Exploring a new form of matter containing an anti-kaon $\bar{u}s$

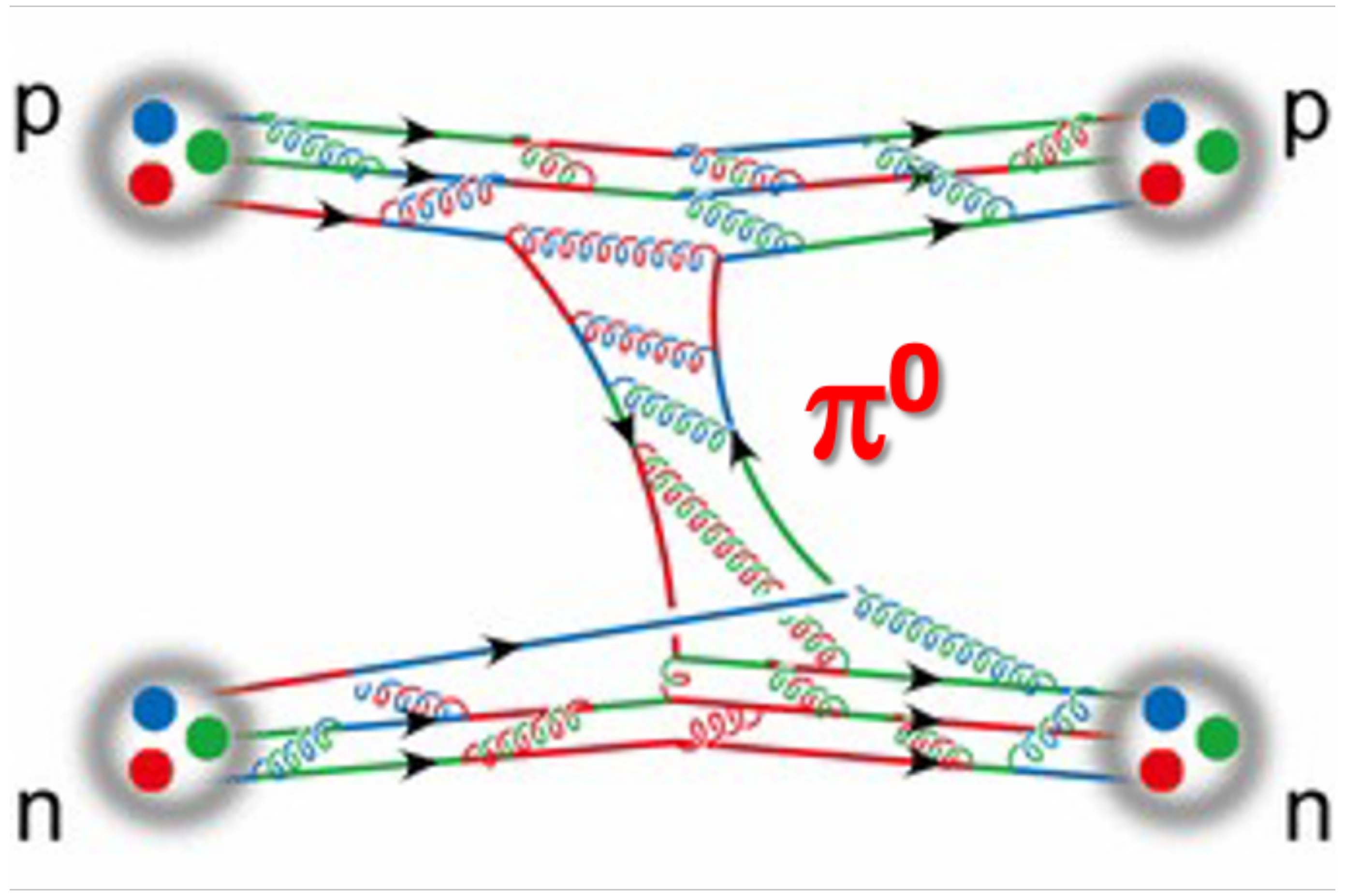
Tadashi Hashimoto (RIKEN)
for J-PARC E15/E31/E57/E62/E73/T77/E80/P89 collaboration

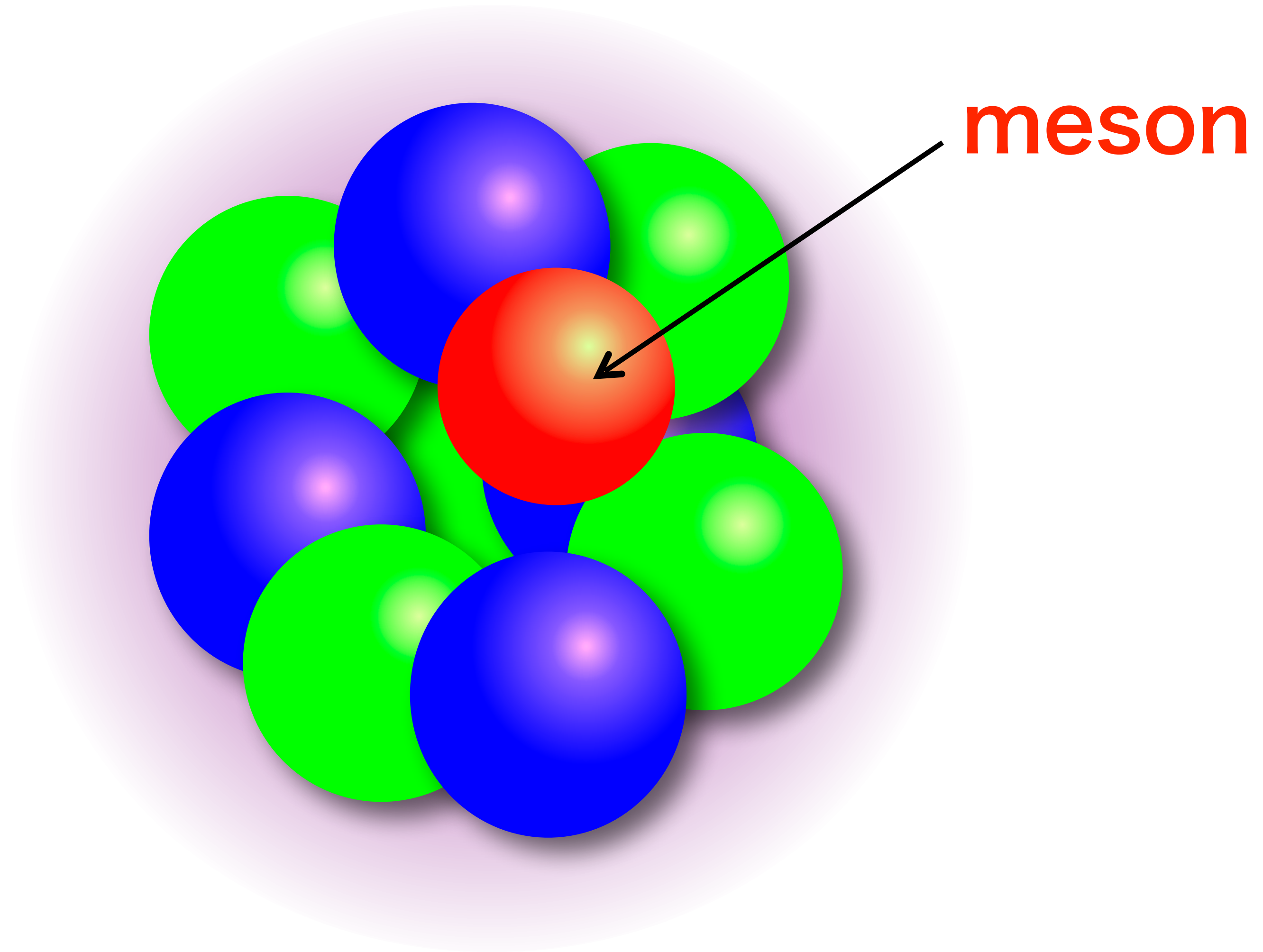
RIKEN
RIKEN NISHINA CENTER

Meson in nuclei

meson: quark-antiquark ($\bar{q}q$) pair

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



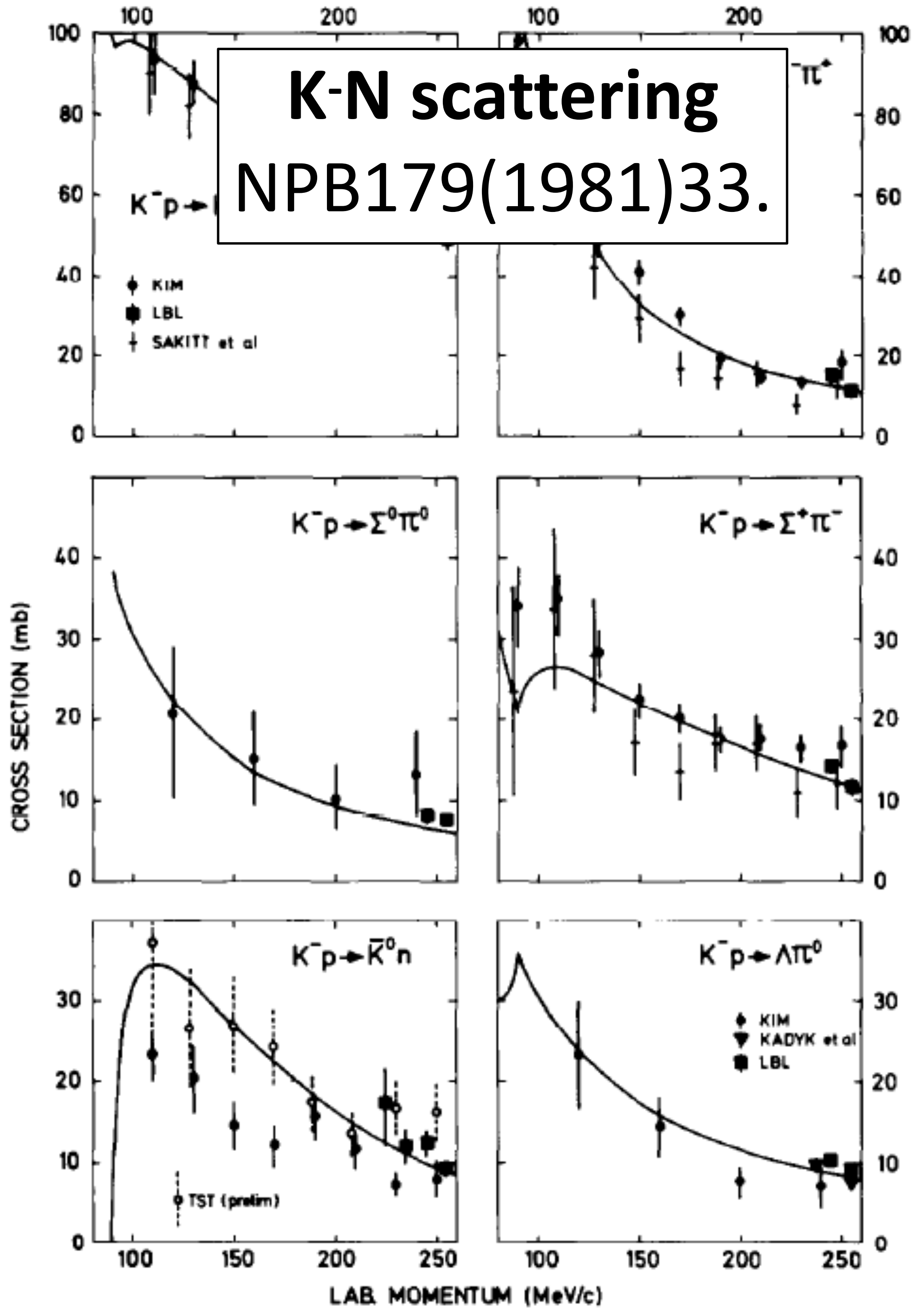


Can meson be a constituent particle forming nuclei?

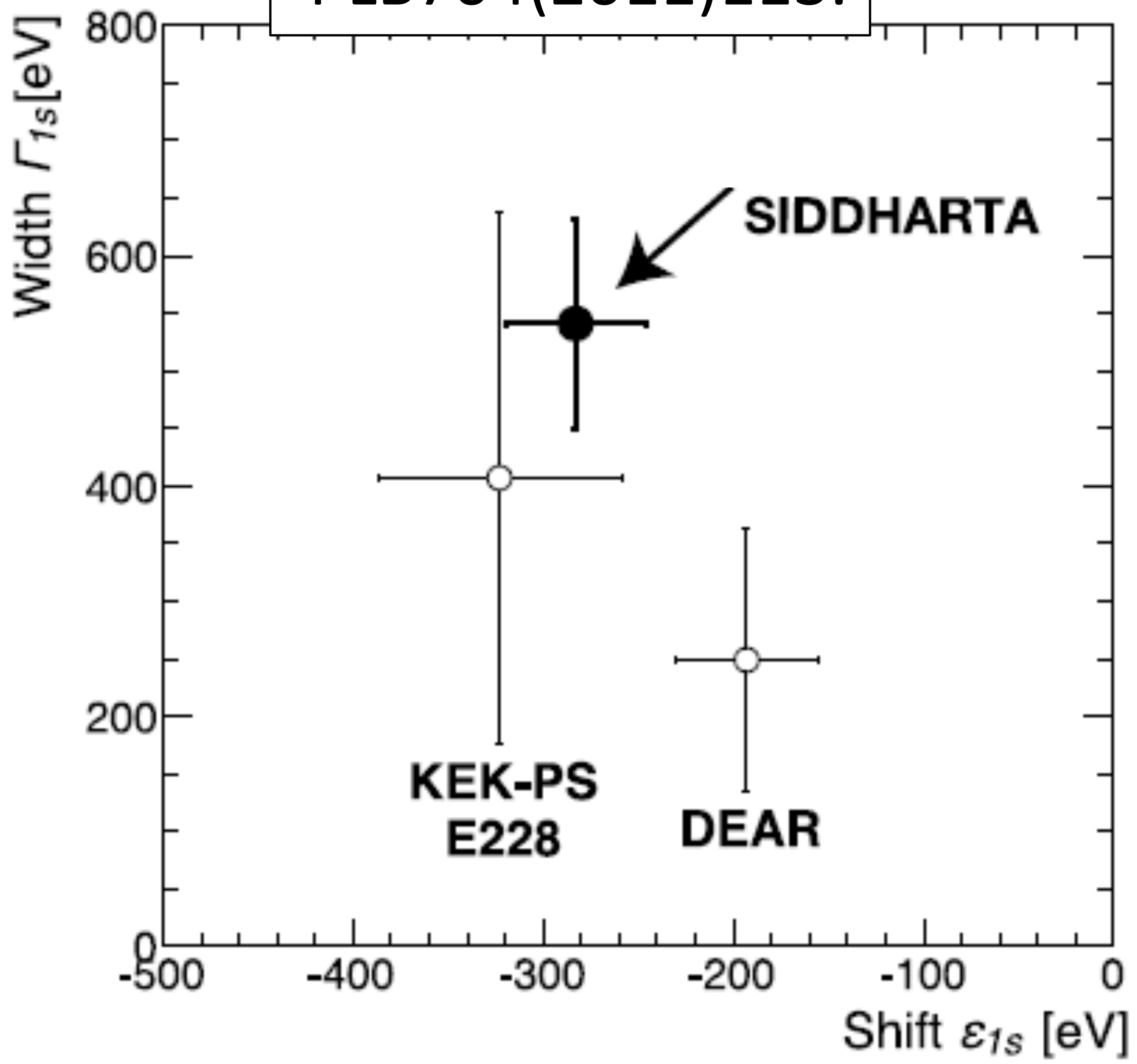
If yes, how do meson and core nucleus change?

K^bar^N interaction

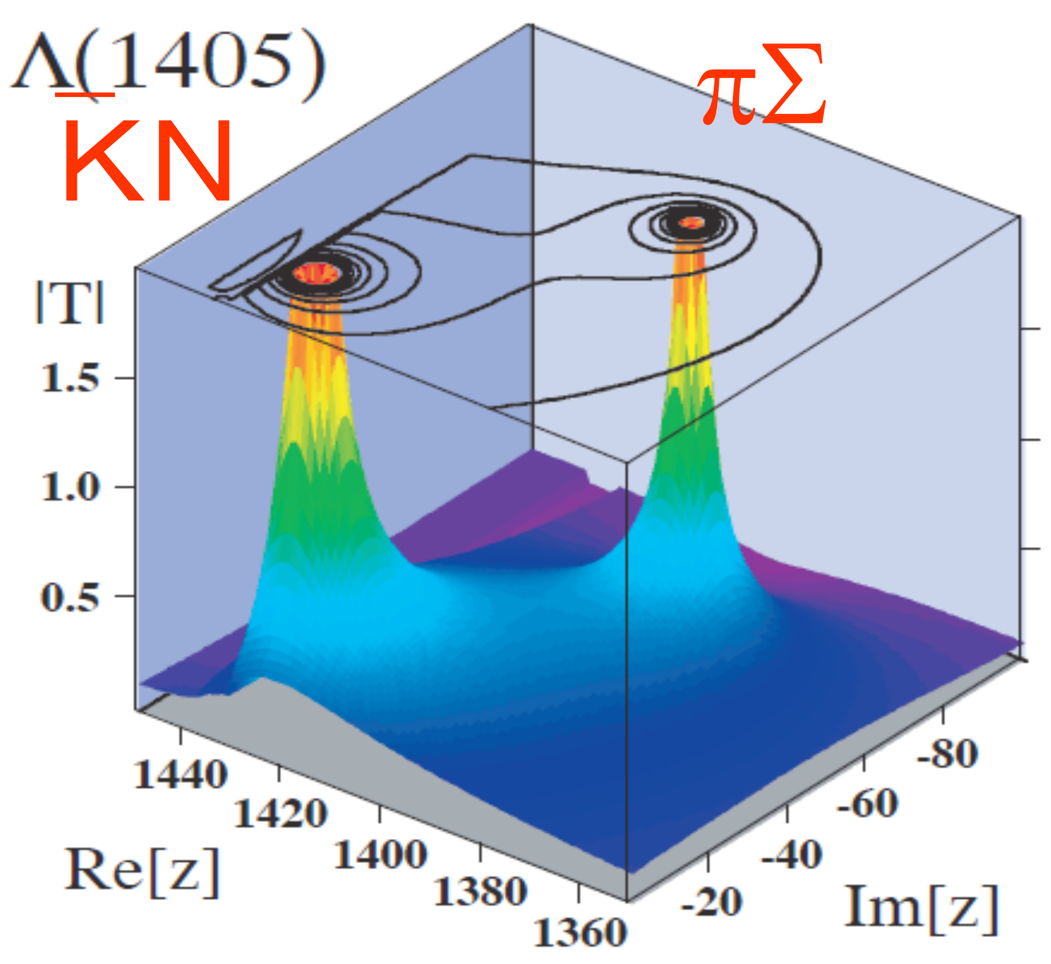
K-N scattering
NPB179(1981)33.



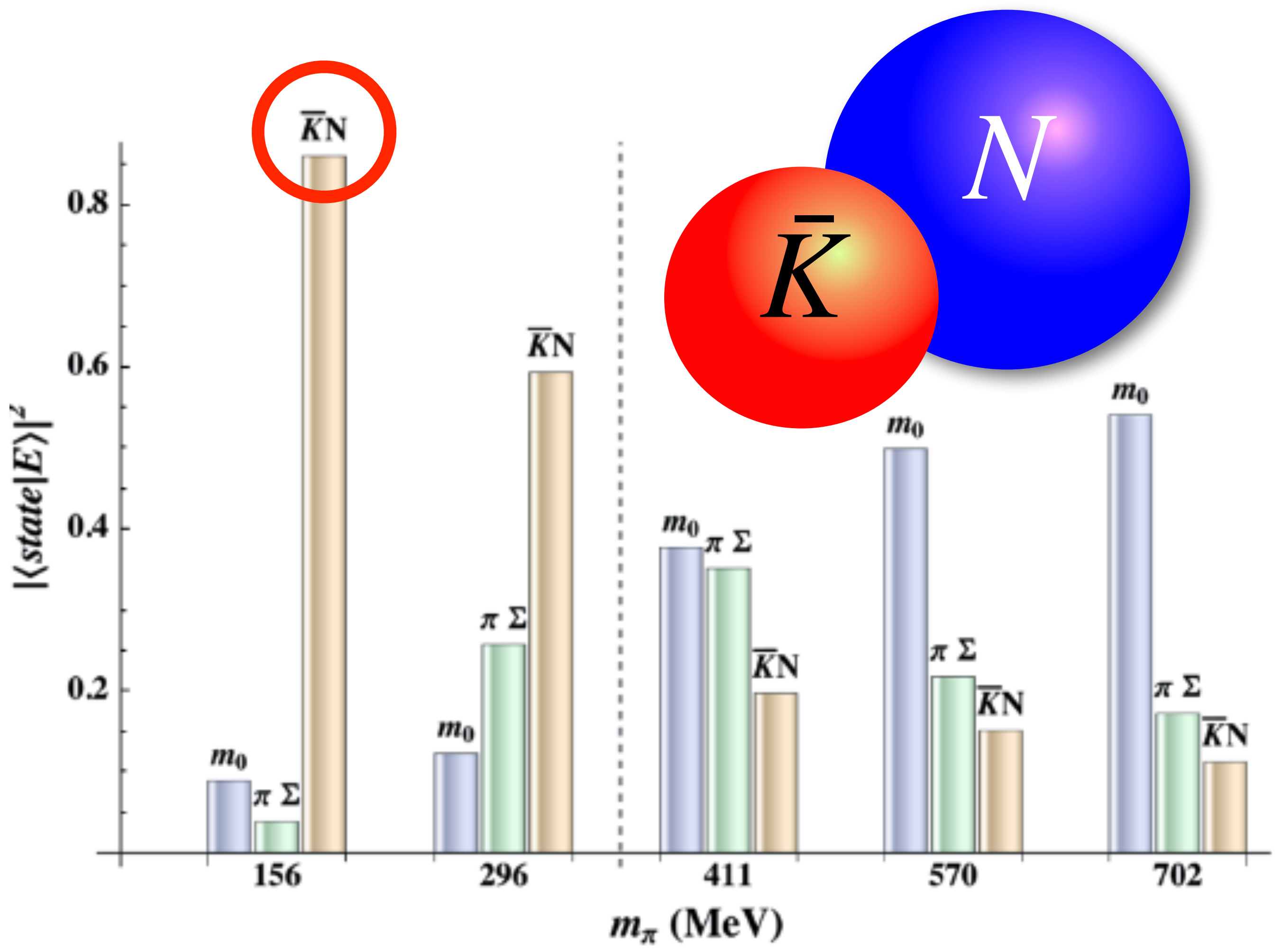
K-p atom
PLB704(2011)113.



Λ(1405) in
chiral unitary model
T. Hyodo

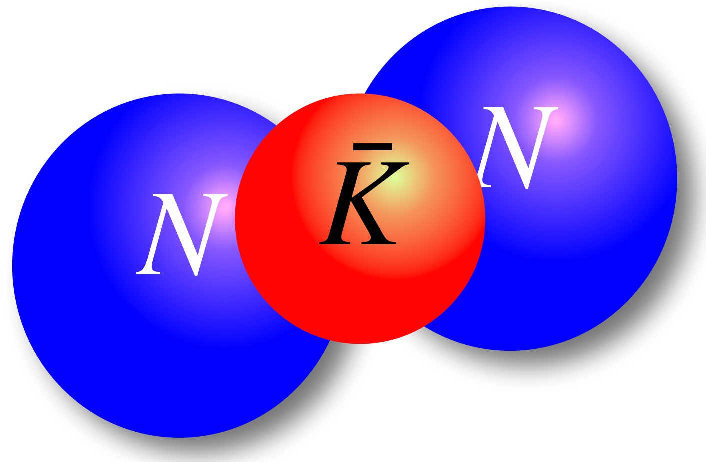


K^bar^N molecule from **Lattice QCD**
PRL114(2015)132002.



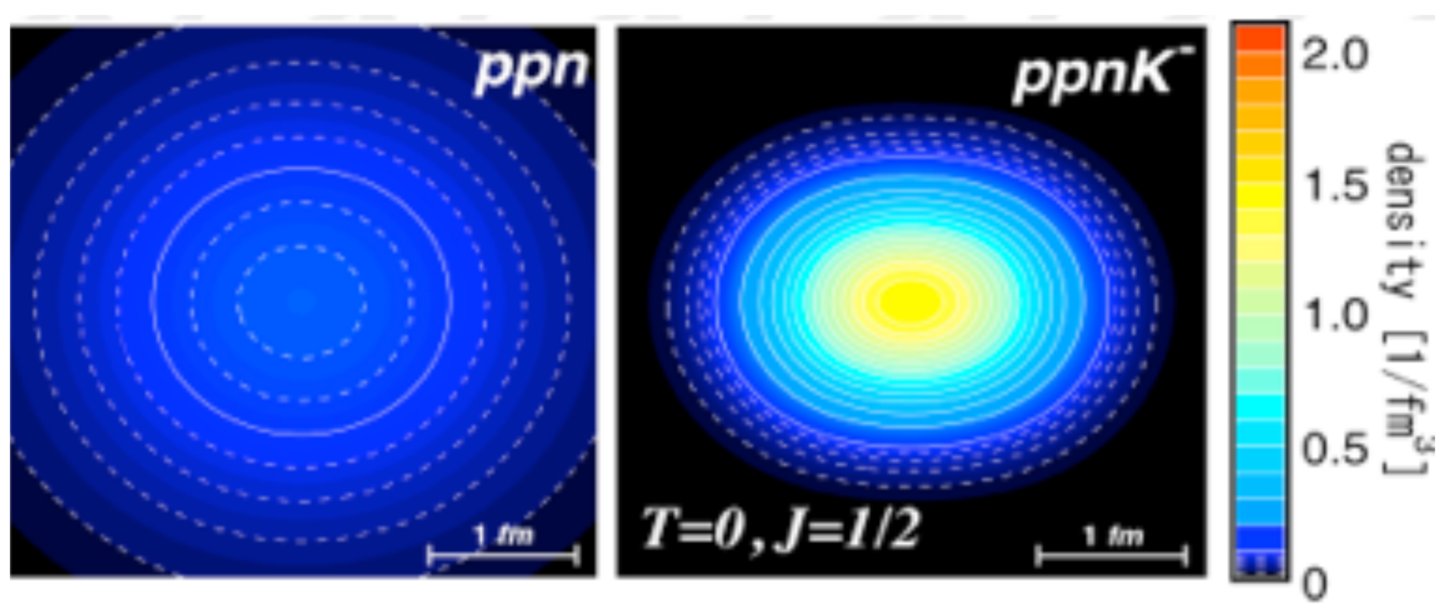
- Strong attraction in I=0 from scattering and X-ray experiements.
- $\Lambda(1405) = \bar{K}N$ molucle picture is now widely accepted

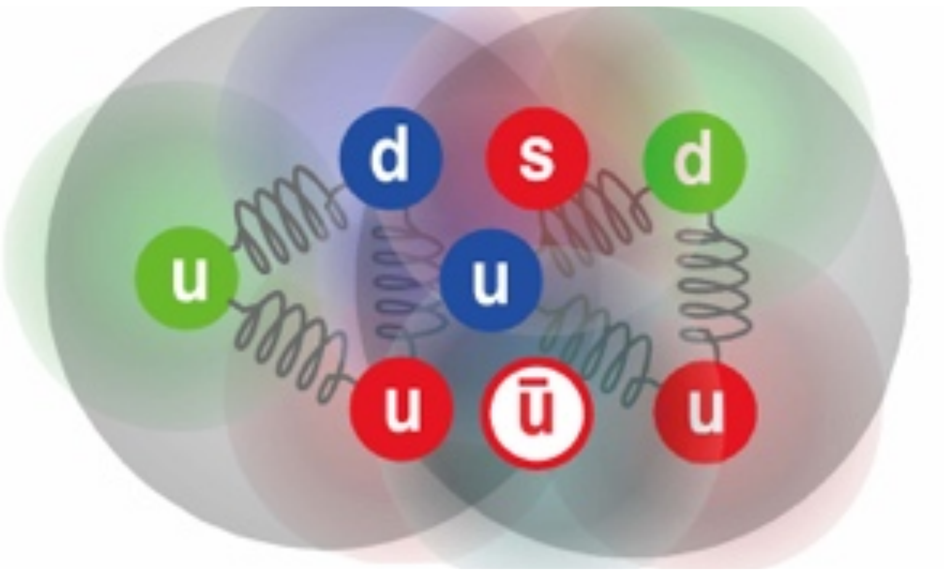
Why not kaonic nucleus with additional nucleons?



Kaon in nuclei

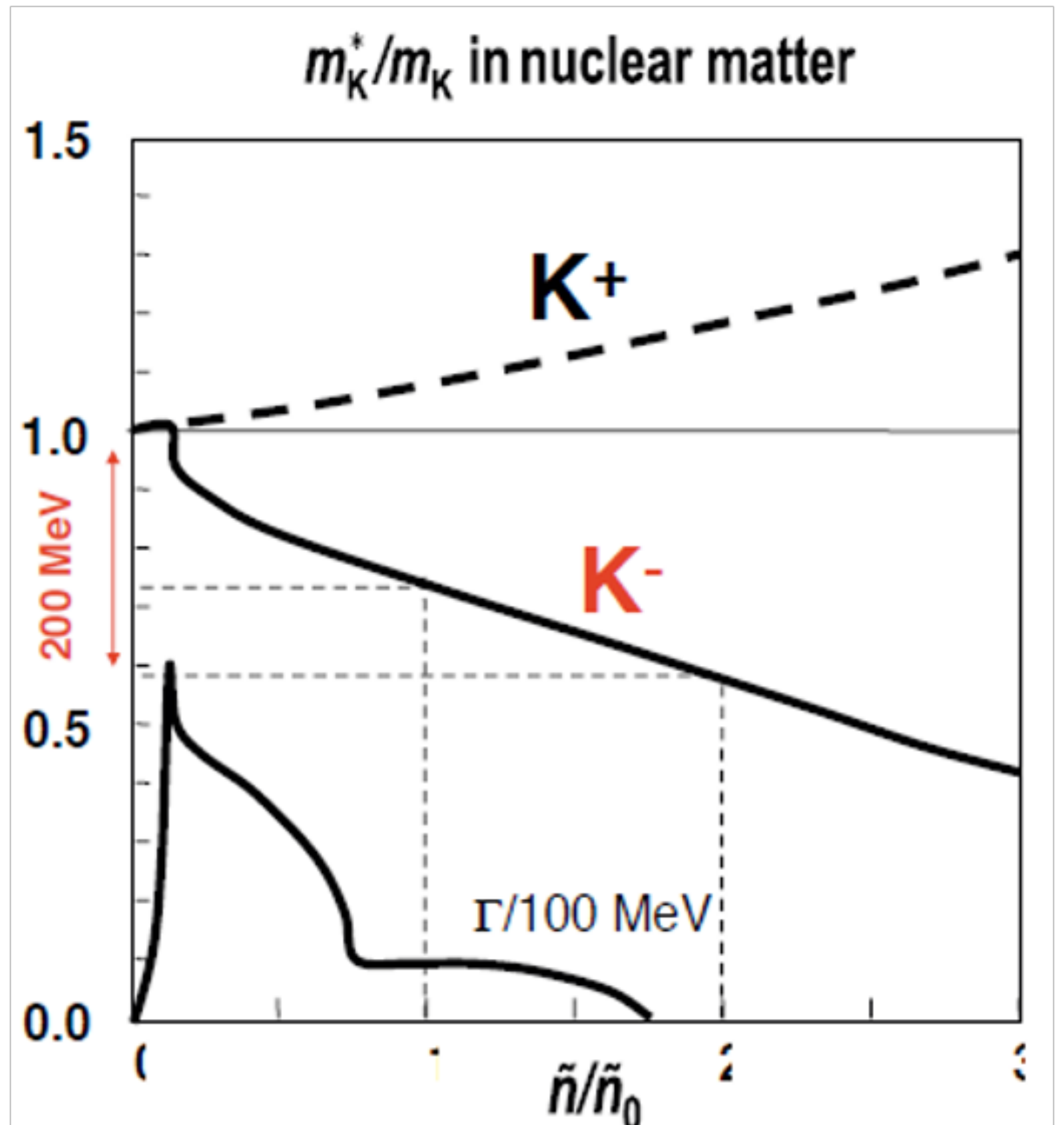
A. Dote, H. Horiuchi, Y. Akaishi and T. Yamazaki, Phys. Lett. B 590 (2004) 51



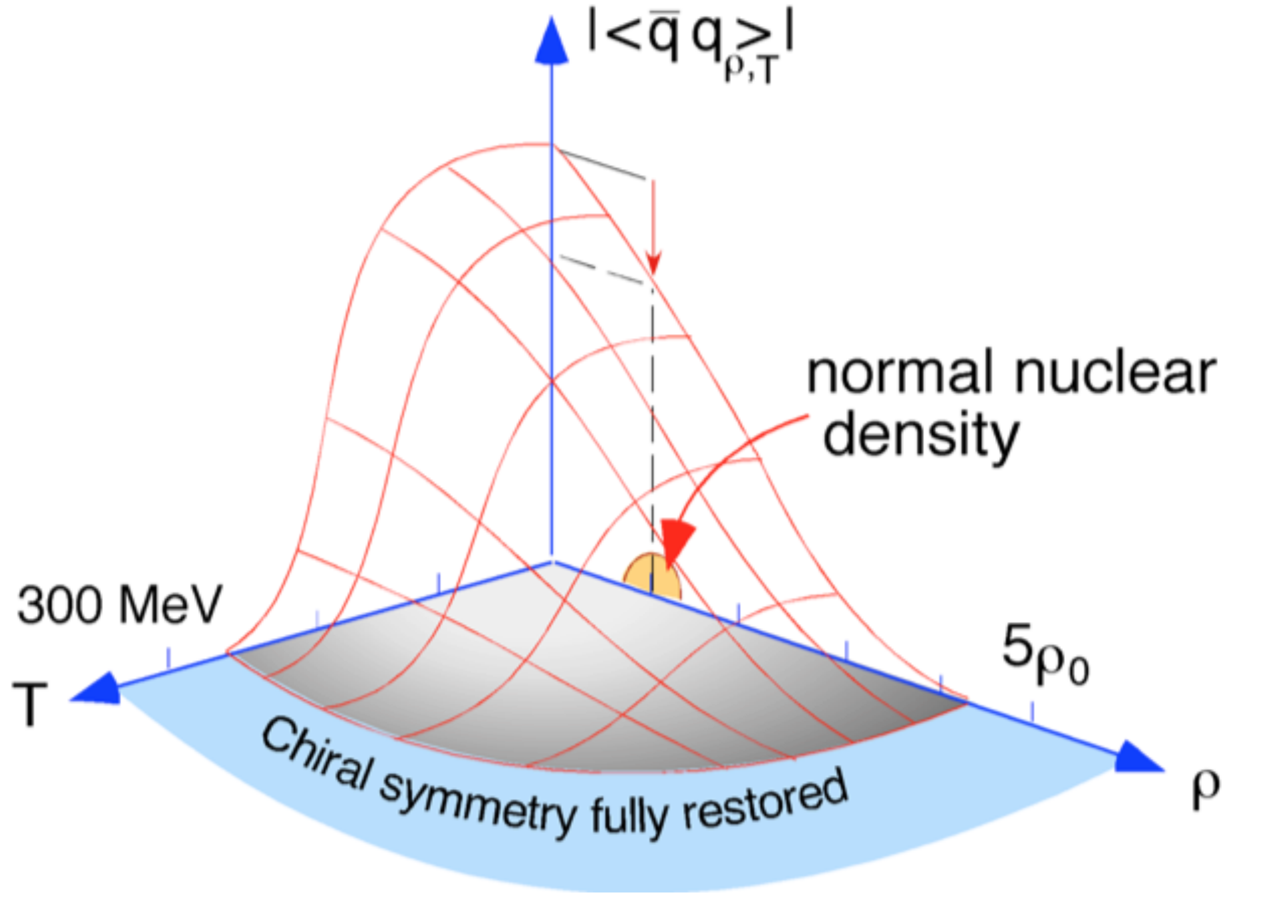


Compact system?

→nucleon overlaps? dense matter?

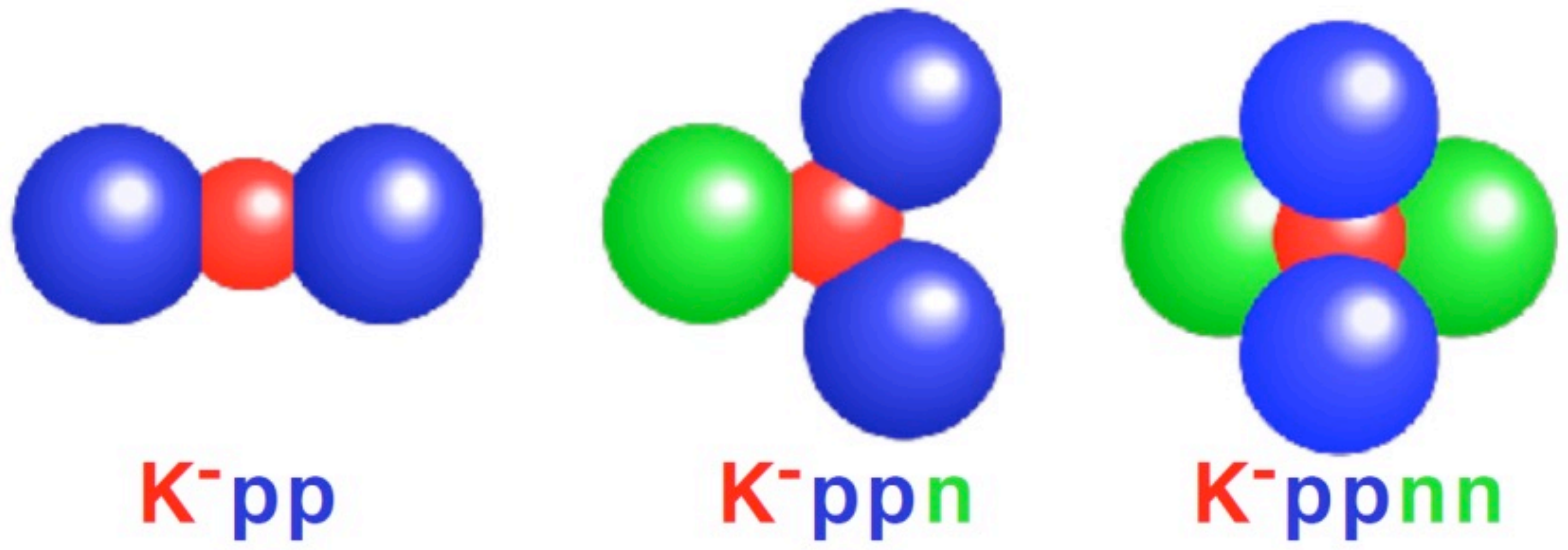


T. Waas, N. Kaiser & W. Weise, Phys. Lett. B379 (1996) 34.



W.Weise NPA553,59 (1993)

Kaon mass changes?

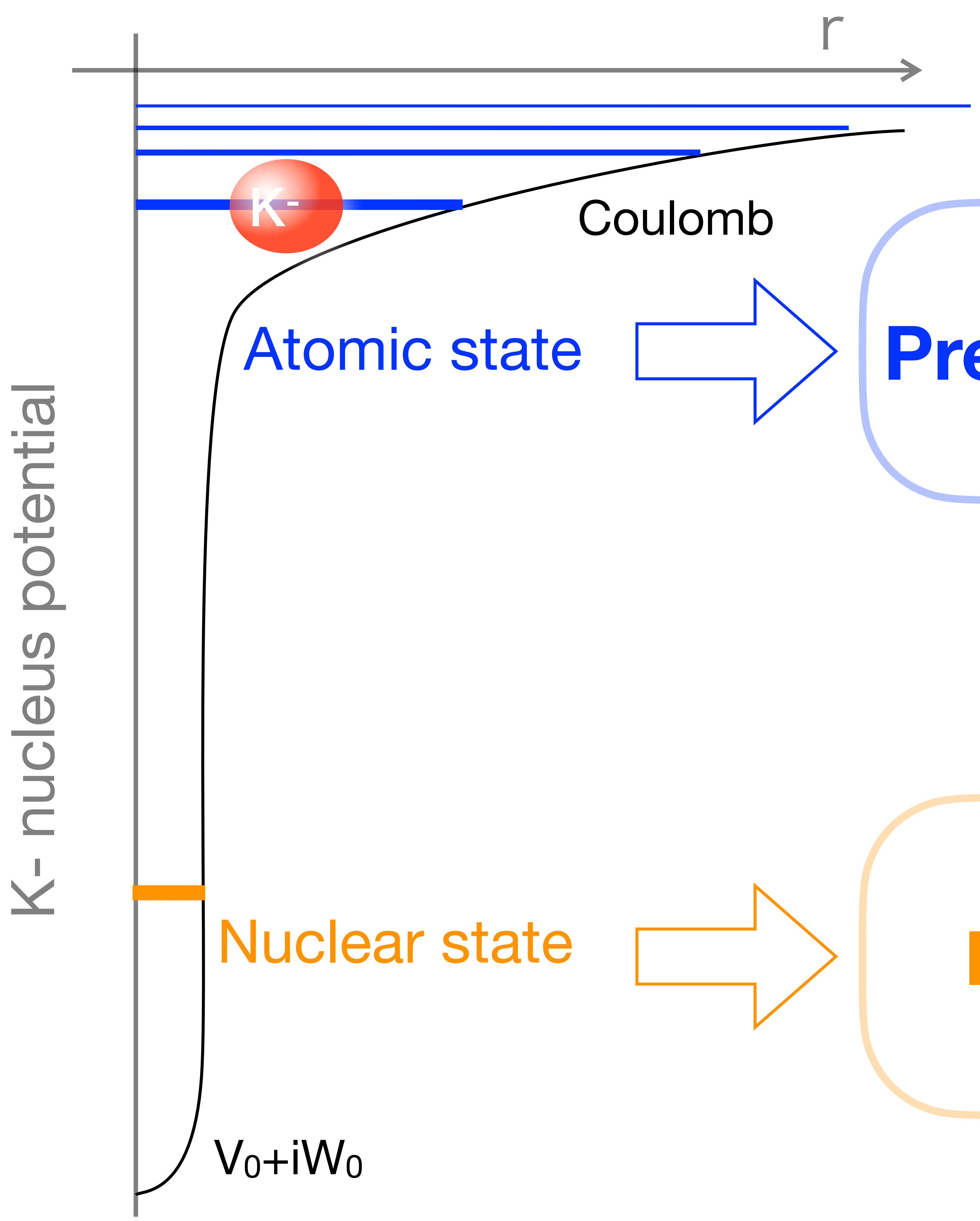


$\bar{K}N$ attraction & NN replusion

→molecule-like structure?

Anti-kaon could be a new & unique probe for low-energy QCD

Two approaches for kaonic nuclear system



Precision X-ray measurement

- ○ Basis of the $\bar{K}N$ interaction
- ○ Experimentally solid
- × Sensitive only to the nuclear surface

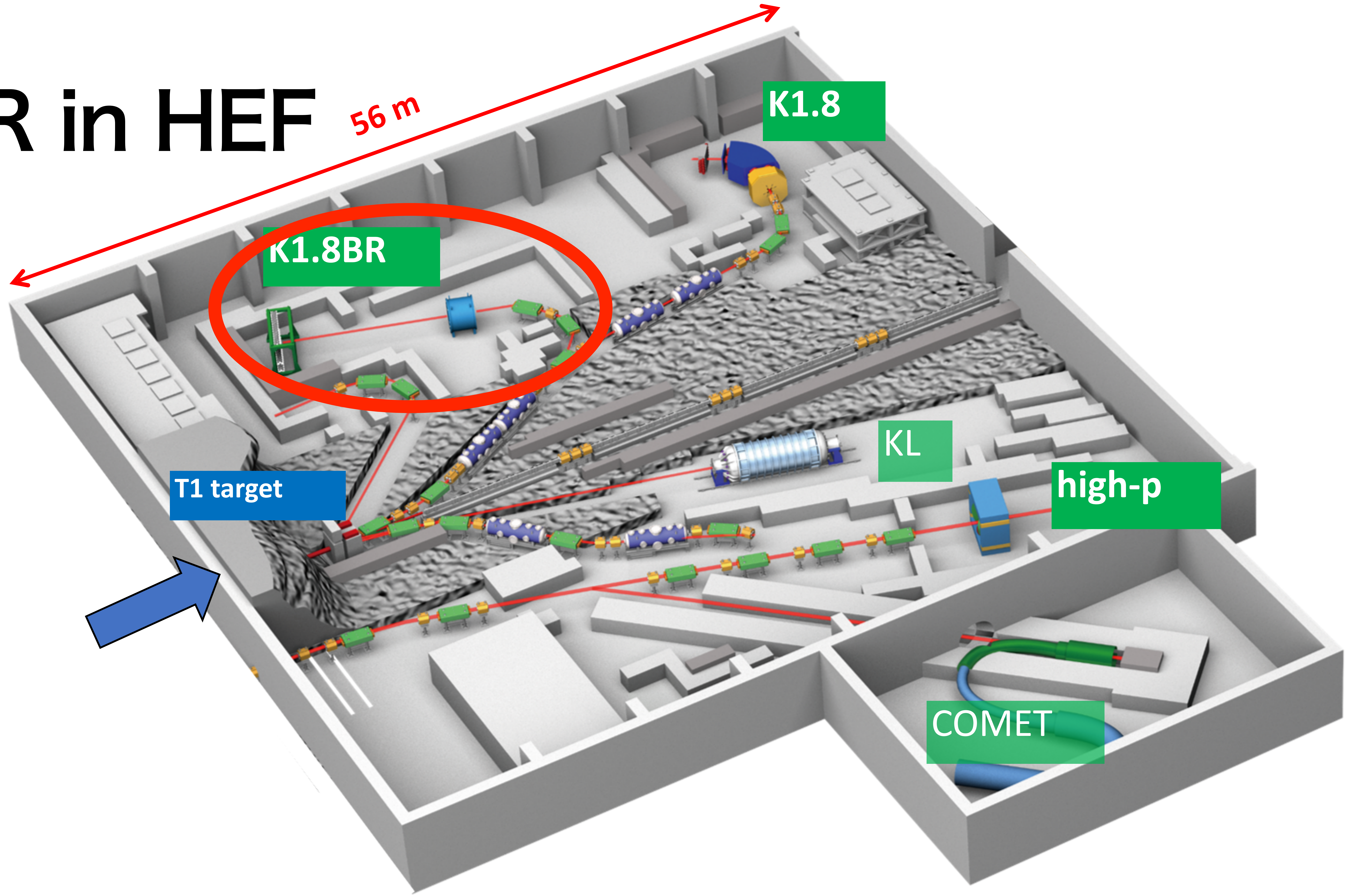
complementary

Direct reaction formation

- ○ Direct information in nuclei
- × No conclusive observation
- × Large widths are expected

A series of experiments probing different energy, density, and isospin

K1.8BR in HEF



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

Experiments at K1.8BR

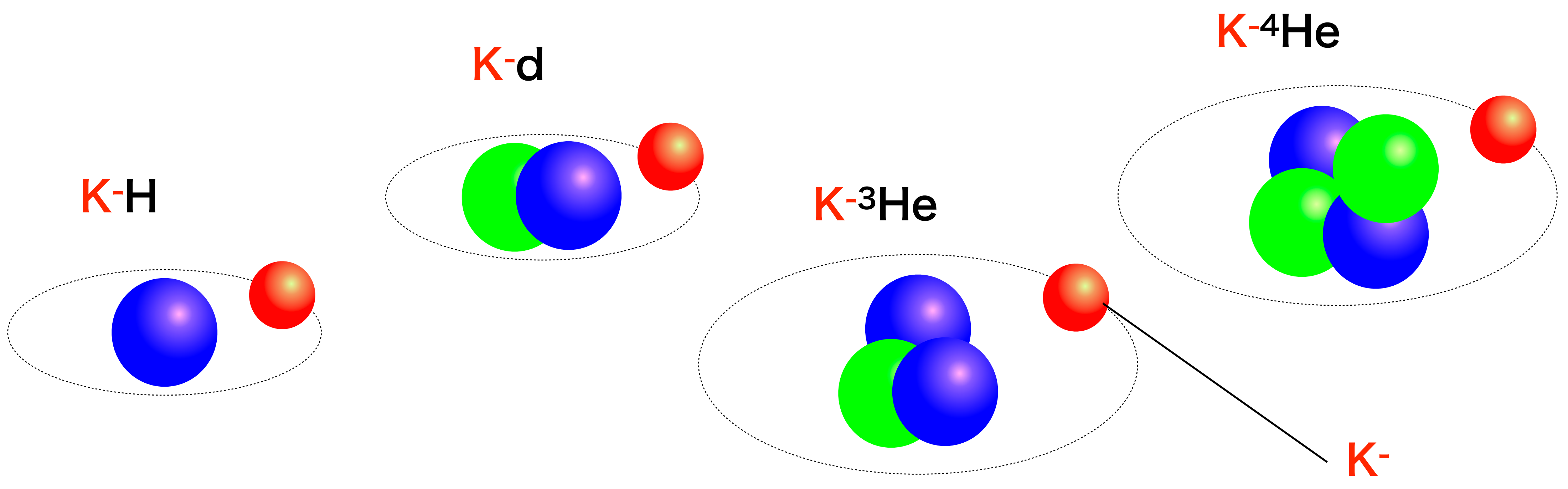
- 2013: E15 1st, “K-pp” search **[PTEP 061D01 (2015), PTEP, 051D01 (2016)}**
- 2015: E15 2nd, “K-pp” search **[PLB789, 620 (2019), PRC102, 044002 (2020), PRC10, 014002 (2024)]**
- 2018: E31, Lambda(1405) **[PLB837,137637(2023)]**
- 2018: E62, Kaonic helium-3/4 with TES **[PRL128, 112503 (2022)]**
- 2019: E57 pilot run, Kaonic hydrogen with SDD
- 2020: T77, ${}^{4}_{\Lambda}\mathrm{H}$ lifetime, “K-ppn” search **[PLB485, 138128 (2023)]**
- 2022/2024: E73, ${}^{3}_{\Lambda}\mathrm{H}$ production cross-section
- 2025?: E72, Λ(1670)
- 2026~?: E80, P89, Kaonic nuclei with a new solenoid spectrometer

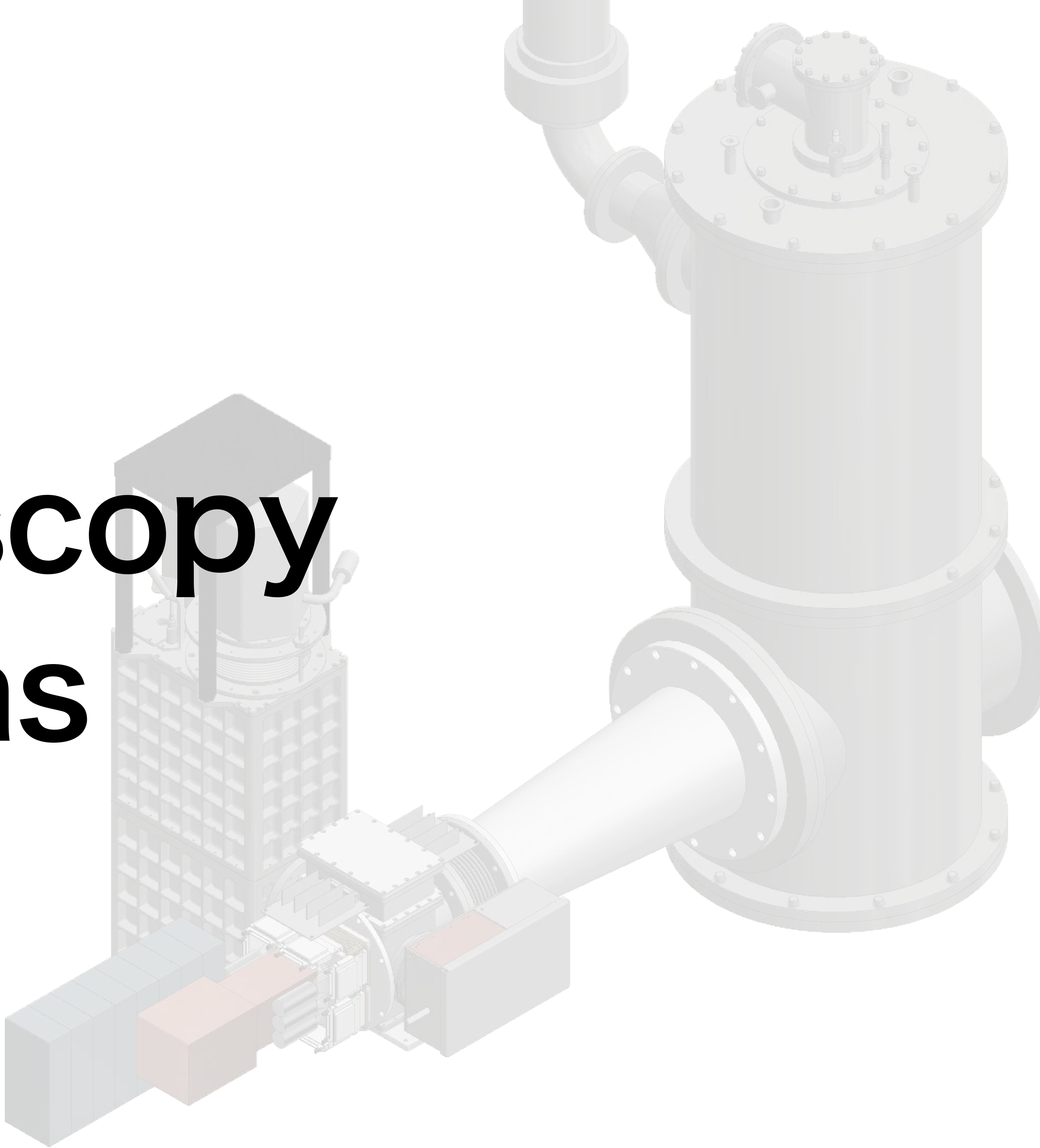
Experiments at K1.8BR

Kaonic nuclei
Kaonic atom

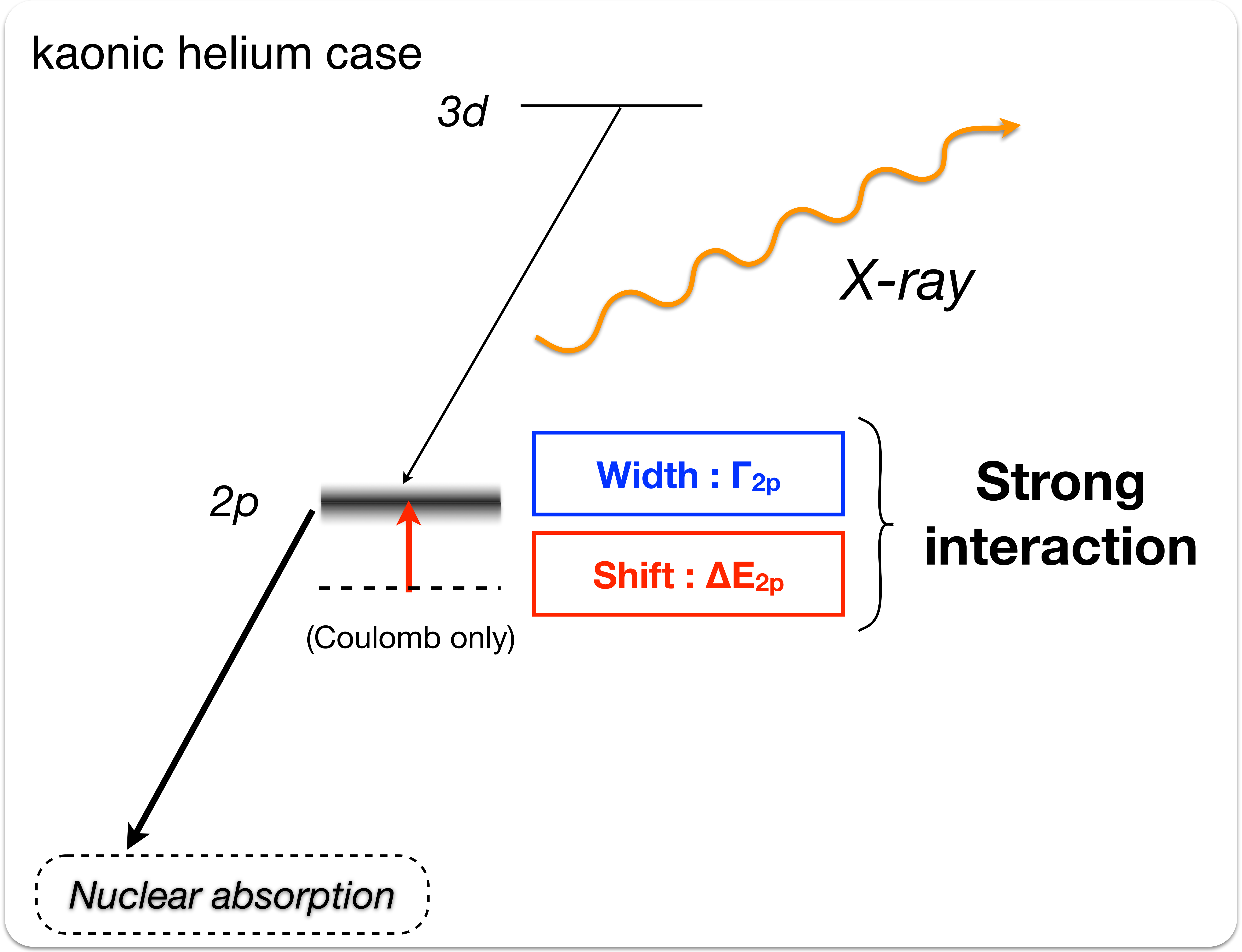
- 2013: E15 1st, “K-pp” search [PTEP 061D01 (2015), PTEP, 051D01 (2016)}
- 2015: E15 2nd, “K-pp” search [PLB789, 620 (2019), PRC102, 044002 (2020), PRC10, 014002 (2024)]
- 2018: E31, Lambda(1405) [PLB837,137637(2023)]
- 2018: E62, Kaonic helium-3/4 with TES [PRL128, 112503 (2022)]
- 2019: E57 pilot run, Kaonic hydrogen with SDD
- 2020: T77, ${}^{4}_{\Lambda}\mathrm{H}$ lifetime, “K-ppn” search [PLB485, 138128 (2023)]
- 2022/2024: E73, ${}^{3}_{\Lambda}\mathrm{H}$ production cross-section
- 2025?: E72, Λ(1670)
- 2026~?: E80, P89, Kaonic nuclei with a new solenoid spectrometer

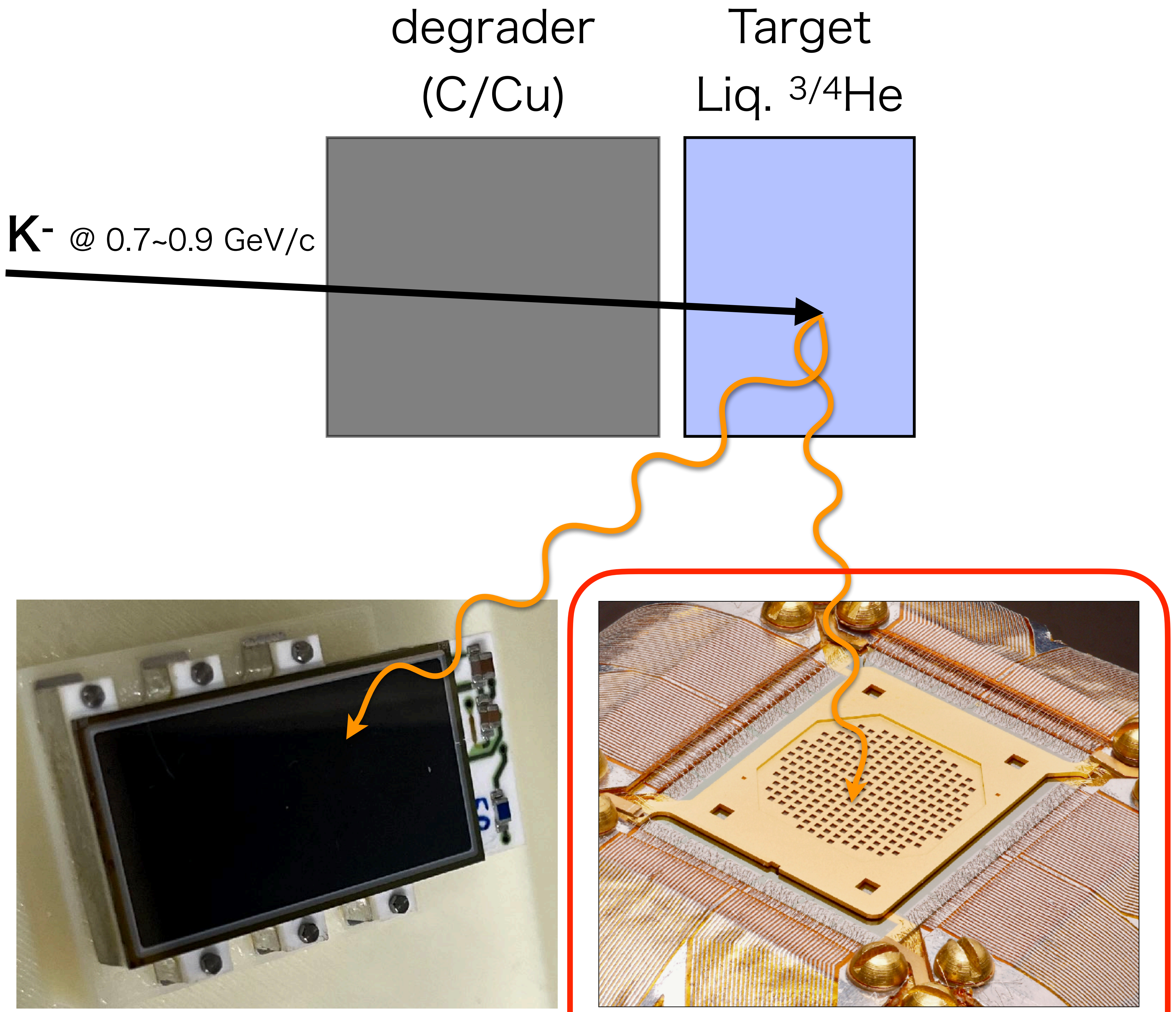
X-ray spectroscopy of kaonic atoms





Kaonic atom X-rays



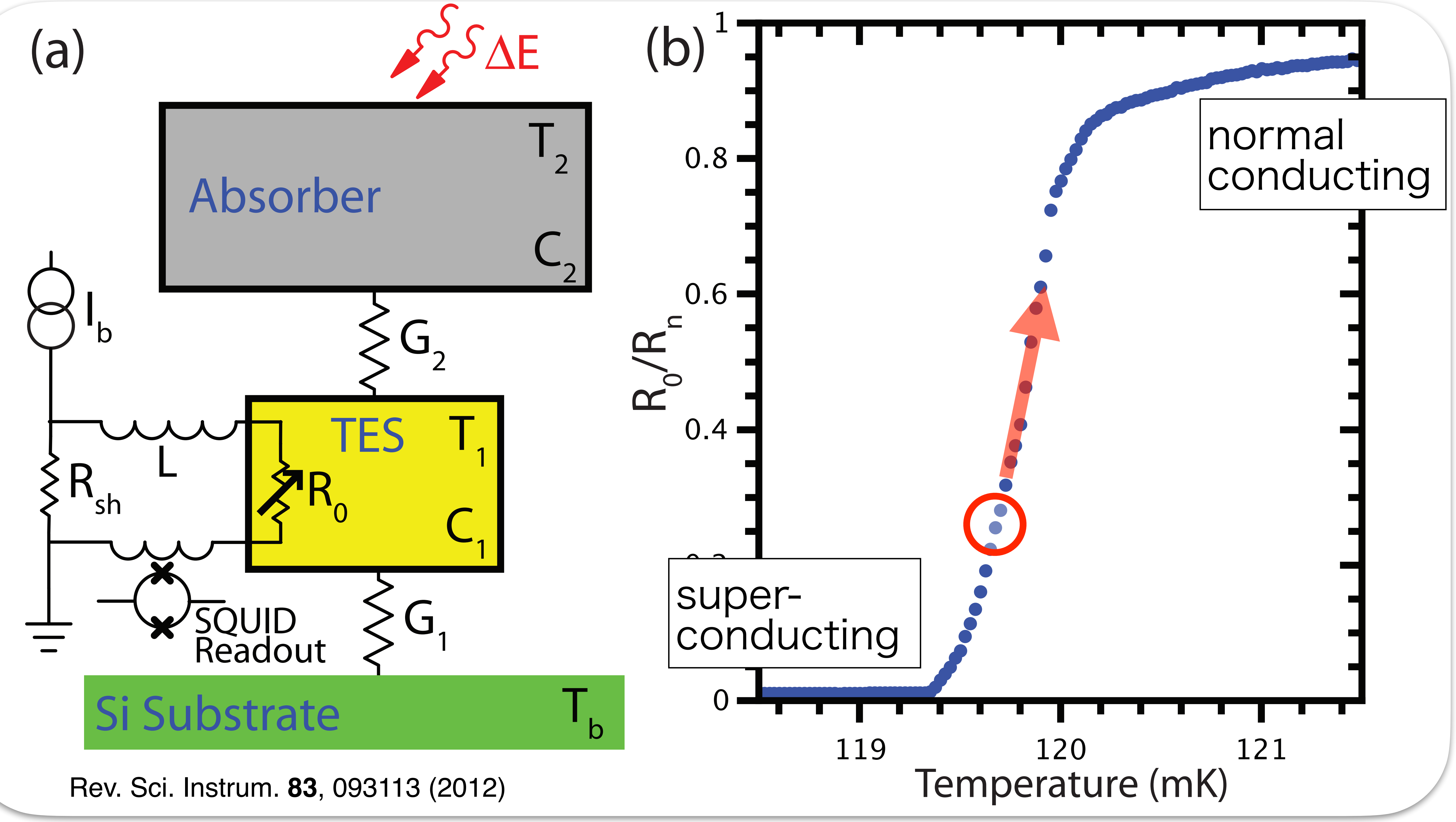


SDDs
Moderate resolution
Large solid angle
K^-p,/K^-d 1s (E57)

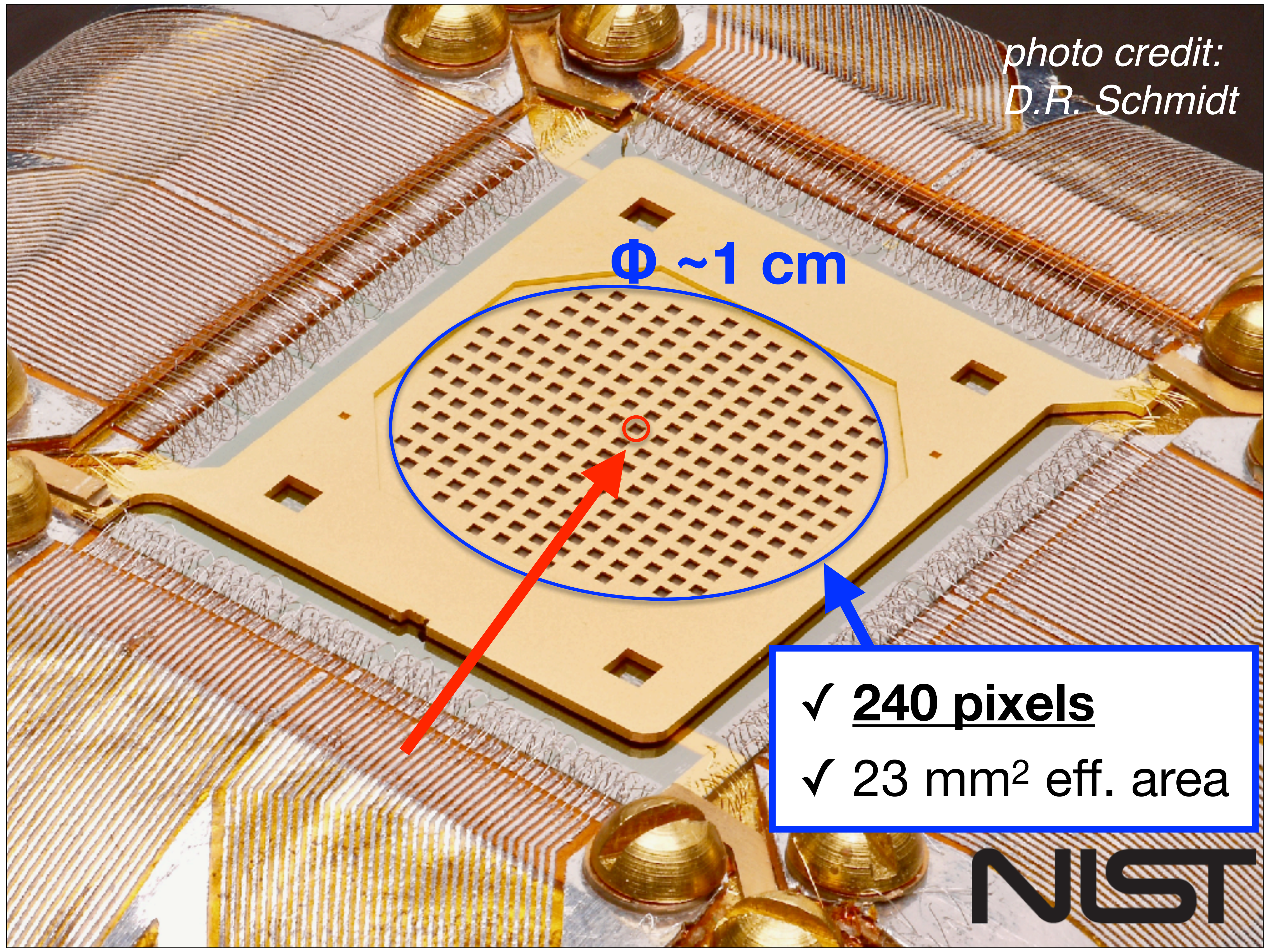
Microcalorimeter
Excellent resolution
Limited effective area
K^-He 2p (E62)

Alternative to a low-E scattering experiment

TES (Transition Edge Sensor) microcalorimeters



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



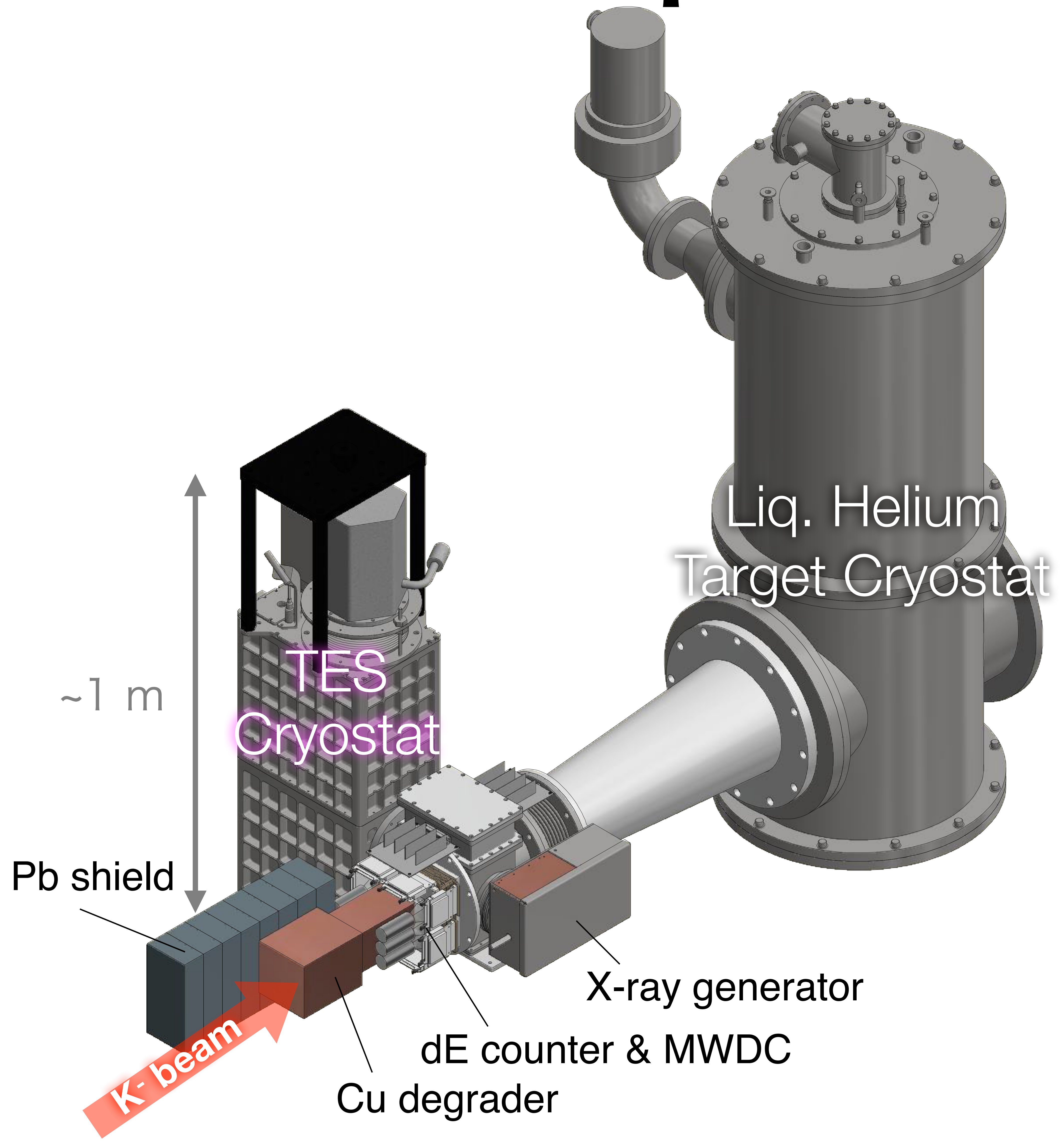
$$\Delta E \propto \sqrt{\frac{k_B T^2 C}{\alpha}}, \quad \alpha \equiv \frac{d \ln R}{d \ln T}$$

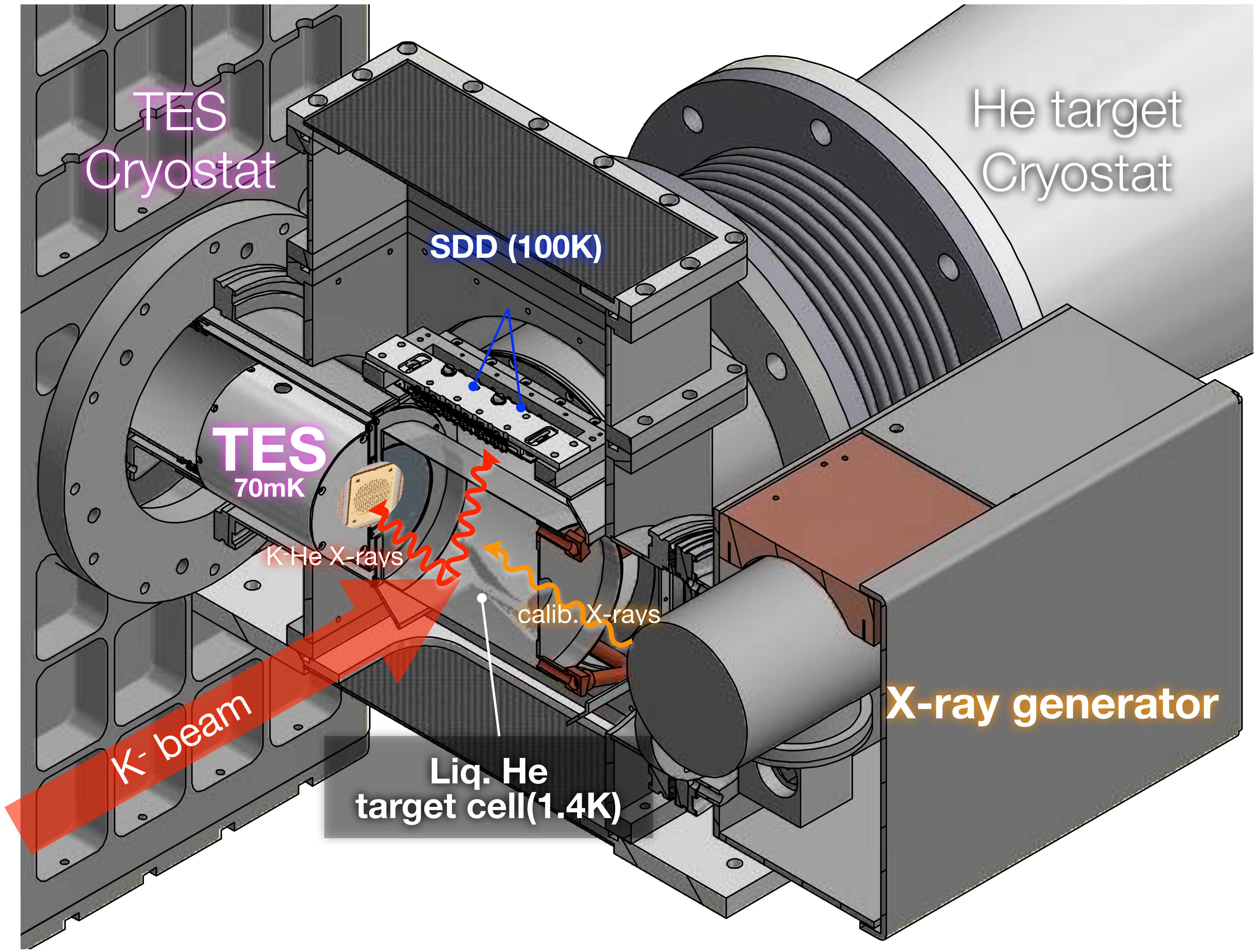
✓ Electro-thermal feedback (ETF) → stable operation

✓ SQUID multiplexing → reasonable effective area

E62 setup

First challenge to use TES in a charged-particle-rich environment





TES (E62)

~6 eV (FWHM)

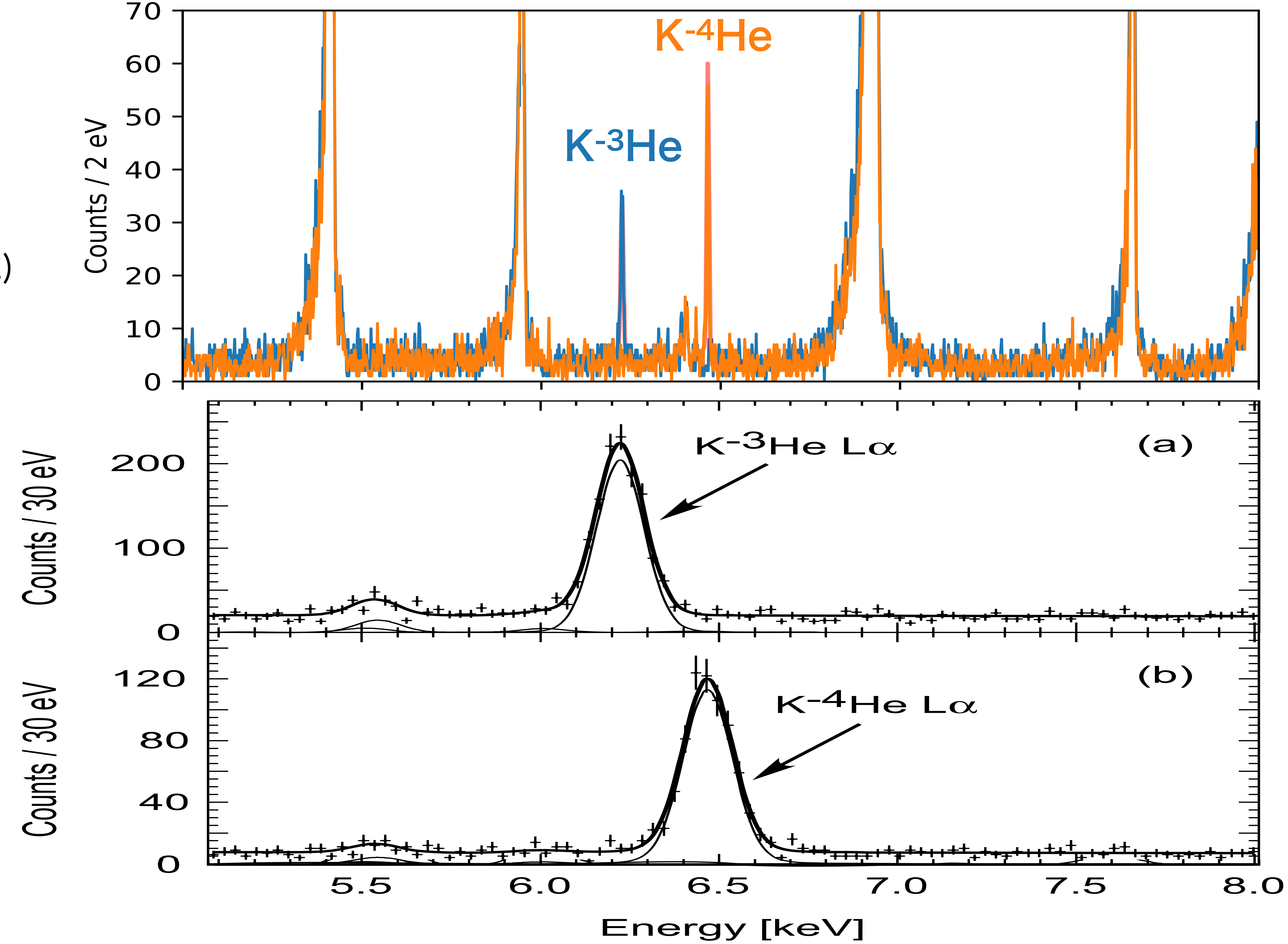
PRL128, 112503 (2022)

x25 better resolution

SDD (SIDDHARTA)

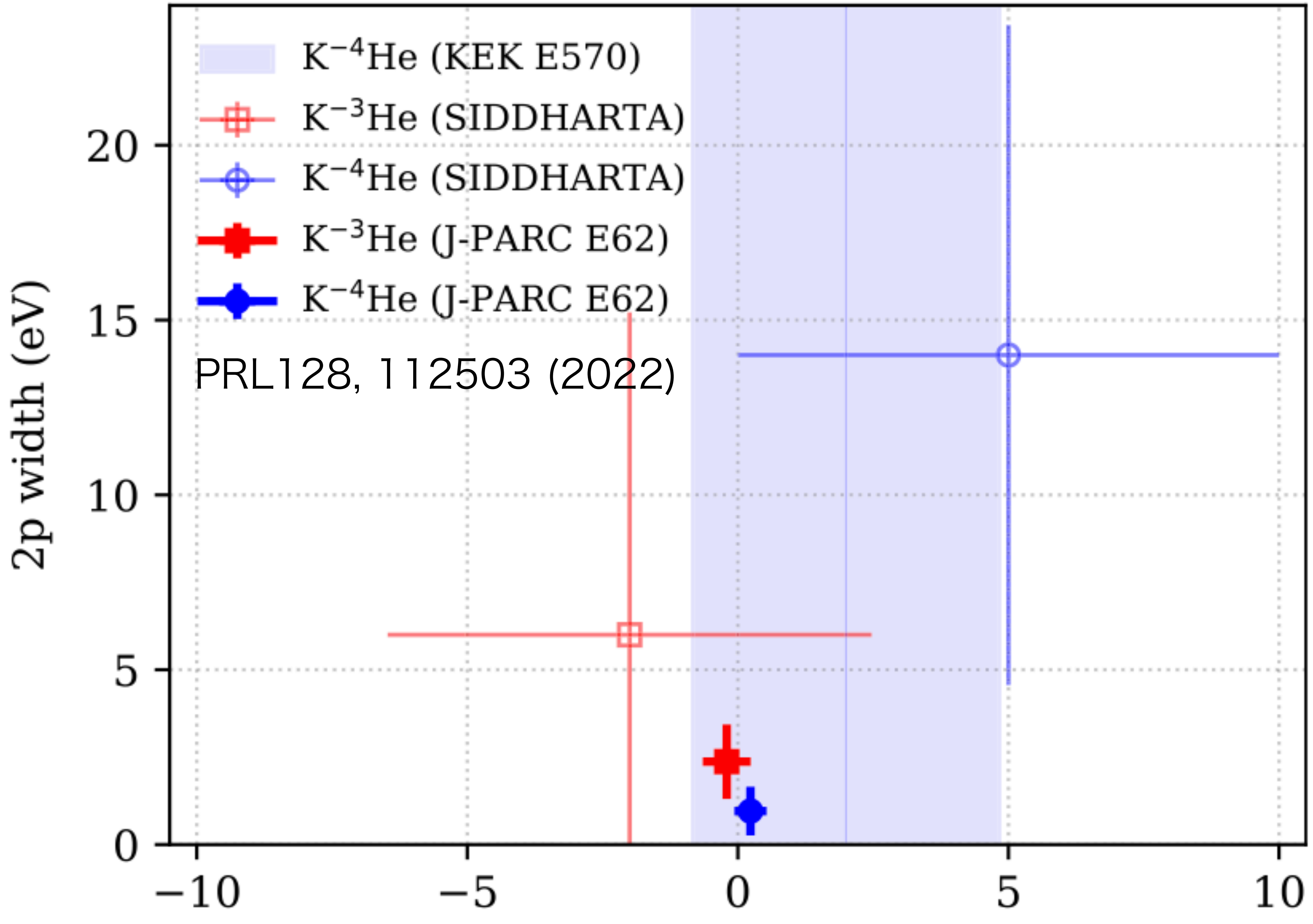
~150 eV (FWHM)

PLB714(2012)40



Comparison with past experiments

Error bar: quadratic sum of stat. & sys.



repulsive

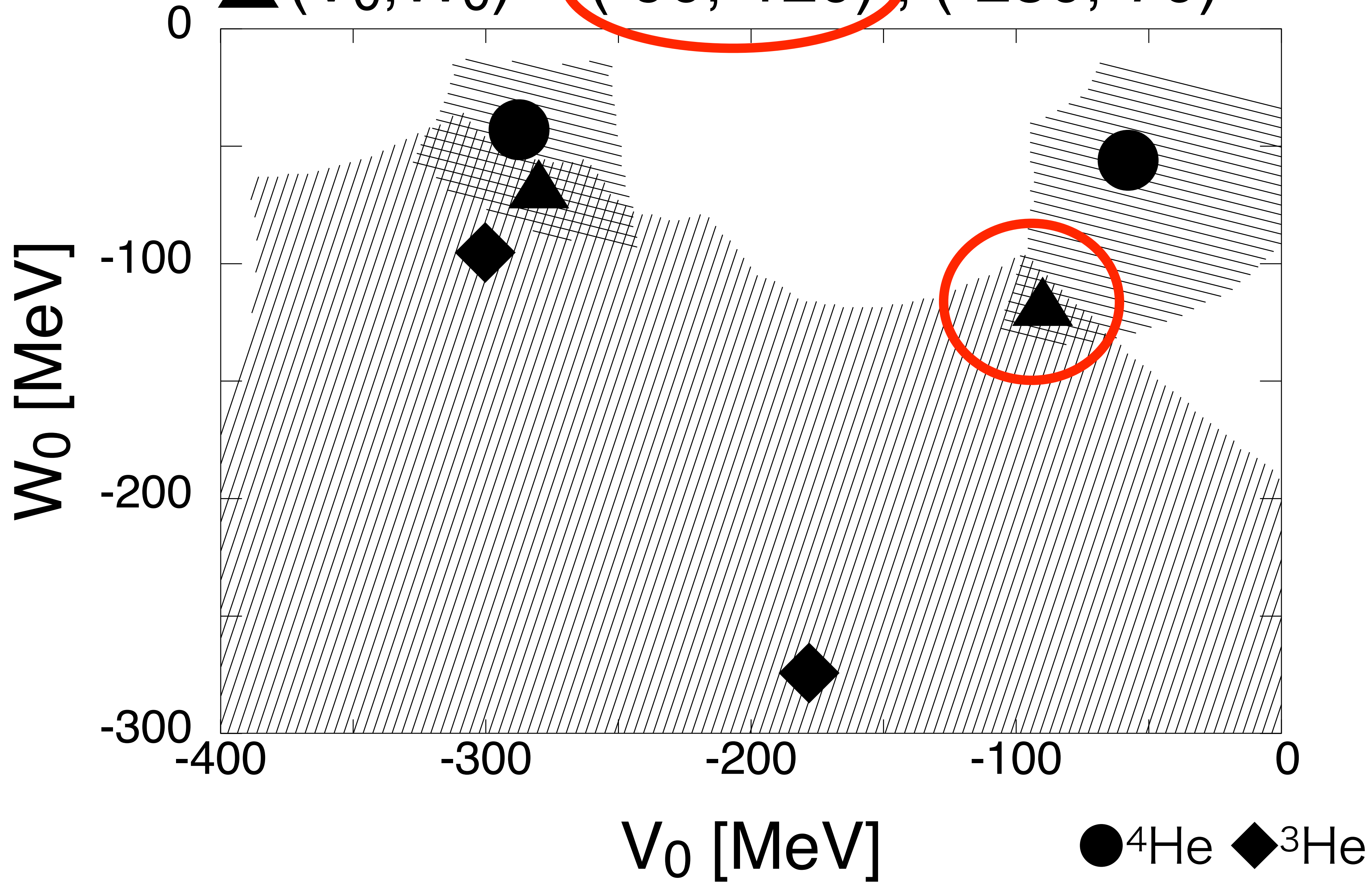
attractive

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

Yamagata-Sekihara et. al., [arXiv: 2407.20012]

$$U(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$$

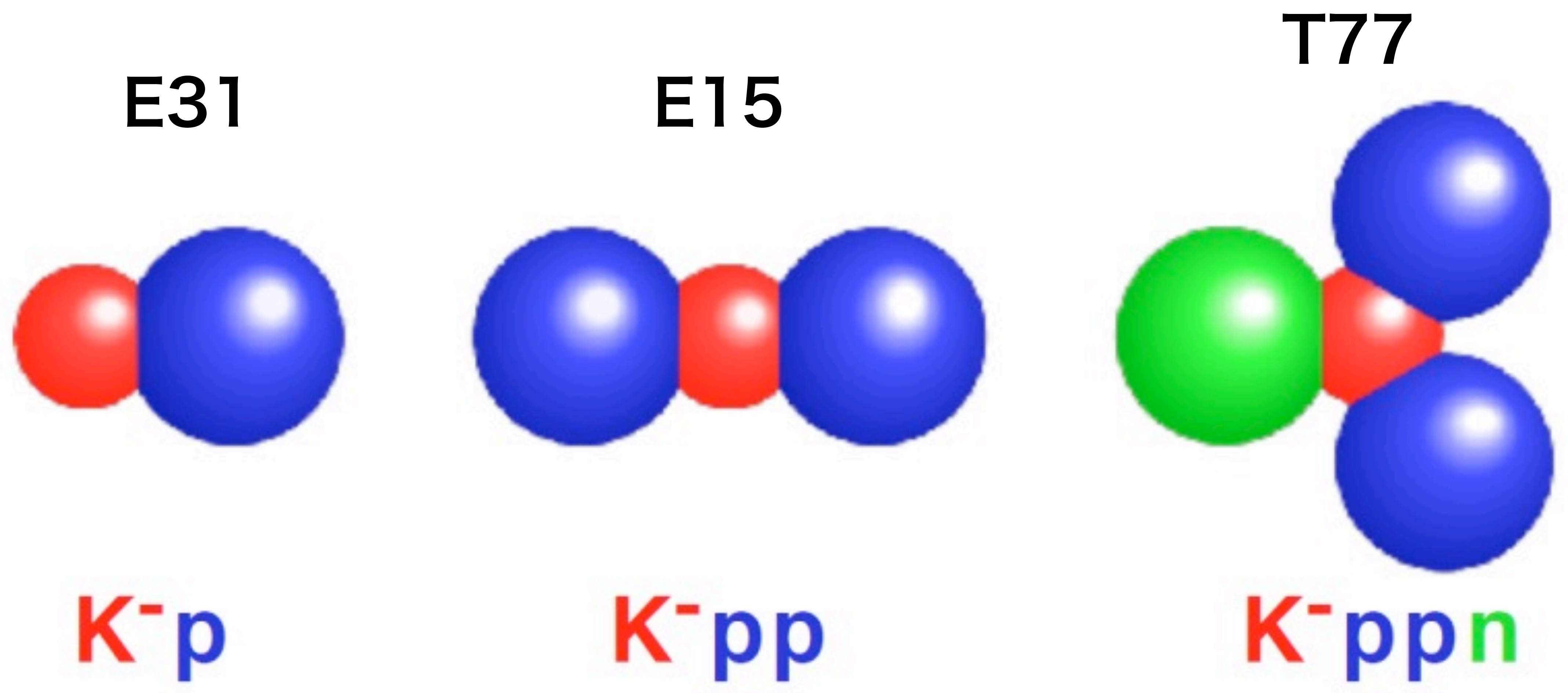
▲ (V_0,W_0) = (-90,-120), (-280,-70)



x10 precision for shift&width

Exclude large shifts&widths

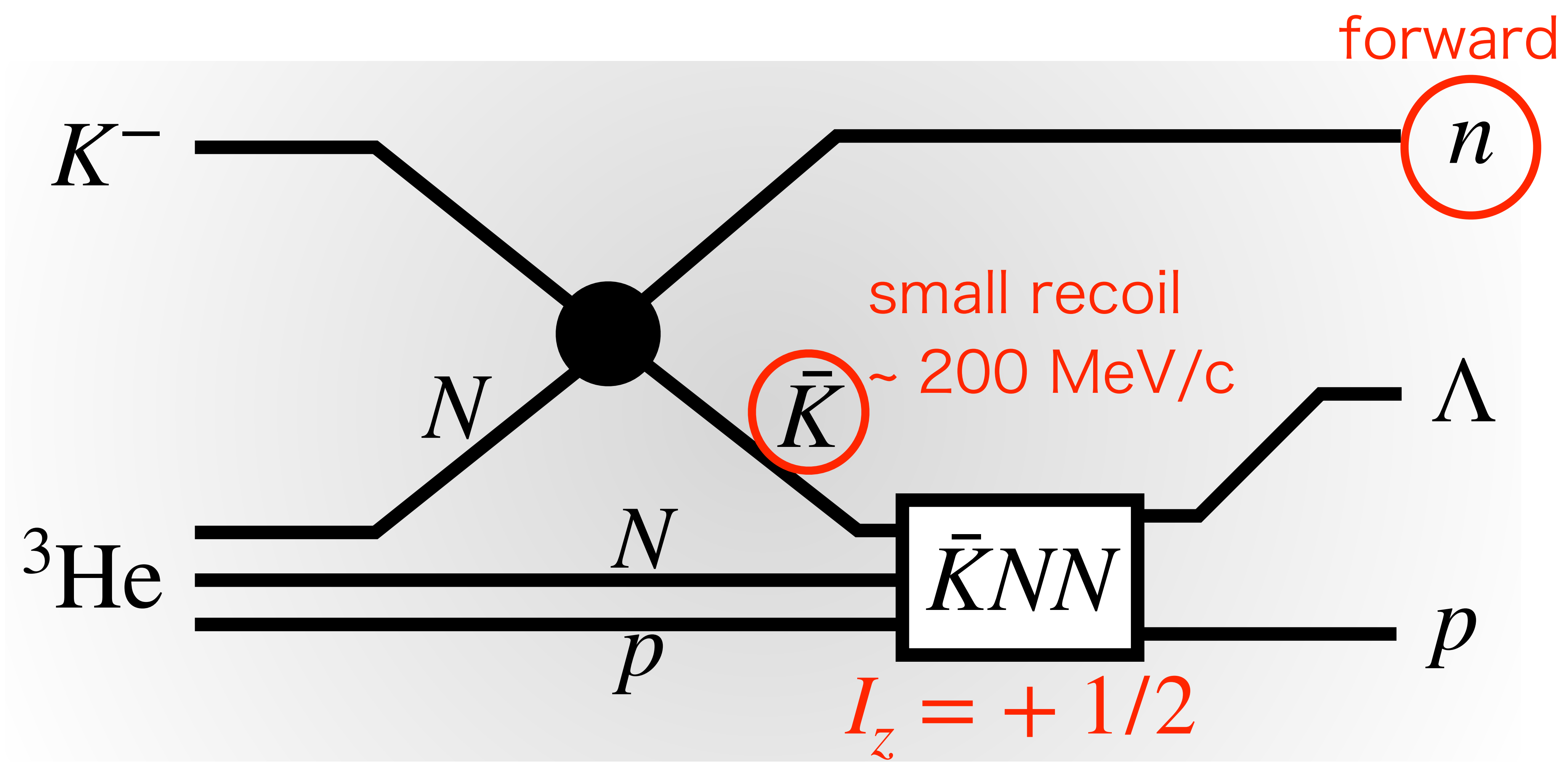
Strong constraint on the potential



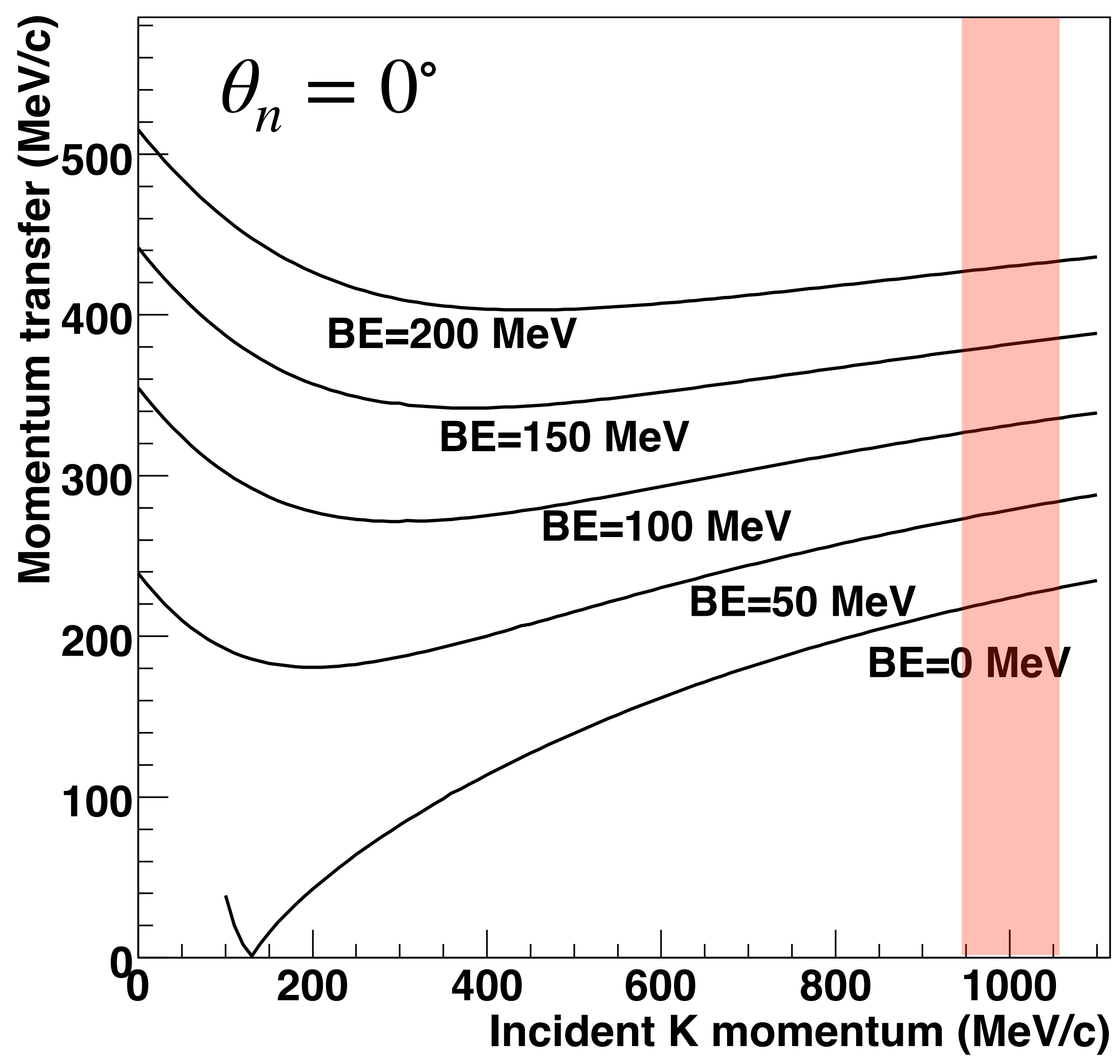
Direct search for kaonic nuclear bound state

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

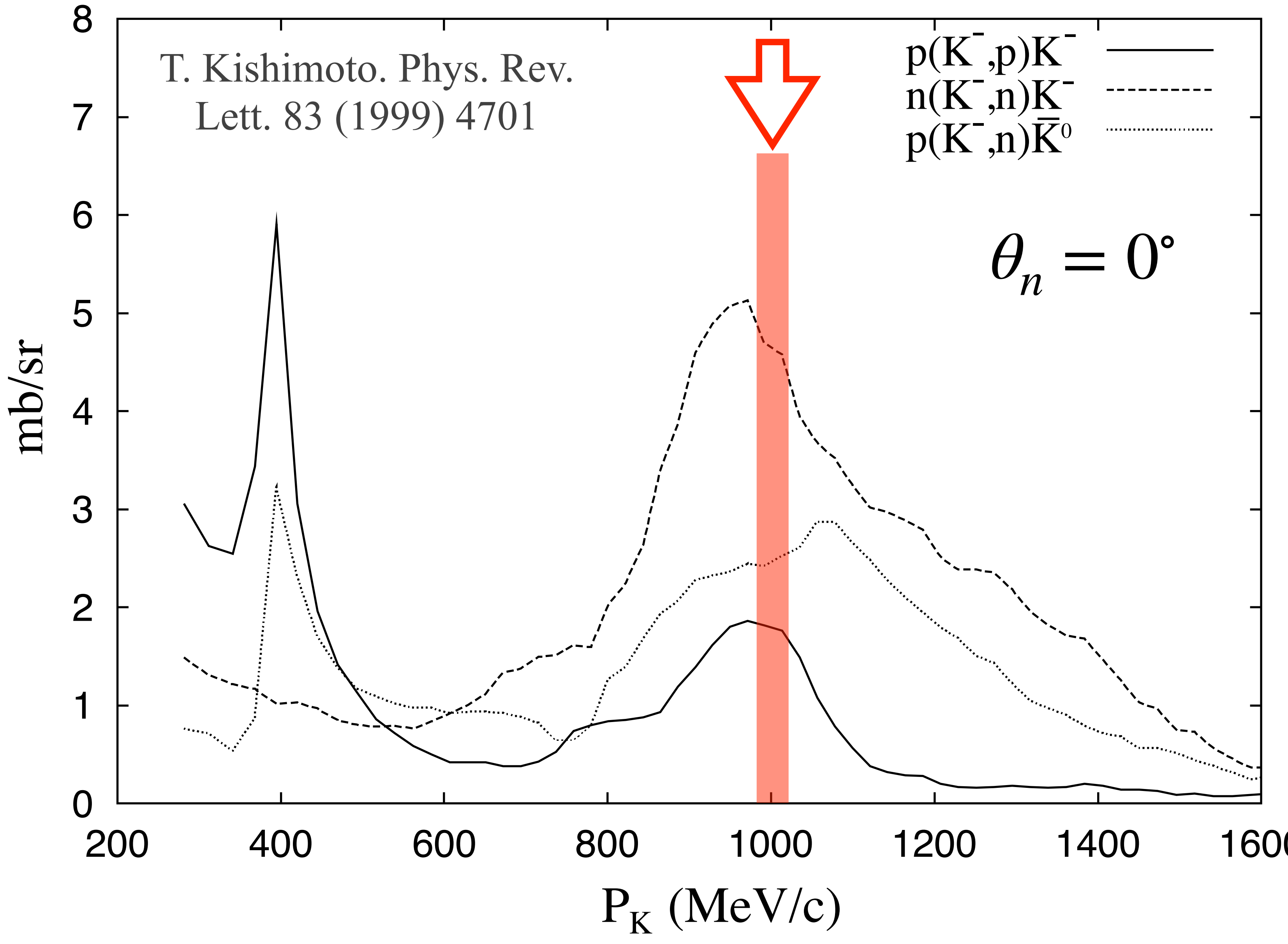
T. Kishimoto
Phys. Rev. Lett. **83**, 4701 (1999).



Momentum transfer



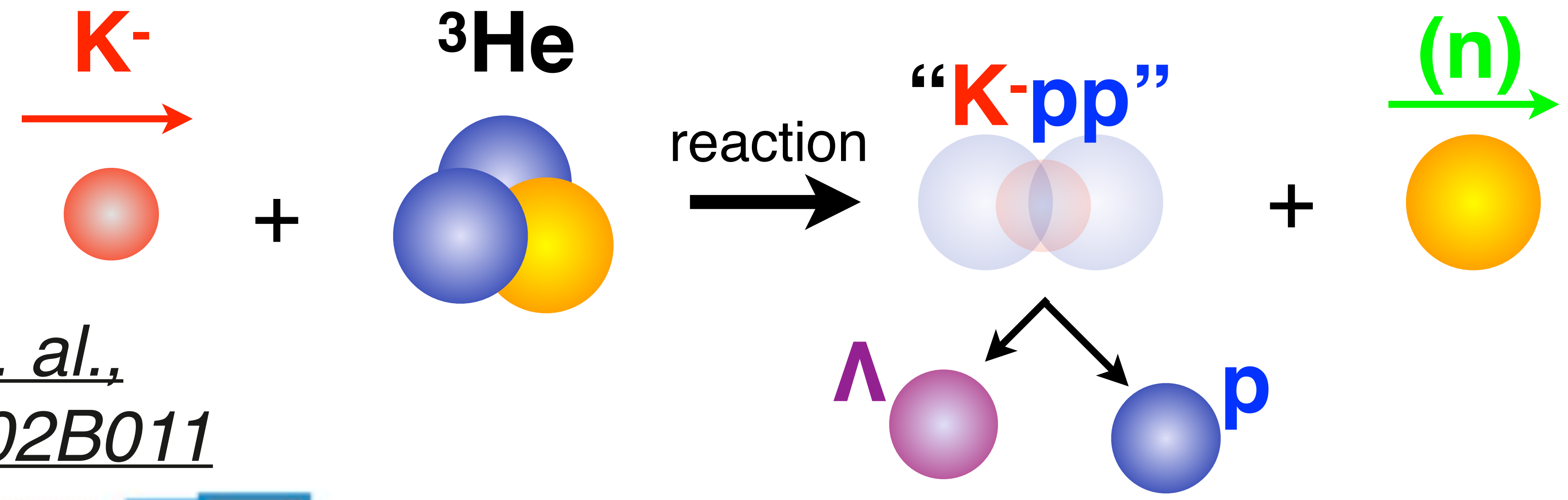
K-N elementaly cross-sections



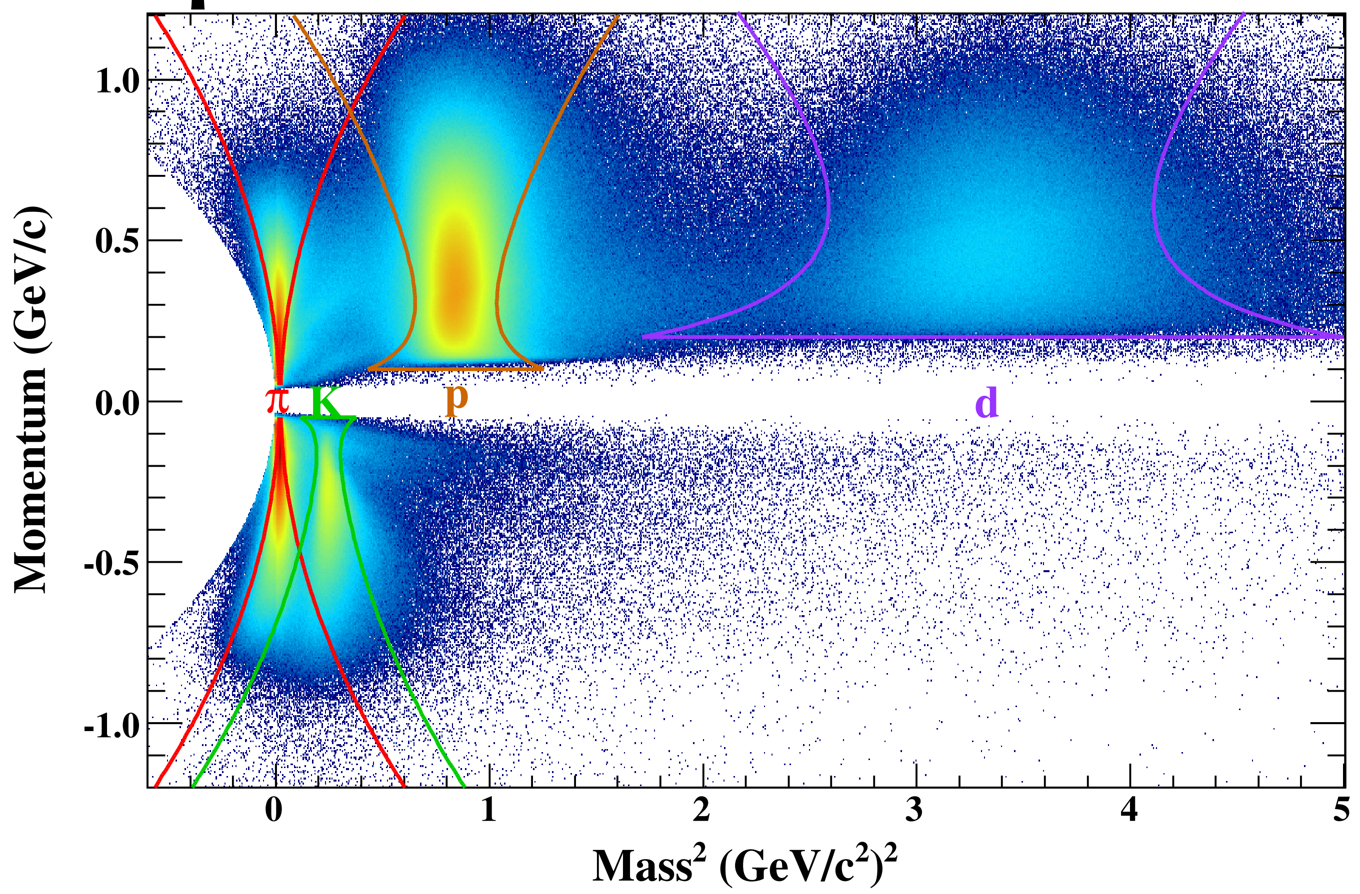
- ✓ Effectively produce sub-threshold virtual $\bar{K}$
- ✓ Most of the background processes can be kinematically separated.
- ✓ Simplest target allows an exclusive analysis
- ✓ Large-acceptance detector to cover a wide range of kinematical region

J-PARC K1.8BR
beam dump
γ, n
p
beam sweeping magnet
15m
Liq. H2/D2/3/4He target system
neutron counter
charge veto counter
proton counter
CDS
K- beam
beam line spectrometer

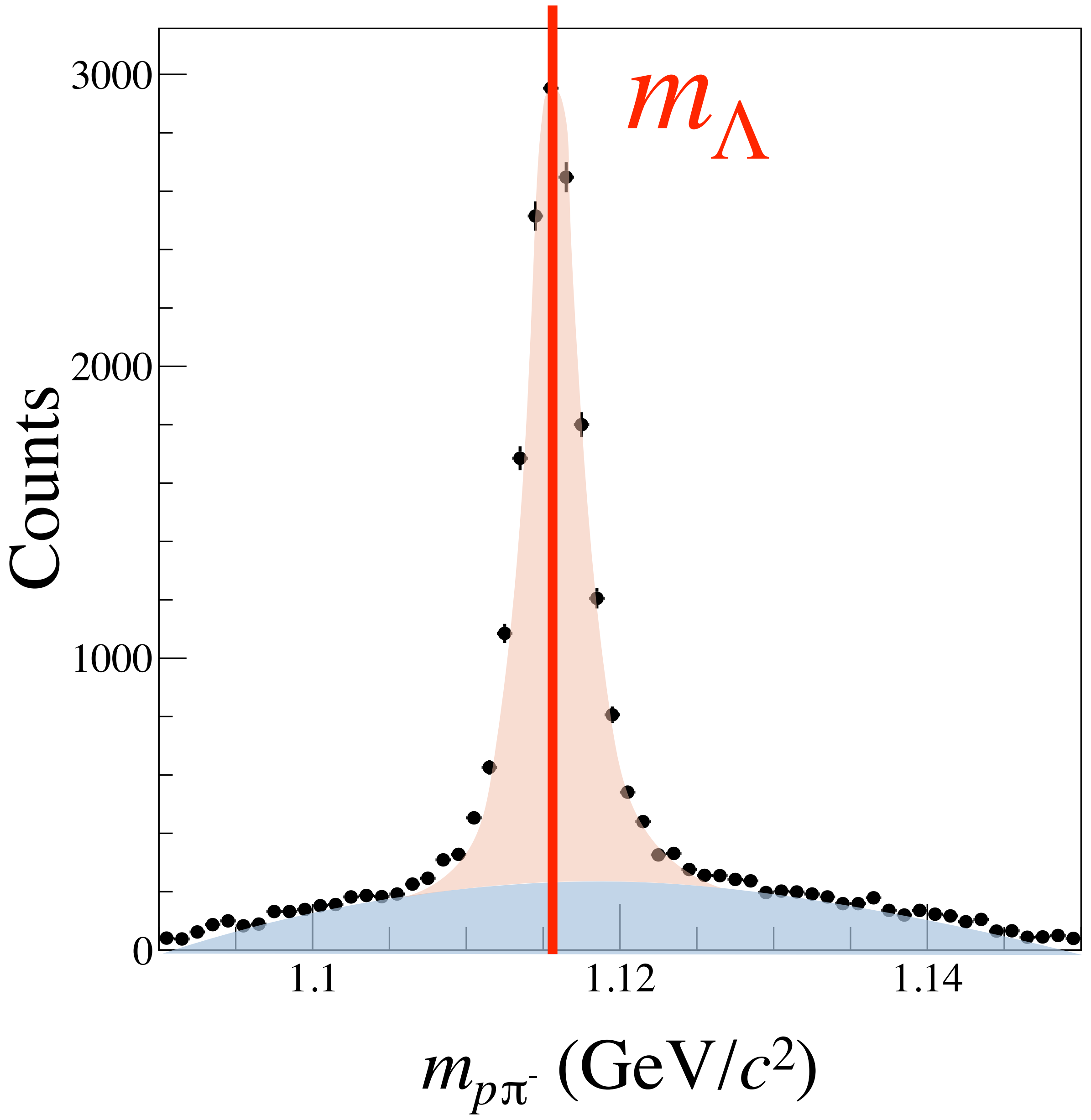
Λpn Exclusive measurement



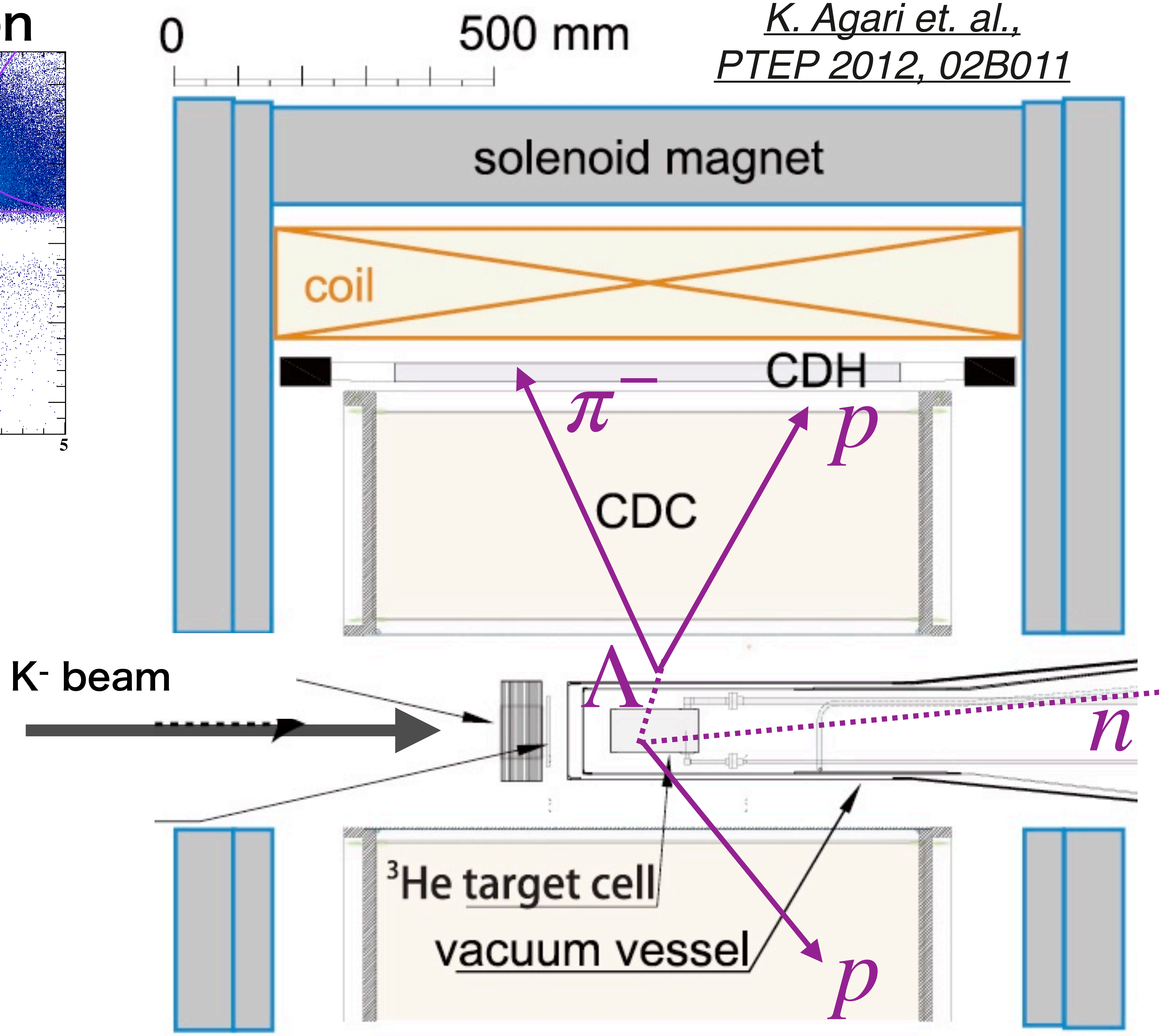
particle identification



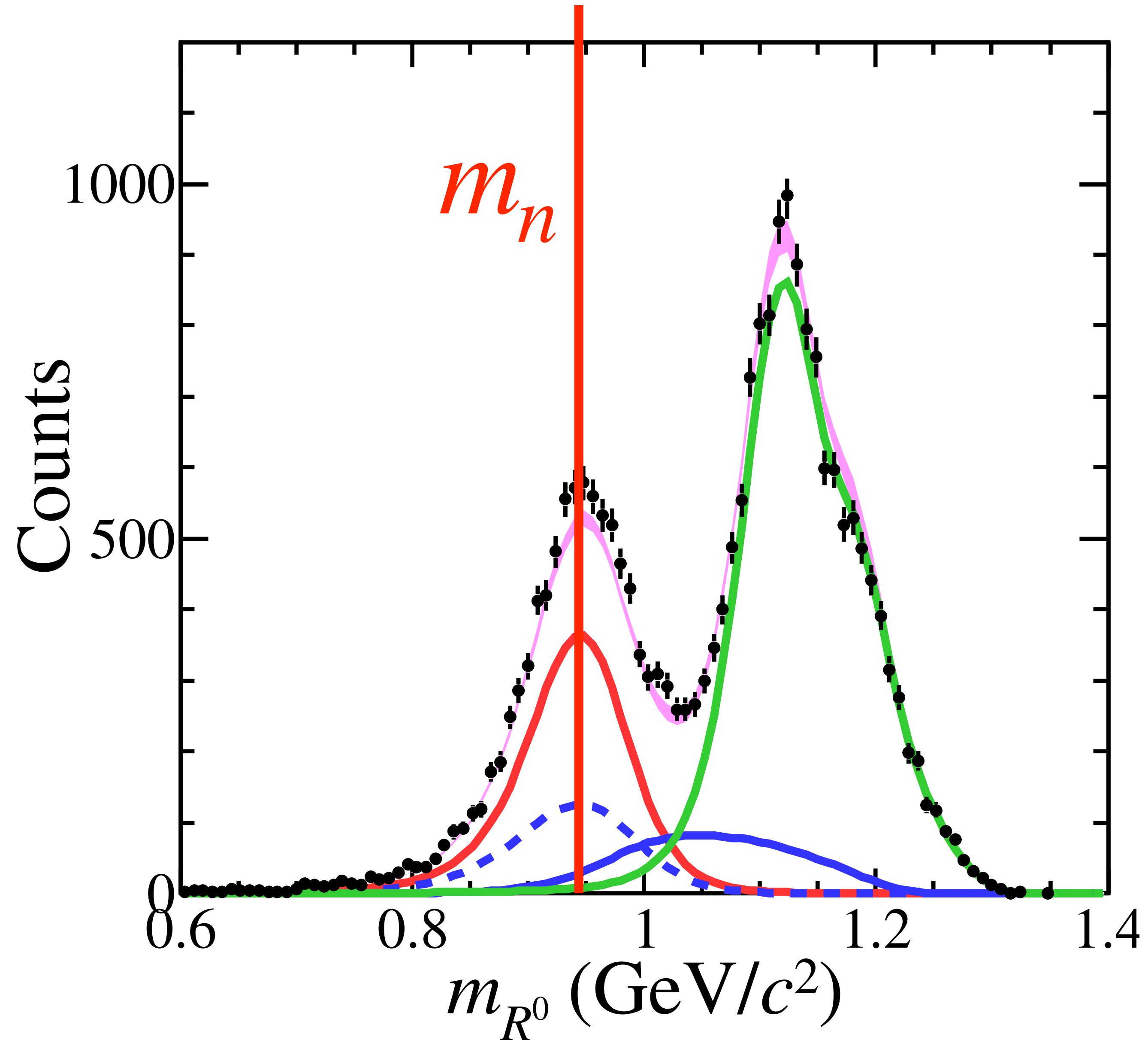
Λ reconstruction



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



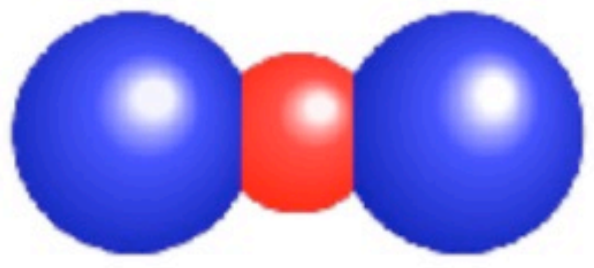
missing neutron selection



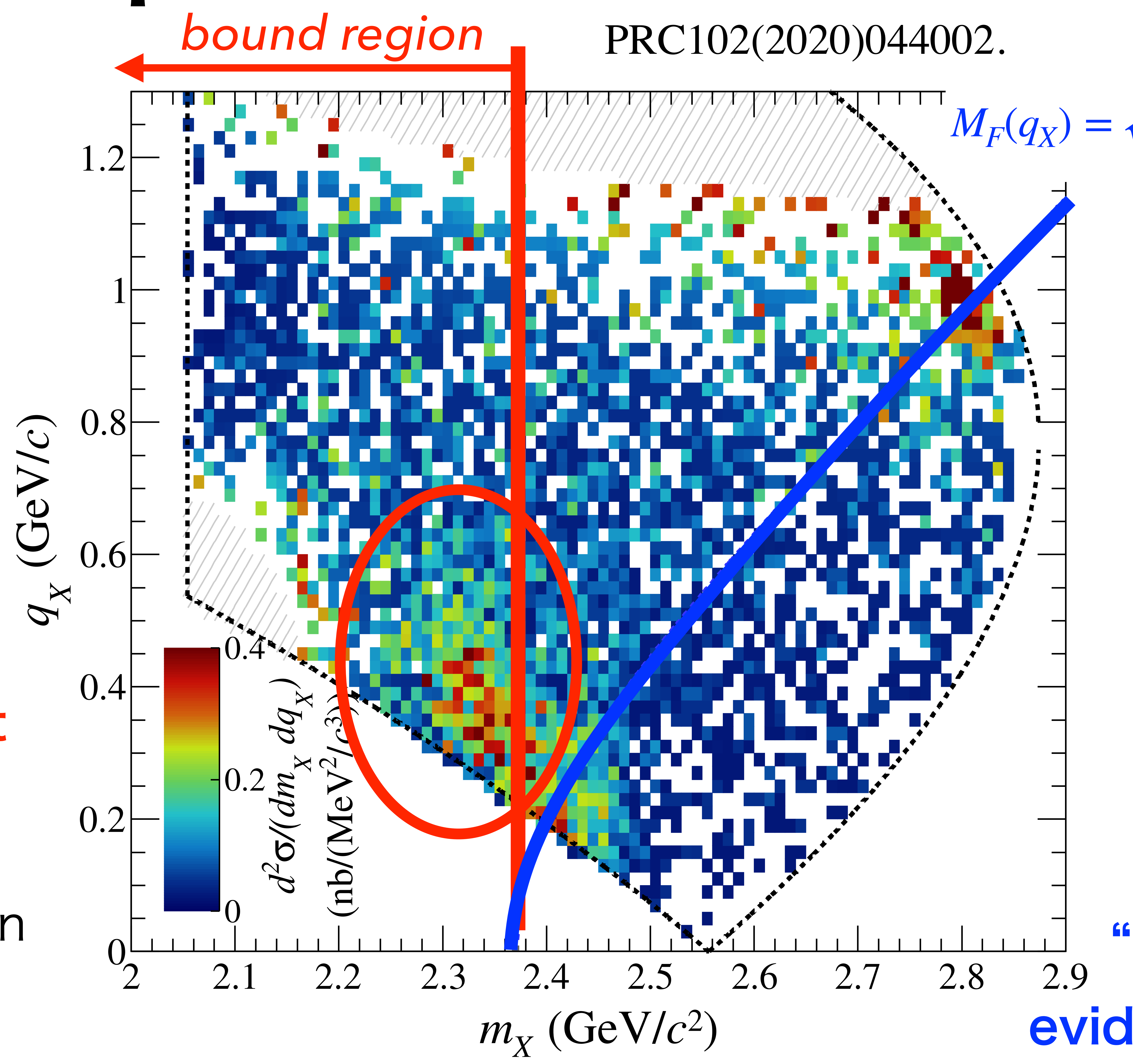
Purity of Λpn events ~ 80%

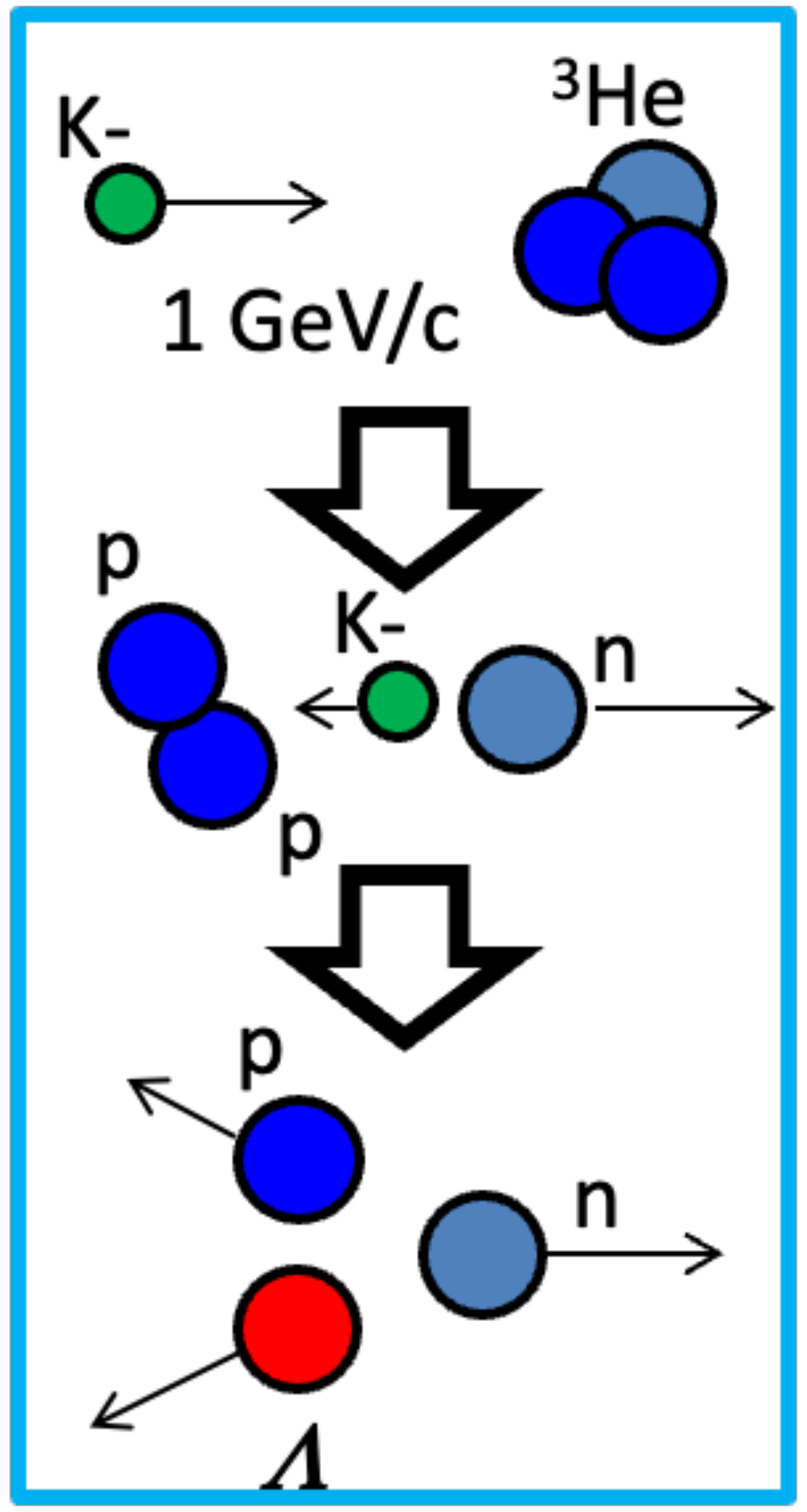
Obtained spectrum in J-PARC E15

m_x: Λp invariant mass
q_x: momentum transfer
to Λp system



qx-indep. component below the threshold
relatively deep, wide,
extend to high-q region





"quasi-free" process
evidence of intermediate $\bar{K}$

E15 results

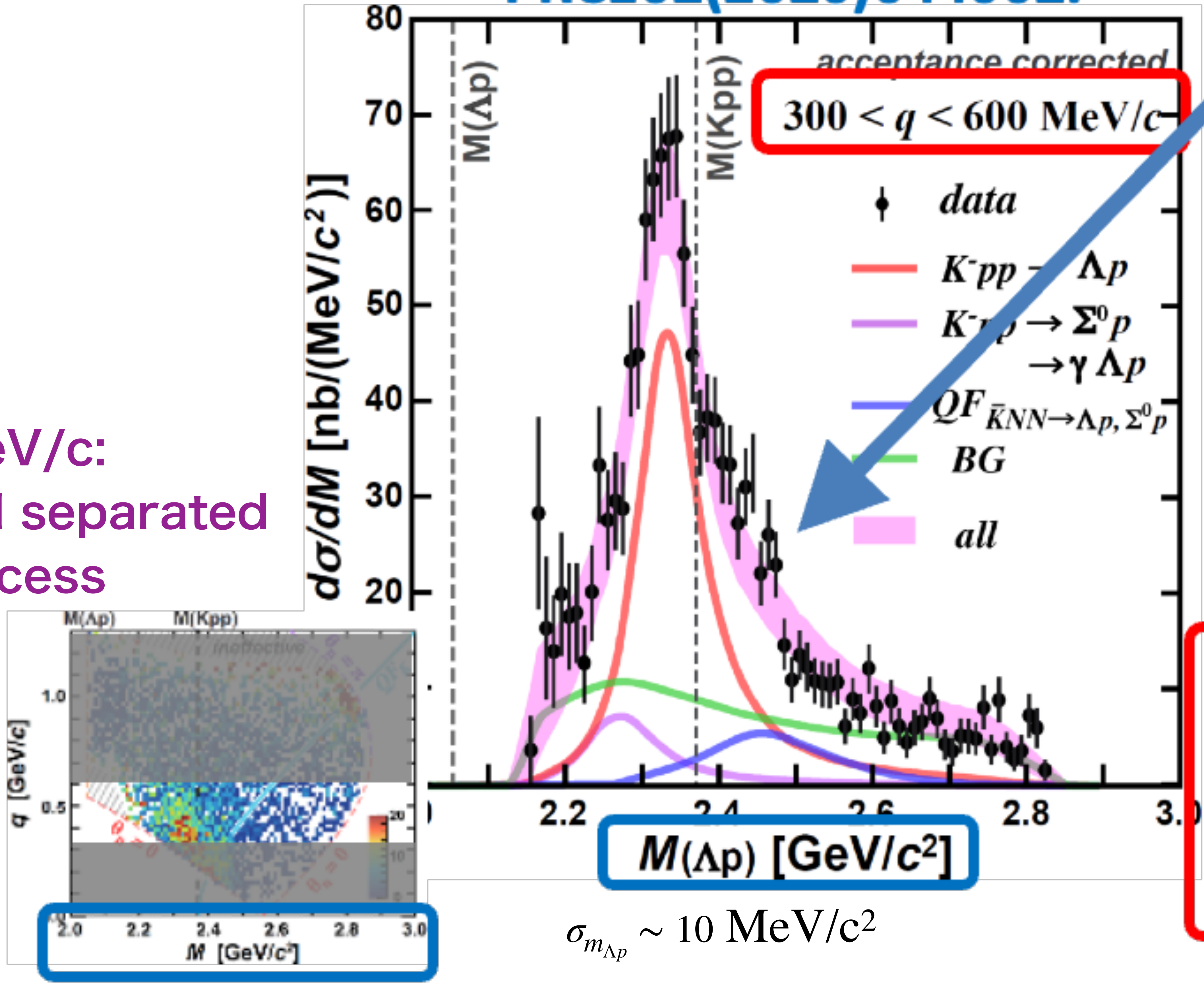
Fit with PWIA

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

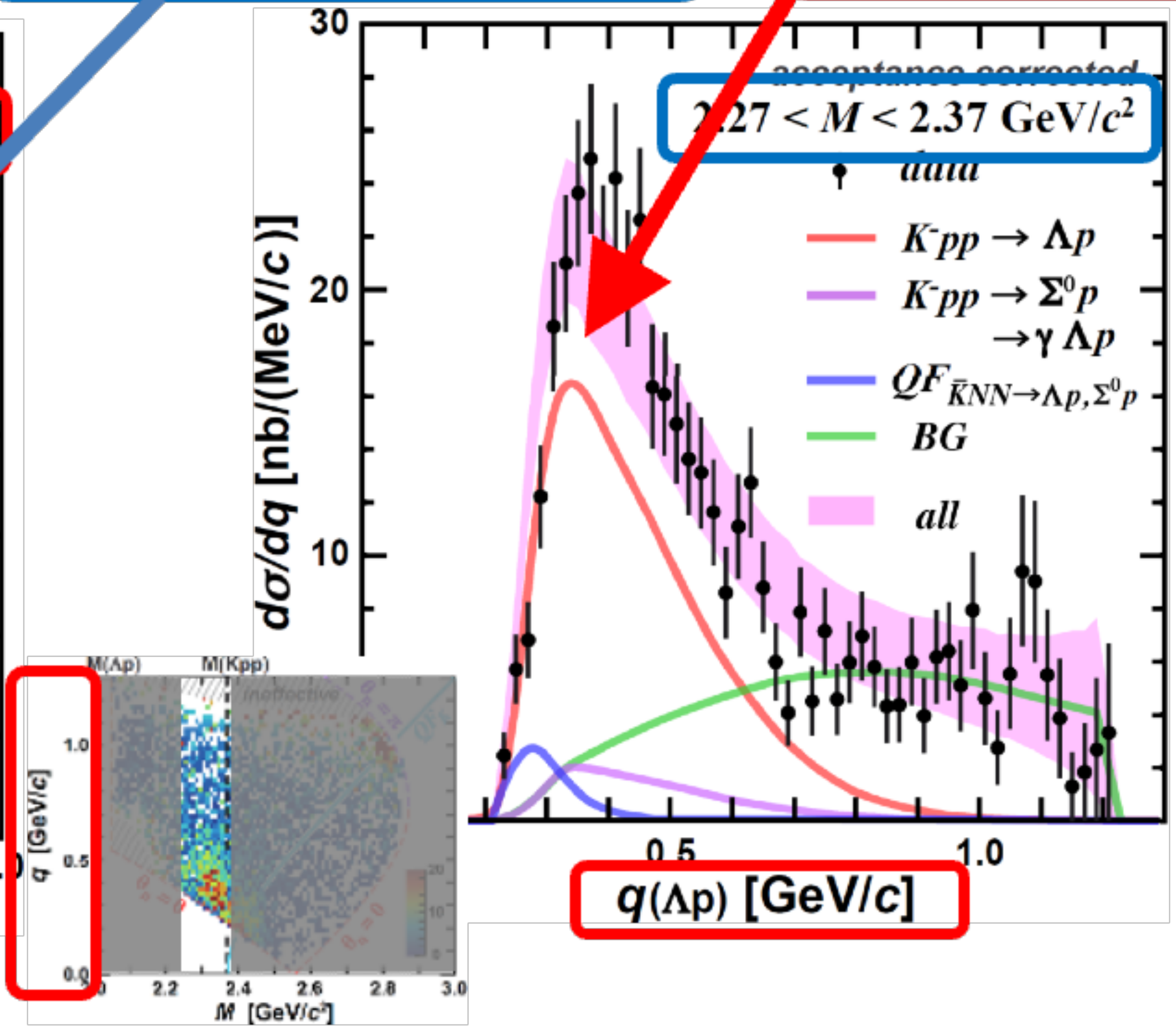
phase space — Breit Wigner — form factor

PRC102(2020)044002.

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



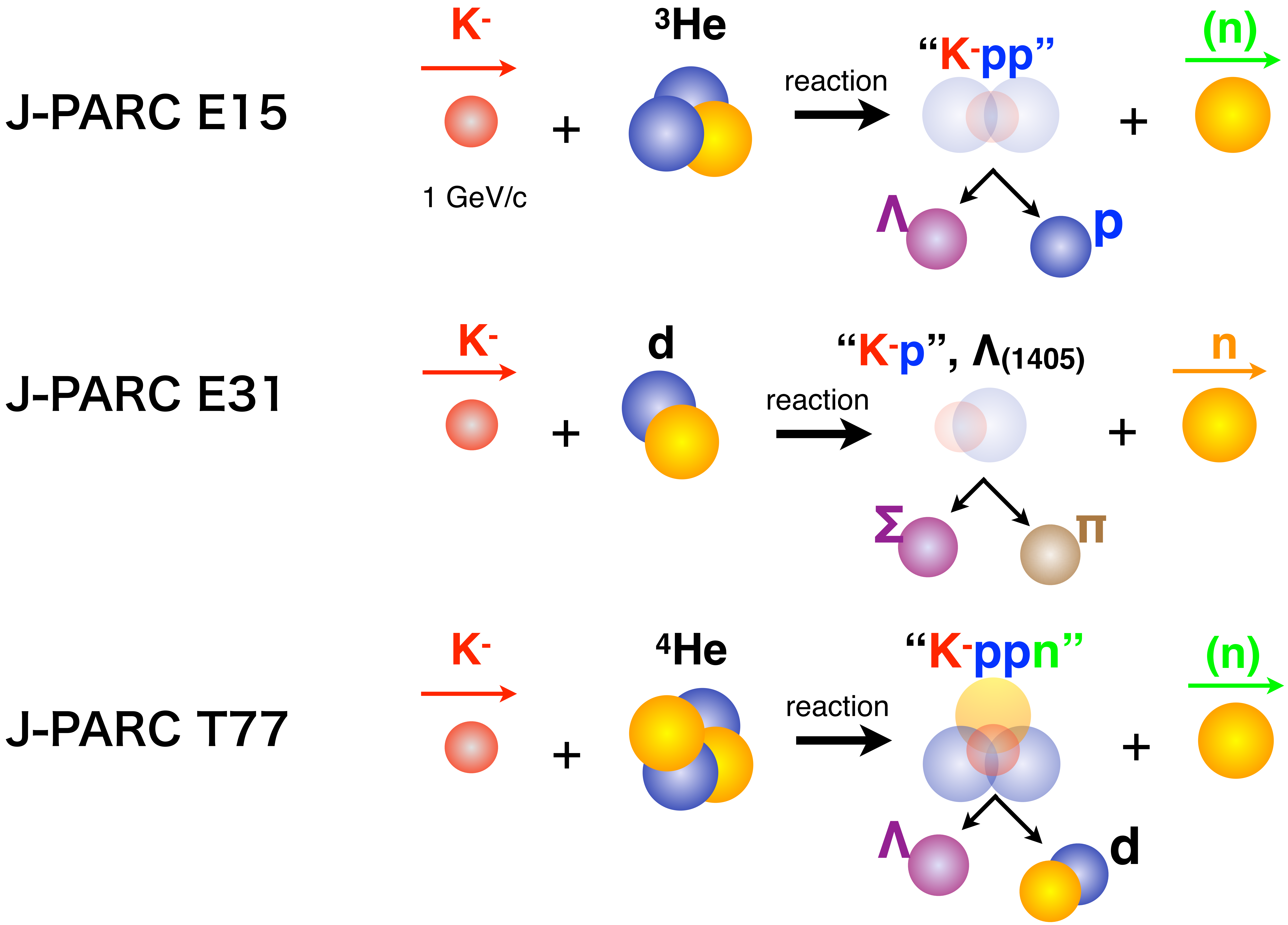
$\sigma_{m_{\Lambda p}} \sim 10$ MeV/c²



B_{Kpp} ~ 40 MeV, Γ_{Kpp} ~ 100 MeV
→ *large binding energy*

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

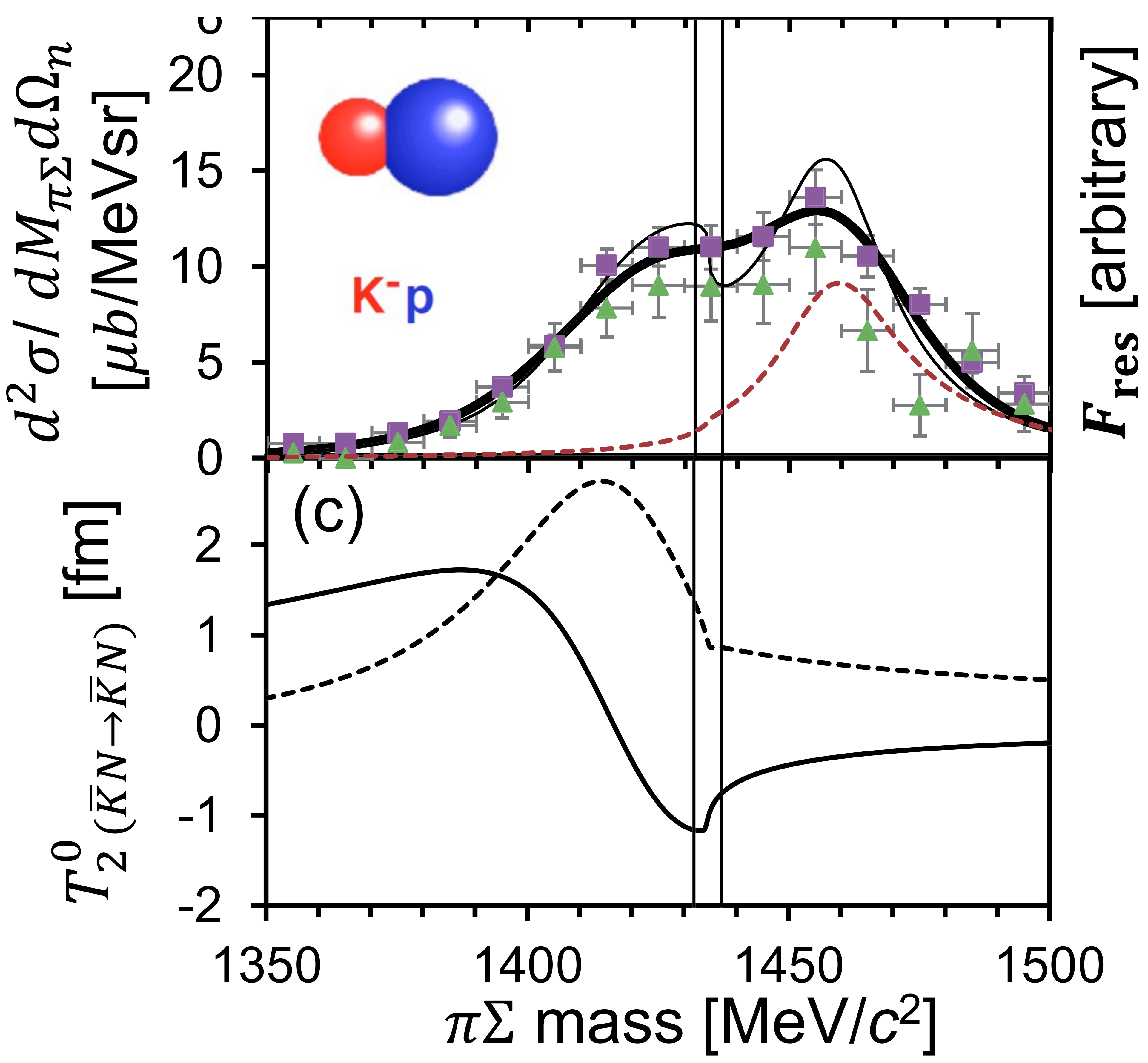
(K-, n) reaction on other targets



(K⁻, n) reaction on other targets

d₂ target

PLB837,137637(2023)



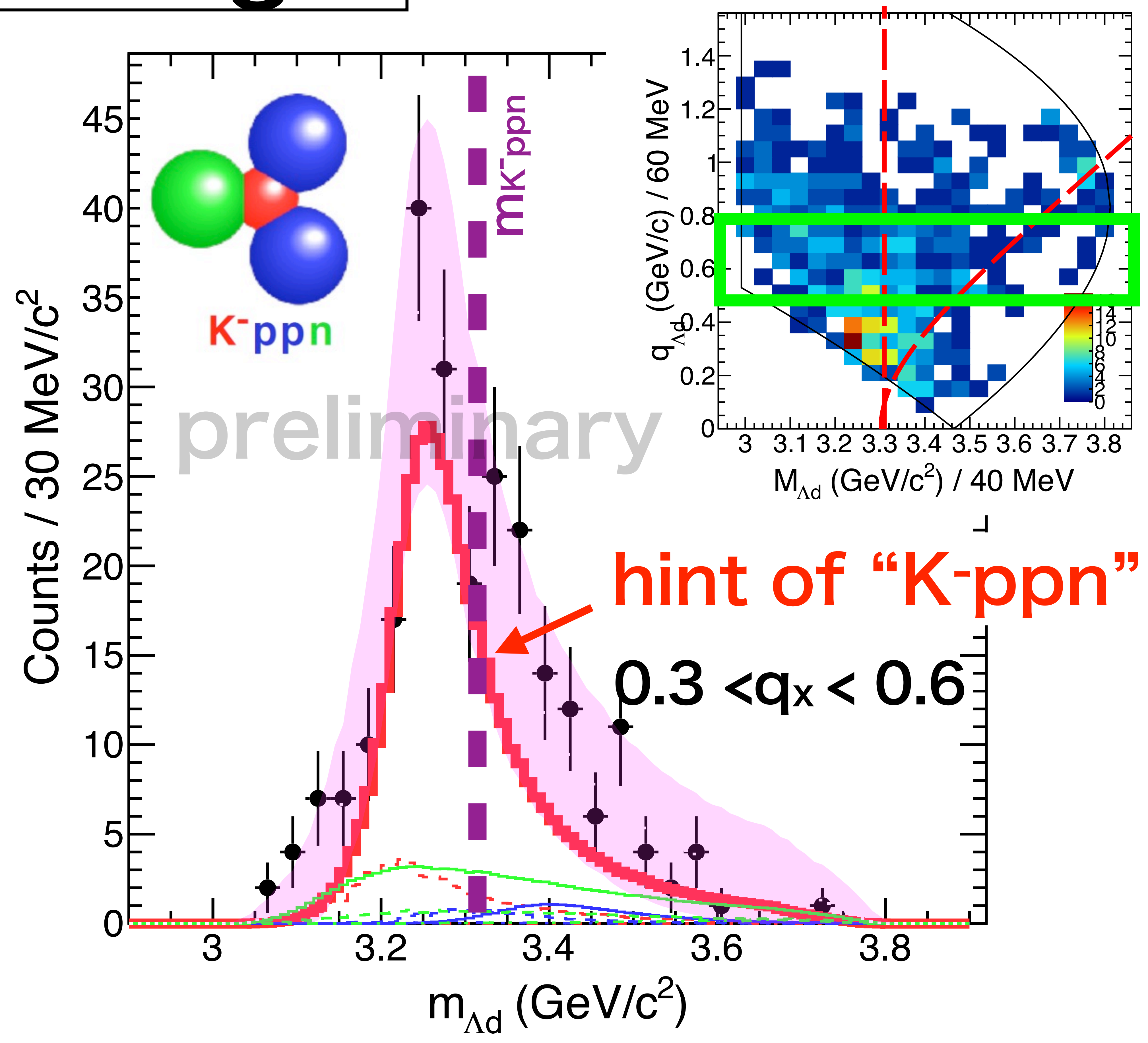
With two-step reaction processes

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

pole: 1417.7 – 26.1i [MeV]

^{4}He target

only ~3 days data-taking



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

Short summary: Achievement so far

- **TES microcalorimeter has been successfully applied to kaonic-atom X rays**
  - Constraint on the $\bar{K}$-nucleus potential parameters
  - Highly sensitive detectors can be operated in a charged-particle-rich environment
    $\rightarrow$ Extended application to muonic atoms **Plenary talk on 17 (Thu) by T. Azuma**
- **We have established the production method of kaonic nuclei**
  - kaonic nuclei seem to exist more or less universally **"K-pp", "K-ppn"**, $\cdots$
  - (K-, n) reaction is effective in exciting sub-threshold $\bar{K}$ amplitude
  - Exclusive analysis is necessary to identify the broad structure.

What is next?

- **Confirmation of "K^-ppn"** $\rightarrow \Lambda + d,\ \Lambda + p + n$

- **Further investigation of the $\bar{K}NN$ system**

Large-acceptance
neutron counter

  - Search for the isospin partner "$\bar{K}^0nn$" via $\bar{K}^0nn \rightarrow \Lambda + n$ decay
  - Determine the spin-parity of "K^-pp"

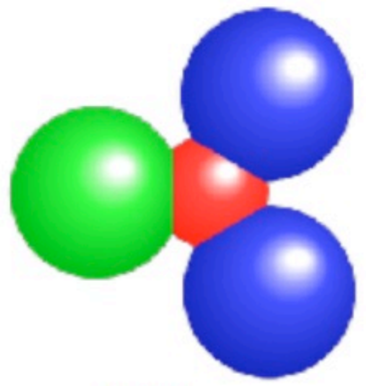
    →spin-spin correlation measurement of Λ & p with **polarimeters**

- **The spatial size of kaonic nuclei is of great interest**
  - Decay branches to 1N$_{KA}$, 2N$_{KA}$, 3N$_{KA}$ ⋯
  - Fermi momentum of the spectator nucleon in the decay

neutron counter
forward TOF

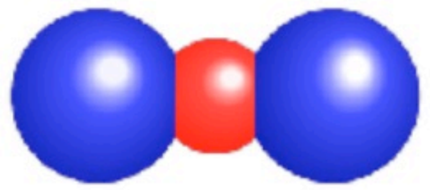
- **Heavier systems, $\bar{K}\bar{K}$ nuclei, ⋯**

Size of kaonic nuclei via data



K^-ppn

forward TOF



K^-pp

$K^- + {}^4He \rightarrow$ "K^-ppn" $+ n_{forward}$

$K^- + {}^3He \rightarrow$ "K^-pp" $+ n_{forward}$

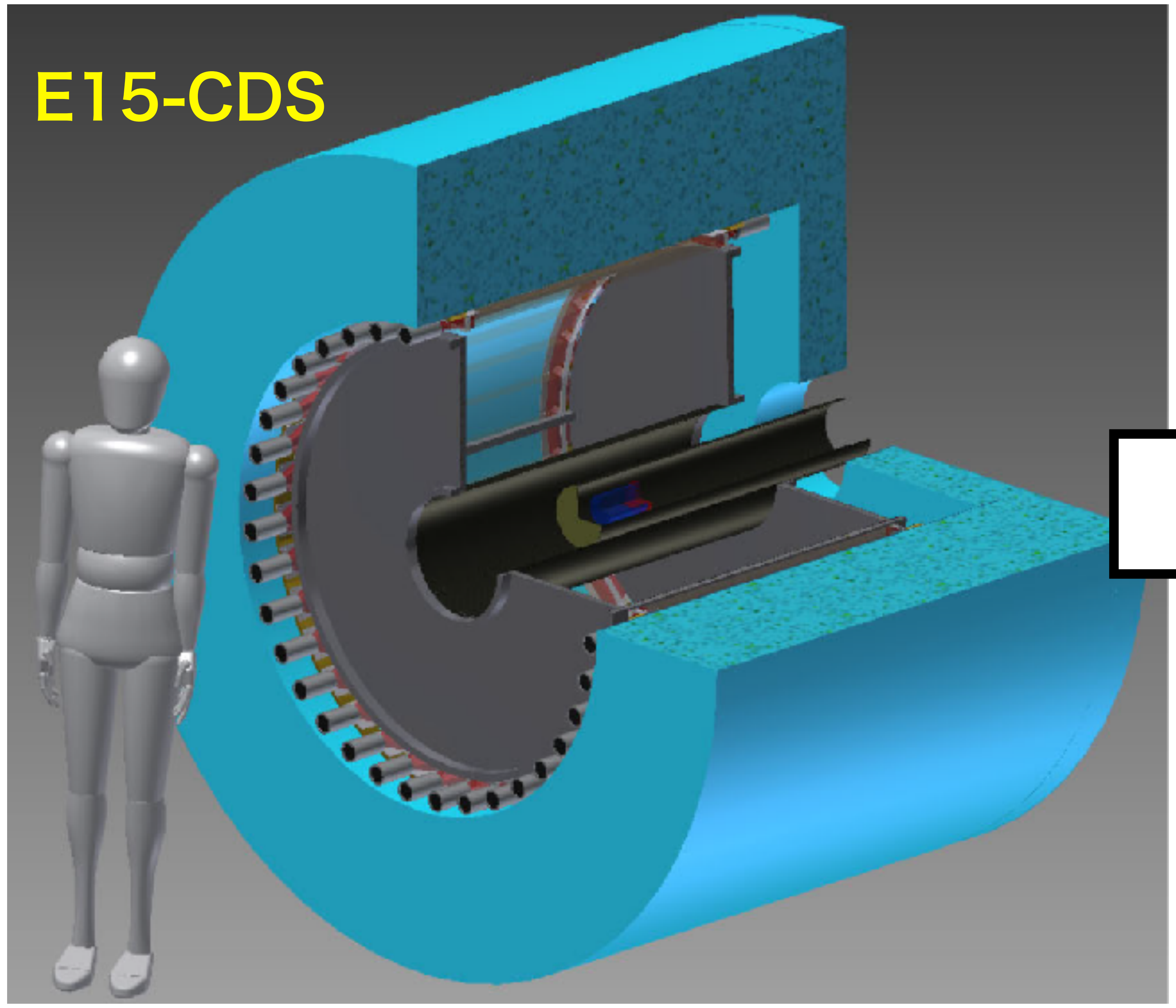
	$K^- + {}^4He$	$K^- + {}^3He$
One nucleon $\bar{K}$ absorption ($1N_{\bar{K}A}$)	$([K^-n]p_sp_s) \rightarrow (\pi^- + \Lambda) + p_sp_s$	$([K^-p]p_s) \rightarrow (\pi + \Sigma) + p_s$ P-269 by T. Yamaga
Two nucleon $\bar{K}$ absorption ($2N_{\bar{K}A}$)	$([K^-pp]n_s) \rightarrow (\Lambda + p) + n_s$ $([K^-pn]p_s) \rightarrow (\Lambda + n) + p_s$	$(K^-pp) \rightarrow \Lambda + p$
Three nucleon $\bar{K}$ absorption ($3N_{\bar{K}A}$)	$(K^-ppn) \rightarrow \Lambda + d$	

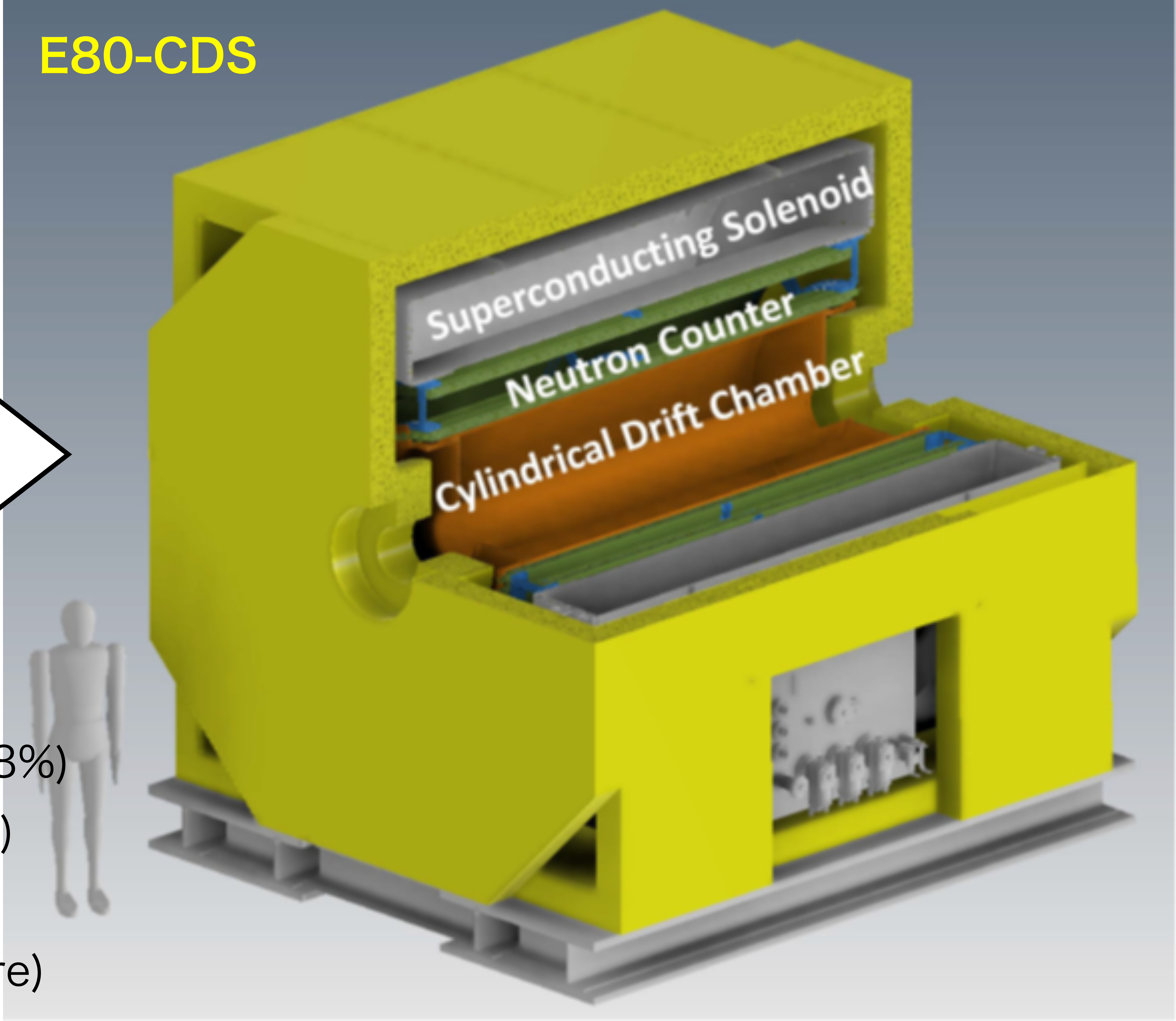
The ratio should be sensitive to the core size

$$1N_{\bar{K}A} : 2N_{\bar{K}A} : 3N_{\bar{K}A} \sim \rho_N : \rho_N^2 : \rho_N^3 \; ?$$

Fermi motion of the spectator nucleon

New CDS





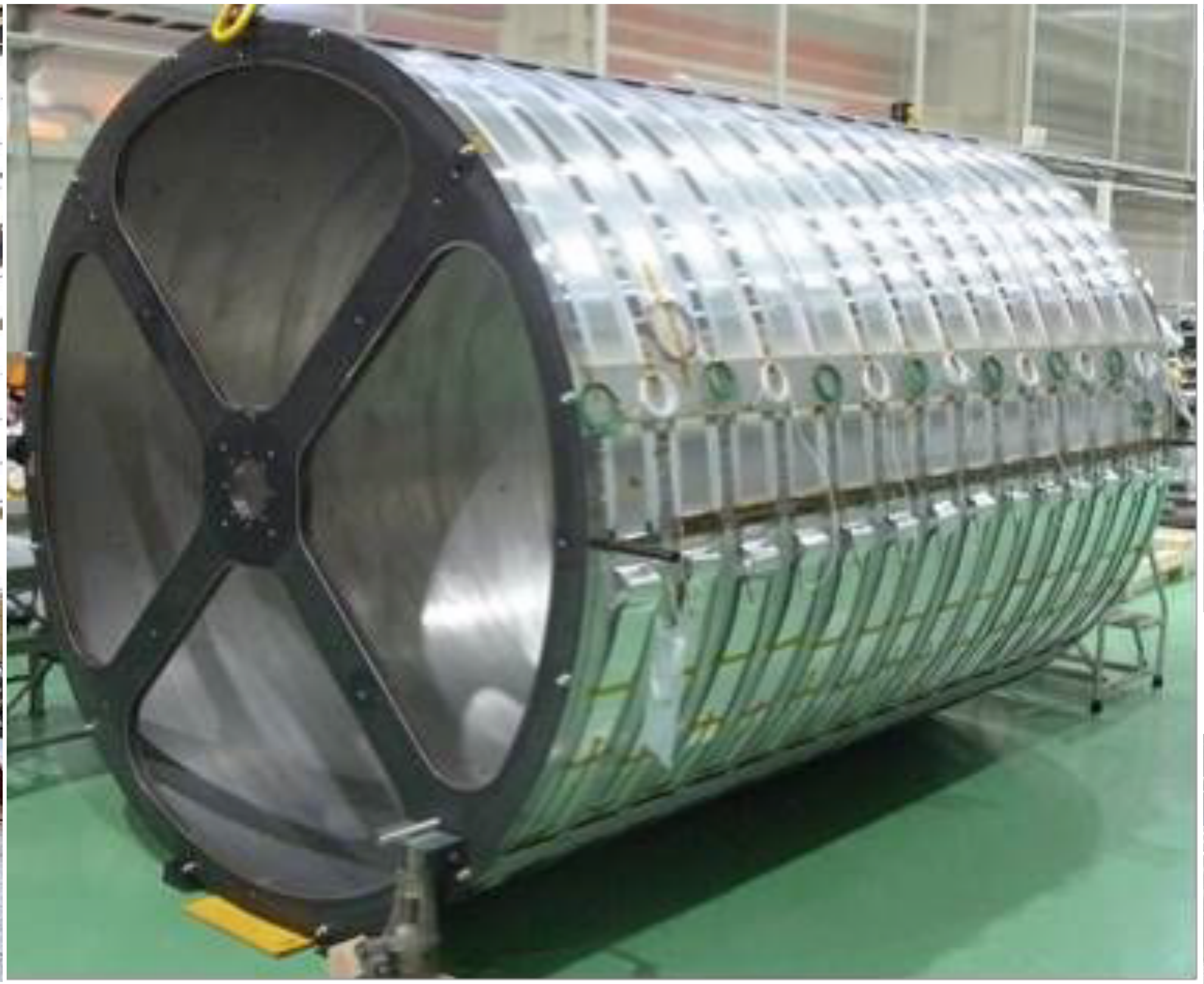
- ✓ **Solid angle: x1.6** (59%→93%)
- ✓ **Neutron eff. x4** (3%→12%)
- ✓ **forward TOF counters**
- ✓ (proton polarimeter in future)

Details in P-273 by Y. Kimura

Construction status

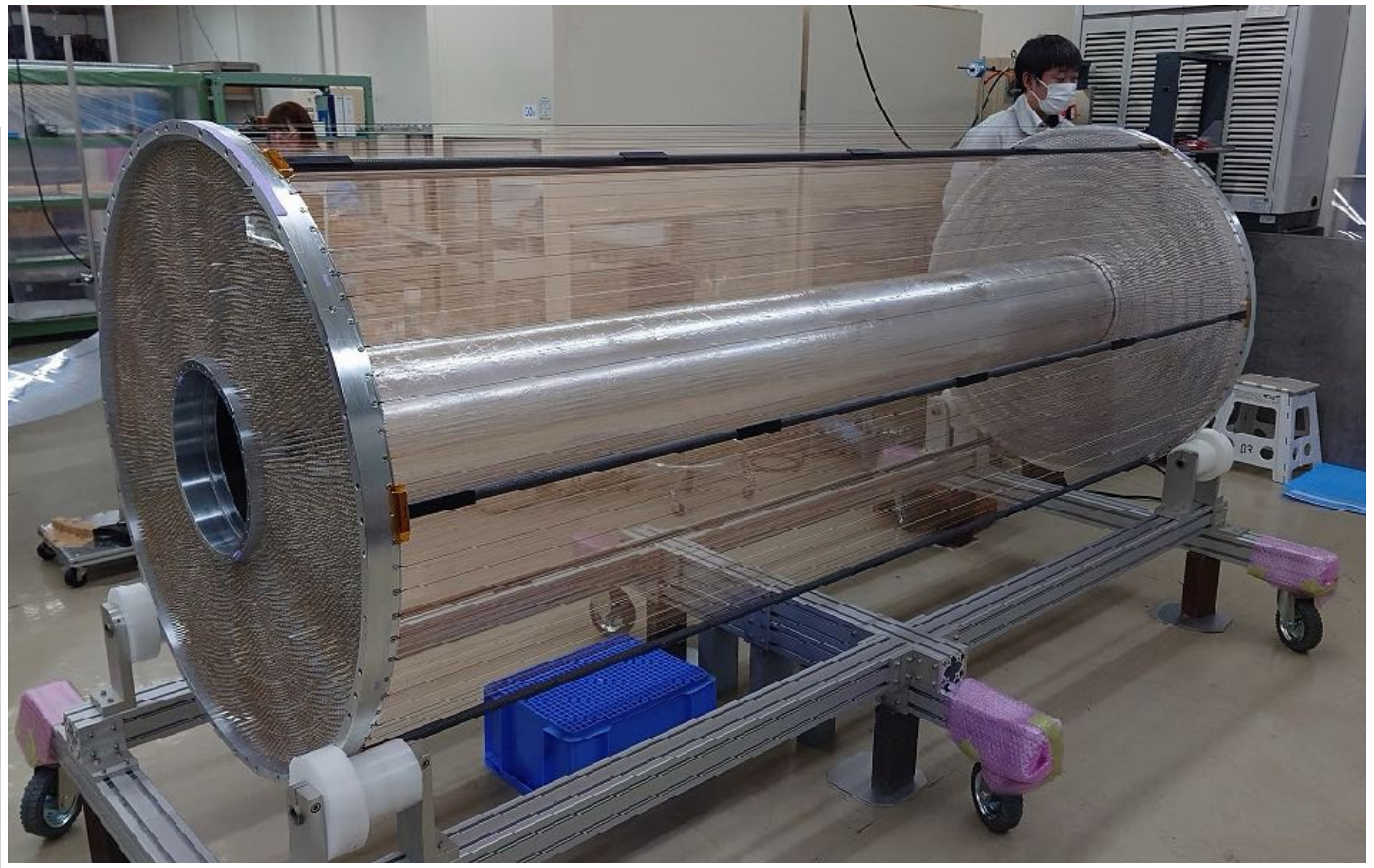
Solenoid york: completed

Superconducting coil

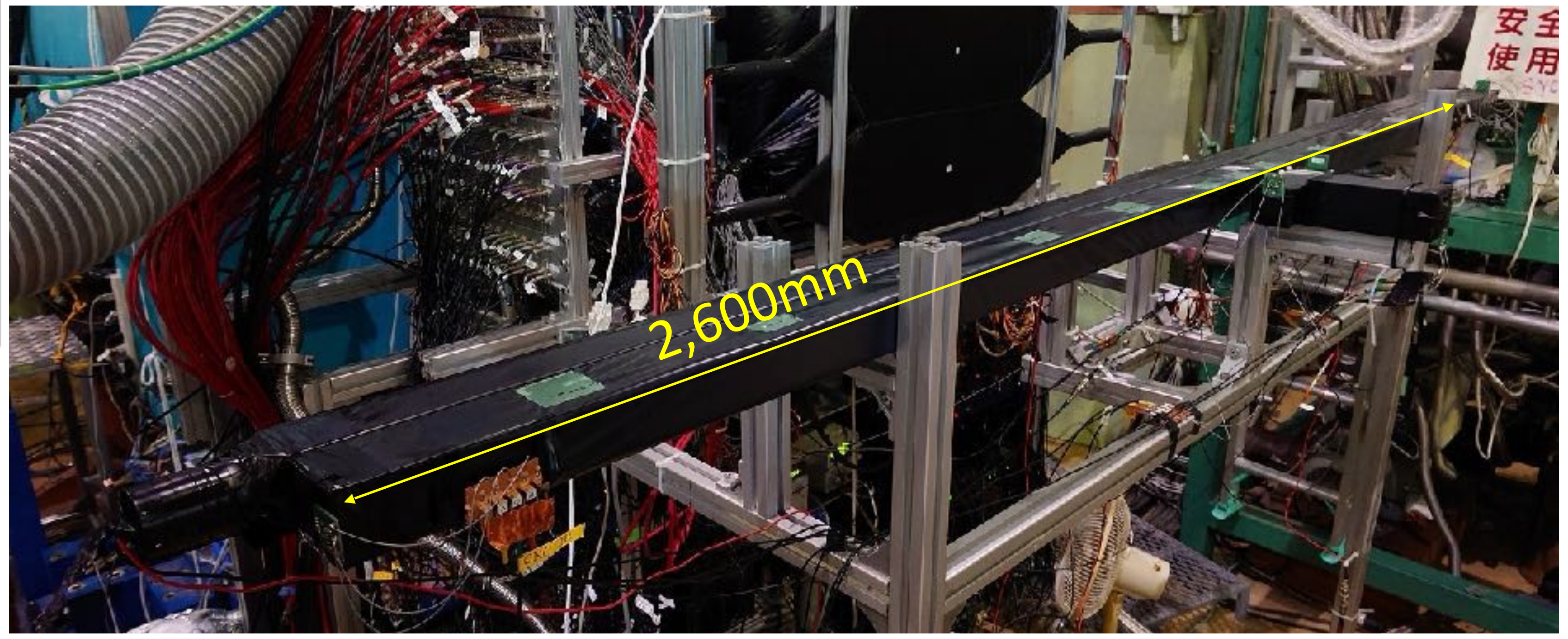


to be completed by the end of JFY2026

CDC: Commissioning started



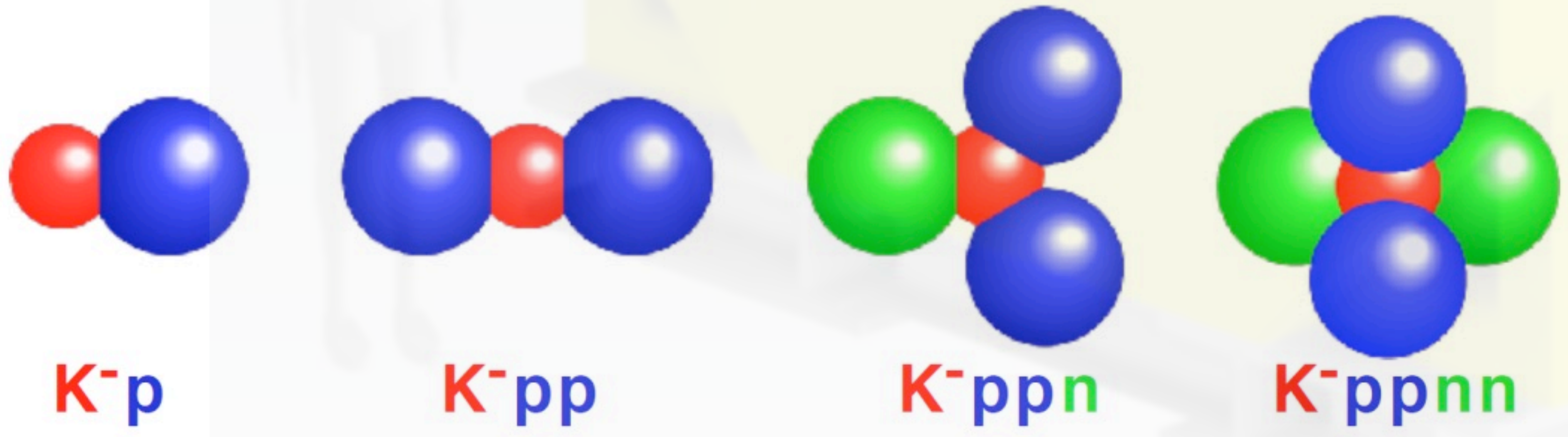
CNC: prototype test



We would like to start data-taking by the end of JFY2026

Summary

- Kaonic nuclei would open a new field of nuclear physics with anti-kaon as a new probe.
- Fruitful results in these 10 years.
  Observation of **“K^-pp”** and **“K^-ppn”**, **TES** application to kaonic atoms
- With a new solenoid spectrometer, we would like to further extend the systematic study of kaonic nuclear systems.



Collaborations

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. 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)

New collaborators are welcome!
Post-doc position is now open at RIKEN

Thank you for your attention !