ECT* workshop EXOTICO @ Trento, Italy
"EXOTIc atoms meet nuclear COllisions for a new frontier precision era in low-energy strangeness nuclear physics"

Experimental study of the four-body kaonic nuclear state, $\bar{K}NNN$

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

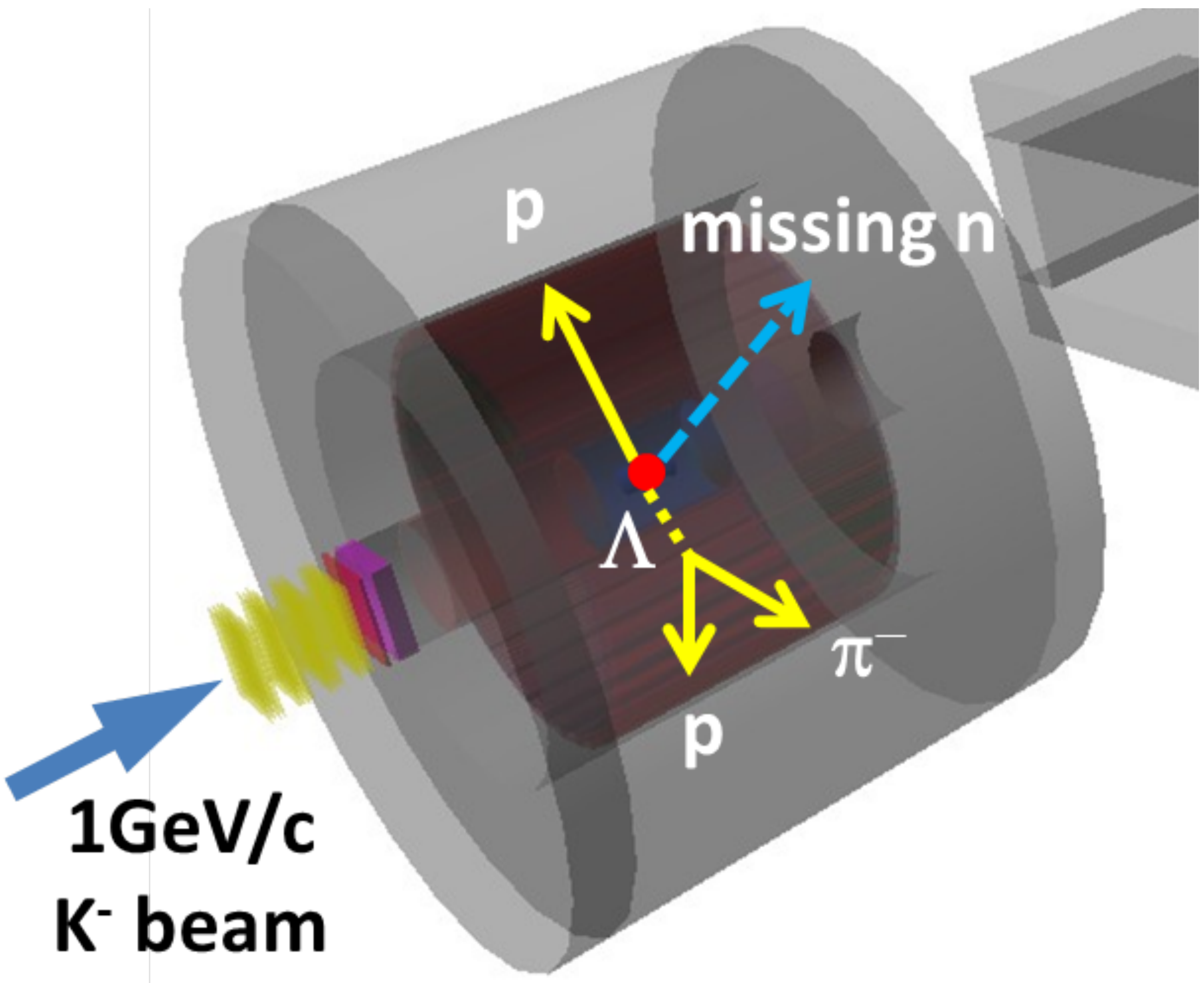
October 21st, 2022

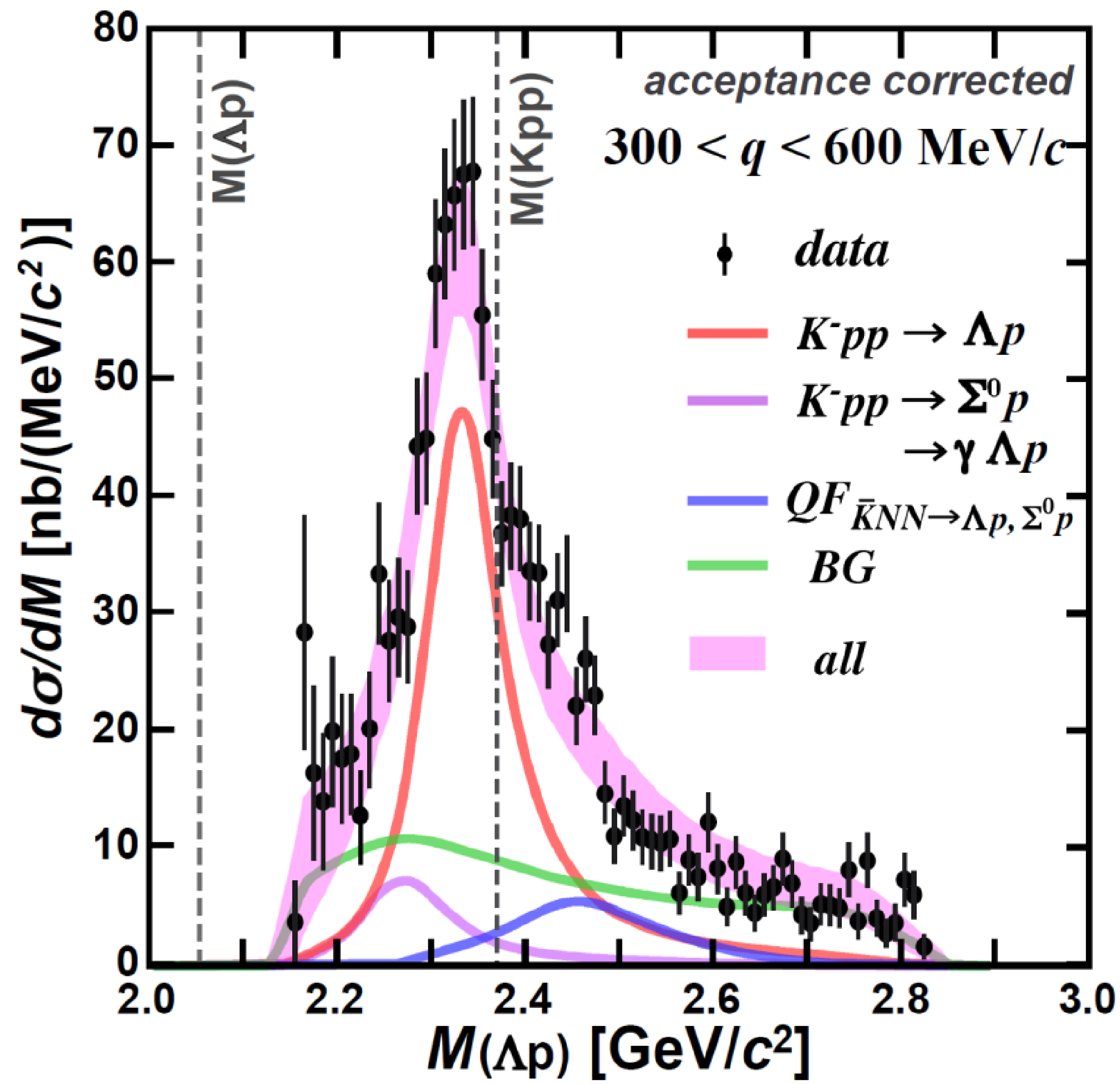
"$\bar{K}NN$" in J-PARC E15

Details in T. Yamaga's talk

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

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



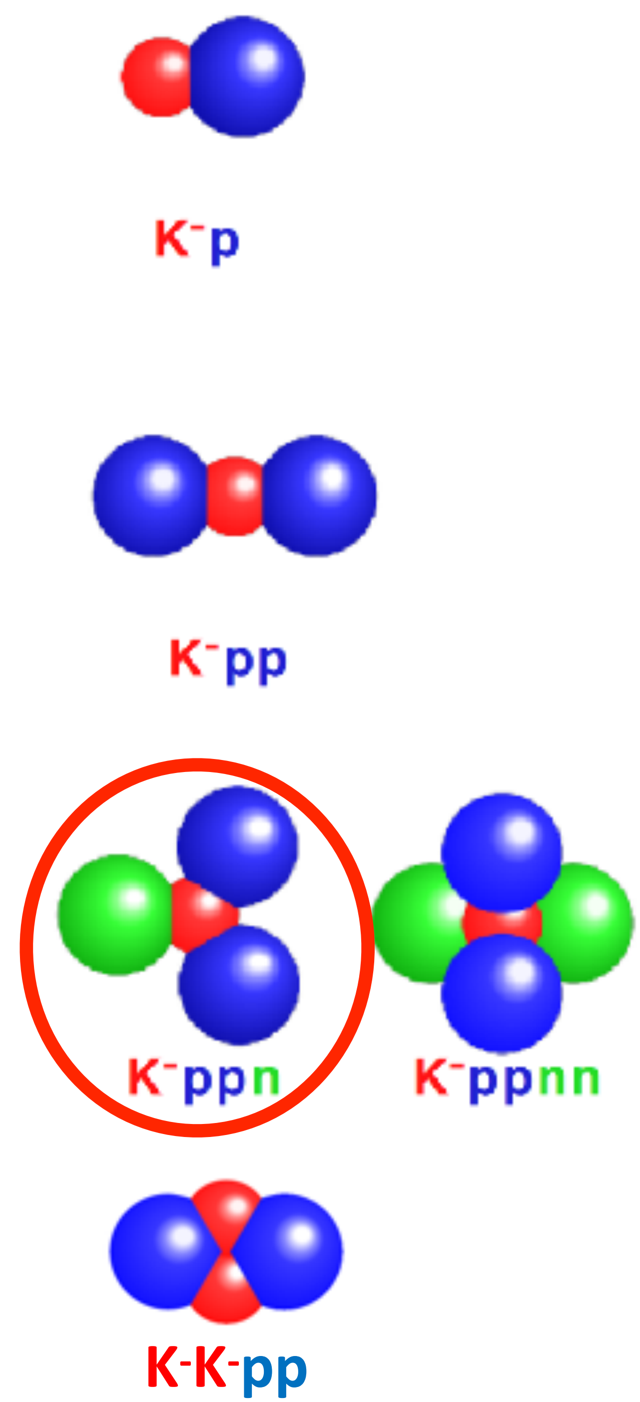


- Exclusive measurement of all the final state particles in a wide q region
- **We have found a way to effectively observe a kaonic nucleus**

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?

