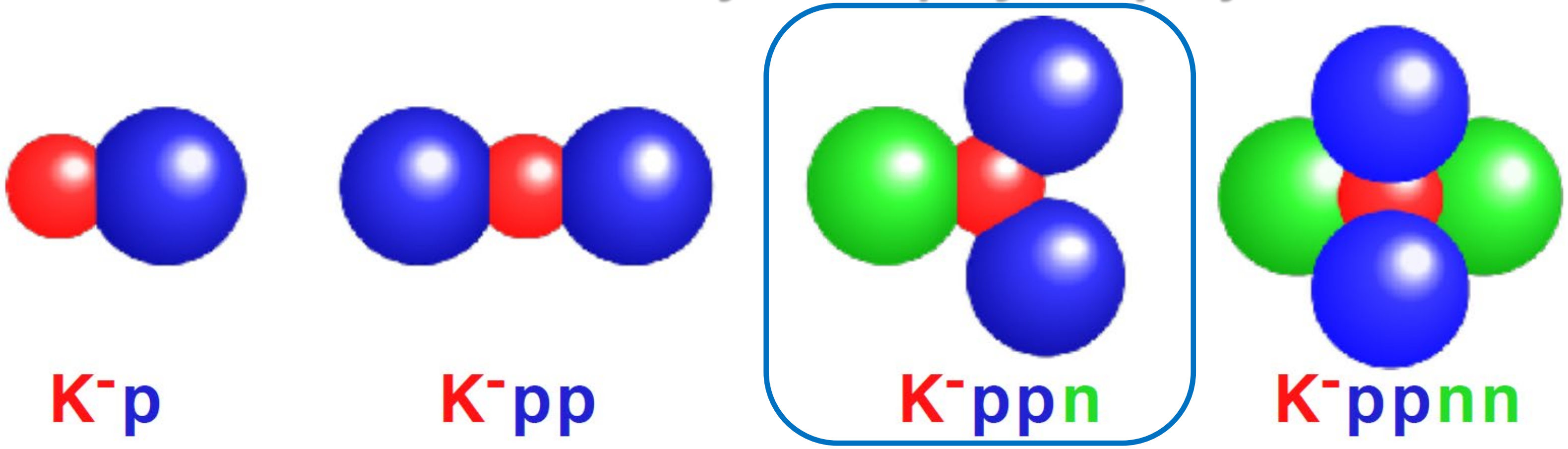






Thank you for your attention!

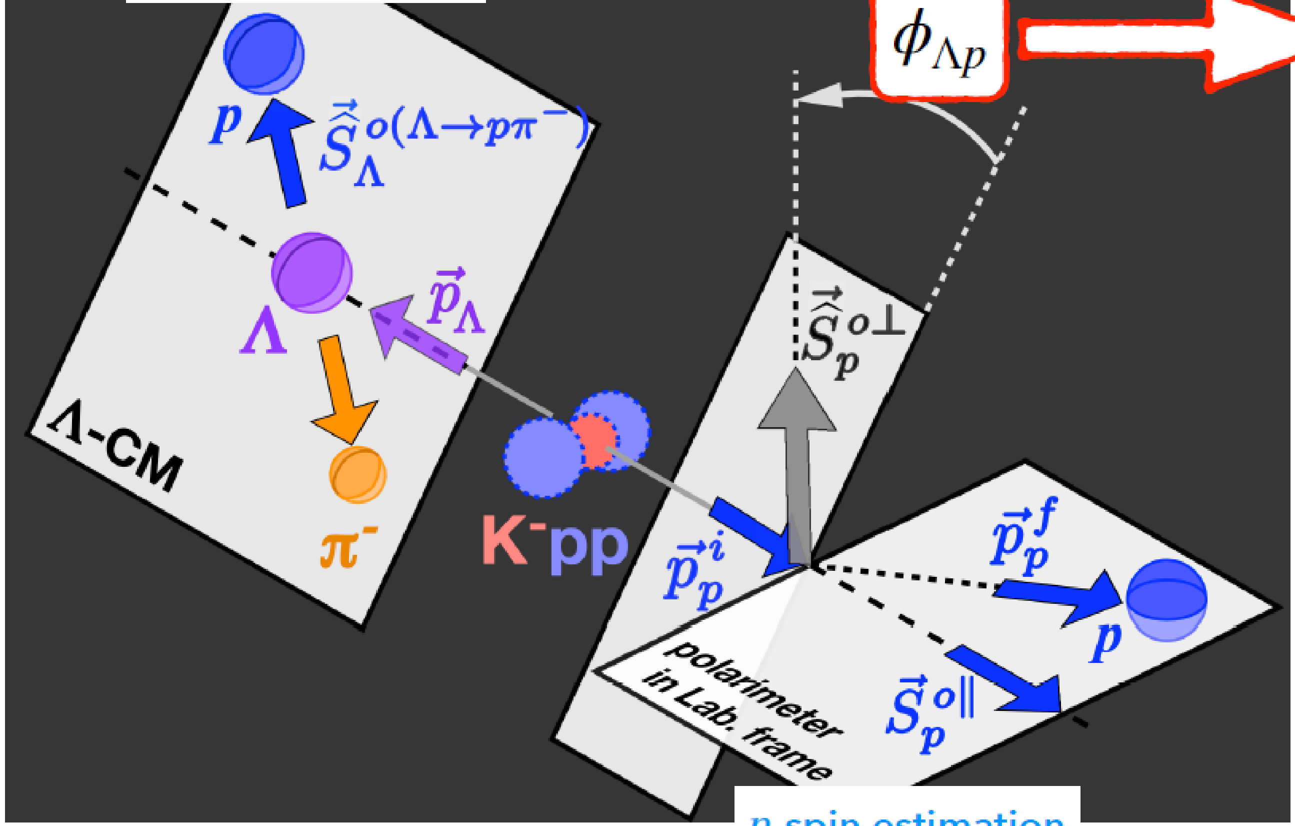
A first step of the project



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

How to measure the spin-spin correlation

Λ-spin estimation
by $\Lambda \to p\pi^-$ asym.



p-spin estimation
by p-C scat. asym.

