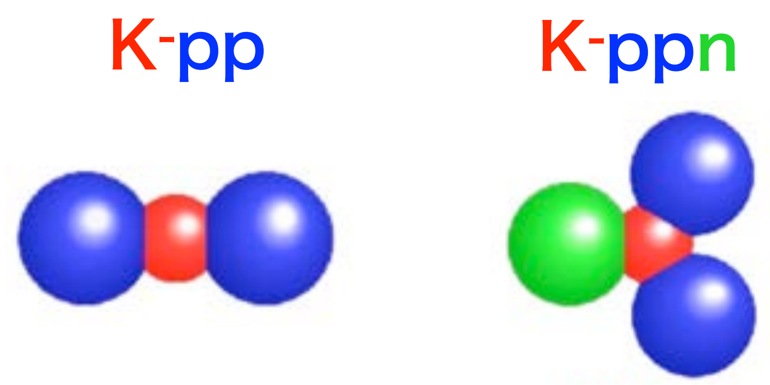
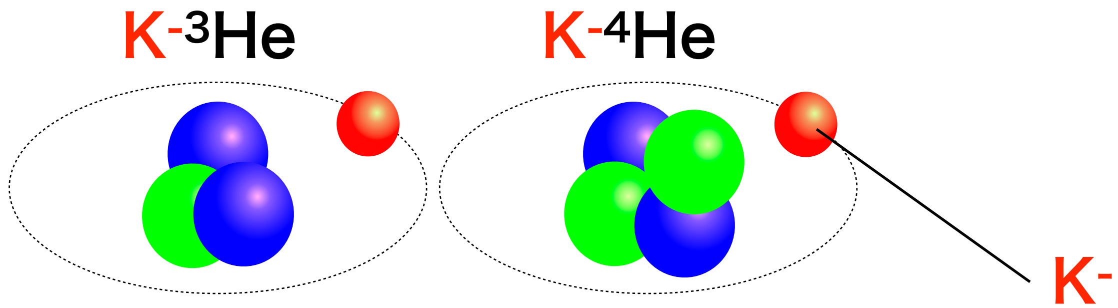


Kaonic nuclei and atoms at J-PARC

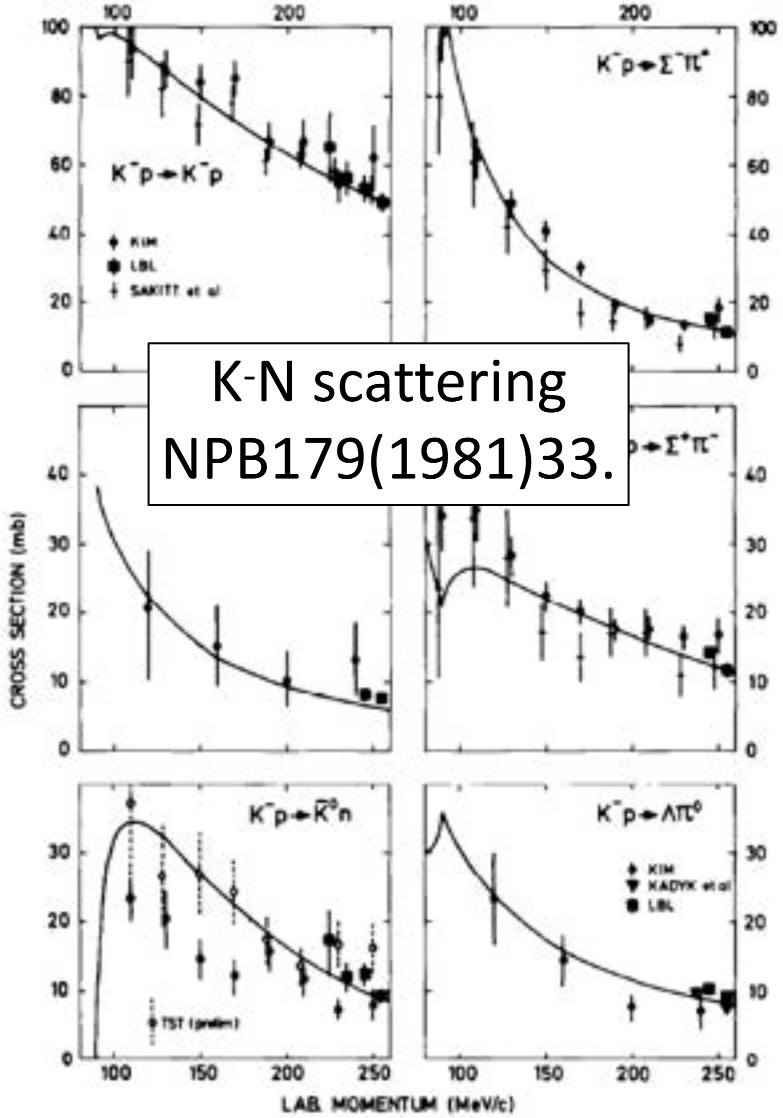


Tadashi Hashimoto (JAEA ASRC)
for the J-PARC E15/E31/E57/E62/E73/T77/E80/P89 collaborations

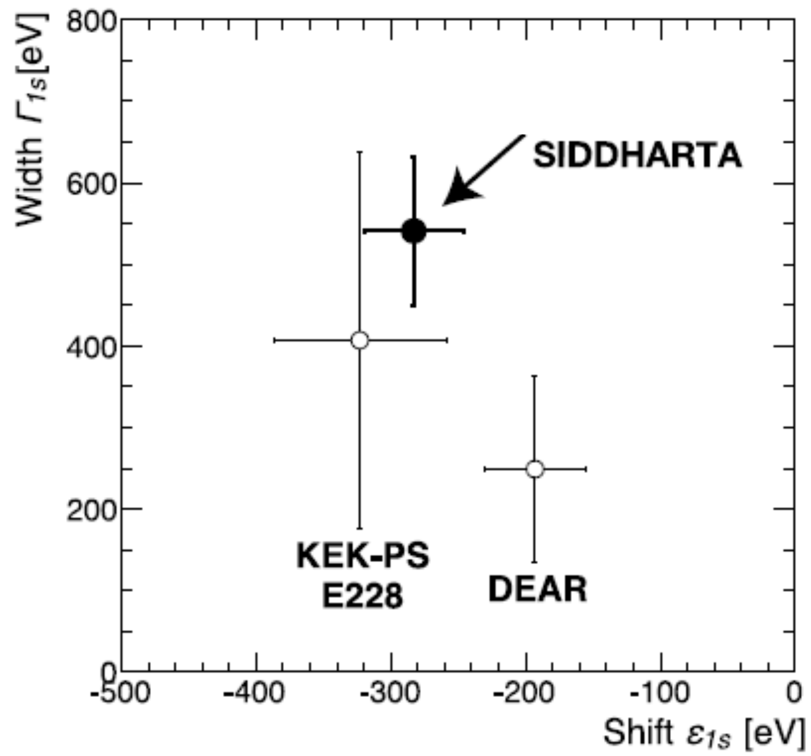
12–15 September 2023 @ J-PARC

$K^{bar}N$ interaction

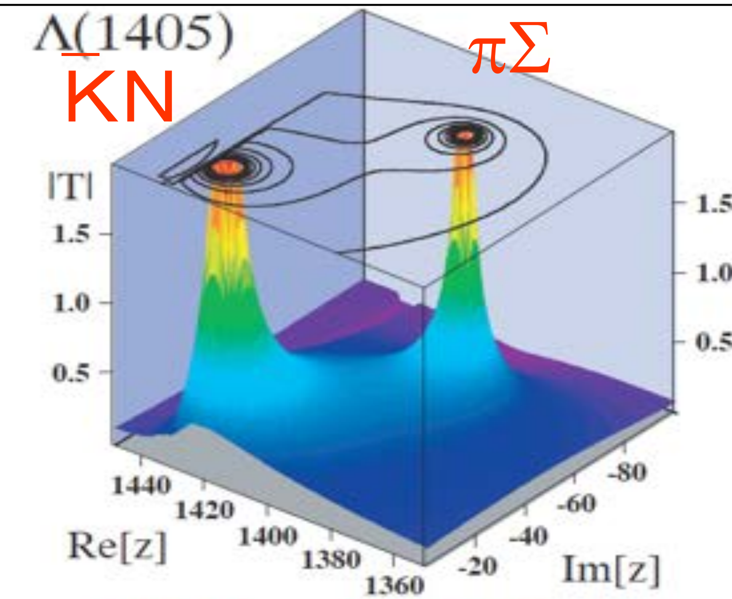
K-N scattering
NPB179(1981)33.



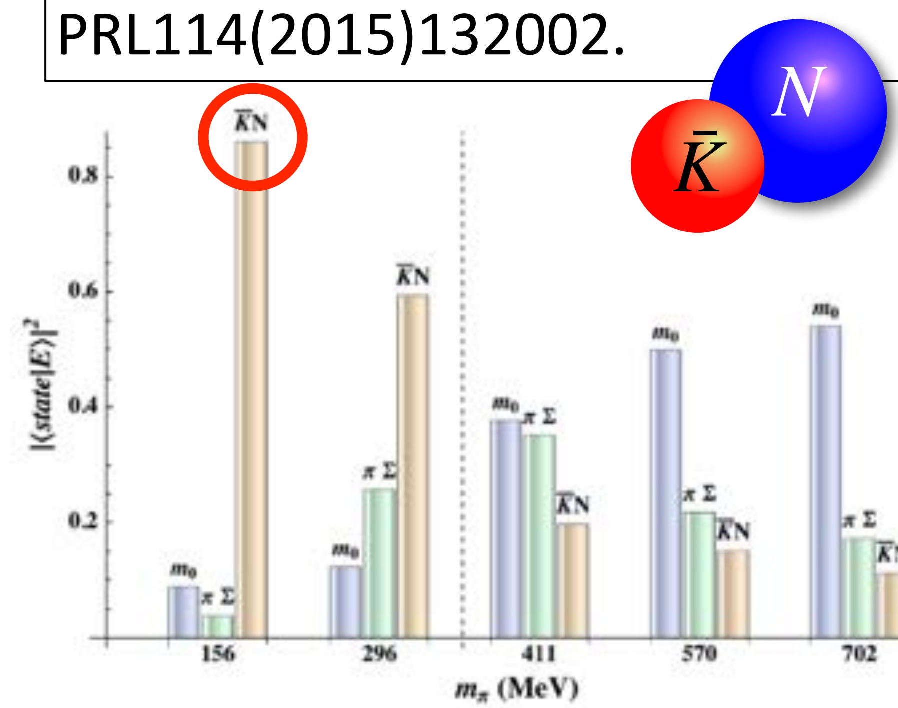
K-p atom
PLB704(2011)113.



Λ(1405) in chiral unitary model
T. Hyodo



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

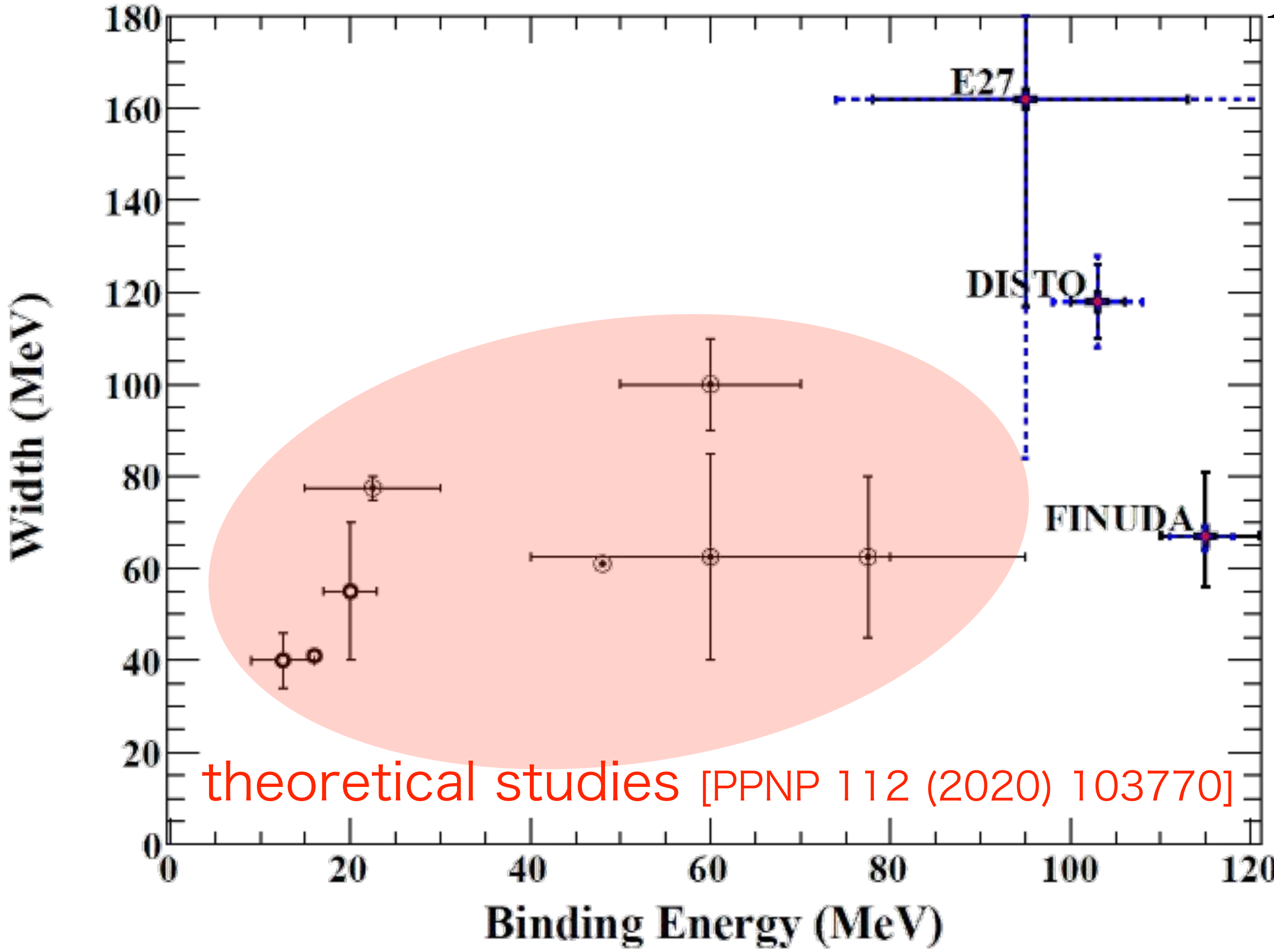


- Strong attraction in I=0 from scattering and X-ray experiements.
- $\Lambda(1405) = \bar{K}N$ molucle picture is now widely accepted

Why not kaonic nucleus with additional nucleons?

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$(K^-_{stopped}, \Lambda p)$

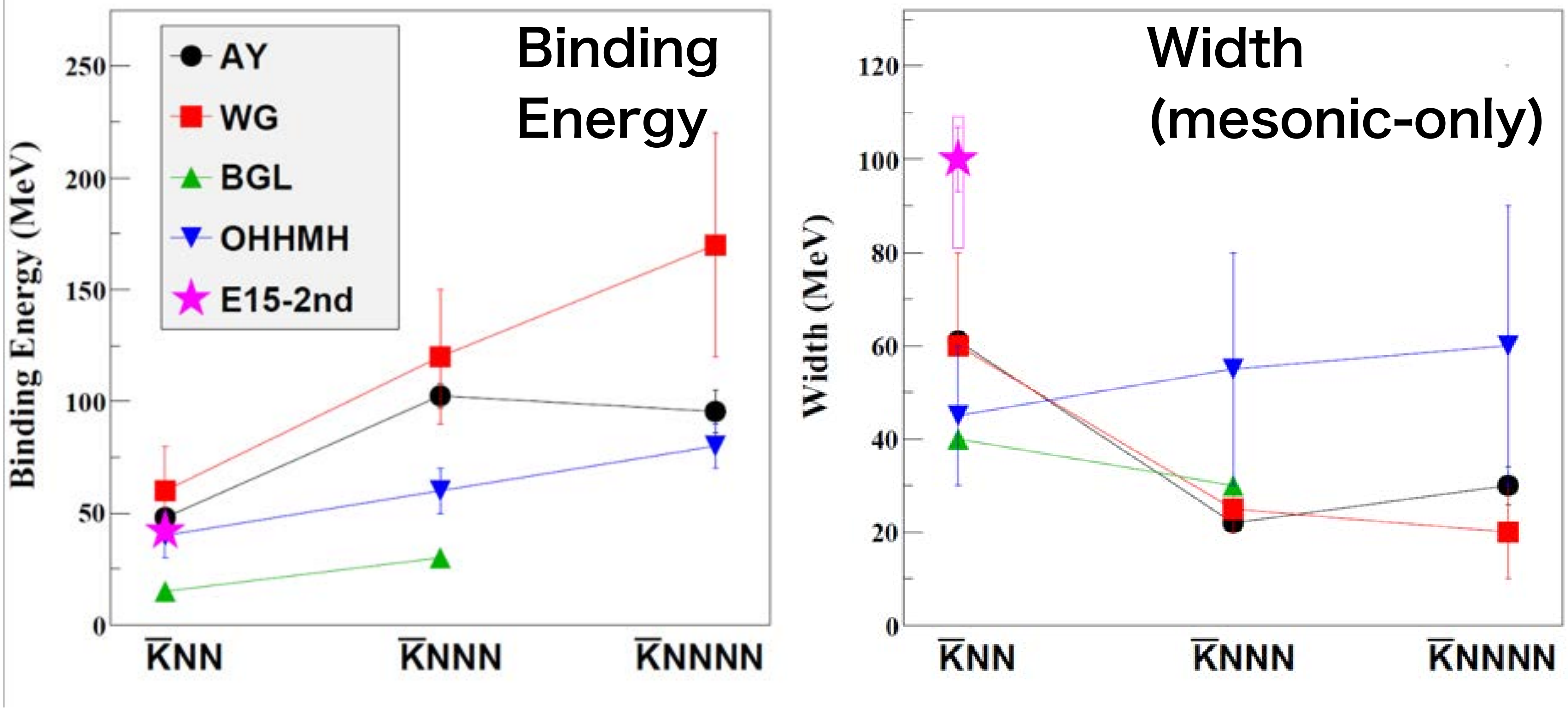
- Theoretical calculations agree on the existence of $\bar{K}NN$, although B.E. and Γ depend on the $\bar{K}N$ interaction models.
- No conclusive experimental evidence before us.

Mass number dependence

Not a complete list. sorry…

$\bar{K}NNN \quad I(J^p) = 0(1/2^-)$

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

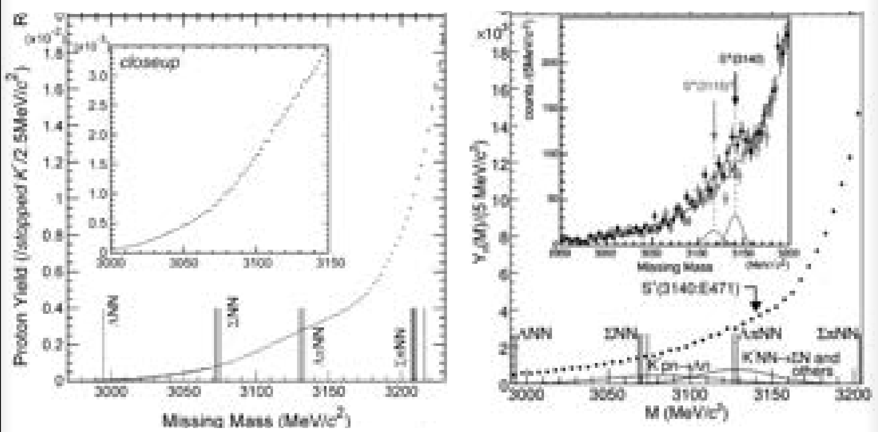


Larger binding than $\bar{K}NN$ and similar width are predicted.

