The 15th International Conference on Hypernuclear and Strange Particle Physics
September 29 to October 3, 2025, Tokyo

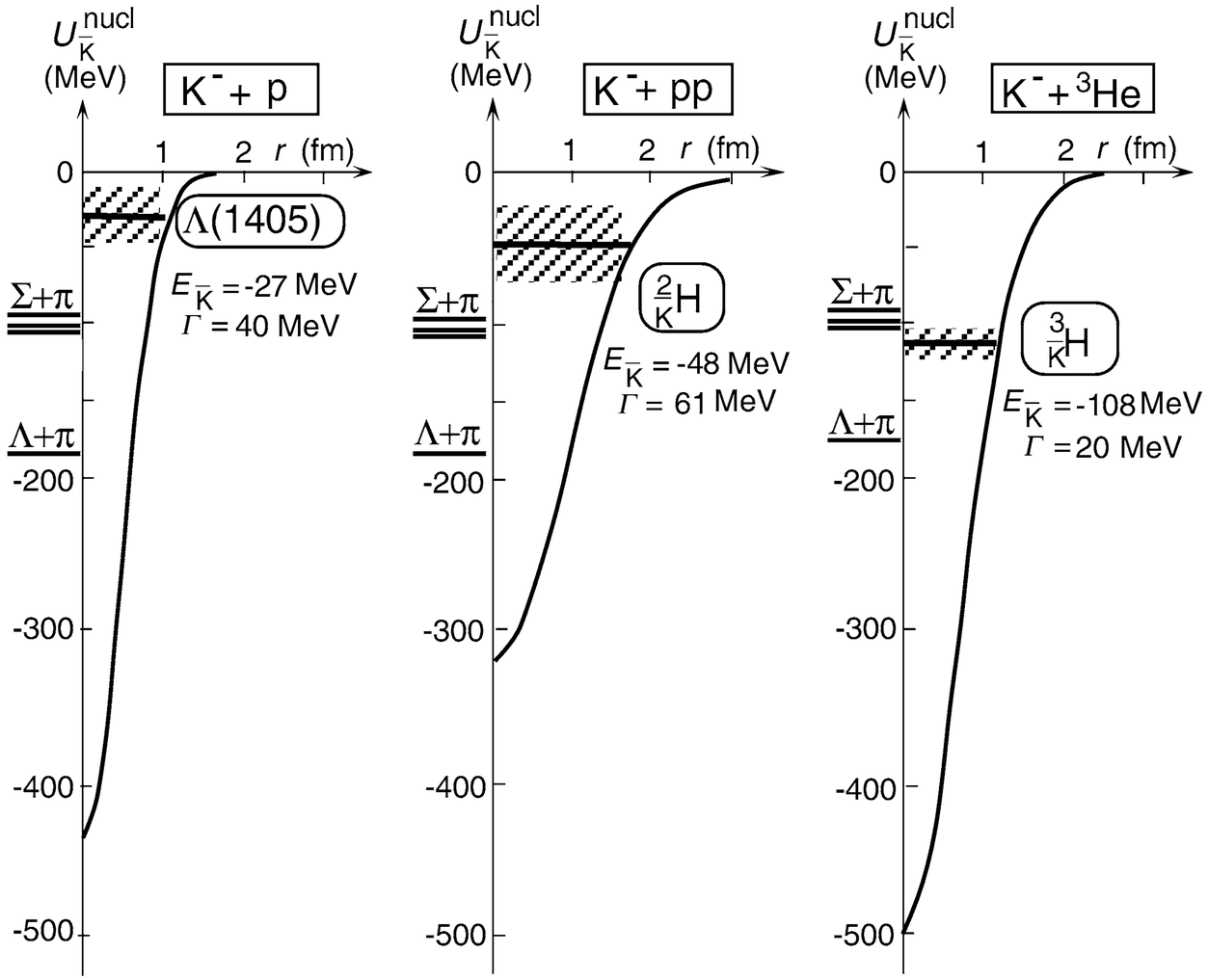
HYP2025 TOKYO

New era of kaonic nuclear states with solenoid-based spectrometers

Tadashi Hashimoto (RIKEN)
for J-PARC E15/E31/E73 + E80/E89 collaboration

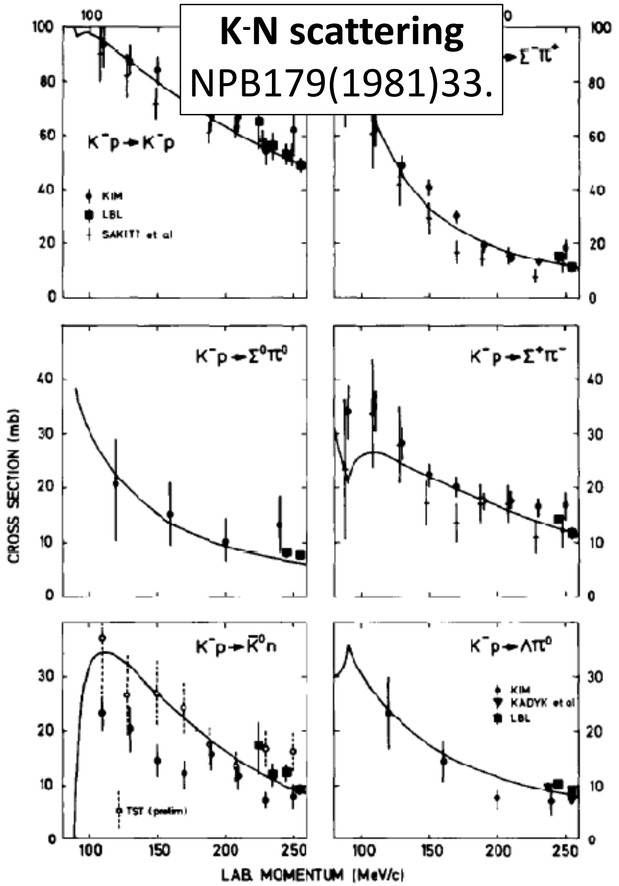
RIKEN PRI RIKEN NiSHiNA CENTER

Pioneering work by T. Yamazaki & Y. Akaishi



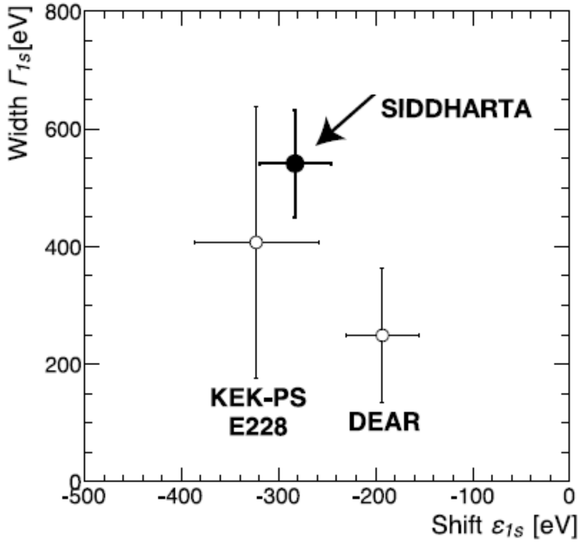
- "Λ(1405) anzats"
- Unique systems to study in-medium hadron properties
- Formation of dense nuclear medium $\rightarrow \bar{K}$ condensation
- Triggered many experimental and theoretical research, continuing to date

$K^{bar}N$ interaction

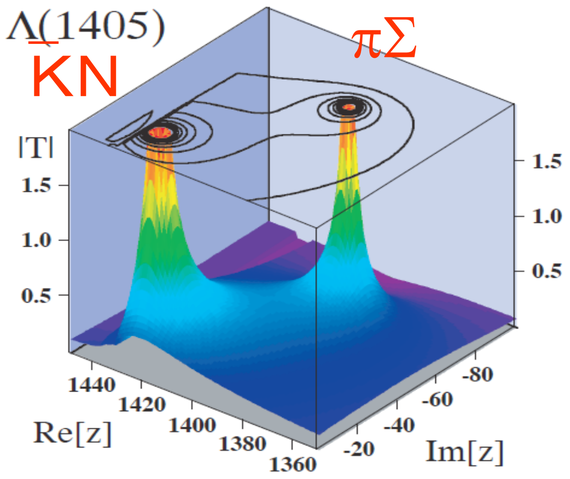


K-N scattering
NPB179(1981)33.

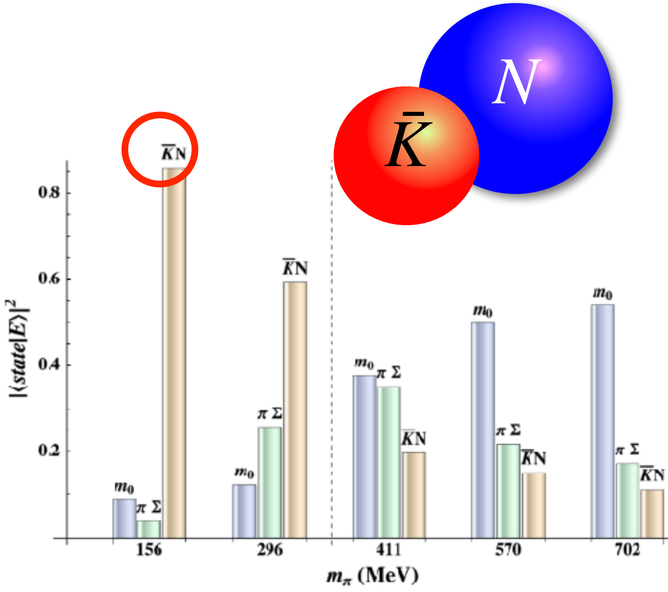
K-p atom
PLB704(2011)113.



Λ(1405) in
chiral unitary model
T. Hyodo



$K^{bar}N$ molecule from **Lattice QCD**
PRL114(2015)132002.

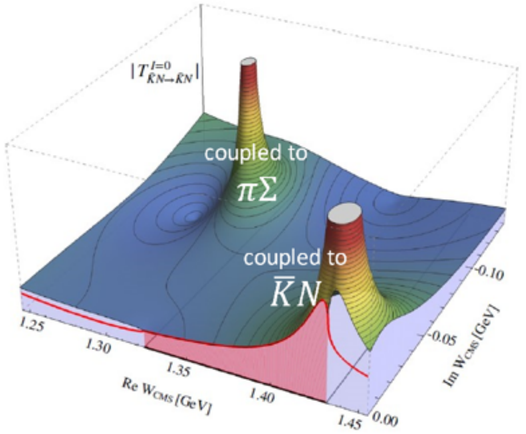


- Strong attraction in I=0 from scattering and X-ray experiements.
- $\Lambda(1405) = \bar{K}N$ molucle picture is now widely accepted

Theoretical calculations of K^{bar}NN $I(J^p) = \frac{1}{2}(0^-)$

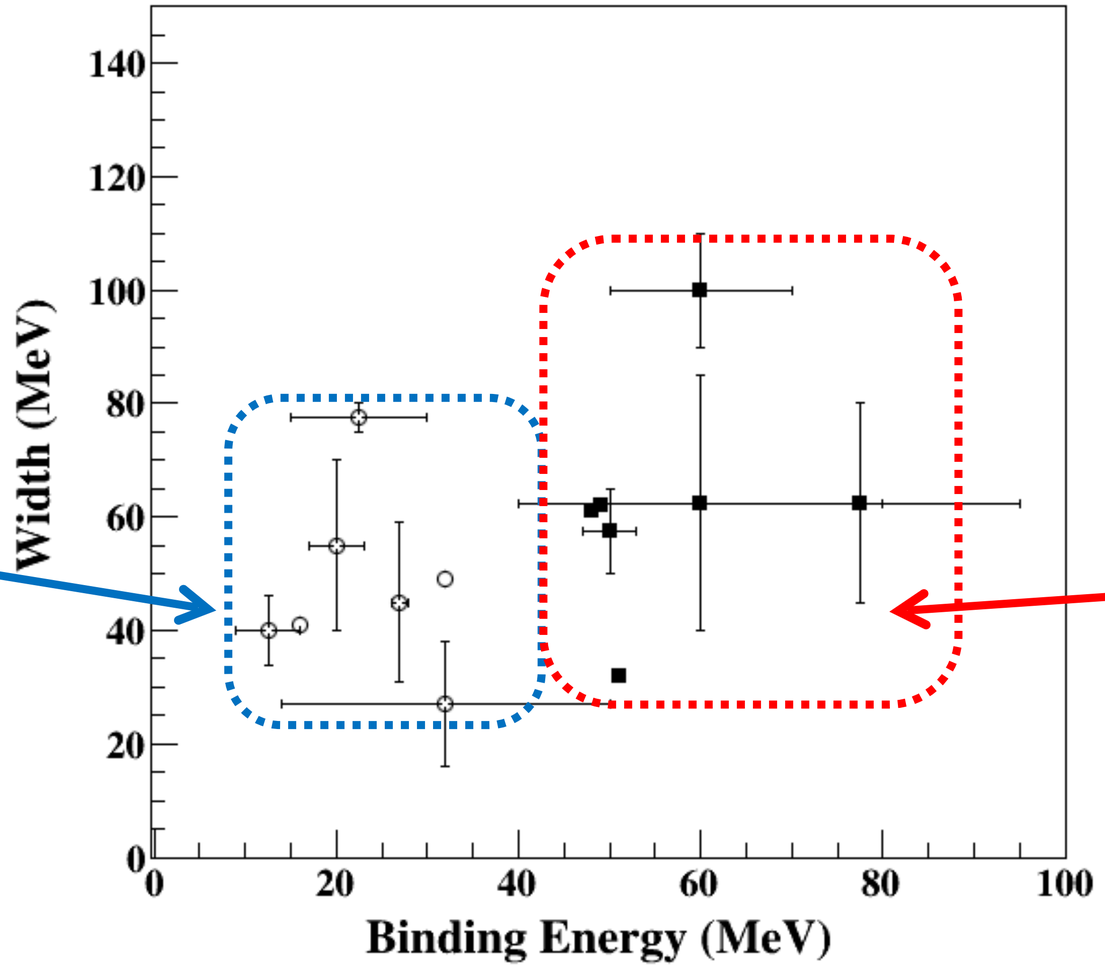
Chiral unitary model (energy dependent)

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



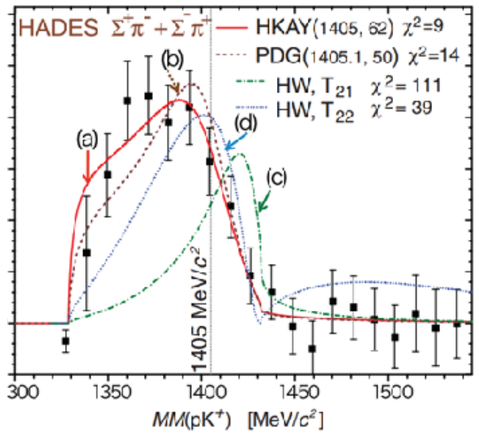
shallow $\bar{K}N$ potential

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

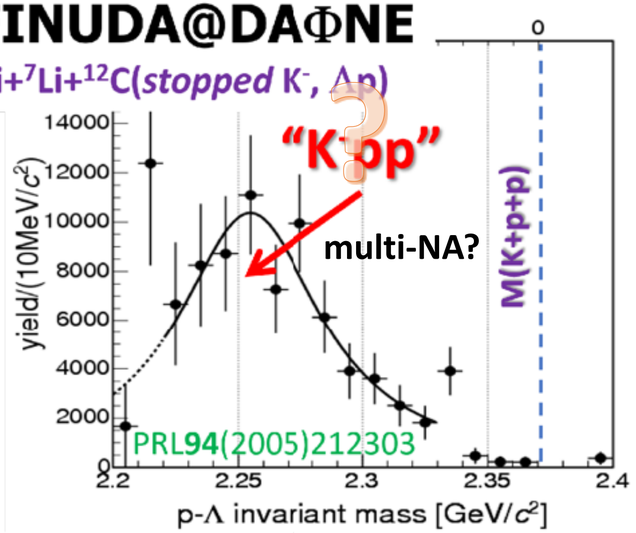
suggesting a more compact and dense system

- K^{bar}NN should exist. Then, how to produce and observe it?

