Experimental study of the $\bar{K}NNN$ state and beyond at J-PARC

Tadashi Hashimoto (JAEA ASRC)
for the J-PARC E73/T77/E80 collaboration

October 12th, 2023

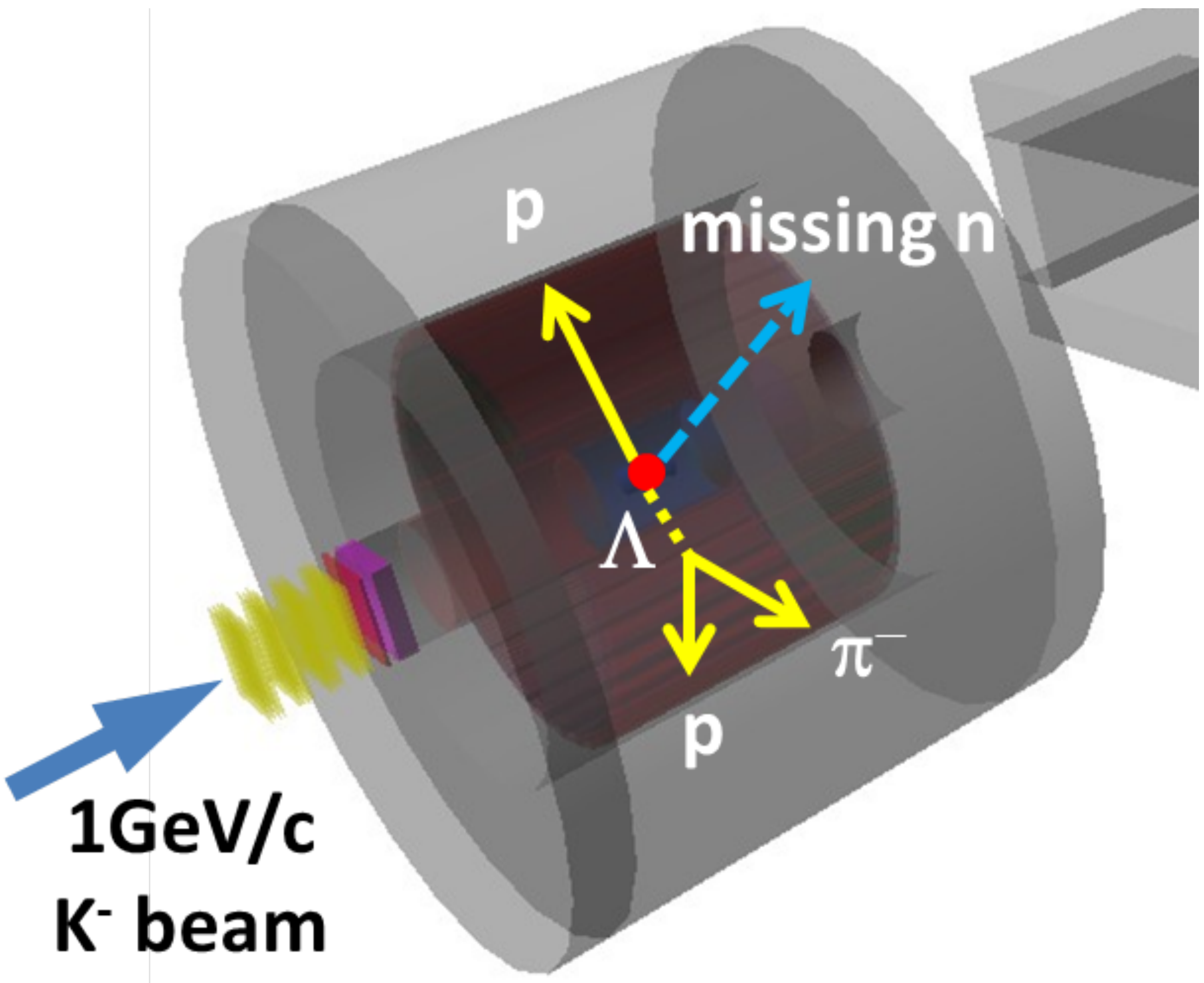
Outline

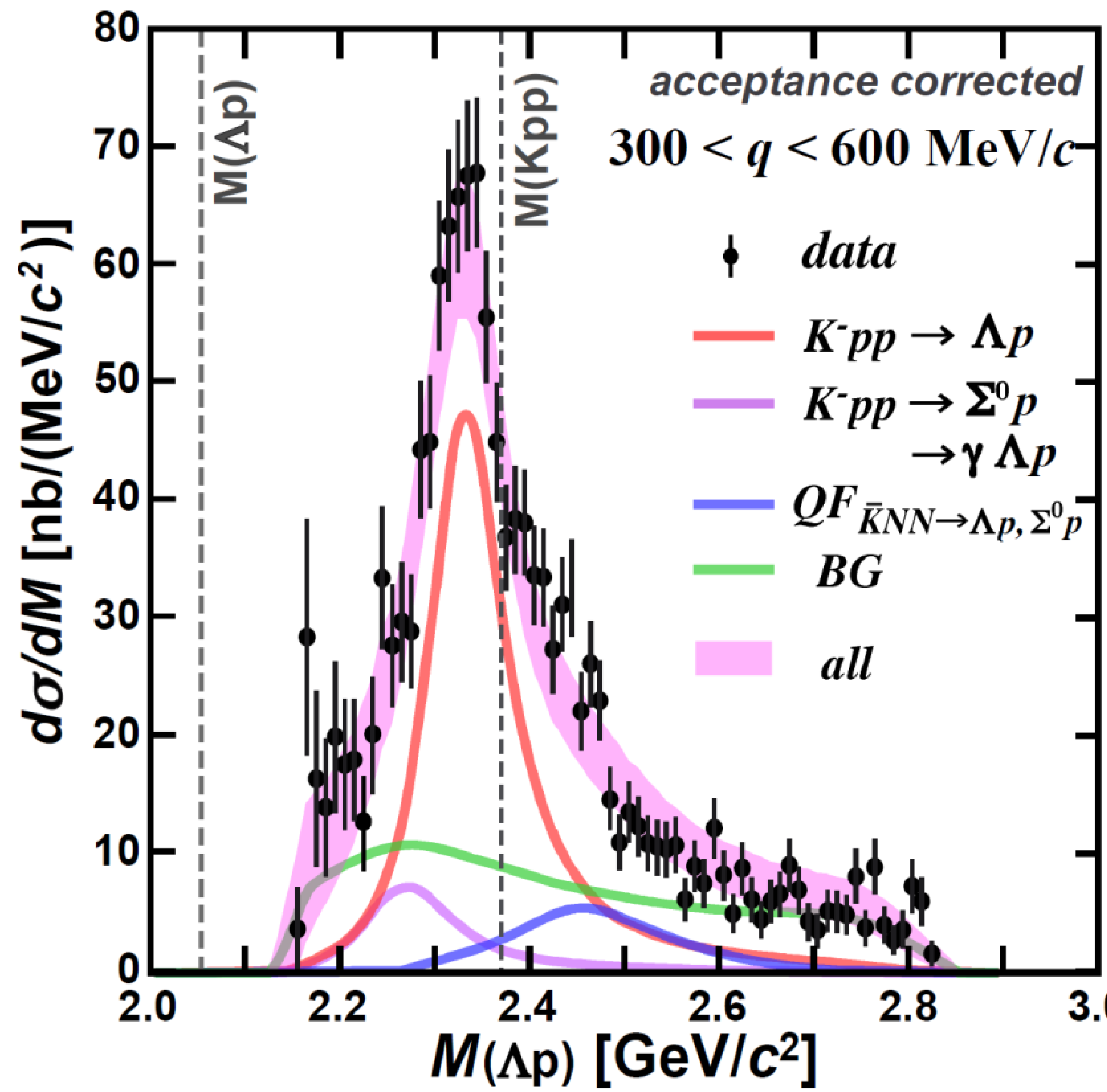
1. Status on $\bar{K}NNN$
2. Preliminary result of $K^- + {}^4\mathrm{He} \to \Lambda + d + n$
3. Future detailed investigation of the $\bar{K}NNN$ (J-PARC E80)
4. Possible strategy to study heviear kaonic nuclei beyond $\bar{K}NNN$

"$\bar{K}NN$" in J-PARC E15

$$I(J^p) = \frac{1}{2}(0^-),\ I_z = +\frac{1}{2}$$

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



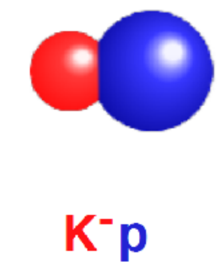


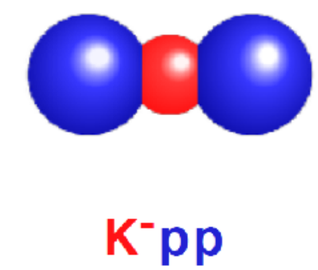
- Exclusive measurement of all the final state particles in a wide q region
- **We have found a way to effectively observe a kaonic nucleus**

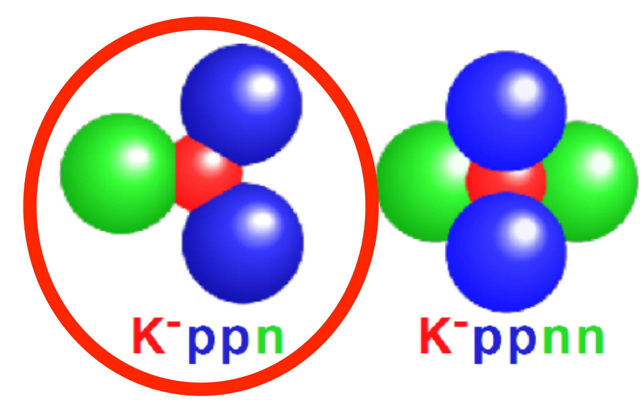
Need further investigation

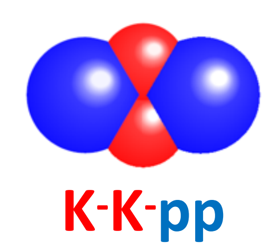
to establish kaonic nuclei

- **Λ(1405) state**
  - $\bar{K}N$ qusi-bound state as considered?
  - Relation between $\bar{K}N$ and $\bar{K}NN$
- **Further details of the $\bar{K}NN$**
  - Spin and parity of the "K-pp"
  - Really compact and dense system?
- **Heavier kaonic nuclei**
  - Mass number dependence
  - Interplay between $\bar{K}N$ & NN
  - Modification of clustering in core nuclei
- **Double kaonic nuclei?**
  - Much compact and dense system?







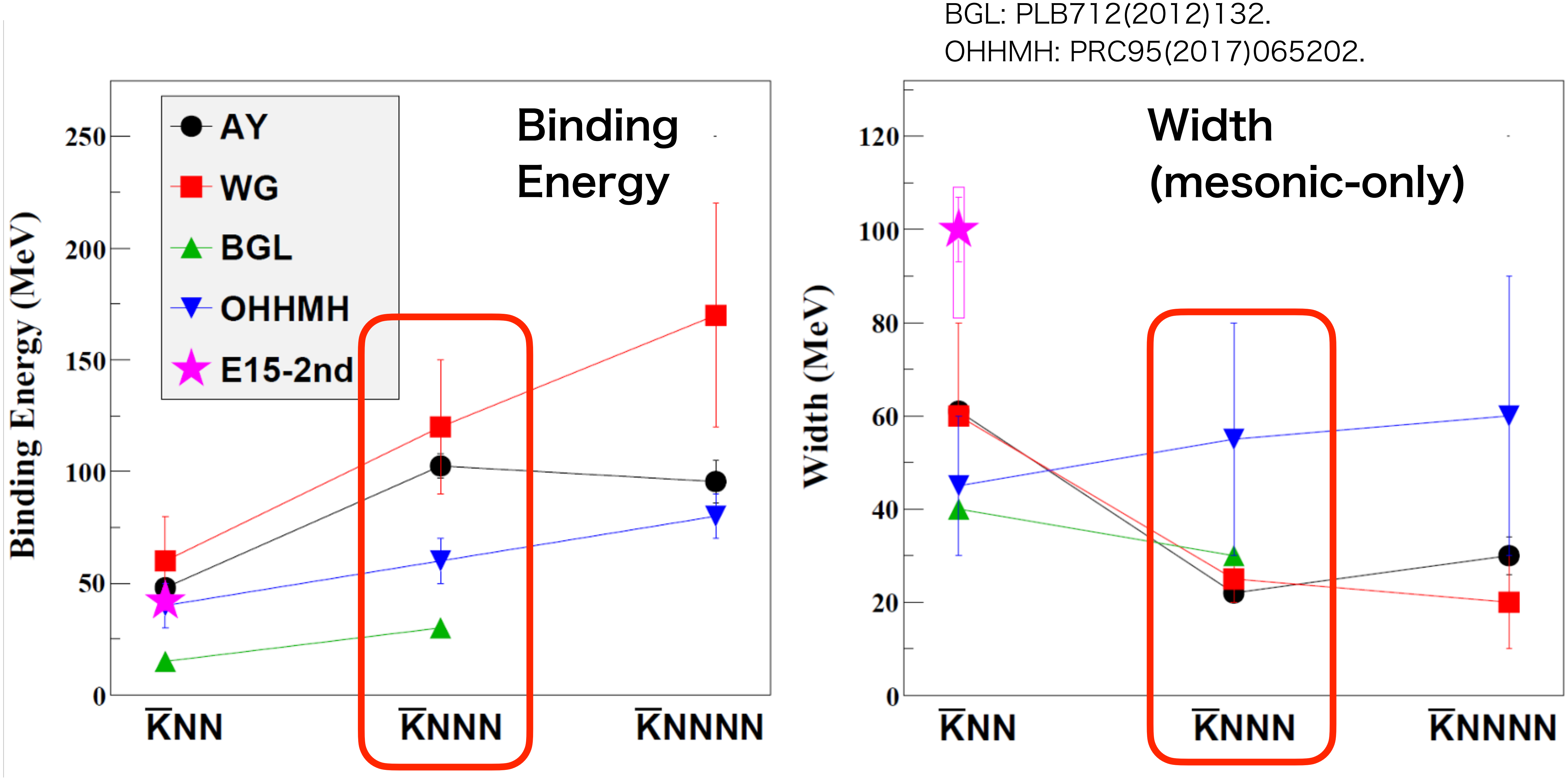


$\bar{K}NNN$: Theoretical situaion

$$I(J^p) = 0(\frac{1}{2}^-)$$

Not a complete list. sorry…

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

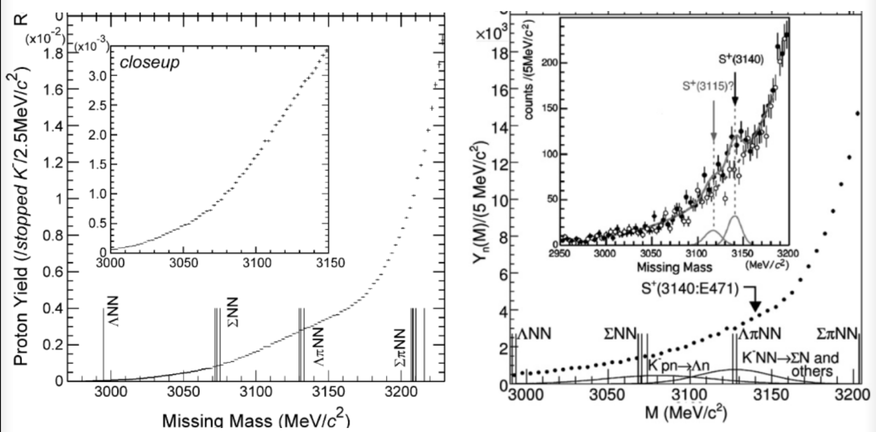


Larger binding than $\bar{K}NN$ and similar width are predicted.

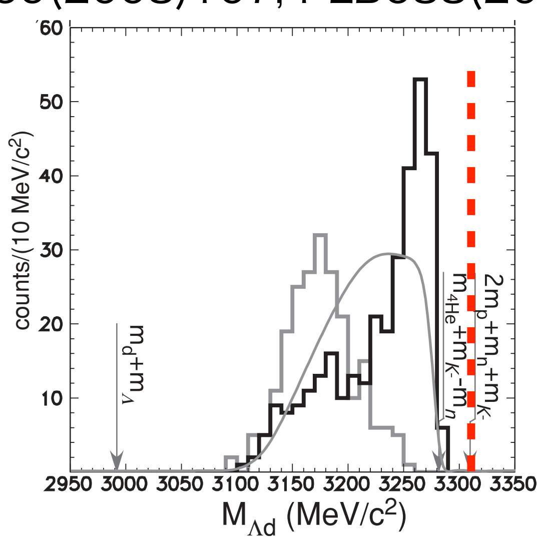
$\bar{K}NNN$: Experimental situaion

Stopped K- on ⁴He

E471/E549@KEK



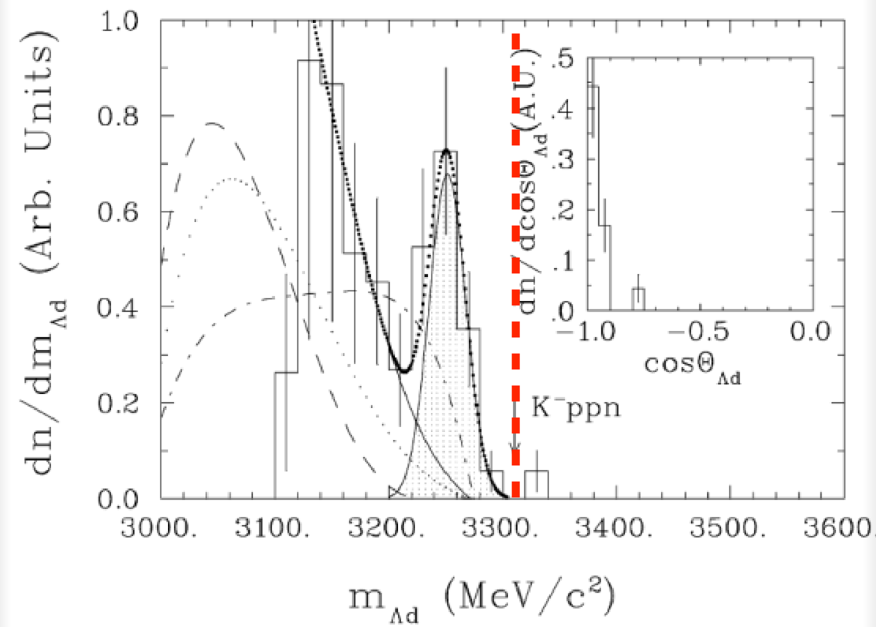
PLB659(2008)107, PLB688(2010)43



PRC76(2007)068202

Stopped K- on Li/C back-to-back Λd

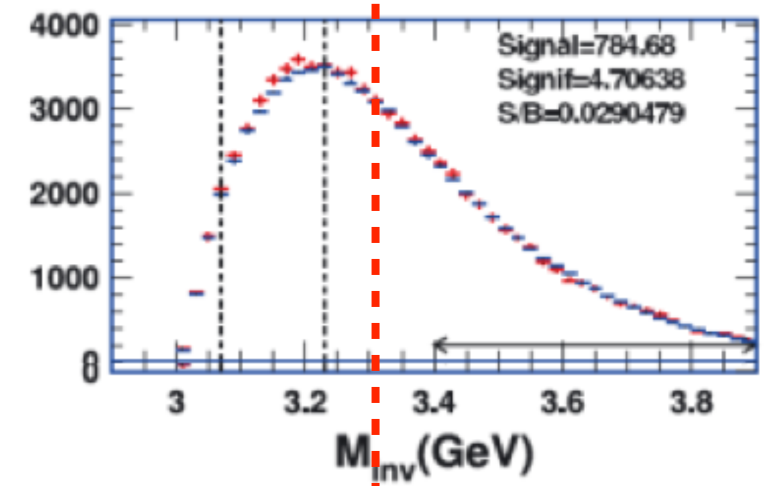
FUNUDA@DAΦNE

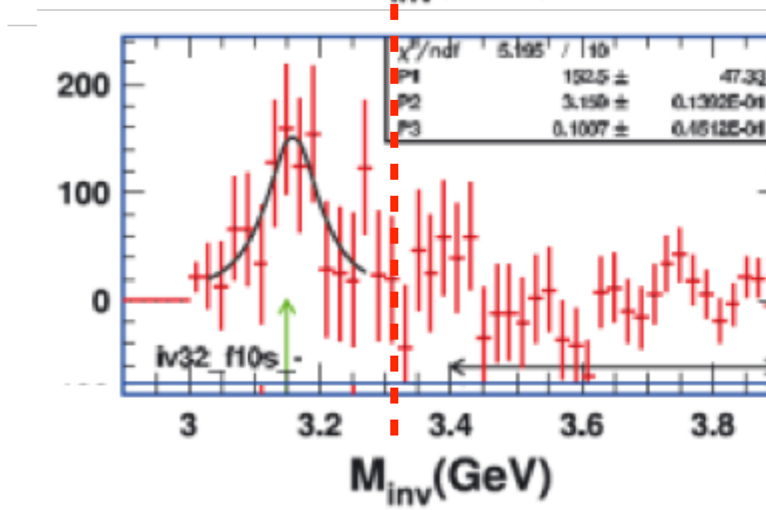


PLB654(2007)80

Λd in Ni+Ni

FOPI@GSI



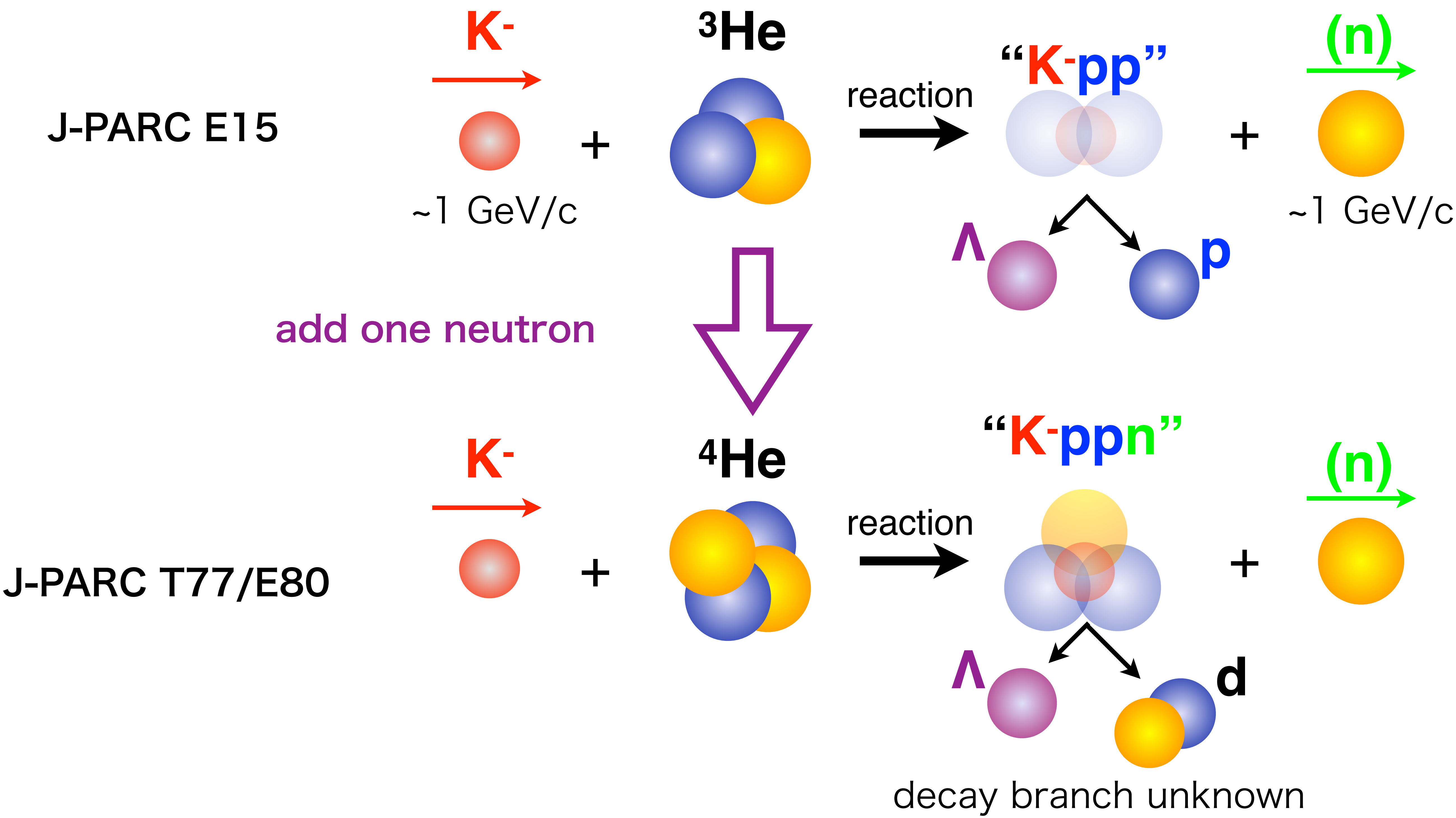


EXA05 Proceedings (2005)

