Forthcoming programs on kaonic nuclei/atoms at J-PARC

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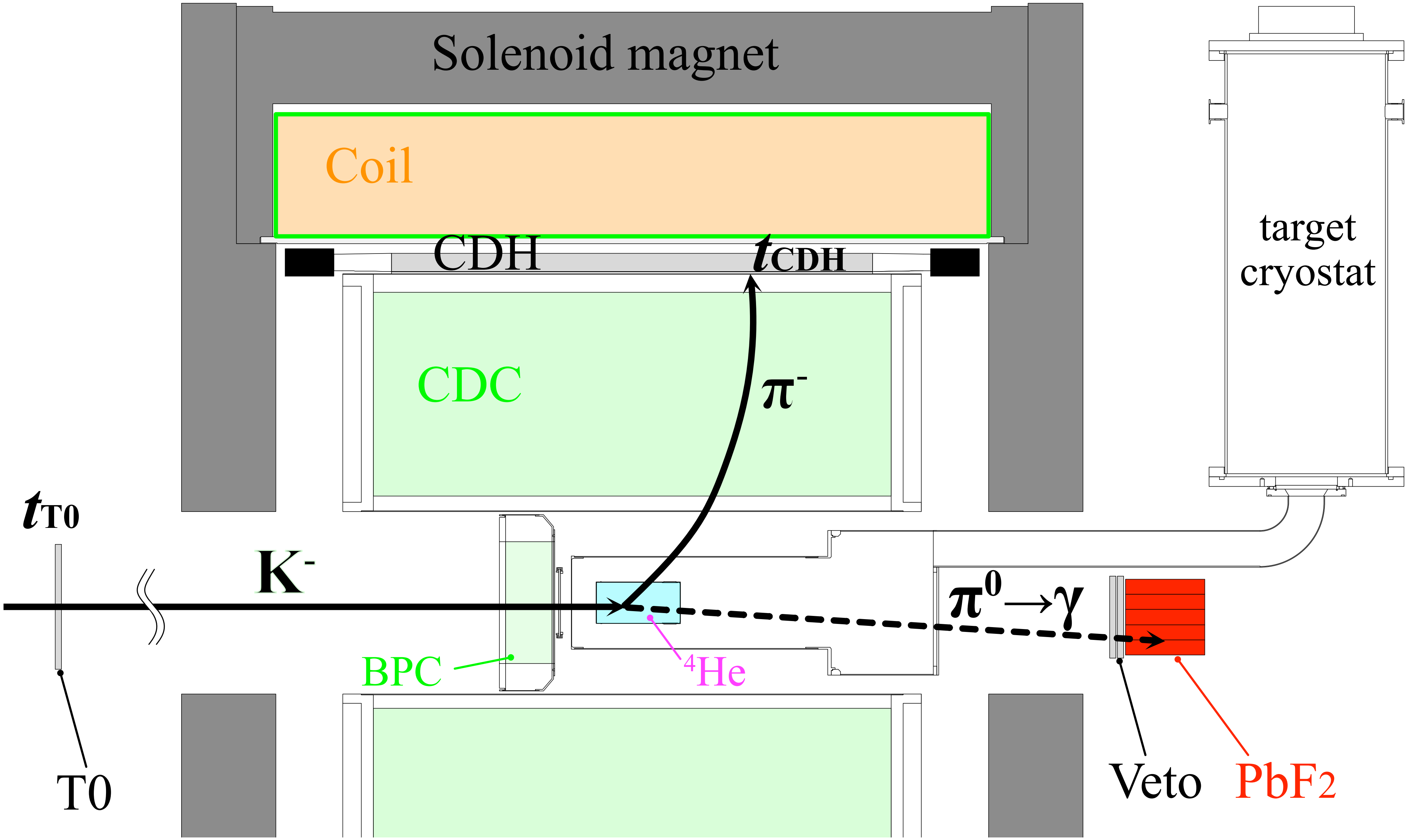
December 14th, 2023

	4	5	6	7	8	9	10	11	12	1	2	3	ver. 2023/11/01
JFY2022	COMET/S2S										phase-α		
K1.8													
BR													
		superconducting wire, return york										yoke	to KEK
JFY2023													
K1.8			E70C								E70C		
BR			T98								E73		
		solenoid and CDC											
JFY2024													
K1.8			E70							E70	E75		
BR			E73	CDS->HypTPC									
	solenoid and CD			**CDC** **to J-PARC**								**solenoid**	**to J-PARC**
JFY2025	COMET-I												
K1.8													
BR	E72	E72	area rearrangement						**solenoid/yoke to K1.8BR**				
									solenoid assembly, test, field measurement				
JFY2026													
K1.8													
BR	solenoid assembly, test, fiel					rea	E80C				E80	E80	
JFY2027													
K1.8													
BR													

+ Kaonic deuterium (E57), and …

Hypertriton lifetime
(J-PARC E73)

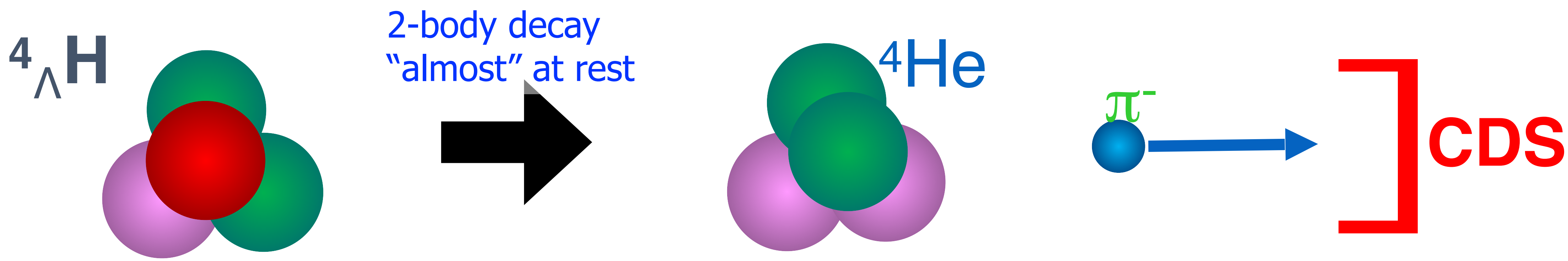
Method

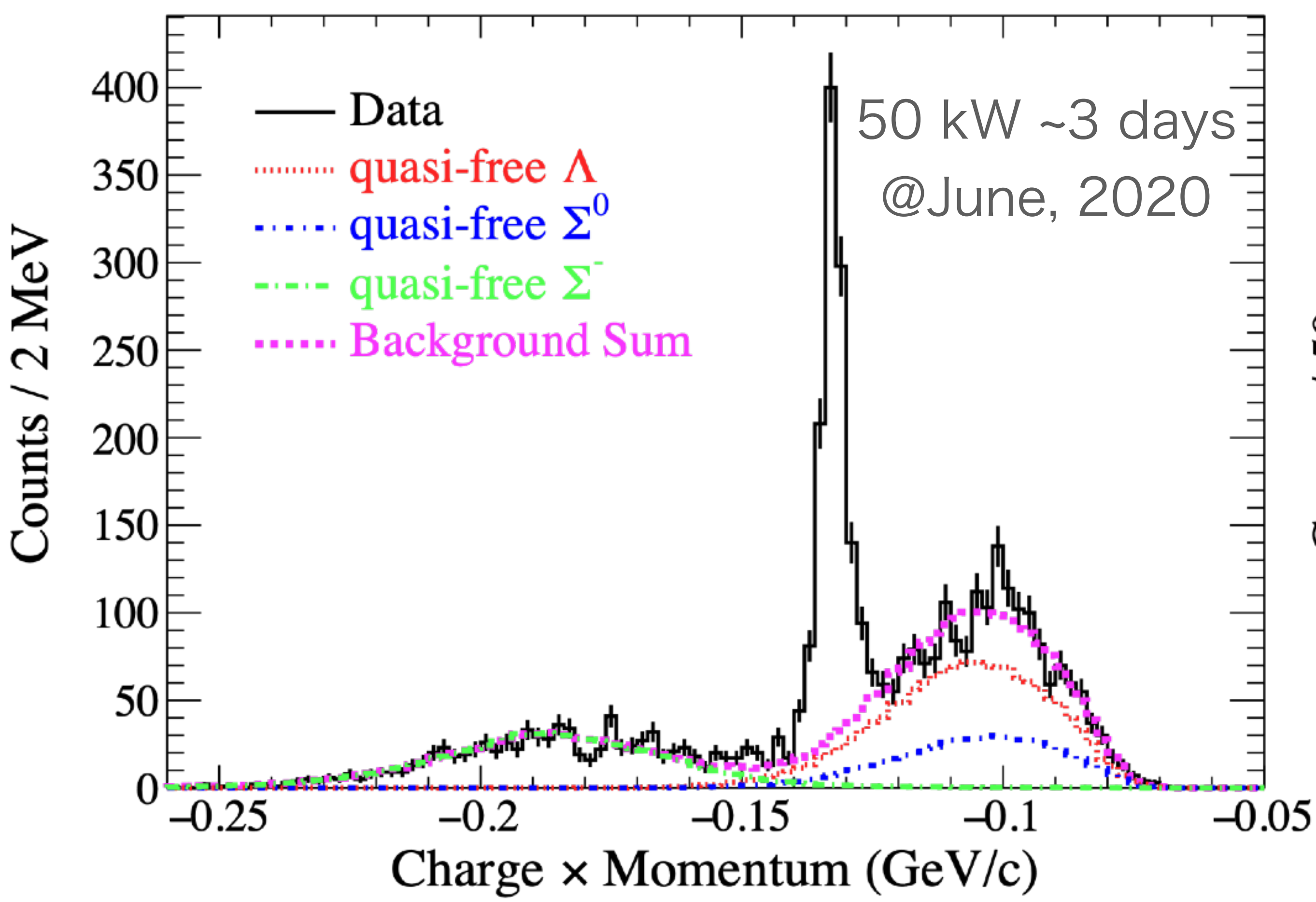


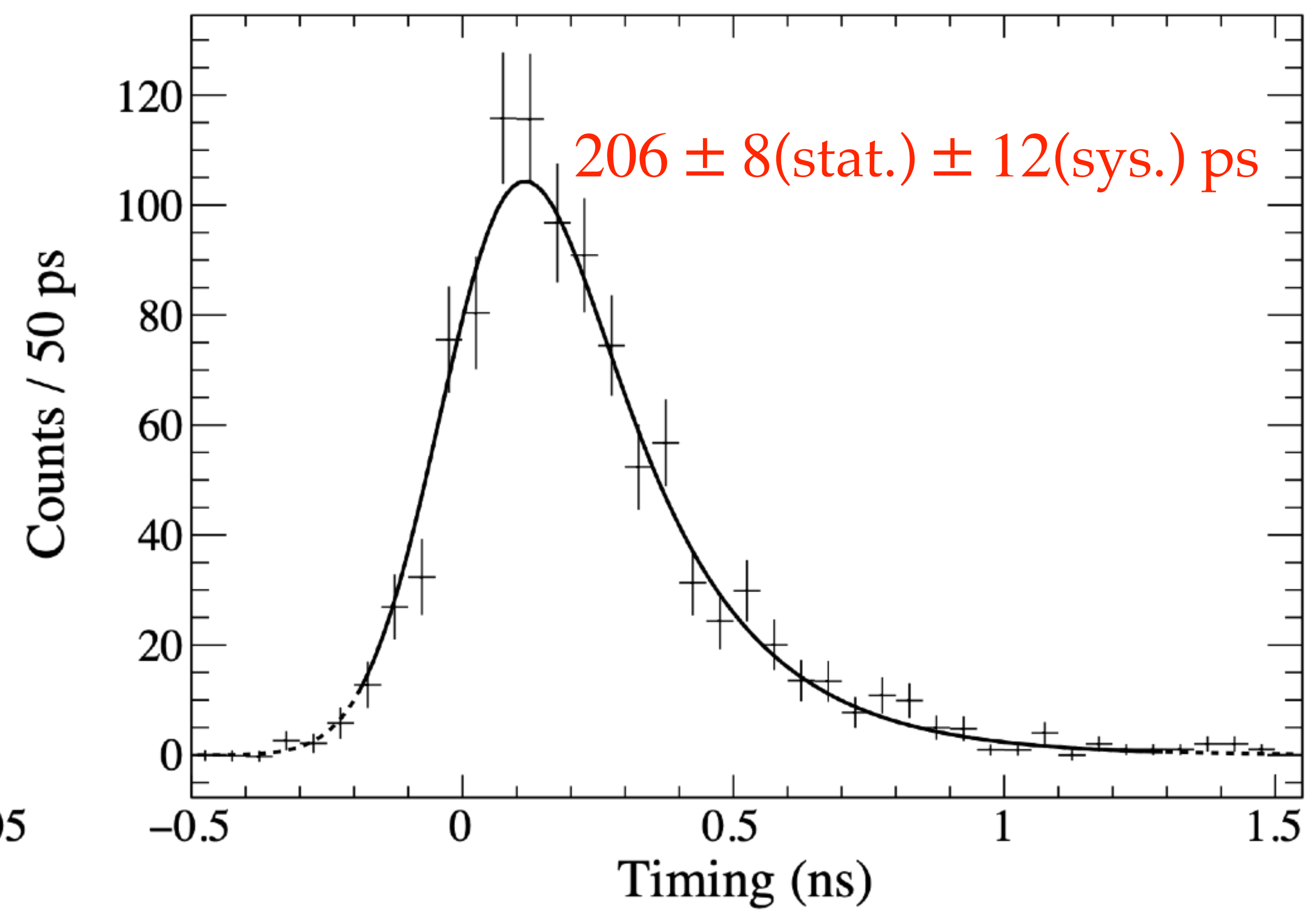
$$t_{\text{decay}} = (t_{\text{CDH}} - t_{\text{T0}}) - t_{\text{CDC}}^{\text{calc.}} - t_{\text{beam}}^{\text{calc.}}$$

$^{4}_{\Lambda}H$ lifetime as a feasibility test (J-PARC T77)

Phys. Lett. B **845**, 138128 (2023).



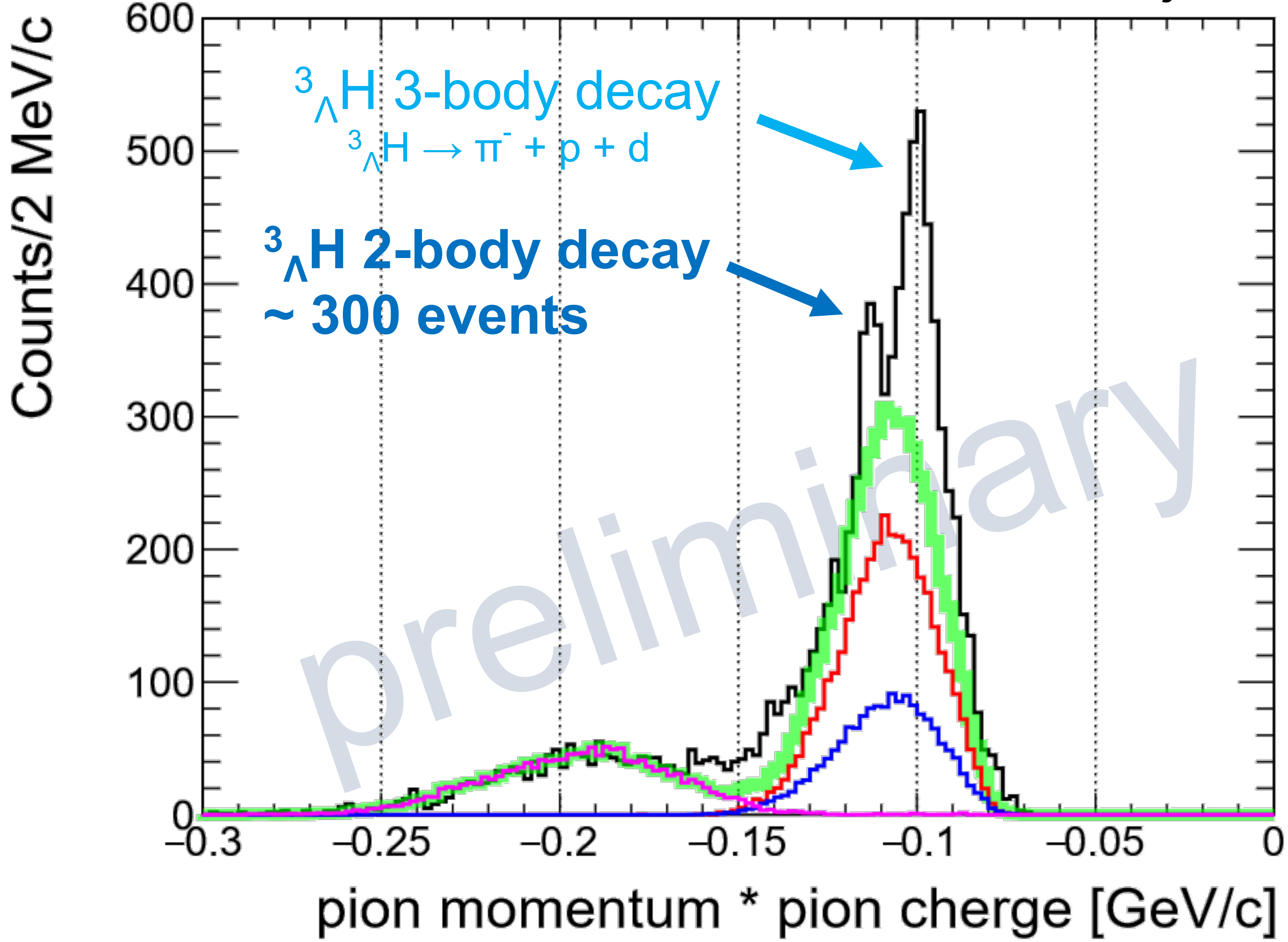




- **Successfully demonstrated the new method!**

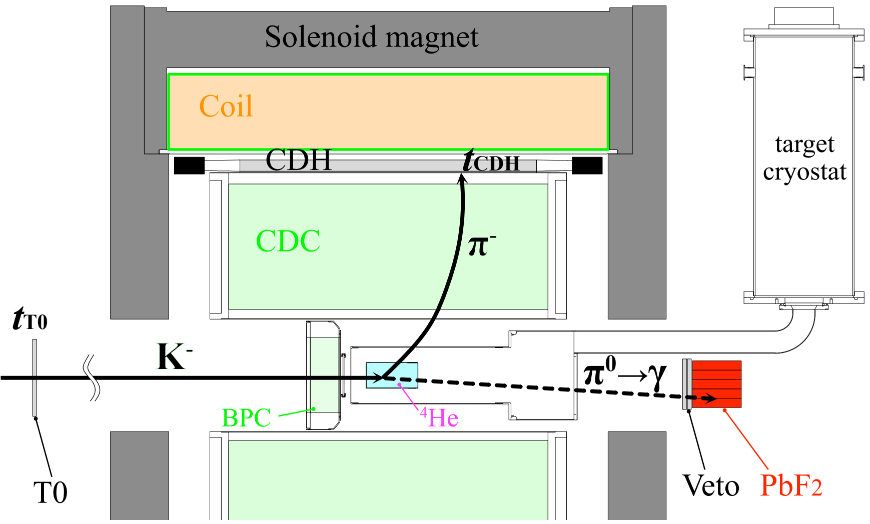
Helium-3 test data

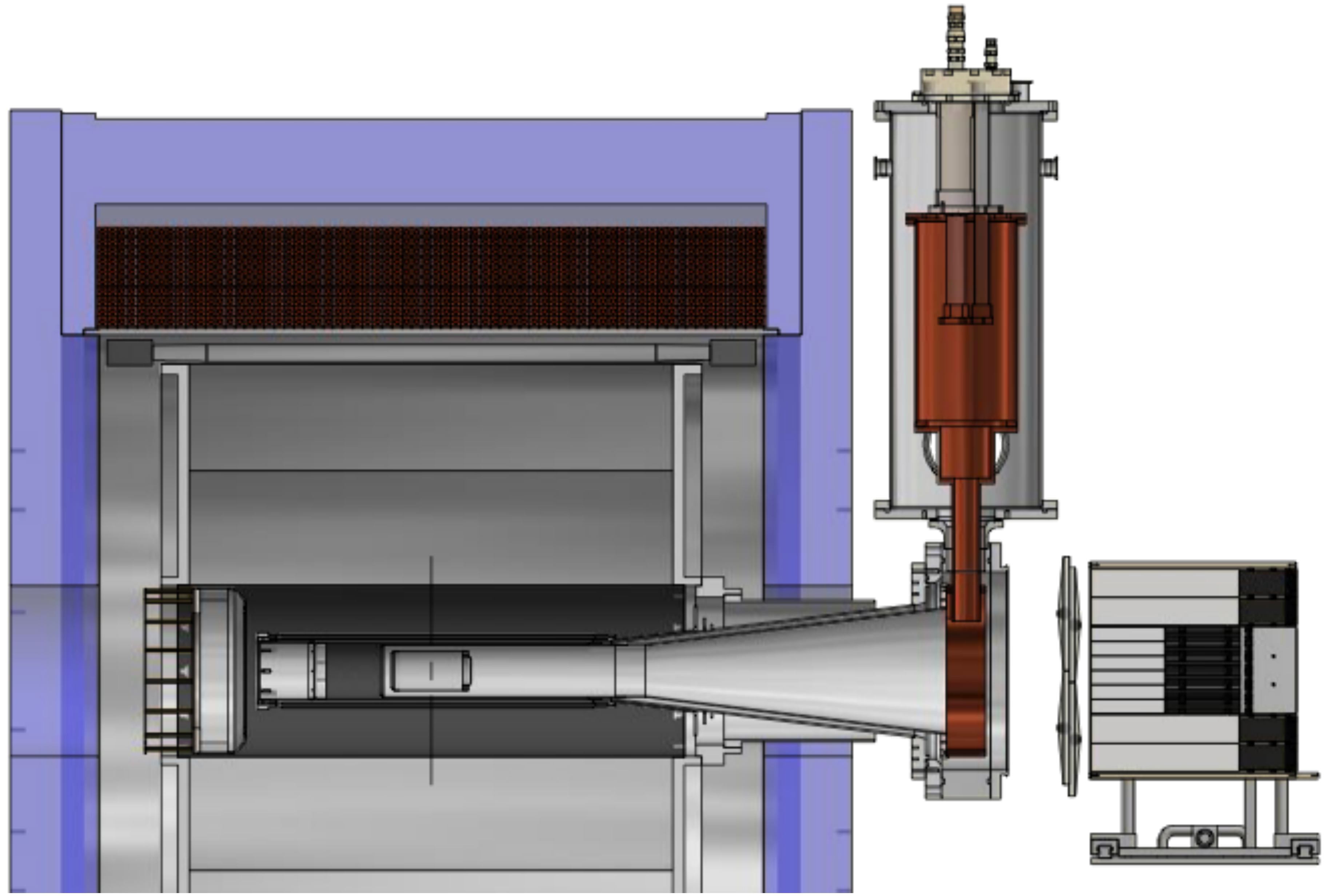
~60 kW x 4 days in 2021



- We succeeded in observing the 2-body decay peak
- 80kW x 25 days beam-time to acquire >1000 events will be scheduled sometime from April to June, 2024.