Spin-spin correlation on ϕ-asymmetry

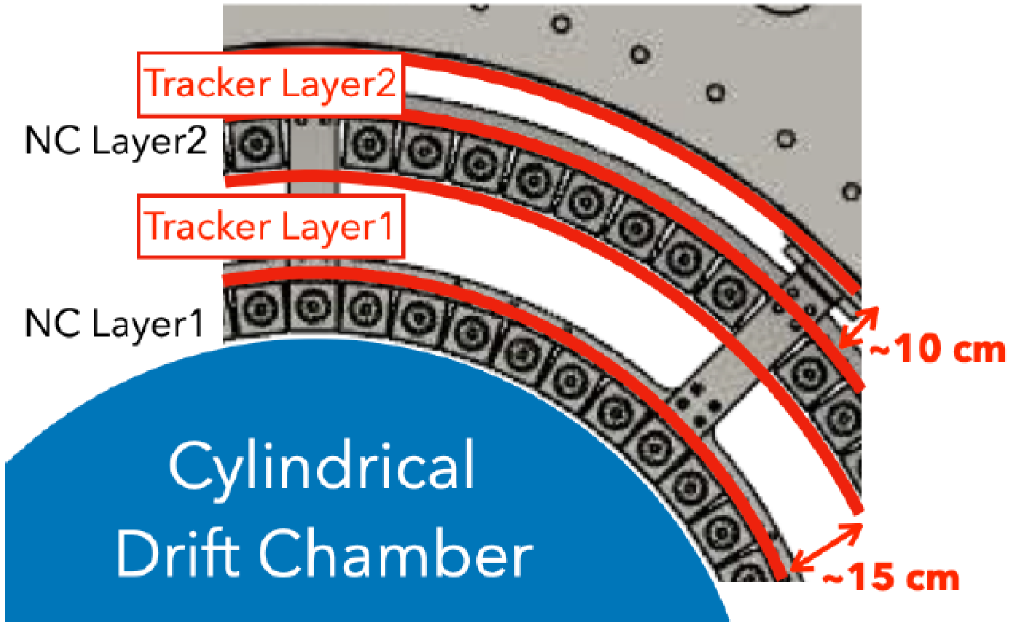
$$N(\phi_{\Lambda p}) = N_0 \cdot (1 + r^{(J^P)} \cdot \alpha_{\Lambda p} \cos \phi_{\Lambda p})$$

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

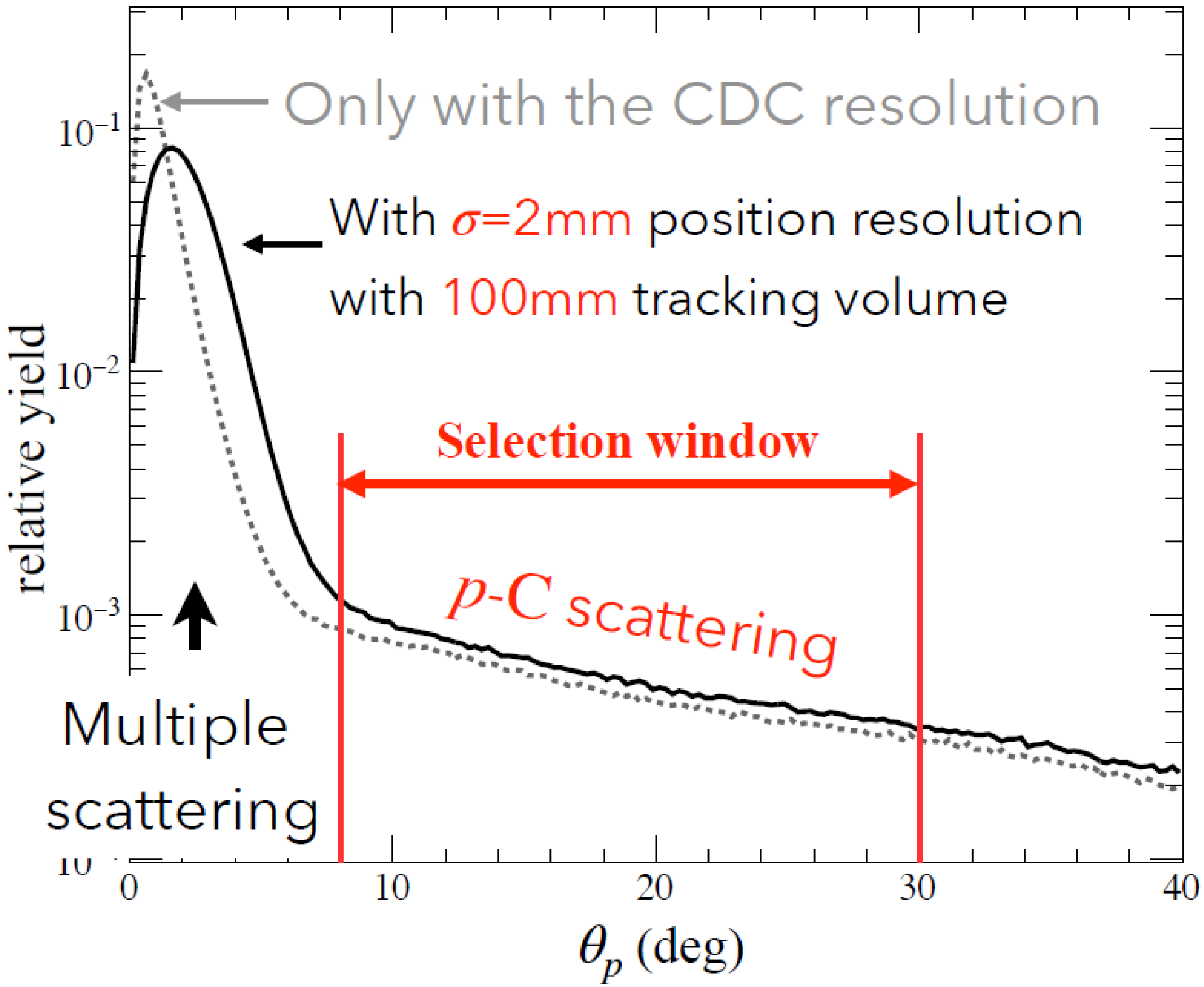
α_- : Λ asym. parameter	B : Magnetic field
A_{pC} : Analyzing power	$B_{\bar{K}}$: Binding energy
$f_{\vec{S}_\Lambda}$: Spin distribution	q : Momentum transfer

