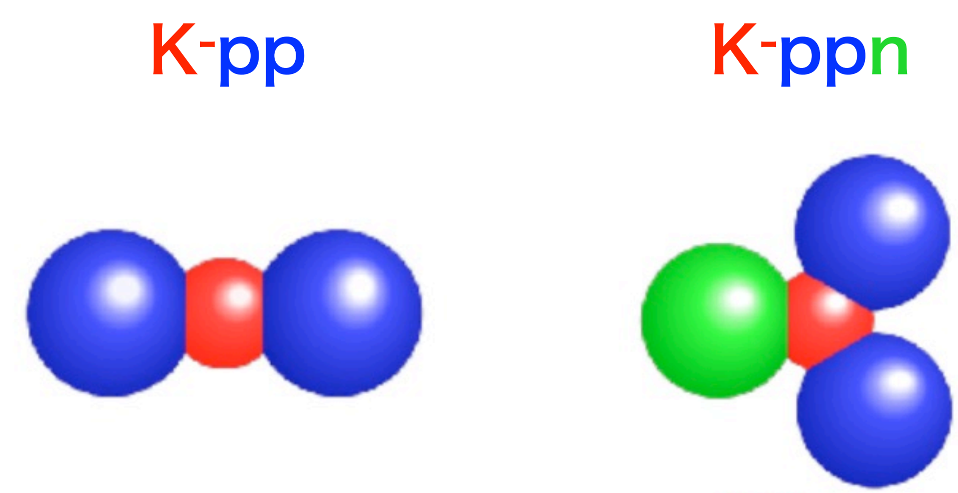


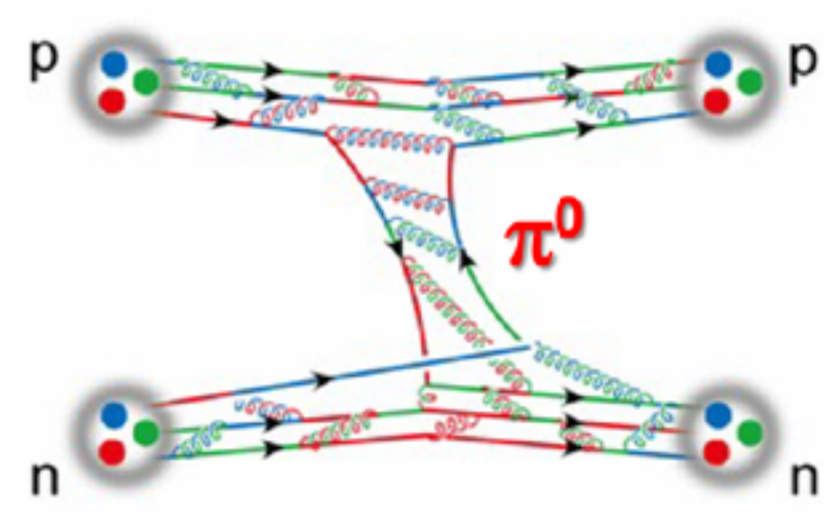
J-PARC (K1.8BR) における K中間子原子核研究の状況と展望

橋本　直 (JAEA ASRC)
for the J-PARC E15/T77/E80 collaboration

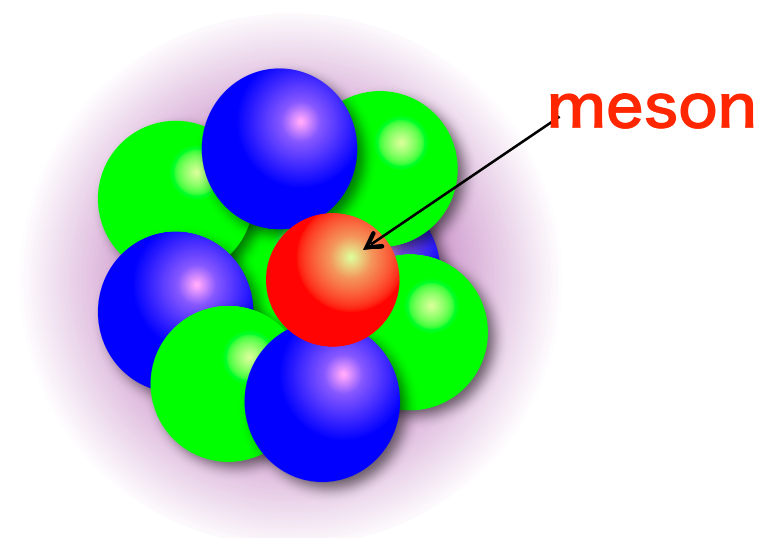
December 6-7, 2022 @ ELPH, Sendai

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)

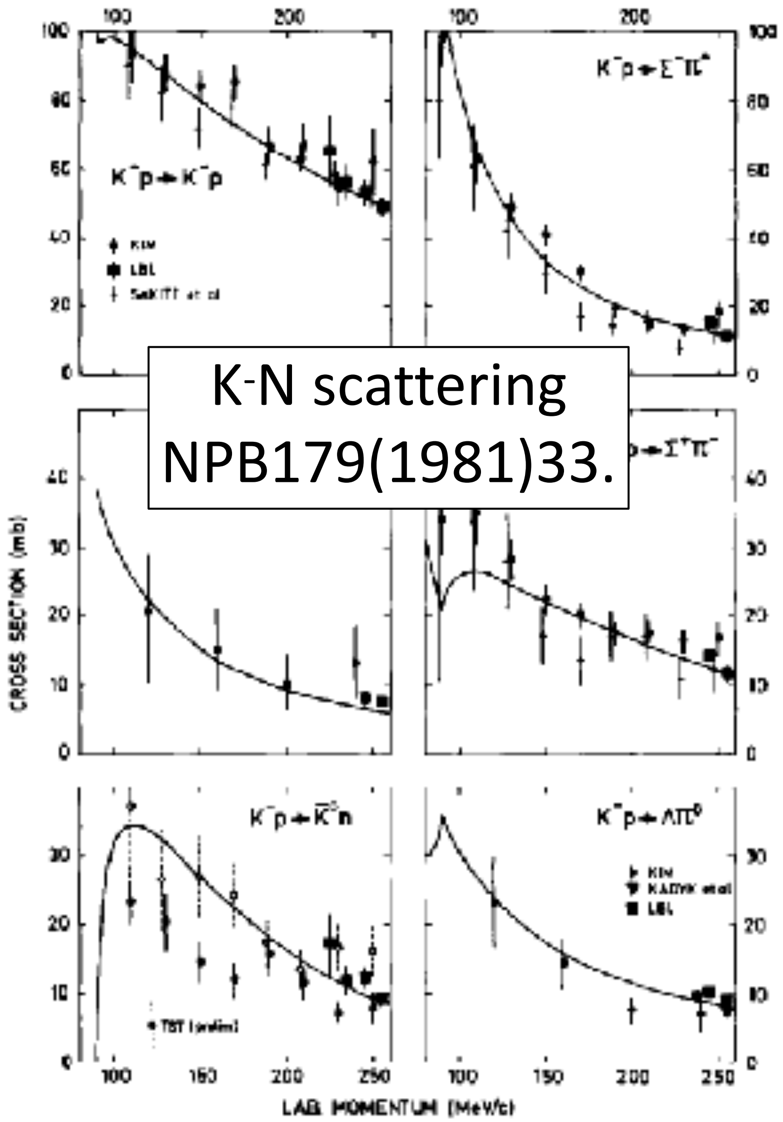


☐ Can meson be a constituent particle forming nuclei?

☐ If yes, how do meson and core nucleus change?

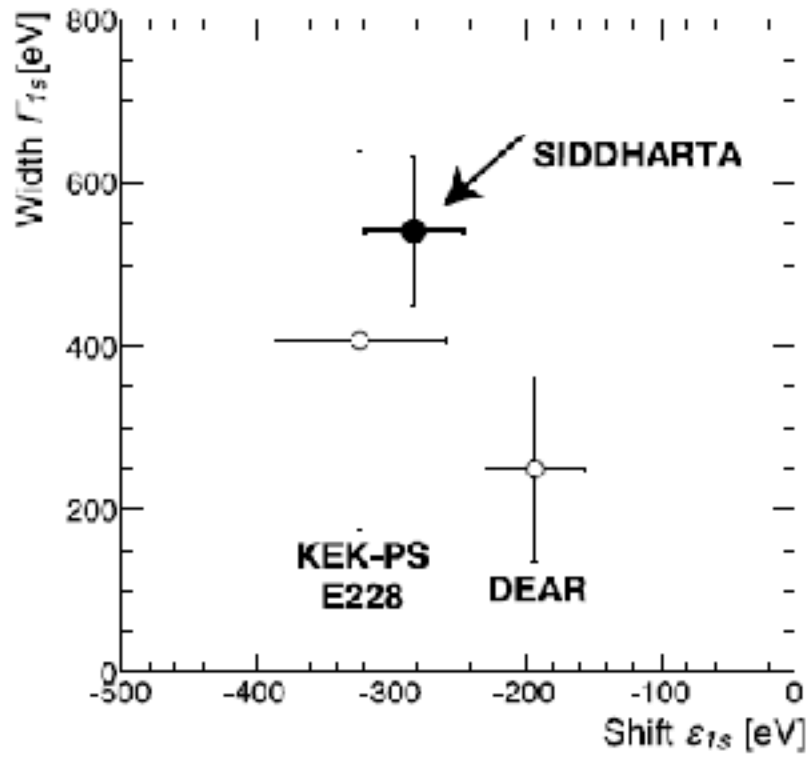
We would like to experimentally establish such exotic nuclei

Kaonic nuclei



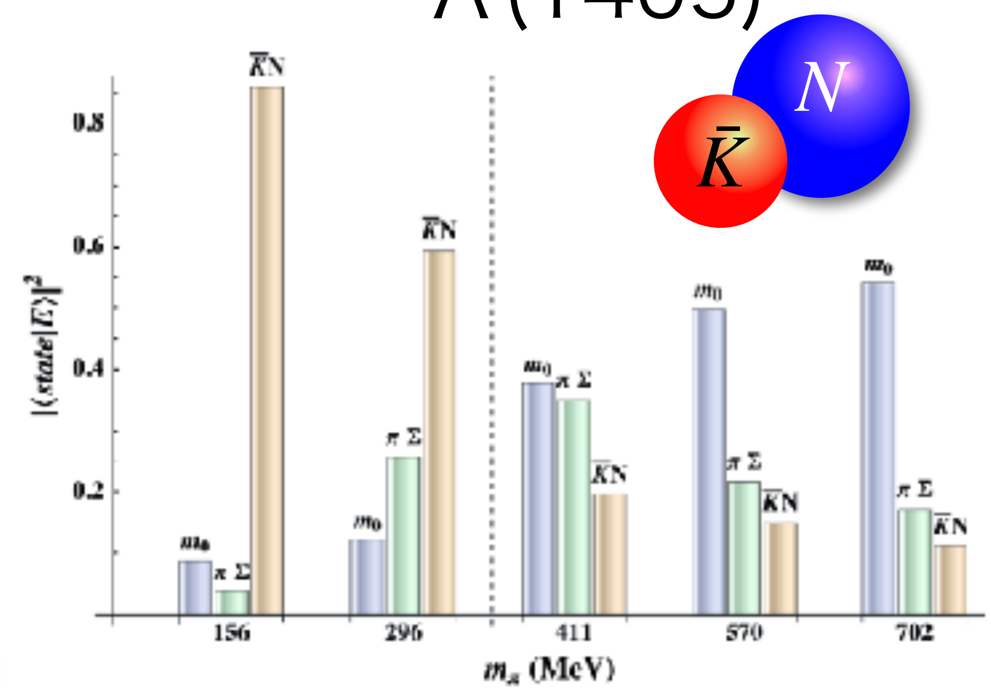
K-N scattering
NPB179(1981)33.

K-p atom
PLB704(2011)113.



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

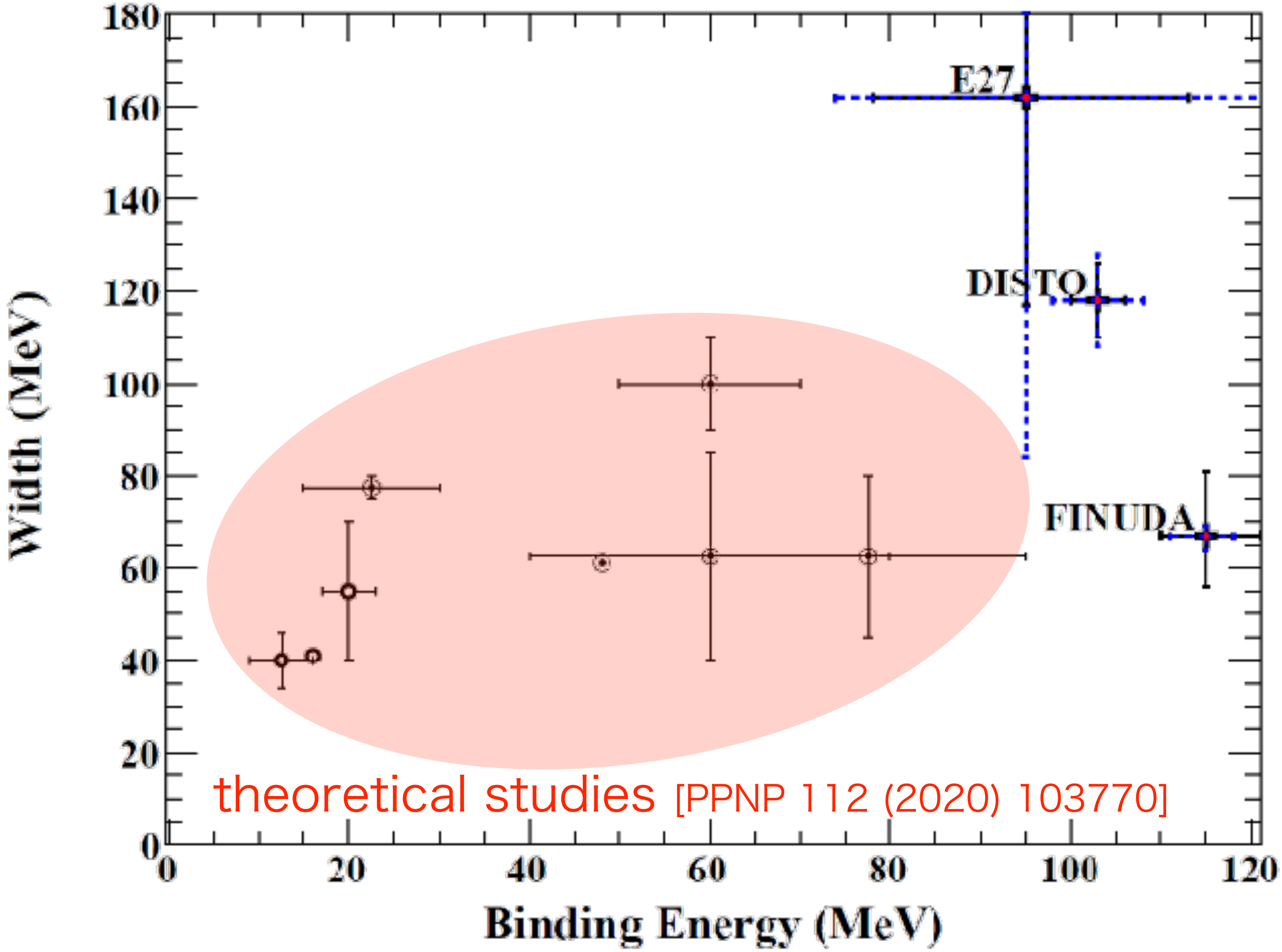
Λ(1405)



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



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

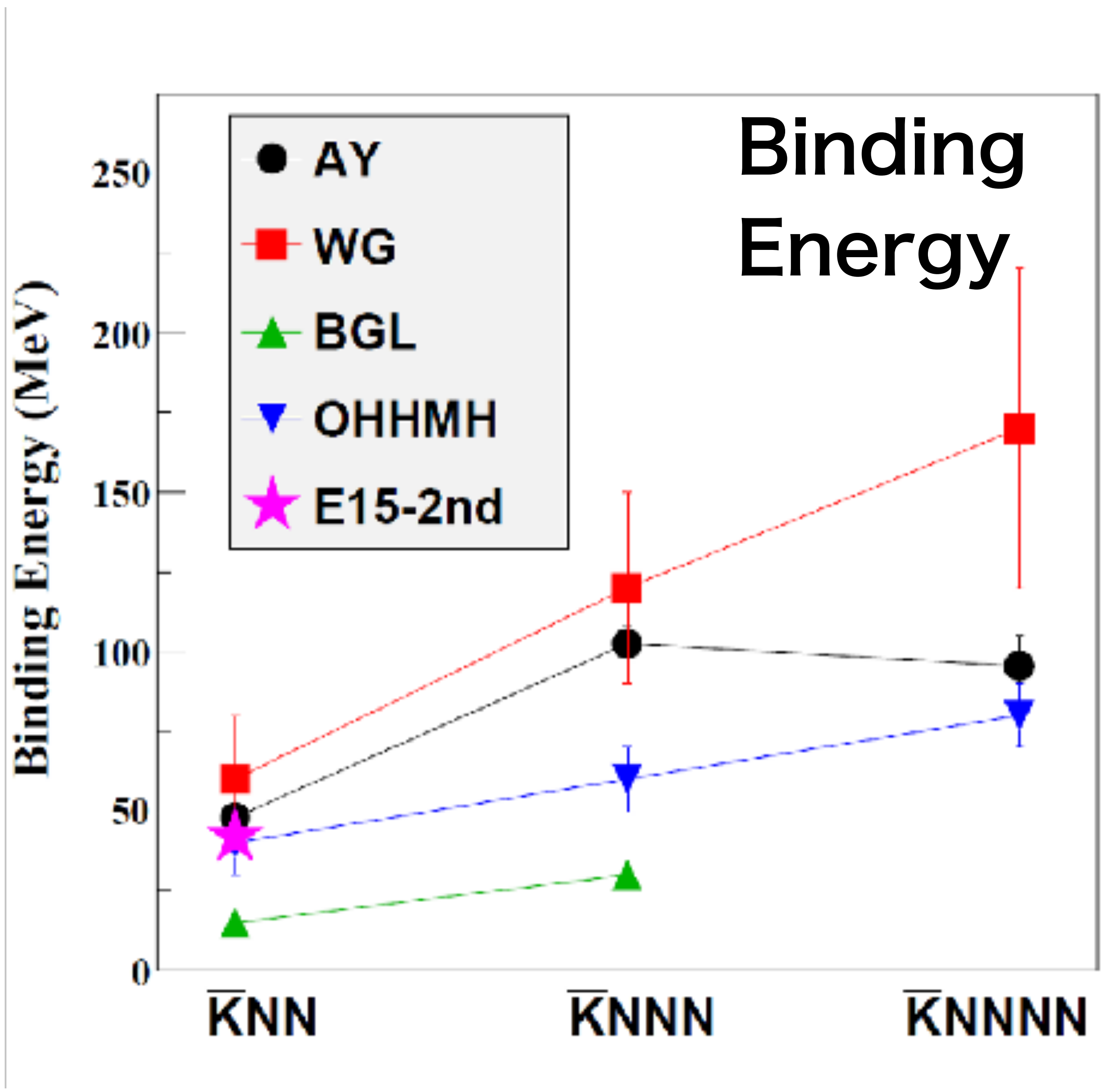
- **Theoretical calculations agree on the existence of $\bar{K}NN$, but B.E. and Γ depend on the $\bar{K}N$ interaction models.**
- **No conclusive experimental evidence so far.**

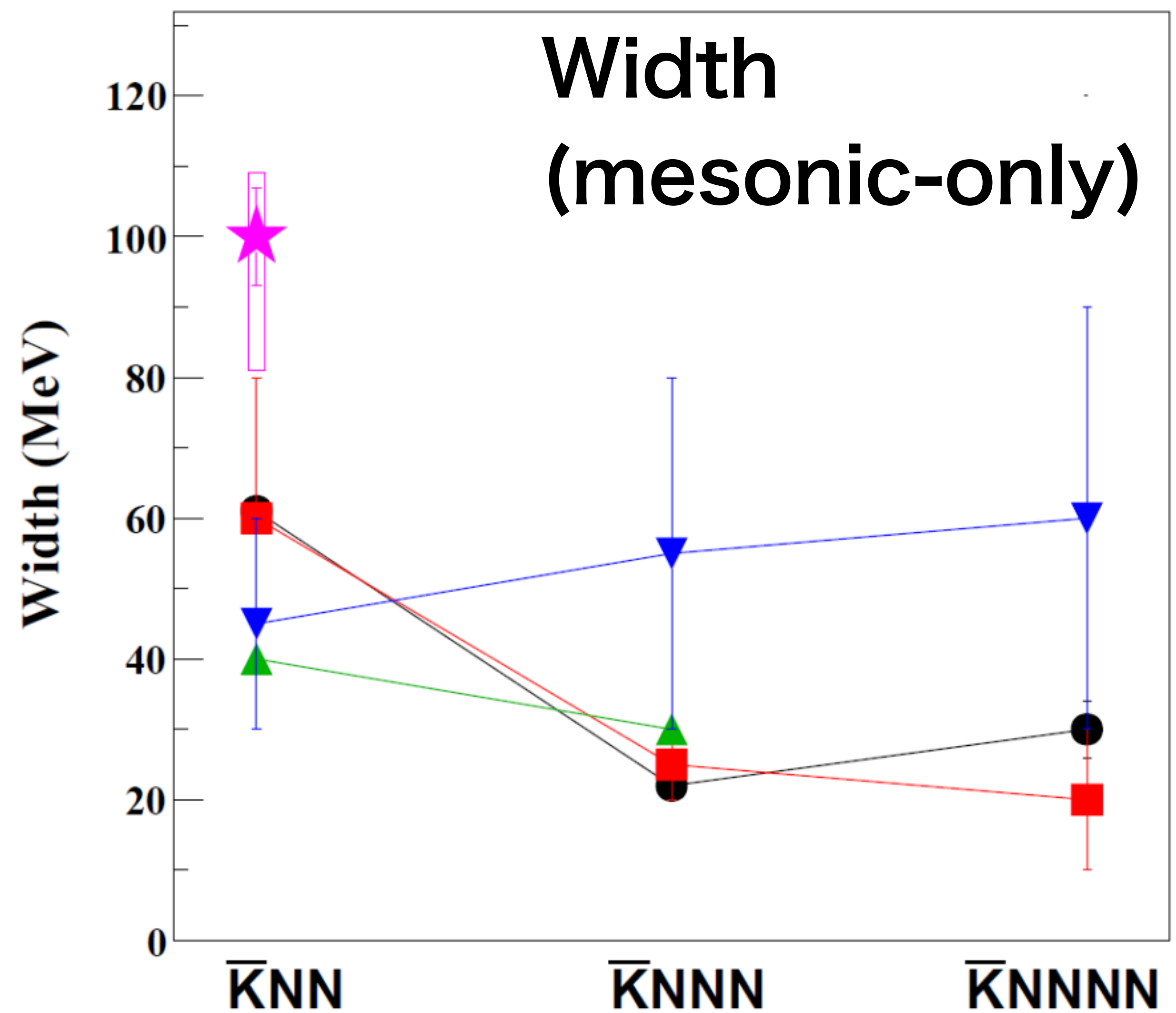
Mass number dependence

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

Not a complete list. sorry…

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



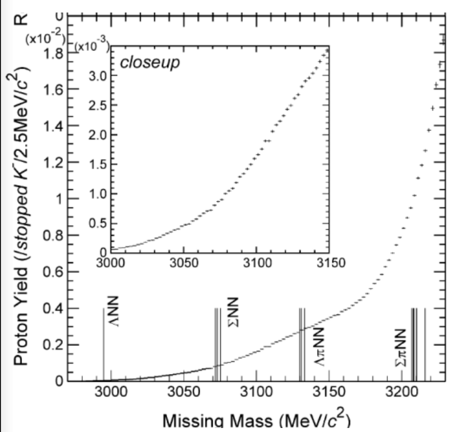


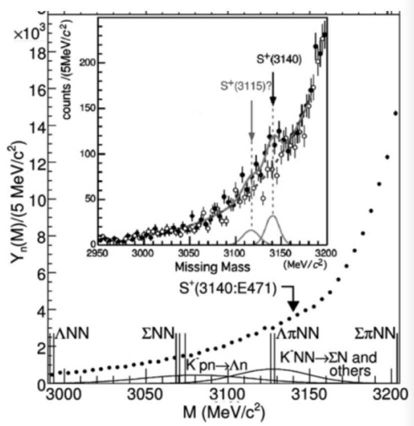
Larger binding than $\bar{K}NN$ and similar width are predicted.