Improvement in setup

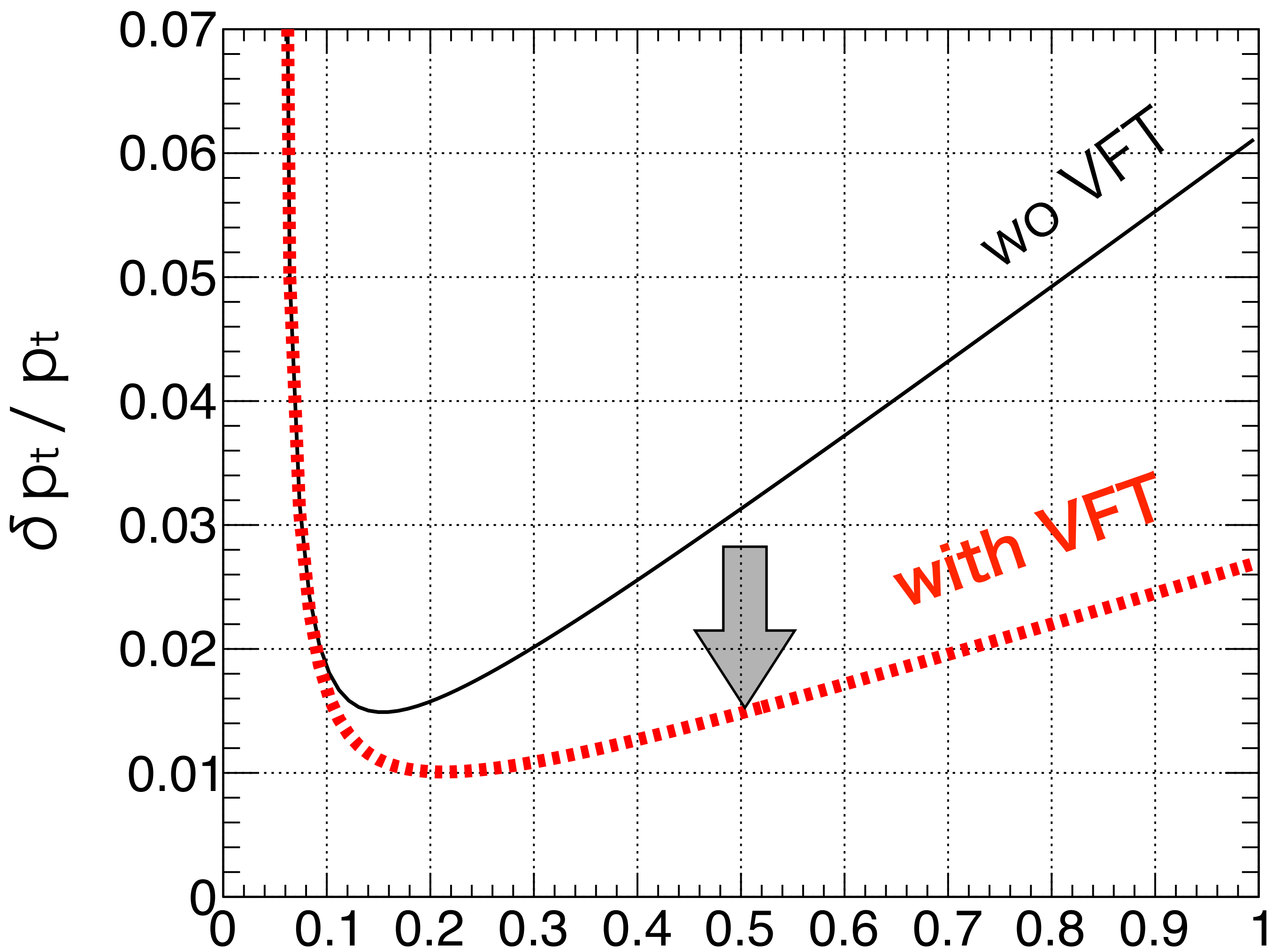




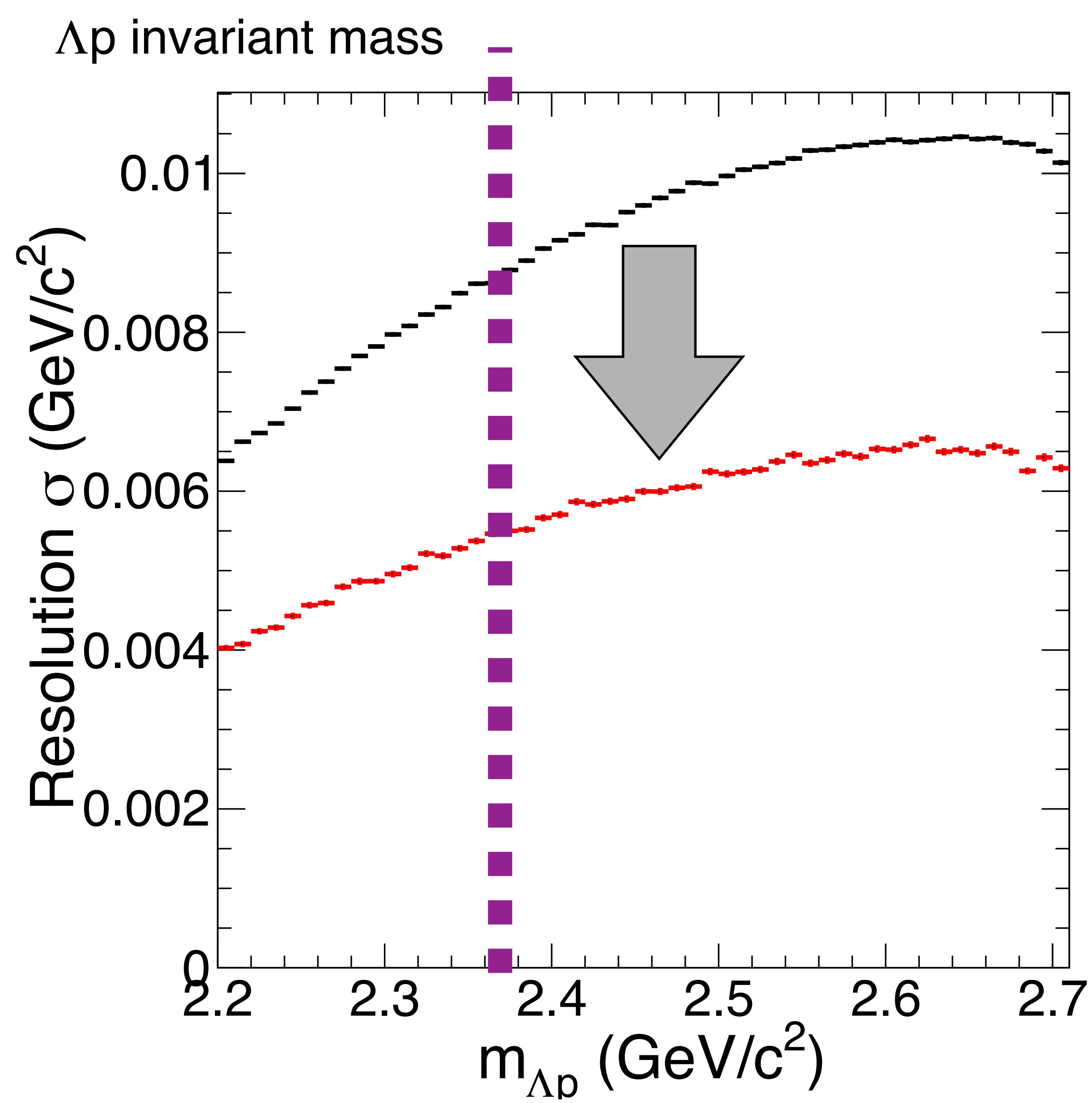
- Forward Calorimeter is enlarged with additional PbG crystals
- Newly install VFT (vertex fiber tracker)
- The target system modified accordingly

Improvement in resolution with VFT

Single track resolution



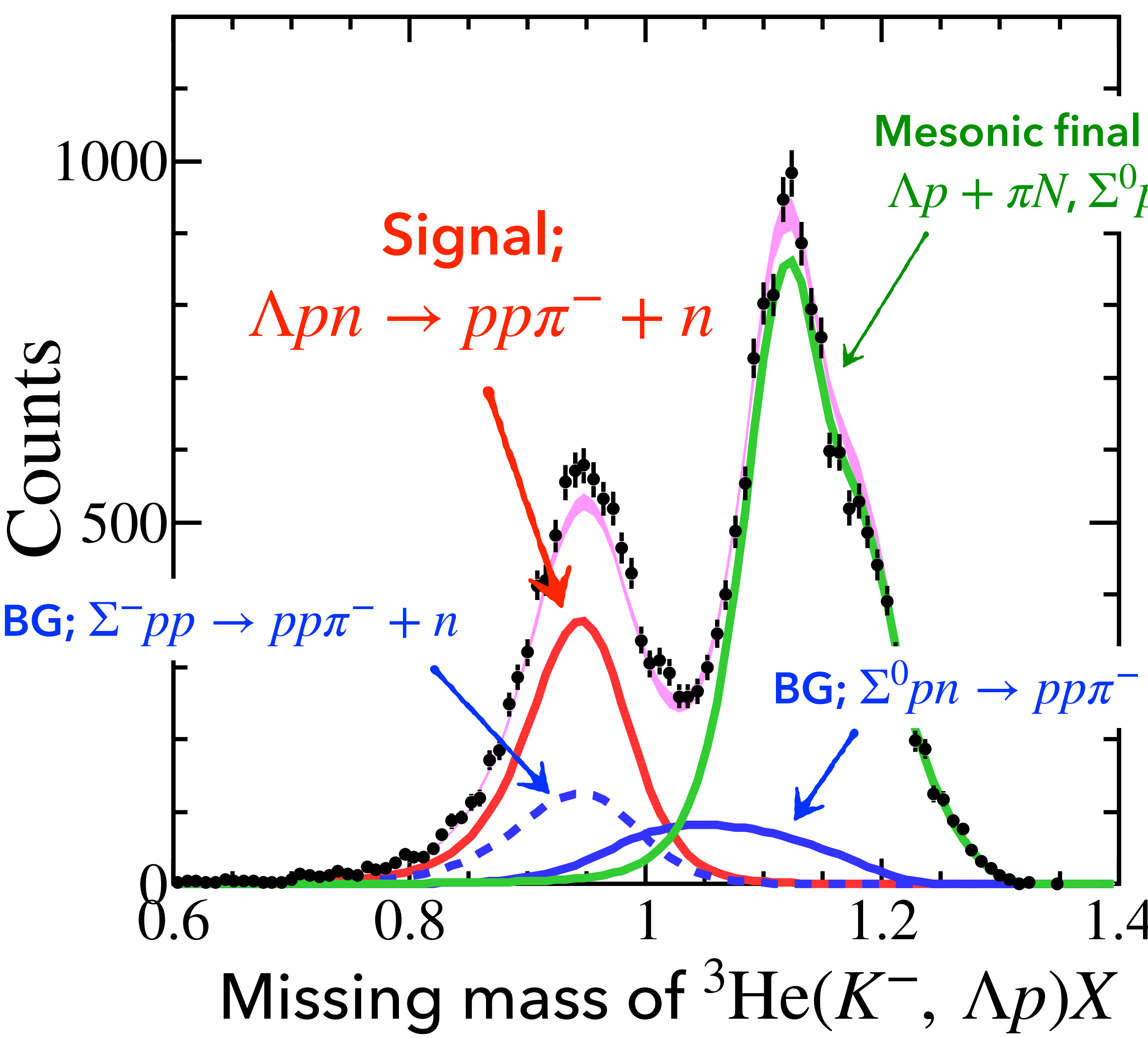
Invariant mass resolution



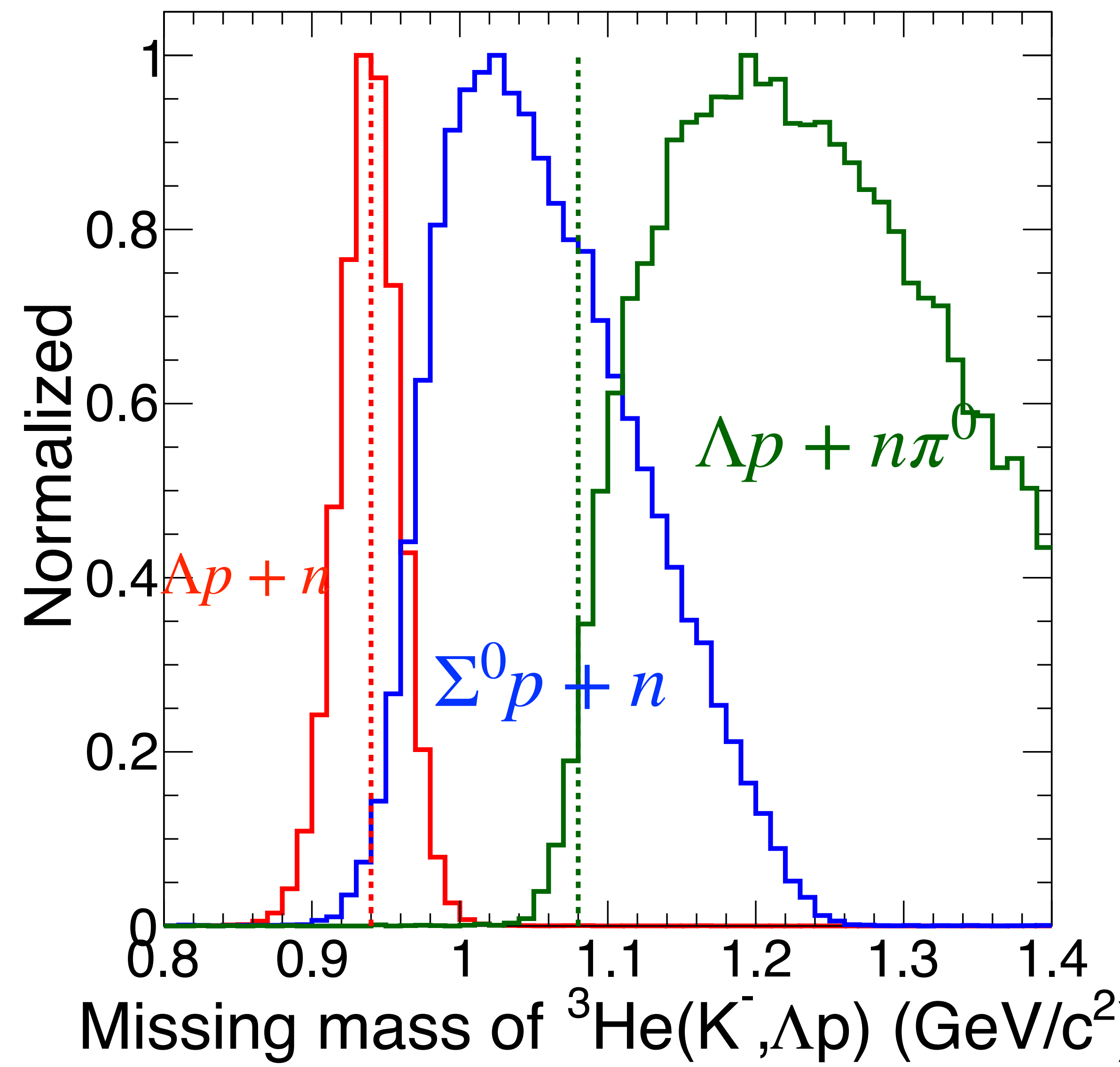
- Z-vertex resolution ~7mm → ~1mm
- x2 better momentum & mass resolution