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

Necessary Position Resolution for the Tracker



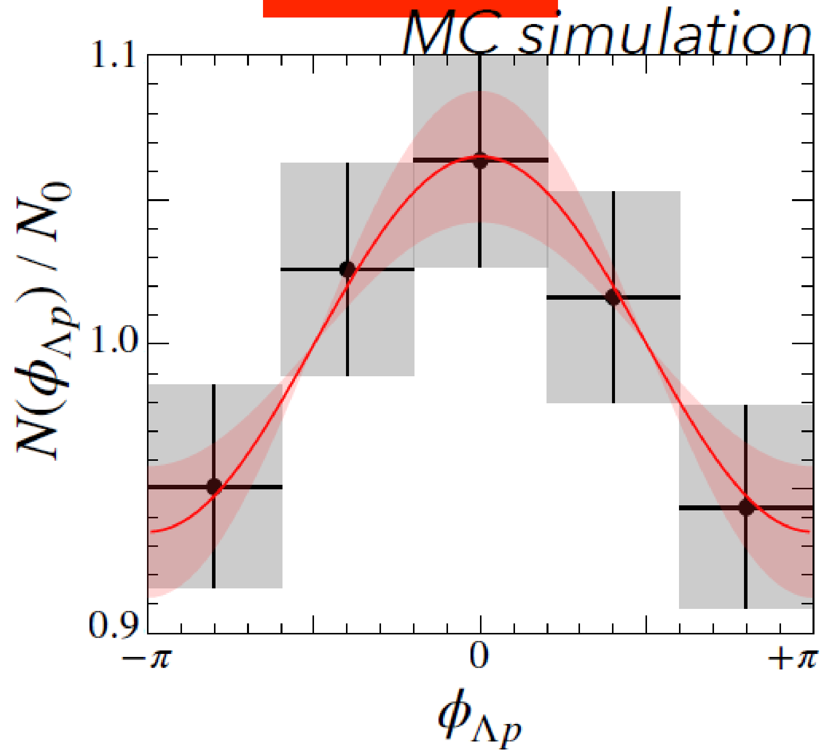
MC simulation



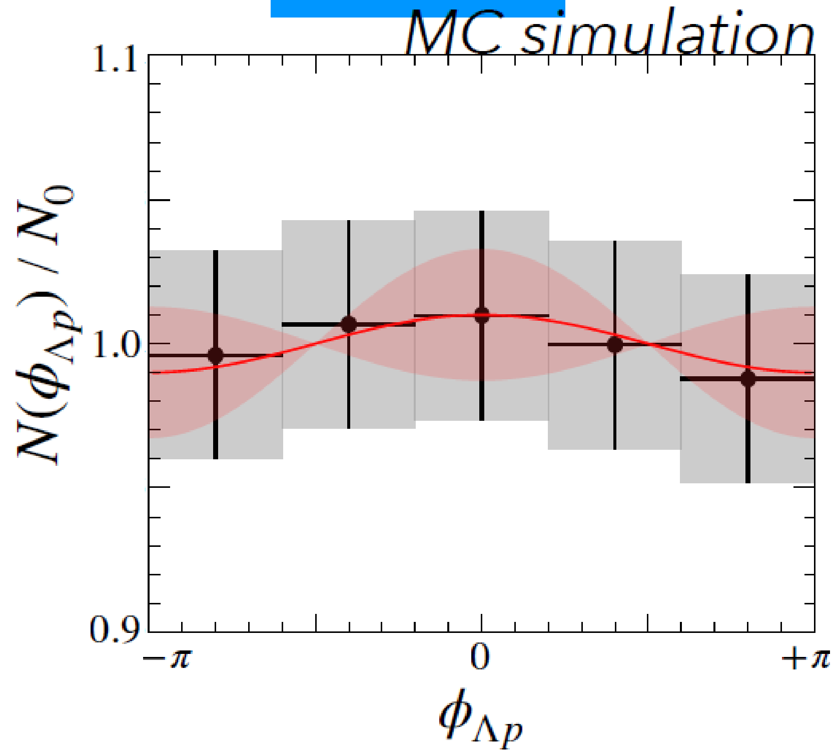
Expected spectra for $\alpha_{\Lambda p}$ measurment

8 weeks $\otimes$ 90 kW

$J^P = 0^-$



$J^P = 1^-$

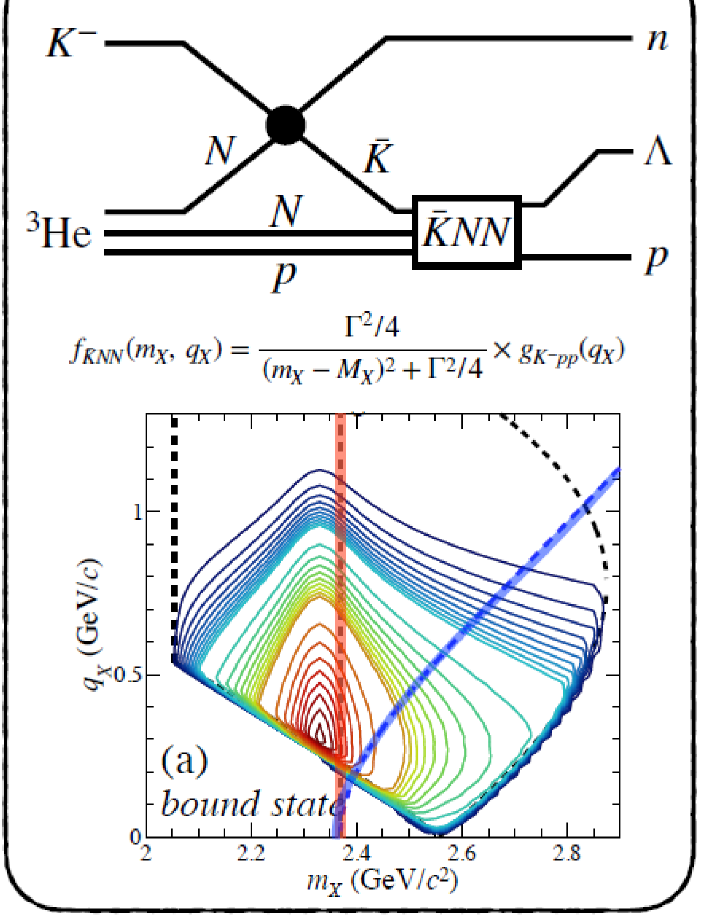


We would exclude $J^P = 1^-$ with **95%** confidence level.