$\bar{K}NNN$: Experimental situaion

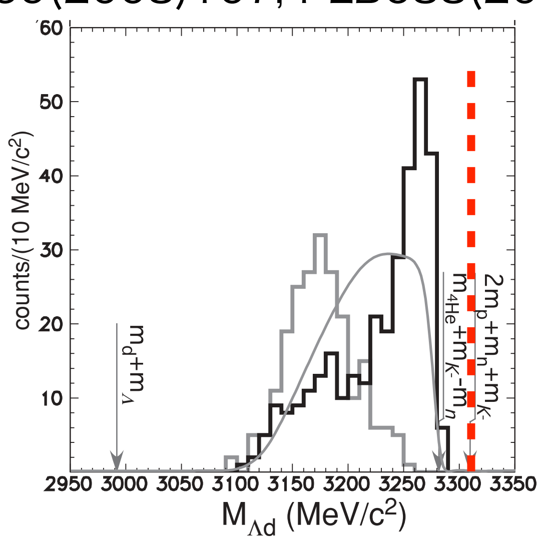
Stopped K⁻ on ⁴He

E471/E549@KEK





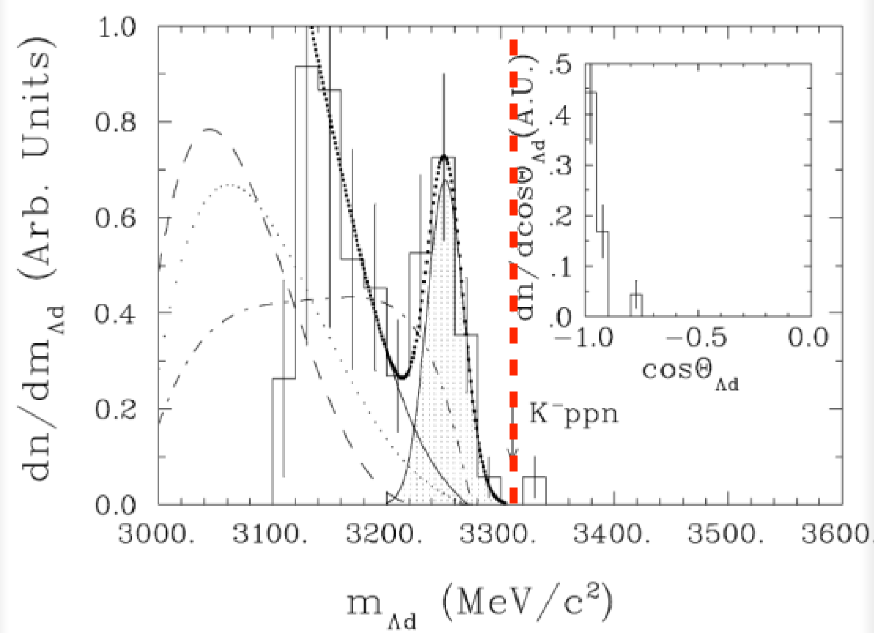
PLB659(2008)107, PLB688(2010)43



PRC76(2007)068202

Stopped K⁻ on Li/C back-to-back Λd

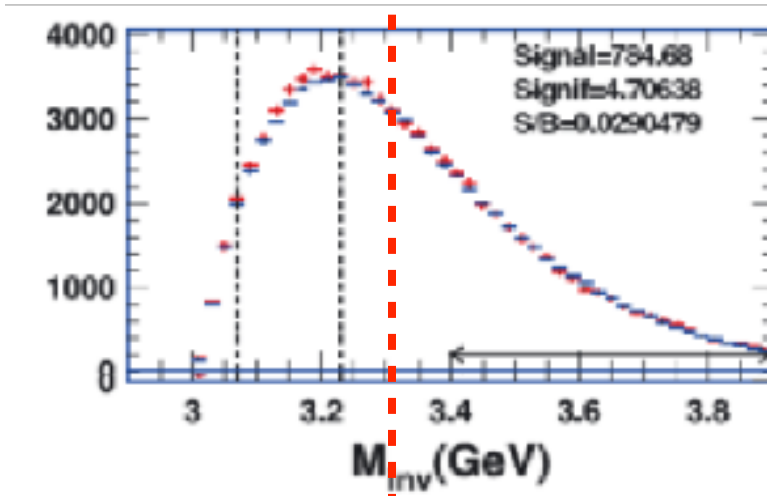
FUNUDA@DAΦNE

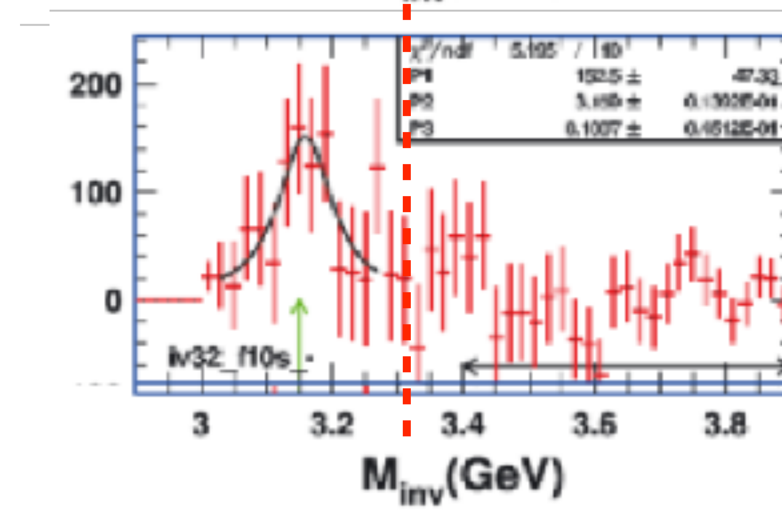


PLB654(2007)80

Λd in Ni+Ni

FOPI@GSI

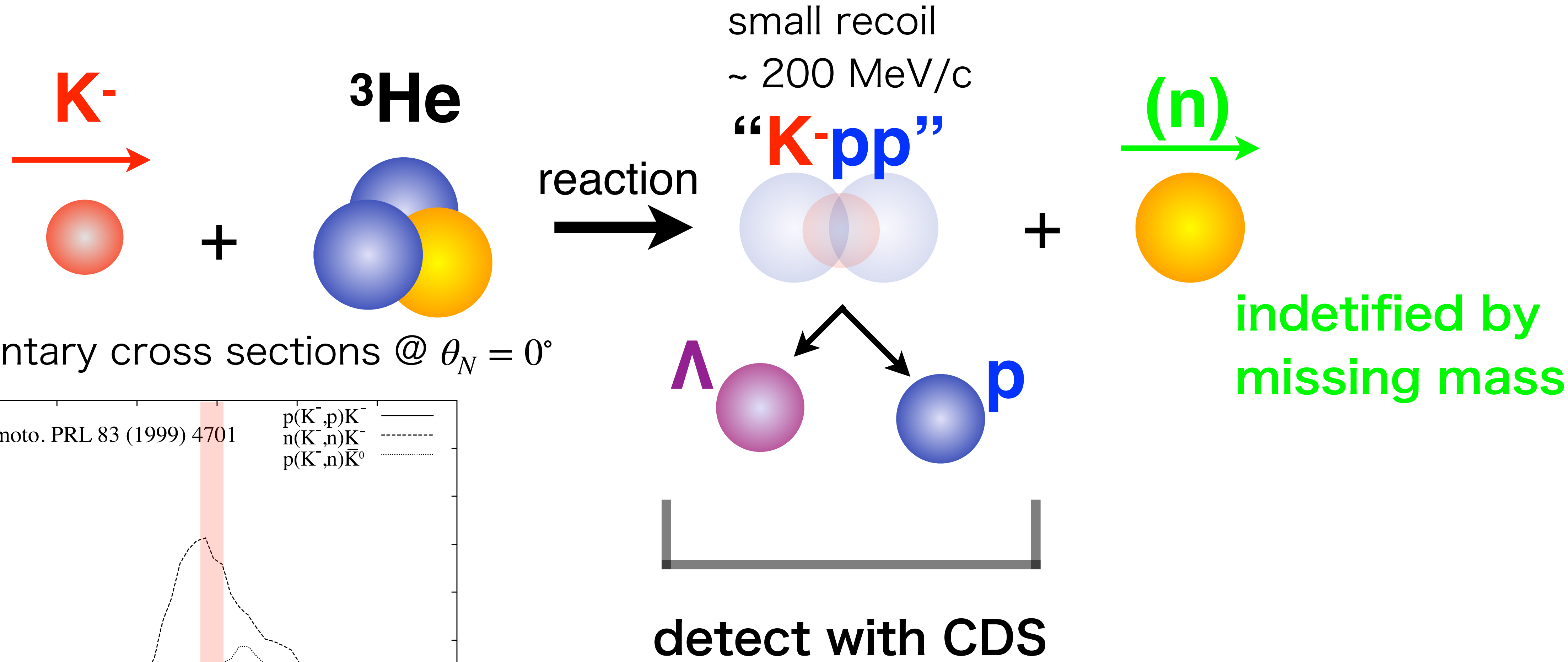




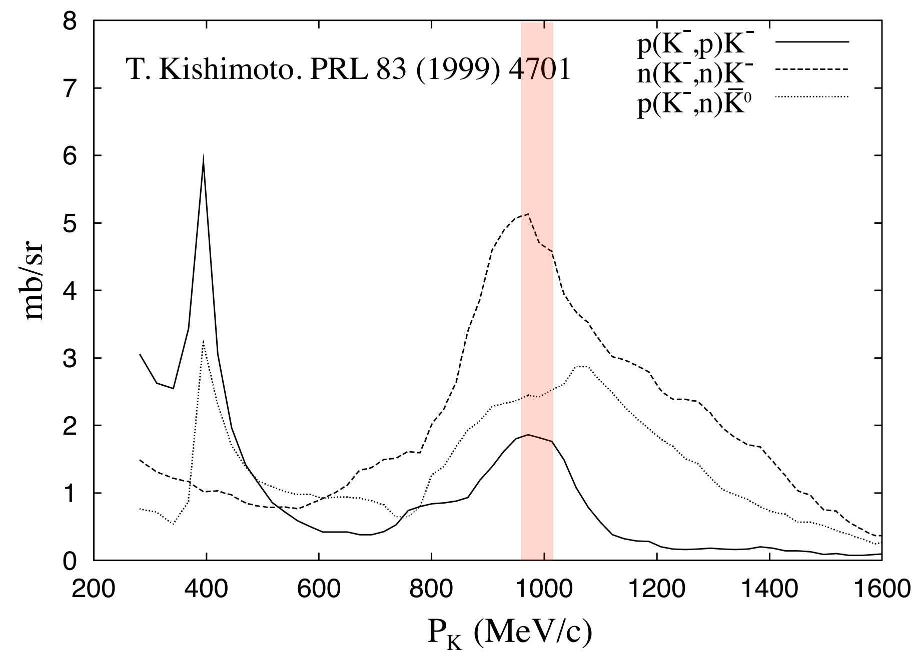
EXA05 Proceedings (2005)

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

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

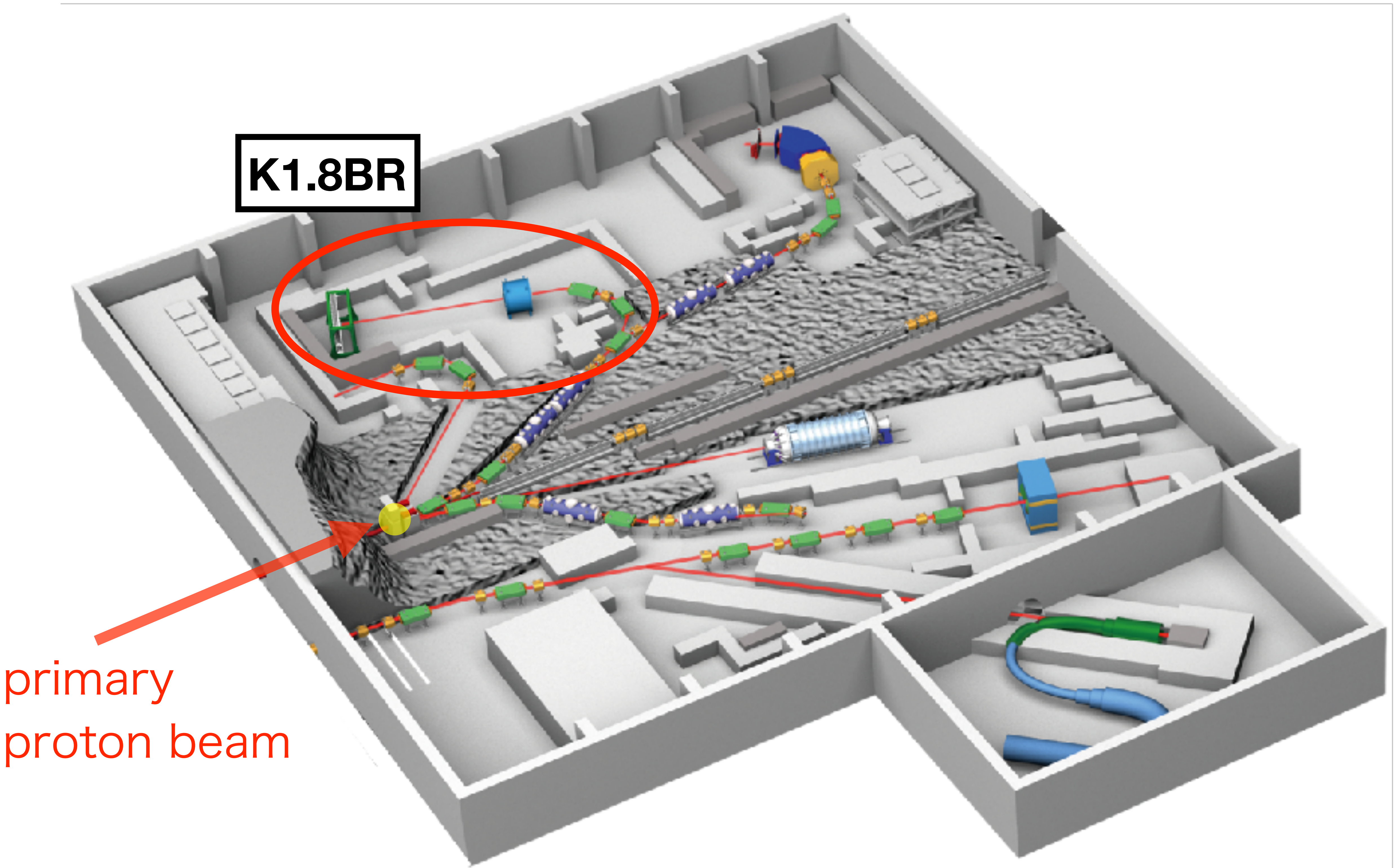


(K^-, N) elementary cross sections @ $\theta_N = 0°$

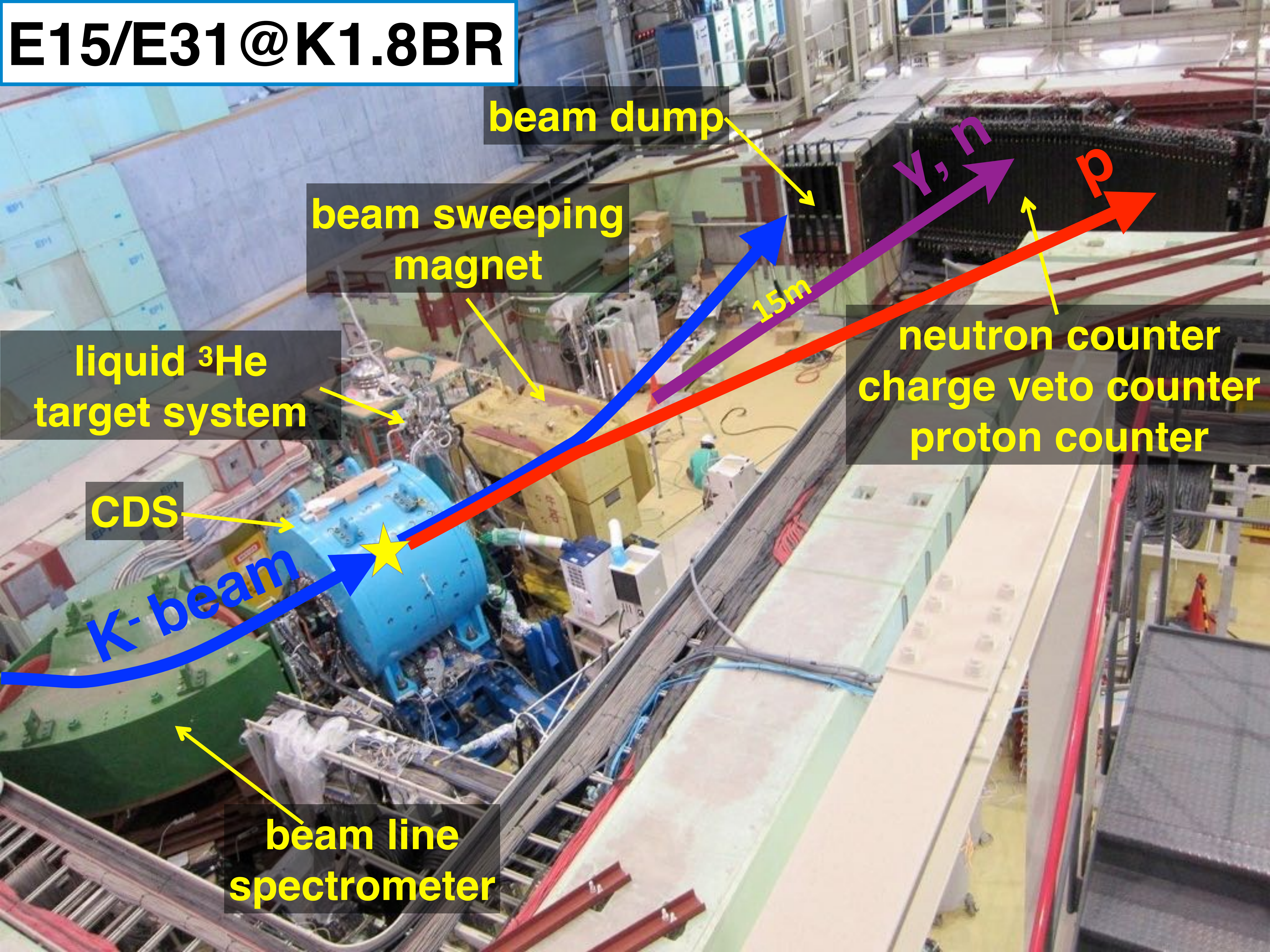


- K$^-$ beam at 1 GeV/c to maximize elementary (K$^-$, N) cross sections
- Most of background processes can be kinematically separated.
  - Hyperon decays and multi-nucleon absorption reactions
- Simplest target allow exclusive analysis.