Λ/Σ^0 separation might be possible

J-PARC E15 data



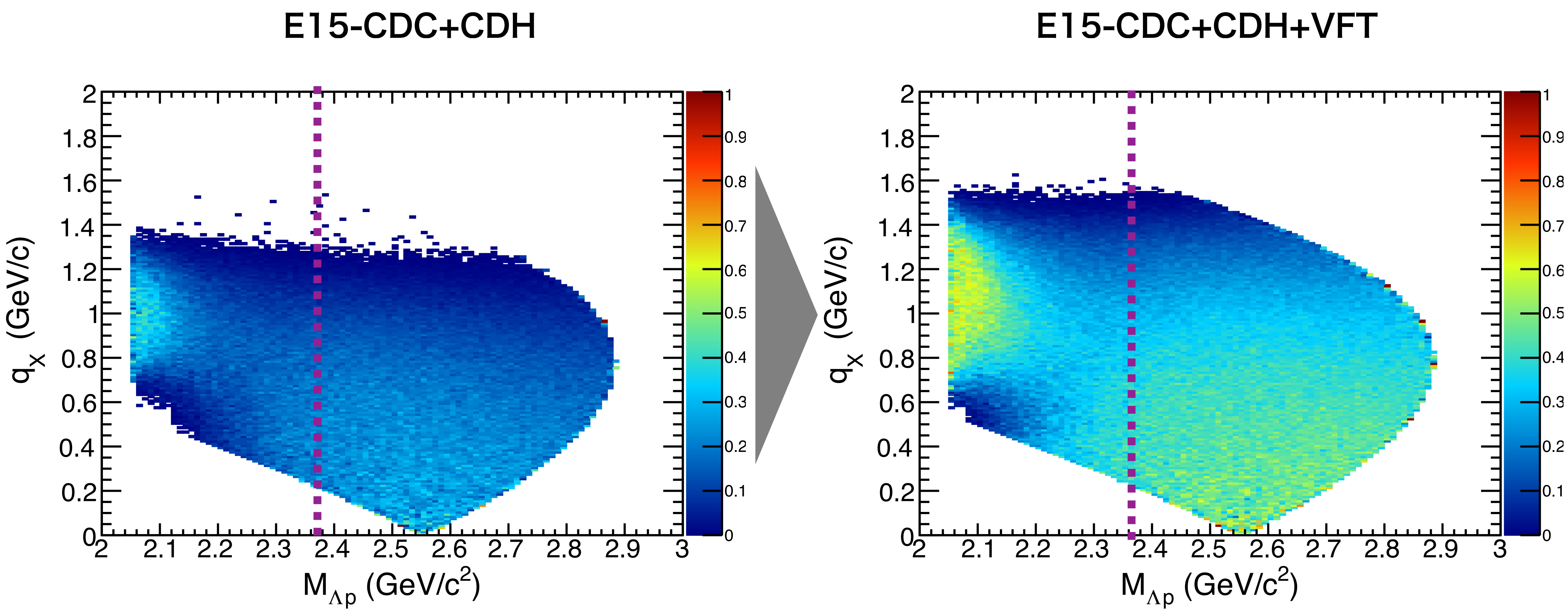
MC with VFT



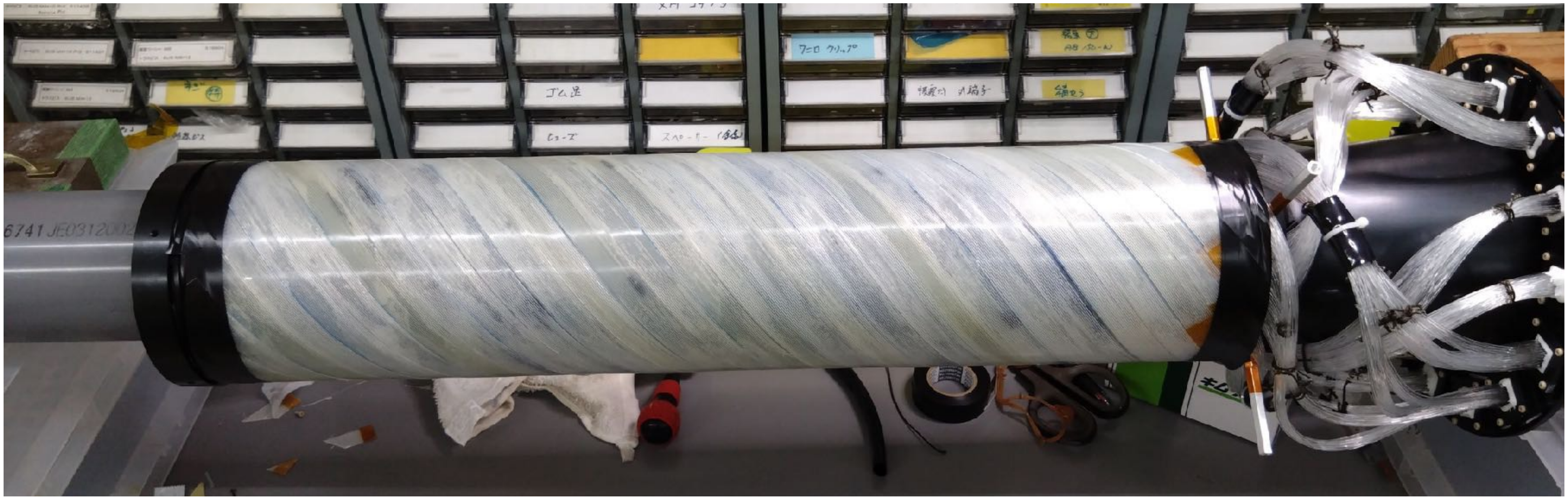
- **Resotluion would be improved ~40 MeV → ~ 25 MeV**
- **We expect different structure in $m_{\Sigma^0 d}$ (I=1) because $\bar{K}NNN \to \Lambda d$ (I=0)**

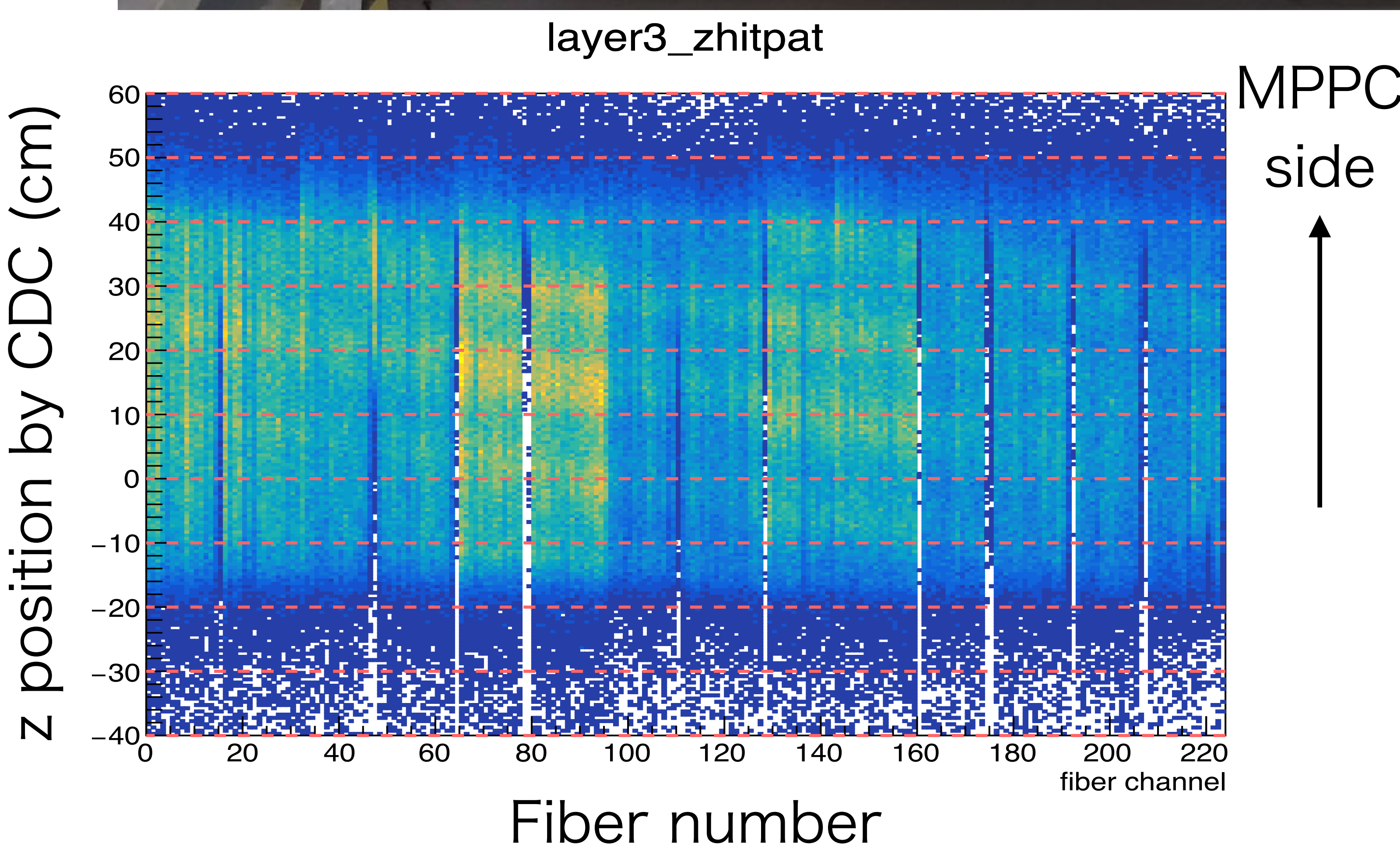
Larger acceptance using “short tracks”

only require to reach the CDC 8th layer



VFT status: many damaged fibers…

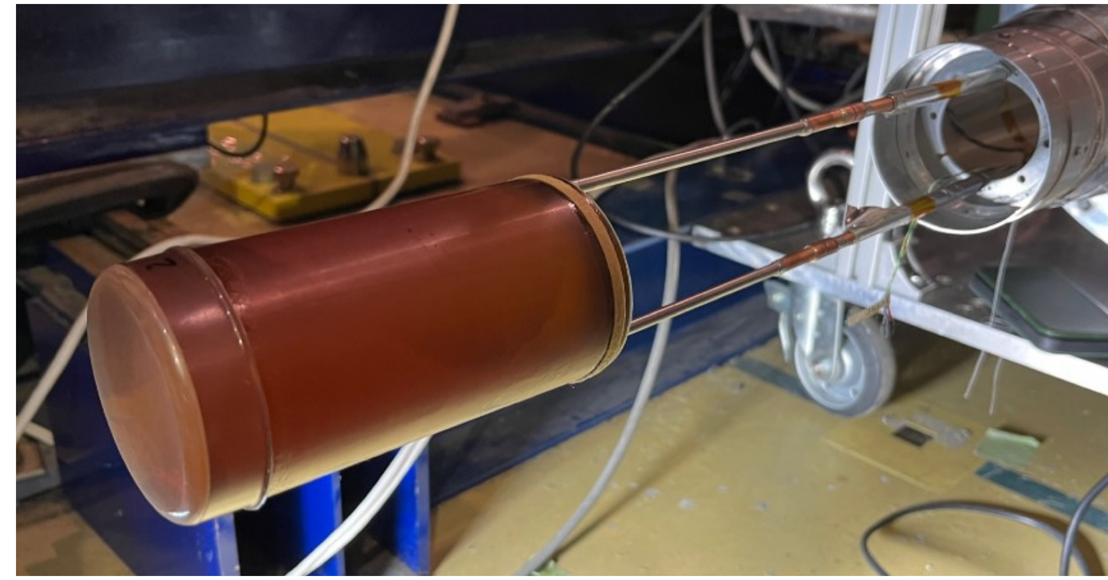


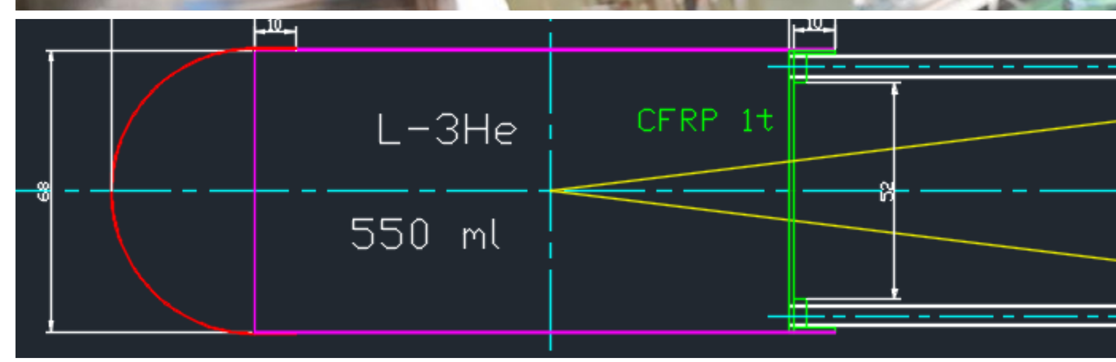


- UU'VV' configuration
- 896 channels in total
- Readout by 8x8 MPPC array
- CIRASAME: ASIC+FPGA board

- **Studying how to fix them…**

Target status

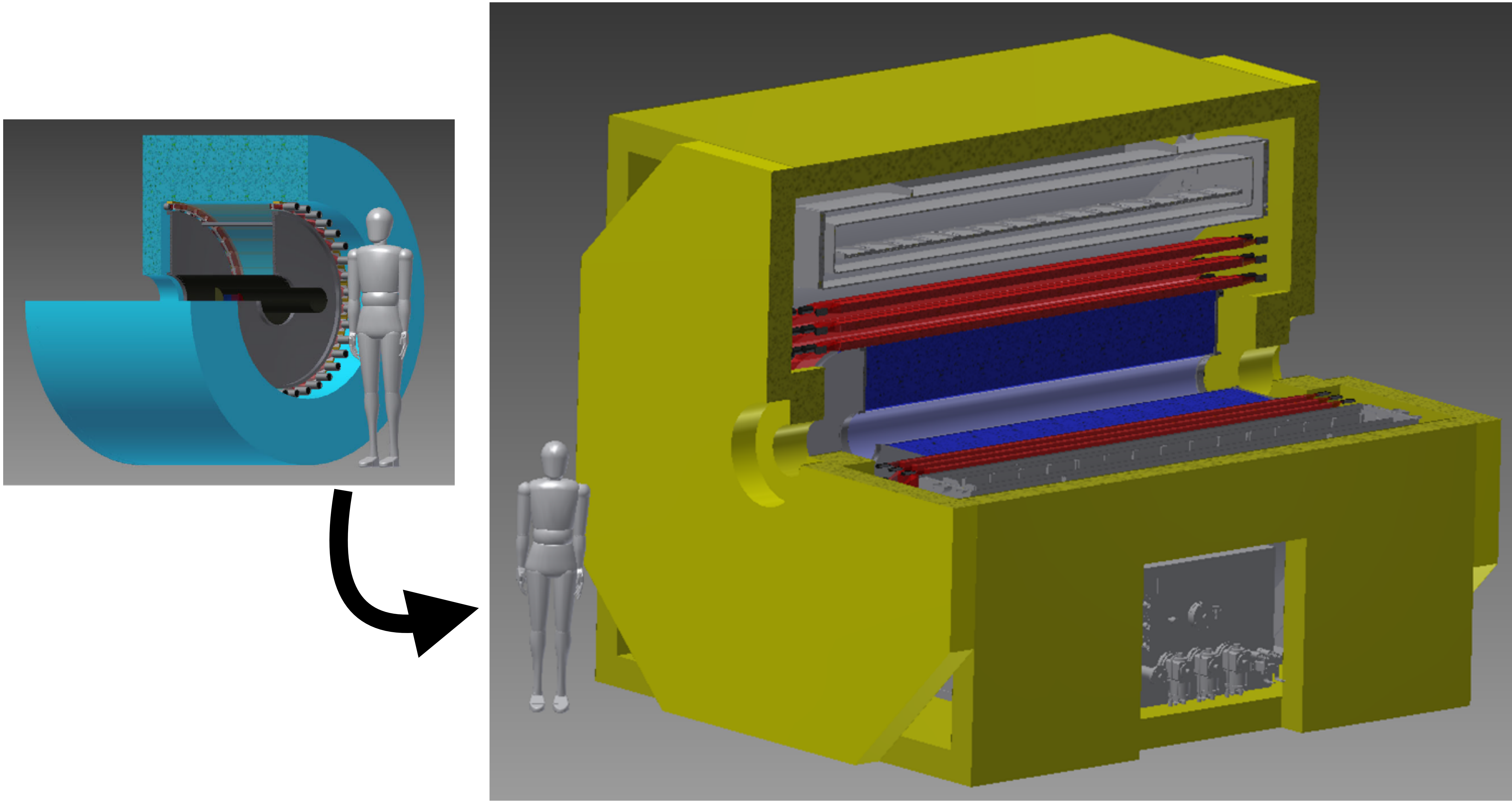




- H2/D2/3He/4He with the same system using a pulse tube cryocooler
- Target cell with less material.

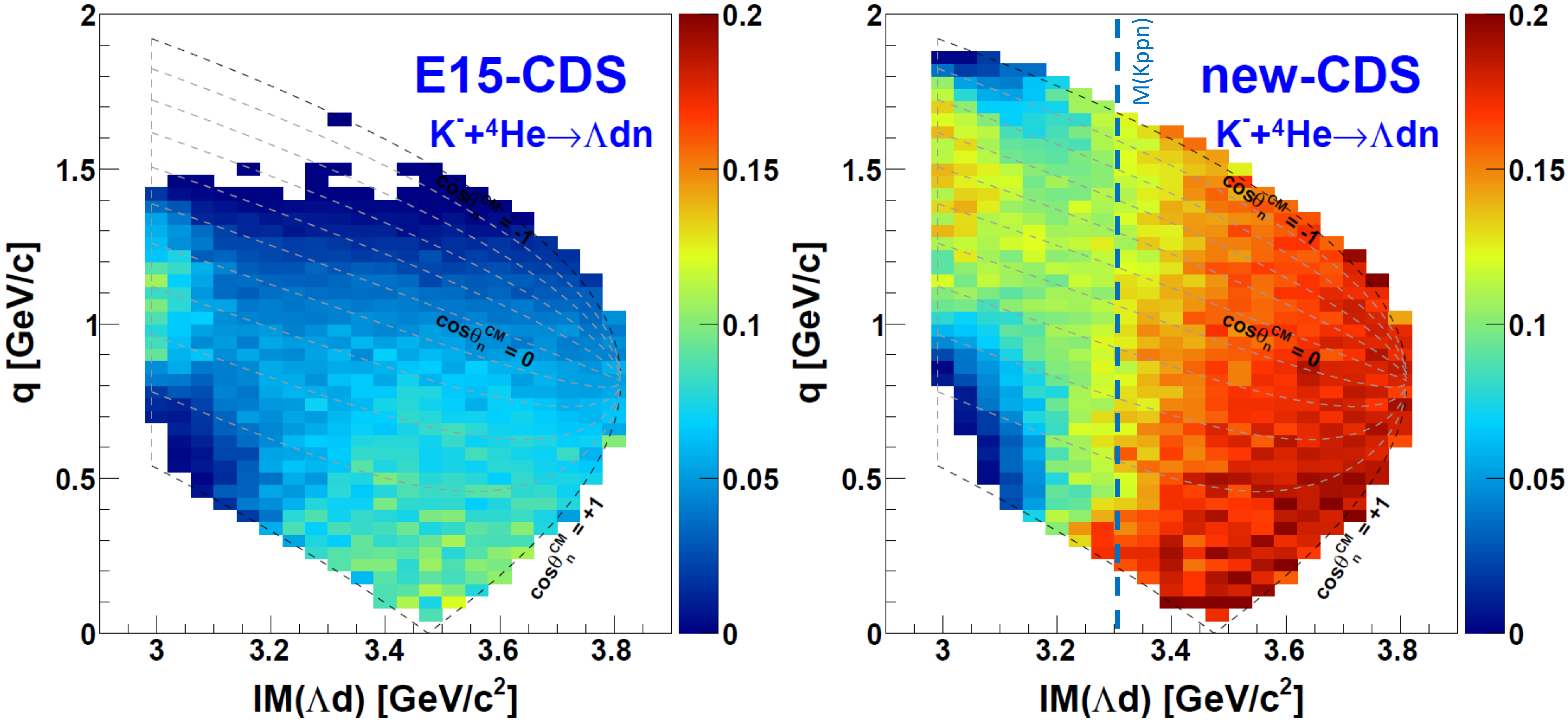
Further experiment on $\bar{K}NNN$ (J-PARC E80)

J-PARC E80 with a new spectrometer



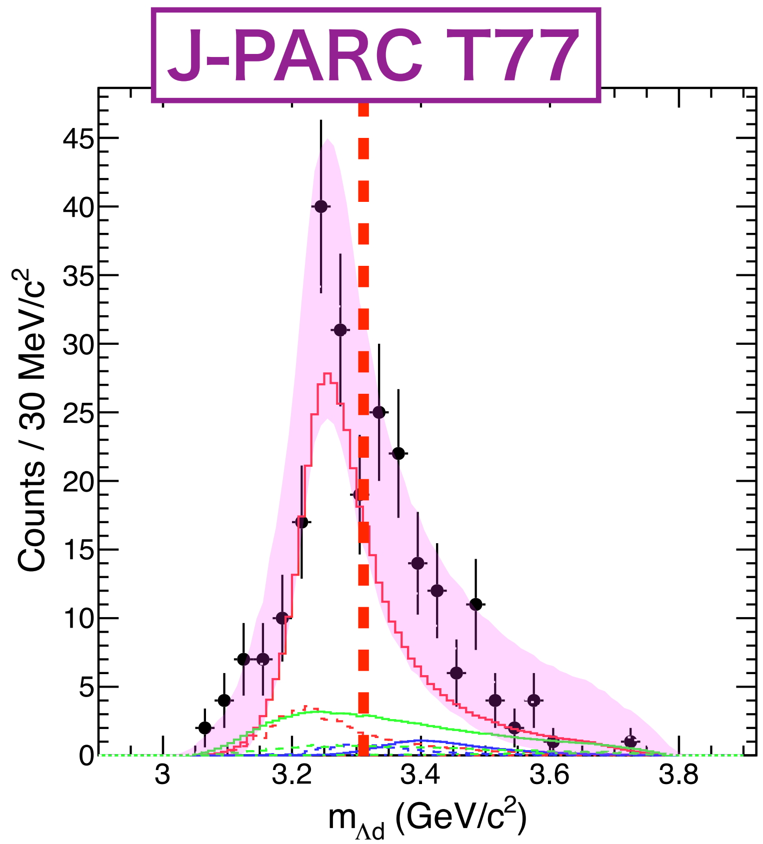
- x3 longer CDC: **solid angle 59%→93%**
- 3-layer barrel NC: **neutron efficiency 3%→15%**