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

Preliminary result of the $\bar{K}NNN$ search

Our approach



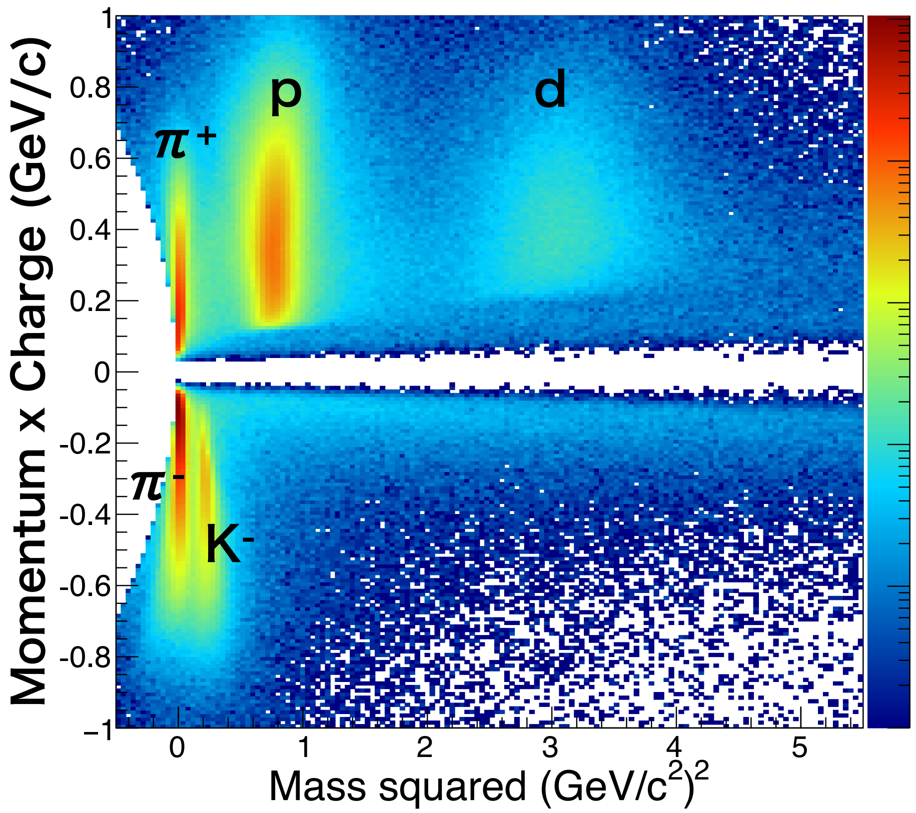
Use in-flight (K^-,n) reaction, just as successful J-PARC E15

Λdn event selection

only 3-day data!

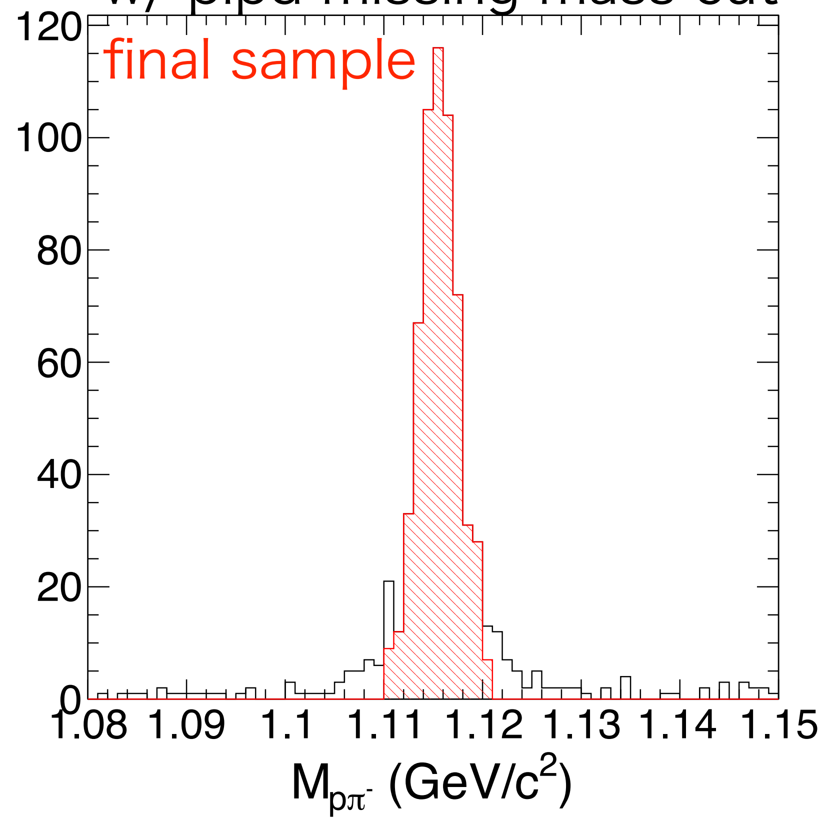
deuteron ID

CDC track curvature &
CDH time of flight



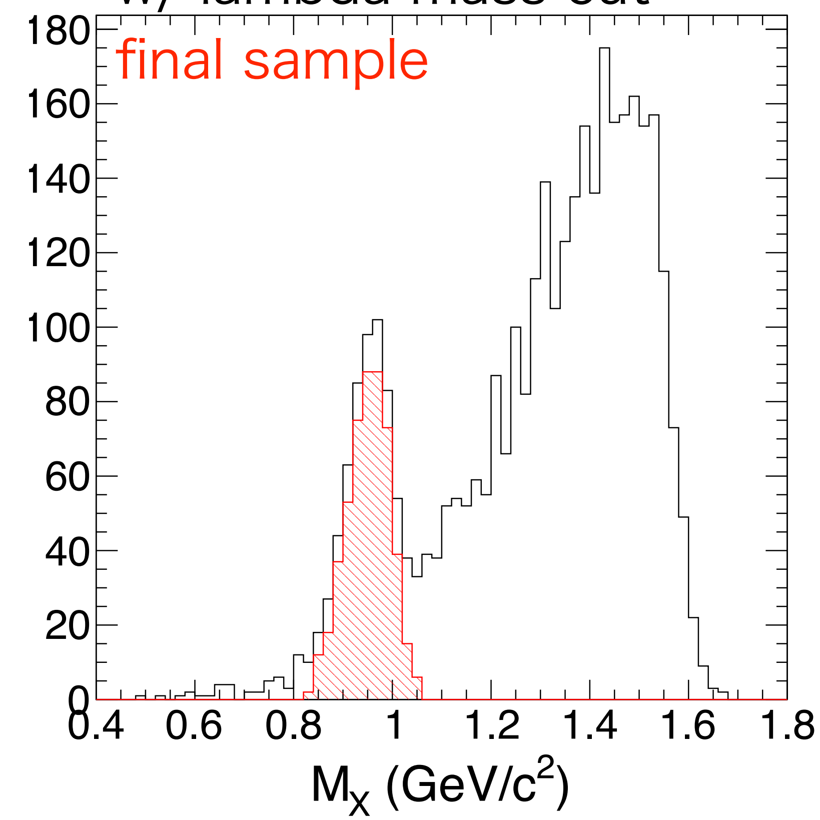
Λ reconstruction

w/ vertex consistency cut
w/ pipd missing mass cut



Missing neutron ID

w/ vertex consistency cut
w/ lambda mass cut

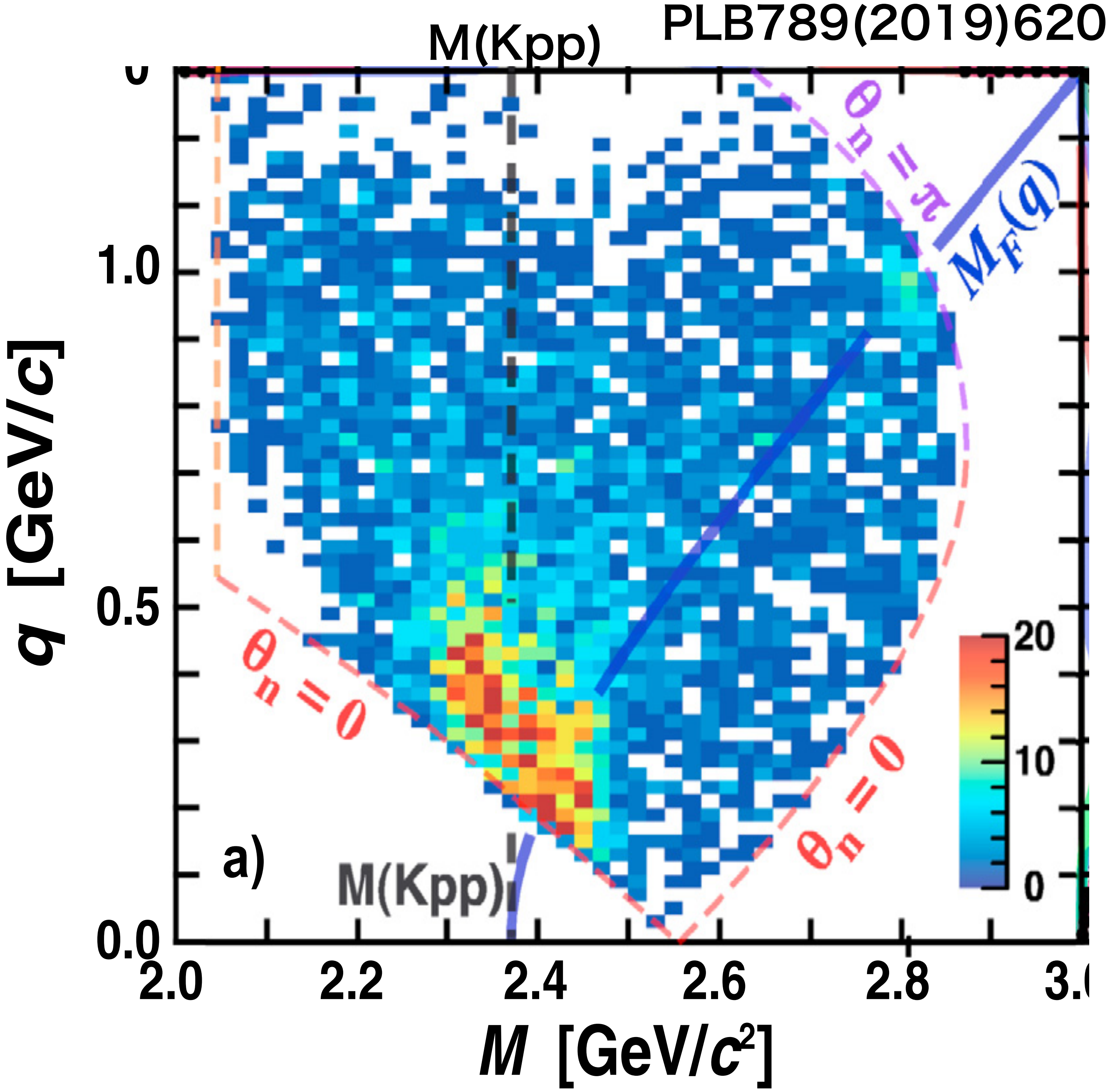


- Λdn final states are identified with a good purity by considering kinematical & topological consistensies
- ~20% contamination from $\Sigma^0 dn/\Sigma^- dp$

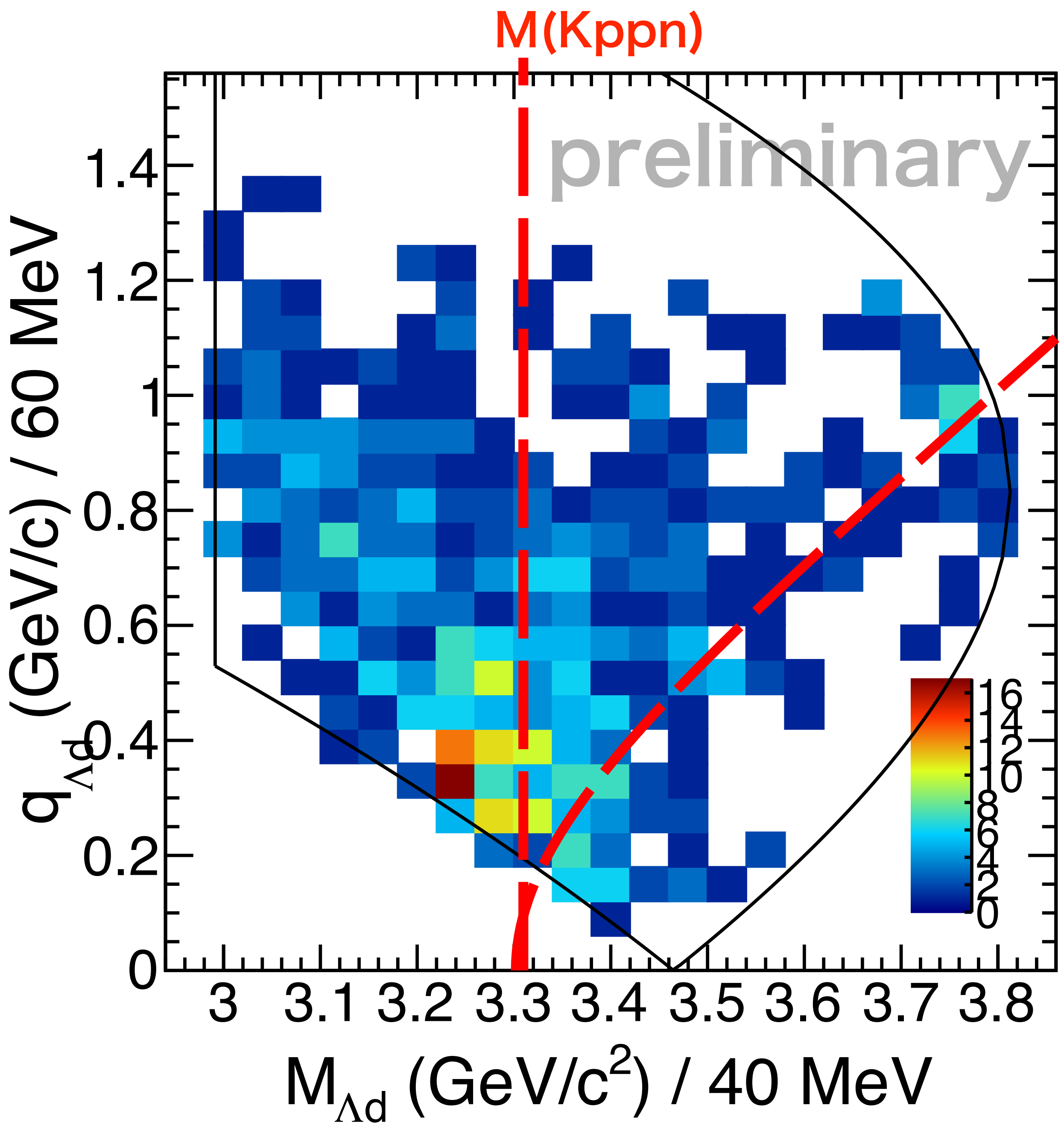
Preliminary result

before acceptance correction

E15: Λp ($\sim 42 \times 10^9\ K^-$)



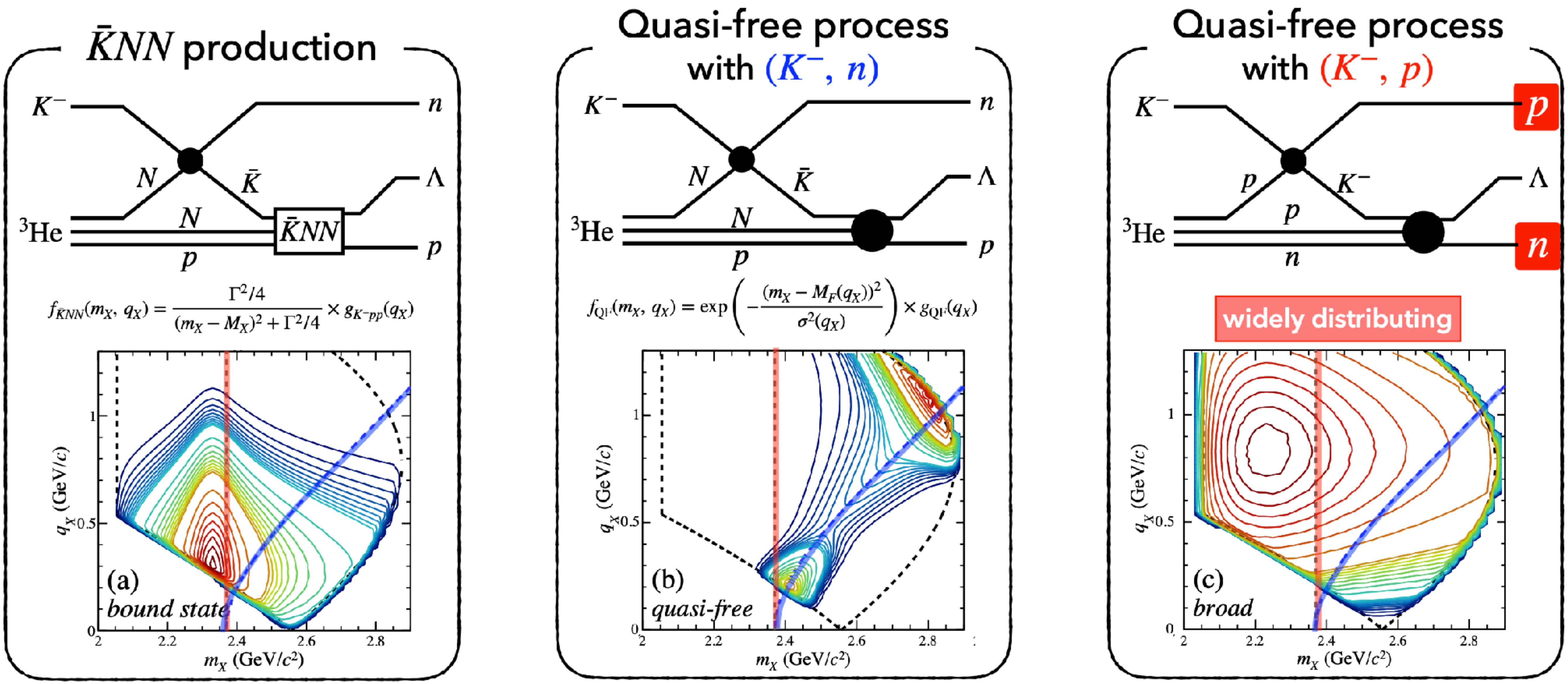
T77: Λd ($\sim 6 \times 10^9\ K^-$)