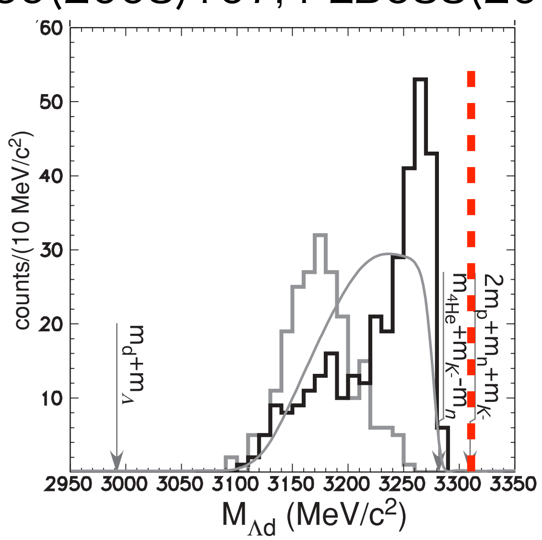
$\bar{K}NNN$: Experimental situaion

Stopped K⁻ on ⁴He

E471/E549@KEK



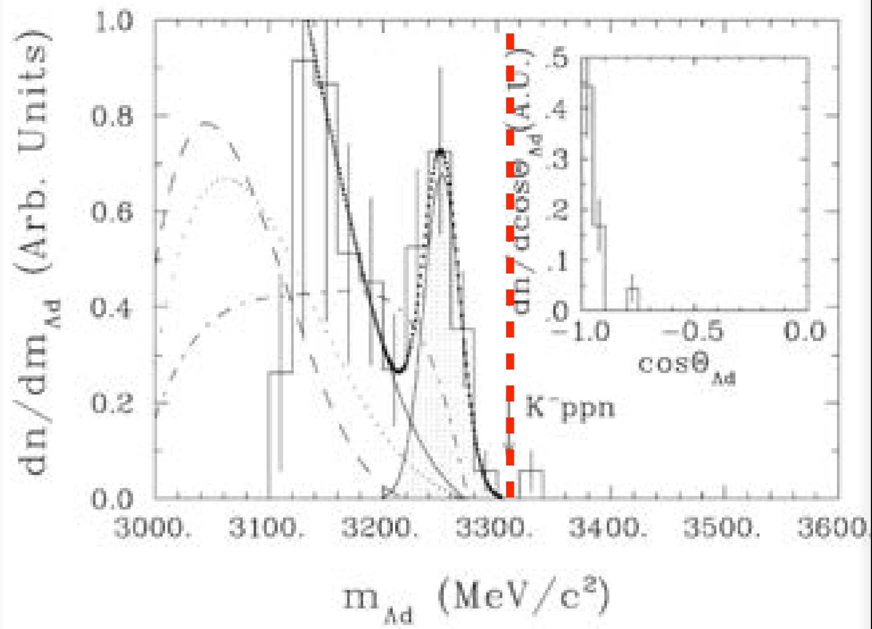
PLB659(2008)107, PLB688(2010)43



PRC76(2007)068202

Stopped K⁻ on Li/C back-to-back Λd

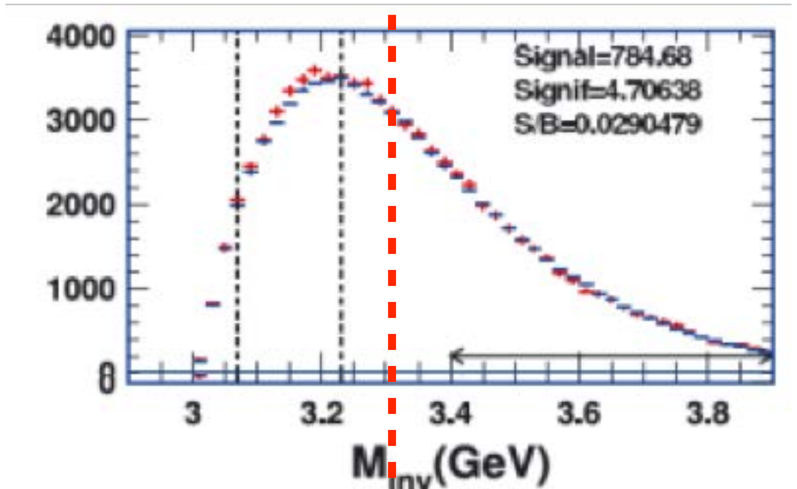
FUNUDA@DAΦNE

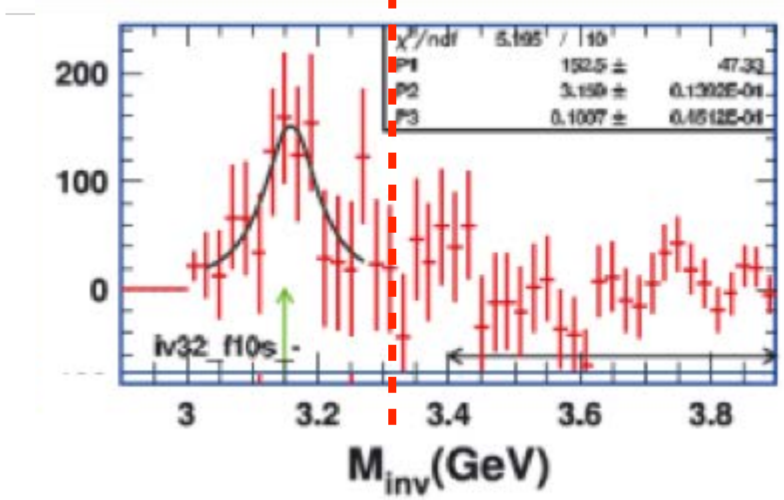


PLB654(2007)80

Λd in Ni+Ni

FOPI@GSI

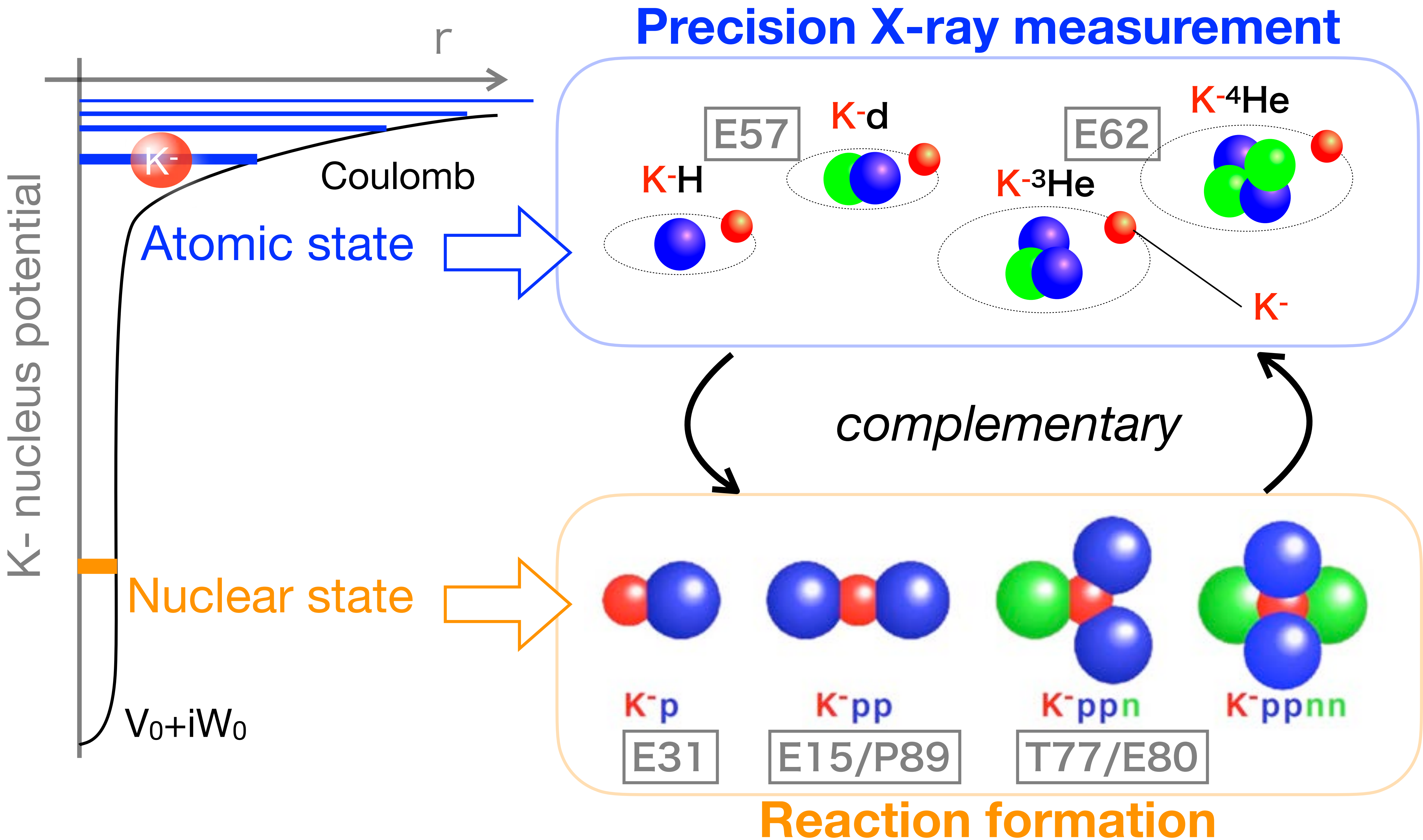




EXA05 Proceedings (2005)

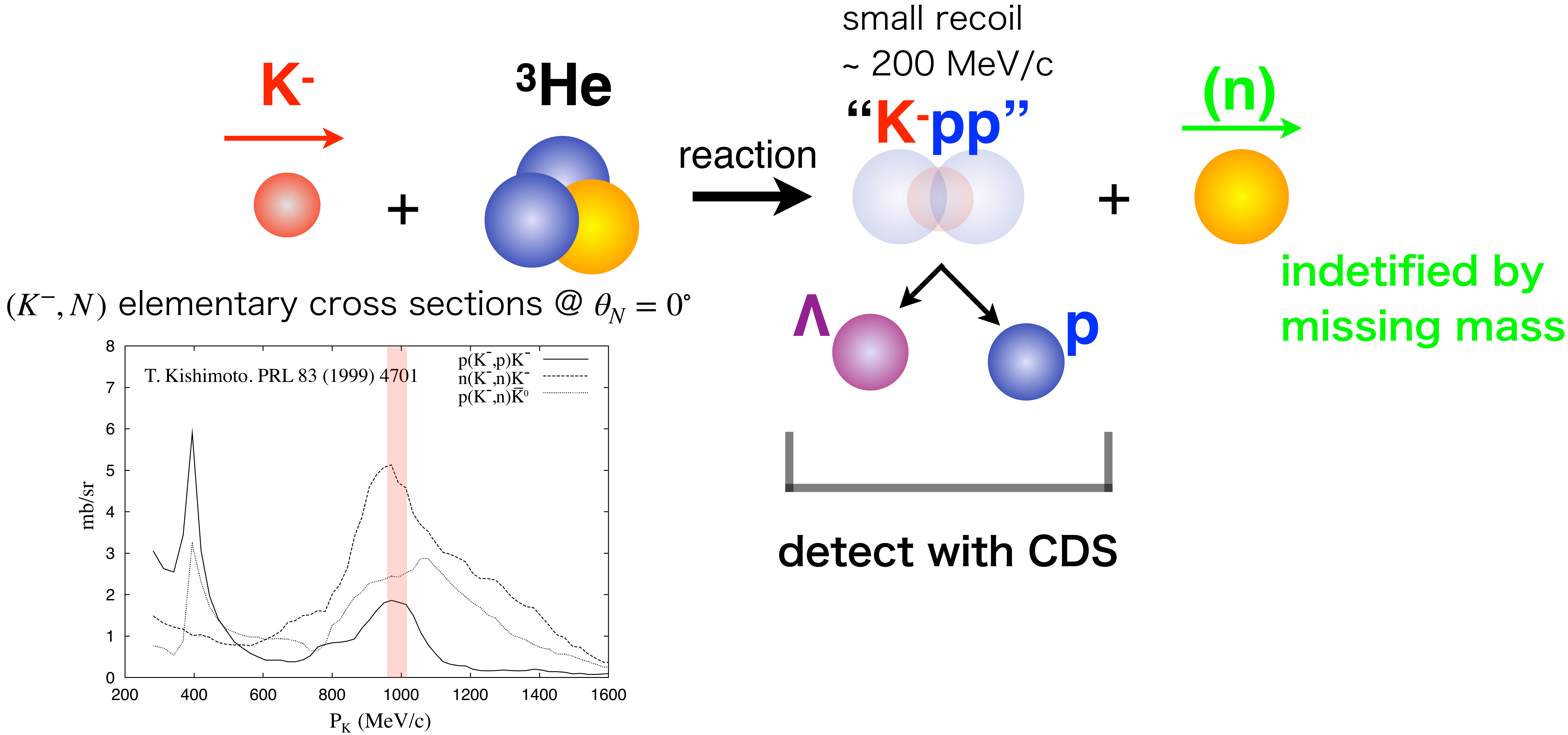
- **Some experimental searches in 2000s. No conclusive result.**
- **multi-N absorptions hide bound-state signals in Stop-K**

Experiments at J-PARC



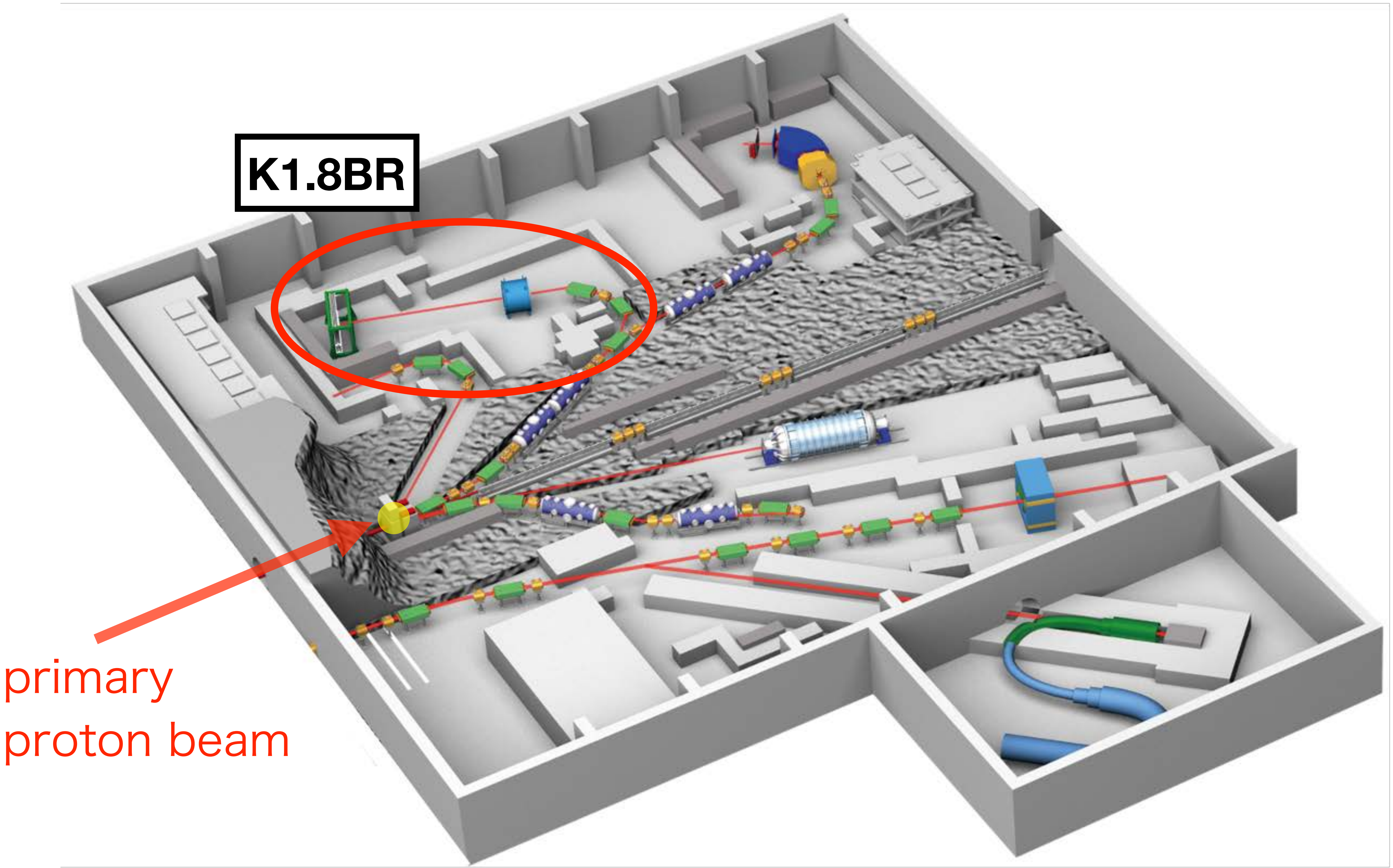
A series of experiments at J-PARC K1.8BR
Probe different energy, density, and isospin

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



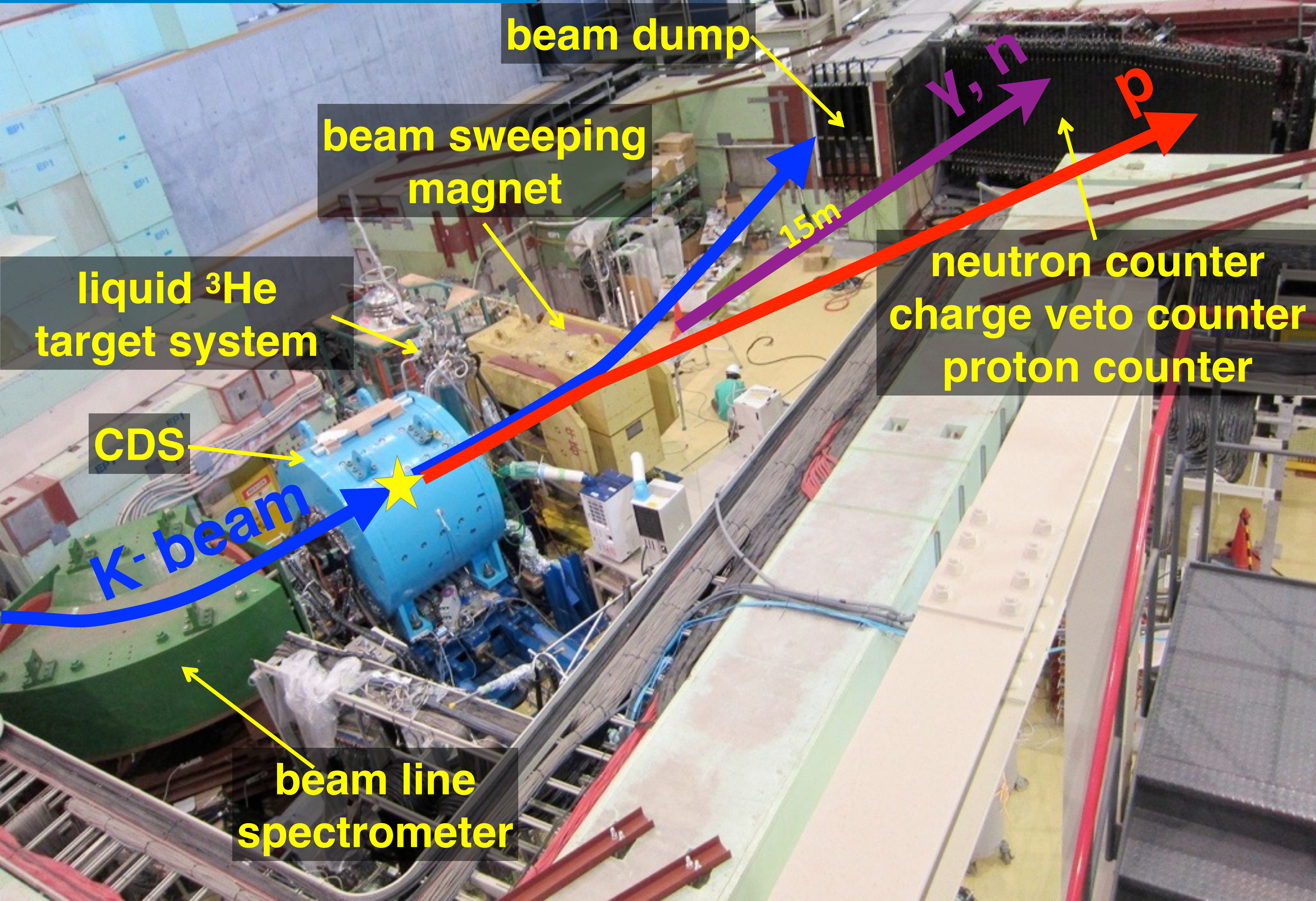
- K^- beam at 1 GeV/c to maximize elementary (K^-, N) cross sections
- Most of background processes can be kinematically separated.
  - Hyperon decays and multi-nucleon absorption reactions
- Simplest target allow exclusive analysis.

J-PARC K1.8BR



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

E15/E31@K1.8BR



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

$\bar{K}NN$ in $^3\text{He}(K^-, \Lambda p)n$

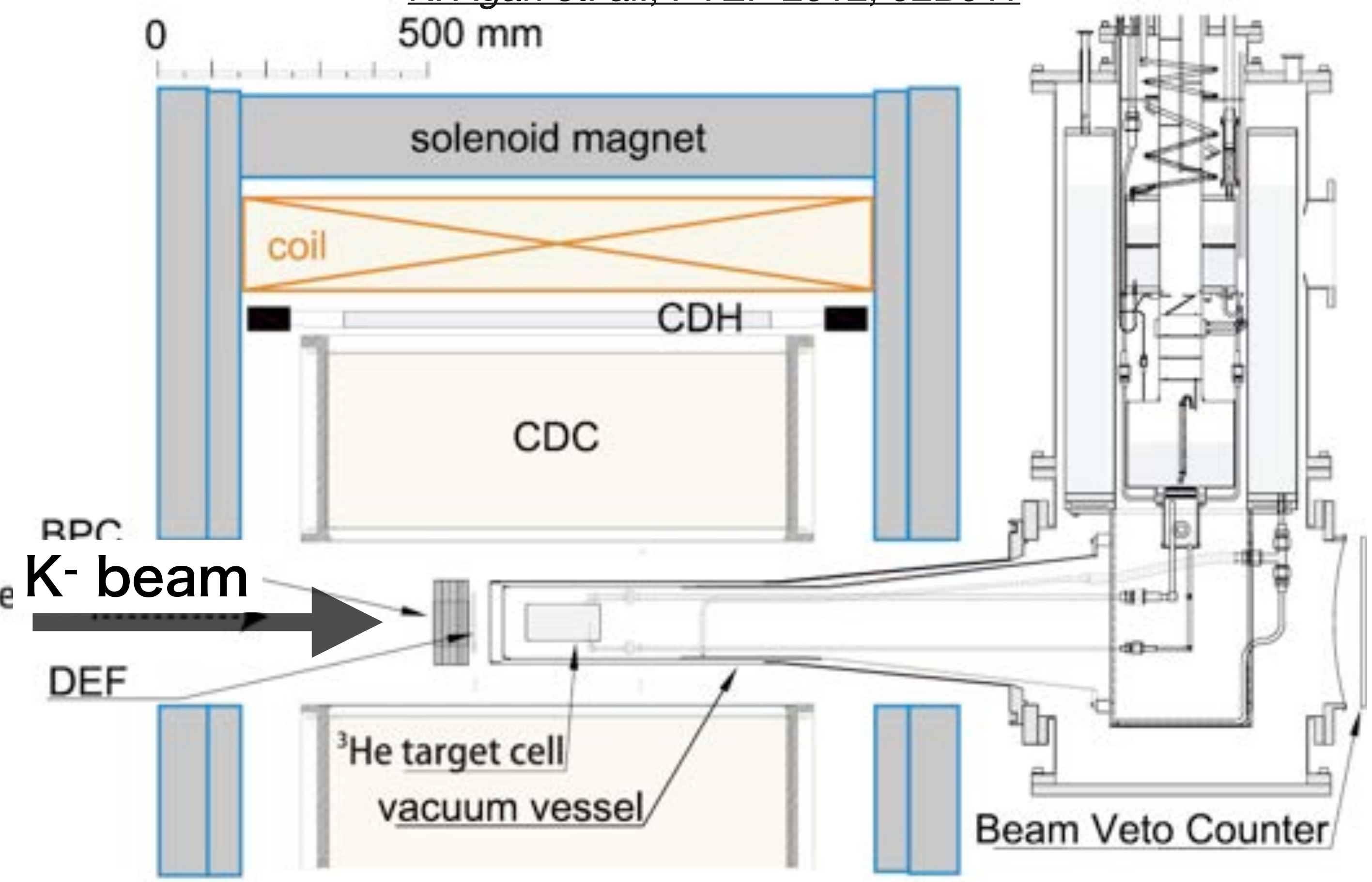
PHYSICAL REVIEW C **102**, 044002 (2020)