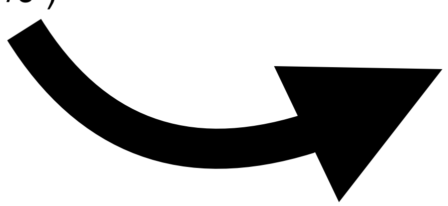
Acceptance for $K^- + {}^4\mathrm{He} \rightarrow \Lambda d + n$



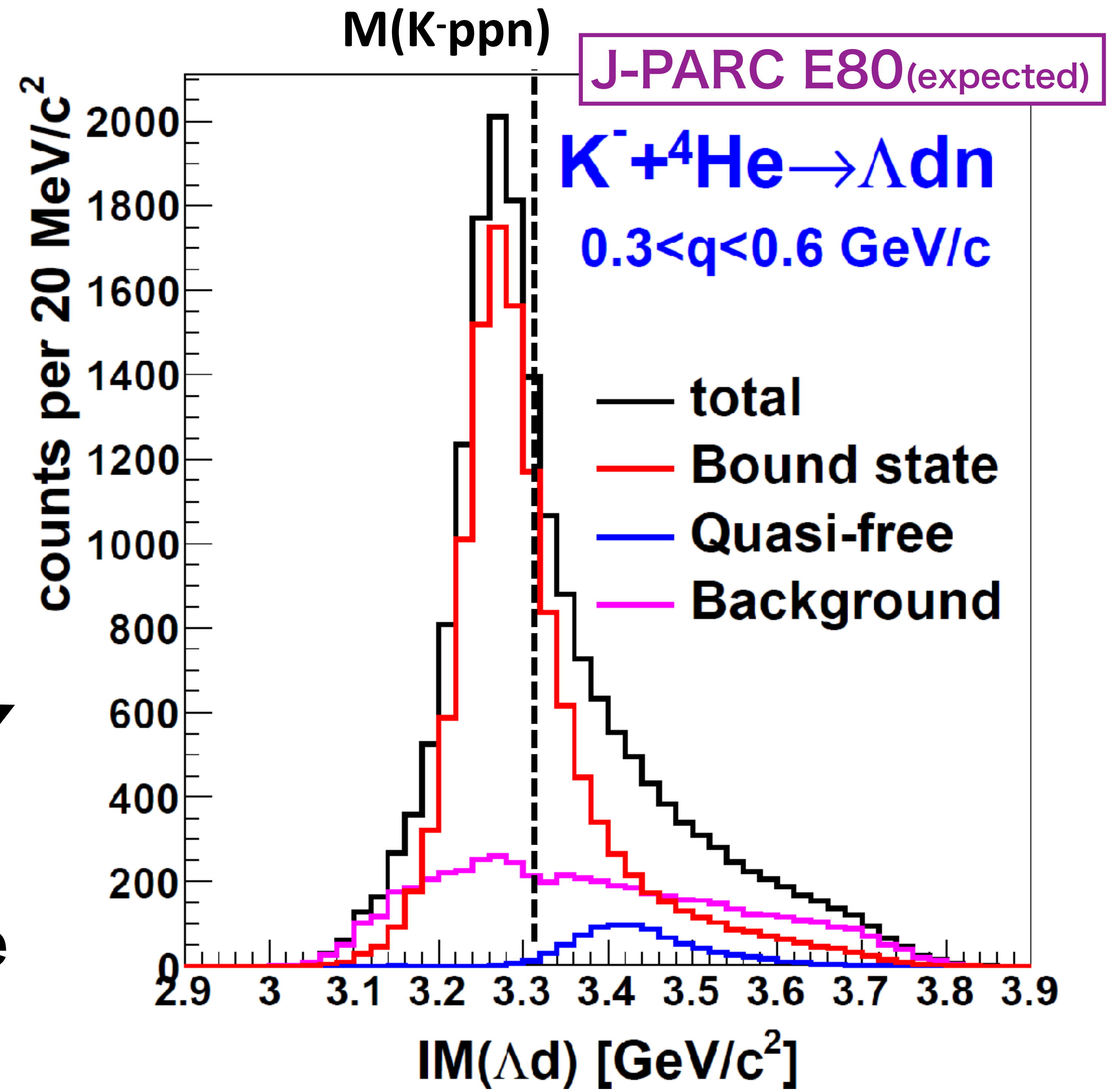
- large kinematical-region coverage & x2 acceptance

Expected spectrum @ 90 kW x 3 weeks



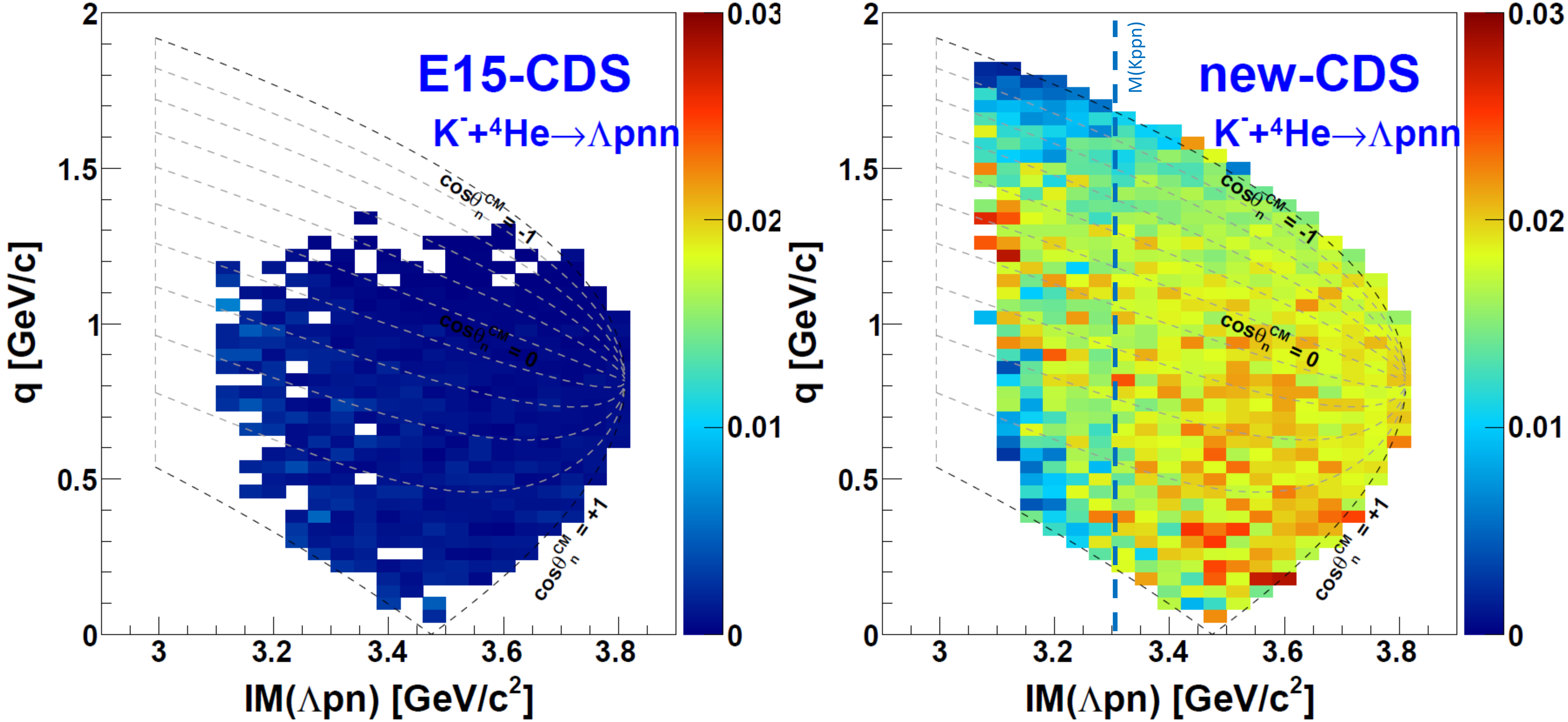


x20 more kaons
x2 larger acceptance



- We expect x40 Λdn events

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



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

Expected spectra

@ 3 weeks, 90kW

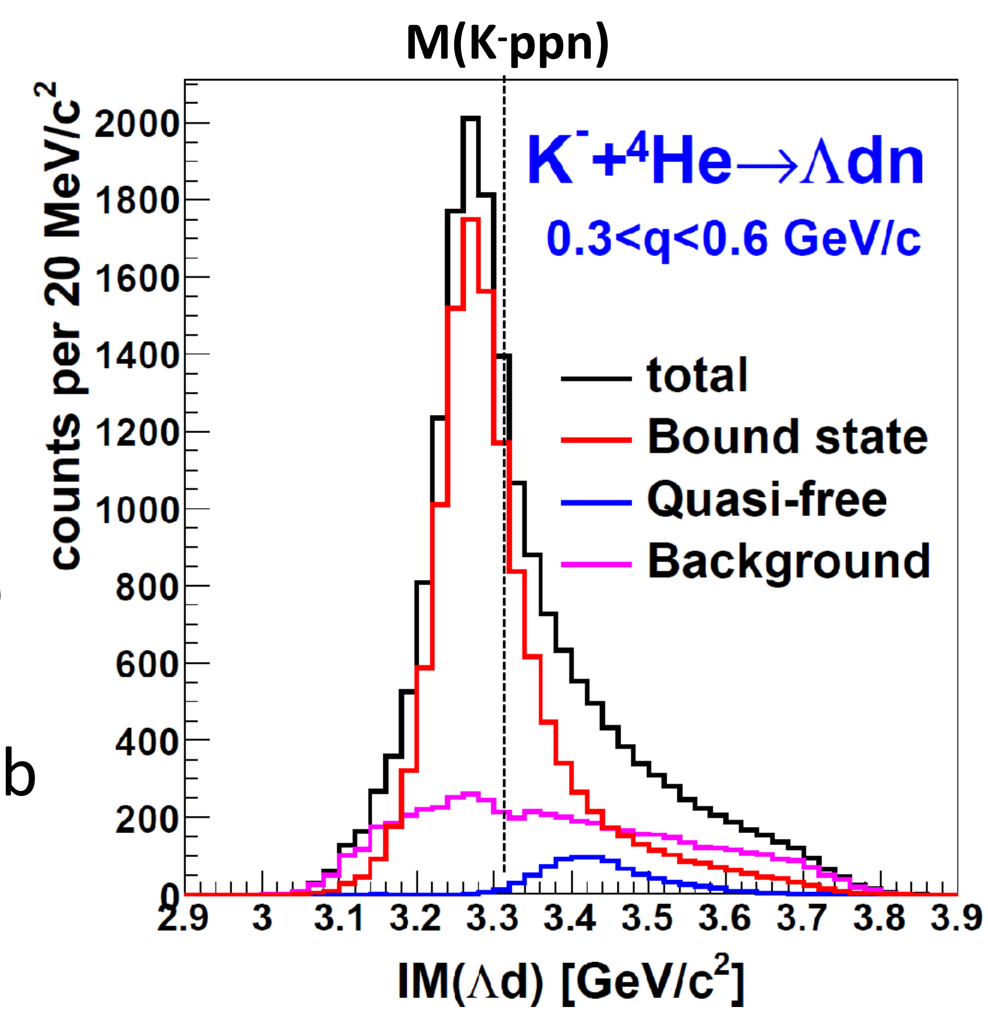
B_{Kppn} ~ 40 MeV

Γ_{Kppn} ~ 100 MeV

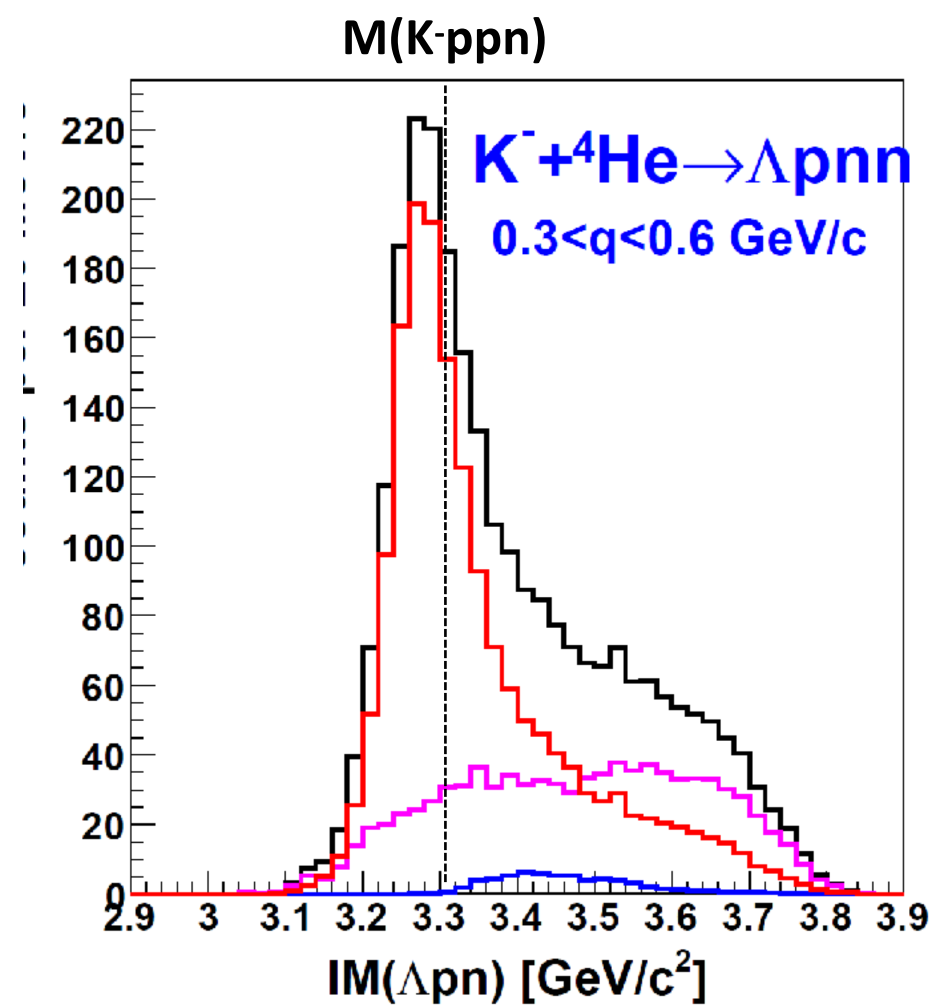
Q_{kppn} ~ 400 MeV/c

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

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



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

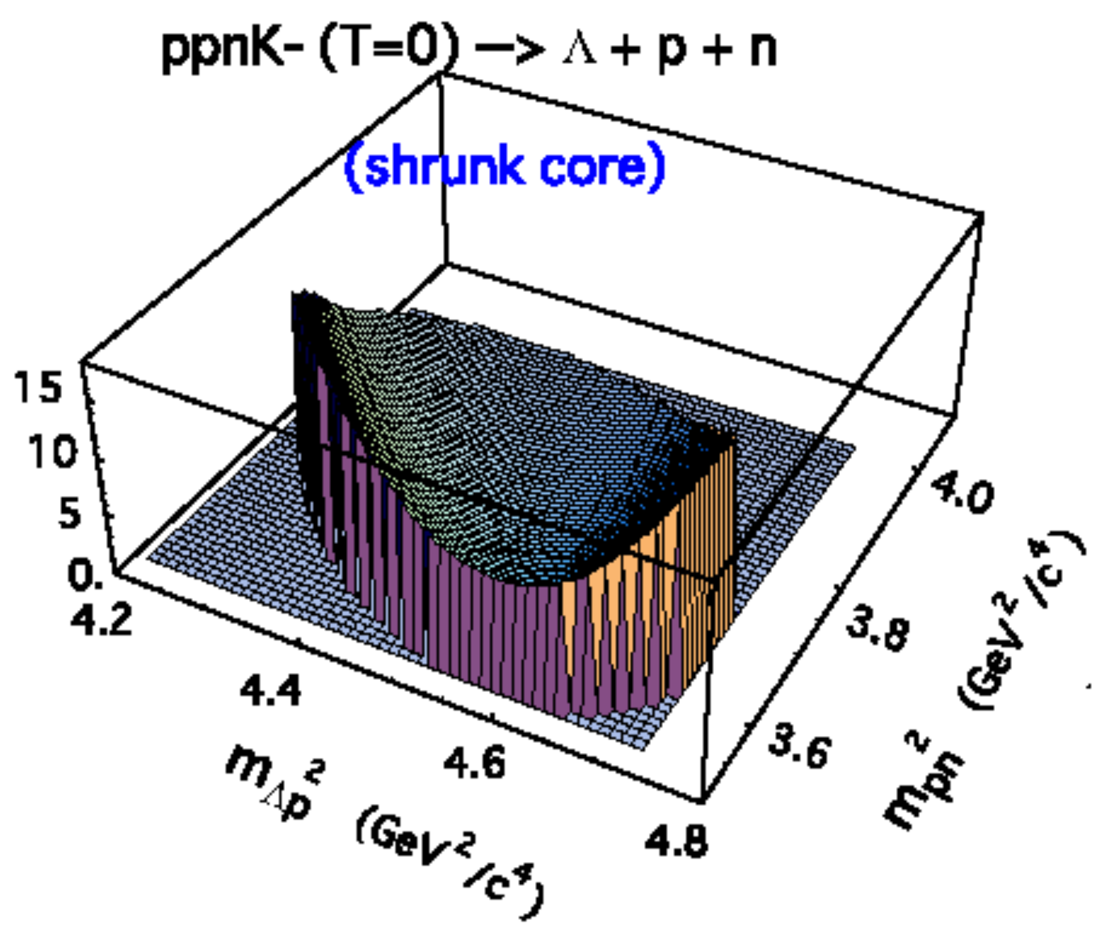


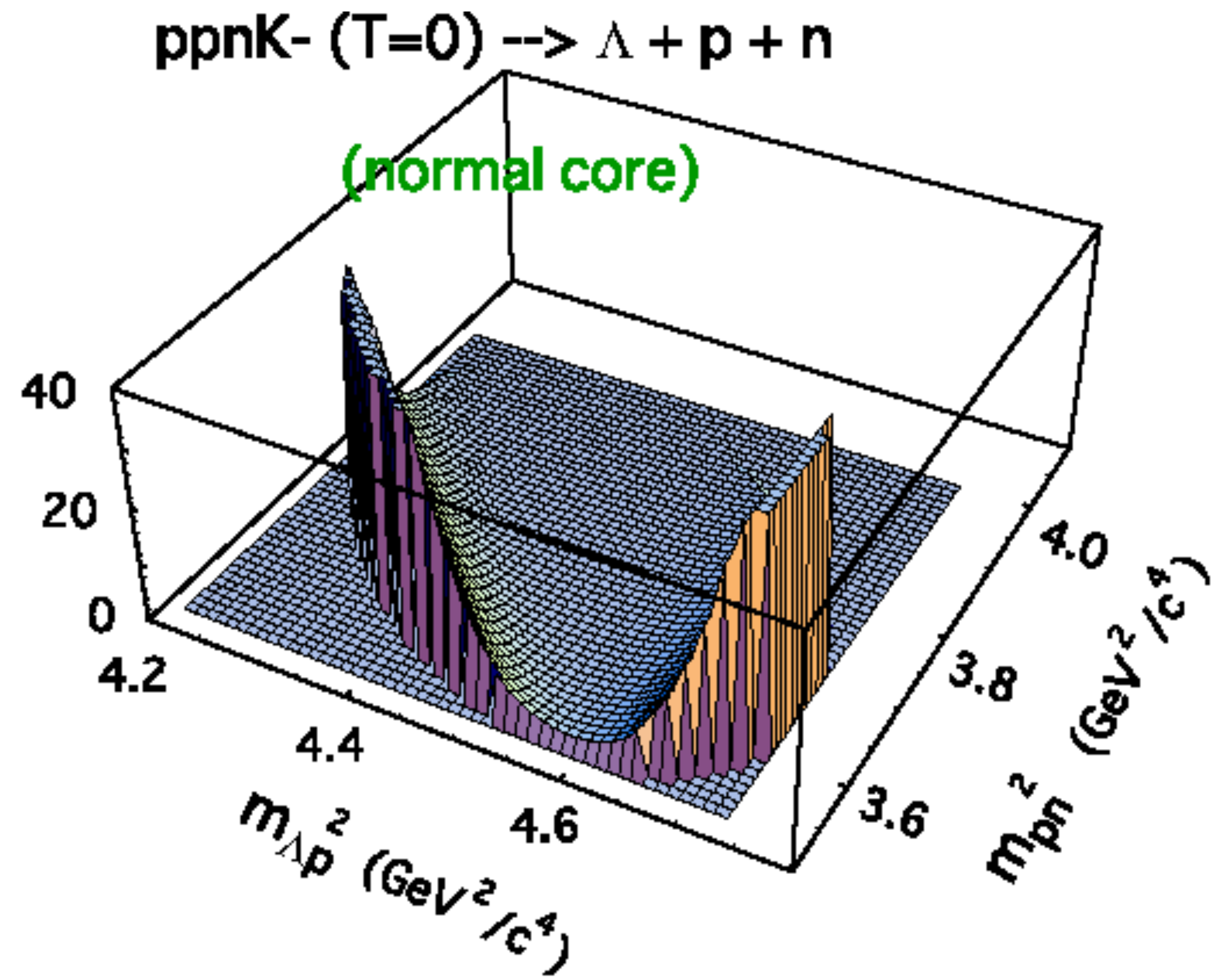
✓ Clear peak would be observed for both modes

