Next-Generation Experiments on Kaonic Nuclei at J-PARC

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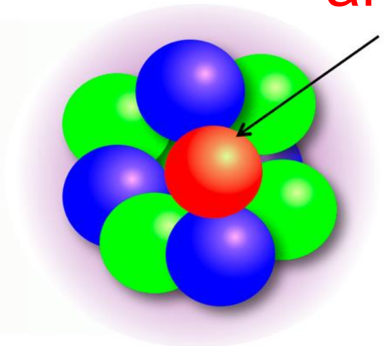
For the J-PARC E80 collaboration

Kaonic Nuclei



Motivation: What will happen when anti-kaon ($\bar{K}$) is embedded in nucleus?

Why anti-kaon?

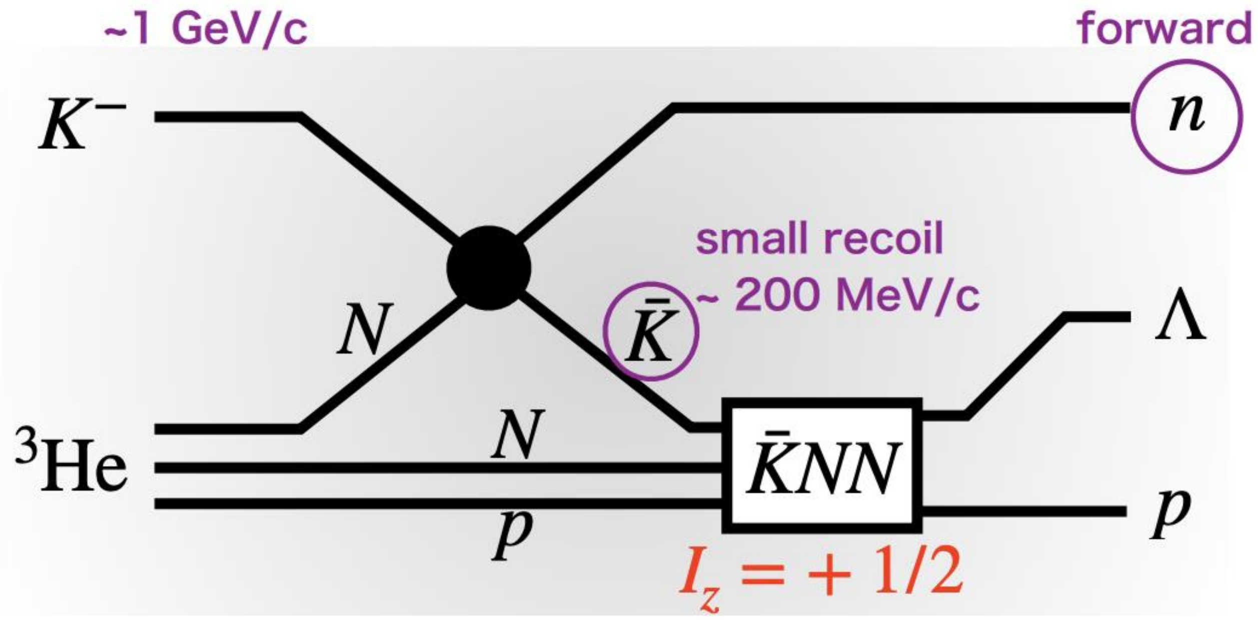
- ✓ $\Lambda(1405)$ = $\bar{K}N$ molucle picture is now widely accepted
  → "$\bar{K}NN$", "$\bar{K}NNN$", "$\bar{K}\bar{K}NN$" … should exist.

- ✓ Strongly attractive interaction between $\bar{K}$ and N in $I = 0$
  → Large binding energy?
  Deep potential?
  Dense nuclear medium?

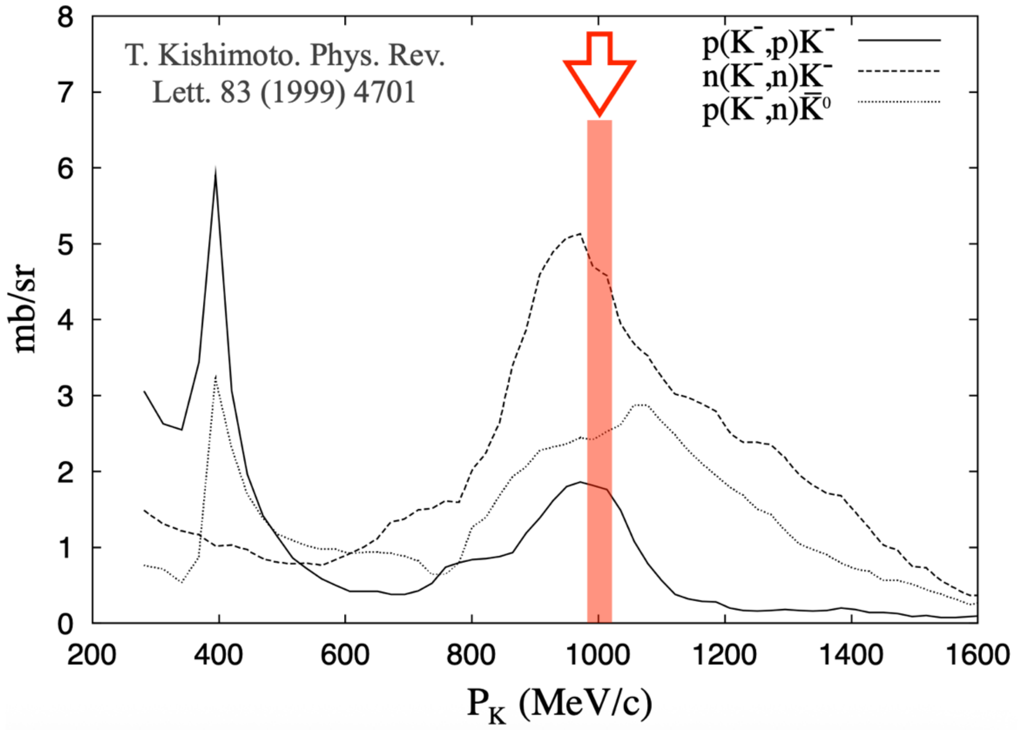
Experimentalists began with simpler systems.
Theory calculations also suggest that these bound states exist.

J-PARC E15: Search for "$K^{-}pp$"

- ✓ In-flight ^{3}He(K^{-}, n) reaction at $P_{K^{-}} \sim 1$ GeV/c:
  Effectively produce kaonic nuclei
- ✓ Simplest target:
  Allow an exclusive analysis



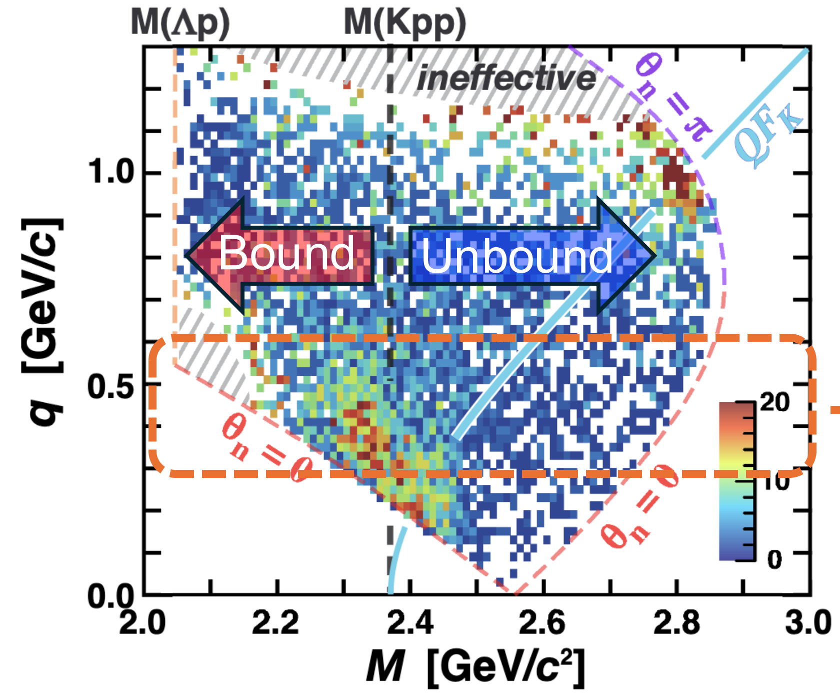
K-N elementaly cross-sections

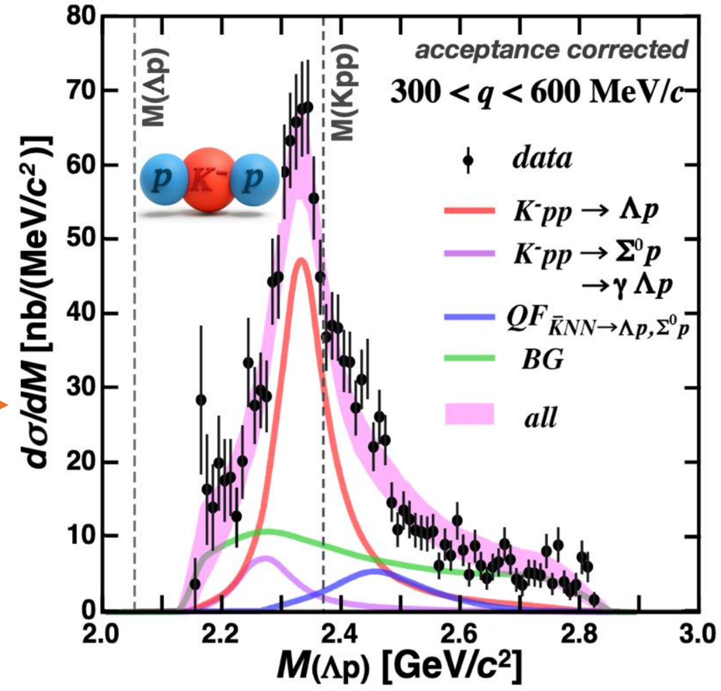


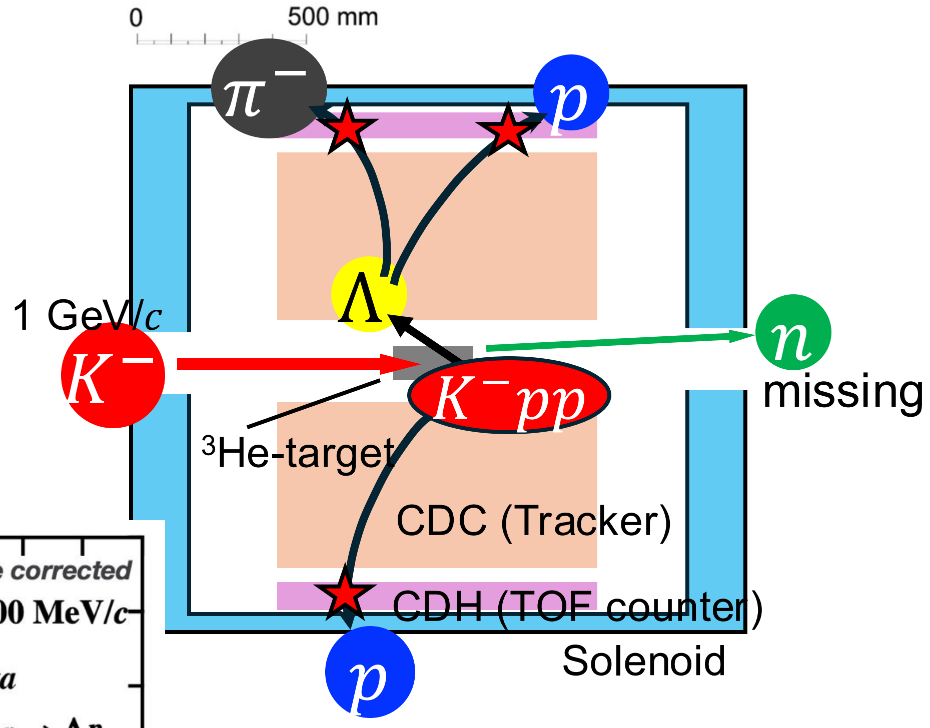
J-PARC E15: Search for "K^-pp"

- ✓ in-flight ^{3}He(K^-, n) reaction at P_{K^-}~1.0 GeV/c
- ✓ Simplest target
- ✓ Covering a wide kinematical region

$$q = |\boldsymbol{p}_{K^-}^{lab} - \boldsymbol{p}_n^{lab}|$$







Large B.E ~40 MeV

Decay width ~ 100 MeV

They could clearly separate signal from background with data of wide kinematical region.

Next Projects

J-PARC E15:

The simplest kaonic nucleus, “$K^{-}pp$”, was successfully observed.

“Existence” → “Properties”

- To heavier systems → J-PARC E80 (This talk)
  - B.E., Γ and spatial size?

