Kaonic nuclear bound states: “Discovery” and beyond

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研修生(2009~), JRA(2011), SPDR(2014~2017)

March 5, 2024 @ RIKEN

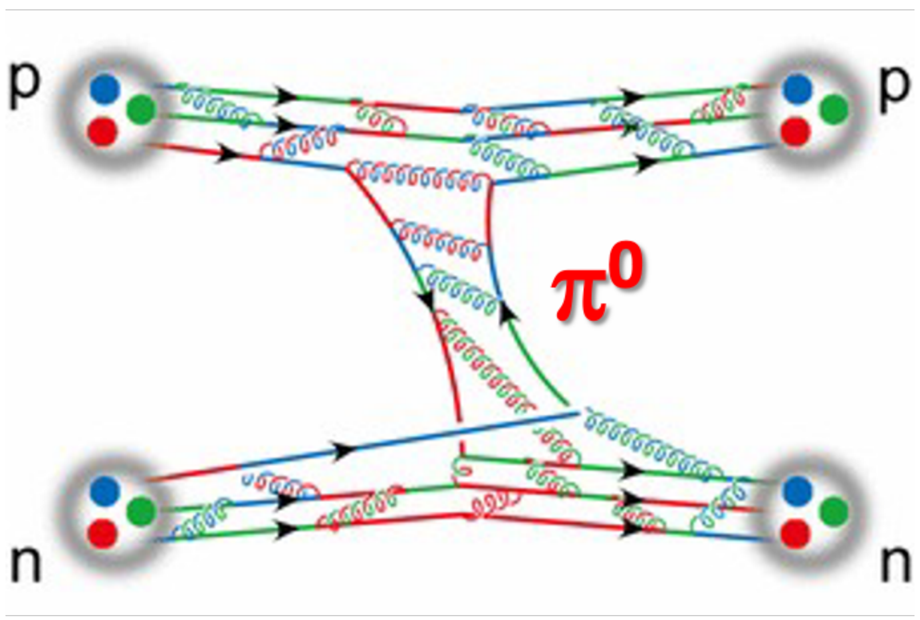
Related members since 2009

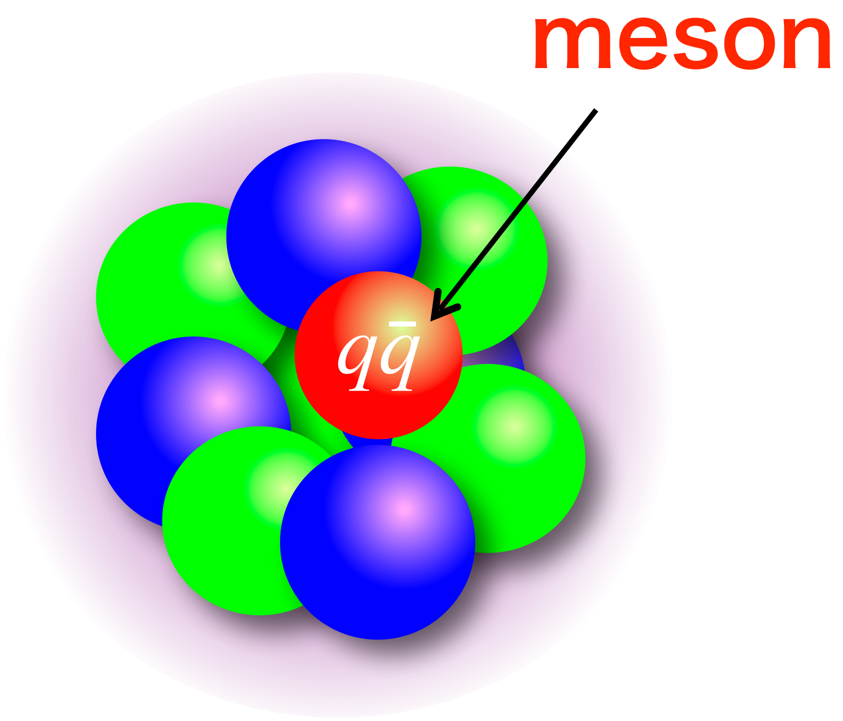
names on PRC(2022)

- Permanent staffs
  - M. Iwasaki, H. Outa, K. Itahashi,
  - H. Ohnishi, F. Sakuma, Y. Ma
- Post-docs
  - M. Iio, S. Okada, M. Sato, K. Tsukada,
  - T. Yamaga, H. Asano, R. Murayama
- Students (JRA, IPA, …)
  - T. Hiraiwa, Y. Sada, M. Tokuda, H. Kou,
  - Q. Zhang
- J-PARC E15/E17/E31/E57/E62/E73/T77/E80/P89 collaborations

Meson in nuclei

- **In nuclei**, mesons appear as **viatual** particles and form nuclear potential (Yukawa theorem)
- **In vacuum**, mesons are **real** particles having own intrinsic masses (cf. meson beam)





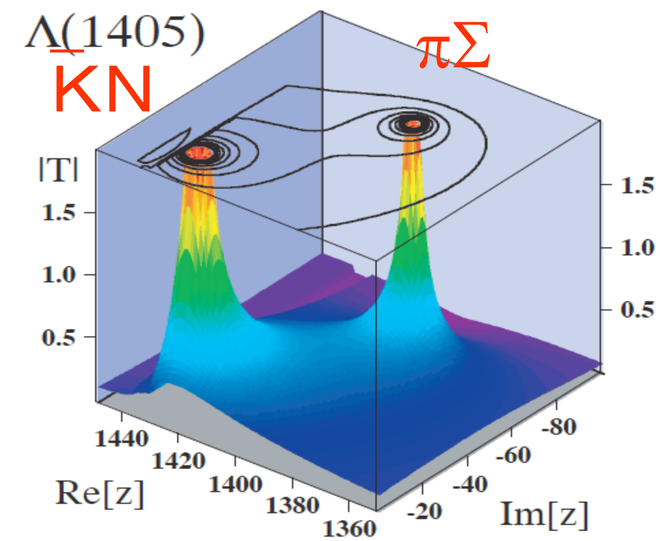
Can meson be a constituent particle forming nuclei?

If yes, how do meson and core nucleus change?

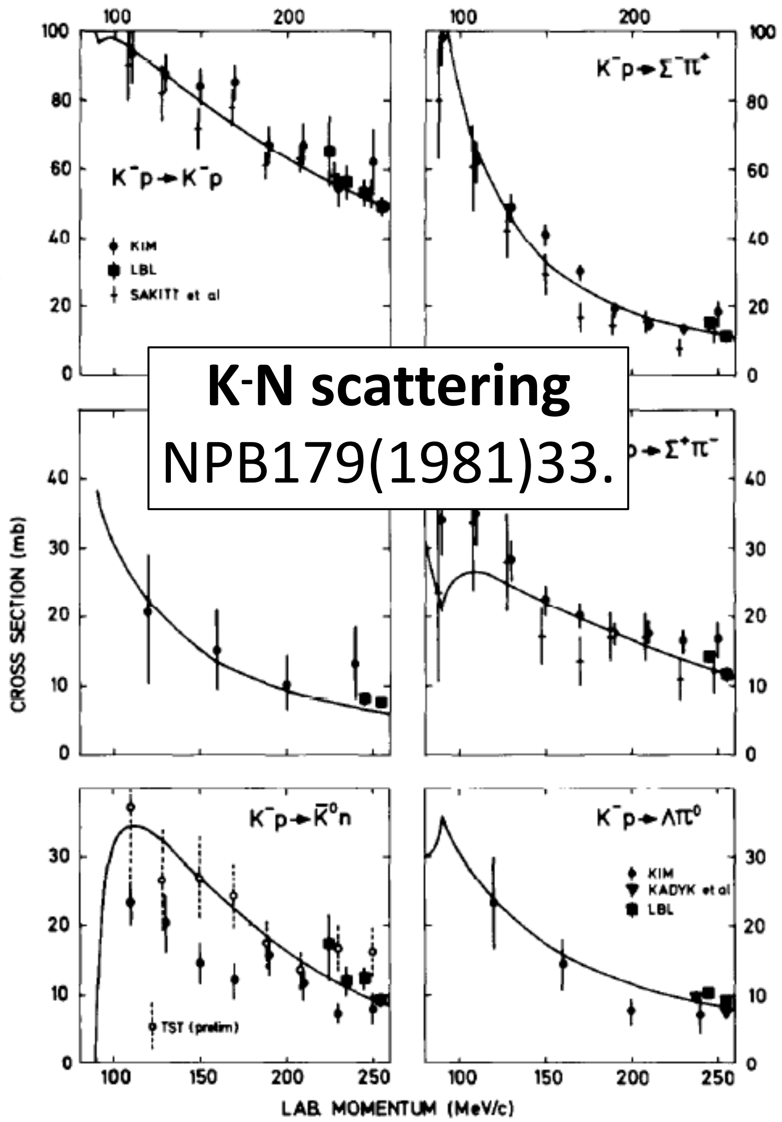
$K^{bar}N$ interaction

$\bar{u}s$

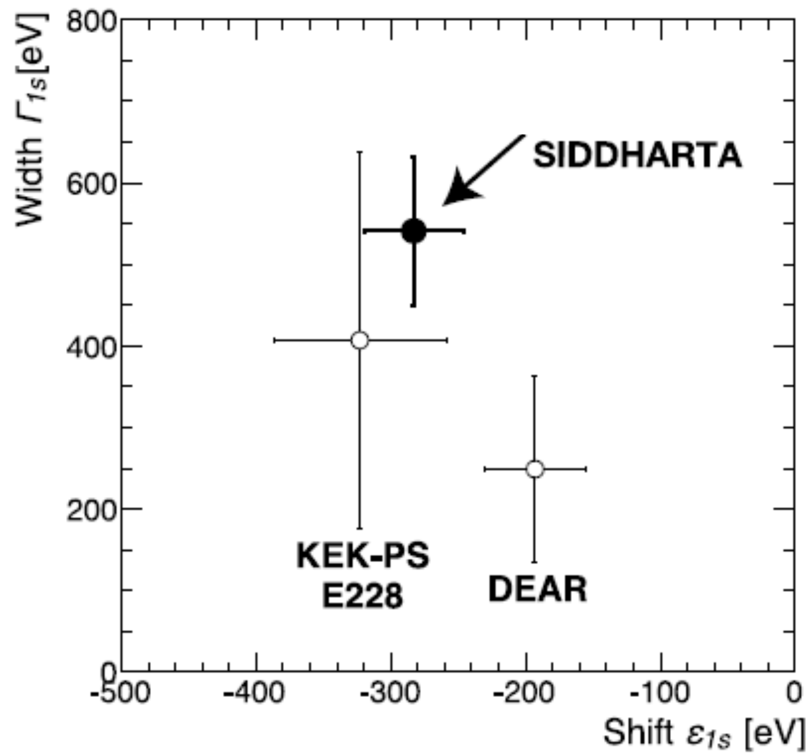
Λ(1405) in **chiral unitary model**
T. Hyodo



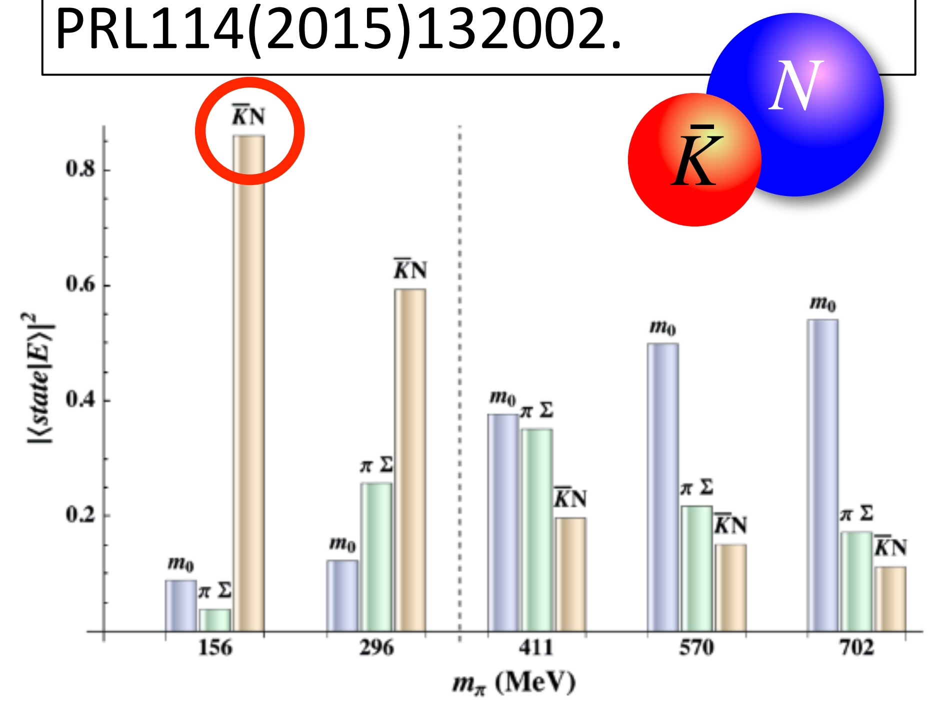
K⁻N scattering
NPB179(1981)33.



K⁻p atom
PLB704(2011)113.



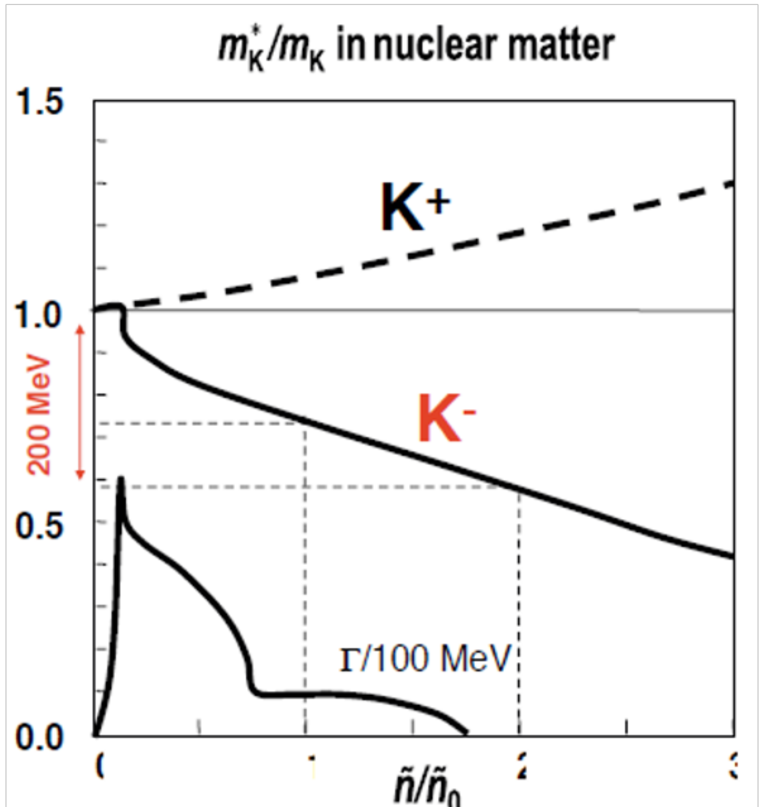
$K^{bar}N$ molecule from **Lattice QCD**
PRL114(2015)132002.