J-PARC K1.8BR

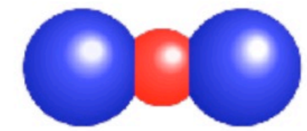


- Relatively short beamline suitable for low-momentum K^- beam


E15/E31@K1.8BR
beam dump
γ, n
p
beam sweeping magnet
15m
liquid ³He target system
neutron counter
charge veto counter
proton counter
CDS
K- beam
beam line spectrometer

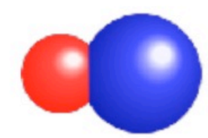
Experiments @ J-PARC K1.8BR

- E15: $\bar{K}NN$ search



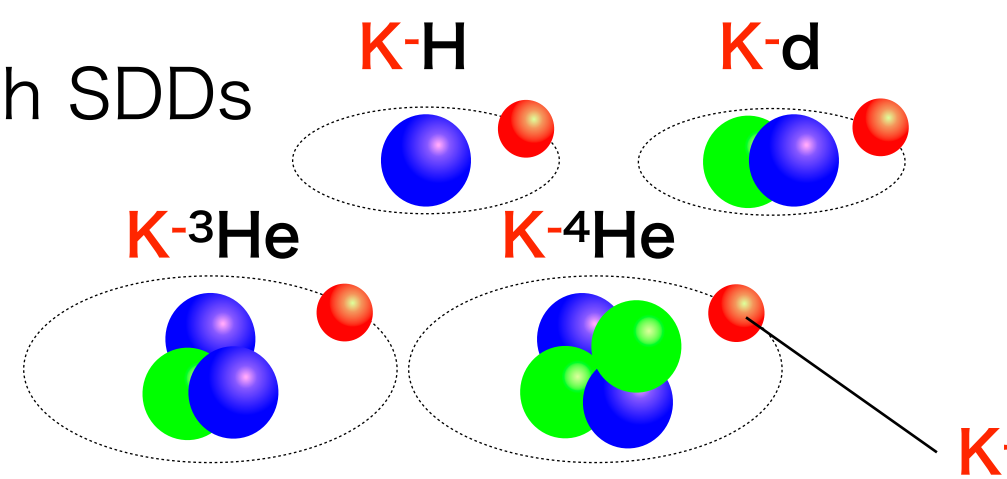
K^-pp

  - 1st data taking in 2013: forward-neutron PTEP (2015) 061D01, Λp PTEP (2016) 051D01.
  - 2nd data taking in 2015 focusing on Λp: PLB 789 (2019) 620, PRC 102 (2020) 044002.
- E31: $\Lambda(1405)$ spectroscopy via $d(K^-, n)$

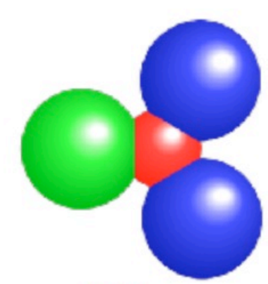


Λ(1405) (K^-p)

  - data taking in 2018: arXiv:2209.08254
- E57: Kaonic hydrogen/deuterium 1s with SDDs
  - test experiment in 2019
- E62: Kaonic helium-3/4 2p with TES
  - data taking in 2018: PRL 128, 112503 (2022).



- E73/T77: lifetime measurement of light hypernuclei
  - test data in 2020(**^{4}He**), 2021(^{3}He)
- E80: $\bar{K}NNN$ study
- P89: $\bar{K}NN$ spin-parity



K^-ppn

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

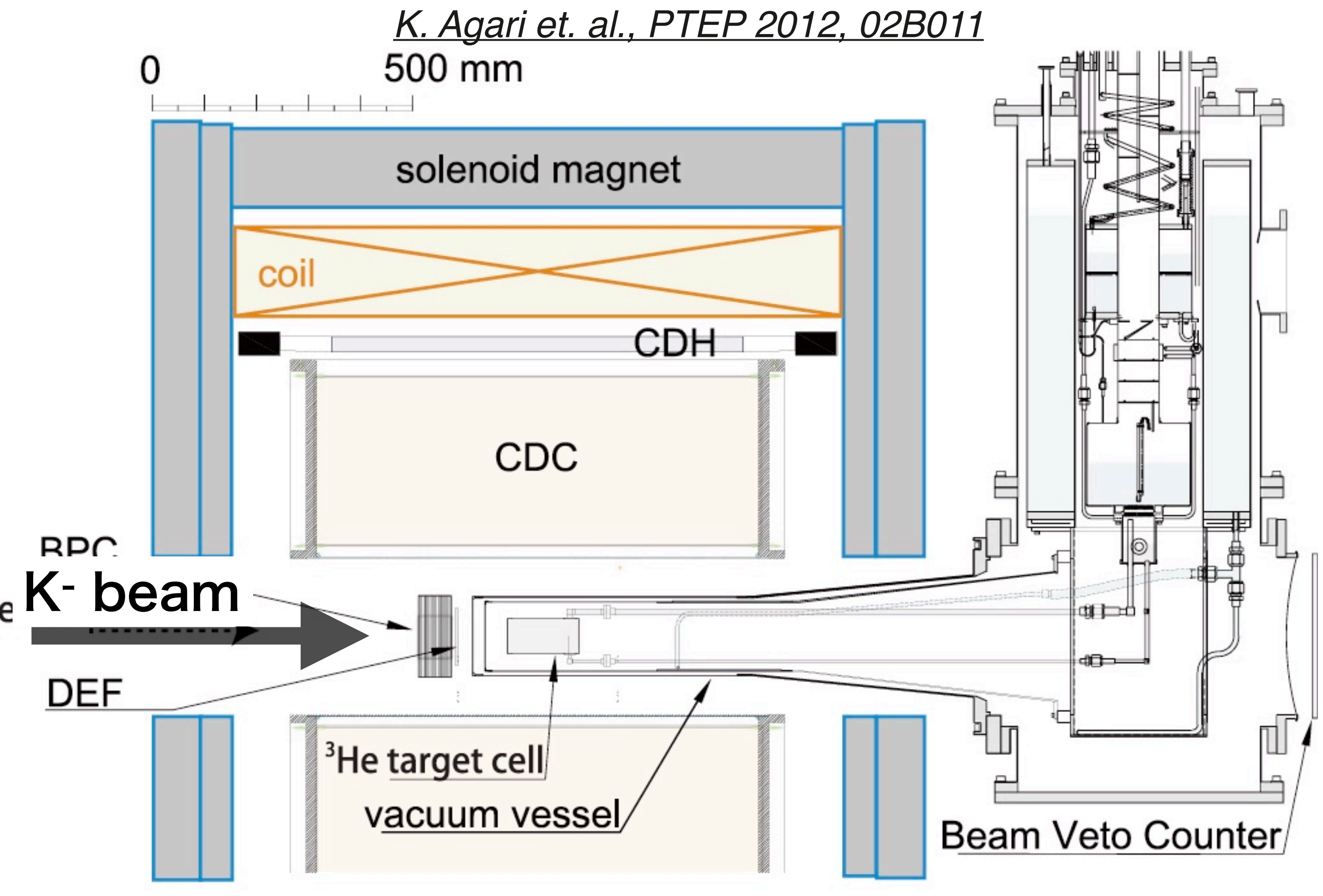
$\bar{K}NN$ in $^3\mathrm{He}(K^-, \Lambda p)n$

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

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

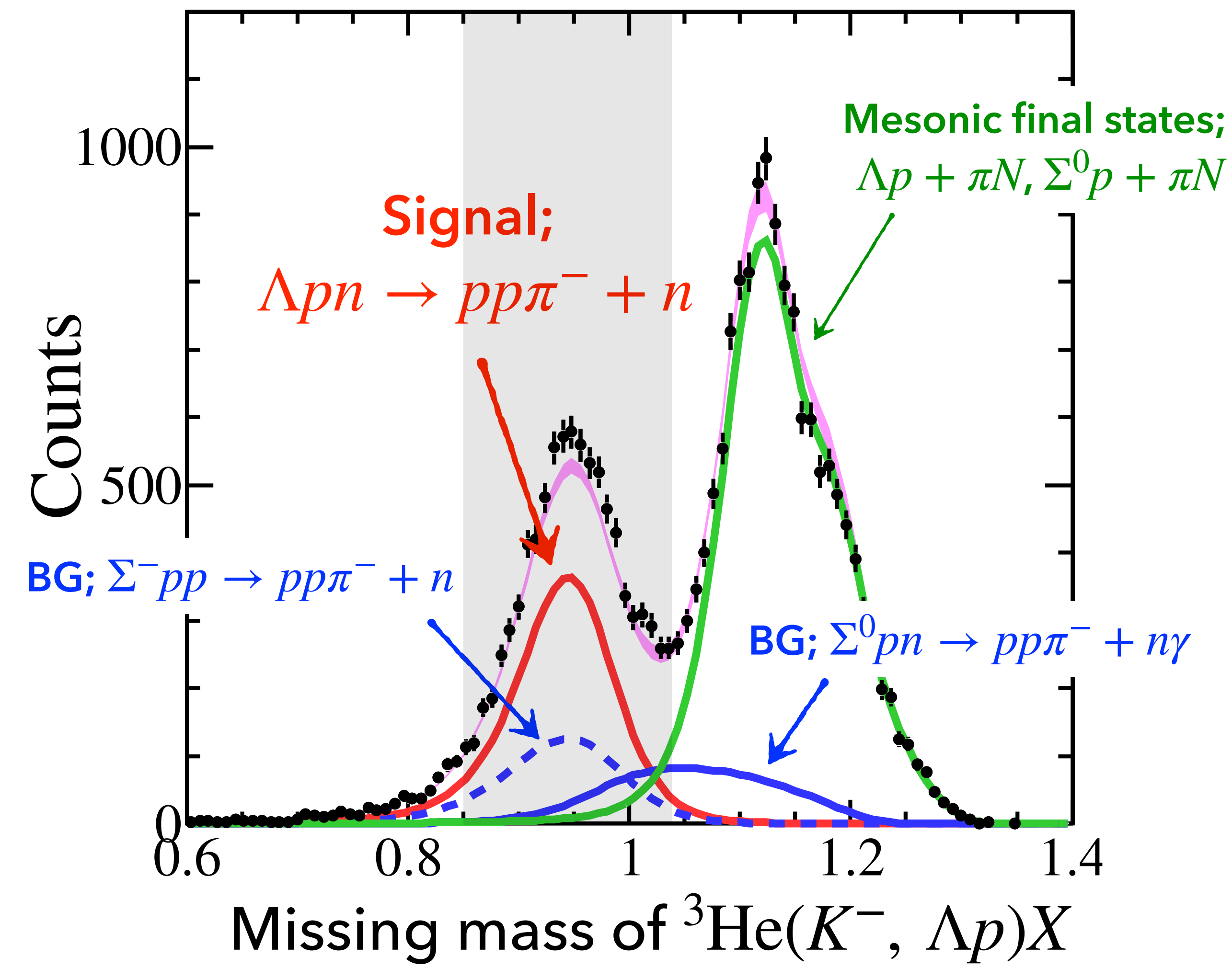
T. Yamaga,[1,*] S. Ajimura,[2] H. Asano,[1] G. Beer,[3] H. Bhang,[4] M. Bragadireanu,[5] P. Buehler,[6] L. Busso,[7,8] M. Cargnelli,[6] S. Choi,[4] C. Curceanu,[9] S. Enomoto,[14] H. Fujioka,[15] Y. Fujiwara,[12] T. Fukuda,[13] C. Guaraldo,[9] T. Hashimoto,[20] R. S. Hayano,[12] T. Hiraiwa,[2] M. Iio,[14]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

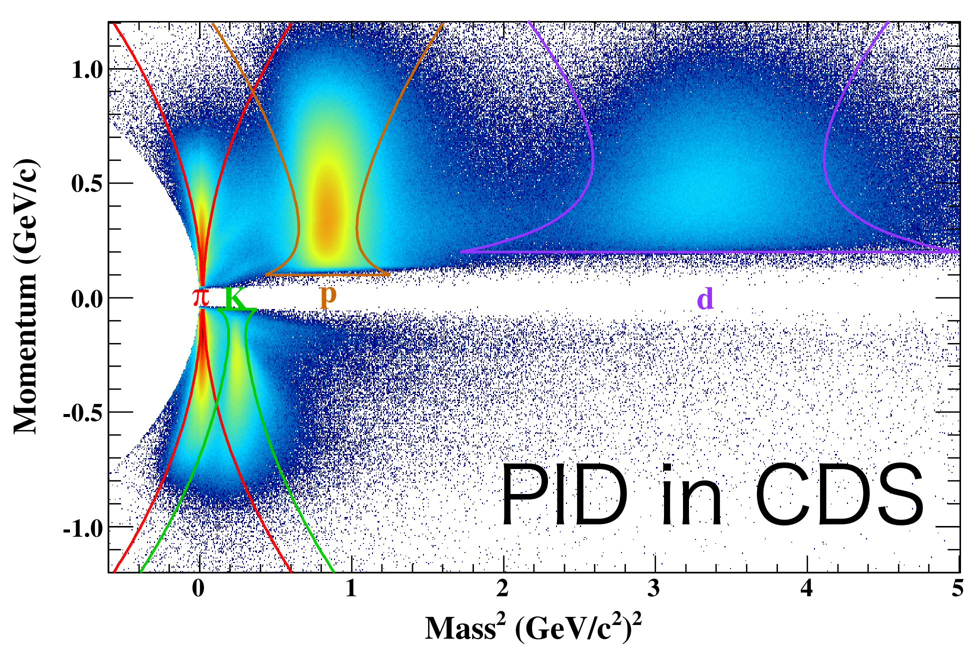
Λpn event selection



15-layer CDC and TOF hodoscopes

missing neutron selection

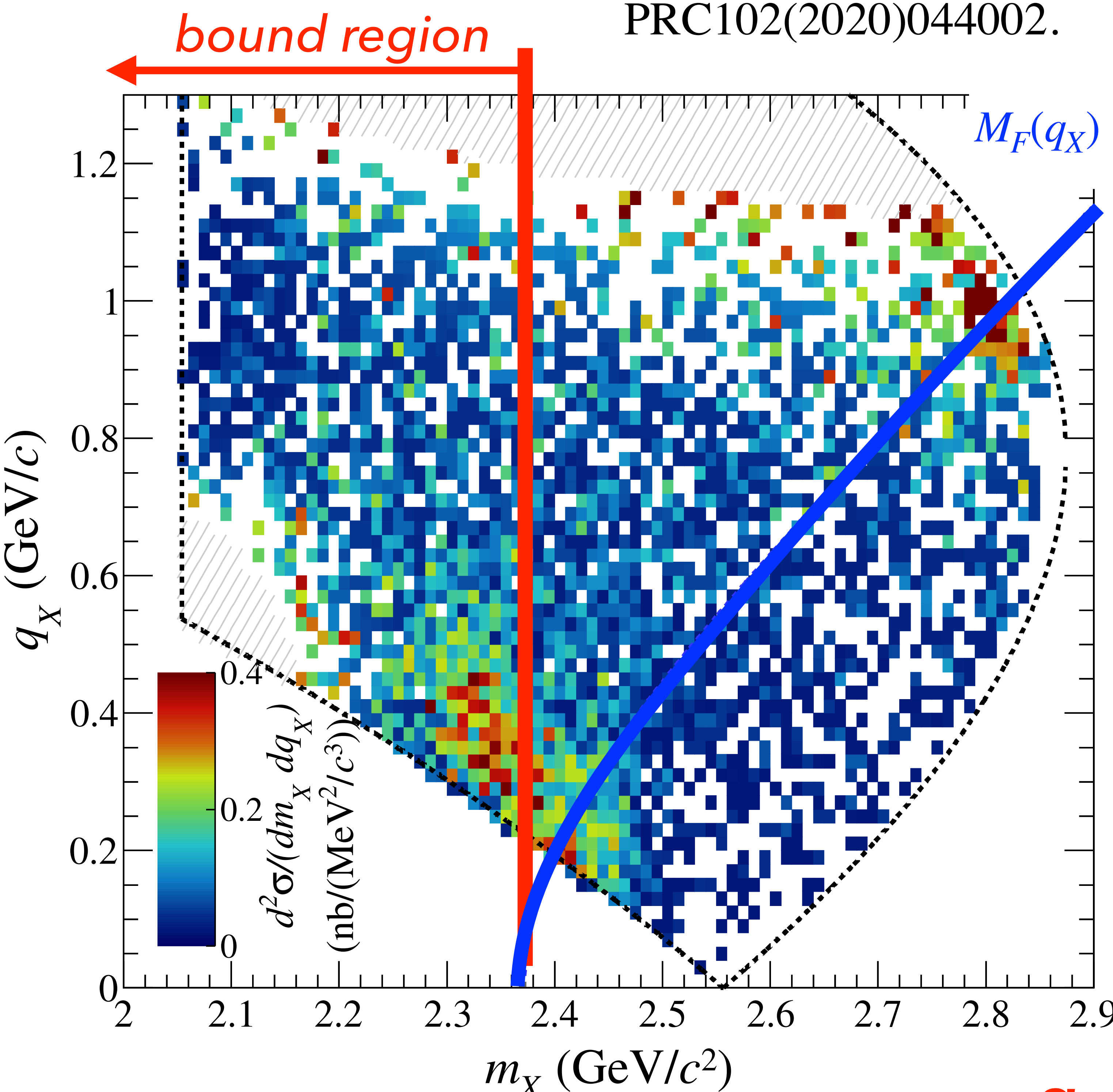


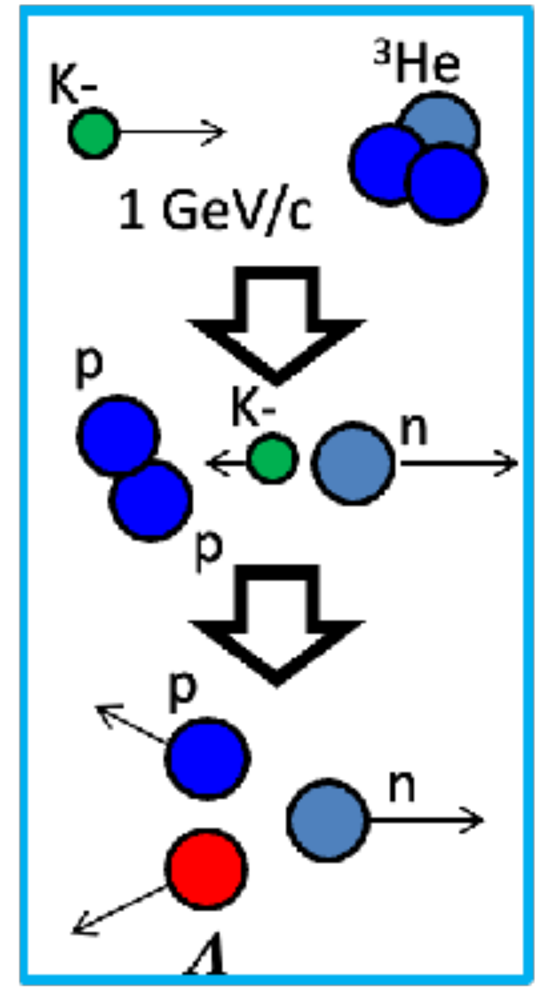


- Λpn events are selected with ~80% purity.
- ~20% $\Sigma^0 pn/\Sigma^- pp$ contamination

Obtained spectrum in J-PARC E15

PRC102(2020)044002.





"quasi-free" process

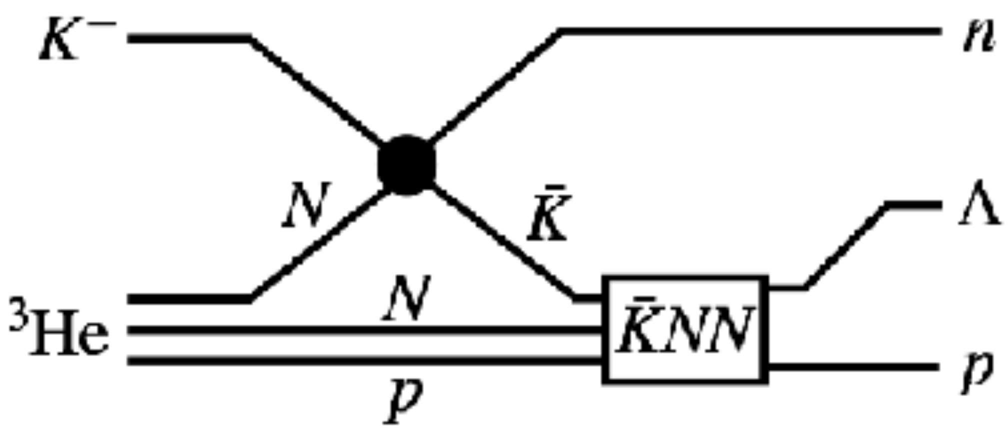
m_x: Λp invariant mass

q_x: momentum transfer to Λp system

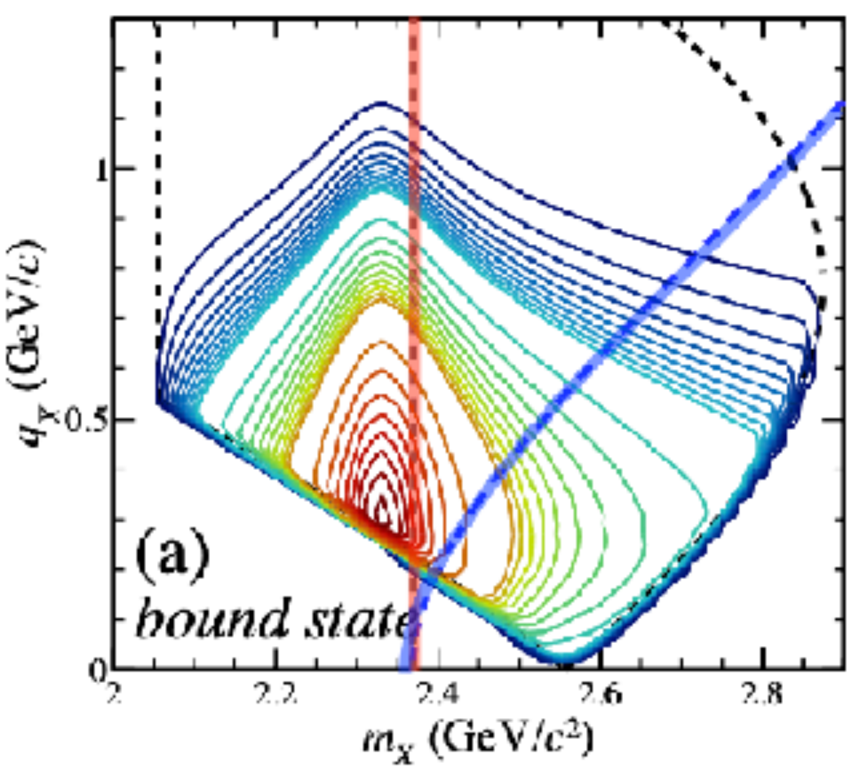
q_x-indep. component below the threshold