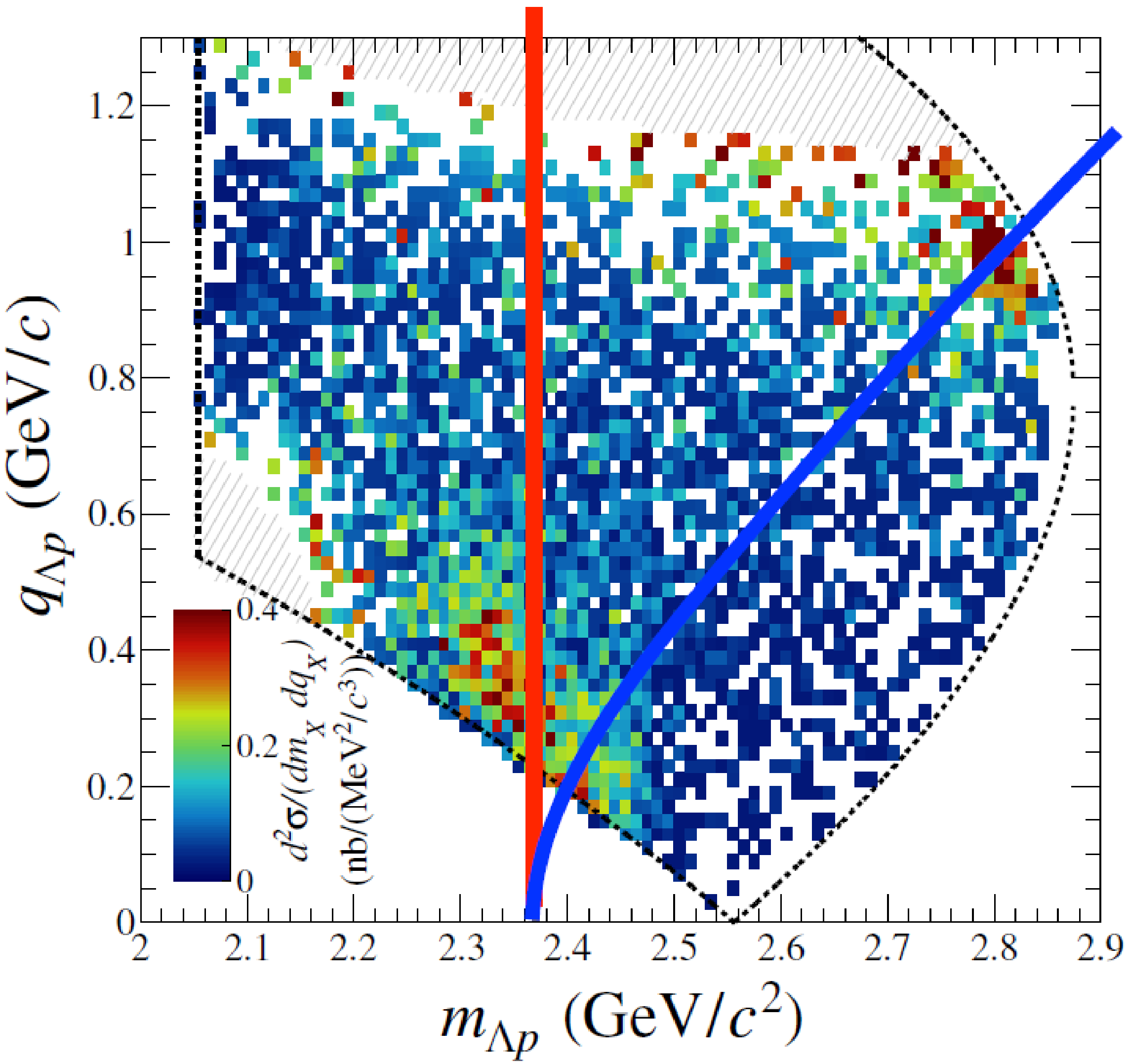
Takumi Yamaga (RIKEN)
for the J-PARC E15/E80/P89 collaboration
WNCP2023 @ Osaka Univ. (2023.11.27–29)

Exclusive measurement

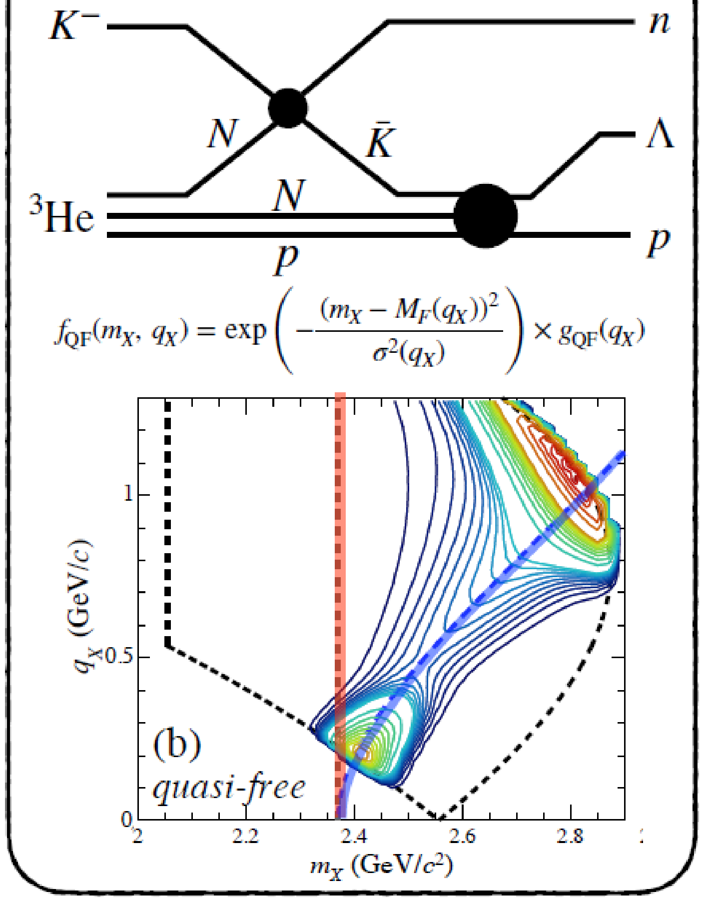
$\bar{K}NN$ production



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



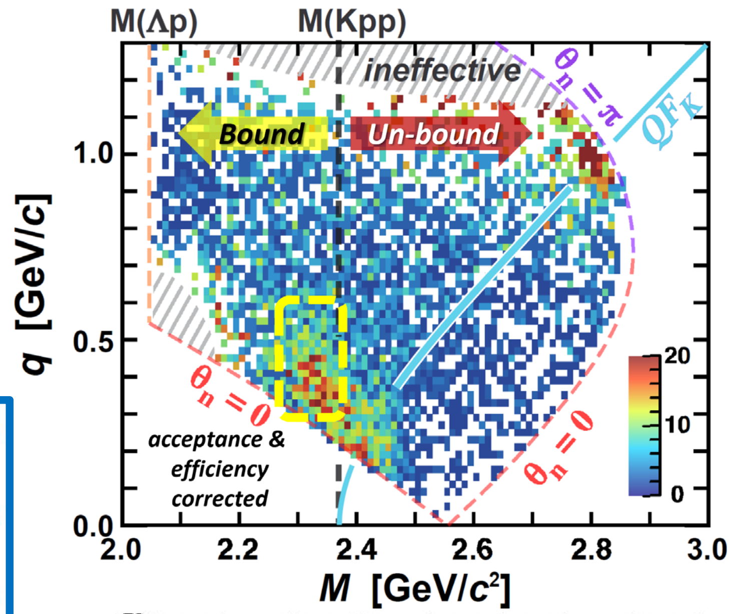
Quasi-free process with (K^-, n)

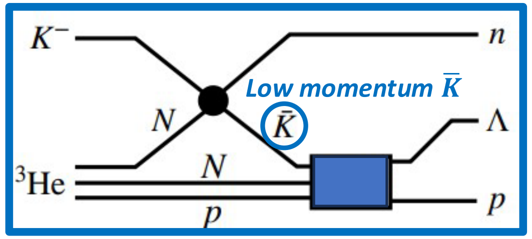


What We Observed at E15?