- Two disributions are quite similar

Model functions

from T. Yamaga's slide

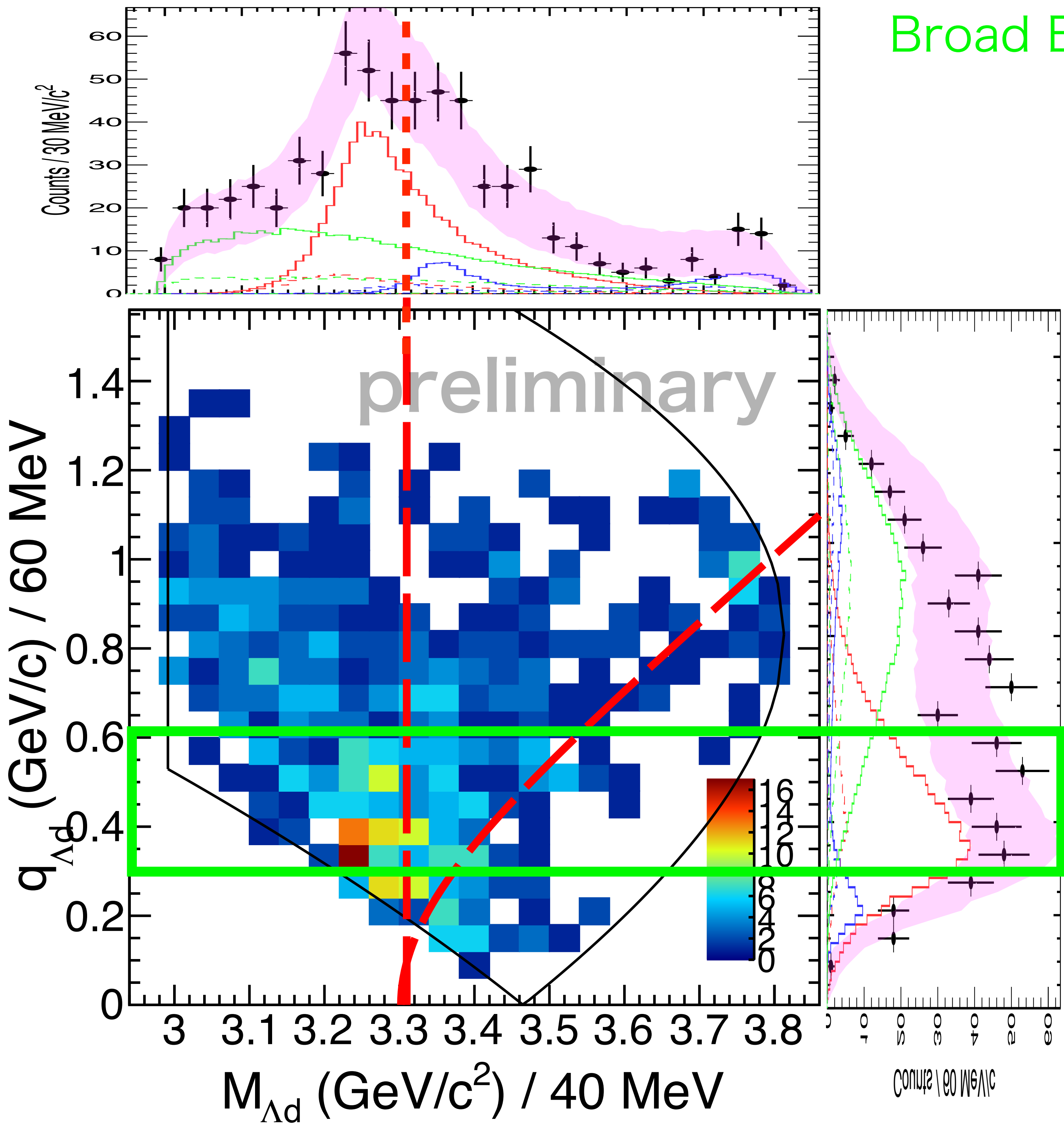


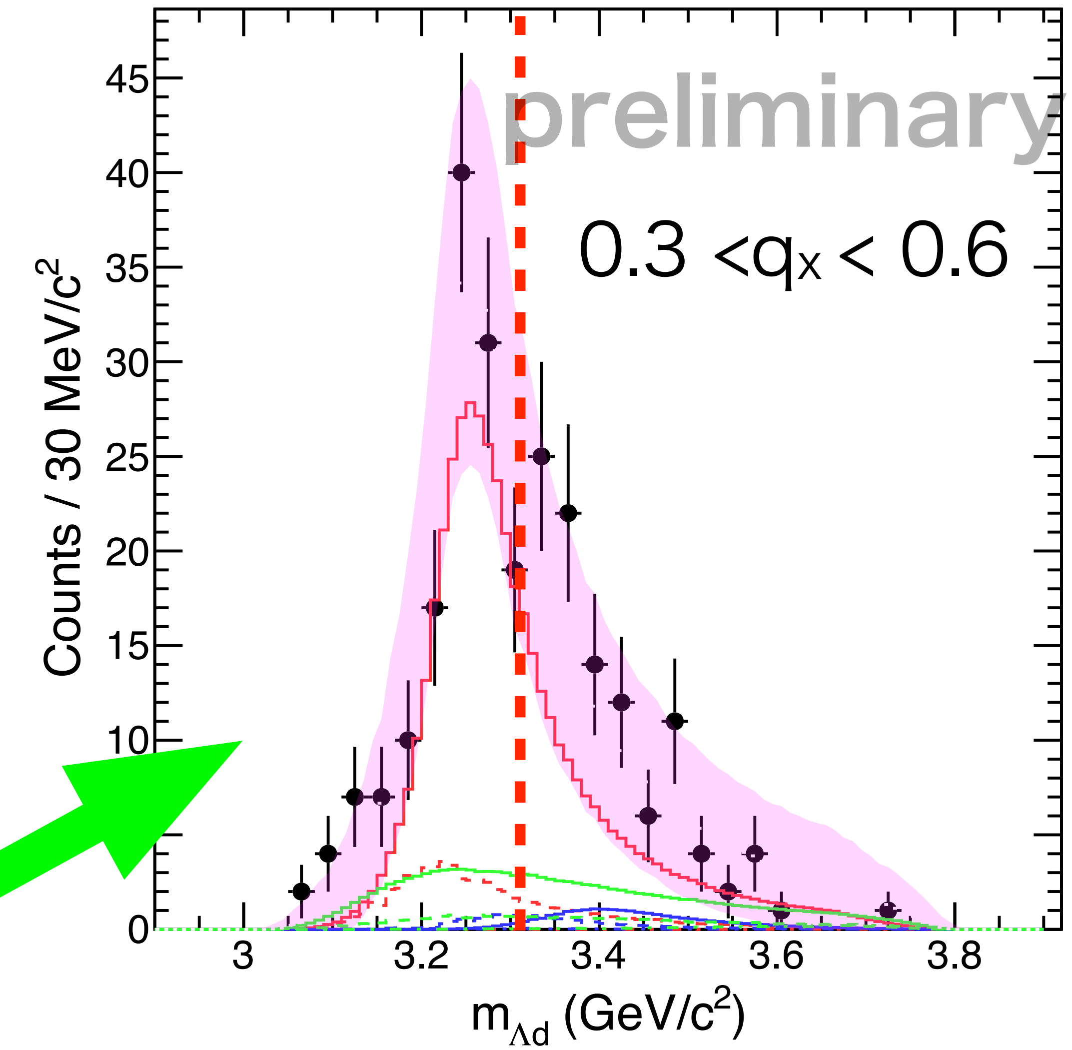
- From E15 functions, simply shift the mass by 1 nucleon mass
- Shapes of the "quasi-free" and "broad" distributions are fixed by E15 results.

Preliminary result

“$\bar{K}NNN$” Breit-Wigner wtih Gaus. form factor

Broad BG and QF-K- shape from E15 PRC





$$B_{\bar{K}NNN} = 64 \pm 11(\text{stat})\ \text{MeV}$$

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

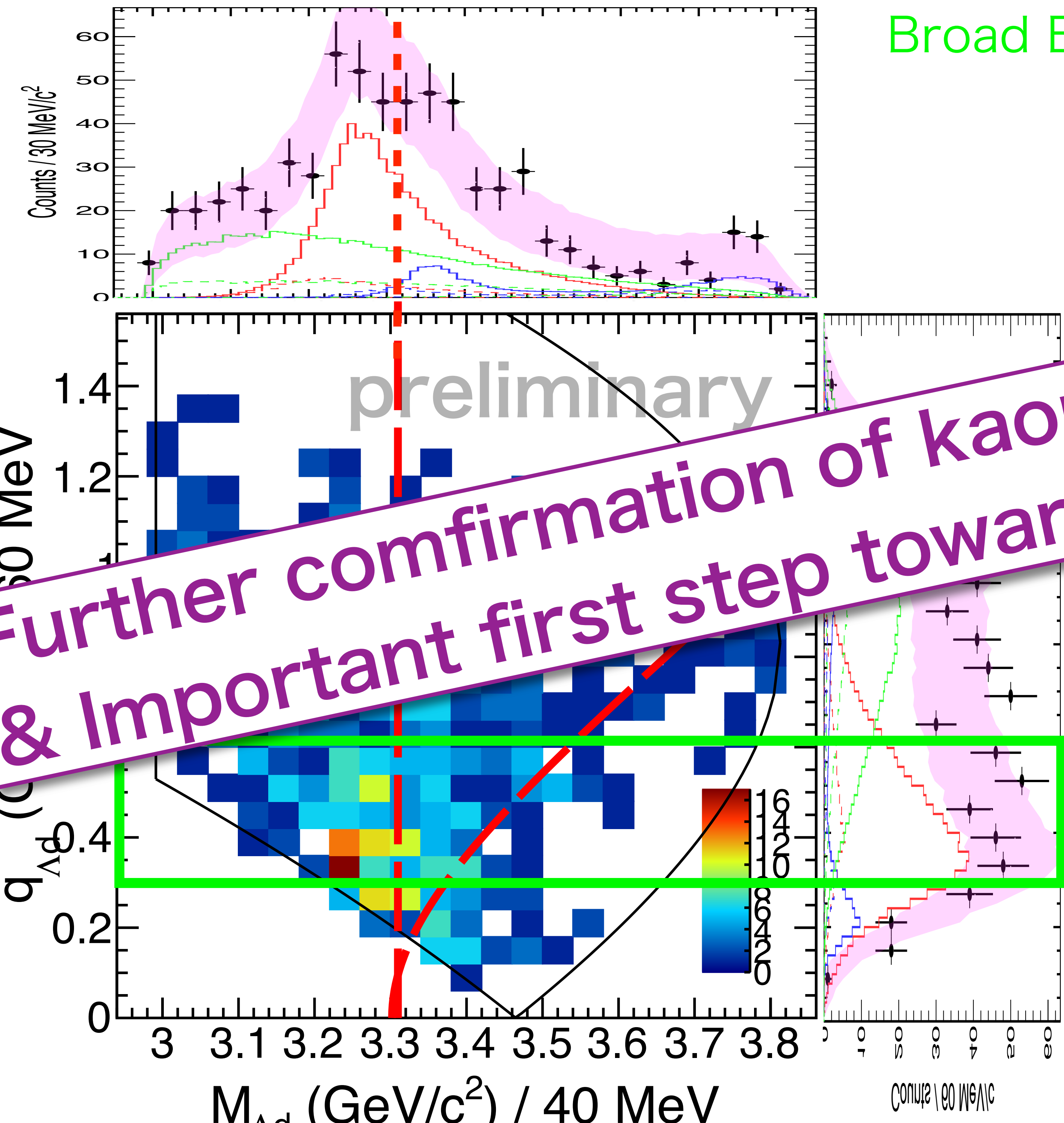
$$\sigma_{\bar{K}NNN \to \Lambda d} \sim 4\ \mu\text{b}$$

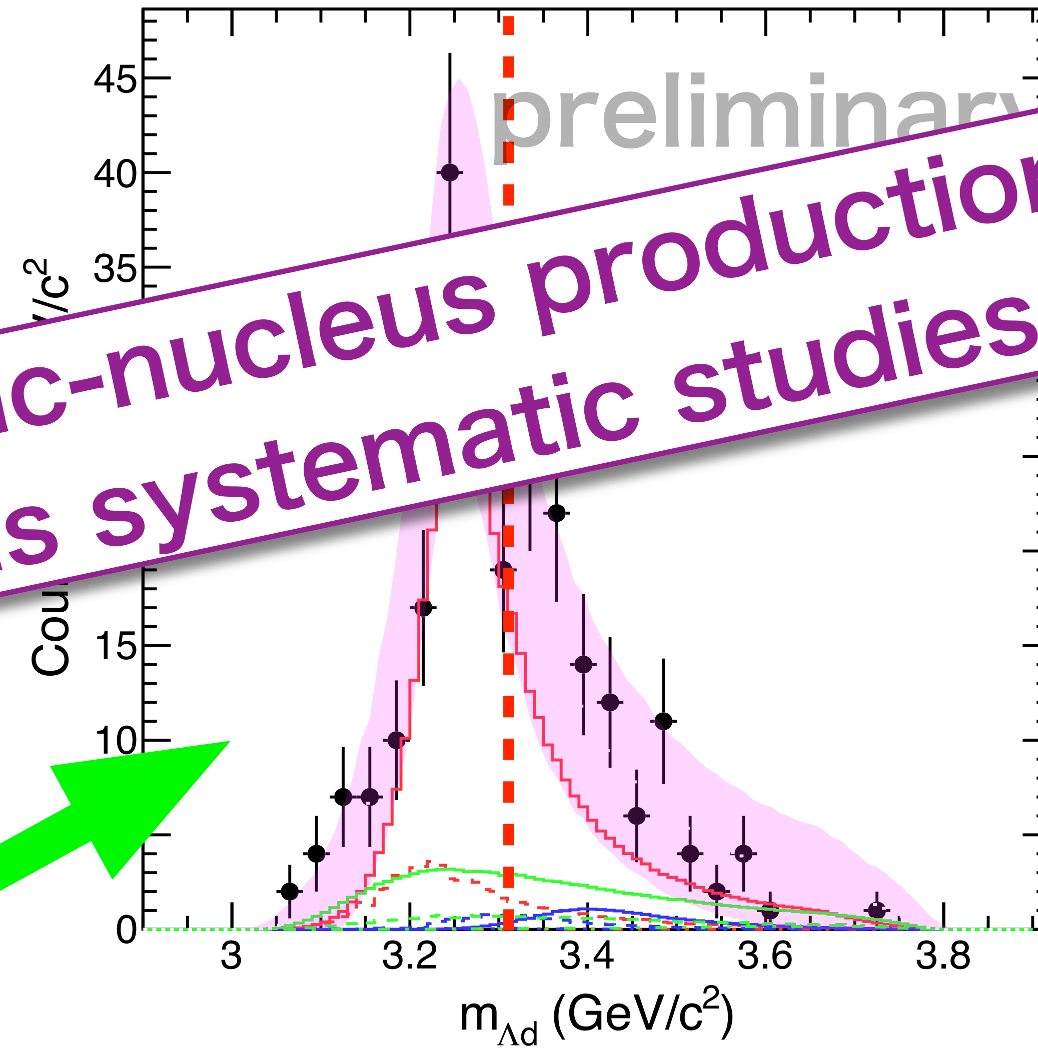
$cf.\ B_{\bar{K}NN} = 42 \pm 3\ (\text{stat})\ ^{+3}_{-4}\ (\text{syst})\ \text{MeV@E15 PRC}$

Preliminary result

"$\bar{K}NNN$" Breit-Wigner wtih Gaus. form factor

Broad BG and QF-K- shape from E15 PRC





Further comfirmation of kaonic-nucleus production & Important first step towards systematic studies

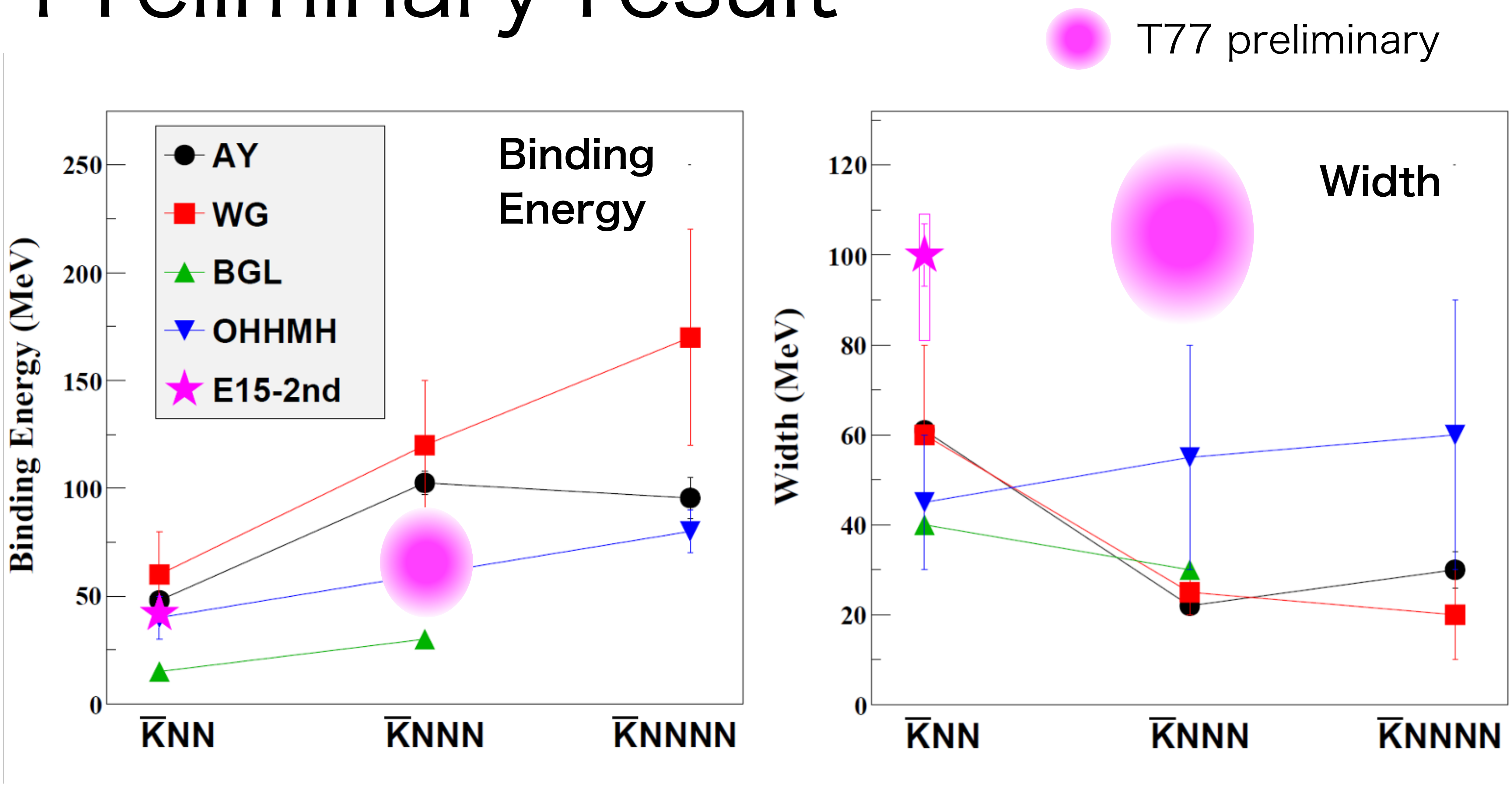
$B_{\bar{K}NNN} = 64 \pm 11(\text{stat})$ MeV

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

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

$cf.\ B_{\bar{K}NN} = 42 \pm 3\ (\text{stat})\ ^{+3}_{-4}\ (\text{syst})$ MeV@E15 PRC

Preliminary result



- The binding energy is compatible with some 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.