Model functions

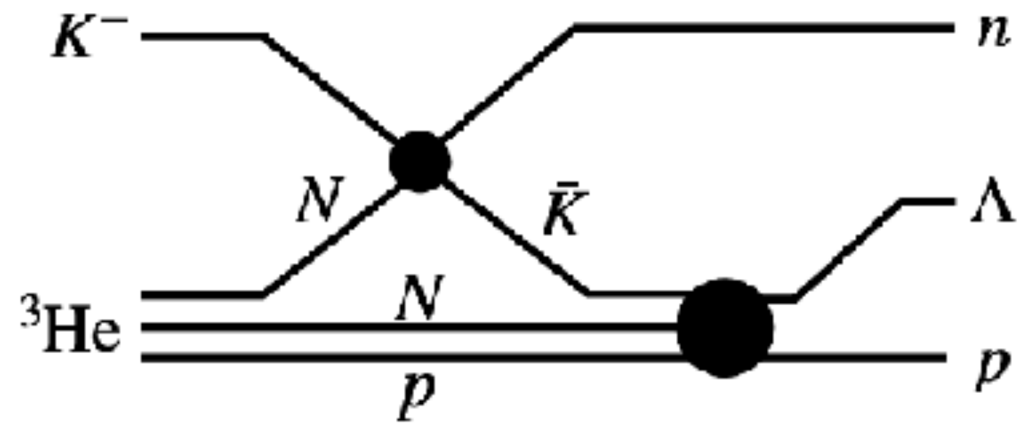
$\bar{K}NN$ production



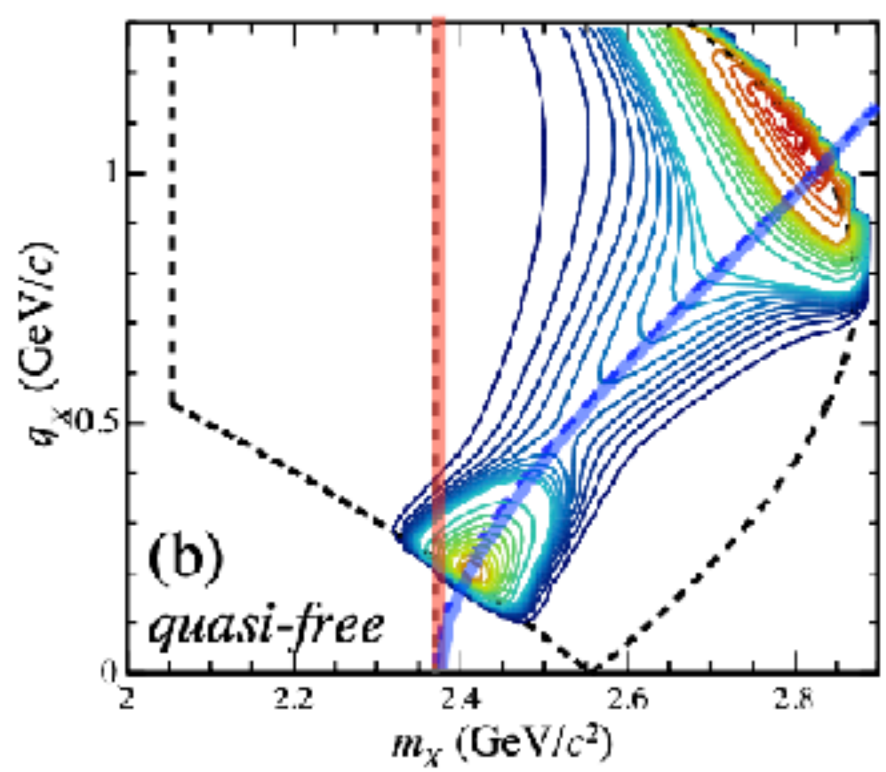
$$f_{\bar{K}NN}(m_X, q_X) = \frac{\Gamma^2/4}{(m_X - M_X)^2 + \Gamma^2/4} \times g_{K^-pp}(q_X)$$



Quasi-free process with (K^-, n)



$$f_{QF}(m_X, q_X) = \exp\left(-\frac{(m_X - M_F(q_X))^2}{\sigma^2(q_X)}\right) \times g_{QF}(q_X)$$



+ 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

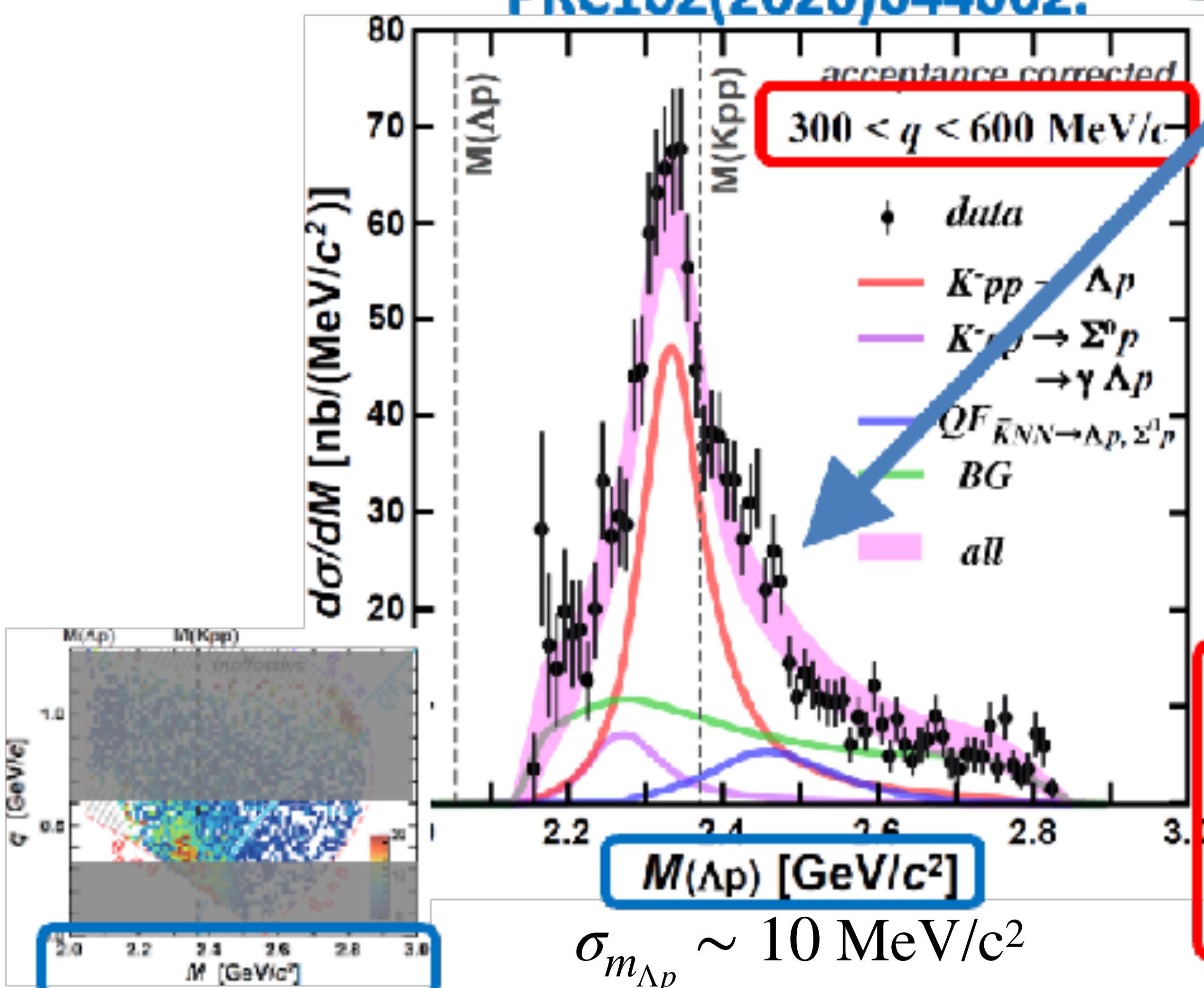
phase space

Breit Wigner

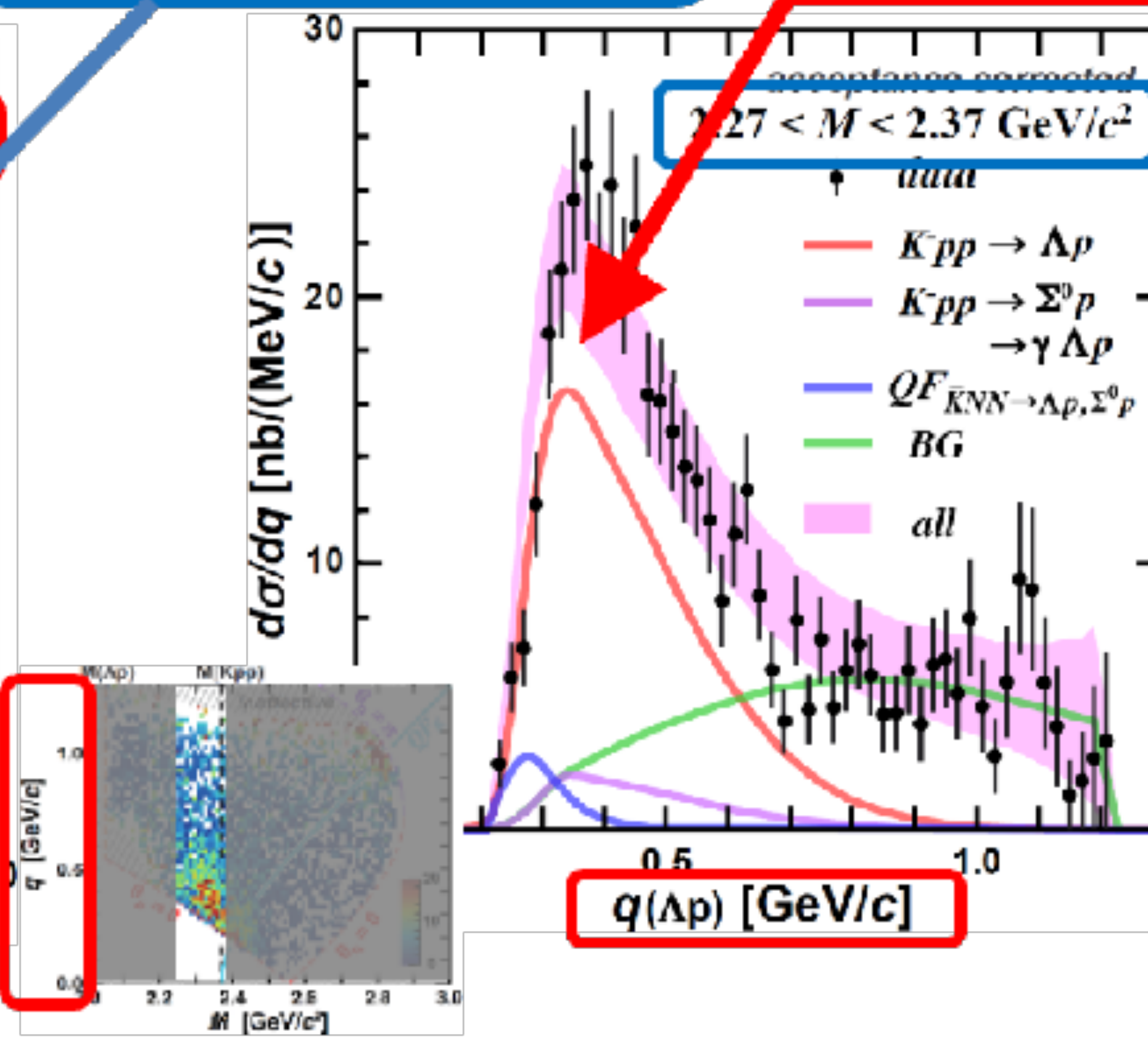
form factor

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

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*

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

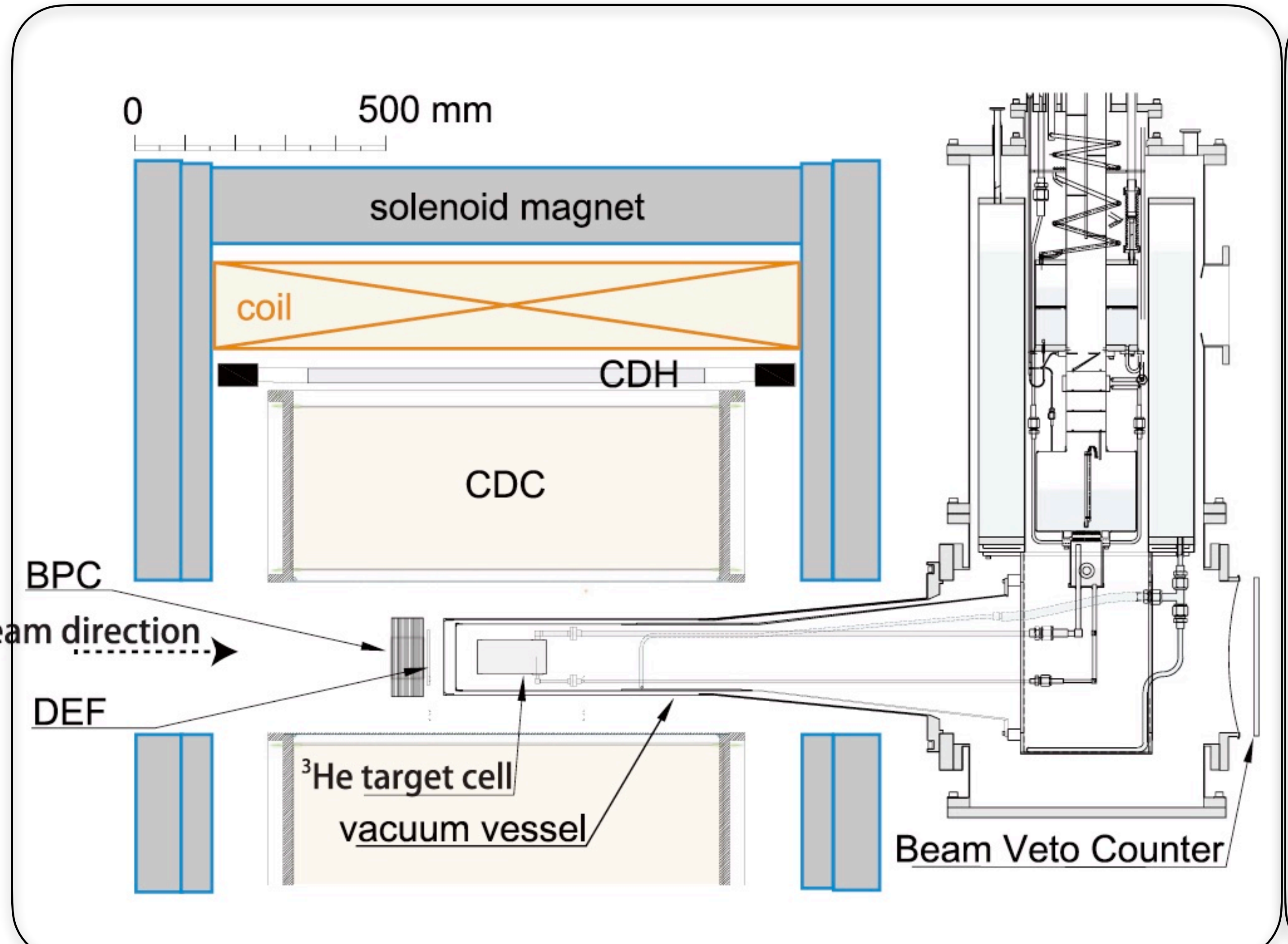
$\bar{K}NNN$ in $^4\mathrm{He}(K^-, \Lambda d)n$

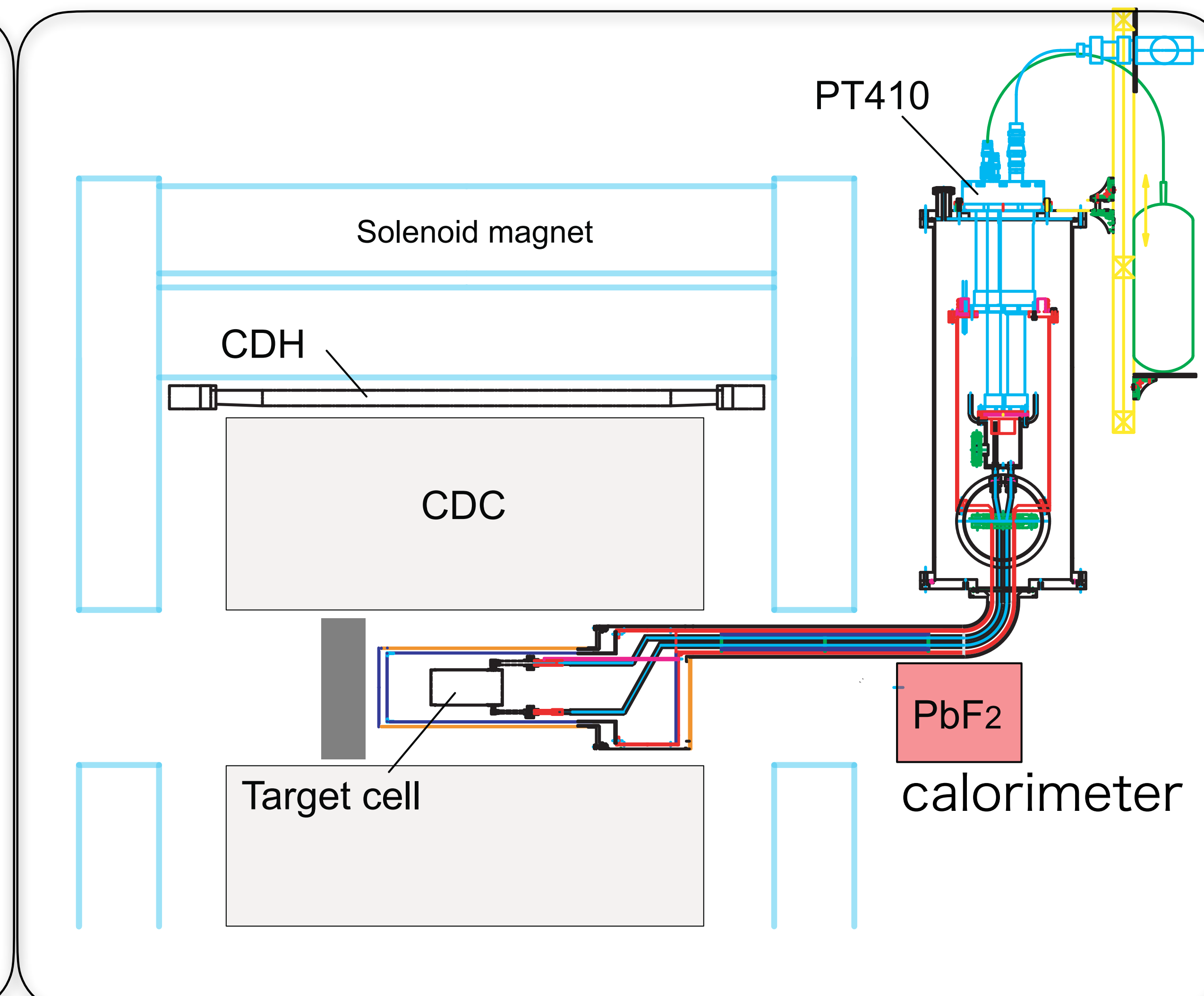
Helium-4 data with the E15 setup as a test experiment in 2020

J-PARC E15 vs T77 @ K1.8BR

We already have small dataset with ^{4}He target

J-PARC E15@2015	J-PARC T77@2020
42G K^- on ^{3}**He**	6G K^- on ^{4}**He** **only 3 days!**





- The same cylindrical detector system

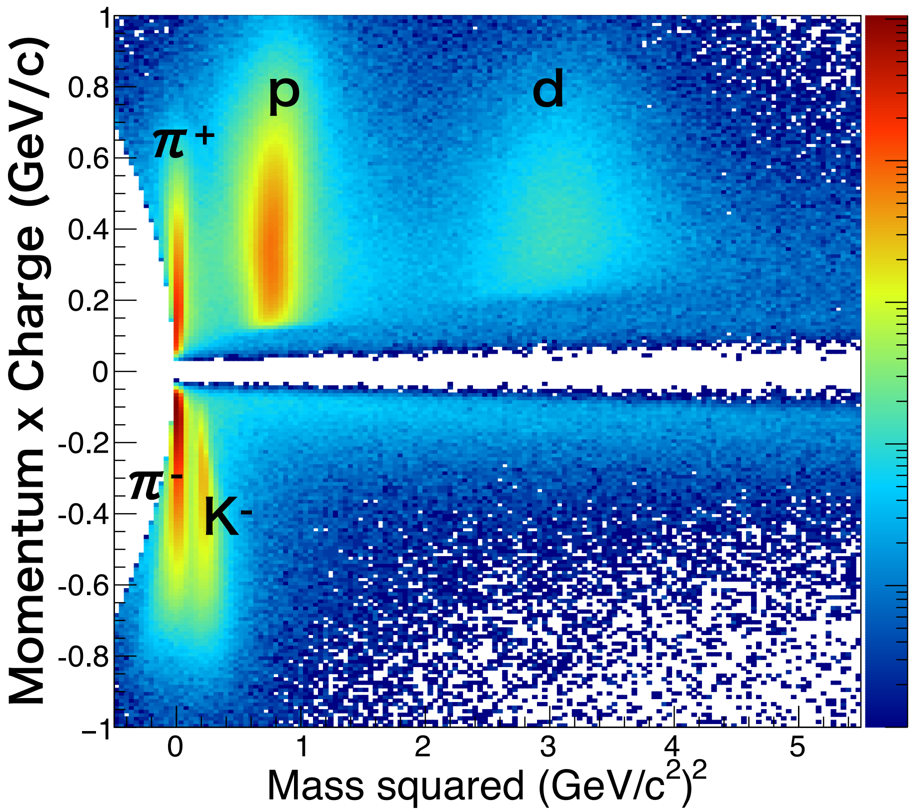
  \+ forward calorimeter in T77 for lifetime measurements of hypernuclei

$^4\mathrm{He}(K^-,\pi^0)^4_\Lambda\mathrm{H}$

Λdn event selection

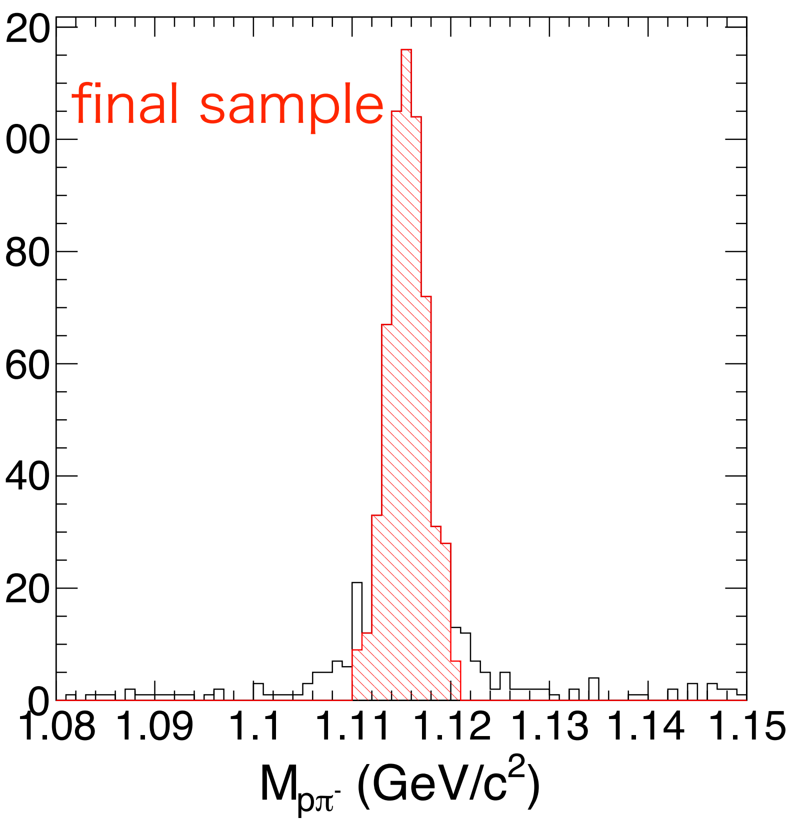
deuteron ID

CDC track curvature &
CDH time of flight



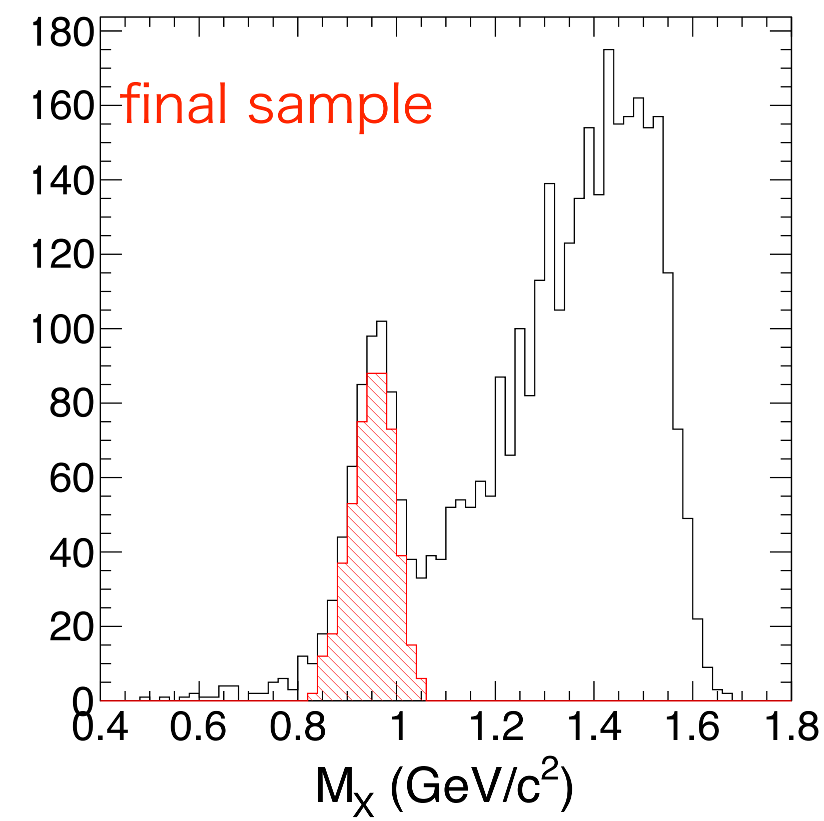
Λ reconstruction

w/ vertex consistency cut
w/ pipd missing mass cut



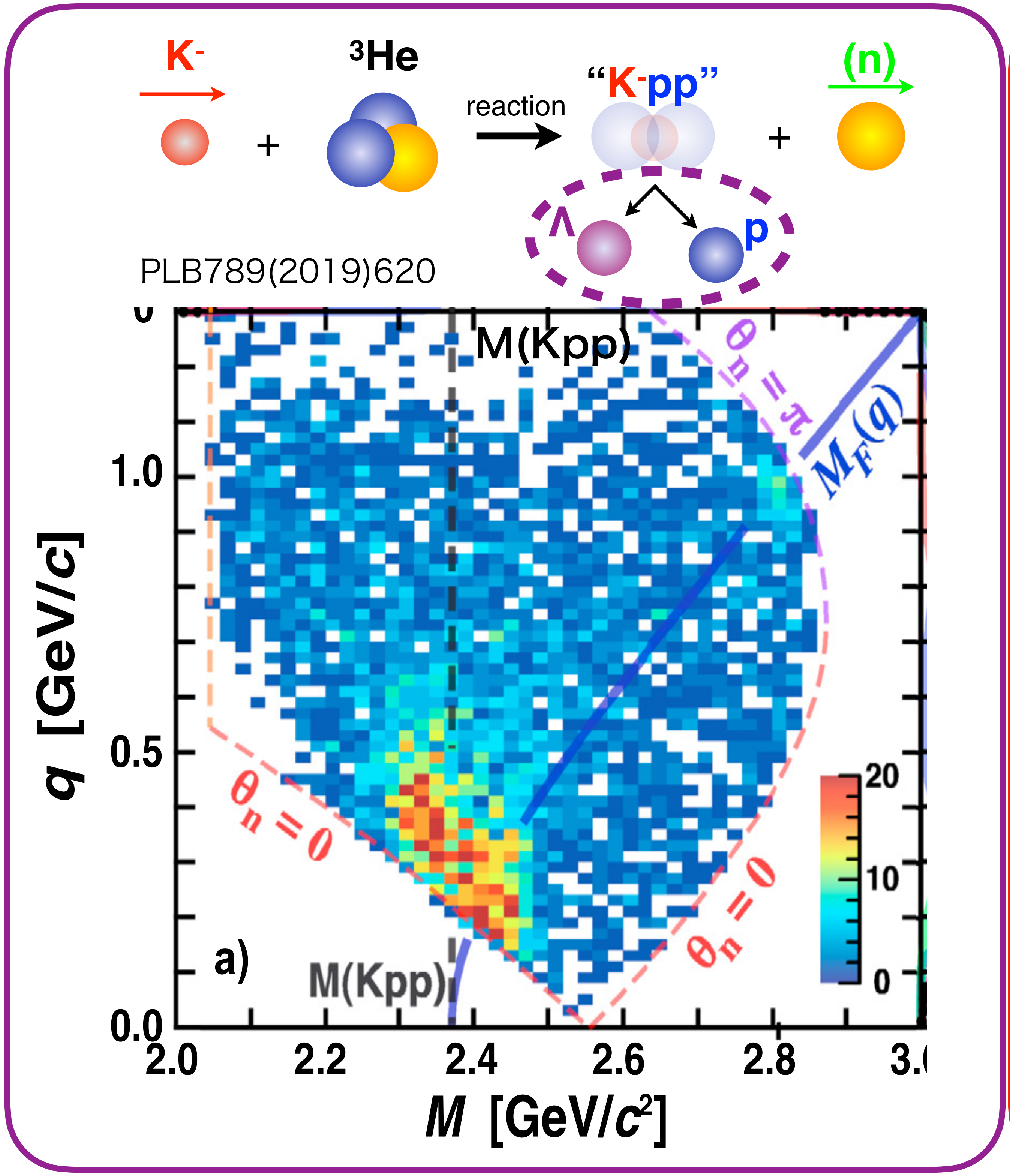
Missing neutron ID

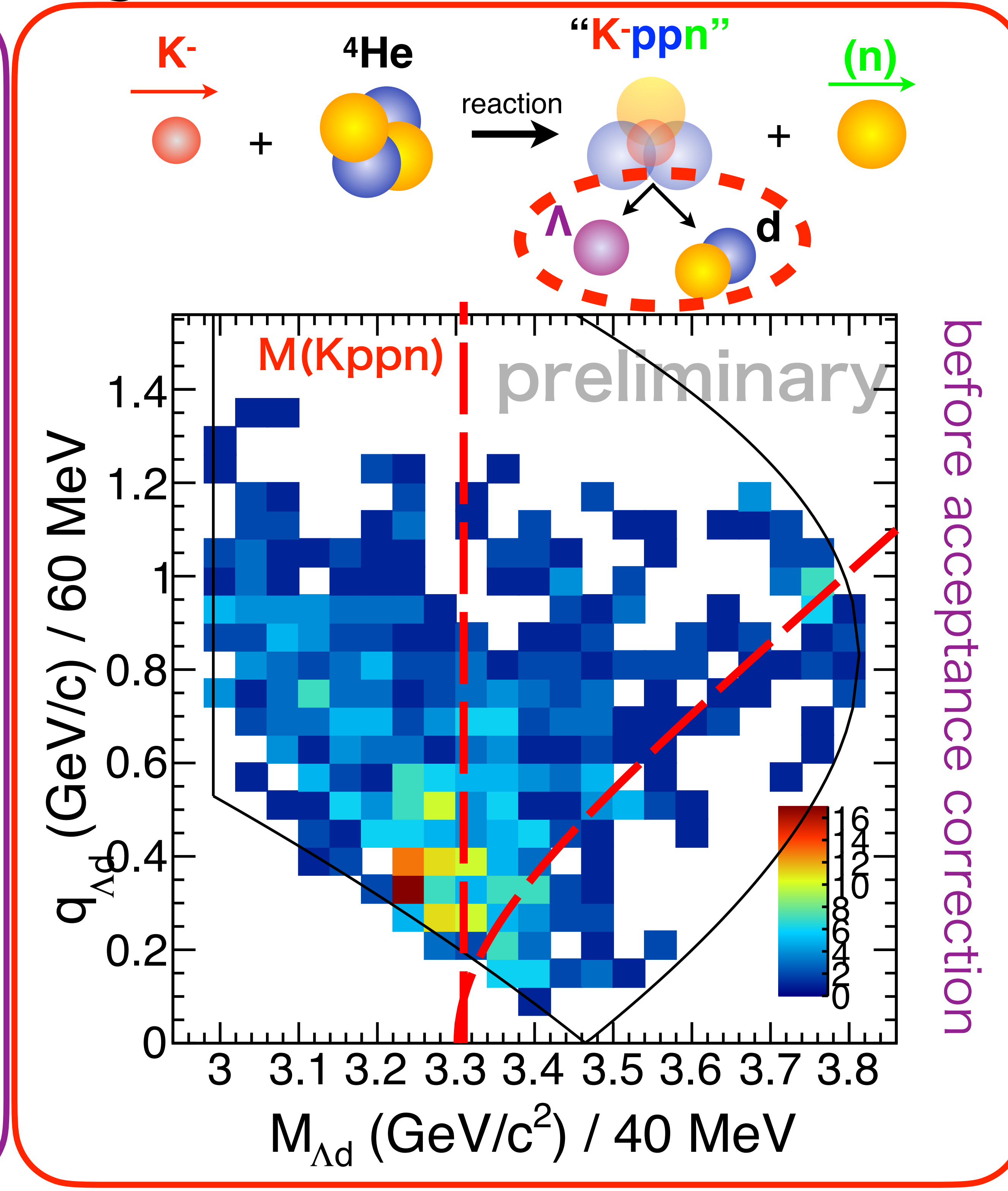
w/ vertex consistency cut
w/ lambda mass cut



- 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



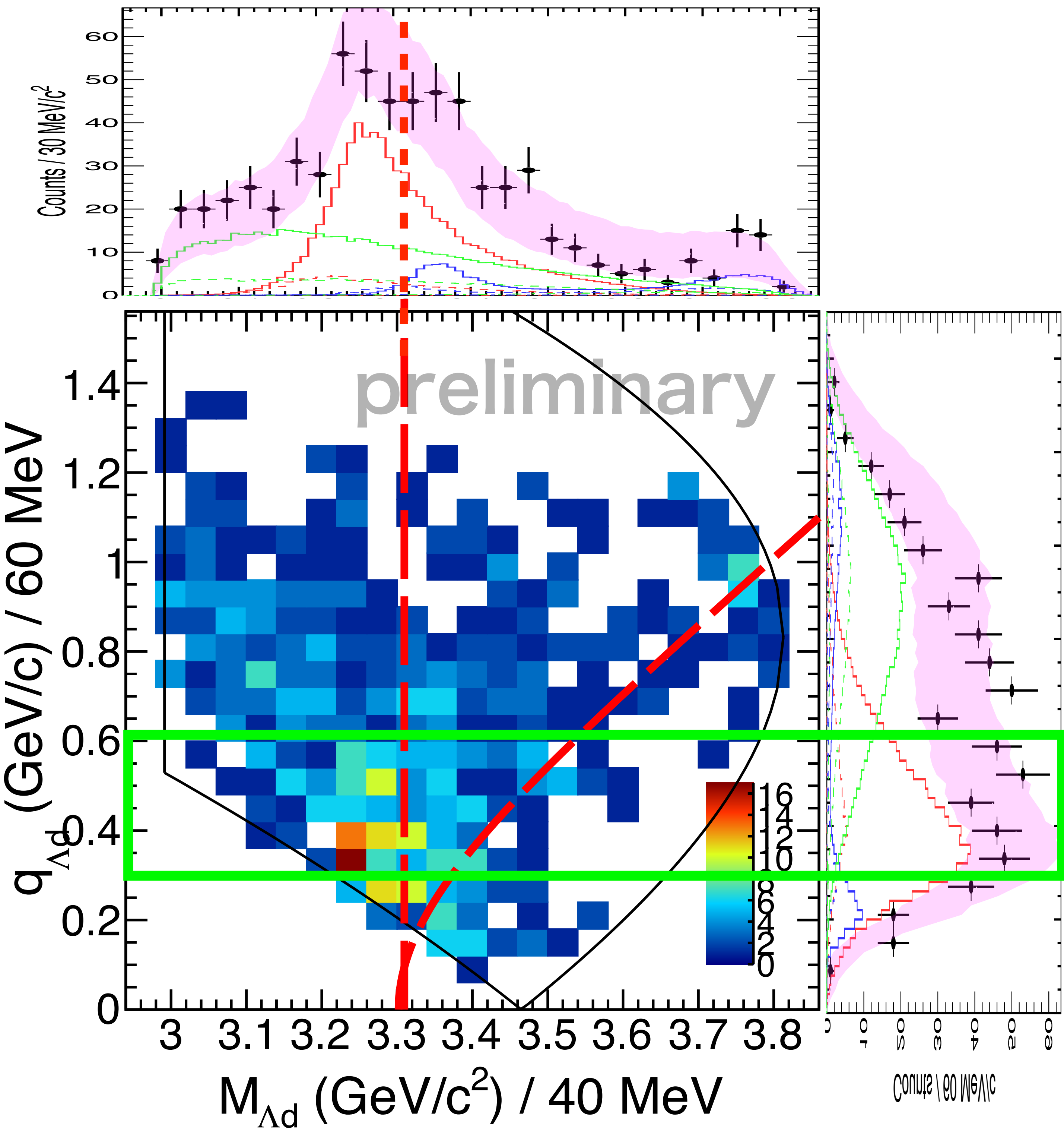


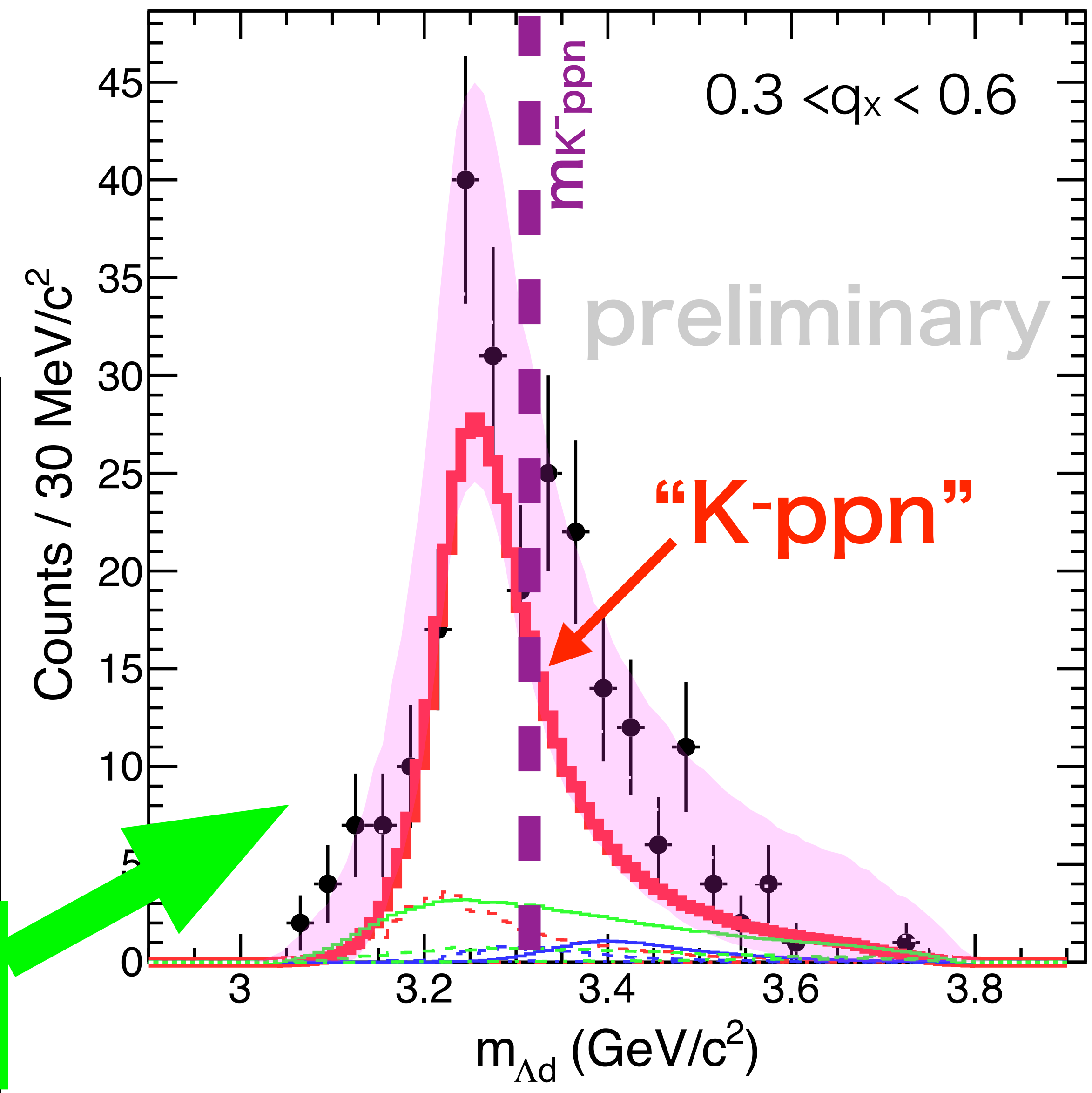
- Two disributions are quite similar
- structure below the threshold, QF-K^-, and broad background

$\bar{K}NNN$: 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⁻



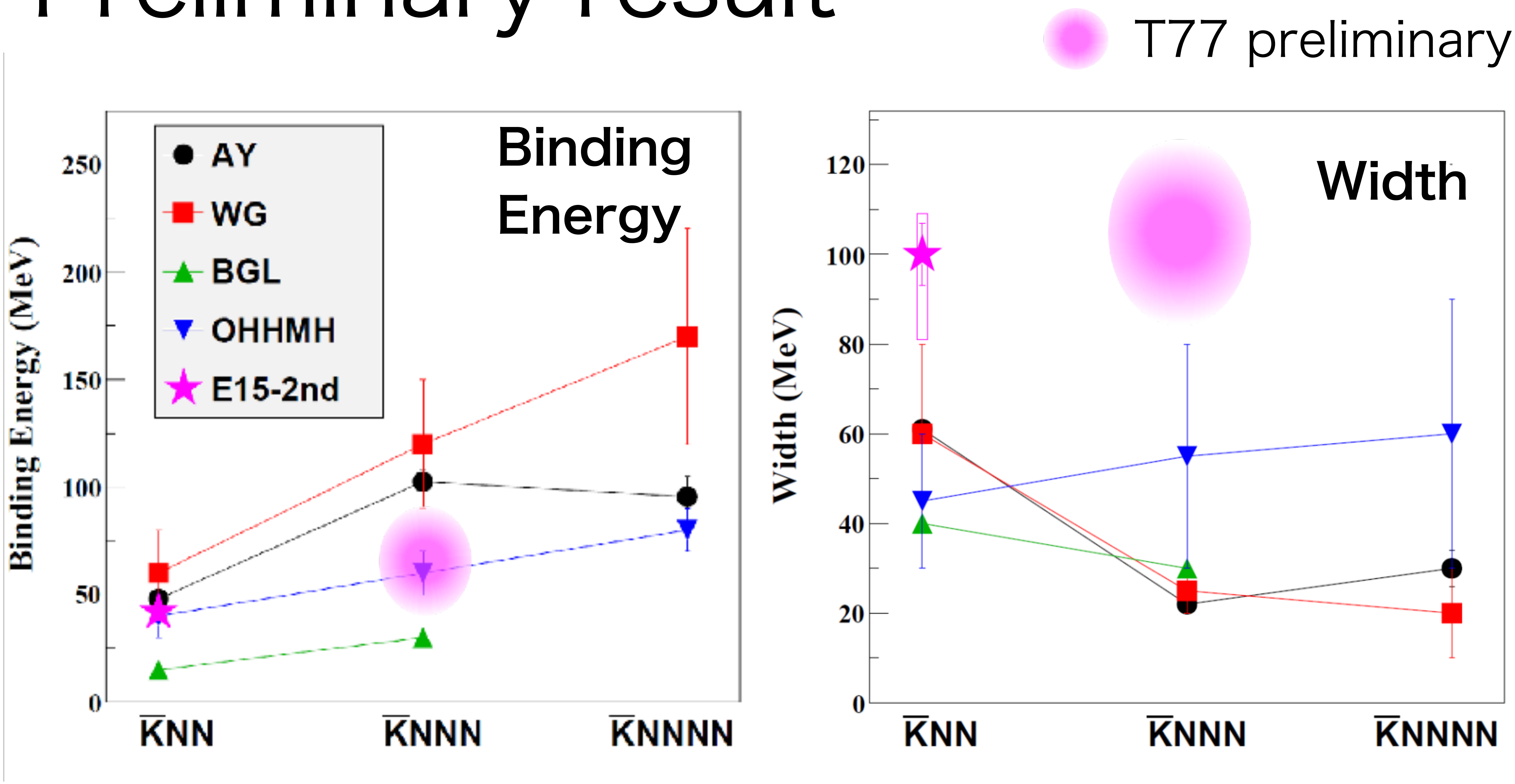


$B_{\bar{K}NNN} \sim 60 \pm 11(\mathrm{stat})$ MeV

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

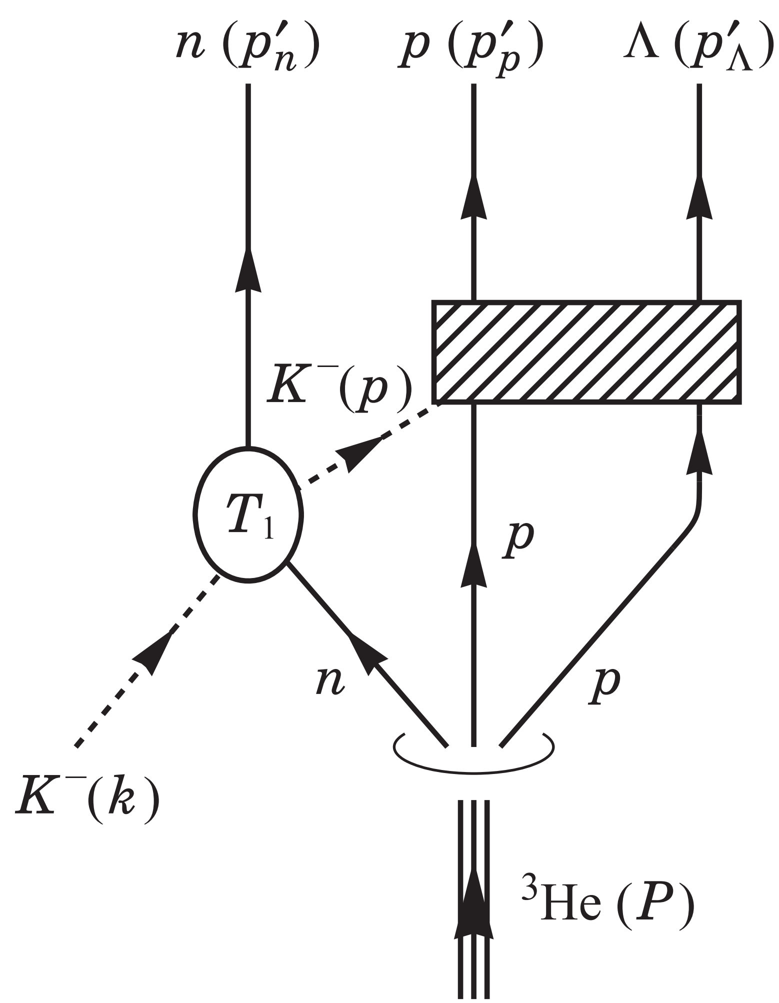
$\sigma_{\bar{K}NNN \to \Lambda d} \sim 4\ \mu$b

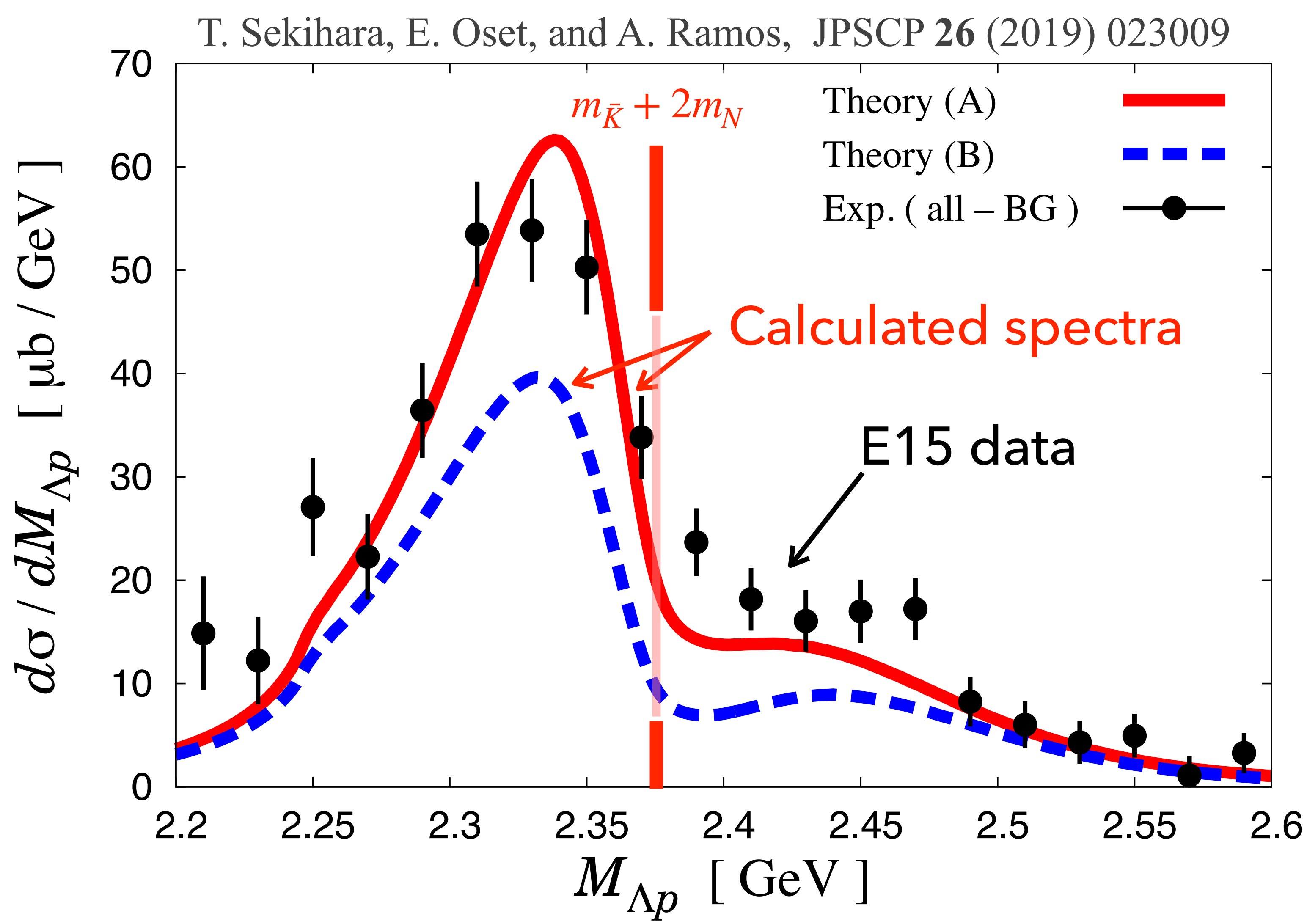
Preliminary result



- The binding energy is compatible with theoretical predictions
- "$\bar{K}NNN$" system might have larger binding than "$\bar{K}NN$", although we expect a large systematic error 10~20 MeV.
- Expereimental width is larger than theoretical predictions.

Comparison with Sekihara calc.



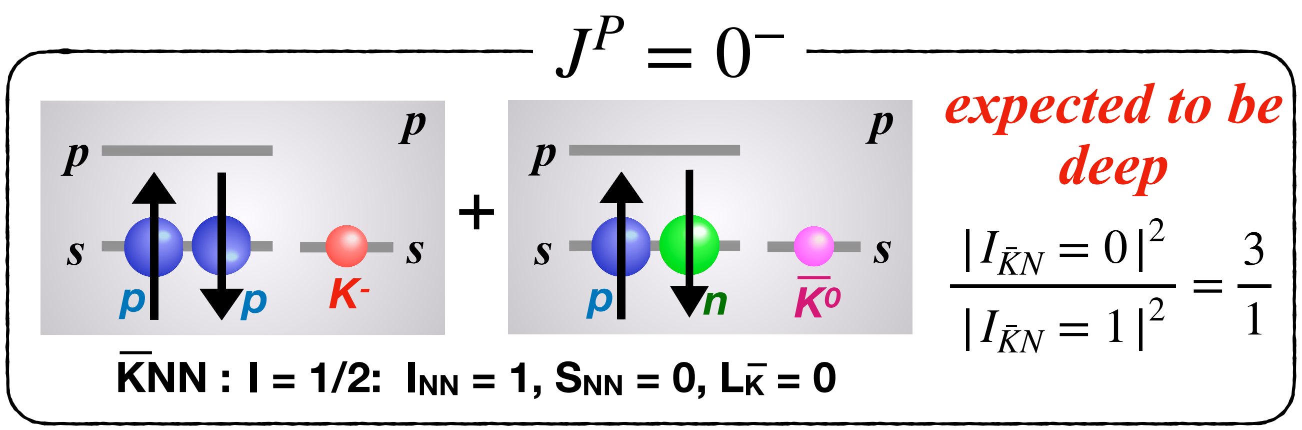


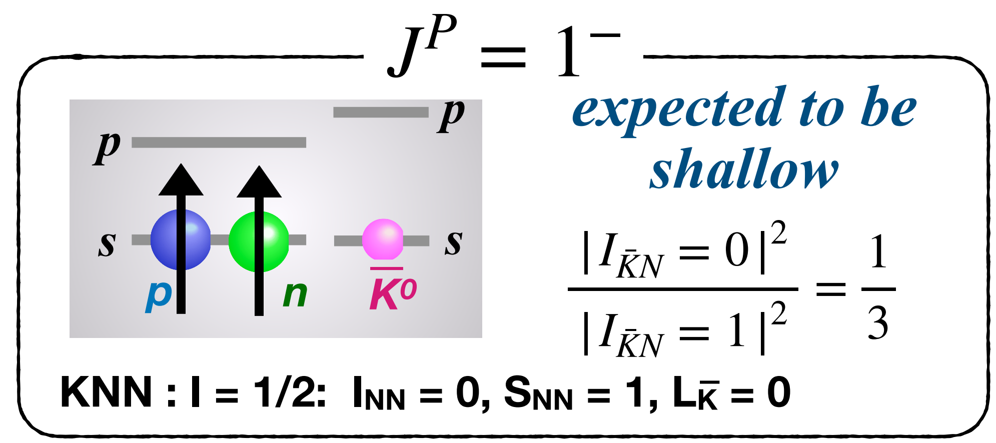
- Good agreement in the mass spectrum.
  (although it failed to explain experimental q spectrum)
- Detailed comparison with theoretical spectrum is important

What's next?

Now we know how to produce "kaonic nuclei" !

- Determine spin-parity of the observed $\bar{K}NN$ state (J-PARC P89)
  - Spin-spin correlation between Λp: need polarimeters
  - Comparison with the isospin partner (Λn)



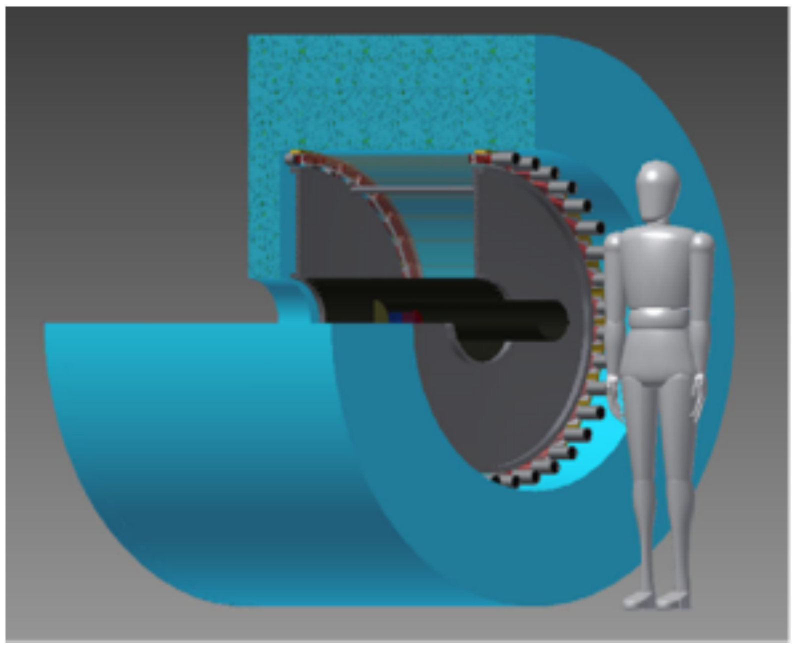


$or\ \Sigma^* N\ [I(J^p) = 1/2(2^+)]$

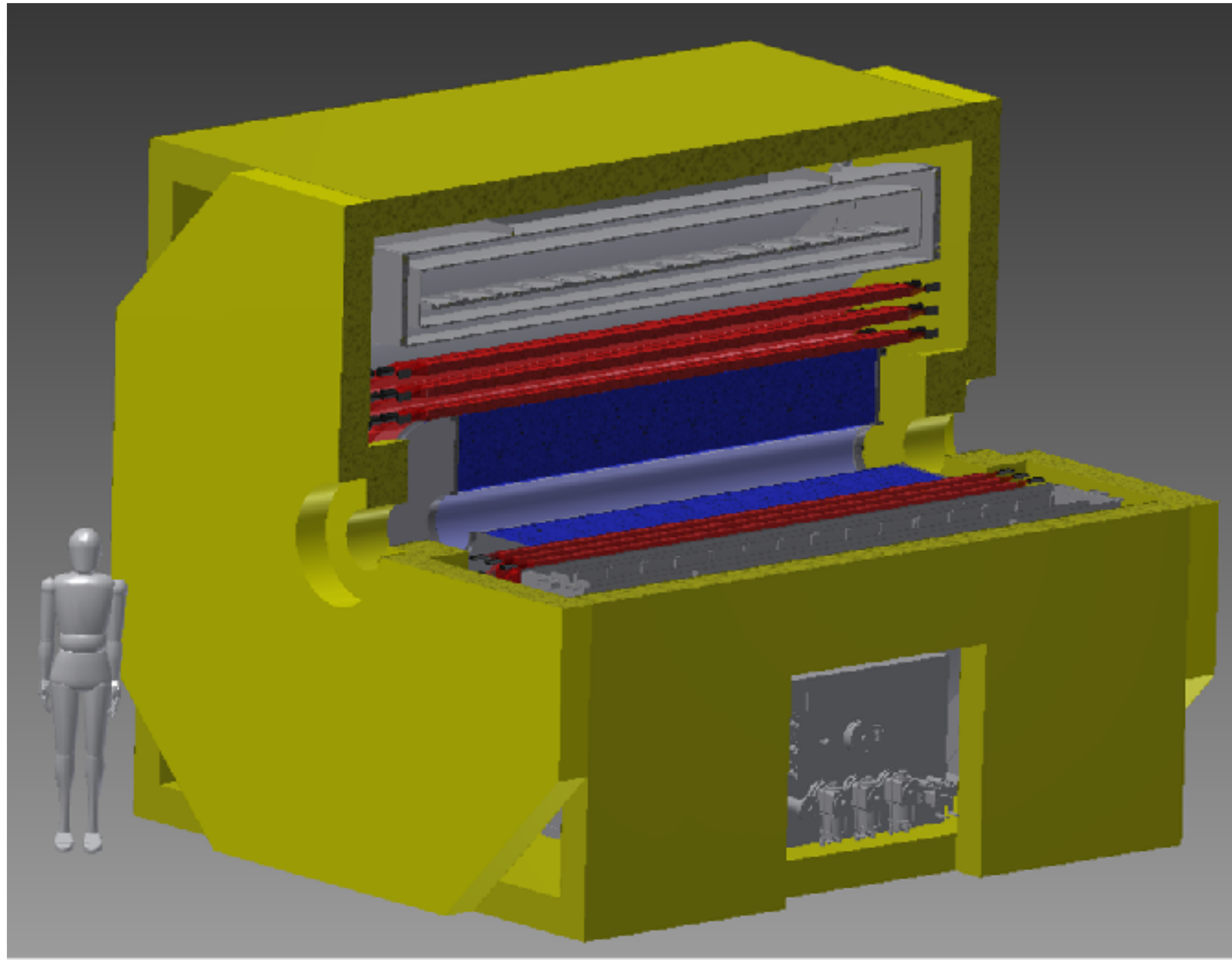
- Confirm $\bar{K}NNN\ [I(J^p) = 0(1/2^-)]$ and study its property (J-PARC E80)
  - Λpn in addition to the Λd decay mode
  - $\Sigma^{*-}pp\ [I(J^p) = 0(3/2^+)]$ possibility should be considered
- Heaviear kaonic nuclei, doulbe kaonic nuclei, ⋯

J-PARC E80 with a new spectrometer

E15 CDS

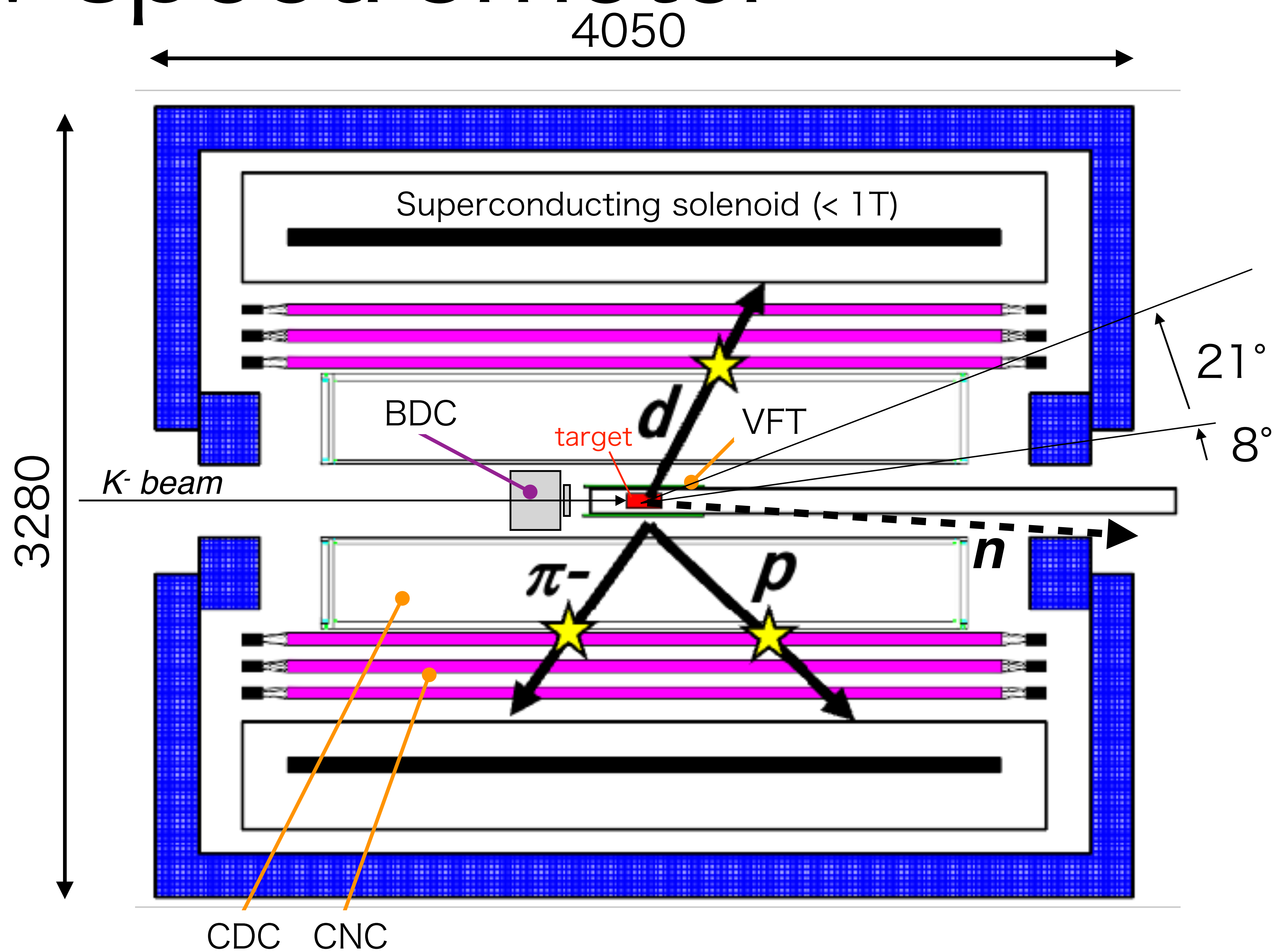


new CDS



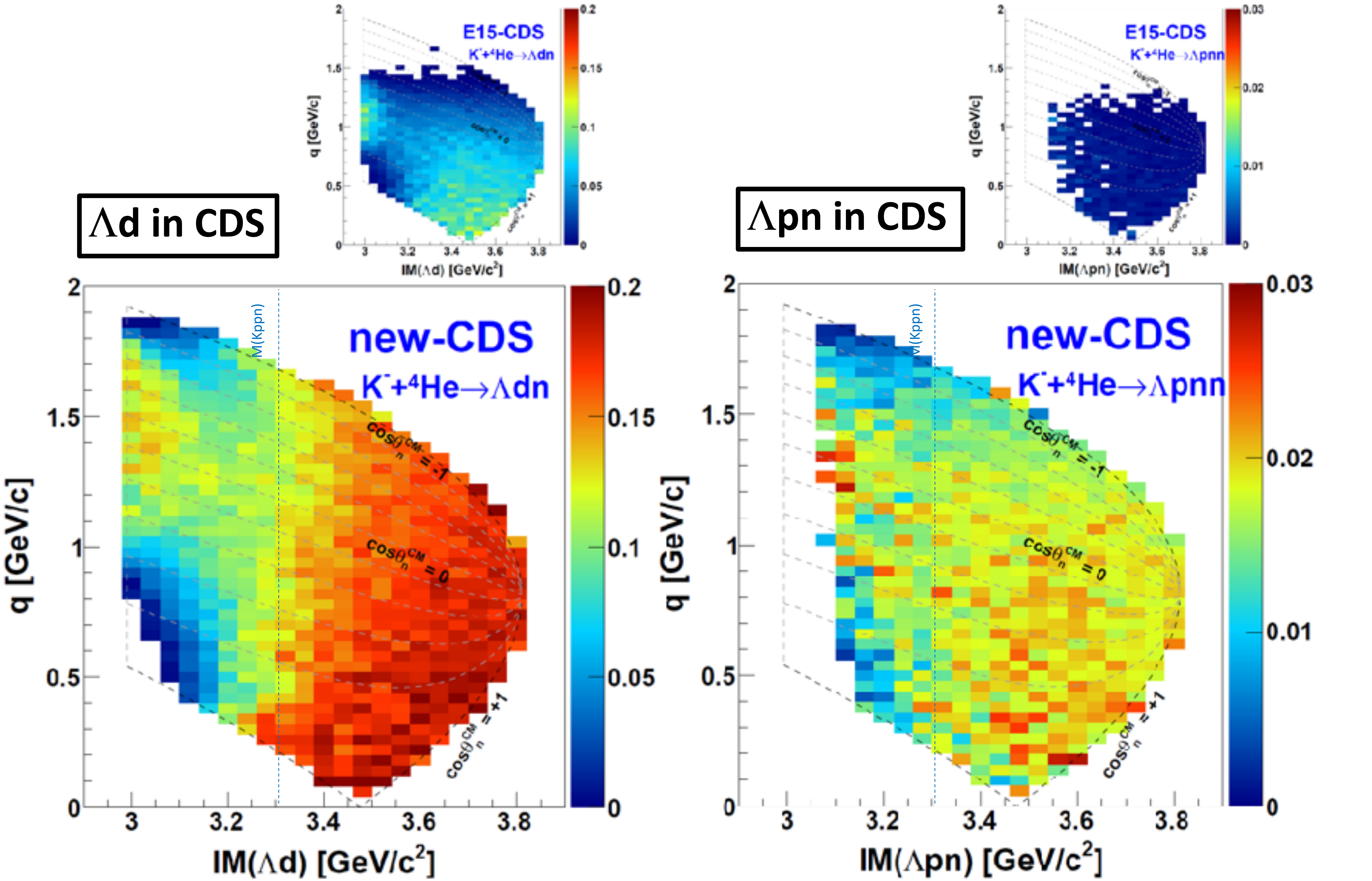
- About 10 times volume
- We got a large budget, 特別推進 (P.I.: M. Iwasaki, JFY2022—JFY2026)