✓ Peak positions etc. should be carefully compared

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

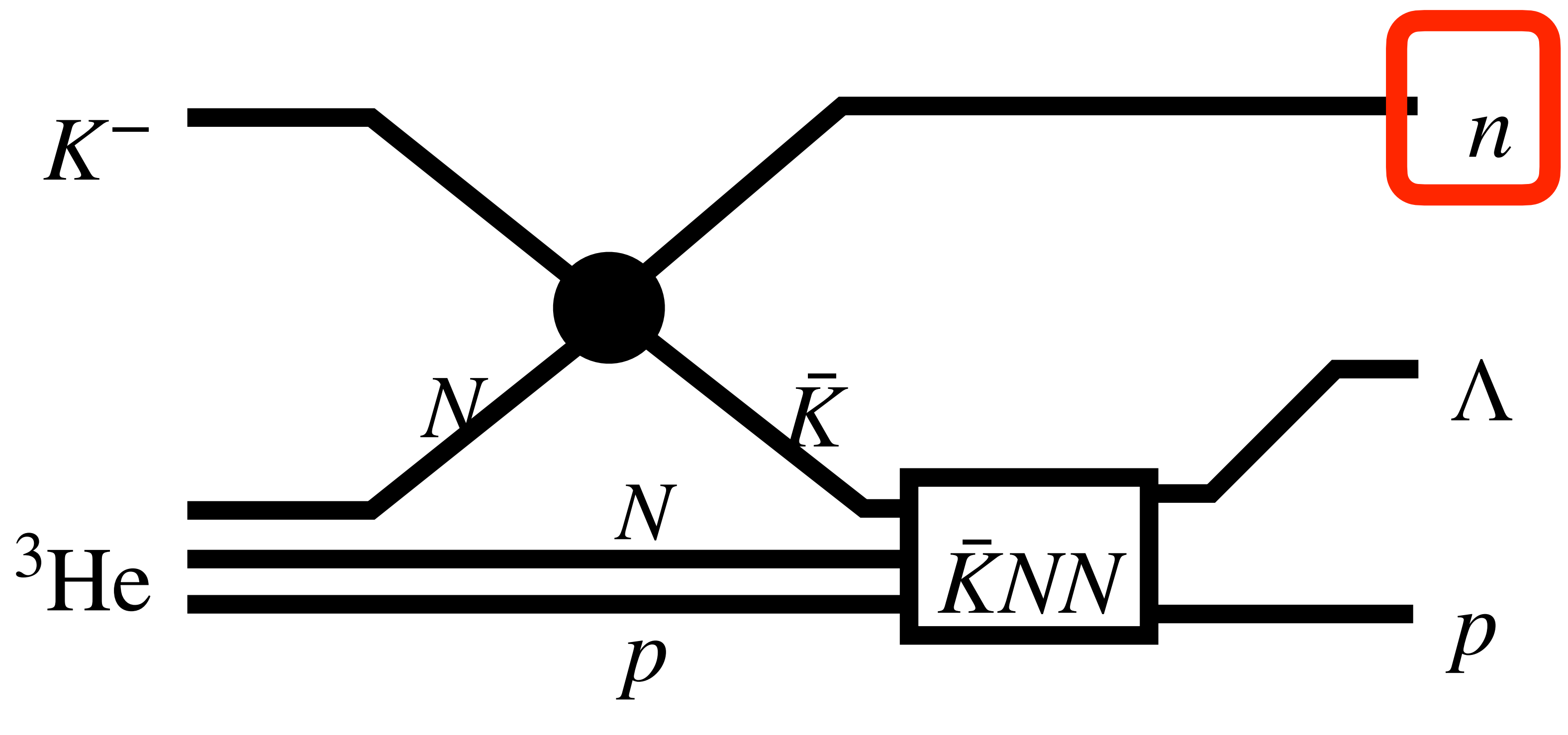
P. Kienle et al., Physics Letters B 632 (2006) 187–191



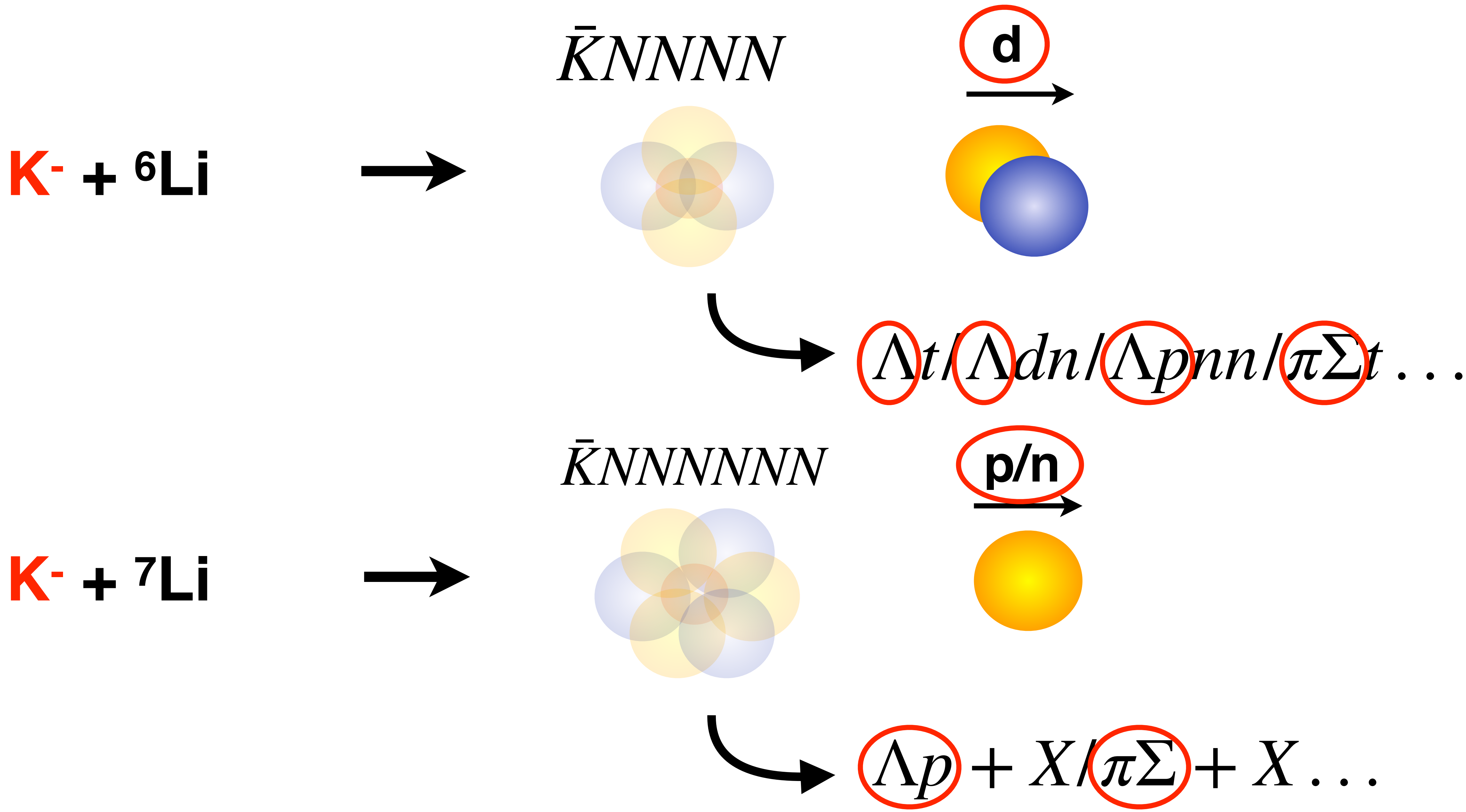


- If $\bar{K}NNN \to \Lambda pn$ is 2NA process, spectator momentum would reflect the system size.
- However, we cannot detect low-momentum protons…

Forward nucleon detection



Heviear system



- 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**

Predictions

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

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

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

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

	Kyoto Type I	Kyoto Type II	AY
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 $J^\pi = 0^-$.

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

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

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

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

	Kyoto Type I	Kyoto Type II	AY
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 $J^\pi = 0^-$.

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

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

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

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

	Kyoto Type I	Kyoto Type II	AY
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 $J^\pi = 1^-$.

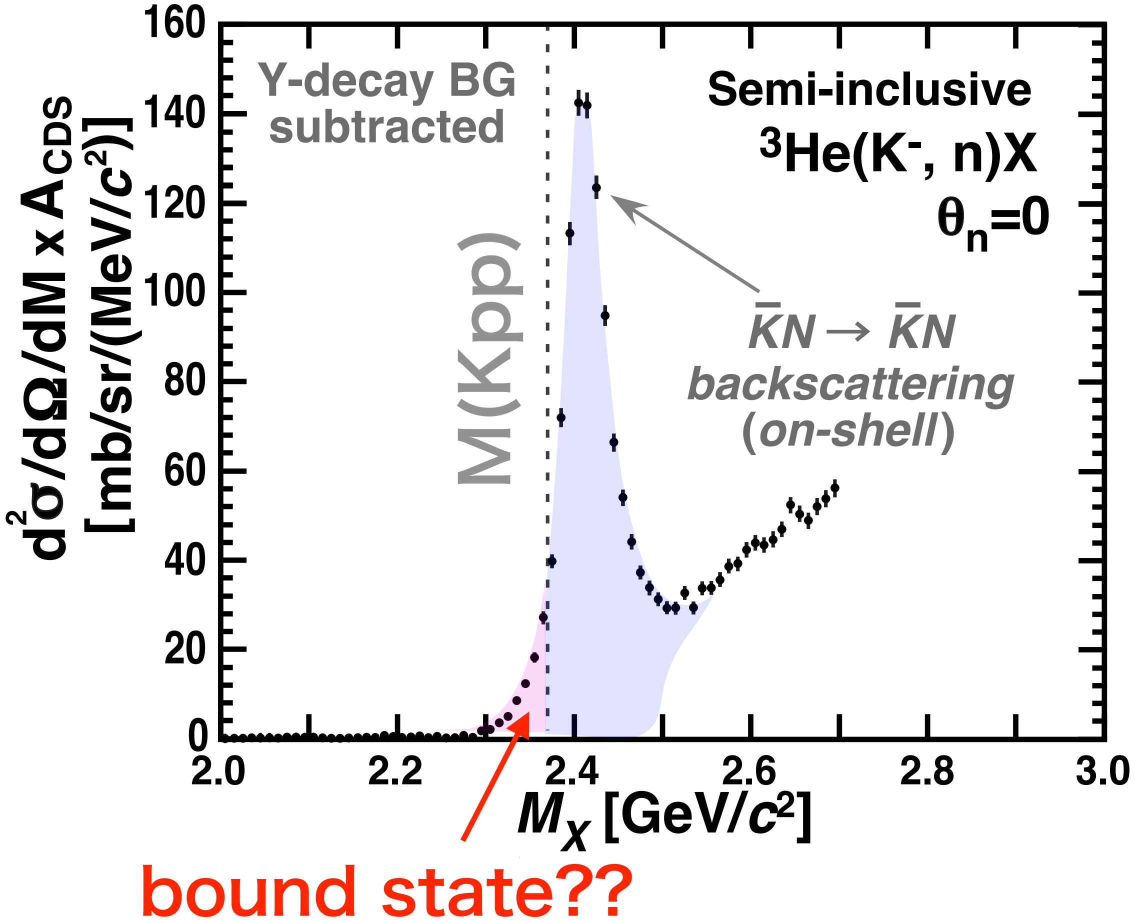
${}^6_{\bar{K}}\mathrm{He}(1^-)$

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

(K⁻, N) at forward angle

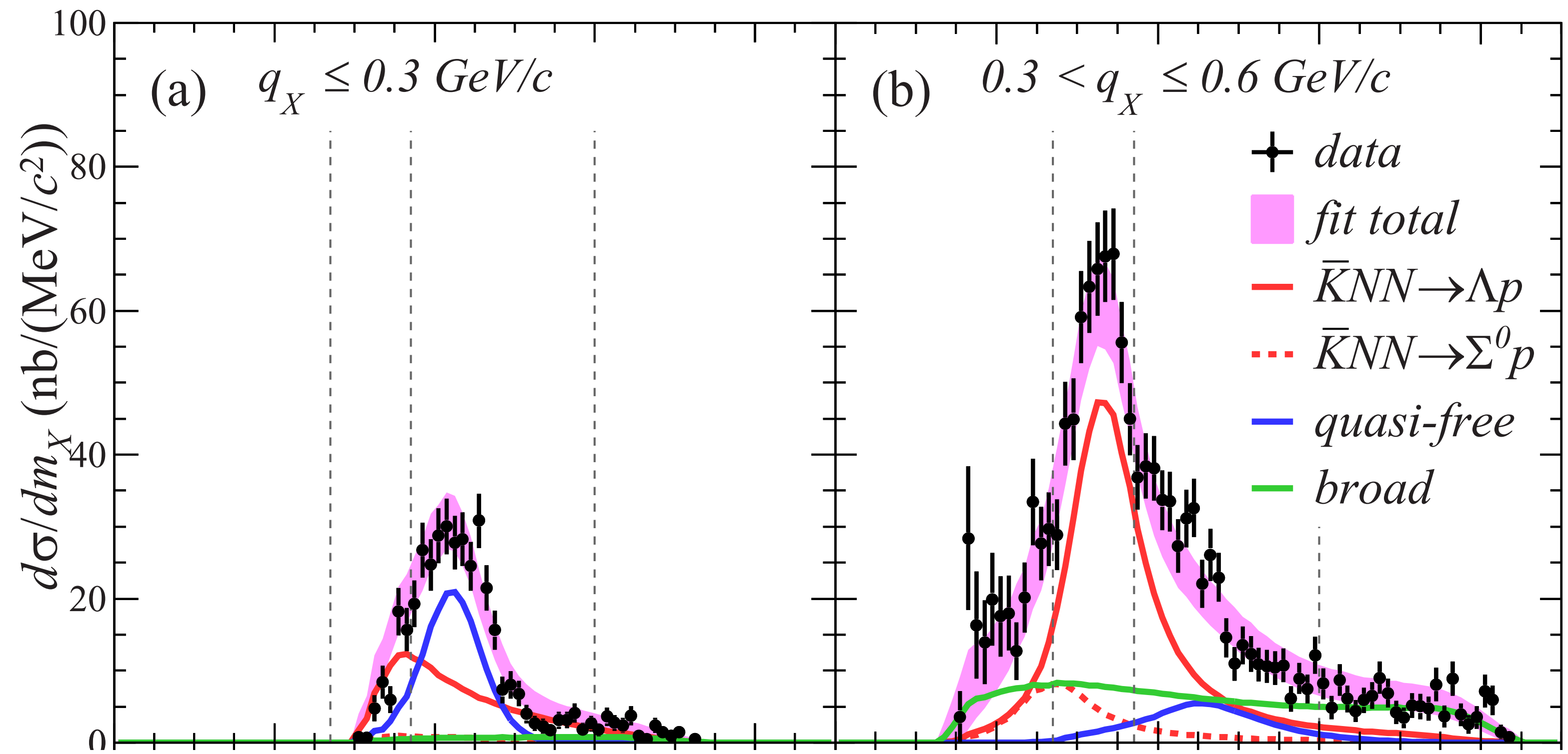
E15 semi-inclusive

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



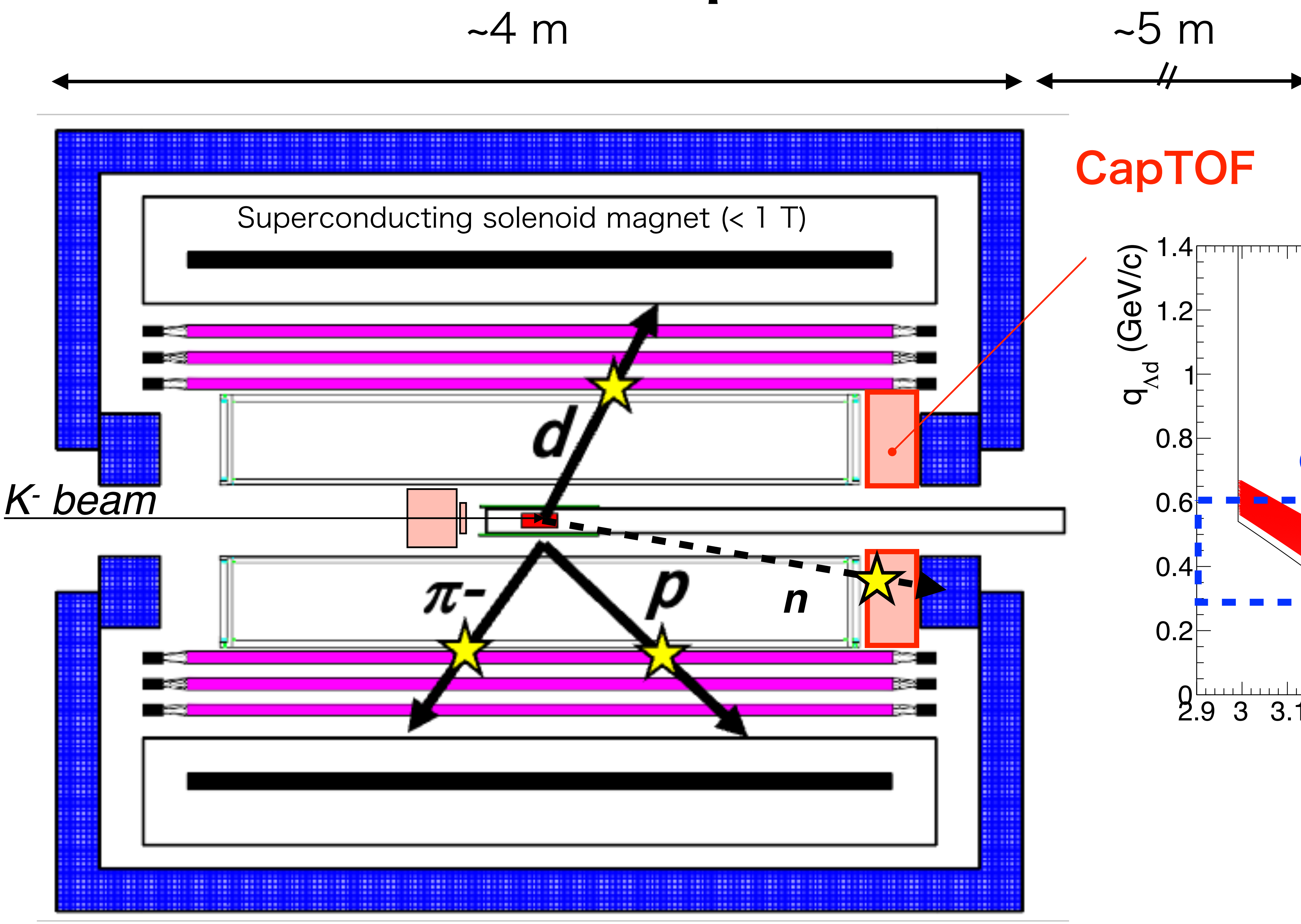
E15 exclusive (Λpn)