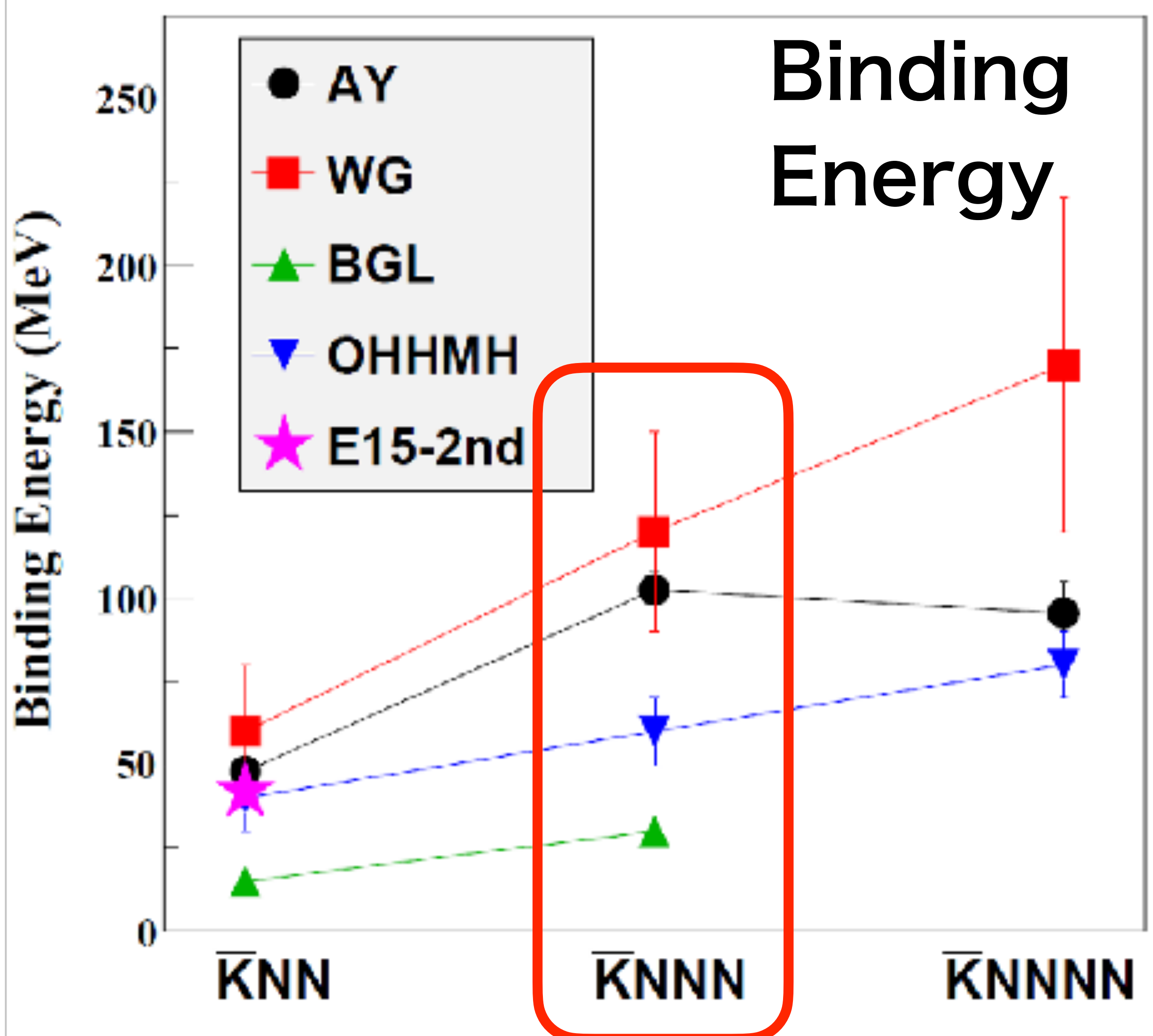


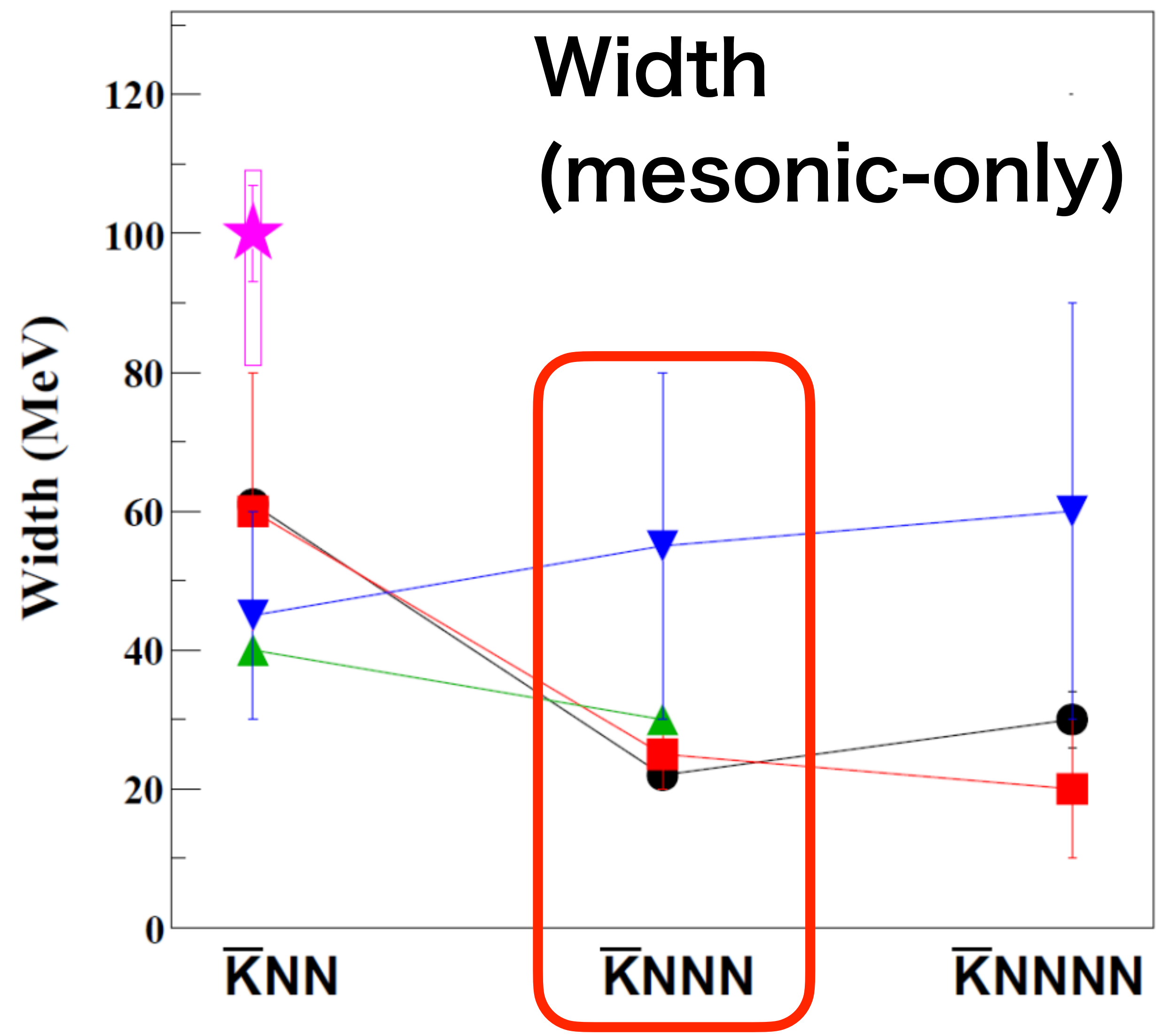
$\bar{K}NNN$: Theoretical situaion

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

Not a complete list. sorry…

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



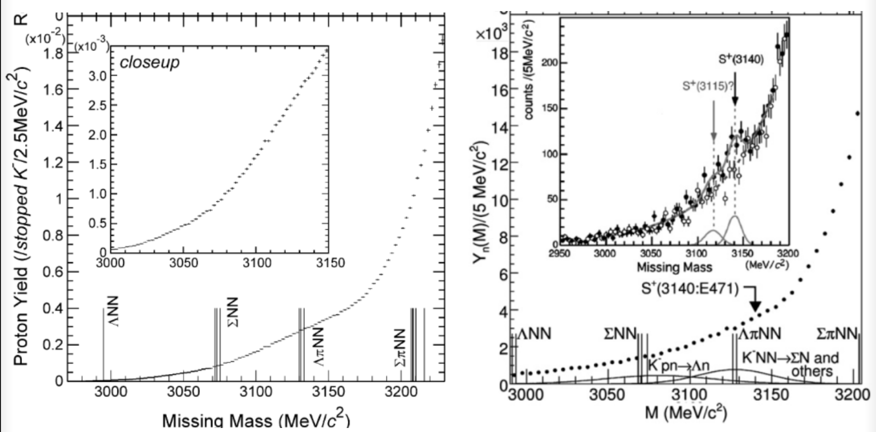


Larger binding than $\bar{K}NN$ and similar width are predicted.