Observation of a $\overline{K}NN$ bound state in the $^3\text{He}(K^-, \Lambda p)n$ reaction

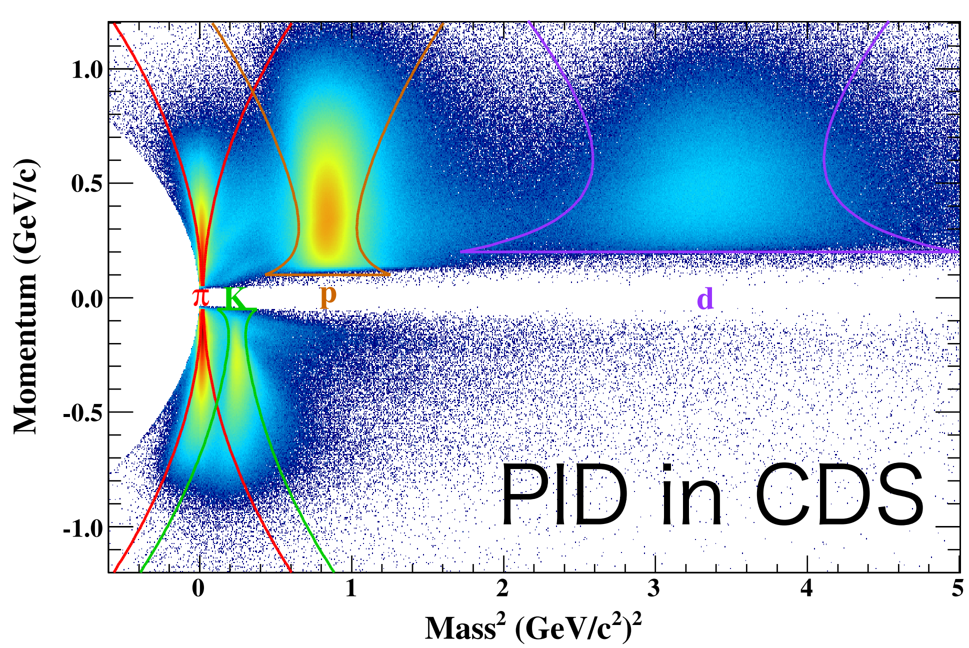
T. Yamaga,[1,*] S. Ajimura,[2] H. Asano,[1] G. Beer,[3] H. Bhang,[4] M. Bragadireanu,[5] P. Buehler,[6] L. Busso,[7,8] M. Cargnelli,[6] S. Choi,[4] C. Curceanu,[9] S. Enomoto,[14] H. Fujioka,[15] Y. Fujiwara,[12] T. Fukuda,[13] C. Guaraldo,[9] T. Hashimoto,[20] R. S. Hayano,[12] T. Hiraiwa,[2] M. Iio,[14] 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

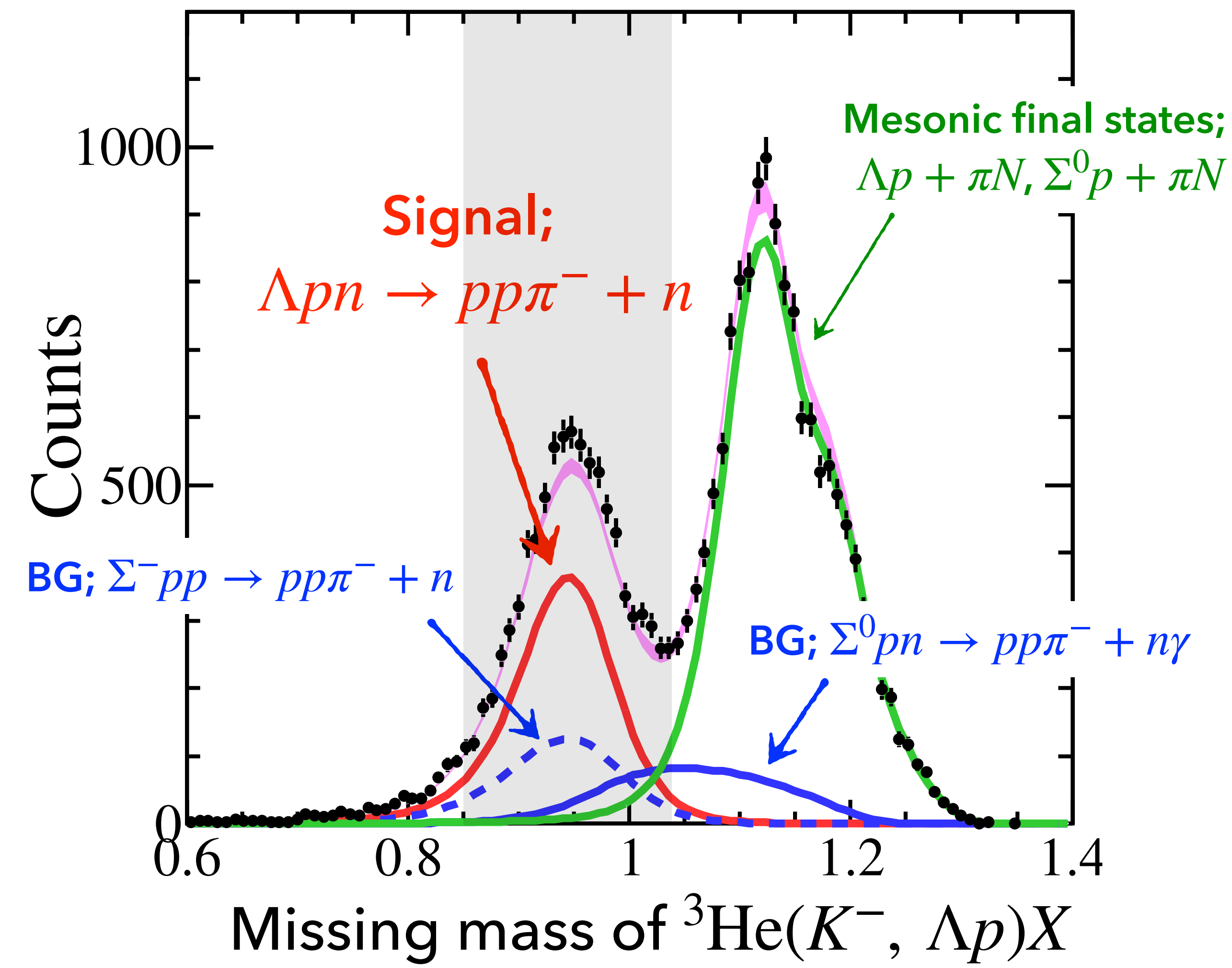
K. Agari et. al., PTEP 2012, 02B011



15-layer CDC and TOF hodoscopes



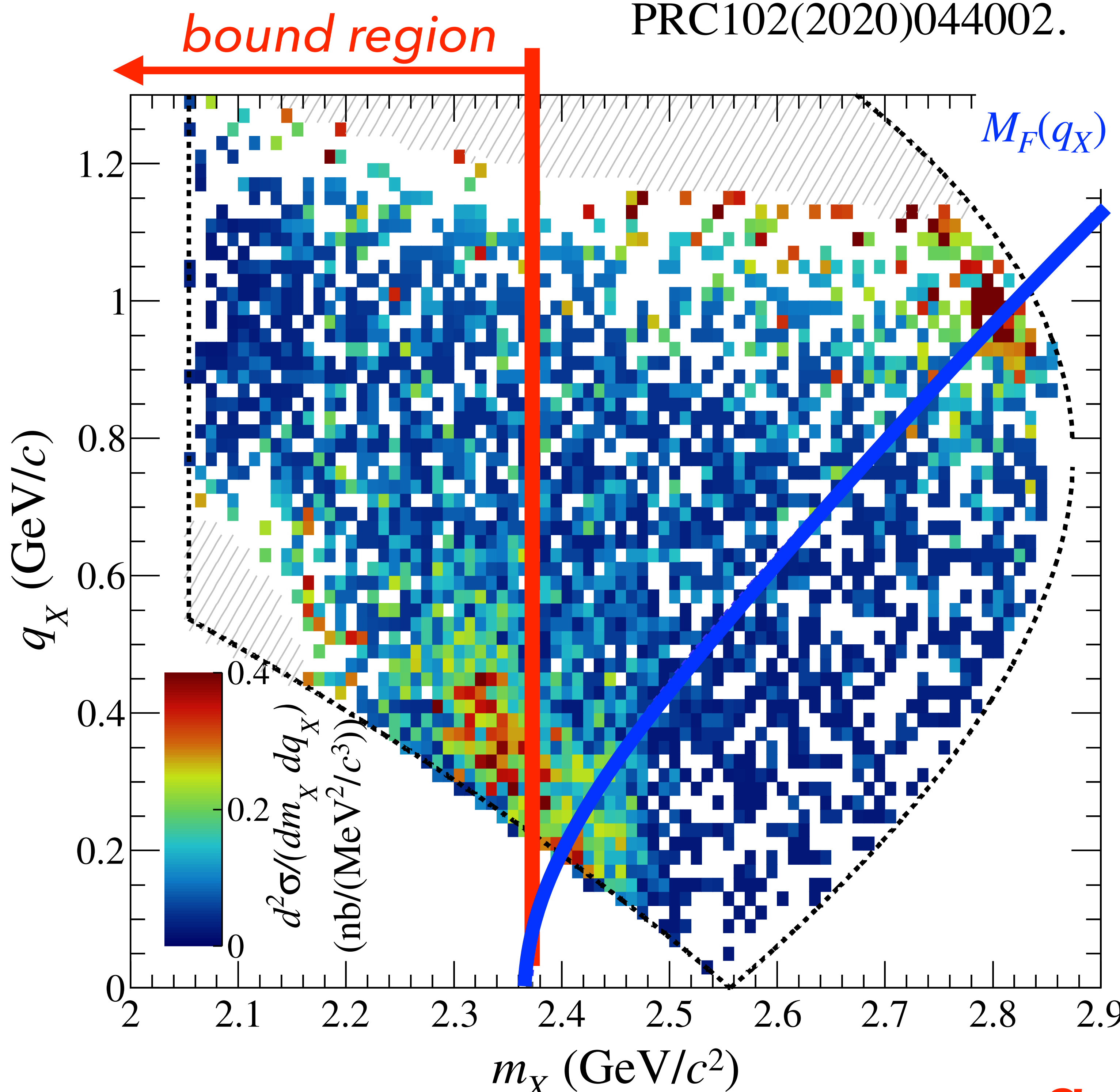
missing neutron selection



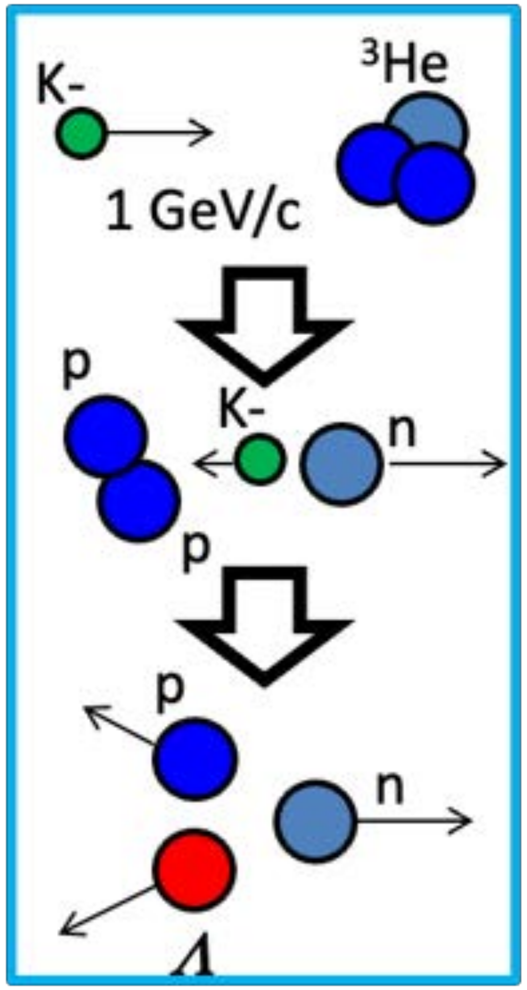
- Λpn events are selected with ~80% purity.
- ~20% $\Sigma^0 pn/\Sigma^- pp$ contamination

Obtained spectrum in J-PARC E15

PRC102(2020)044002.



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



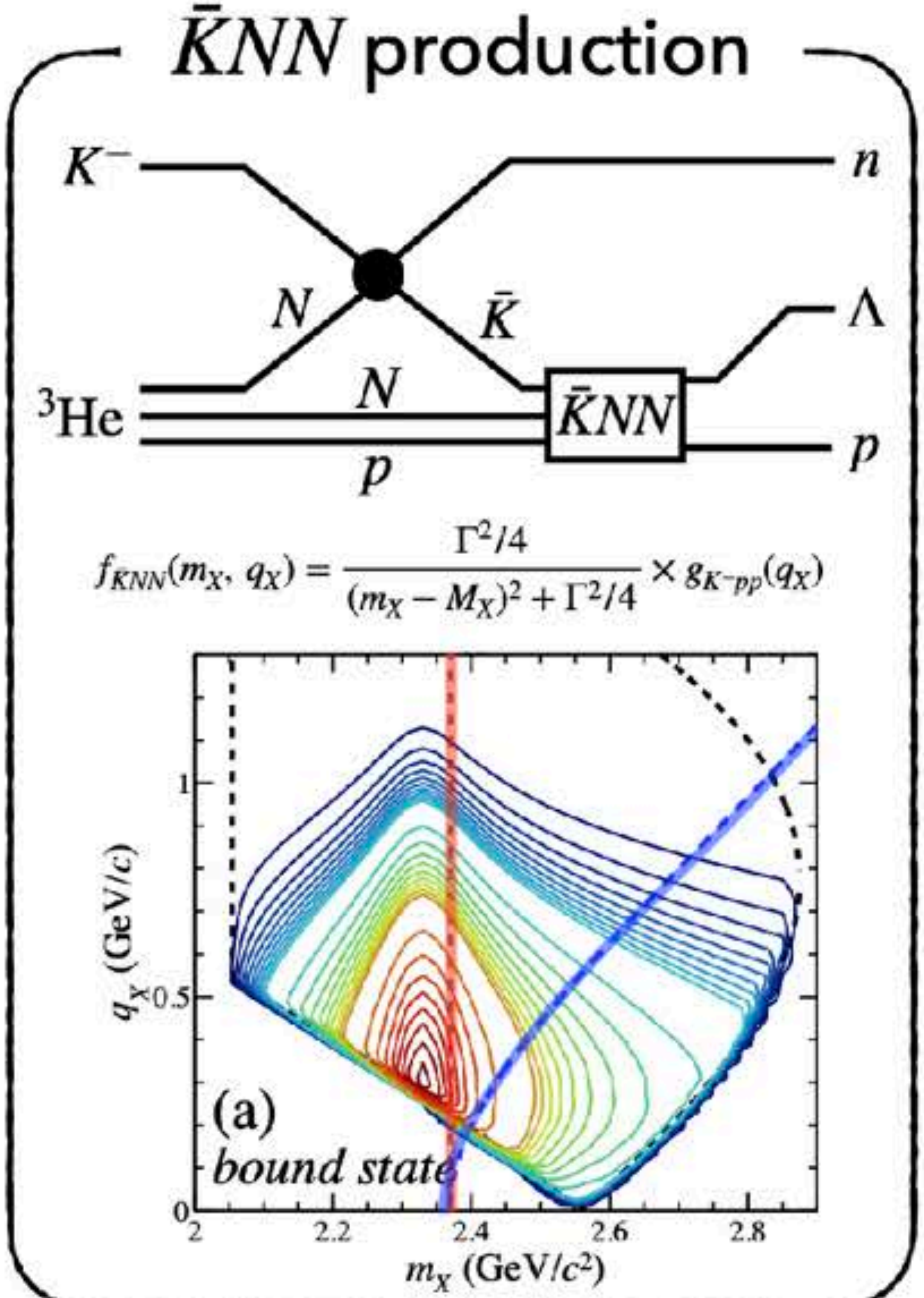
"quasi-free" process

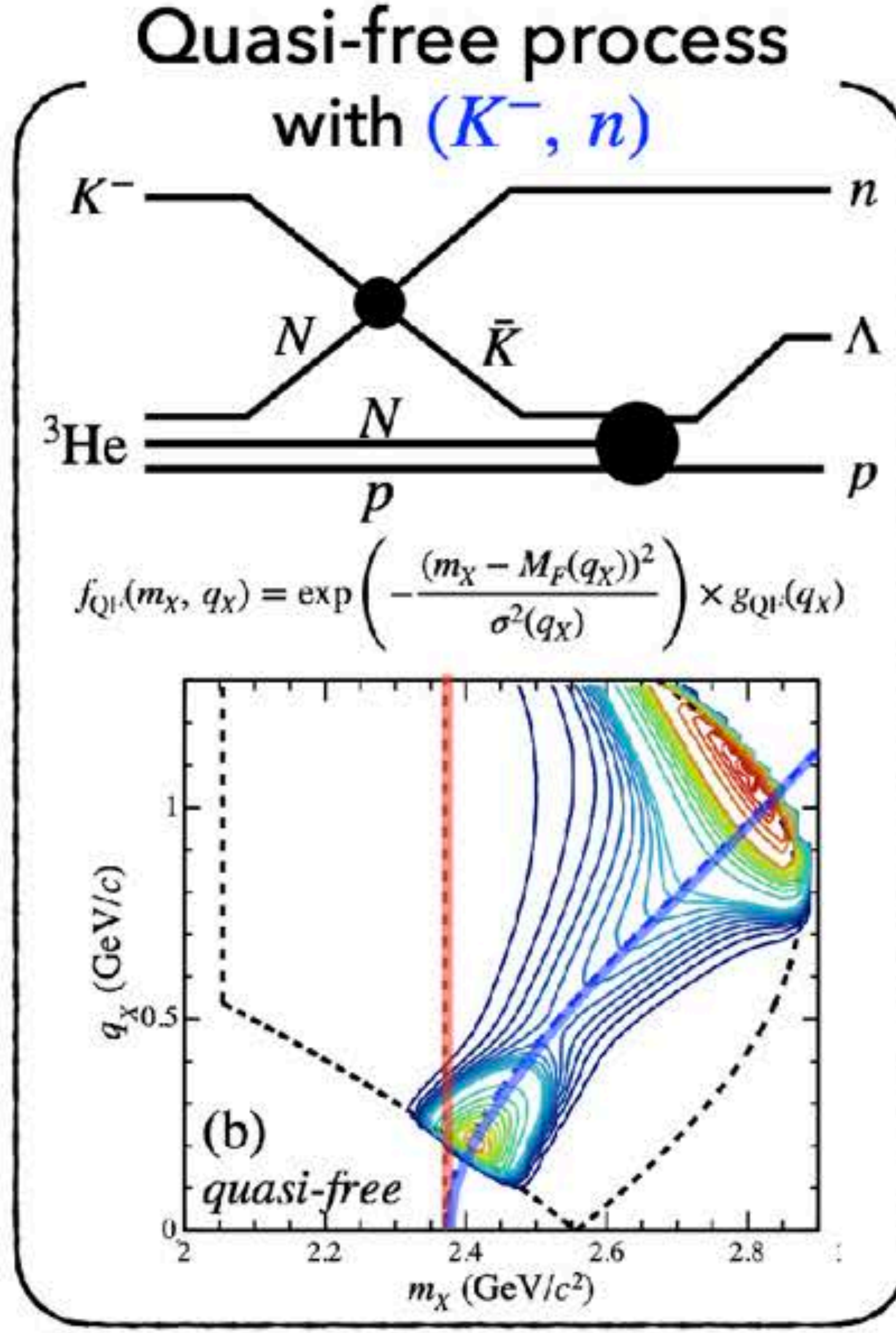
m_x: Λp invariant mass

q_x: momentum transfer to Λp system

q_x-indep. component below the threshold

Model functions





+ Broad component

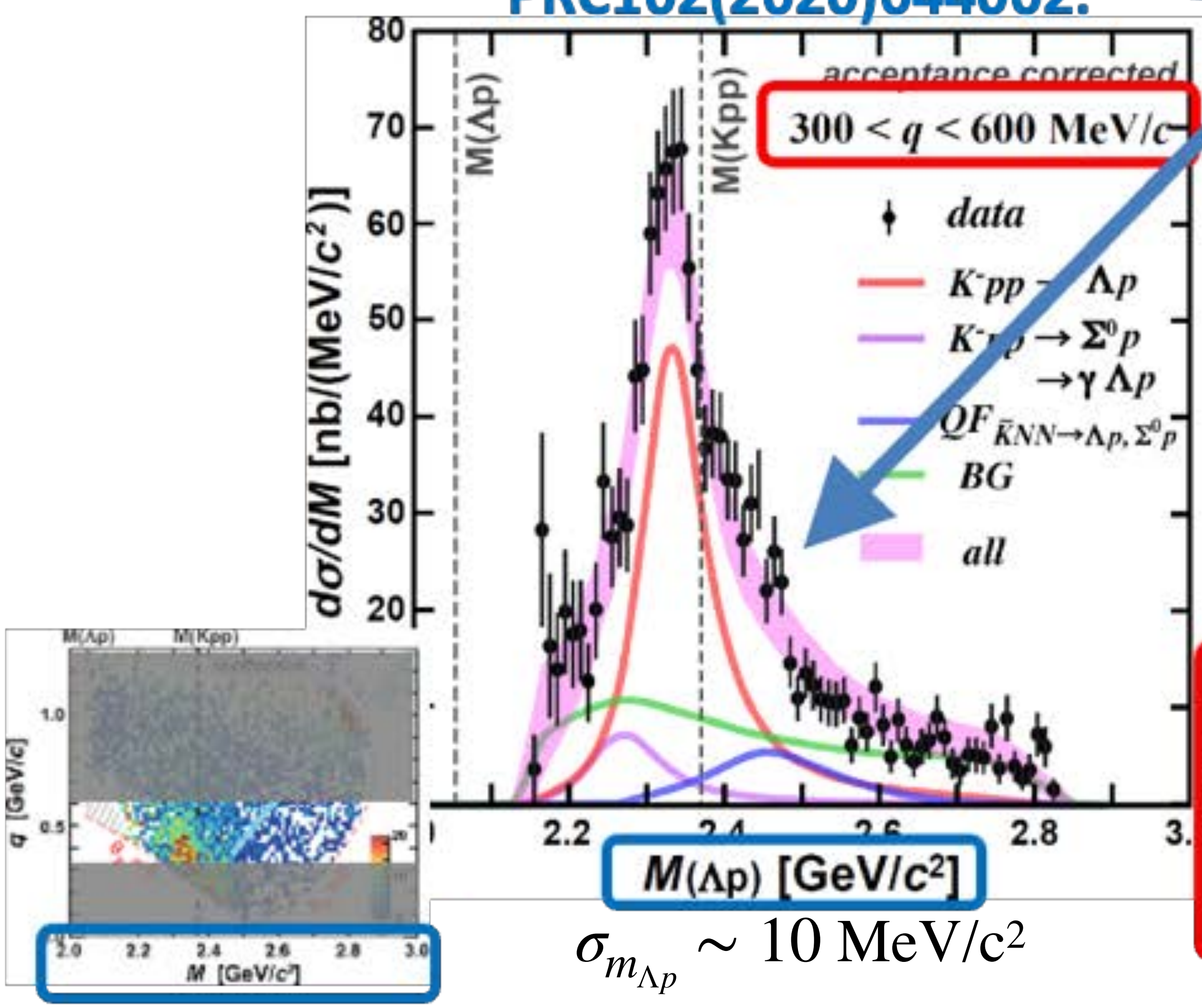
2D Fit for the "$\bar{K}NN$" state

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

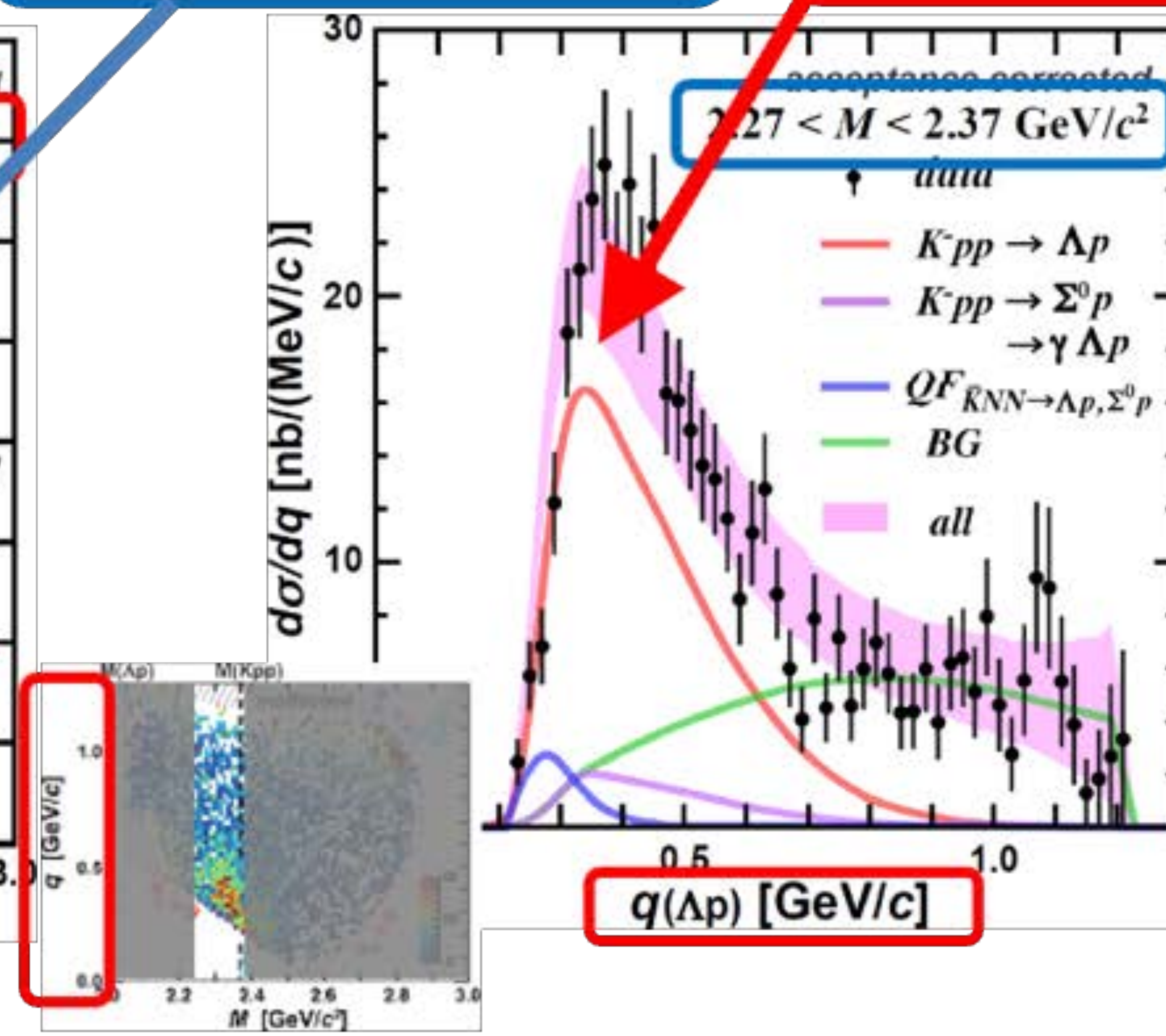
Fit with PWIA $\sigma(M,q) \propto \rho(M,q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2} \times exp\left(-\frac{q^2}{{Q_{Kpp}}^2}\right)$

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*

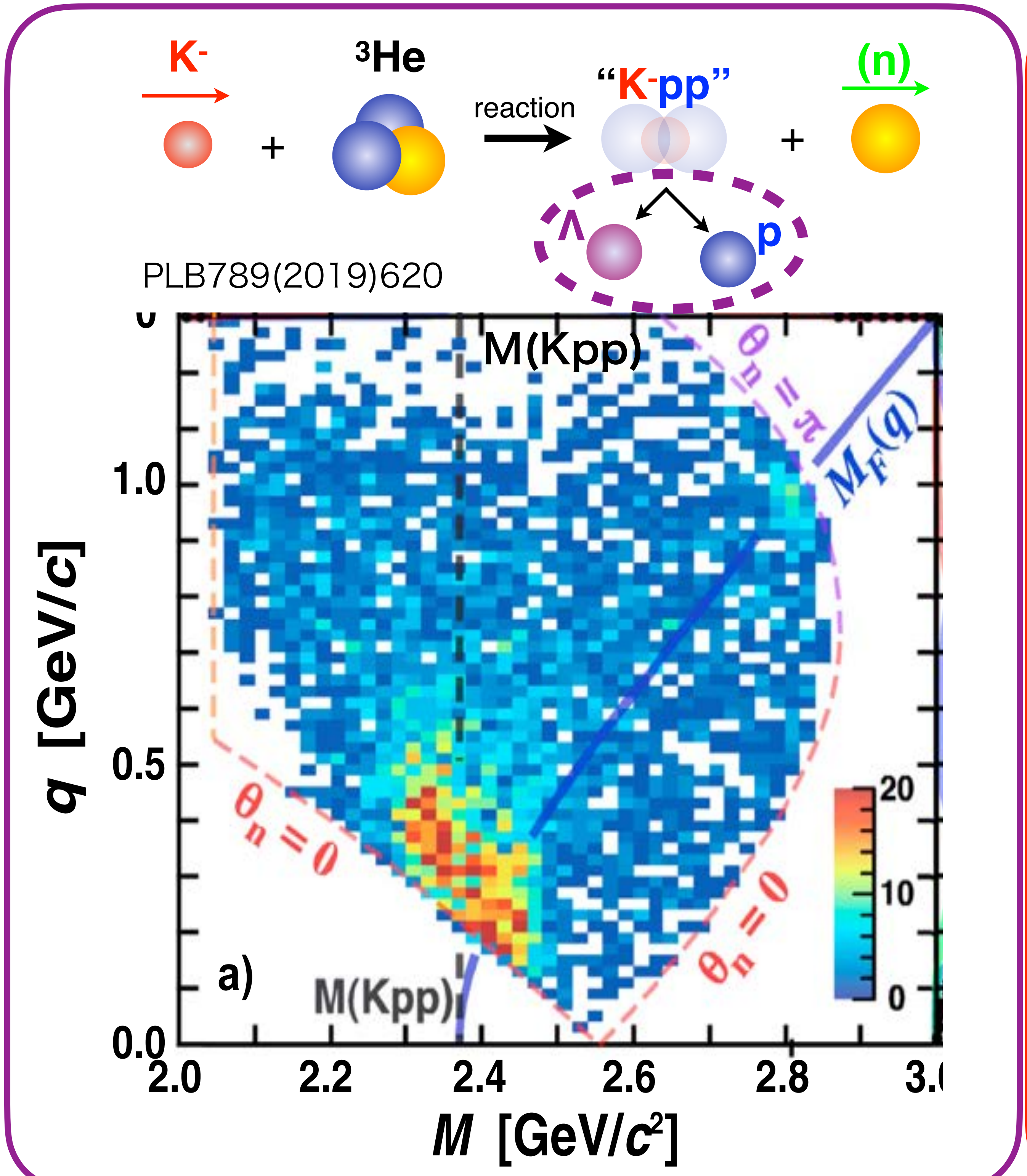
Q_{kpp} ~ 400 MeV (c.f. Q_{QF} ~ 200 MeV)
→ *wide momentum transfer*

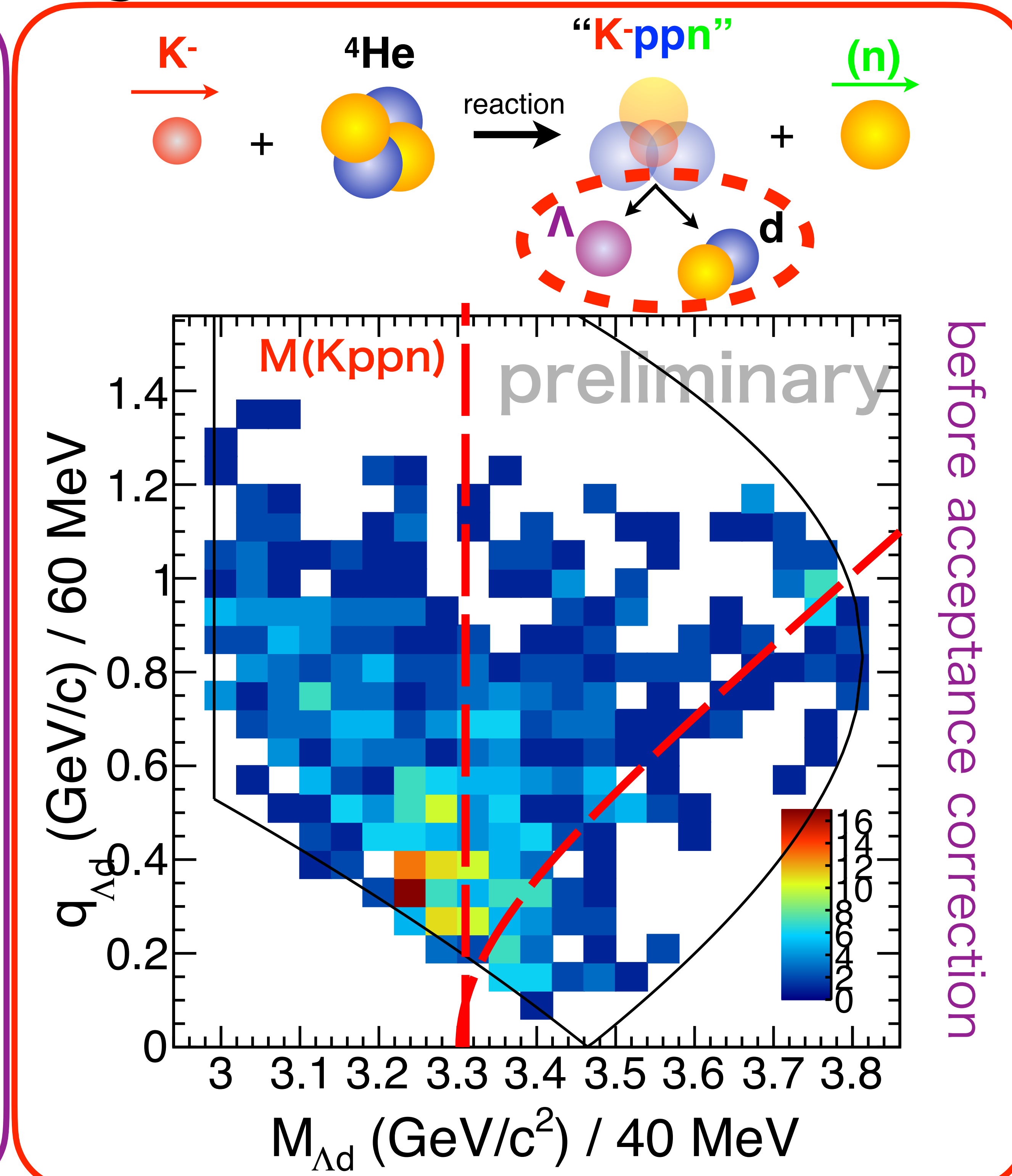
$I(J^p) = 0(1/2^-)$

$\bar{K}NNN$ in $^4\mathrm{He}(K^-, \Lambda d)n$

Helium-4 data with the E15 setup as a test experiment in 2020

$\bar{K}NNN$: Preliminary result



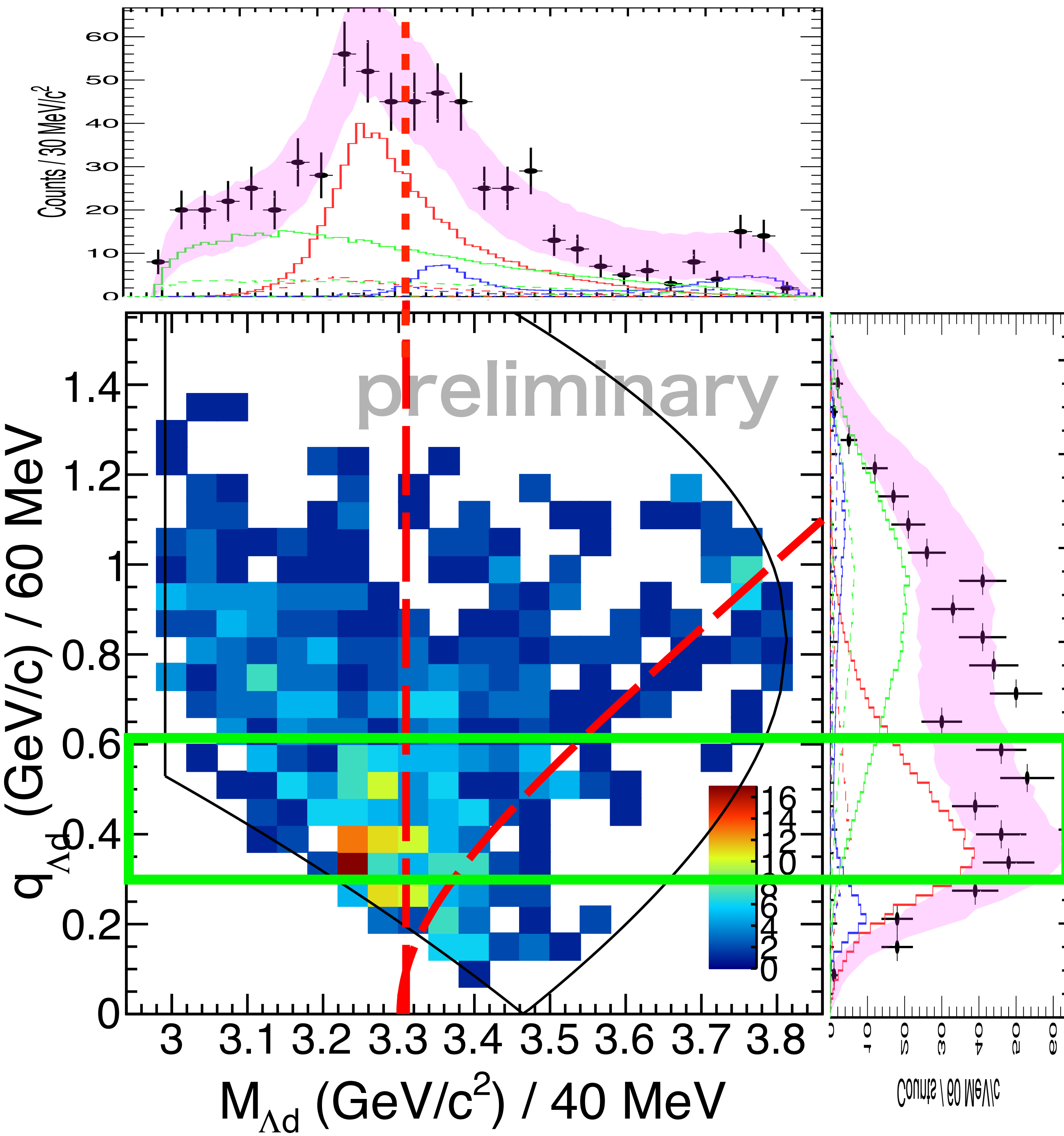


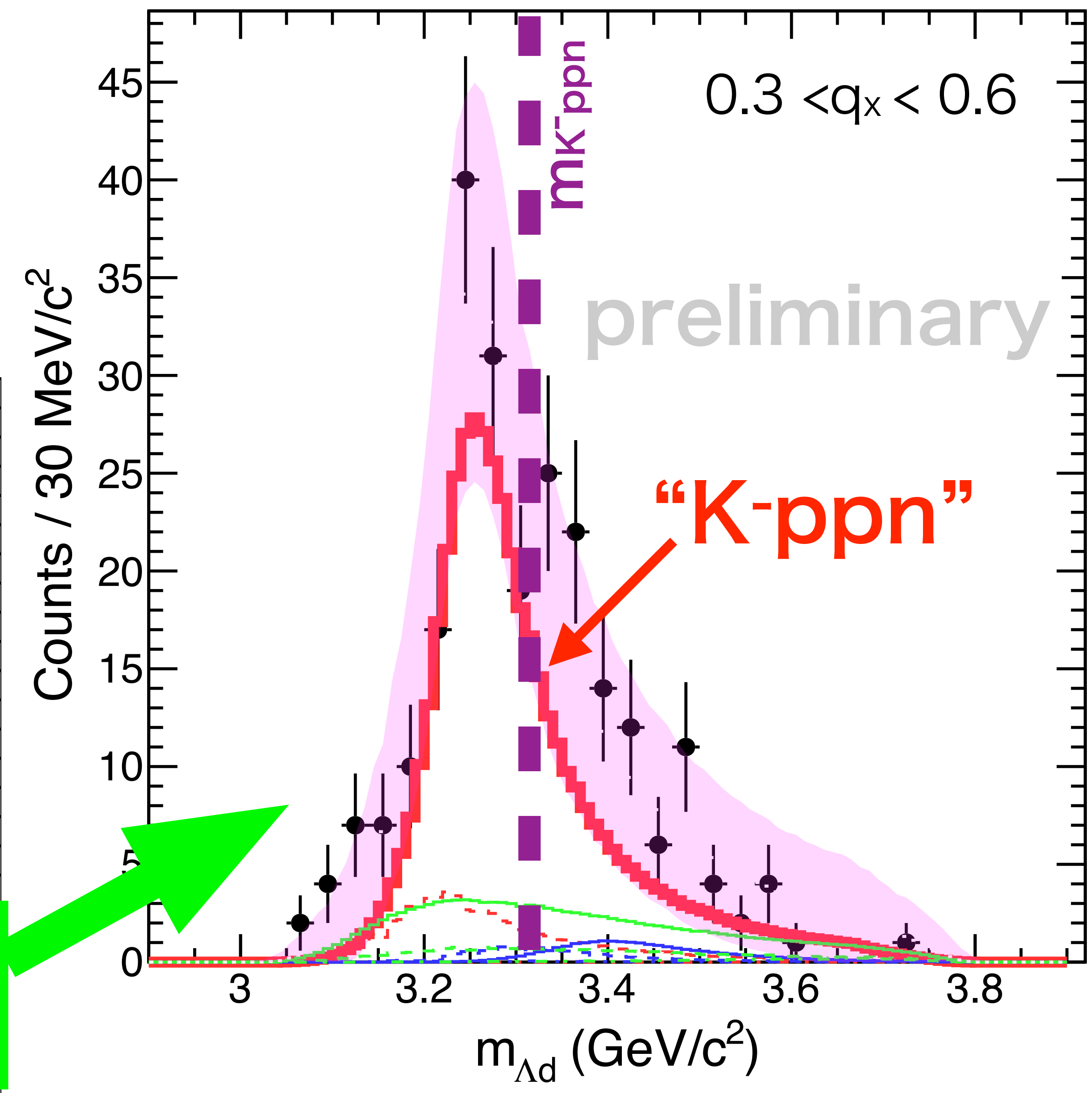
- Two disributions are quite similar
- structure below the threshold, QF-K^-, and broad background

$\bar{K}NNN$: 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-



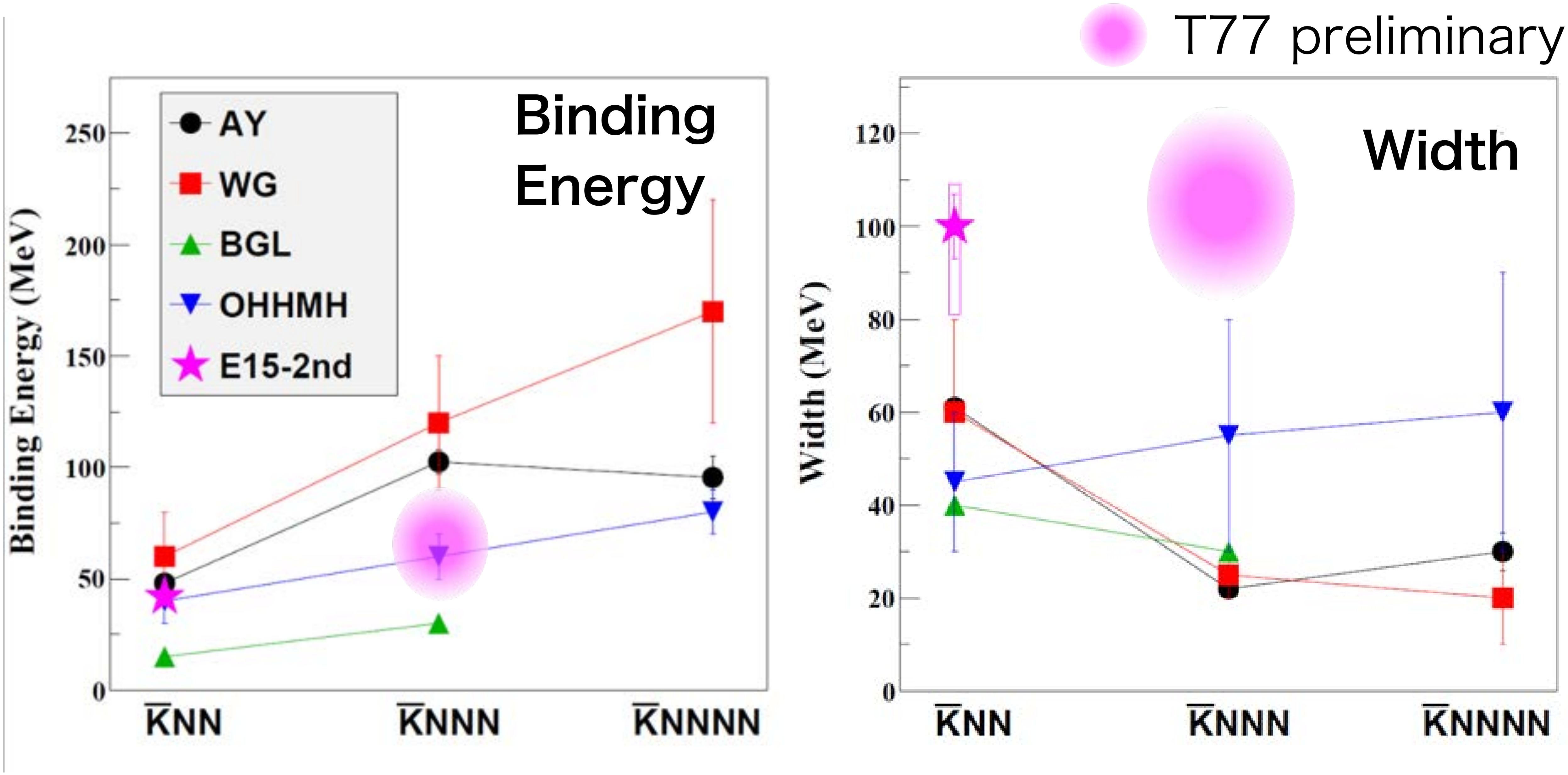


$B_{\bar{K}NNN} \sim xx \pm 11(\text{stat})$ MeV

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

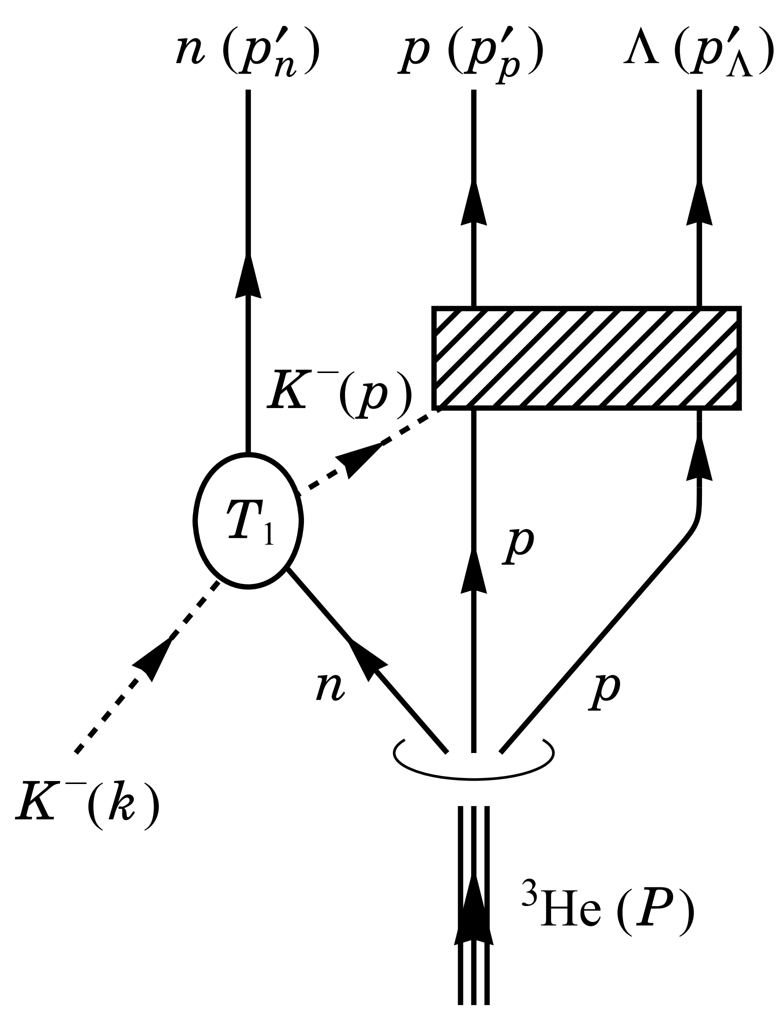
$\sigma_{\bar{K}NNN \to \Lambda d} \sim 4\ \mu$b

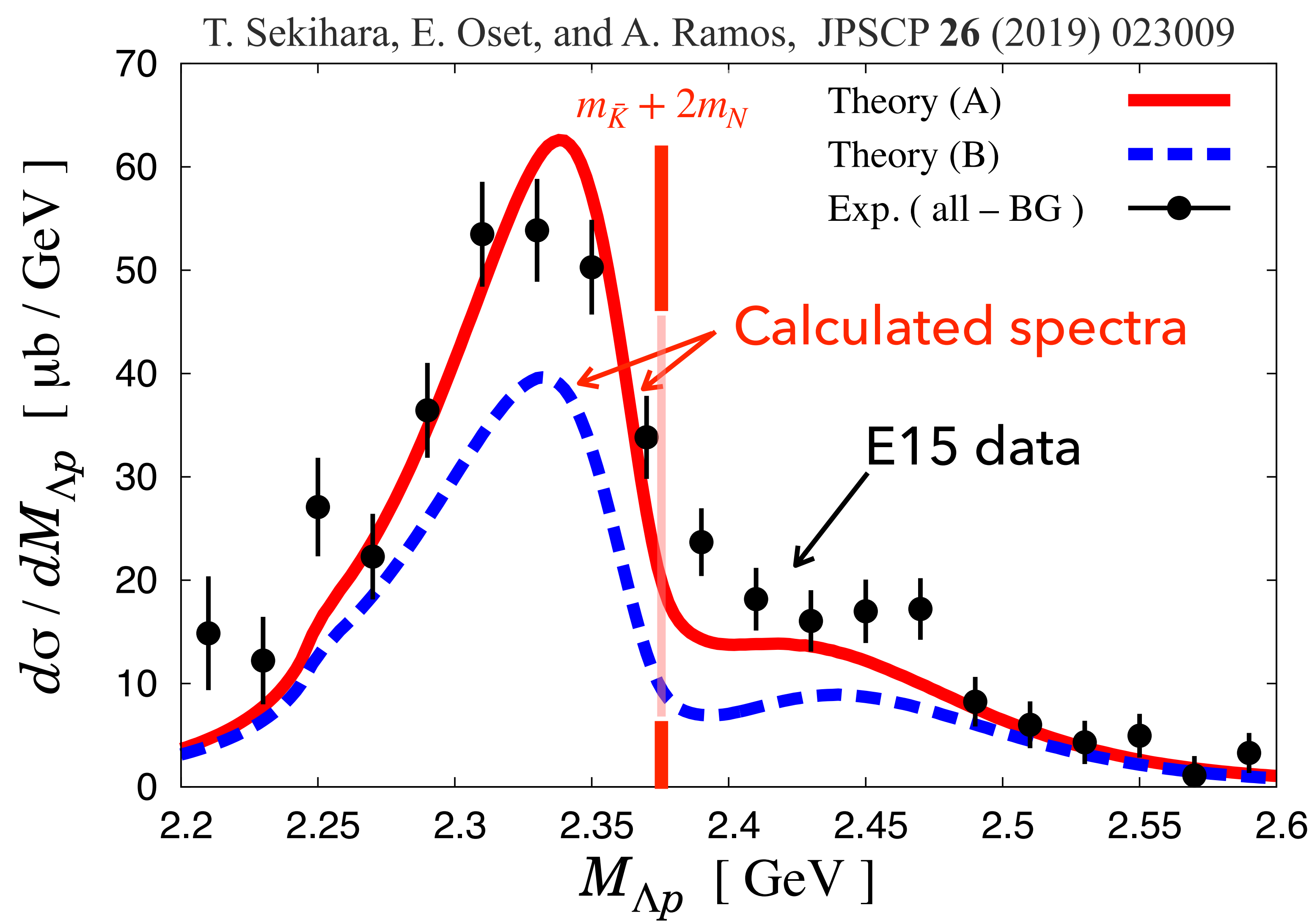
Comparison with theoretical calc.



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

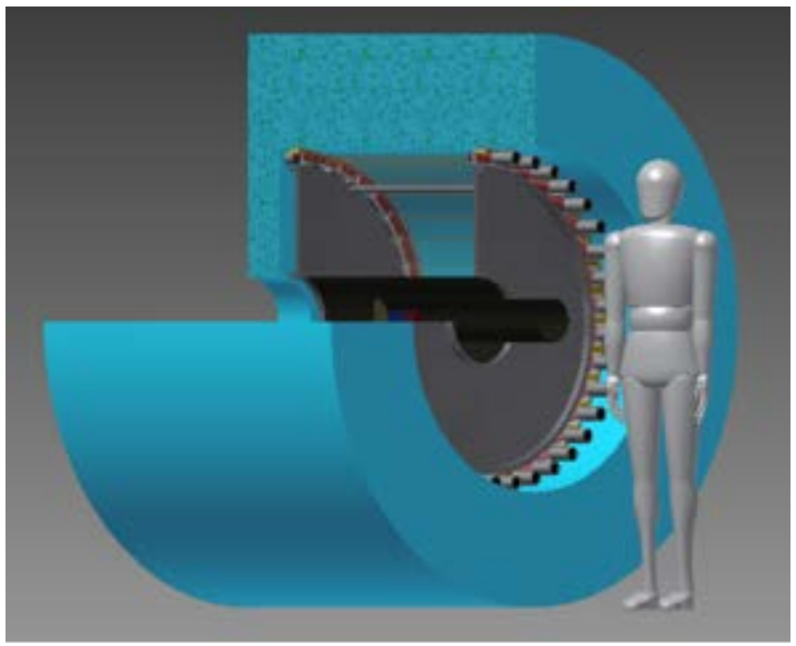
Future programs for $\bar{K}$ nuclei

- $\bar{K}N(\Lambda(1405))$
  - $d(K^-, n)$ reaction with a wide q-region
    neutron detection is required to reconstruct $\pi^{\pm}\Sigma^{\mp}$ decay
- $\bar{K}NN$ J-PARC P89
  - spin-parity determination by spin-spin correlation of Λp
  - Search for isospin partner: $(\bar{K}NN)^{I_z=-1/2} \to \Lambda n$
  - Decay branch: Non-mesonic $(\Lambda p, \Sigma^0 p, \Sigma^+ n)$, Mesonic $(\pi\Lambda N, \pi\Sigma N)$
- $\bar{K}NNN$ J-PARC E80
  - Λpn decay mode in addition to Λd
- Heaviear systems
  - $K^-\alpha$ via $^6Li(K^-, d)$, $\cdots$

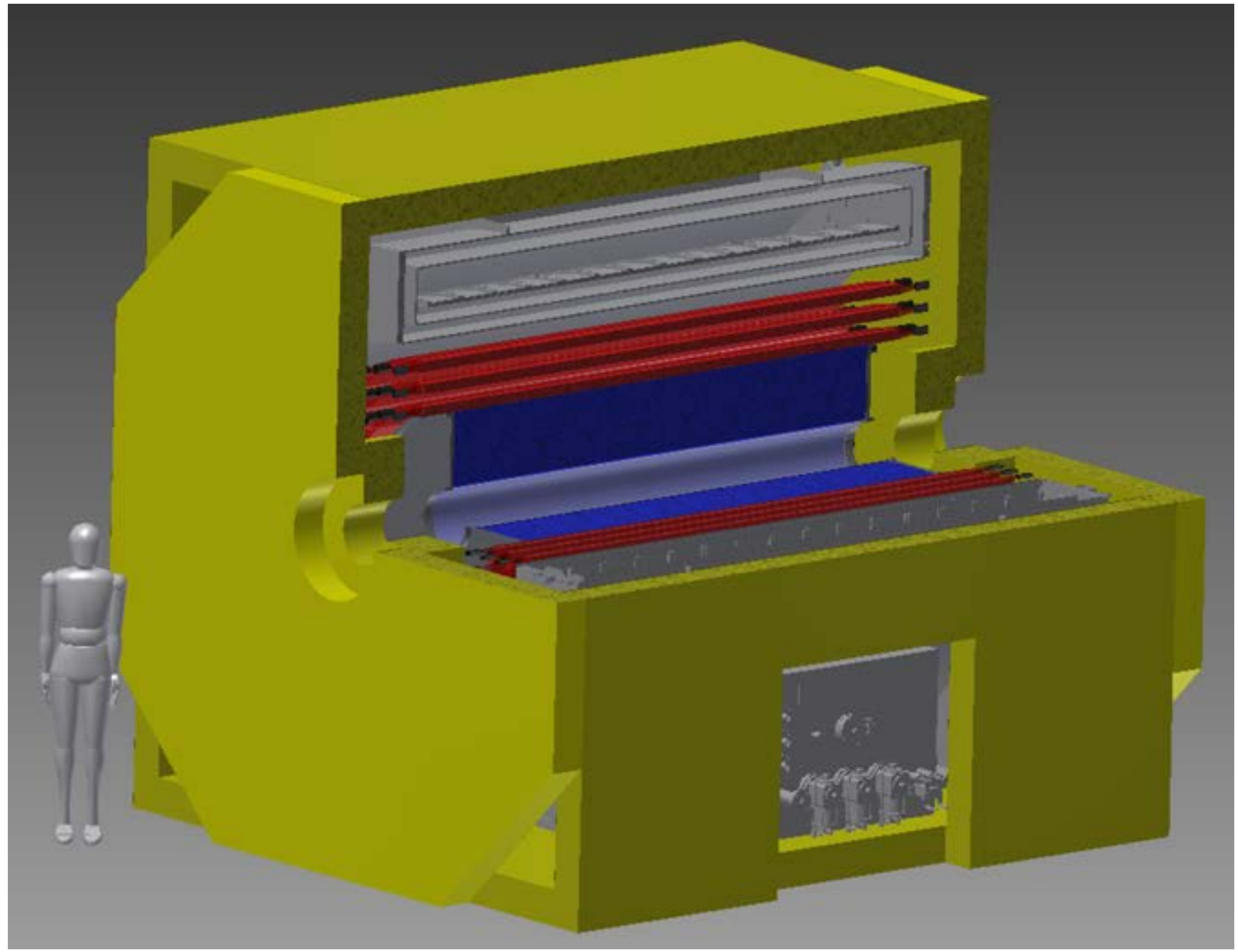
neutron detection
polarimeter

J-PARC E80 with a new spectrometer

E15 CDS

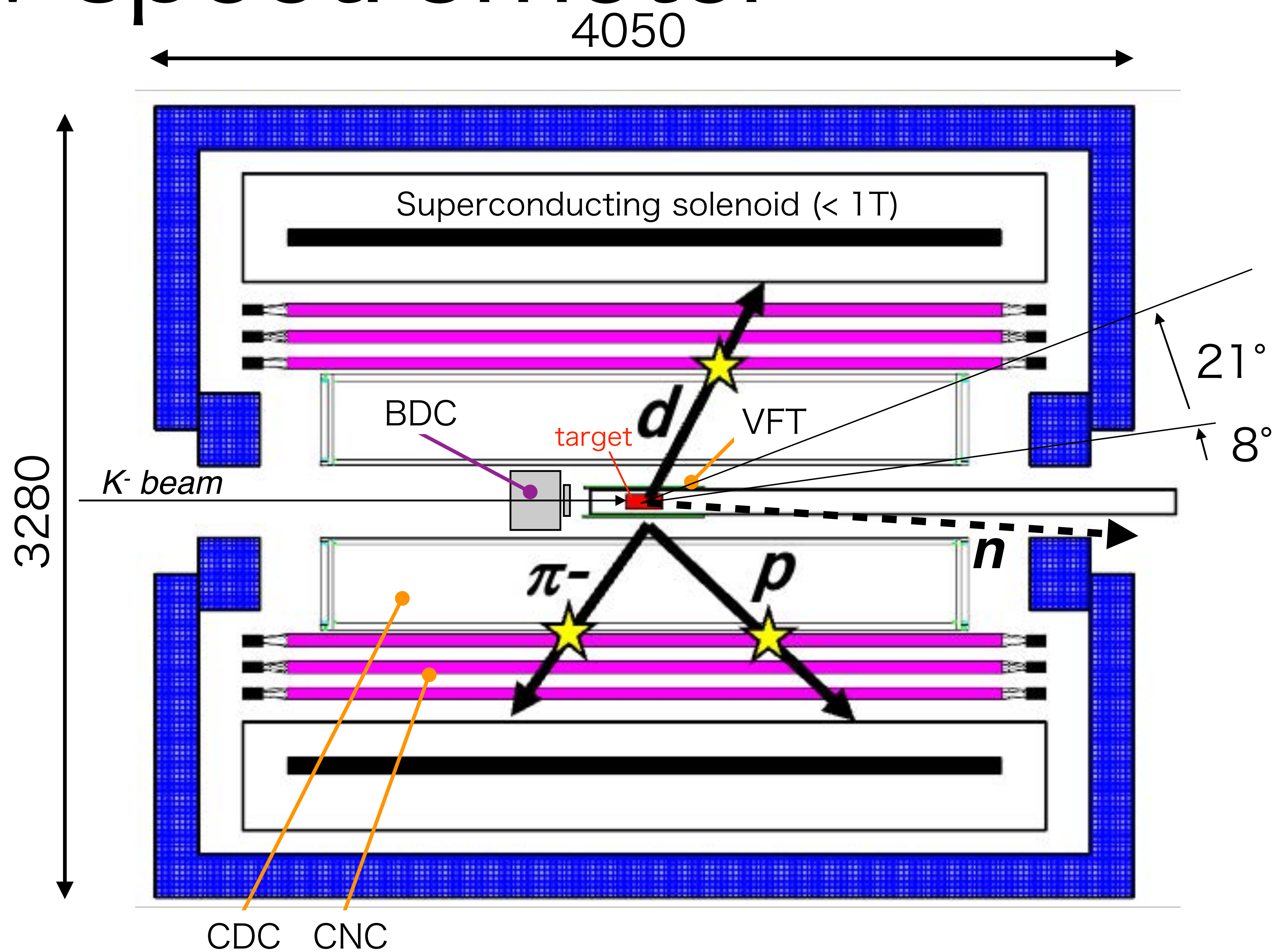


new CDS



- About 10 times volume
- We got a large budget, 特別推進 (P.I.: M. Iwasaki, JFY2022—JFY2026)

New spectrometer



- x3 longer CDC: **solid angle 59%→93%**
- 3-layer barrel NC (CNC): **neutron efficiency 3%→15%**
  - **polalimeter** trackers between CNCs in future
- VFT to improve z-vertex & momentum resolution