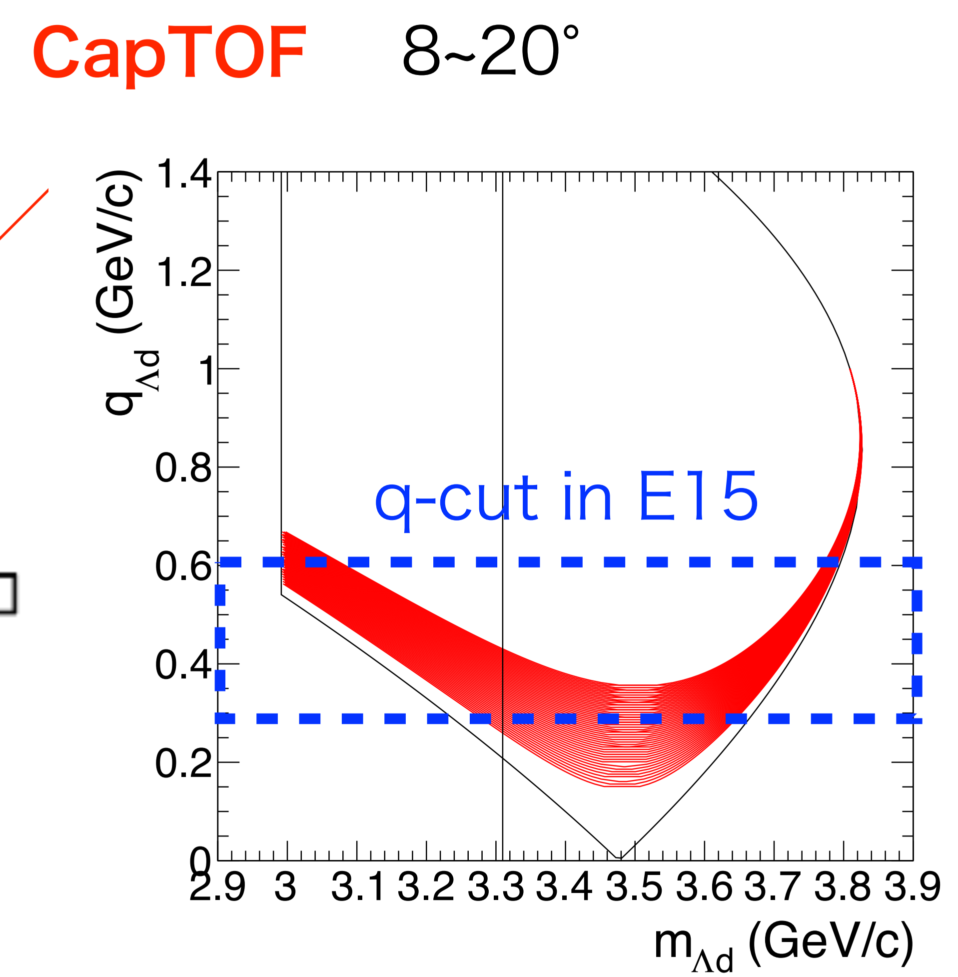
Phys.Rev.C102,044002(2020)



- 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

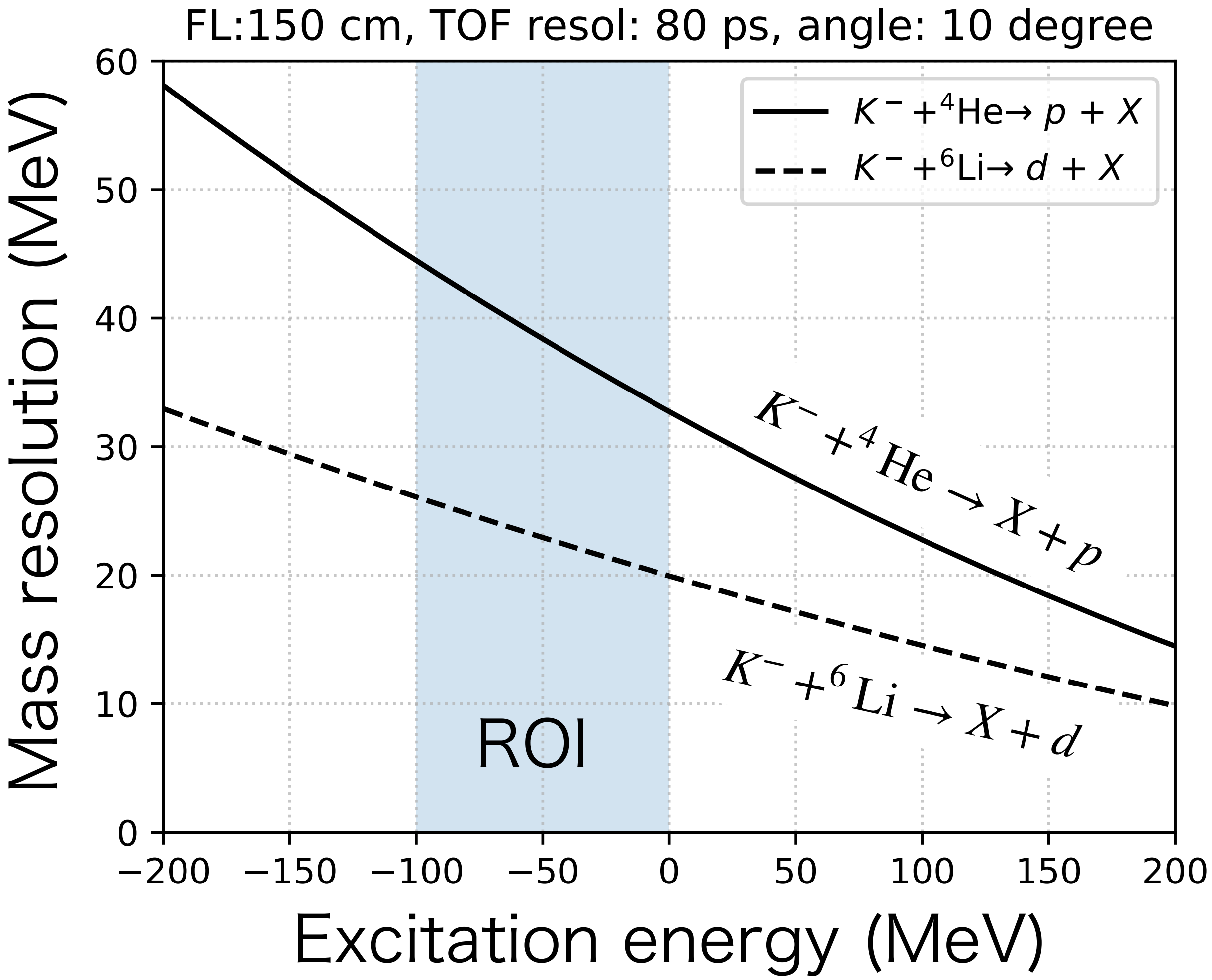


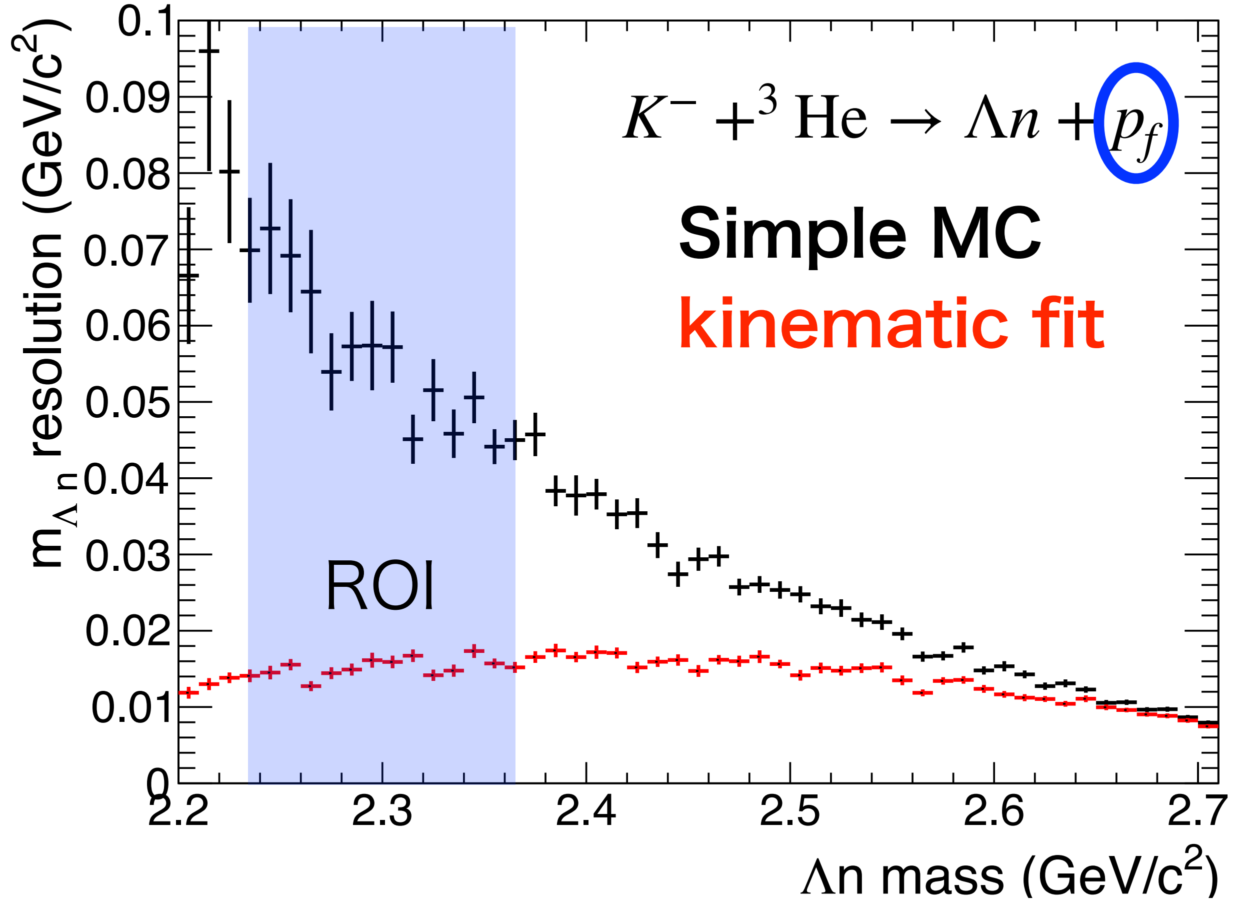


- **large-q region** would be better to isolate the bound state.
- **Wide angular acceptance** to study q-dependence.

Expected resolution

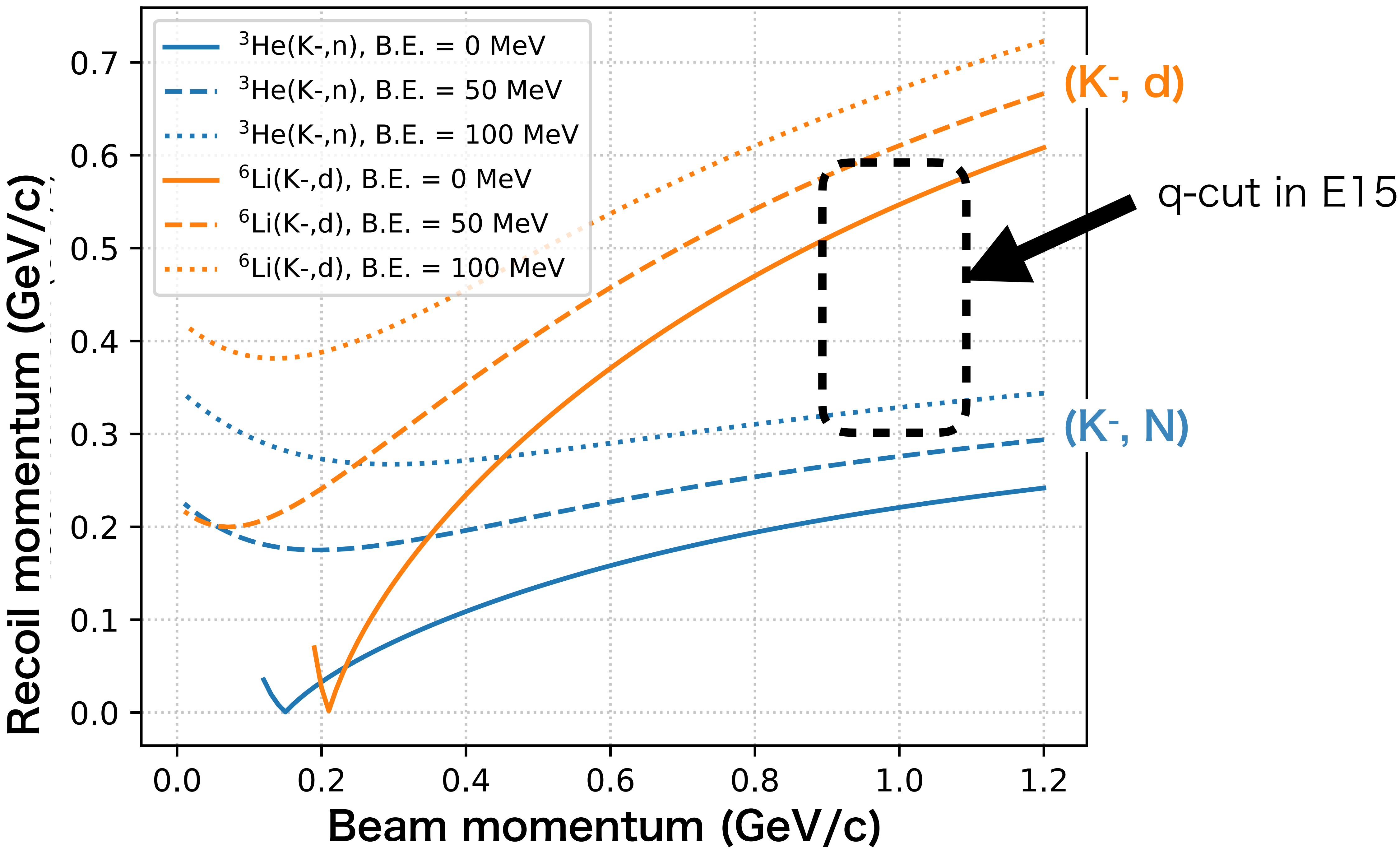
	L_{TOF} (m)	time resolution (ps)	mass resolution (MeV)
E15 NC	14	150	10
Cap	2	80	**40**
Forward	7	150	20





- 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

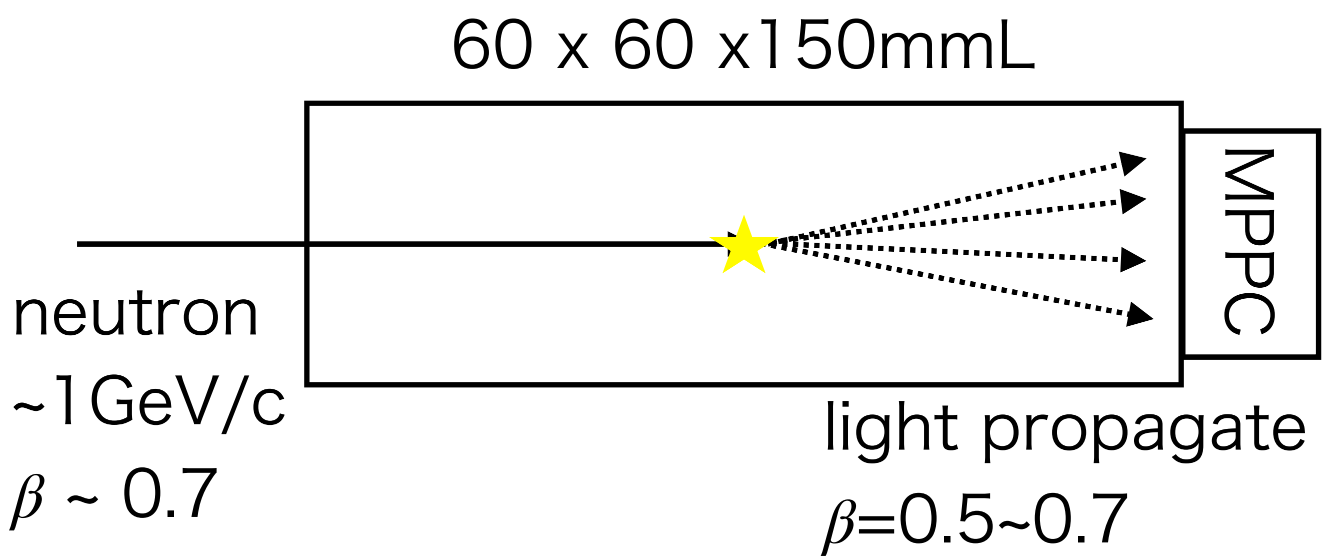
- We can reconstruct full reaction kinematics without detecting one of the decay particle
  - neutral paritcle
  - low-momentum proton. (cf. spectator in decay)

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

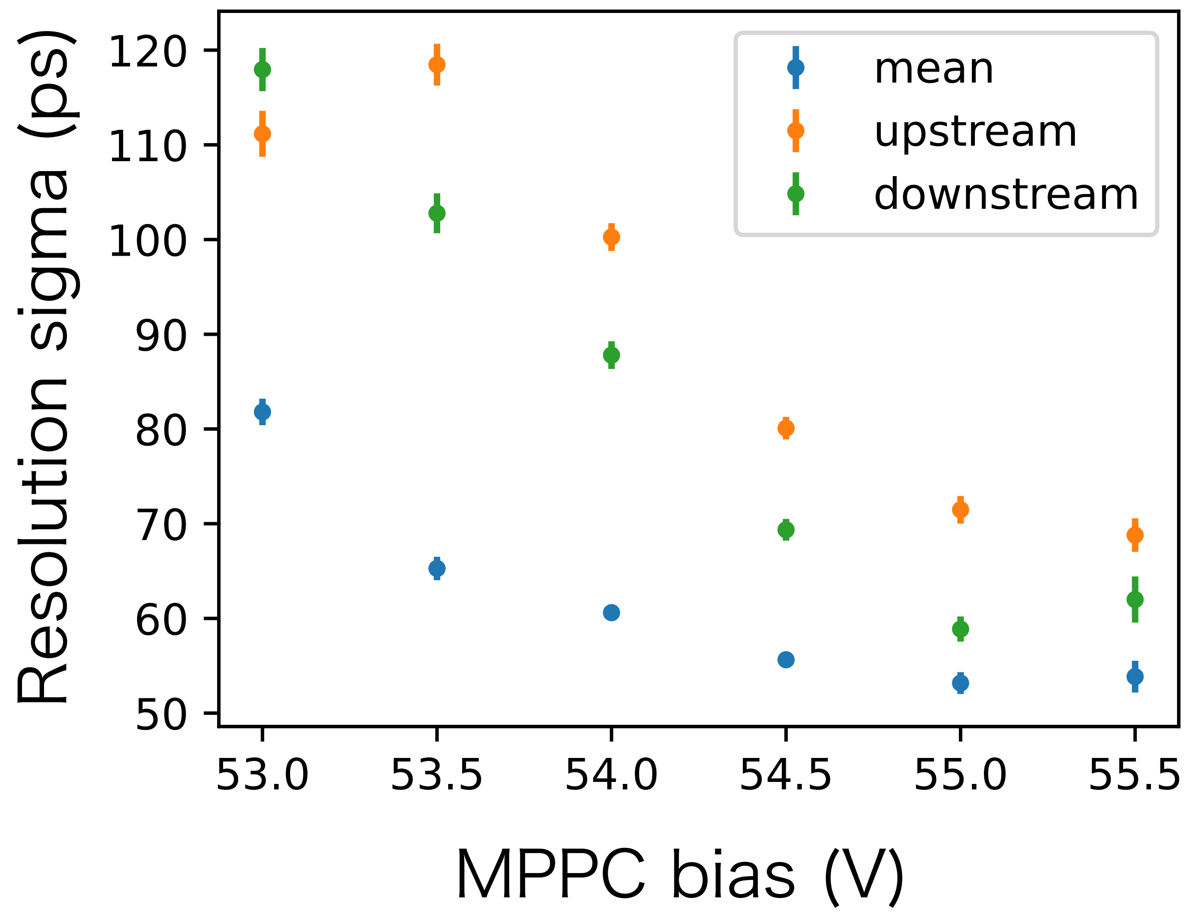
$$K^- + {}^4\mathrm{He} \rightarrow \bar{K}NNN + n$$
$$\rightarrow \begin{cases} \Lambda p n_s + n \\ \Lambda n p_s + n \end{cases}$$

