Kaonic nuclei at J-PARC

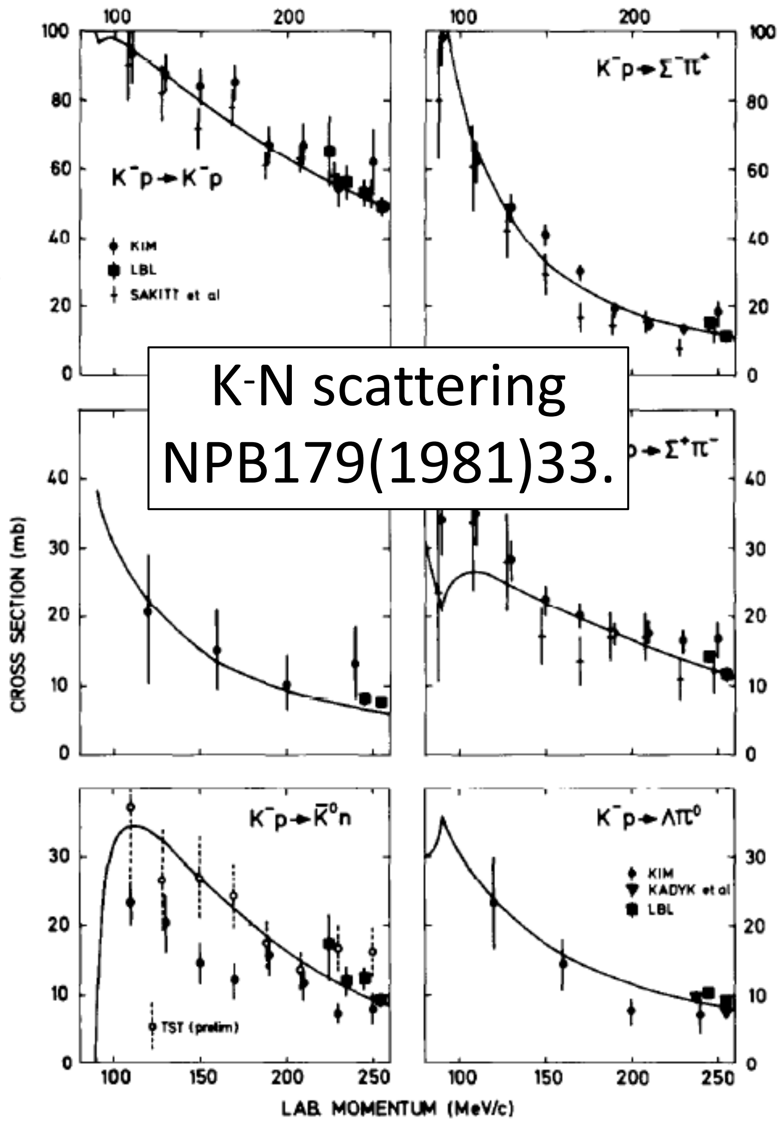
K1.8BR

Tadashi Hashimoto (RIKEN)

on behalf of J-PARC E15/T77/E80/P89 collaboration

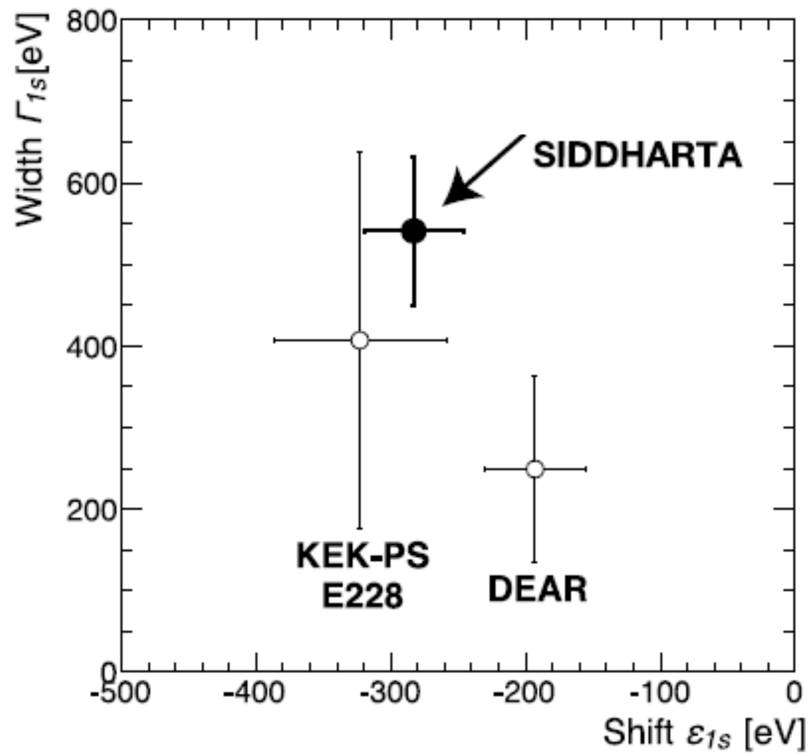
July 24, 2024 @ J-PARC

K^barN interaction

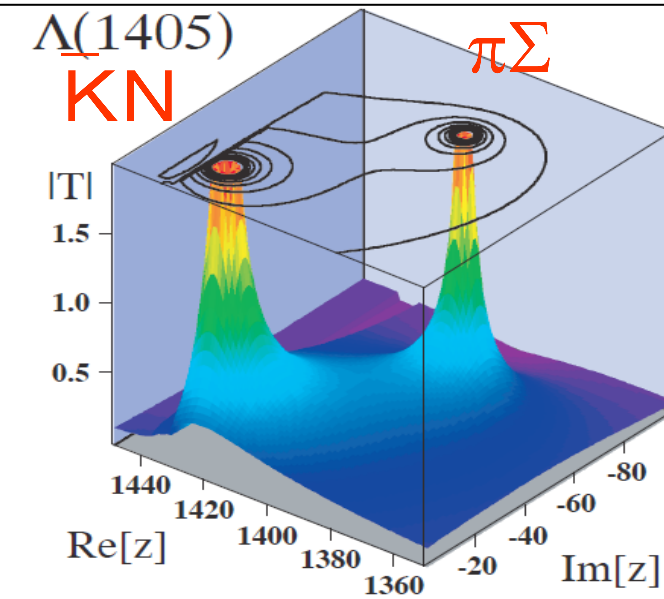


K-N scattering
NPB179(1981)33.

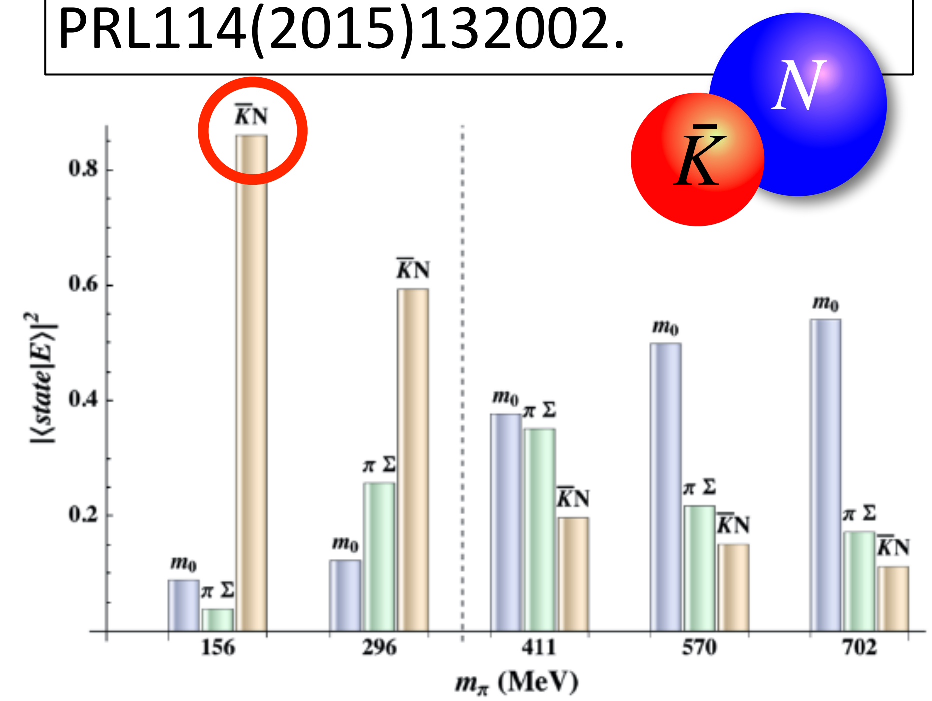
K-p atom
PLB704(2011)113.



Λ(1405) in chiral unitary model
T. Hyodo



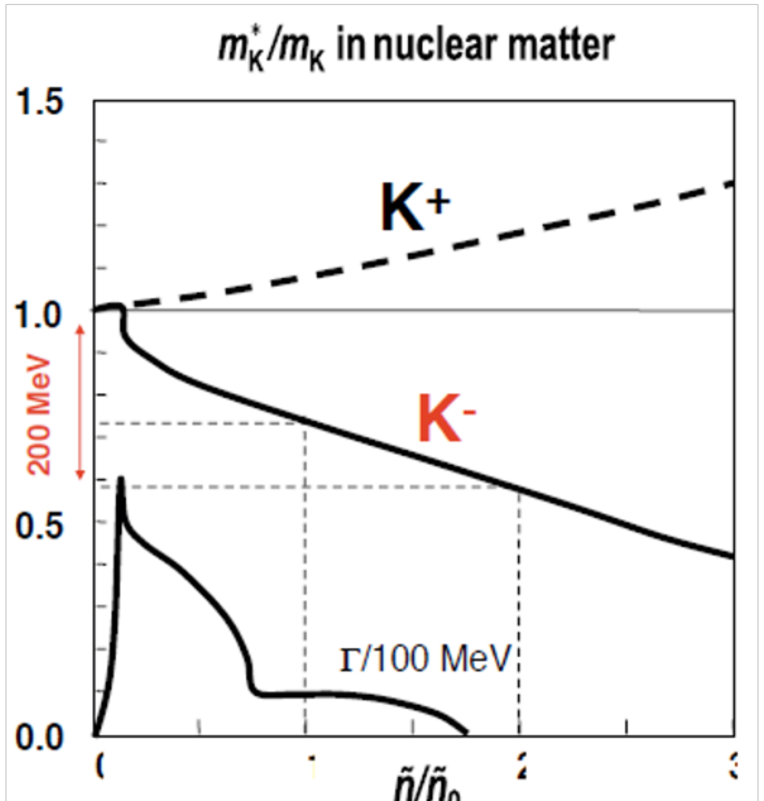
K^barN molecule from Lattice QCD
PRL114(2015)132002.



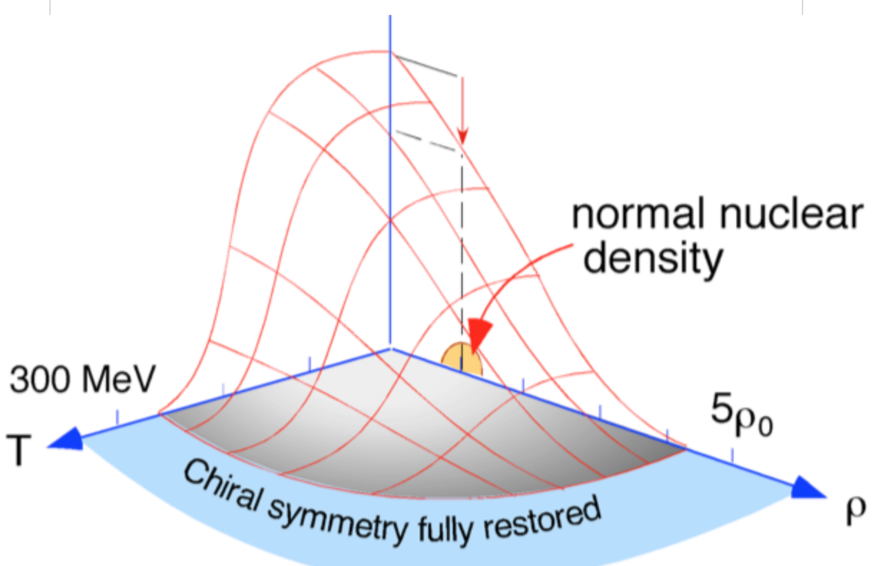
- Strong attraction in I=0 from scattering and X-ray experiements.
- $\Lambda(1405) = \bar{K}N$ molucle picture is now widely accepted

Why not kaonic nucleus with additional nucleons?

Kaon in nuclei

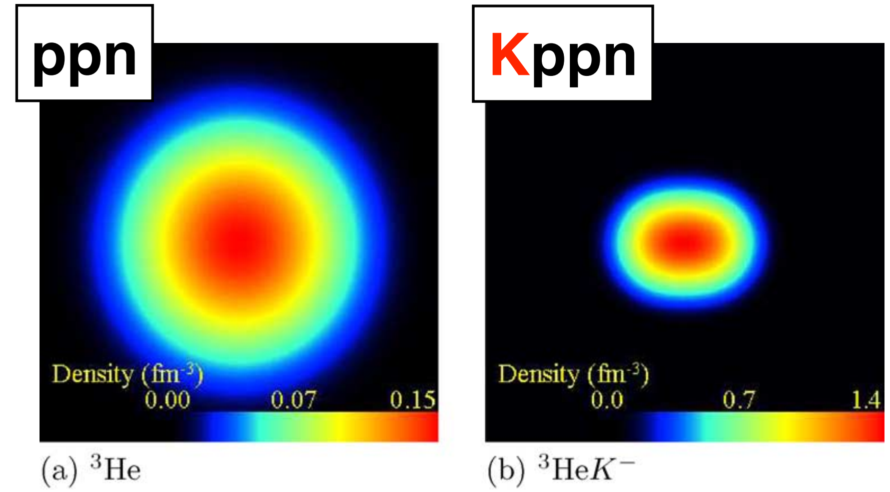


T. Waas, N. Kaiser & W. Weise, Phys. Lett. B379 (1996) 34.

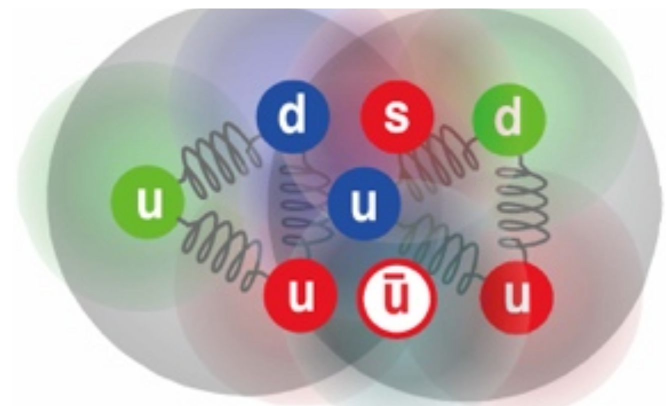


W.Weise NPA553,59 (1993)

Kaon mass changes?

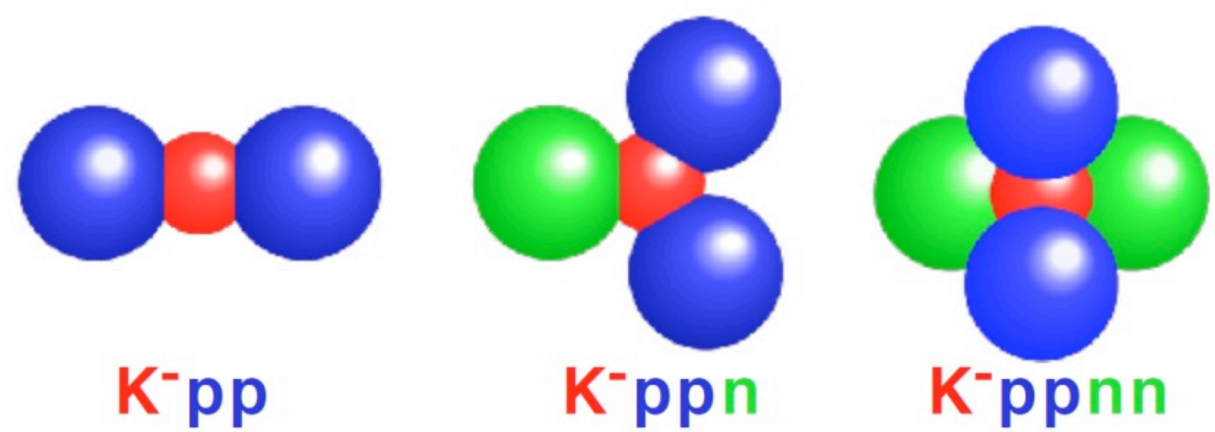


A. Dote, H. Horiuchi, Y. Akaishi and T. Yamazaki, Phys. Lett. B 590 (2004) 51



Compact system?

→nucleon overlaps? dense matter?

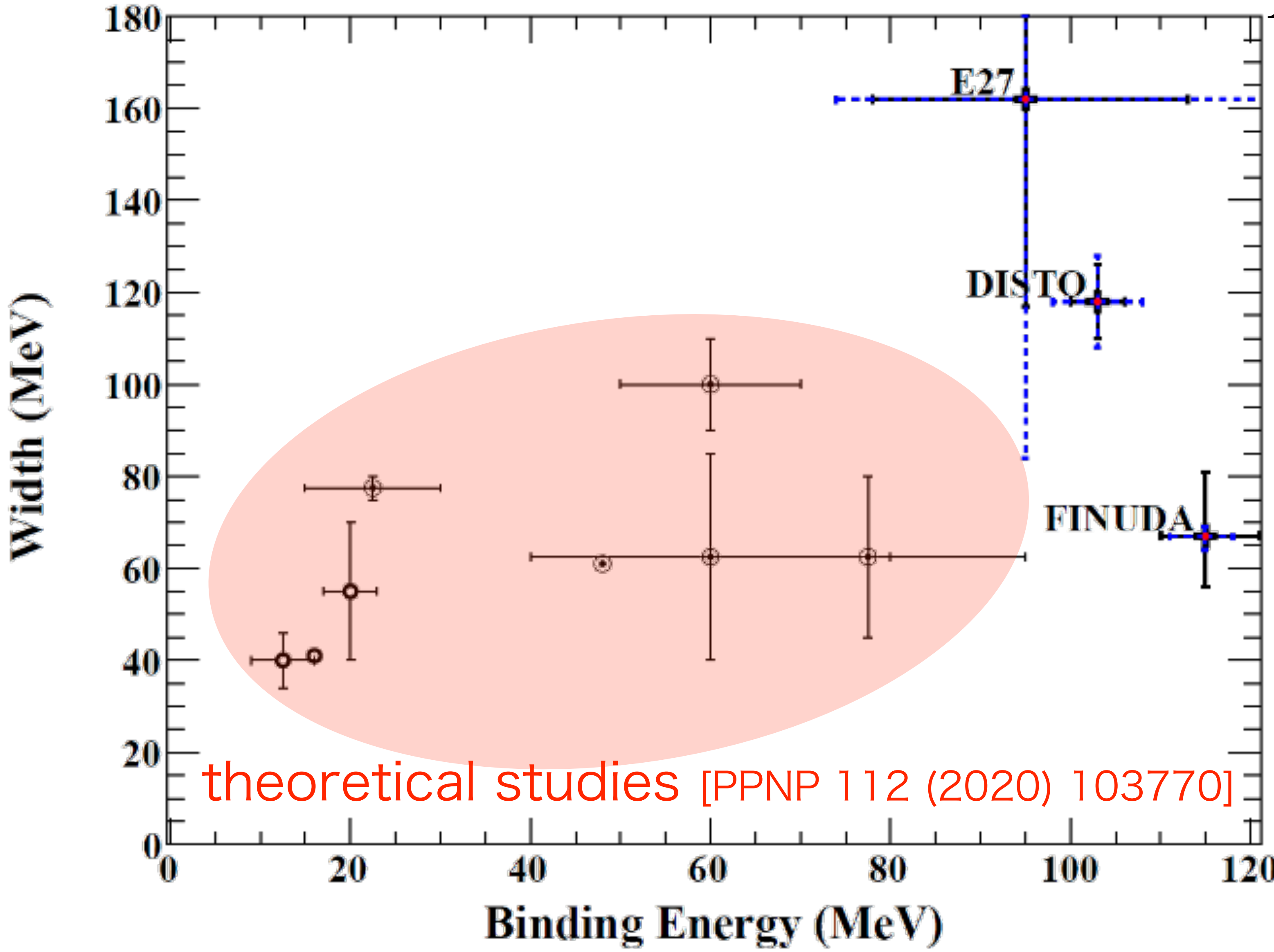


$\bar{K}N$ attraction & NN replusion

→molecule-like structure?

