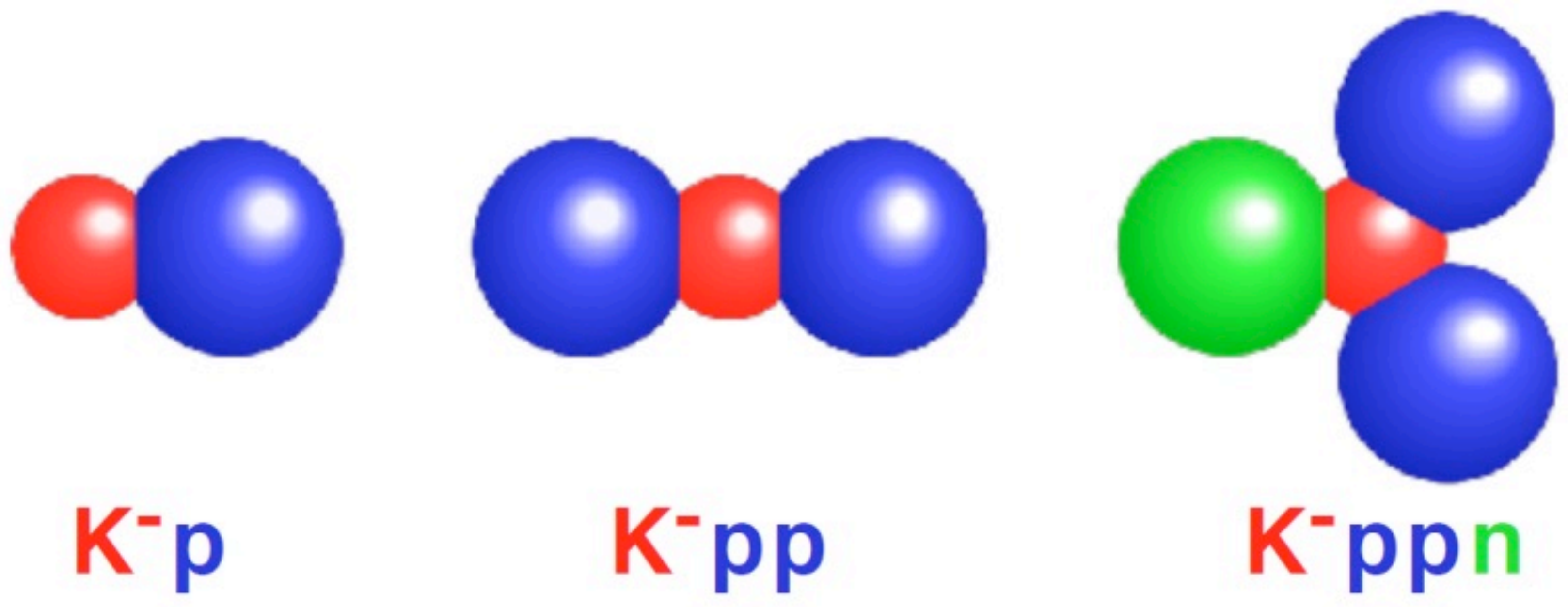
INPC 2025

May 25-30, 2025
DCC, Daejeon, Korea



Recent progress and prospects of kaonic nuclear bound states at J-PARC

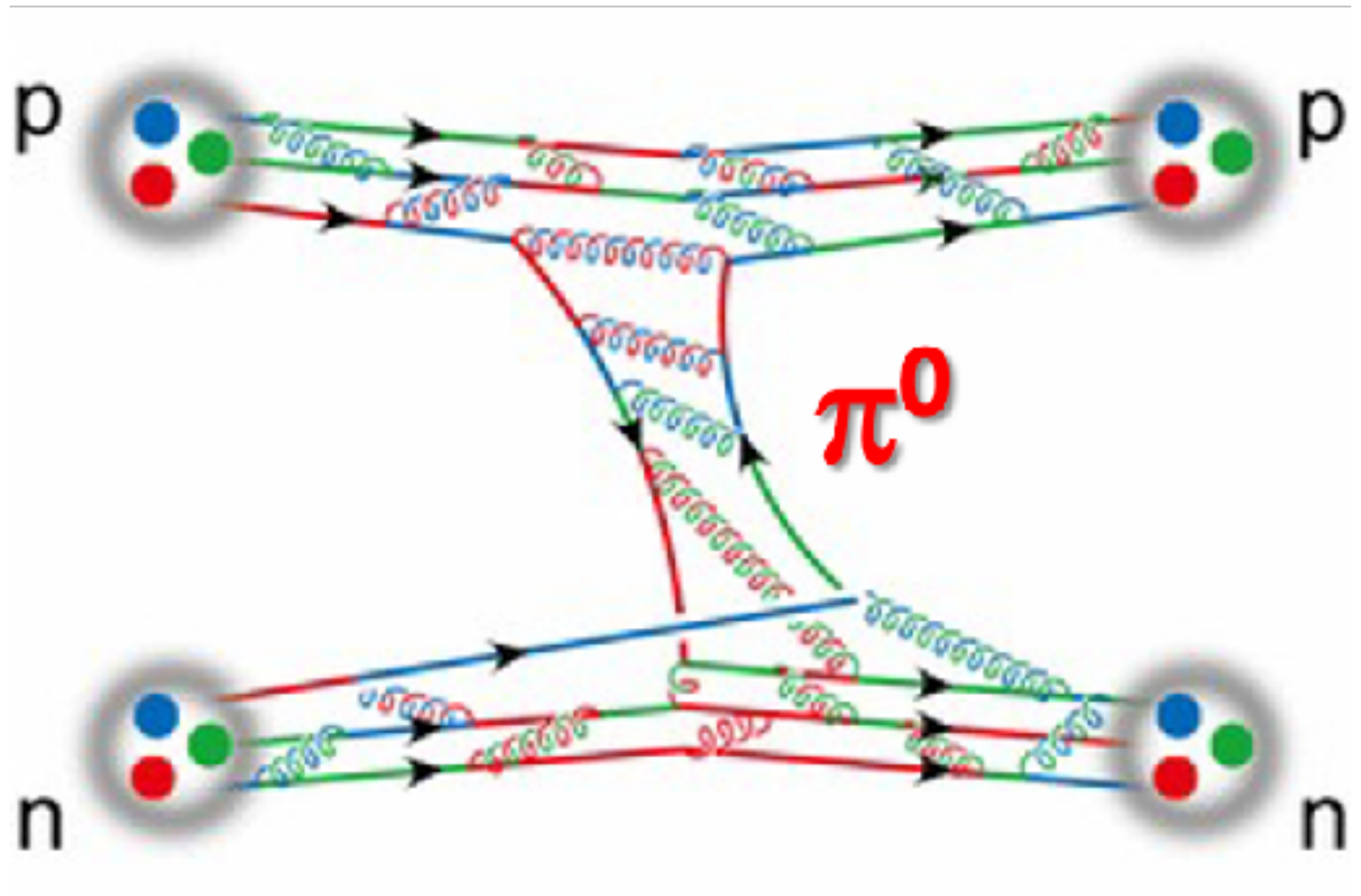
Tadashi Hashimoto (RIKEN)
for J-PARC E15/E31/E73/E80 collaboration

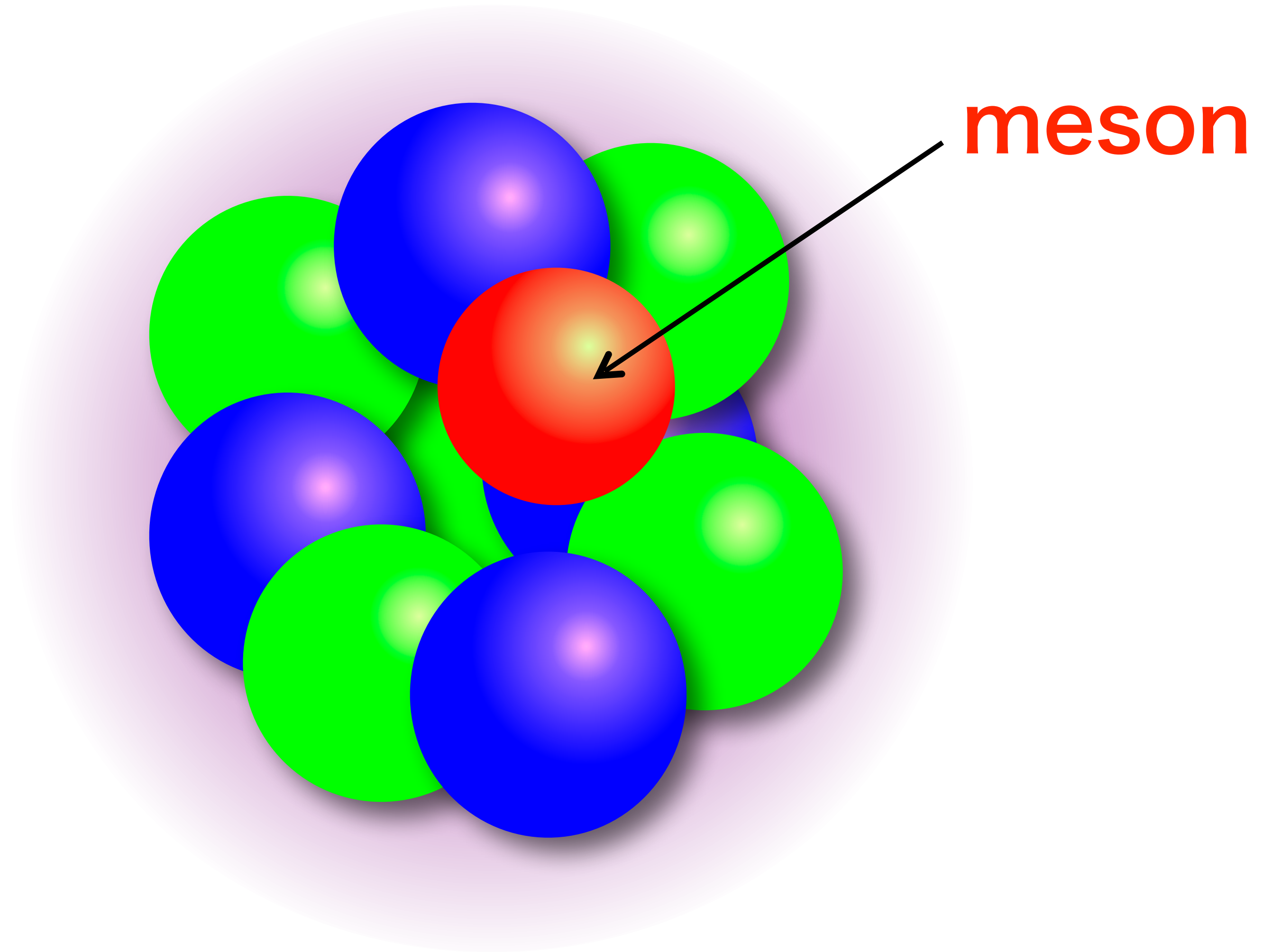
RIKEN PRI RIKEN NISHINA CENTER

Meson in nuclei

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

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



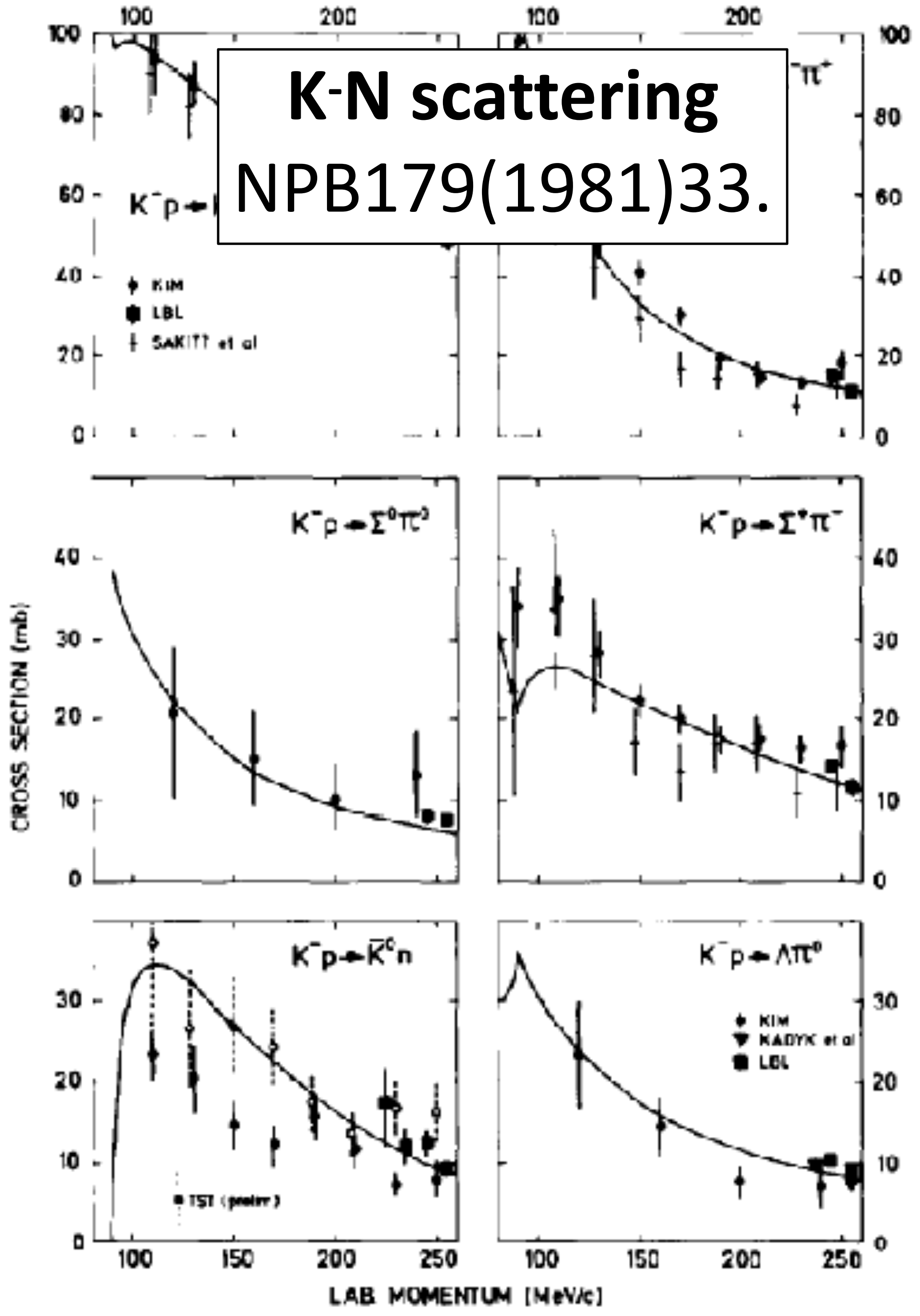


Can meson be a constituent particle forming nuclei?

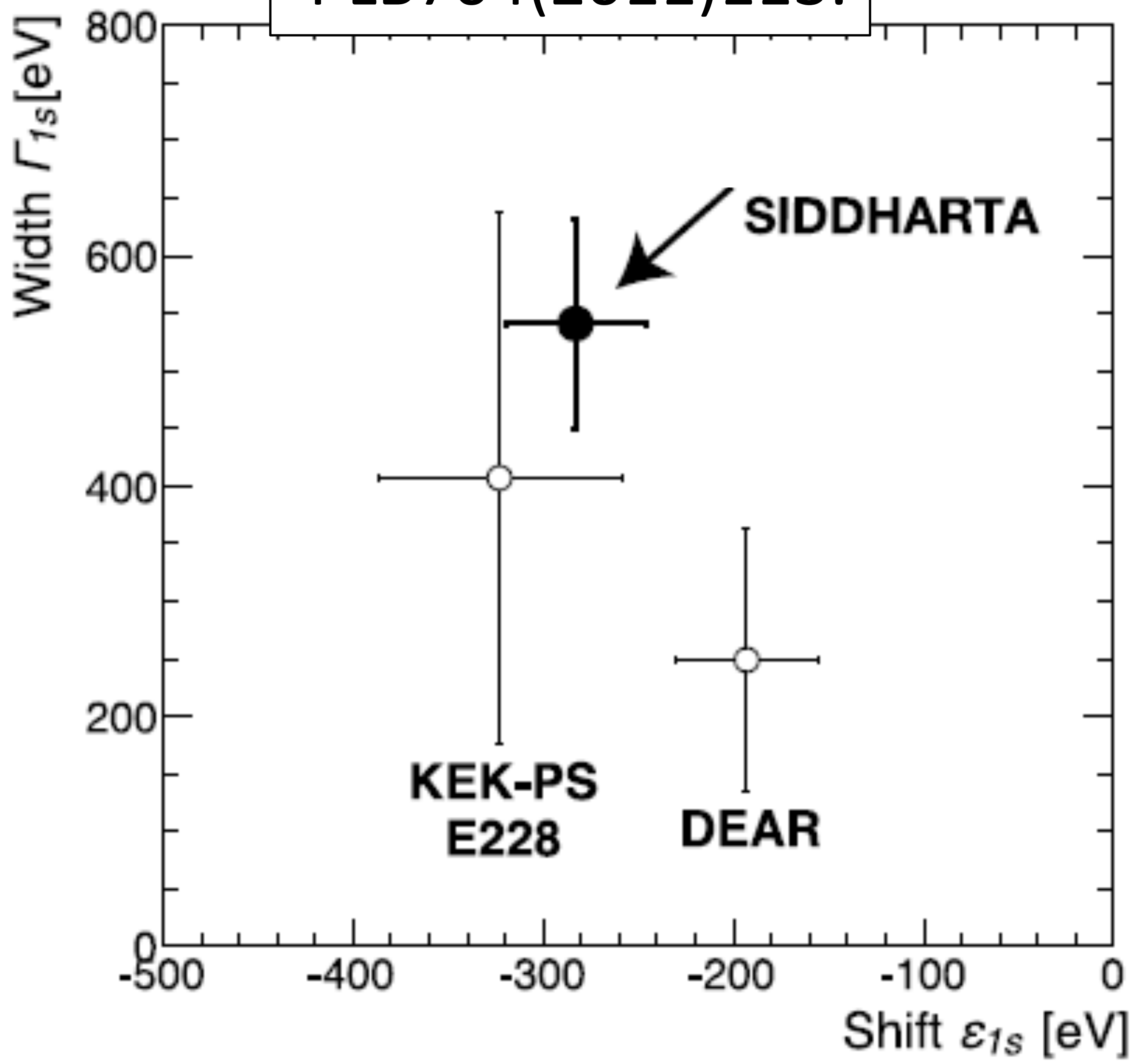
If yes, how do meson and core nucleus change?

K^{bar}N interaction

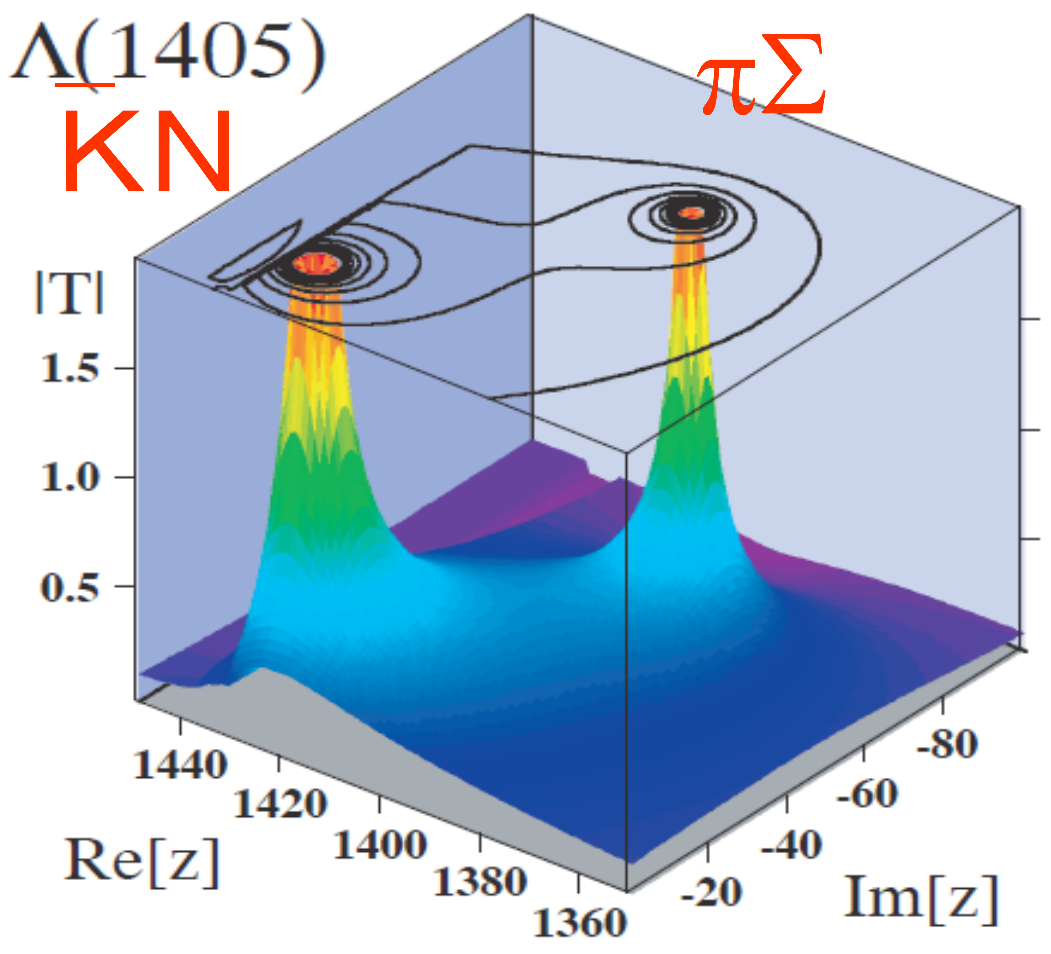
K-N scattering
NPB179(1981)33.



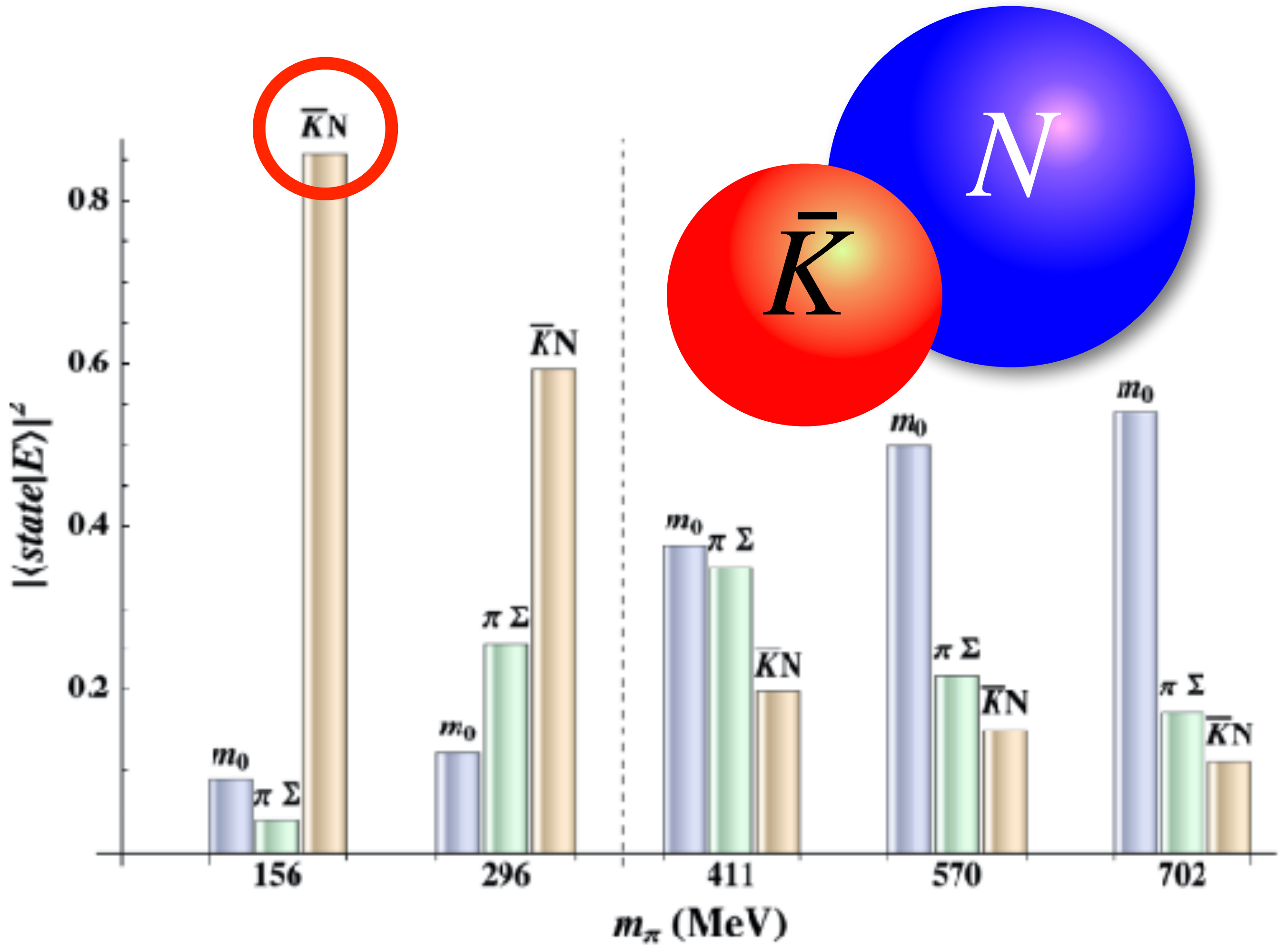
K-p atom
PLB704(2011)113.