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

Acceptance



- large kinematical-region coverage & better acceptance

Expected yields

$$N = \sigma \times N_{beam} \times N_{target} \times \epsilon,$$
$$\epsilon = \epsilon_{DAQ} \times \epsilon_{trigger} \times \epsilon_{beam} \times \epsilon_{fiducial} \times \Omega_{CDS} \times \epsilon_{CDS},$$

- N_{beam} = **100 G** K- on target
  - MR beam power of **90 kW**
  - **3 weeks** data taking (90% up-time)

$$\sigma(K^-ppn) \bullet Br(\Lambda d) \sim 5\ \mu b$$
$$\sigma(K^-ppn) \bullet Br(\Lambda pn) \sim 5\ \mu b$$

from the T77 preliminary result and an assumption

- **N(K-ppn→Λd) ~ 1.2 x 10^4**
- **N(K-ppn→Λpn) ~ 1.5 x 10^3**
  - c.f. 1.7 x 10^3 "K-pp"→Λp accumulated in E15-2nd (40 G K-)

	Λd / Λpn
σ(K-ppn)*Br	5 μb
N(K- on target)	100 G x ~20
N(target)	2.56 x 10^{23}
ε(DAQ)	0.92
ε(trigger)	0.98
ε(beam)	0.72
Ω(CDC)	0.23 / 0.059 x ~2
ε(CDC)	0.6 / 0.3
N(K-ppn)	12 k / 1.5 k

✓ ~ 40 times more Λd events than existing data in T77

✓ Similar number of Λpn events to Λp in E15

Expected spectra

@ 3 weeks, 90kW

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

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

B_{Kppn} ~ 40 MeV

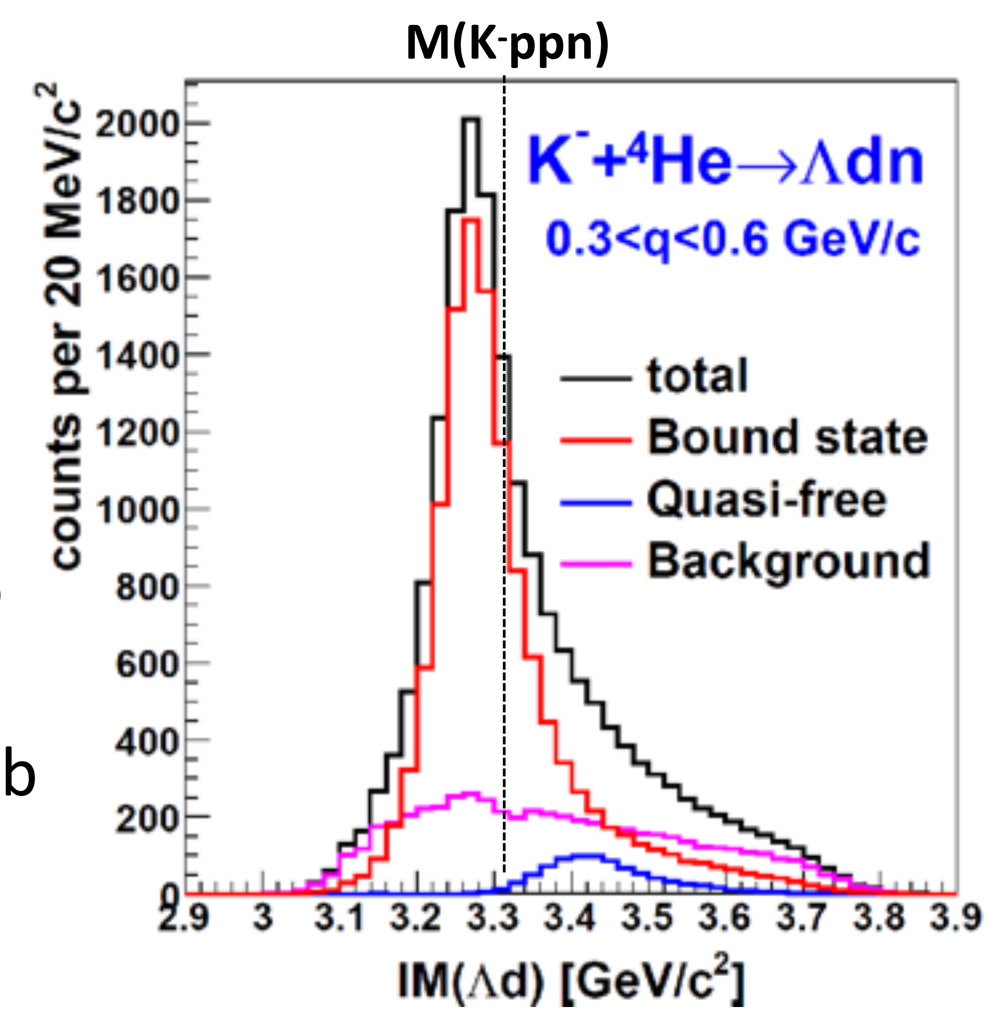
Γ_{Kppn} ~ 100 MeV

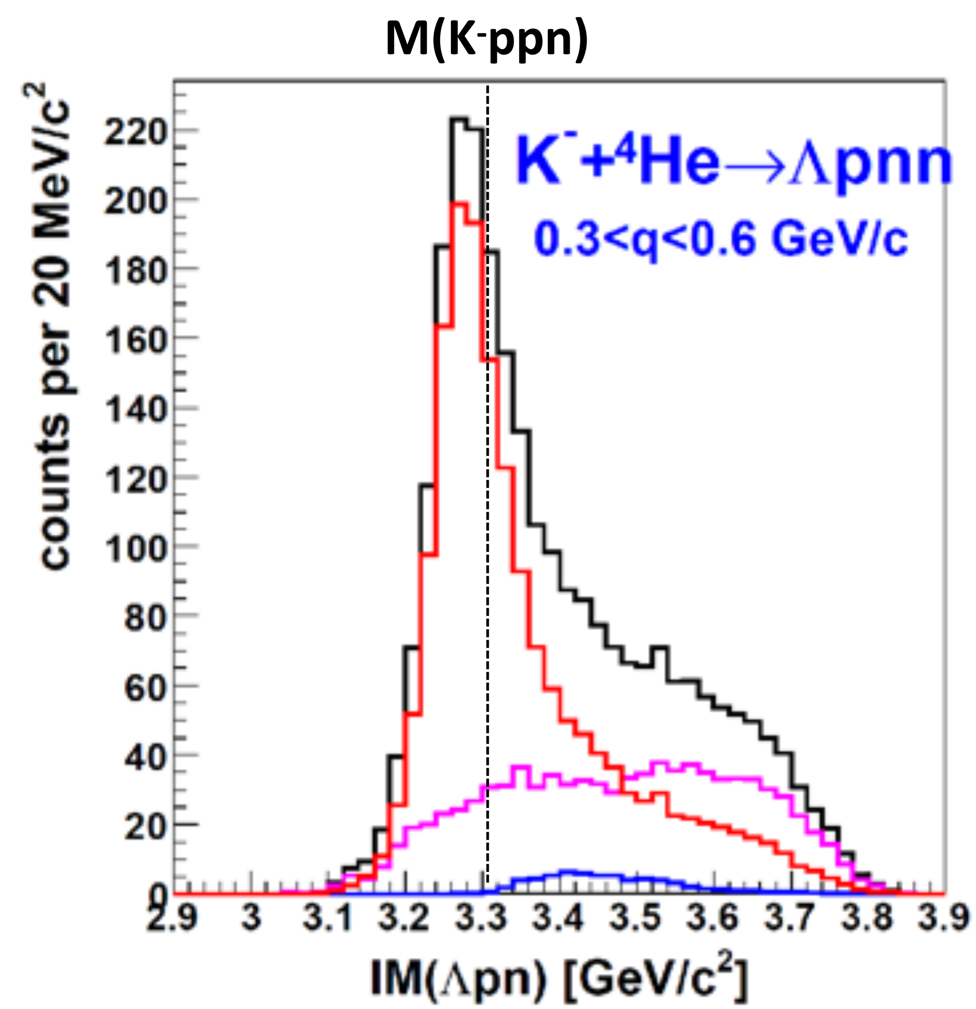
Q_{kppn} ~ 400 MeV/c

$\sigma(K^{-}ppn)$*Br ~ 5 μb

$\sigma(QF)$ ~ 5 μb

$\sigma(BG)$ ~ 10 μb



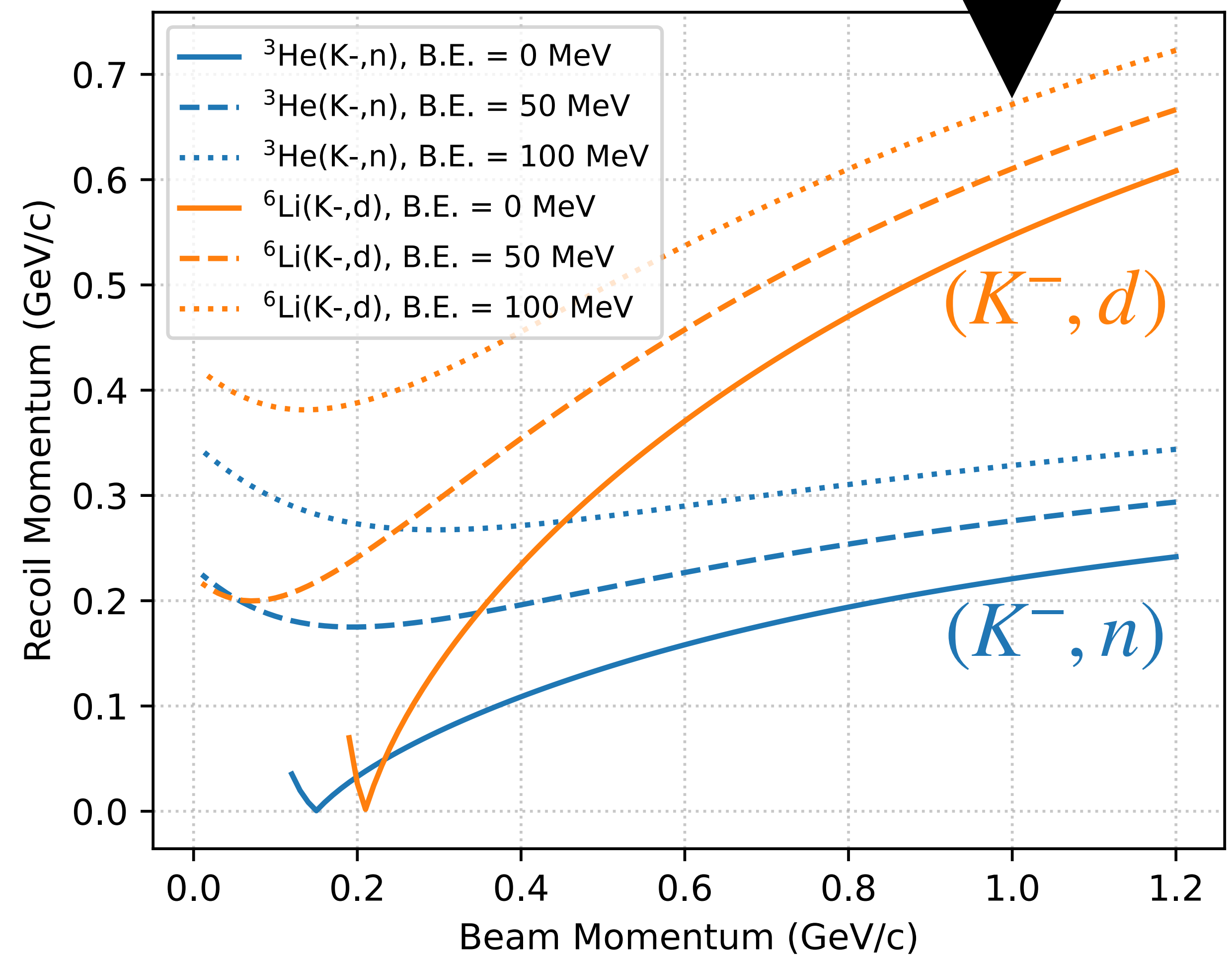


✓ Clear peak would be observed for both modes

Heavier systems

-1.0 GeV/c

Knucl	reaction	decay
"K⁻α"	^{6}Li(K$^-$, d)	Λt/Λdn/ Λpnn…
"K⁻^{6}Li"	^{7}Li(K$^-$, n)	Λαn… etc?
"K⁻αα"	^{9}Be(K$^-$, n)	?



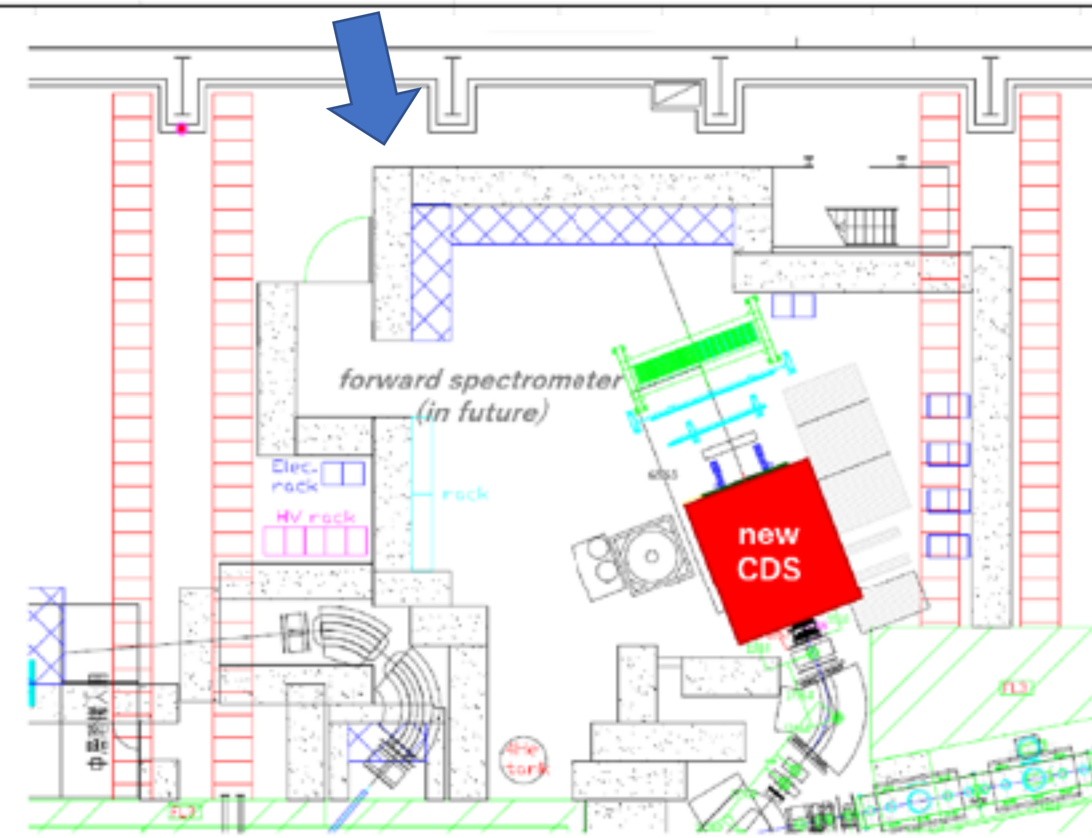
- Deuteron knock-out reaction has a larger momentum transfer
  - → We would like test in E80: ^{6}Li(K$^-$,d)"K$^-$α", ^{4}He(K$^-$,d)"K^{0bar}nn"

- Larger decay particle (like α) can not be detected by the CDS. many-particle decay modes are also difficult to reconstruct.
  - Forward knocked-out particle spectroscopy at relatively large angle would be an altanative way

Schedule

now

	FY2022				FY2023				FY2024				FY2025				2026~
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
SC Solenoid	Design		Purchase (SC Wire)		Construction							Installation & Test			Integration	Commissioning	Physics Run / Analysis & Pblication
NC	Design		Purchase (Scinti.)		Assembly				Test & Commissioning								
CDC	Design				Construction				Test & Commissioning								
K1.8BR Beam Line	E73(CDC) -> E72(HypTPC) Experiments										Upgrade		E80 Experiment				



Aiming to complete detector construction in 4 years.

- Superconducting solenoid magnet
- CDC (cylindrical drift chamber)
- CNC (cylindrical neutron counter)
- K1.8BR area modification

- We plan to be ready by the end of JFY2025

Summary

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

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

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

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

Kaonic nuclear state is getting more solid

J-PARC E80/P89 collaboration

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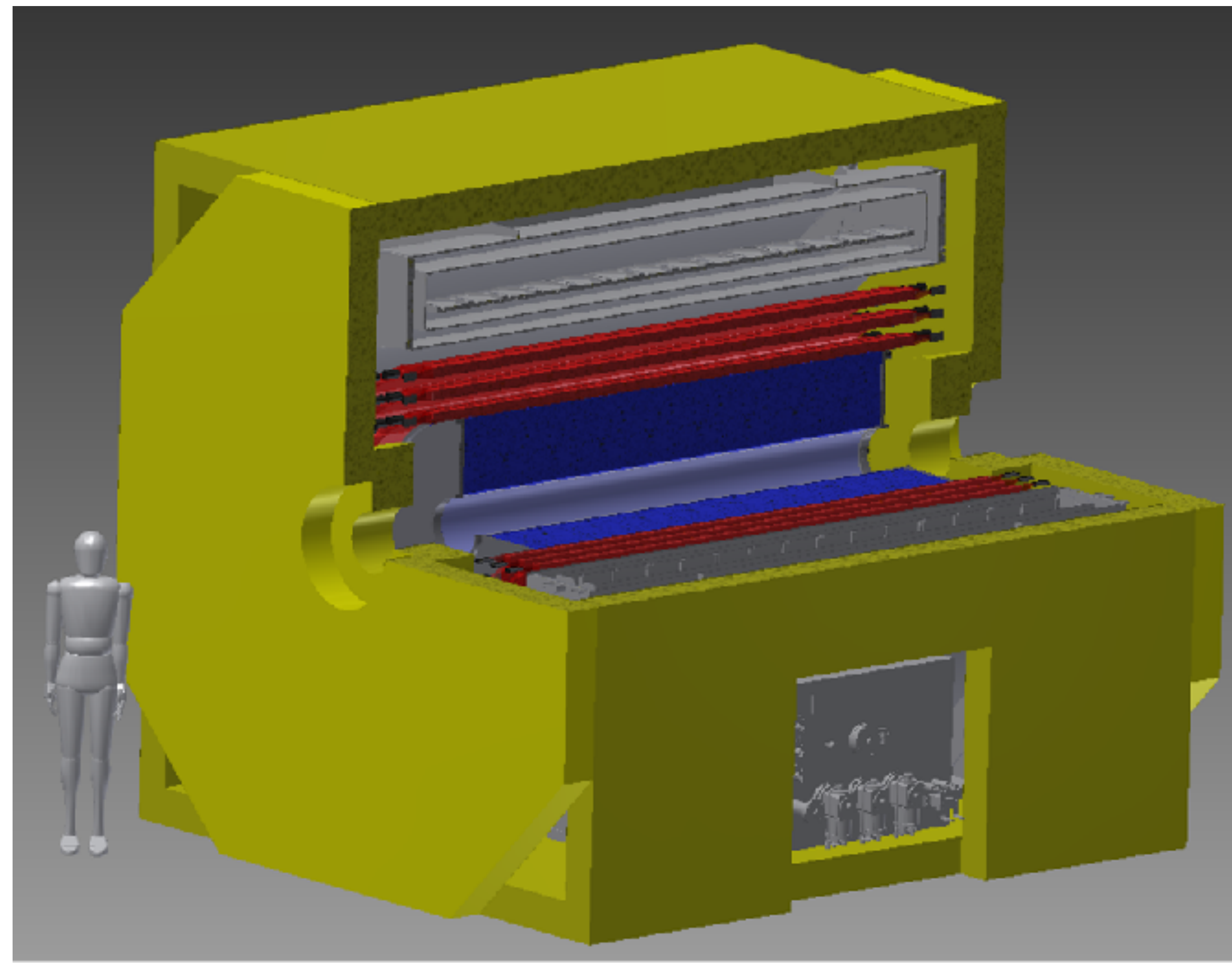
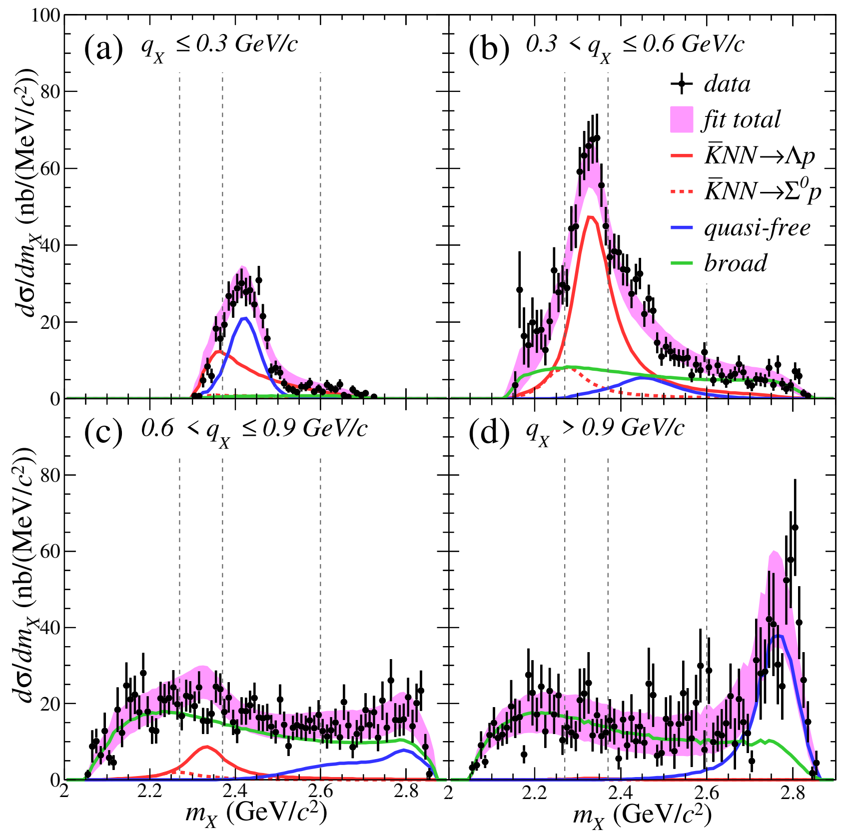


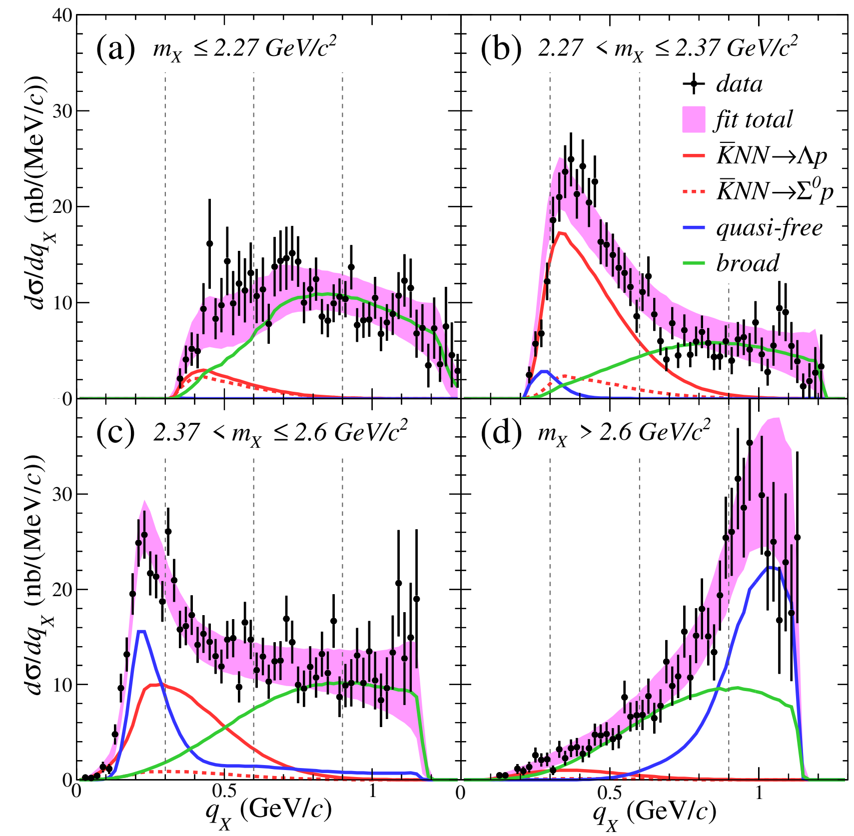
- We welcome new collaborators !
- Now 1 postdoc position is open at JAEA (deadline: Dec. 23)

Fit result

Λp invariant-mass

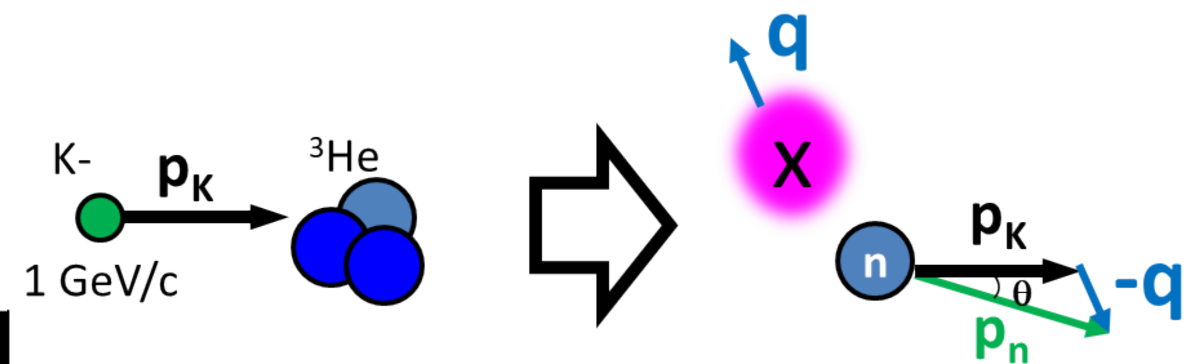


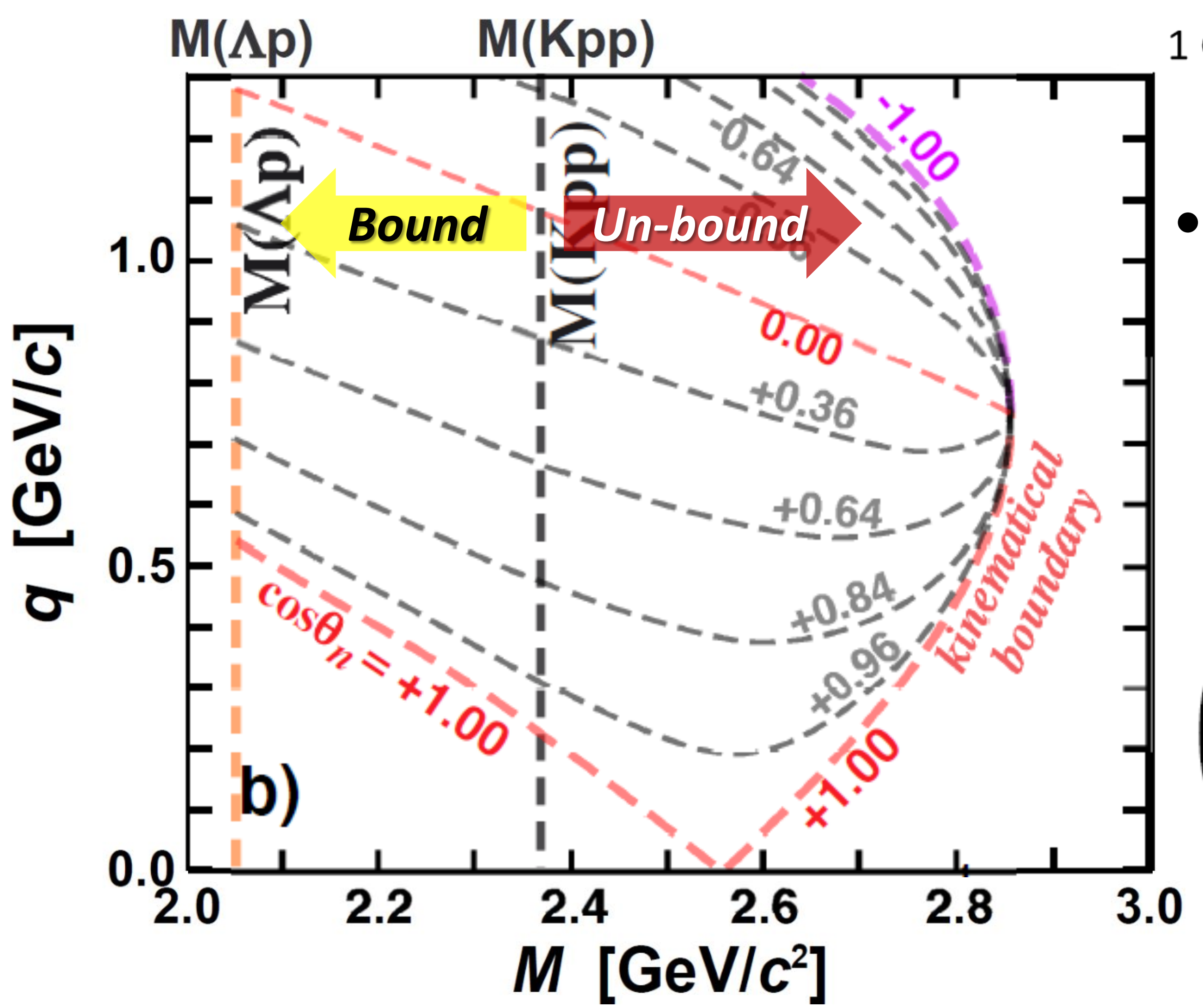
Momentum transfer to Λp



→ **The whole 2D distribution is well reproduced.**

Exclusive ^{3}He(K$^-$,Λp)n

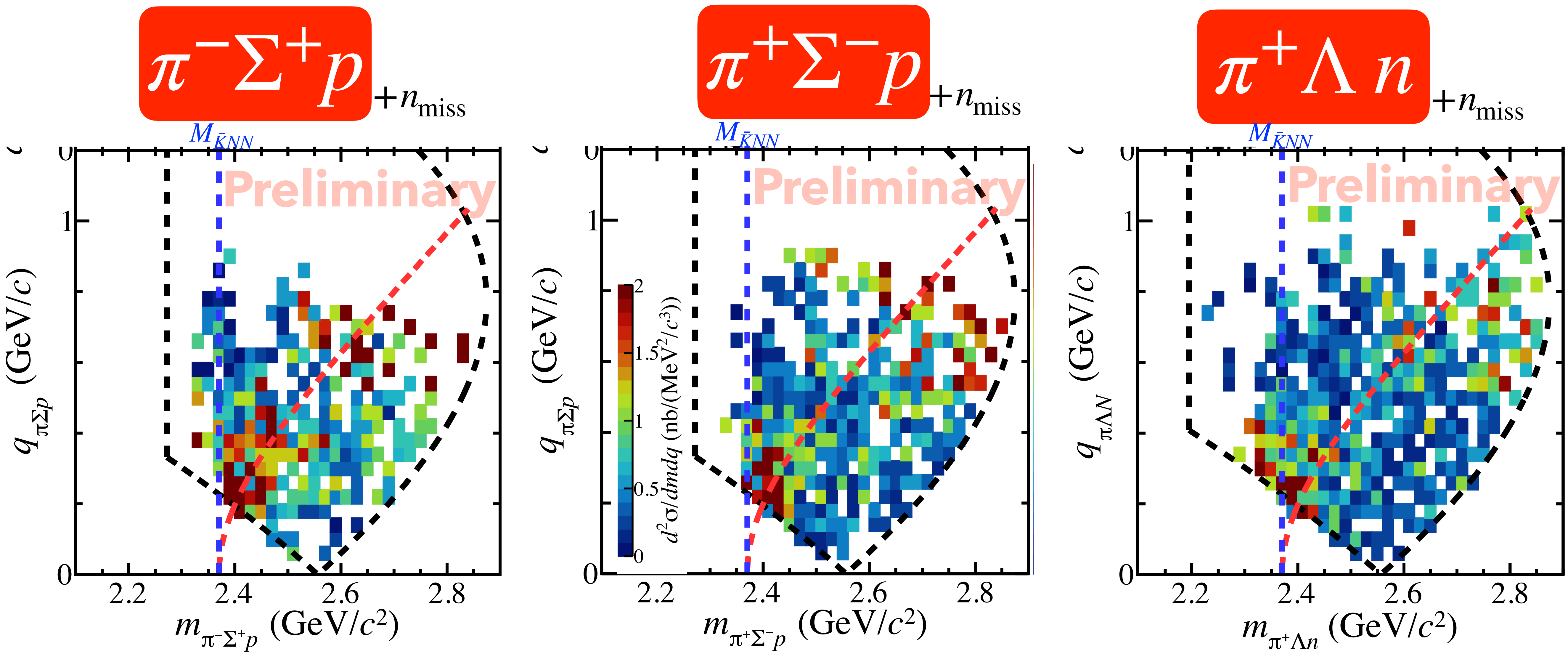




q *: momentum transfer of (K-,n)*
M *: invariant mass of Λp*

- **Momentum transfer analysis using the (K$^-$,n) reaction**
  - ✓M(Λp) vs. q
  - ✓give a clear information on reaction processes

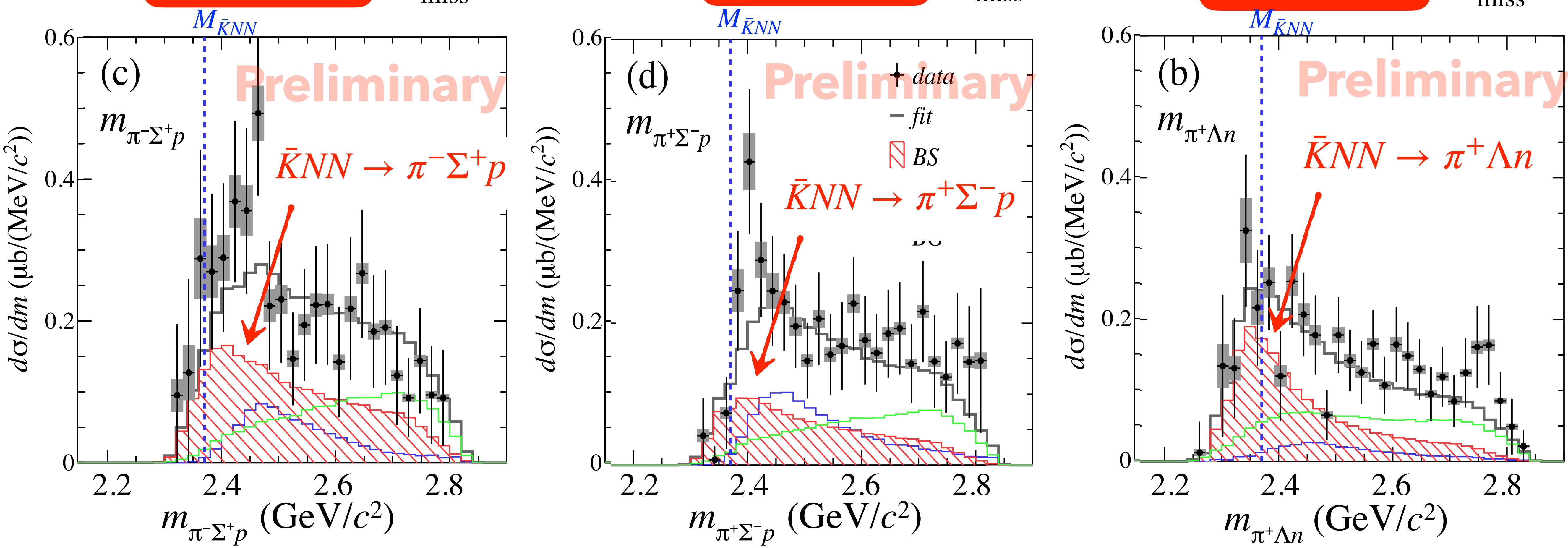
$$\begin{pmatrix}\sqrt{m_K^2+p_K^2}\\ p_K\\ 0\end{pmatrix} + \begin{pmatrix} M_{^3\mathrm{He}}\\ 0\\ 0\end{pmatrix} = \begin{pmatrix}\sqrt{M^2+q^2}\\ q\cos\theta\\ q\sin\theta\end{pmatrix} + \begin{pmatrix}\sqrt{m_n^2+p_K^2-2p_K q\cos\theta+q^2}\\ p_K-q\cos\theta\\ -q\sin\theta\end{pmatrix}$$



Similar to Λp $+n_{\rm miss}$

→ The reaction could be understood as $\bar{K}NN$ production & quasi-free process

$\pi^-\Sigma^+p$ $+n_{\text{miss}}$ | $\pi^+\Sigma^-p$ $+n_{\text{miss}}$ | $\pi^+\Lambda n$ $+n_{\text{miss}}$

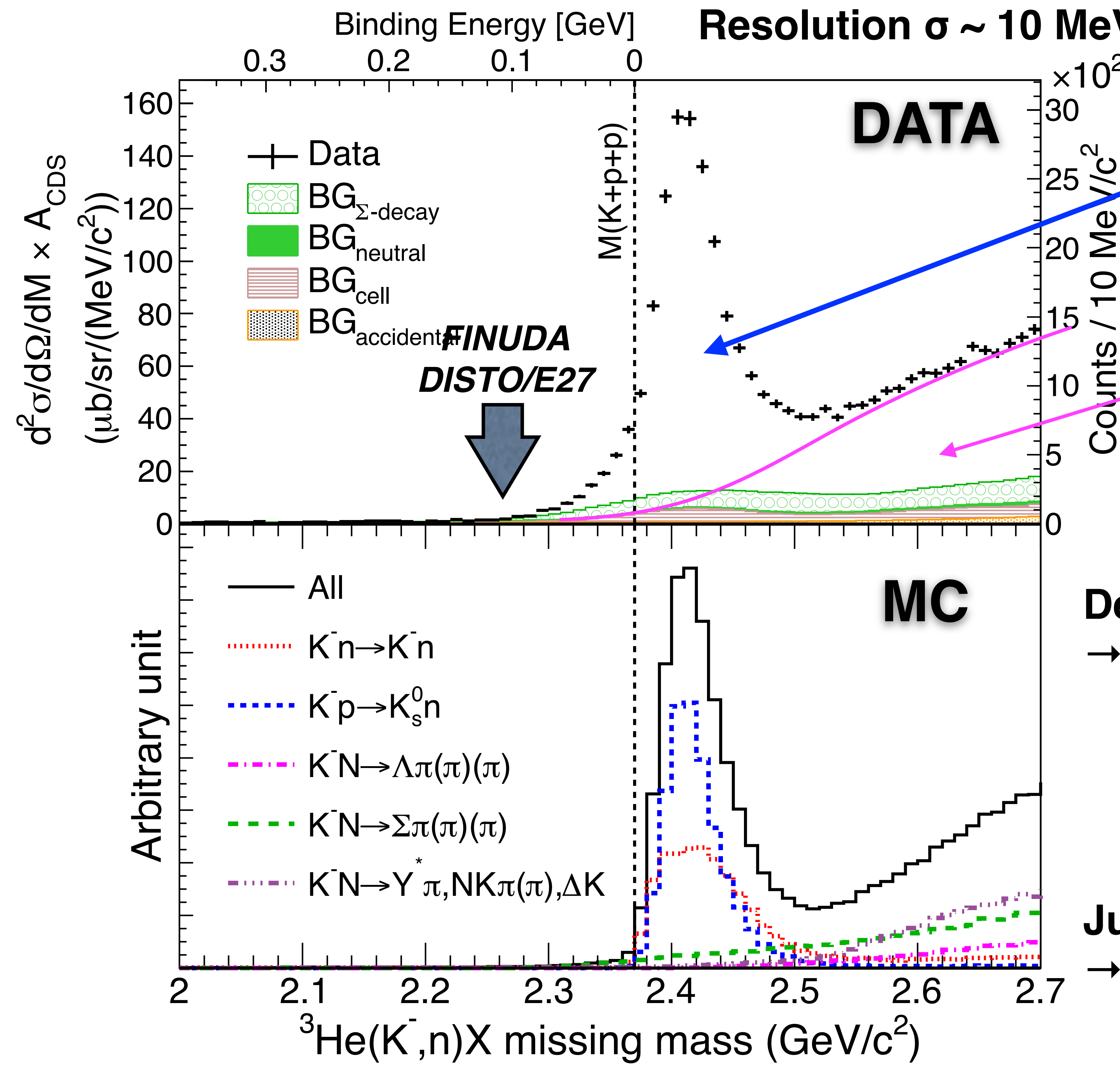


$$\Gamma_{\text{non-mesonic}} \ll \Gamma_{\text{mesonic}}$$

Γ_{mesonic} would be $\mathcal{O}(10)$ times larger than $\Gamma_{\text{non-mesonic}}$.

Forward neutron semi-inclusive spectrum

Resolution σ ~ 10 MeV/c² @ threshold



Quasi-elastic

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

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

Hyperon decay

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

$Y \to n + \pi$

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)