- Further investigation of “$\bar{K}NN$” system → J-PARC E89
  - Confirmation of iso-spin partner “$\overline{K^{0}}nn$”
  - Spin-parity J^{P}

- Multi $\bar{K}$ systems…

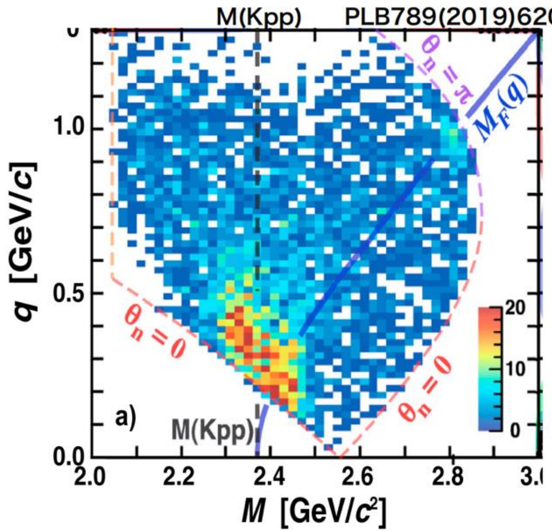
J-PARC E80: “$K^- ppn$”

Confirmation of “$K^- ppn$”

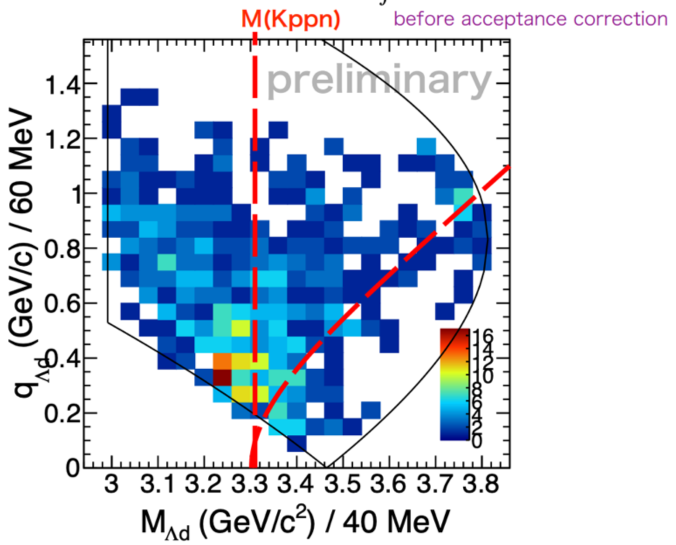
Using “$K^- ppn$” → $\Lambda + d$

- ✓ With the current statistics, we cannot reliably compare with K^-pp.

E15: $K^- + {}^3\mathrm{He} \rightarrow \Lambda p + n_f$ ($\sim 42 \times 10^9$ K^-)



T77: $K^- + {}^4\mathrm{He} \rightarrow \Lambda d + n_f$ ($\sim 6 \times 10^9$ K^-)



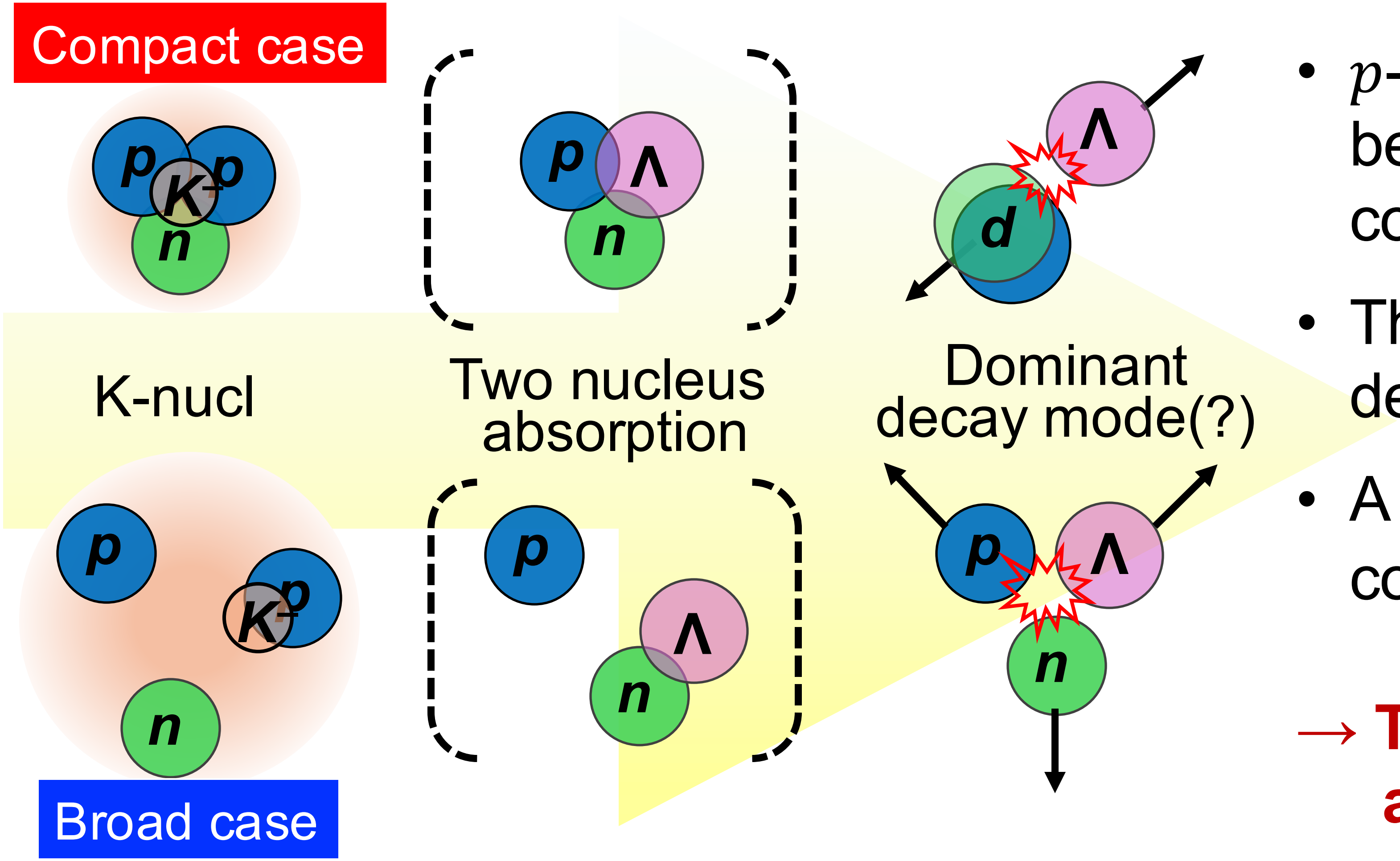
Using “$K^- ppn$” → $\Lambda + p + n$

Limited statistic…

- ✓ Whether it can be clearly observed in a different decay mode.

J-PARC E80: "$K^- ppn$"

Spatial size from comparison Λd with Λpn decay mode

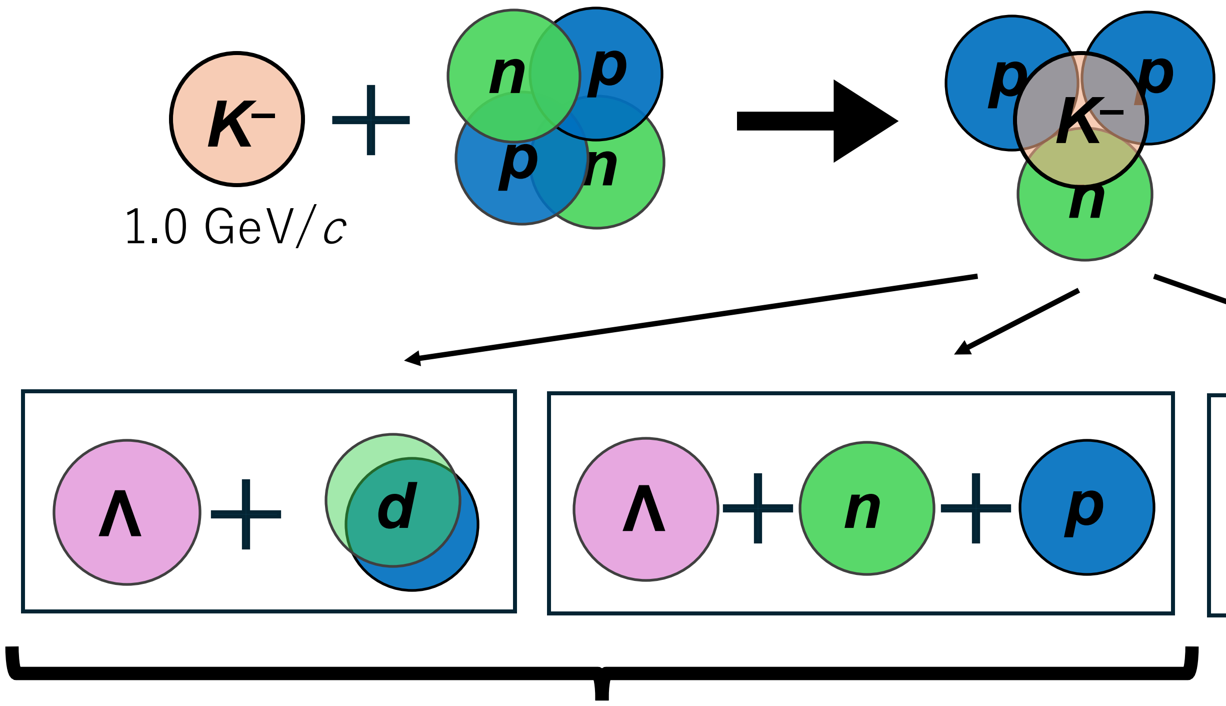


- p-n separation differs between compact and broad configurations.
- This may alter the d vs. $p + n$ decay fractions.
- A potential probe of the compactness of "$K^- ppn$".

→ **Three-body decay studies are essential.**

J-PARC E80: “K^-ppn”

What and how we will measure:

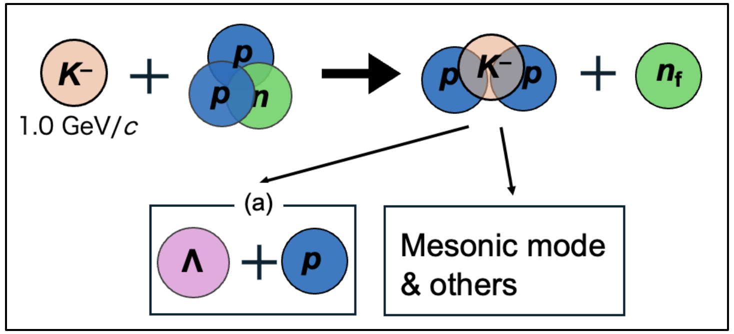


Missing Mass
or
forward TOF counter

Mesonic mode
& others

Measured by Cylindrical Detector System (CDS)

c.f.) Case of E15

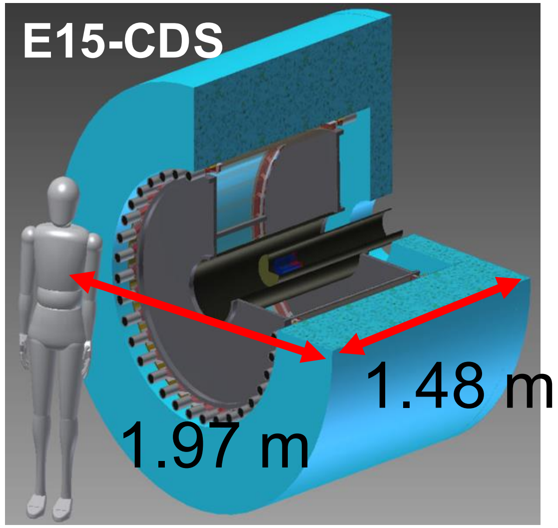


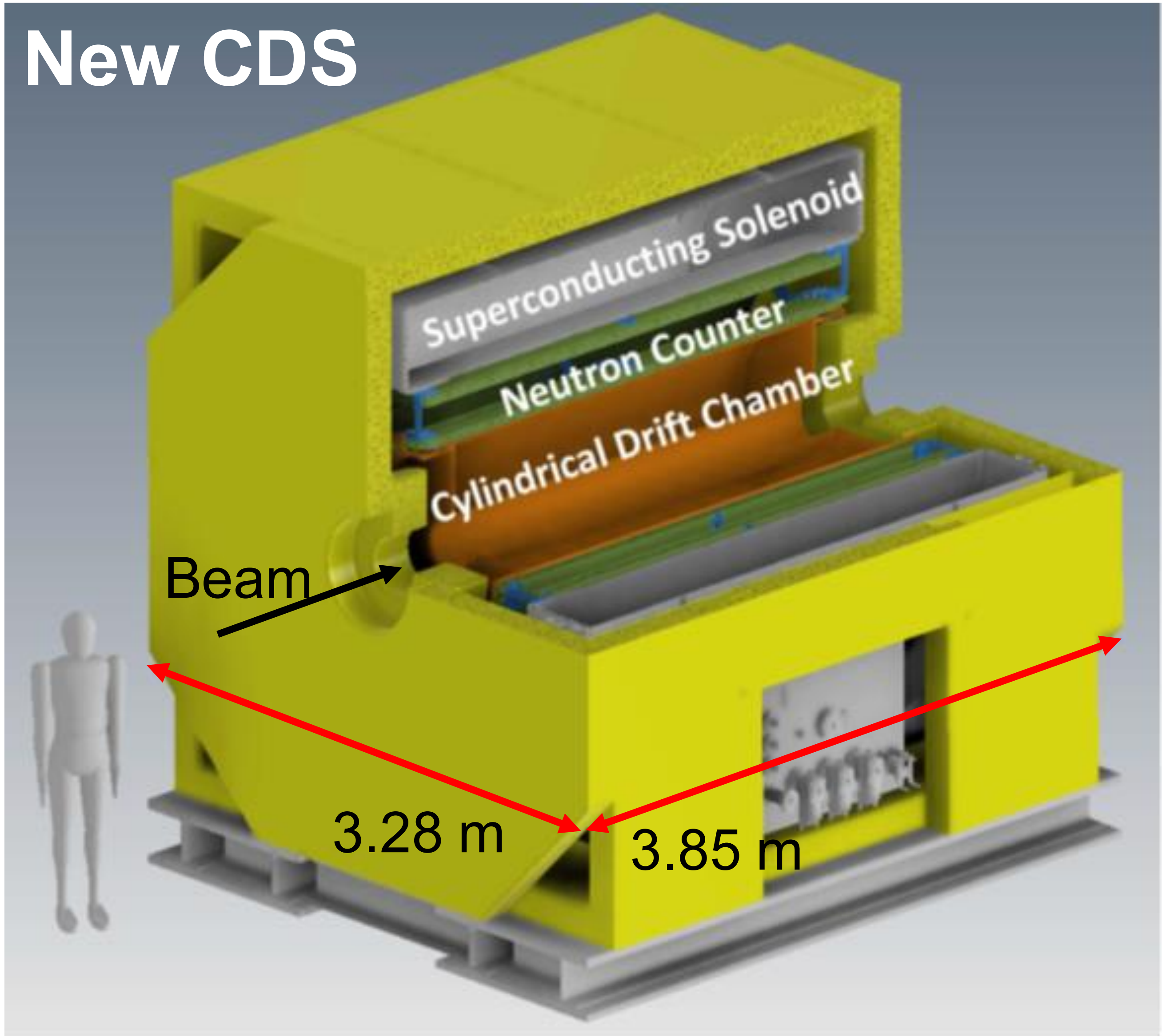
Compared with E15 (“K^-pp”),

✓ **More decay particles**

✓ **Neutron must be detected…**

New Cylindrical Detector System





Solid Angle:
x1.6 (59% → 93%)