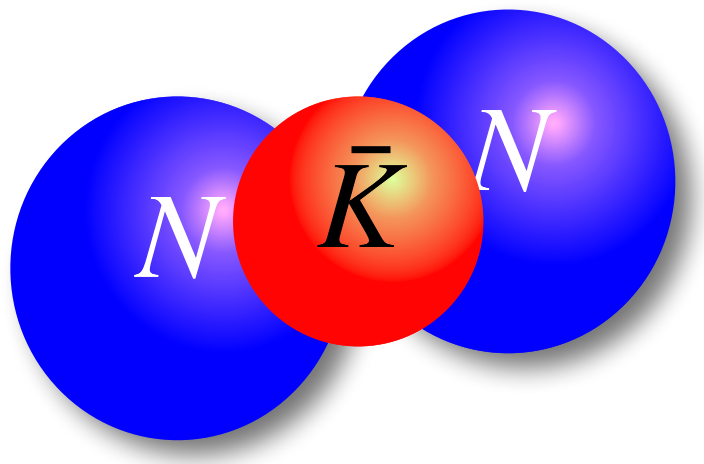
Λ(1405) in
chiral unitary model
T. Hyodo



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

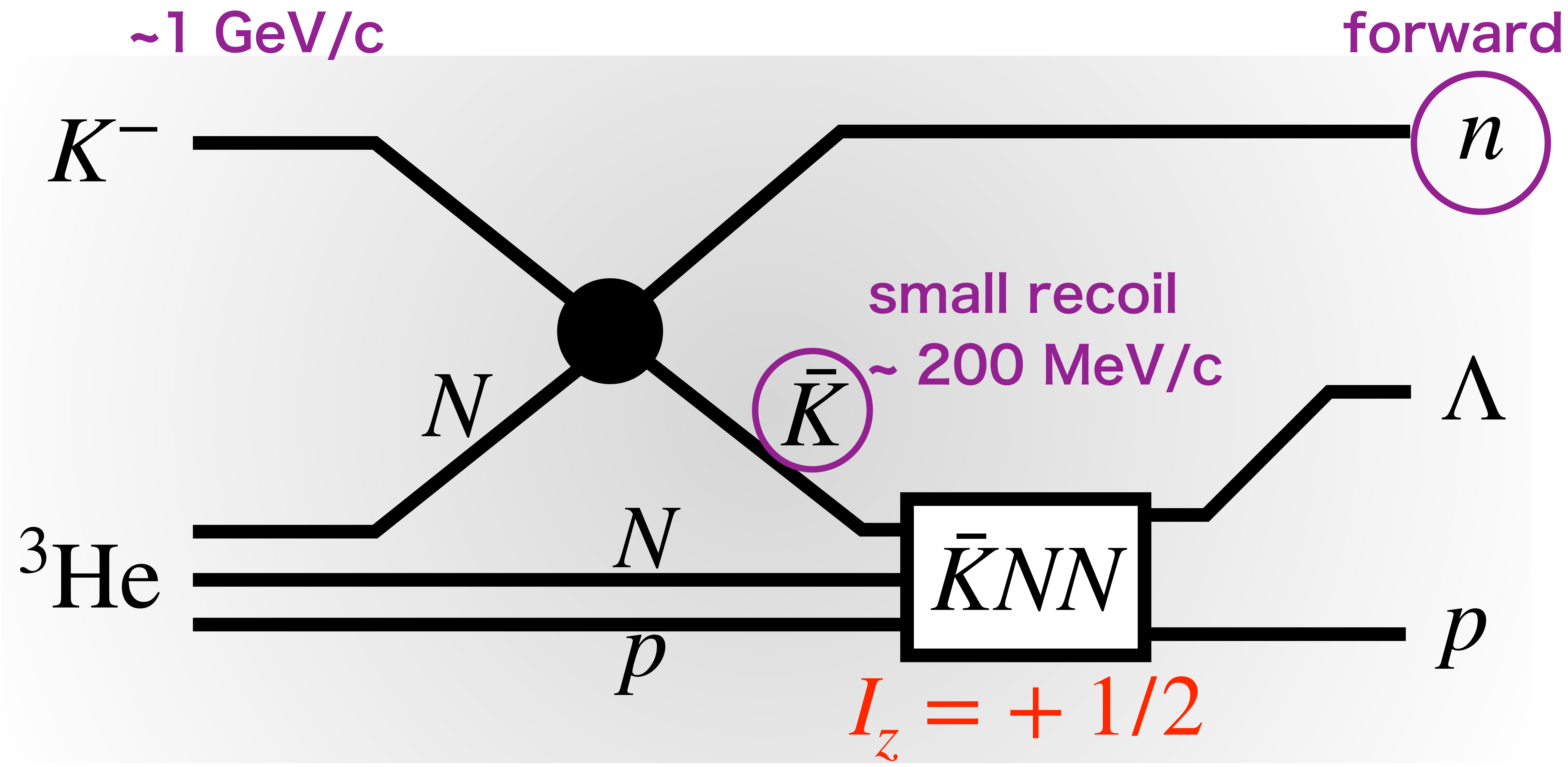


Why not kaonic nucleus with additional nucleons?

no conclusive evidence so far despite the worldwide efforts for decades…

How to embed $\bar{K}$: in-flight (K-, n)

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

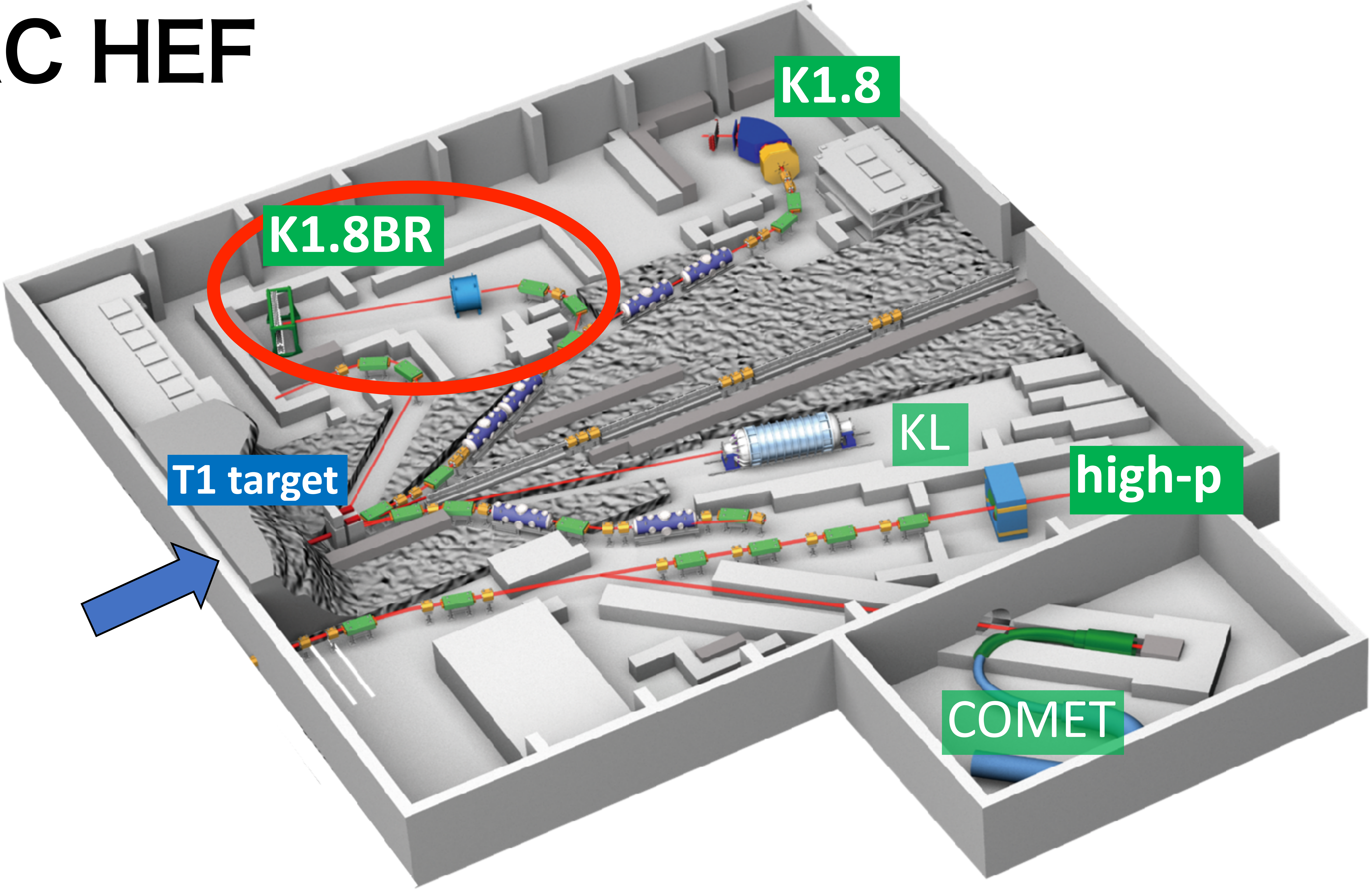


✓ Effectively produce sub-threshold virtual $\bar{K}$

✓ Simplest target allows an exclusive analysis

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

J-PARC HEF



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

J-PARC K1.8BR
beam dump
beam sweeping magnet
γ, n
p
15m
Liq. $H_2/D_2/^{3/4}He$ target system
neutron counter
charge veto counter
proton counter
CDS
K^- beam
beam line spectrometer

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).]
- 2018: **E31**, $\Lambda(1405)$
  [PLB837,137637(2023)]
- 2020: **T77**, ${}^4_\Lambda\mathrm{H}$ lifetime, ("K^-ppn" search)
  [PLB485, 138128 (2023)]
- 2021: **E73** 1st, ${}^3_\Lambda\mathrm{H}$ production cross section
- 2024~2025: **E73** 2nd, ${}^3_\Lambda\mathrm{H}$ lifetime, ("K^-pp" study)
  just completed!

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

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

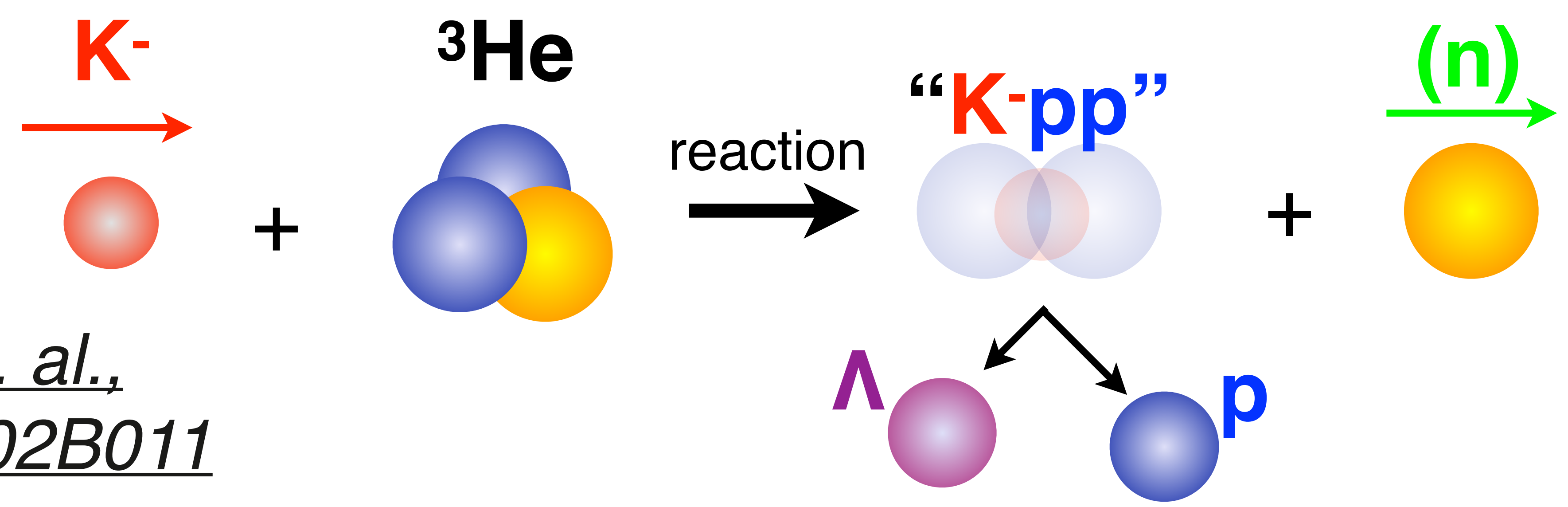
$$K^- + \boxed{{}^4\mathrm{He}} \to {}^4_\Lambda\mathrm{H} + \pi^0$$

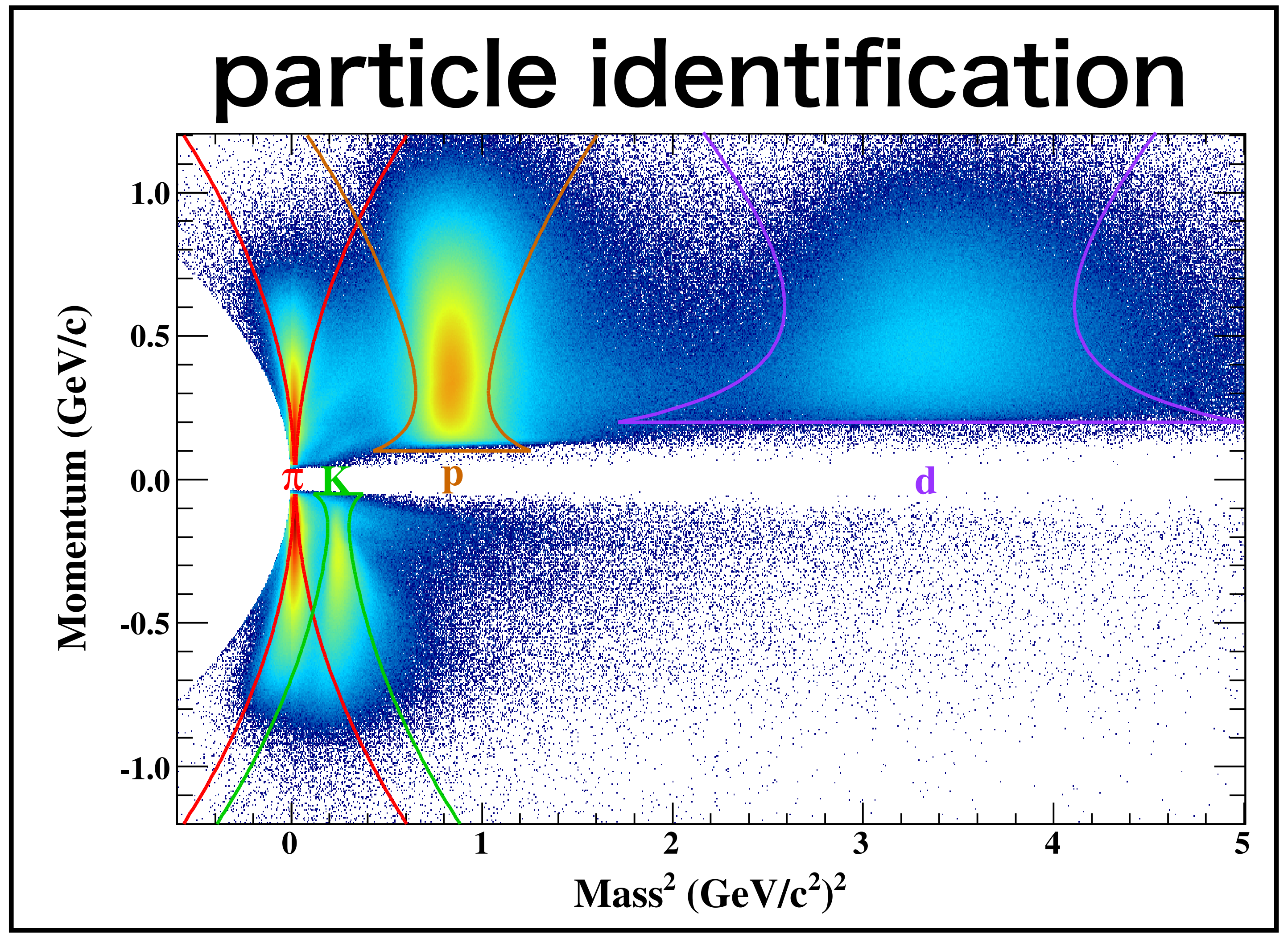
$$(K^- + {}^4\mathrm{He} \to K^-ppn + n)$$

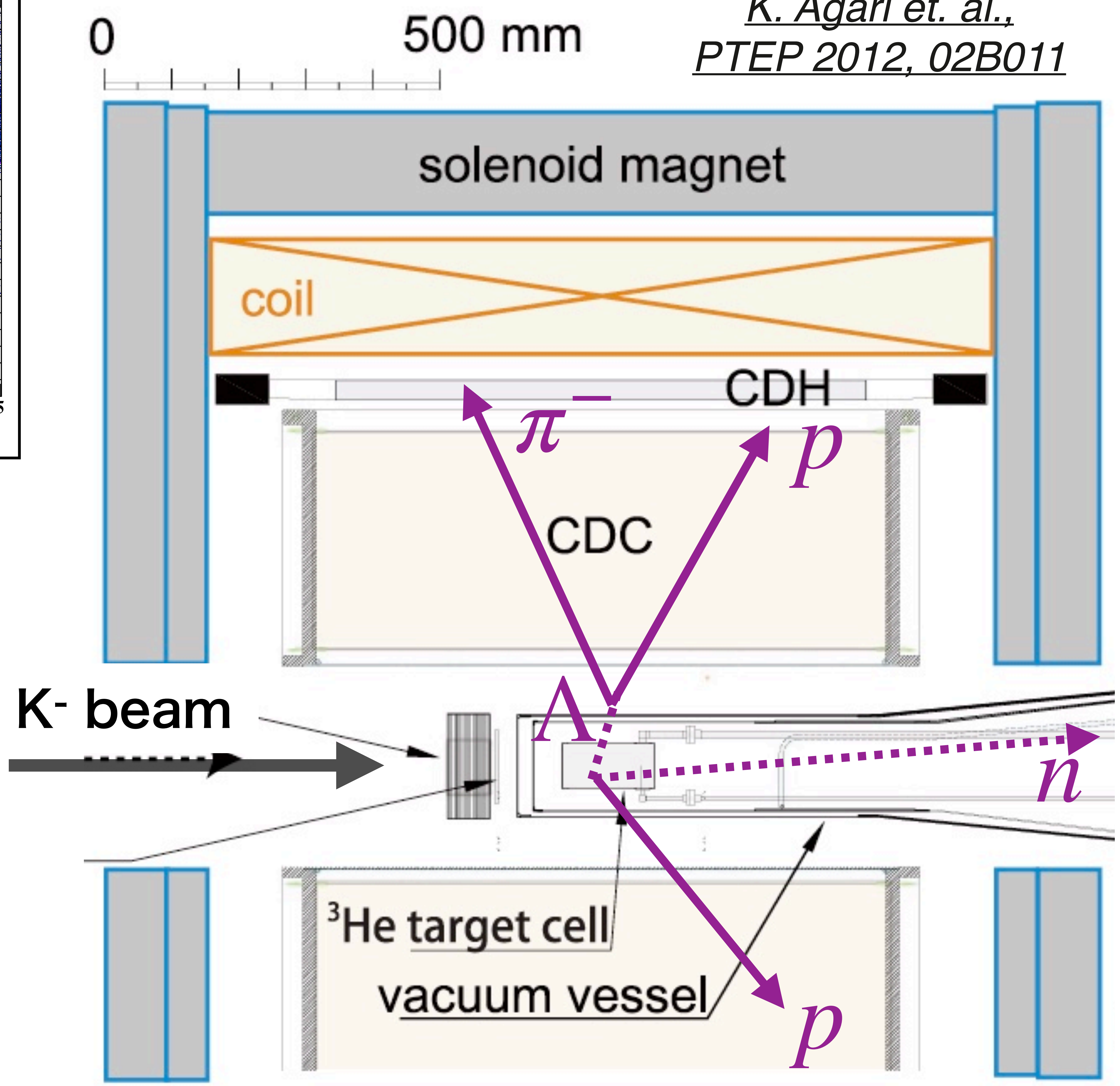
$$K^- + \boxed{{}^3\mathrm{He}} \to {}^3_\Lambda\mathrm{H} + \pi^0$$

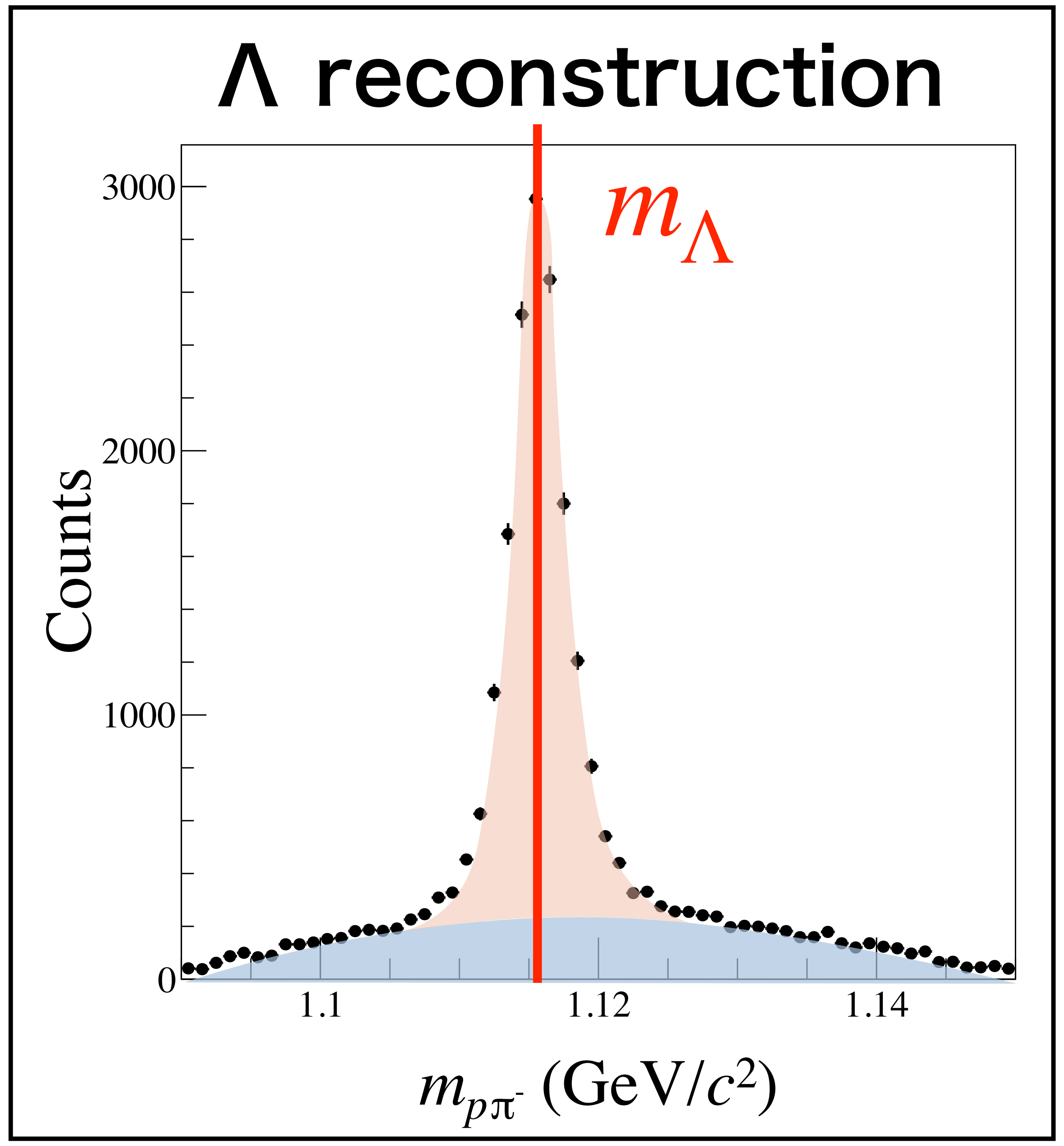
$$(K^- + {}^3\mathrm{He} \to K^-pp + n)$$