The simplest kaonic nucleus

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



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

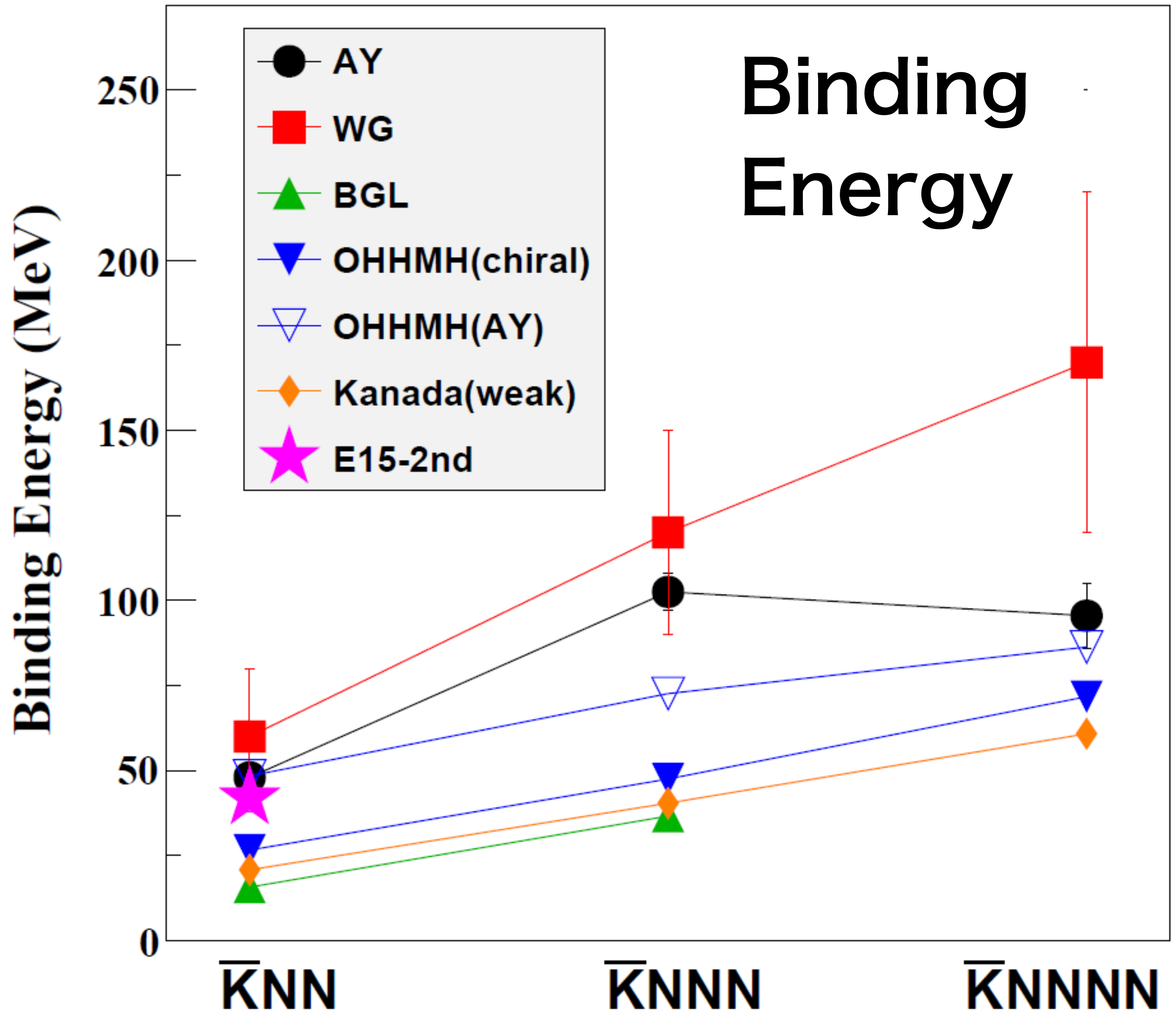
Null results

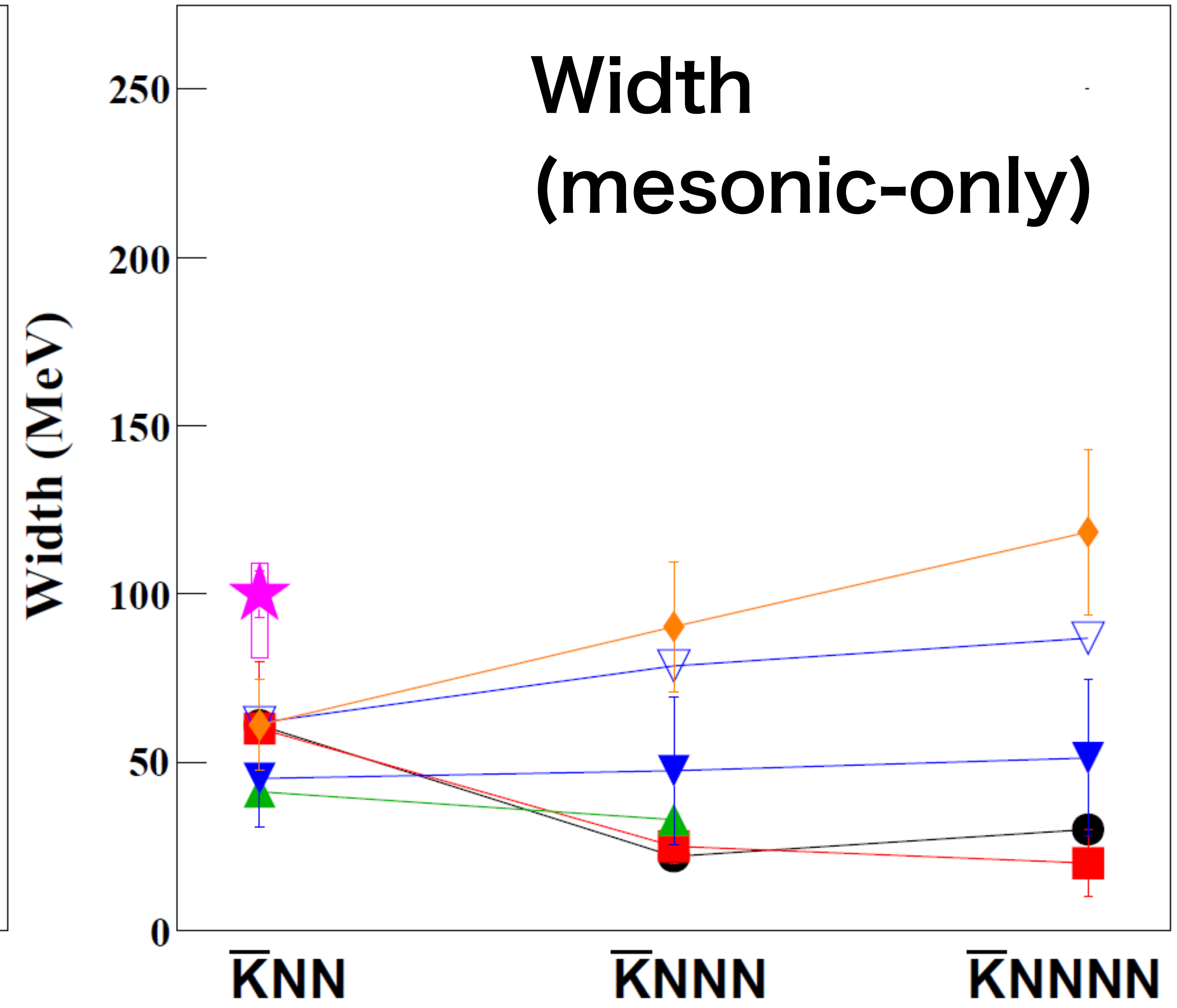
- LEPS: $p(\gamma, \pi^- K^+)X$
- HADES: $pp \to \Lambda p K^+$
- AMADEUS: C$(K^-_{stopped}, \Lambda p)$

- **Theoretical calculations agree on the existence of $\bar{K}NN$, although B.E. and Γ depend on the $\bar{K}N$ interaction models.**
- **No conclusive experimental evidence before us.**

Mass number dependence

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



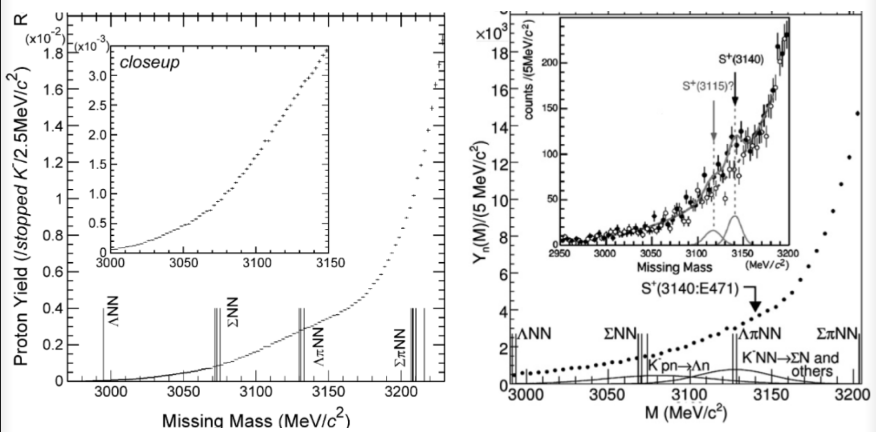


The larger the nucleus, the larger the binding.
Systematic measurements will establish kaonic nuclei

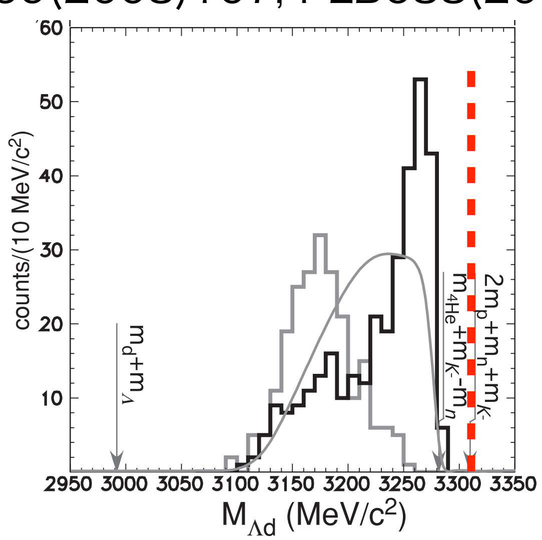
$\bar{K}NNN$: Experimental situaion

Stopped K⁻ on ⁴He

E471/E549@KEK



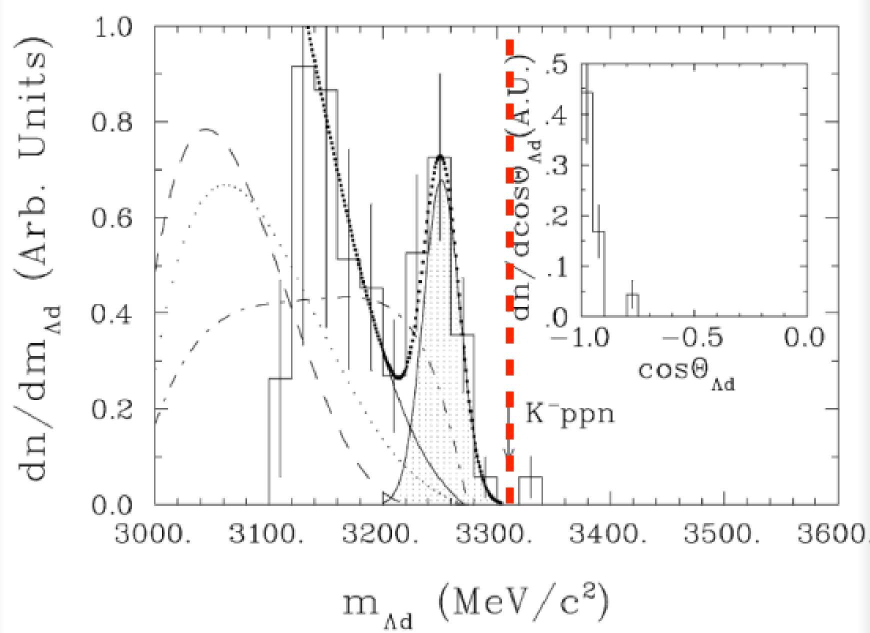
PLB659(2008)107, PLB688(2010)43



PRC76(2007)068202

Stopped K⁻ on Li/C back-to-back Λd

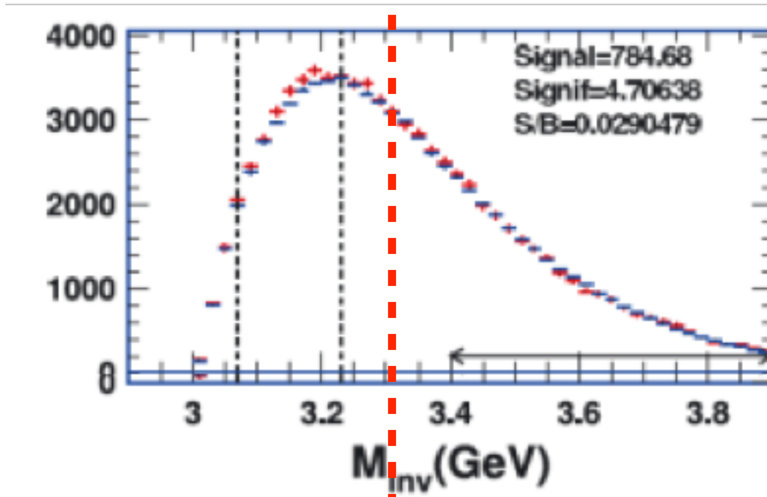
FUNUDA@DAΦNE

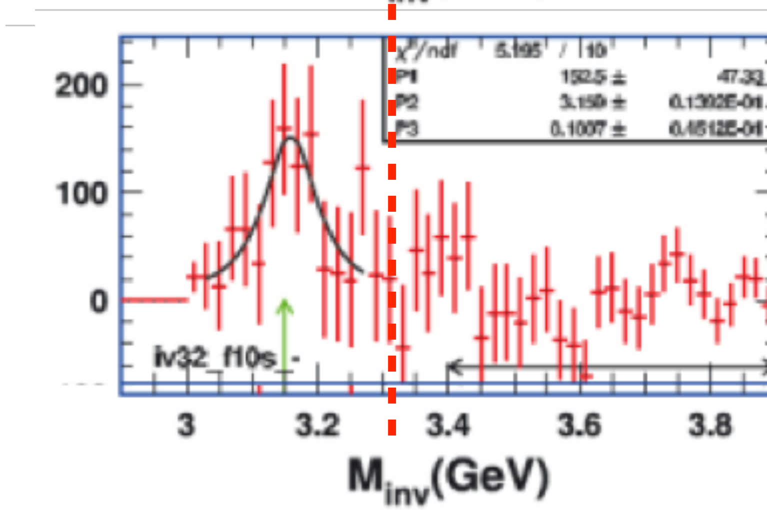


PLB654(2007)80

Λd in Ni+Ni

FOPI@GSI

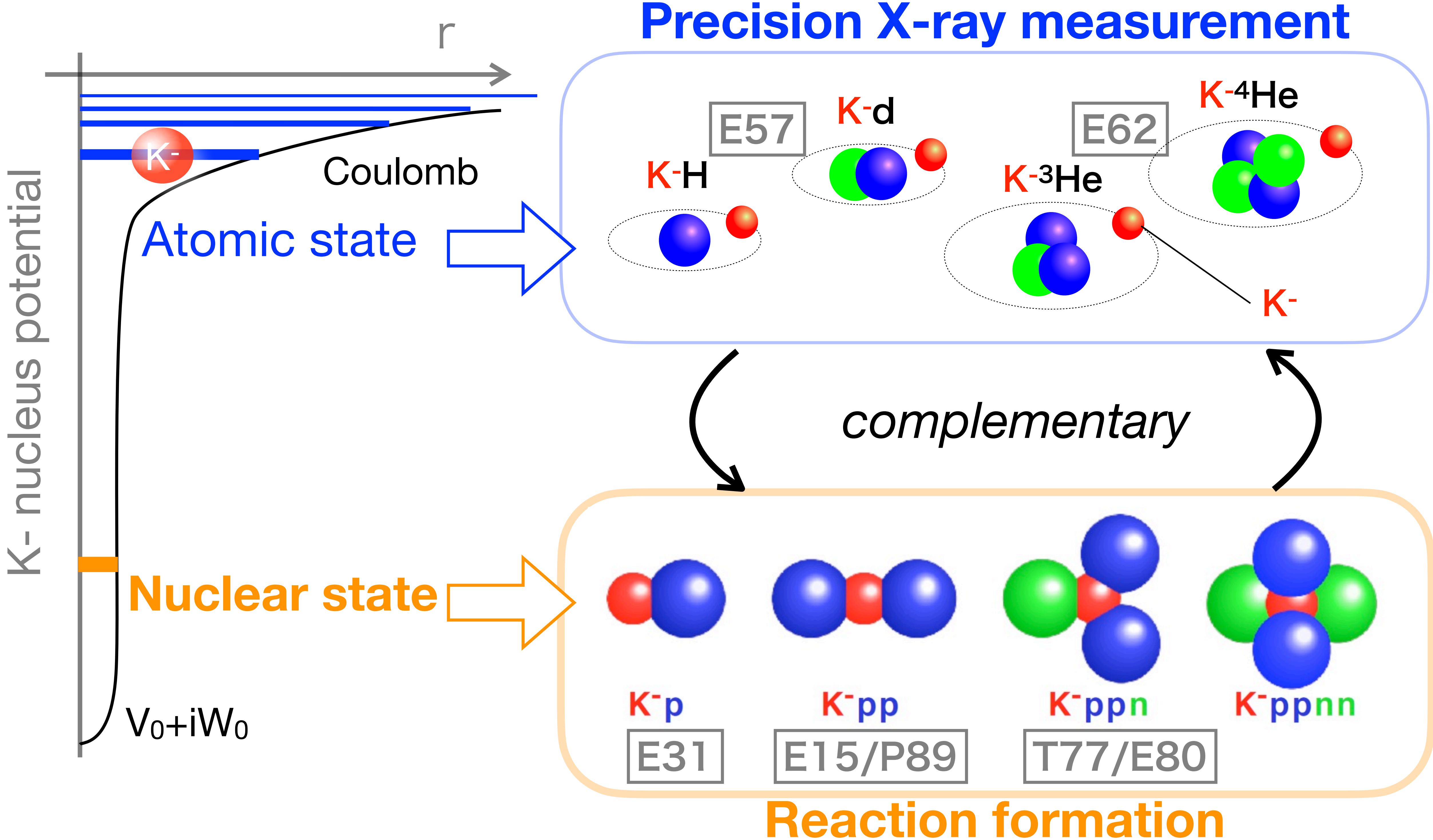




EXA05 Proceedings (2005)

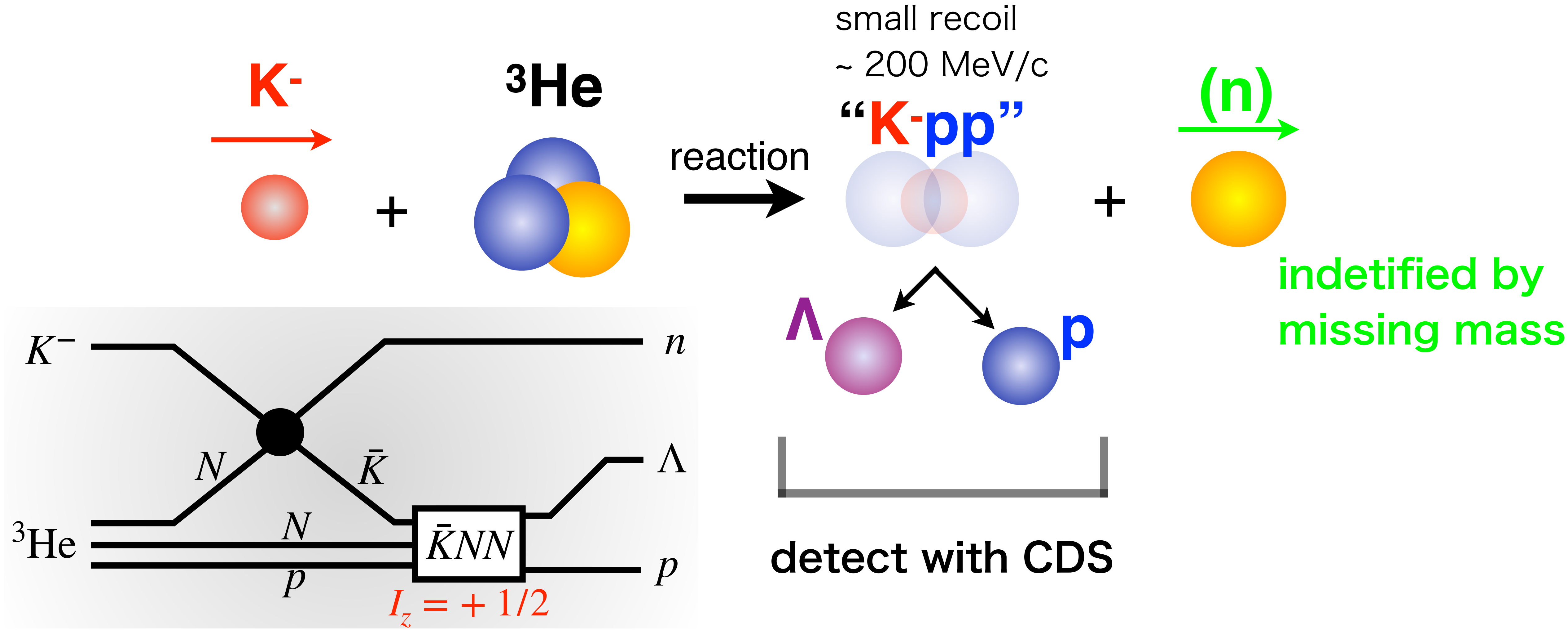
- **Some experimental searches in 2000s. No conclusive result.**
- **multi-N absorptions hide bound-state signals in Stop-K**