Expected spectra

@ 3 weeks, 90kW

x20 K- on target, x2 acceptance, x5 neutron efficiency

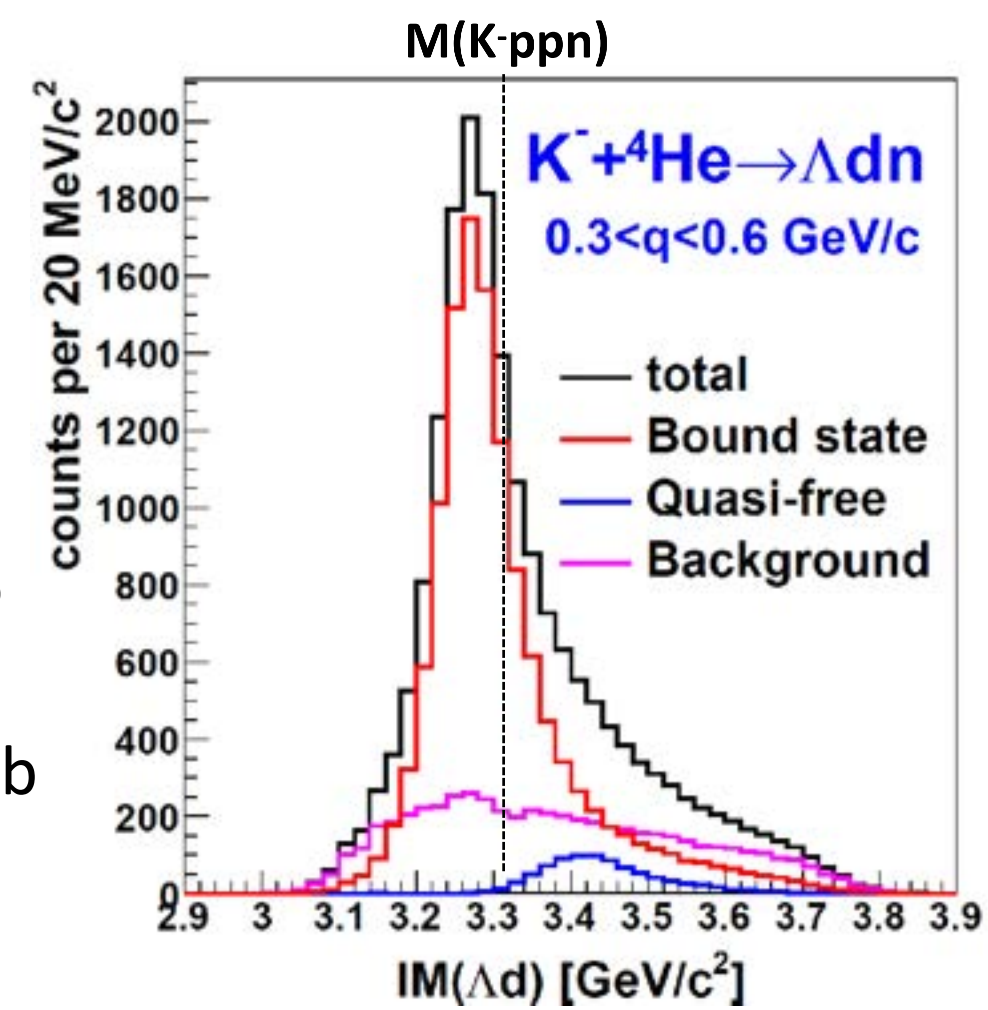
B_{Kppn} ~ 40 MeV

Γ_{Kppn} ~ 100 MeV

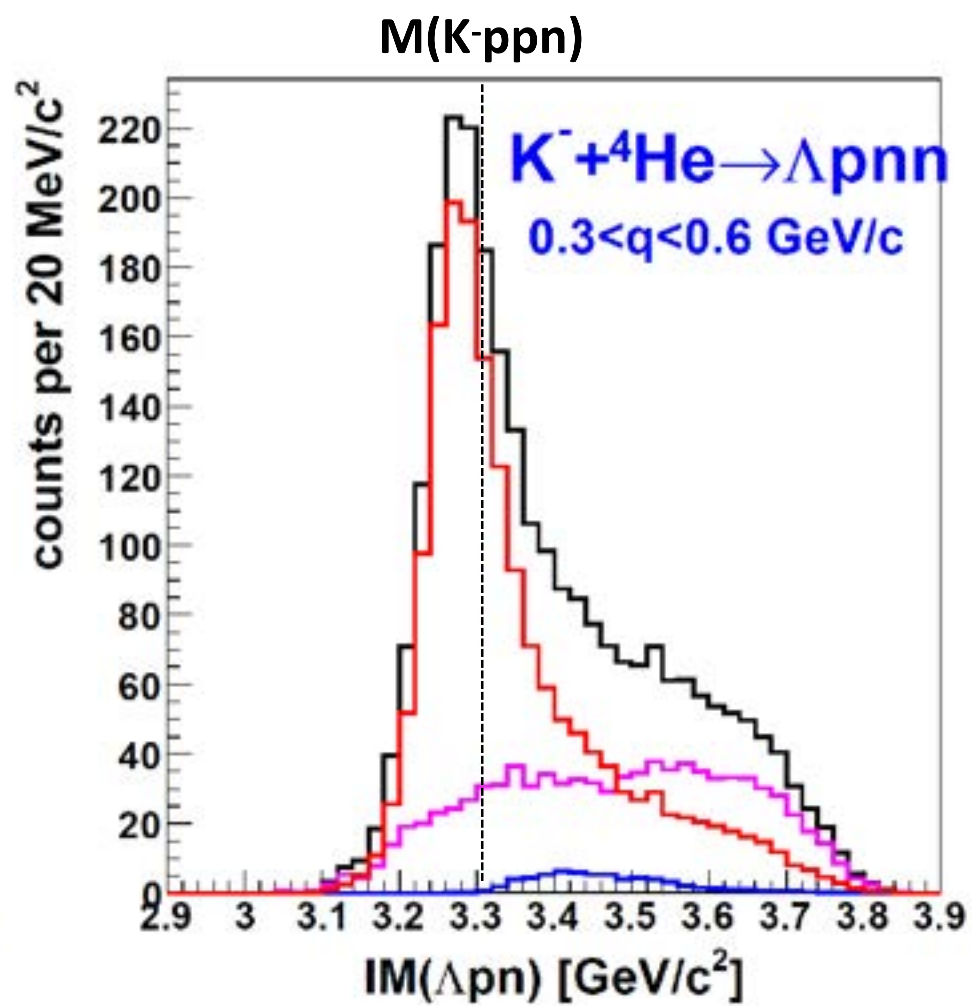
Q_{kppn} ~ 400 MeV/c

σ(K-ppn)*Br ~ 5 μb
σ(QF) ~ 5 μb
σ(BG) ~ 10 μb

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



$K^- + {}^4He \rightarrow \Lambda pn + n$



✓ Clear peak would be observed for both modes

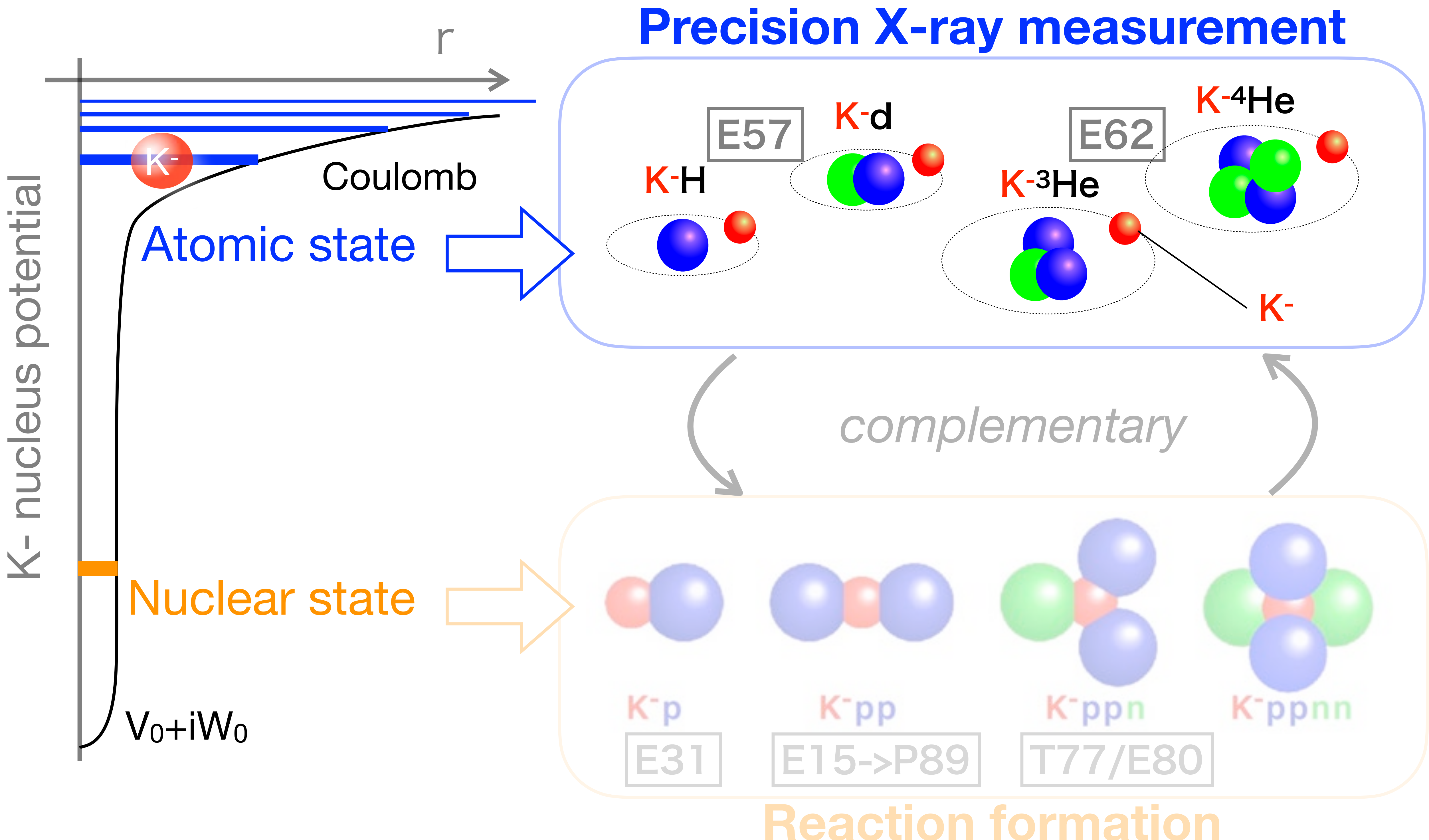
Construction status

Return yoke for the solenoid

Cylindrical drift chamber

- JFY2024: Solenoid magnet will be completed
- JFY2025: Installation &commissioning
- JFY2026: Physics data taking

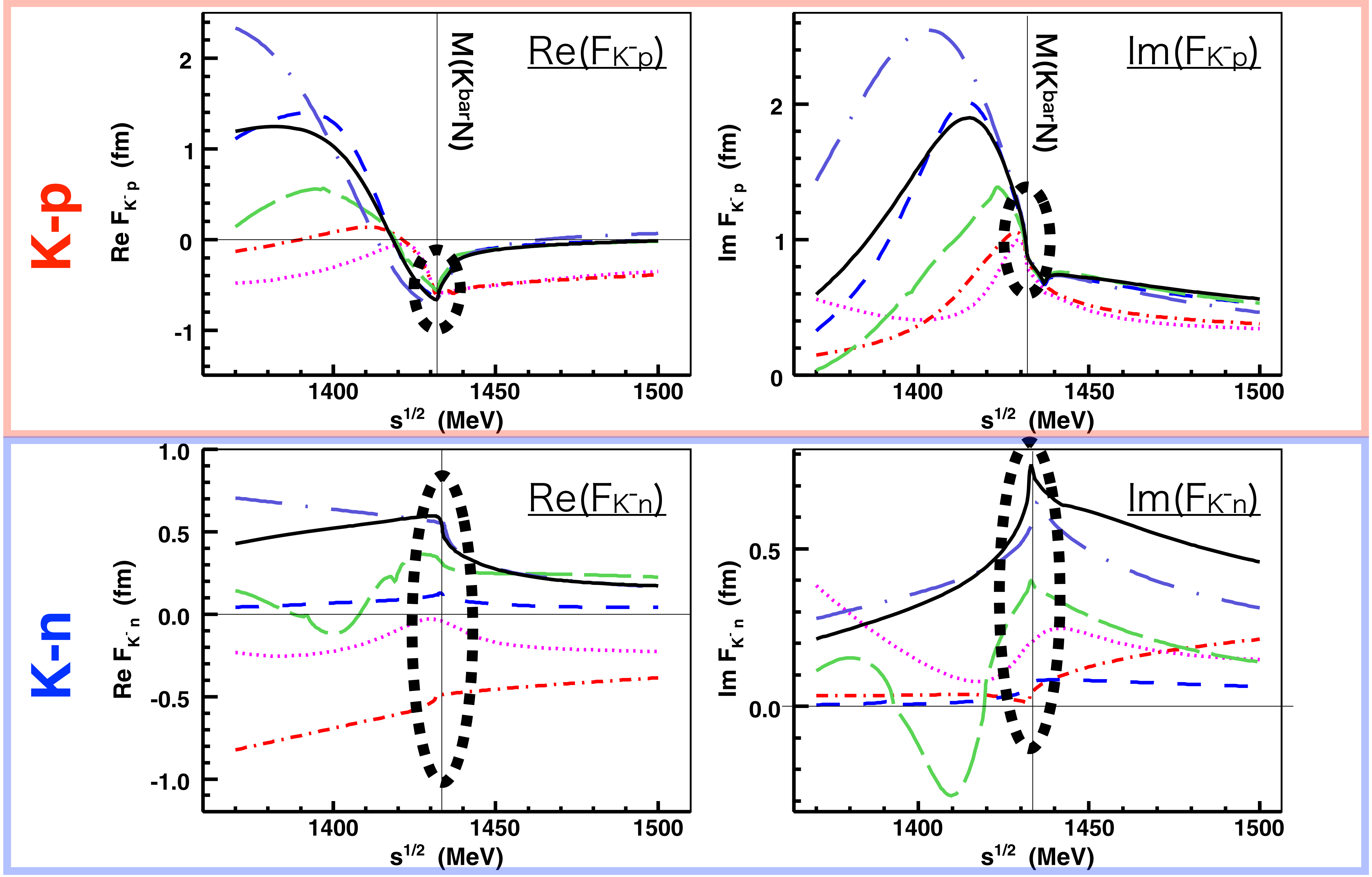
Study of K^{bar}-nucl. interaction



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

Kaonic deuterium

A. Cieplý et al. NPA 954 (2016) 17–40



Need K^-d data to constrain isospin 1 component

→ SIDDHARTA2 (runnning) / **J-PARC E57 (future)**

K^- $^{3/4}He$ atom X-rays with a cryogenic detector

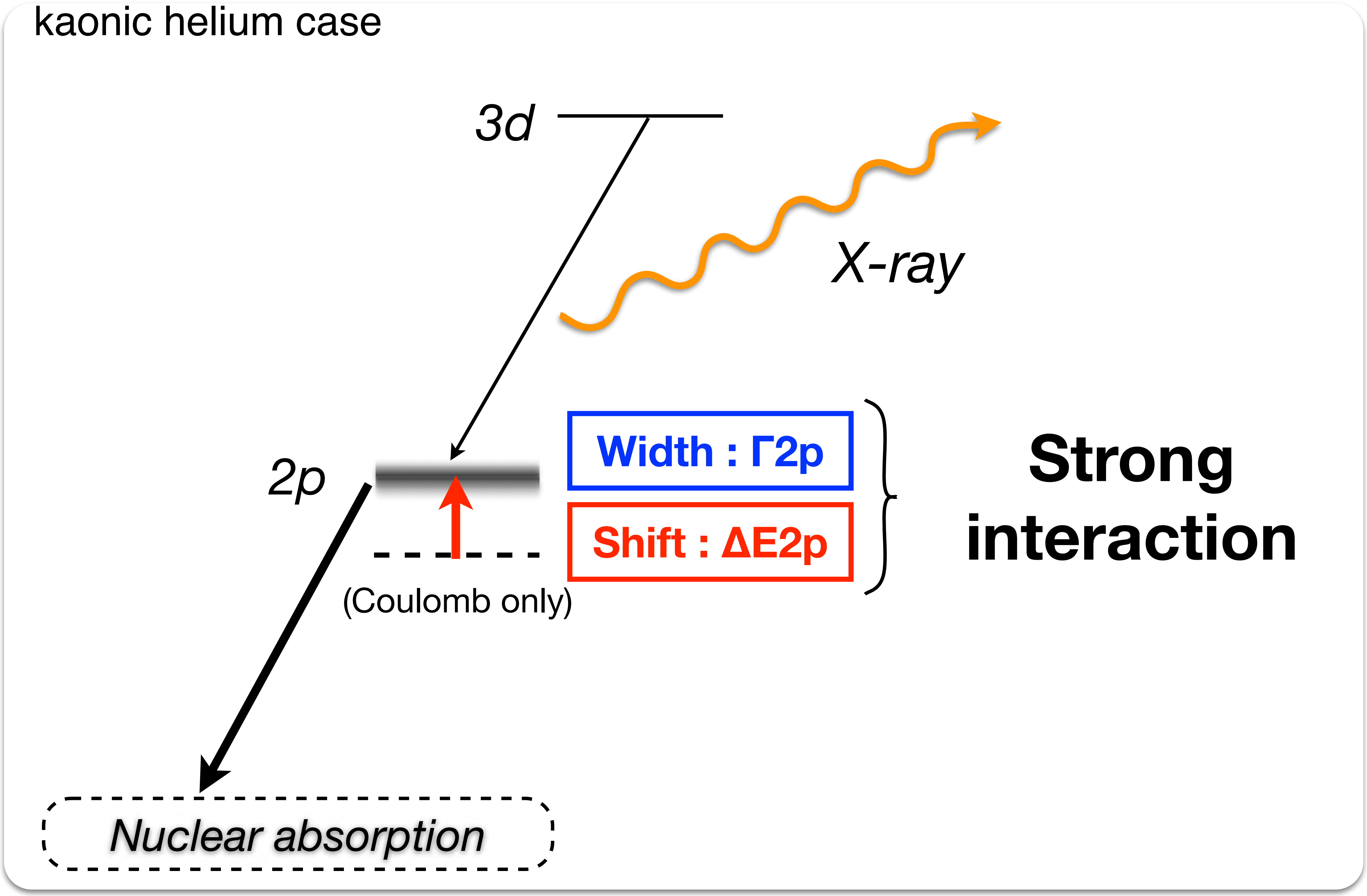
PHYSICAL REVIEW LETTERS **128,** 112503 (2022)

Measurements of Strong-Interaction Effects in Kaonic-Helium Isotopes at Sub-eV Precision with X-Ray Microcalorimeters

T. Hashimoto,[1,2,*] S. Aikawa,[3] T. Akaishi,[4] H. Asano,[2] M. Bazzi,[5] D. A. Bennett,[6] M. Berger,[7] D. Bosnar,[8] A. D. Butt,[9] C. Curceanu,[5] W. B. Doriese,[6] M. S. Durkin,[6] Y. Ezoe,[10] J. W. Fowler,[6] H. Fujioka,[3] J. D. Gard,[6] C. Guaraldo,[5] F. P. Gustafsson,[7] C. Han,[2] R. Hayakawa,[10] R. S. Hayano,[11] T. Hayashi,[12] J. P. Hays-Wehle,[6] G. C. Hilton,[6] T. Hiraiwa,[13] M. Hiromoto,[4] Y. Ichinohe,[14] M. Iio,[15] Y. Iizawa,[3] M. Iliescu,[5] S. Ishimoto,[15] Y. Ishisaki,[10] K. Itahashi,[2] M. Iwasaki,[2] Y. Ma,[2] T. Murakami,[11] R. Nagatomi,[4] T. Nishi,[16] H. Noda,[17] H. Noumi,[13] K. Nunomura,[10] G. C. O'Neil,[6] T. Ohashi,[10] H. Ohnishi,[18] S. Okada,[19,2,†] H. Outa,[2] K. Piscicchia,[5] C. D. Reintsema,[6] Y. Sada,[18] F. Sakuma,[2] M. Sato,[15] D. R. Schmidt,[6] A. Scordo,[5] M. Sekimoto,[15] H. Shi,[7] K. Shirotori,[13] D. Sirghi,[5] F. Sirghi,[5] K. Suzuki,[7] D. S. Swetz,[6] A. Takamine,[2] K. Tanida,[1] H. Tatsuno,[10] C. Trippl,[7] J. Uhlig,[20] J. N. Ullom,[6] S. Yamada,[14] T. Yamaga,[2] T. Yamazaki,[11] and J. Zmeskal[7]

(J-PARC E62 Collaboration)

Kaonic atom X-rays

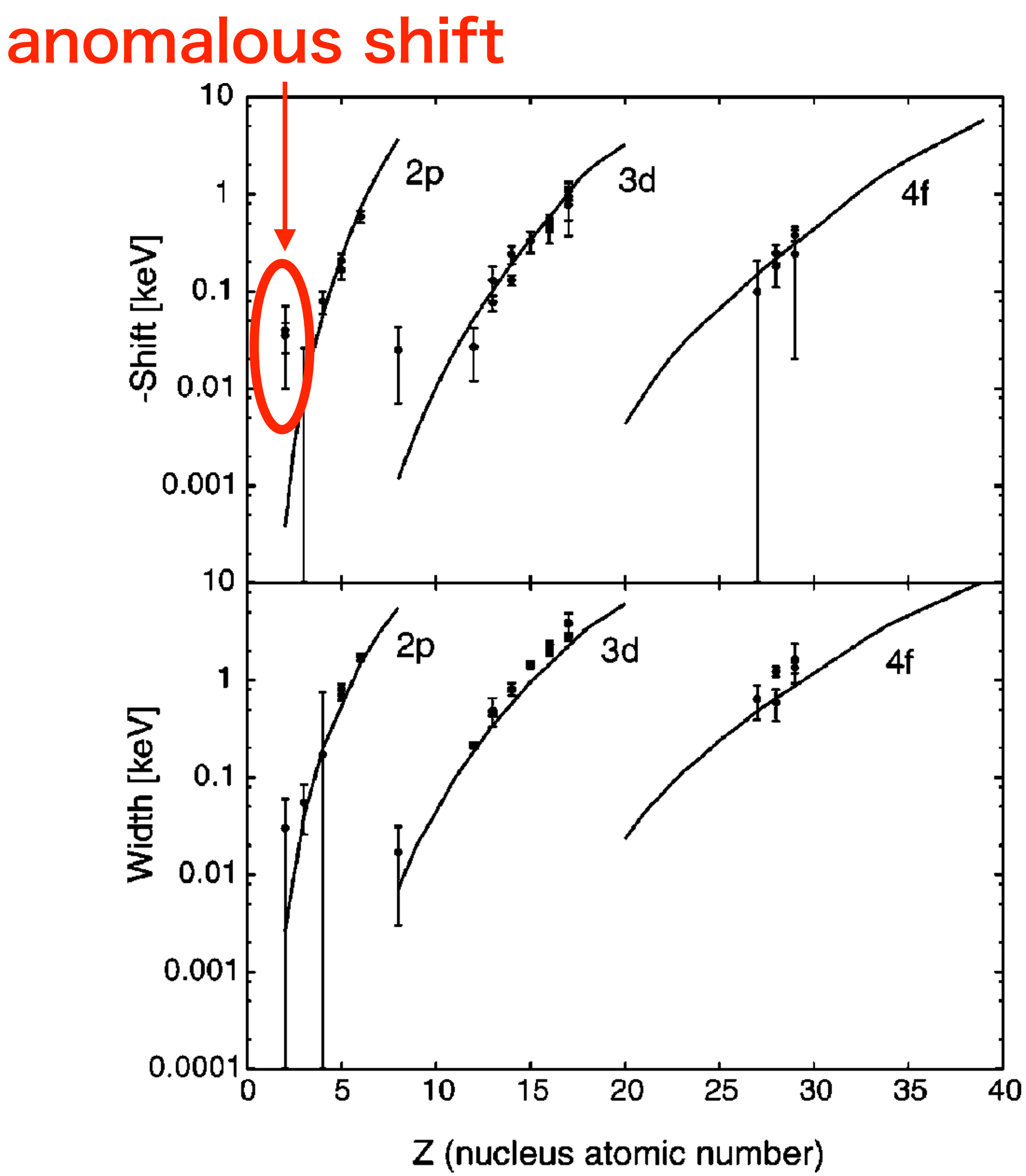


Unique probe of the K^{bar}-nucleus strong interaction **at the threshold energy**

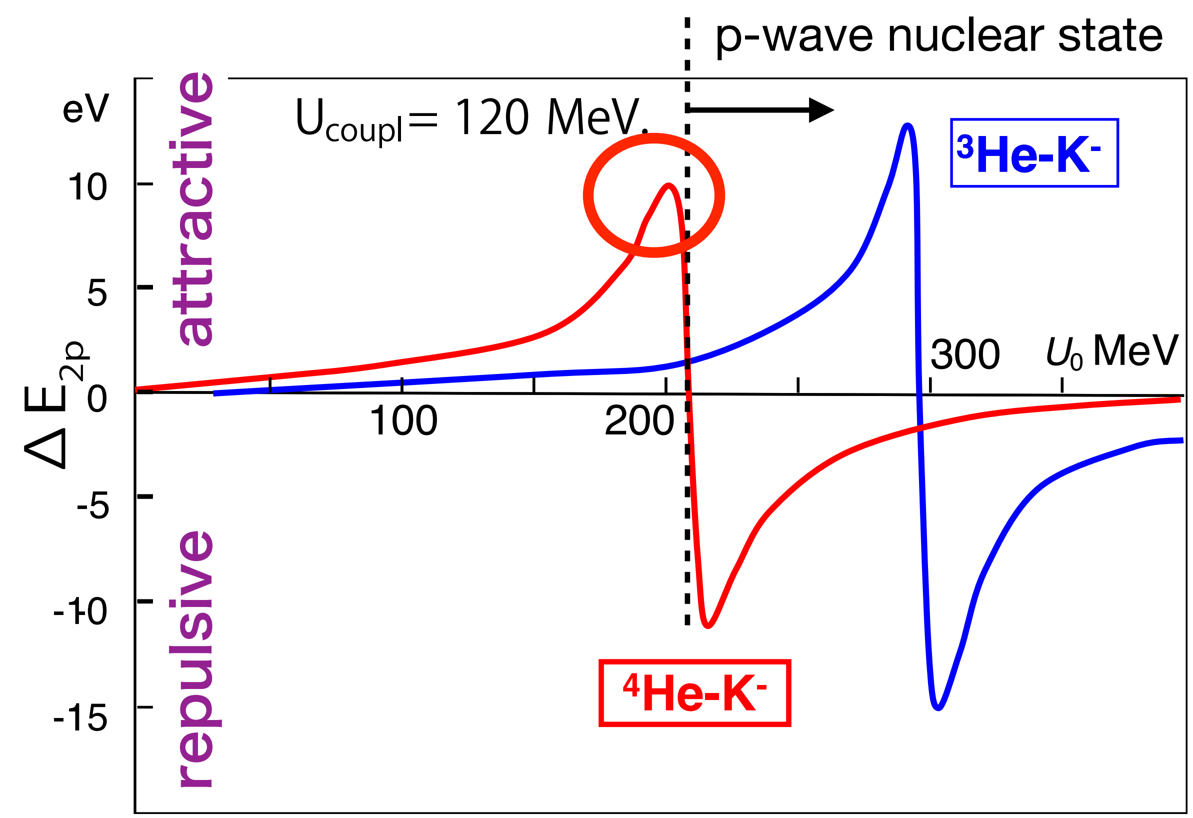
Observables: **Shift**, **Width**, **and Yield**

"Kaonic helium puzzle"

S. Hirenzaki et al., PRC 61, 055205 (2000)



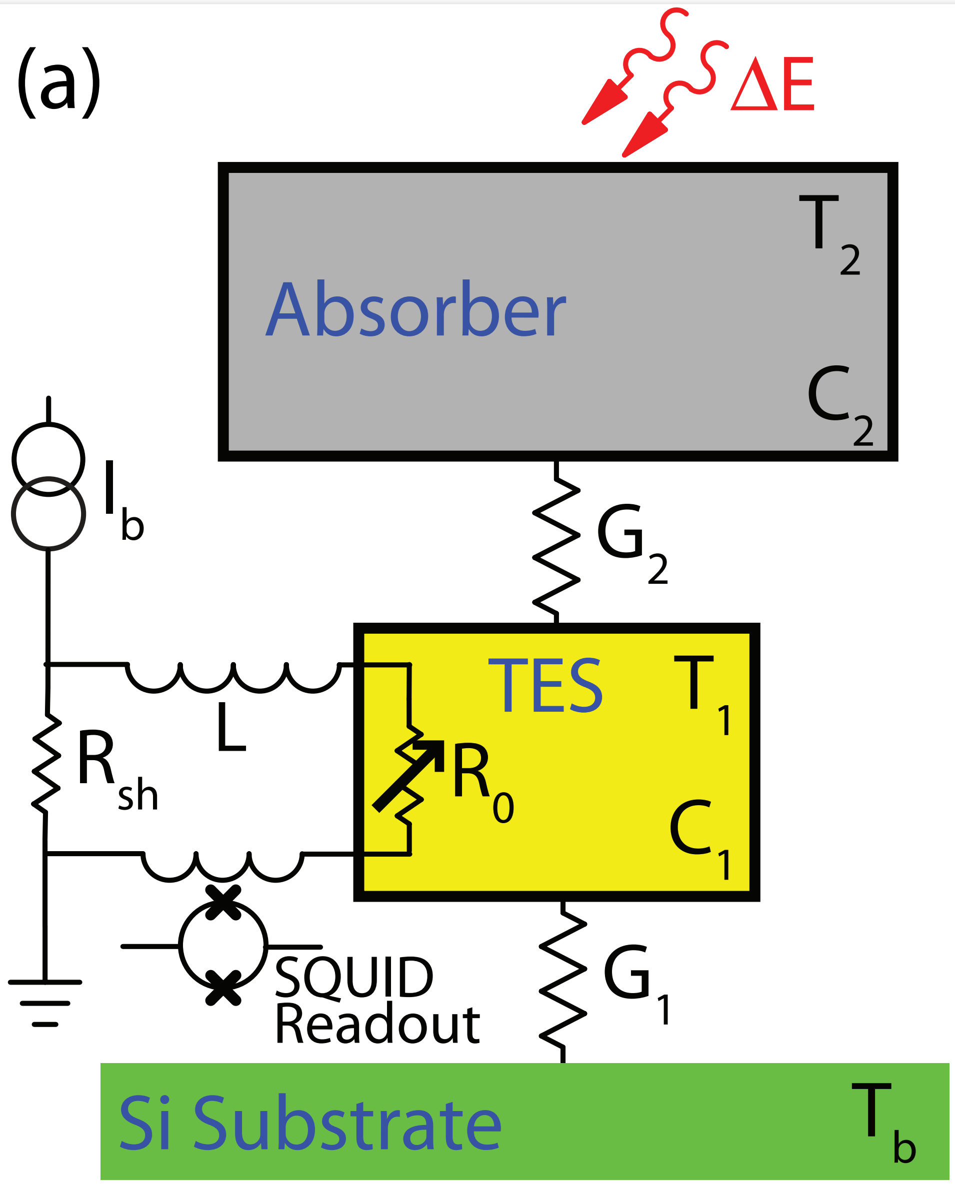
Y. Akaishi, EXA2005 proceedings



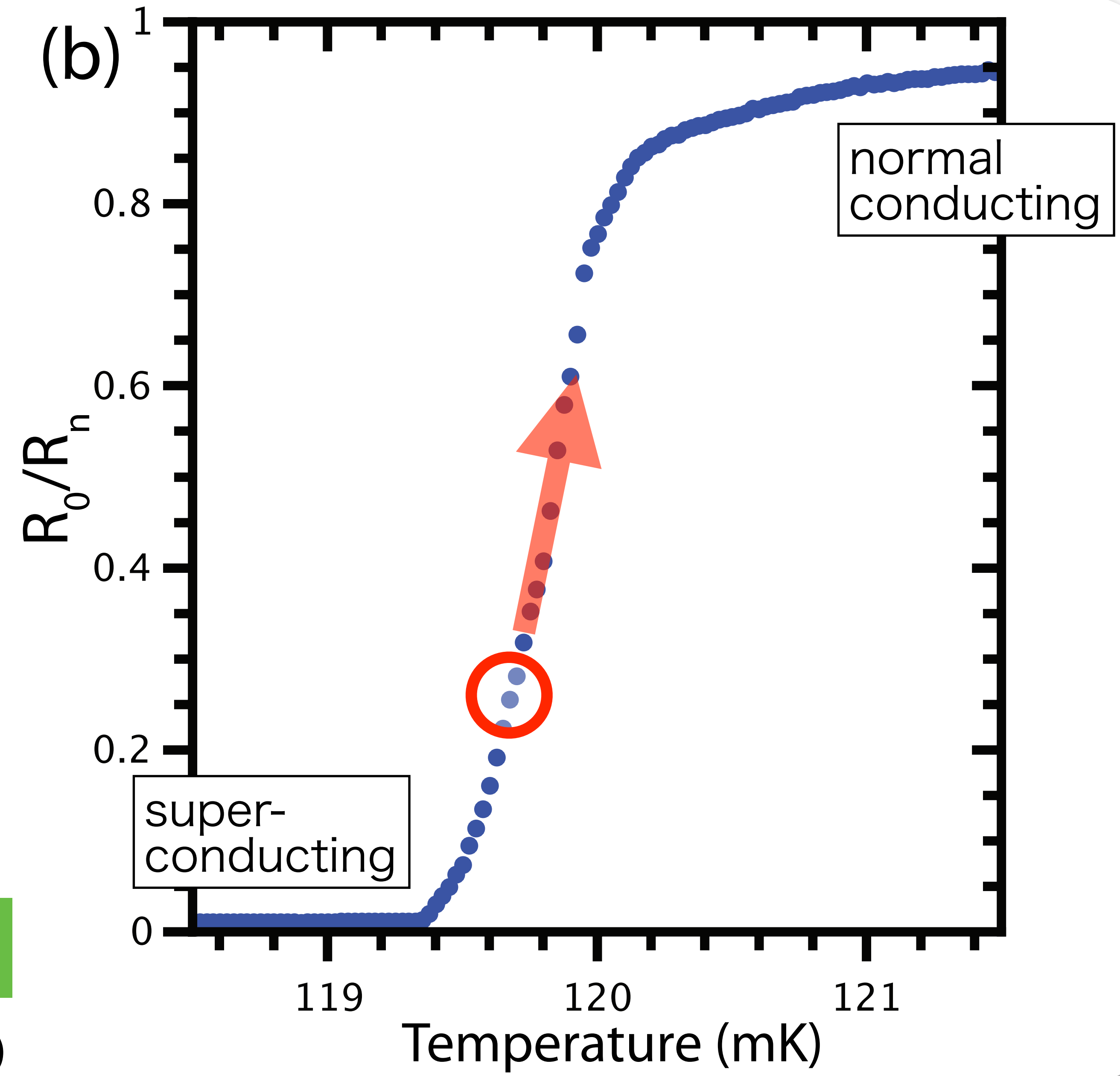
coupled-channel potential

- Large shift and width imply the generation of a nuclear state

Transition-Edge-Sensor microcalorimeters



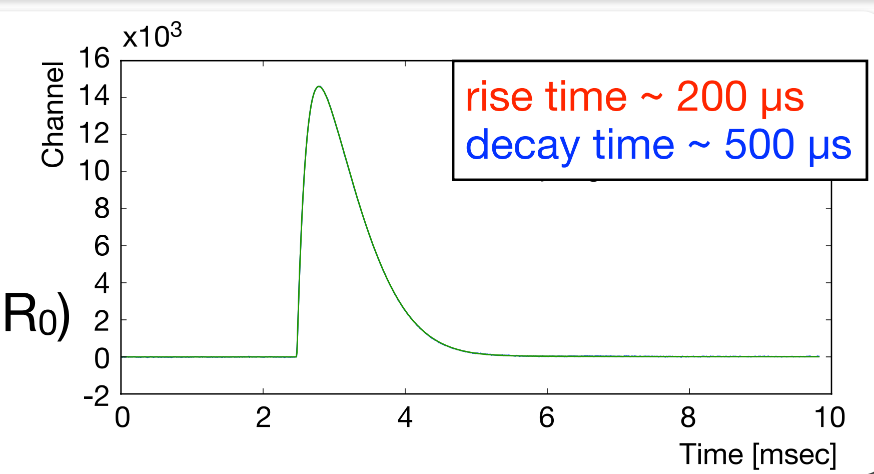
Rev. Sci. Instrum. **83**, 093113 (2012)



Typical pulse

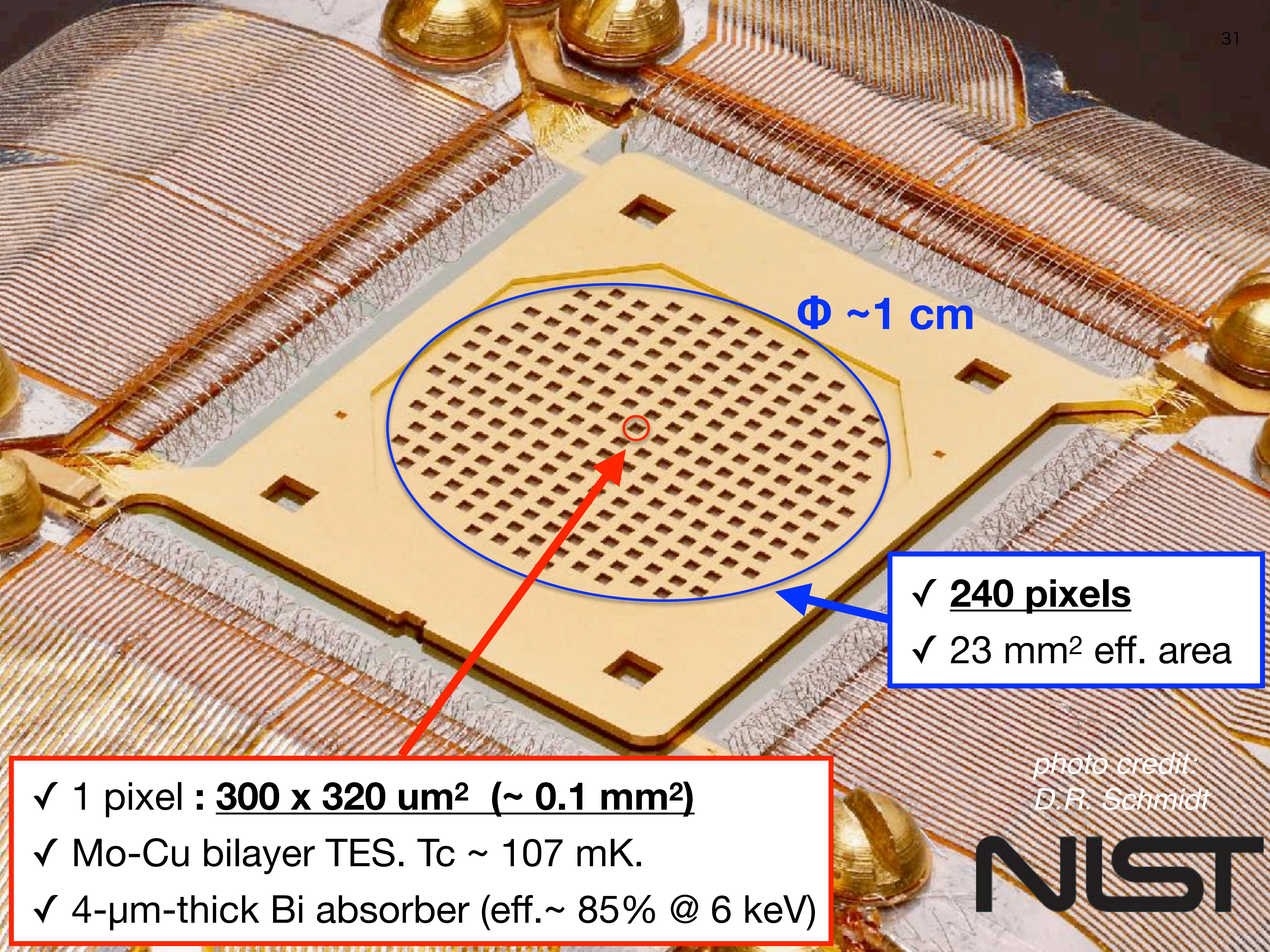
$\tau_{rise} \sim L/(R_{sh}+R_0)$

$\tau_{fall} \sim C/G$



Resolution: ~ 5 eV FWHM @ 6 keV

cf.) silicon drift detector ~ 150 eV

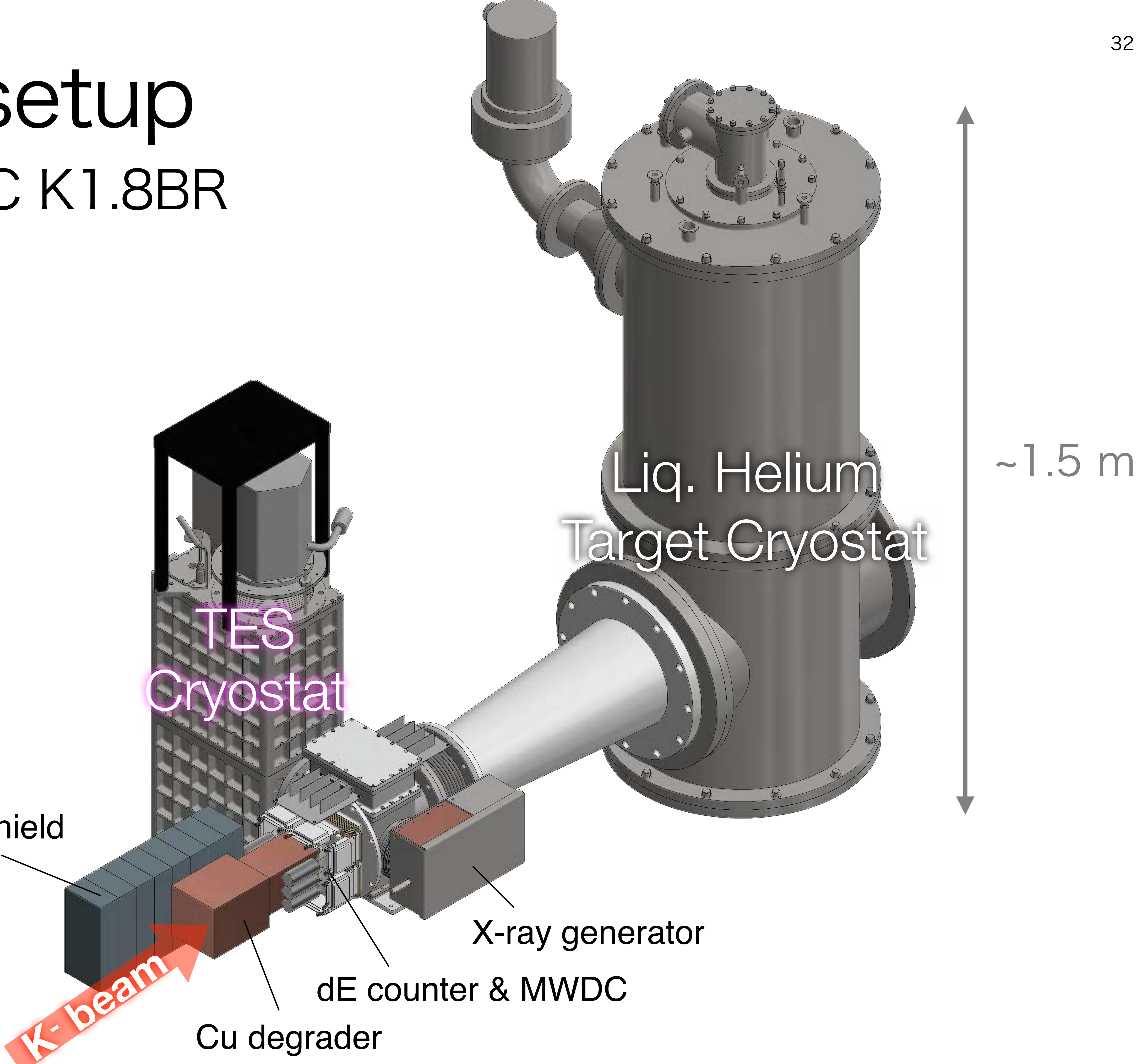


- ✓ **240 pixels**
- ✓ 23 mm² eff. area

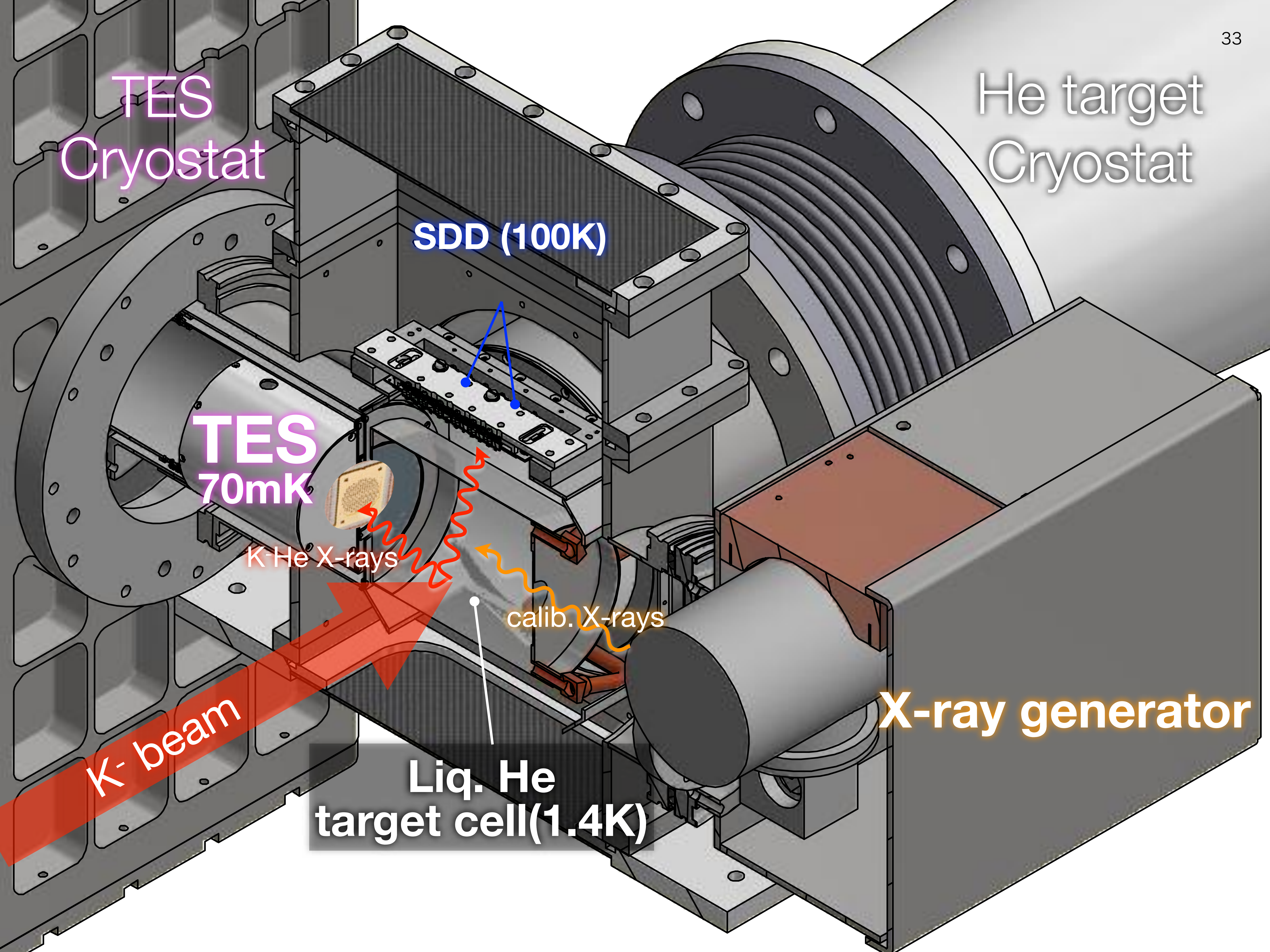
- ✓ 1 pixel **: 300 x 320 um² (~ 0.1 mm²)**
- ✓ Mo-Cu bilayer TES. Tc ~ 107 mK.
- ✓ 4-μm-thick Bi absorber (eff.~ 85% @ 6 keV)