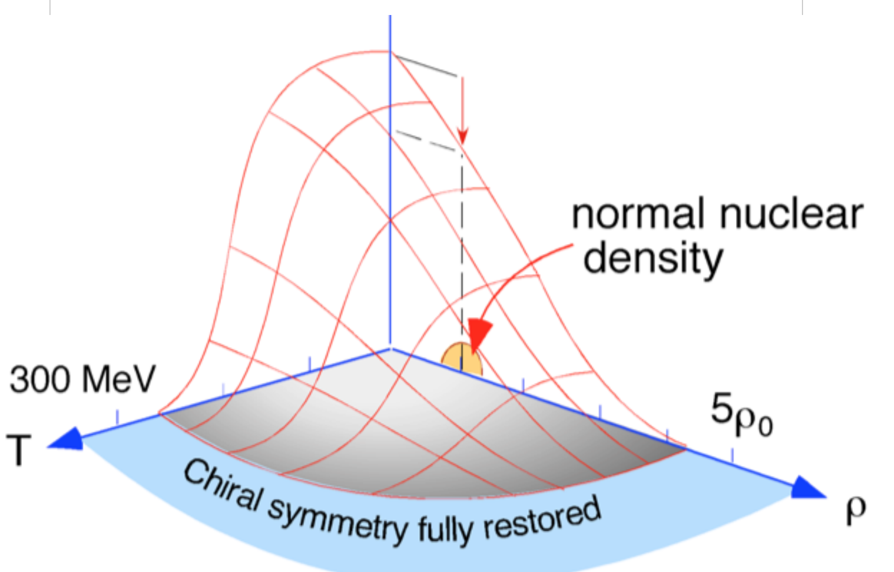
- Strong attraction in I=0 from scattering and X-ray experiements.
- $\Lambda(1405) = \bar{K}N$ molucle picture is now widely accepted

Why not kaonic nucleus with additional nucleons?

Kaon in nuclei

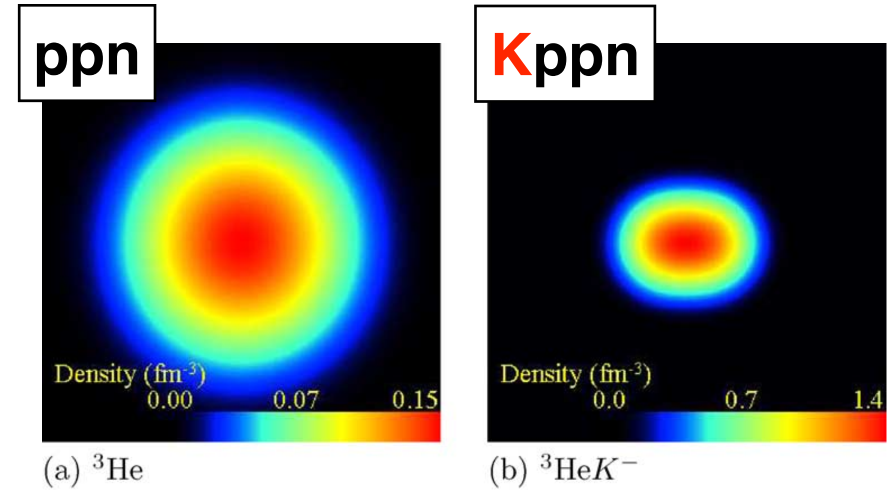


T. Waas, N. Kaiser & W. Weise, Phys. Lett. B379 (1996) 34.

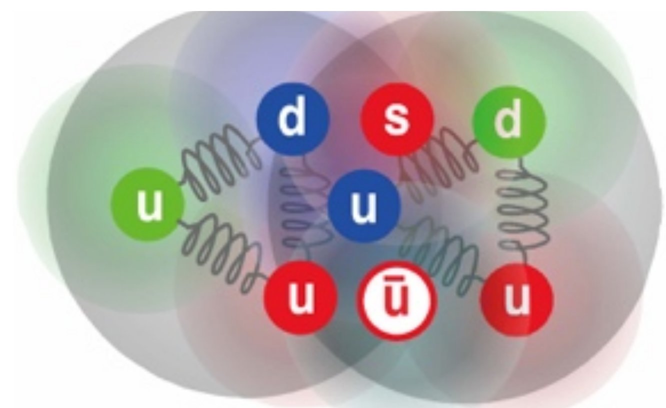


W.Weise NPA553,59 (1993)

Kaon mass changes?

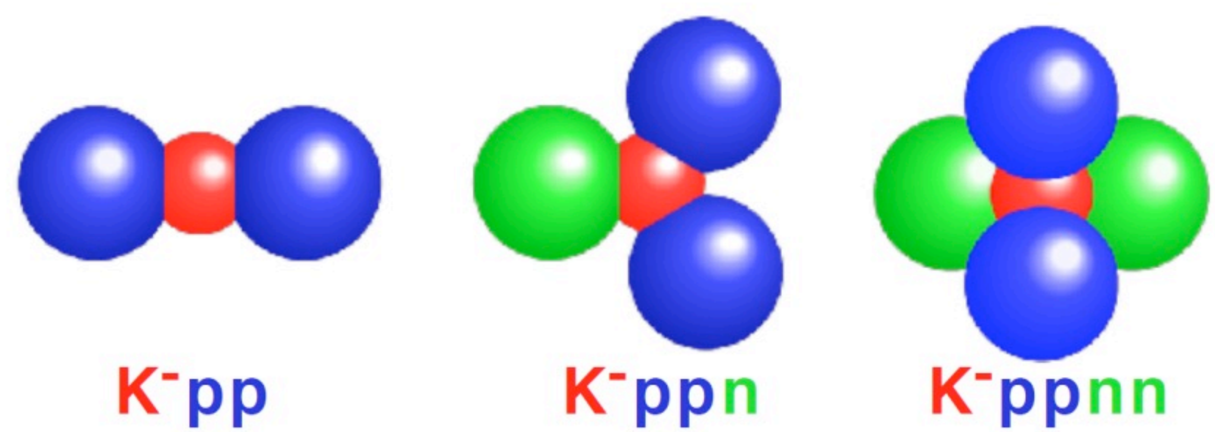


A. Dote, H. Horiuchi, Y. Akaishi and T. Yamazaki, Phys. Lett. B 590 (2004) 51



Compact system?

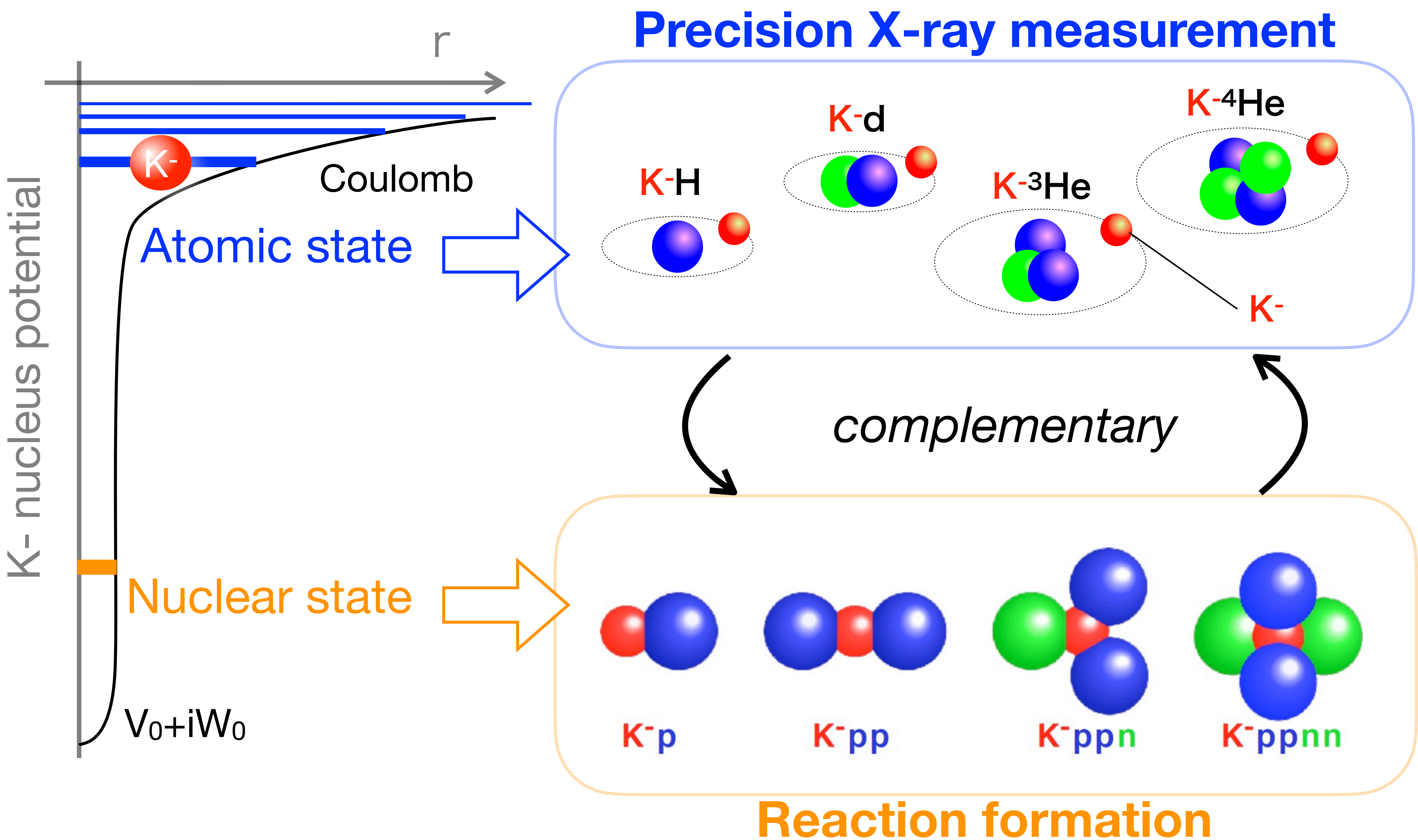
→nucleon overlaps? dense matter?



$\bar{K}N$ attraction & NN replusion

→molecule-like structure?

Two approaches for kaonic systems

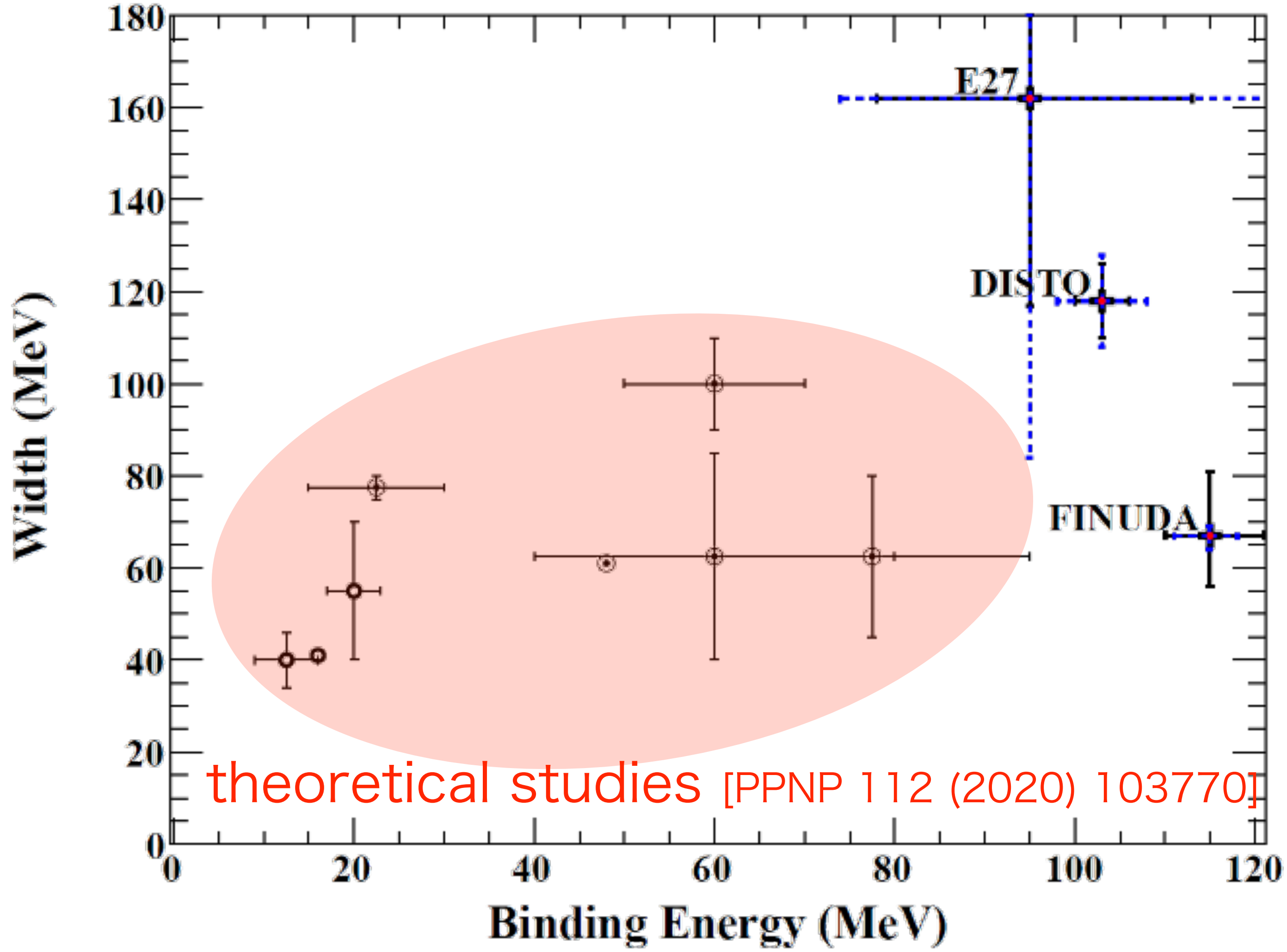


A series of experiments at J-PARC K1.8BR

Probe different energy, density, and isospin

The simplest kaonic nucleus

$\bar{K}NN(I = 1/2, J^P = 0^-)$



Experiments

- FINUDA: $(K^-_{stopped}, \Lambda p)$
- DISTO: $pp \to \Lambda p K^+$
- J-PARC E27: $d(\pi^+, K^+)X$