Experiments at J-PARC K1.8BR



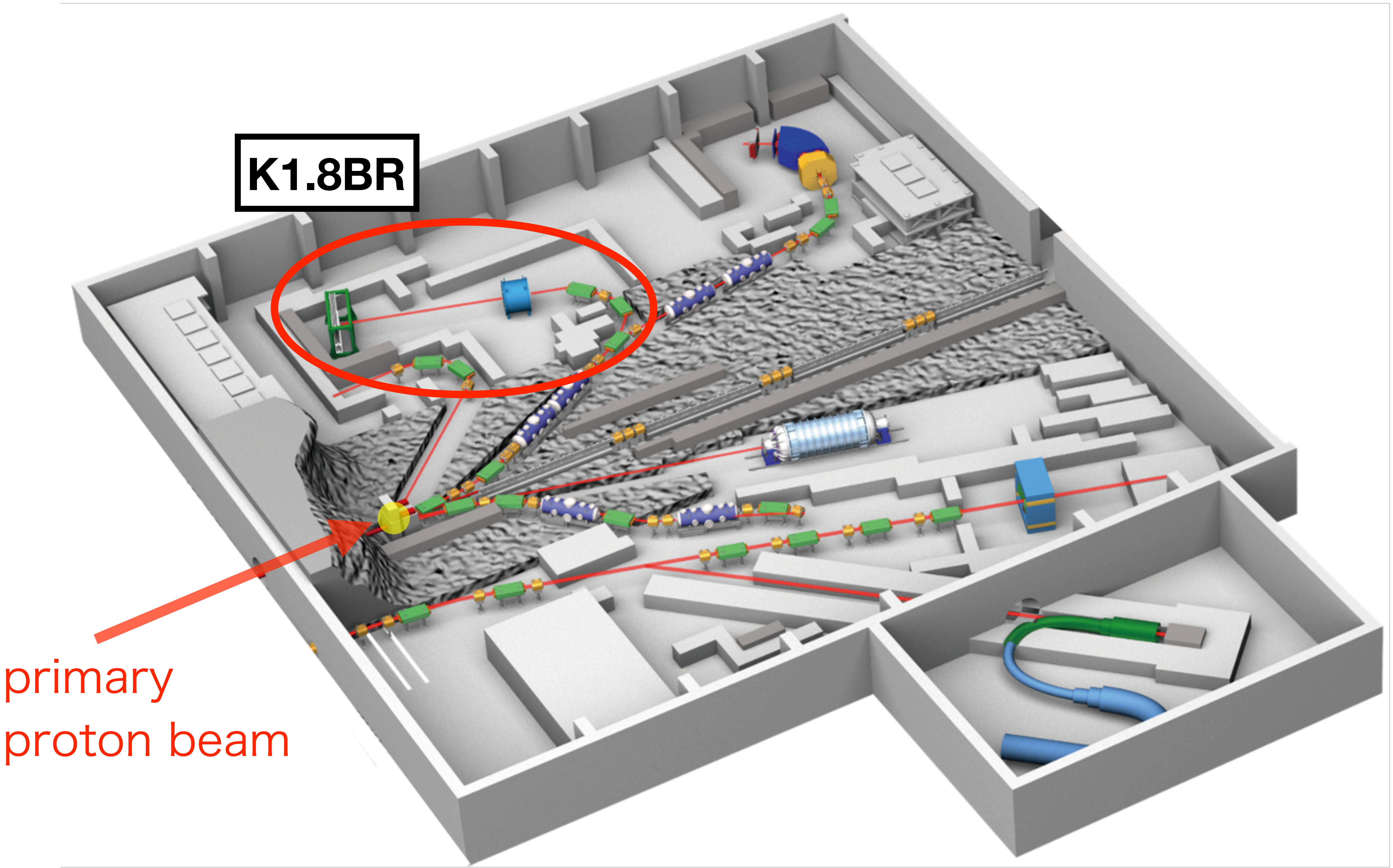
A series of experiments at J-PARC K1.8BR
Probe different energy, density, and isospin

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



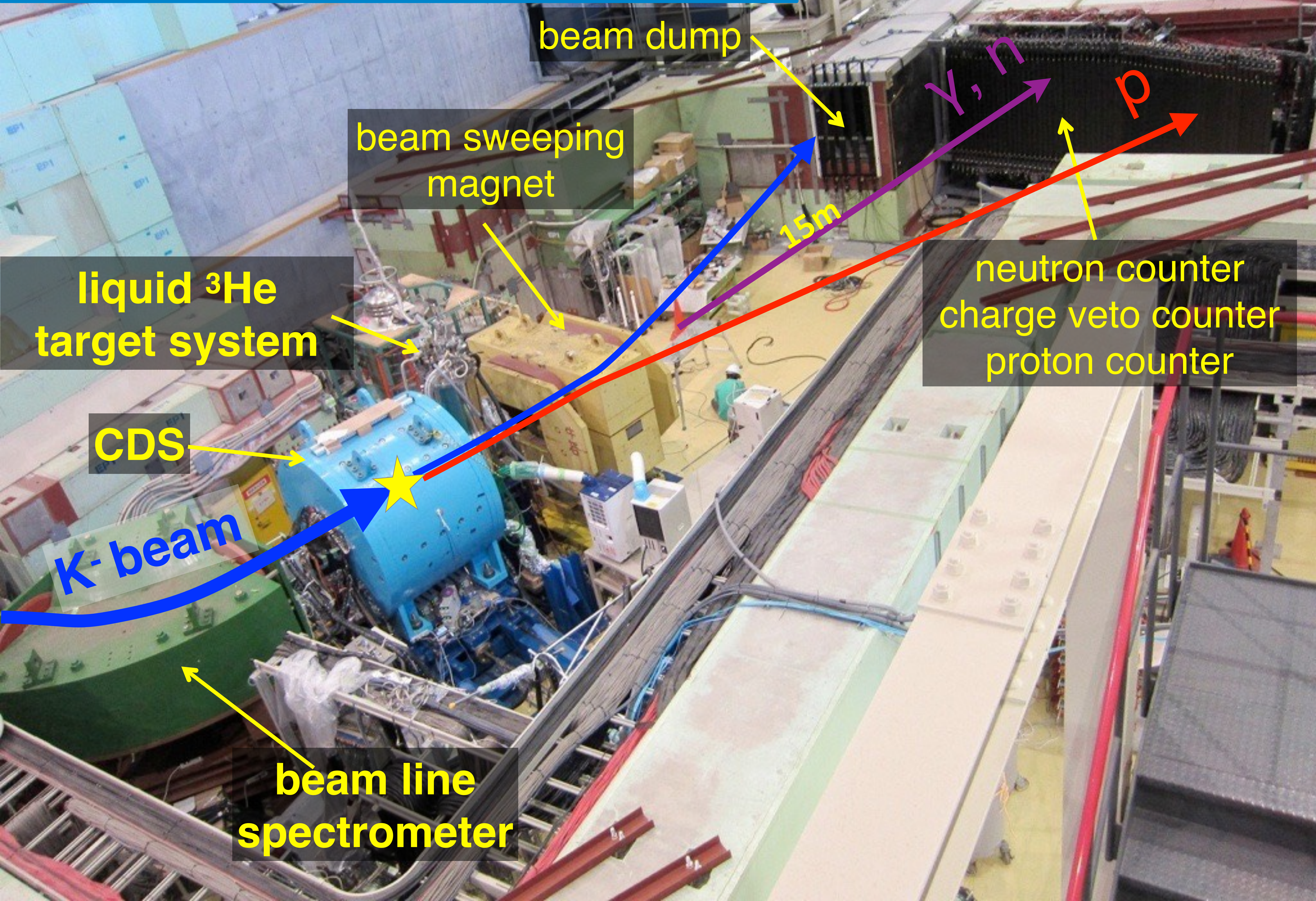
- ✓ Effectively produce sub-threshold virtual $\bar{K}$ beam
- ✓ K- beam at 1 GeV/c to maximize elementary (K-, N) cross sections
- ✓ Most of background processes can be kinematically separated.
  - ✓ Hyperon decays and multi-nucleon absorption reactions
- ✓ Simplest target allow exclusive analysis.

J-PARC K1.8BR



- Relatively short beamline suitable for low-momentum K^- beam

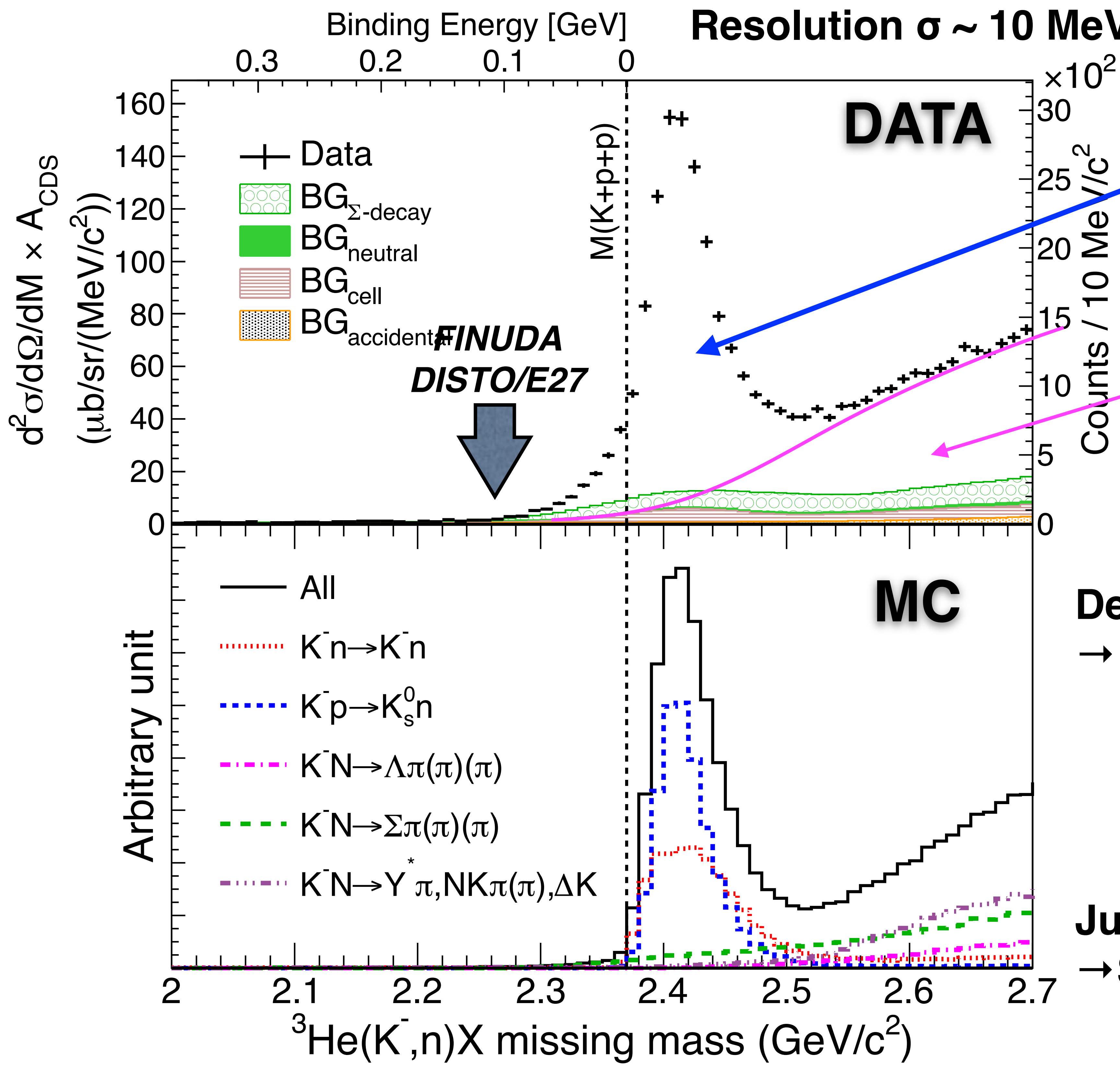
J-PARC K1.8BR as of 2012



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

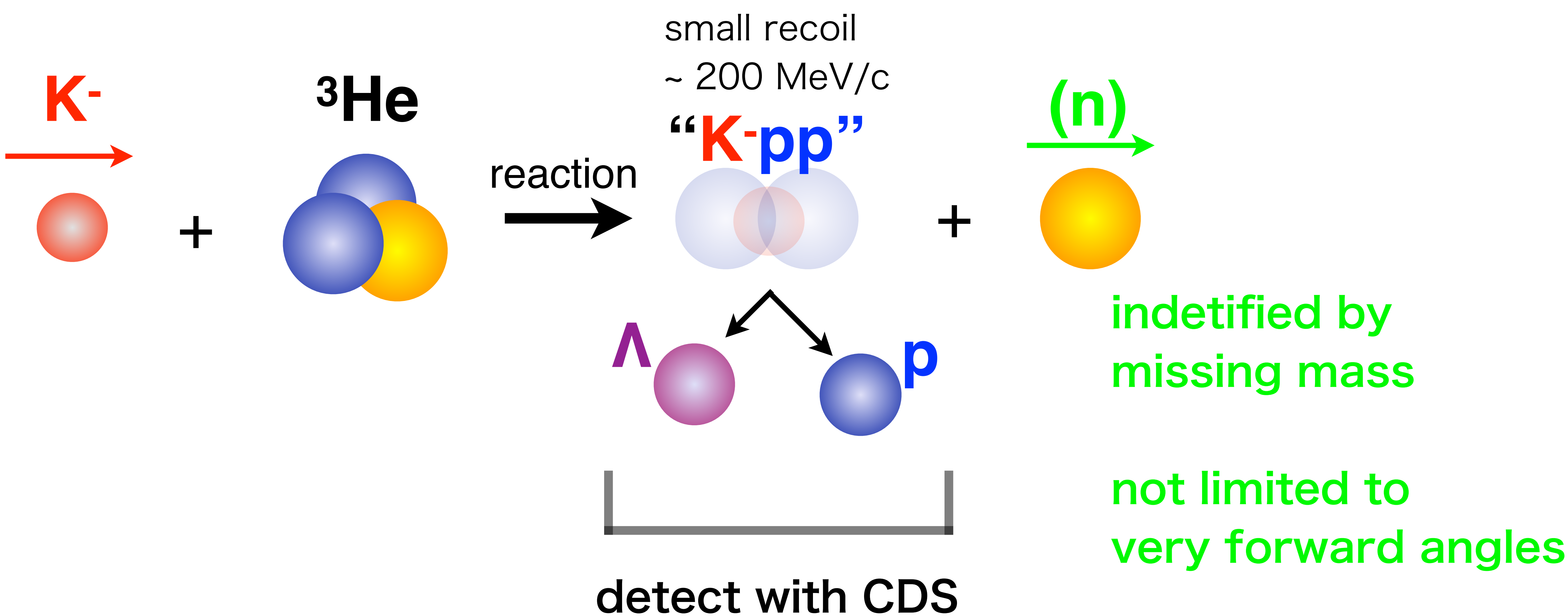
→Significant yield ~ 1 mb/sr
should include quasi-free Λ(1405)

Exclusive analysis: ^{3}He(K^-, Λp)n

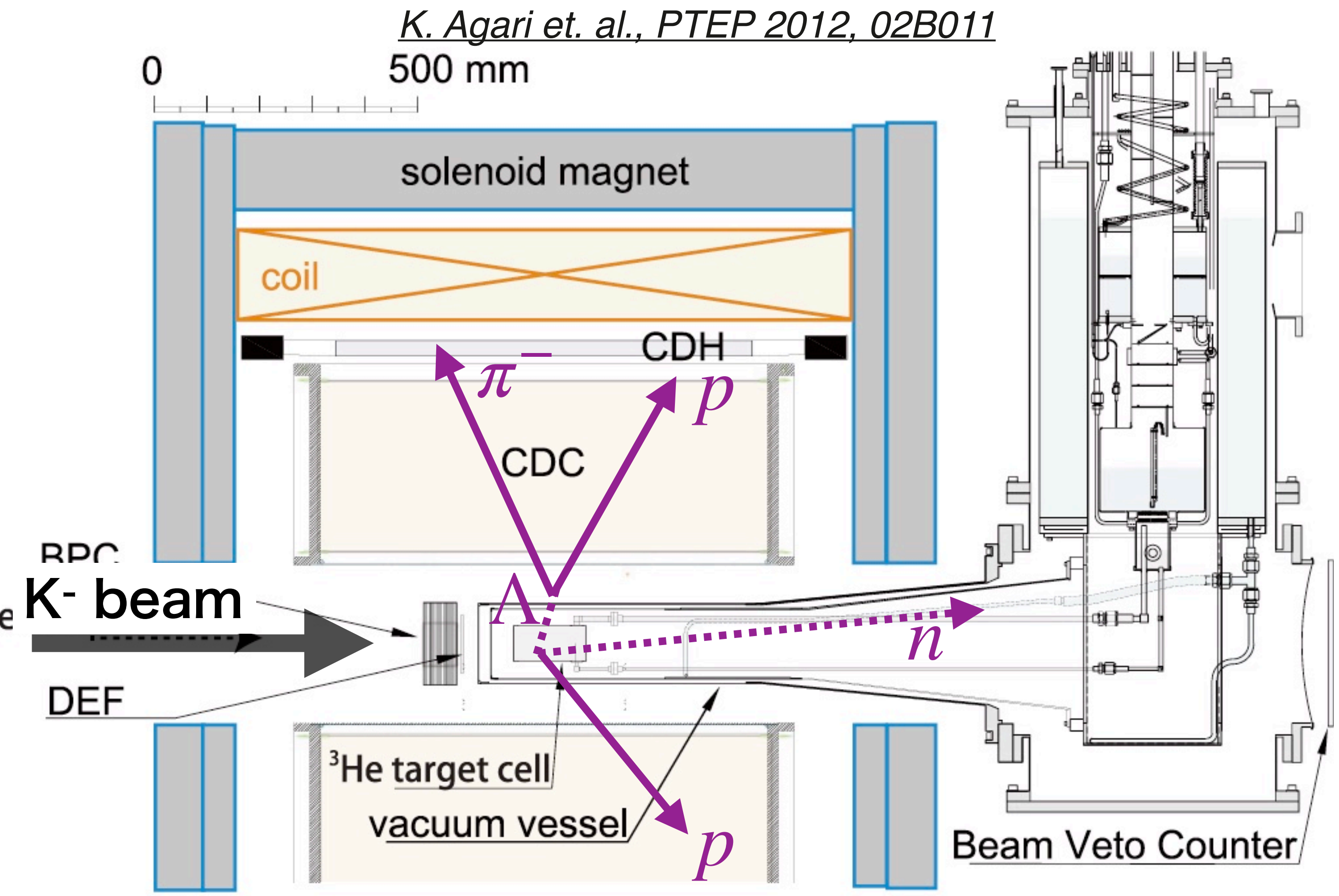
PHYSICAL REVIEW C **102**, 044002 (2020)

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)