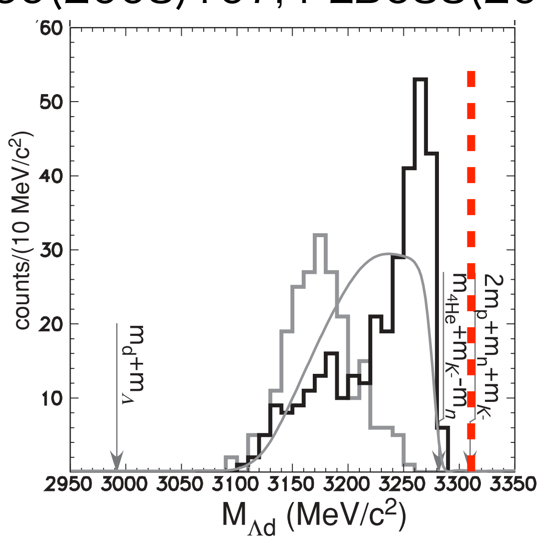
$\bar{K}NNN$: Experimental situaion

Stopped K⁻ on ⁴He

E471/E549@KEK



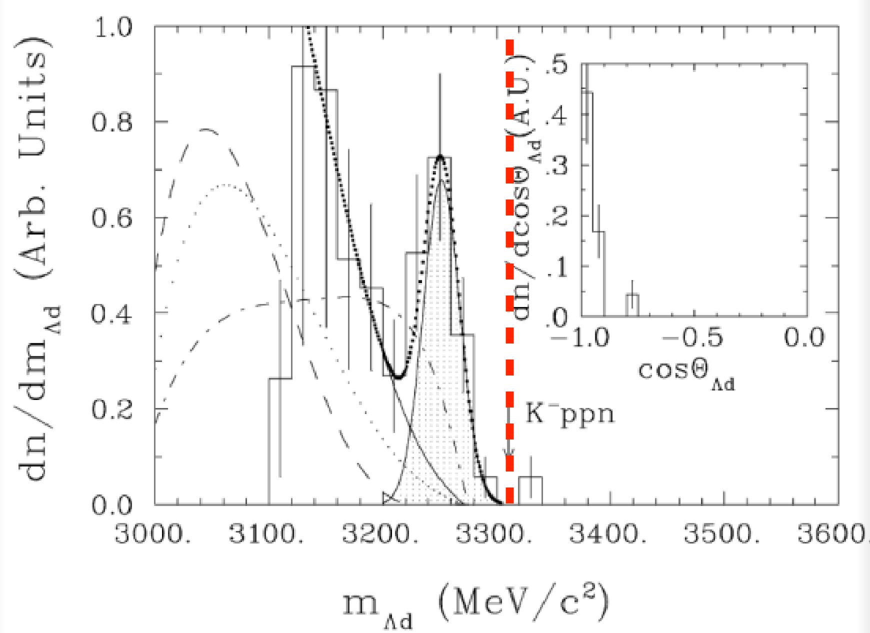
PLB659(2008)107, PLB688(2010)43



PRC76(2007)068202

Stopped K⁻ on Li/C back-to-back Λd

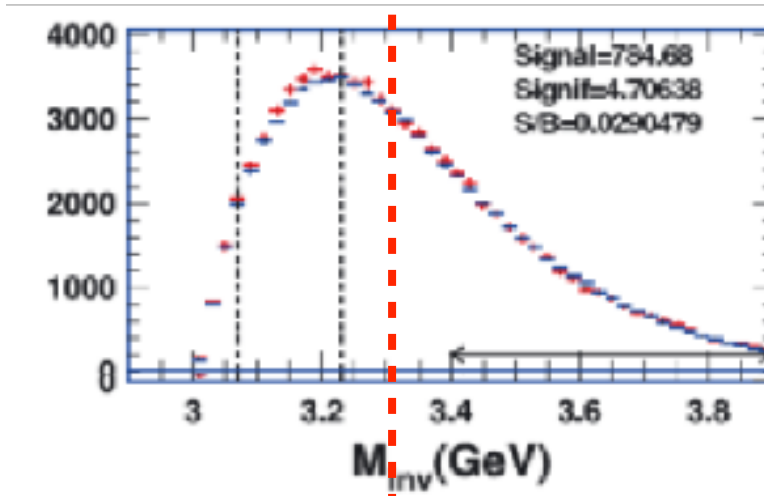
FUNUDA@DAΦNE

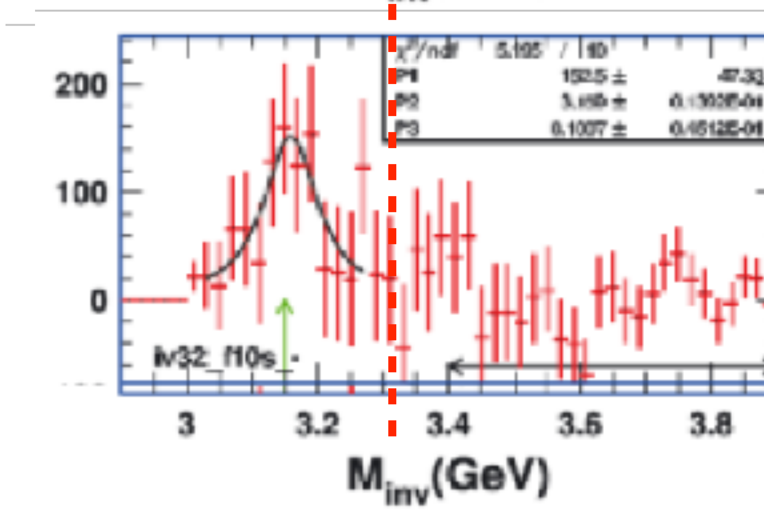


PLB654(2007)80

Λd in Ni+Ni

FOPI@GSI

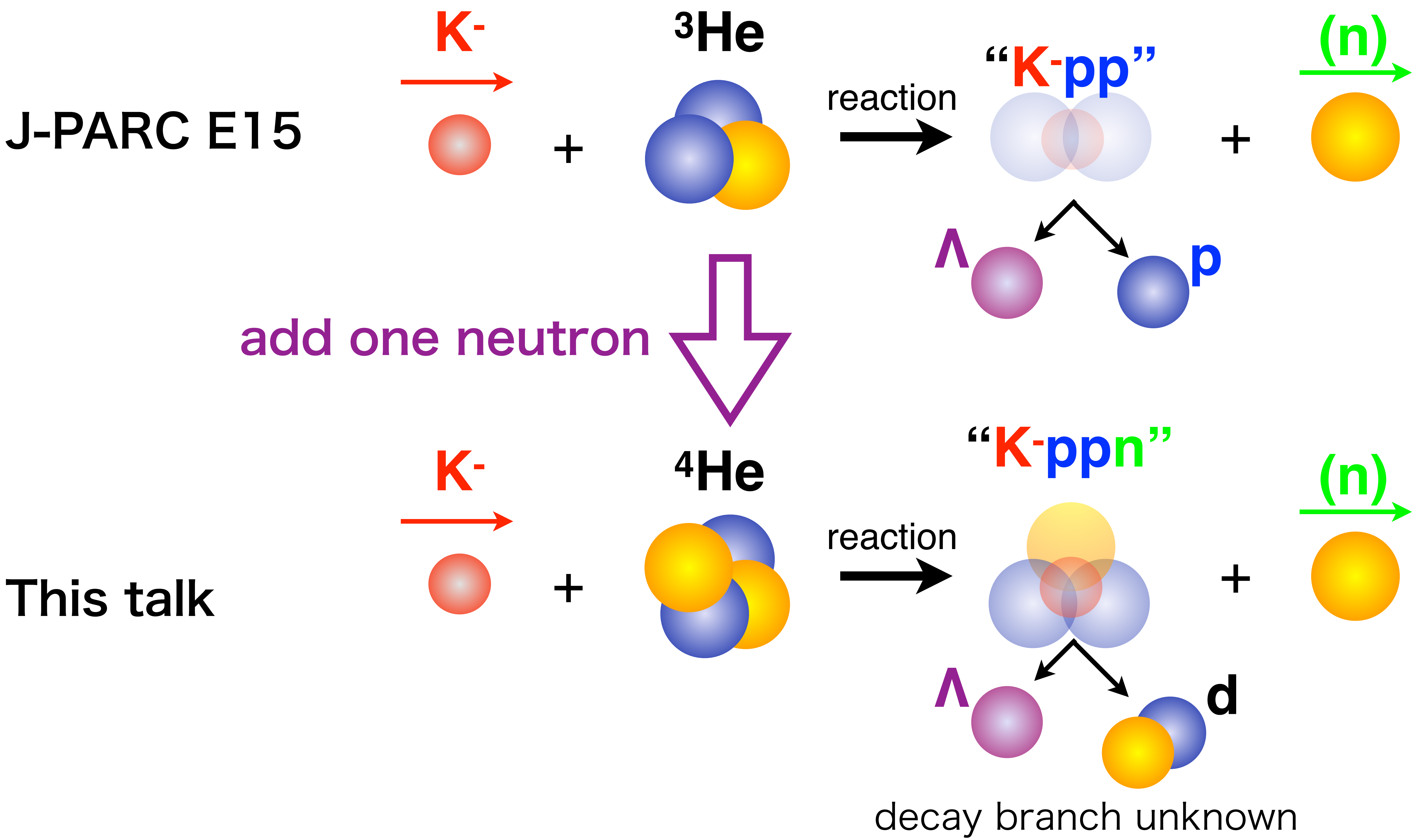




EXA05 Proceedings (2005)

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

Our approach

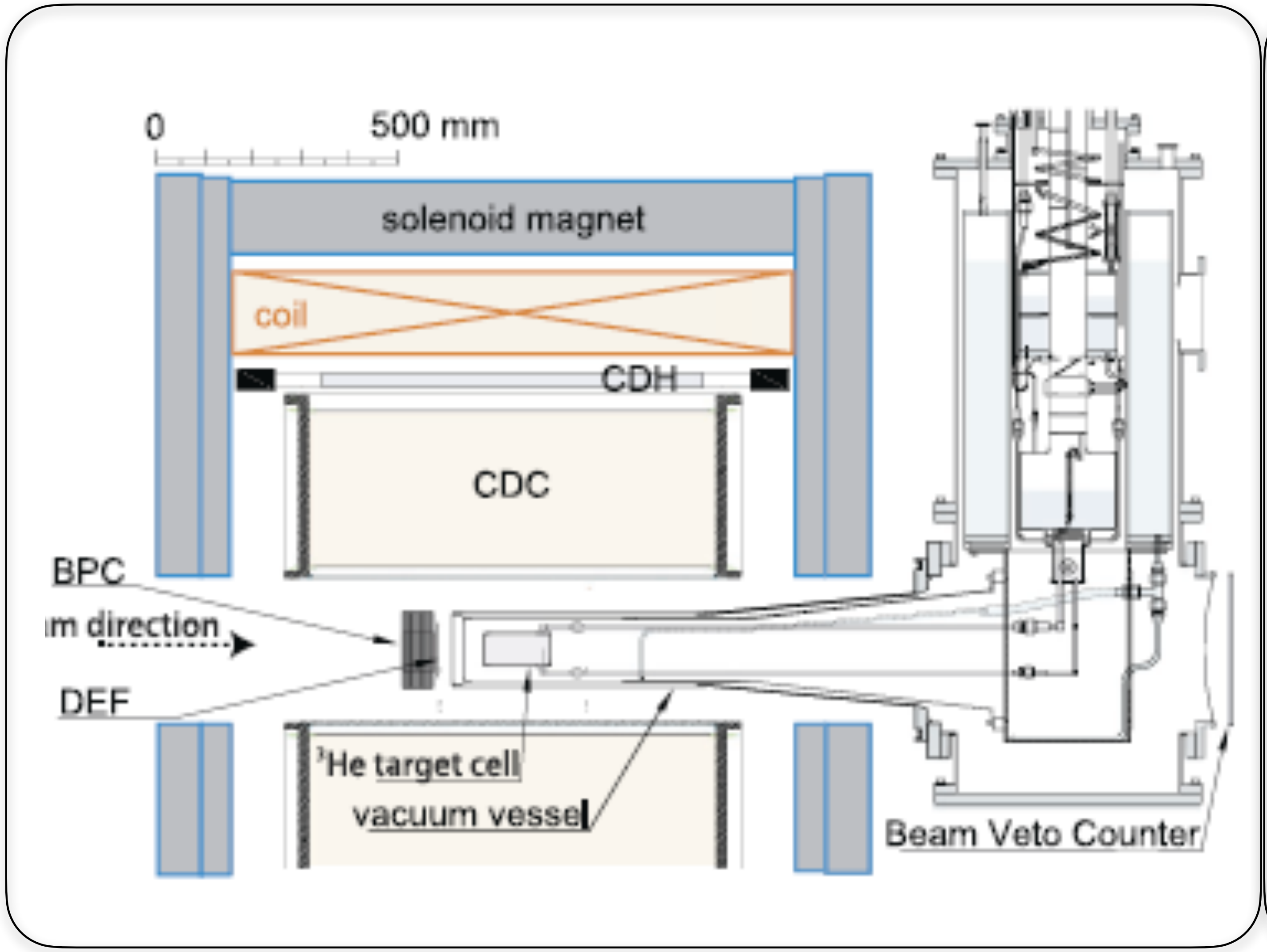


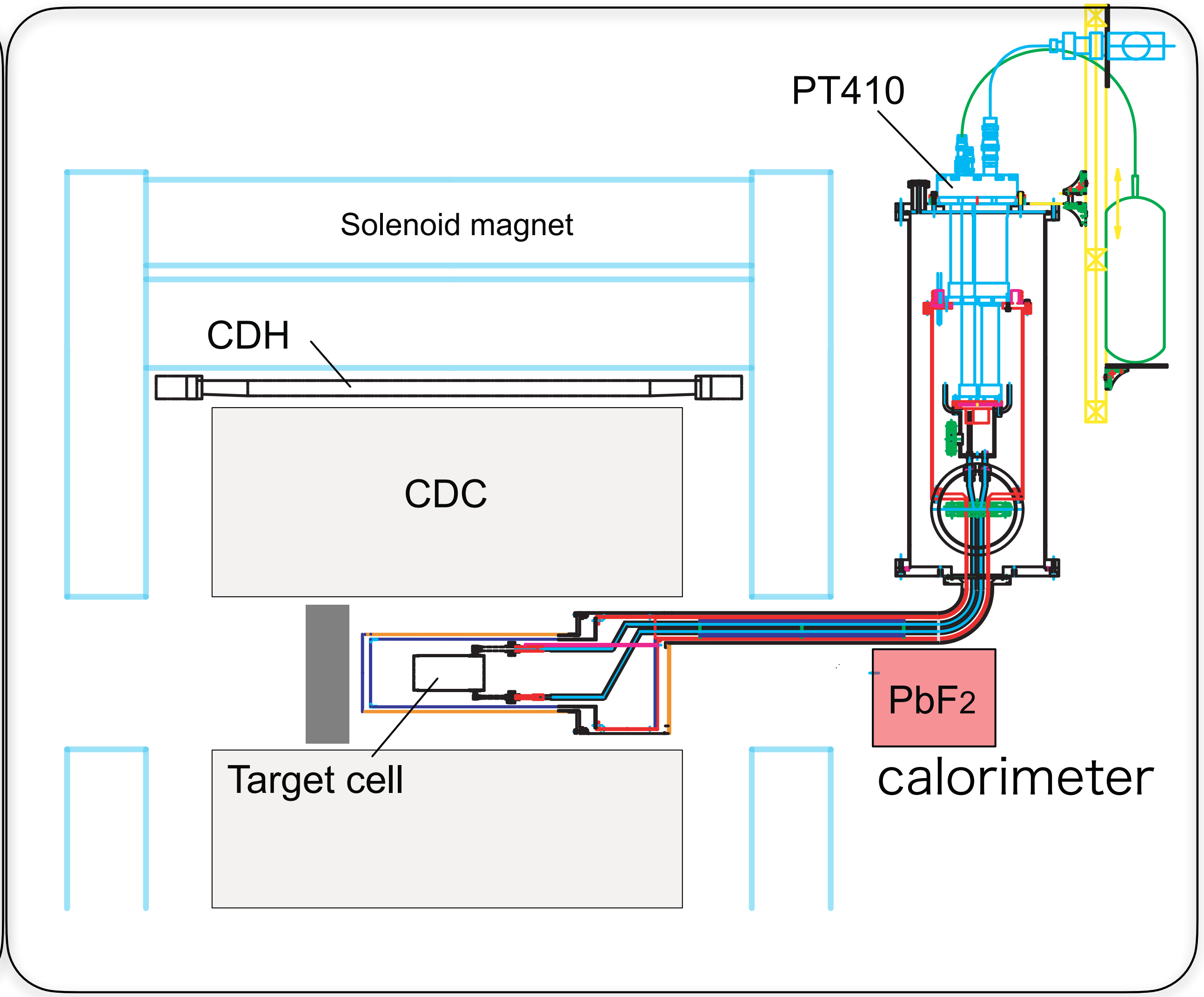
Use in-flight (K^-,n) reaction, just as J-PARC E15

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

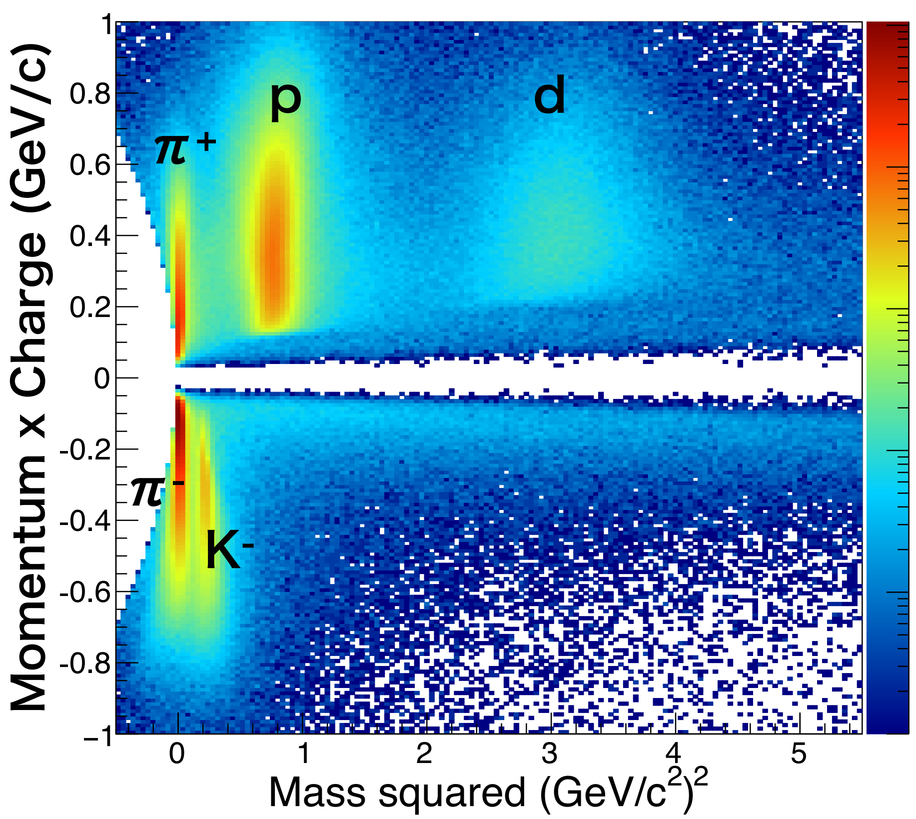
  + forward calorimeter in T77 for lifetime measurements of hypernuclei