Neutron Detection Efficiency:
x4 (3% → 12%)

+ forward TOF counter
+ proton polarimeter

New Cylindrical Detector System

Cylindrical Neutron Counter

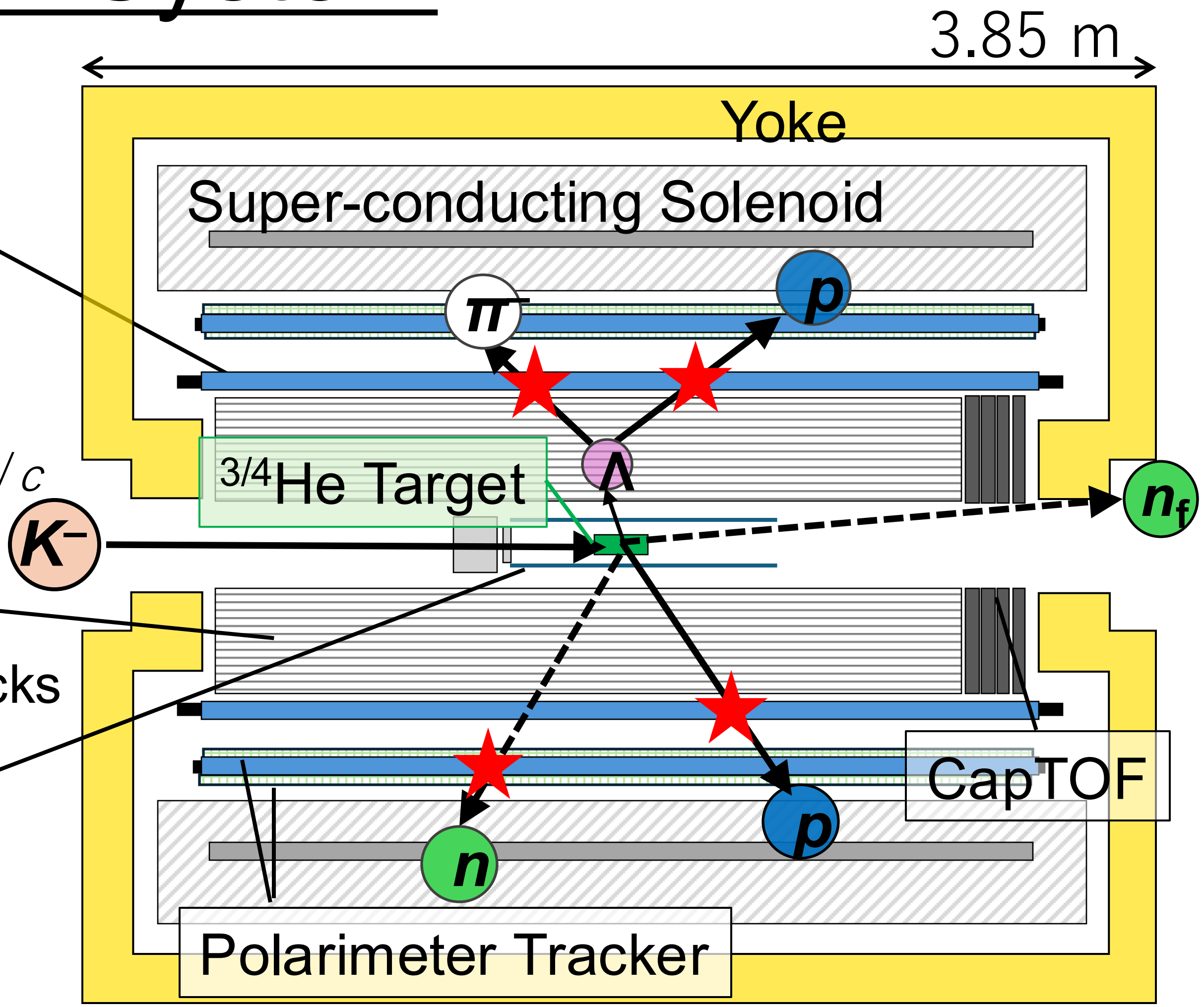
- Neutron detection
- PID for charged particles
- Resolution
  - σ_{time} ~ 80 ps (same as E15)
  - σ_{mom_n} < 7% (momentum dep.)

Cylindrical Drift Chamber

- Momentum calculation from curvature of tracks
- Momentum Resolution is equal to the same as E15-CDC.

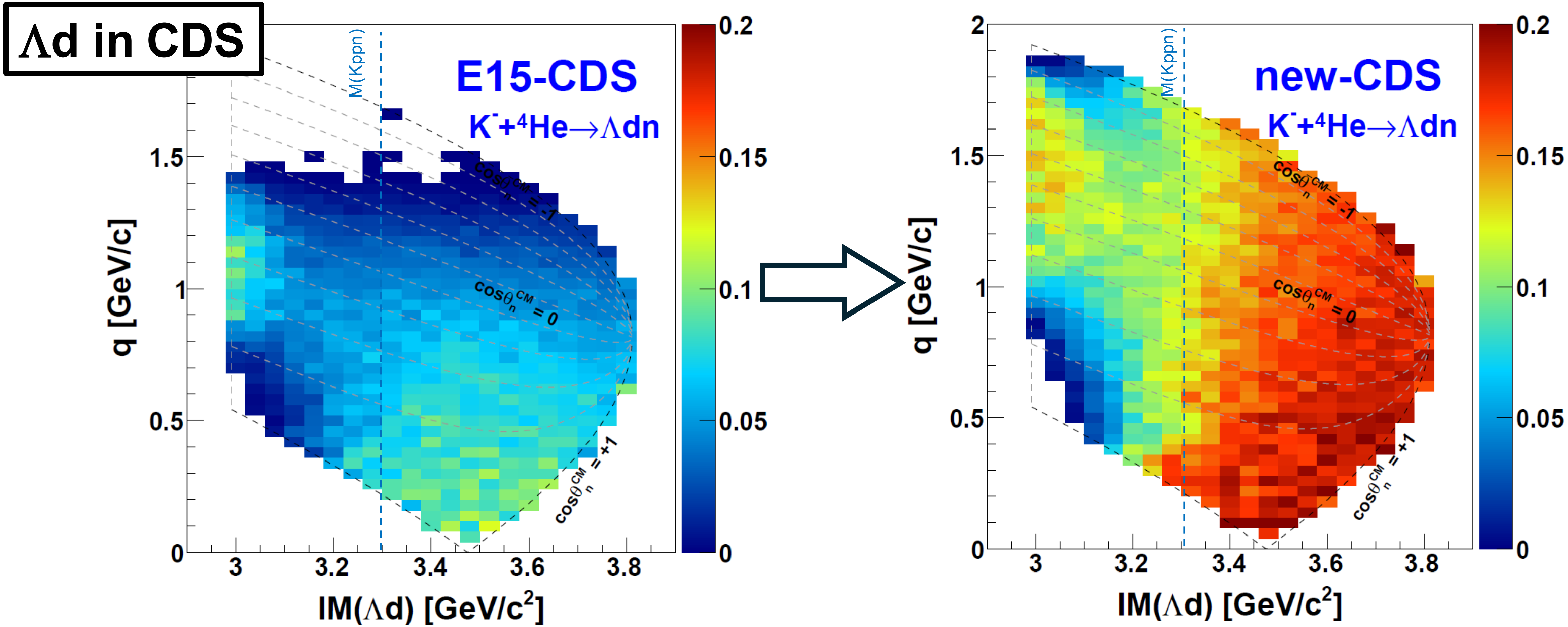
Vertex Fiber Tracker

- To reinforce the vertex point resolution, especially Z-pos resolution.



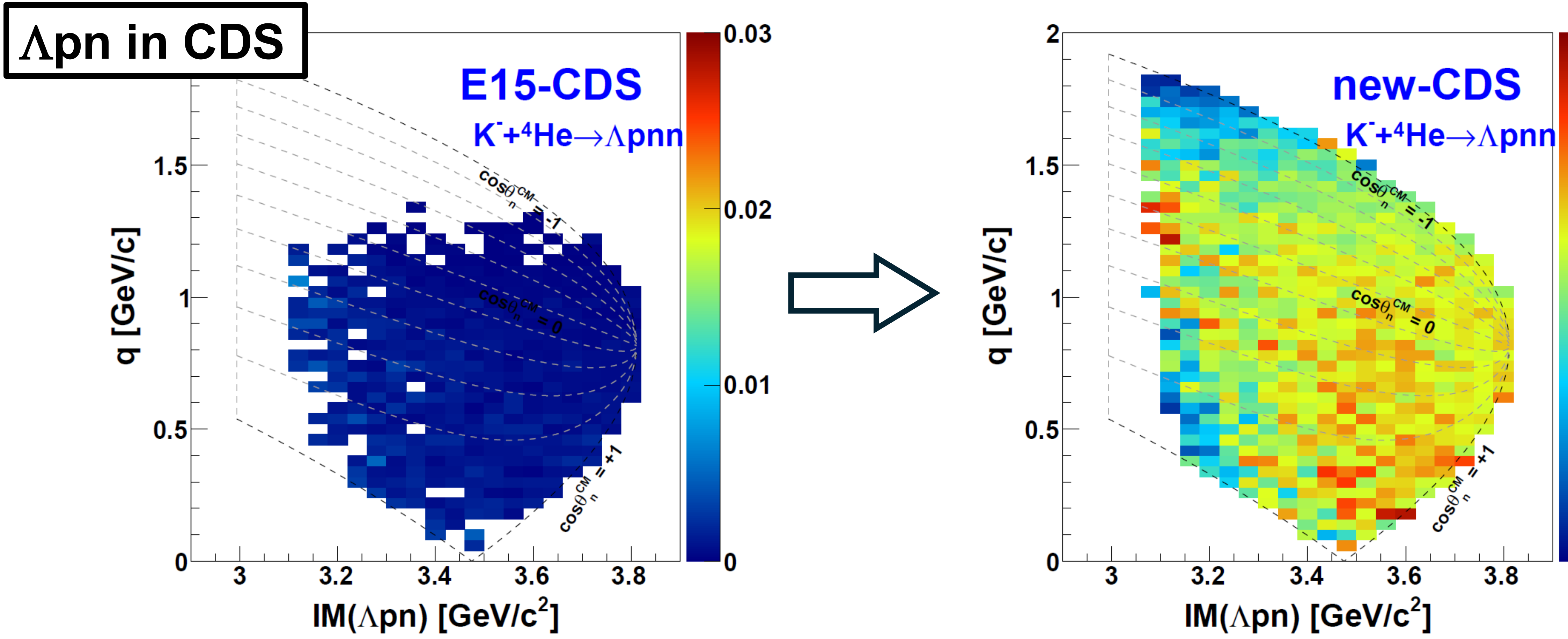
The overall resolution is comparable to, or better than, that of the E15 CDS.

Improvement of Detector Acceptance



Overall, the efficiency increases by ~2x, and the key sub-threshold region maintains a high acceptance in wide q region.

Improvement of Detector Acceptance



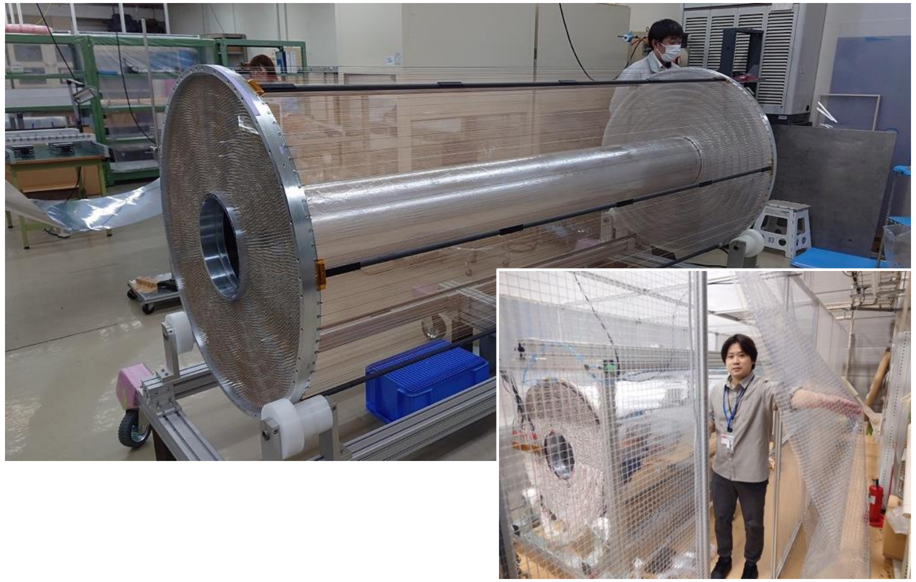
For three-body decays, the acceptance will be dramatically improved compared to the E15-CDS, more than a factor of five.