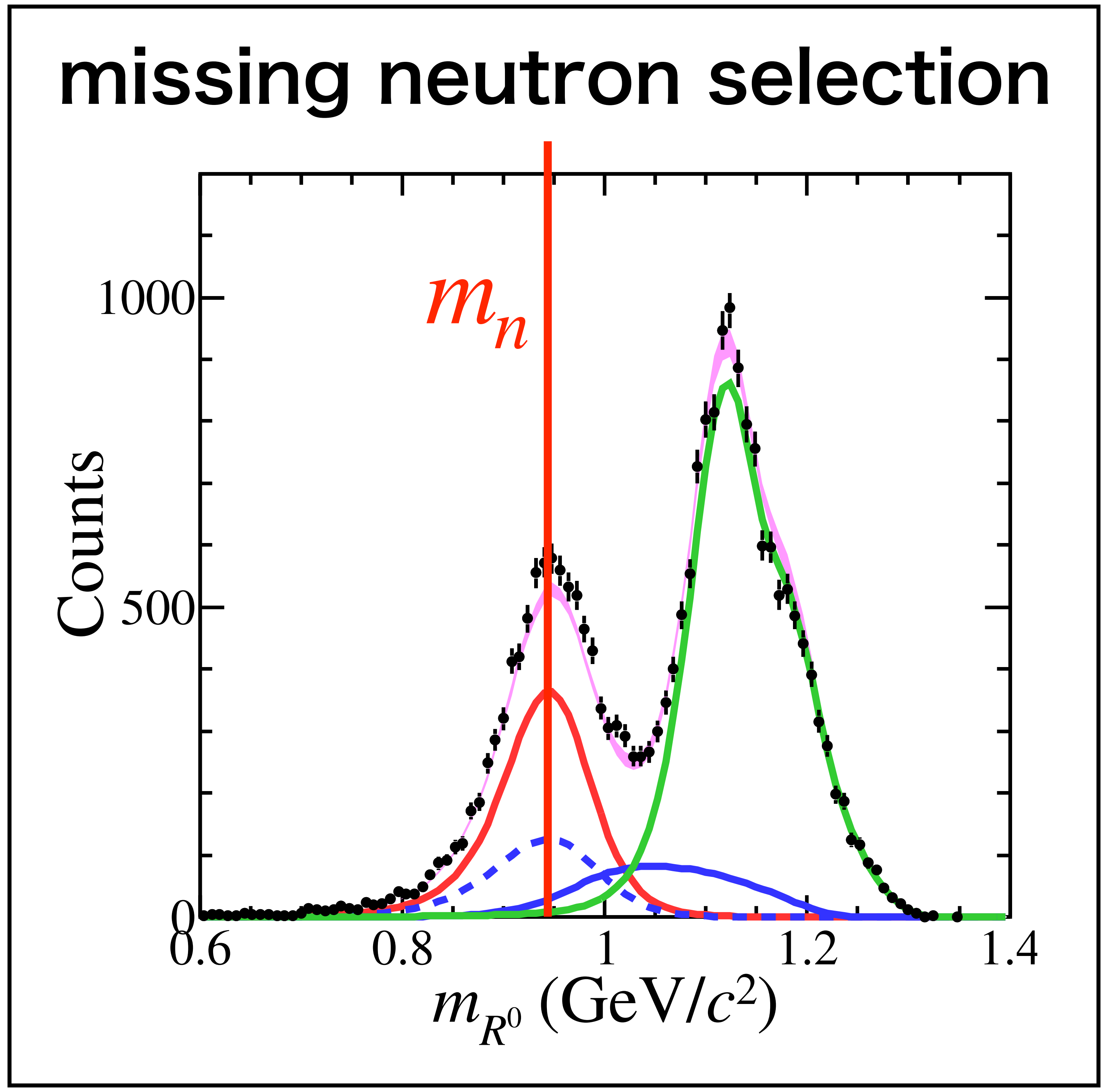
Λpn Exclusive measurement







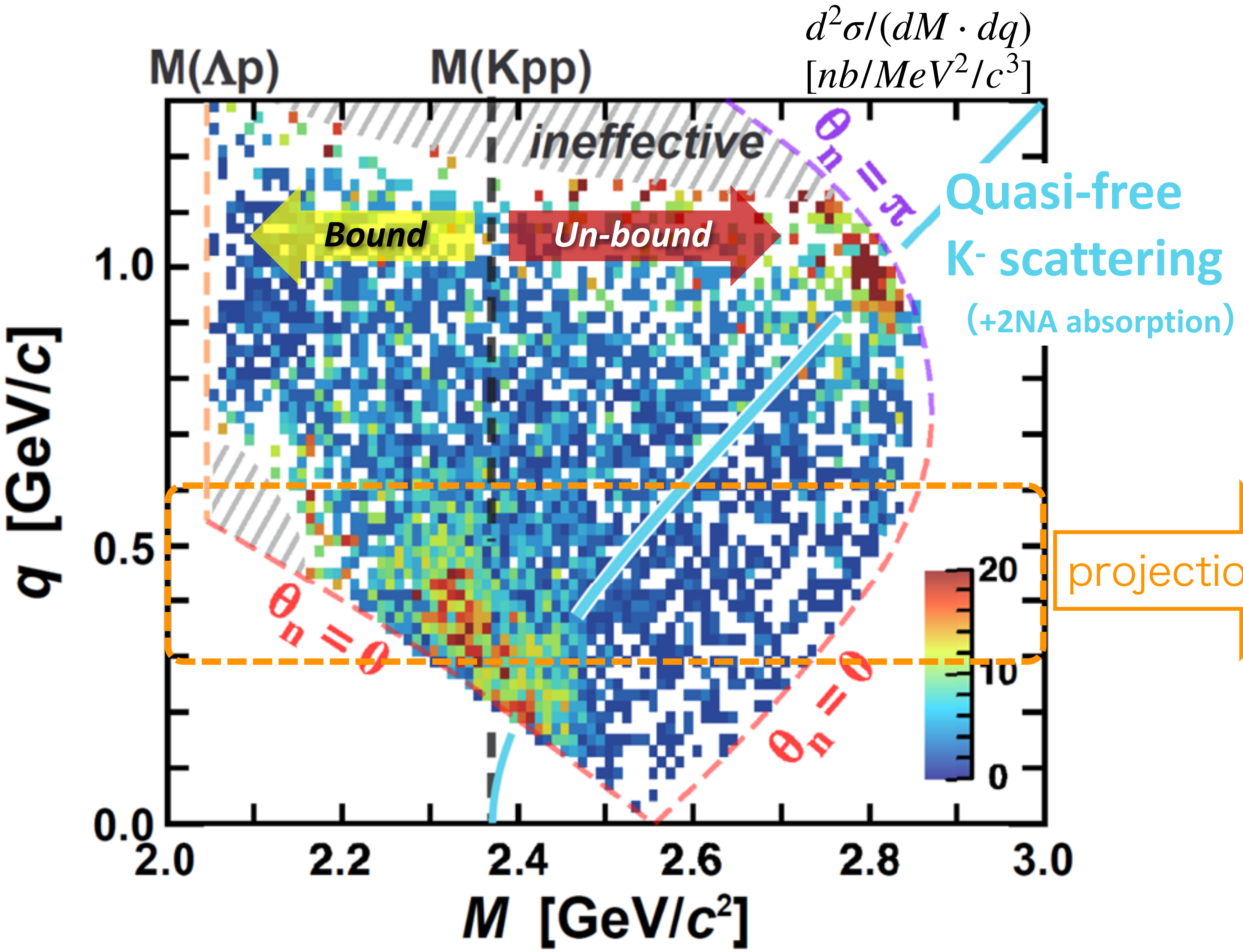




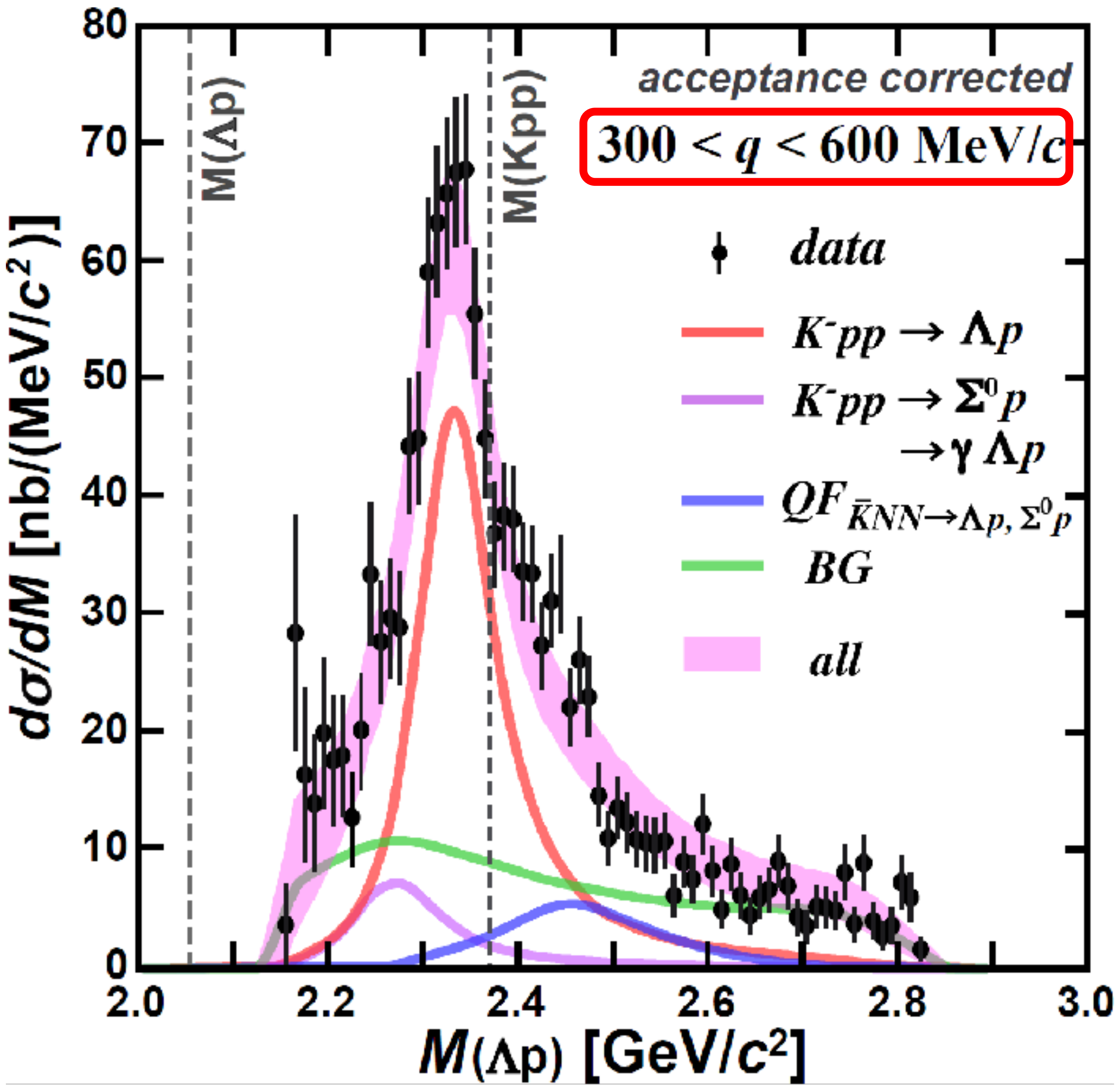
Purity of Λpn events ~ 80%

"K-pp" observation in J-PARC E15

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



projection



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

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

“K⁻pp”: Mesonic decay modes

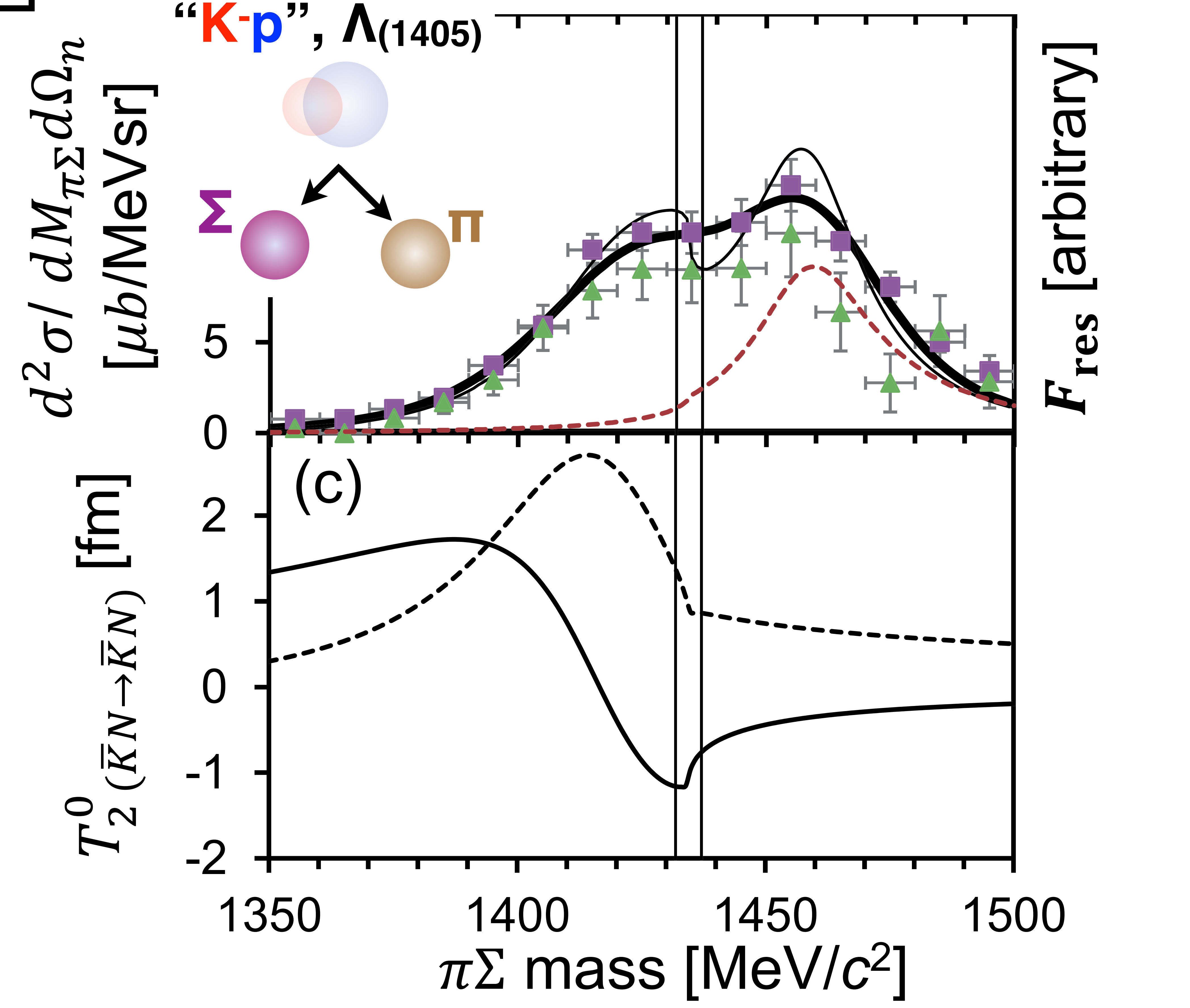
T. Yamaga et al., PRC 110, 014002 (2024)

$\pi^-\Lambda p(p)$ $\pi^+\Lambda n(n)$ $\pi^-\Sigma^+ p(n)$ $\pi^+\Sigma^- p(n)$

Can be explained in common with $\Lambda p(n)$ events. $\Gamma_{\pi YN} \sim 10 \times \Gamma_{YN}$. $\Gamma_{\pi\Sigma N} \sim \Gamma_{\pi\Lambda N}$.

(K⁻, n) reaction on other targets

d₂

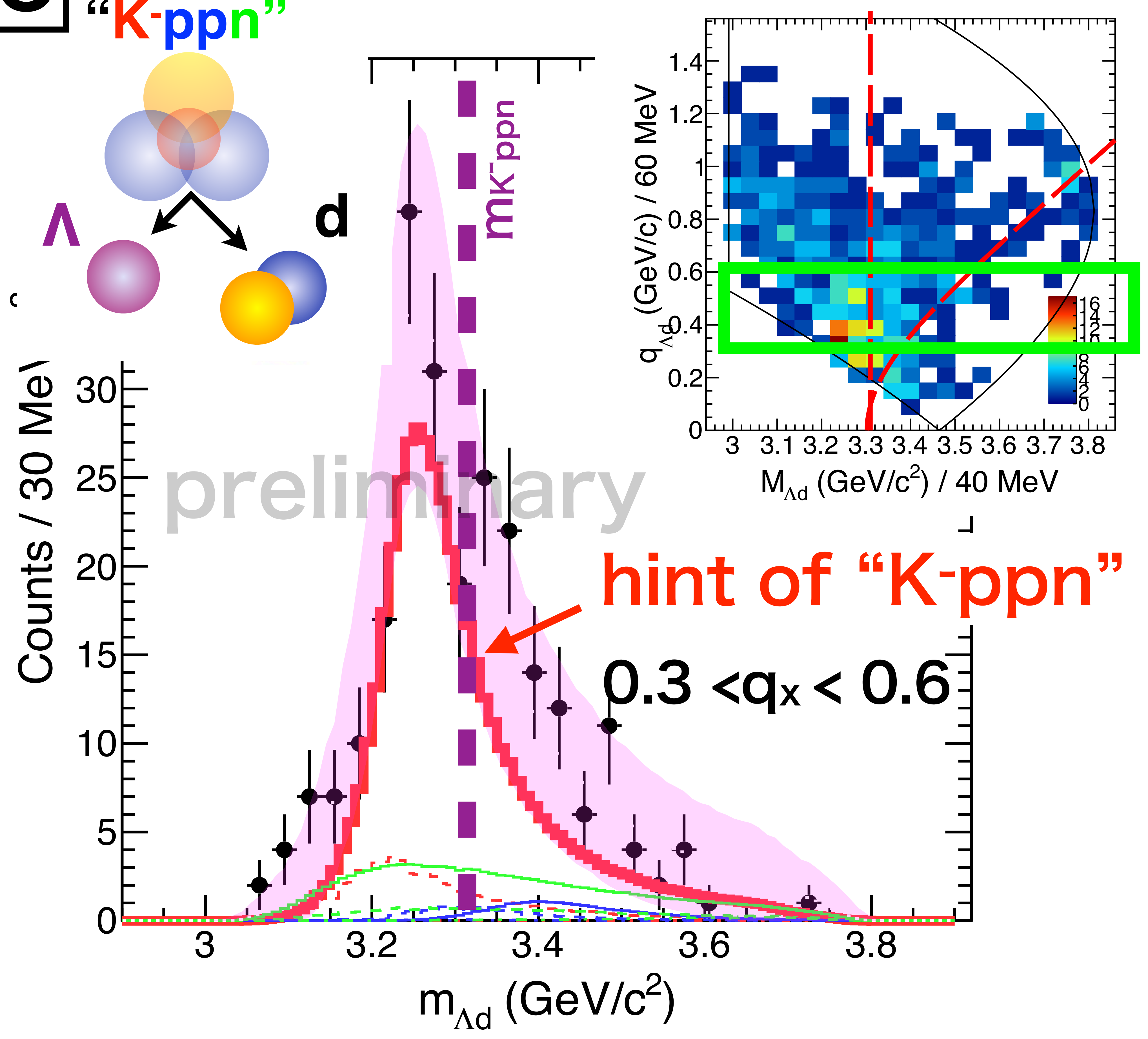


S-wave $\bar{K}N$ amplitude (I=0) was deduced with two-step reaction models

pole: 1417.7 – 26.1i [MeV]

⁴He

only ~3 days data-taking



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

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

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

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

with high certainty

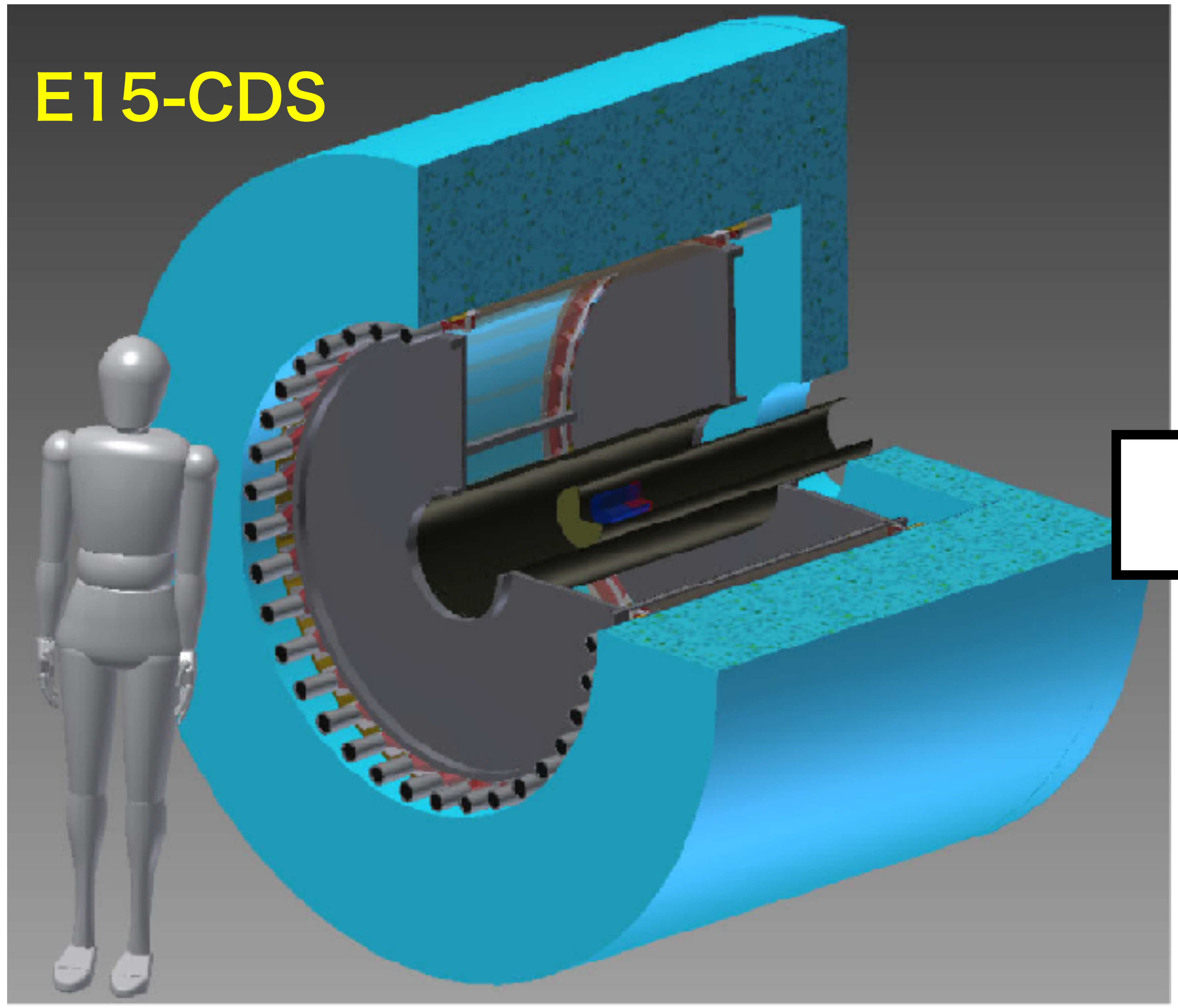
Achievement so far:
Established the production method of $\bar{K}$ nuclei

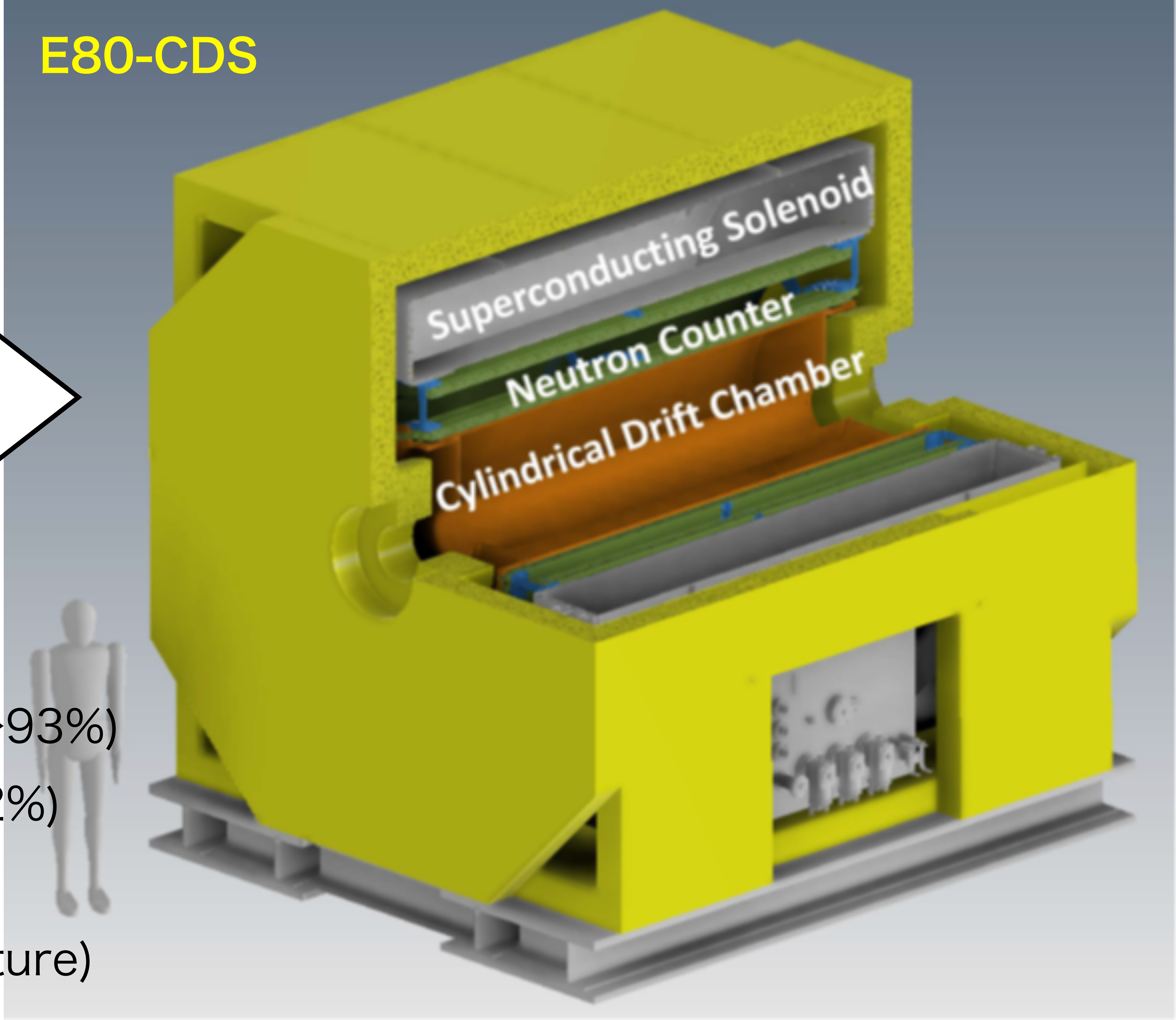
- **In-flight (K$^-$, n)** is effective in exciting the sub-threshold $\bar{K}$ amplitude
- kaonic nuclei seem to exist more or less universally **"K$^-$pp", "K$^-$ppn"**, ⋯

What is Next?: systematic study

- **Further investigation of the $\bar{K}NN$ system J-PARC E89**
  - Search for the isospin partner "$\bar{K}^0 nn$" via $\bar{K}^0 nn \to \Lambda + n$ decay
  - Spin-parity of "$K^- pp$"→spin-spin correlation measurement of Λ & p
- **Confirmation of "$K^- ppn$" $\to \Lambda + d,\ \Lambda + p + n$ J-PARC E80**
  - mass-number dependence
- **Spatial size, heavier system, double $\bar{K}$ nuclei…**