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

Λdn event selection

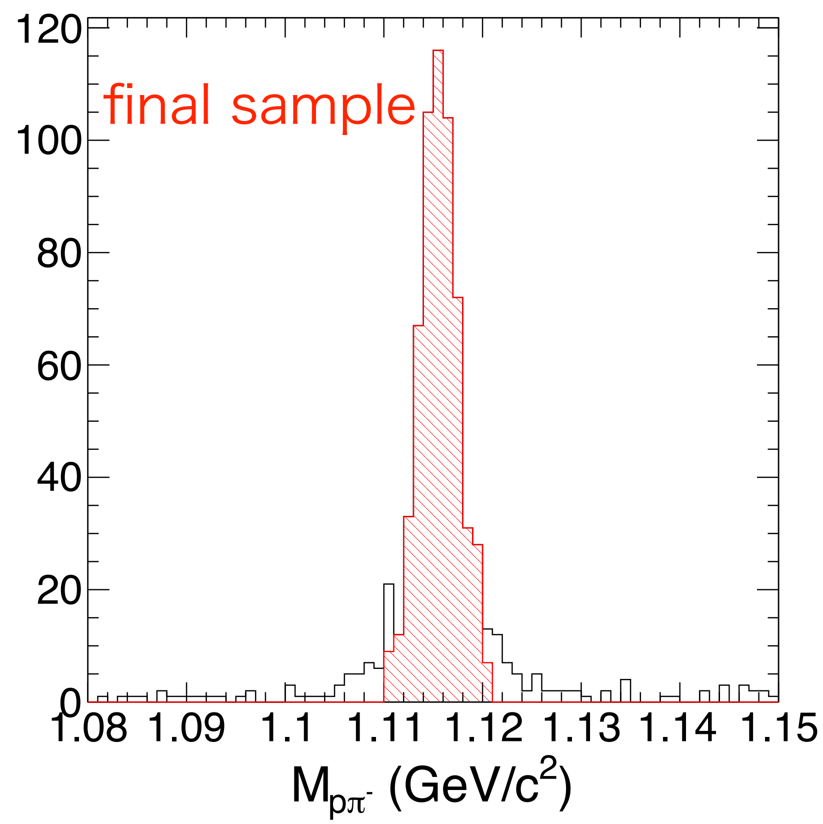
deuteron ID

CDC track curvature &
CDH time of flight



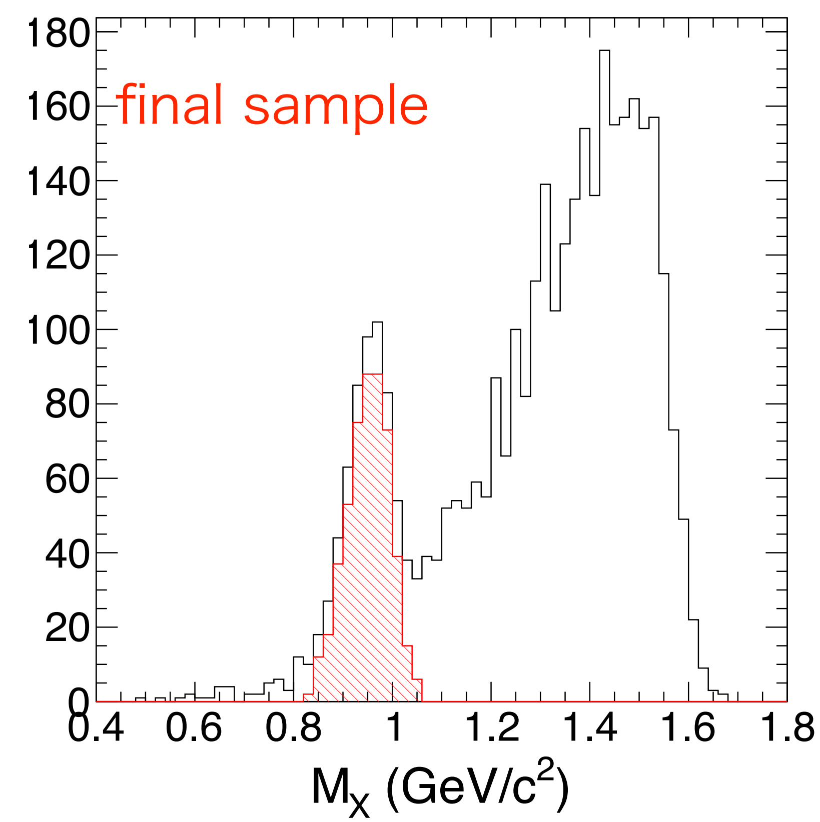
Λ reconstruction

w/ vertex consistency cut
w/ pipd missing mass cut



Missing neutron ID

w/ vertex consistency cut
w/ lambda mass cut



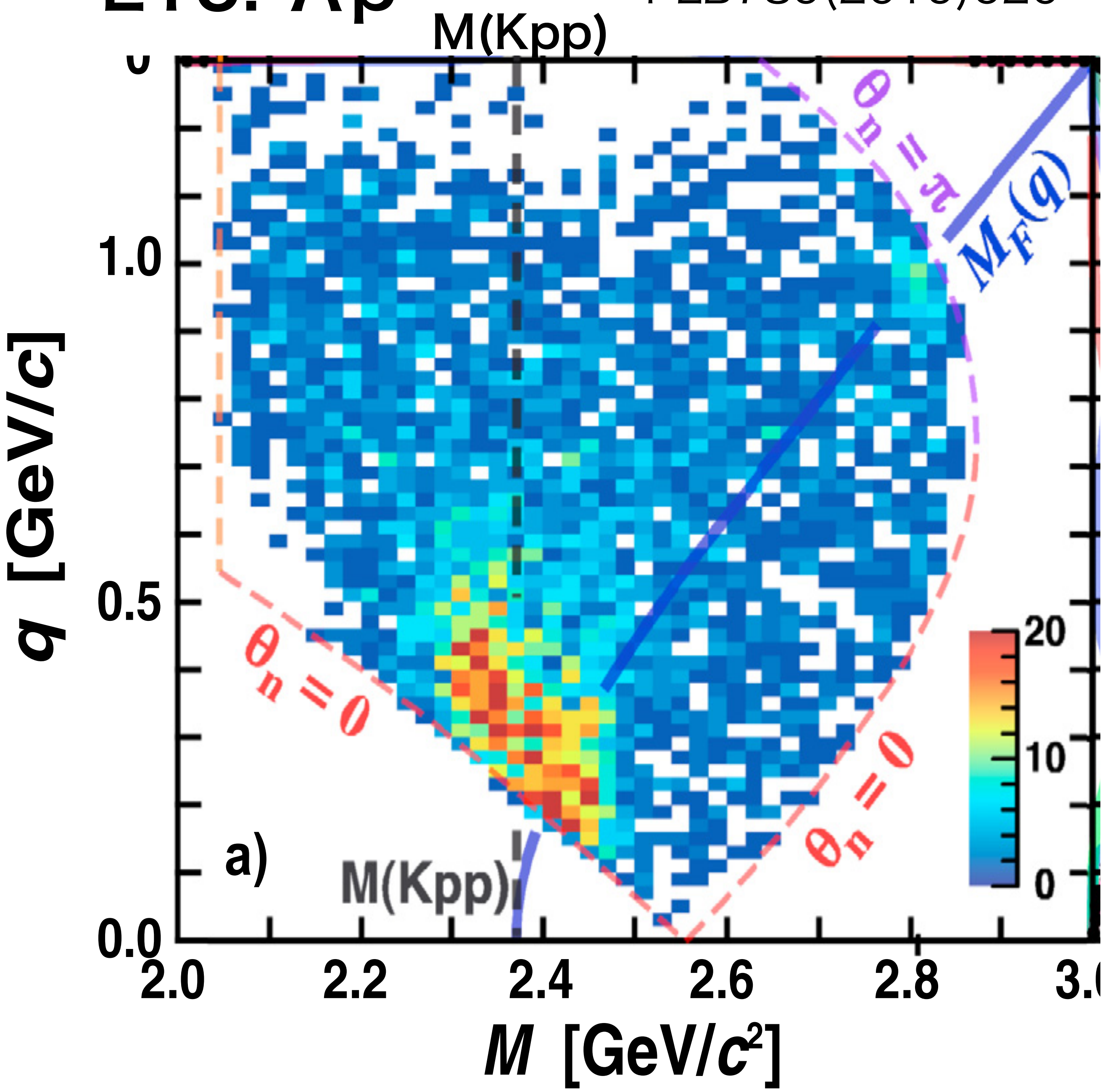
- Λdn final states are identified with a good purity by considering kinematical & topological consistensies
- ~20% contamination from $\Sigma^0 dn/\Sigma^- dp$

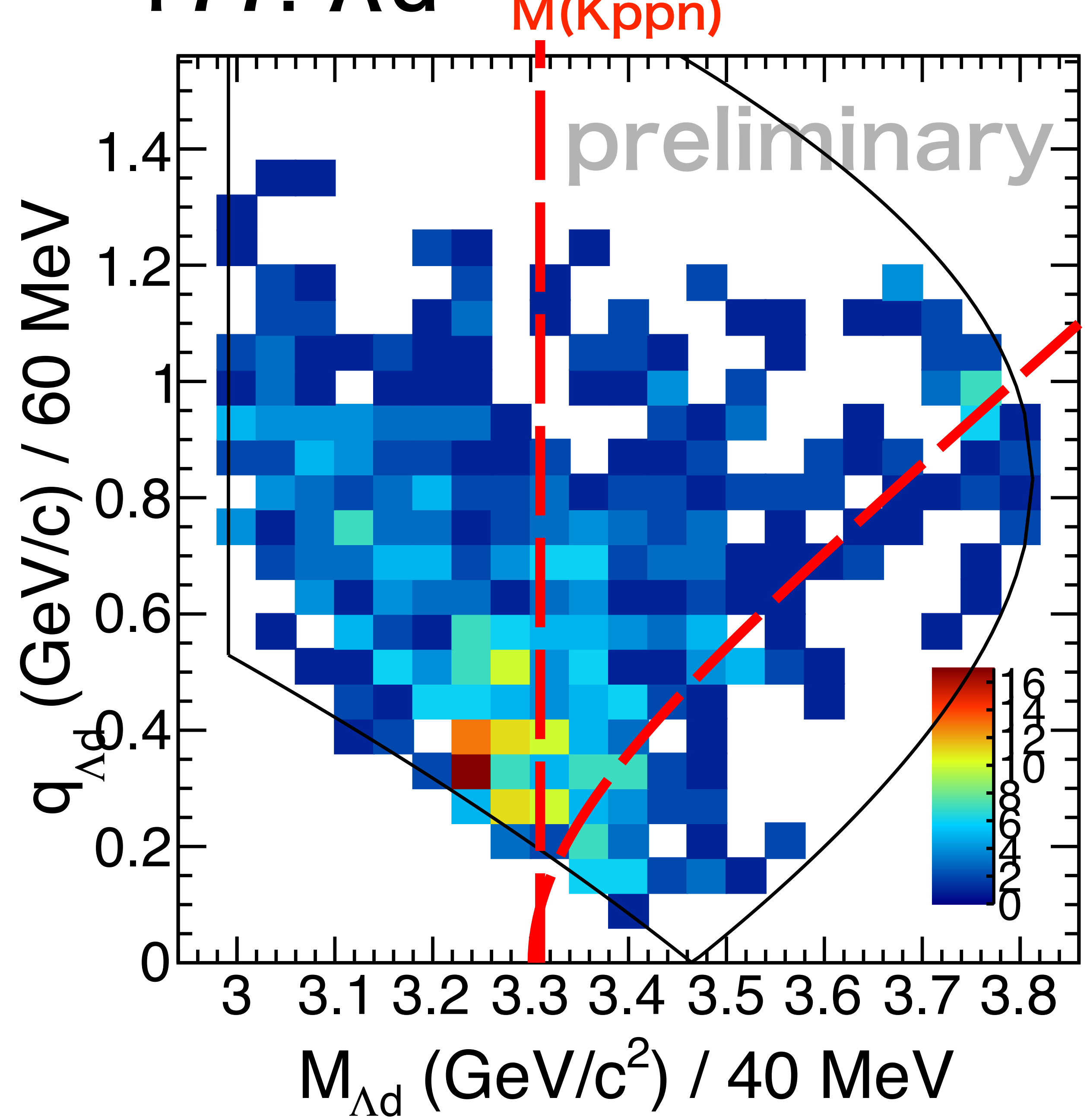
Preliminary result

before acceptance correction

E15: Λp PLB789(2019)620

T77: Λd

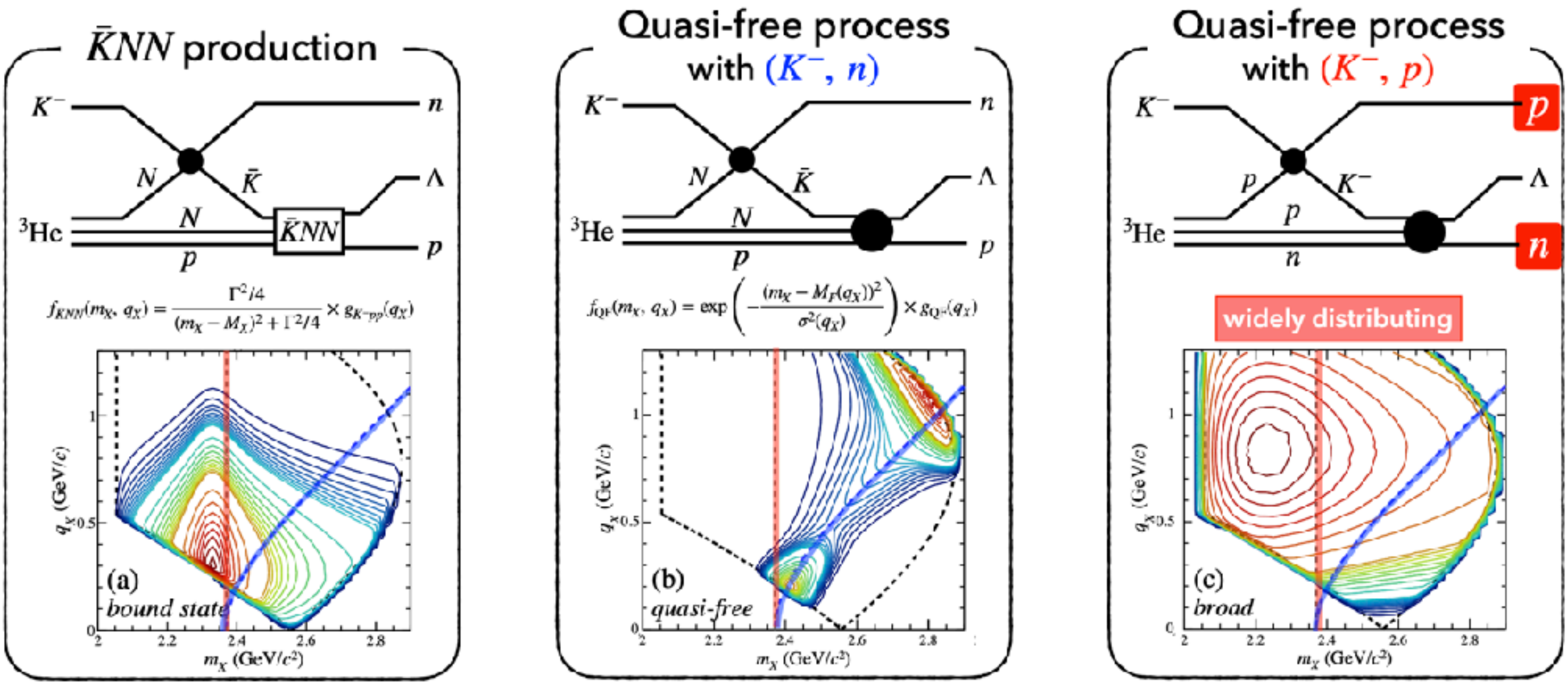




- Two disributions are quite similar
- structure below the threshold, QF-K^-, and broad background

Model functions

from T. Yamaga's slide

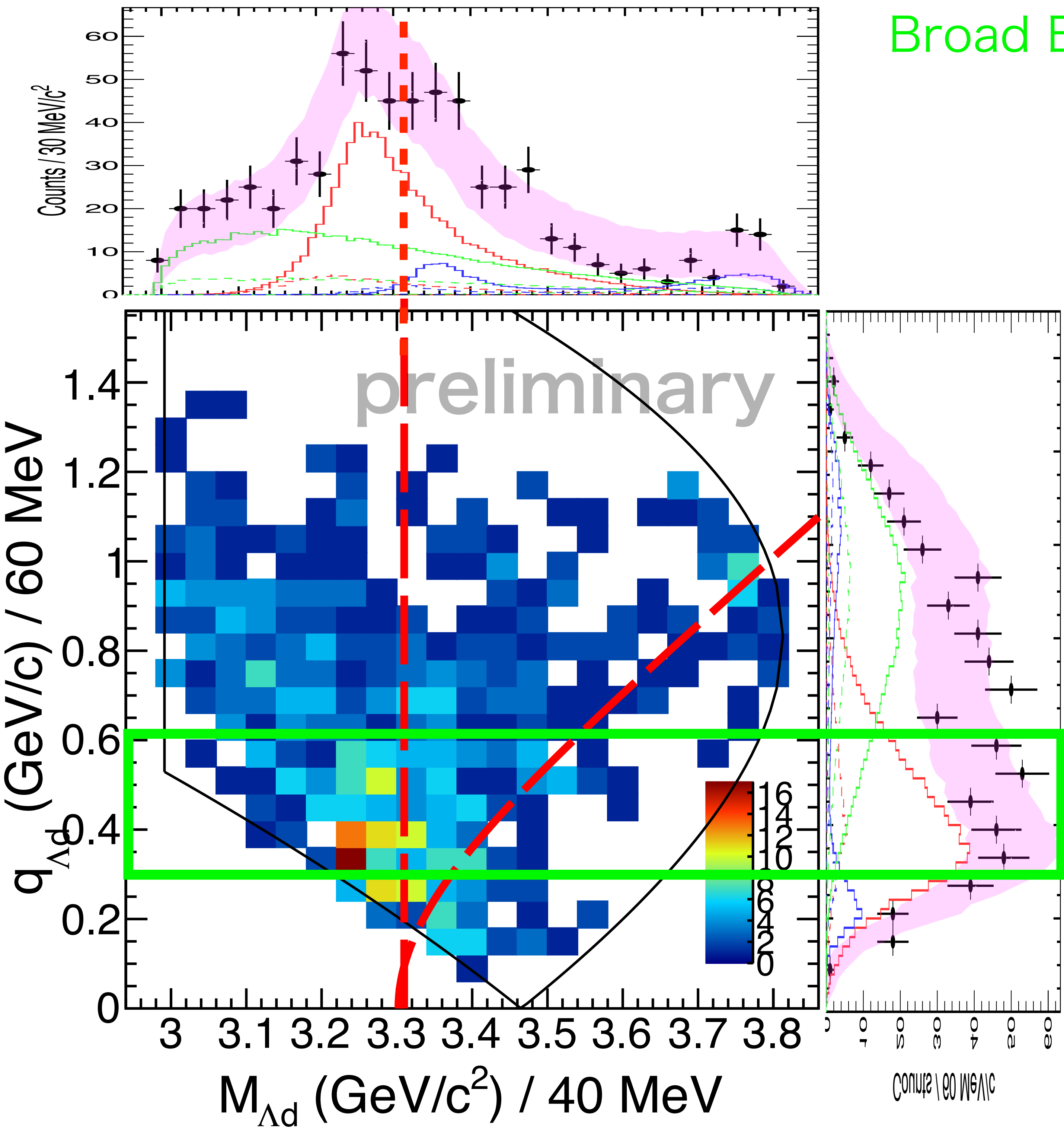


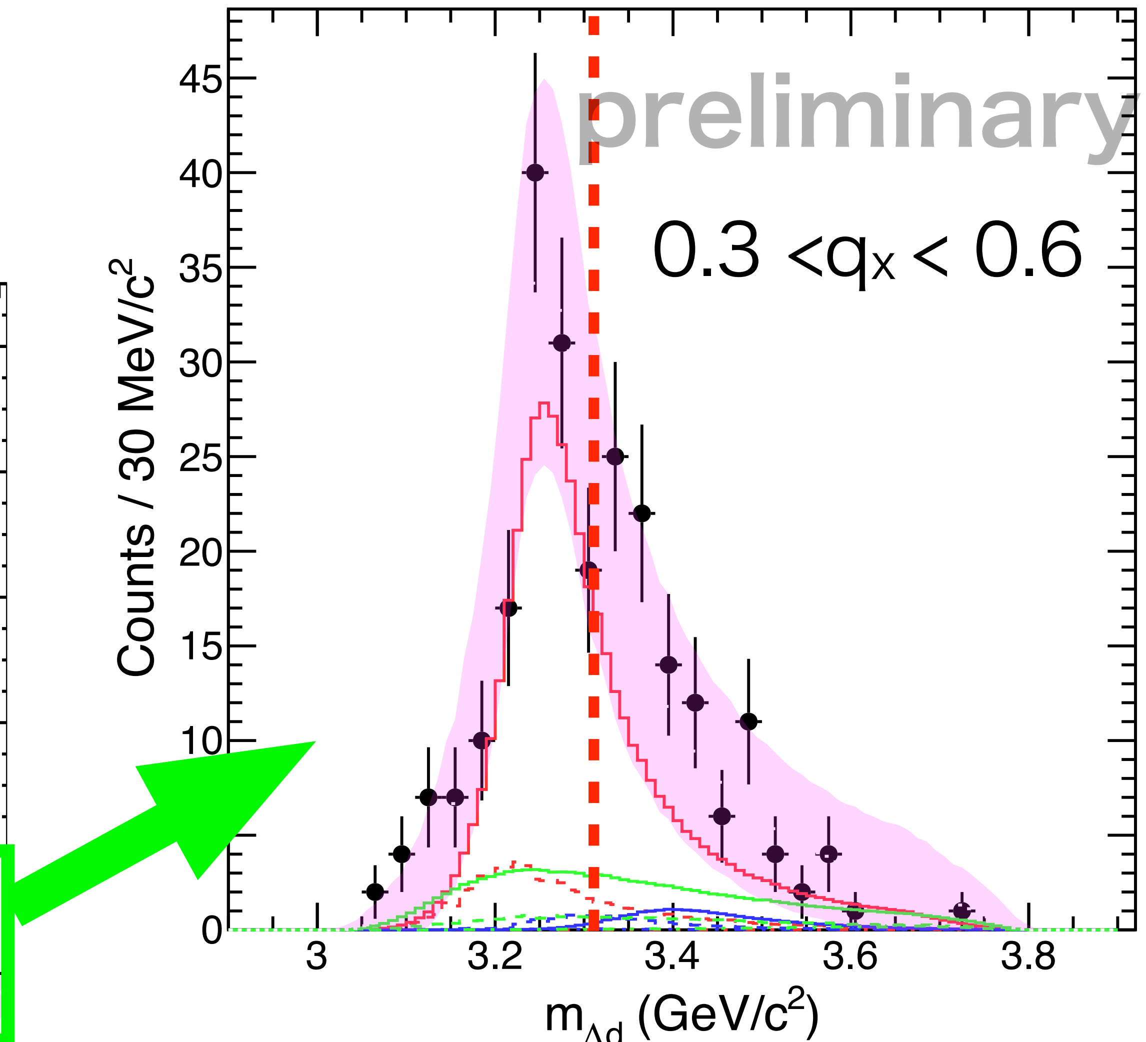
- From E15 functions, simply shift the mass by 1 nucleon mass
- Shapes of the “quasi-free” and “broad” distributions are fixed by E15 results.

Preliminary result

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

Broad BG and QF-K$^-$ shape from E15 PRC





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

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

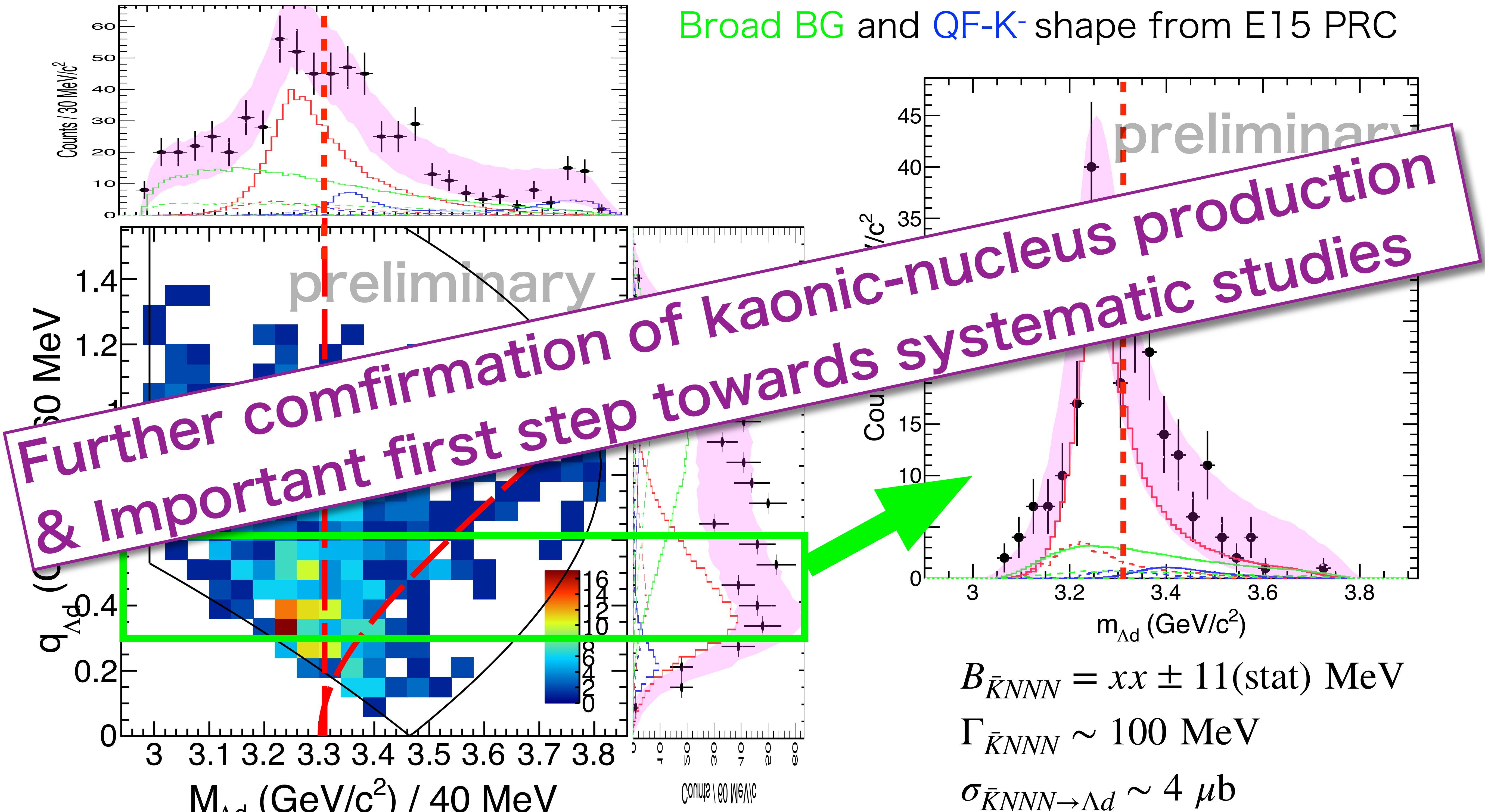
$\sigma_{\bar{K}NNN \to \Lambda d} \sim 4\ \mu$b

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

Preliminary result

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

Broad BG and QF-K- shape from E15 PRC



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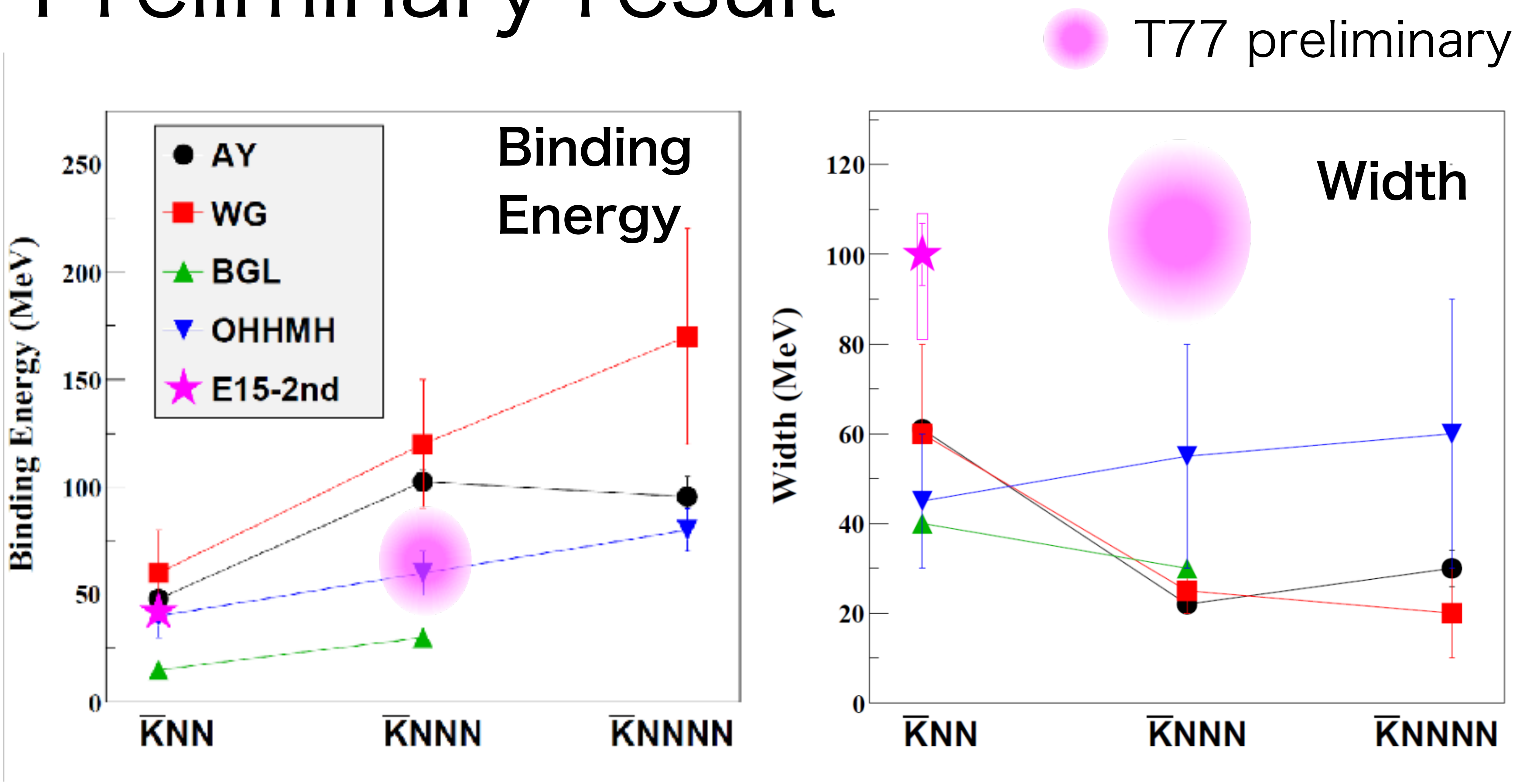
Preliminary result



- 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.

Further studies on $\bar{K}NNN$

- More data to determine binding energy and other parameters to compare with E15 "$\bar{K}NN$" results.

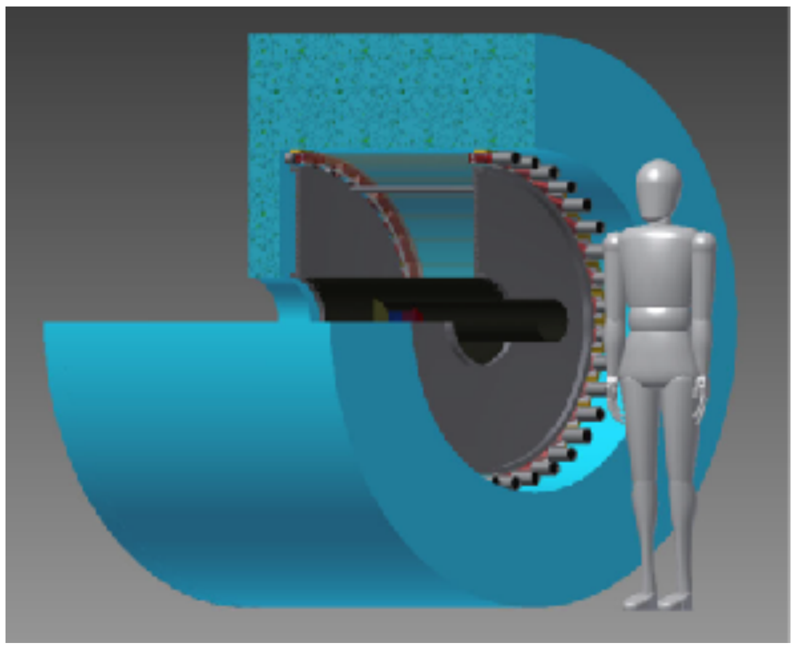
- The isospin of the observed state is uniquely assinged as $I = 0$ from the its decay to $\Lambda(I = 0)$ $d(I = 0)$, but how about spin-parity?
  - $J^P = 1/2^-$ assuming all the consistuents are in S-wave
    $$\bar{K}NNN\ (I = 0,\ J^p = 1/2^-)$$
  - $\Sigma^* NN\ (I = 0,\ J^p = 3/2^+)$ possibility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

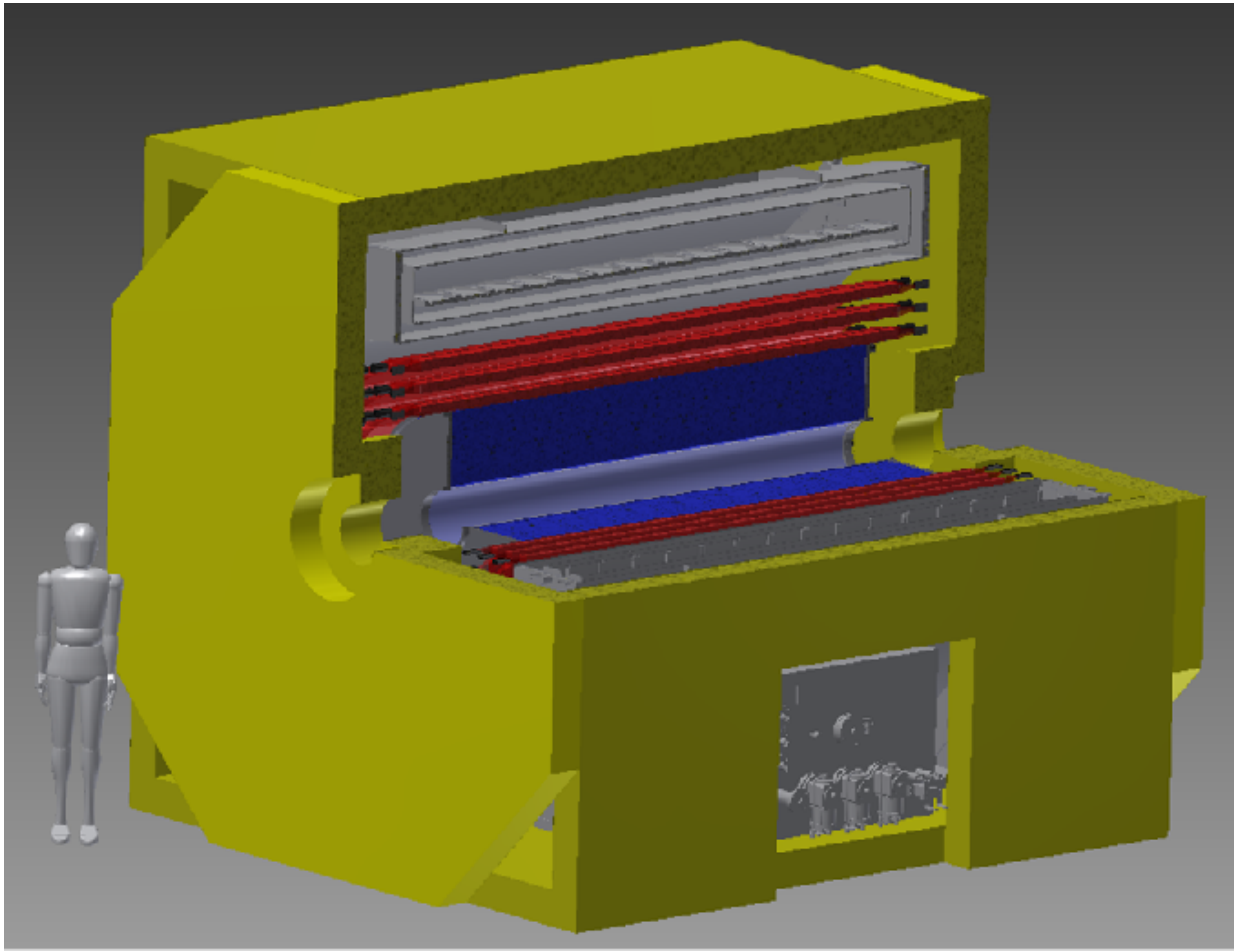
- Comparison with the Λpn decay mode
  - peak position, branching ratio,⋯
  - I=1 component could be contaminated