E62 setup

@J-PARC K1.8BR



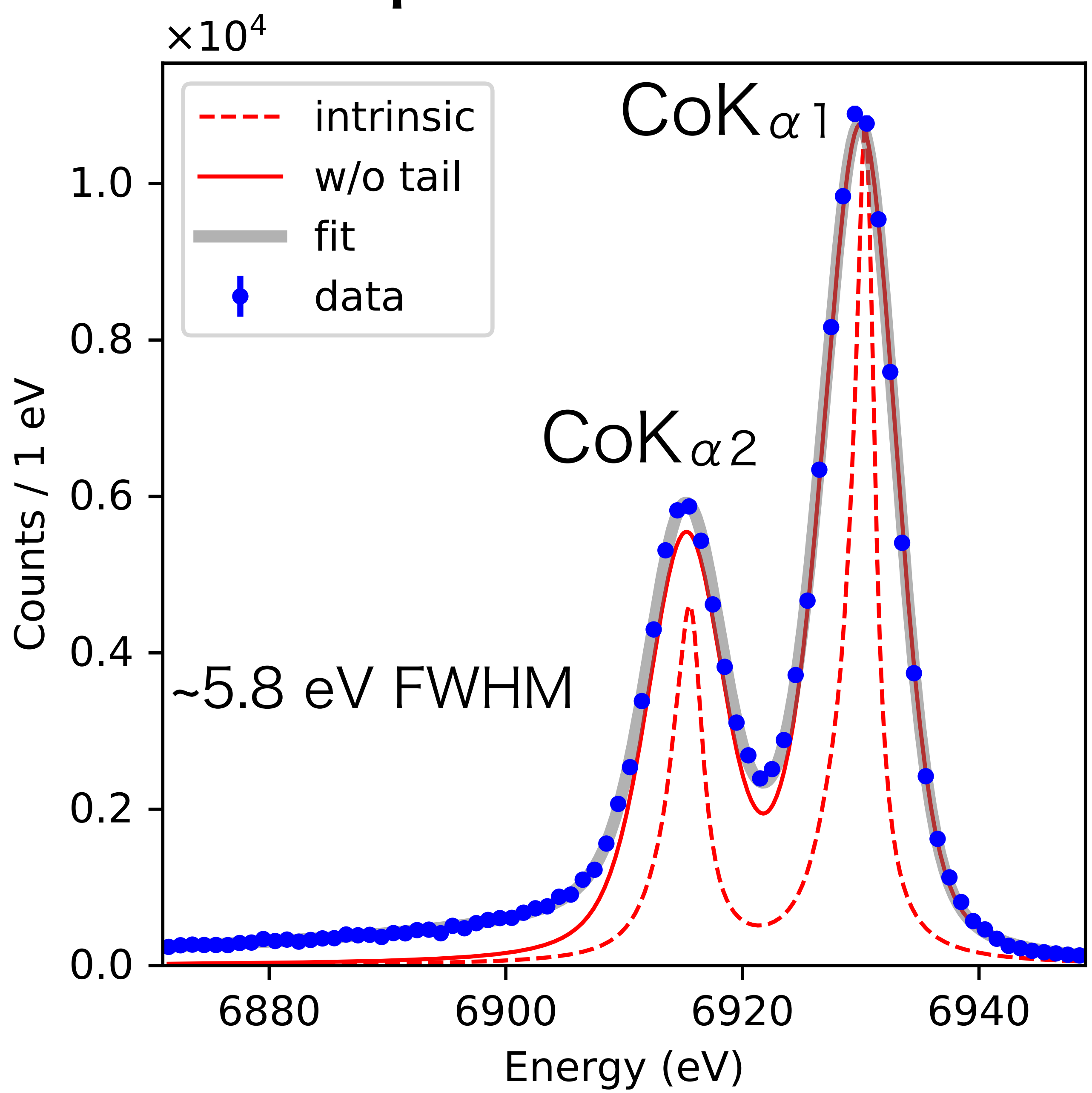
900 MeV/c


TES
Cryostat
He target
Cryostat
SDD (100K)
TES
70mK
K-He X-rays
calib. X-rays
X-ray generator
K- beam
Liq. He
target cell(1.4K)

TES in-beam performance

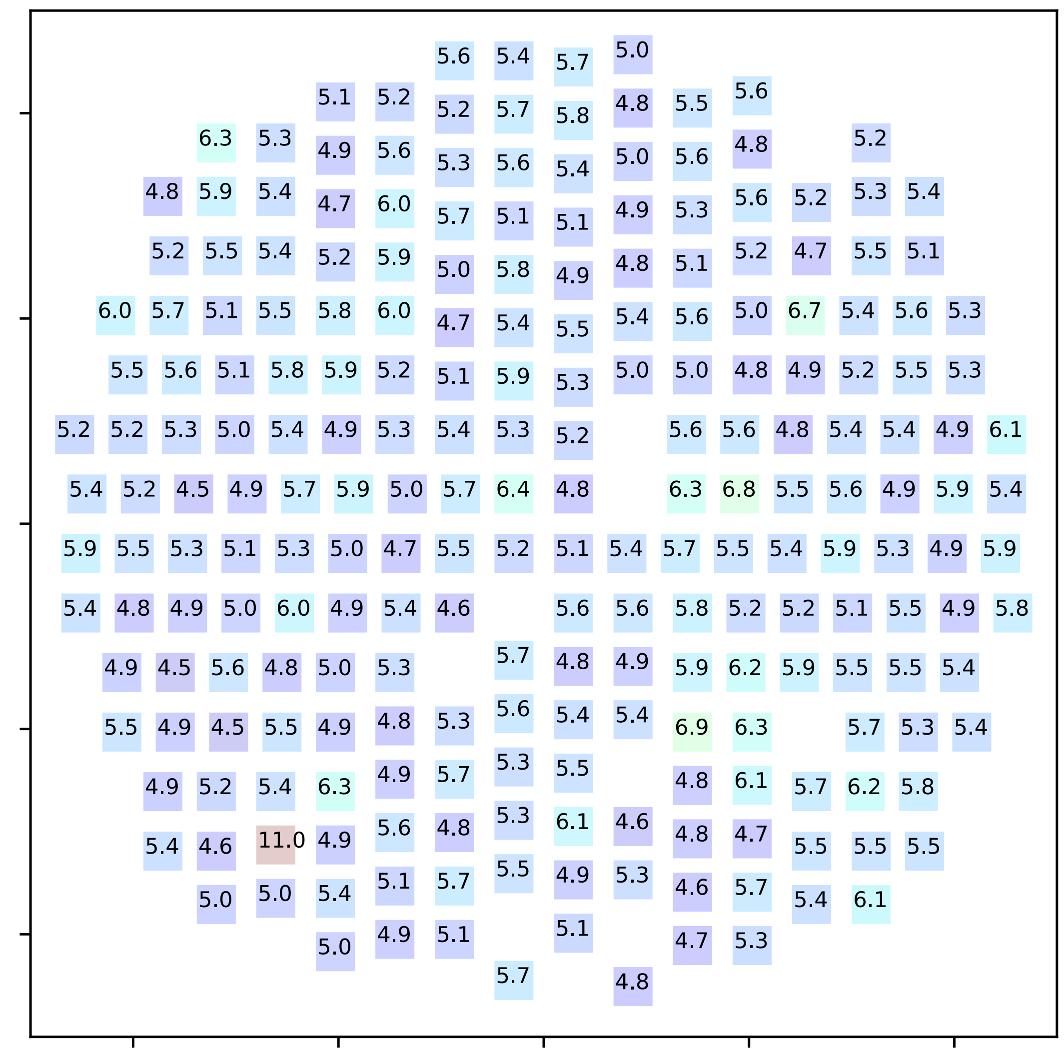
After all the analysis optimization (mainly reduction of charge-particle effects)

Response function



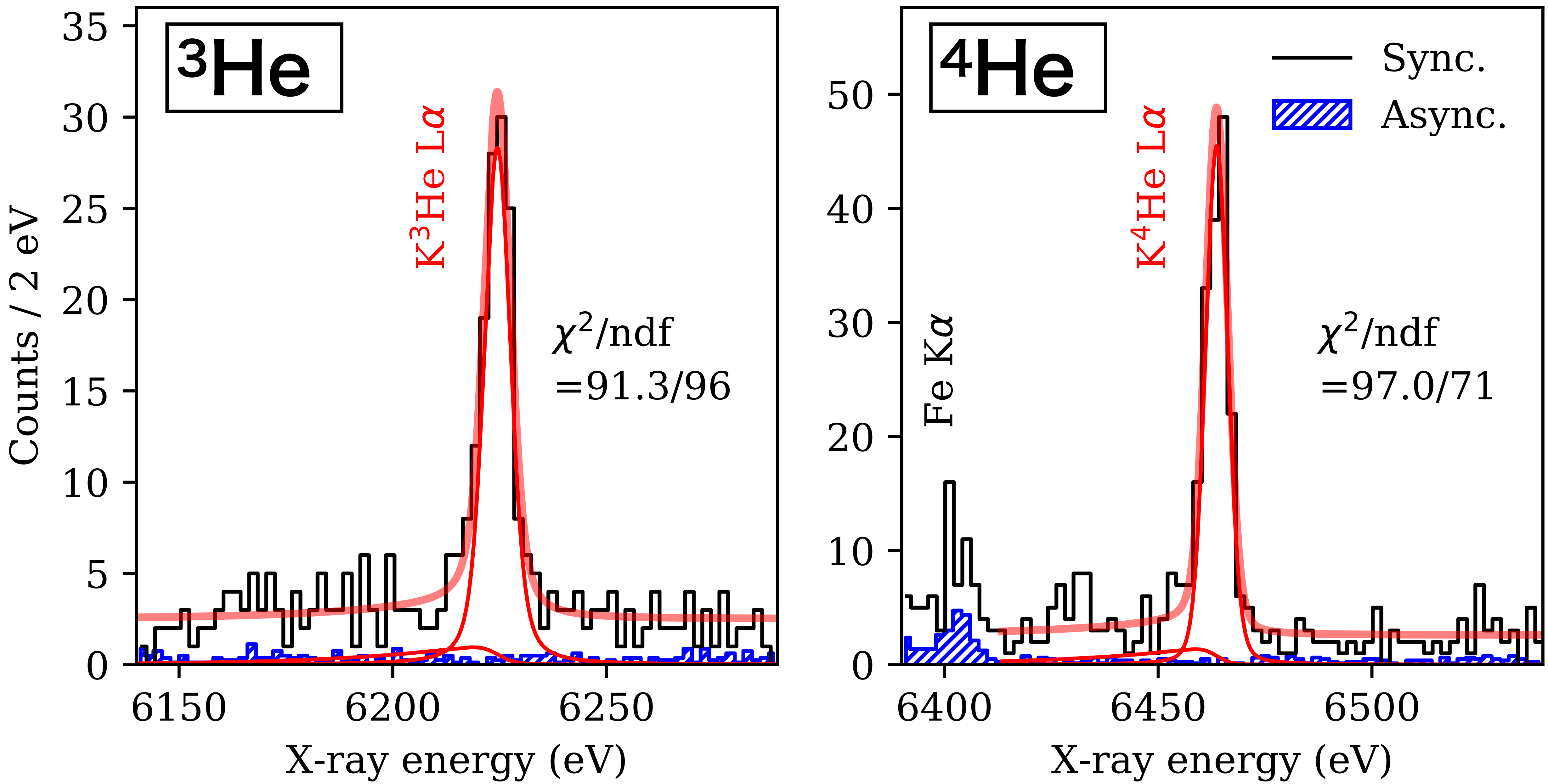
Detector response is well described
by a gaussian and a low-energy exponential tail

Resolution geometrical map



Resolution at CoKα
no box : doesn't work at all (12 pixel)

Kaonic X-ray spectra



$$E^{K^{-3}\mathrm{He}}_{3d\to 2p} = 6224.5 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})\ \mathrm{eV}$$

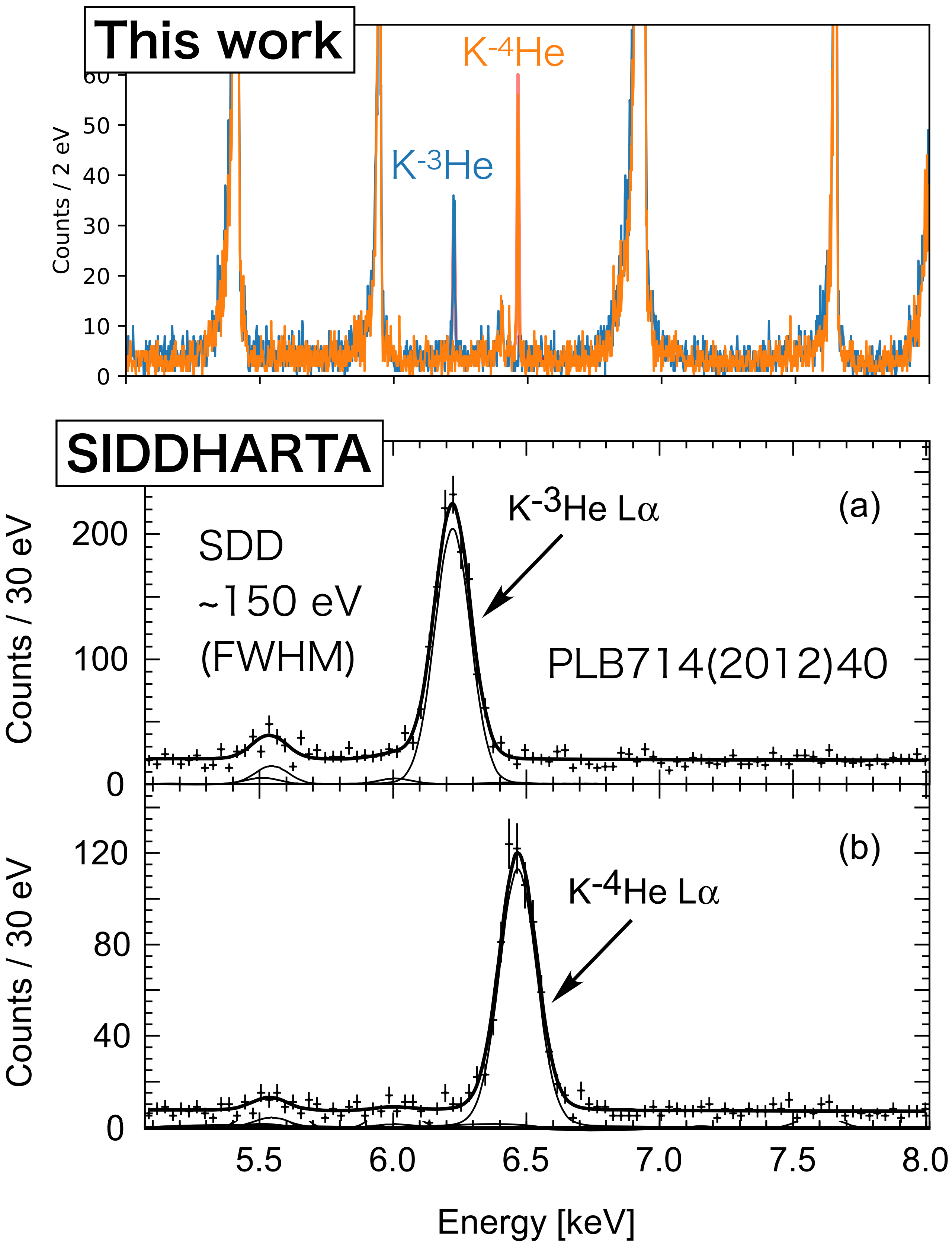
$$\Gamma^{K^{-3}\mathrm{He}}_{2p} = 2.5 \pm 1.0(\mathrm{stat}) \pm 0.4(\mathrm{syst})\ \mathrm{eV}$$

$$E^{K^{-4}\mathrm{He}}_{3d\to 2p} = 6463.7 \pm 0.3(\mathrm{stat}) \pm 0.1(\mathrm{syst})\ \mathrm{eV}$$

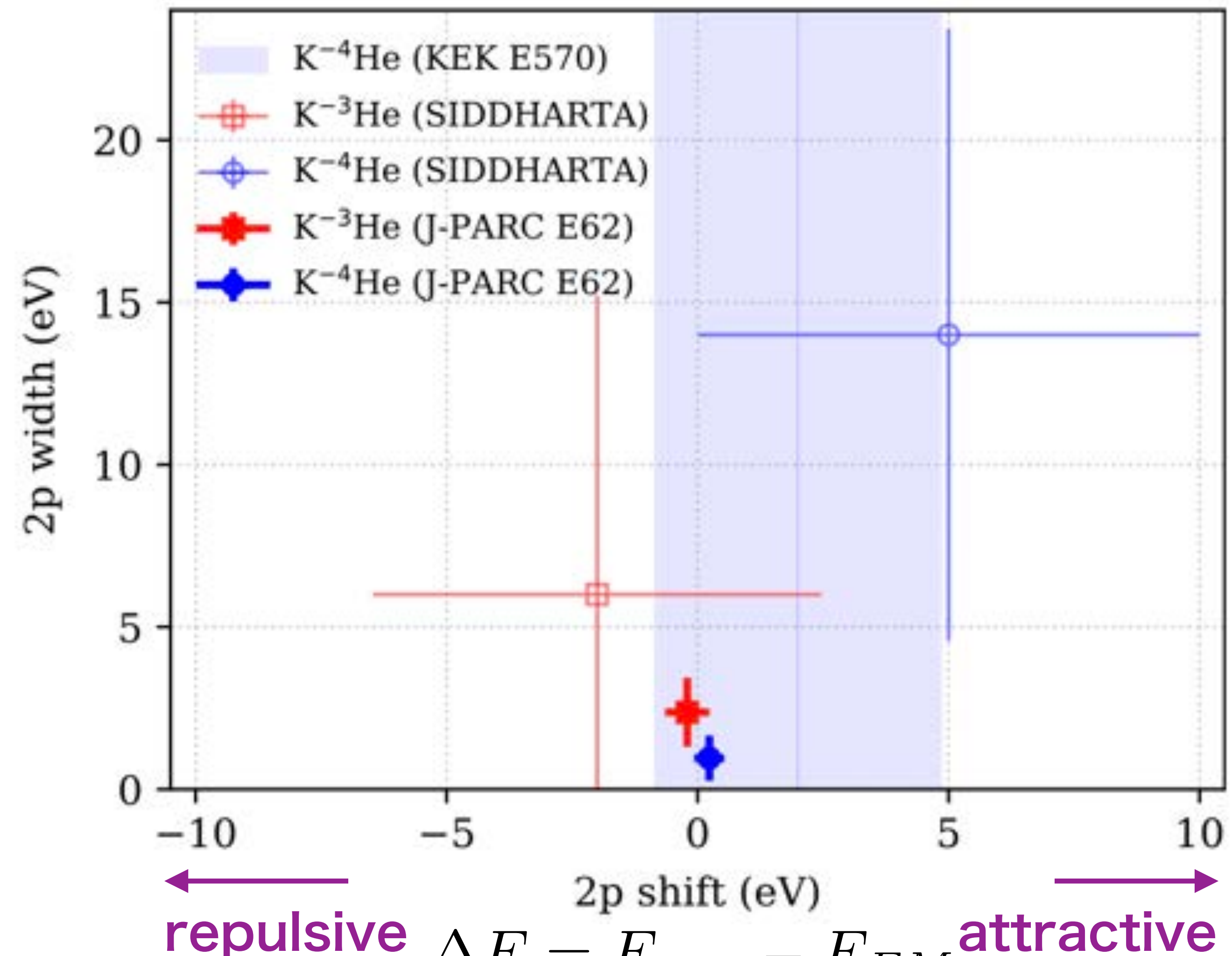
$$\Gamma^{K^{-4}\mathrm{He}}_{2p} = 1.0 \pm 0.6(\mathrm{stat}) \pm 0.3(\mathrm{syst})\ \mathrm{eV}$$

Main source of the systematic error is the uncertainty in absolute energy scale.

Comparison with past experiments



Error bar: quadratic sum of stat. & sys.



$$\Delta E = E_{exp.} - E_{EM}$$

x 25 energy resolution

x 10 precision (shift&width)

Exclude large shifts&widths

Theoretical investigation is under way

→ Talk by S. Hirenzaki

Summary

- Anti-kaon could be a unique probe for hadron physics.
  We are performing systematic experiments at J-PARC K1.8BR.

- **$\Lambda(1405)$** are investigated via **d(K$^-$,n)$\pi\Sigma$** reaction in J-PARC E31.
  Physics Letters B 837 (2023) 137637

- $\bar{K}NN$ signals were observed in **^{3}He(K$^-$,Λp)n** channel in J-PARC E15.

- $\bar{K}NNN$ hint in **^{4}He(K$^-$,Λd)n** events as a by-product of J-PARC T77.

- **Kaonic atom X-rays**: K-He isotopes with unprecedented precisions.

- More systematic study from JFY2026 with a new spectrometer
  - $\bar{K}NNN$ detailed study (J-PARC E80)
  - $\bar{K}NN$ spin-parity (J-PARC P89)

Kaonic nuclear state is getting more solid