✓**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

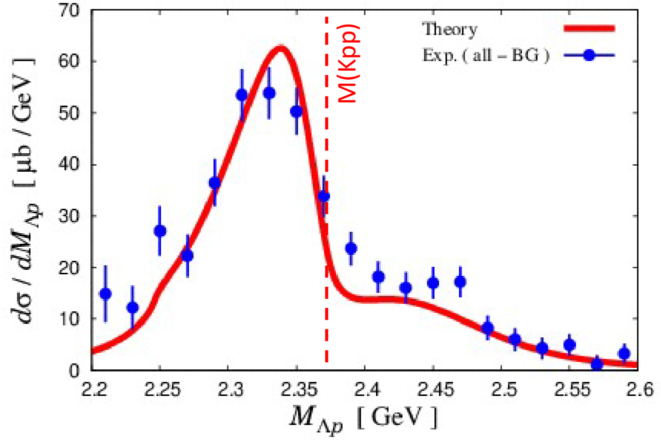




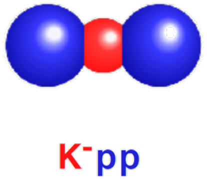
✓**Evidence of quasi-free K⁻ scattering**

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

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



Observed structure = "K-pp" bound state

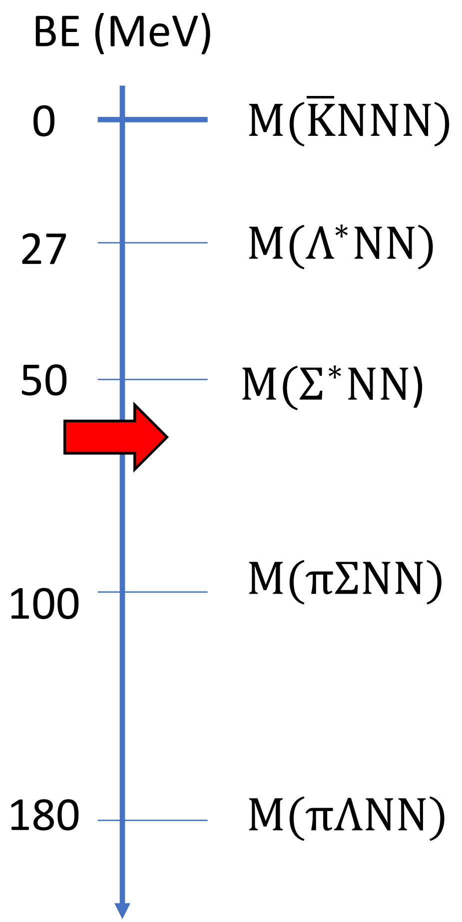


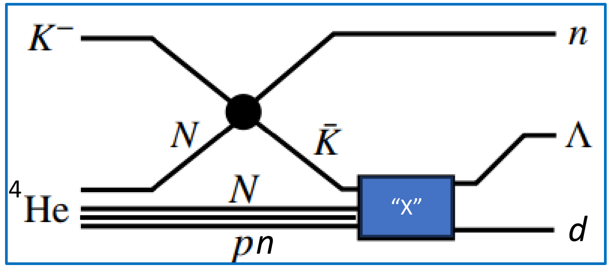
$K^{-}\,{}^4He \rightarrow \Lambda dn$ Analysis with the T77 Data

What is the observed structure?

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

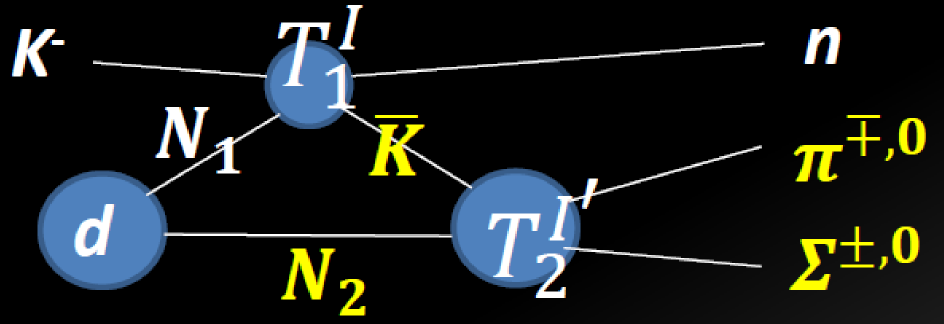
2. <u>**"X"="K^-ppn" with $J_{\text{"X"}}$ = 1/2** would be likely</u>
   - **$J_{\text{"X"}}$ = 1/2:**
     - ➢ ^{4}He initial state is I(J) = 0(0), and remaining "NNN" would be I(J) = 1/2(1/2)
     - ➢ low-momentum intermediate $\bar{K}$ would react with "NNN" in S-wave
   - **Exclusion of "X"="Y*(I=1)NN"**:
     - ➢ "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"





Extracting Scattering Amplitude

- 2-step process



$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=3^\circ} \sim \left|\left\langle n\pi\Sigma\middle| T_2^{I'}(\bar{K}N_2 \to \pi\Sigma) G_0 T_1^I(K^- N_1 \to \bar{K}n) \middle| K^-\Phi_d \right\rangle\right|^2$$

$$\sim \left|T_2^{I'}(\bar{K}N \to \pi\Sigma)\right|^2 F_{\mathrm{res}}(M_{\pi\Sigma})$$

Factorization Approximation

$$F_{\mathrm{res}}(M_{\pi\Sigma}) \sim \left|\int_0^\infty dq_{N_2}^3\, T_1^I \frac{1}{E_{\bar{K}} - E_{\bar{K}}(q_{\bar{K}}) + i\epsilon} \Phi_d(q_{N_2})\right|^2, q_{\bar{K}} + q_{N_2} = q_{\pi\Sigma}$$