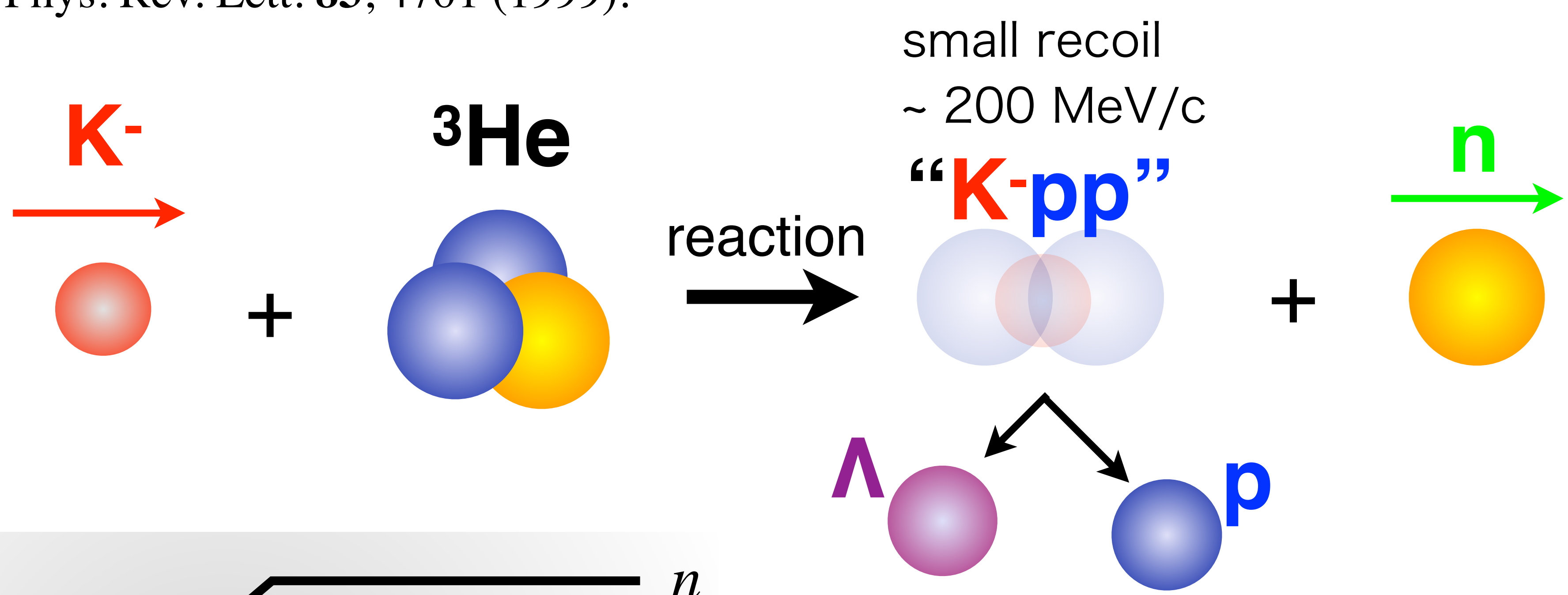
Null results

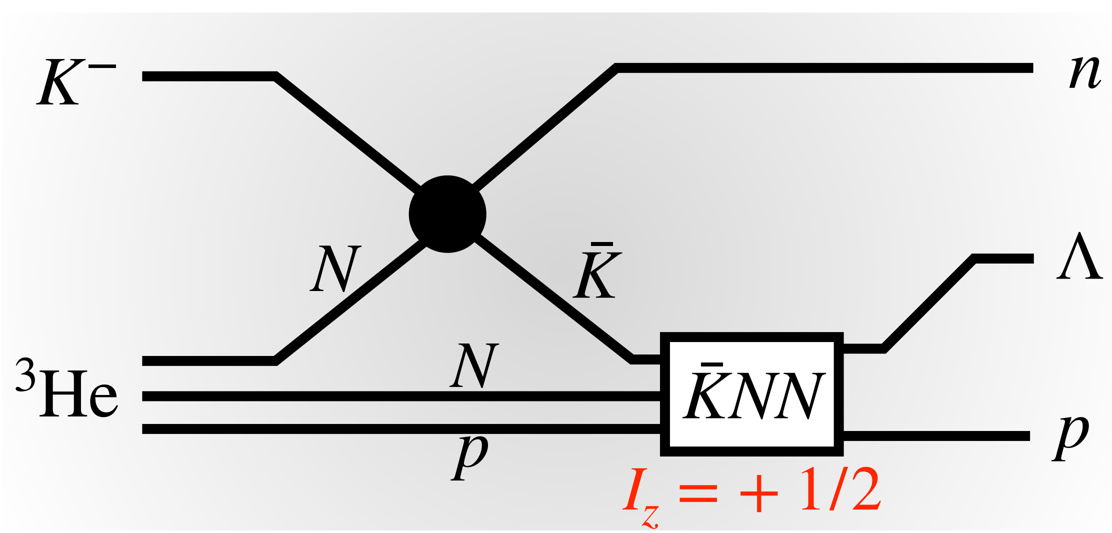
- LEPS: $p(\gamma, \pi^- K^+)X$
- HADES: $pp \to \Lambda p K^+$
- AMADEUS: C$(K^-_{stopped}, \Lambda p)$

- **Theoretical calculations agree on the existence of $\bar{K}NN$, although B.E. and Γ depend on the $\bar{K}N$ interaction models.**
- **Heaviear systems, $\bar{K}NNN, \bar{K}NNNN, \ldots$ should also exist**
- **However, no conclusive experimental evidence before us.**

Our approach: in-flight (K⁻, n)

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





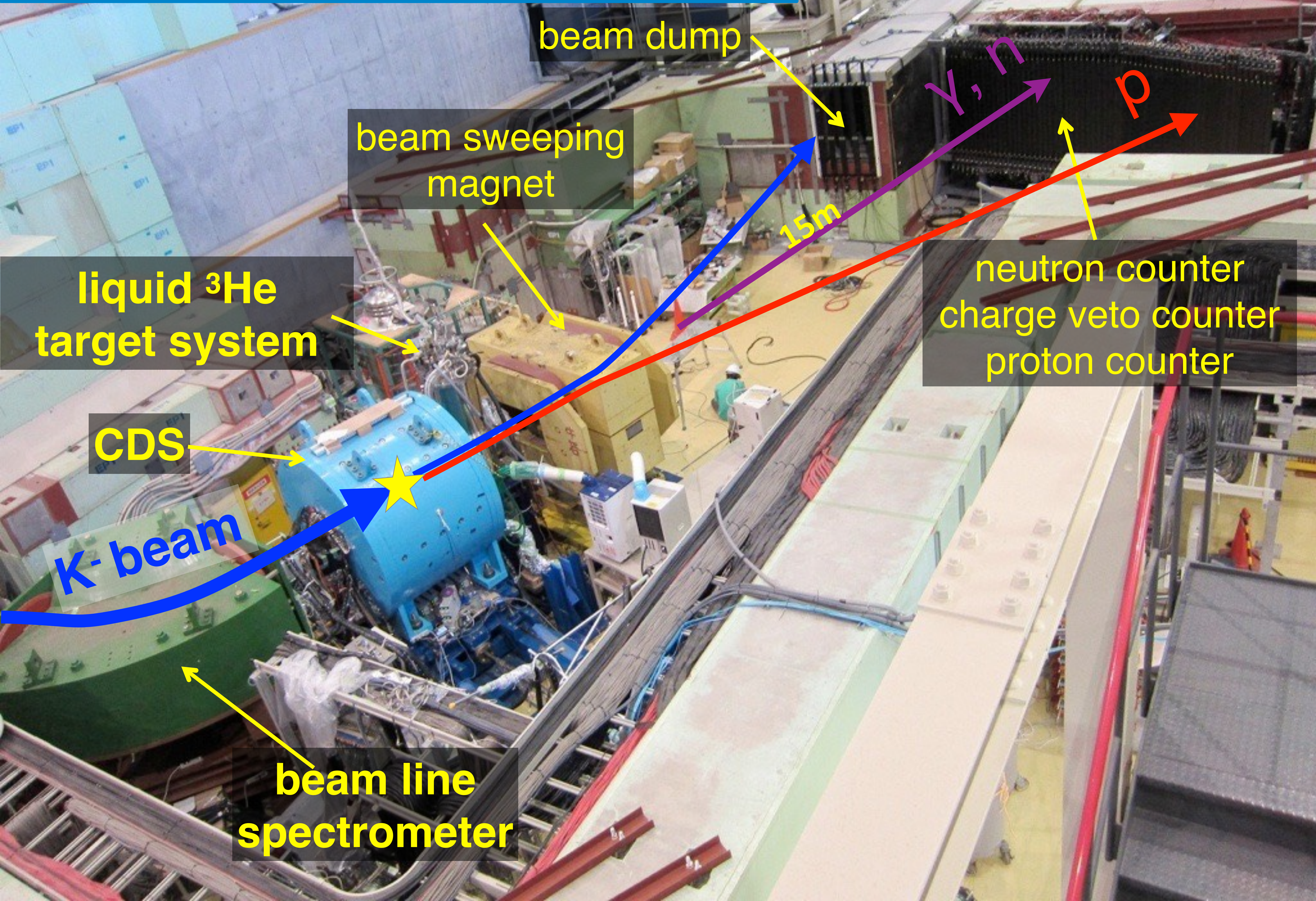
✓ Effectively produce sub-threshold virtual $\bar{K}$ beam

✓ Most of background processes can be kinematically separated.

✓ Simplest target allow exclusive analysis.

✓ Cover a wide range of kinematical region

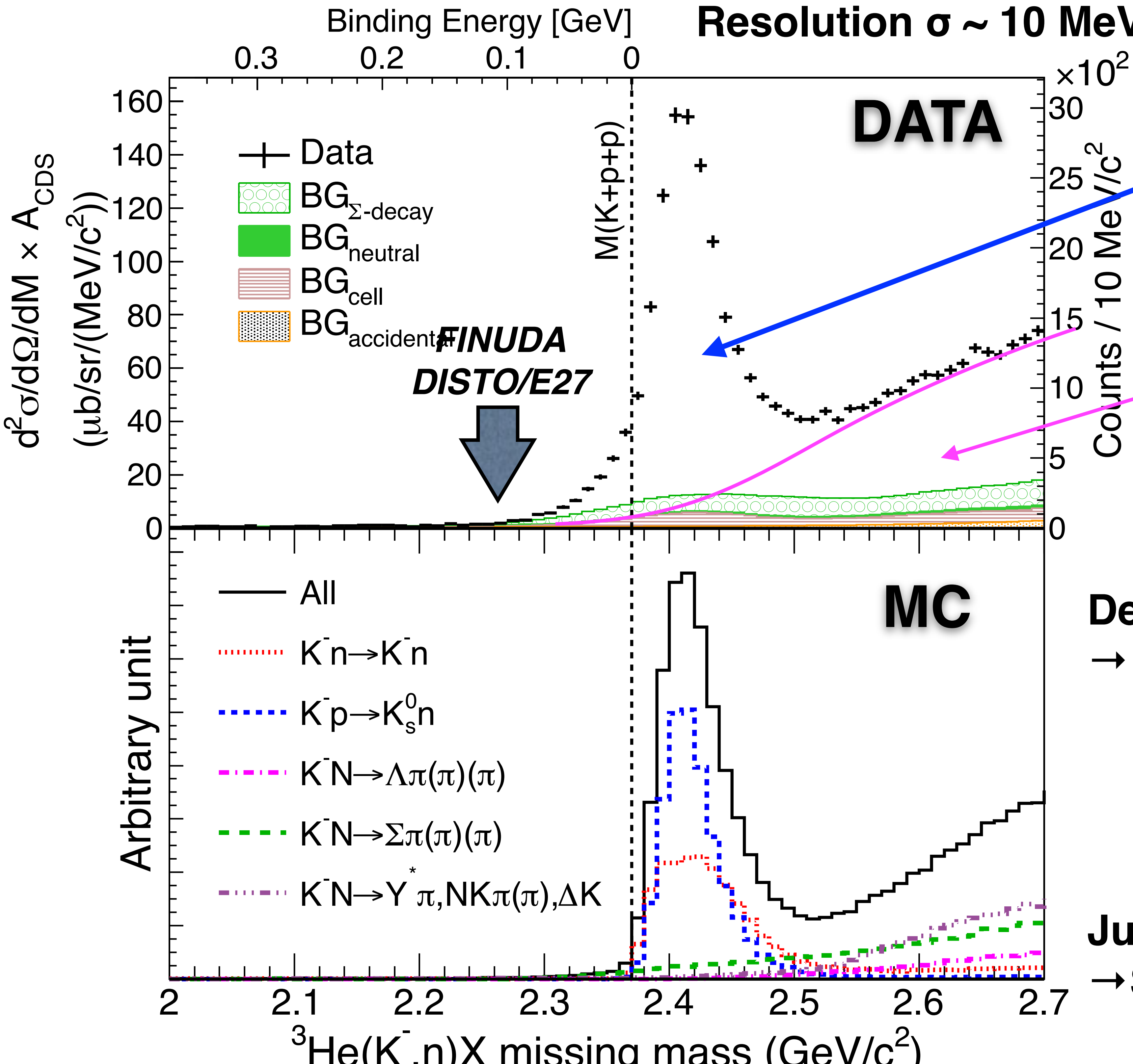
J-PARC K1.8BR as of 2012



Forward neutron semi-inclusive spectrum

PTEP **2015**, 061D01 (2015)