- Study I=1 state via (K^-, p) reaction

→ **J-PARC E80 with a larger spectrometer**

J-PARC E80 with a new spectrometer





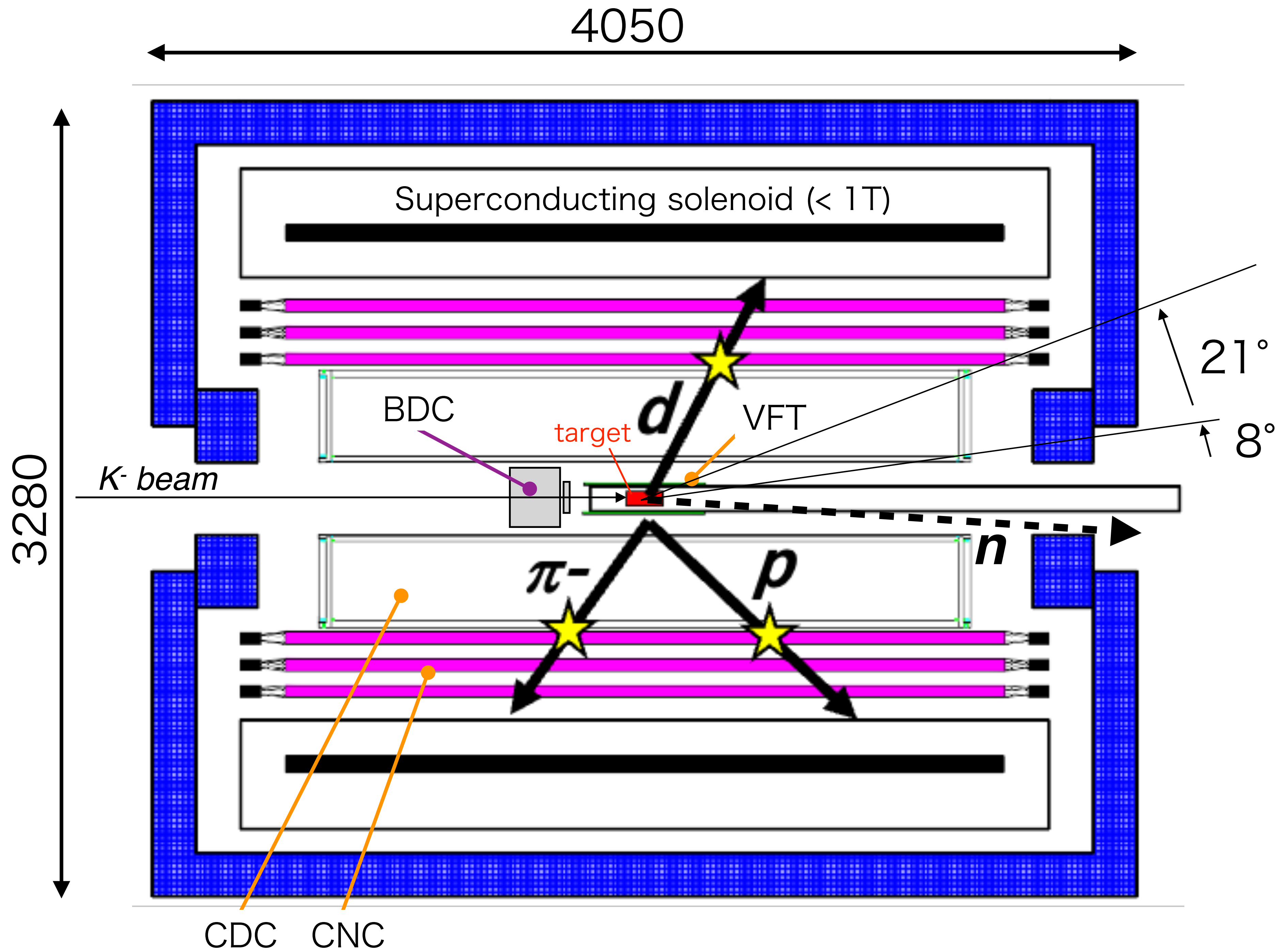
- About 10 times volume !!

New spectrometer

Solenoid:
Copy of COMET DS

CDC:
15-layer DC

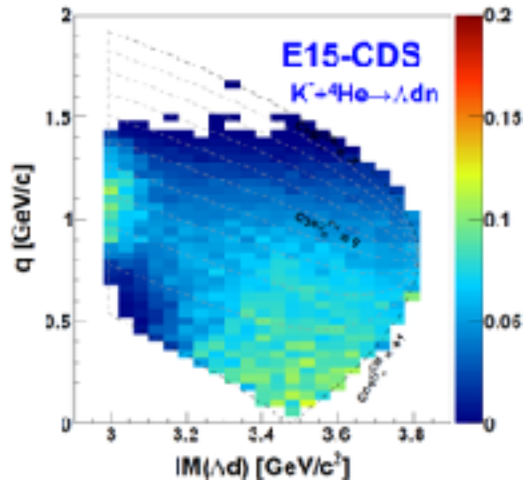
CNC:
3-layer 5-cm thick plastic scintillator

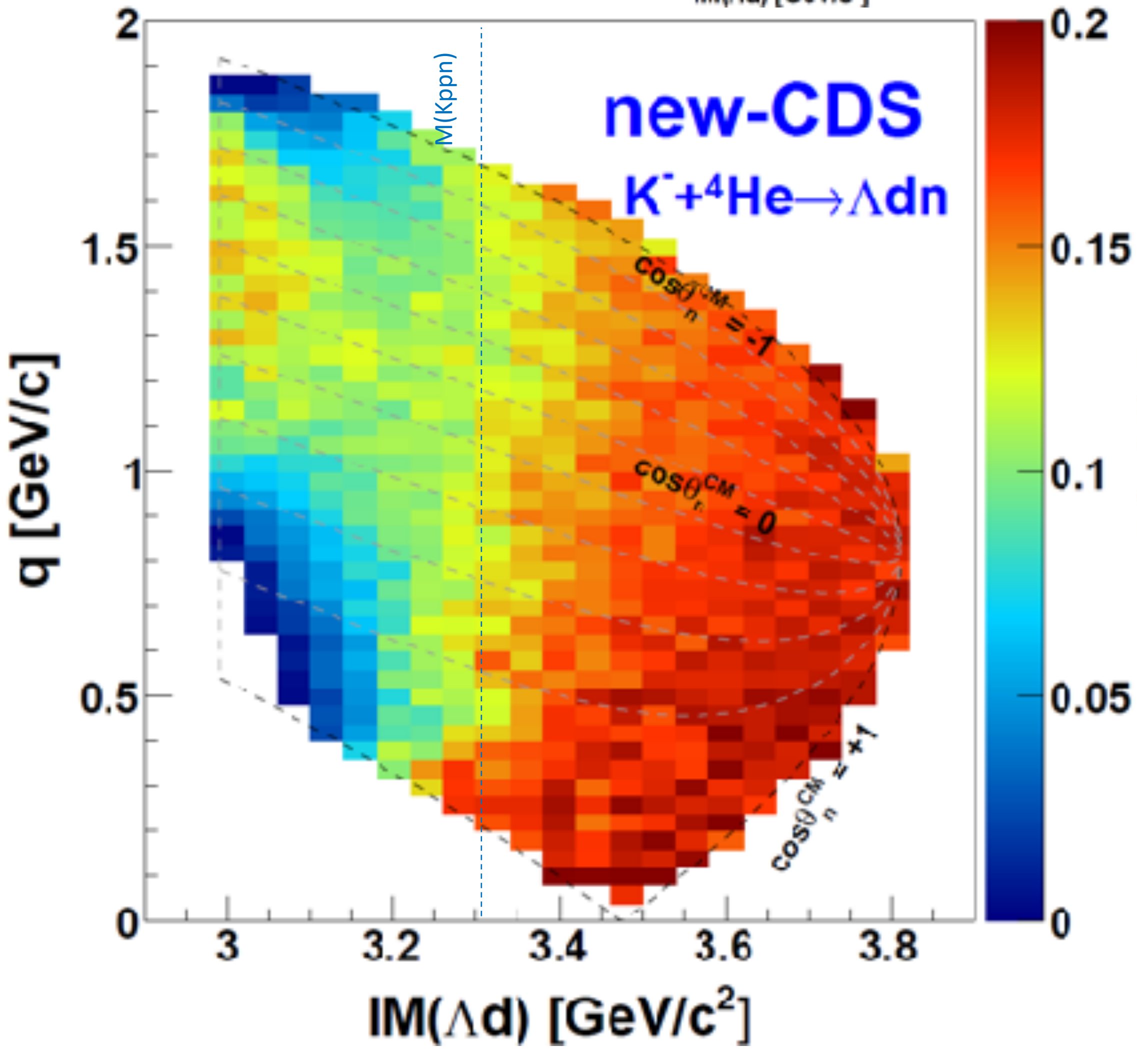


- x3 longer CDC: **solid angle 59%→93%**
- 3-layer barrel NC: **neutron efficiency 3%→15%**

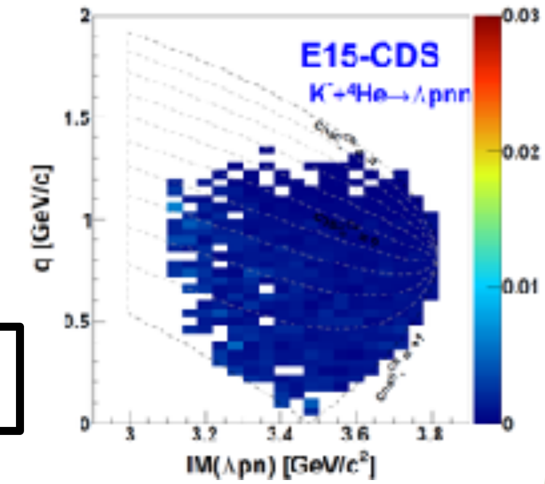
Acceptance

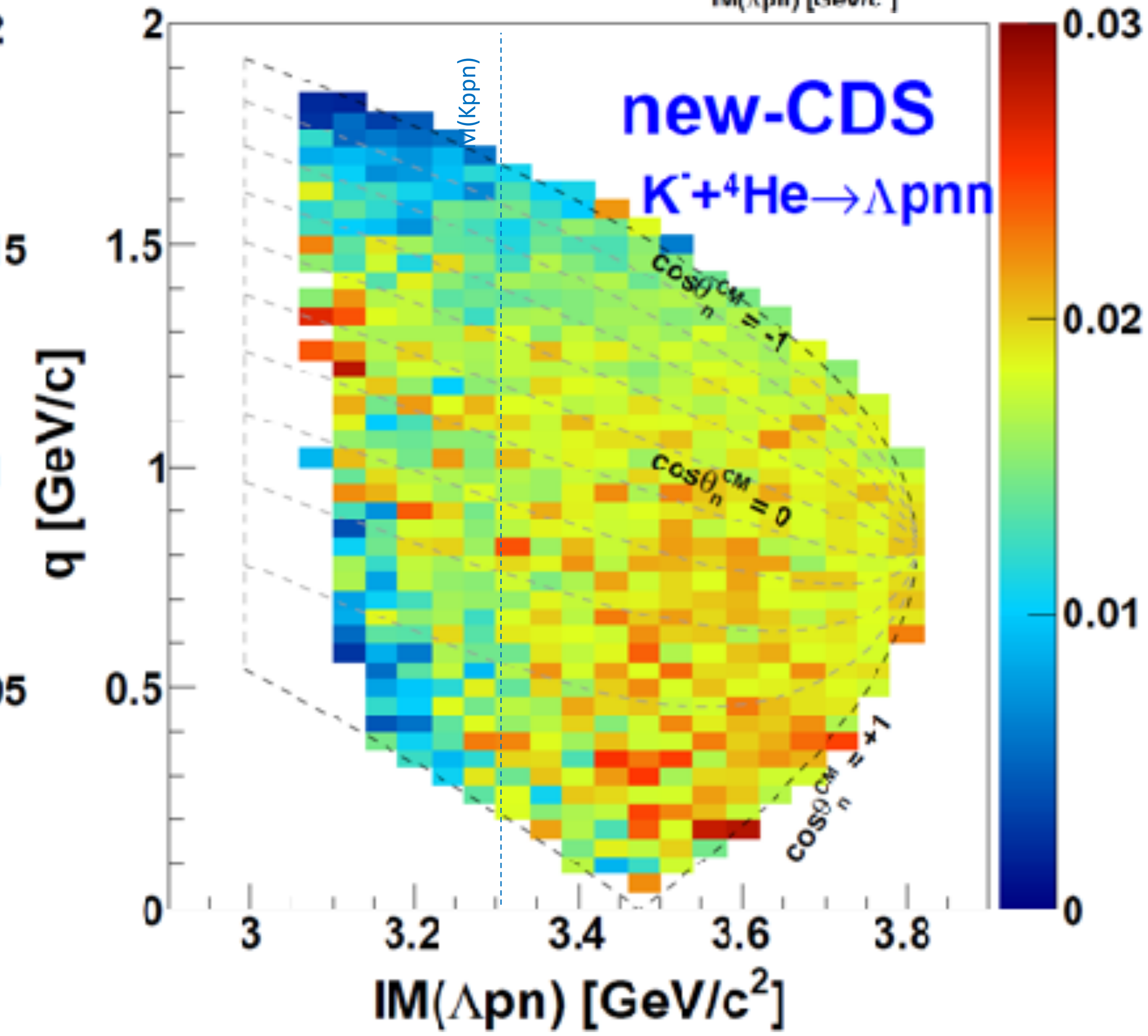
Λd in CDS





Λpn in CDS





- 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

- **$N(K^- ppn \rightarrow \Lambda d)$ ~ 1.2 x 10^4**
- **$N(K^- ppn \rightarrow \Lambda pn)$ ~ 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
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
ε(CDC)	0.6 / 0.3
N(K^-ppn)	12 k / 1.5 k