Status of the main components

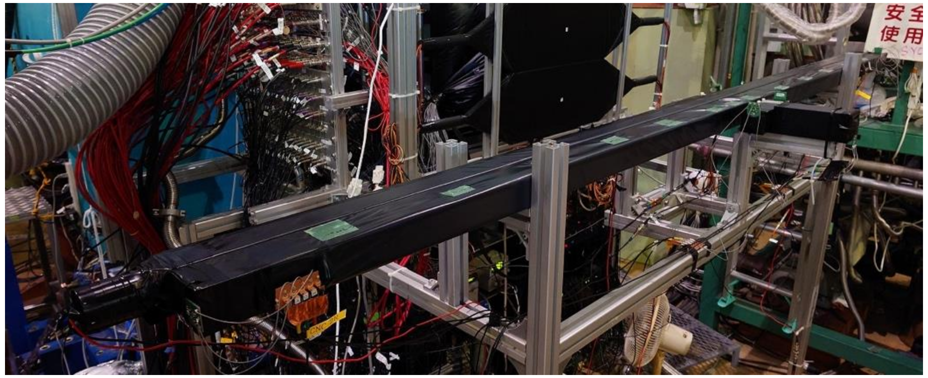
Return York:
completed

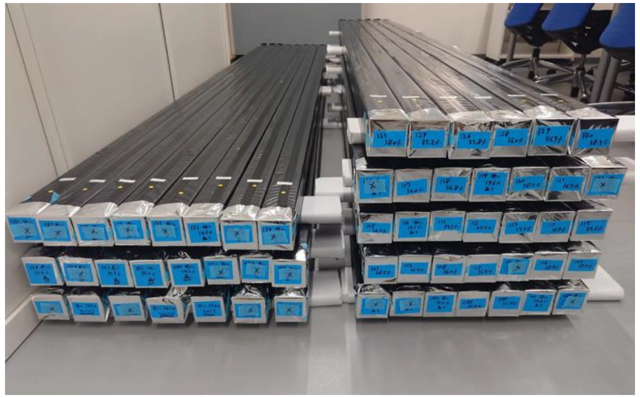
SC Solenoid:
completed

CDC:
completed, in commissioning

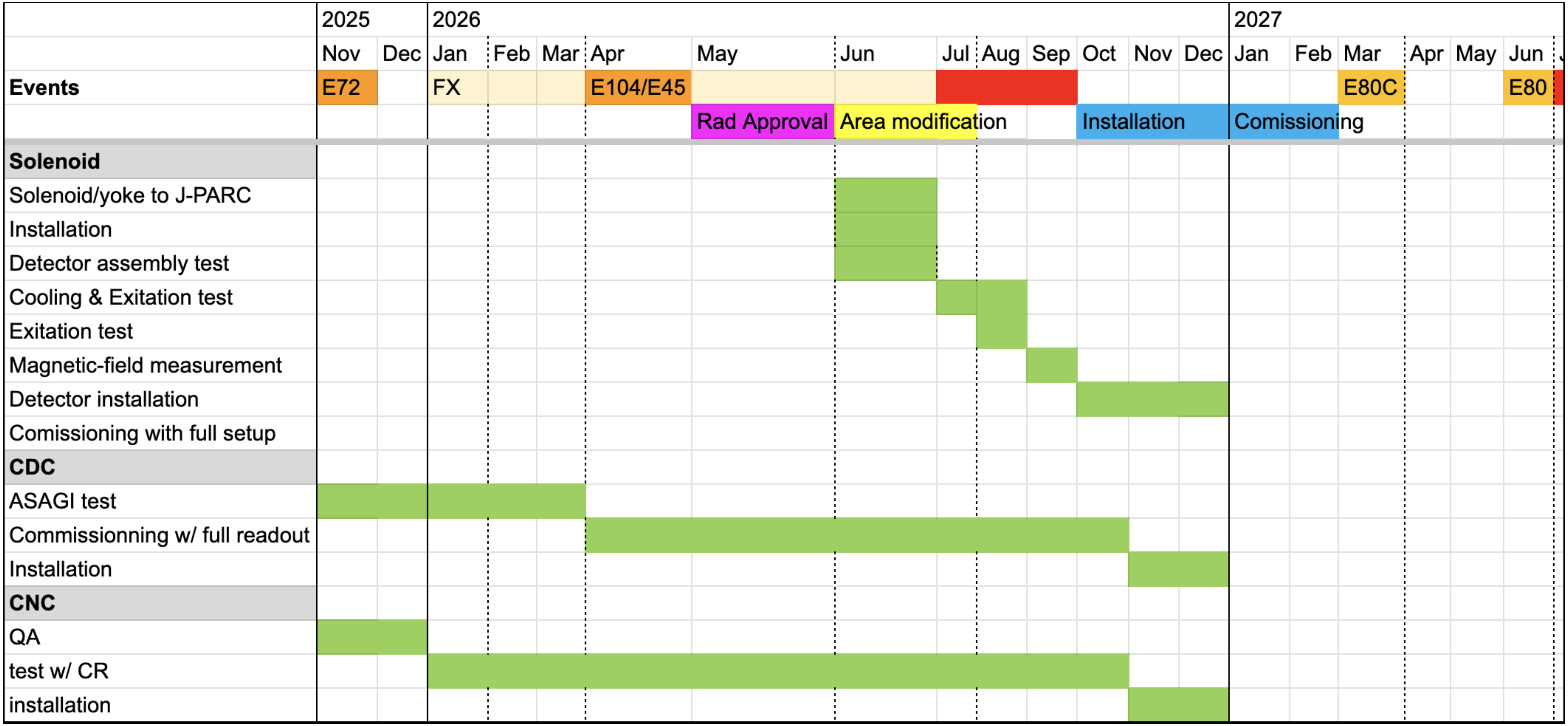


CNC:
development with prototypes,
to be completed this year





Plan for the main components



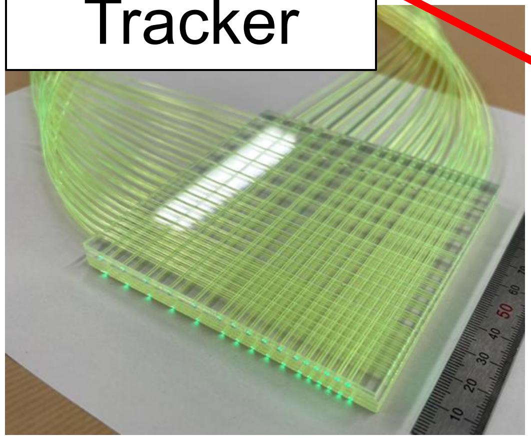
Status of the other new detectors

J-PARC E72 Parasite exp.
for R&D is ongoing.

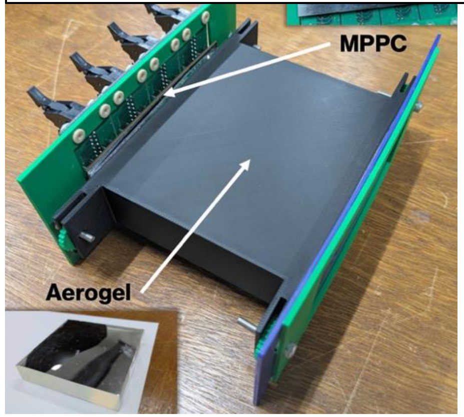
Y. Tsutsumi (U Tokyo, M1) for AC
S. Ohtaka (RARiS, M1) for pol. tracker

The other beam line detectors, VFT and the target system will basically be reused, with only minor modifications.

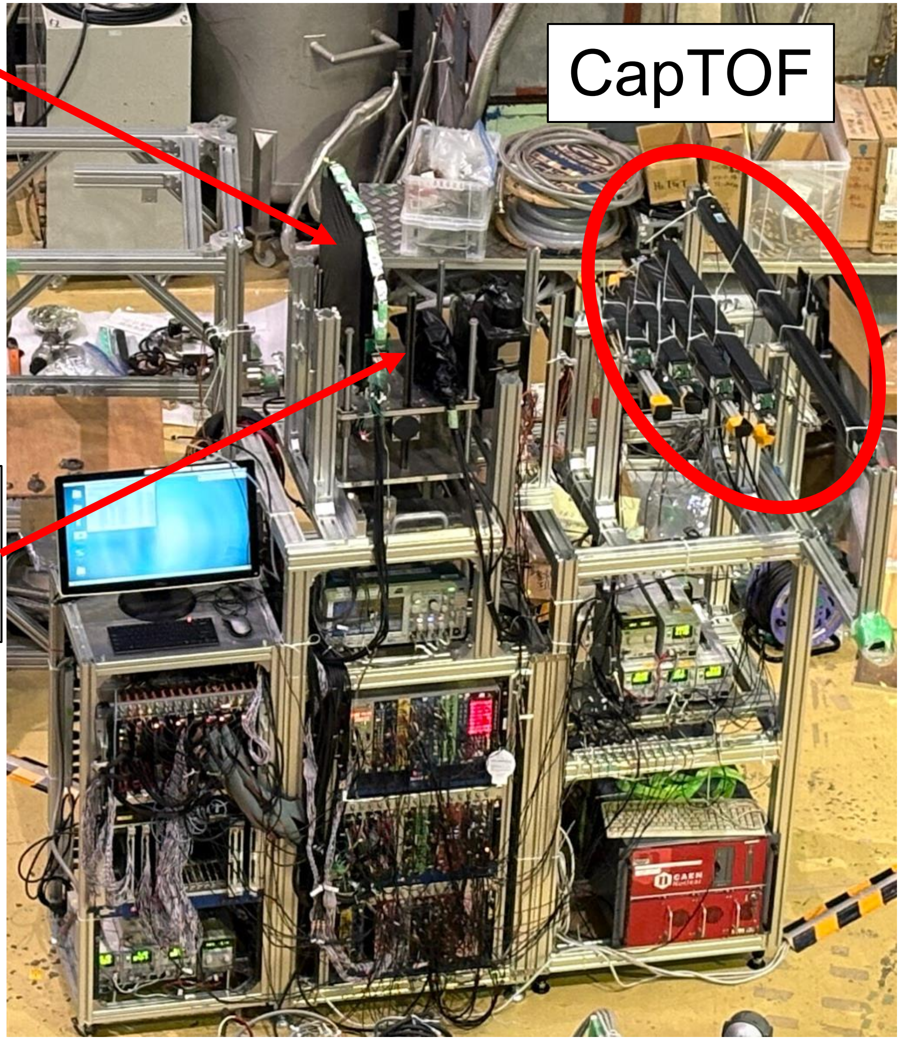
Polarimeter Tracker



Aerogel Čerenkov Counter



@J-PARC K1.8BR



Summary and Prospect

- We are preparing a new experiment on kaonic nuclei at J-PARC.
- The construction of a large–solid-angle Cylindrical Detector System (CDS) is in progress.
- Installation to the beamline is planned for next autumn, and the first physics data-taking for the J-PARC E80 experiment is expected by the end of FY2026.

A new era of kaonic-nuclei experiments is just ahead!

Thank you for your attention.