“K⁻pp” searches

FINUDA@DAΦNE

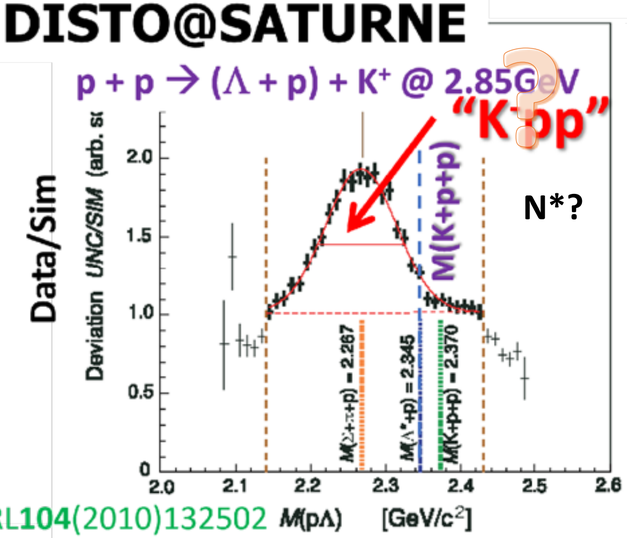
^{6}Li+^{7}Li+^{12}C(*stopped* K$^-$, Λp)



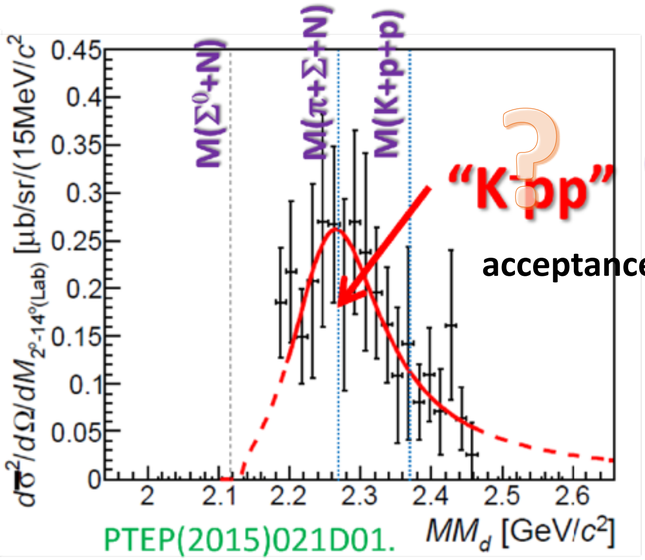
PRL**94**(2005)212303

DISTO@SATURNE

p + p → (Λ + p) + K⁺ @ 2.85GeV



PRL**104**(2010)132502



PTEP(2015)021D01.

E27@J-PARC

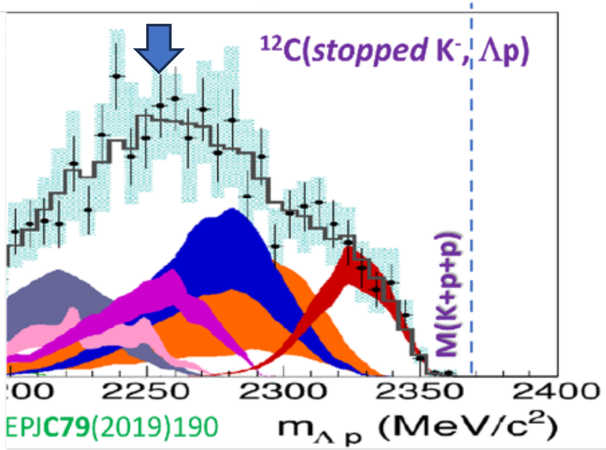
d(π⁺, K⁺)Σ⁰p @ 1.69 GeV/c

LEPS@SPring-8

d(γ, K⁺π⁻)X @ 1.3-2.4 GeV/c

PLB728(2014)616.

AMADEUS@DAΦNE

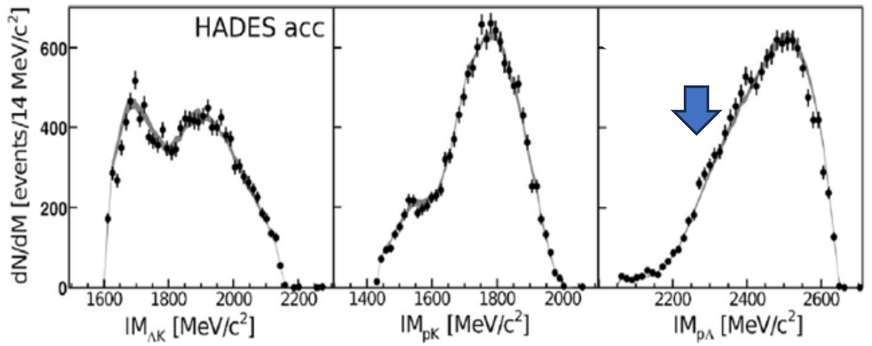


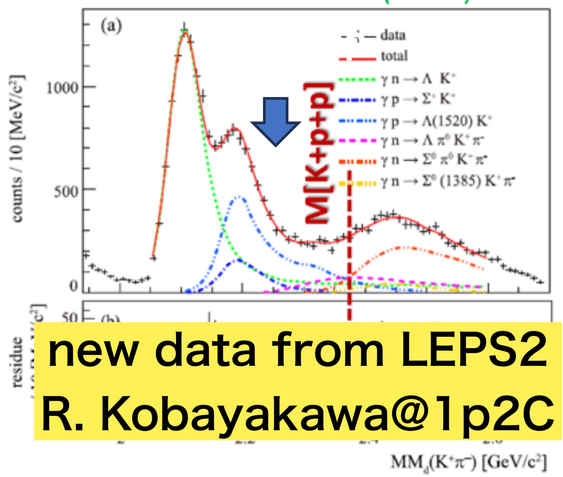
EPJ**C79**(2019)190

HADES@GSI

PL**B742**(2015)242

p + p → (Λ + p) + K⁺ @ 3.5GeV





new data from LEPS2

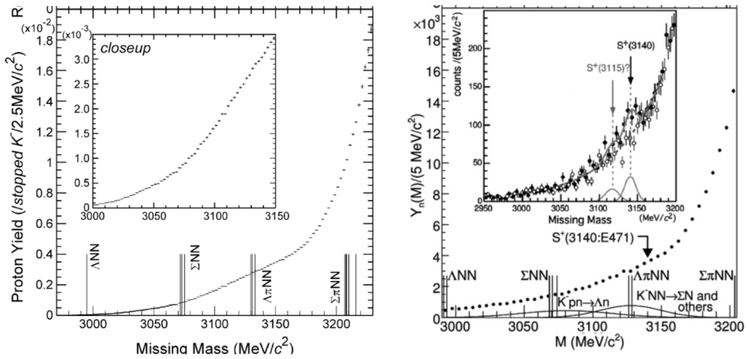
R. Kobayakawa@1p2C

- No conclusive result because of complex reactions & background…

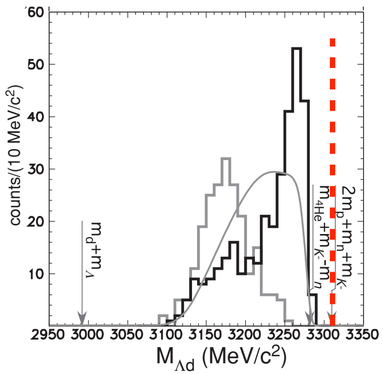
$\bar{K}NNN$: Experimental situation

Stopped K^- on ^{4}He

E549@KEK



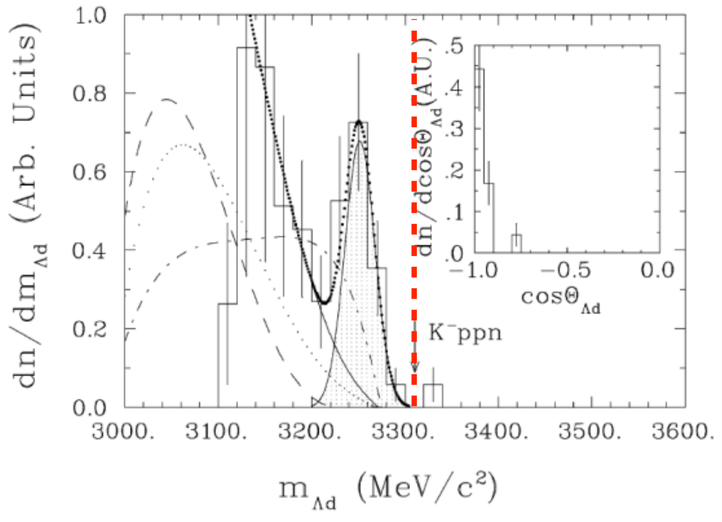
PLB659(2008)107, PLB688(2010)43



PRC76(2007)068202

Stopped K^- on Li/C back-to-back Λd

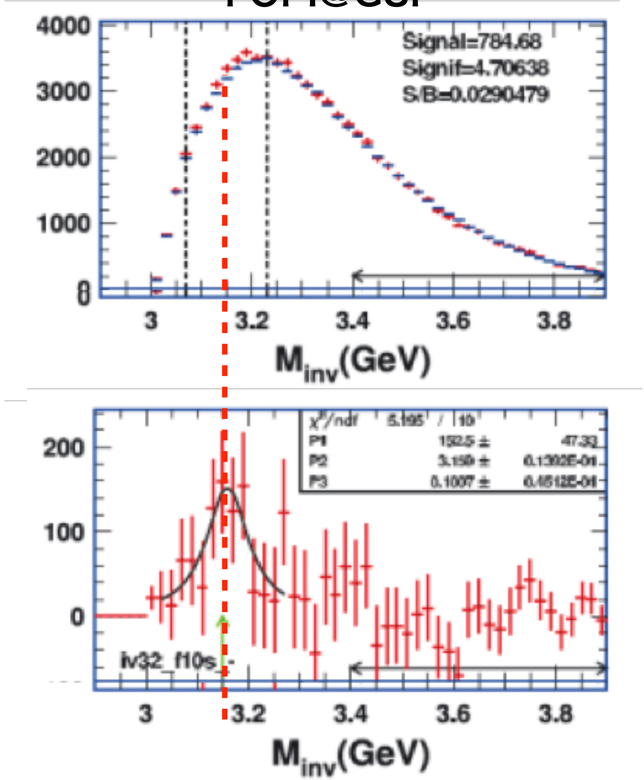
FUNUDA@DAΦNE



PLB654(2007)80

Λd in Ni+Ni

FOPI@GSI

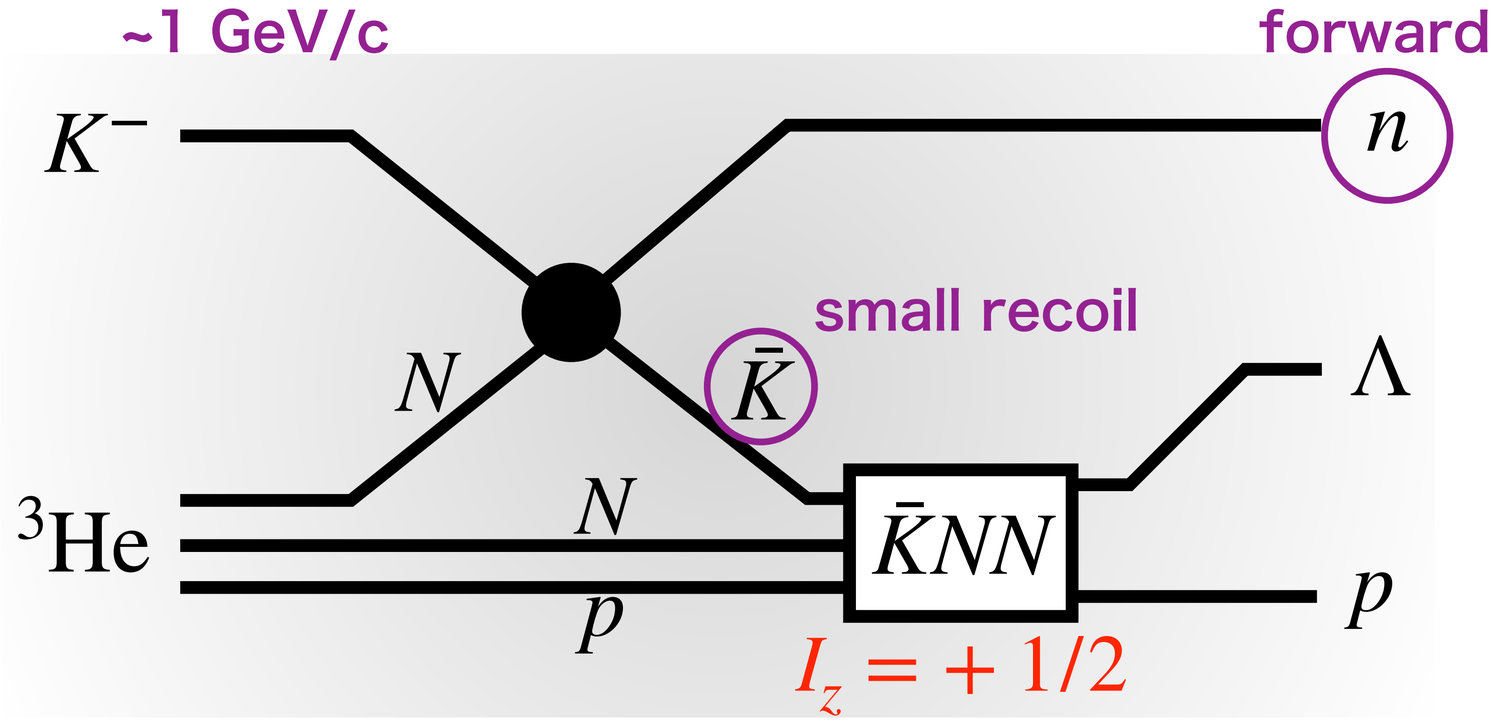


EXA05 Proceedings (2005)

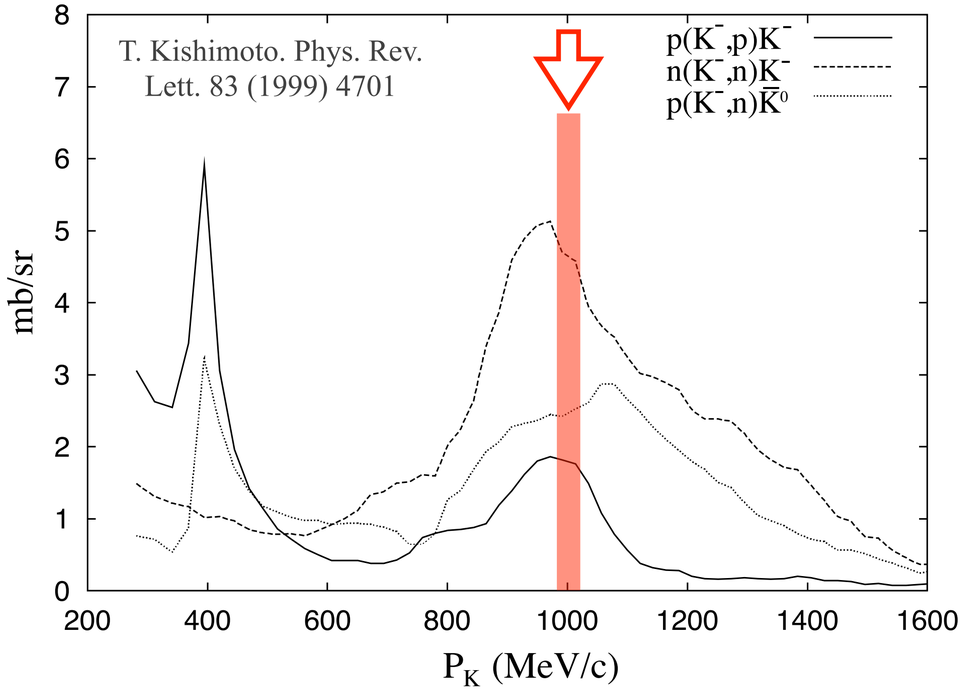
- Some experimental searches in 2000s. No conclusive result.
- multi-N absorptions hide bound-state signals in Stop-K