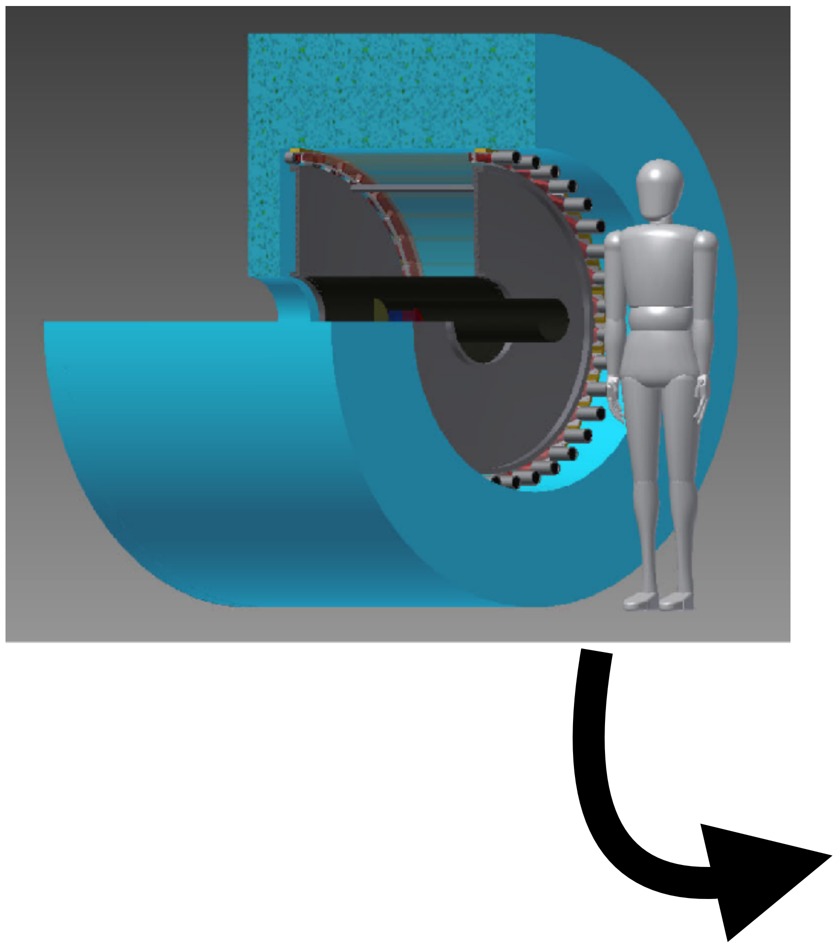
Status on $\bar{K}NNN$

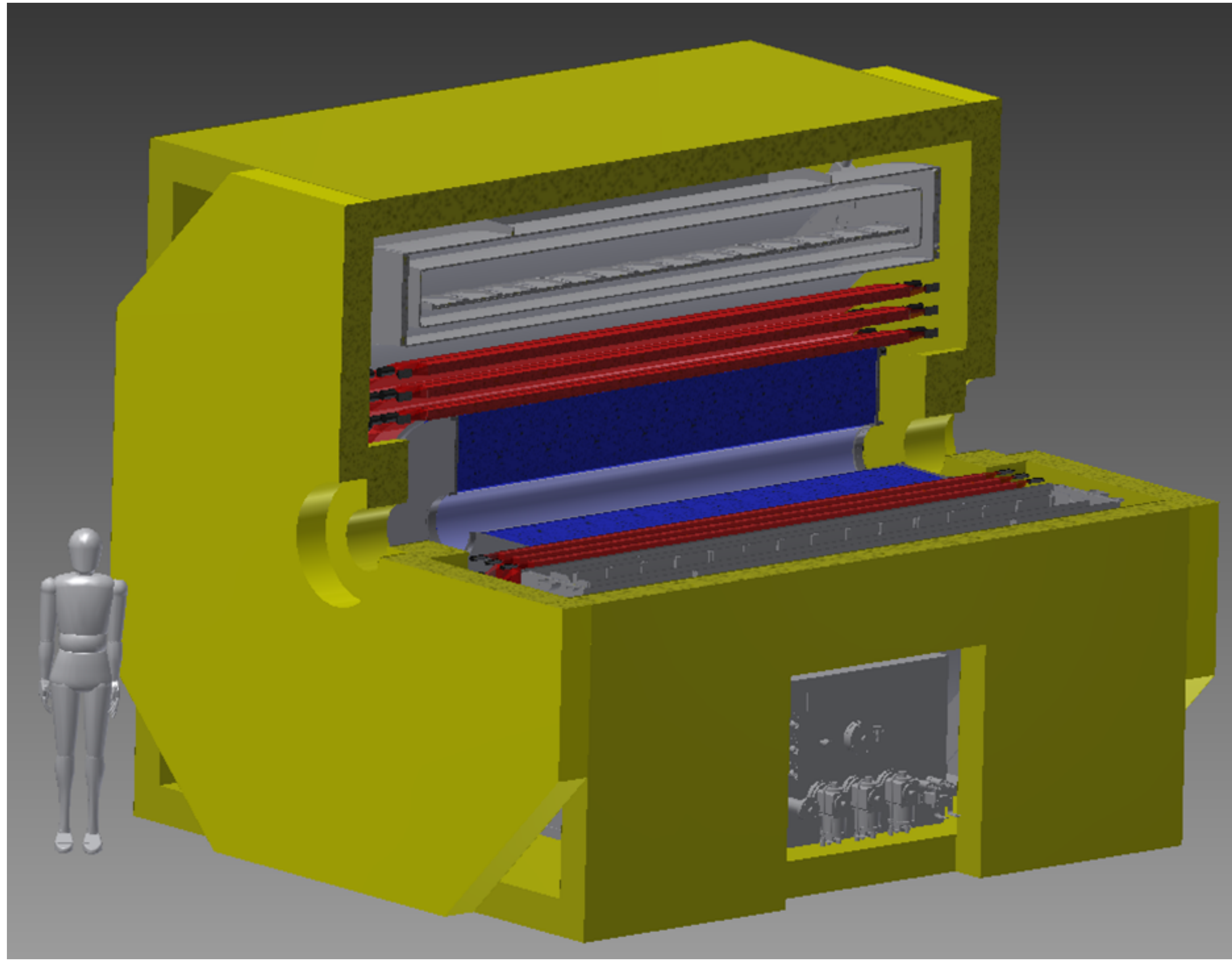
- The isospin of the observed state is uniquely assinged as $I = 0$ from the its decay to $\Lambda(I = 0)\ d(I = 0)$, but how about spin-parity?
  - J^{P}=1/2^{-} assuming all the consistuents are in S-wave
    $\bar{K}NNN\ (I = 0,\ J^{p} = 1/2^{-})$
  - $\Sigma^{*}NN\ (I = 0,\ J^{p} = 3/2^{+})$ possibility still remains

- We need more data
  - to compare with $\bar{K}NN$ in E15
  - to study other decay mode: $\bar{K}NNN \to \boldsymbol{\Lambda pn, \pi\Sigma d, \pi\Sigma pn}, \cdots$
    - peak position, branching ratio,⋯
    - I=1 component could be contaminated
  - to study I=1 state via (K^{-}, p) reaction

Further experiment on $\bar{K}NNN$
(J-PARC E80)

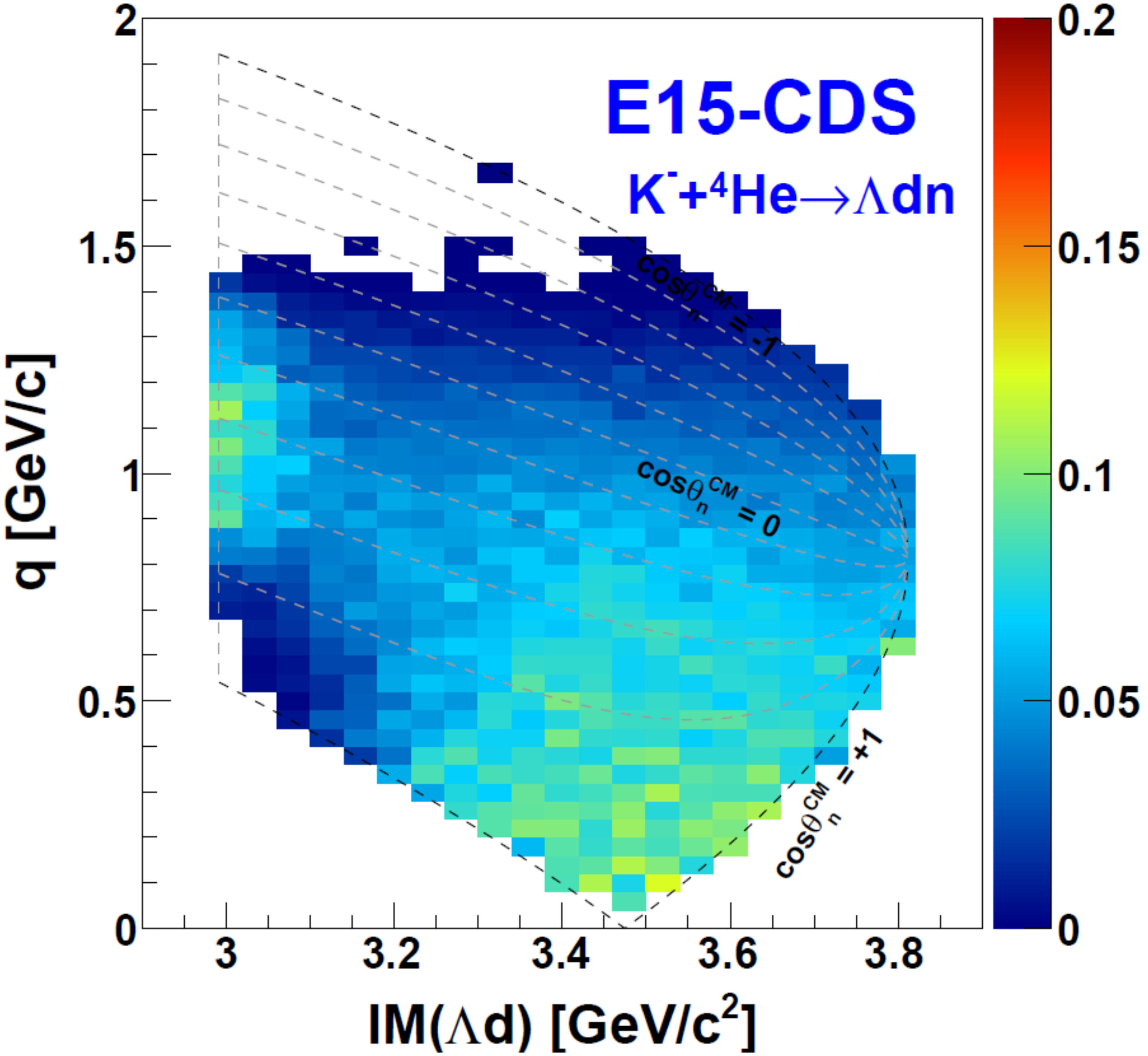
J-PARC E80 with a new spectrometer

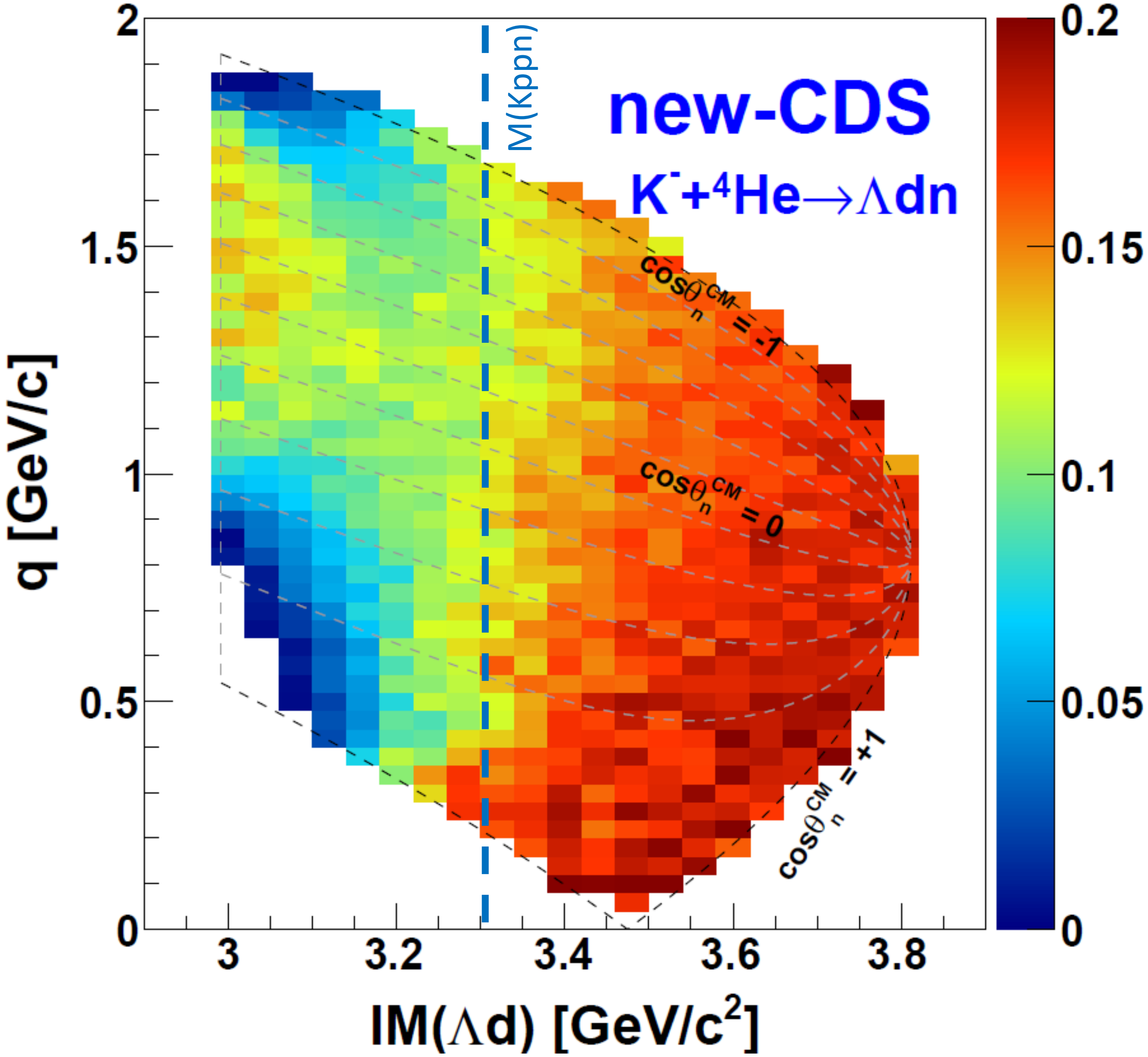




- x3 longer CDC: **solid angle 59%→93%**
- 3-layer barrel NC: **neutron efficiency 3%→15%**

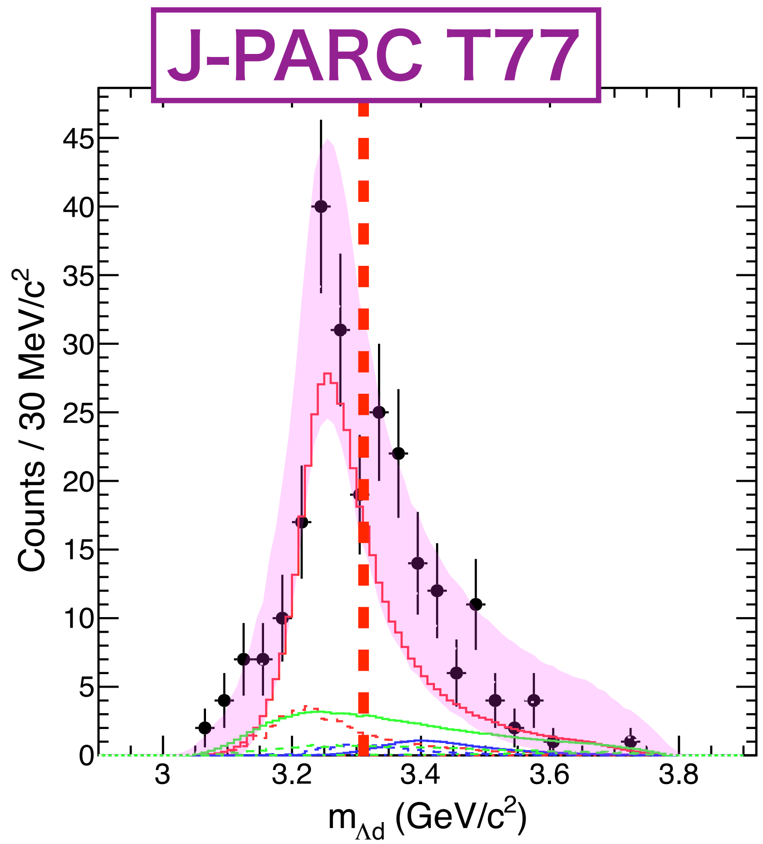
Acceptance for $K^- + {}^4\mathrm{He} \to \Lambda d + n$