E31: Response Function, $F_{\mathrm{res}}(M_{\pi\Sigma})$

- $F_{\mathrm{res}}(M_{\pi\Sigma}) = \left|\int G_0(q_2,q_1)T_1\Phi_d(q_2)\,d^3q_2\right|^2$
  - $G_0(q_2,q_1) = \frac{1}{q_0^2-q'^2+i\varepsilon}f(q_0,q')\frac{\left(\sqrt{P_{\pi\Sigma}^2+M_{\pi\Sigma}^2}+\sqrt{P_{\pi\Sigma}^2+W(q')^2}\right)}{M_{\pi\Sigma}+W(q')}$,

    $f(q_0,q')^{-1} = [E_1(q_0)+E_1(q')]^{-1} + [E_2(q_0)+E_2(q')]^{-1}$

    Miyagawa and Haidenbauer, PRC85, 065201(2012)
  - $T_1: K^-n \to K^-n\ (I=1), K^-p \to \bar{K}^0 n(I=0,1)$ amplitude,

    Gopal et al., NPB119, 362(1977)
    - $T_1(K^-n \to K^-n) = f(I=1)$
    - $T_1(K^-p \to \bar{K}^0 n) = [f(I=1) - f(I=0)]/2$

Off-shell treatment :See eq.(17) in PRC94, 065205

  - $\Phi_d(q_2)$: deuteron wave function, PRC63, 024001(2001)

$\bar{K}N$ Scattering Amplitude

L. Lensniak, arXiv:0804.3479v1(2008)

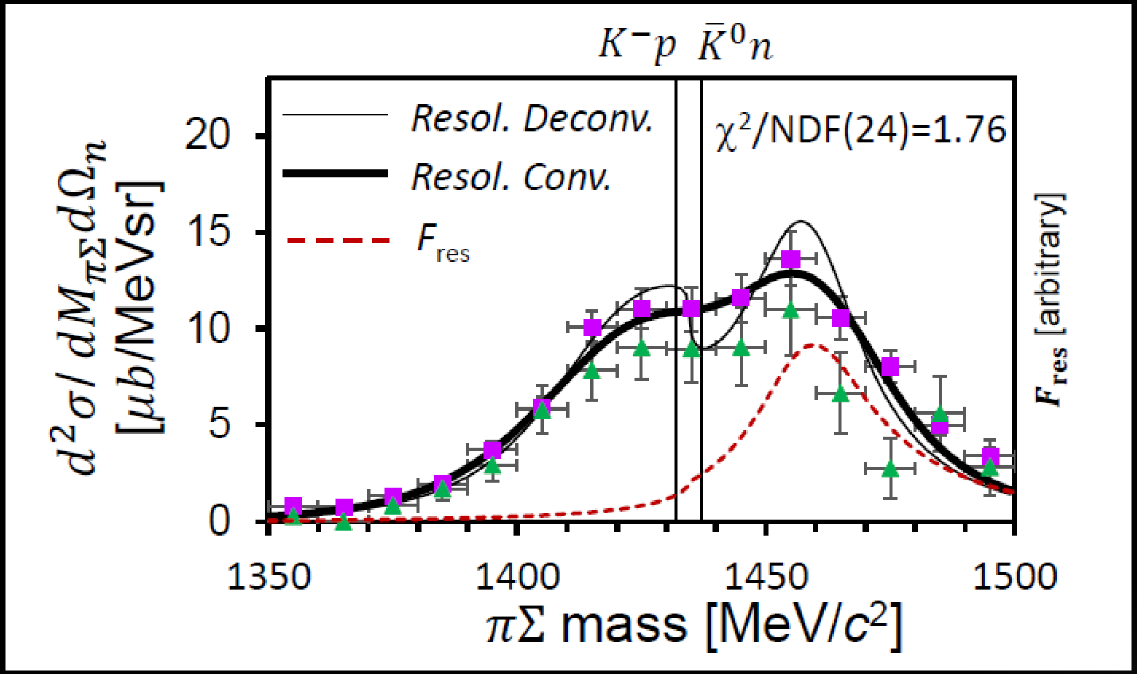
- $T_{\frac{1}{2}}^{I'}(\bar{K}N \to \bar{K}N) = \frac{A}{1 - iAk_2 + \frac{1}{2}ARk_2^2}$
- $T_{\frac{1}{2}}^{I'}(\bar{K}N \to \pi\Sigma) = \frac{1}{\sqrt{k_1}} e^{i\delta_0} \frac{\sqrt{ImA - \frac{1}{2}|A|^2 ImRk_2^2}}{1 - iAk_2 + \frac{1}{2}ARk_2^2}$
- $T_{\frac{1}{2}}^{I'}(\pi\Sigma \to \pi\Sigma)$

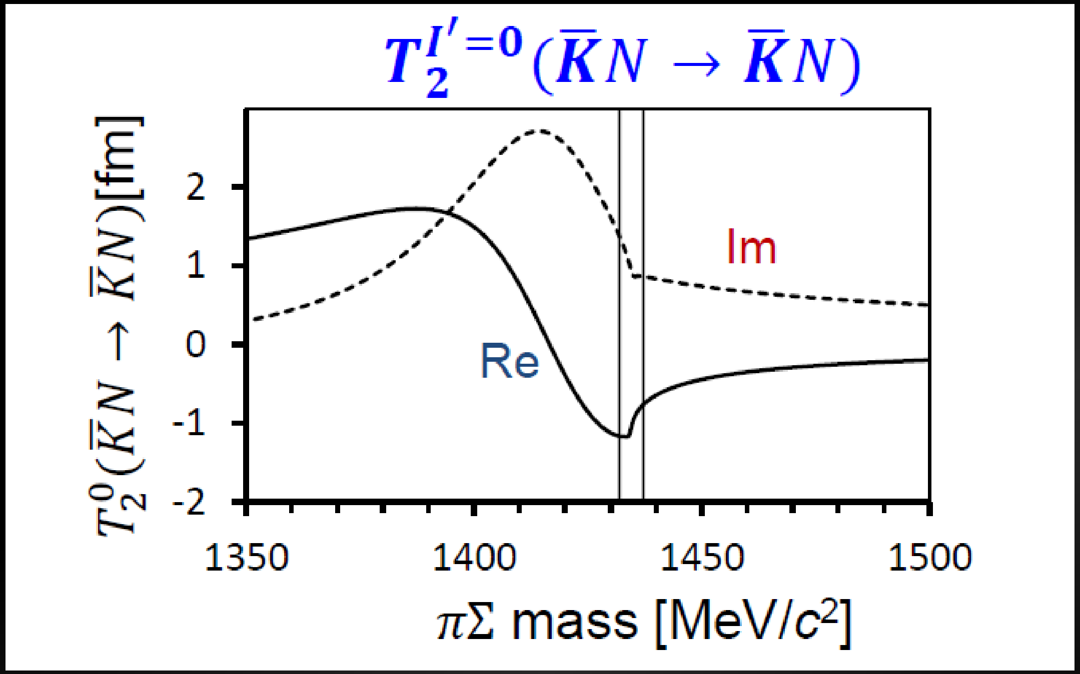
$$= \frac{e^{i\delta_0}}{k_1} \frac{\left(\sin\delta_0 + iIm\left(e^{-i\delta_0}A\right)k_2 - \frac{1}{2}Im\left(e^{-i\delta_0}AR\right)k_2^2\right)}{1 - iAk_2 + \frac{1}{2}ARk_2^2}$$

$$T_{11} = k_2 T_{\frac{1}{2}}^{I'}(\bar{K}N \to \bar{K}N),$$
$$T_{12} = \sqrt{k_1 k_2} T_{\frac{1}{2}}^{I'}(\bar{K}N \to \pi\Sigma),$$
$$|T_{11}|^2 + |T_{12}|^2 = ImT_{11},$$
$$\boldsymbol{S} = \boldsymbol{I} + 2i\boldsymbol{T},$$

- 5 real number parameters (effective range expansion)
  - *A*: scattering length, *R*: effective range, δ_0: phase

Best fit $\bar{K}N$ scattering amplitude





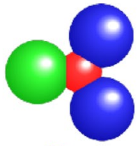
A pole at $(1417.7^{+6.0+1.1}_{-7.4-1.0}) + (-26.1^{+6.0+1.7}_{-7.9-2.0})i$ MeV/c^2

$$\left|T_2^{I'=0}(\bar{K}N \to \bar{K}N)\right|^2 / \left|T_2^{I'=0}(\bar{K}N \to \pi\Sigma)\right|^2 = 2.2^{+1.0+0.3}_{-0.6-0.3}$$

$$\boldsymbol{A}^{I'=0} = (-1.12 \pm 0.11^{+0.10}_{-0.07}) + i(0.84 \pm 0.12^{+0.08}_{-0.07}) \text{ fm}$$

$$\boldsymbol{R}^{I'=0} = (-0.18 \pm 0.31^{+0.08}_{-0.06}) + i(0.41 \pm 0.13^{+0.09}_{-0.09}) \text{ fm}$$

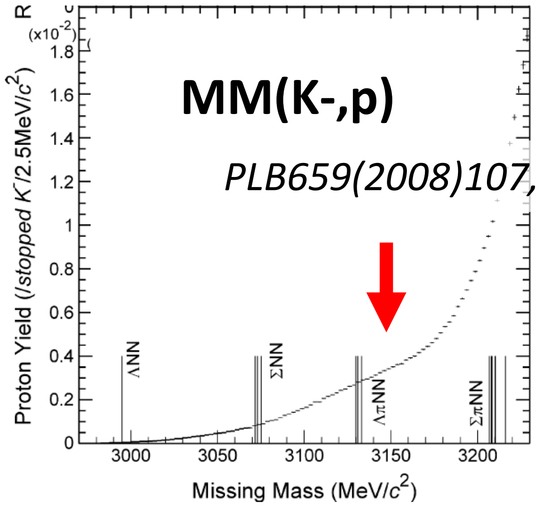
*best fit value ± fitting error ± systematic error
systematic errors assuming the K^-p/K^0n mass threshold

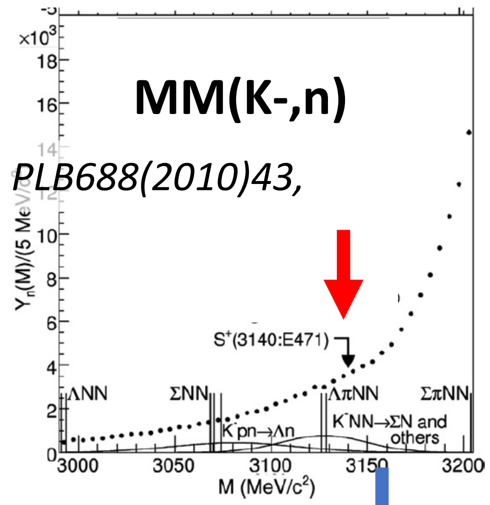


$\bar{K}$NNN Searches so far

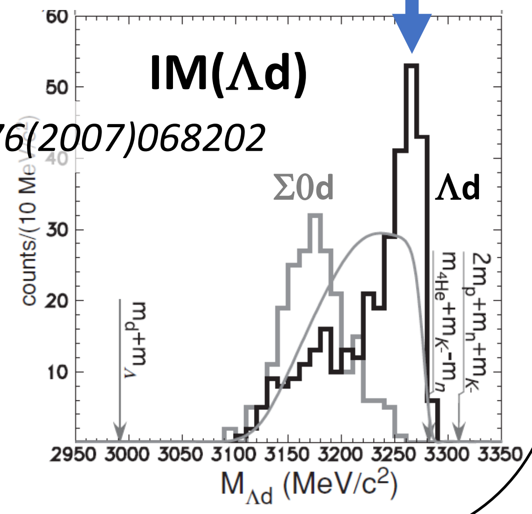
E471/E549@KEK

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





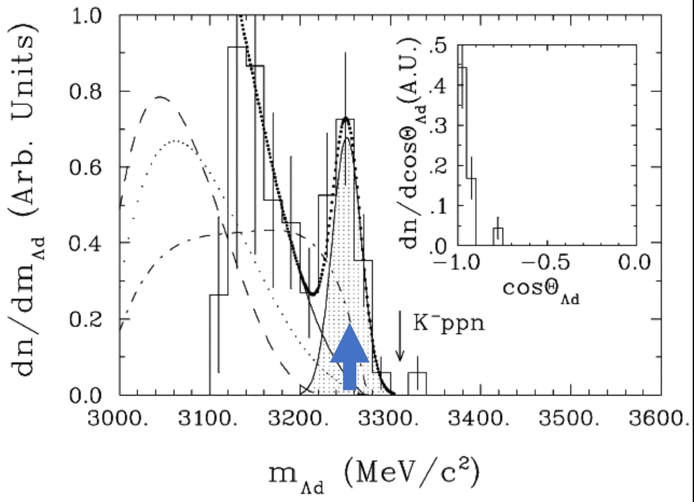
PLB659(2008)107, PLB688(2010)43,



PRC76(2007)068202

FINUDA@DAΦNE

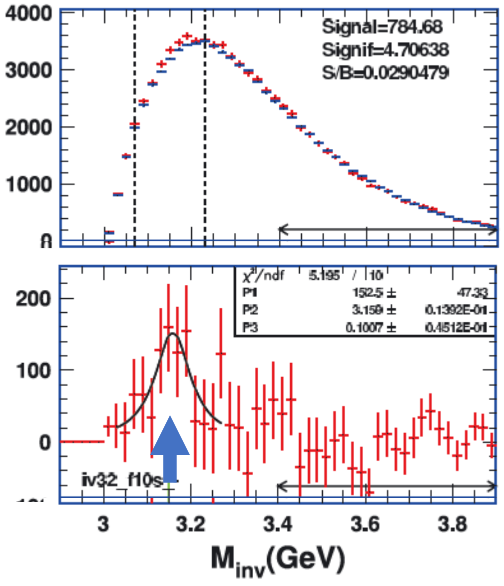
Li/C(stopped-K$^-$,Λd)



PLB654(2007)80

FOPI@GSI

Λd in Ni+Ni

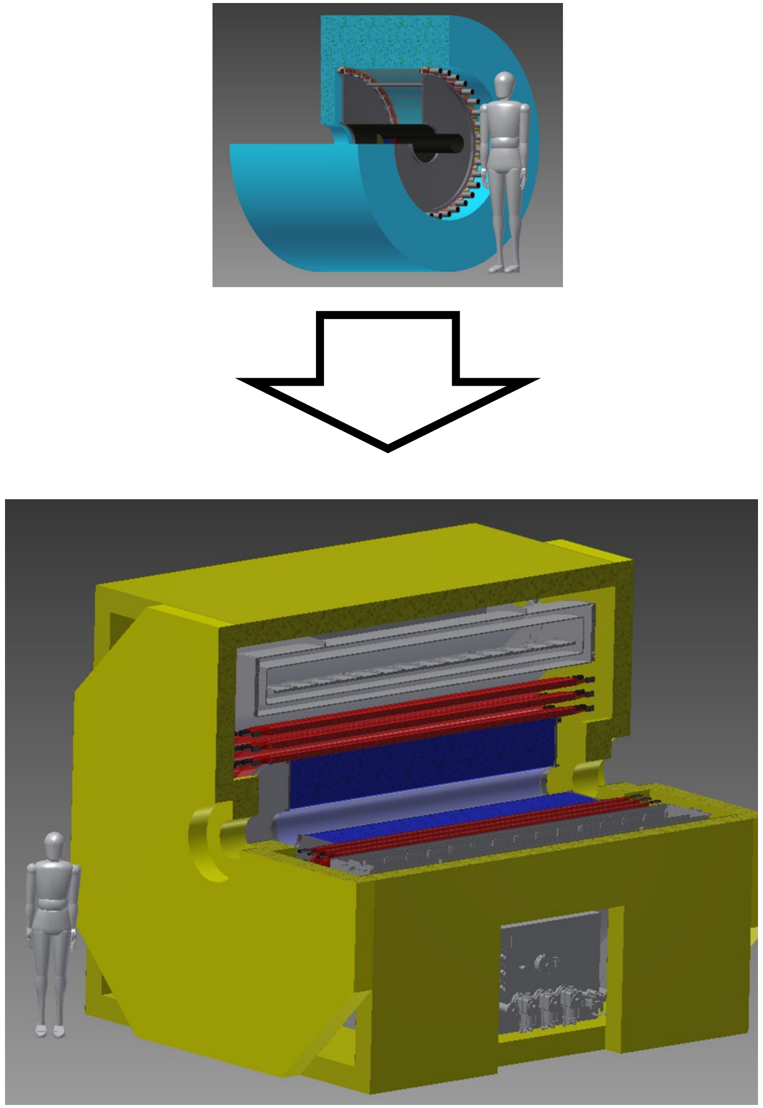


EXA05 Conference (2005)

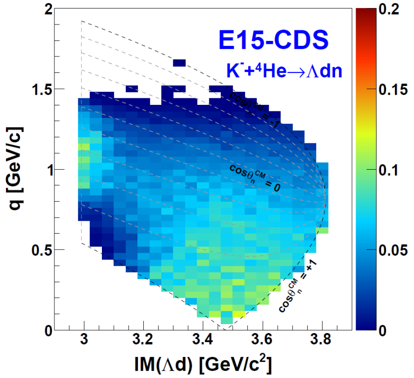
No conclusive results.

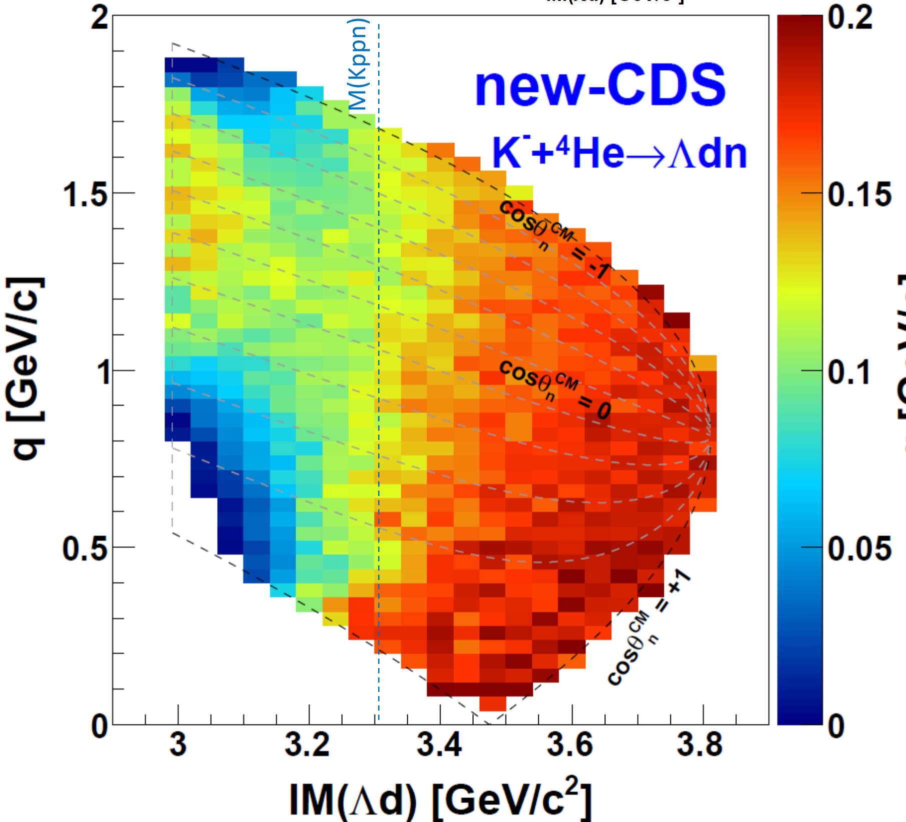
multi-N absorption in stopped-K reaction makes interpretation difficult

Acceptance for K^{-4}He reaction



Λd in CDS





Λpn in CDS