Our approach: in-flight (K^-, n) reaction

T. Kishimoto, Phys. Rev. Lett. **83**, 4701 (1999).



K^-N elementaly cross-sections

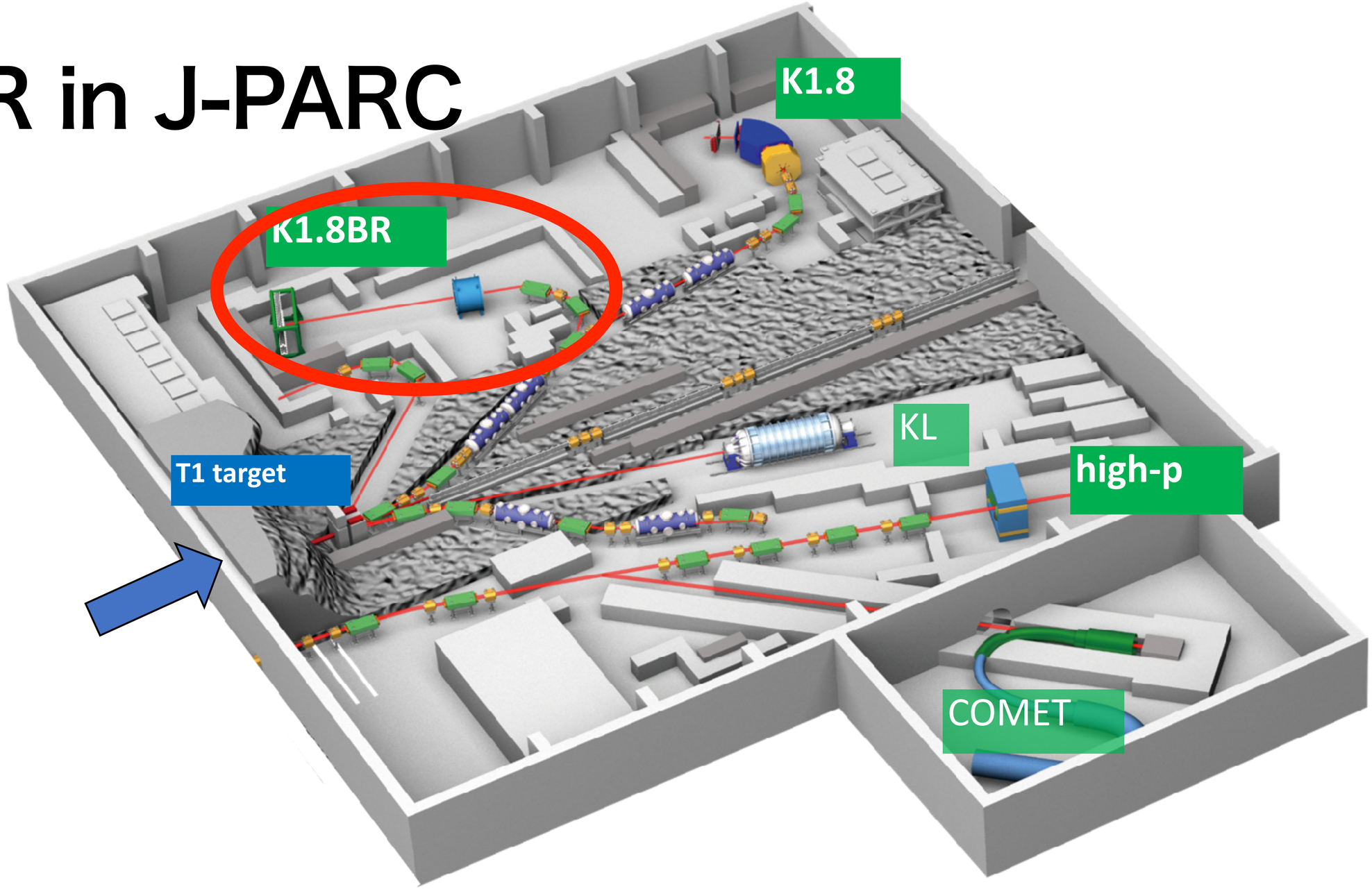


✓ Effectively produce sub-threshold virtual $\bar{K}$

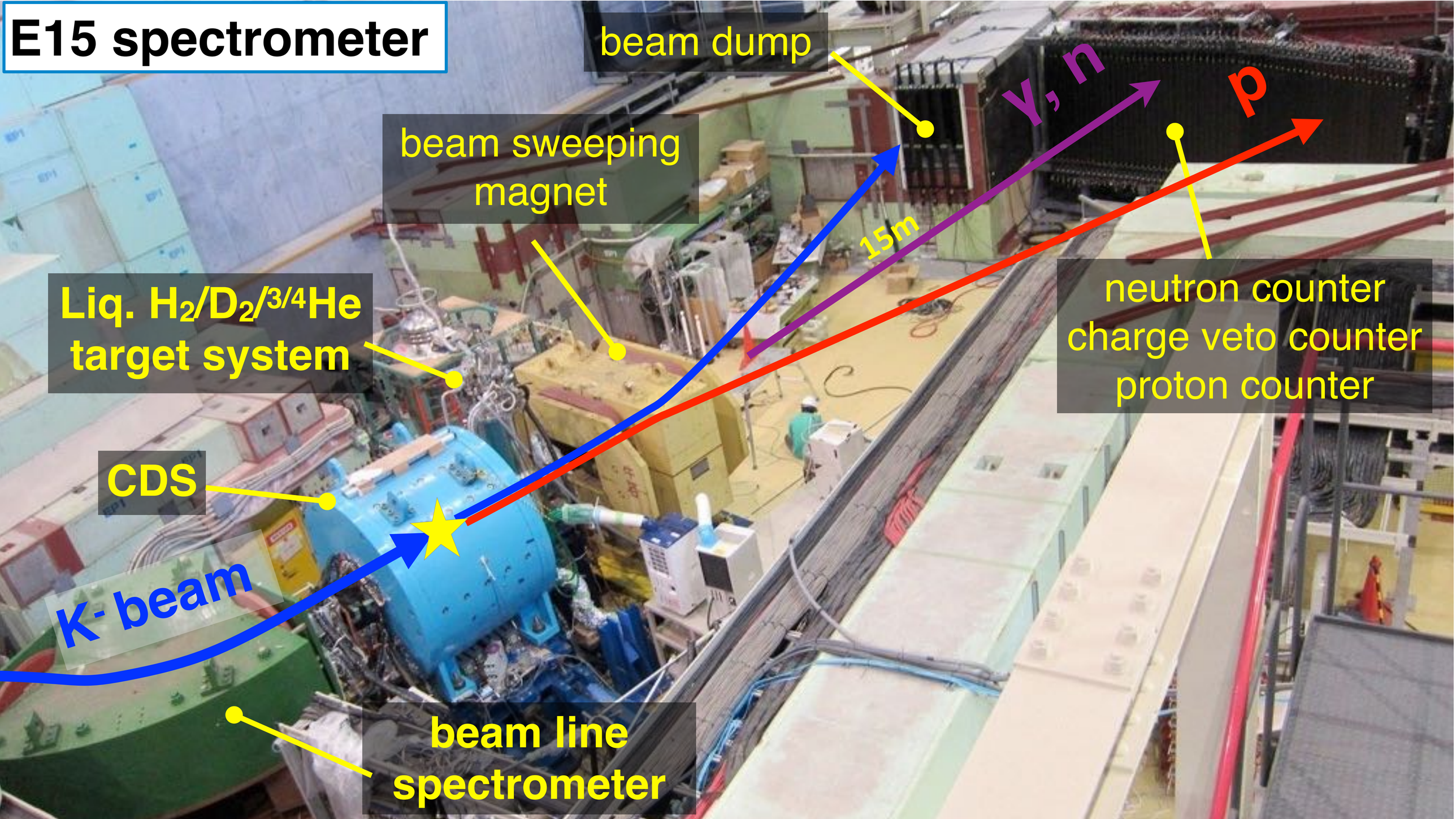
✓ Simplest target allows an exclusive analysis

✓ Large-acceptance detector to cover a wide range of kinematical region

K1.8BR in J-PARC



K1.8BR suitable for low-energy K^- beam below 1 GeV/c


E15 spectrometer
beam dump
beam sweeping magnet
Liq. H2/D2/3/4He target system
CDS
K- beam
beam line spectrometer
y, n
p
15m
neutron counter
charge veto counter
proton counter

Experiments with E15-CDS

- 2012: Completed the construction **[PTEP 02B011(2012)]**
- 2013: **E15** 1st, **"K-pp"** search.
  [PTEP 061D01 (2015), PTEP, 051D01 (2016)]
- 2015: **E15** 2nd, **"K-pp"** search
  [PLB789, 620 (2019), PRC102, 044002 (2020), PRC10, 014002 (2024)]

$K^- + {}^3\mathrm{He} \to K^- pp + n$

- 2018: **E31**, **Λ(1405)**
  [PLB837,137637(2023) + 2 in preparation]

$K^- + d \to \Lambda(1405) + n$

- 2020: **T77**, ${}^4_\Lambda\mathrm{H}$ lifetime, (**"K-ppn"** search)
  [PLB485, 138128 (2023) + 1 in preparation]

$K^- + {}^4\mathrm{He} \to {}^4_\Lambda\mathrm{H} + \pi^0$

$(K^- + {}^4\mathrm{He} \to K^- ppn + n)$

- 2021: **E73** 1st, ${}^3_\Lambda\mathrm{H}$ production cross section
  [arXiv:2509.16967]

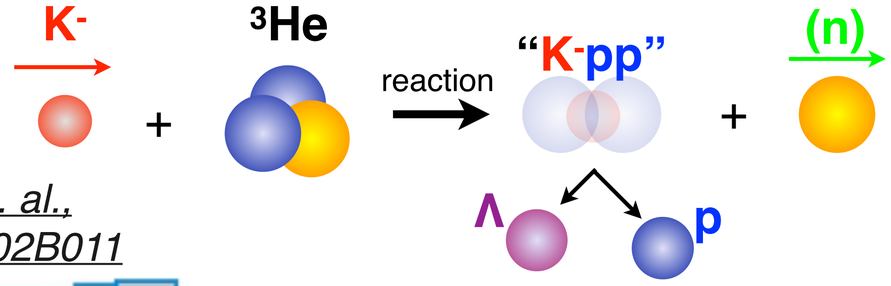
Y. Ma@30p1A
T. Akaishi@poster

$K^- + {}^3\mathrm{He} \to {}^3_\Lambda\mathrm{H} + \pi^0$

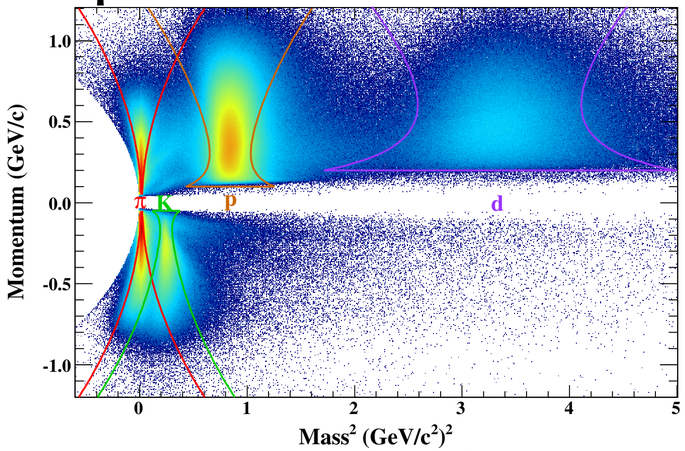
- 2024~2025: **E73** 2nd, ${}^3_\Lambda\mathrm{H}$ lifetime, (**"K-pp"** study)
  [>3 publications expected]

$(K^- + {}^3\mathrm{He} \to K^- pp + n)$

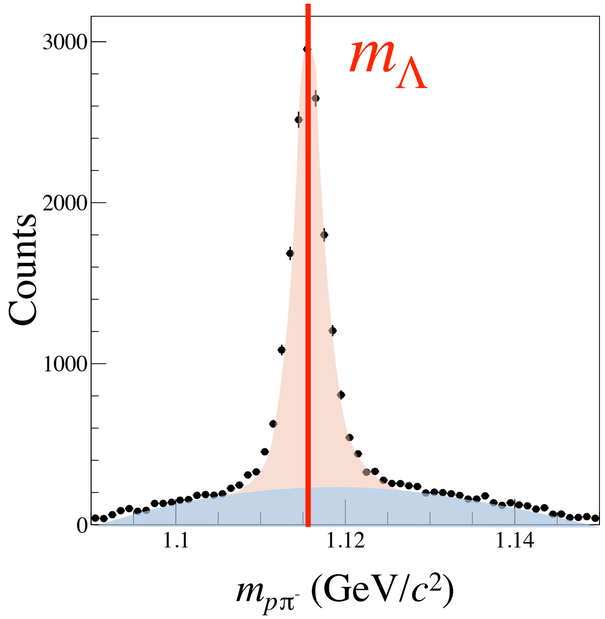
Λpn Exclusive measurement

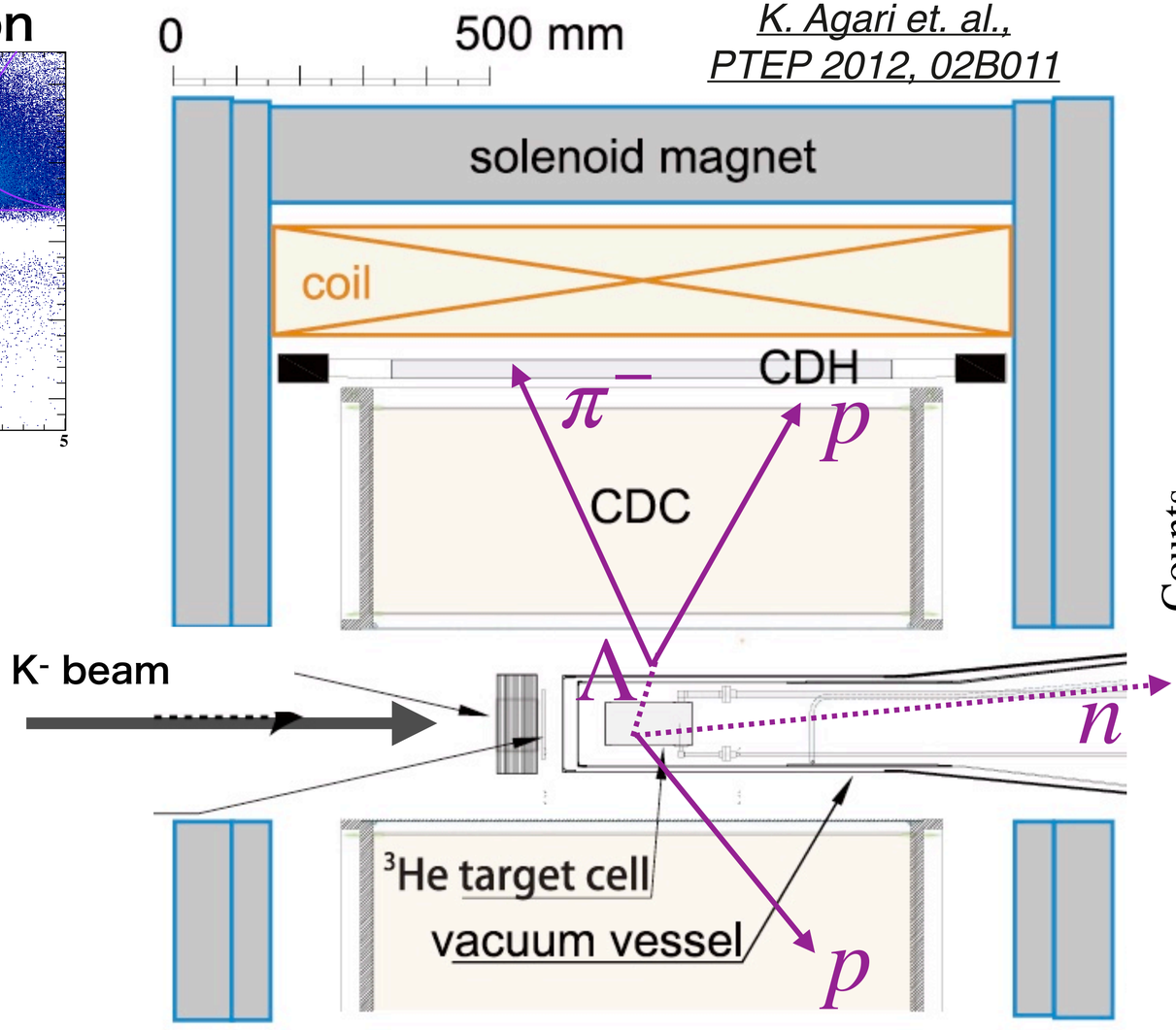


particle identification



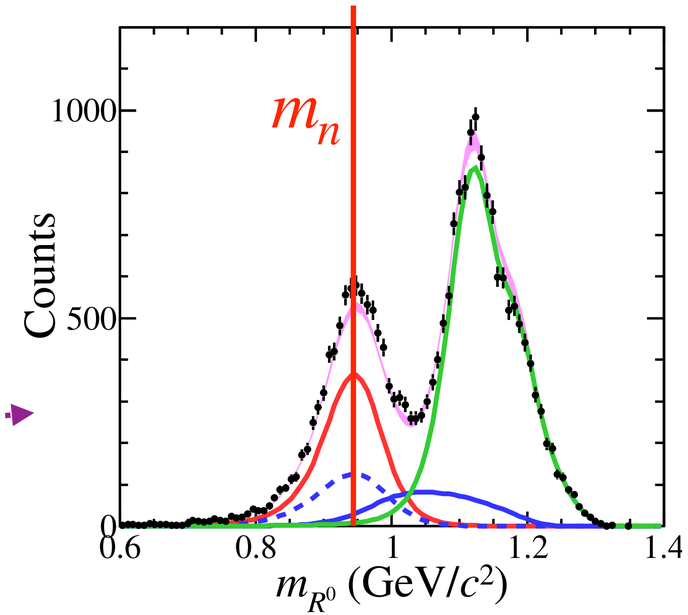
Λ reconstruction





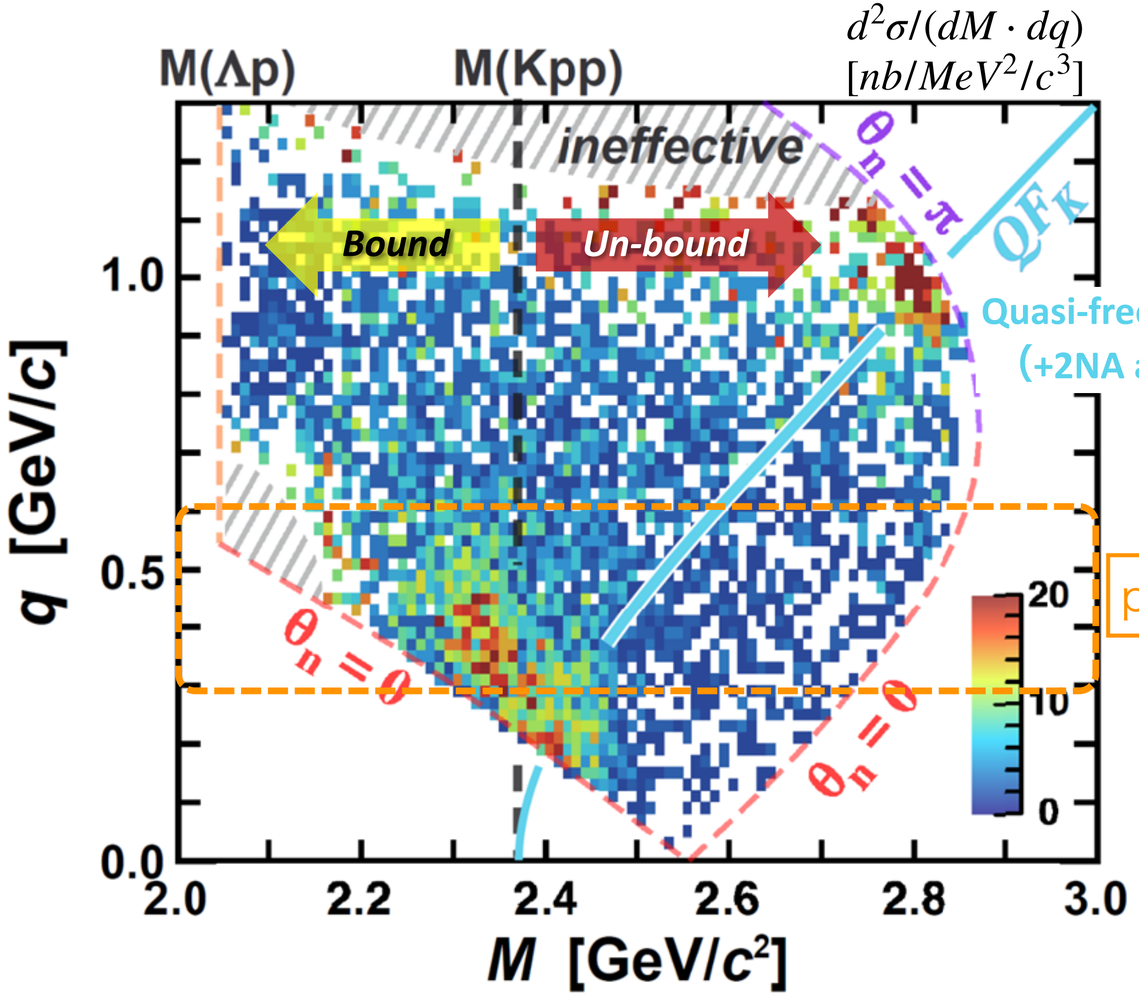
K. Agari et. al., PTEP 2012, 02B011

missing neutron selection



Purity of Λpn events ~ 80%

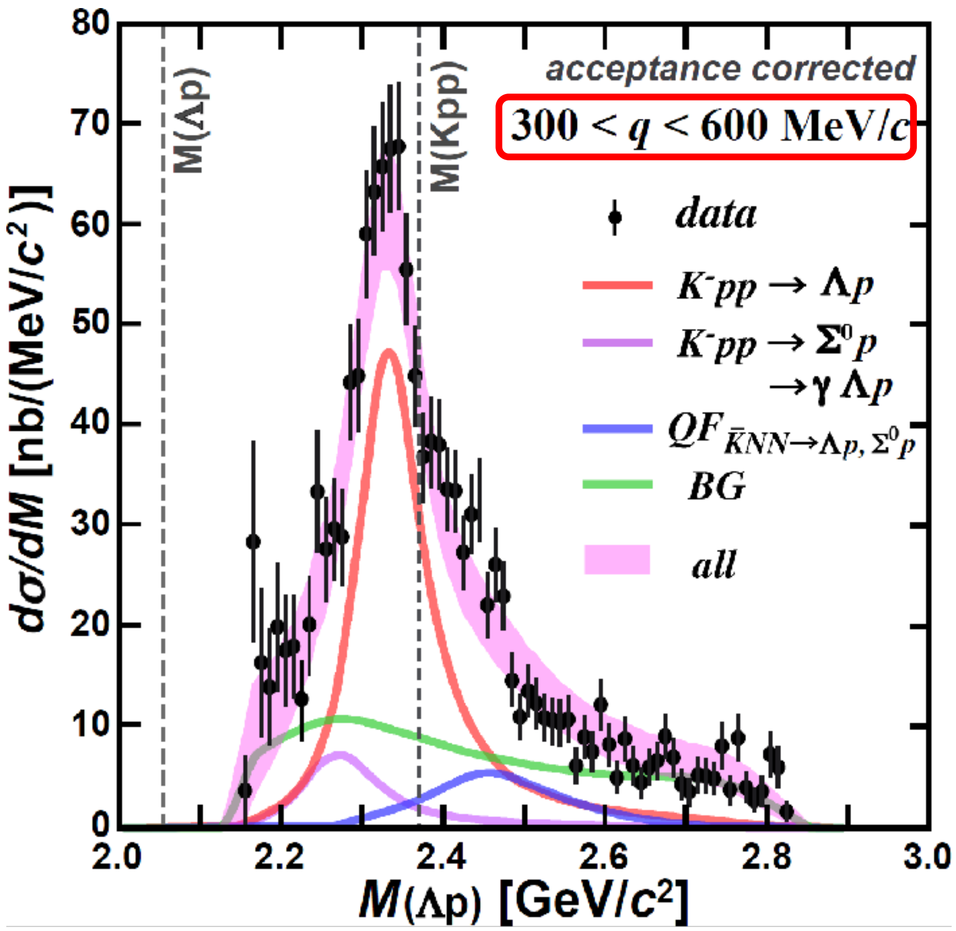
“K-pp” observation in J-PARC E15



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

projection

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

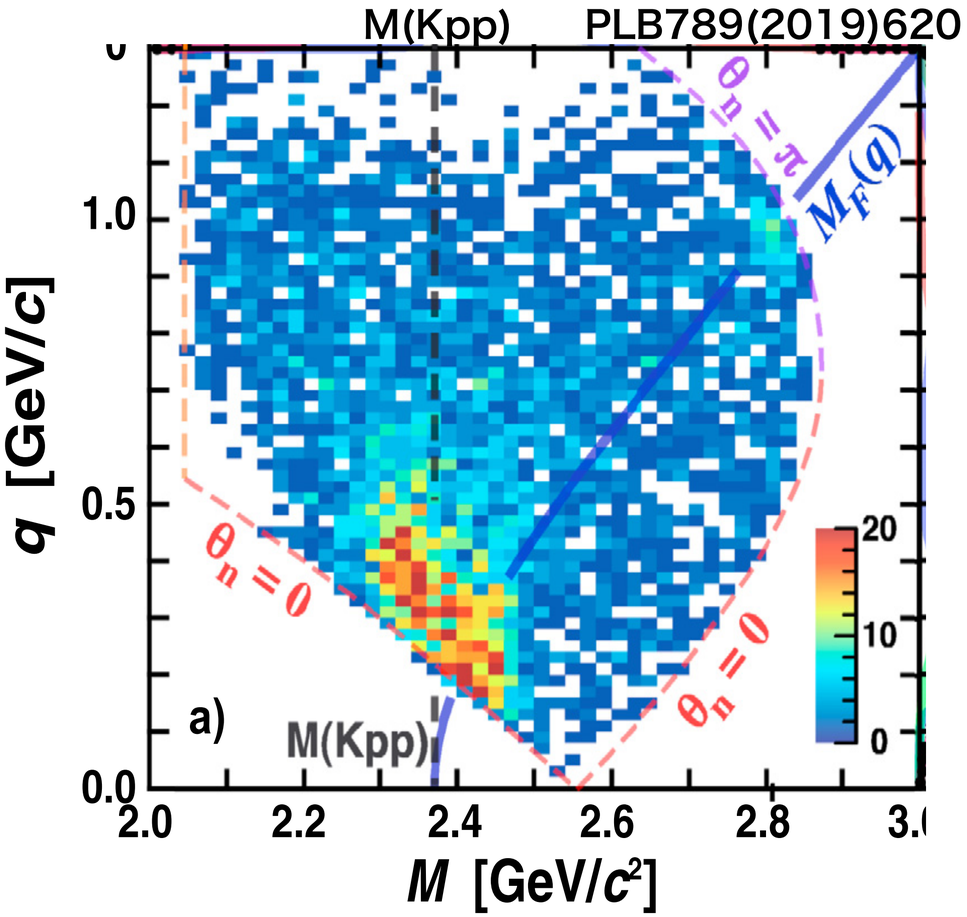


q : (K^-,n) momentum transfer, ***M*** : Λp invariant mass

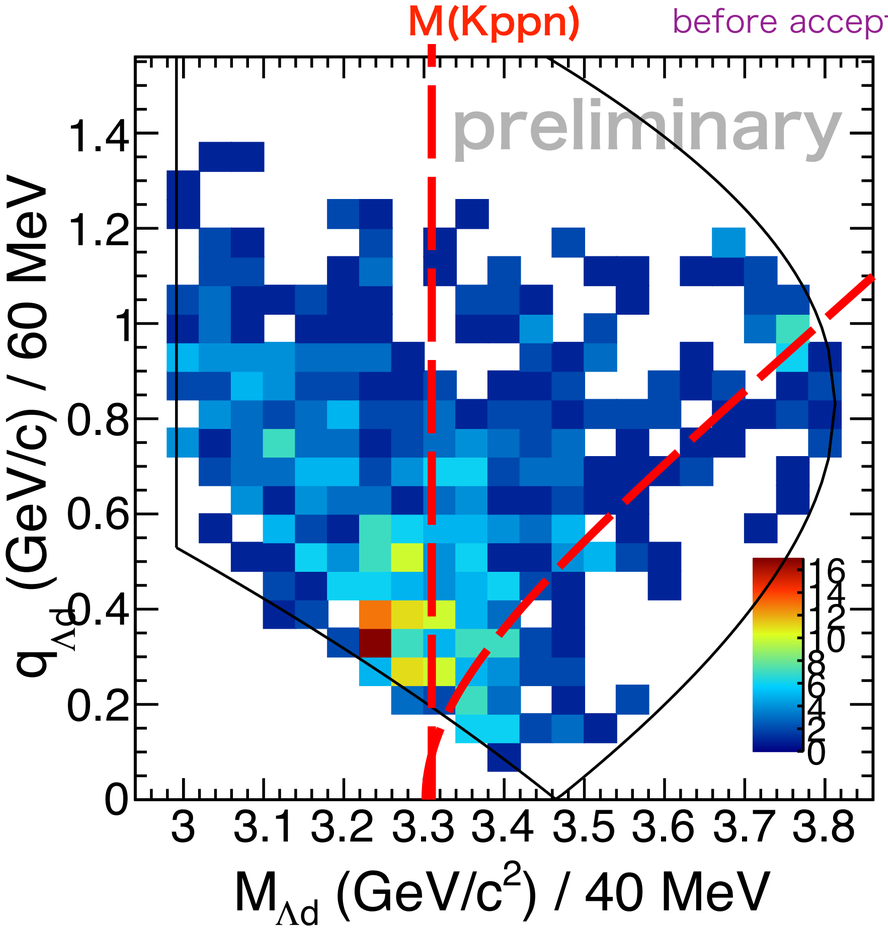
Deep biding (B.E. ~ 40 MeV), Large decay width (Γ~ 100 MeV), Large momentum transfer

Λd analysis with the ^{4}He target

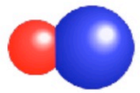
E15: $K^- + {}^3\mathrm{He} \rightarrow \boldsymbol{\Lambda p} + n_f\ (\sim 42 \times 10^9\ K^-)$



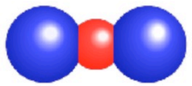
T77: $K^- + {}^4\mathrm{He} \rightarrow \boldsymbol{\Lambda d} + n_f\ (\sim 6 \times 10^9\ K^-)$



- Similar distribution as ^{3}He data. Publication coming soon with x3 ^{4}He data.



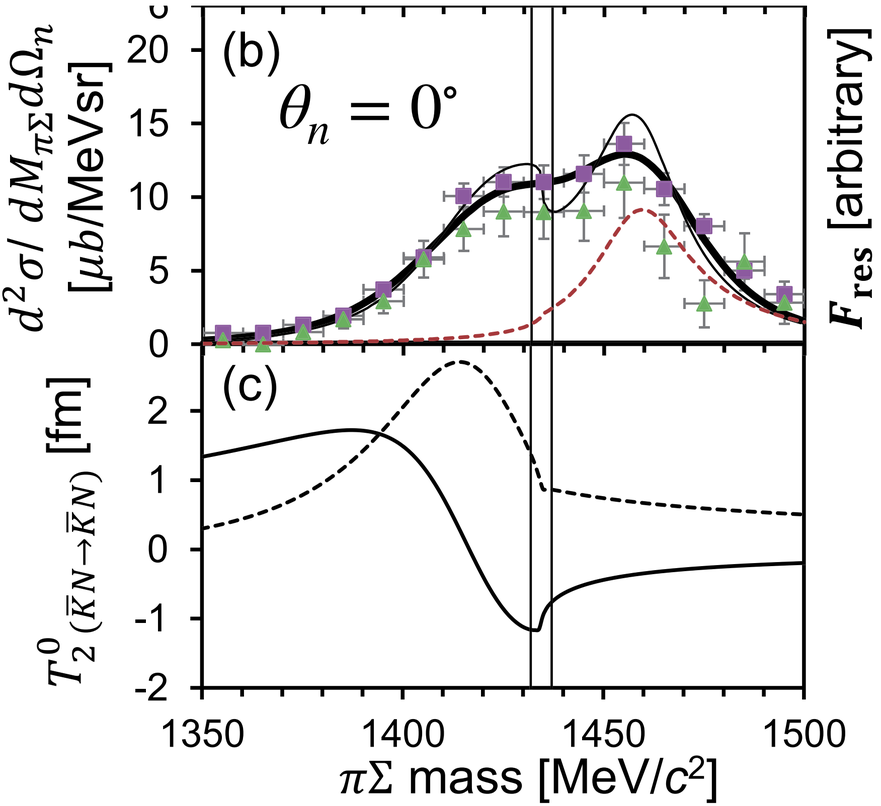
K⁻p



K⁻pp

K⁻ppn

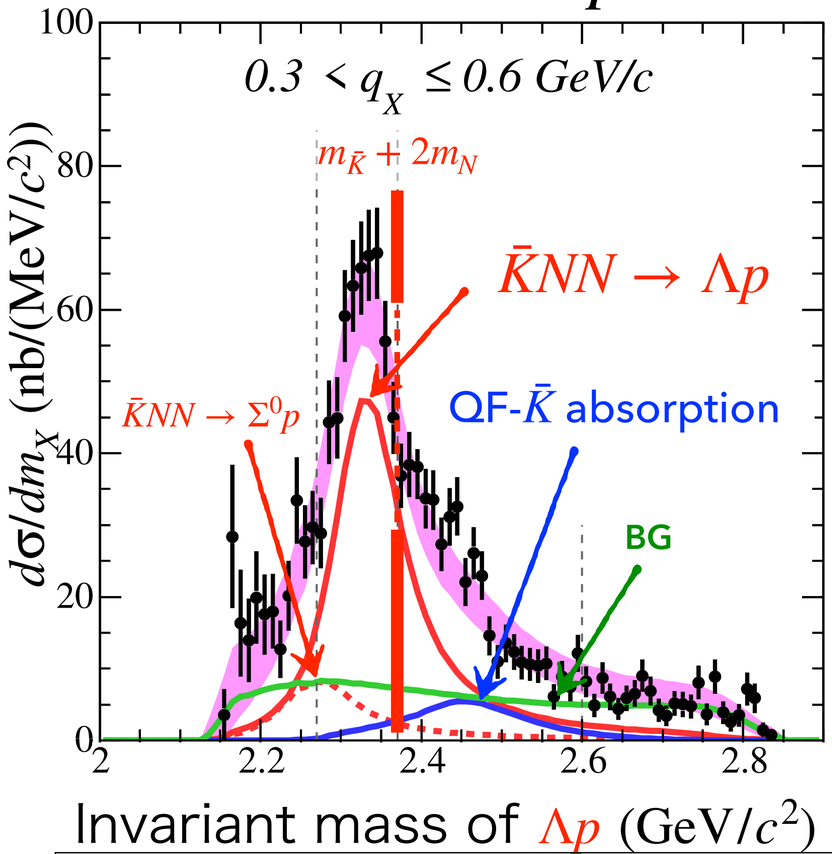
$$K^- + d \to \pi\Sigma + n_f$$



With two-step reaction processes
S-wave $\bar{K}N$ amplitude (I=0) was deduced
pole: 1417.7 – 26.1i [MeV]

PLB 736, 137637 (2023)

$$K^- + {}^3\mathrm{He} \to \Lambda p + n$$



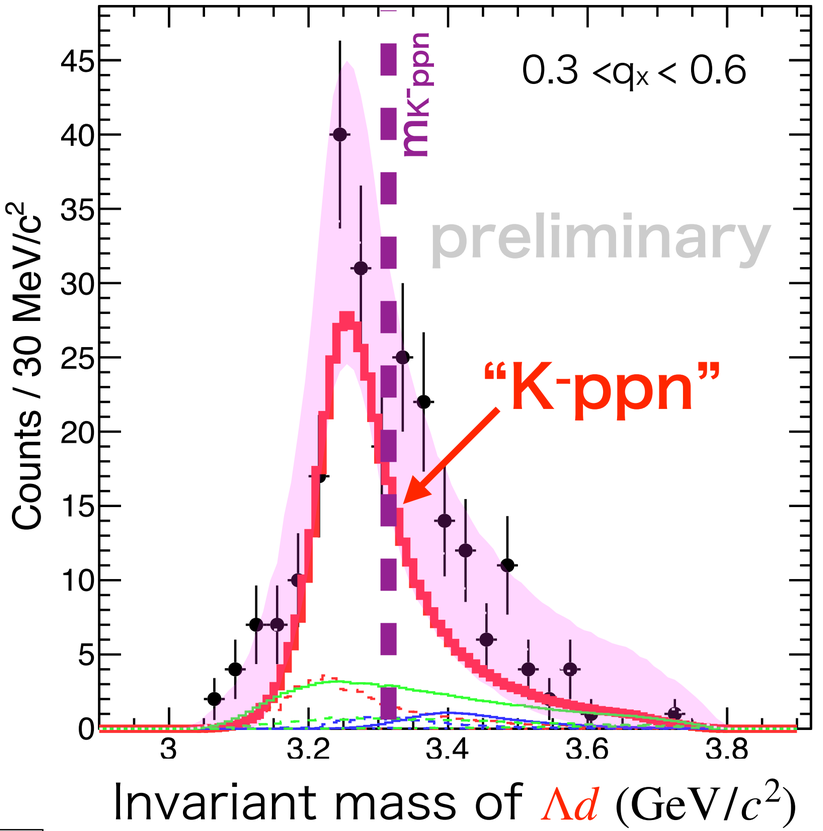
$B_{\bar{K}NN} = 42 \pm 3$ (stat.) $^{+3}_{-4}$ (syst.) MeV

$\Gamma_{\bar{K}NN} = 100 \pm 7$ (stat.) $^{+19}_{-9}$ (syst.) MeV

$\sigma_{\bar{K}NN\to\Lambda p} = 9.3 \pm 0.8$ (stat.) $^{+1.4}_{-1.0}$ (syst.) μb

PRC102, 044002 (2020).

$$K^- + {}^4\mathrm{He} \to \Lambda d + n$$



$B_{\bar{K}NNN} \sim 60 \pm 11$(stat) MeV

$\Gamma_{\bar{K}NNN} \sim 100$ MeV

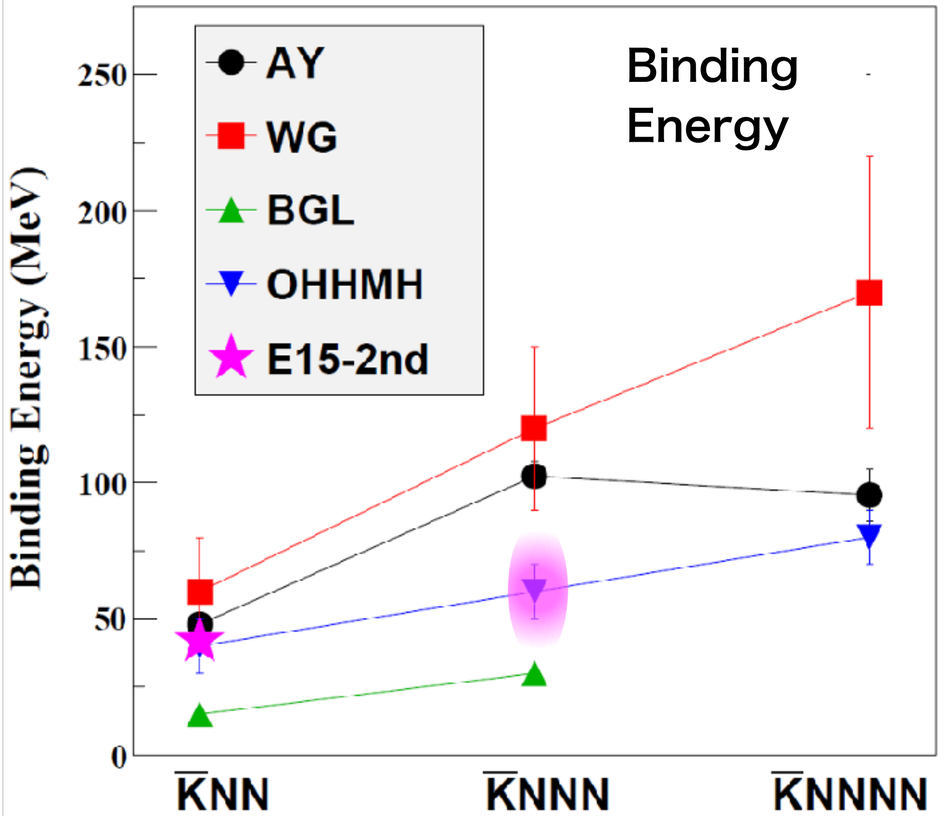
$\sigma_{\bar{K}NNN\to\Lambda d} \sim 4\ \mu$b

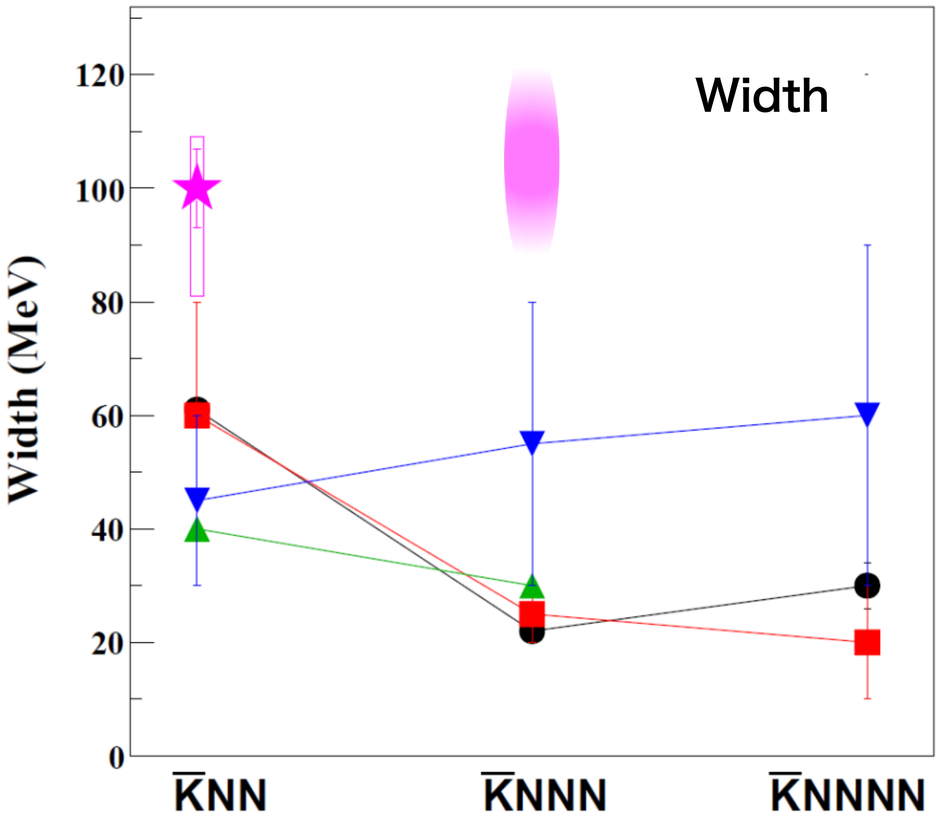
$I(J^p) = 0(1/2^-)$ with high certainty

Preliminary results

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

T77 preliminary



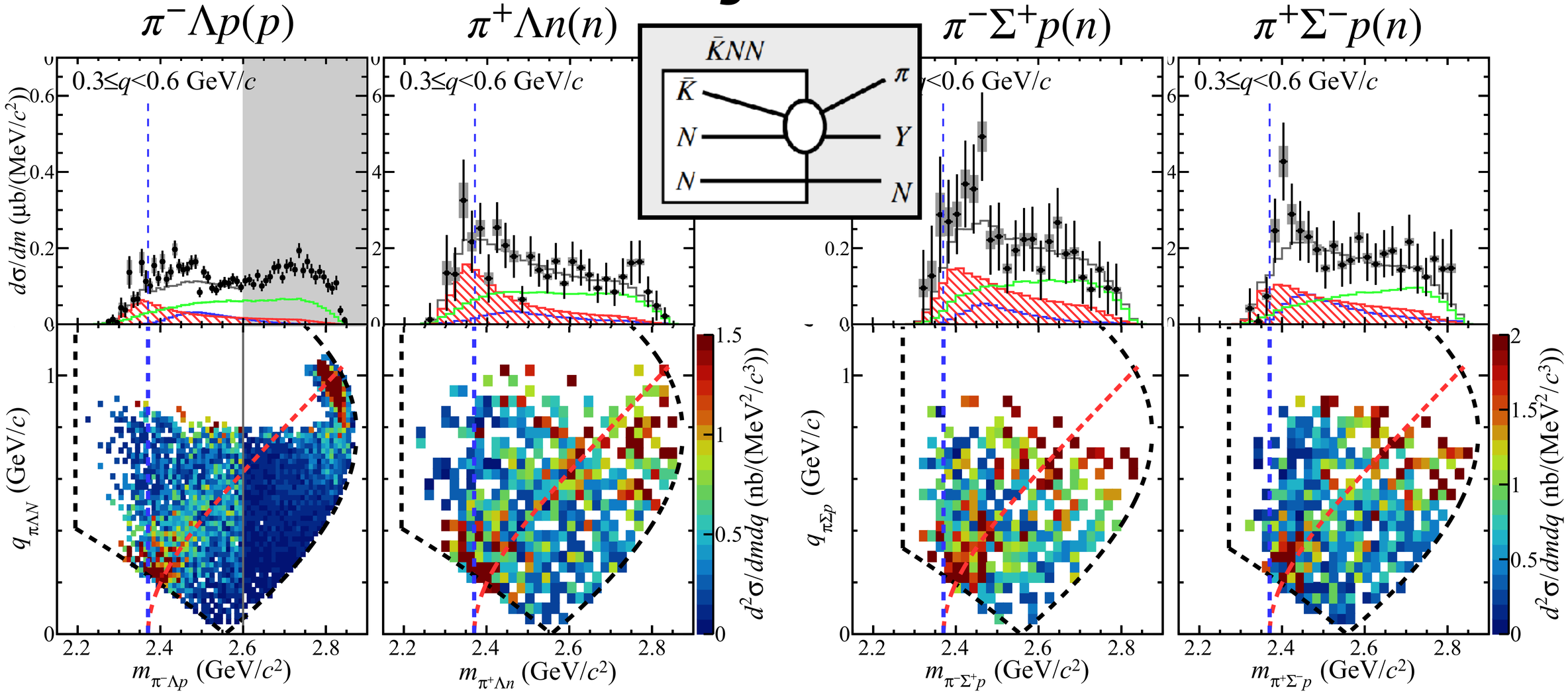


- The binding energy is compatible with some theoretical predictions
- "$\bar{K}NNN$" system might have larger binding than "$\bar{K}NN$".
- Experimental width is larger than theoretical predictions.

New calculation result
N. Shevchenko@1p2C

$\bar{K}NN$ mesonic decay

T. Yamaga et al., PRC 110, 014002 (2024)



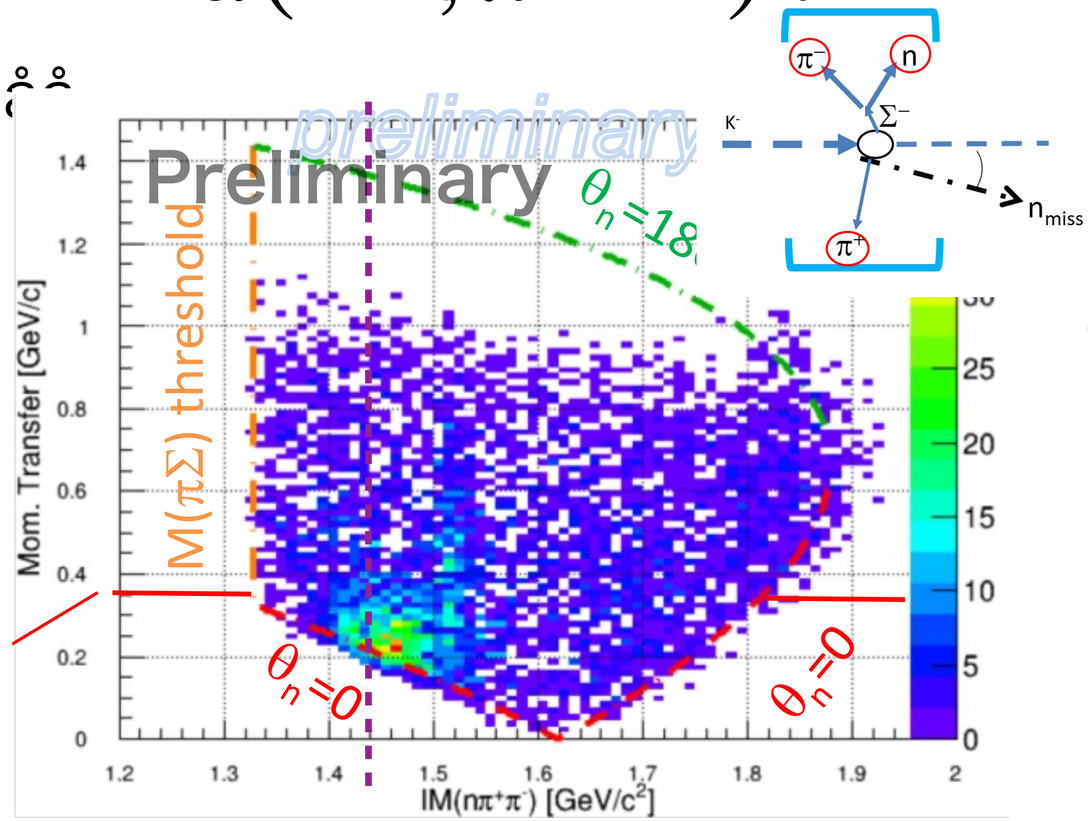
- Consistently interpreted with the "$\bar{K}NN$" component obtained in the Λp channel.
- $\Gamma_{\text{mesonic}} \gg \Gamma_{\text{non-mesonic}}$

although phase-space and acceptance are limited…

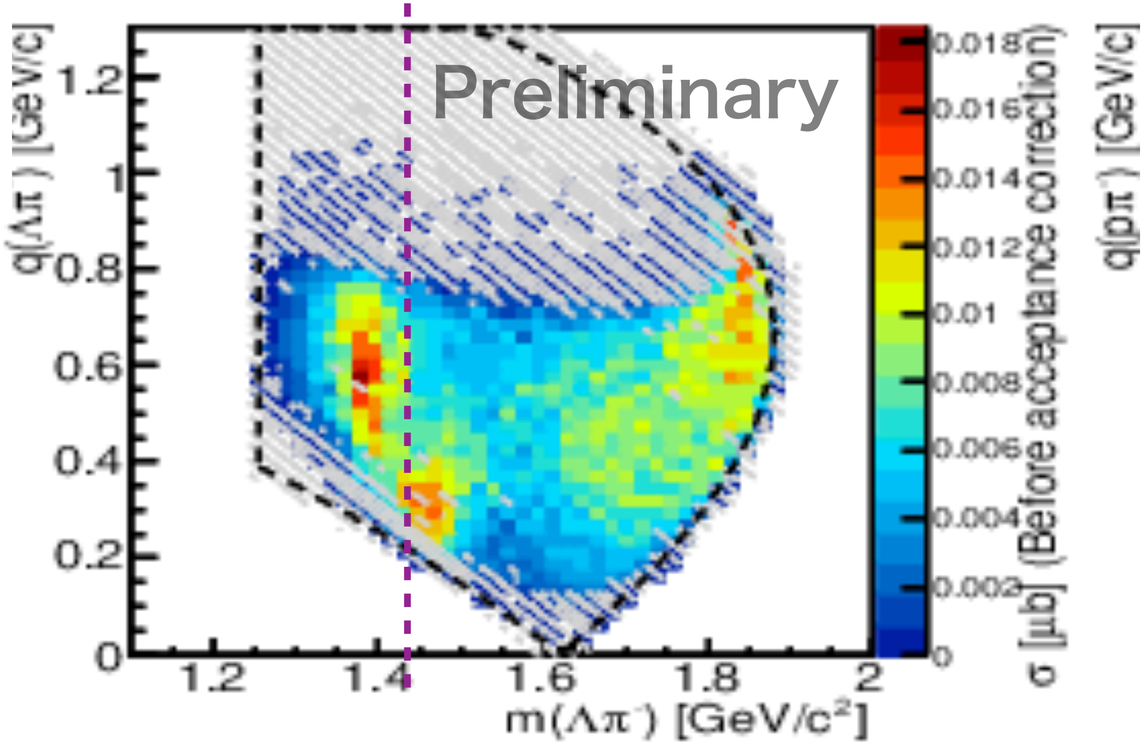
Λ^*/Σ^* production in $d(K^-, N)$

R. Murayama@1p2C

$d(K^-, \pi^{\pm}\Sigma^{\mp})n$



$d(K^-, \pi\Lambda)p$



- Interesting to compare the q-dependence (angular distribution)
- Isospin-dependence can be investigated.

E15-CDS experiments 2012~2025

Established the existence of Kaonic nuclei and the production method via (K^-, N)

What is next?

Confirmation of "K^-ppn" → J-PARC E80

Further investigation of the $\bar{K}NN$ system → J-PARC E89

Quantum number, Spatial size, heavier system, double $\bar{K}$ nuclei…

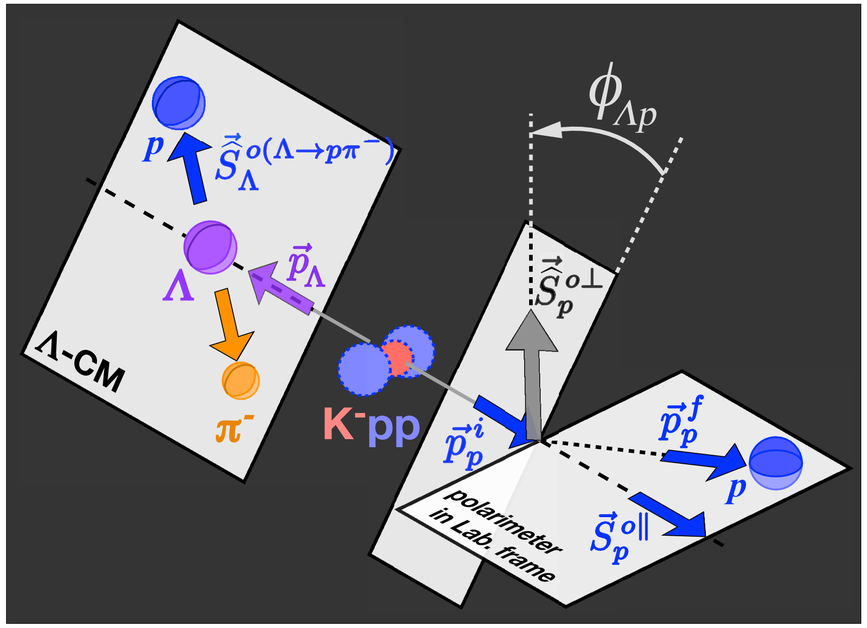
Is the observed state really $\bar{K}NN$?

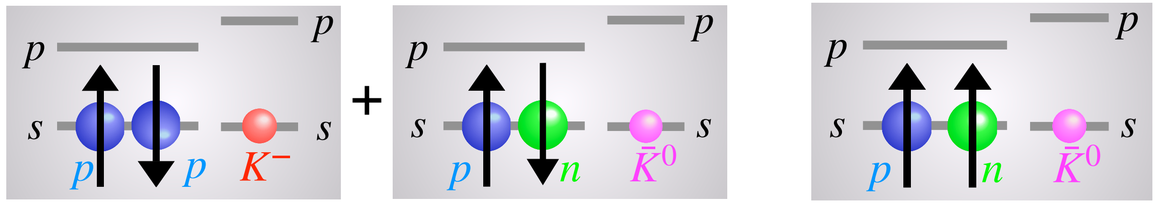
- **Isospin partner should exist**
  - "$\bar{K}^0nn$" $\rightarrow \Lambda n, \Sigma^- p$ analysis
  - need neutron detection
- **Spin-parity measurement:**
  - spin-spin correlation between Λ and p
  - need polarimeter for proton

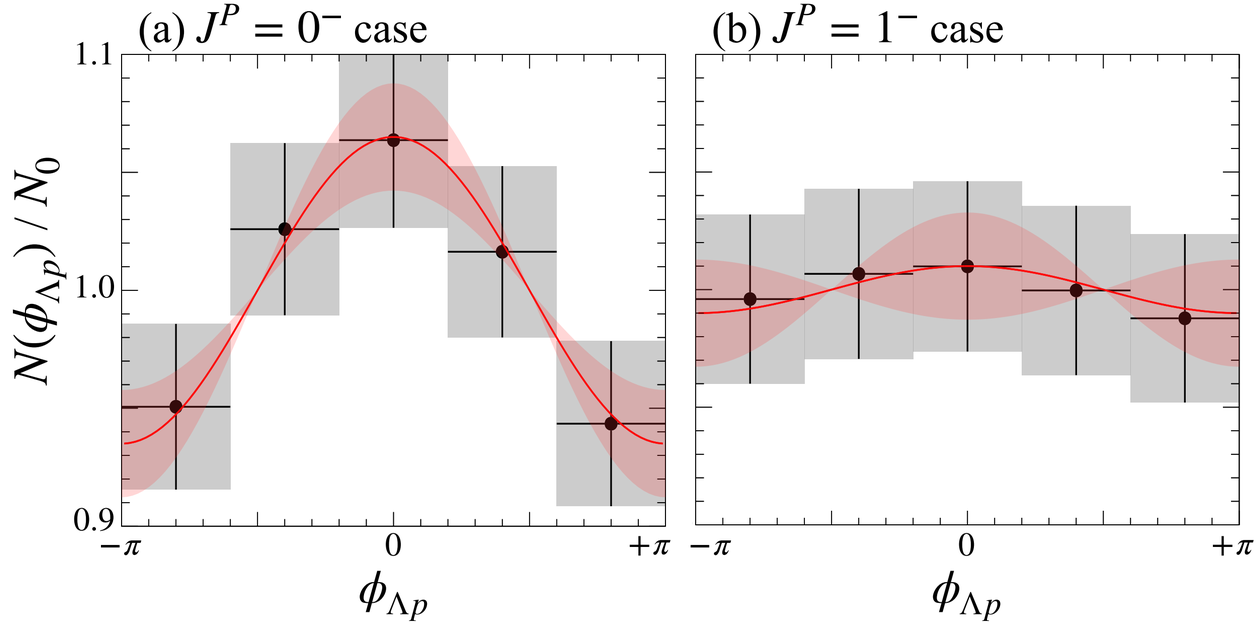
$\bar{K}NN(I=1/2)$

$I_z = +1/2$: K^-pp - $\bar{K}^0pn$

$I_z = -1/2$: K^-pn - $\bar{K}^0nn$



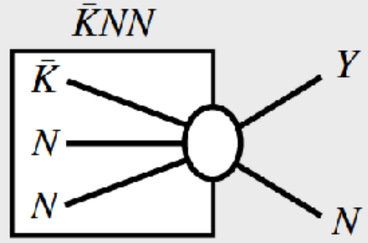




How compact is the system?

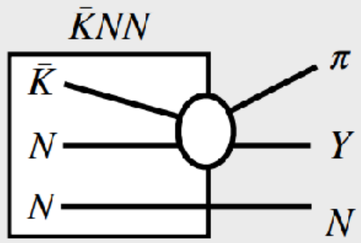
- **Momentum-transfer distribution**
  - large S-wave gauss. form factor Q ~ 400 MeV/c
- **Decay branching ratio** $1N_{\bar{K}A}$: $2N_{\bar{K}A}$: $3N_{\bar{K}A} = \rho_N : \rho_N^2 : \rho_N^3$?
  - $\bar{K}NN \to \Lambda N$ vs. $\bar{K}NN \to \pi Y N_s$, $\Sigma^{\pm} \to \pi^{\pm} n$ neutron detection

Non-mesonic



2N absorption

Mesonic

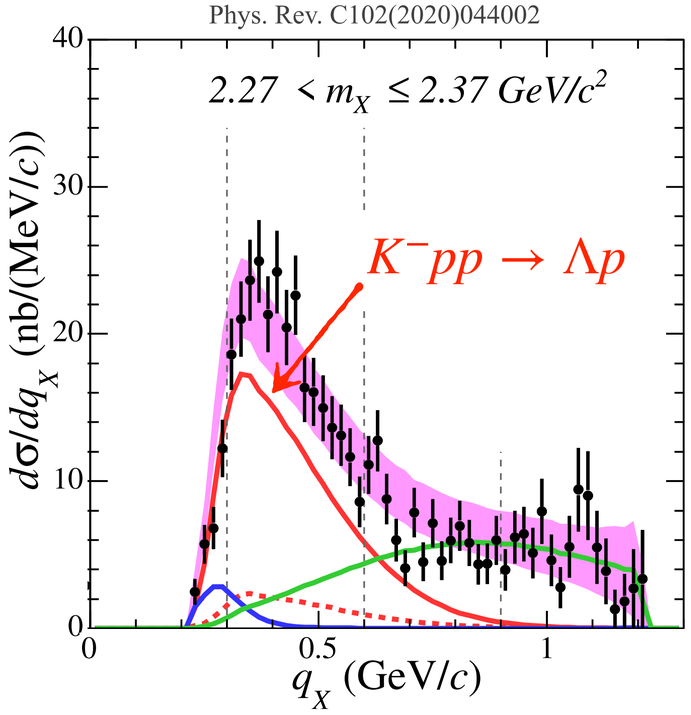


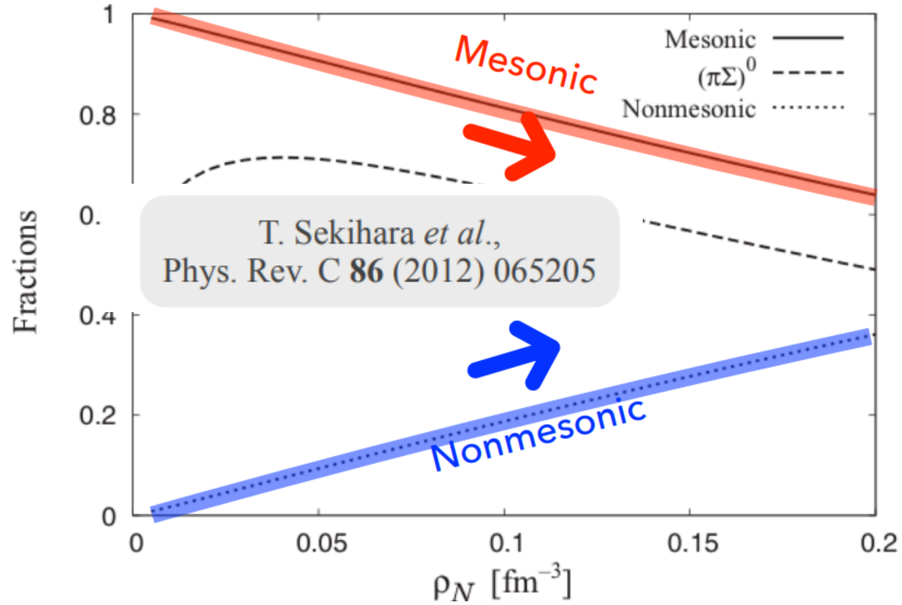
1N absorption

- $\bar{K}NNN \to \Lambda d$ vs. $\bar{K}NNN \to \Lambda p n$ neutron detection

3N absorption　　2N absorption

Phys. Rev. C102(2020)044002

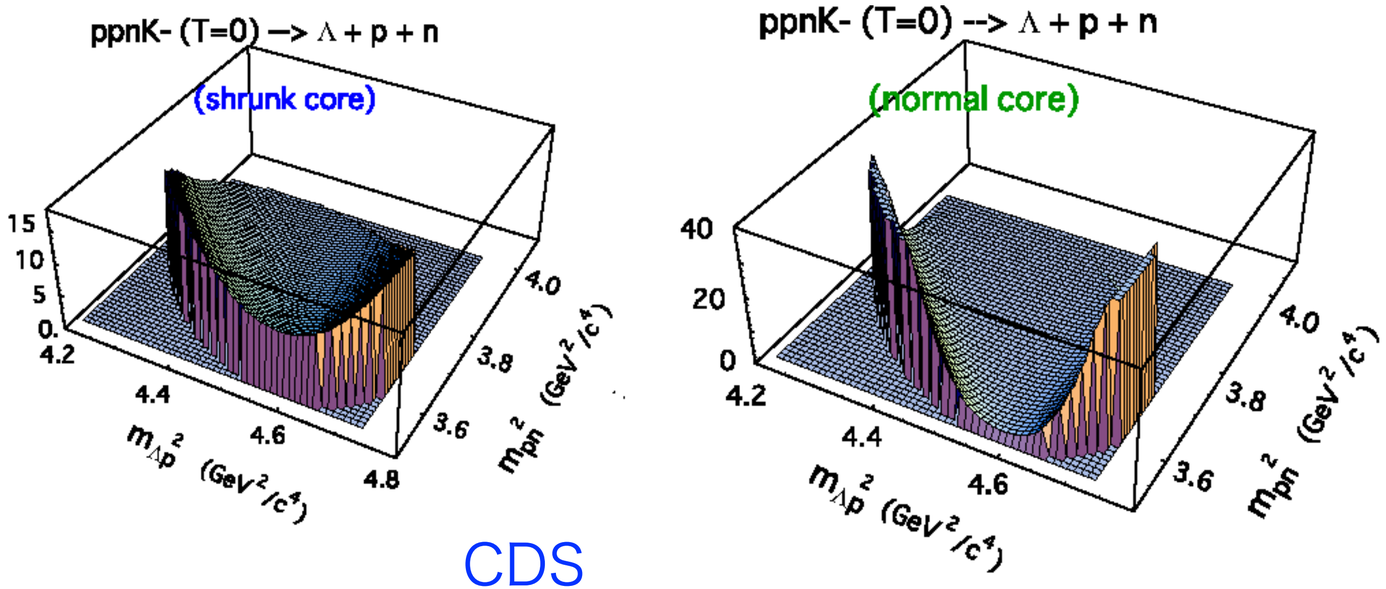


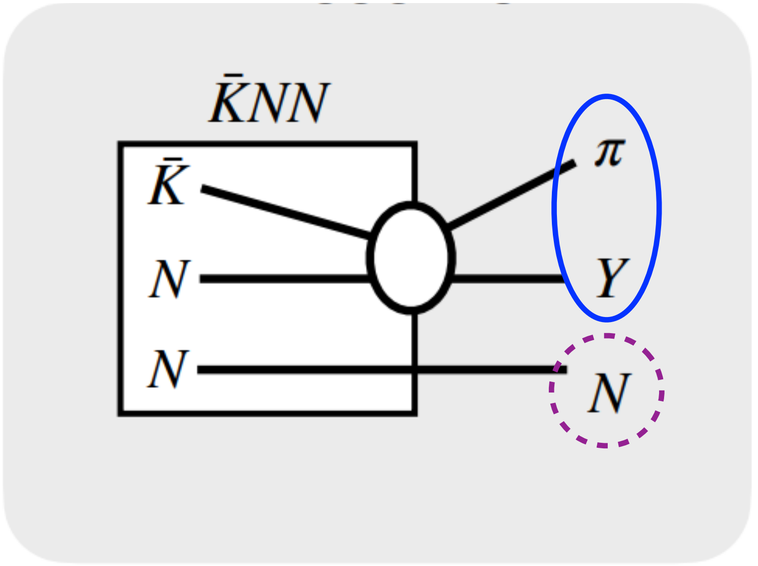


T. Sekihara *et al.*,
Phys. Rev. C **86** (2012) 065205

How compact is the system?

P. Kienle et al., PLB 632 (2006) 187–191





1N absorption

CDS

$$K^- + {}^4\mathrm{He} \rightarrow (\Lambda N + N_s) + n_f$$

forward TOF

CDS

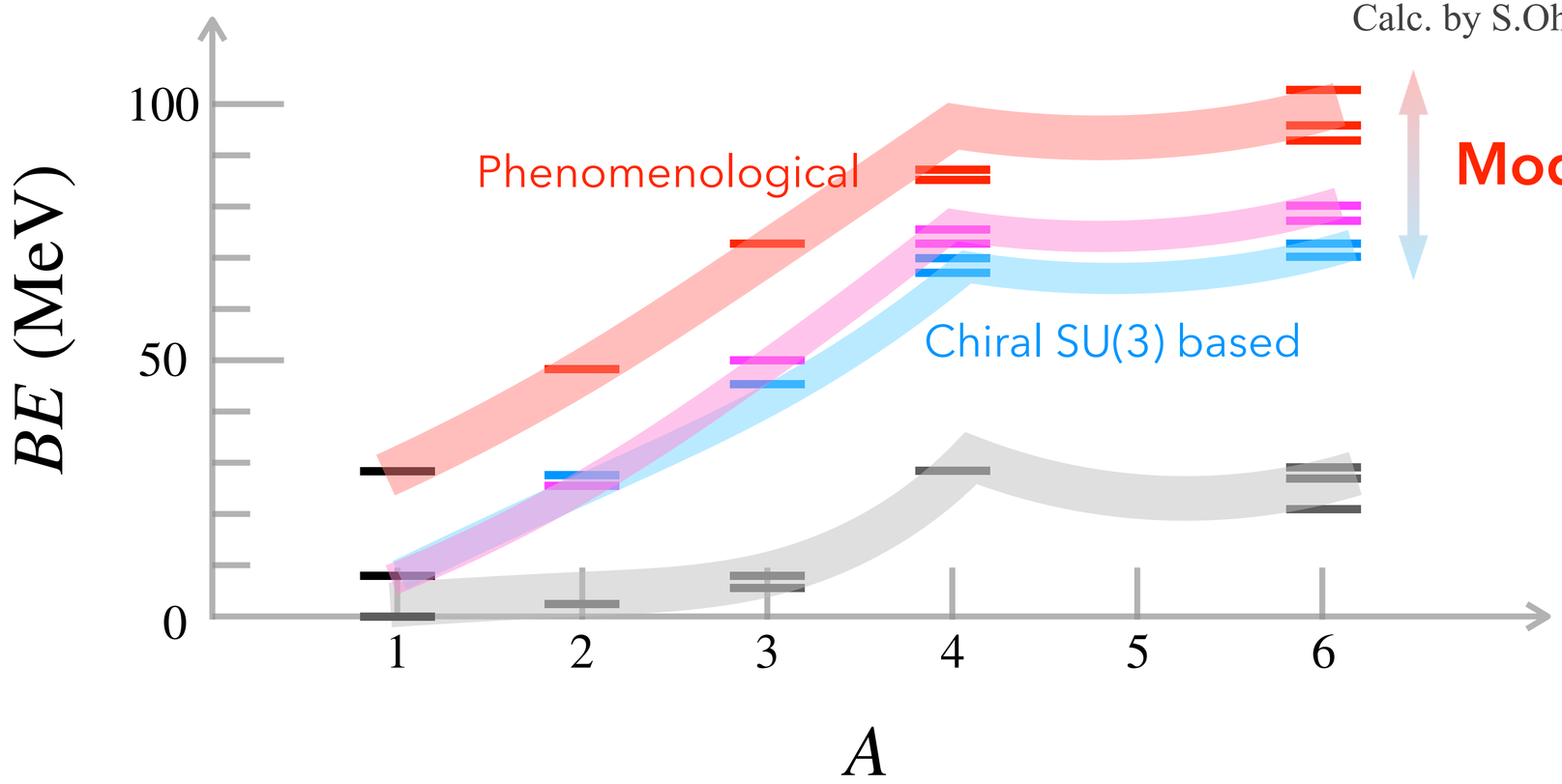
$$K^- + {}^3\mathrm{He} \rightarrow (\pi Y + N_s) + N_f$$

forward TOF

- Momentum of the “spectator” nucleon should reflect the system size.
- Most of the spectator nucleons have too low momentum to be detected.
  → detect the forward knocked-out nucleon in the production reaction

How general are the K^{bar}-nuclei?

Calc. by S.Ohnishi et al. in PRC 95 (2017) 065202



Model dependence

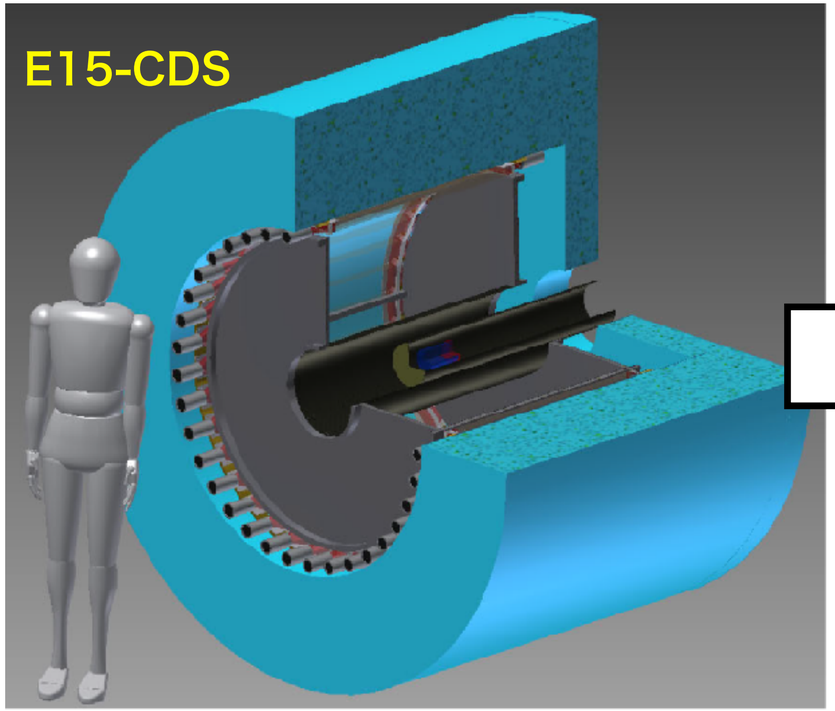
- E-dep. of $\bar{K}N$ int.
- $E_{\bar{K}N}$ in system

- $K^- + {}^4\mathrm{He} \rightarrow \bar{K}NNN + n$
- $K^- + {}^6\mathrm{Li} \rightarrow \bar{K}NNNN + d$
- $K^- + {}^7\mathrm{Li} \rightarrow \bar{K}NNNNNN + n/p$ forward TOF

Exclusive analysis becomes difficult.
→ Inclusive + strangeness tag.

C(K$^-$, p) at 1.8 GeV/c
F. Oura@1p2C

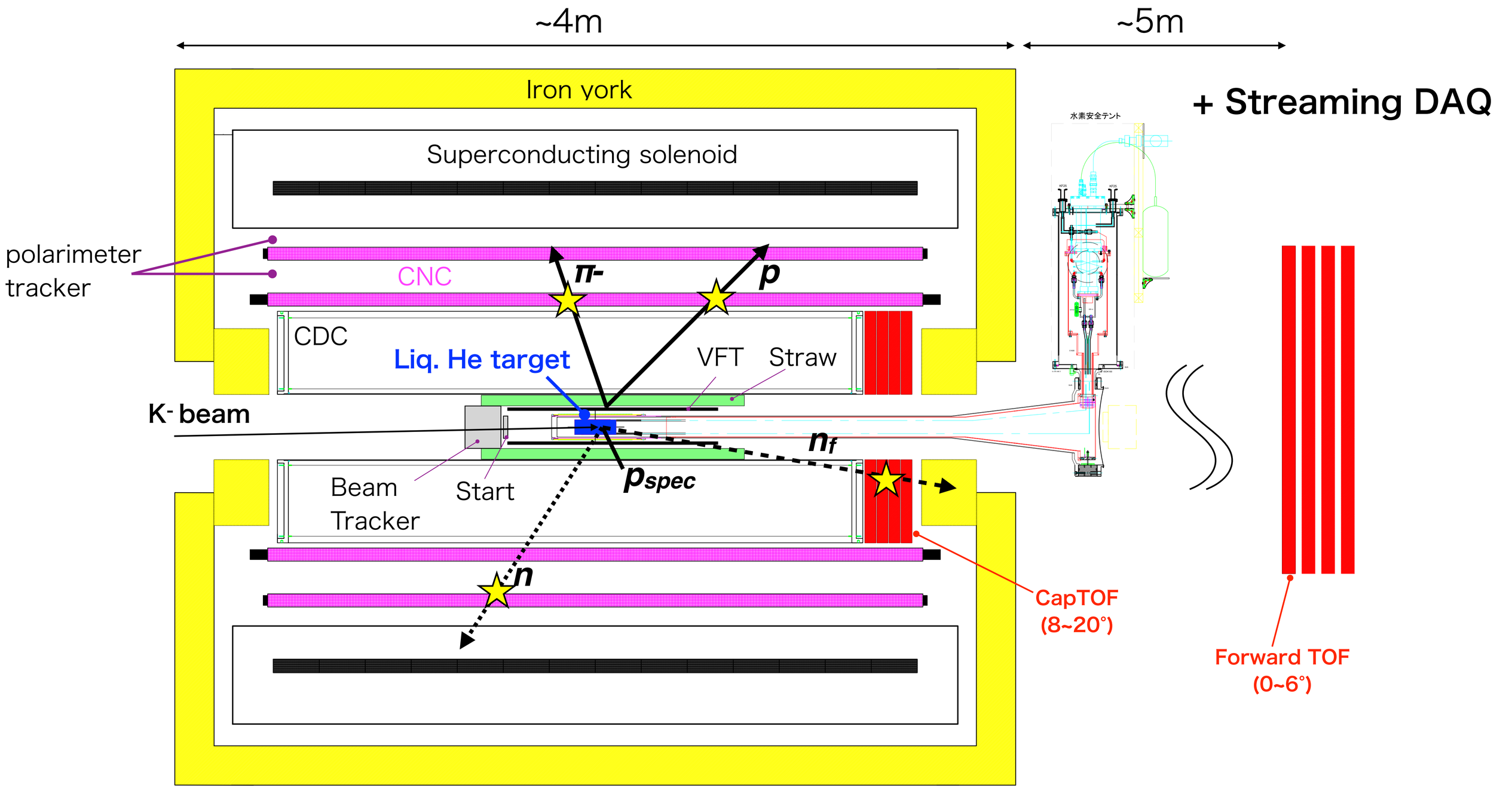
New CDS



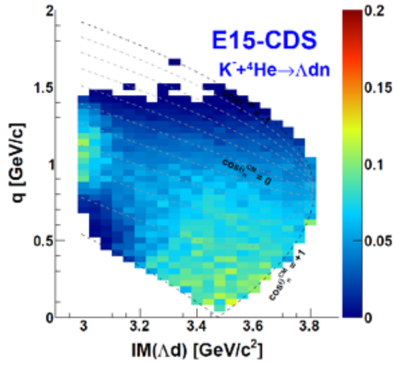
E80-CDS

Superconducting Solenoid
Neutron Counter
Cylindrical Drift Chamber

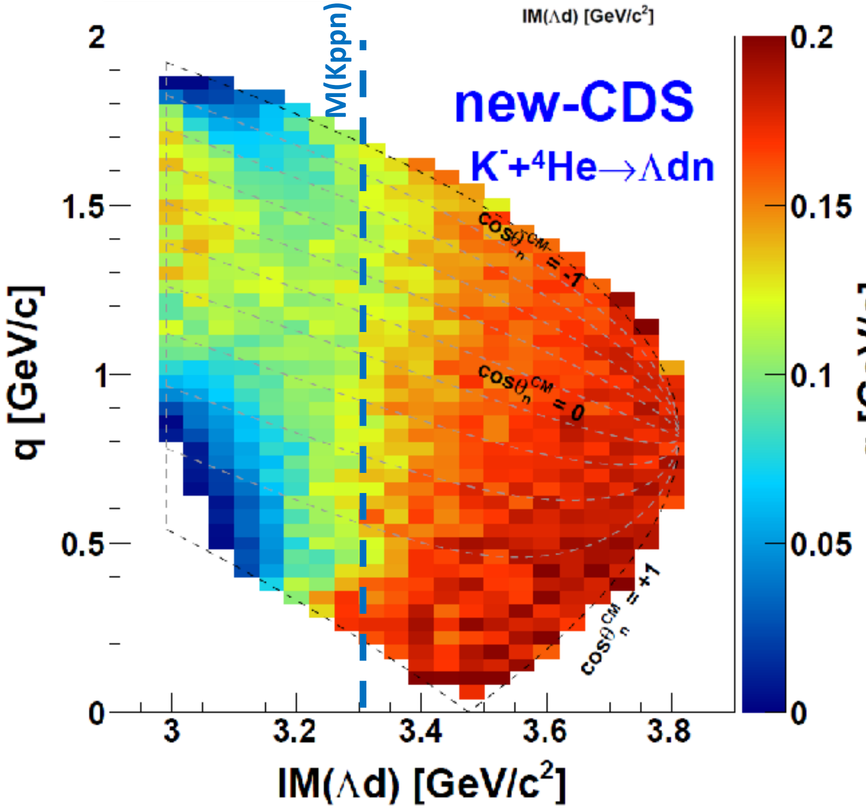
- ✓ **Solid angle: x1.6** (59%→93%)
- ✓ **Neutron eff. x4** (3%→12%)
- ✓ forward TOF counters
- ✓ proton polarimeter in future


~4m
~5m
Iron york
Superconducting solenoid
polarimeter
tracker
CNC
π-
p
CDC
Liq. He target
VFT
Straw
K- beam
nf
pspec
Beam
Tracker
Start
n
水素安全テント
CapTOF
(8~20°)
Forward TOF
(0~6°)
+ Streaming DAQ

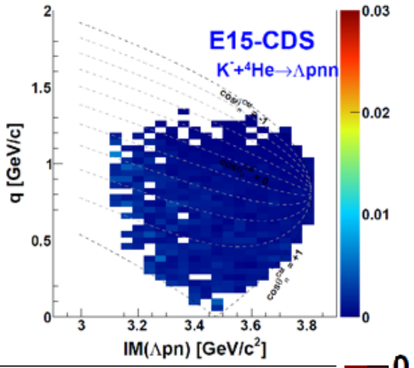
Acceptance for $K^- + {}^4\mathrm{He} \to \Lambda d / \Lambda pn + n$



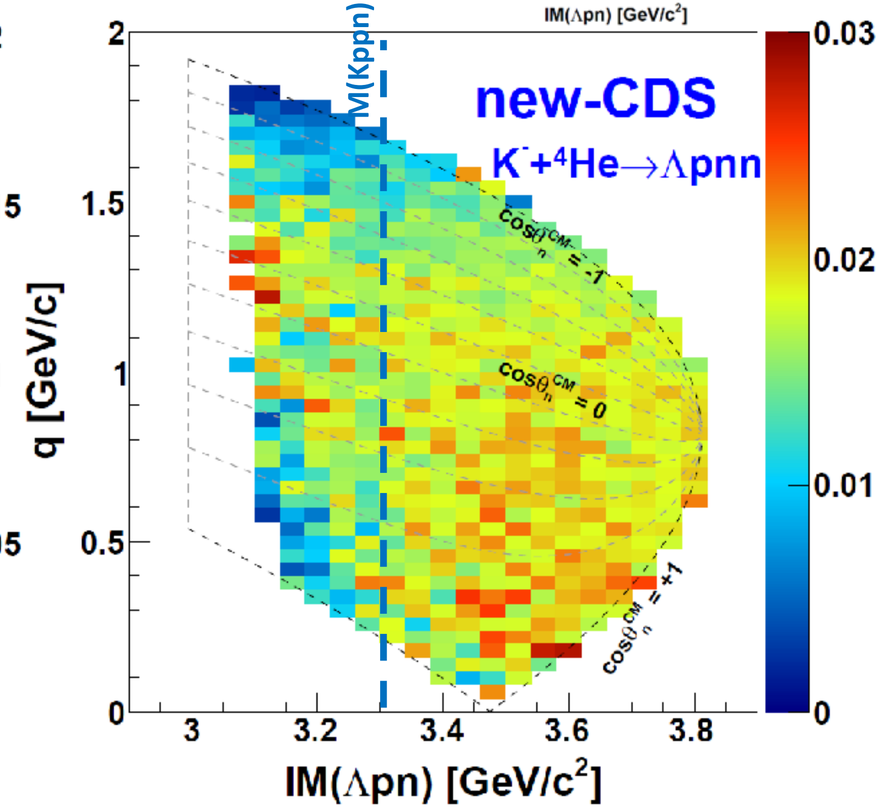
Λd in CDS



x2 in ROI

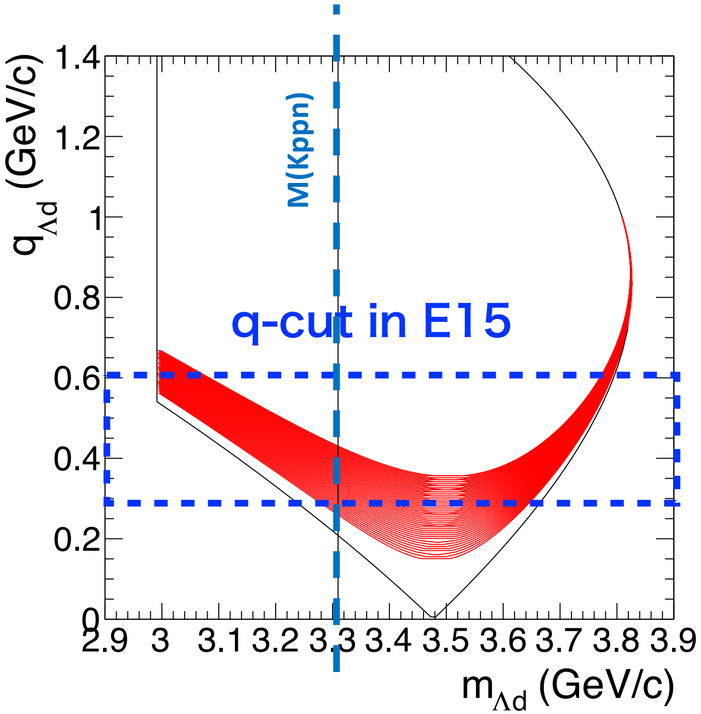


Λpn in CDS



> x10

n_f in Forawrd TOF



Construction status

Y. Kimura@29p1C
Y. Tsutusmi@poster

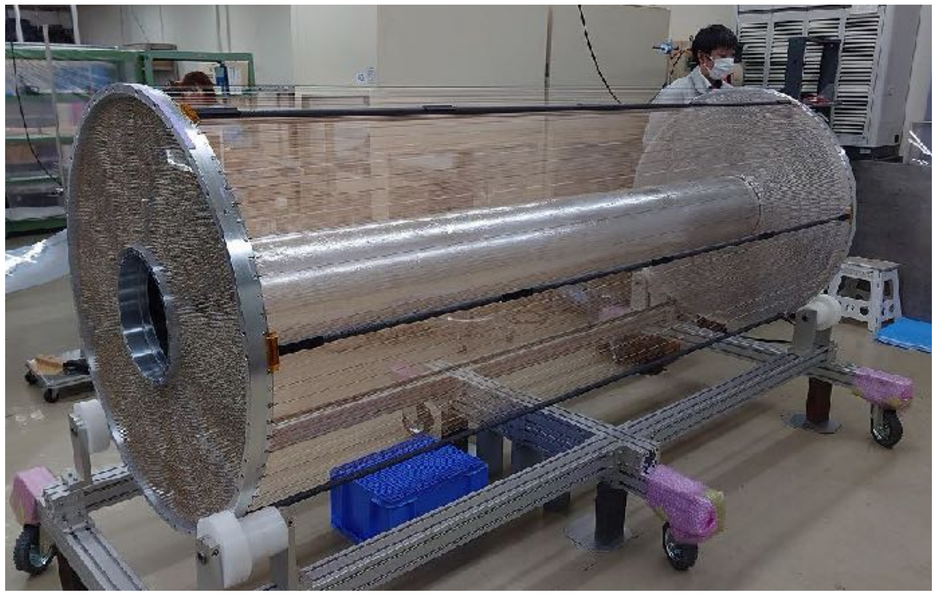
Solenoid york

completed in JFY2022

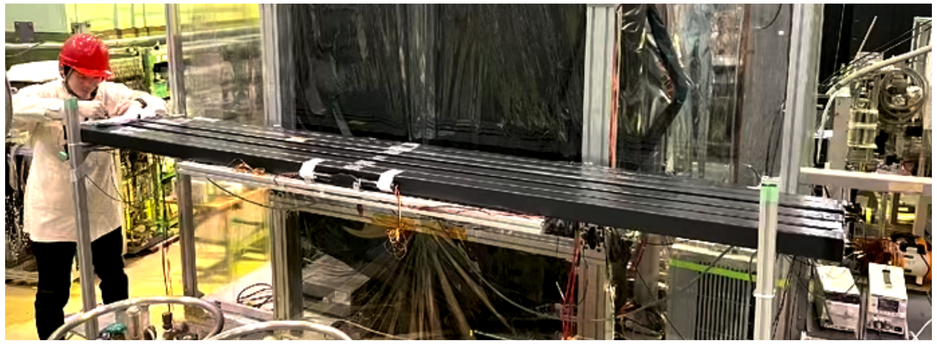
Superconducting solenoid

completed in JFY2024

CDC: completed, in commissioning



CNC: prototype tested, in production



Installation from summer 2026

Beam commissioning in early 2027

Summary

- **Established Kaonic nuclei production by (K^-, N) reaction**
  - E15-CDS data-taking just completed.
  - $\Lambda(1405)$, "K^-pp", "K^-ppn"
  - More analysis results to come. (d, ^{3}He, ^{4}He)
- **Next-generation experiments start in 2027 with the upgraded solenoid detector**
  - J-PARC E80: "K^-ppn"
  - J-PARC E89: "K^-pp" spin-parity, "$\bar{K}^0nn$"
  - **key issues: quantum number, spatial size from the decay observables**
  - Many opportunities with E80-CDS: hypernuclei, p^{bar} beam, K^+ beam, …

Collaboration

T. Yamaga,[1,*] S. Ajimura,[2] H. Asano,[1] G. Beer,[3] H. Bhang,[4] M. Bragadireanu,[5] P. Buehler,[6] L. Busso,[7,8] M. Cargnelli,[6] S. Choi,[4] C. Curceanu,[9] S. Enomoto,[14] H. Fujioka,[15] Y. Fujiwara,[12] T. Fukuda,[13] C. Guaraldo,[9] T. Hashimoto,[20] R. S. Hayano,[12] T. Hiraiwa,[2] M. Iio,[14] M. Iliescu,[9] K. Inoue,[2] Y. Ishiguro,[11] T. Ishikawa,[12] S. Ishimoto,[14] K. Itahashi,[1] M. Iwai,[14] M. Iwasaki,[1,†] K. Kanno,[12] K. Kato,[11] Y. Kato,[1] S. Kawasaki,[10] P. Kienle,[16,‡] H. Kou,[15] Y. Ma,[1] J. Marton,[6] Y. Matsuda,[17] Y. Mizoi,[13] O. Morra,[7] T. Nagae,[11] H. Noumi,[2,14] H. Ohnishi,[22] S. Okada,[23] H. Outa,[1] K. Piscicchia,[24,9] Y. Sada,[22] A. Sakaguchi,[10] F. Sakuma,[1] M. Sato,[14] A. Scordo,[9] M. Sekimoto,[14] H. Shi,[6] K. Shirotori,[2] D. Sirghi,[9,5] F. Sirghi,[9,5] S. Suzuki,[14] T. Suzuki,[12] K. Tanida,[20] H. Tatsuno,[21] M. Tokuda,[15] D. Tomono,[2] A. Toyoda,[14] K. Tsukada,[18] O. Vazquez Doce,[9,16] E. Widmann,[6] T. Yamazaki,[12,1] H. Yim,[19] Q. Zhang,[1] and J. Zmeskal[6]

(J-PARC E15 Collaboration)

T. Akaishi, M. Bazzi, P. Buehler, A. Clozza, C. Curceanu, H. Fujioka, M. Fujita, T. Hashimoto, M. Iio, M. Iliescu, K. Inoue, S. Ishimoto, K. Itahashi, M. Iwasaki, S. Kawasaki, Y. Kimura, T. Kishimoto, G. Kojima, Y. Ma, Y. Makida, S. Manti, R. Murayama, T. Nagae, S. Nagao, S.N. Nakamura, T. Nanamura, H. Noumi, H. Ohhata, H. Ohnishi, S. Okada, M. Oonaka, K. Ozawa, F. Sakuma K. Sasaki, S. Sasaki, A. Scordo, F. Sgaramella, K. Shirotori, D. Sirghi, F. Sirghi, N. Sumi, K. Suzuki, S. Suzuki, K. Tanida, K. Toho, M. Tsuruta, Y. Tsutsumi, E. Widmann, T. Yamaga, M. Yoshida

(J-PARC E80 collaboration)

Thank you for your attention !