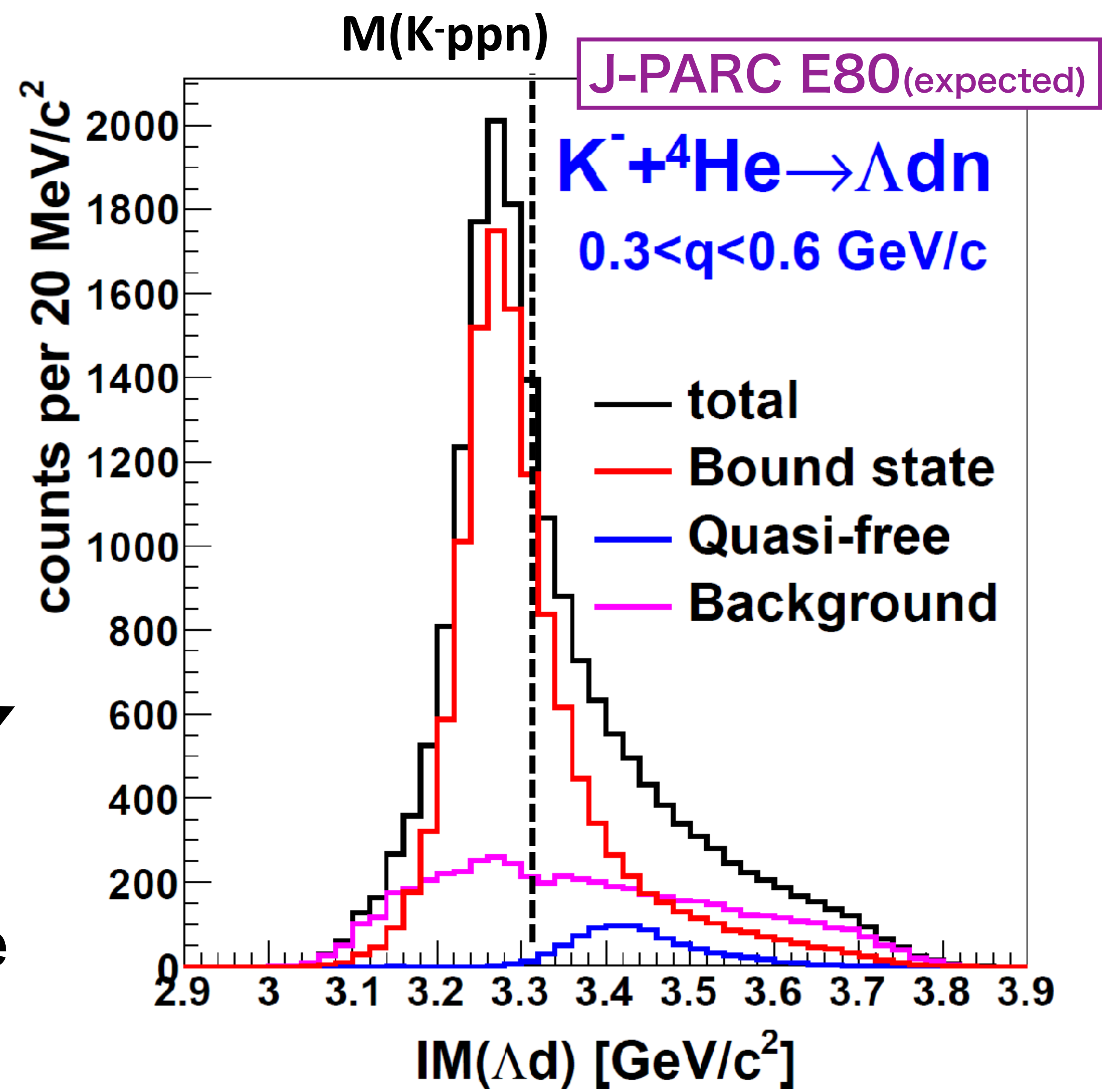




- large kinematical-region coverage & x2 acceptance

Expected spectrum @ 90 kW x 3 weeks



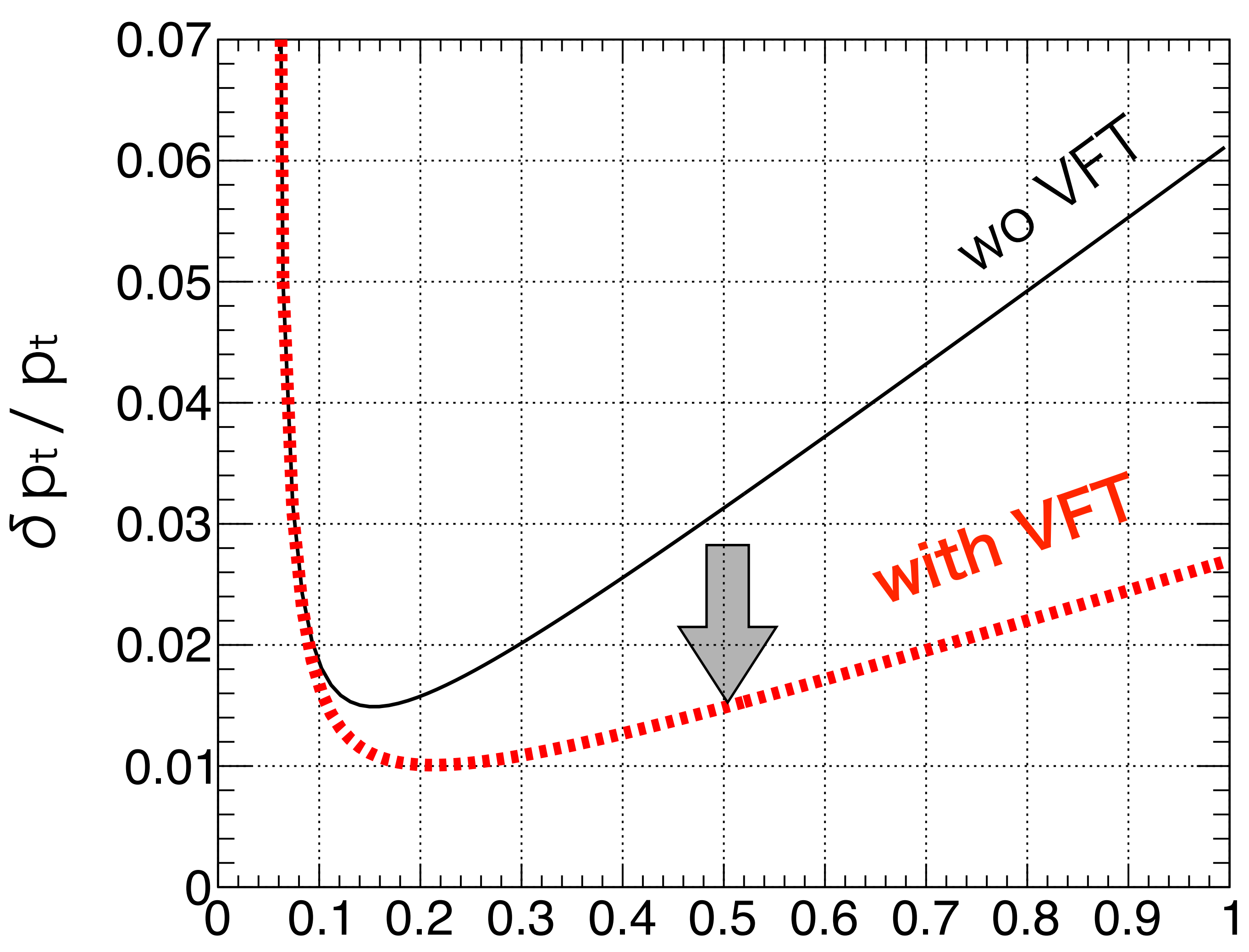


x20 more kaons
x2 larger acceptance

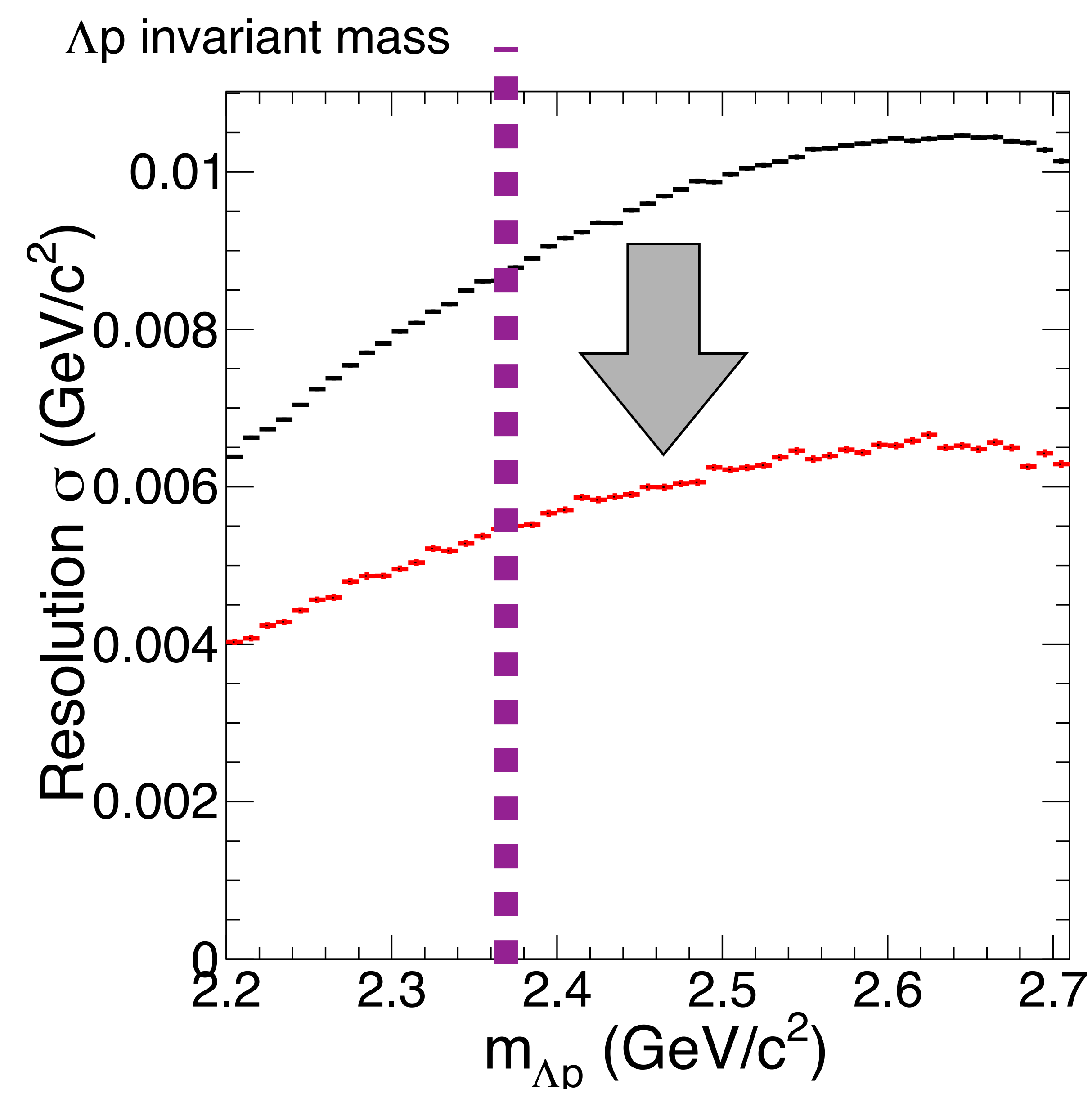
- We expect x40 Λdn events

Improvement in resolution with VFT

Single track resolution



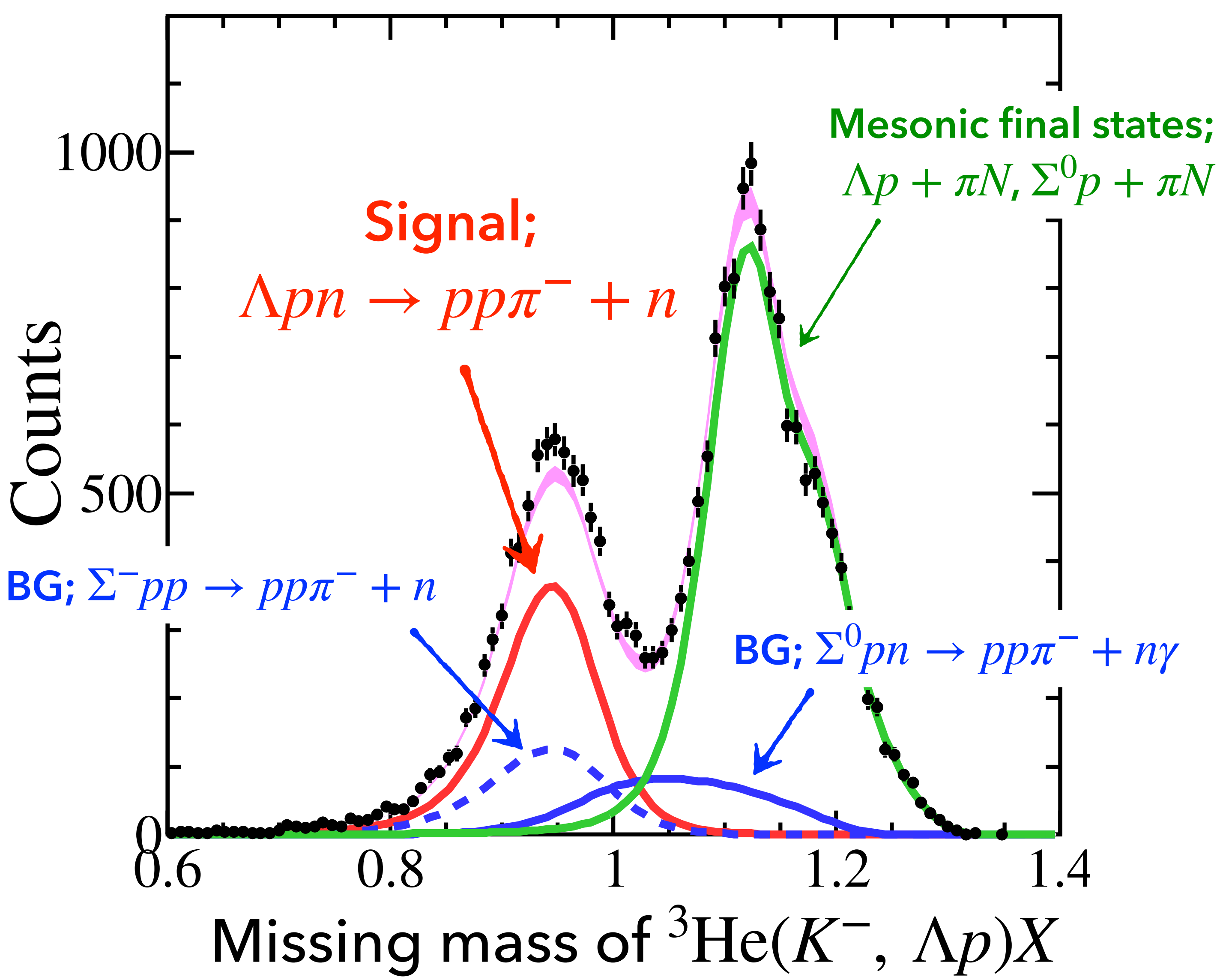
Invariant mass resolution



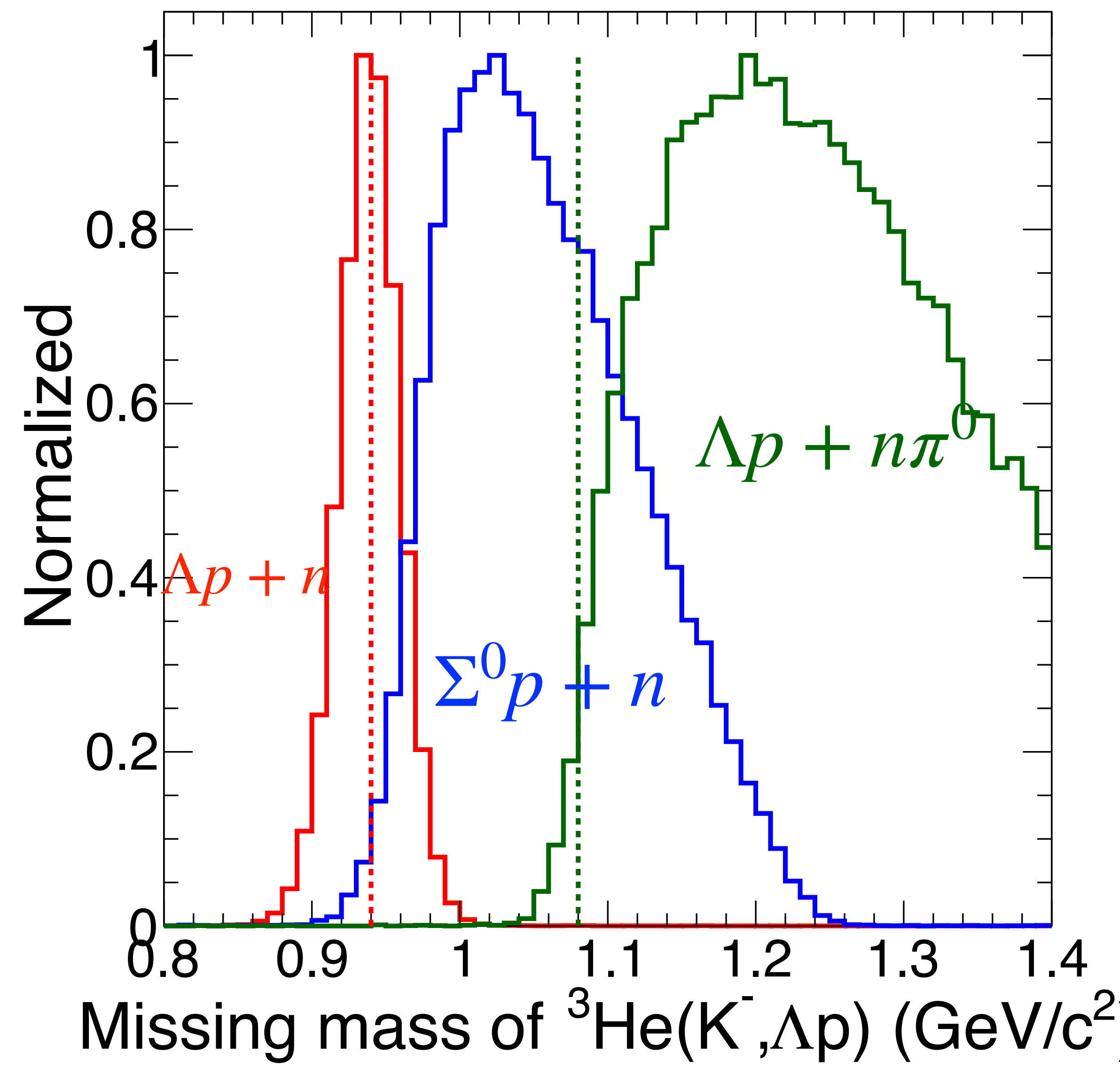
- Z-vertex resolution ~7mm → ~1mm
- x2 better momentum & mass resolution

Λ/Σ^0 separation might be possible

J-PARC E15 data

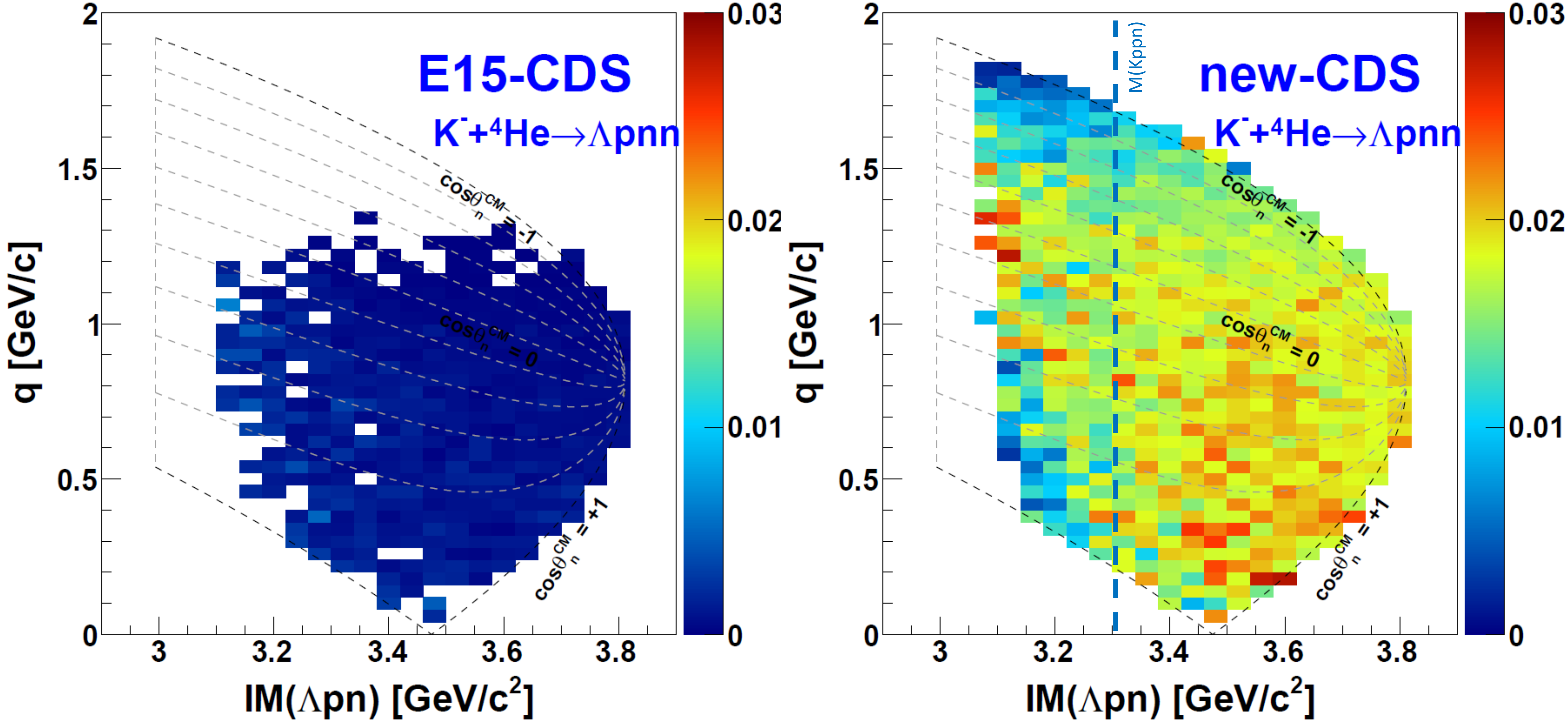


MC with VFT



- Resotluion would be improved ~40 MeV → ~ 25 MeV
- We expect different structure in $m_{\Sigma^0 d}$ (I=1) because $\bar{K}NNN \to \Lambda d$ (I=0)

Acceptance for $K^- + {}^4\mathrm{He} \to \Lambda pn + n$



- > x10 acceptance compared with E15 setup
- Still, one order of magnitude smaller compared with Λdn