Resolution σ ~ 10 MeV/c² @ threshold



Quasi-elastic

$K^- + {}^3He \rightarrow K^0 + d_s + n$

$K^- + {}^3He \rightarrow K^- + 2p_s + n$

Hyperon decay

$K^- + {}^3He \rightarrow Y + \pi(\pi)(\pi) + 2N_s$

$Y \rightarrow n + \pi$

Deep-bound region

→ No significant peak
set upper limit:
a few hundreds μb/sr
= a few % of quasi-elastic K

Just below the threshold

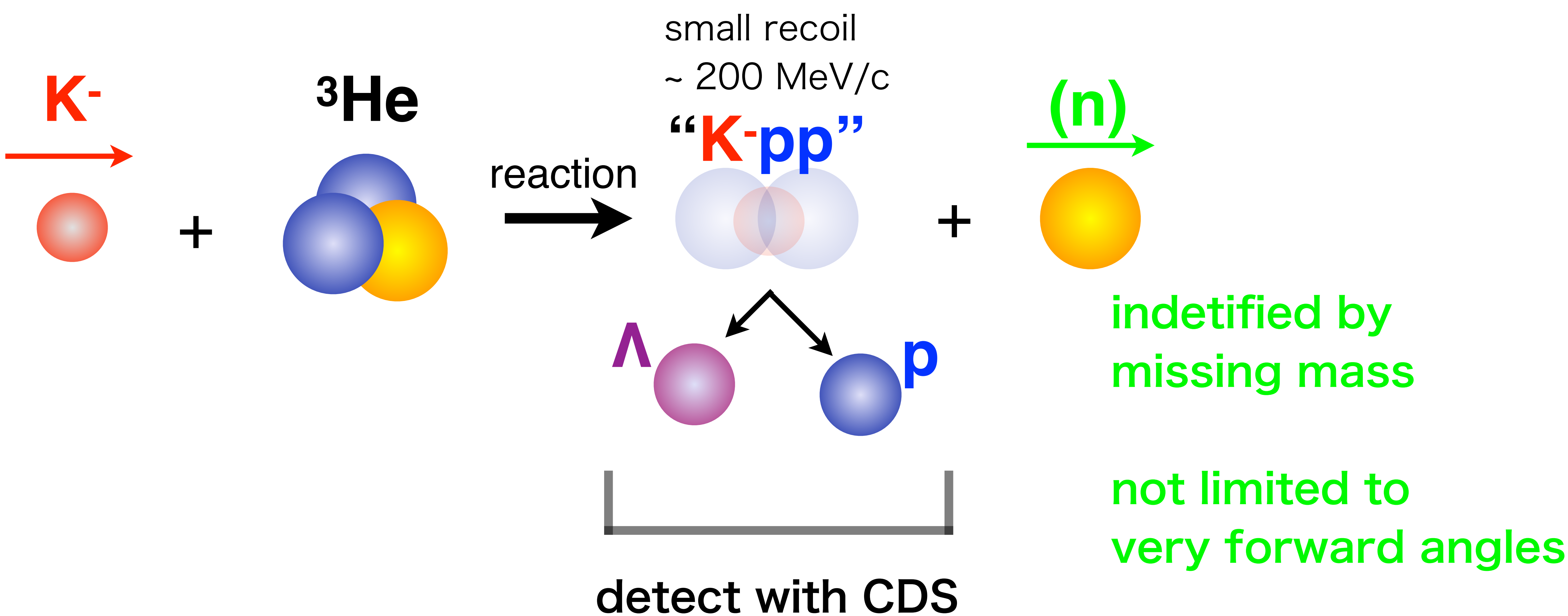
→Significant yield ~ 1 mb/sr
should include quasi-free Λ(1405)

Exclusive analysis: ^{3}He(K^-, Λp)n

PHYSICAL REVIEW C **102**, 044002 (2020)

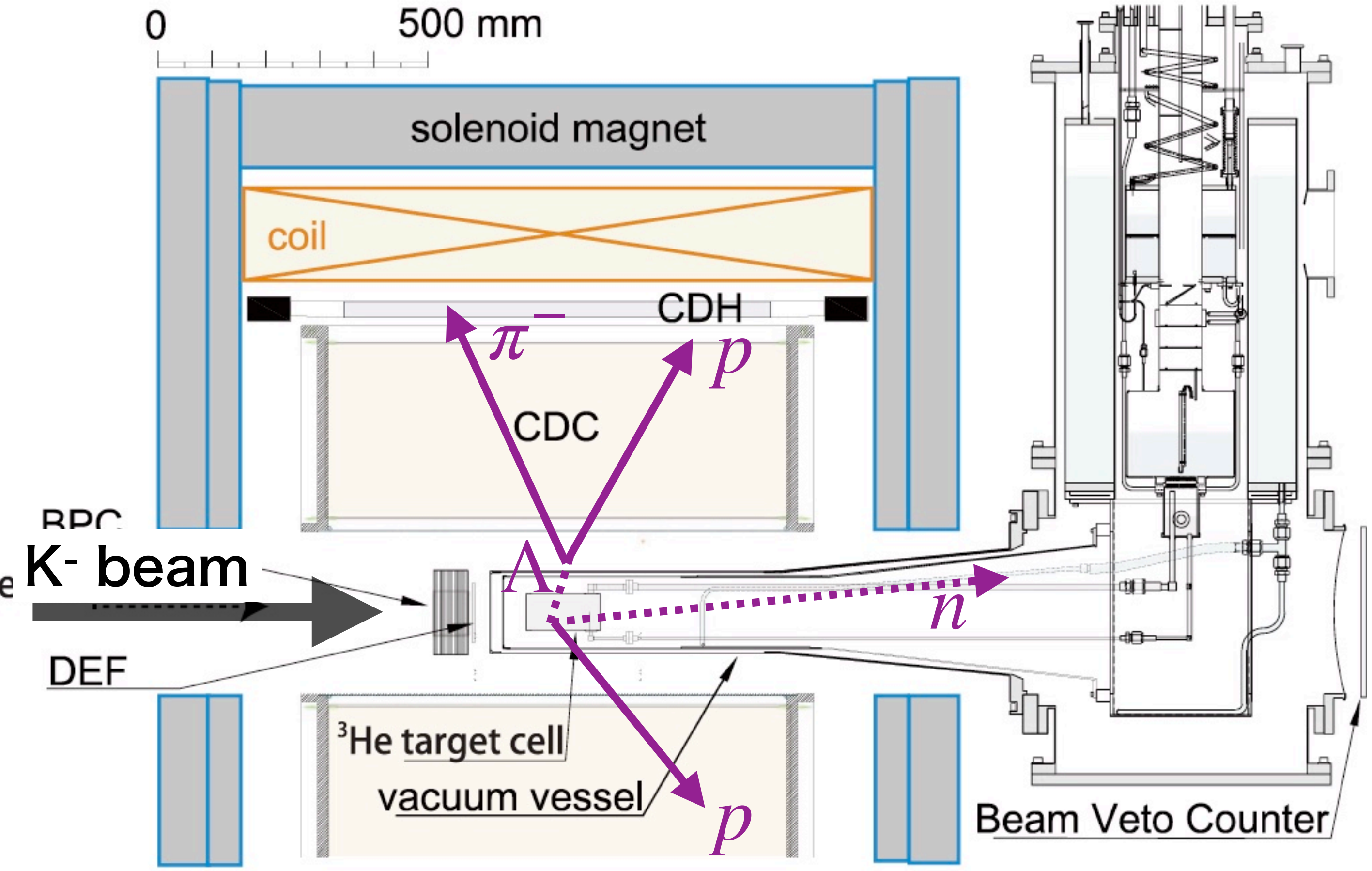
Observation of a $\bar{K}NN$ bound state in the ^{3}He(K^-, Λp)n reaction

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)



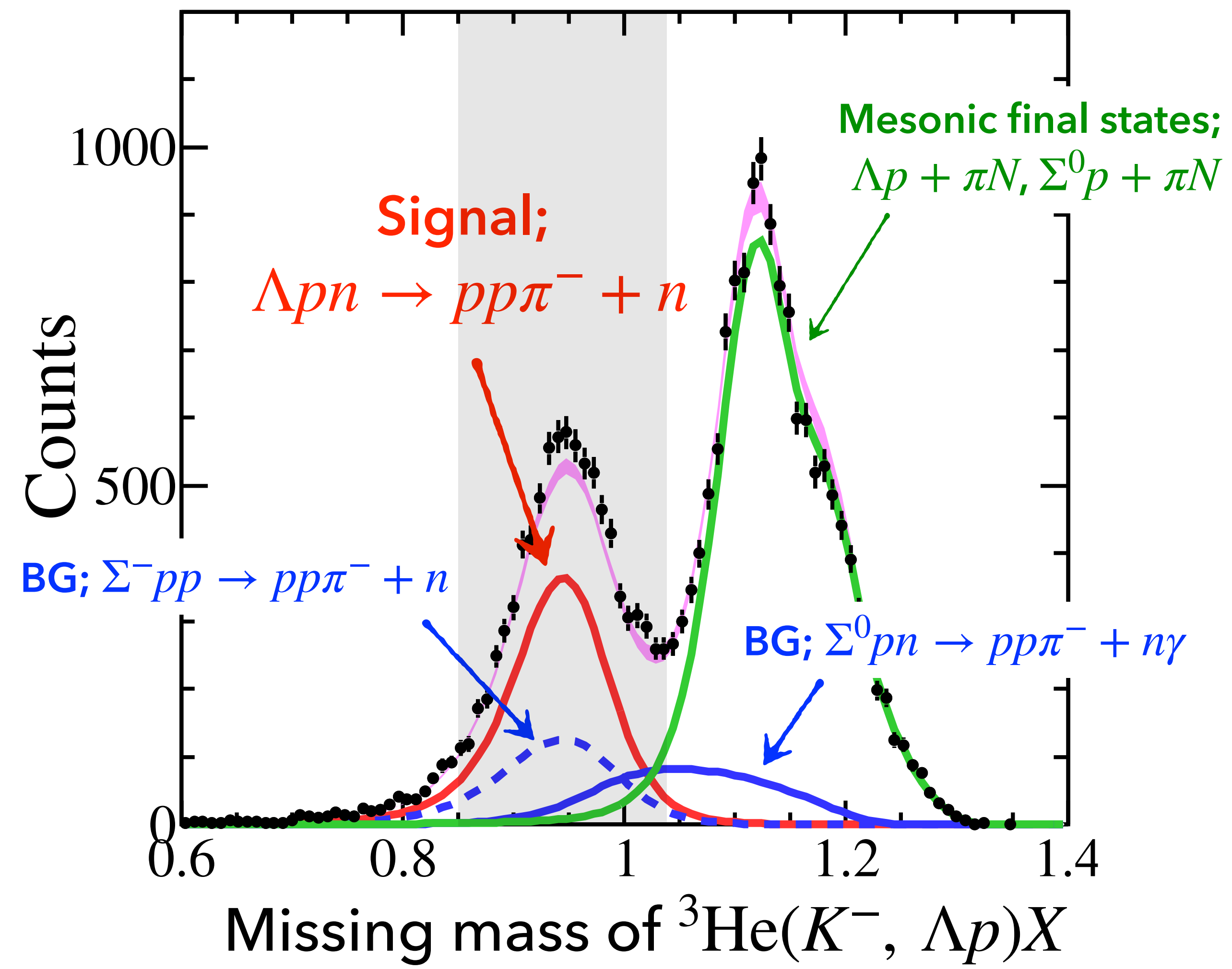
Λpn event selection

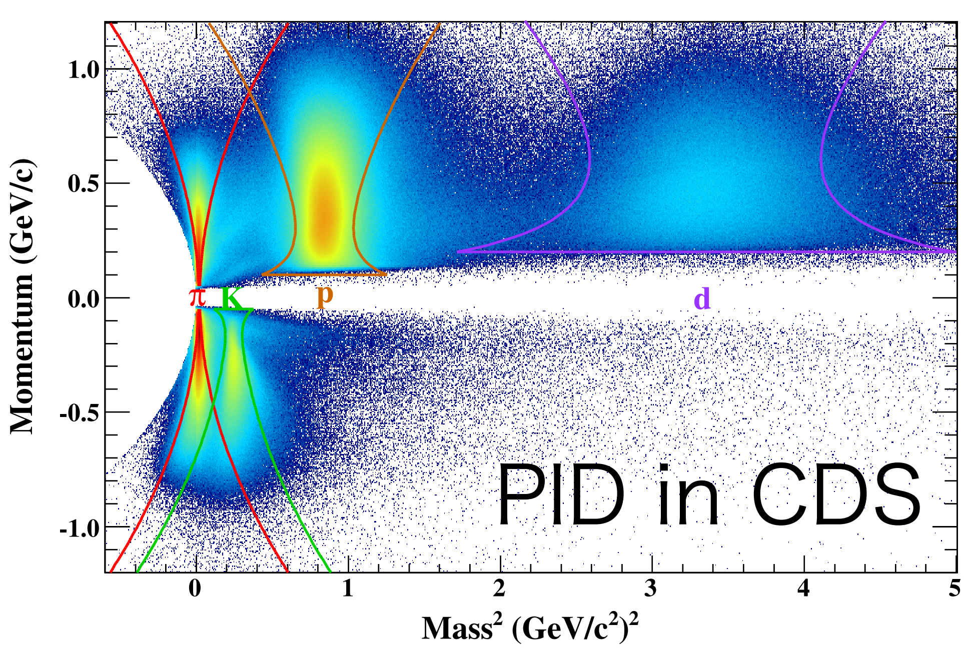
K. Agari et. al., PTEP 2012, 02B011



15-layer CDC and TOF hodoscopes

missing neutron selection

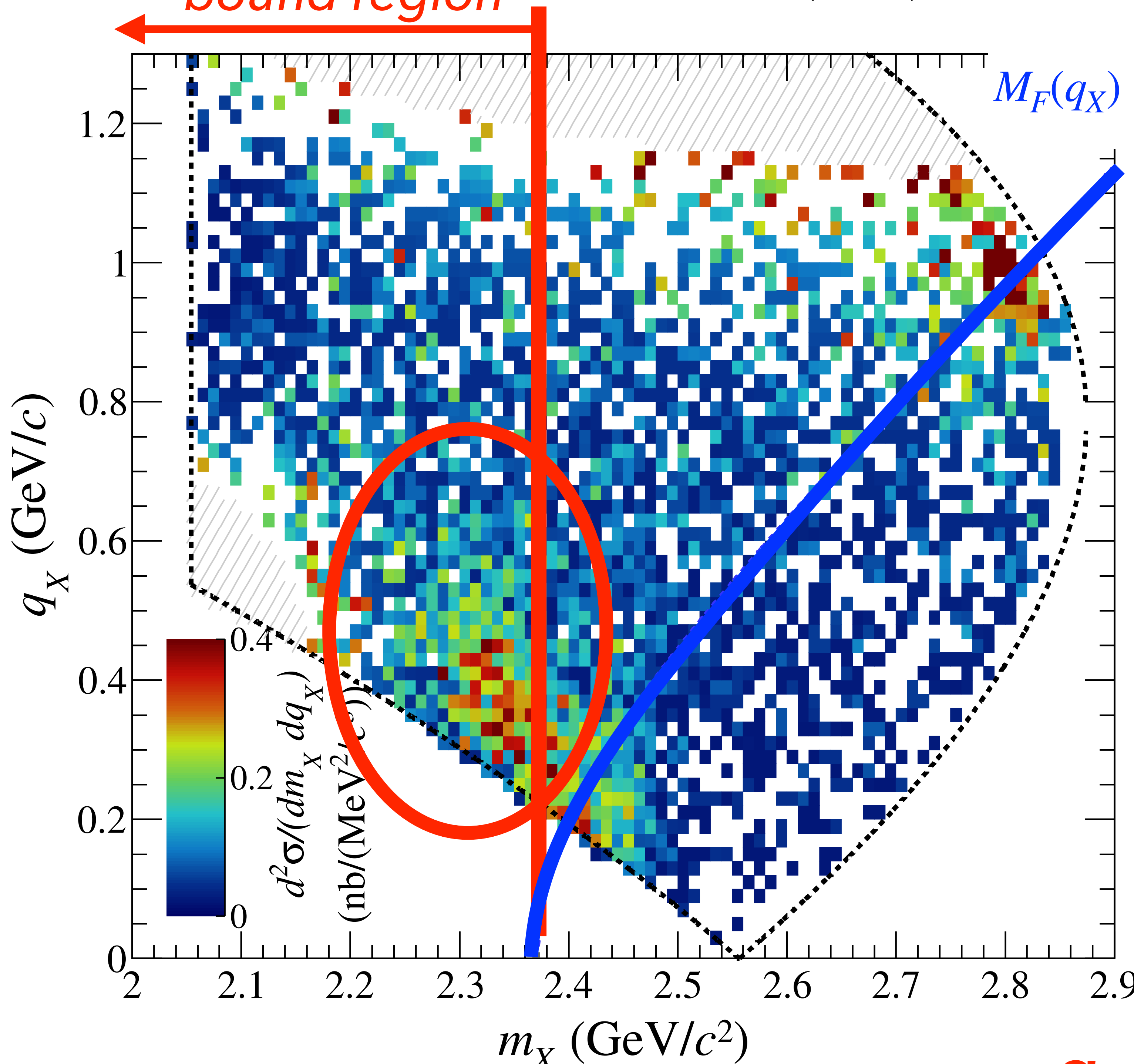




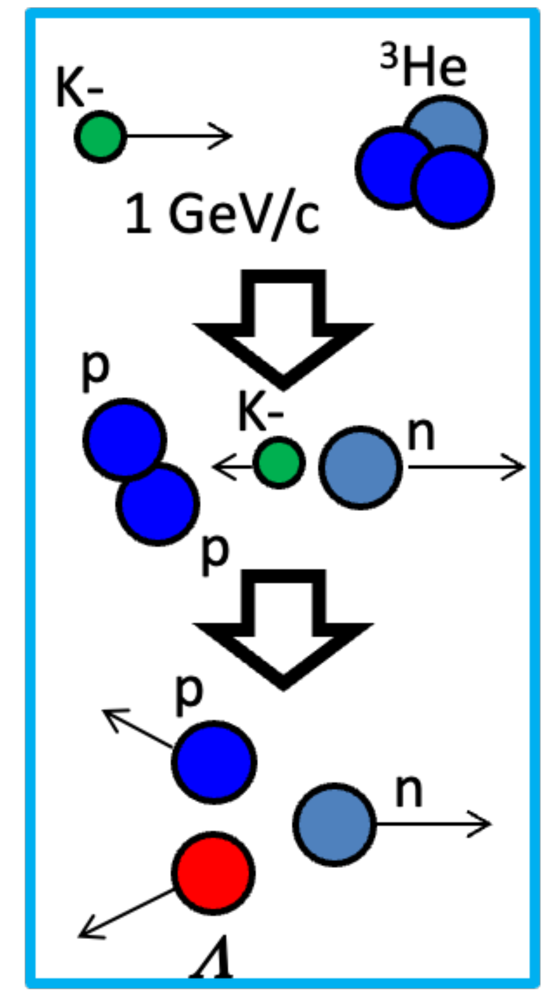
- Λpn events are selected with ~80% purity.
- ~20% $\Sigma^0 pn/\Sigma^- pp$ contamination

Obtained spectrum in J-PARC E15

PRC102(2020)044002.



$$M_F(q_X) = \sqrt{4m_N^2 + m_{\bar{K}}^2 + 4m_N\sqrt{m_{\bar{K}}^2 + q_X^2}}$$



"quasi-free" process

m_x: Λp invariant mass

q_x: momentum transfer to Λp system

q_X-indep. component below the threshold

2D Fit for the “$\bar{K}NN$” state

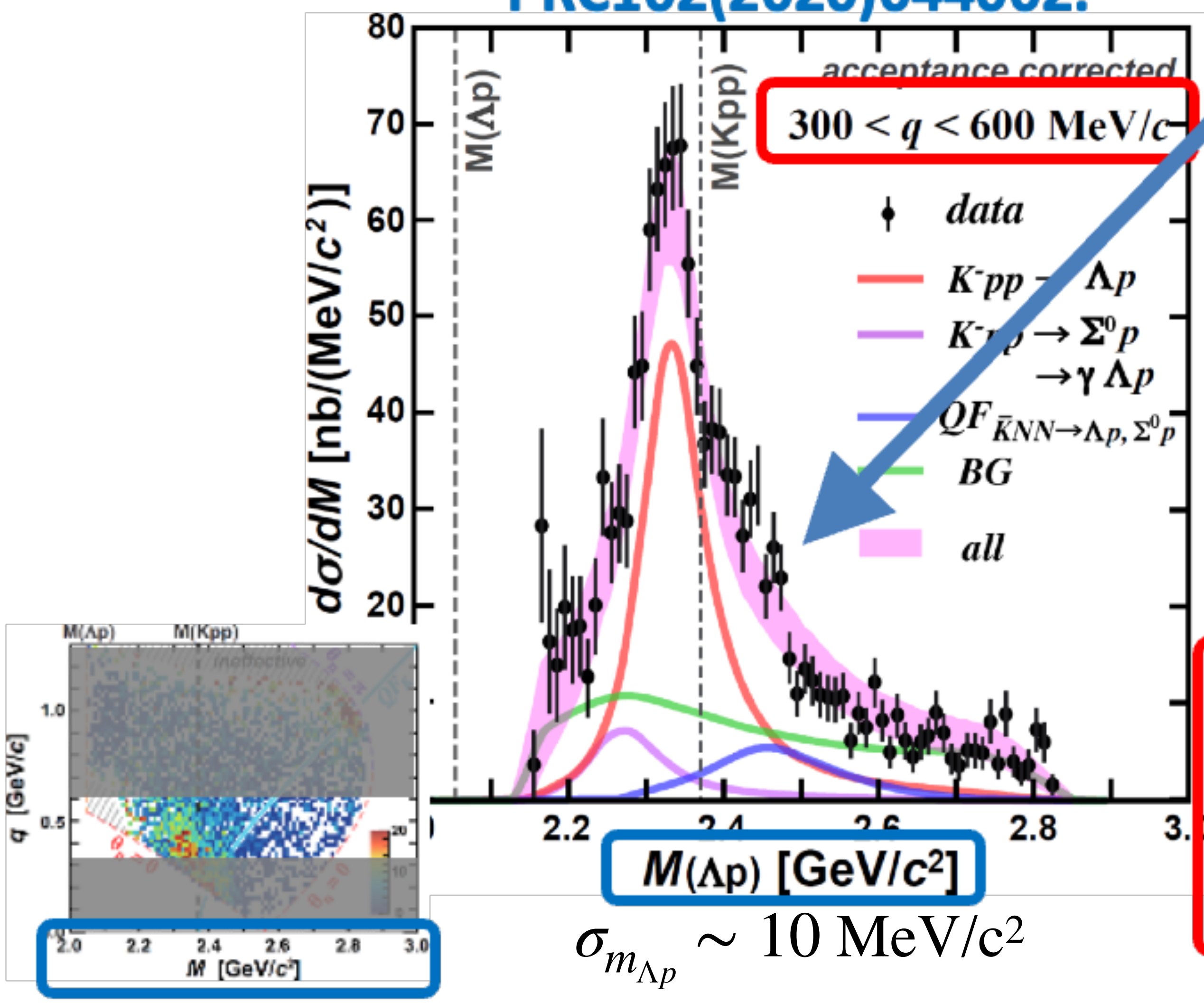
0.3 < q_x <0.6 GeV/c: Signals are well separated from other process

Fit with PWIA

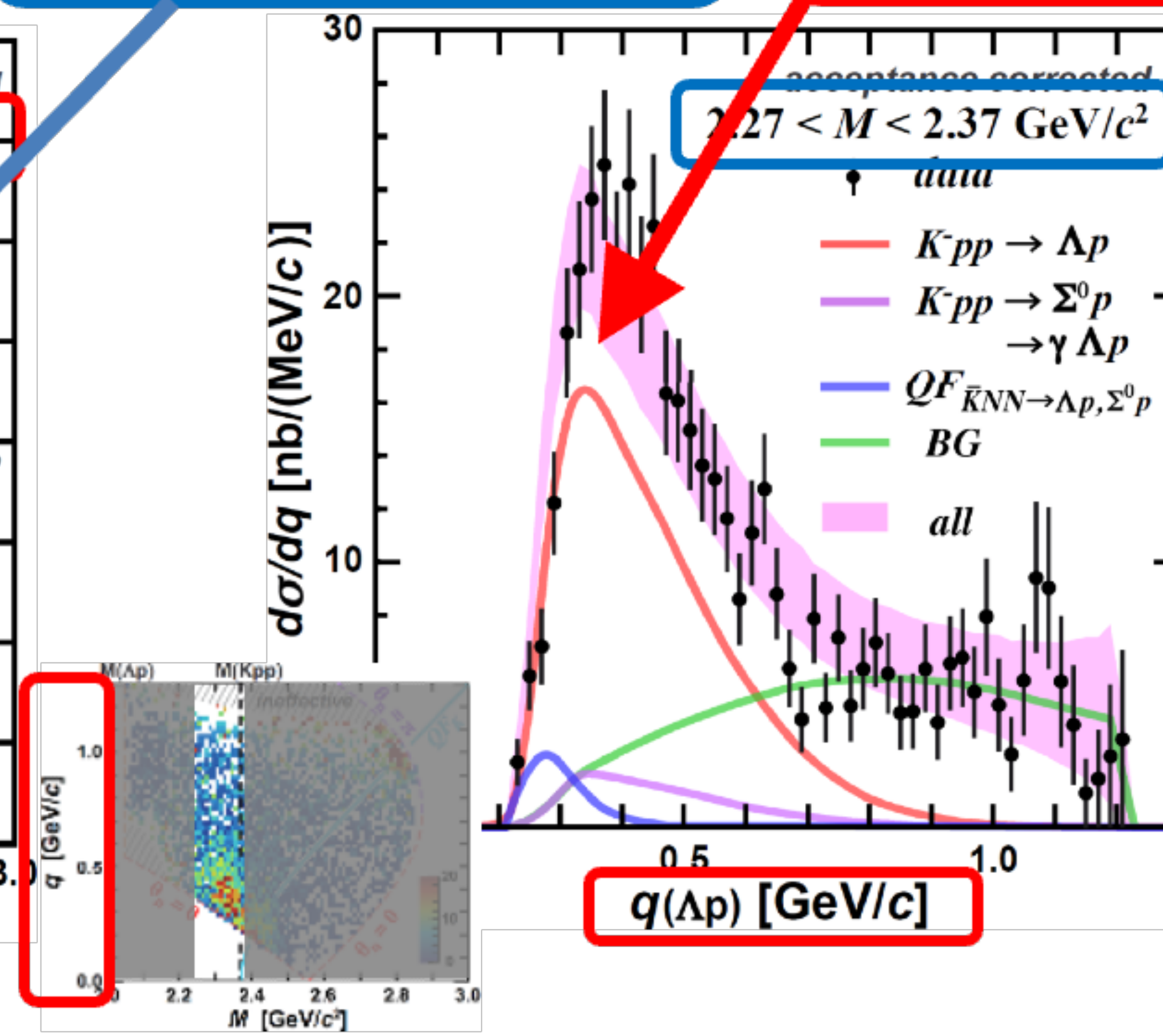
$$\sigma(M,q) \propto \rho(M,q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2} \times exp\left(-\frac{q^2}{{Q_{Kpp}}^2}\right)$$

phase space — Breit Wigner — form factor

PRC102(2020)044002.



$\sigma_{m_{\Lambda p}} \sim 10$ MeV/c²



B_{Kpp} ~ 40 MeV, Γ_{Kpp} ~ 100 MeV

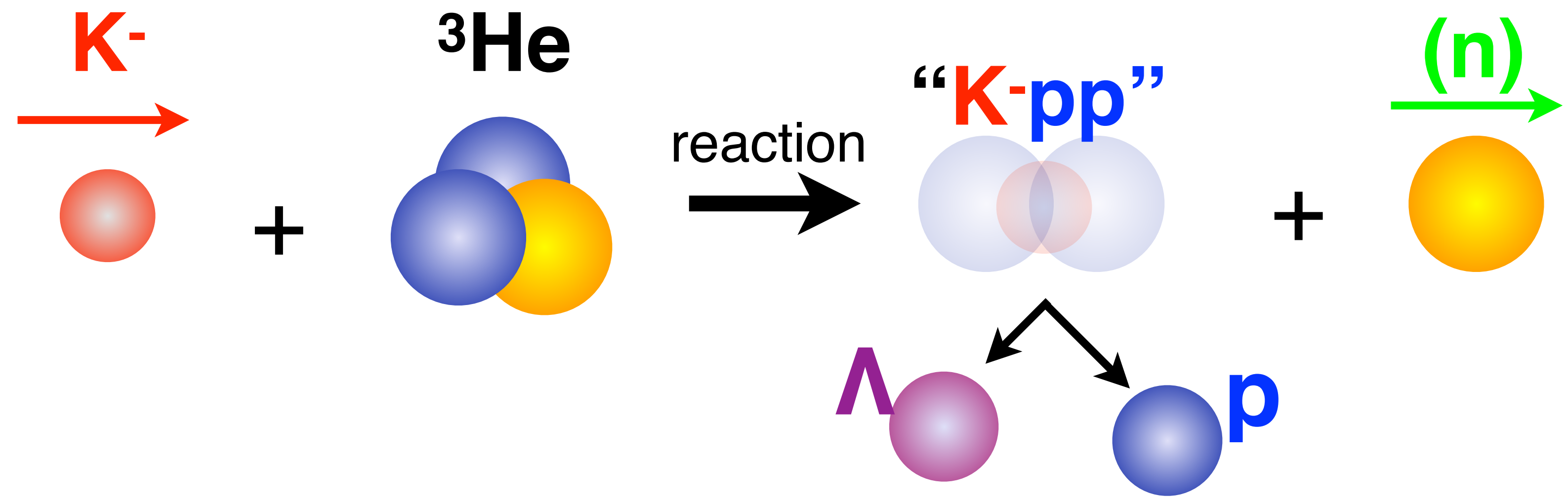
→ *large binding energy*

Q_{kpp} ~ 400 MeV (c.f. Q_{QF} ~ 200 MeV)

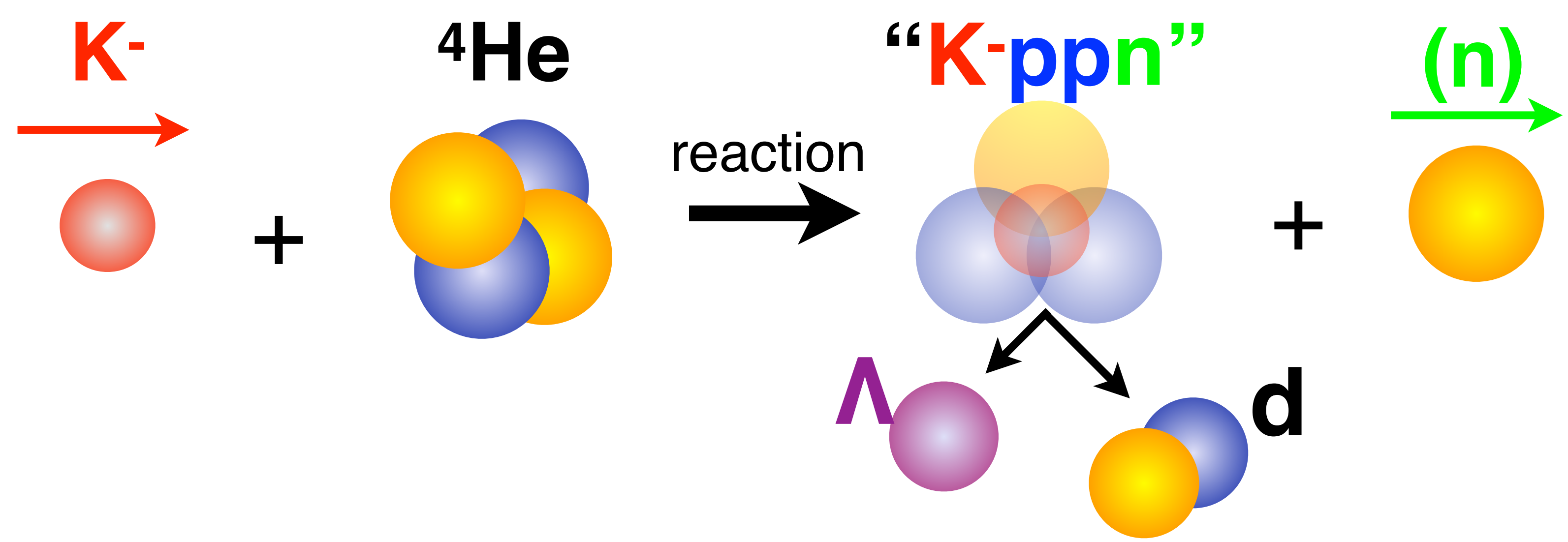
→ *wide momentum transfer*

(K-, n) reaction on other targets

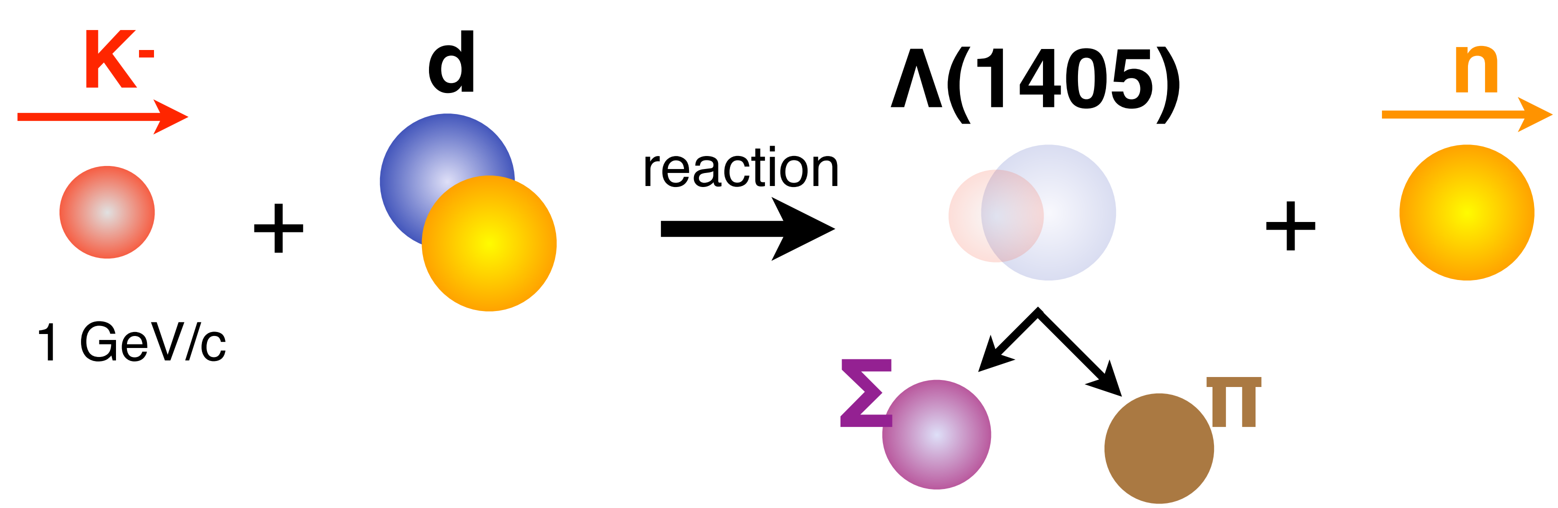
J-PARC E15



J-PARC T77

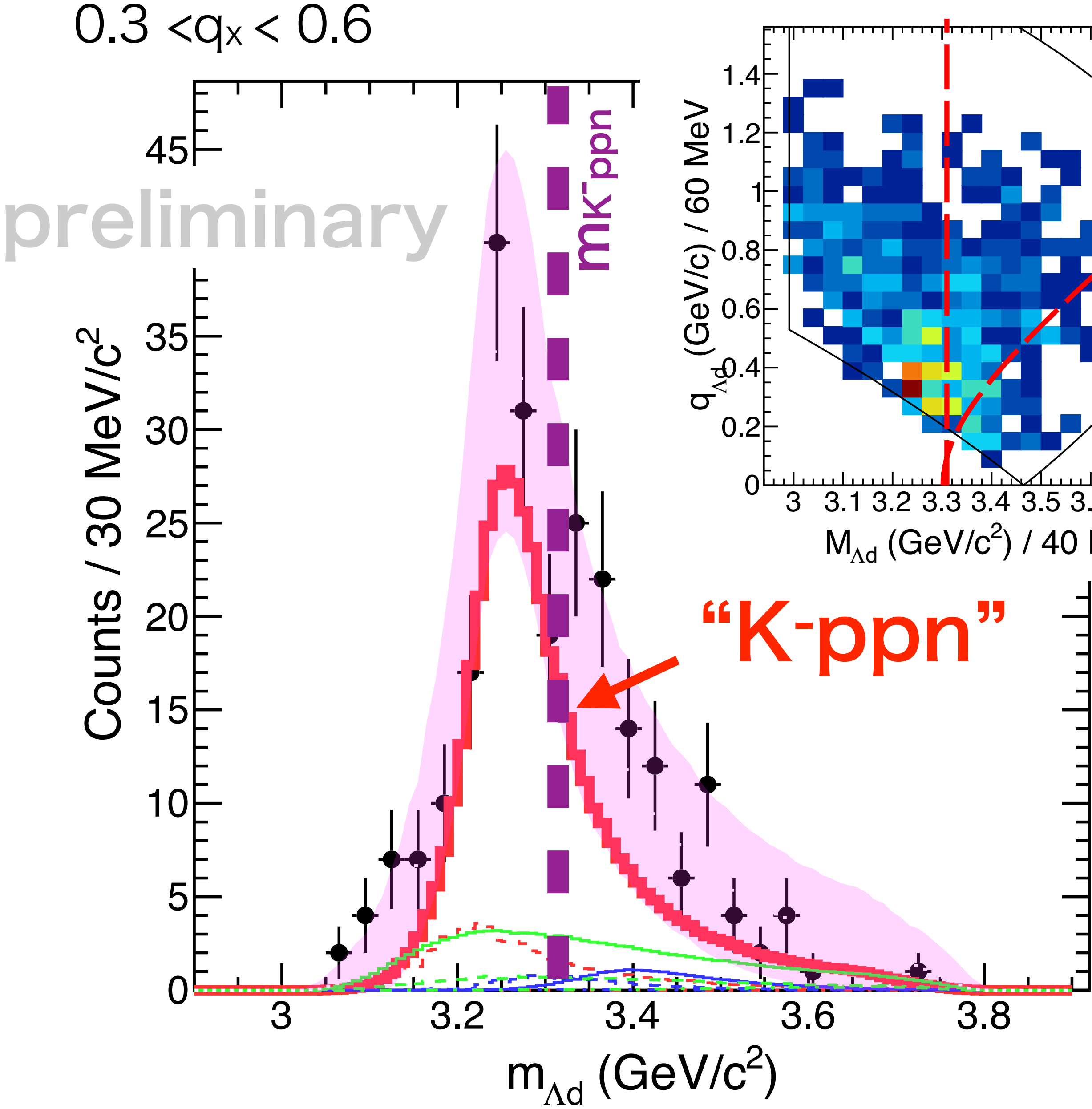


J-PARC E31



(K^-, n) reaction on other targets

0.3 <q_x < 0.6



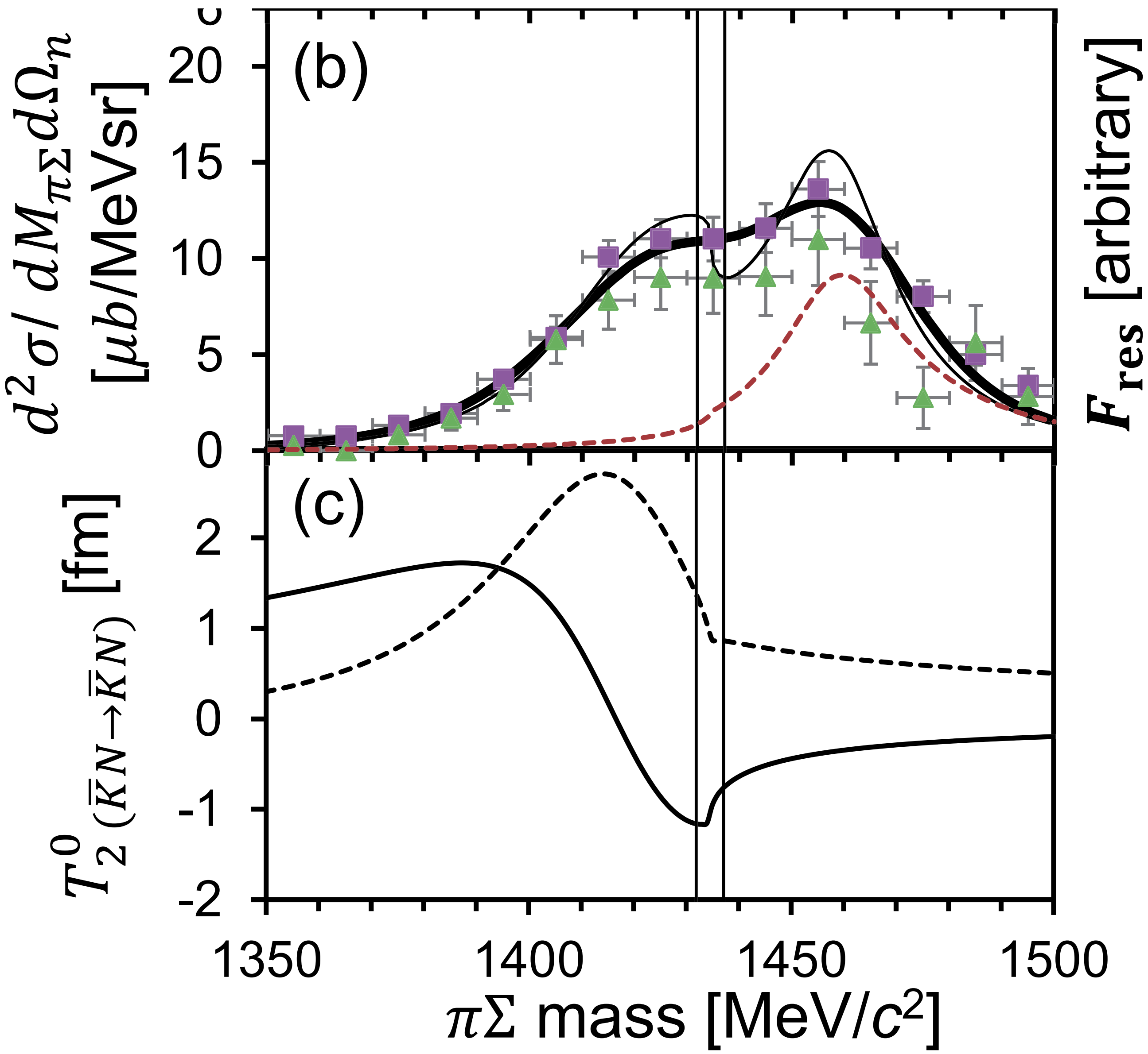
$B_{\bar{K}NNN} \sim 60 \pm 11(\text{stat})$ MeV