x ~20

x ~2

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

✓ Similar number of Λpn events to Λp in E15

Expected spectra

@ 3 weeks, 90kW

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

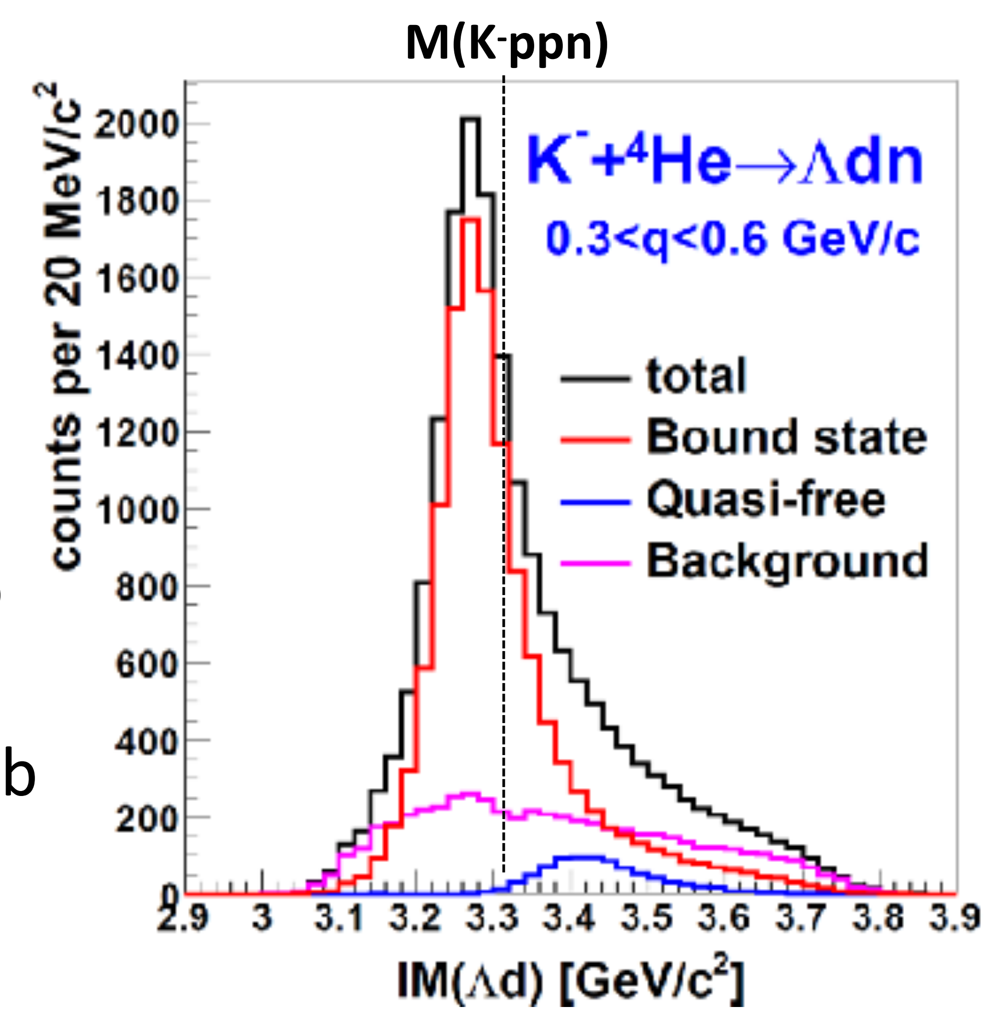
$K^- + {}^4He \rightarrow \Lambda pn + n$

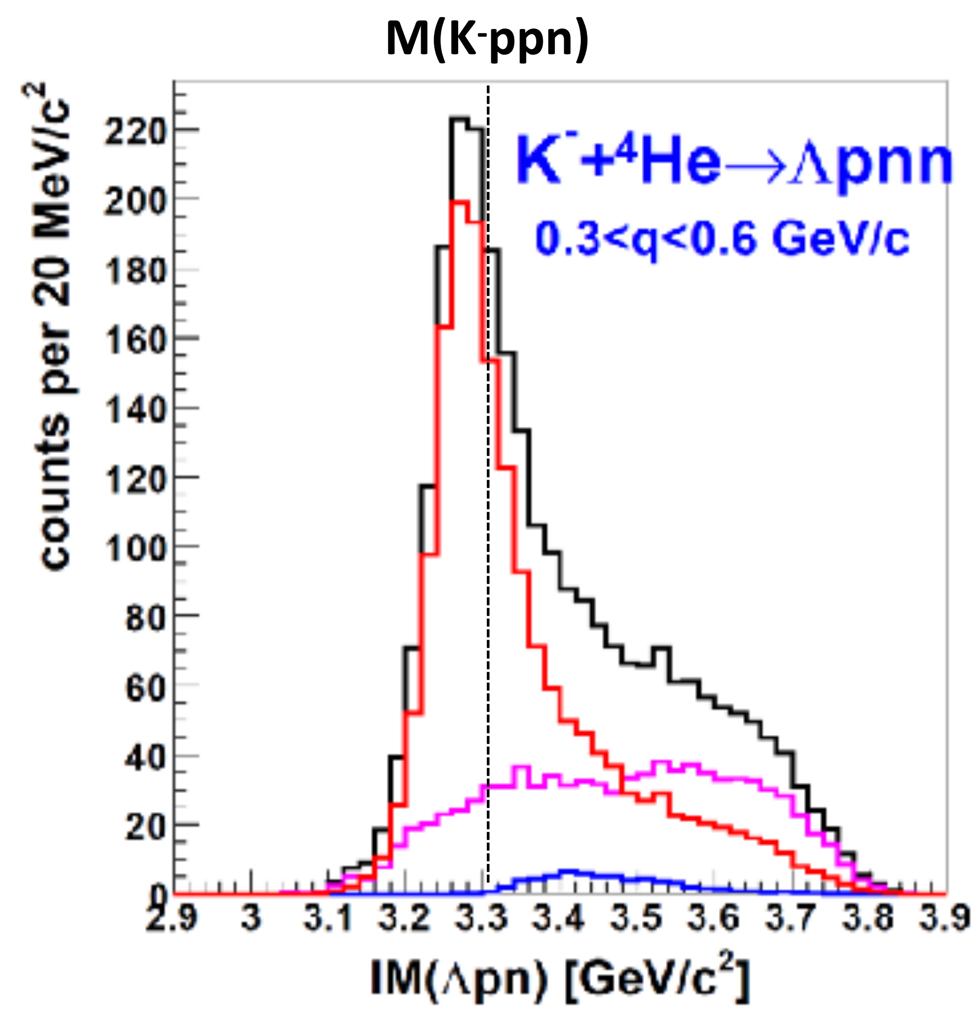
B_{Kppn} ~ 40 MeV

Γ_{Kppn} ~ 100 MeV

Q_{kppn} ~ 400 MeV/c

$\sigma(K^-ppn)$*Br ~ 5 μb
$\sigma(QF)$ ~ 5 μb
$\sigma(BG)$ ~ 10 μb



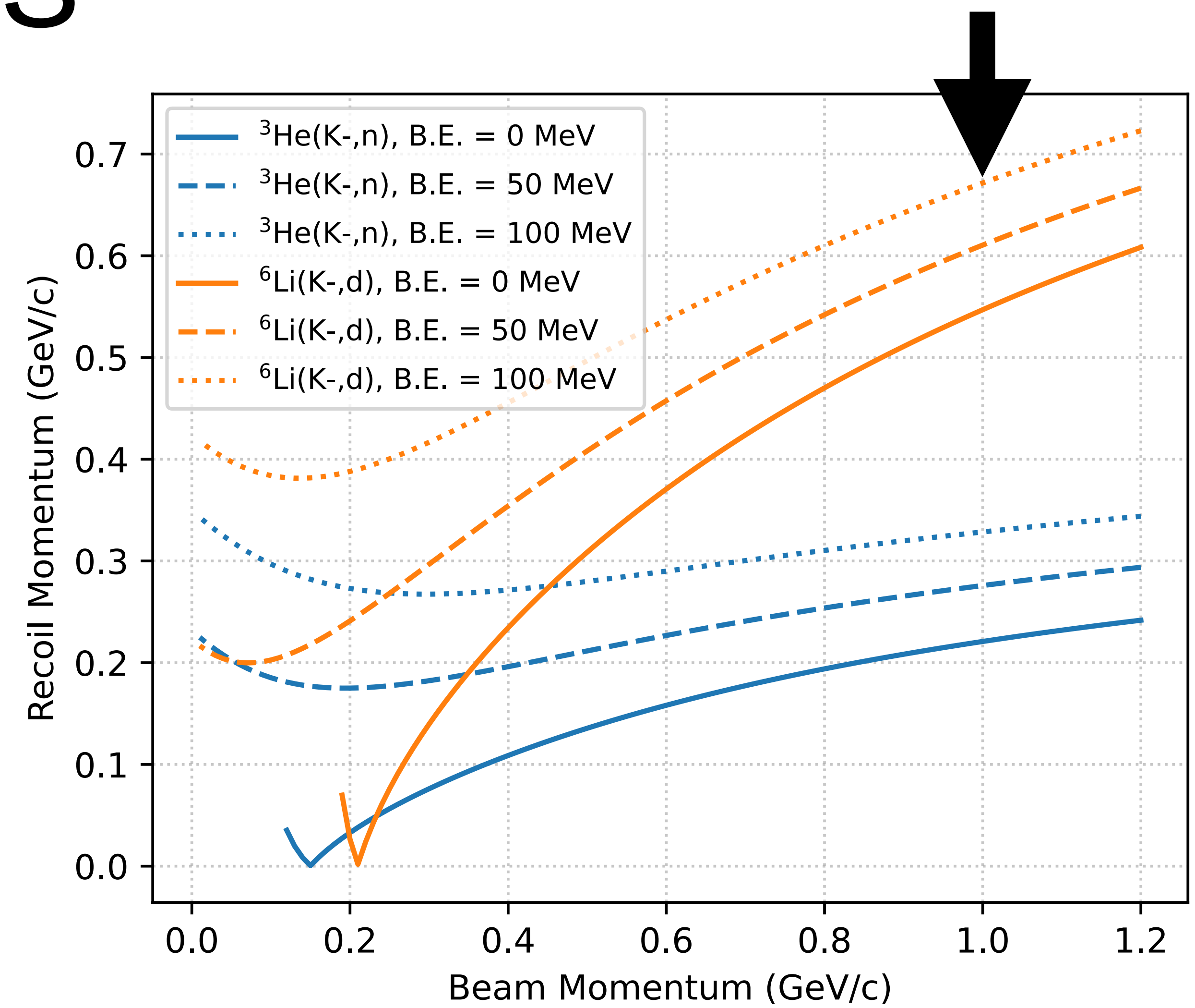


✓ Clear peak would be observed for both modes

Heavier systems

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

-1.0 GeV/c



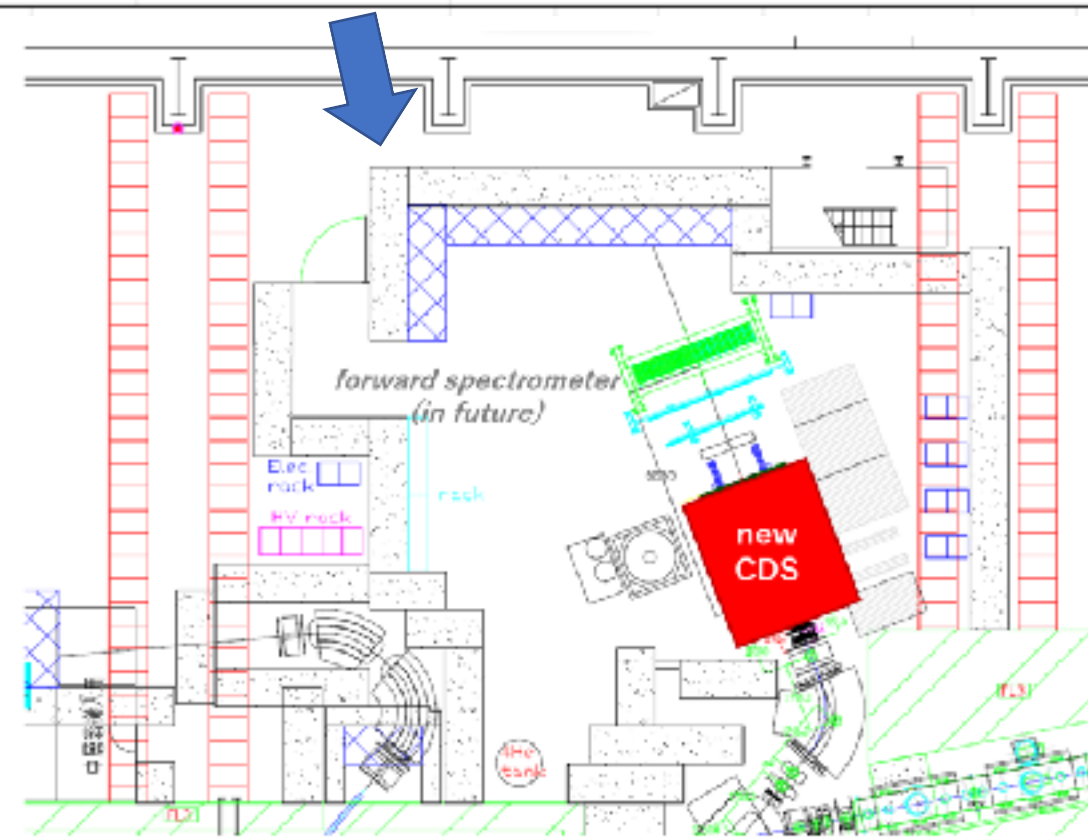
- Deuteron knock-out reaction has a larger momentum transfer
  - → We would like test in E80: $^{6}Li(K^{-},d)$"K-α", $^{4}He(K^{-},d)$"K0barnn"

- 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 are working hard to be ready at the end of JFY2025 !!

Summary

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

- We observed **^{4}He(K$^-$,Λd)n** events as a by-product
  (J-PARC T77: Lifetime measurement of hypernuclei.)
  - The observed distribution is similar to that of Λp in E15, and would include signals of $\boldsymbol{\bar{K}NNN}$.
    →**further confirmation of the existence of kaonic nuclei**

- We are constructing **new large solenoid spectrometer** for further study of $\bar{K}NNN$ (J-PARC E80) and other kaonic nuclei
  - ~4π acceptance & enhanced neutron detection capability
  - We hope to start experiments in JFY2025~2026 (before HD-ext)

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