Expected spectra

@ 3 weeks, 90kW

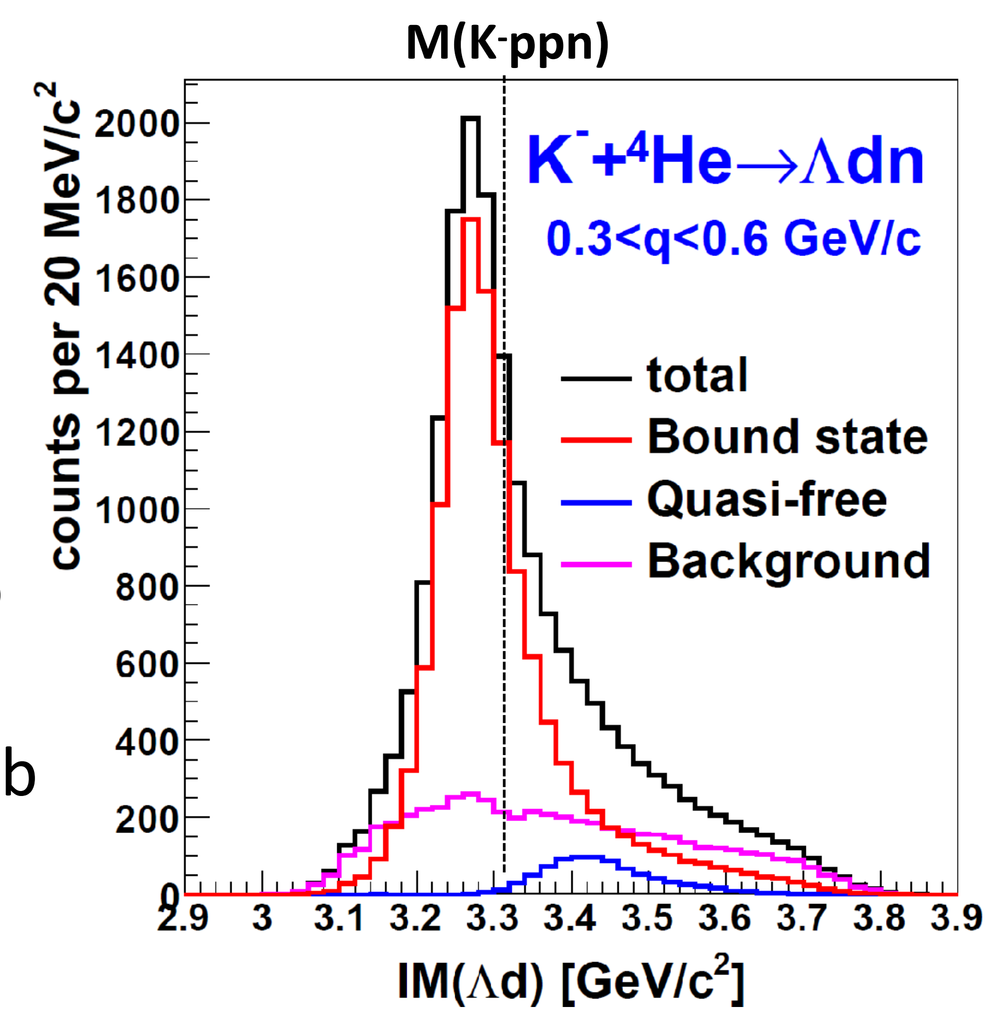
B_{Kppn} ~ 40 MeV

Γ_{Kppn} ~ 100 MeV

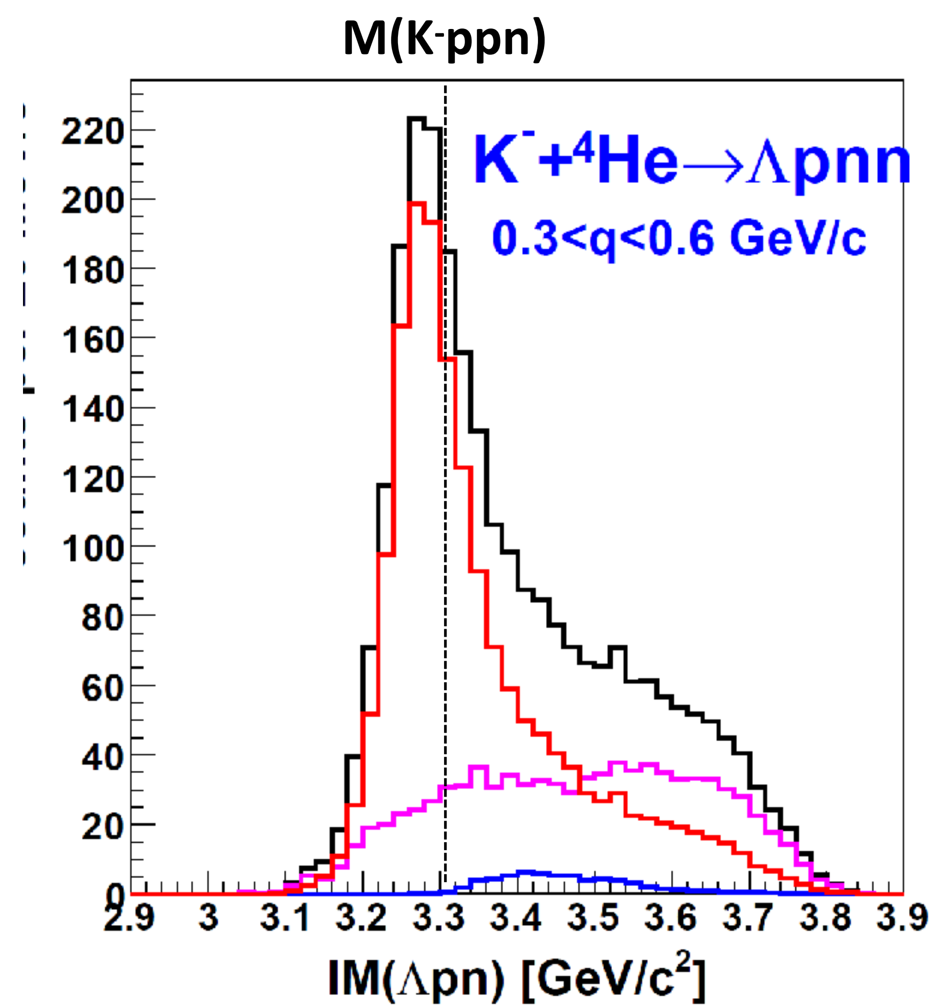
Q_{kppn} ~ 400 MeV/c

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

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



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

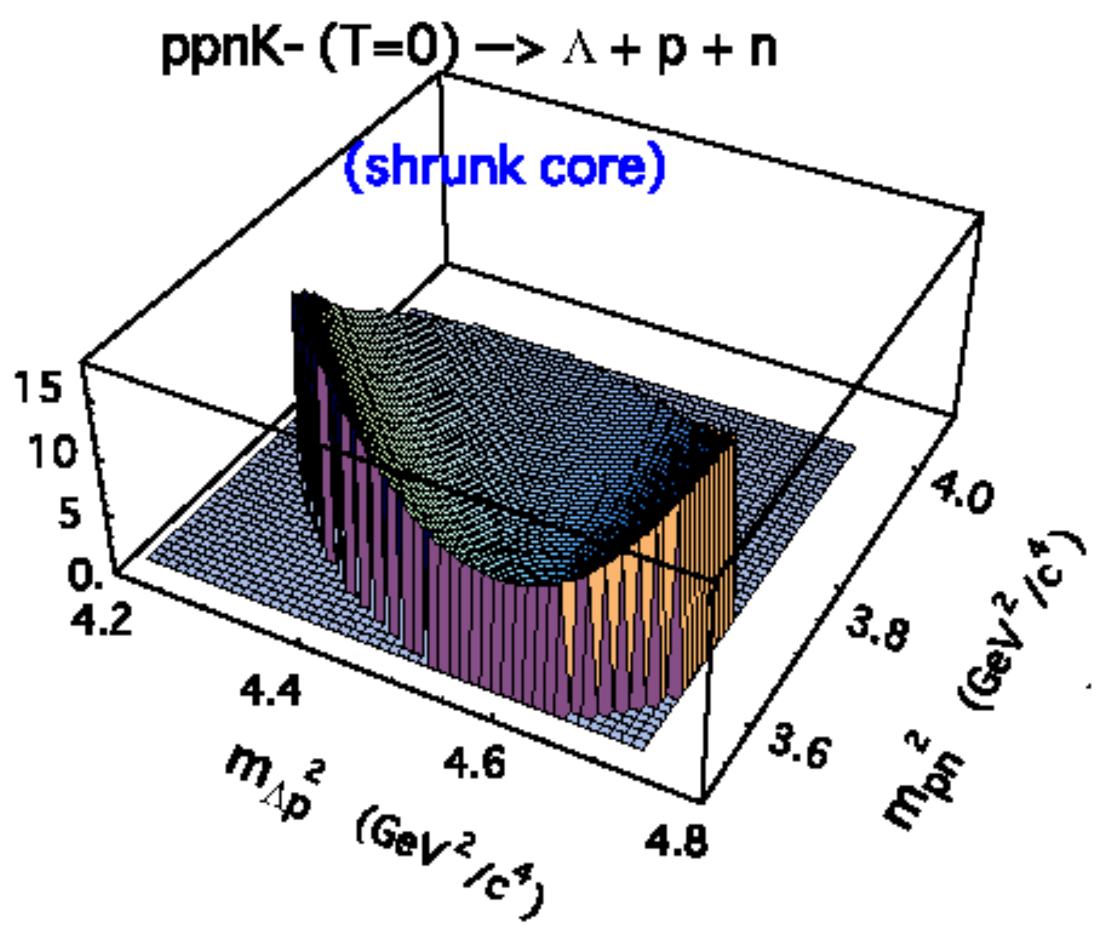


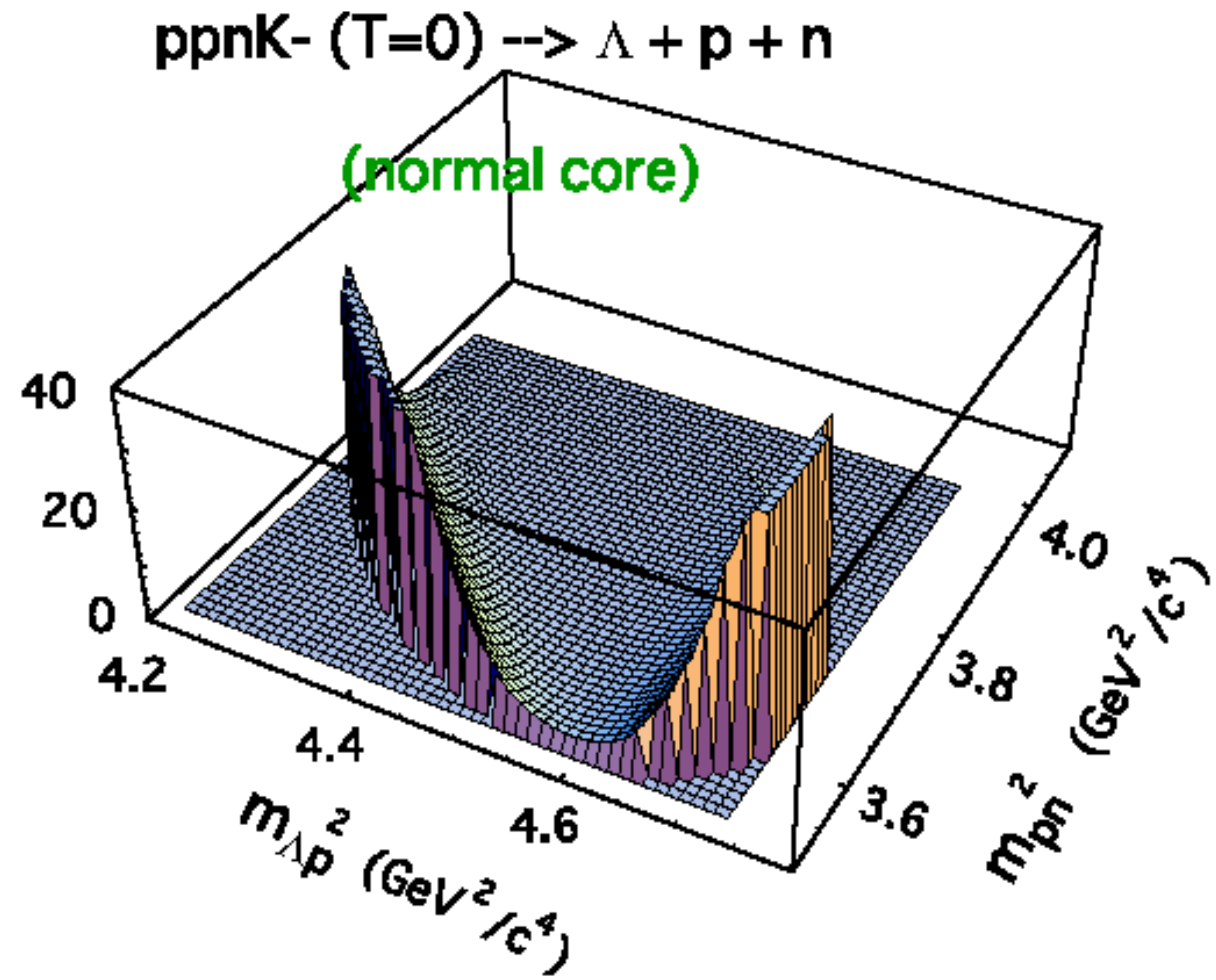
✓ Clear peak would be observed for both modes

✓ Peak positions etc. should be carefully compared

Spacial information $\bar{K}NNN \to \Lambda pn$ decay

P. Kienle et al., Physics Letters B 632 (2006) 187–191





- If $\bar{K}NNN \to \Lambda pn$ is 2NA process, spectator momentum would reflect the system size.
- However, we cannot detect low-momentum protons…

Heviear systems

Predictions

Y. Kanada-En'yo
EPJA 57, 185 (2021)

		present set-I	present set-II
ν_N (fm^{-2})		0.16	0.25
kaonic nuclei(J^π, T)			
$\bar{K}NNNN(0^-, 1/2)$	B.E. (MeV)	60.8	93.2
	R_{NN} (fm)	1.77	1.41
	$R_{\bar{K}N}$ (fm)	2.17	1.73

S. Ohnishi et al.
PRC 95, 065202 (2017).

TABLE VIII. Properties of the $^6_{\bar{K}}$Li system with $J^\pi = 0^-$.

$^6_{\bar{K}}$Li(0^-)

	Kyoto		AY
	Type I	Type II	
B (MeV)	69.8	79.7	103
Γ (MeV)	23.7	75.6	88.0

TABLE IX. Properties of the $^6_{\bar{K}}$He system with $J^\pi = 0^-$.

$^6_{\bar{K}}$He(0^-)

	Kyoto		AY
	Type I	Type II	
B (MeV)	70.6	80.0	103
Γ (MeV)	23.9	75.5	88.0

TABLE V. Properties of the $^4_{\bar{K}}$He system with $J^\pi = 0^-$.

$^4_{\bar{K}}$He(0^-)

	Kyoto		AY
	Type I	Type II	
B (MeV)	67.9	72.7	85.2
Γ (MeV)	28.3	74.1	86.5

TABLE VI. Properties of the $^4_{\bar{K}}$H system with $J^\pi = 0^-$.

$^4_{\bar{K}}$H(0^-)

	Kyoto		AY
	Type I	Type II	
B (MeV)	69.6	75.5	87.4
Γ (MeV)	28.0	74.5	87.2

TABLE X. Properties of the $^6_{\bar{K}}$Li system with $J^\pi = 1^-$.

$^6_{\bar{K}}$Li(1^-)

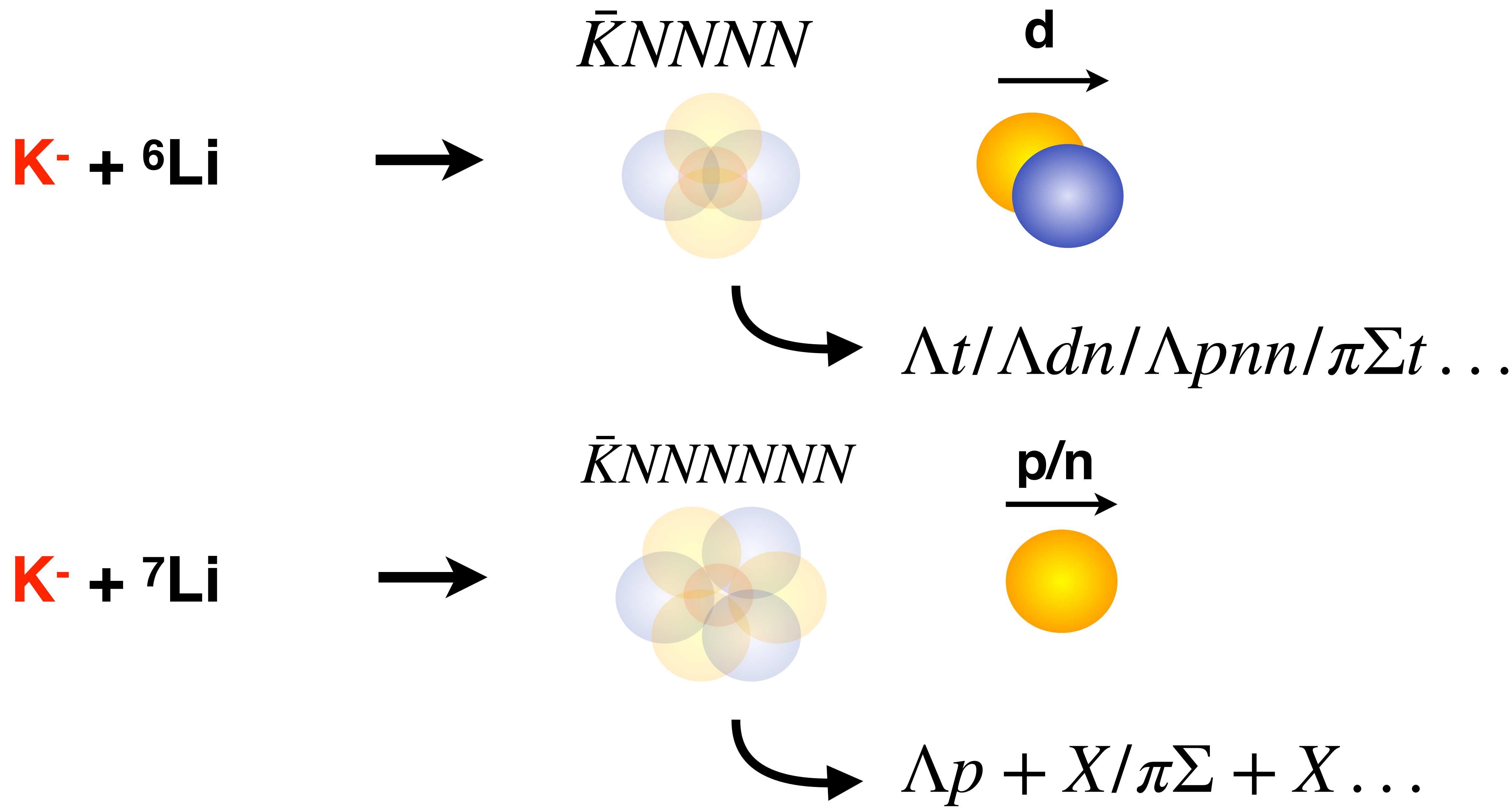
	Kyoto		AY
	Type I	Type II	
B (MeV)	70.8	77.5	92.9
Γ (MeV)	26.4	75.2	88.0

TABLE XI. Properties of the $^6_{\bar{K}}$He system with $J^\pi = 1^-$.

$^6_{\bar{K}}$He(1^-)

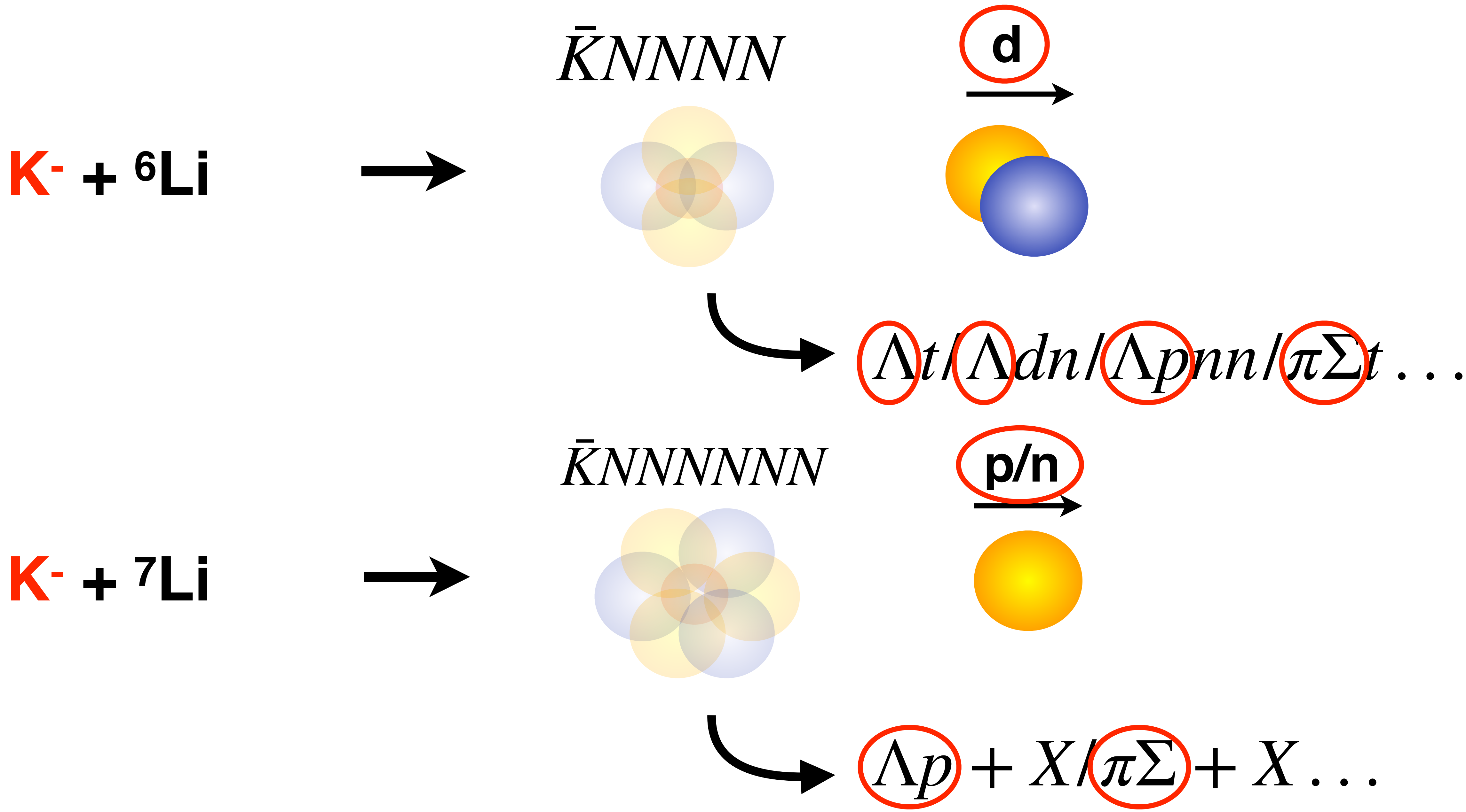
	Kyoto		AY
	Type I	Type II	
B (MeV)	72.8	80.7	95.6
Γ (MeV)	26.0	75.6	88.5

Experimental strategy



- Exclusive analysis by detecting all the decay product becomes more and more difficult with increasing mass number.
- Instead, detect **forward knock-out nucleons with hyperon tag**

Experimental strategy

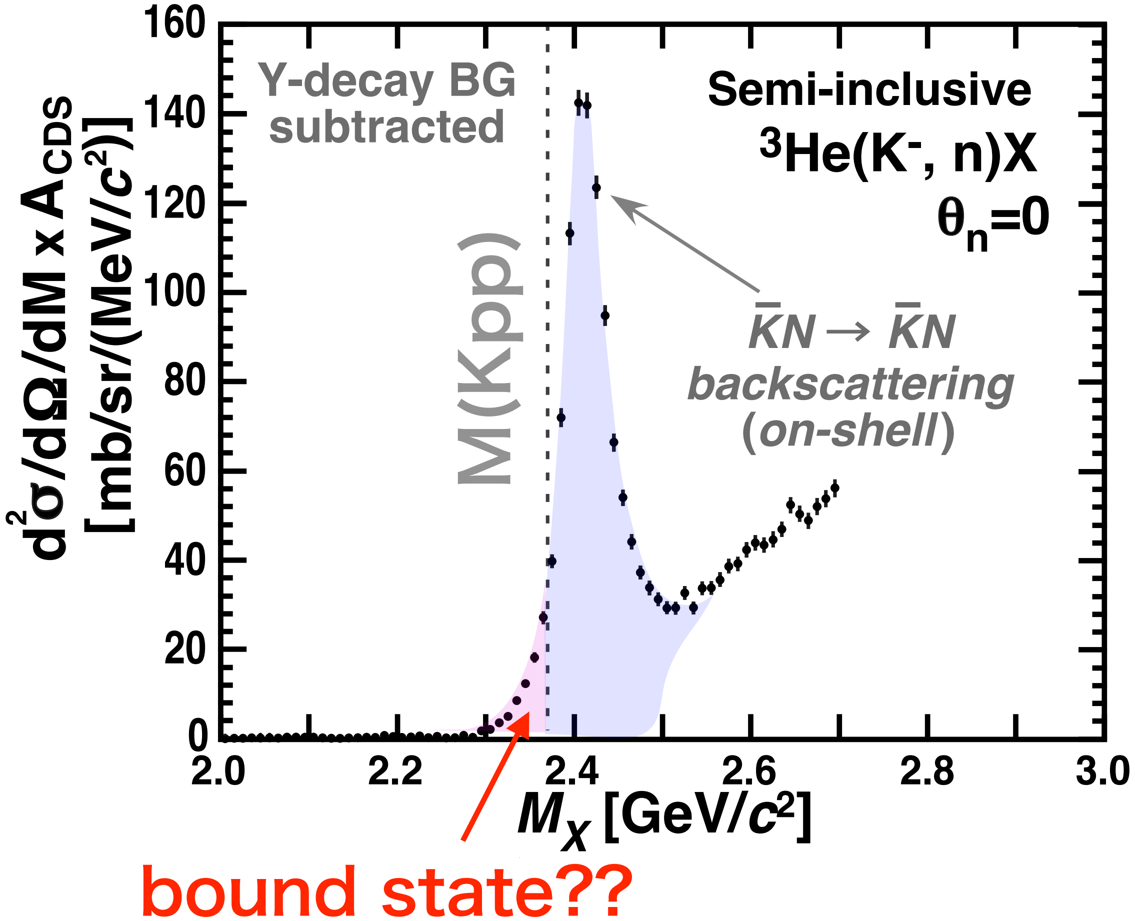


- Exclusive analysis by detecting all the decay product becomes more and more difficult with increasing mass number.
- Instead, detect **forward knock-out nucleons with hyperon tag**

(K⁻, N) at forward angle

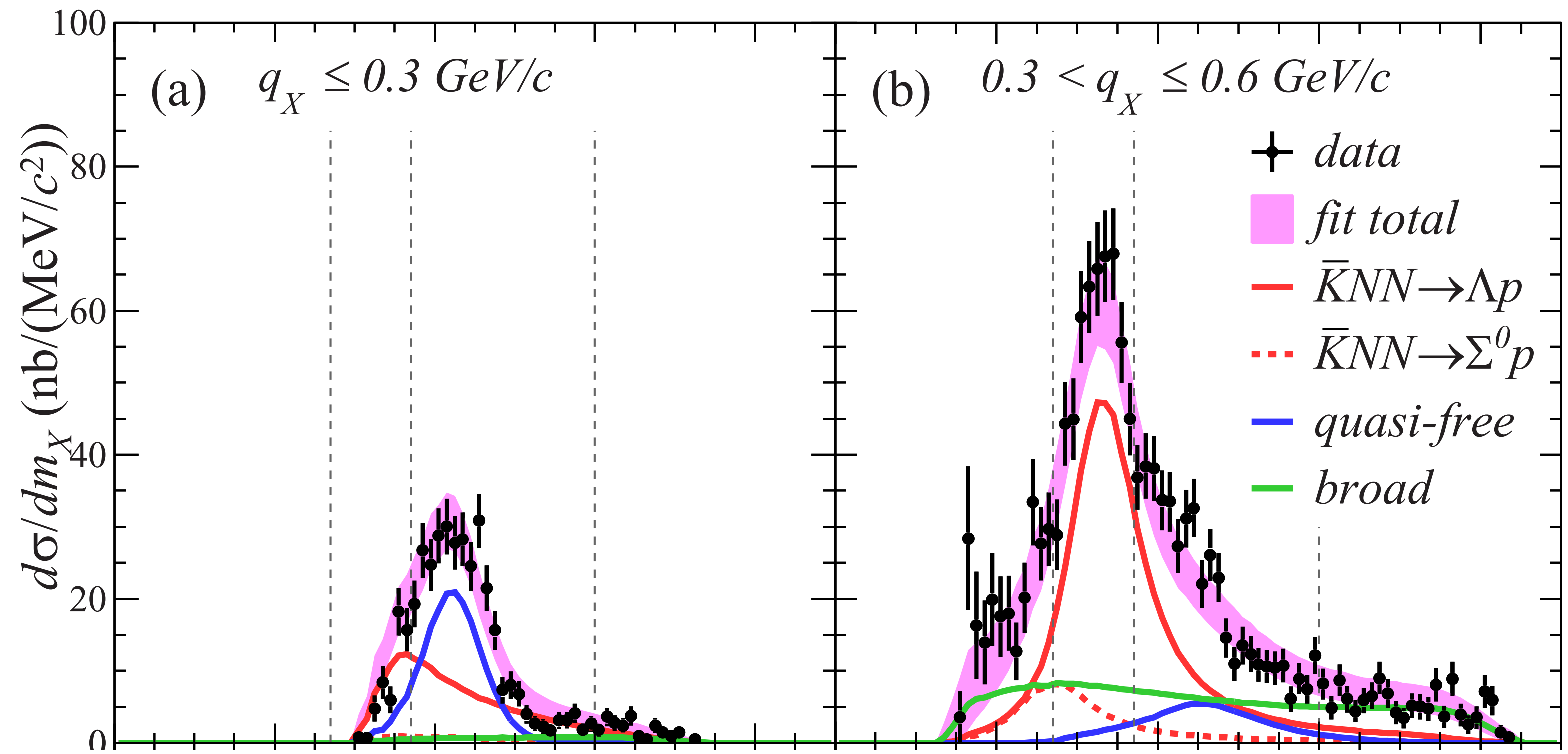
E15 semi-inclusive

- PTEP **2015**, 061D01 (2015).