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

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

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

PLB837,137637(2023)



With two-step reaction processes

S-wave $\bar{K}N$ amplitude (I=0) was deduced

pole: 1417.7 – 26.1i [MeV]

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

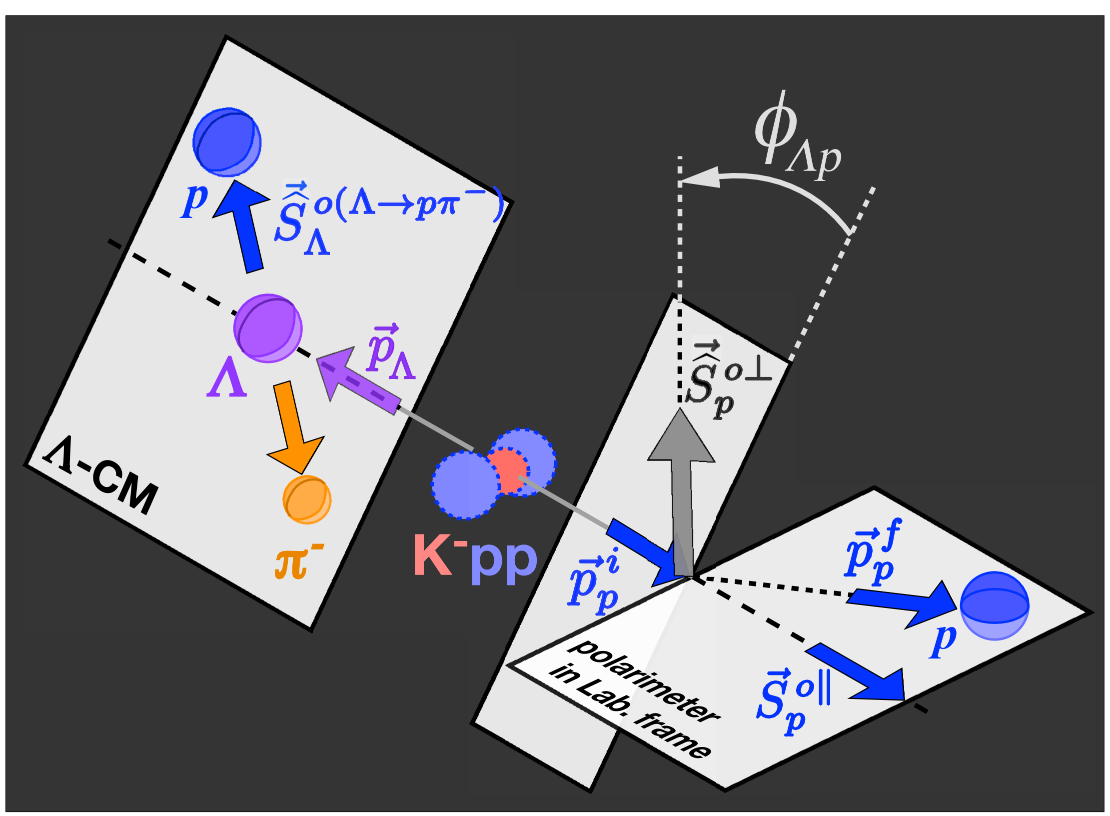
- Isospin partner should exist
  - $\Lambda n, \Sigma^- p$ analysis
  - need neutron detection

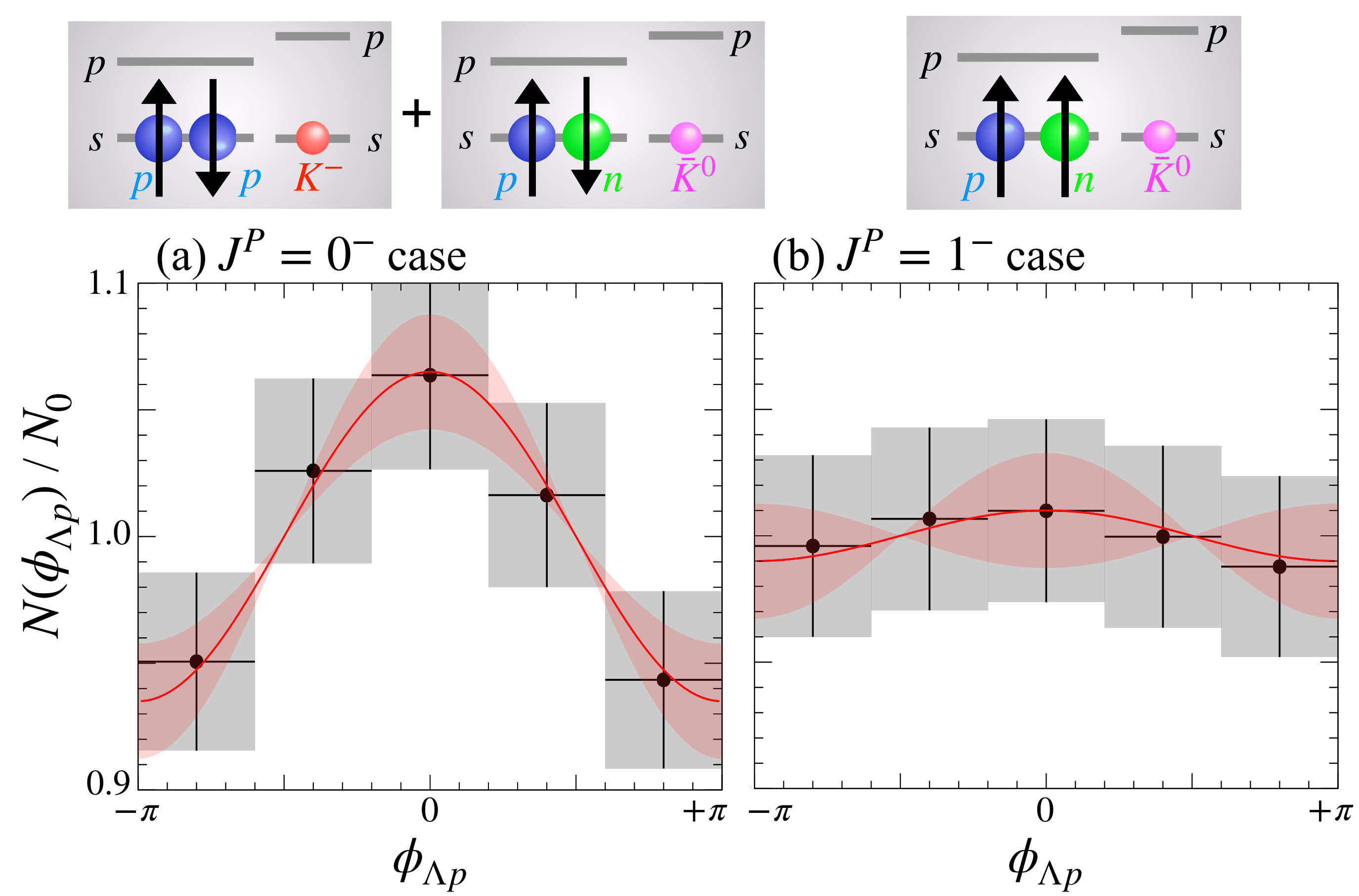
$\bar{K}NN(I = 1/2)$

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

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

- Spin-parity measurement:
  - spin-spin correlation between Λ and p
  - need polarimeter for proton





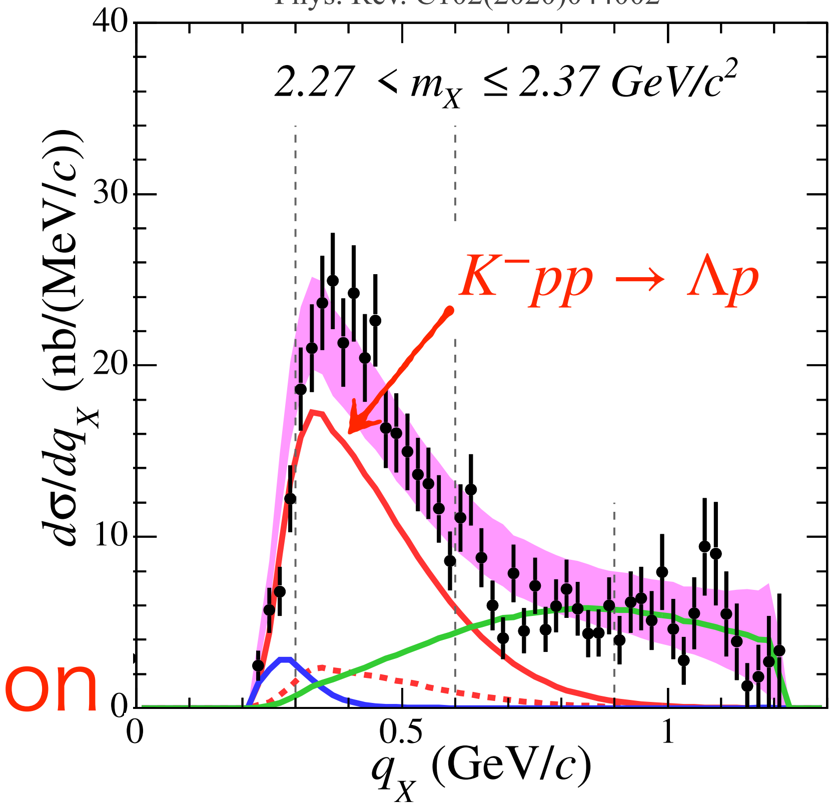
How compact is the system?

- Momentum-transfer distribution
  - large S-wave gauss. form factor
  - Q ~ 400 MeV/c
- Decay branching ratio
  - $\bar{K}NN \to \Lambda N$ vs. $\bar{K}NN \to \pi Y N_s$
  - $\bar{K}NNN \to \Lambda d$ vs. $\bar{K}NNN \to \Lambda N N_s$
  - forward nucleon detection would be useful: $K^- + {}^3\mathrm{He} \to \bar{K}NN + N$
- Momentum of the "spectator" nucleon

neutron detection

forward TOF

Phys. Rev. C102(2020)044002



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

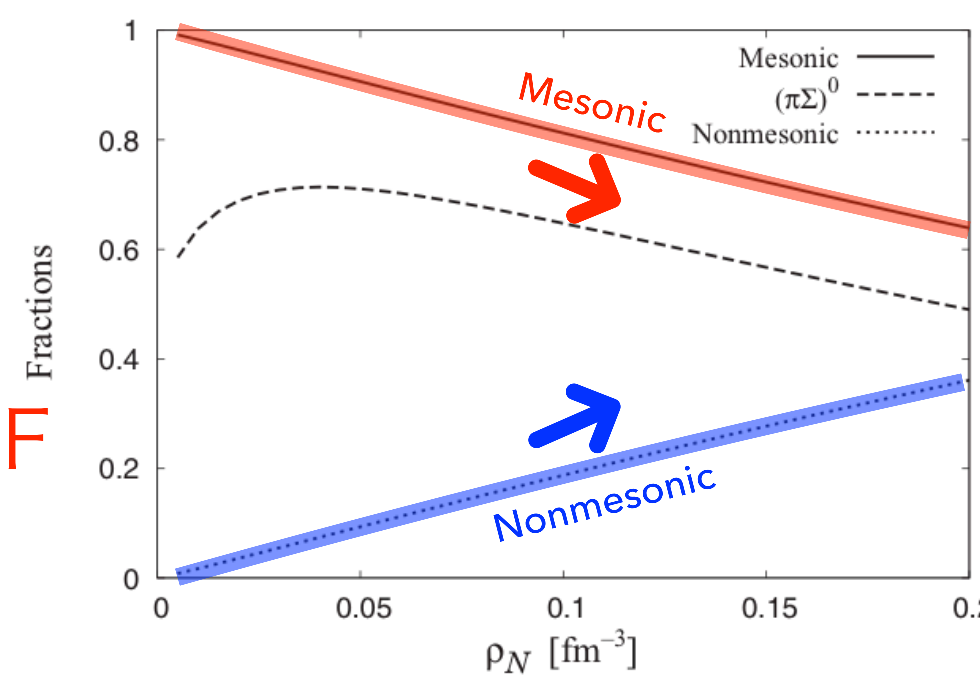
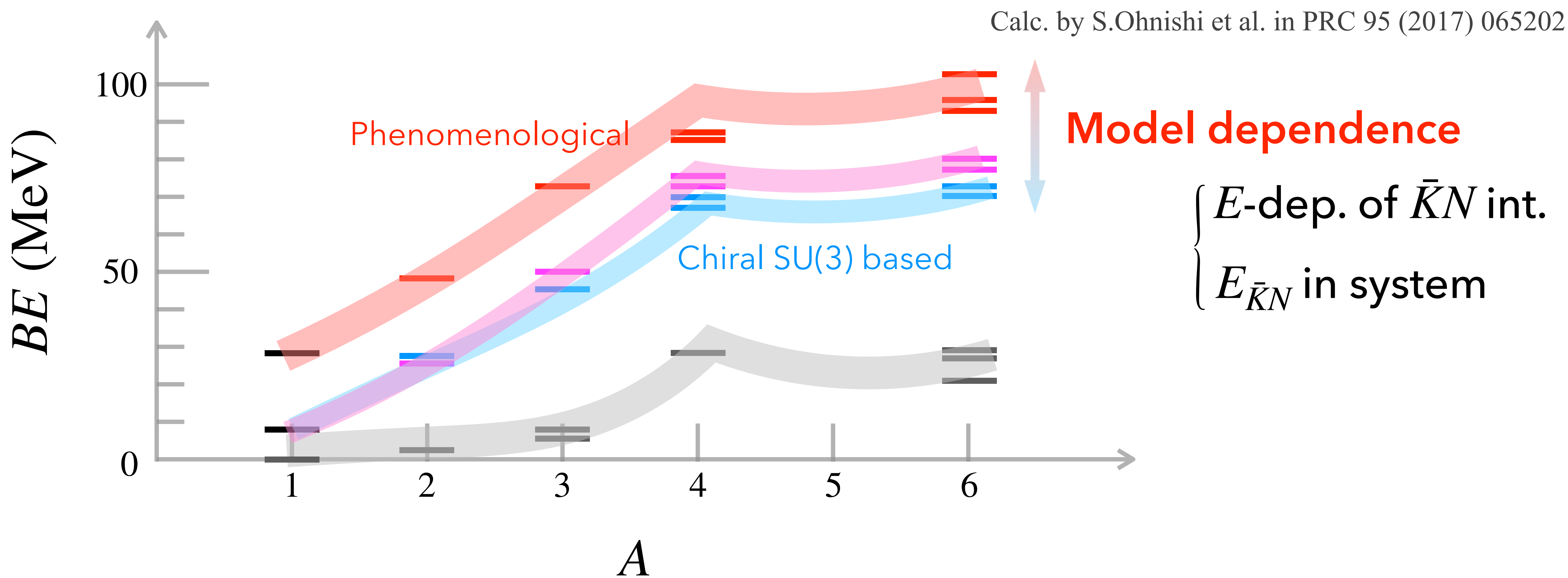


FIG. 13. Fractions of mesonic, sum of $(\pi\Sigma)^0$, and nonmesonic absorption to total absorption.

How general are the K^bar-nuclei?

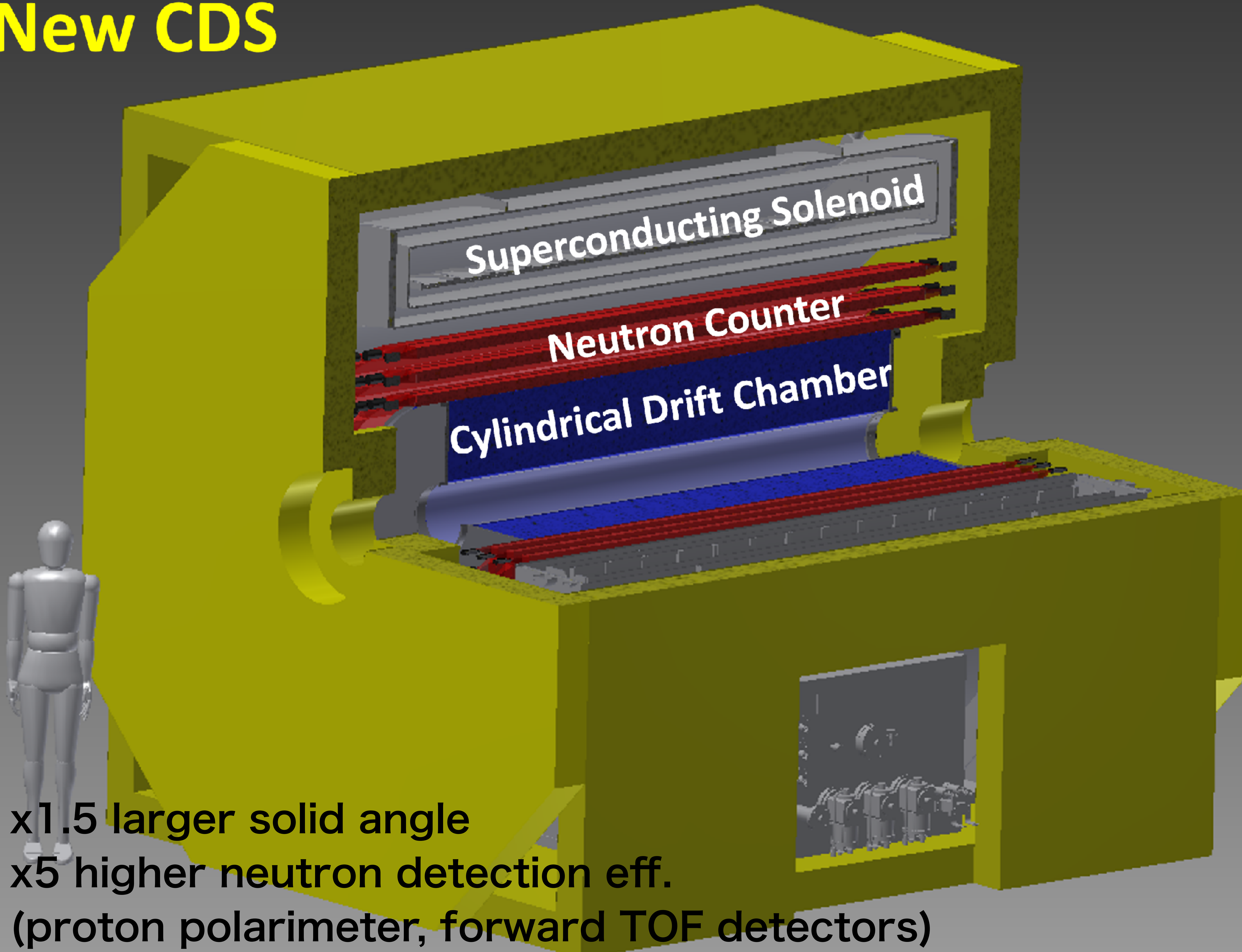


- $K^- + {}^4\mathrm{He} \rightarrow \bar{K}NNN + n$
- $K^- + {}^6\mathrm{Li} \rightarrow \bar{K}NNNN + d$
- $K^- + {}^7\mathrm{Li} \rightarrow \bar{K}NNNNNN + n/p$

forward TOF

Exclusive analysis becomes difficult.→ Inclusive + tag.

New CDS

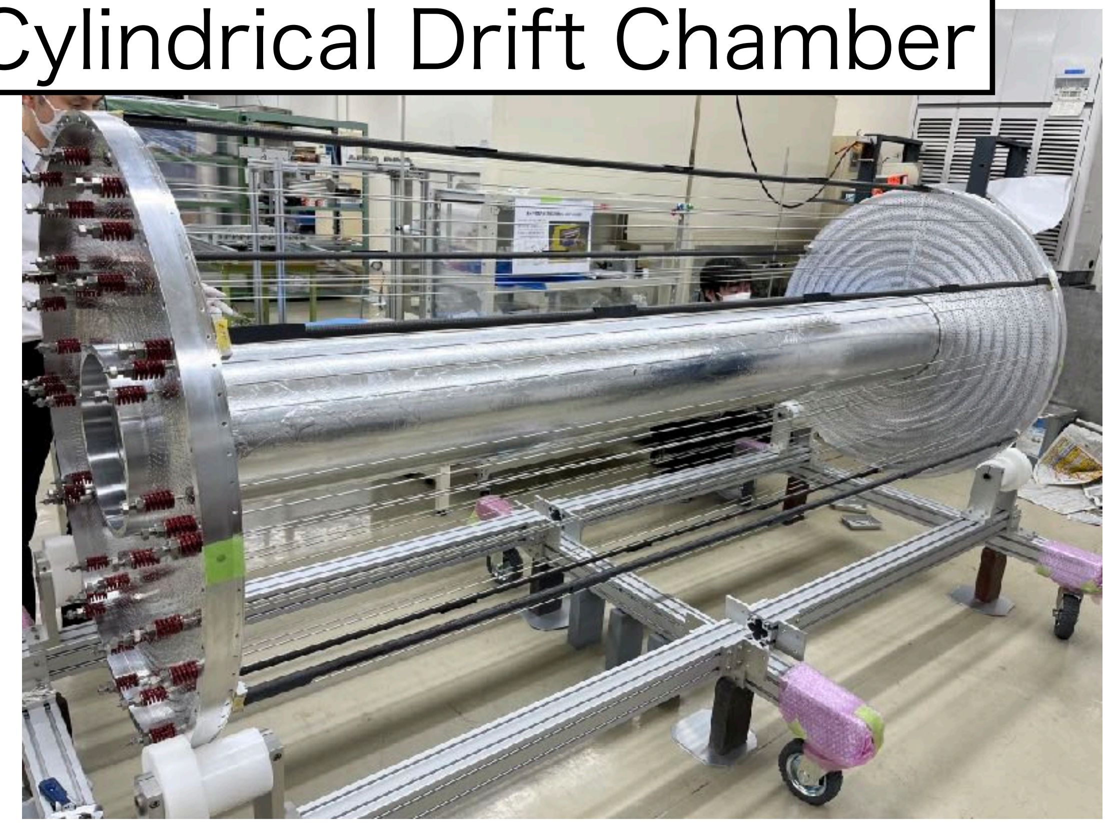


x1.5 larger solid angle
x5 higher neutron detection eff.
(proton polarimeter, forward TOF detectors)

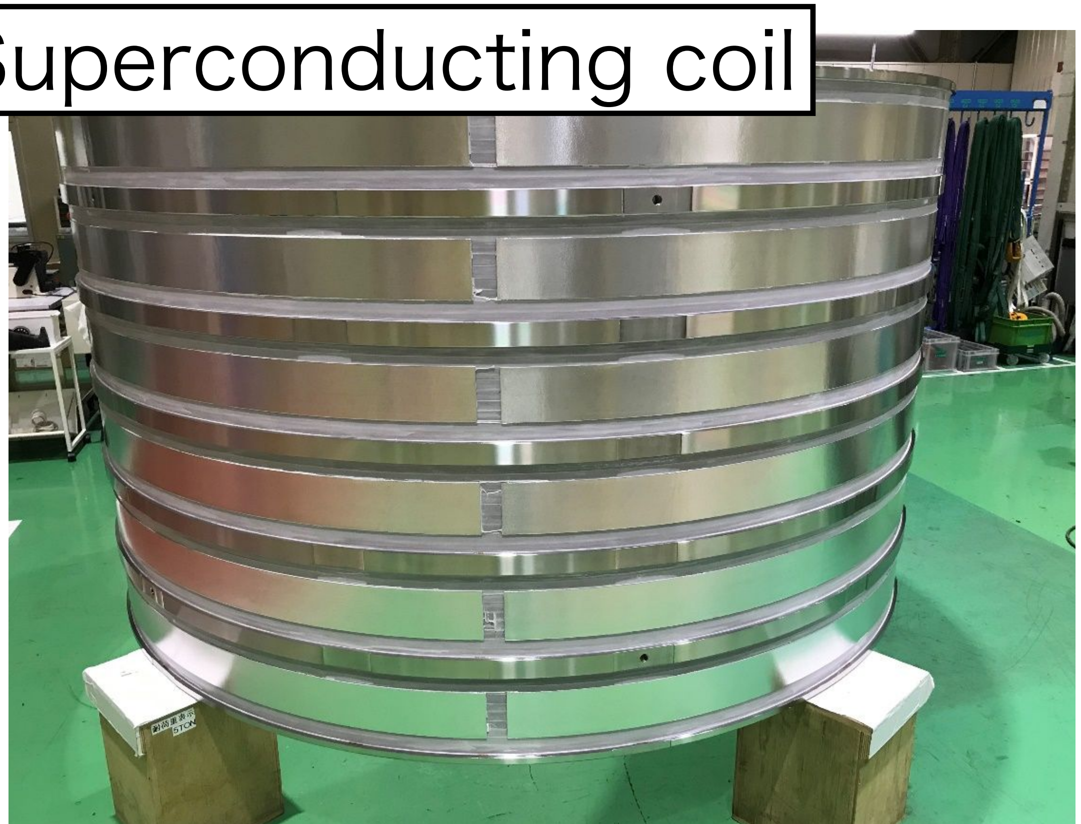
Construction status

Solenoid york

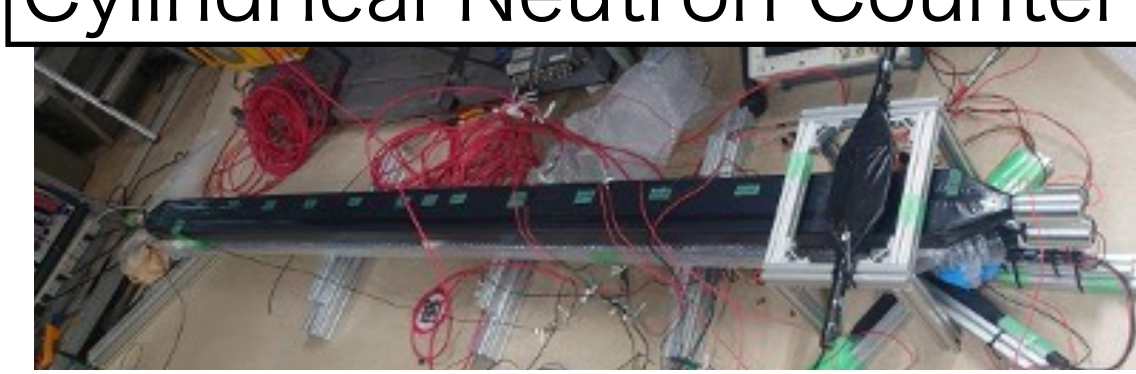
Cylindrical Drift Chamber



Superconducting coil



Cylindrical Neutron Counter



- JFY2024: complete solenoid
- JFY2025: start installation
- JFY2026: first beam?

Summary

- **Anti-kaon** could be a unique probe for hadron physics.
  We are performing systematic experiments at J-PARC.

- $\bar{K}NN$ signals are observed in **^{3}He(K^{-},Λp)n** channel.

- $\bar{K}NNN$ hint in **^{4}He(K^{-},Λd)n** events in a test experiment.

- New-generation experiment starts from JFY2026 with a new solenoid spectrometer

- **Looking for more collaborators including theorists!**