New CDS





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

Construction status

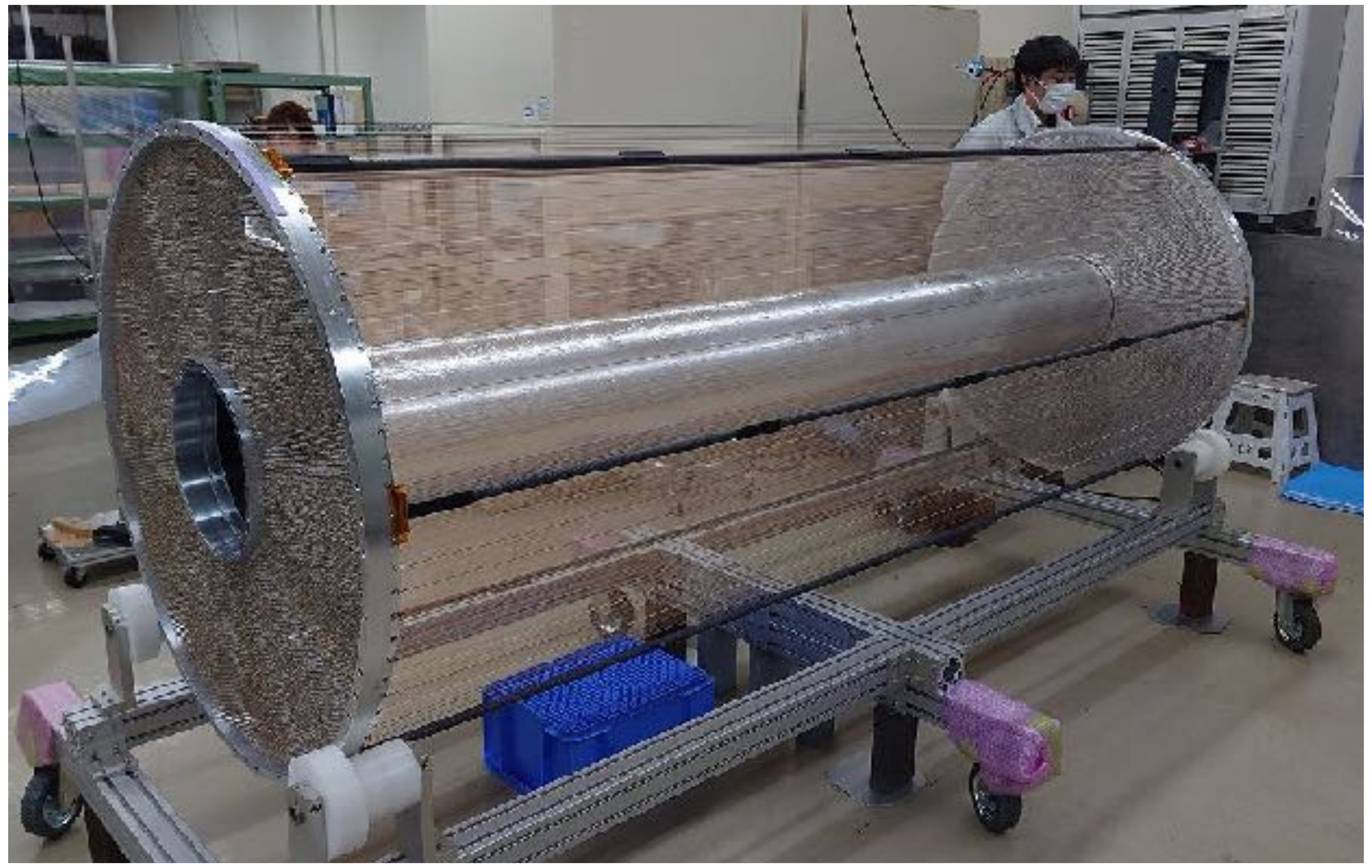
Solenoid york

completed in JFY2022

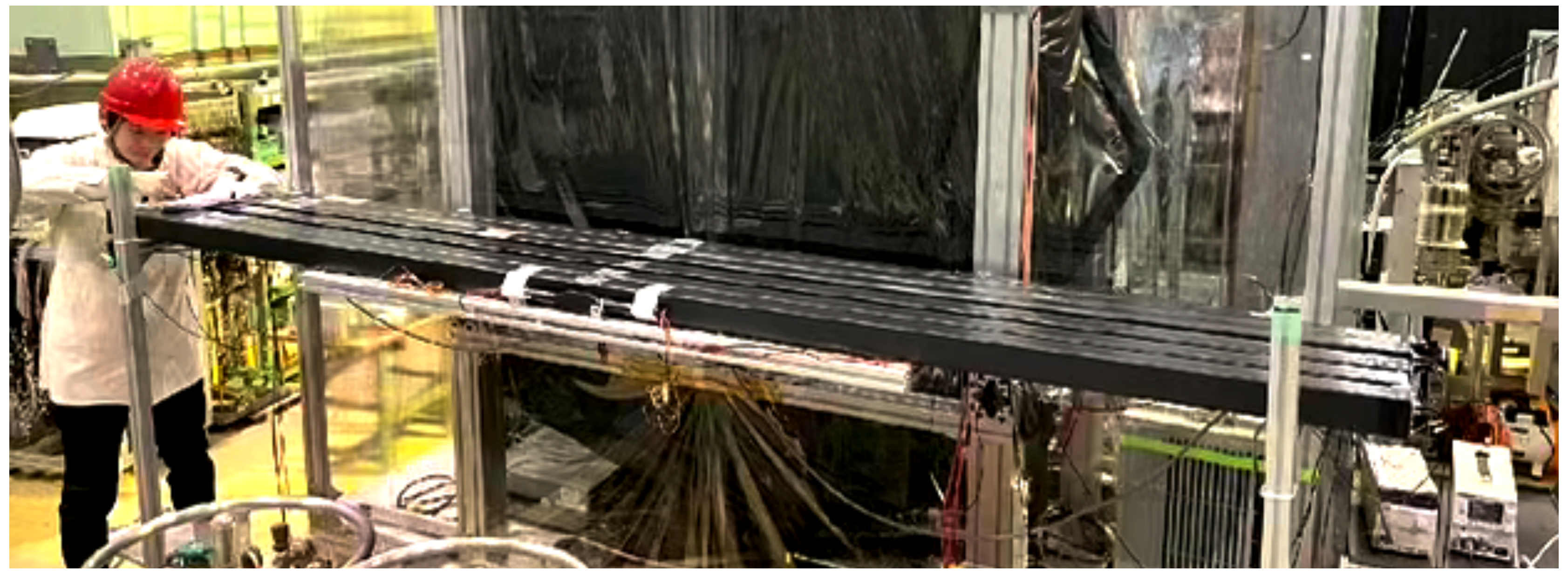
Superconducting solenoid

completed in JFY2024
(copy of COMET-DS)

CDC: Commissioning started



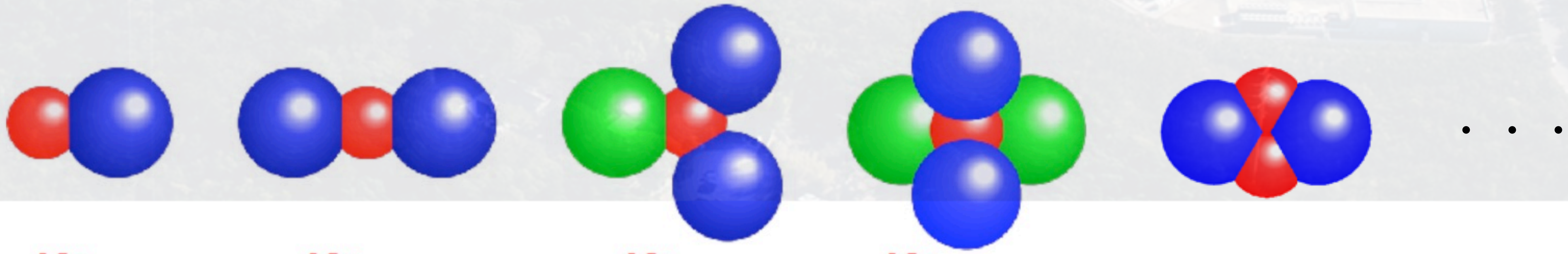
CNC: readout test with beam



We would like to start beam commissioning by the end of JFY2026

Summary

- Kaonic nuclei would open a new field of nuclear physics with anti-kaon as a new probe.
- We established the production of kaonic nuclei via (K^-, n).
  "K⁻p" as $\Lambda(1405)$, **"K⁻pp", "K⁻ppn"**
- We are developing a new solenoid spectrometer, aiming to elucidate the properties of kaonic nuclear systems.



K^-p K^-pp K^-ppn K^-ppnn K^-K^-pp

J-PARC E80/E89 Collaboration

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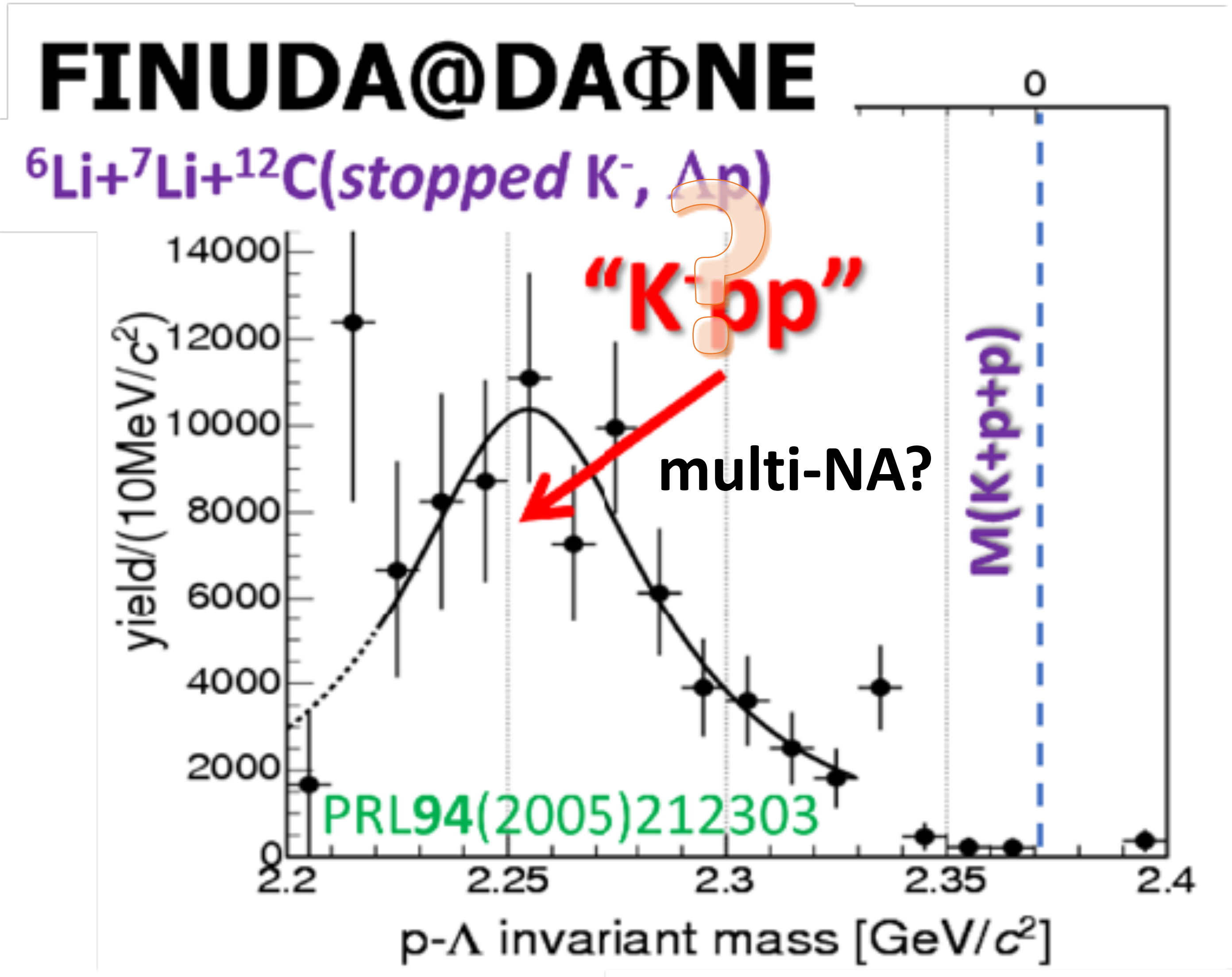
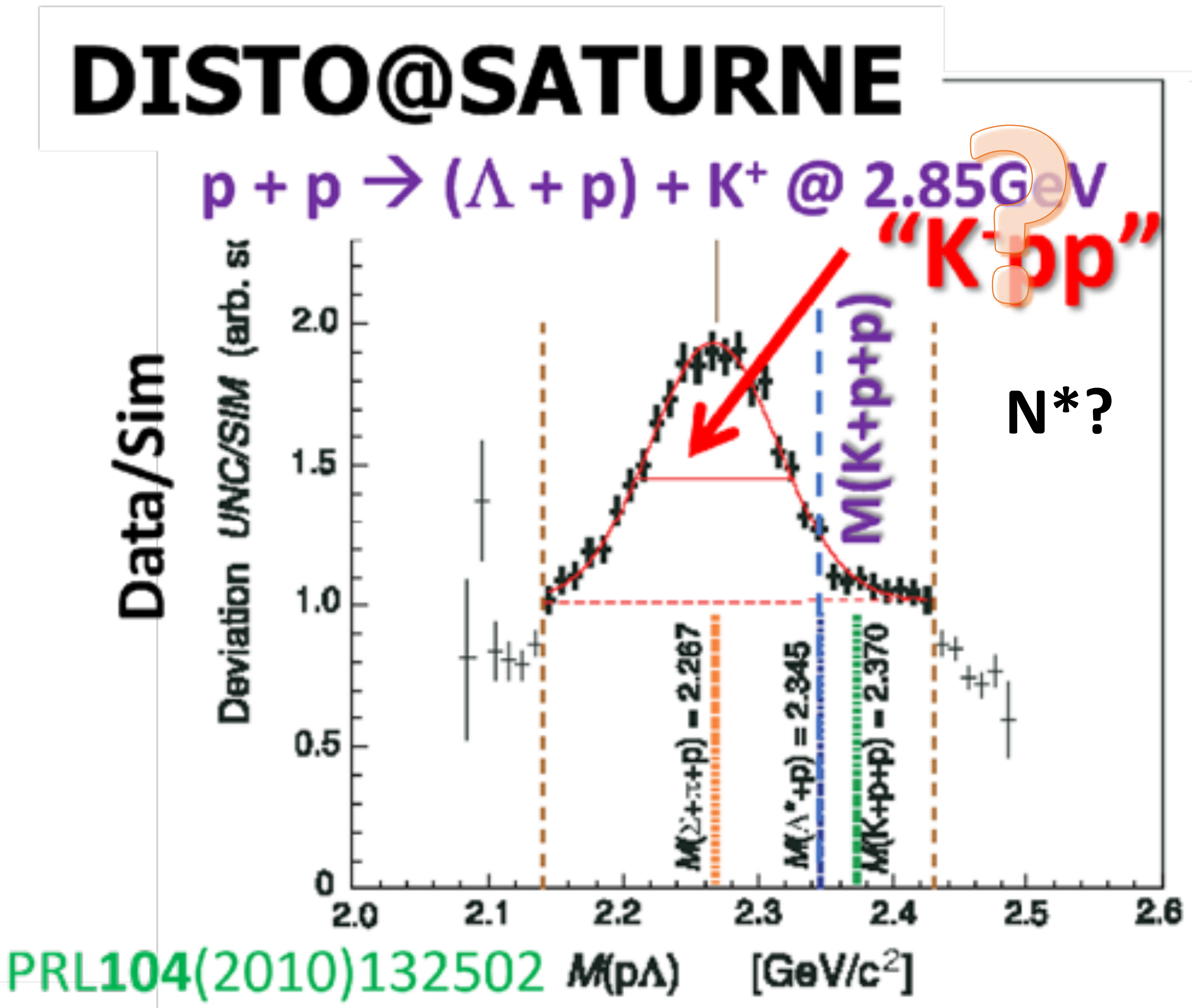
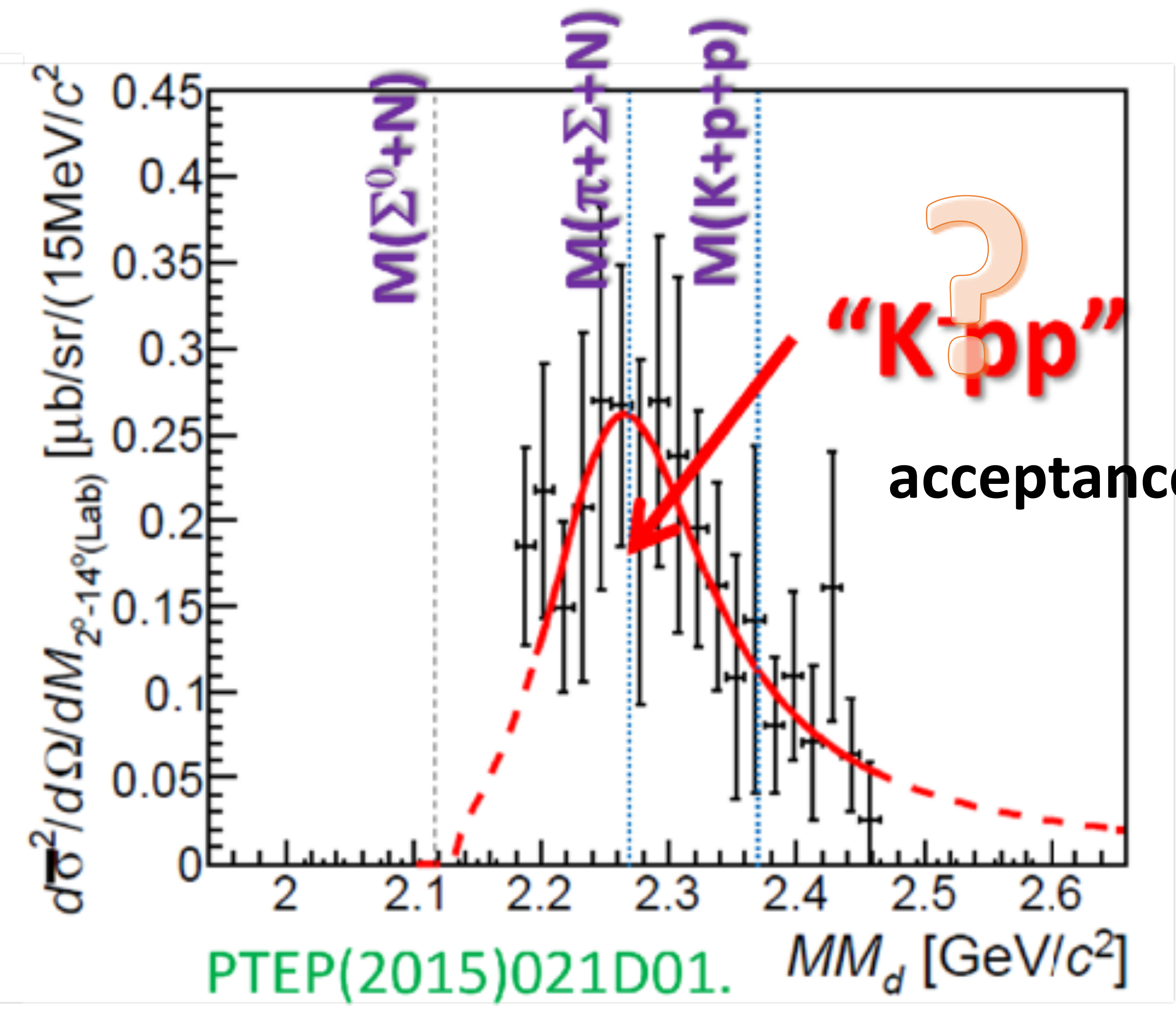
Appendix

“K-pp” Bound State Searches - History







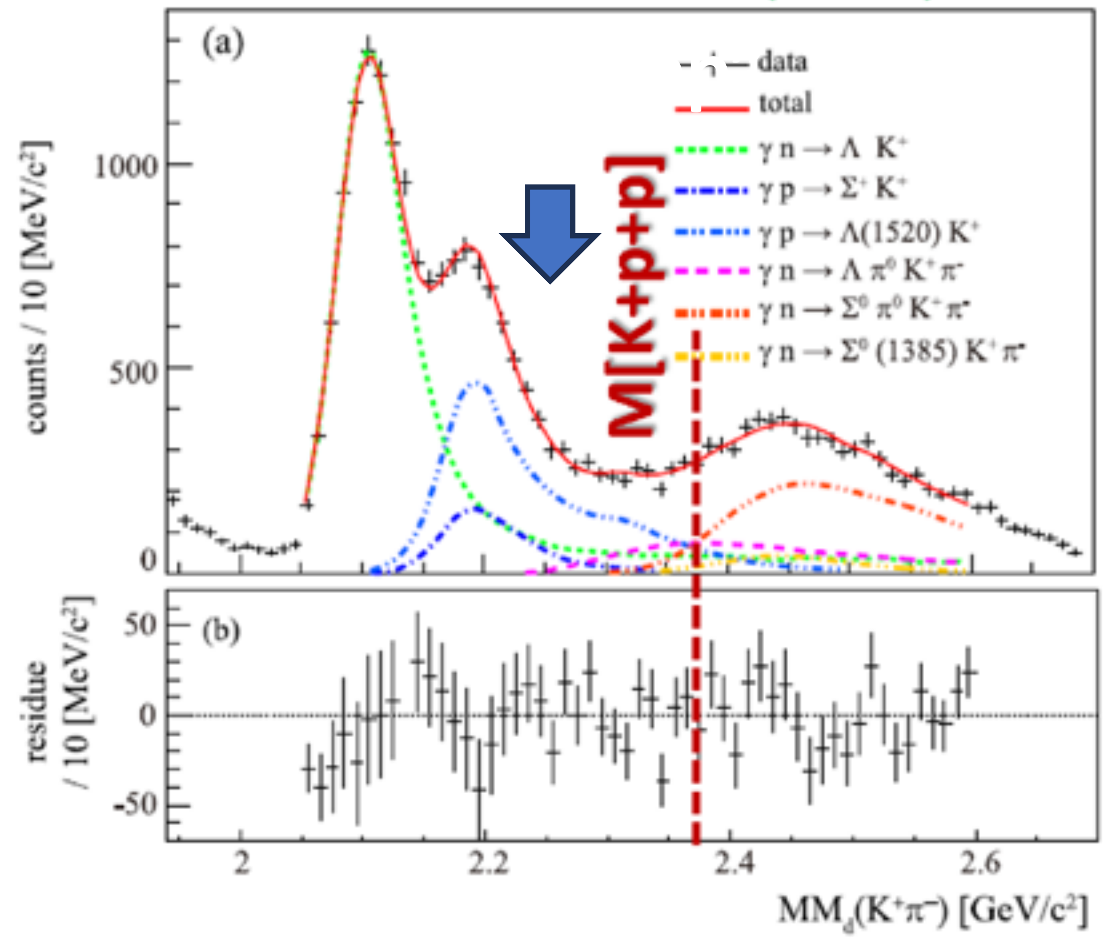
E27@J-PARC

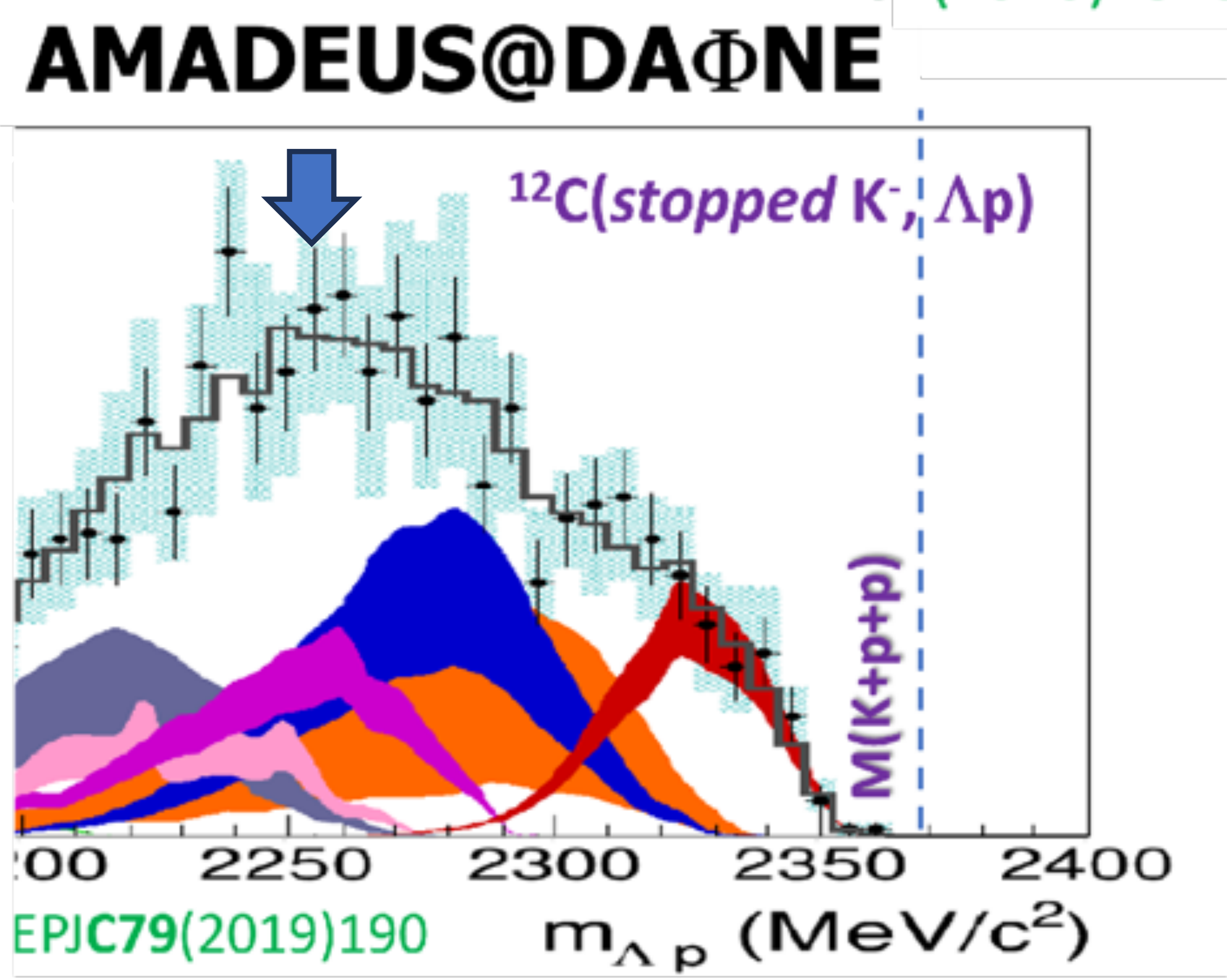
d(π$^+$, K$^+$)Σ^{0}p @ 1.69 GeV/c

LEPS@SPring-8

d(γ, K$^+$π$^-$)X @ 1.3-2.4 GeV/c

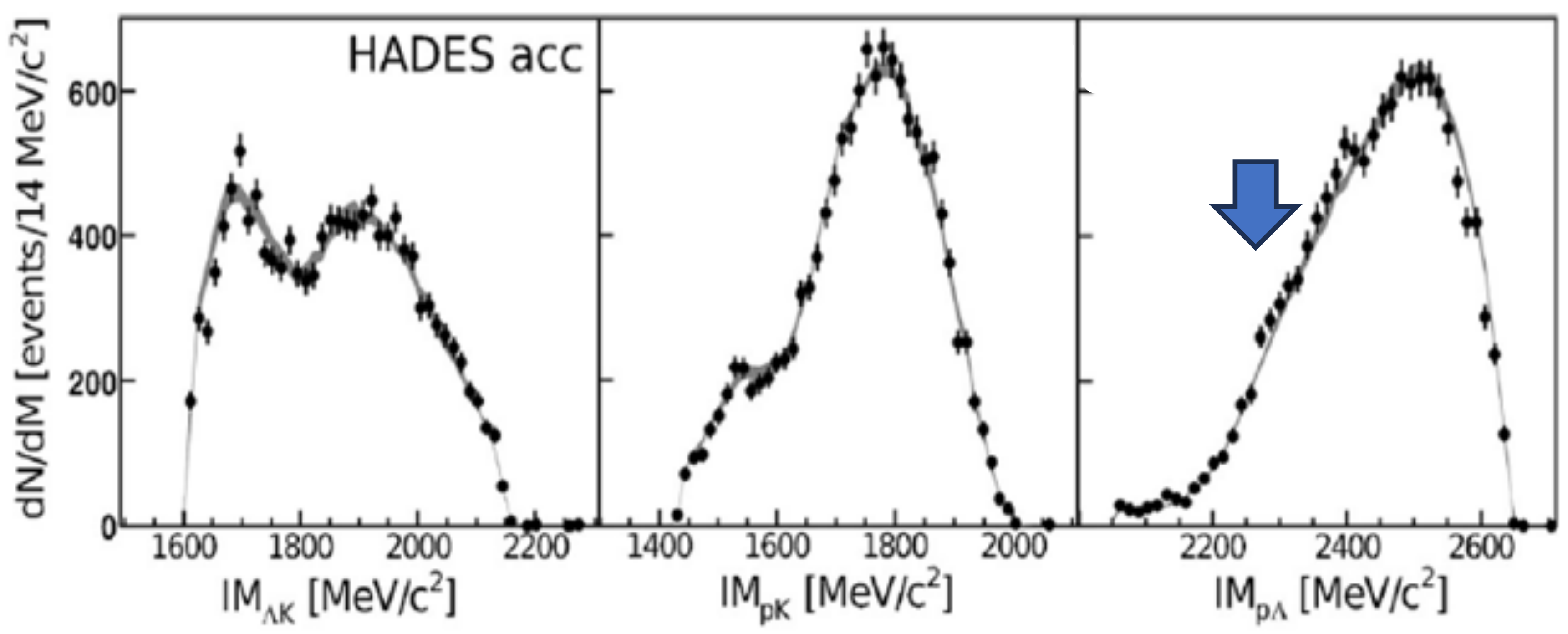
PLB728(2014)616.





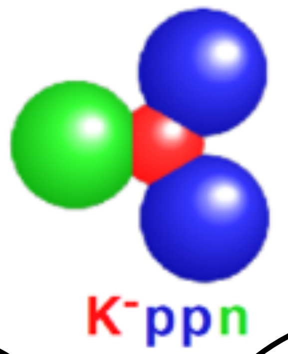
HADES@GSI PLB742(2015)242

p + p → (Λ + p) + K$^+$ @ 3.5GeV



- Despite of many “K-pp” searches, NO conclusive results
  - ➢ Complex reactions & difficult to understand background

$\bar{K}NNN$ Searches so far



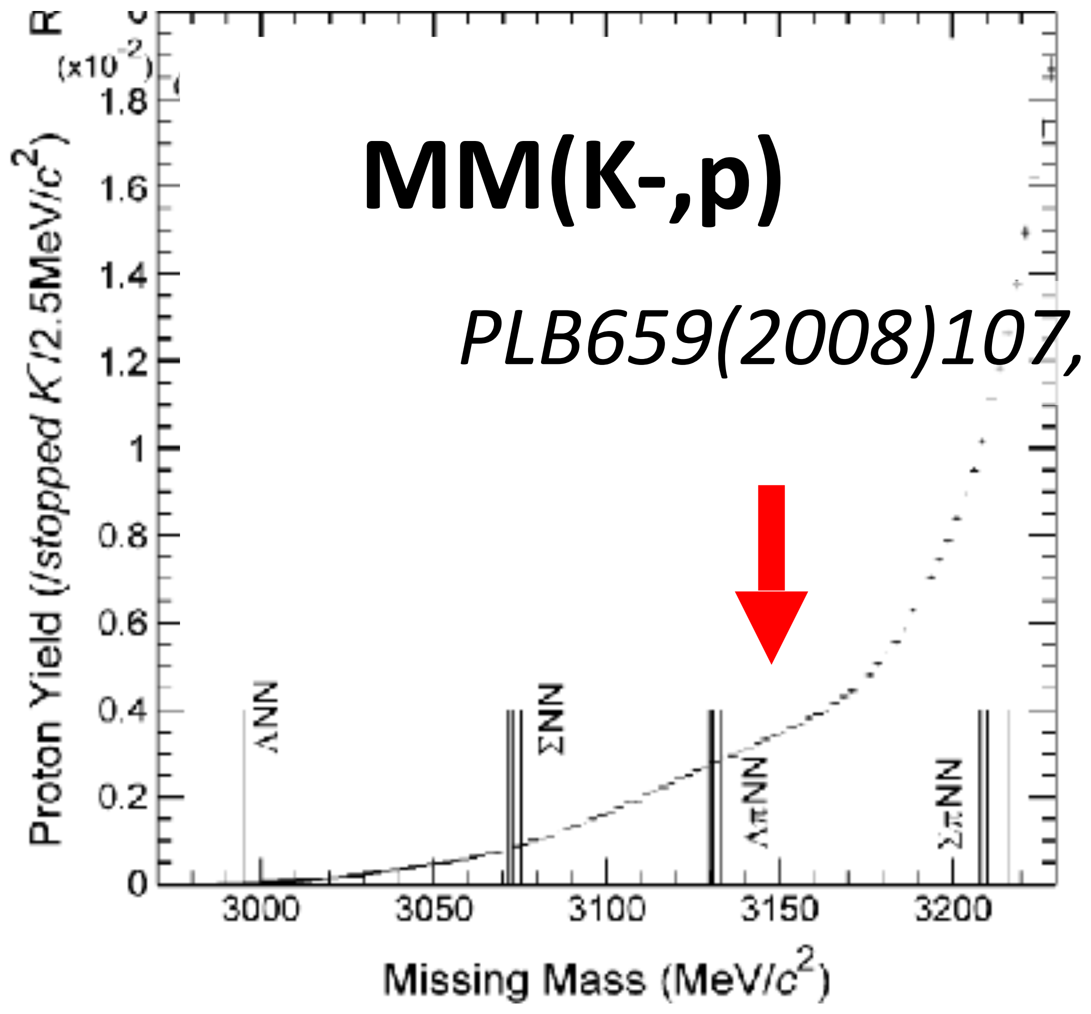
E471/E549@KEK

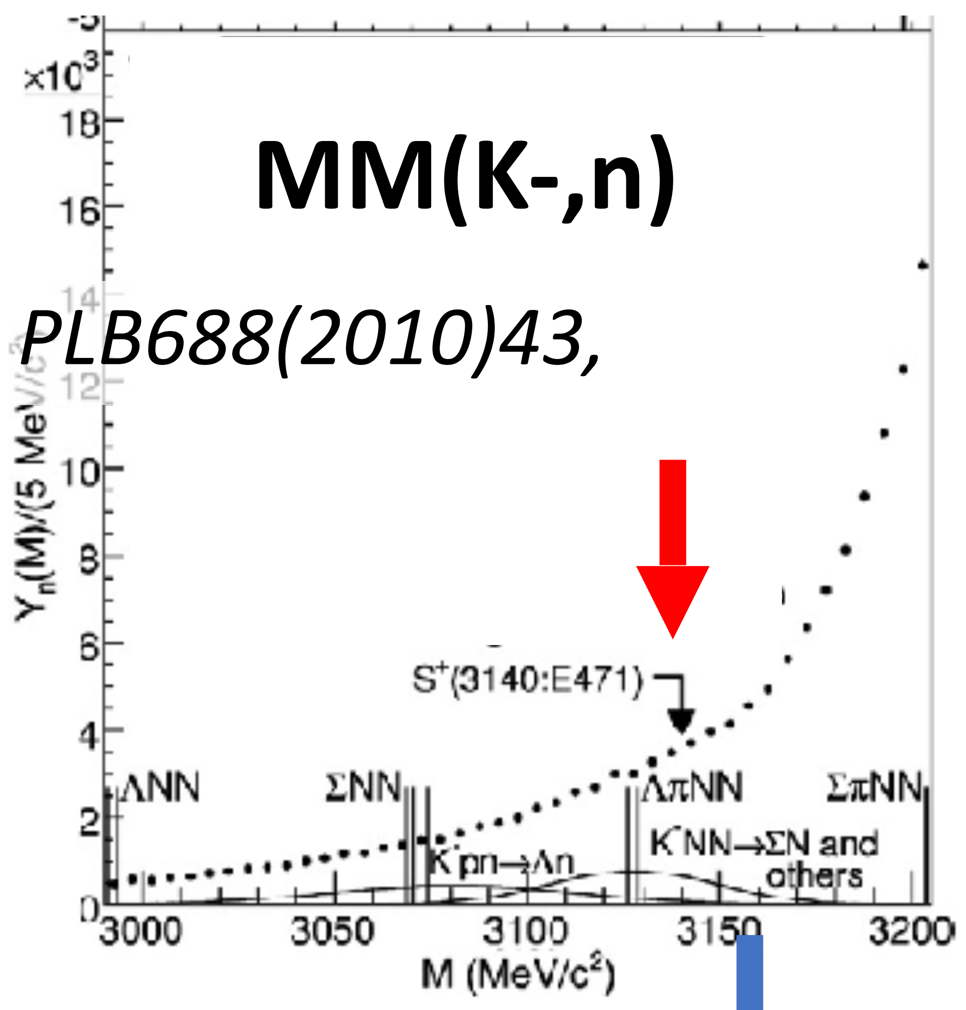
^{4}He(stopped-K$^-$,p/n/Yd)

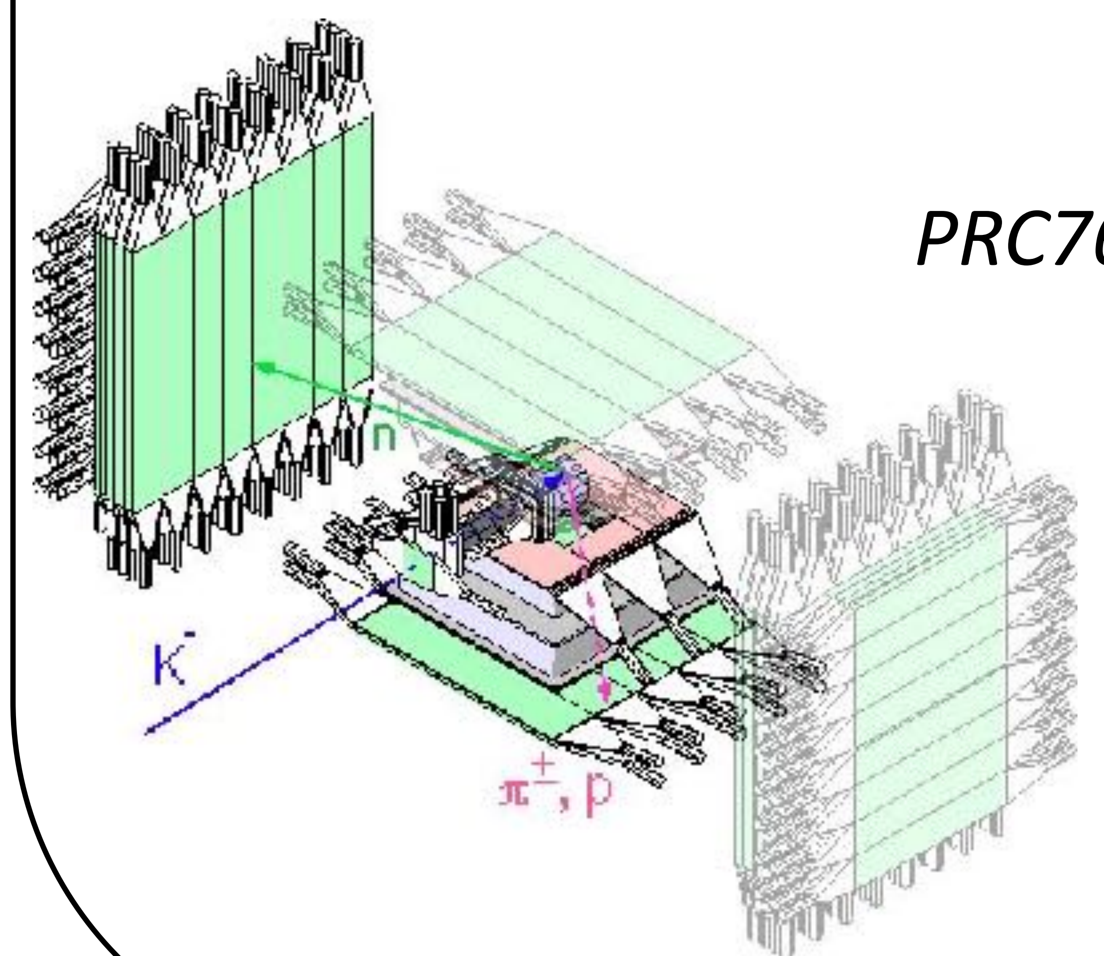
MM(K-,p)

MM(K-,n)

PLB659(2008)107, PLB688(2010)43,

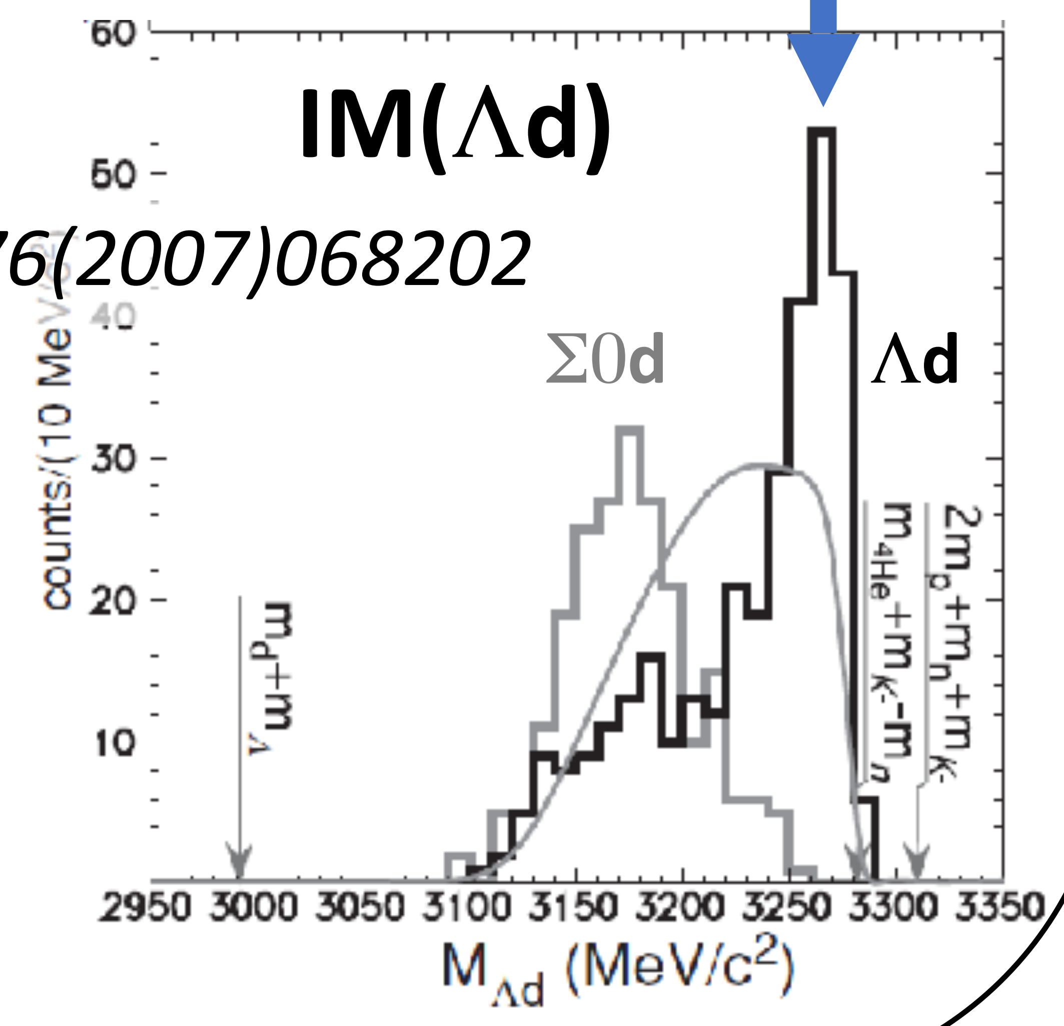






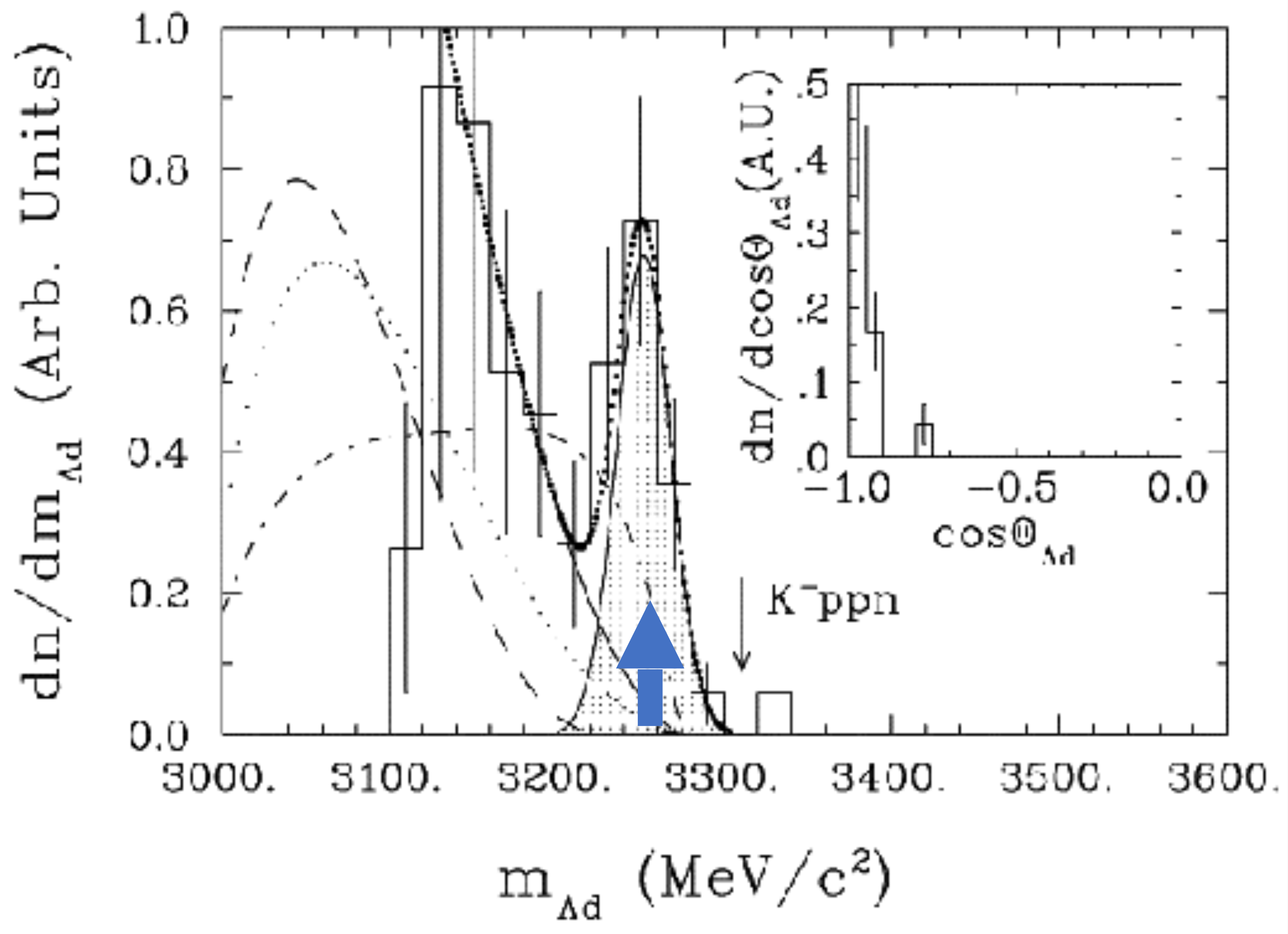
IM(Λd)

PRC76(2007)068202



FINUDA@DAΦNE

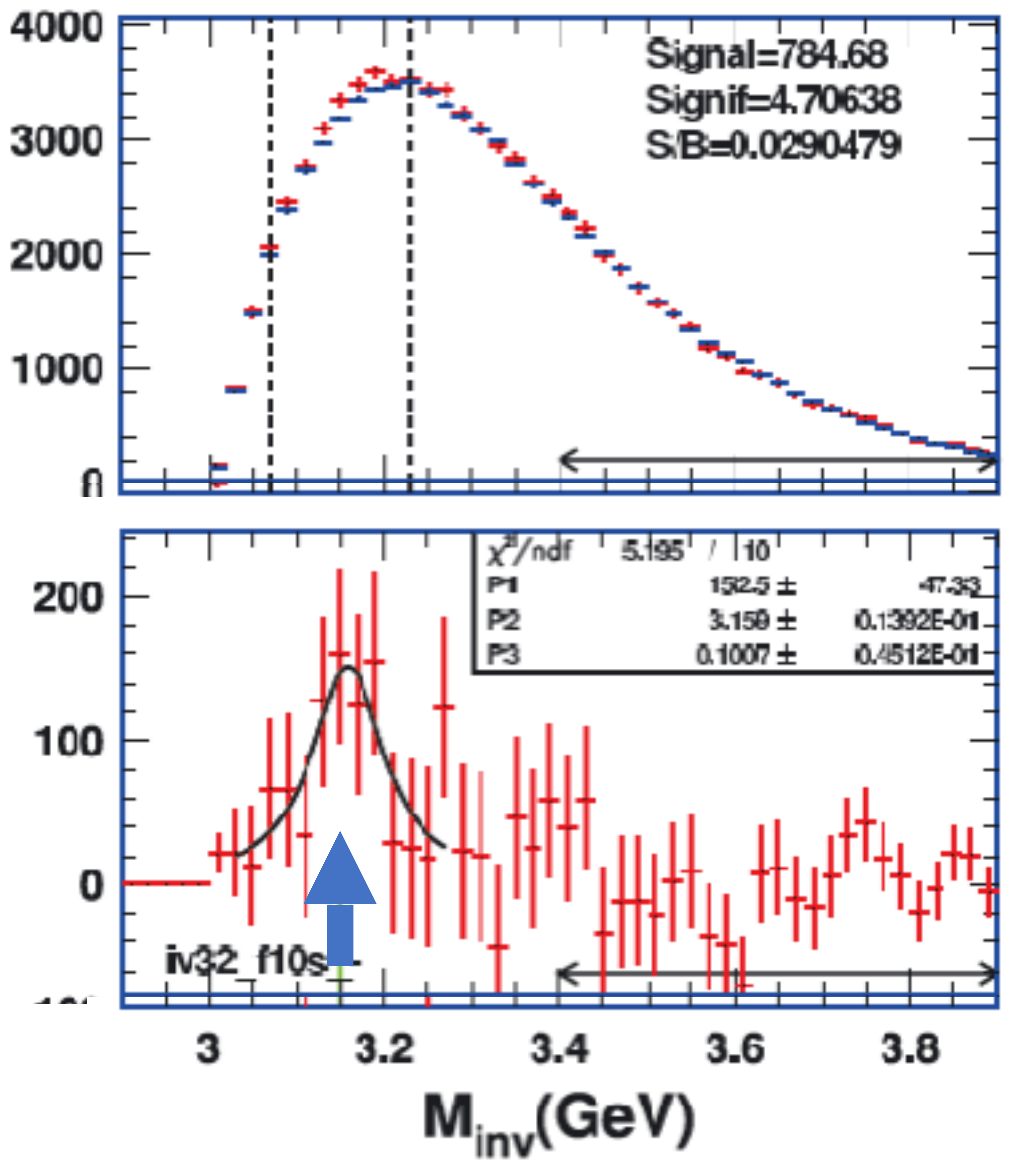
Li/C(stopped-K$^-$,Λd)



PLB654(2007)80

FOPI@GSI

Λd in Ni+Ni



EXA05 Conference (2005)

No conclusive results.

multi-N absorption in stopped-K reaction makes interpretation difficult

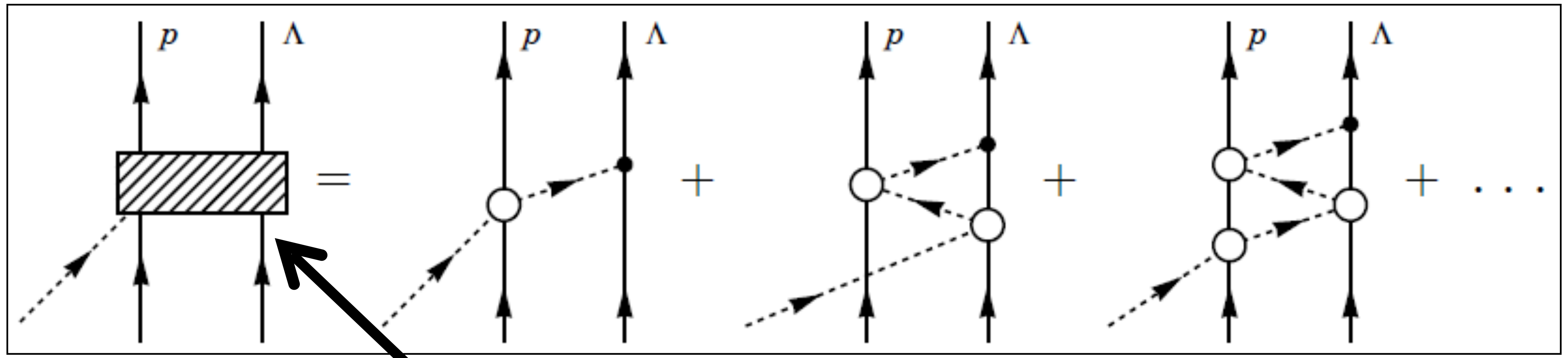
A Theoretical Interpretation

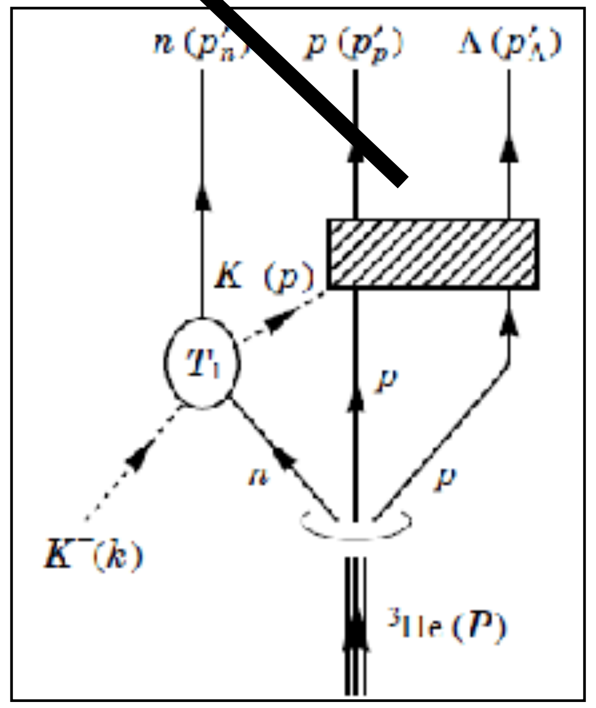
A calculation based on chiral unitary approach **reproduces the data well using the $\bar{\mathrm{K}}$NN bound state**


PTEP
Prog. Theor. Exp. Phys. 2016, 123D03 (27 pages)
DOI: 10.1093/ptep/ptw166

On the structure observed in the in-flight ^{3}He$(K^-, \Lambda p)n$ reaction at J-PARC

Takayasu Sekihara[1,*], Eulogio Oset[2], and Angels Ramos[3]

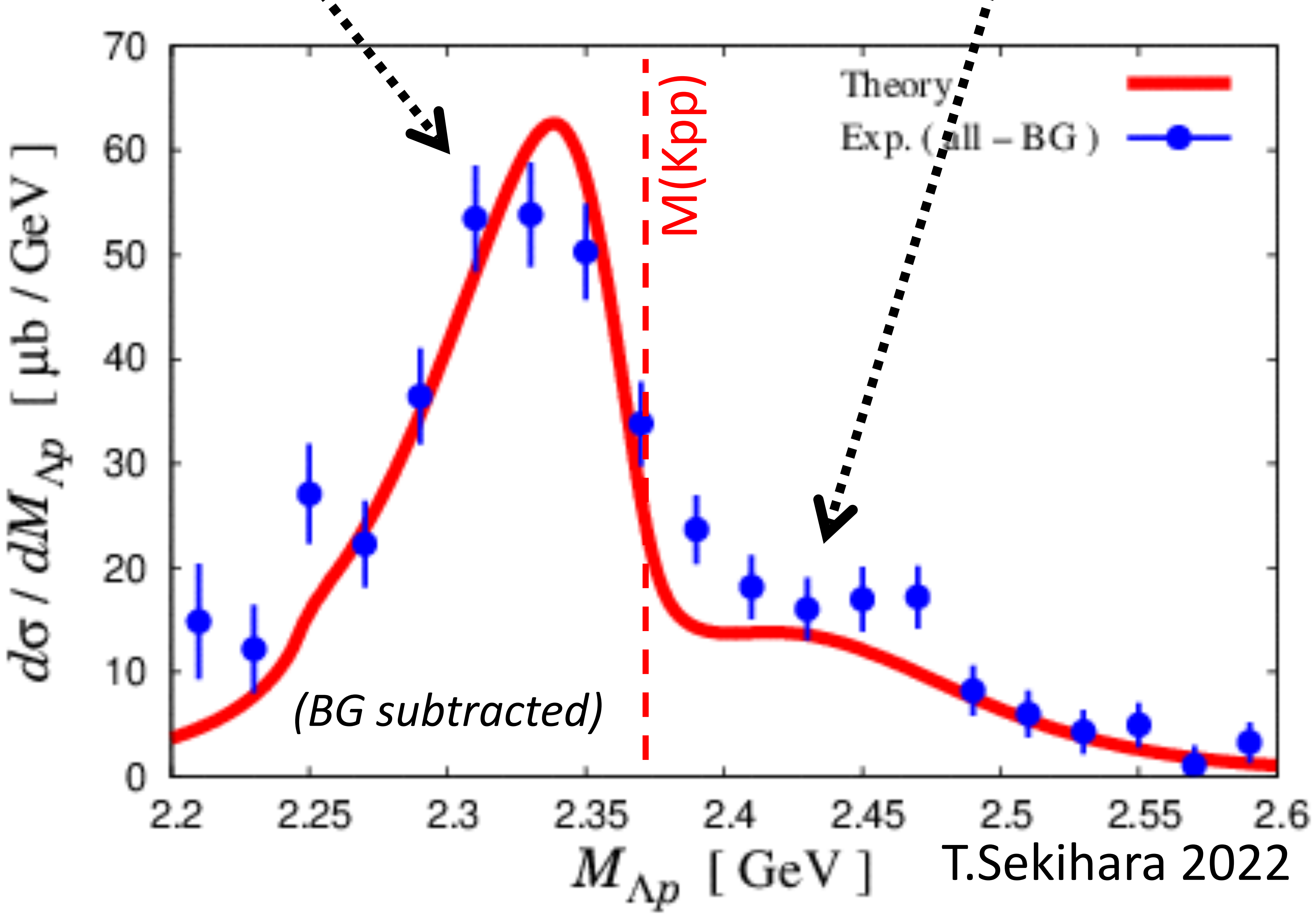




Theoretical investigations are indispensable!

K^bar NN bound state

Quasi-free K⁻ scattering

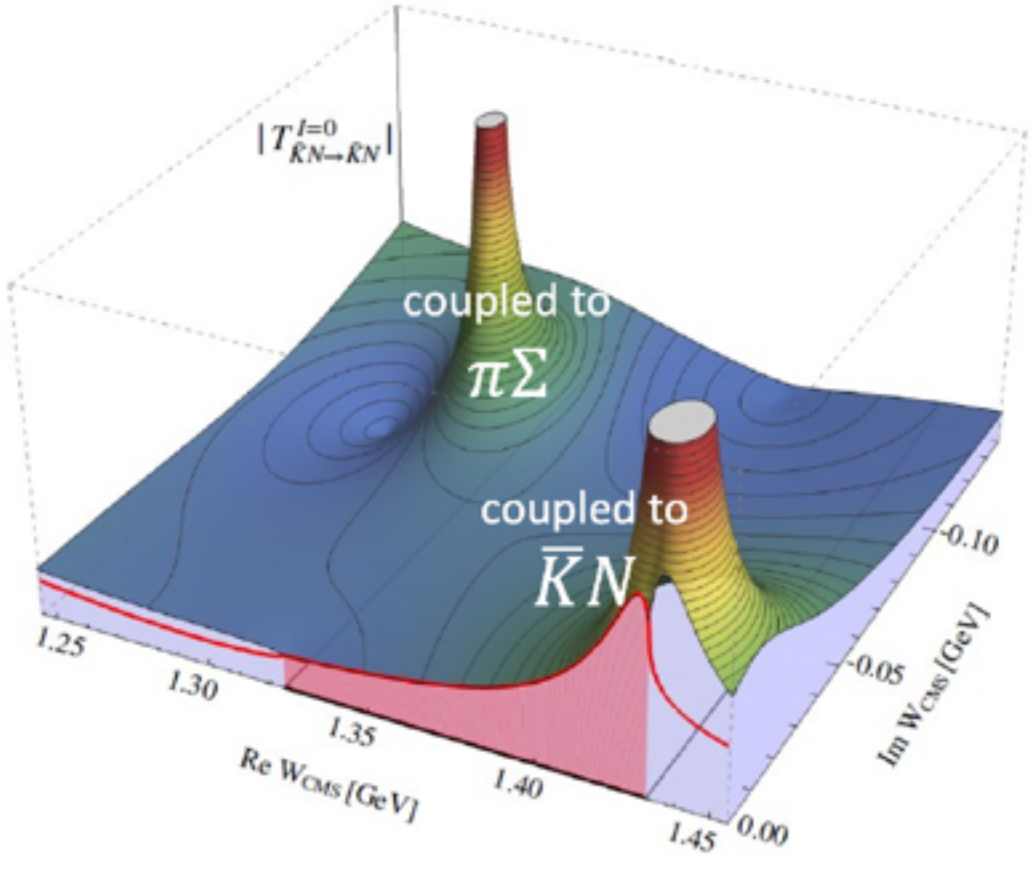


T.Sekihara 2022

Theoretical Calculations of $\bar{K}NN$

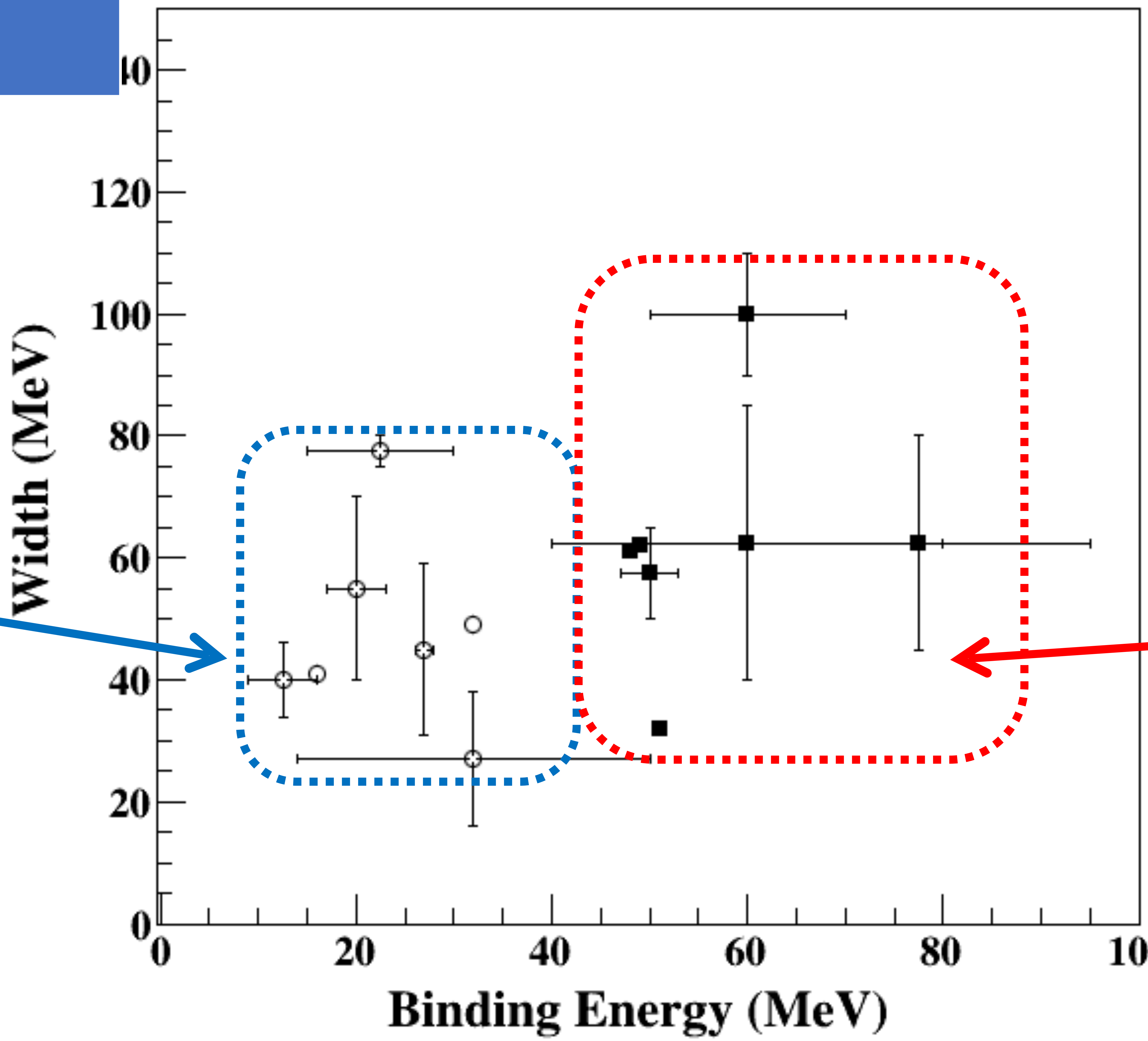
Chiral unitary model (energy dependent)

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



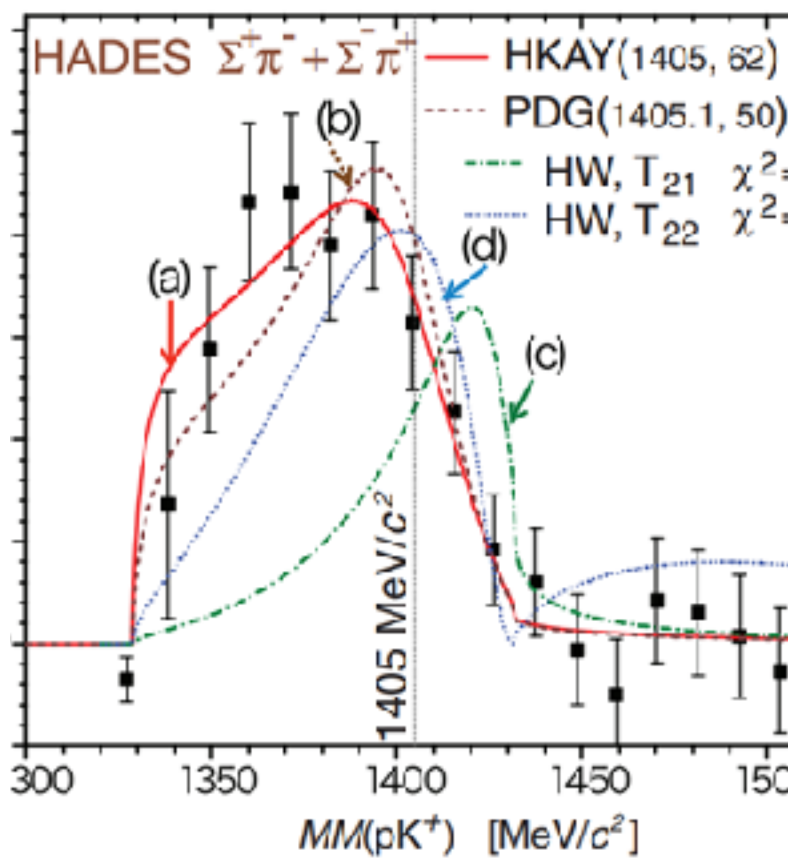
shallow $\bar{K}N$ potential

B.E. ~ 10-30 MeV



Phenomenological model (energy independent)

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

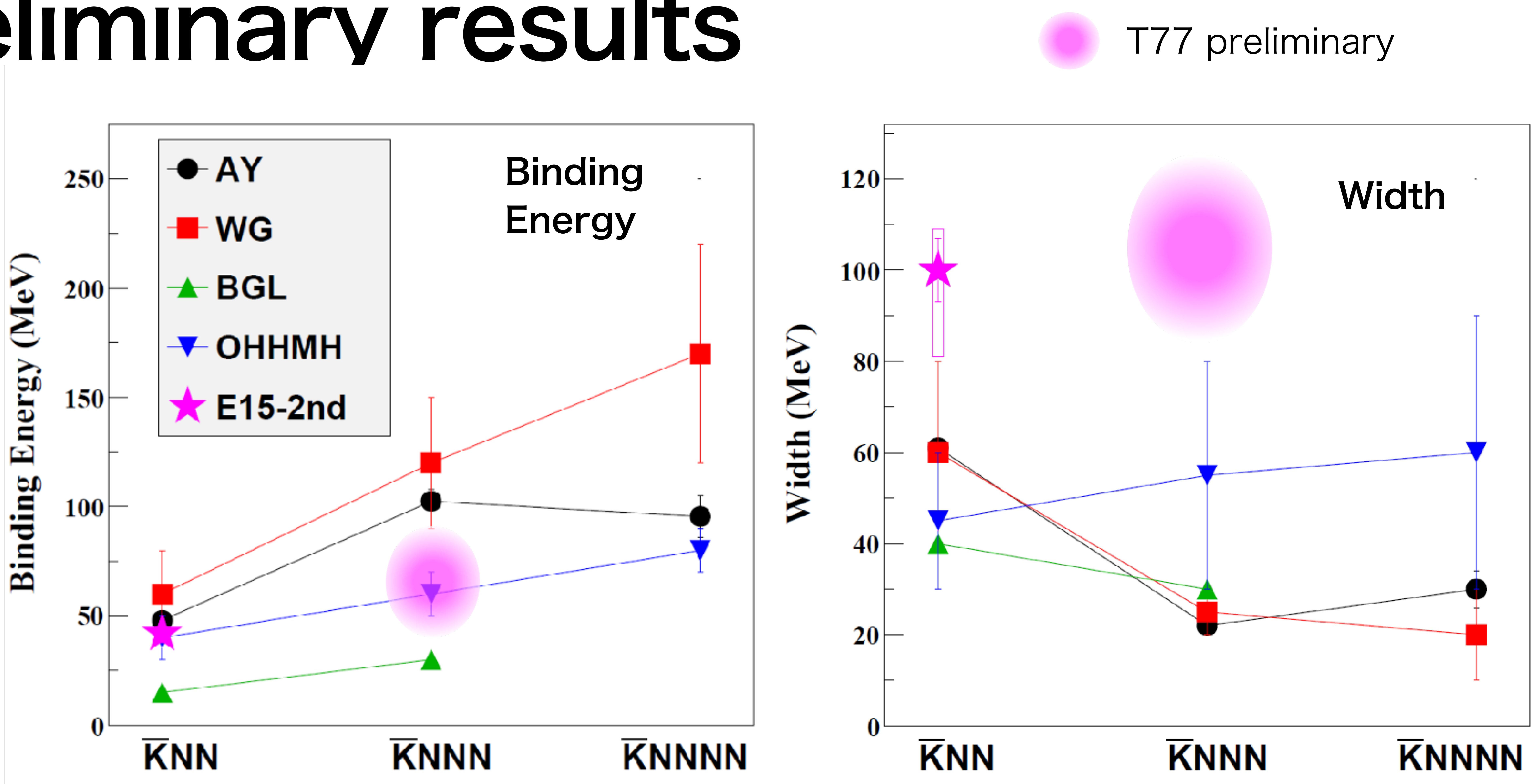


deep $\bar{K}N$ potential

B.E. ~ 40-70 MeV

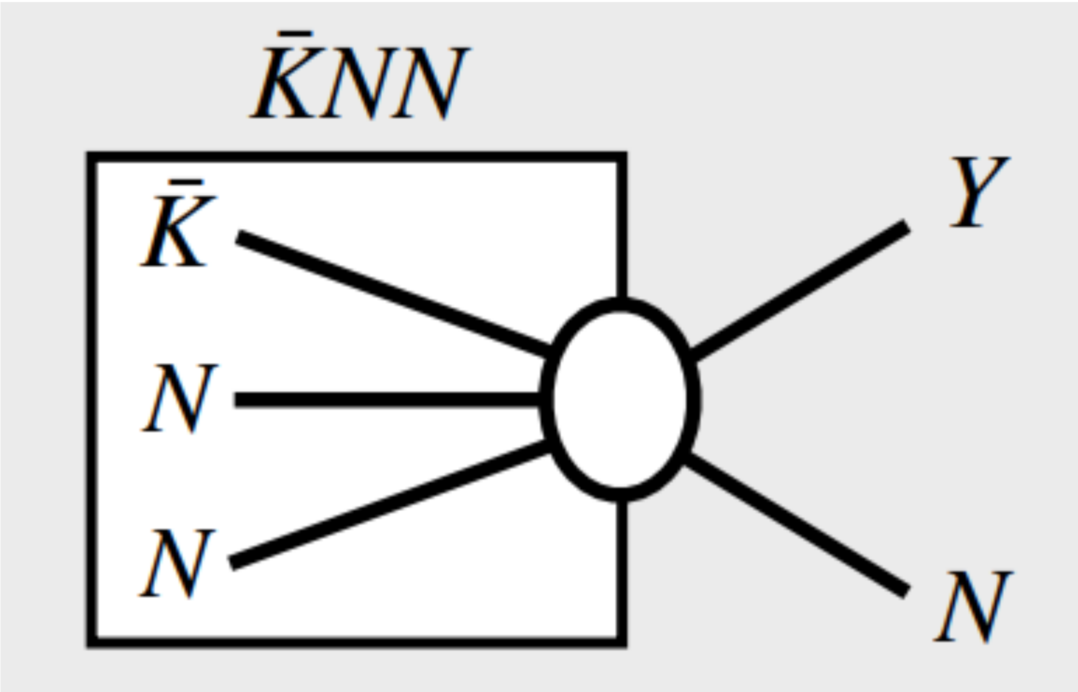
suggesting a more compact and dense system

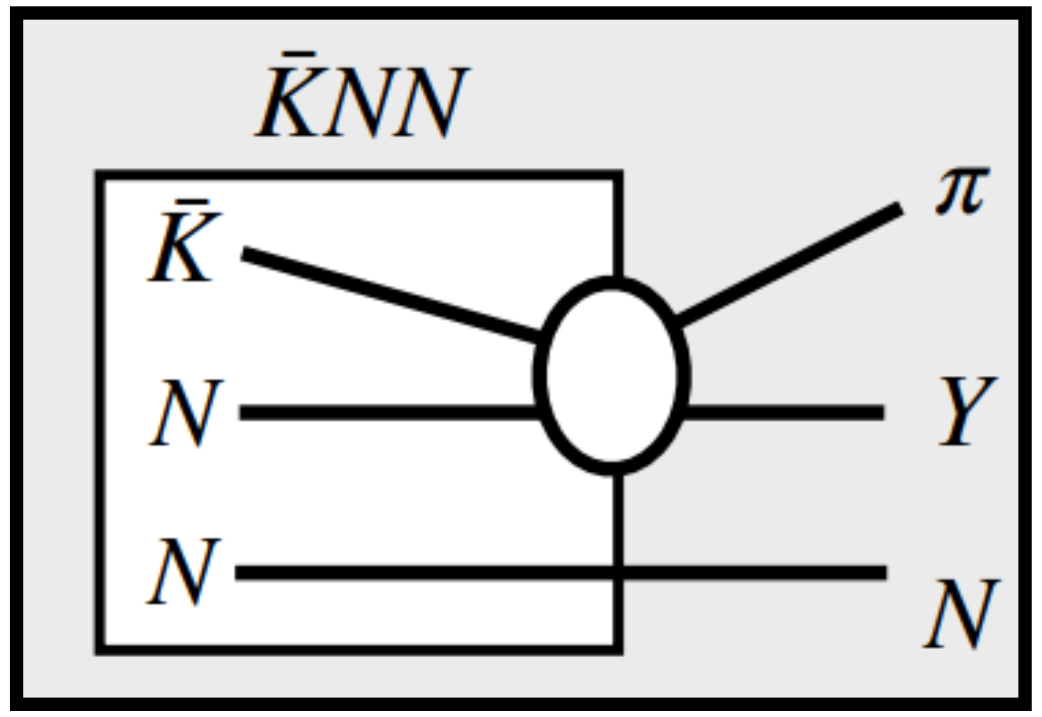
Preliminary results

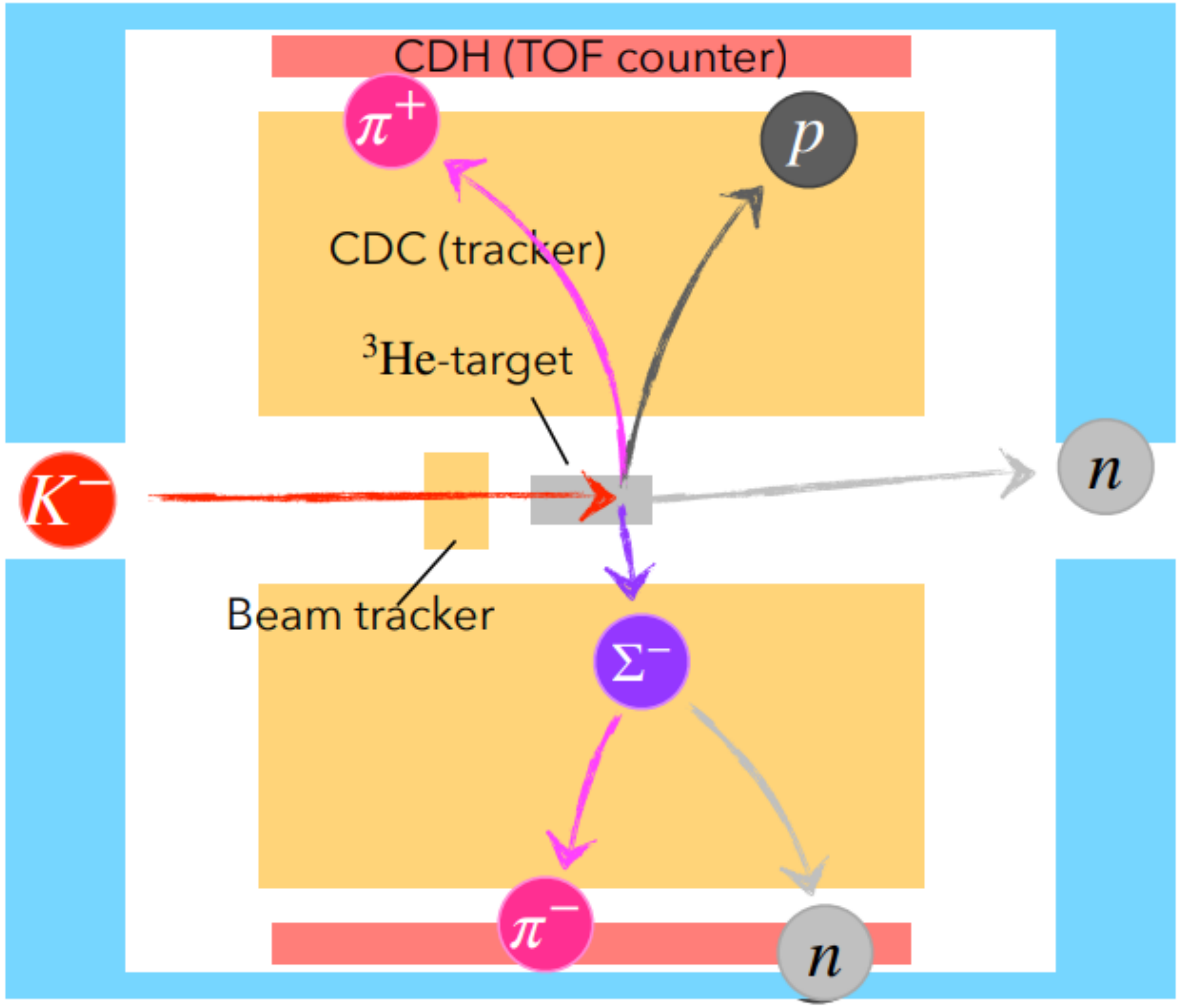


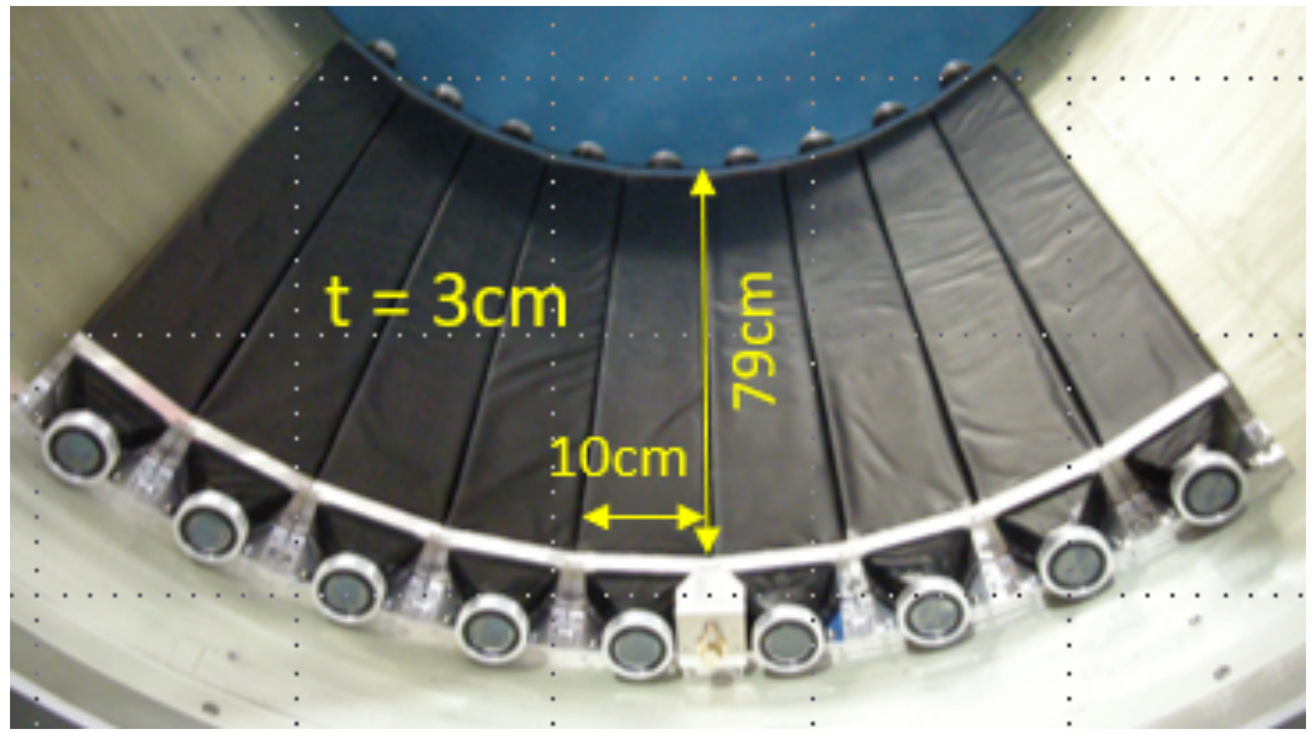
- The binding energy is compatible with some theoretical predictions
- "$\bar{K}NNN$" system might have larger binding than "$\bar{K}NN$".
- Experimental width is larger than theoretical predictions.

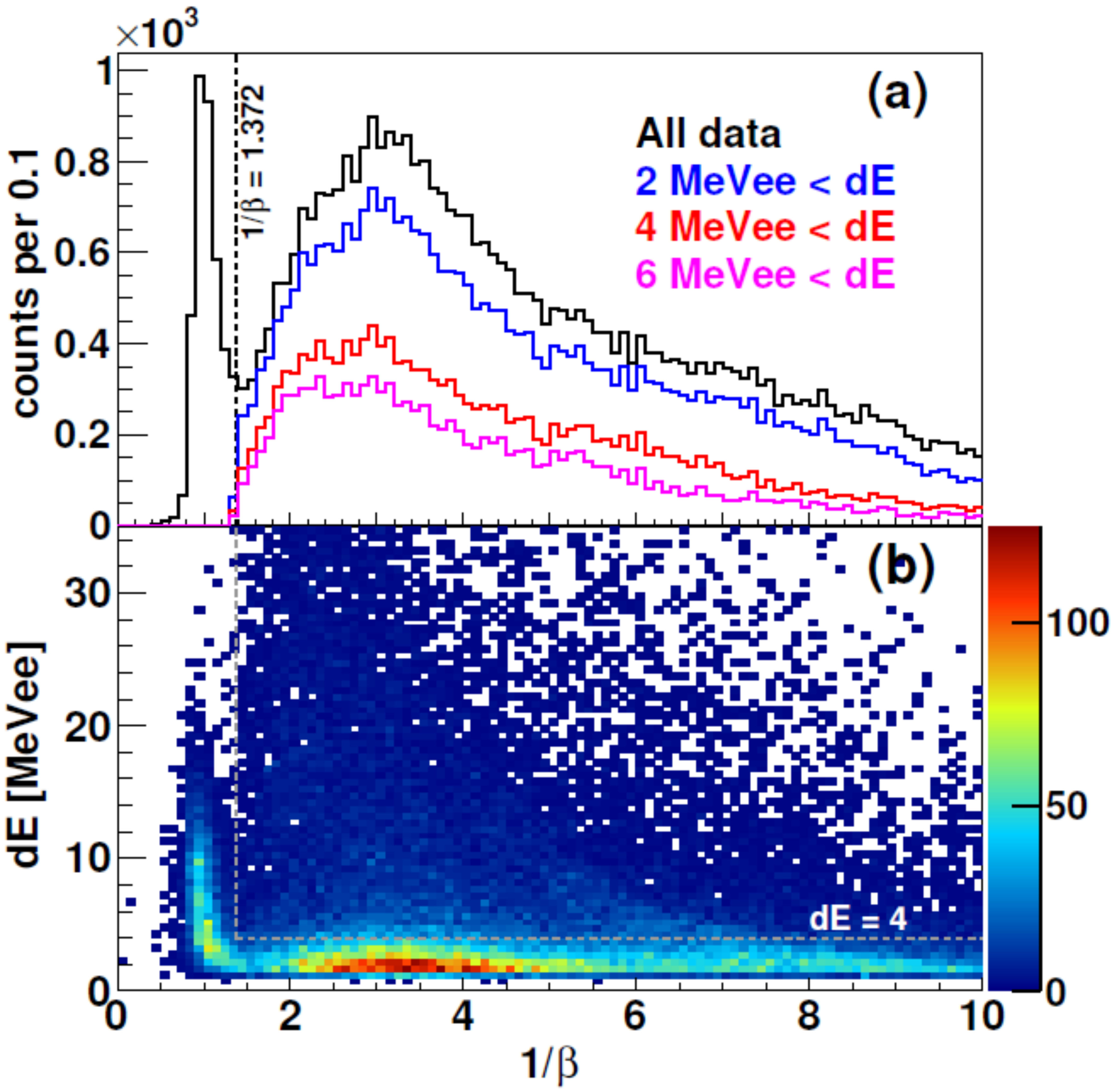
Mesonic Decay Analysis with the E15 Data











Neutron efficiency 3~9%

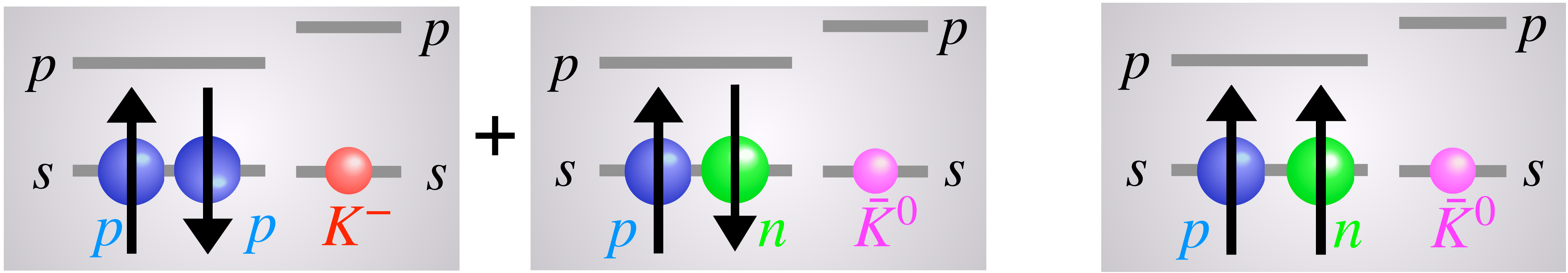
Is the observed state really $\bar{K}NN$?

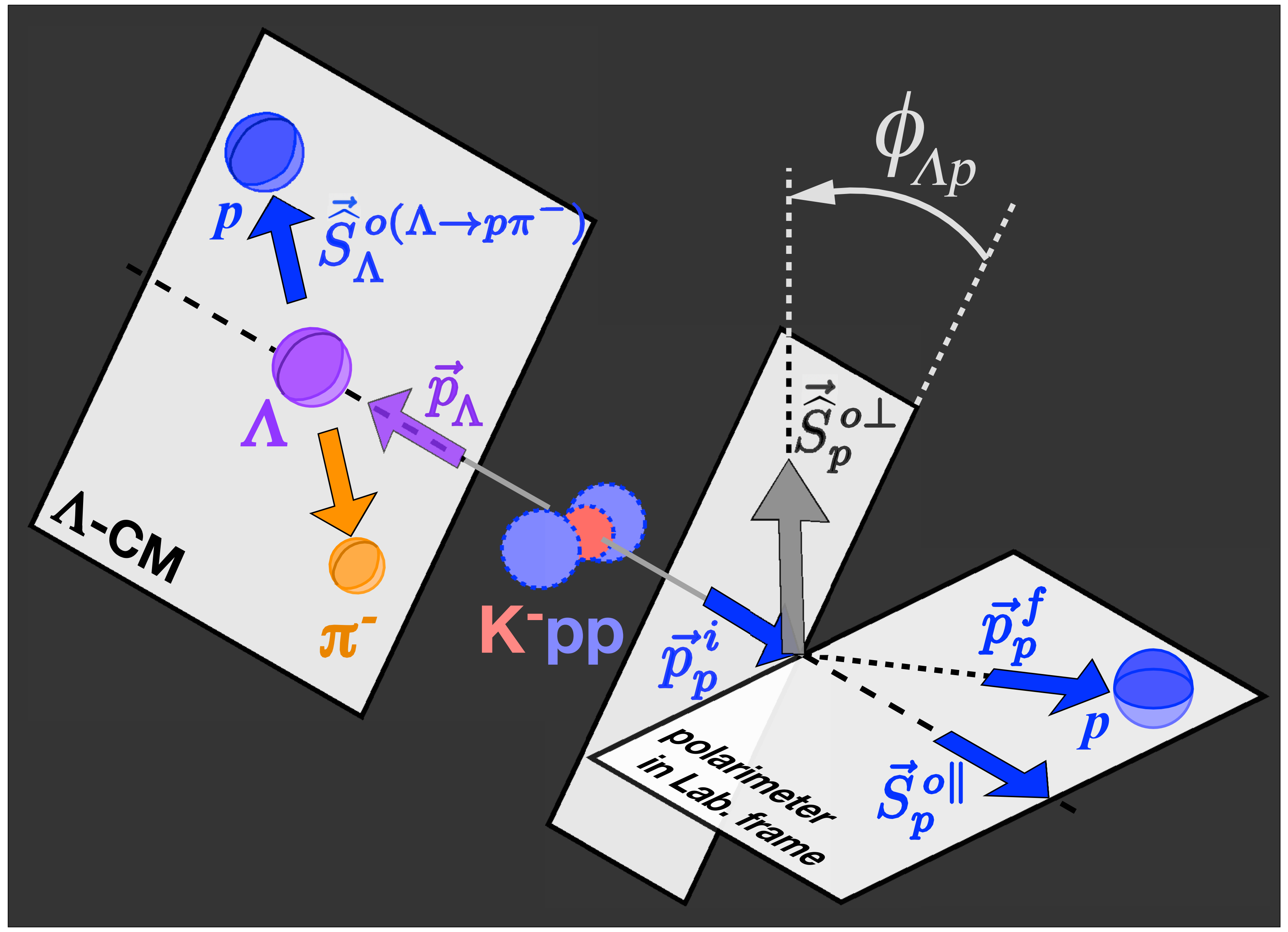
- Isospin partner should exist
  - "$\bar{K}^0nn$" $\rightarrow \Lambda n, \Sigma^- p$ analysis
  - need neutron detection
- Spin-parity measurement:
  - spin-spin correlation between Λ and p
  - need polarimeter for proton

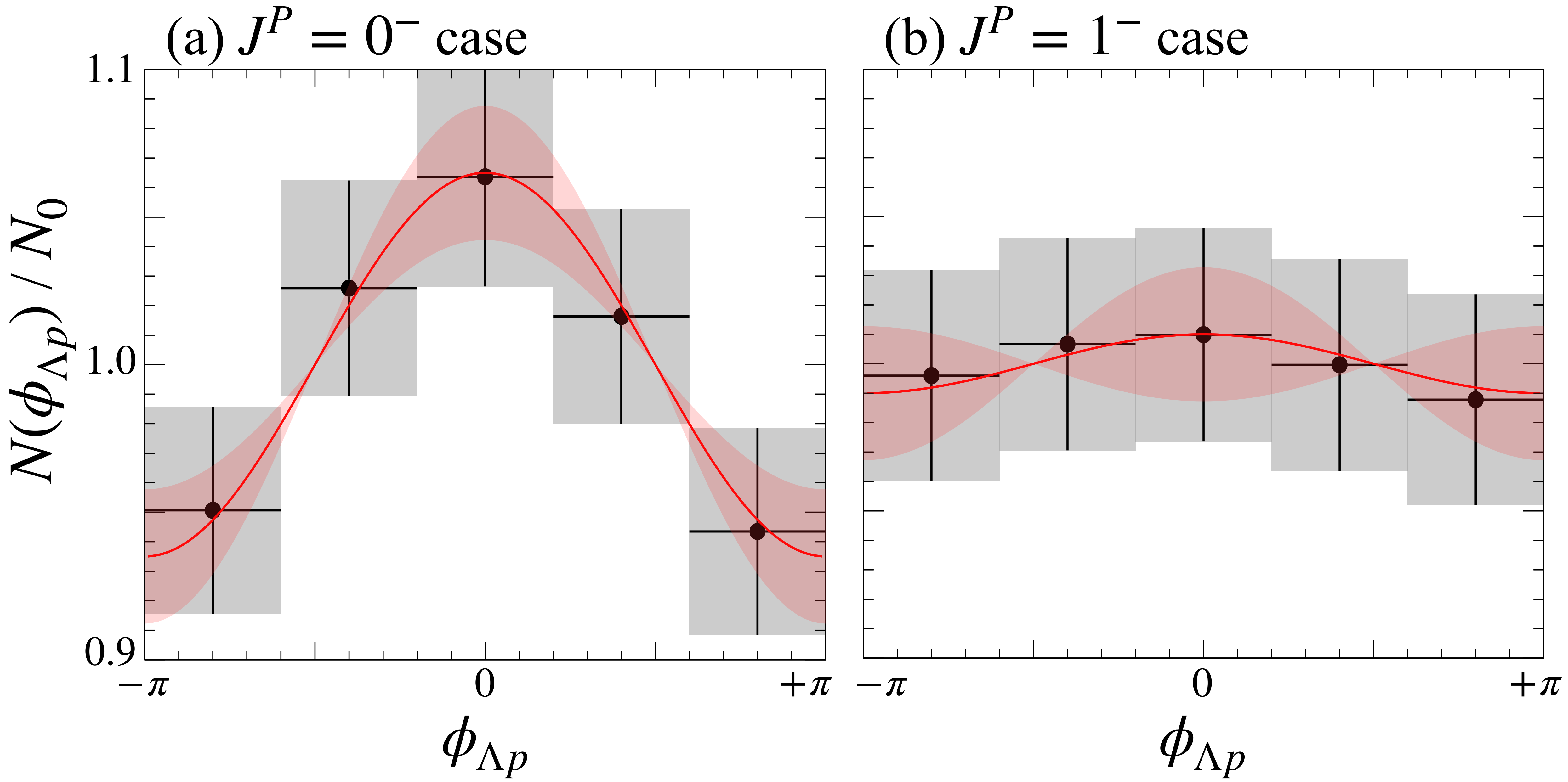
$\bar{K}NN(I = 1/2)$

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

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

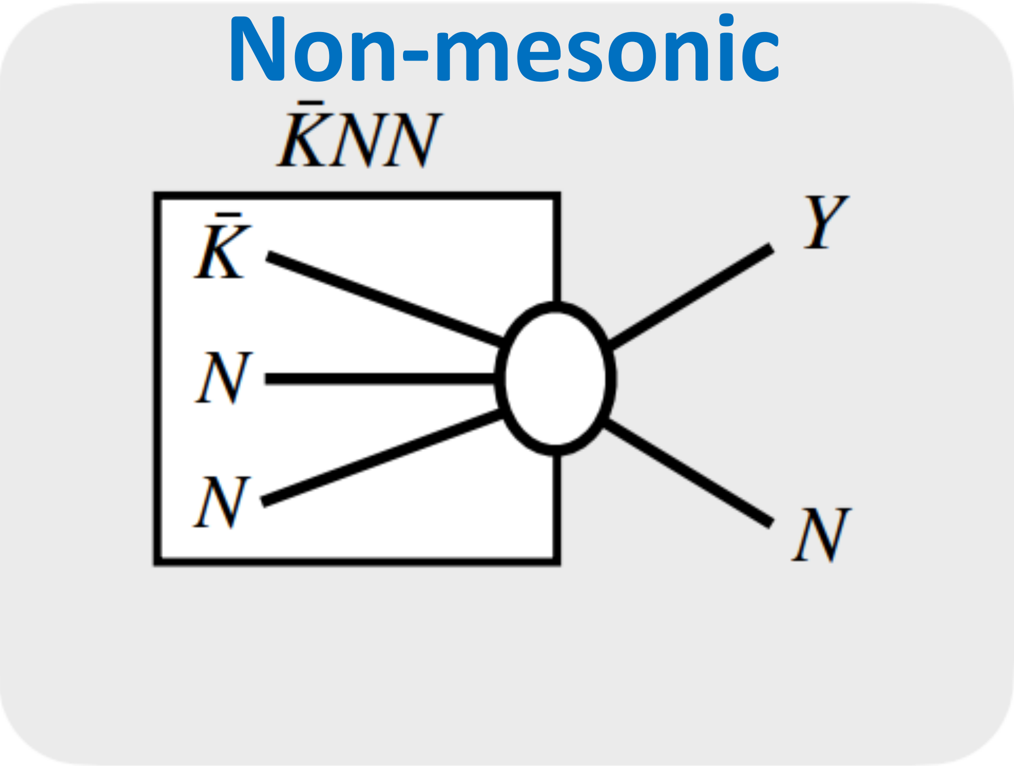




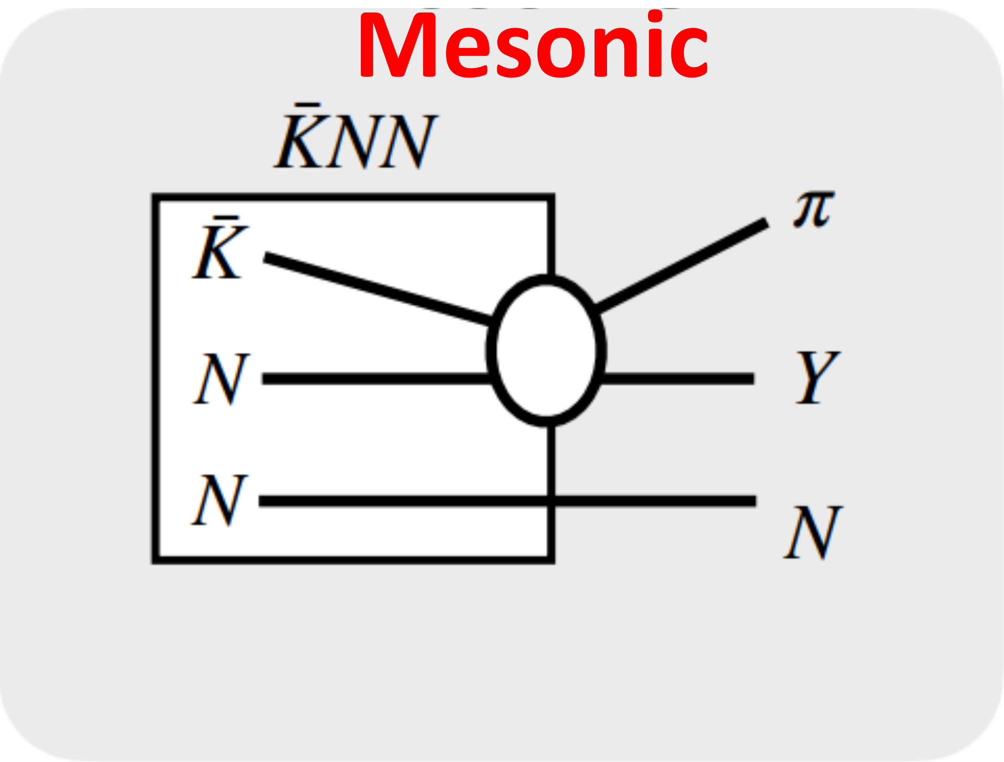


How compact is the system?

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



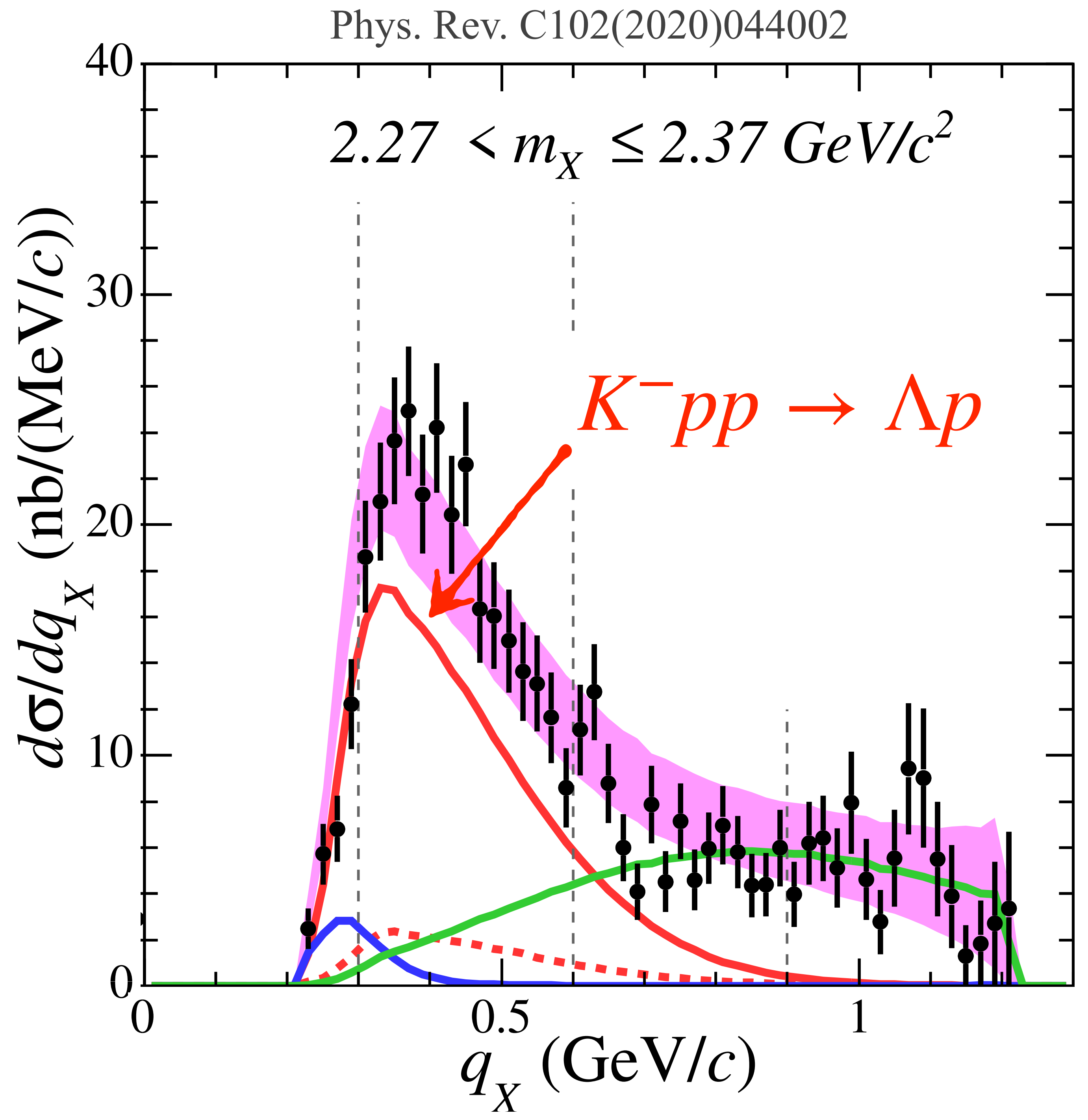
2N absorption

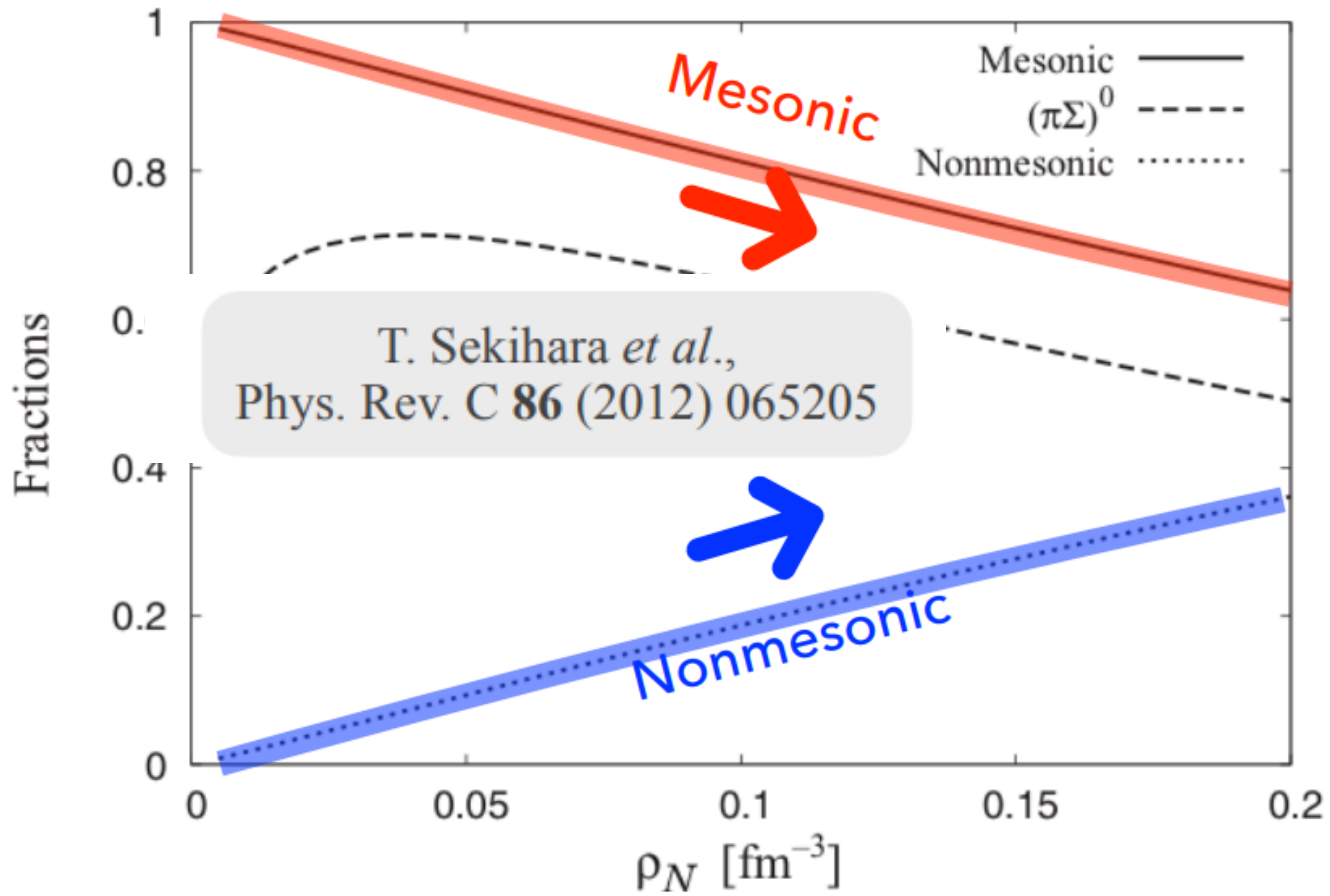


1N absorption

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

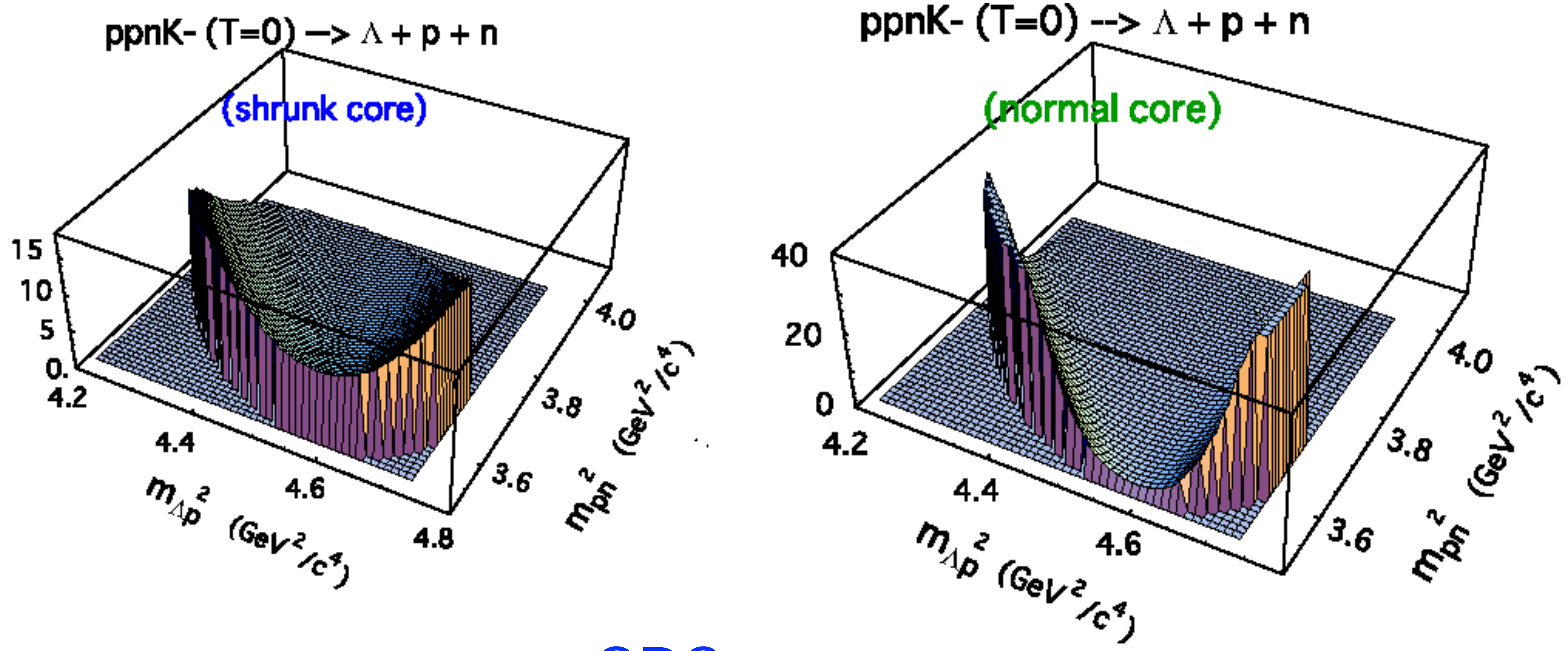
3N absorption 2N absorption

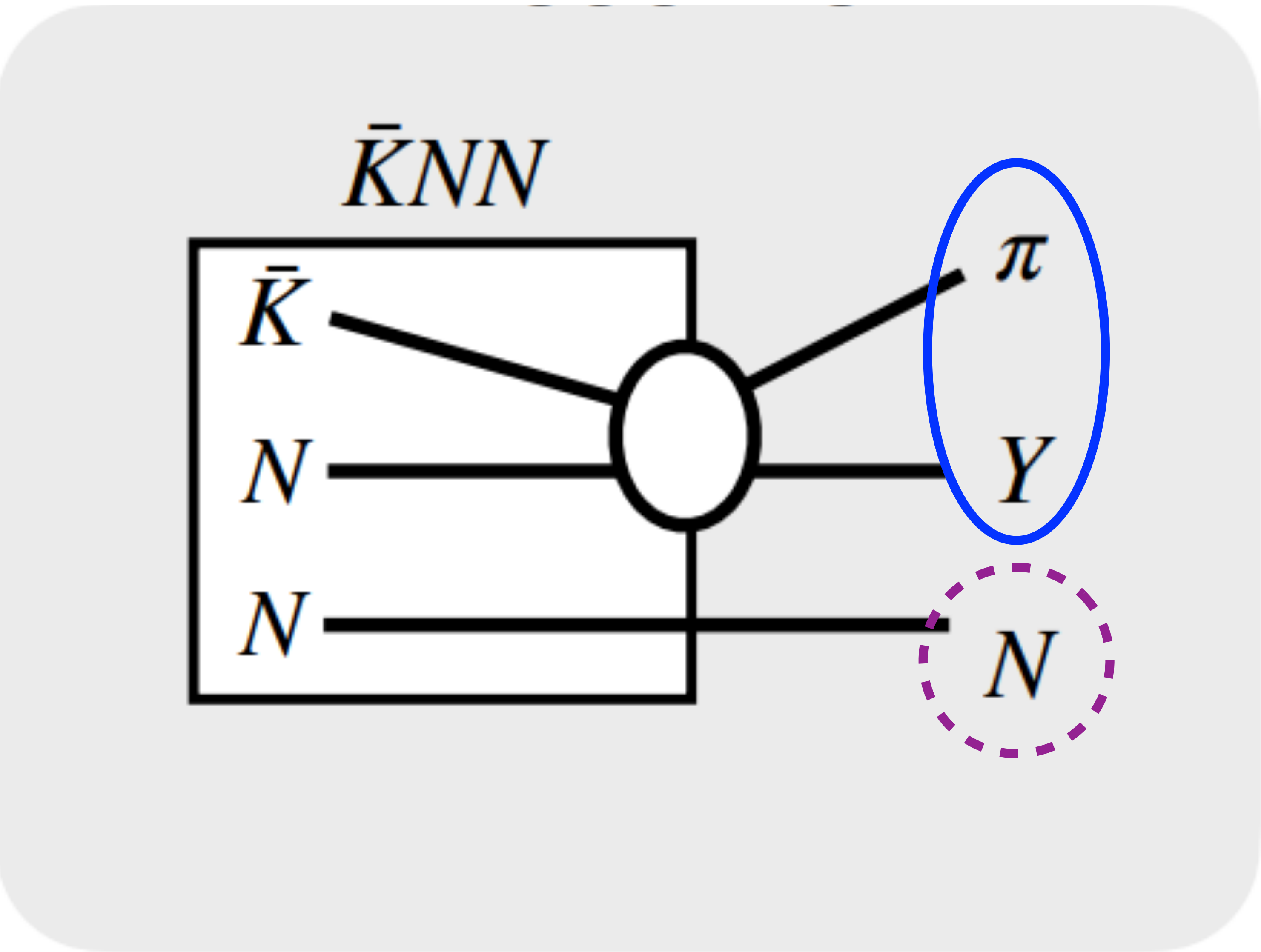




How compact is the system?

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

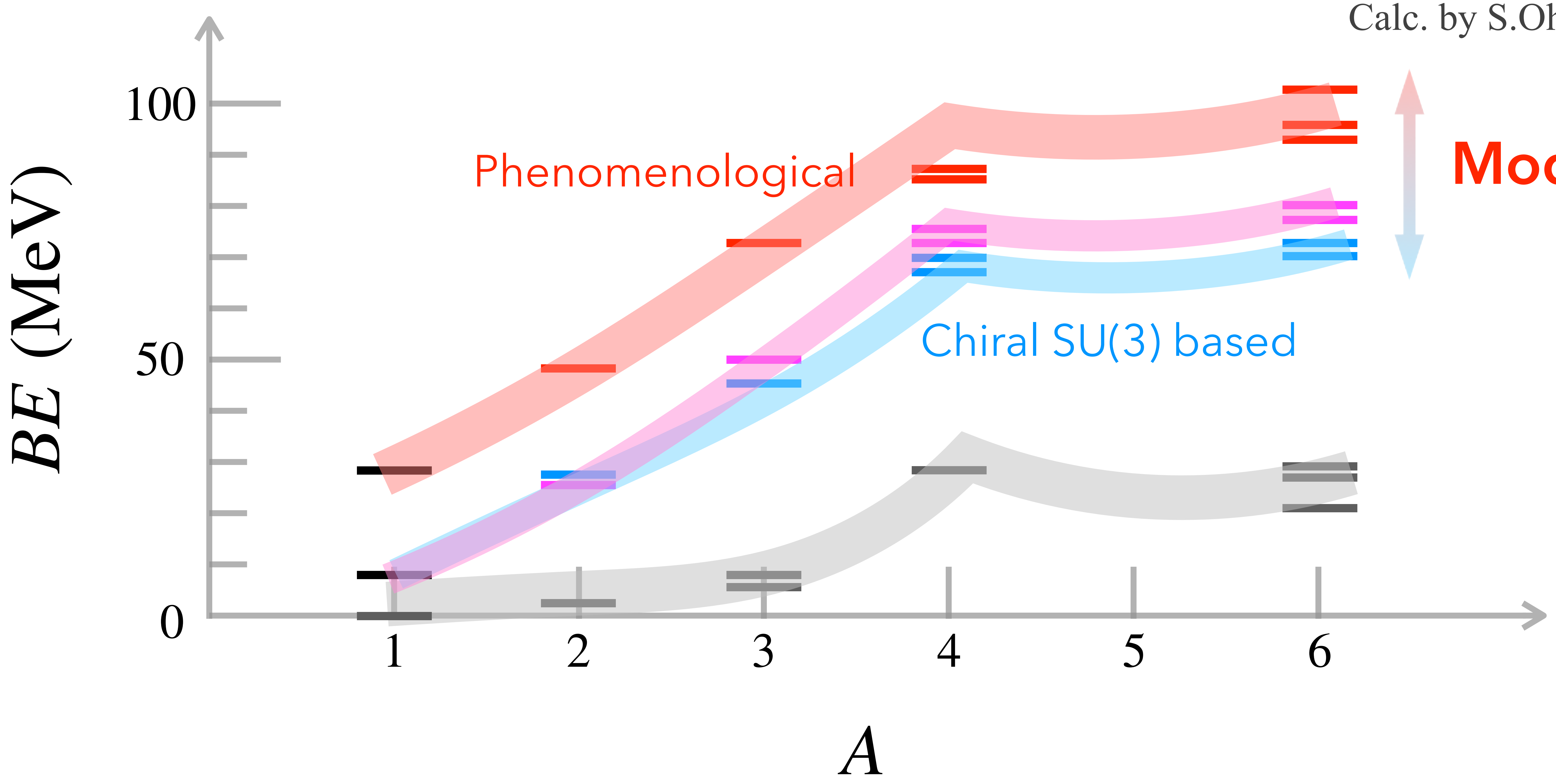
$$K^- + {}^3\mathrm{He} \rightarrow (\pi Y + N_s) + N_f$$

forward TOF

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

How general are the K^bar-nuclei?

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



Model dependence

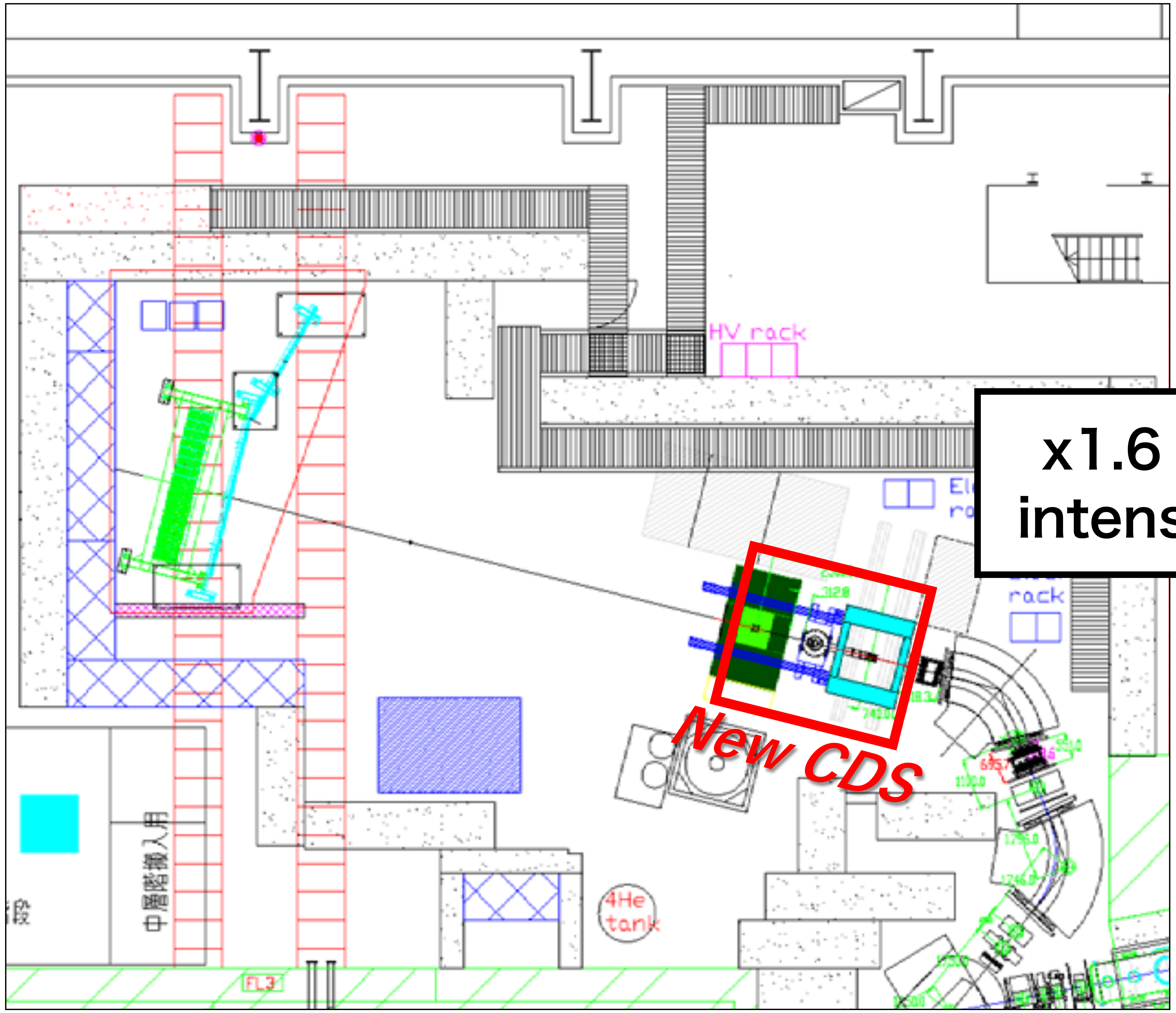
$\left\{ \begin{array}{l} E\text{-dep. of } \bar{K}N \text{ int.} \\ E_{\bar{K}N} \text{ in system} \end{array} \right.$

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

Exclusive analysis becomes difficult.
→ Inclusive + tag.

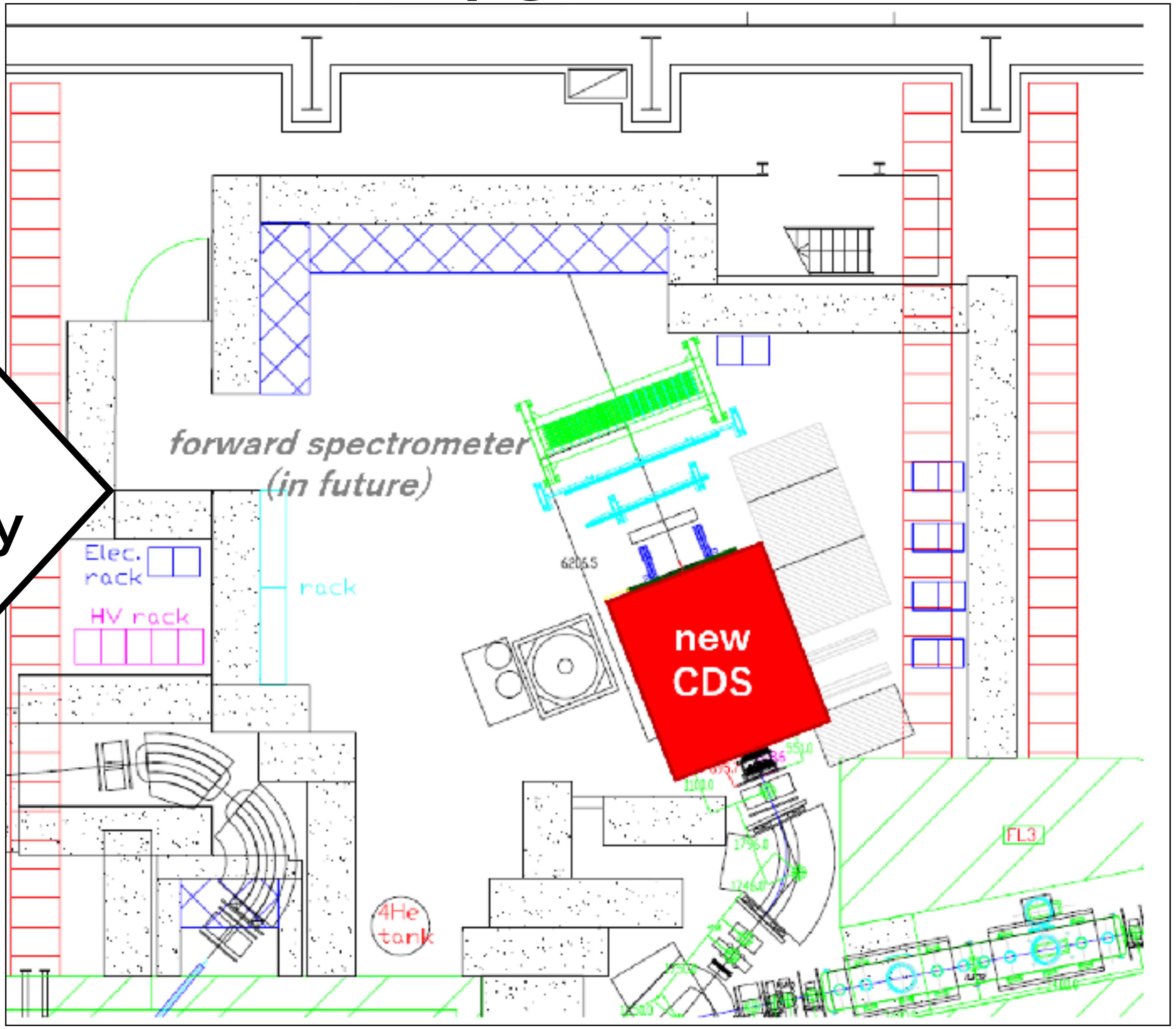
HEF K1.8BR beamline upgrade (in JFY2026?)

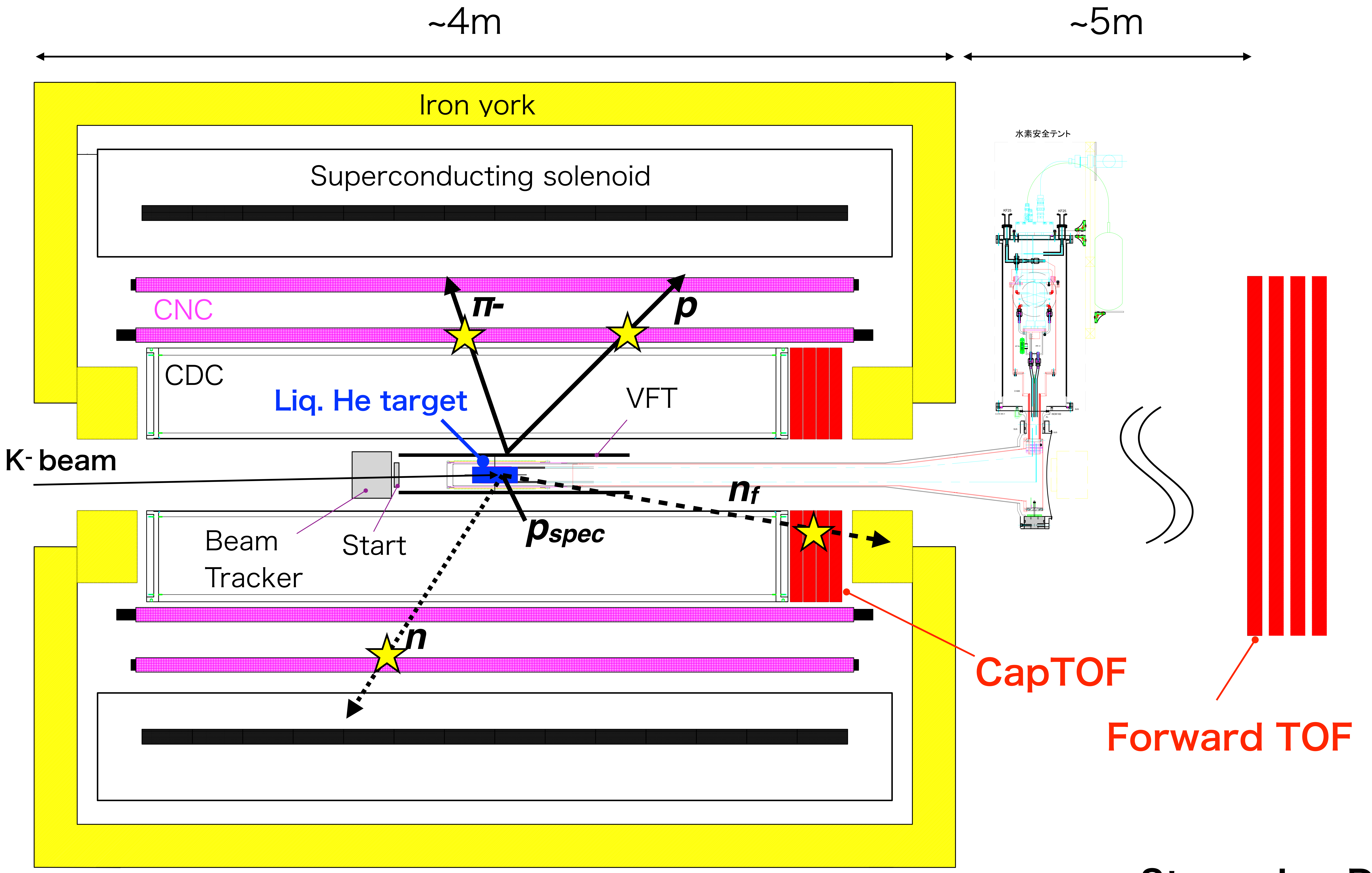
Present



x1.6 K- intensity

Upgraded





+ Streaming DAQ