J-PARC E80 Collaboration

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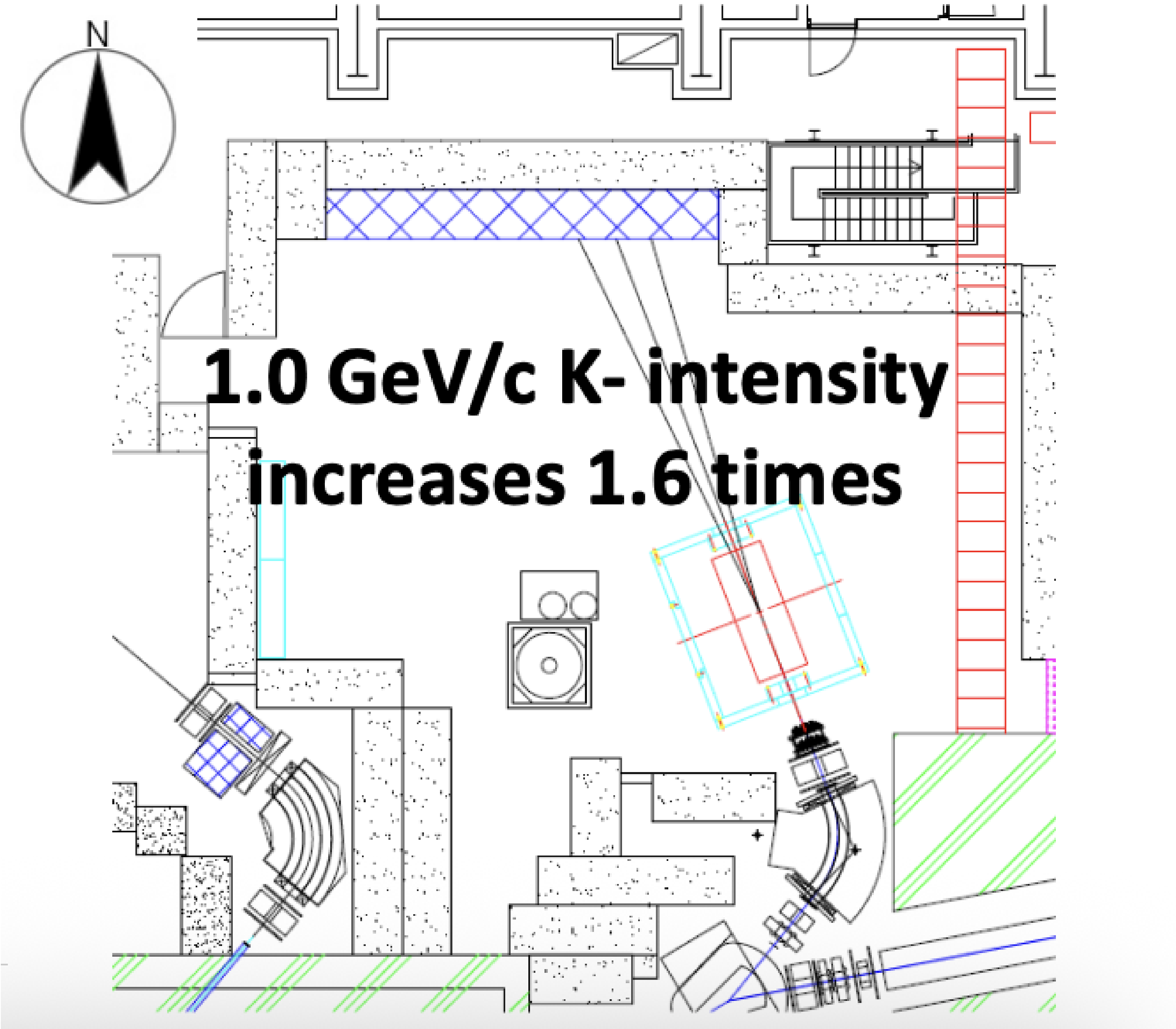
Back up

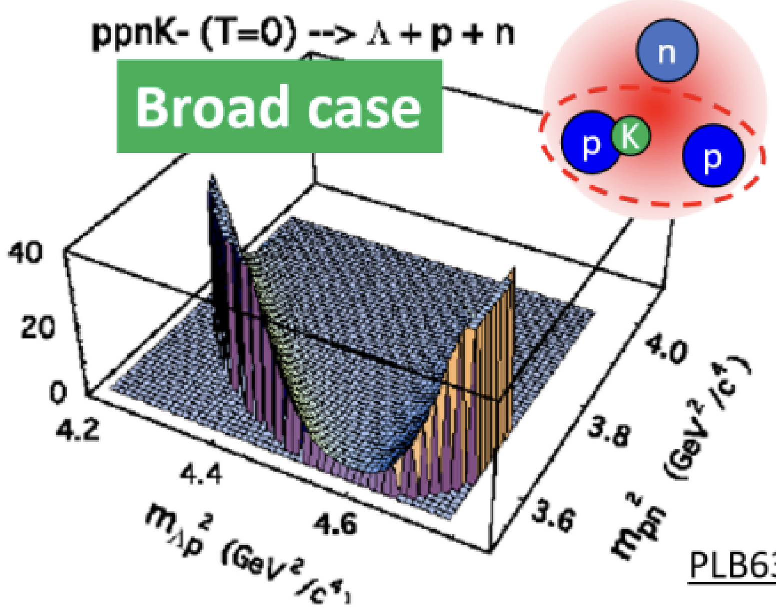

N
1.0 GeV/c K- intensity
increases 1.6 times

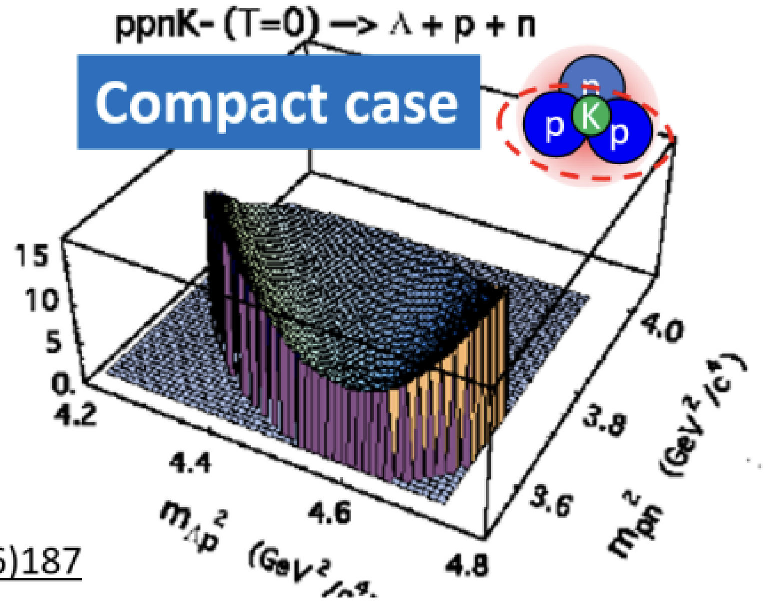
Study the multi-particle decay mode of $\bar{K}NNN$ toward understanding its internal structure

- “K-ppn”→Λpn 3-body decay

Paul Kienle [a,b], Yoshinori Akaishi [c,d], Toshimitsu Yamazaki [d,e,*]

Utilize Dalitz plots → Differences in distribution





PLB632(2006)187

Distributed in parts of the plane

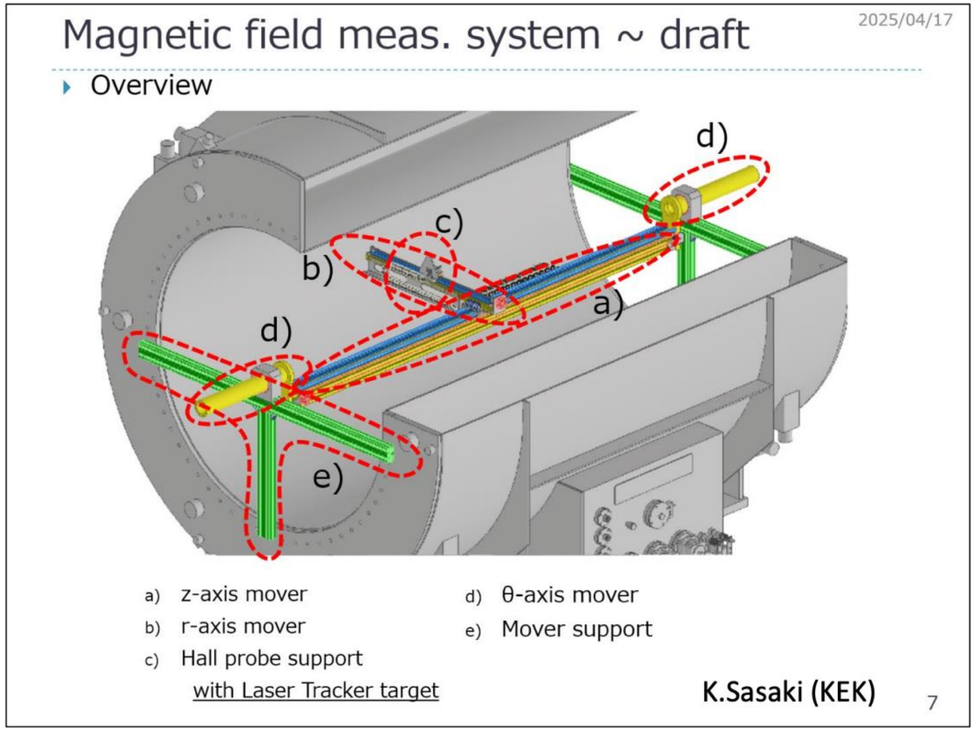
- 1 nucleon has the Fermi momentum

Widely distributed in the plane

- All particles have a momentum larger than the Fermi momentum

Superconducting Solenoid Magnet

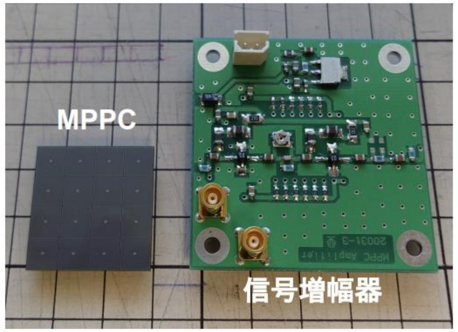
- **Preparing magnetic field measurement**
  - 3D measurement using 3-axis movable mechanism
- The basic design is the same as that of the COMET
  - Design work is ongoing in collaboration with the COMET Group
- Schedule:
  - Test the moving components this summer
  - Magnetic field measurement with return yoke at K1.8BR in autumn 2026



3.　円筒型中性子検出器(CNC)

CNCの読み出し素子

FM-PMT(Hamamatsu)
- 1.5 inch H8409(R7761)
- 19-dynodes
- 面積: ~ 570 mm^2(Φ=27 mm)
- 量子効率: 20 %



MPPC(Hamamatsu)
- S13361-6050AE-04
- 6 mm角の4×4 array
  hybrid × pararell結合で
  1 ch読出
- 面積: ~ 580 mm^2
- 量子効率: 40 %

信号増幅器
- 2段のRF増幅器
- PZC回路

→オプティカルグリースで両端に接着

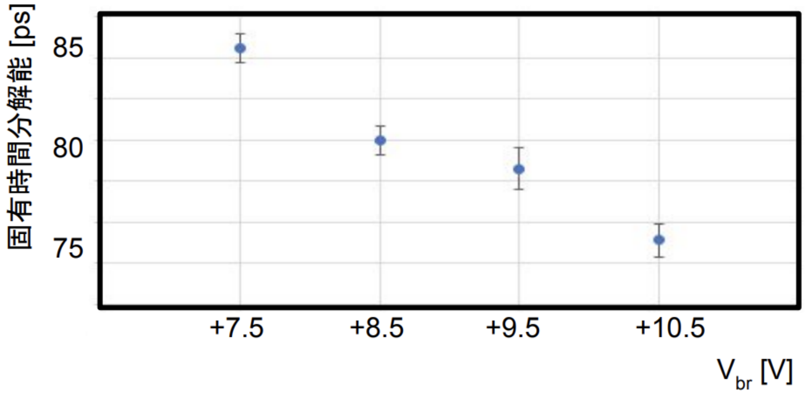
相対光量
FM-PMT : ~ 1
MPPC : ~ 2

MPPCの方が良い時間分解能が期待される

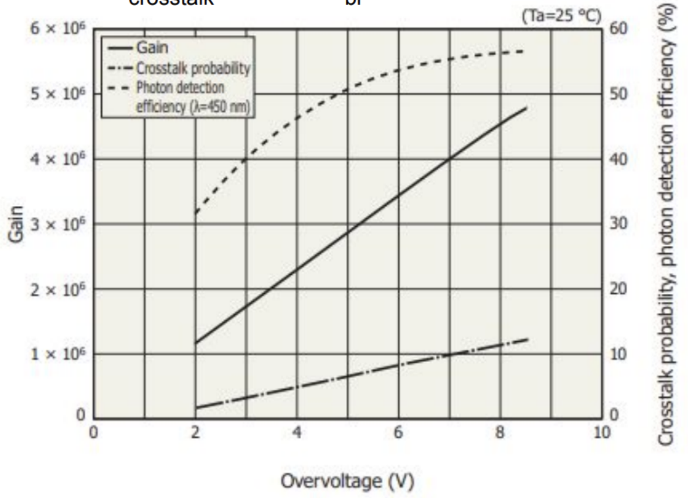
日本物理学会2025年春季大会　佐々木舜世（東北大RARiS 修士課程1年）　2025/3/20　11

解析結果

MPPCの時間分解能のバイアス依存性



Gain、$P_{crosstalk}$、eff.の V_{br}依存性（Hamamatsu）



要求性能達成！

σ_{MPPC}= 84.5 ± 0.7 ps @V_{br}= +7.5 V

σ_{PMT} = 118.6 ± 0.5 ps

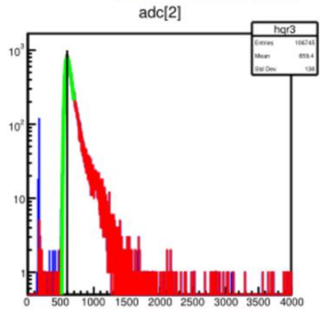
高バイアス
→eff., gain up
→光量up
→**良い時間分解能**

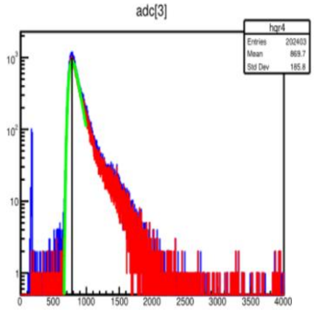
CNC: 時間分解能悪化の原因

時間分解能~90ps

時間分解能~75ps

QDC(raw, tdc cut)





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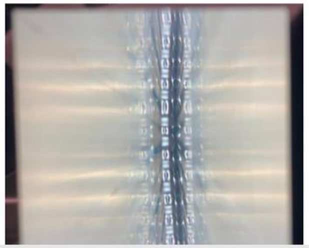
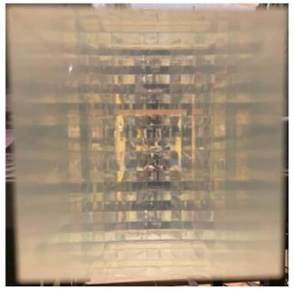