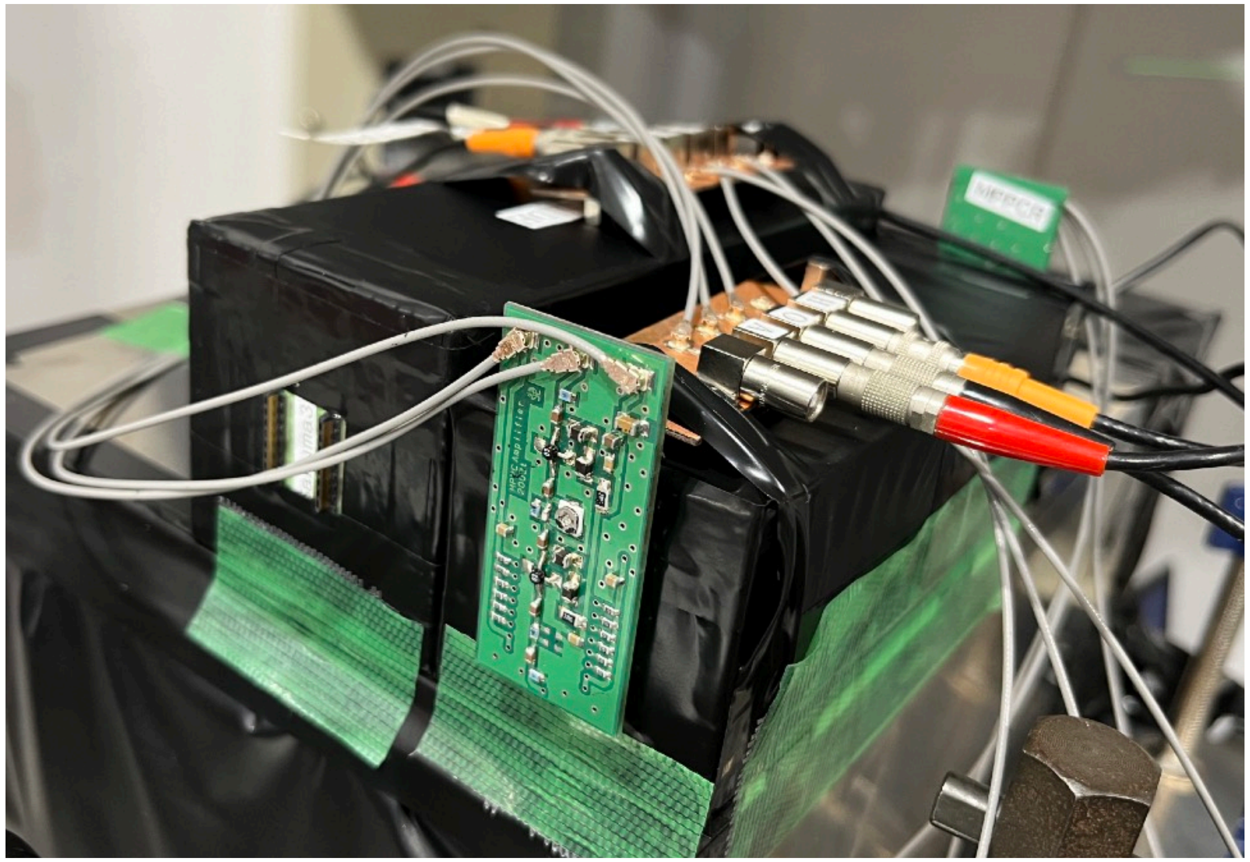
Useful to analyze decay kinematics and to understand background processes

Prototype test with electron beam at ELPH



neutron interaction point should not effect significantly





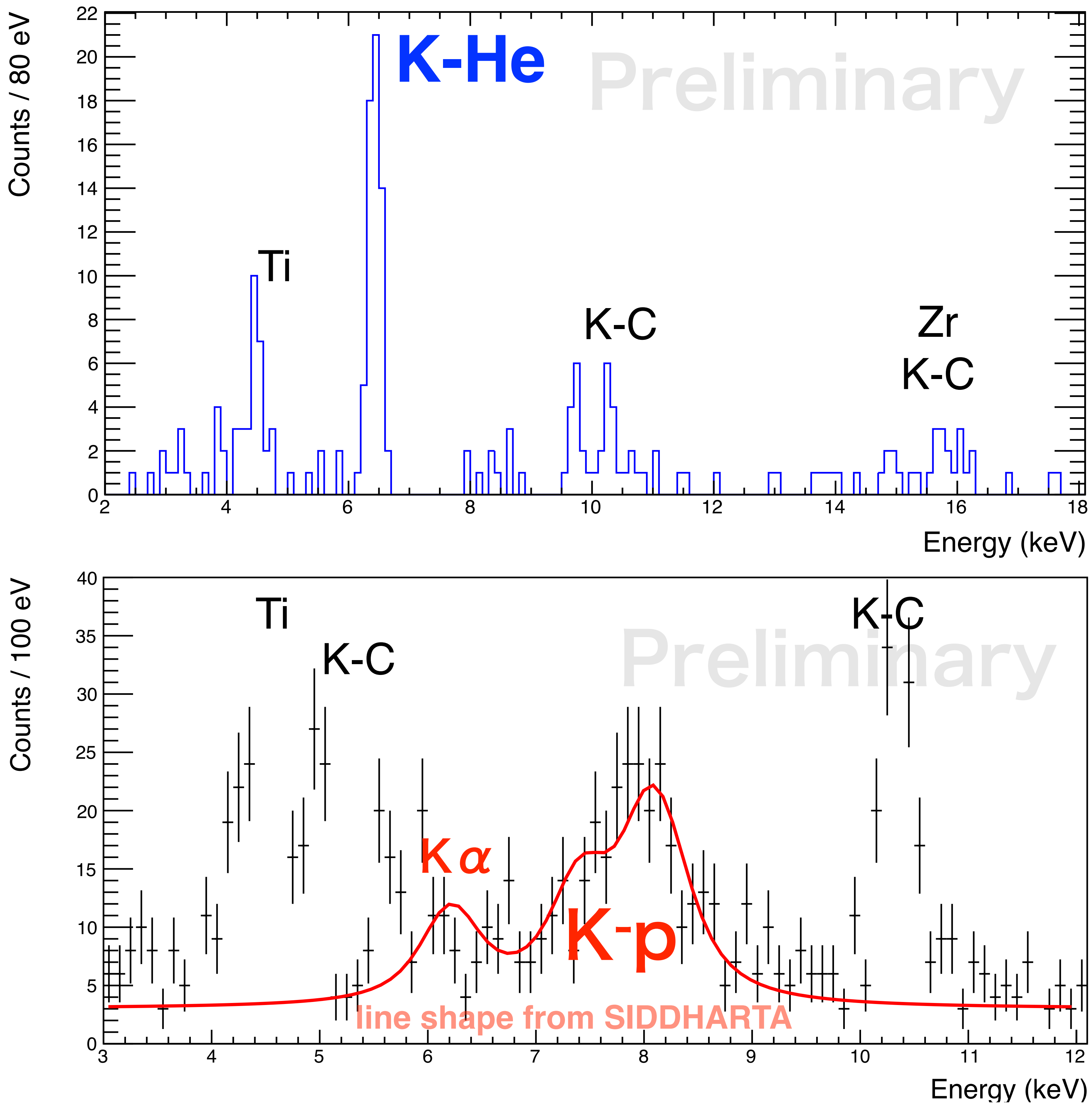
MPPC: S13361-6050NE-04
4 hybrid x 4 parallel readout
AMP: HP MSA-0385x2
(Cascadable Silicon Bipolar MMIC Amplifier)

60 ps resolution is achieved with one side readout

Room to optimize a bit more (MPPC amp is saturated now)

Kaonic deuterium

E57 test run in 2019



He target: ~6 hours

✓ almost background free as designed

H_2 target: ~4 days

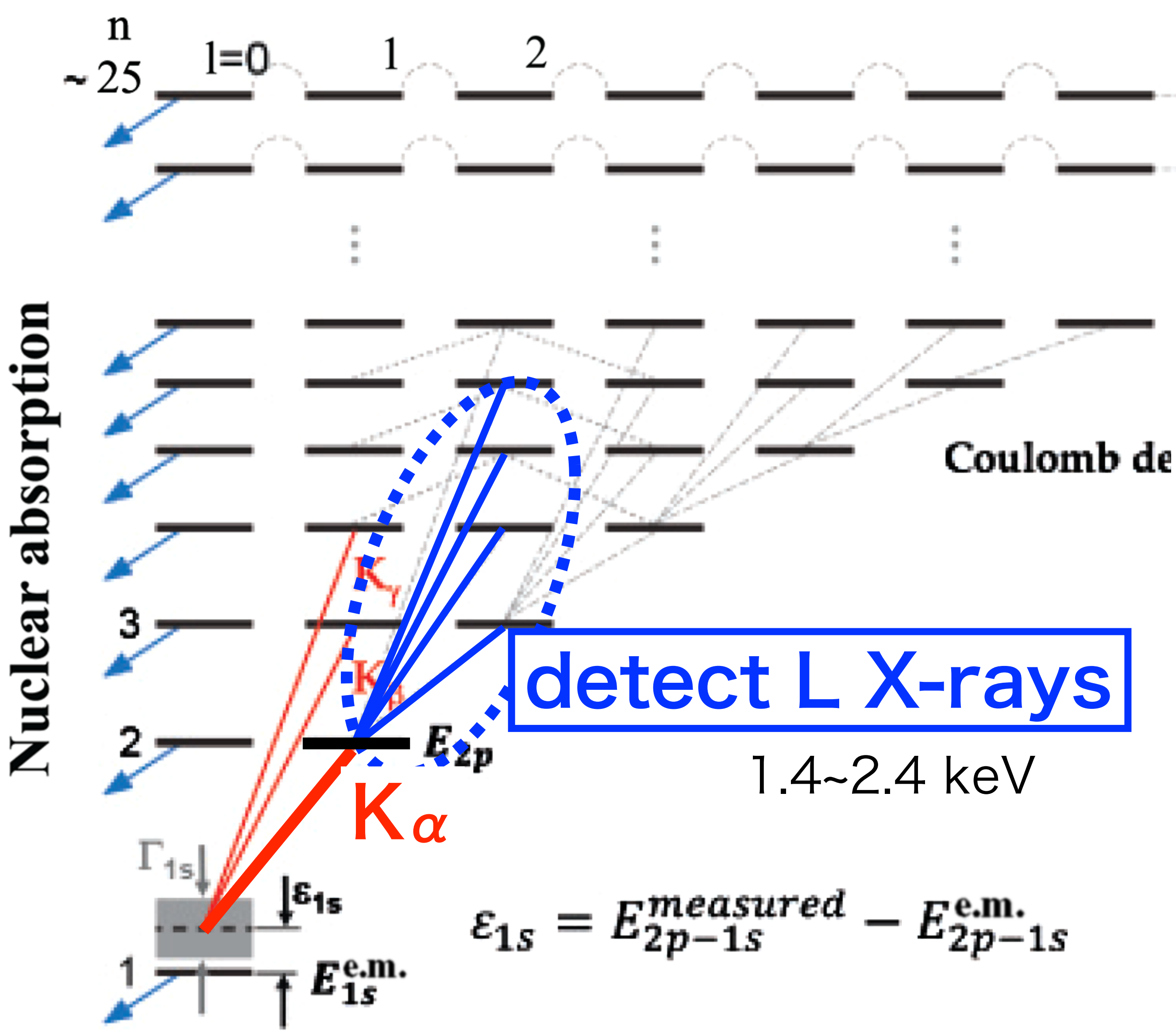
✓ Higher transitions are observed.

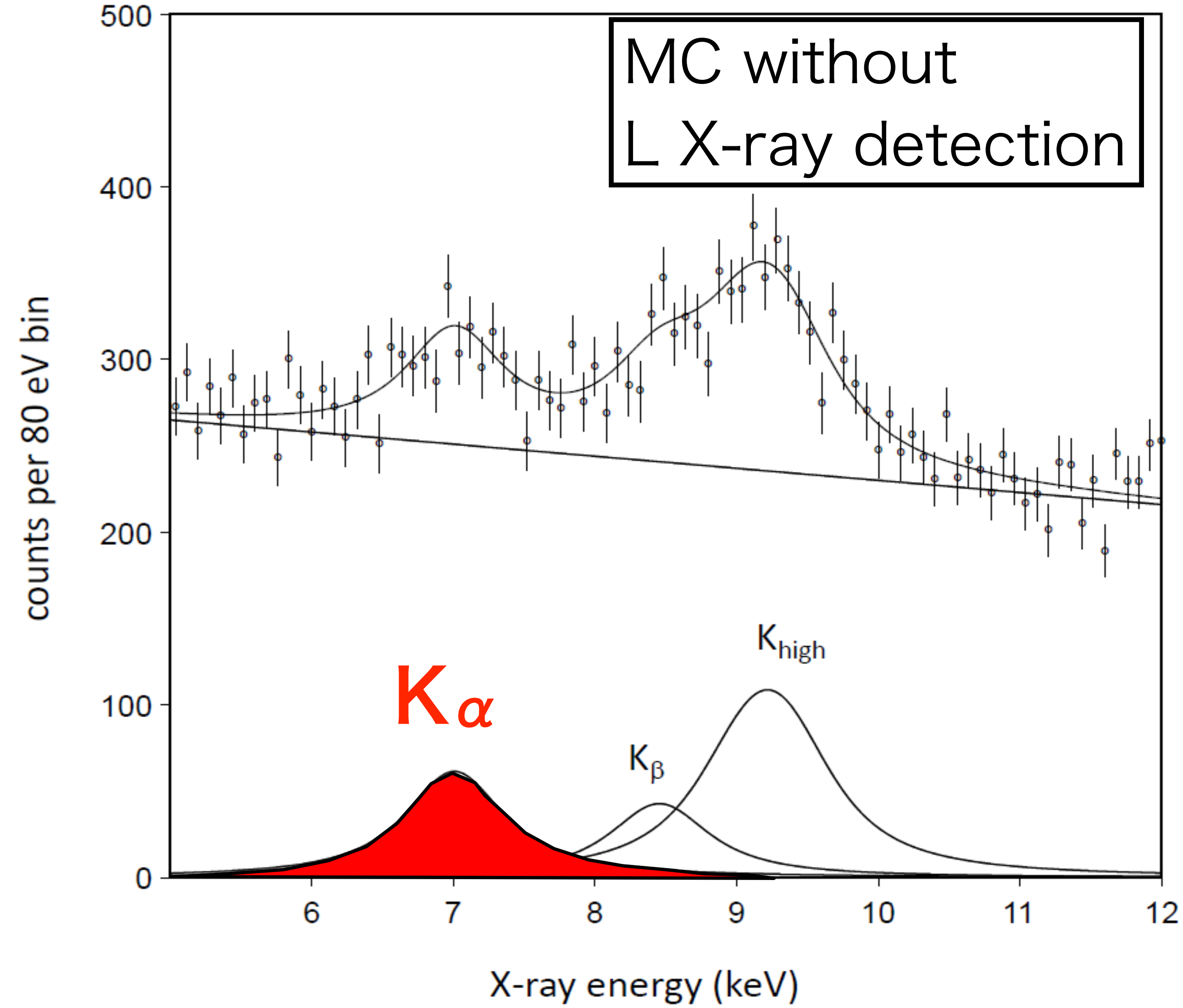
x no clear Kα peak

x Low yields

Meanwhile, SIDDHARTA2 started data taking …

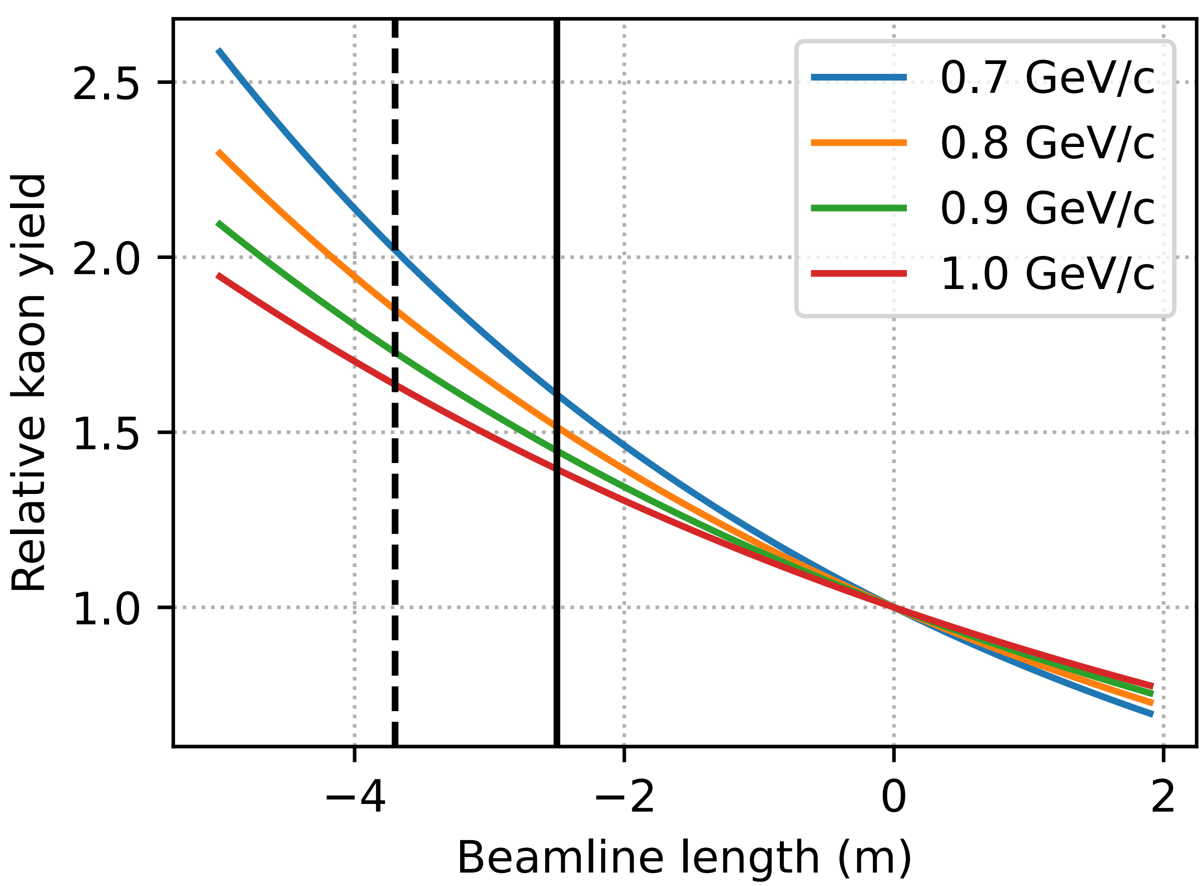
Updated strategy: X-ray coincidence

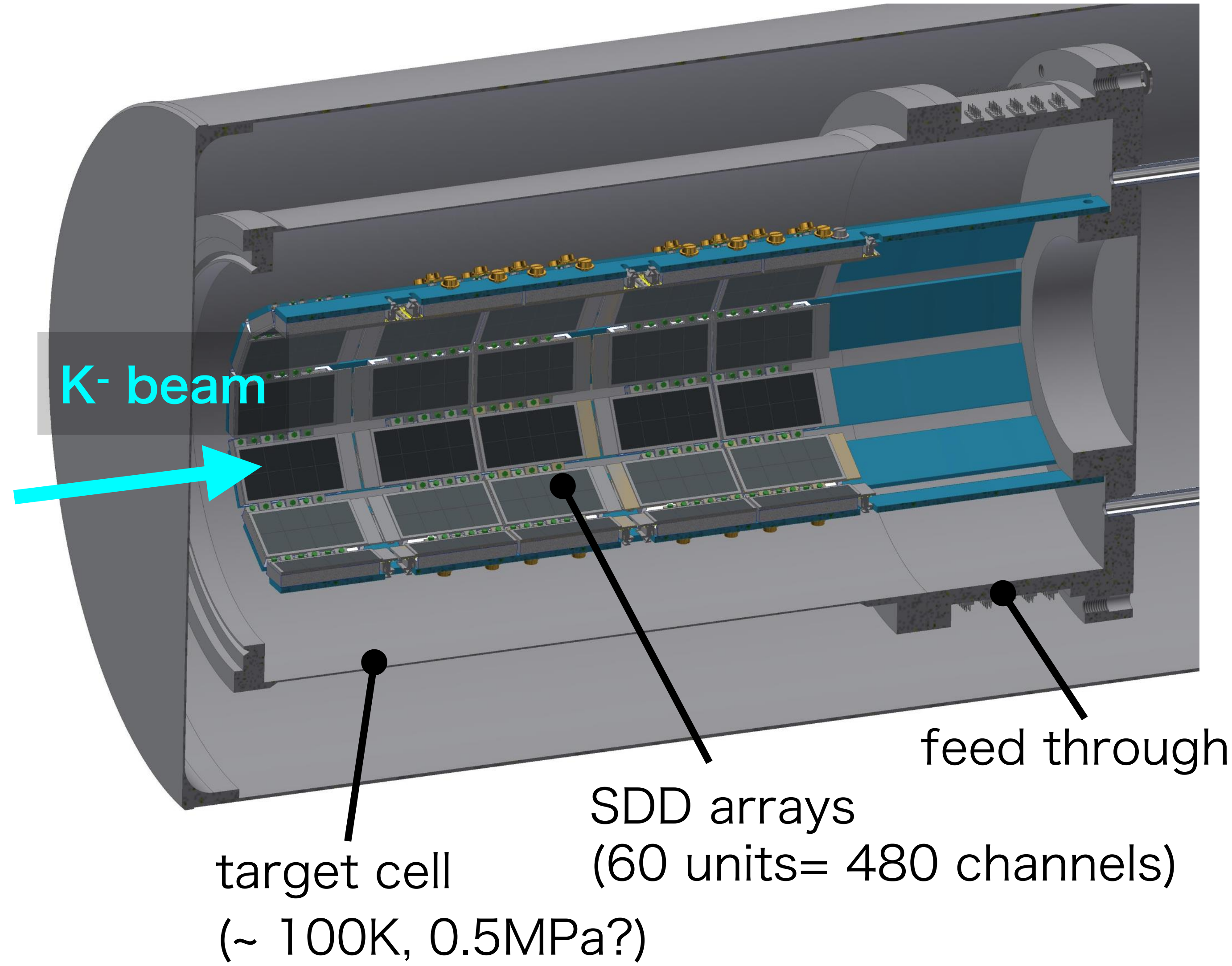




- ✓ Drastic background reduction by detecting K and L X-rays in coincidence
- ✓ Install SDDs into the target gas to avoid attenuation at the target container
- ✓ KHe 1s & Σ-He can be measured in a similar way

With shorter beamline & Dorami

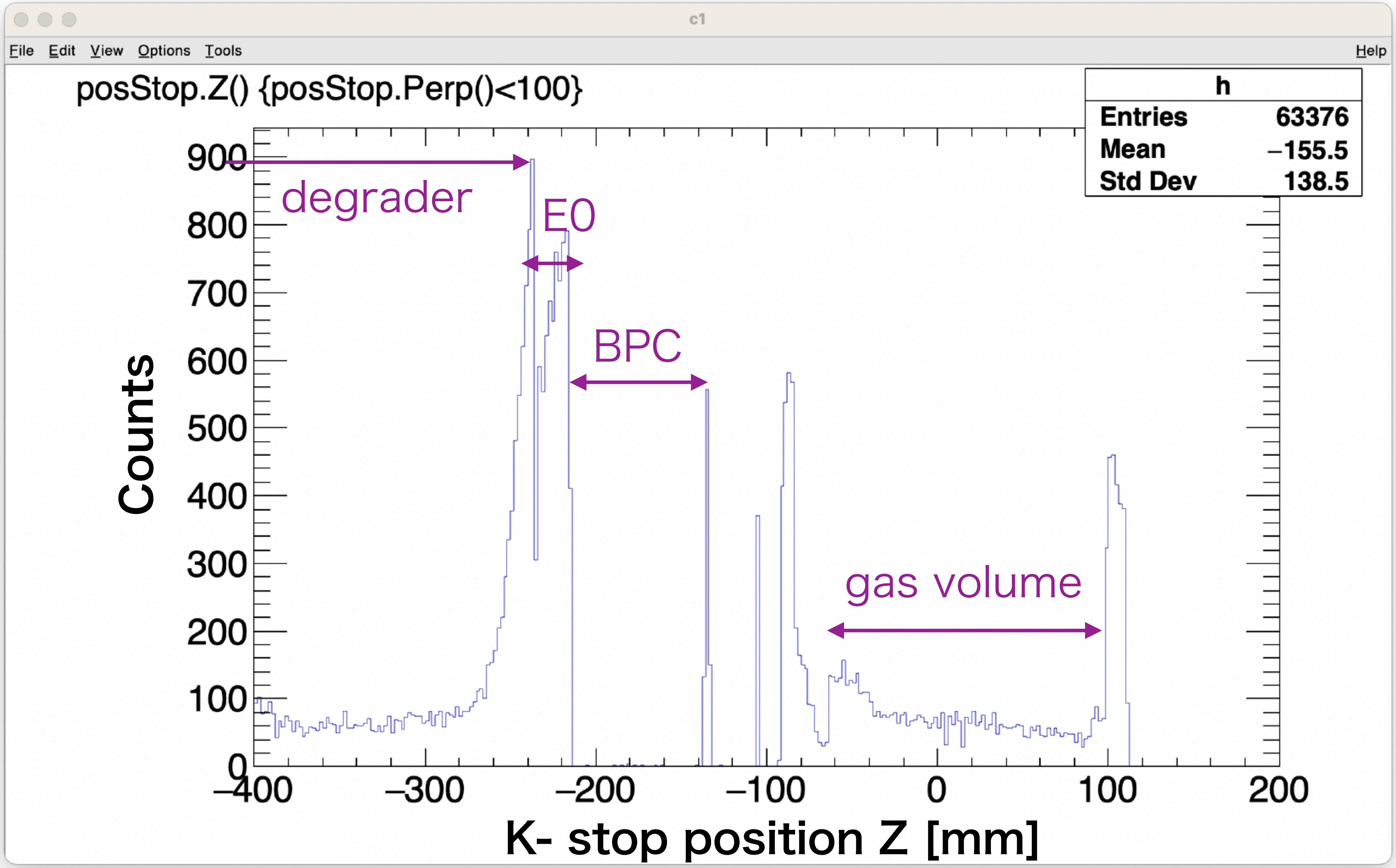




~20% coincidence acceptance

- ✓ x1.6 kaons with the shortened beamline by ~2.5 m
- ✓ Longer horizontal vacuum chamber + ~1.3m
  →no problem. we have enough cooling power
- ✓ Larger acceptance for secondary particles.
- ✓ ~4 week x 80 kW to get ~ 700/200 Ka X-rays wo/w L X-ray coincidence
  assumption: 0.1% X-ray yield, 80% active SDD channels

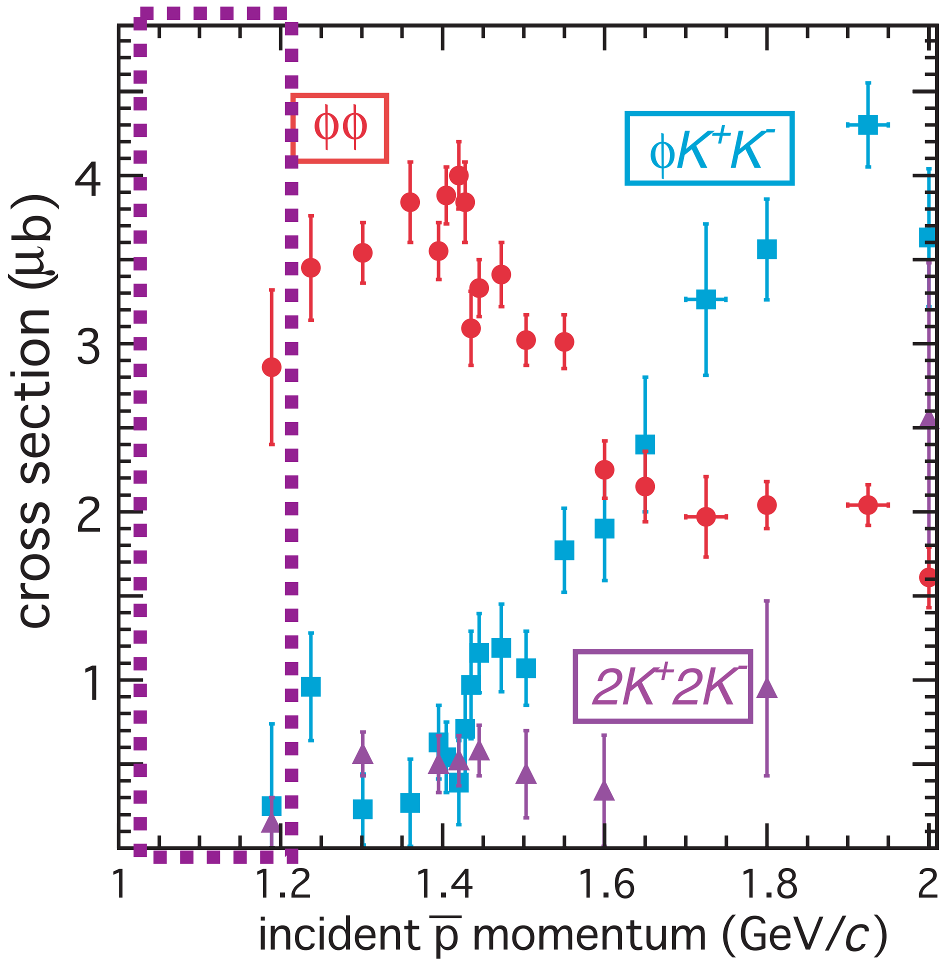
by-product with CdZnTe?

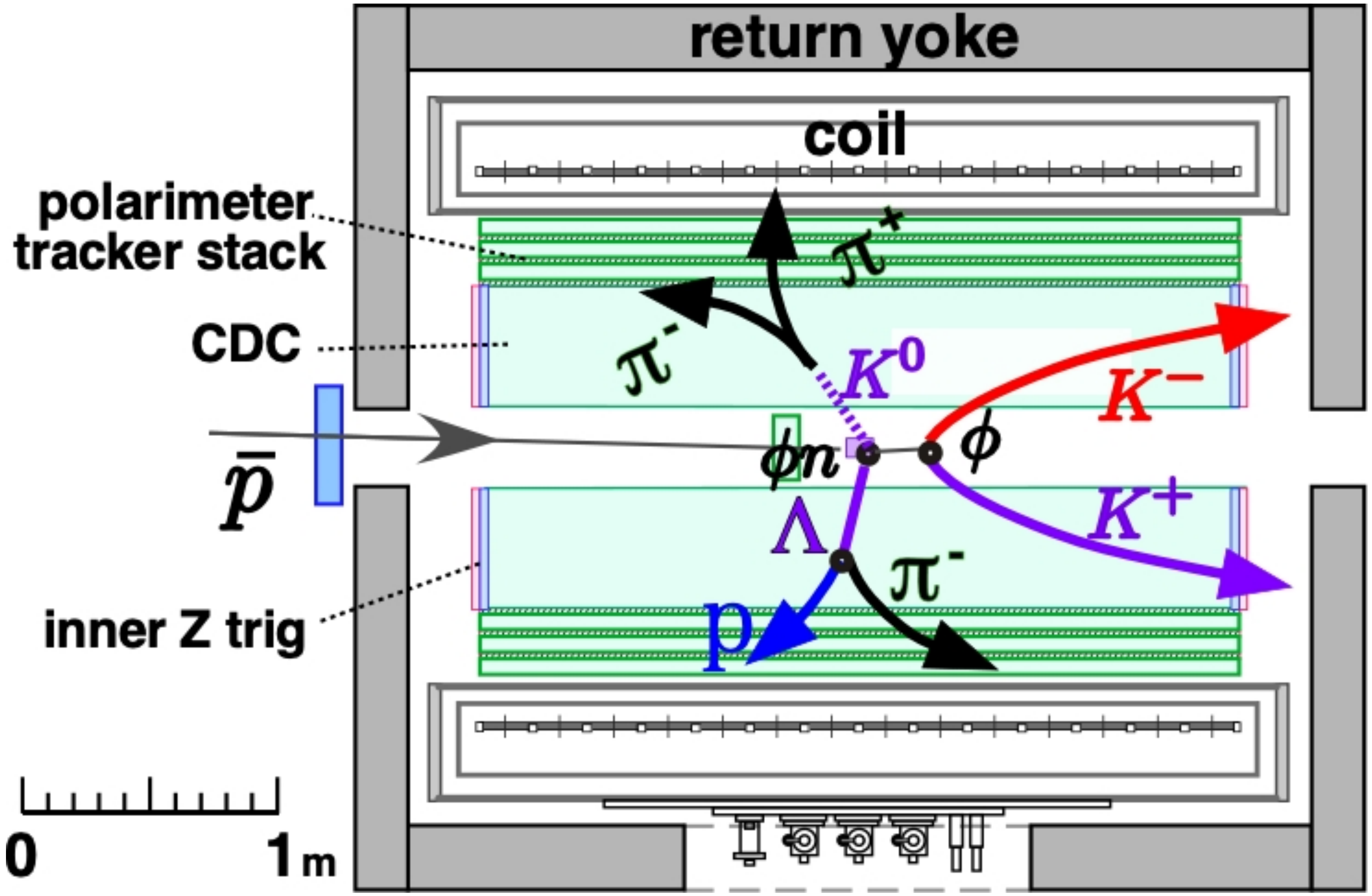


- Alessandro is proposing to put CdZnTe detectors surrounding degrader
- Kaonic C, S, Al, ···

anti-proton

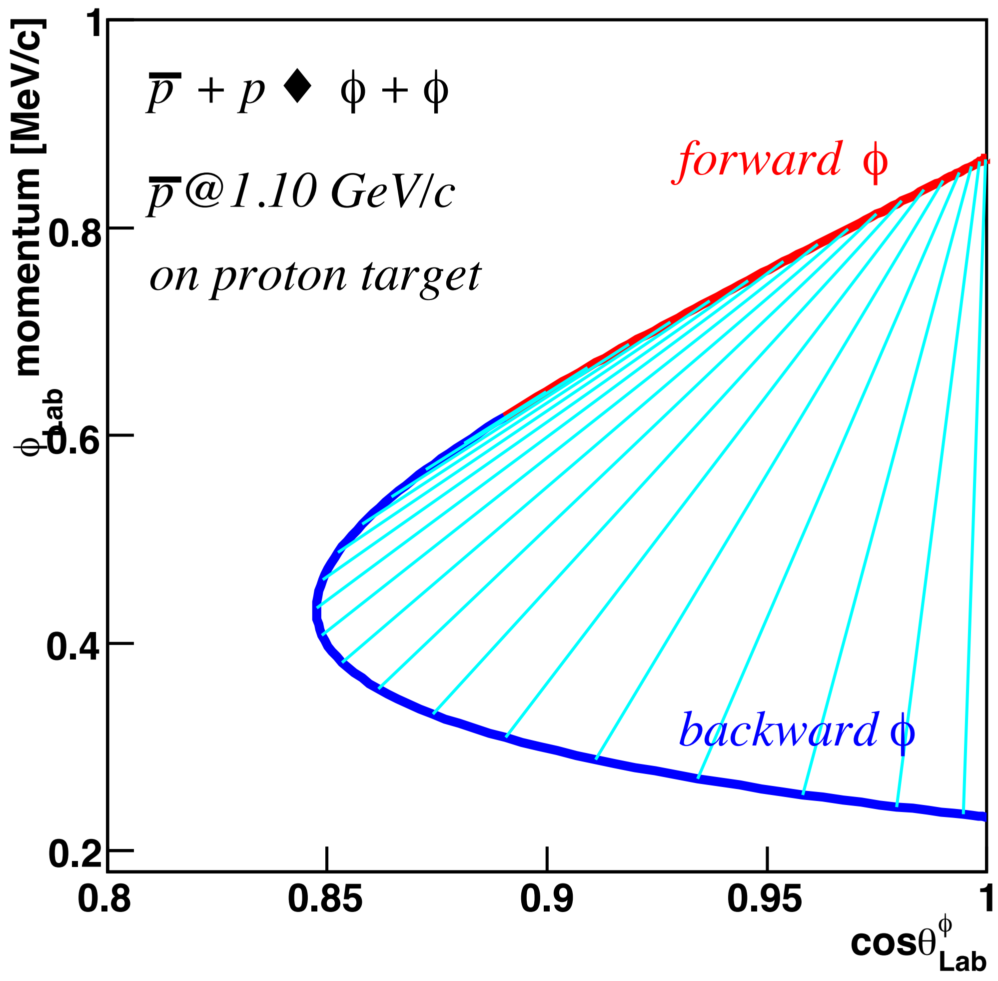
anti-proton beam experiment

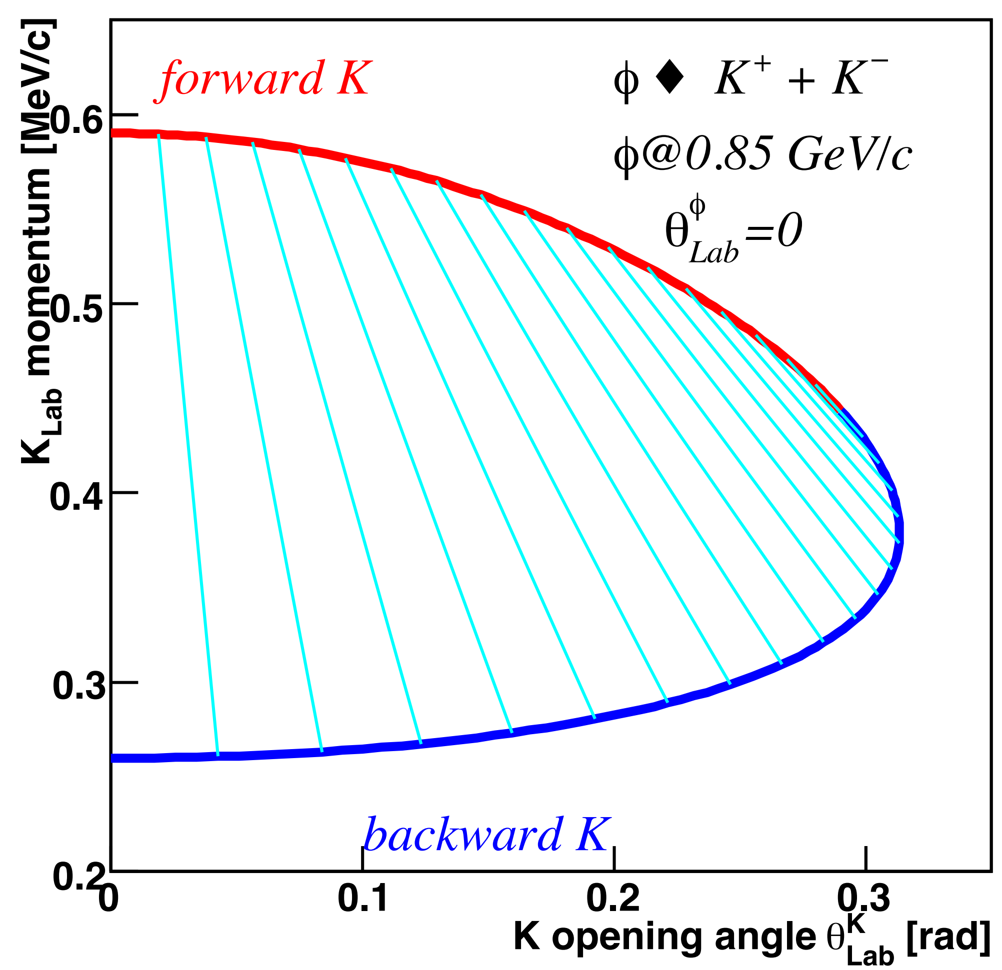




- double K- production
- recent study on the possibility of ϕn bound state …

Kinematics of $\phi\phi$ events





- Almost impossible to detect ϕ
  - Additional detectors on the beamline downstream of the target might help
- Exclusive decay measurement is still possible ($\phi n \rightarrow \Lambda K^0$)
- Does “dorami” have any advantage over the hyperon spectrometer?
- Streaming DAQ would be useful for a flexible data-taking

Summary

~2024

- J-PARC E73 (hypertriton lifetime)
  - $\bar{K}NN$ with x2 larger K-s, x2 acceptance, x2 resolution

~2027?

- J-PARC E80 ($\bar{K}NNN$)
  - x40 times Λdn events (~20k events)
  - Λpn decay (~1000 events?)
  - Forward nucleon detection
  - Feasibility test of the proton polarimeter

Kaonic deuterium?
anti-proton experiment?

Heavier kaonic nuclei
L(1405)
K-/K+/Σ scattering
...

~2030?

- J-PARC P89 (spin-parity of $\bar{K}NN$)