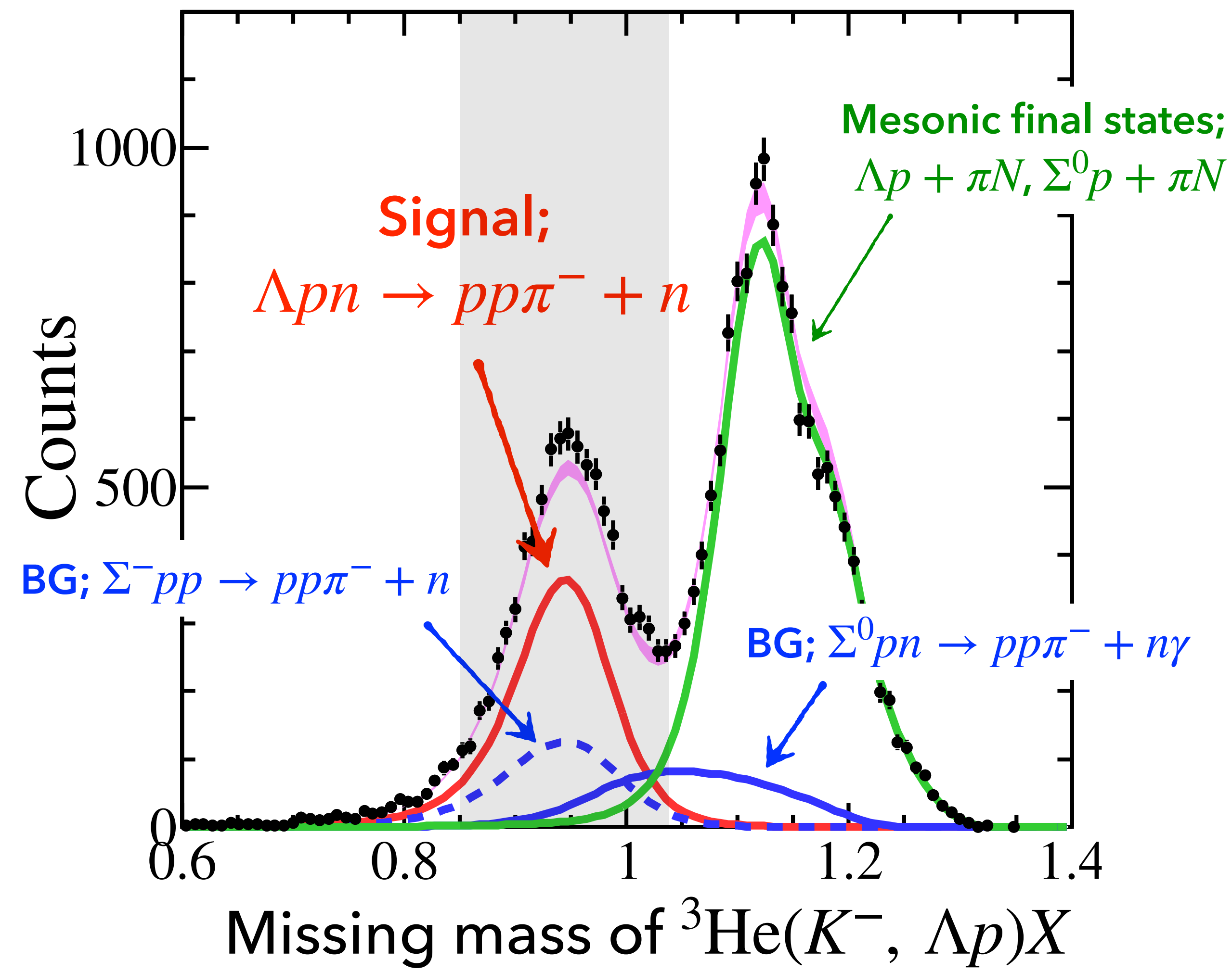


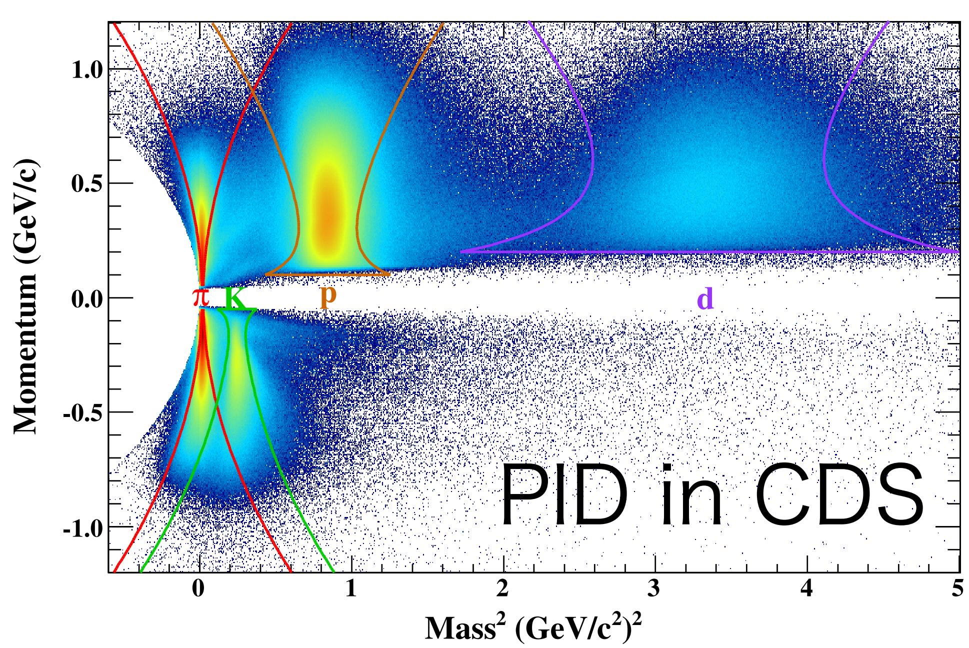
Λpn event selection



15-layer CDC and TOF hodoscopes

missing neutron selection

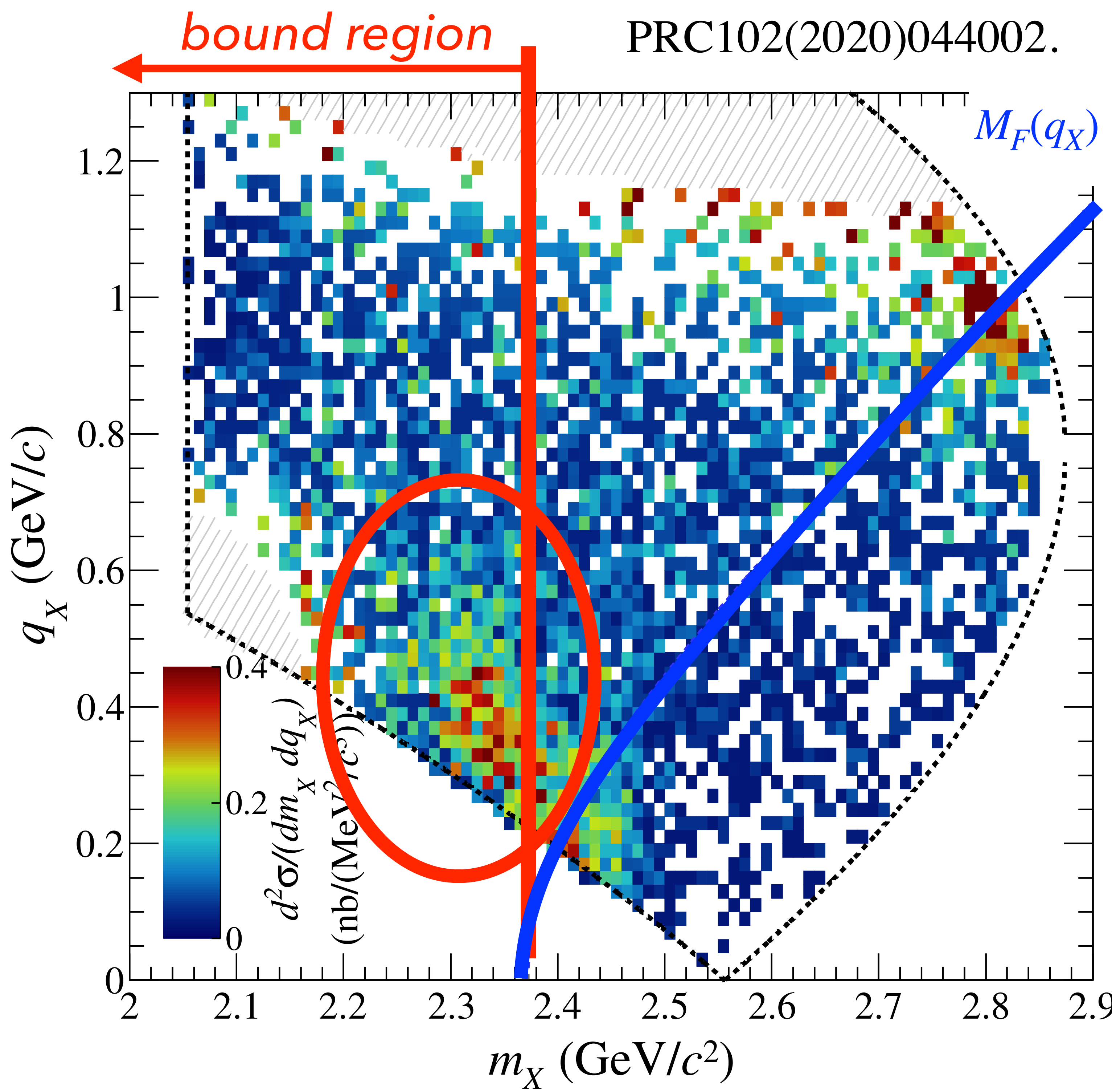




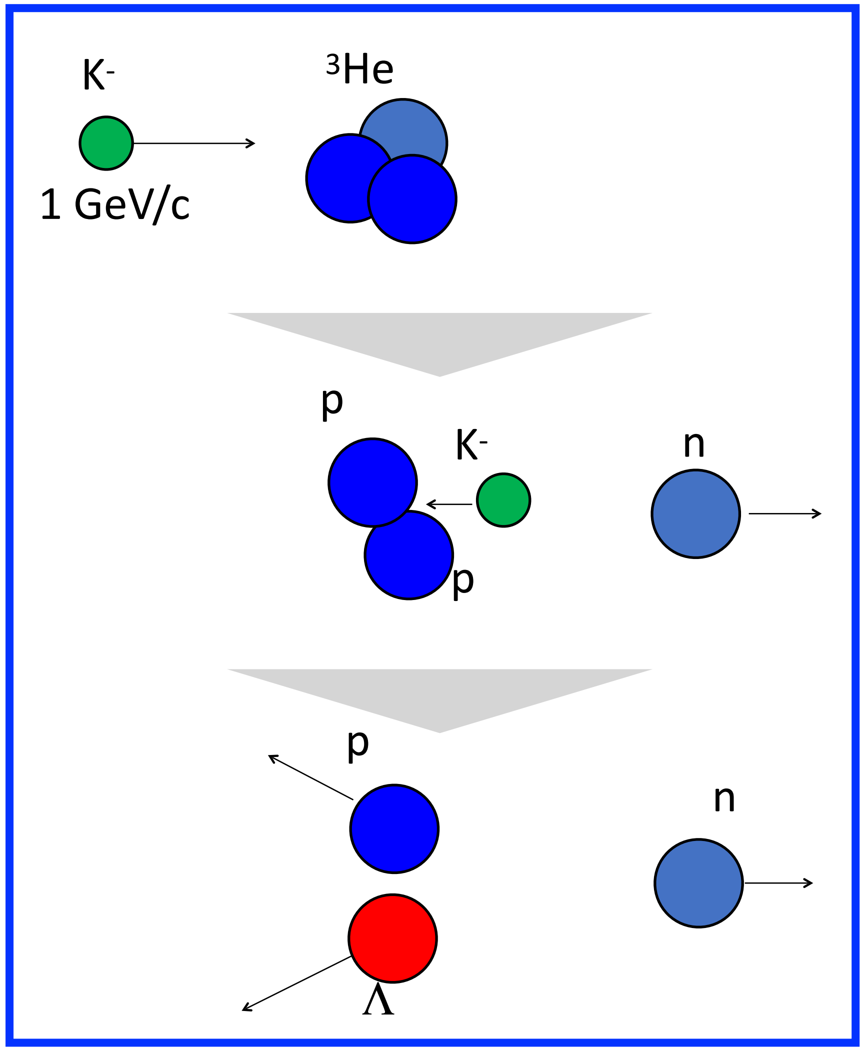
- Λpn events are selected with ~80% purity.
- ~20% $\Sigma^0 pn/\Sigma^- pp$ contamination

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

intermediate $\bar{K}$ exist!

q_x-indep. component below the threshold

m_x: Λp invariant mass

q_x: momentum transfer to Λp system

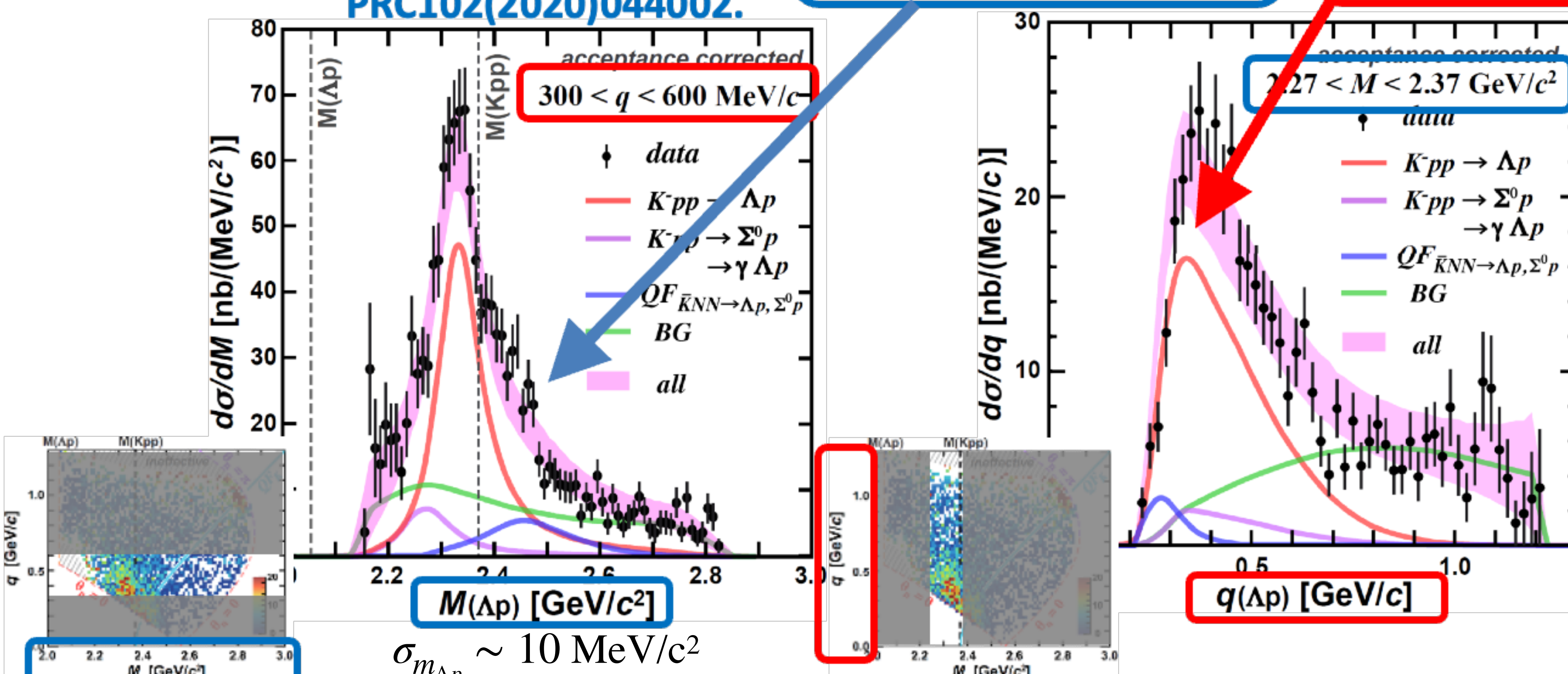
"$\bar{K}NN$" model fitting

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

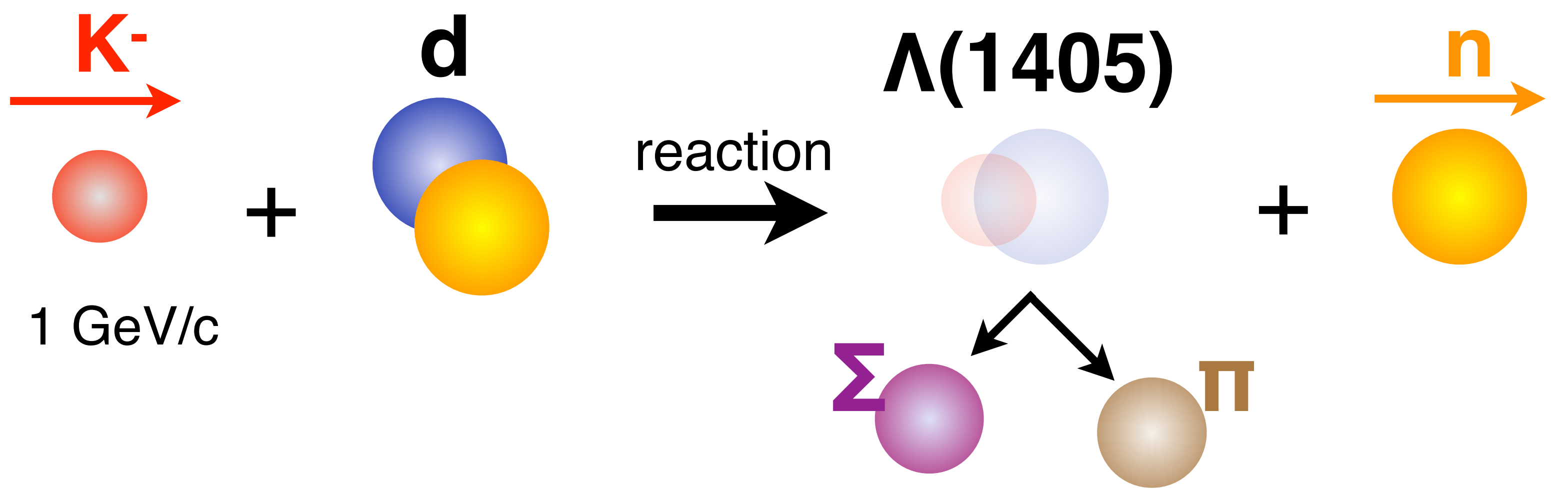
B_{Kpp} ~ 40 MeV, Γ_{Kpp} ~ 100 MeV

→ *large binding energy*

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

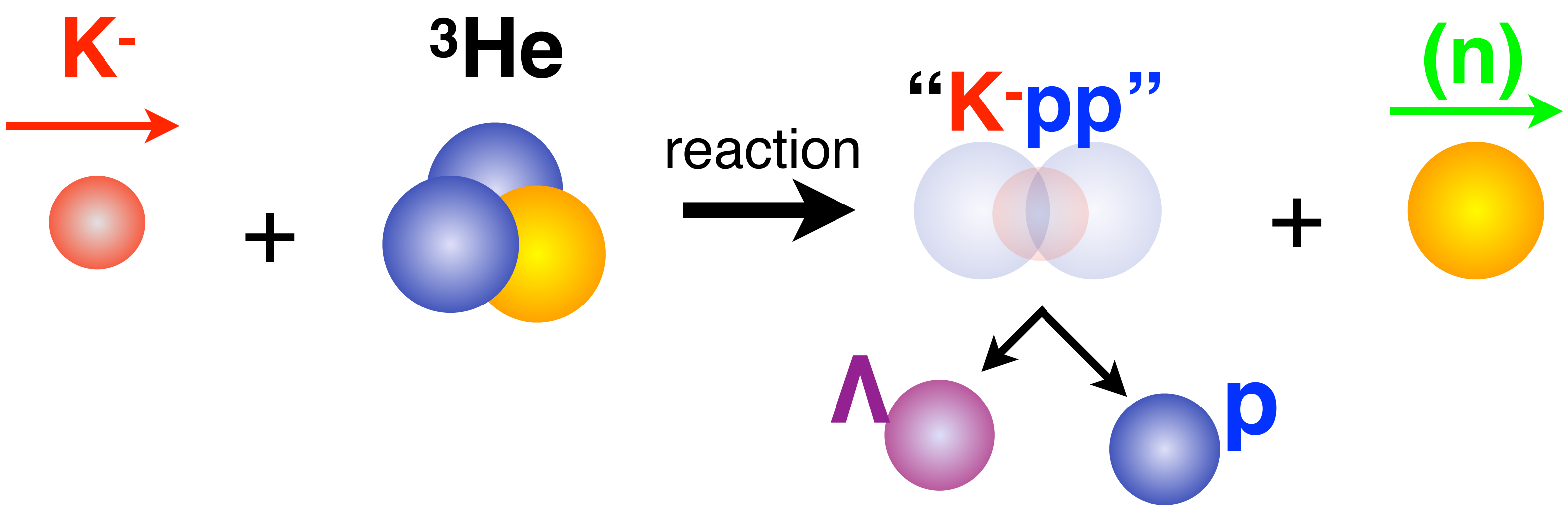
→ *wide momentum transfer*

(K-, n) reaction on other targets



$39 \times 10^9\ K^-$ @ E31

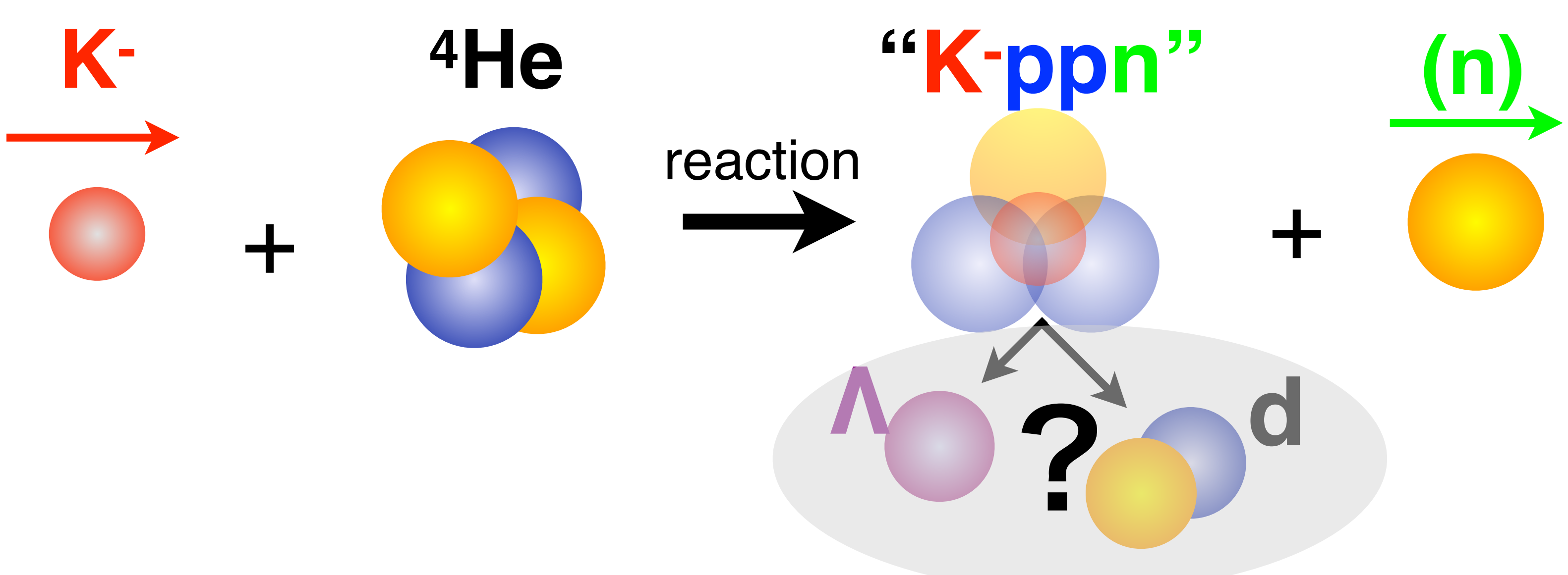
Physics Letters B 837 (2023) 137637



$42 \times 10^9\ K^-$ @ E15

$(11 + 24 + 36) \times 10^9\ K^-$

@ E73 (hypertriton lifetime)



$6 \times 10^9\ K^-$ @ T77

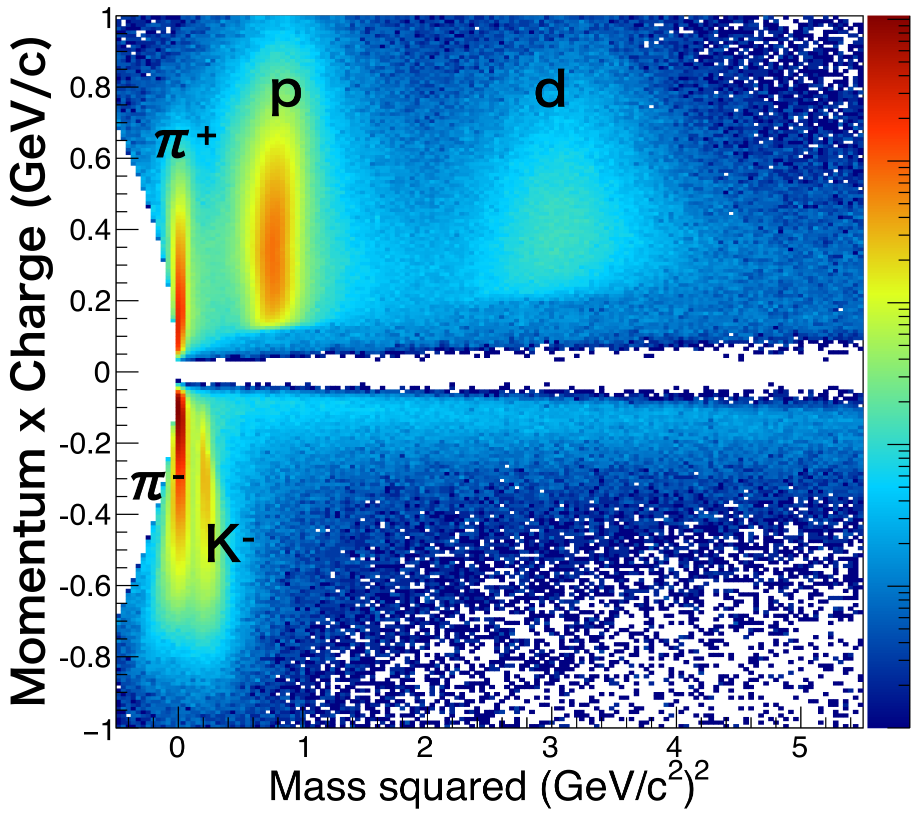
$5.5 \times 10^9\ K^-$ @ E73

Λdn event selection

only 3-day data!

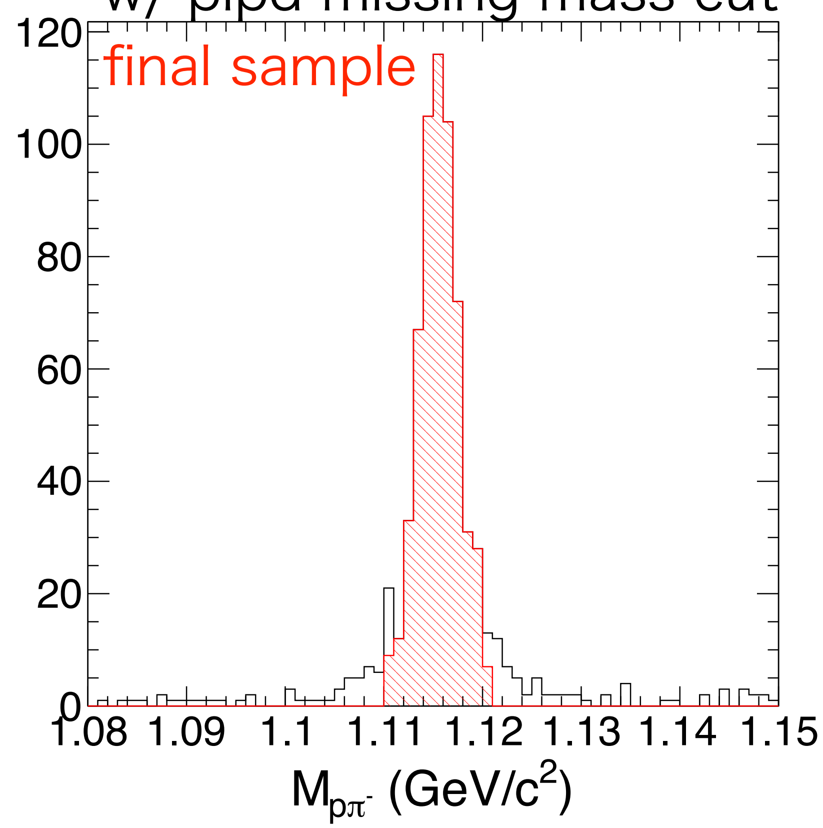
deuteron ID

CDC track curvature &
CDH time of flight



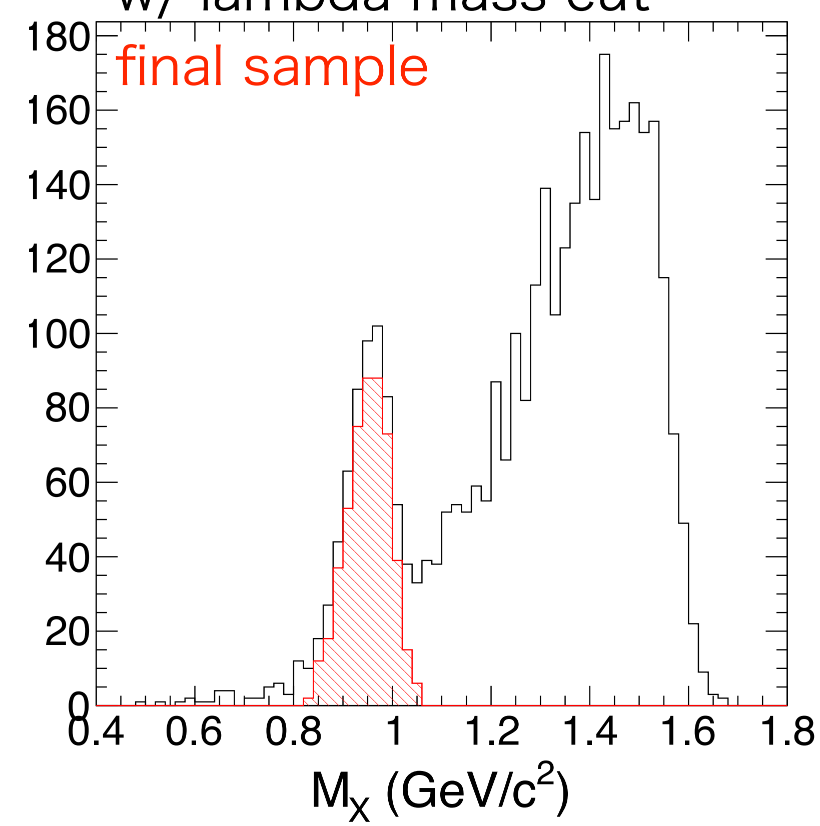
Λ reconstruction

w/ vertex consistency cut
w/ pipd missing mass cut



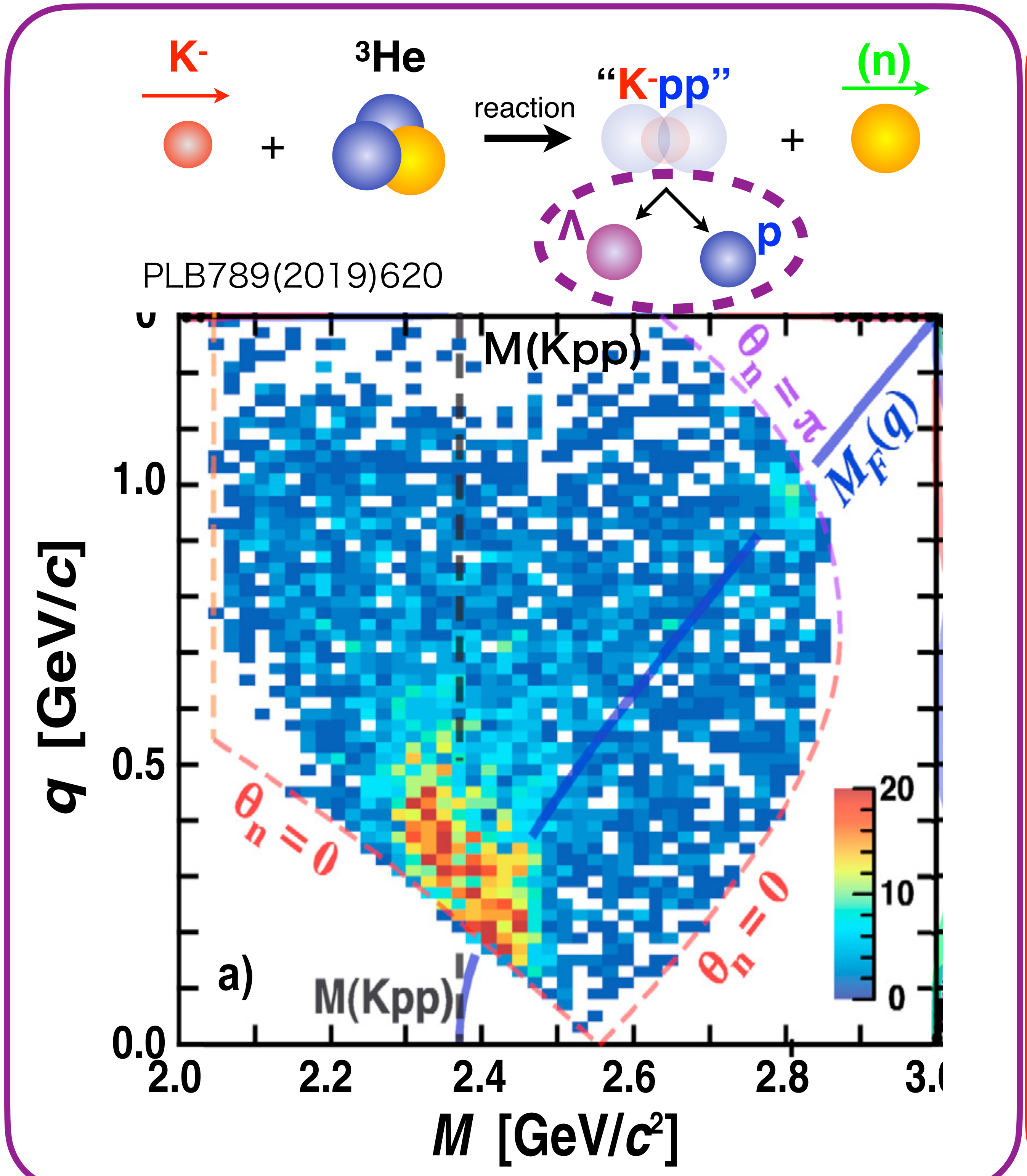
Missing neutron ID

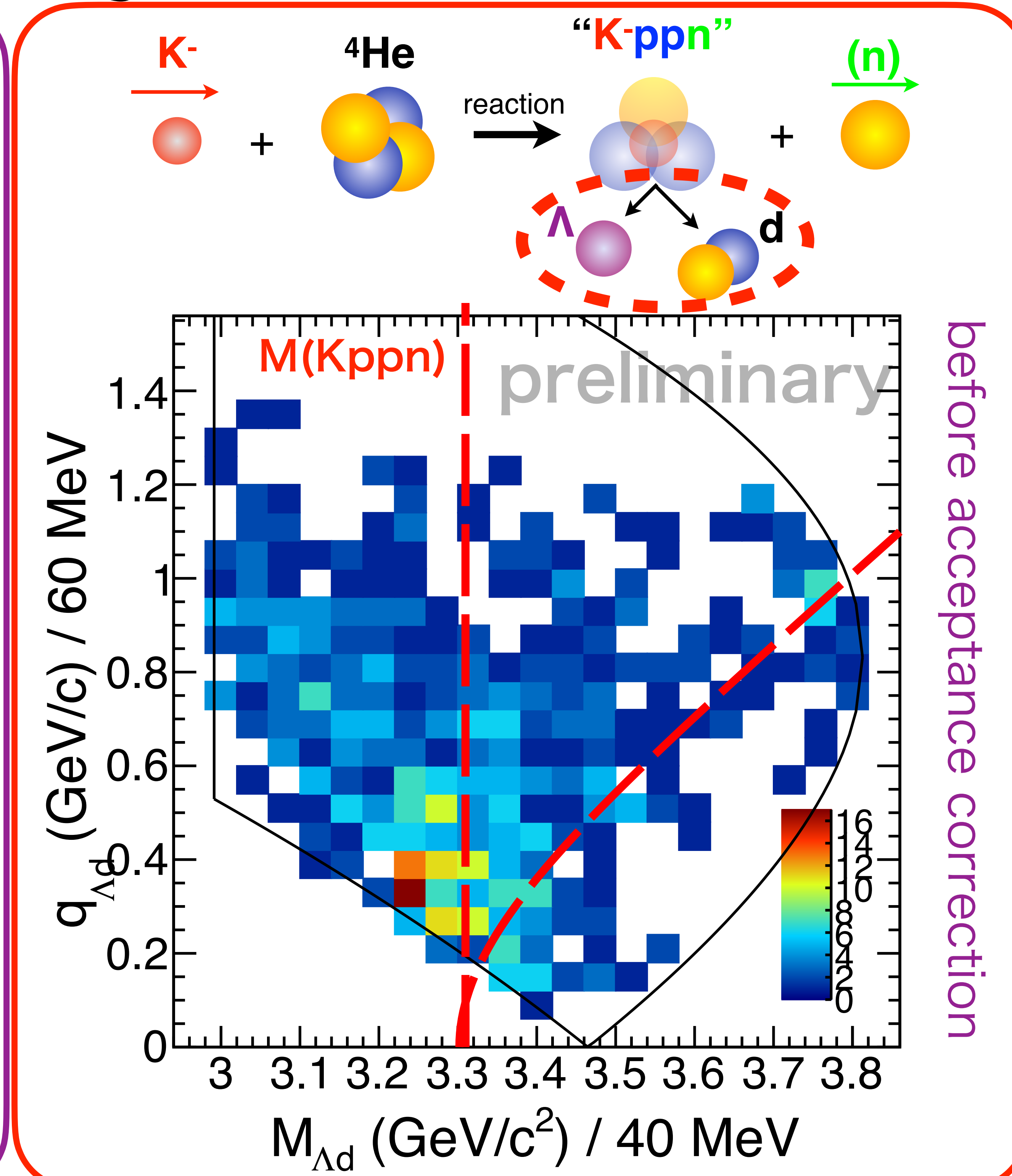
w/ vertex consistency cut
w/ lambda mass cut



- Λdn final states are identified with a good purity by considering kinematical & topological consistensies
- ~20% contamination from $\Sigma^0 dn/\Sigma^- dp$

$\bar{K}NNN$: Preliminary result

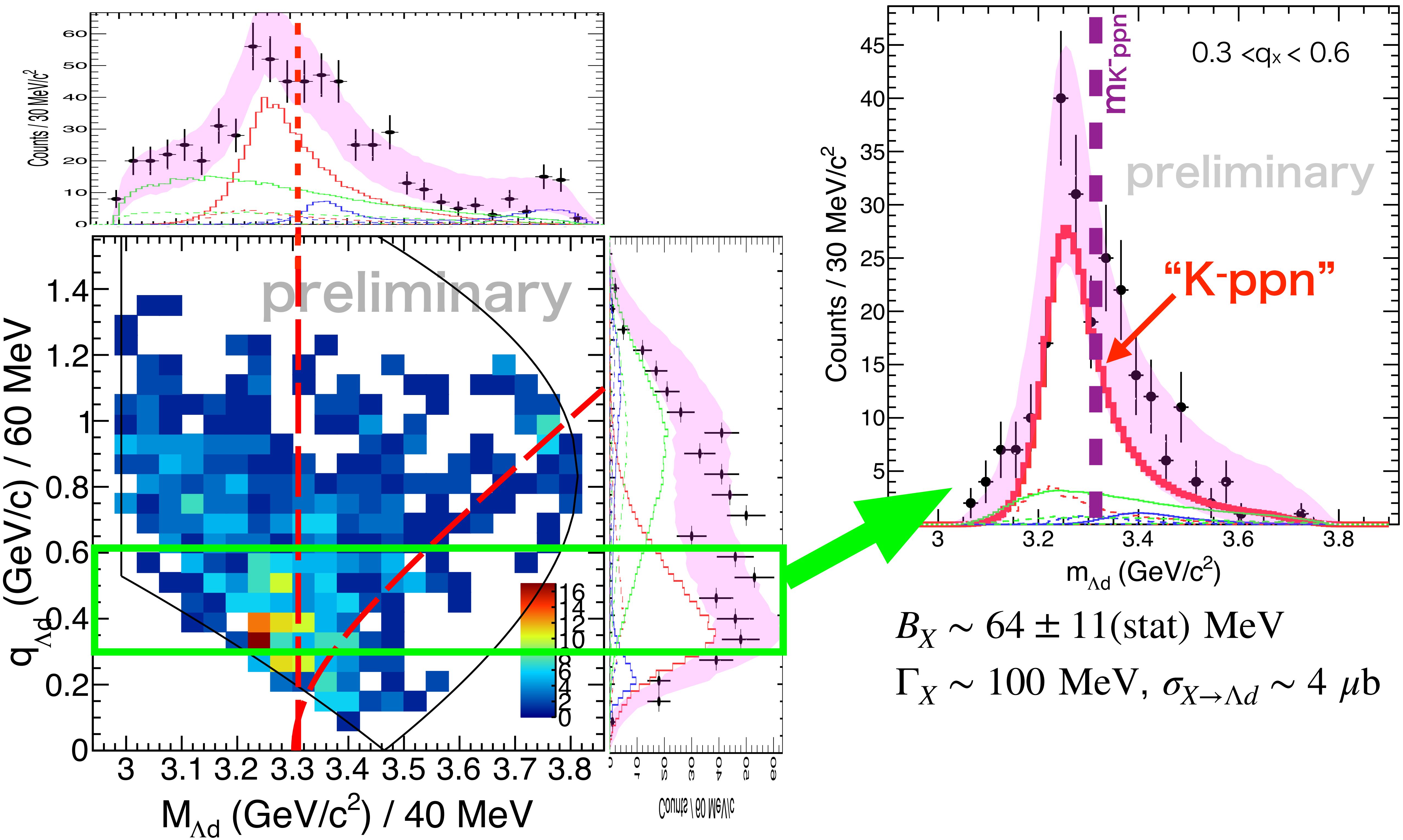




- Two disributions are quite similar
- structure below the threshold, QF-K^-, and broad background

$\bar{K}NNN$: Preliminary result

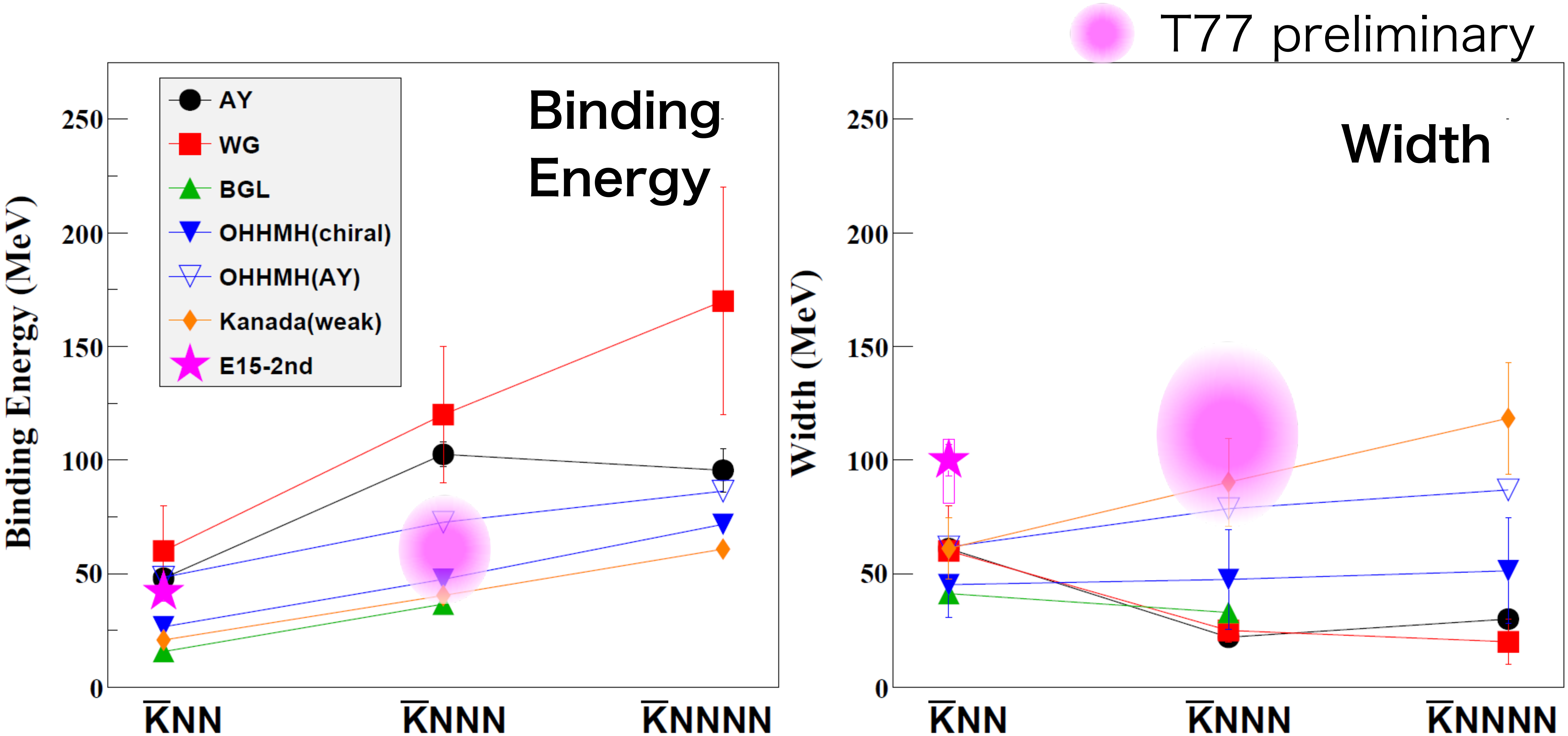
2D fit on the (M,q) space with simlar shapes to E15:
"$\bar{K}NNN$" Breit-Wigner wtih Gaus. form factor, Broad BG and QF-K^-



$B_X \sim 64 \pm 11(\text{stat})$ MeV

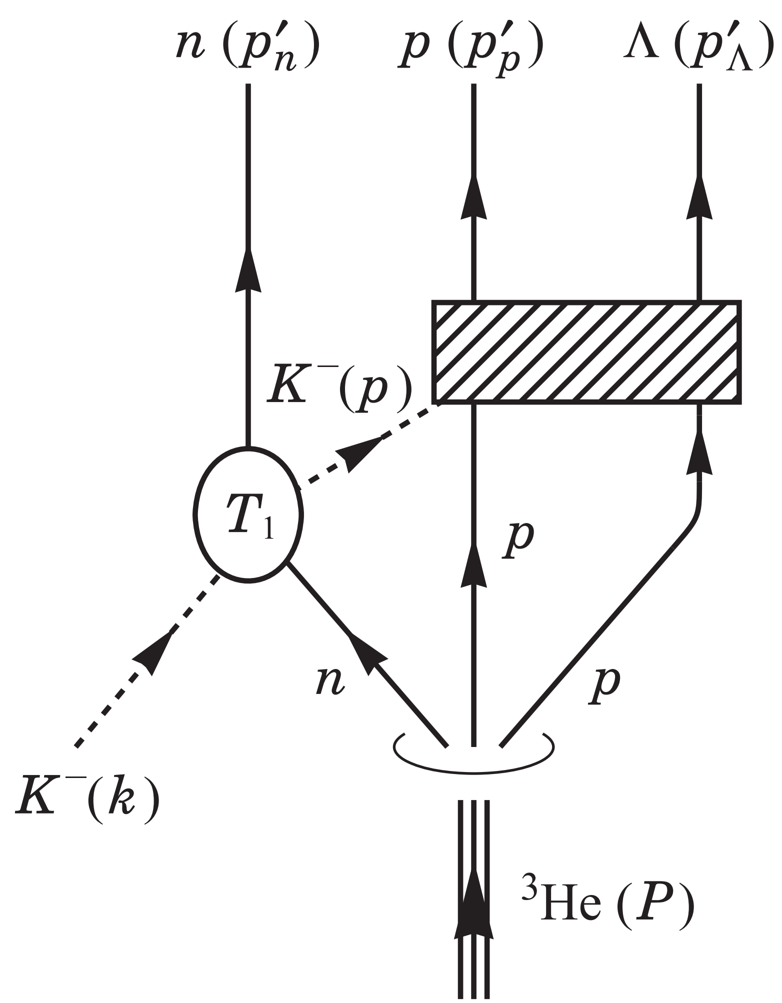
$\Gamma_X \sim 100$ MeV, $\sigma_{X \to \Lambda d} \sim 4\ \mu$b

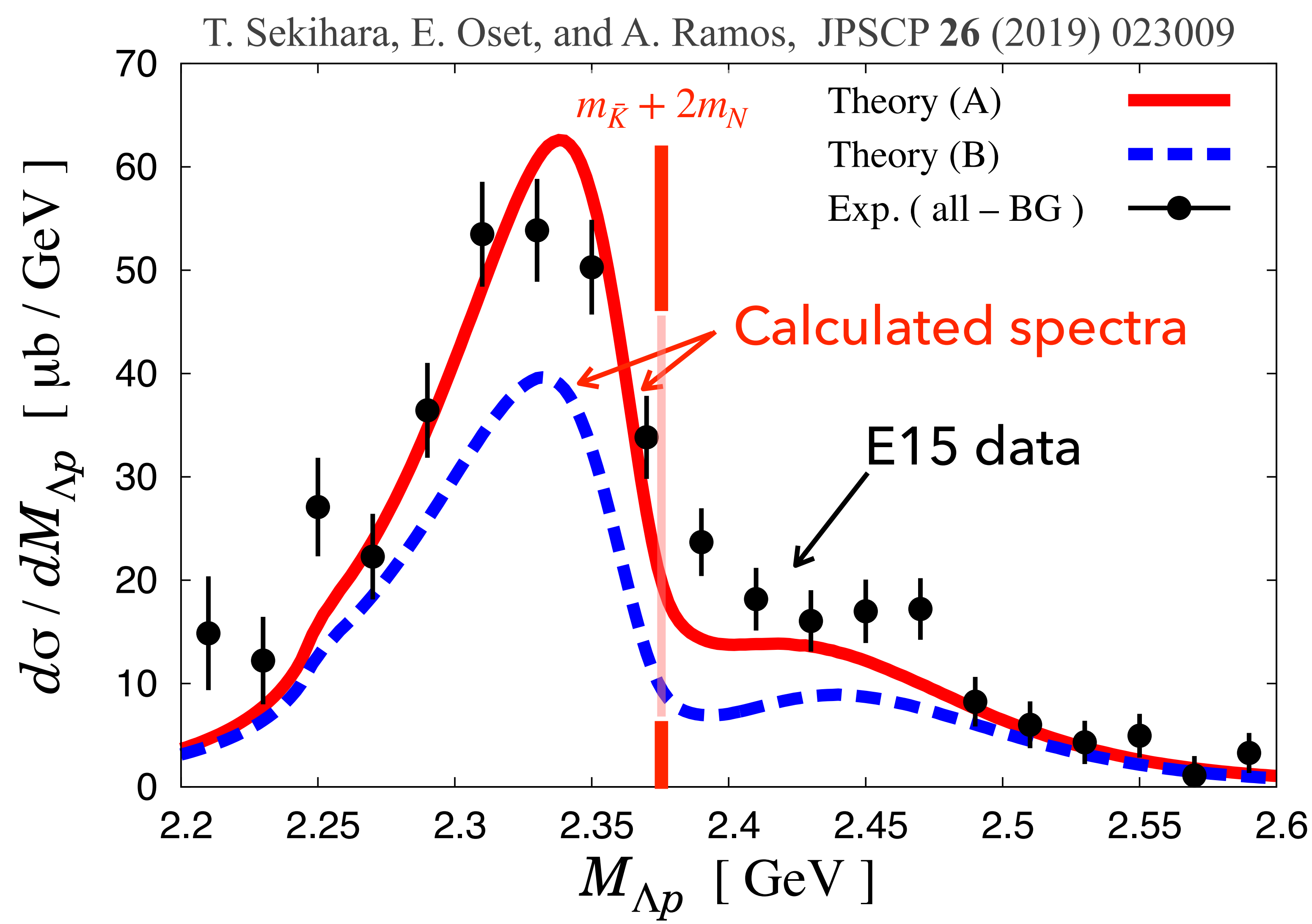
Comparison with theoretical calc.



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

Comparison with Sekihara calc.





- Good agreement in the mass spectrum.
  (although it failed to explain experimental q spectrum)
- Detailed comparison with theoretical spectrum is important

New project

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

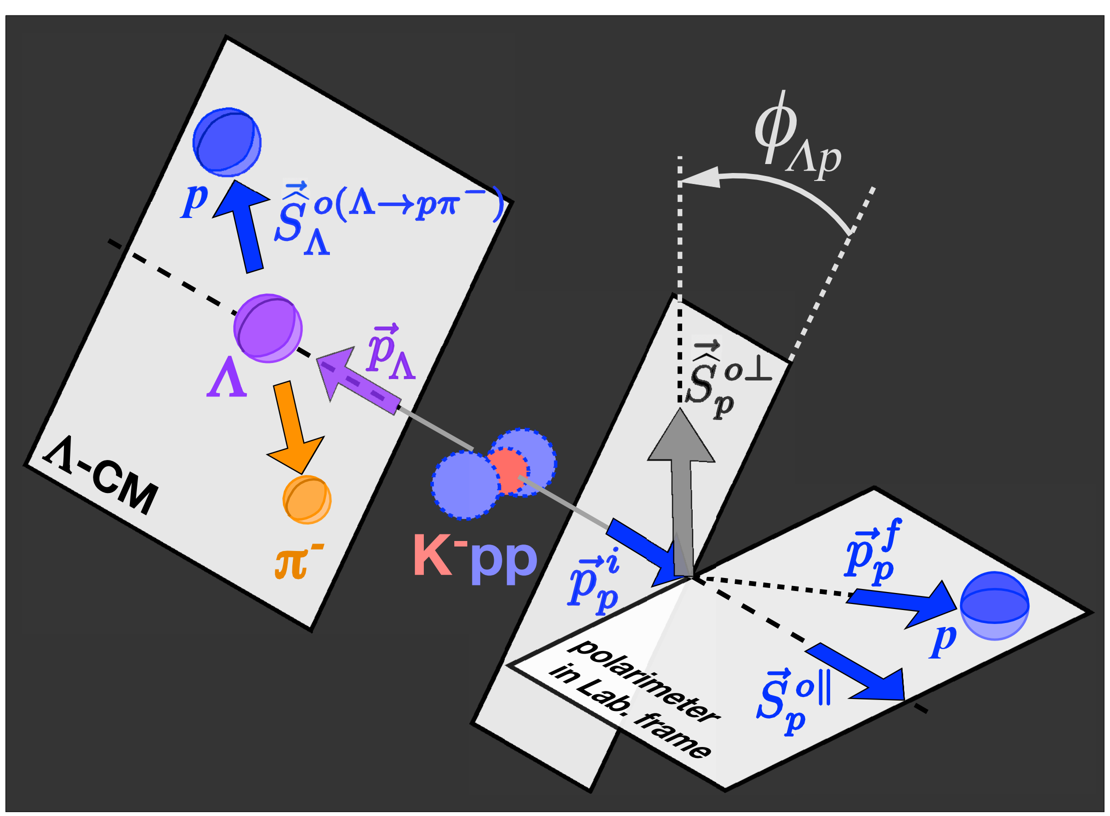
- Isospin partner should exist
  - $\Lambda n, \Sigma^- p$ analysis
  - need **neutron detection**

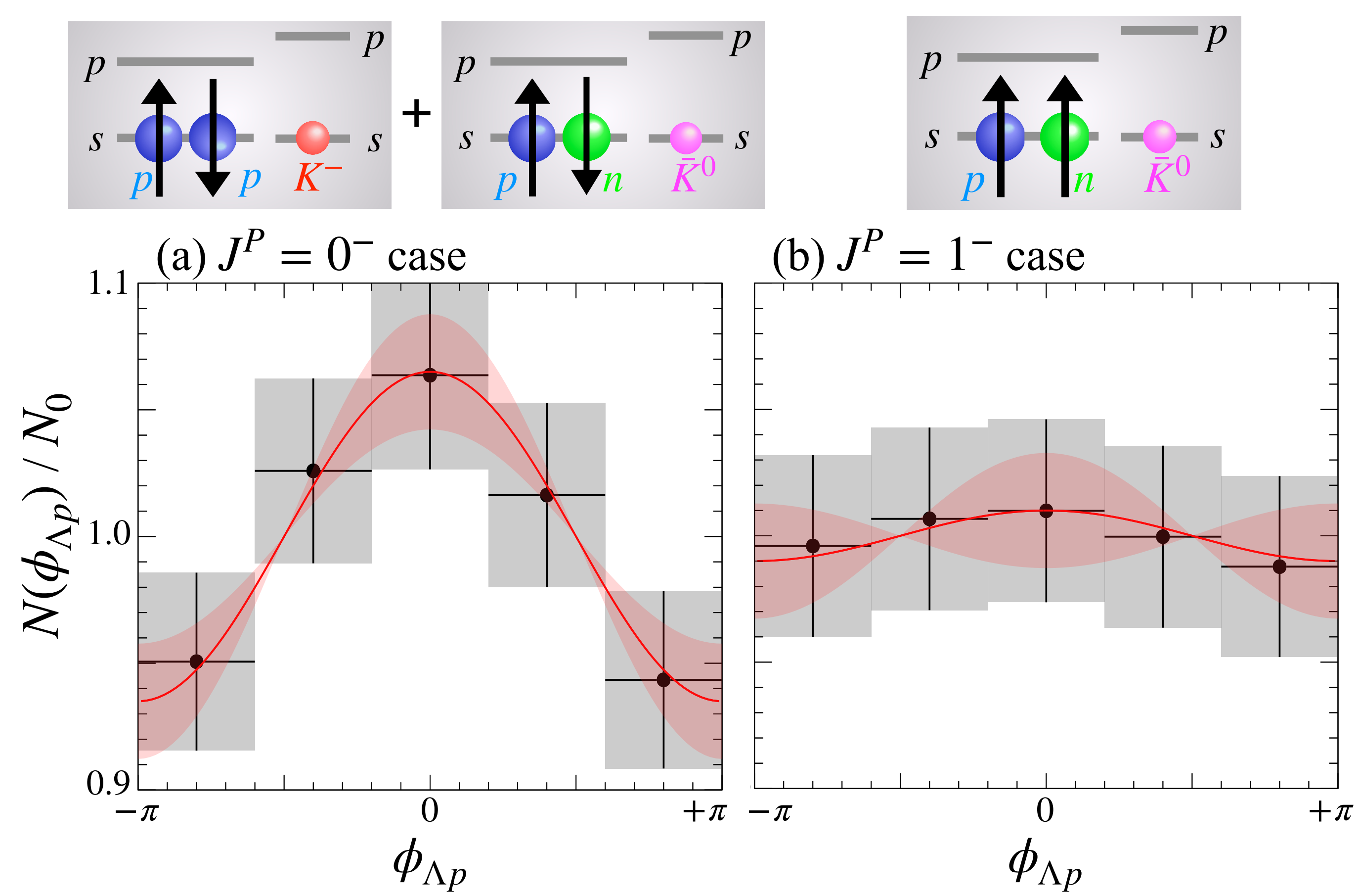
$\bar{K}NN(I=1/2)$

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

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

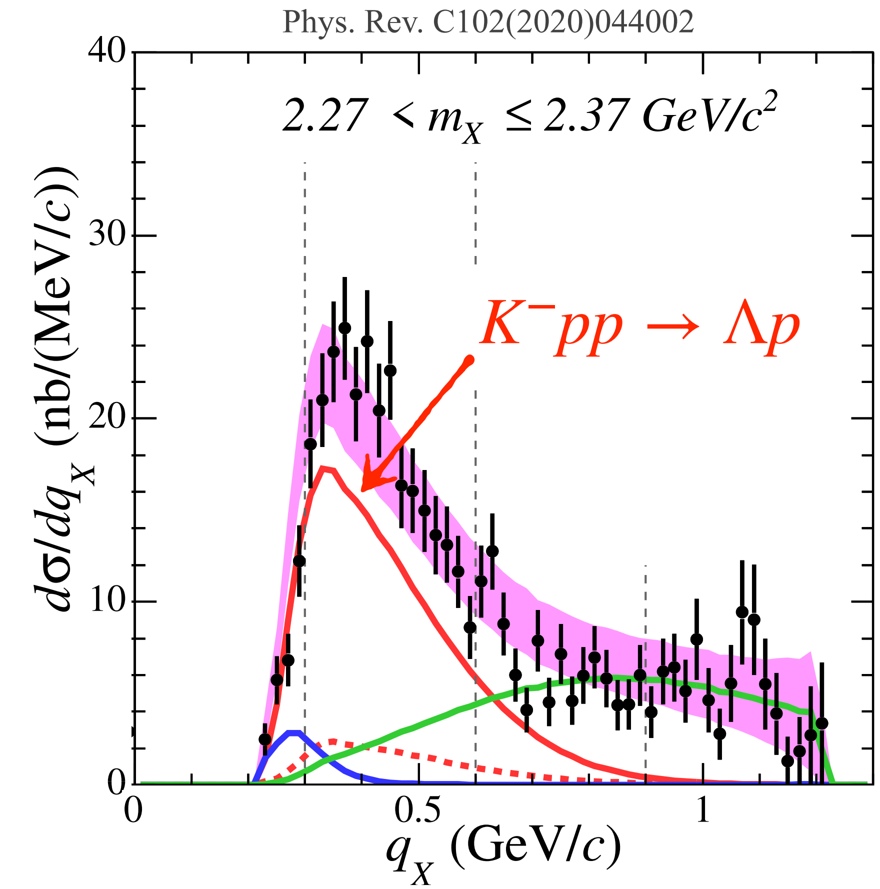
- Spin-parity measurement:
  - spin-spin correlation between Λ and p
  - need **polarimeter** for proton





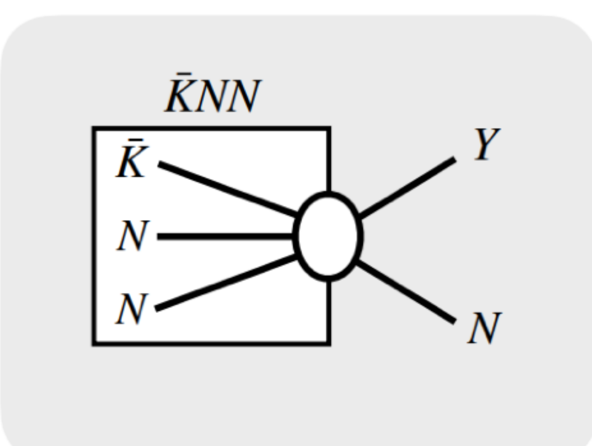
How compact is the system?

- **Momentum-transfer distribution**
  - large S-wave gauss. form factor
  - Q ~ 400 MeV/c



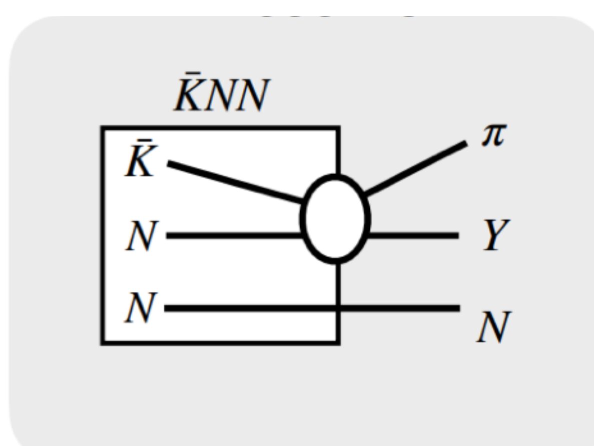
- **Decay branching ratio**
  - $\bar{K}NN \to \Lambda N$ vs. $\bar{K}NN \to \pi Y N_s$, $\Sigma^{\pm} \to \pi^{\pm} n$ — neutron detection

Non-mesonic

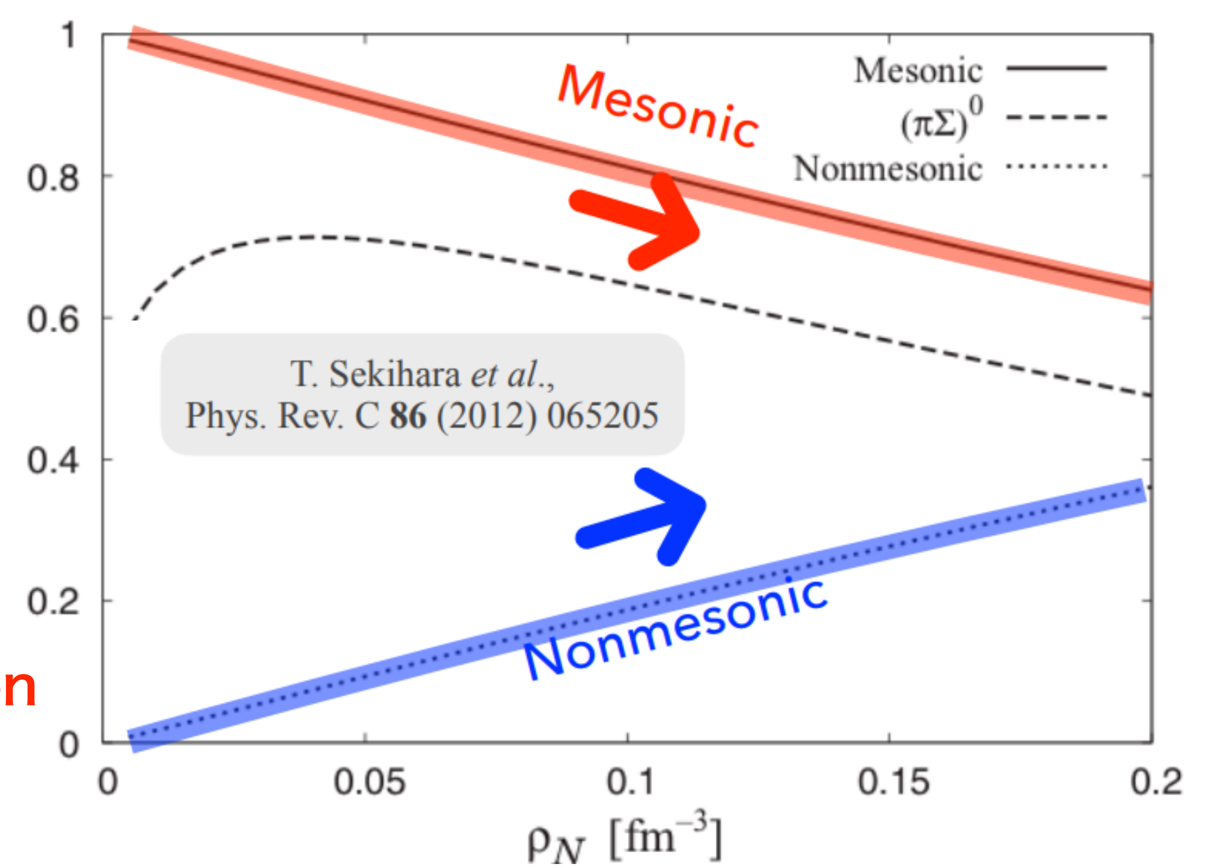


2N absorption

Mesonic



1N absorption

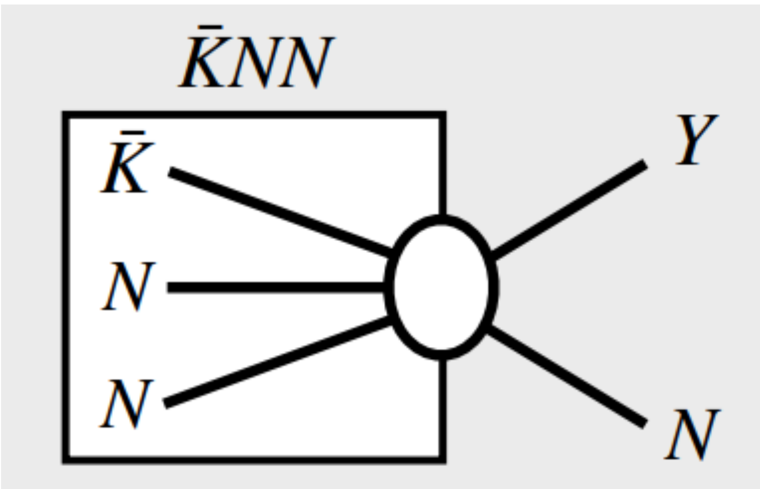


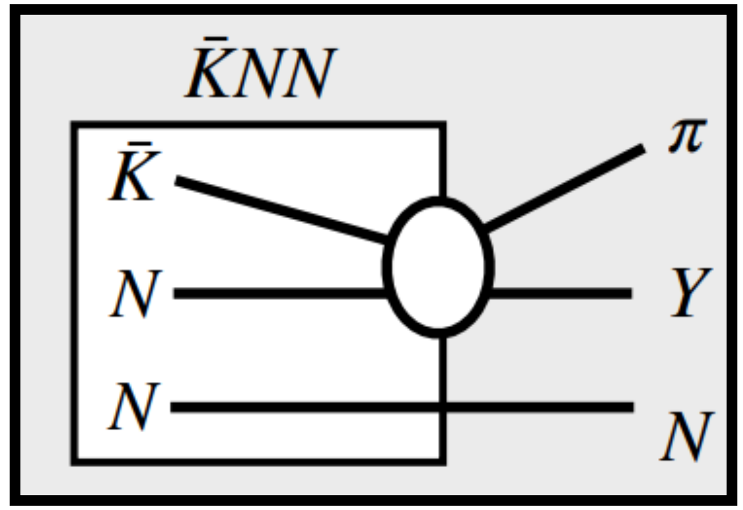
neutron detection

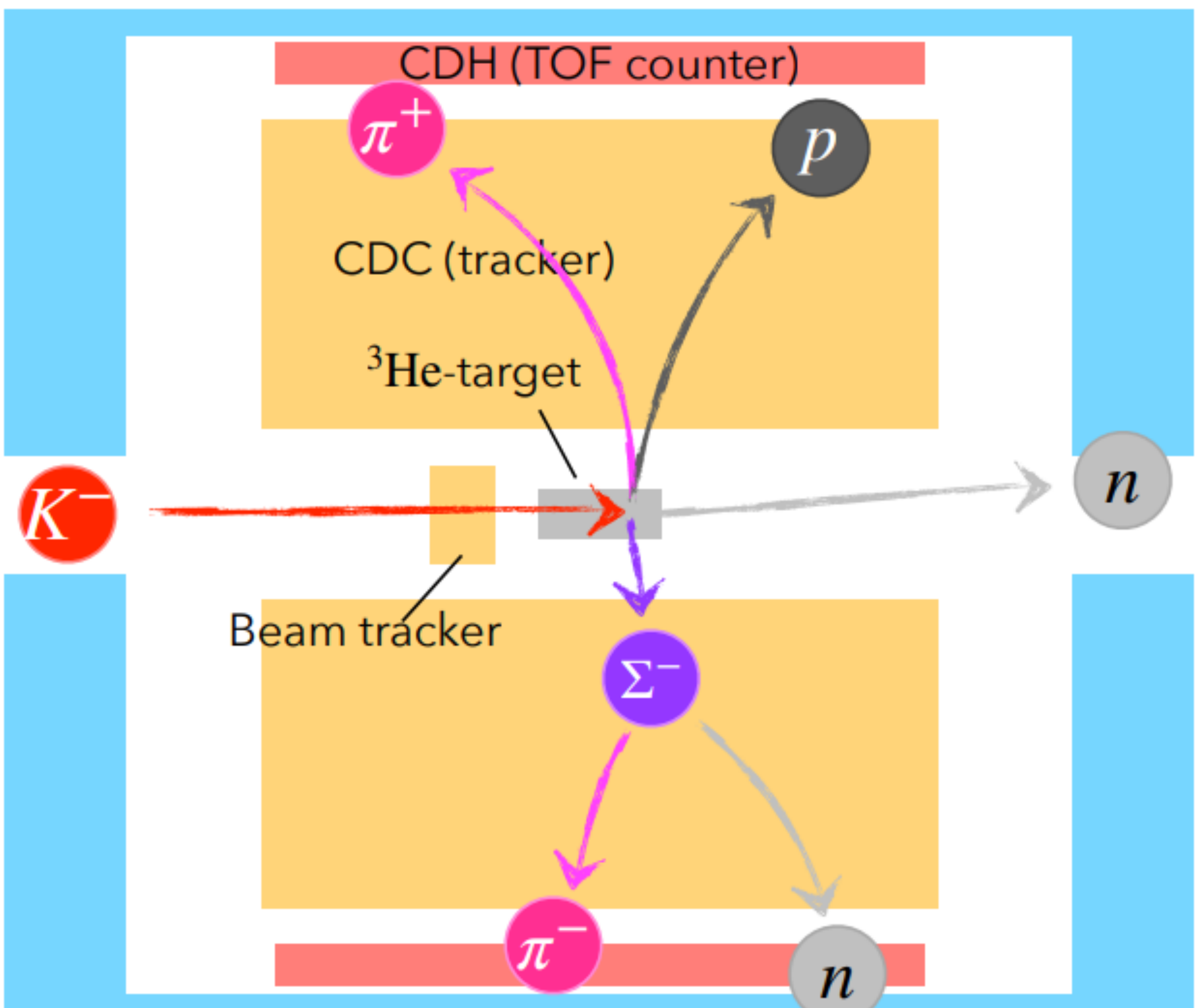
  - $\bar{K}NNN \to \Lambda d$ vs. $\bar{K}NNN \to \Lambda p n$

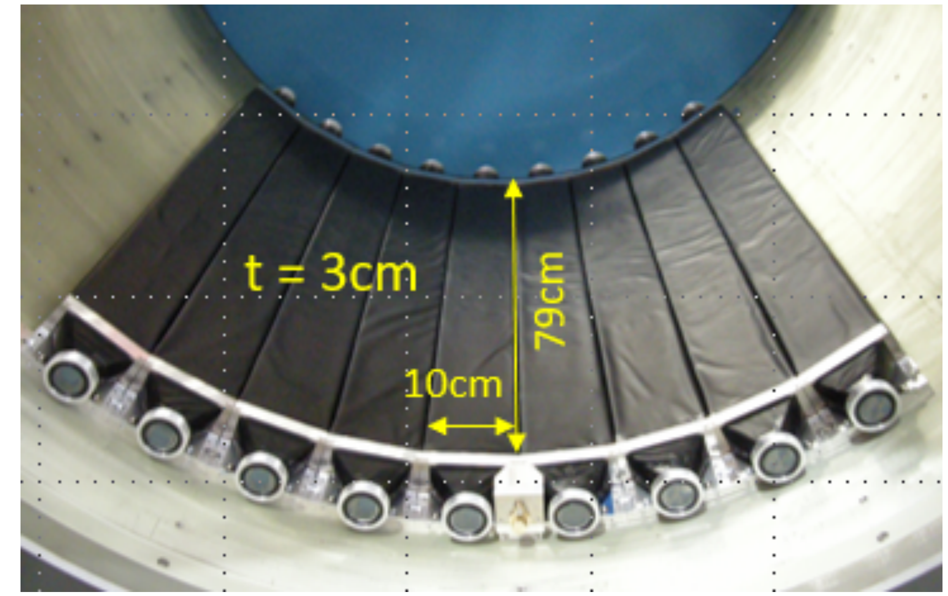
3N absorption — 2N absorption

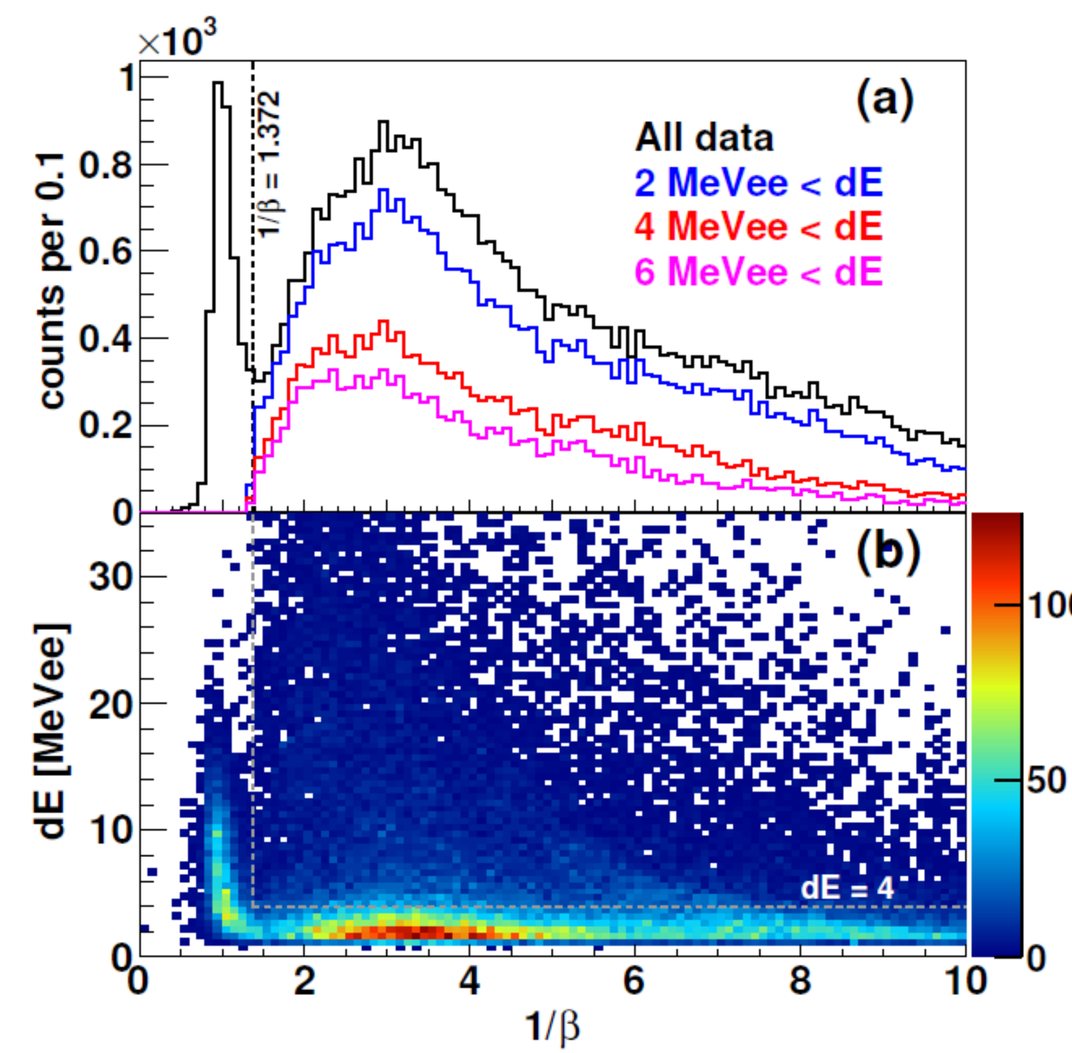
Mesonic Decay Analysis with the E15 Data









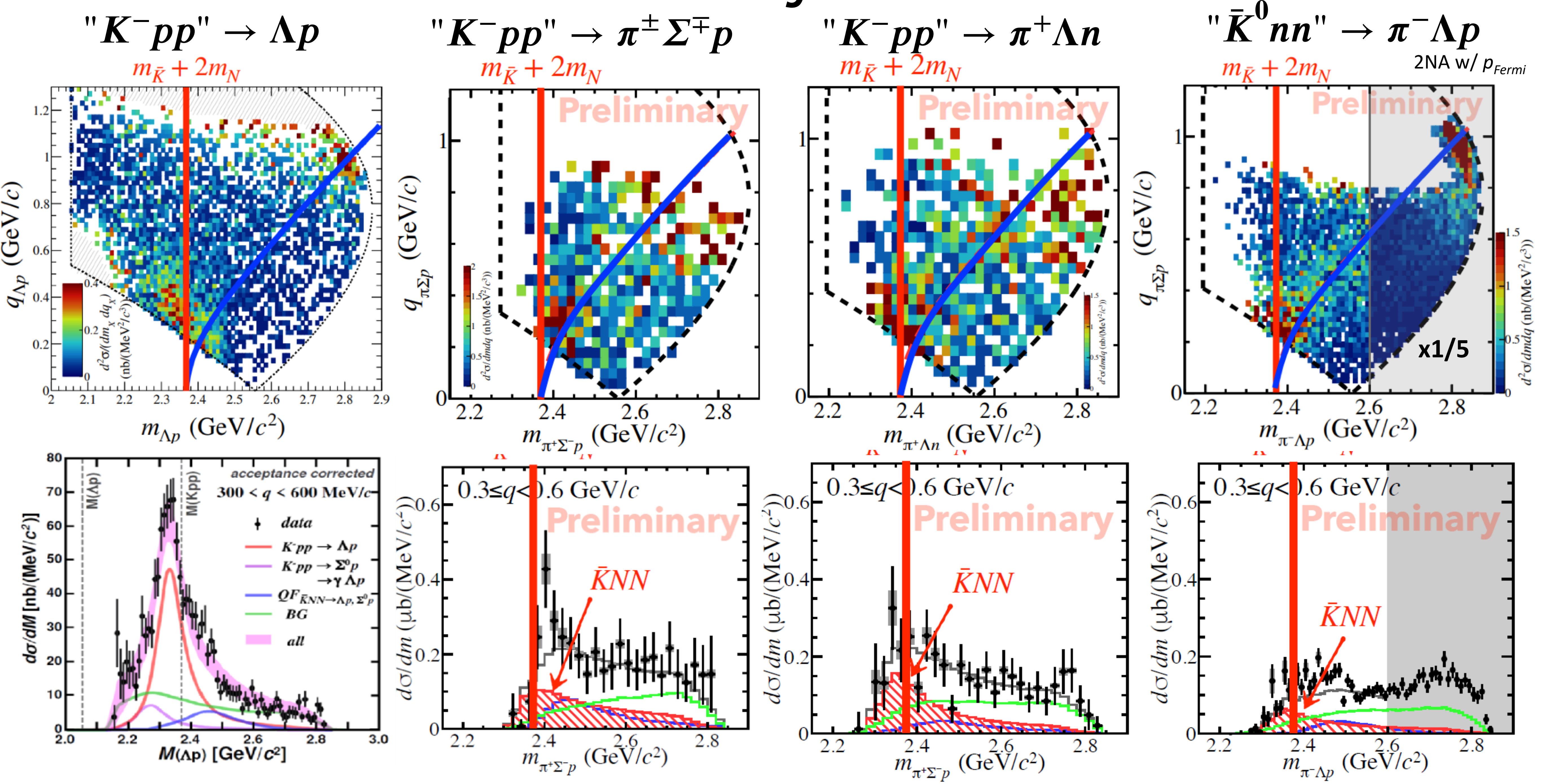


Neutron efficiency 3~9%

$\bar{K}NN$: Mesonic decay

Recently published!

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

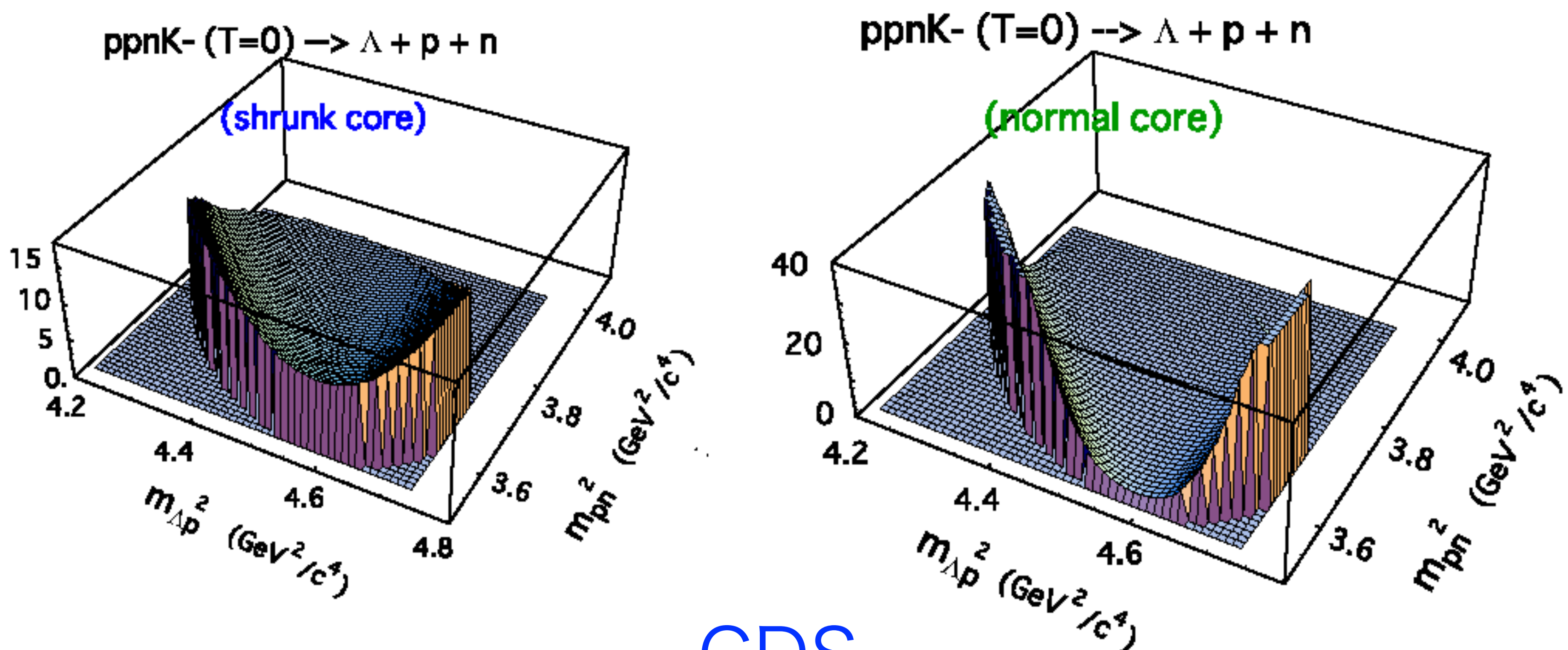


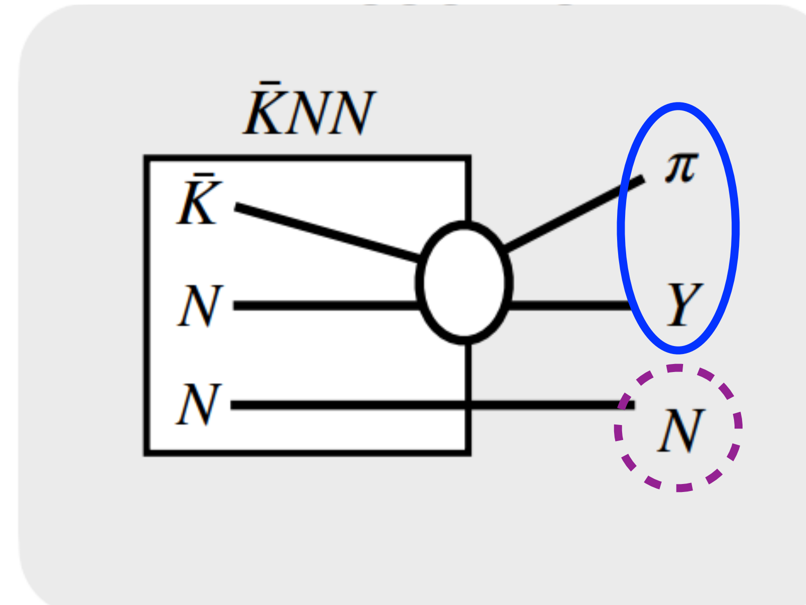
- Mesonic spectra could be consistently interpreted with the "$\bar{K}NN$" component obtained in the Λp channel.
- $\Gamma_{\text{mesonic}} \gg \Gamma_{\text{non-mesonic}}$

although phase-space and acceptance are limited…

How compact is the system?

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





1N absorption

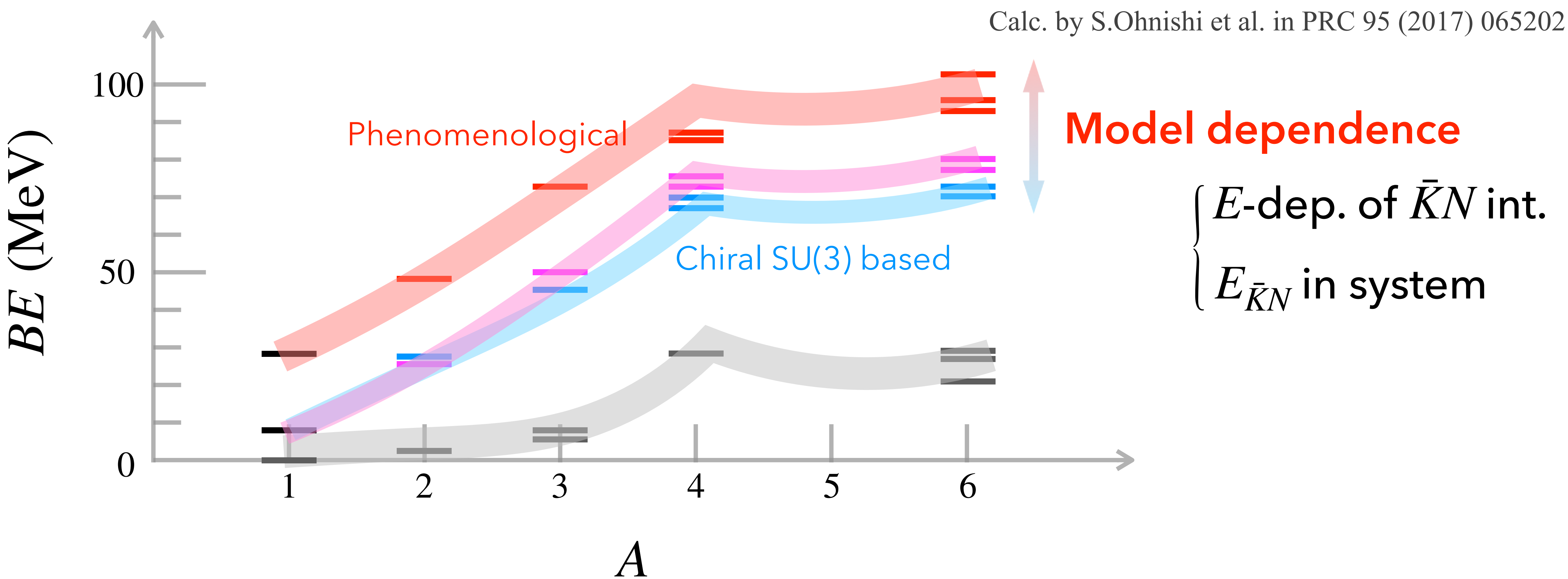
CDS

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

forward TOF

- Momentum of the "spectator" nucleon should reflect the system size.
- Better to use missing method with forward neutron detection

How general are the K^bar-nuclei?



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

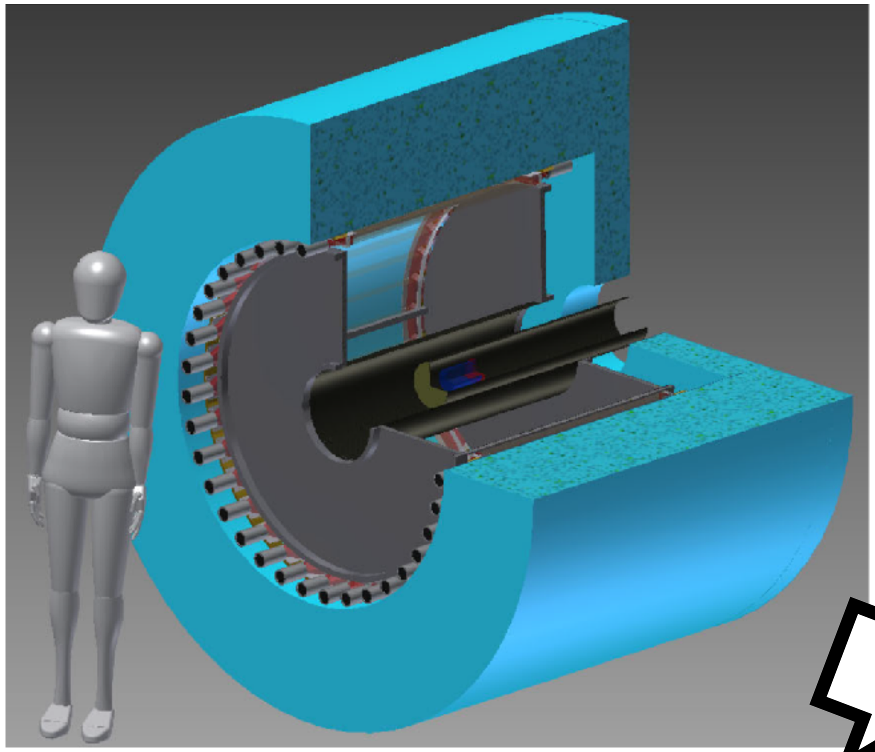
$E_{\bar{K}N}$ in system

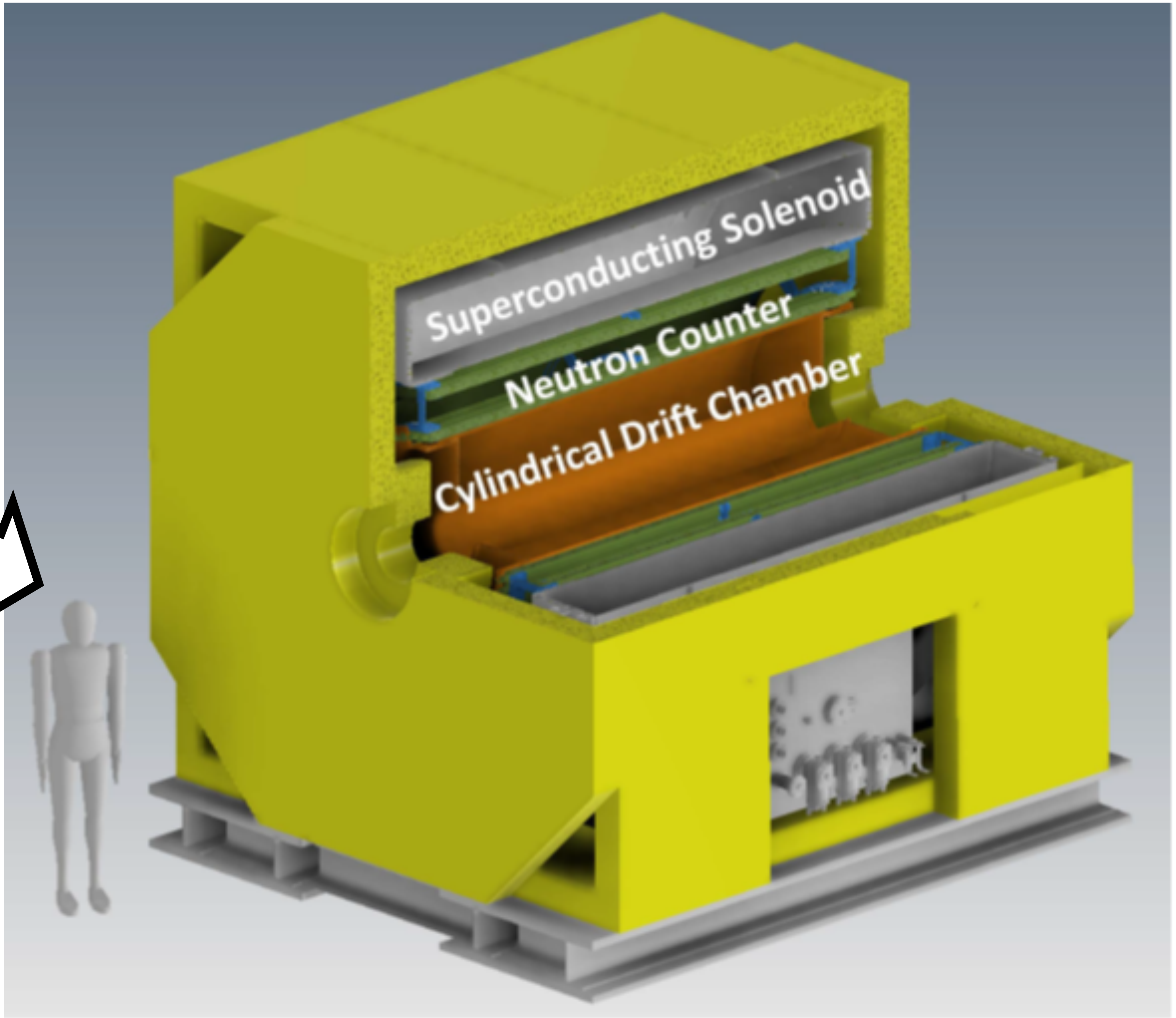
- $K^- + {}^4\text{He} \rightarrow \bar{K}NNN + n$
- $K^- + {}^6\text{Li} \rightarrow \bar{K}NNNN + d$
- $K^- + {}^7\text{Li} \rightarrow \bar{K}NNNNNN + n/p$

forward TOF

Exclusive analysis becomes difficult.→ Inclusive + tag.

New CDS



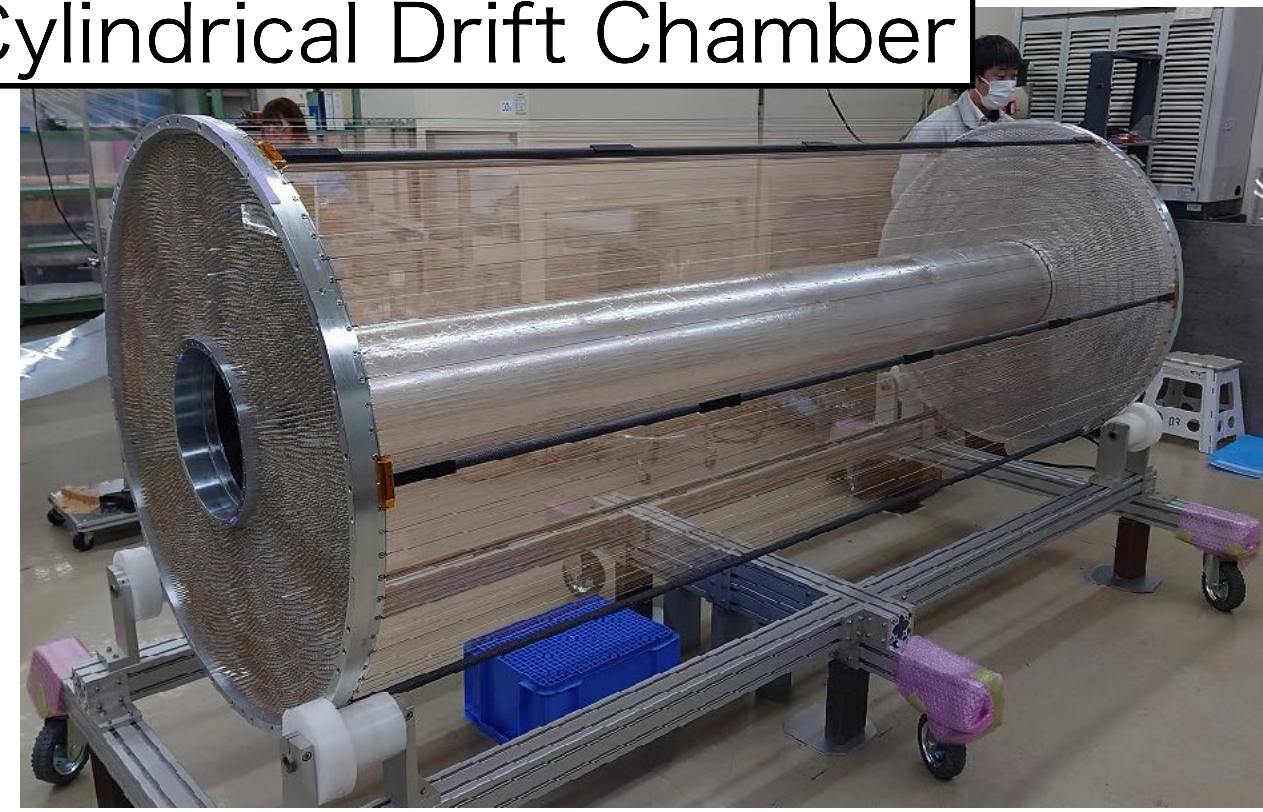


x1.6 larger solid angle (59%→93%)
x4 higher neutron detection eff. (3cm→12cm)
(proton polarimeter, forward TOF detectors)

Construction status

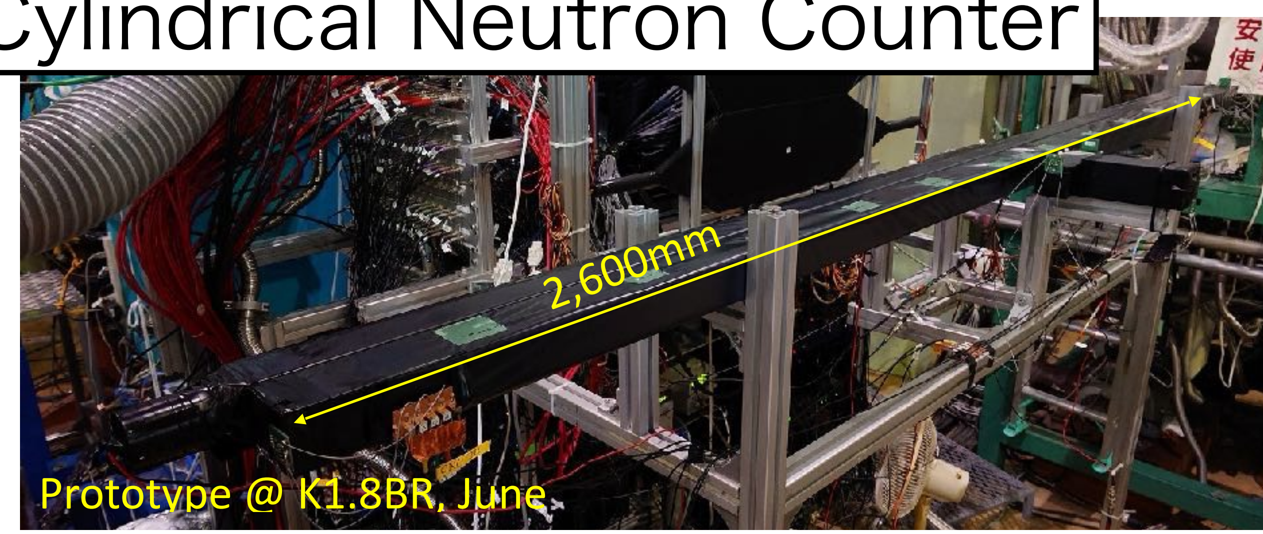
Solenoid york

Cylindrical Drift Chamber



Superconducting coil

Cylindrical Neutron Counter



- JFY2024: Complete solenoid
- JFY2025: Start installation
- **JFY2026: First beam !?**

Summary

- **Outputs with the E15-CDS (Doraemon) 2013~**
  - Demonstrated the advantage of **in-flight (K^-, n) reaction**
  - $\bar{K}NN \rightarrow \Lambda p$ signals are observed PLB789(2019)620., PRC102(2020)044002.
  - $\Lambda(1405)$ strongly couples to $\bar{K}N$ Physics Letters B 837 (2023) 137637
  - hints of $\bar{K}NN$ mesonic decay and $\bar{K}NNN \rightarrow \Lambda d$ PRC110, 014002 (2024).
- **Expected outputs with the new solenoid (Dorami): 2026~**
  - $\bar{K}NNN \rightarrow \Lambda d, \Lambda pn$ ← J-PARC E80
  - $\bar{K}NN(I_z = -1/2) \rightarrow \Lambda n, \pi^- \Lambda p$
  - $\bar{K}NN$: spin-parity
  - spatial size/density via decay branches and kinematics

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, N. Sumi, S. Suzuki, T. Yamaga, M. Yoshida

High Energy Accelerator Research Organization (KEK), Ibaraki, 305-0801, Japan

T. Nagae

Department of Physics, Kyoto University, Kyoto, 606-8502, 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