切断面表面の状態が悪い

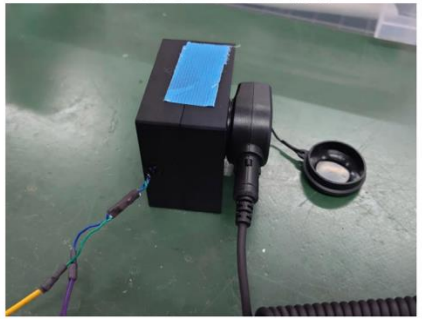


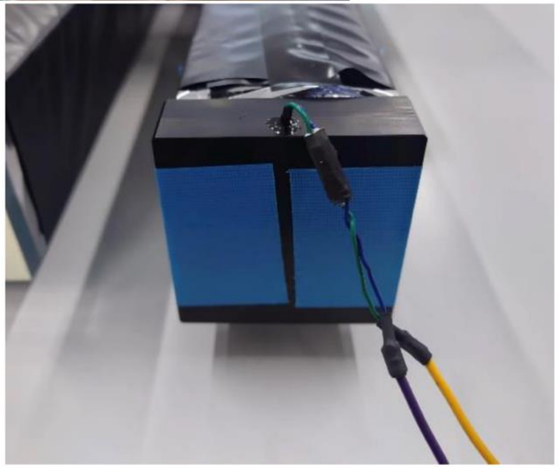
工場で簡易的に評価できないか？

8

CNC: 評価方法

LEDと照度計を用いた
透過度測定
CNC有とCNC無で
照度を比較





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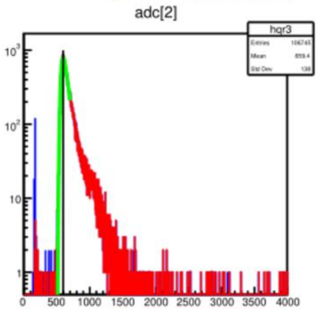
CNC: 時間分解能悪化の原因

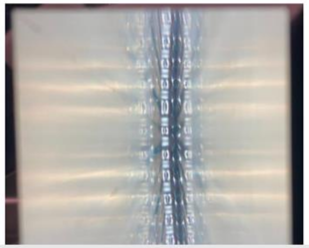
QDC(raw, tdc cut)

見た目

時間分解能~90ps

透過度測定値 28%

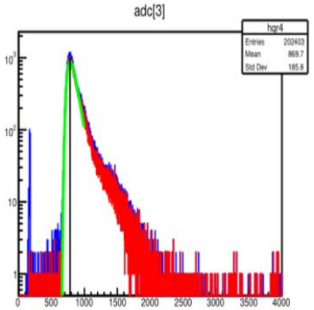


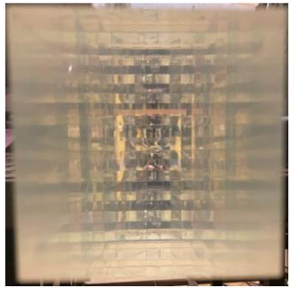


切断面表面の状態が悪い

時間分解能~75ps

透過度測定値 37%





簡易評価法を確立

By Shunto Sasaki (RARiS, M2)

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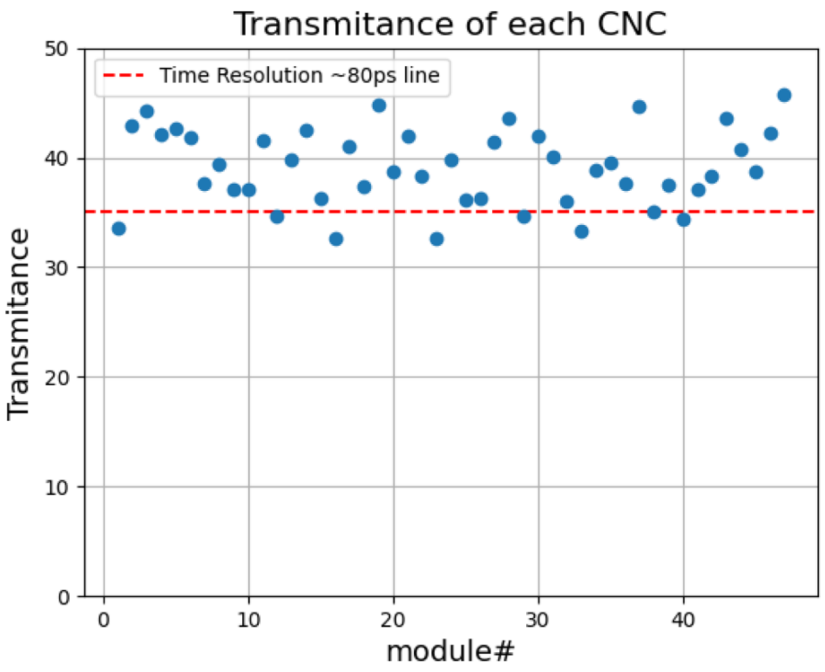
CNC: QA

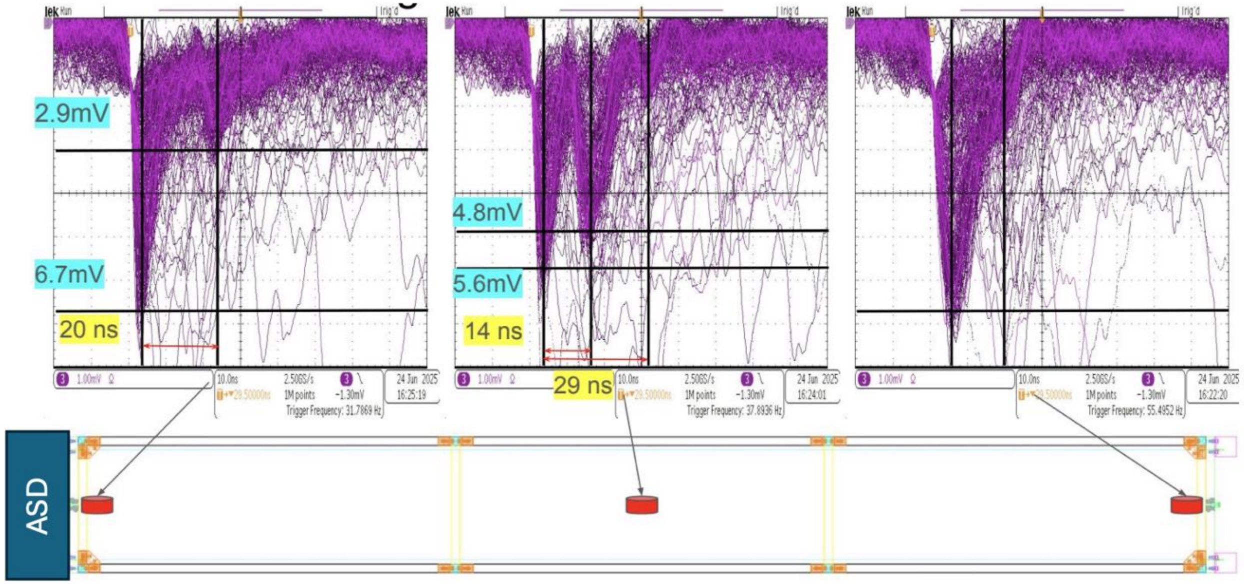


35%以下は再研磨予定　　**今年度中に完成予定**

11

CDC: 生波形

- 反射波の影響が見える
  - ✓ **double-peak構造**
  - ✓ **波高の位置依存がある**



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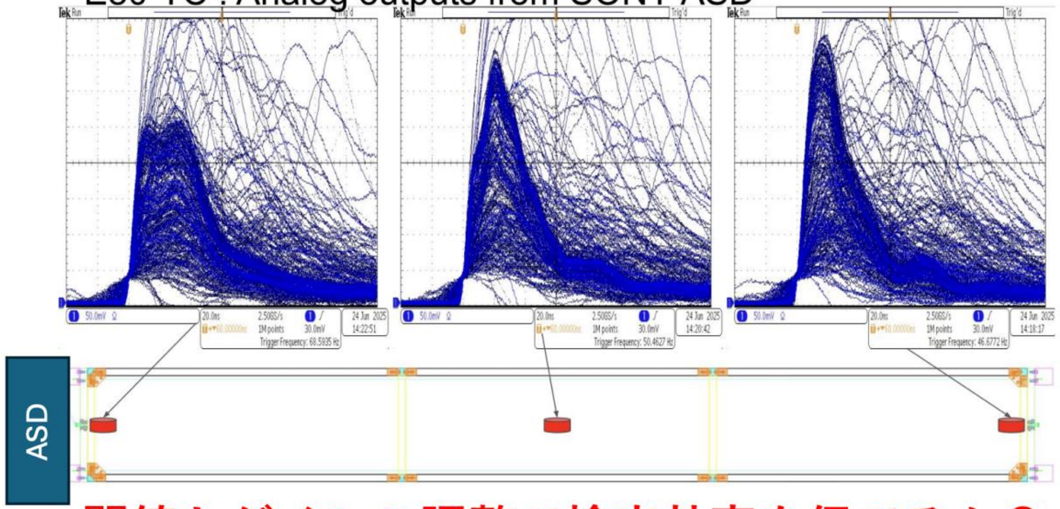
CDC : 整形後波形

- ■ 時定数16nsのプリアンプ出力でも同様に反射波の影響
  - ✓ 波形の位置依存がある
  - ✓ 電荷量（面積）は一定

E80-TC : Analog outputs from SONY-ASD



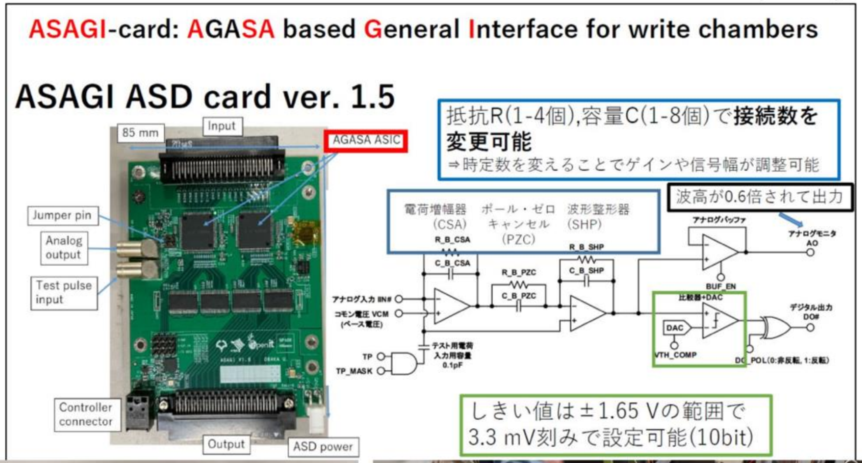
閾値とゲインの調整で検出効率を保てるか？

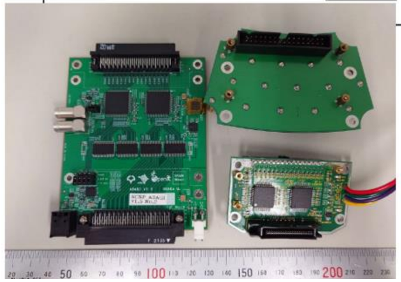
14

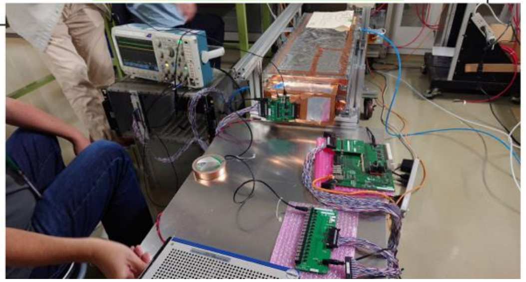
Cylindrical Drift Chamber (CDC)

K.Shirotori (RCNP)

- **Developing a new preamp card - ASAGI - in cooperation with SPADI/E50/NEOLITH**
  - Variable time constant and gain
  - New version of ASIC, AGASA v3.0, is currently under design
  - A new preamp card with the same dimensions as the current one is also being designed







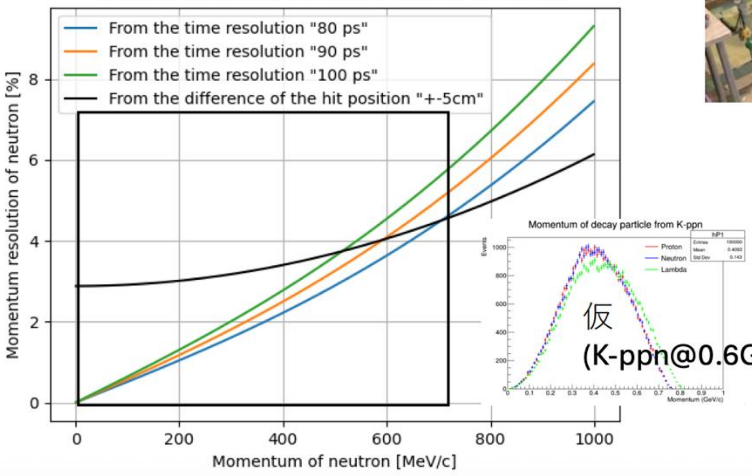
- ASAGI schedule:
  - Completed in JFY2025
  - Mass production in early JFY2026

The required performance

$$\sigma_{thick} > \sigma_{time}$$

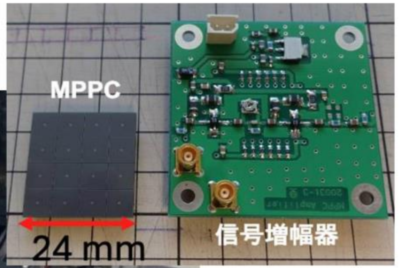
$$\Rightarrow \sigma_{time} \sim 80\text{ps}$$

Momentum resolution of neutron from each error

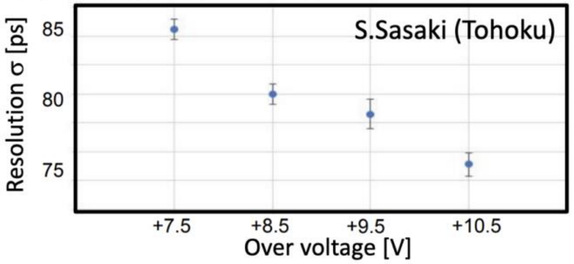


仮
(K-ppn@0.6GeV)

Proto-type test exp. in 2025



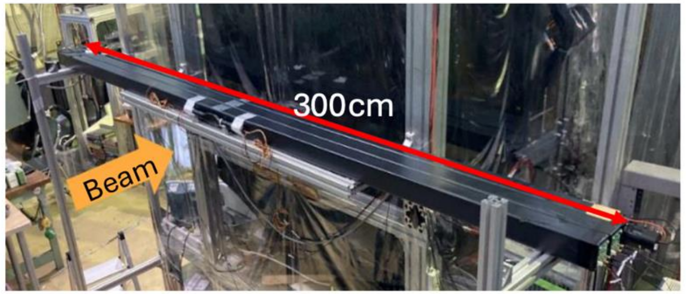
Bias-voltage dependence of time resolution

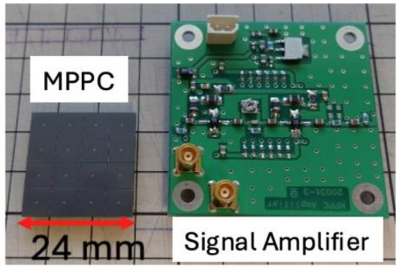


The required performance has been achieved:
σ_{CNC} ~ 80ps @ V_{OV} ~ +9V

Status: CNC

Proto-type test exp. in 2025





MPPC (Hamamatsu)
- S13361-6050AE-04
- 6 mm square, 4 × 4 array

Signal Amplifier
- Two-stage RF amplifier
- PZC circuit

Result

Counter	Read out	Length	thickness	Time Reso.
E15-CDH	PMT	80 cm	3 cm	~ 80 ps
CNC	PMT	300 cm	6 cm	~ 120 ps
CNC	MPPC	300 cm	6 cm	~ 80 ps

- ➢ Readout method of E15-CDH is not applicable for 300cm length.
- ➢ To improve light collection efficiency, we dicided to use MPPCs w/o light guides.

✓ **Readout study w/ prototype done (achieved required value σ ~80 ps even if 3m length counter)**
✓ **138 modules is in hand.**

K1.8BR Upgrade

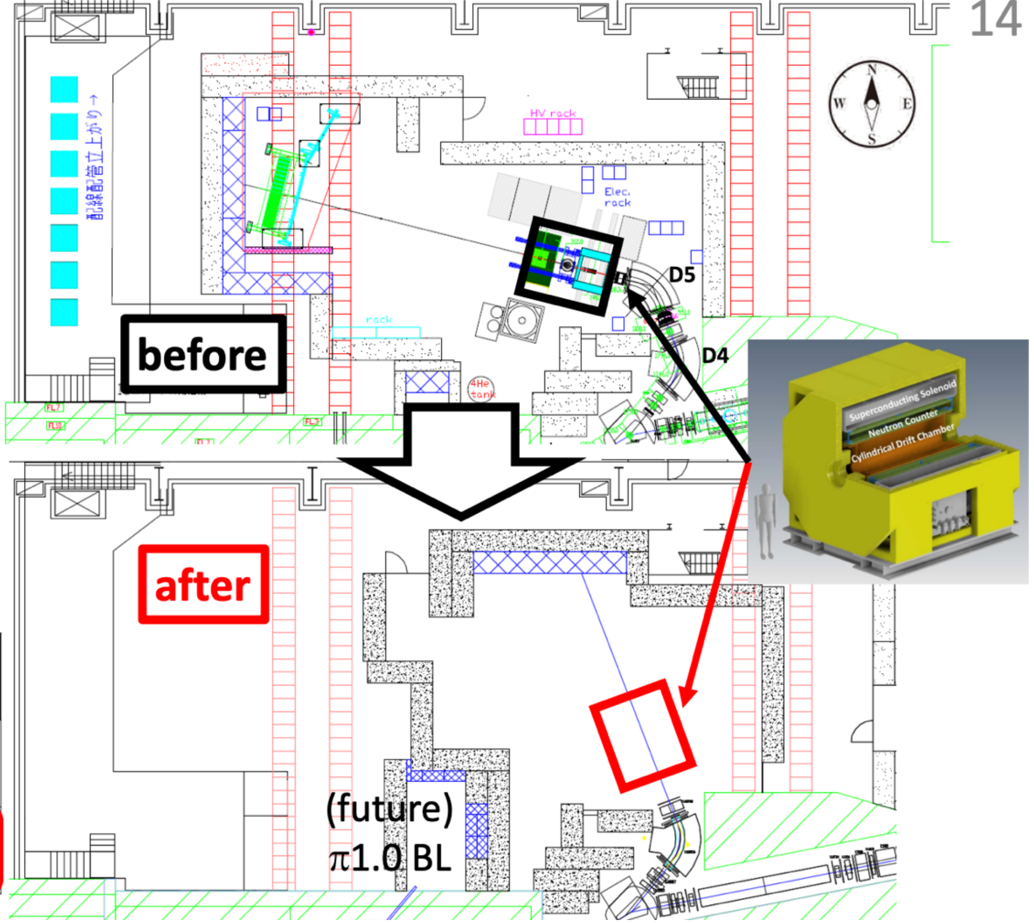
- We have proposed a new configuration of the beam line

Shorten the beamline (~3.7m) by removing the final D5 magnet

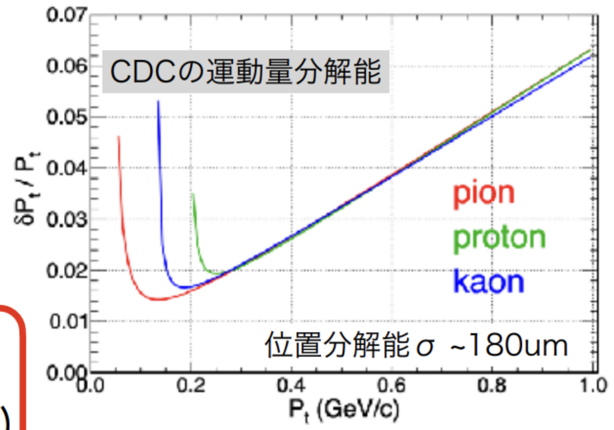
➢1.0 GeV/c K⁻ intensity increases 1.6 times

with π/K ~ 2

Relative beam-line length (beam yield)	D4+D5	D4
Present CDS	0 (x1)	-3.7m (x1.6)
New CDS	+1.2m (x0.9)	**-2.5m (x1.4)**

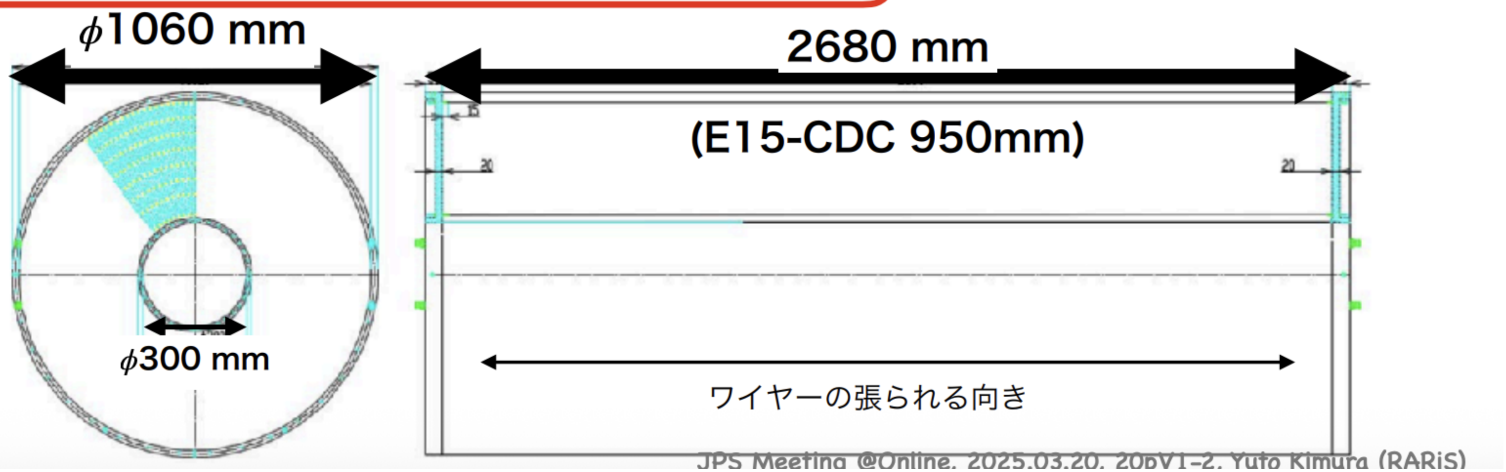


- E15の検出器システムではMass Resolution (σ) ~ 10 MeV/c^2。
  —> CDC運動量分解能はすでに十分な値。
  —> 基本設計はE15のCDCと同様に。



- ソレノイドが大きくなるため、
  合わせてできるだけビーム軸方向に長くして
  立体角を稼ぐ。

E15-CDC 立体角 2.6π ⟶ new-CDC 立体角 3.9π (93%/4π)



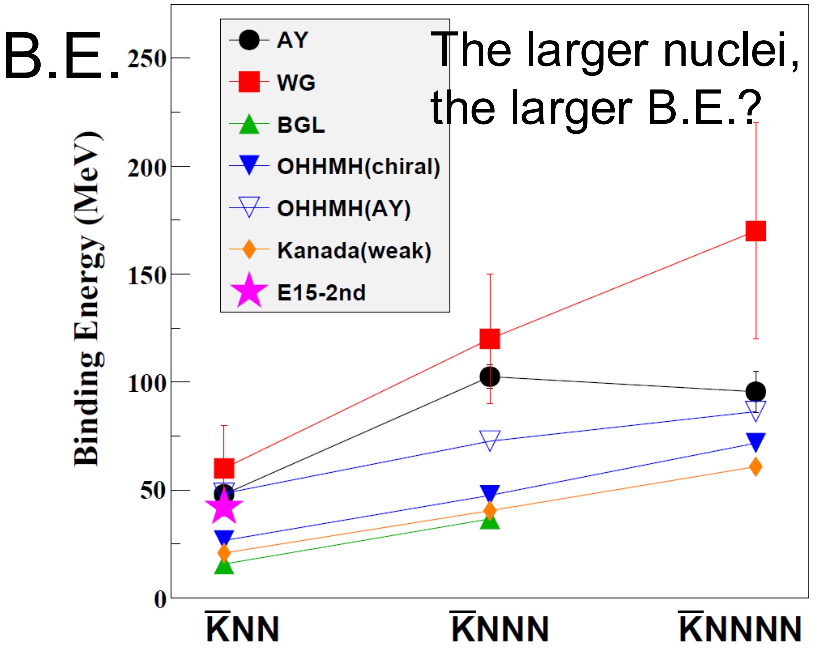
J-PARC E80: "$K^{-}ppn$"

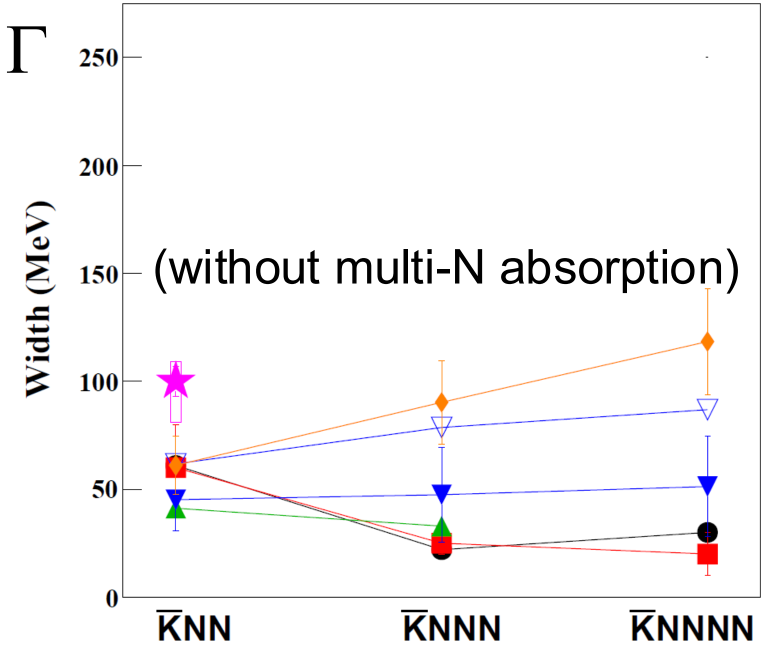
AY: PRC65(2002)044005,
PLB535(2002)70.
WG: PRC79(2009)014001.
BGL: PLB712(2012)132.
OHHMH: PRC95(2017)065202.
Kanada: EPJA57(2021)185.

Motivation:

- ✓ Confirmation of **"$K^{-}ppn$"** (It should exist.) as a first step of the systematic investigation

Theory indicates kaonic nuclei beyond "$K^{-}pp$".

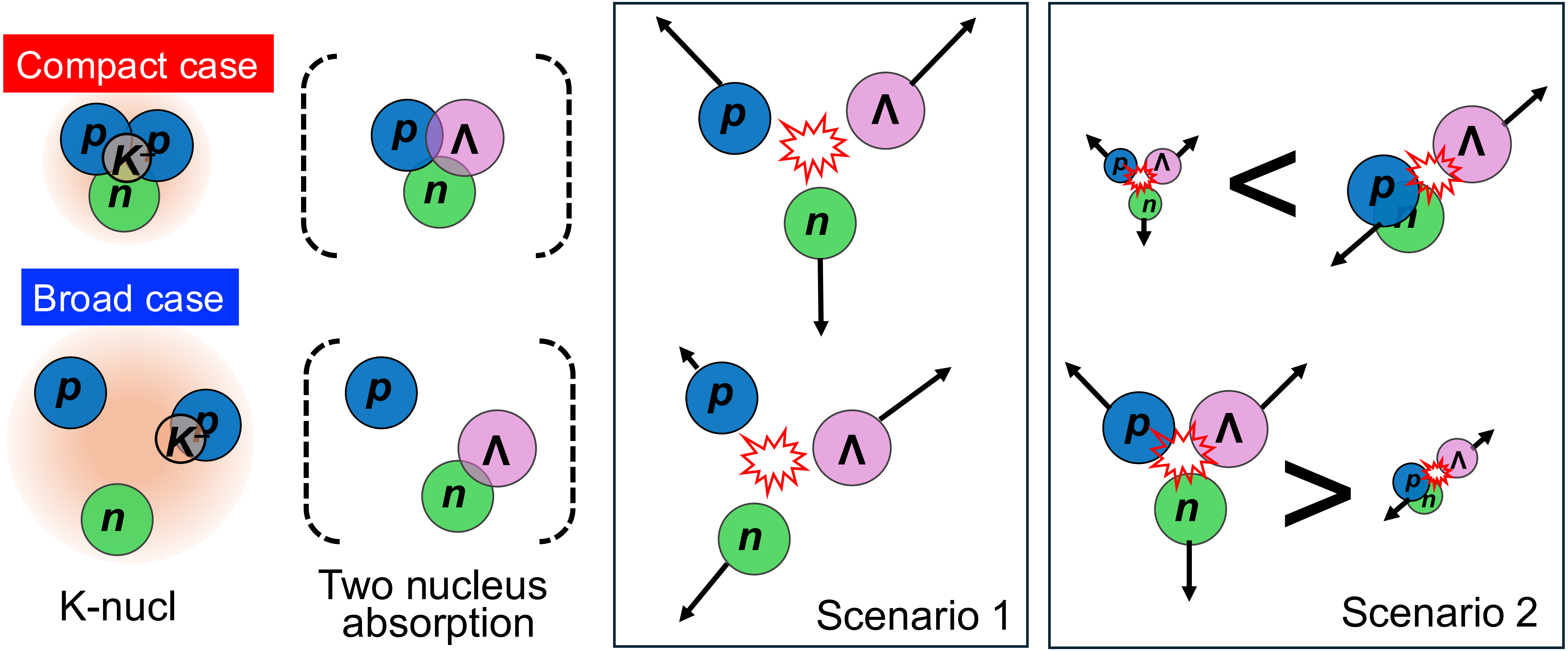




Systematic measurement will provide more conclusive evidence toward the general (heavier) kaonic nuclei.

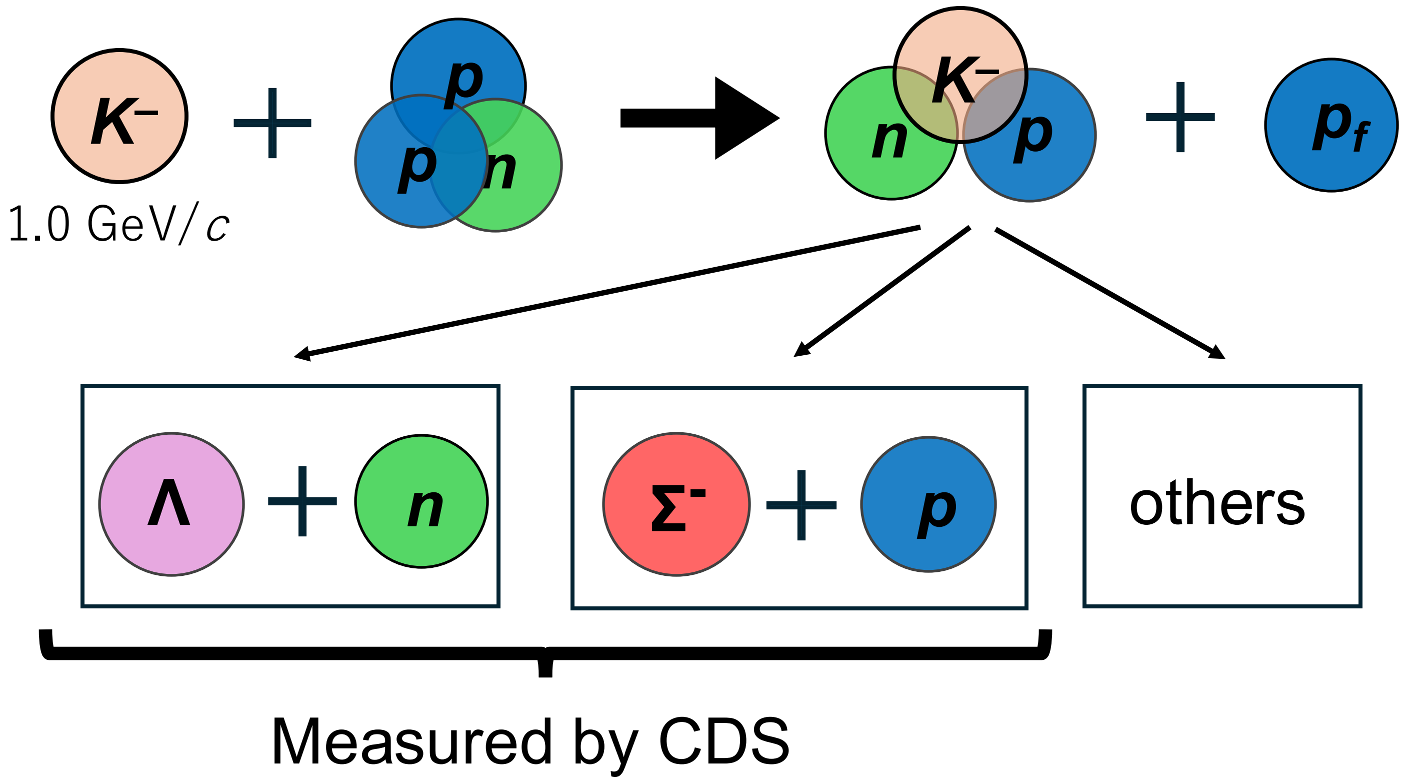
J-PARC E80: "$K^- ppn$"

Spatial size from three body decay



J-PARC E89: Further study of "$\bar{K}NN$"

1. Confirmation of **"$\overline{K^0}nn$"**, iso-spin partner of "$K^- pp$"

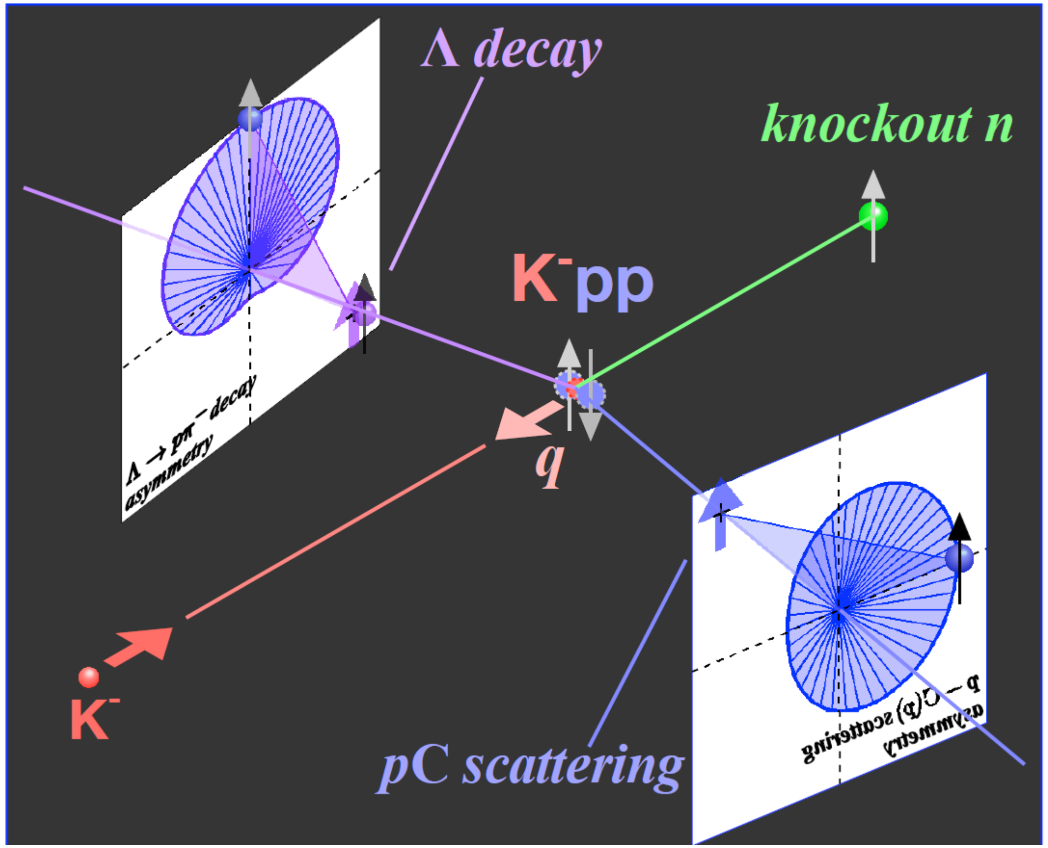


Neutron should be detected.

J-PARC E89: Further study of “$\bar{K}NN$”

2. Determine **the spin-parity of “$\bar{K}NN$”**

spin-spin correlation between Λ and p



We will use

- the Λ -> pi- + p week decay asymmetry
- proton scattering asymmetry
    - Proton is to be scattered by CNC.

Tracker for p-C scattering is necessary.

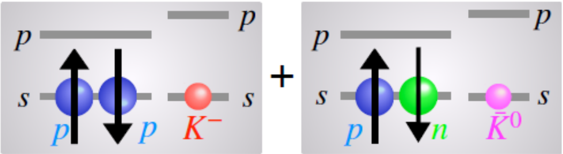
J-PARC E89: Further study of “$\bar{K}NN$”

2. Determine **the spin-parity of “$\bar{K}NN$”**

There are two possible configurations for the $\bar{K}NN$ ground state.

" $(NN)_{(I.sym\times S.asym)} \otimes \bar{K}$ "

$J^P = 0^-$

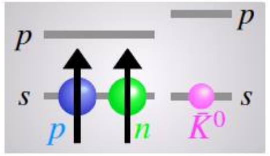


$$\frac{|I_{\bar{K}N}=0|^2}{|I_{\bar{K}N}=1|^2} = \frac{3}{1}$$

Deeper bound expected

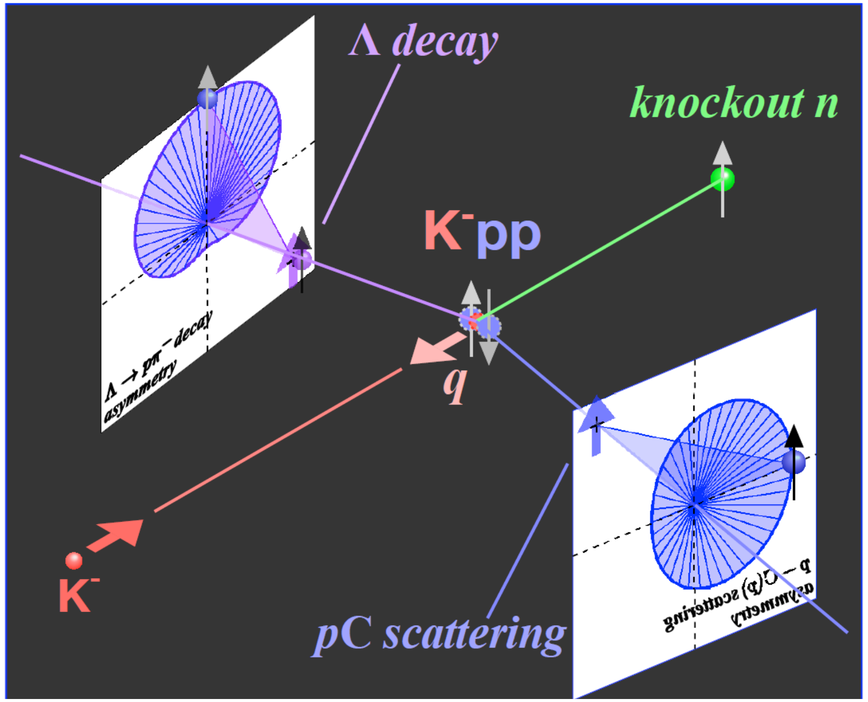
" $(NN)_{(I.asym\times S.sym)} \otimes \bar{K}$ "

$J^P = 1^-$



$$\frac{|I_{\bar{K}N}=0|^2}{|I_{\bar{K}N}=1|^2} = \frac{1}{3}$$

Shallower bound expected



Polarimeter for *pC* scattering is necessary.

Construction Status (Main Detectors)