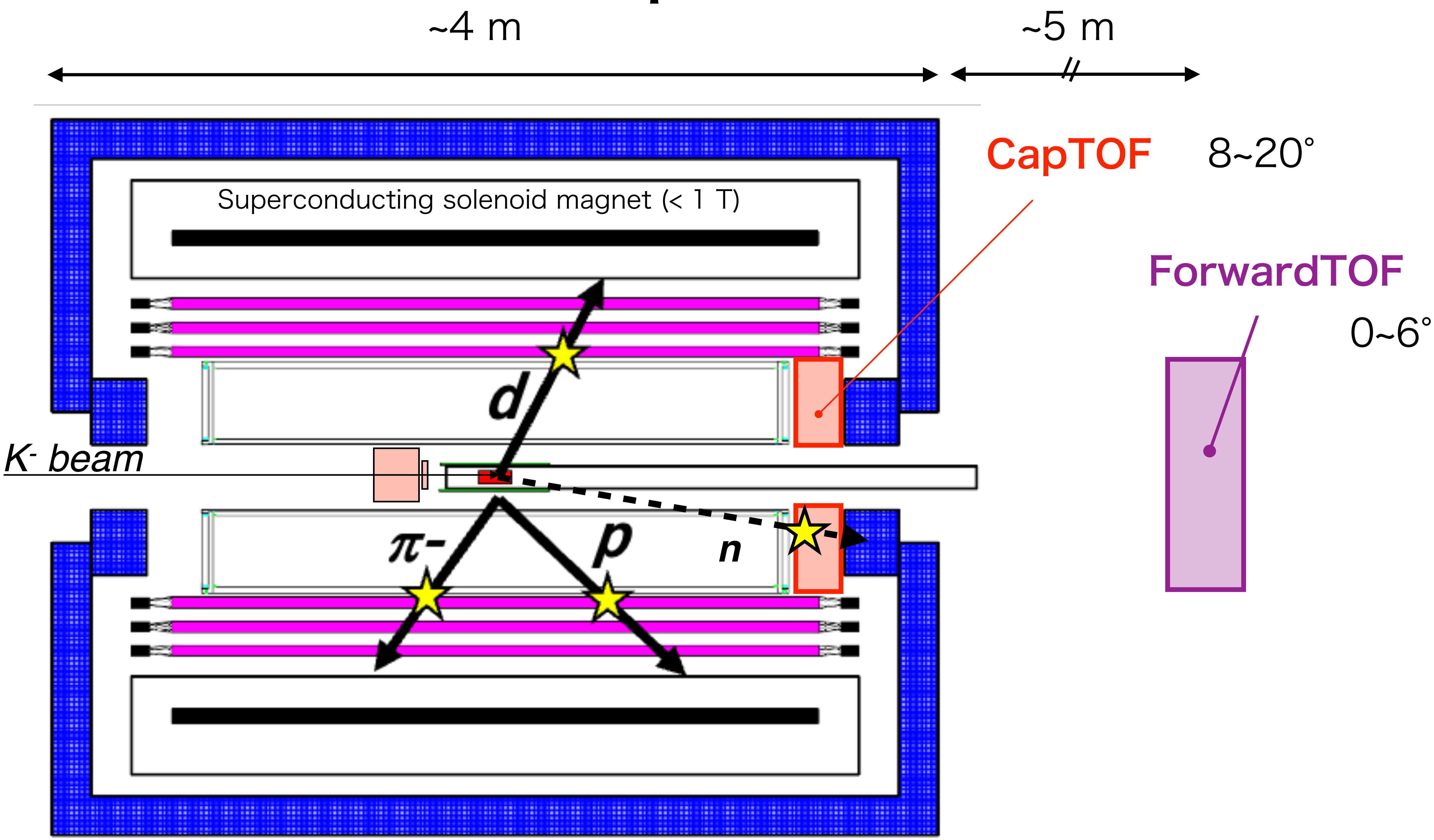
E15 exclusive (Λpn)

Phys.Rev.C102,044002(2020)



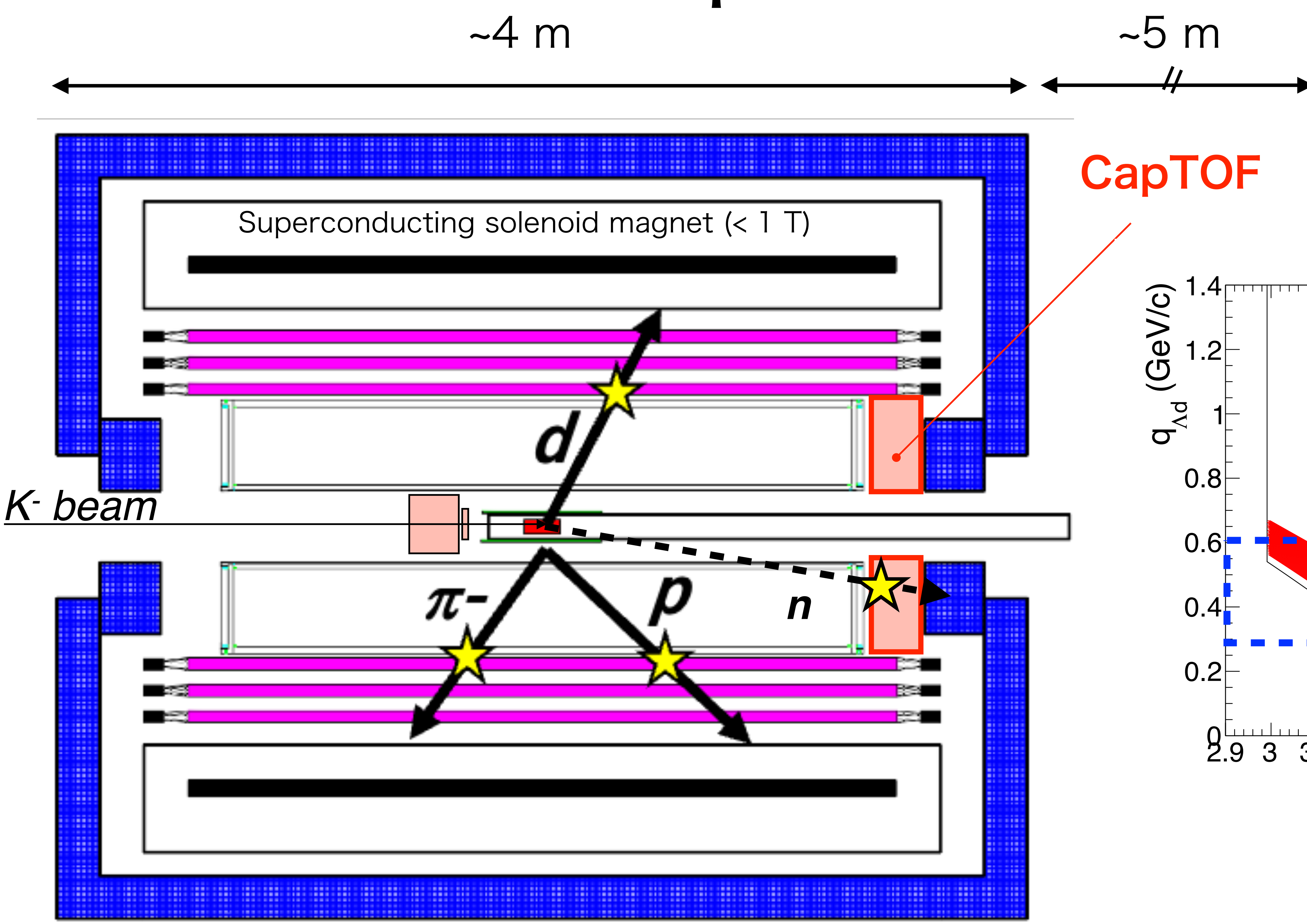
- In **semi-inclusive** spectrum at forward angle, we clearly see the quasi-free peak but cannot isolate the bound state.
- The situation does not change in Λpn **exclusive** analysis

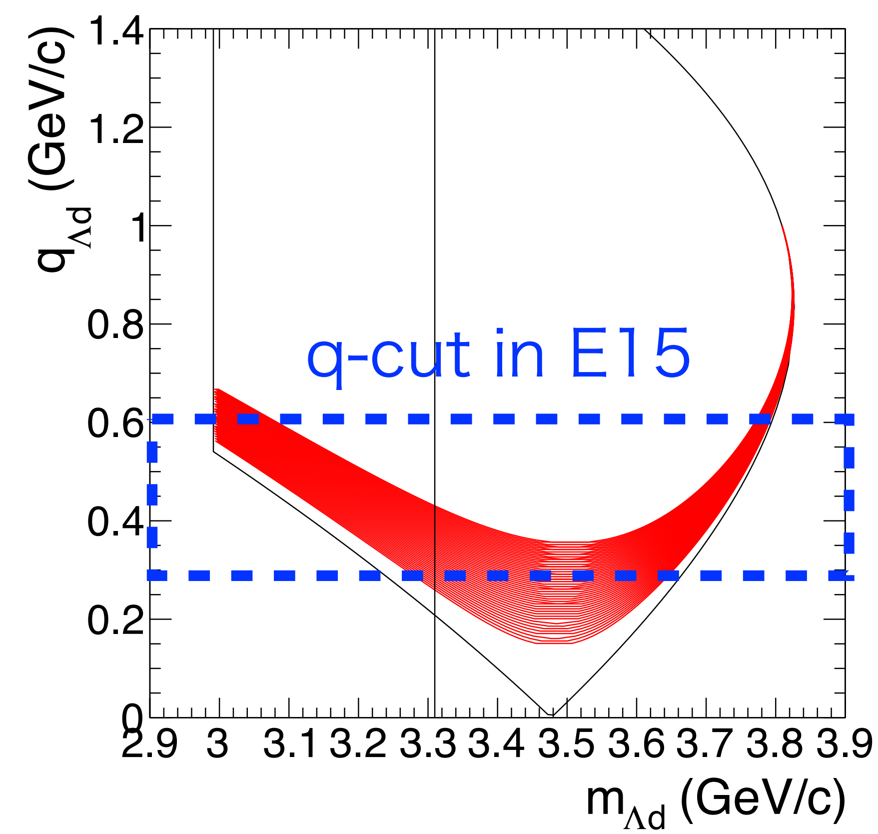
Possible setup



- **large-q region** would be better to isolate the bound state.
- **Wide angular acceptance** to study q-dependence.

Possible setup





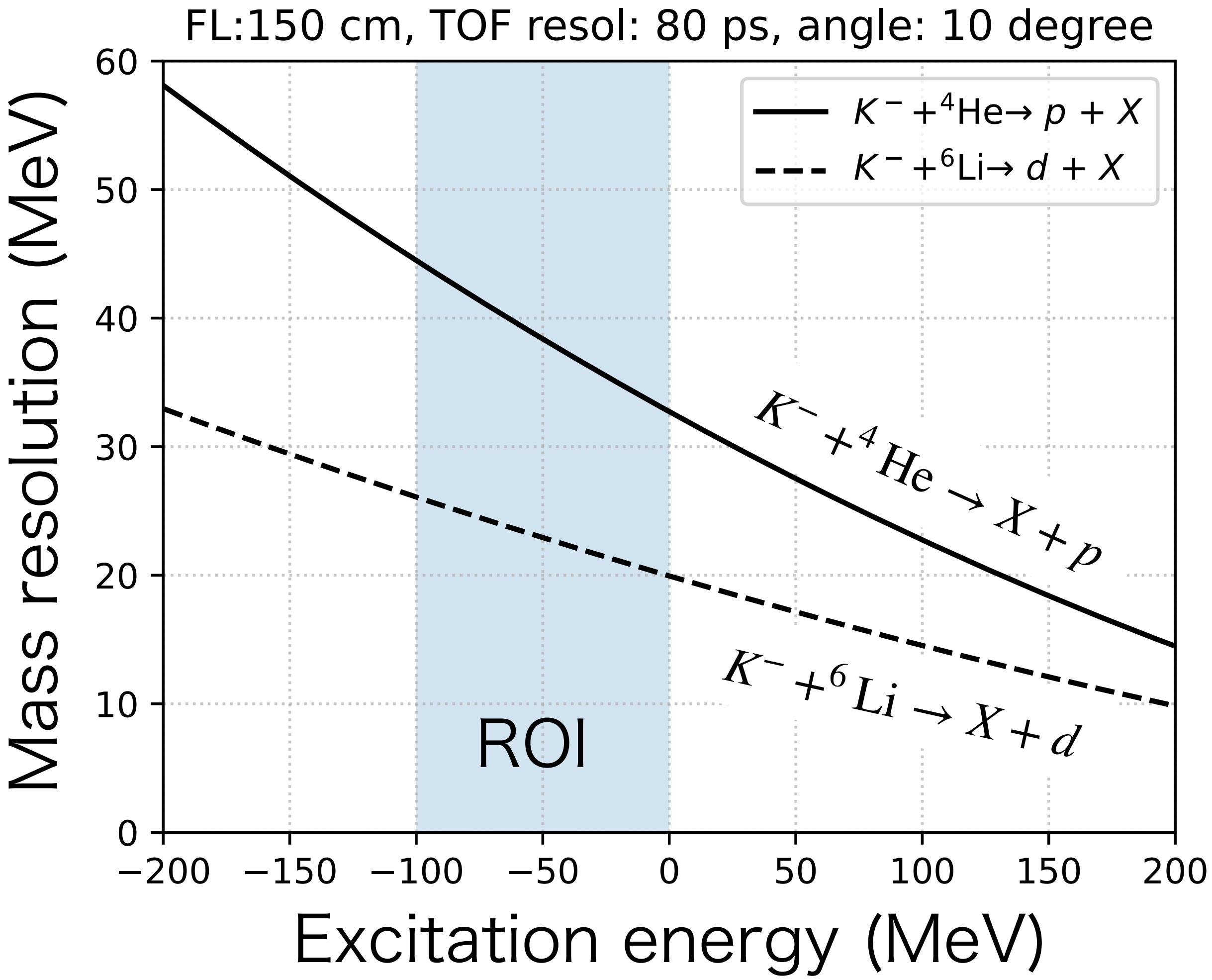
- **large-q region** would be better to isolate the bound state.
- **Wide angular acceptance** to study q-dependence.

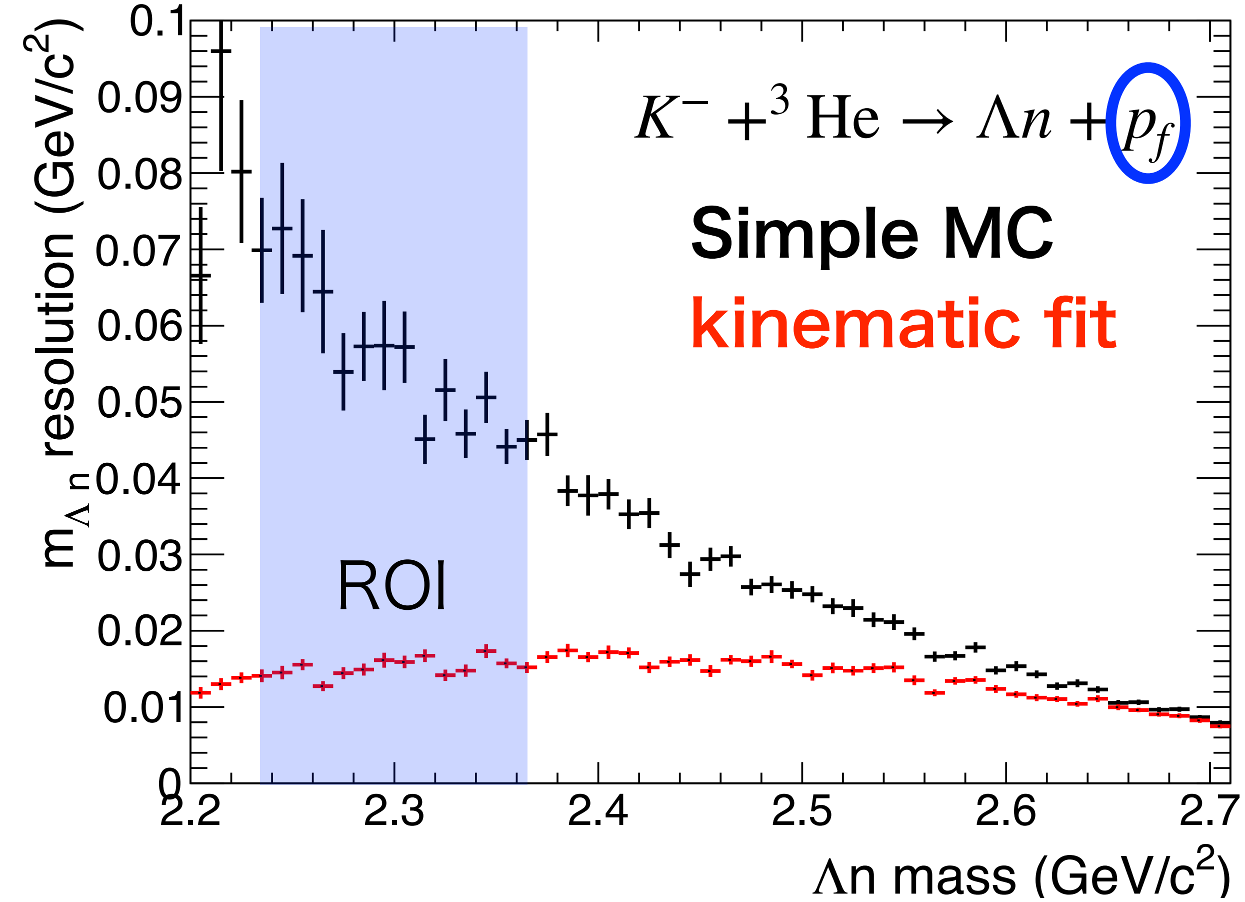
Expected resolution

	L_{TOF} (m)	time resolution (ps)	mass resolution (MeV)
E15 NC	14	150	10
Cap	2	100	**50**
Forward	7	150	20

Expected resolution

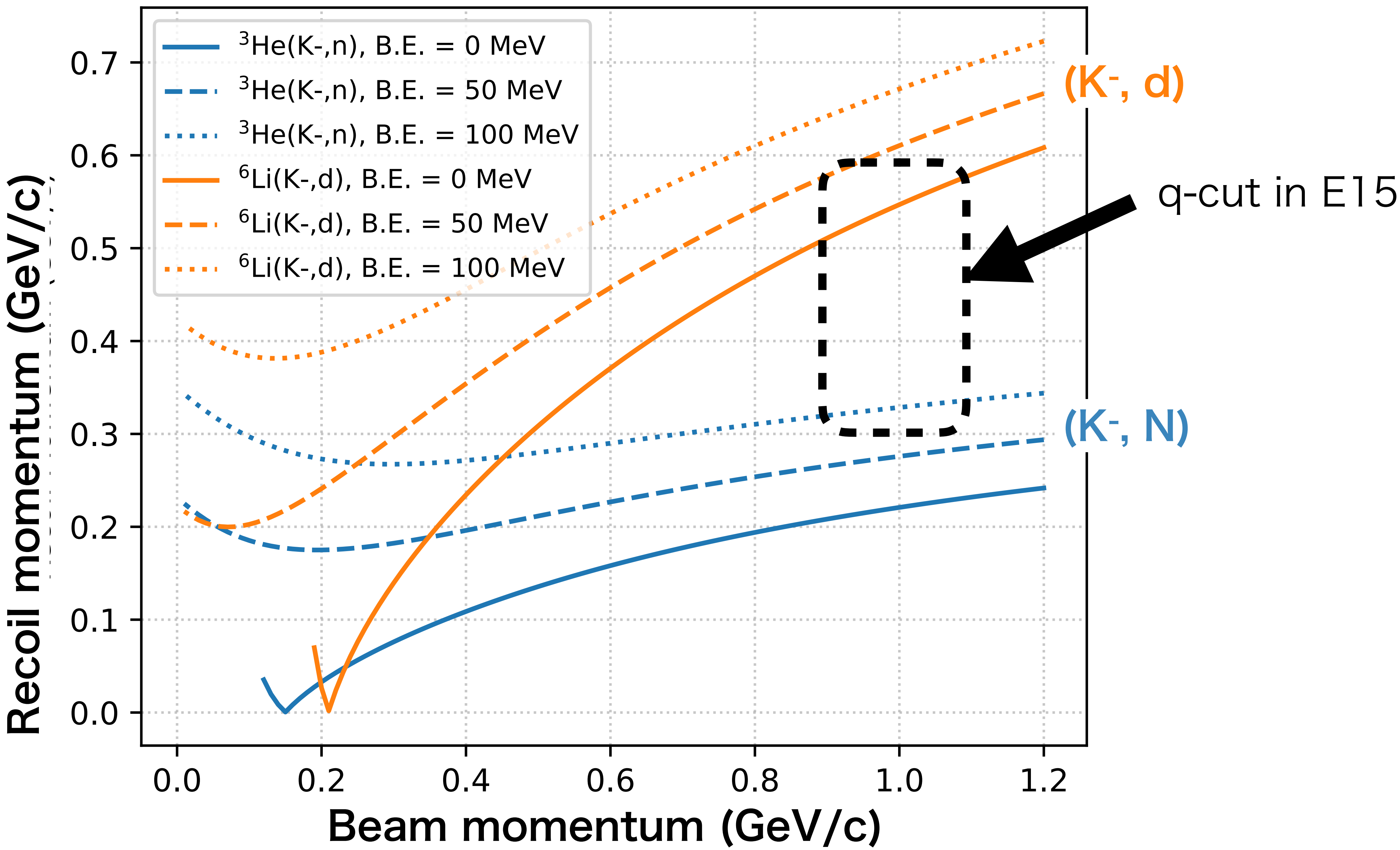
	L_{TOF} (m)	time resolution (ps)	mass resolution (MeV)
E15 NC	14	150	10
Cap	2	100	**50**
Forward	7	150	20





- Moderate resolution ~50 MeV
  can be improved to <20 MeV with a kinematic fit.
- Reasonable resolution to identify missing nucleon ~50 MeV

(K-, N) vs. (K-, d)



- momentum transfer is large in (K-,d)
- no clear signal of quasi-elastic process $^3\mathrm{He}(K^-, d)$

Other merits with the forward counter

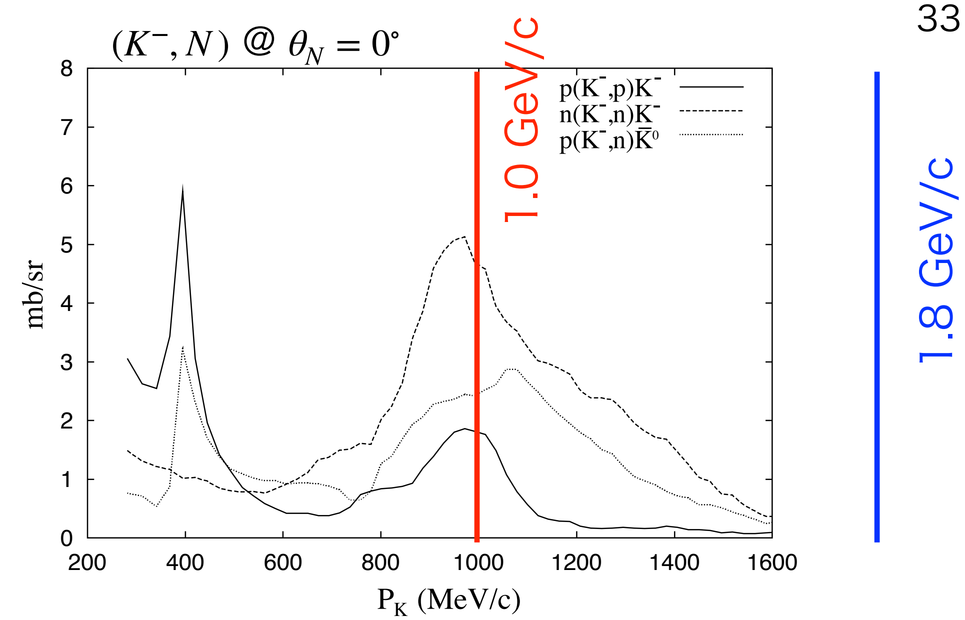
- We can reconstruct full reaction kinematics without detecting one of the decay particle
  - neutral paritcle
  - low-momentum proton. (cf. spectator in decay)

$$K^- + {}^3\text{He} \to \bar{K}NN + n$$
$$\to \pi\Sigma p_s + n$$

$$K^- + {}^4\text{He} \to \bar{K}NNN + n$$
$$\to \begin{cases} \Lambda p n_s + n \\ \Lambda n p_s + n \end{cases}$$

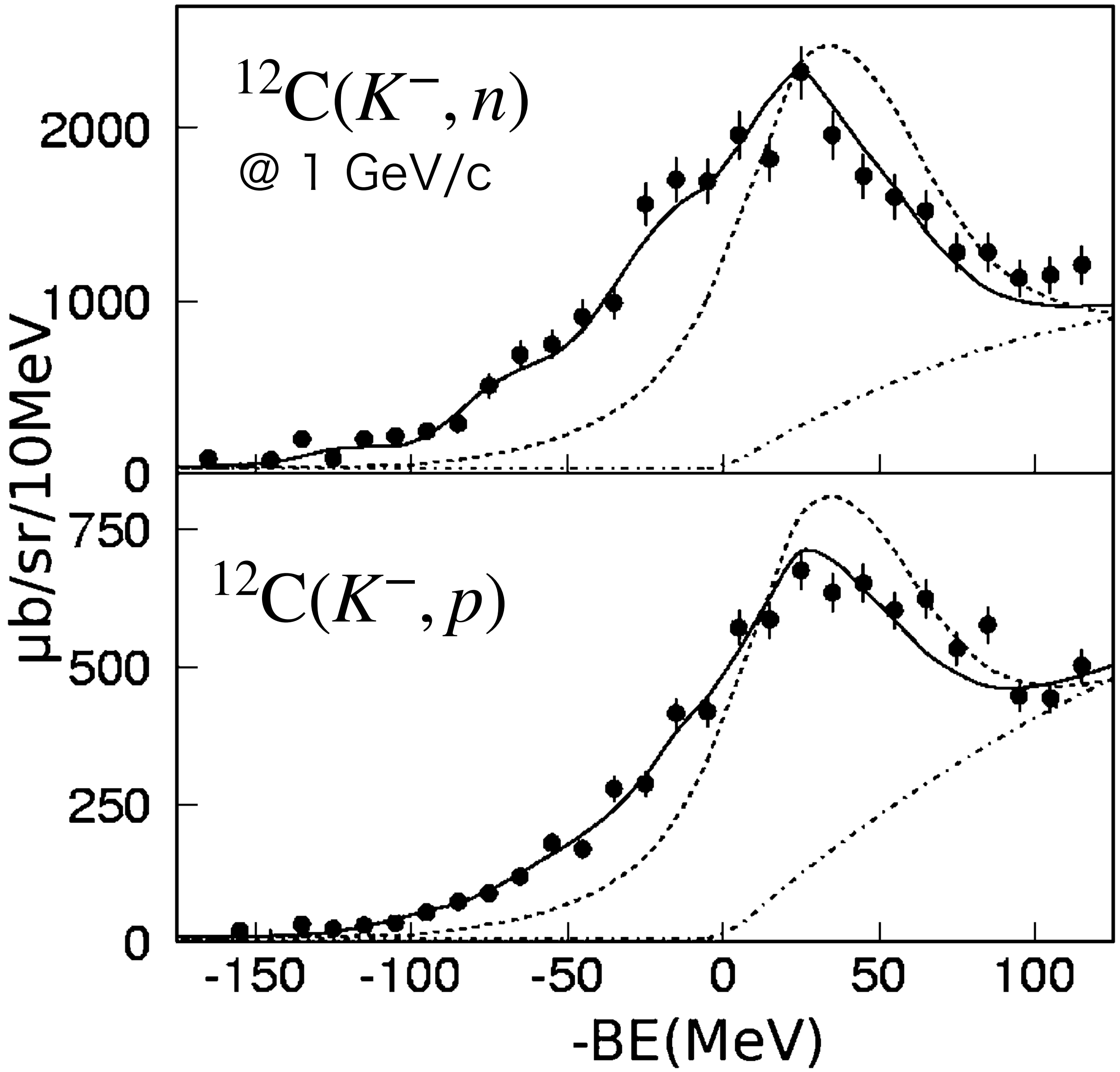
Useful to analyze decay kinematics and to understand background processes

(K-, N) on Carbon



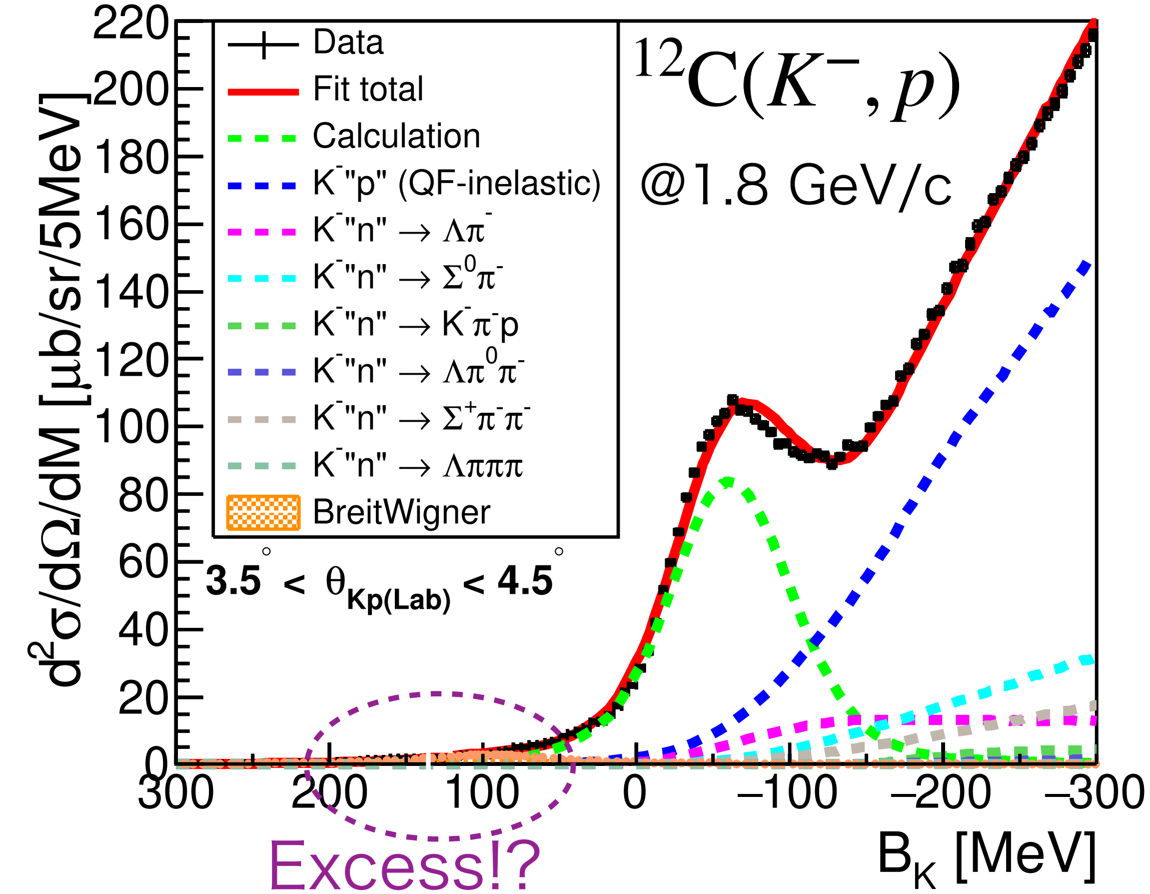
"Semi"-Inclusive

Prog. Theor. Phys 118, 181 (2007).



Inclusive

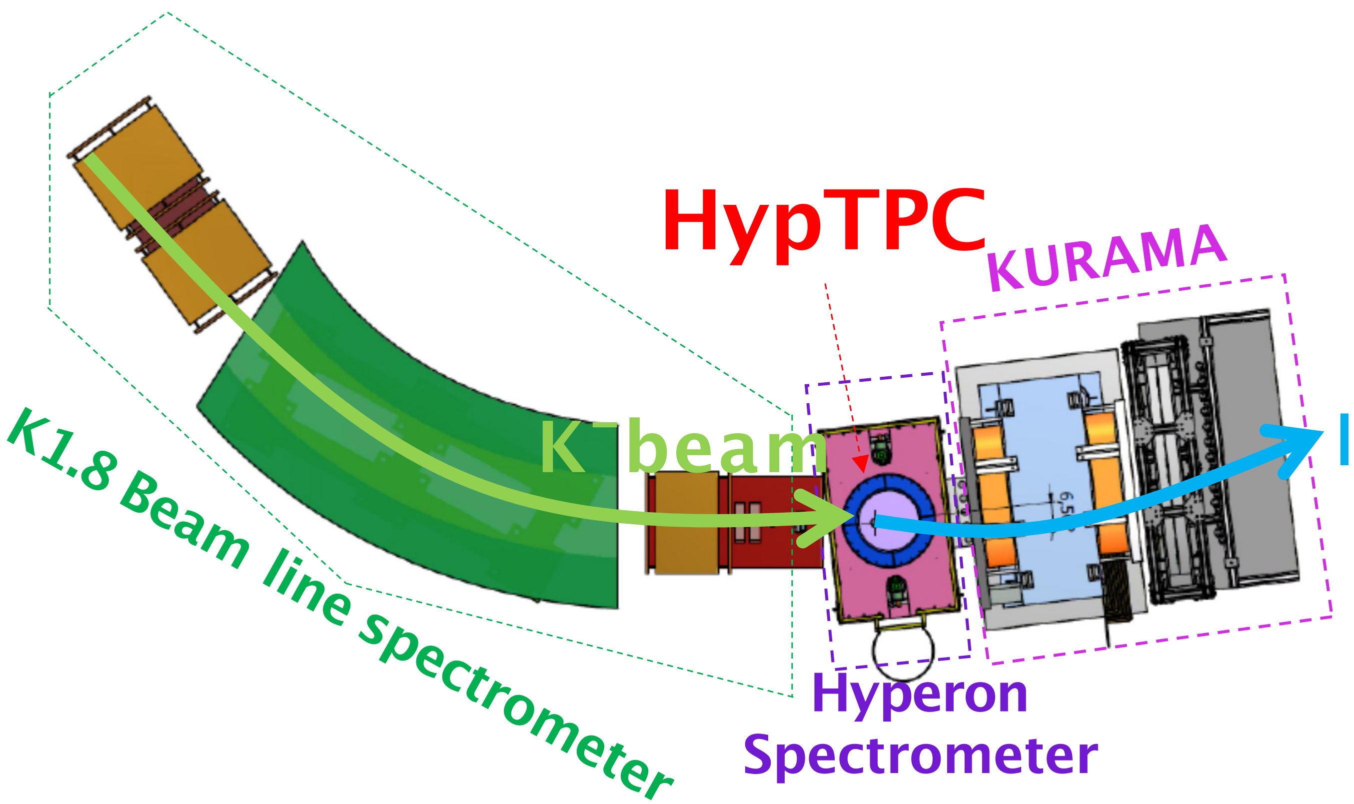
(a) PTEP 2020, 123D01(2020)

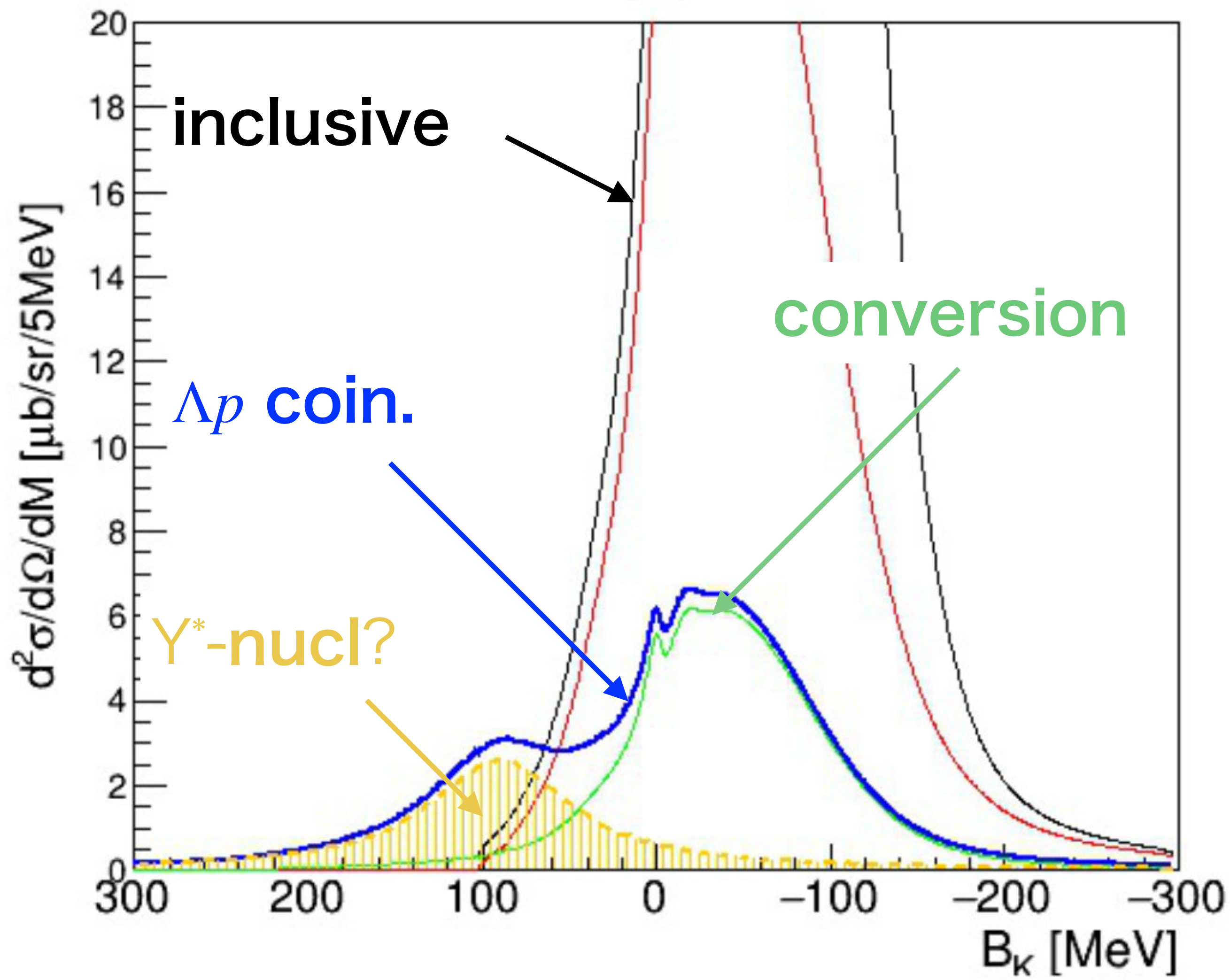


- The situation is similar to what we observed with a helium-3 target

(K⁻, p) semi-exclusive in E42

figures from Y. Ichikawa





- By-product of H-dibaryon search. under analysis…
- Resolution can be potentially improved as good as 1 MeV using S-2S, but the acceptance is quite limited.

Complementary to the measurement in wide angular coverage & moderate resolution

Summary

- Investigation of **heavier systems beyond** $\bar{K}NN$ has been already started.

- We observed **^{4}He(K$^-$,Λd)n** events, which would be signals of $\bar{K}NNN$.

- We are constructing **new large solenoid spectrometer**
  - large acceptance
  - neutron detection capability
  - additional forward counter would be useful

- Kaonic systems to be investigated includes
  - $\bar{K}NNN \to \Lambda d, \Lambda pn, \pi\Sigma d, \ldots$ (J-PARC E80)
  - $K^-\alpha$ via $^6\mathrm{Li}(K^-, d)$
  - $K^-\alpha d$ via $^7\mathrm{Li}(K^-, n)$
  - $K^-\alpha\alpha$ via $^9\mathrm{Be}(K^-, n)$

Collaboration

J-PARC E73/T77 collaboration

T. Akaishi[1], H. Asano[2], X. Chen[5], A. Clozza[7], C. Curceanu[7], R. Del Grande[7], C. Guaraldo[7], C. Han[5], T. Hashimoto[4], M. Iliescu[7], K. Inoue[1], S. Ishimoto[3], K. Itahashi[2], M. Iwasaki[2], Y. Ma[2], M. Miliucci[7], R. Murayama[2], H. Noumi[1], H. Ohnishi[10] S. Okada[2], H. Outa[2], K. Piscicchia[7,9], A. Sakaguchi[1], F. Sakuma[2], M. Sato[3], A. Scordo[7], K. Shirotori[1], D. Sirghi[7,8], F. Sirghi[7,8], S. Suzuki[3] K. Tanida[4], T. Toda[1], M. Tokuda[1], T. Yamaga[2], X. Yuan[5], P. Zhang[5], Y. Zhang[5], H. Zhang[6]

[1]Osaka University, Toyonaka, 560-0043, Japan
[2]RIKEN, Wako, 351-0198, Japan
[3]High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan
[4]Japan Atomic Energy Agency, Ibaraki 319-1195, Japan
[5]Institute of Modern Physics, Gansu 730000, China
[6]School of Nuclear Science and Technology, Lanzhou University, Gansu 730000, China
[7]Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy
[8]Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Magurele, Romania
[9]CENTRO FERMI - Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, 00184 Rome, Italy
[10]Tohoku University, 982-0826, Sendai, Japan

J-PARC E80 collaboration

H. Asano K. Itahashi, M. Iwasaki, Y. Ma, R. Murayama, H. Outa, F. Sakuma*, T. Yamaga
RIKEN Cluster for Pioneering Research, RIKEN, Saitama, 351-0198, Japan

K. Inoue, S. Kawasaki, H. Noumi, K. Shirotori
Research Center for Nuclear Physics (RCNP), Osaka University, Osaka, 567-0047, Japan

H. Ohnishi, Y. Sada, C. Yoshida
Research Center for Electron Photon Science (ELPH), Tohoku University, Sendai, 982-0826, Japan

T. Hashimoto
Japan Atomic Energy Agency (JAEA), Ibaraki 319-1195, Japan

M. Iio, S. Ishimoto, K. Ozawa, S. Suzuki
High Energy Accelerator Research Organization (KEK), Ibaraki, 305-0801, Japan

T. Akaishi
Department of Physics, Osaka University, Osaka, 560-0043, 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

M. Bazzi, A. Clozza, C. Curceanu, C. Guaraldo, M. Iliescu, M. Miliucci, A. Scordo, D. Sirghi, F. Sirghi
Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy

P. Buehler, M. Simon, E. Widmann, J. Zmeskal
Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria