FUTURE EXPERIMENTS ON KAONIC NUCLEI AT K1.8BR

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for the J-PARC E80 and P89 collaboration

Contents

- KbarN interaction and K1.8 BR beamline
  - *Milestone experiment: J-PARC E15(-2nd)*

- Upgrade plan of beamline and solenoidal spectrometer system

- Proposed physics programs
  - E80: Systematic investigation of the light kaonic nuclei
    - via the in-flight ^{4}He(K^{-}, N) reactions
  - P89: spin-parity measurement of "K^{-}pp" and "K^{0}nn" search

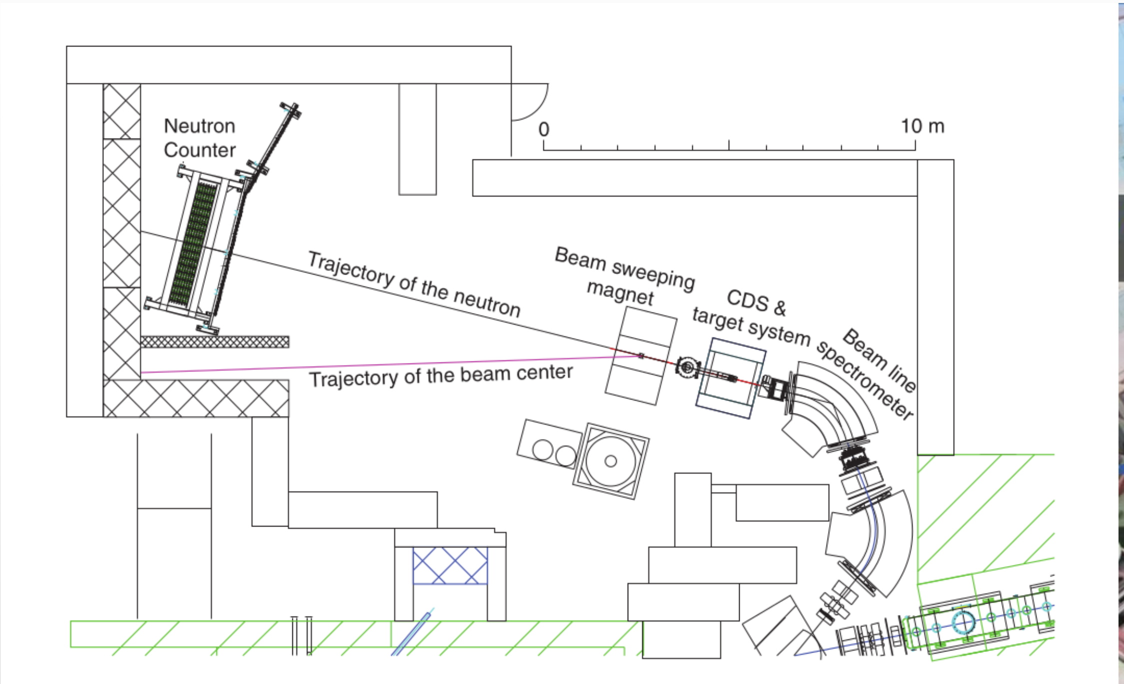
KbarN interaction

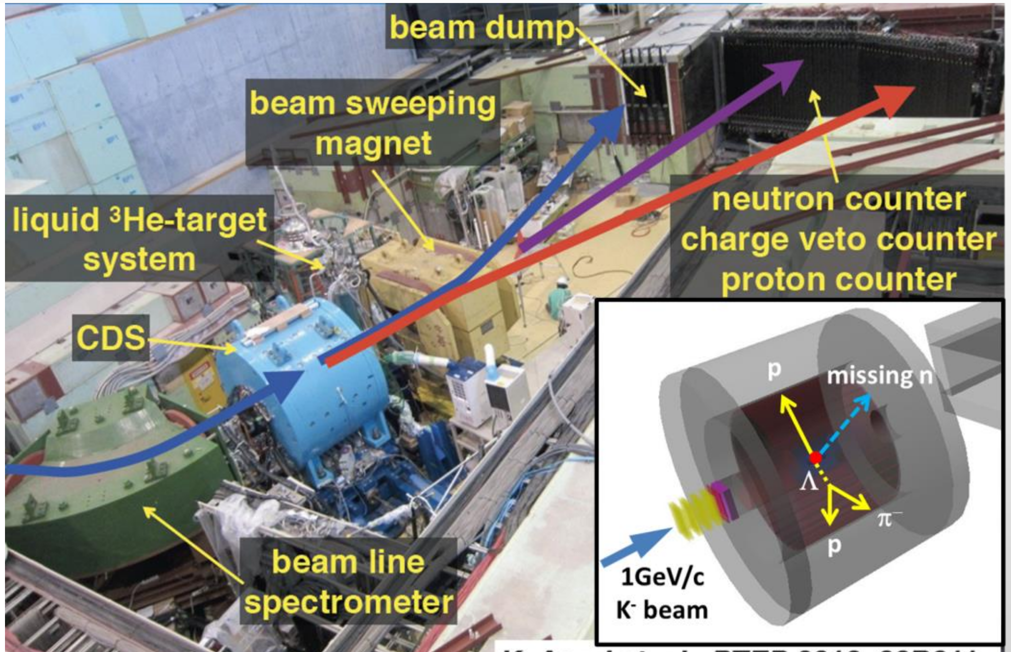
- Important subjects to understand meson-baryon interactions in low-energy QCD
- Attractive KbarN (I=0) interaction
  - *Specific property of KbarN interaction*

    ⇔πN interaction is repulsive in S-wave
  - *Λ(1405) can be interpreted as a quasi-bound state of KbarN*
    - The existence of kaonic nuclei is also discussed
  - *The lightest Kaonic nuclei: "K^-pp"*
    - Many experiments tried to establish the existence
      - *However, various results have been reported.*
      - *Positive: FINUDA@DAFNE, DISTO@SATURNE, E27@J-PARC*
      - *Negative:AMADEUS@DAFNE, HADES@GSI, LEPS@SPring-8*

Present K1.8 BR beamline @J-PARC

- 31.3 m beamline with 1-stage electrostatic separator
  - *Maximum momentum:1.2 GeV/c, $\pi^{\pm}$, $K^{\pm}$, p, pbar beams are available*
  - *Typical K^- beam (accelerator power 51kW) :*1.0 GeV/c, 210 k /(spill=5.2 s), K^-/pi$^-$=0.5,
- Many physics programs on KbarN interaction have been performed!
  - *Kaonic atom : X-ray spectroscopy of K^-d (E57), K^-^{3}He(E62)*
  - *Λ(1405) : Spectroscopy of Λ(1405) (E31)*
  - *Kaonic nuclei : search for **“K^-pp” (E15)** and “KbarNNN” (T77-byproduct)*





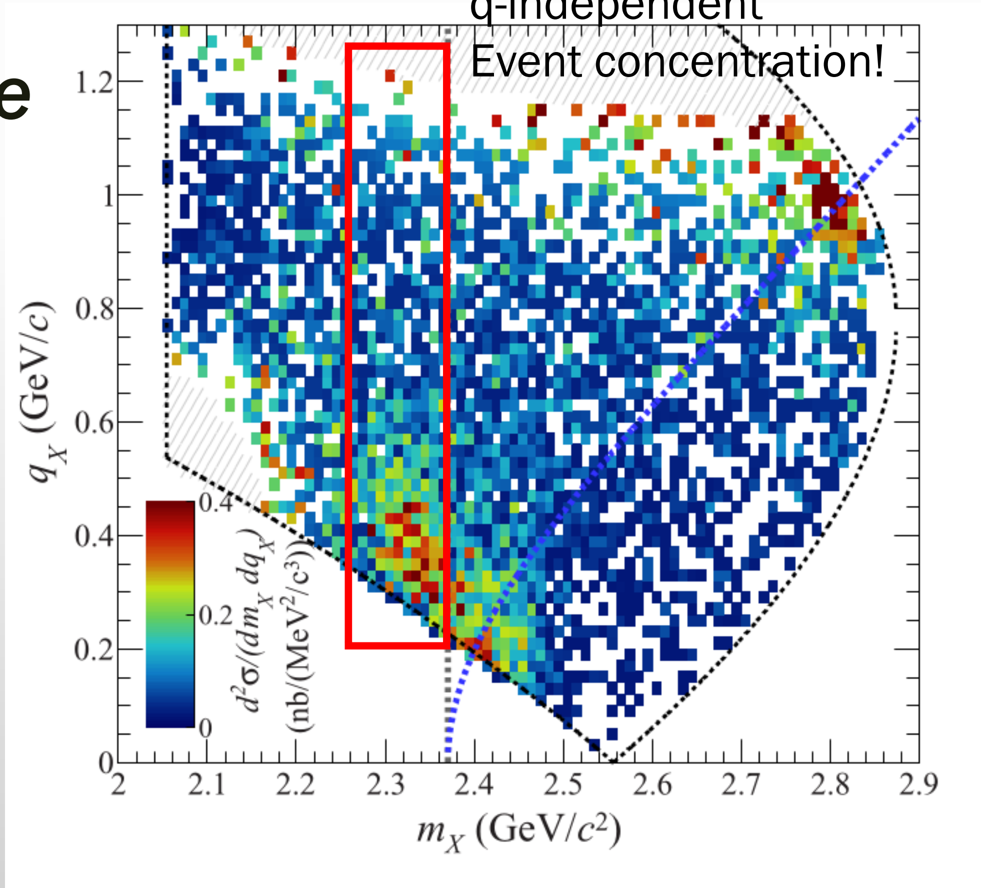
K. Agari et. al., PTEP 2012, 02B011

Milestone experiment : J-PARC E15(-2nd)

- "$K^{-}pp$" search experiment
  - *Using the in-flight $K^{-}+^{3}He$ reaction*
    - reaction process is clear
  - ***Exclusive analysis of the Λpn final state***
    - Not only the Λp invariant-mass (m_X) but also momentum transfer to the Λp system (q_X) were reconstructed
      - *"Bound state" is efficiently distinguished from Quasi-free K^{-} absorption*

PRC102(2020)044002.

q-independent
Event concentration!

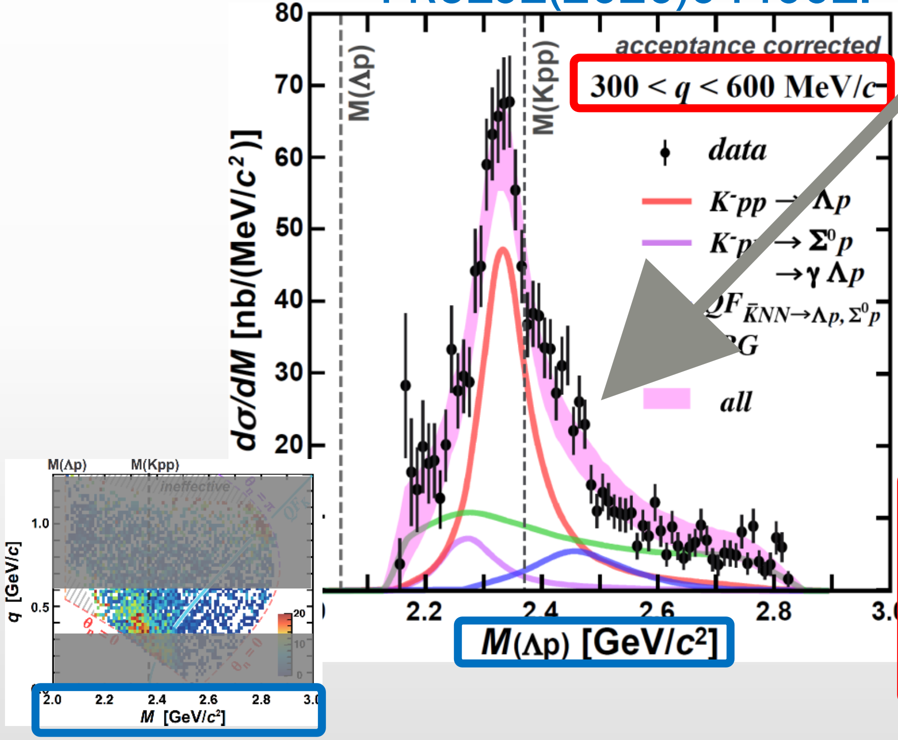


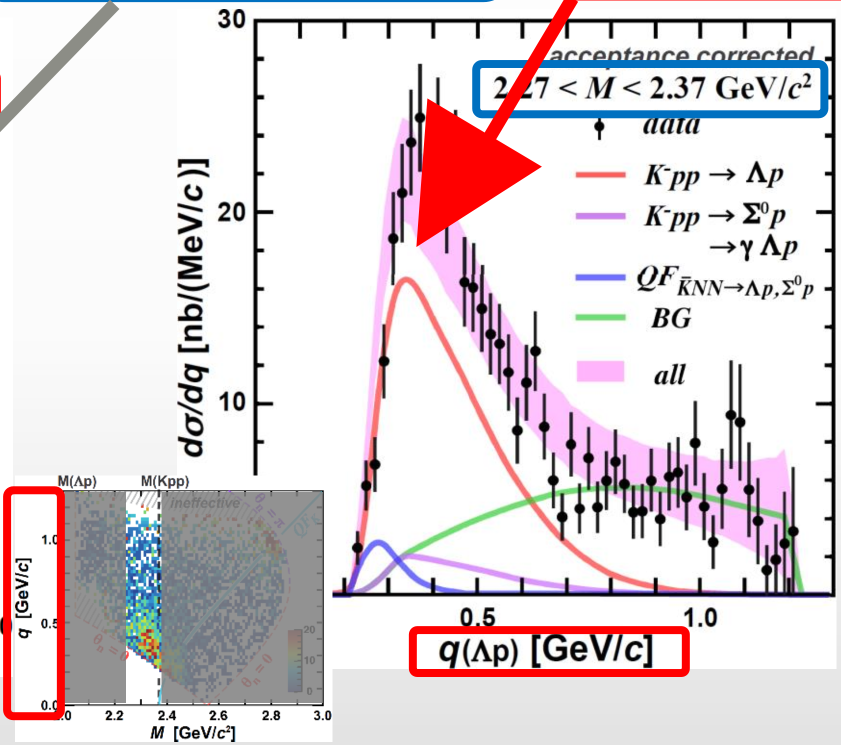
Milestone experiment : J-PARC E15(-2nd)

- Fitting 2D-plot with PWIA

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

PRC102(2020)044002.





B_{Kpp} ~ 40 MeV, Γ_{Kpp} ~ 100 MeV

→ *large binding energy*

Q_{kpp} ~ 400 MeV (c.f. Q_{QF} ~ 200 MeV)

→ *wide momentum transfer*

suggest the "K⁻pp" is quite compact($R_{Kpp} = \hbar/Q$ ~ 0.6 fm)

Further study on kaonic nuclei

- We want to apply successful E15 method to other kaonic nuclei
  - *Mesonic decay channel (πΛN, πΣN)*
    - Branching ratio between mesonic/non-mesonic channel provide information on density
  - *Heavier systems (KbarNNN, KbarNNNN,...)*
    - Mass dependence of binding energy? Density (size)?
  - *"K^0nn" search*
    - "K^0nn" →Λn decay etc...
    - Production cross section
      - *Provide information on J^π of KNN (spin-isospin selection rule)*

  ->More decay particles including neutron

  - *Determining detailed properties of "K^-pp" such as J^π*

- Required experimental upgrades
  - *Exclusive analysis needs detection of all particles from kaonic nuclei*
    - Solid angle, neutron detection efficiency
  - *More statistics*
    - Increase K^- beam intensity

  ->we are planning to upgrade beamline and spectrometer system

T. Sekihara et al., Phys. Rev. C, 86, 065205 (2012).

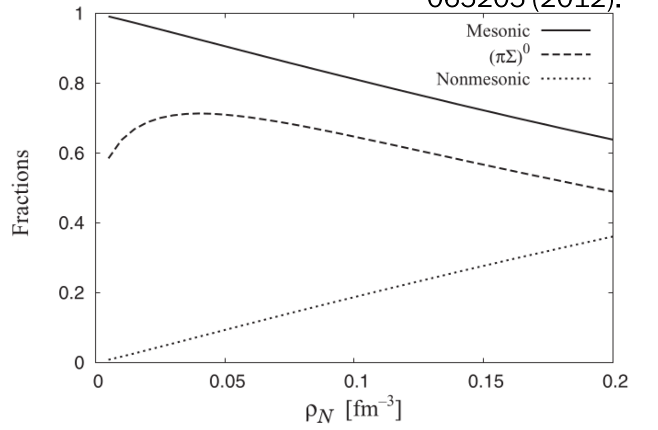
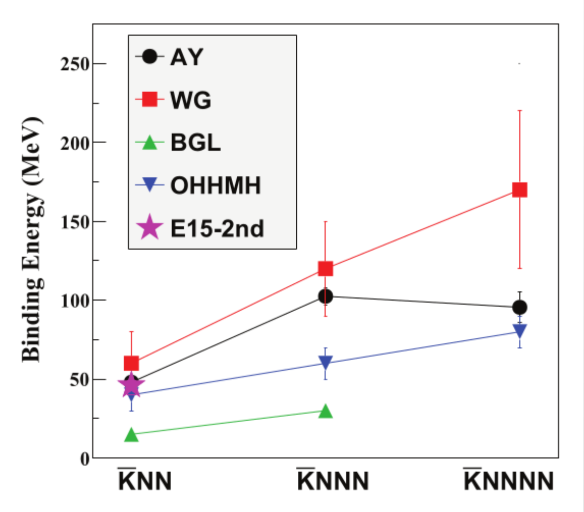
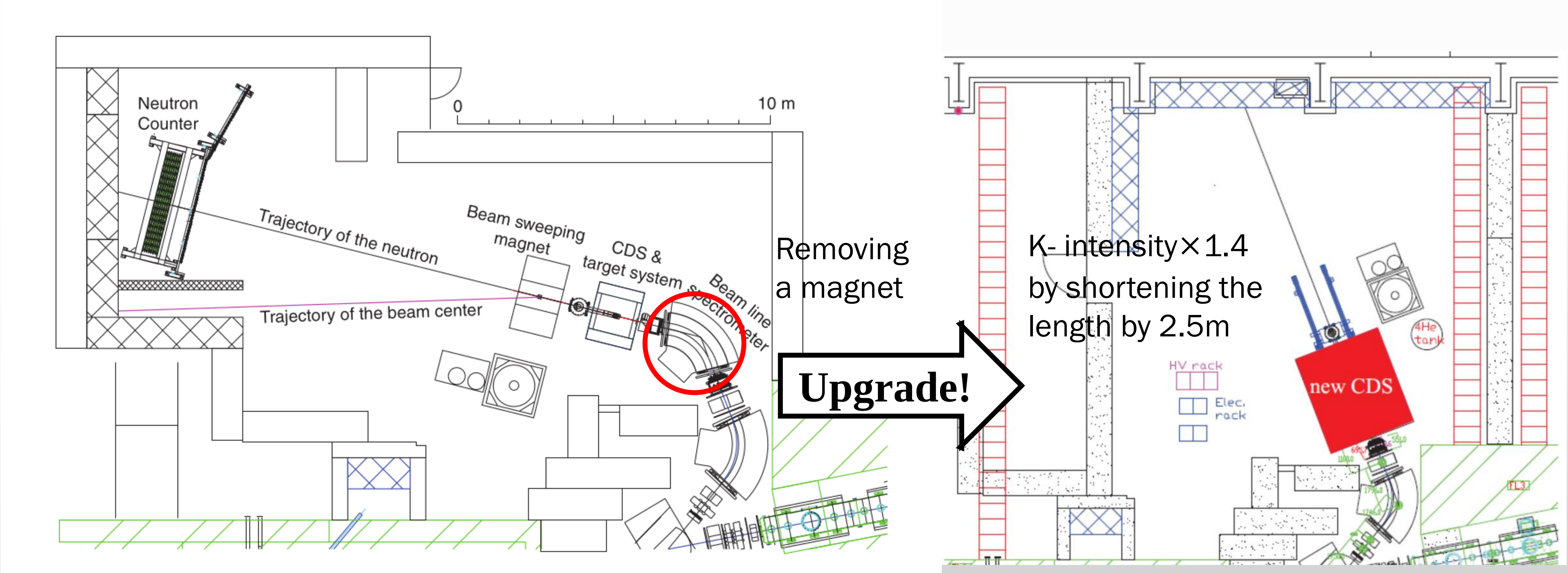


FIG. 13. Fractions of mesonic, sum of $(\pi\Sigma)^0$, and nonmesonic absorption to total absorption.



Upgrade plan of K1.8 BR beamline

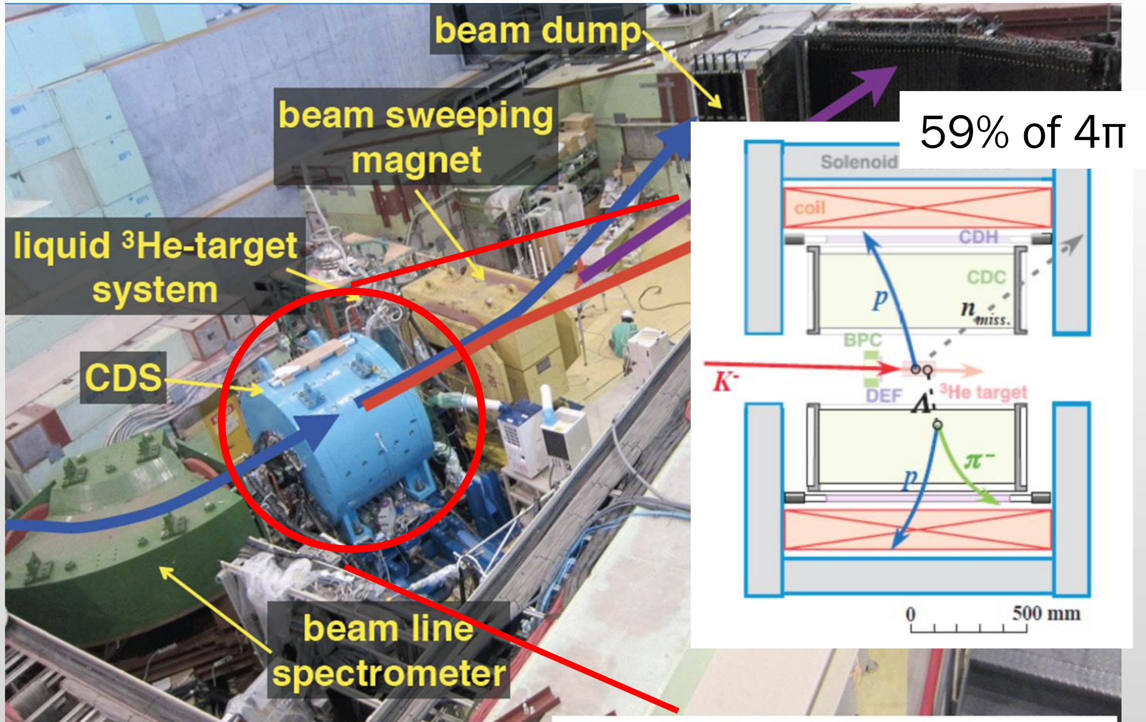
- **Beamline length: 31.3 → 28.8 m** by removing a magnet
- Expected K^- beam (accelerator power **90kW**)
  - 1.0 GeV/c, **420 k/(spill=4.2 s), K^-/pi$^-$=~**_**0.7**_ *(1.2M particle /spill)*
    - On target: 270k/spill
    - Spill cycle will be shortened due to upgrade of Accelerator



Present Spectrometer system @J-PARC

Momentum resolution 5.3 % for p_T
Vertex resolution:
σ_r～2-3 mm, σ_z～1cm
β resolution 0.5 %

- solenoidal spectrometer
  - *Normal-conducting solenoid magnet (0.7T over tracking volume)*
  - *CDC (Cylindrical Drift Chamber)*
  - *CDH (Cylindrical Detector Hodoscope)*
    - 3cm-thickness, neutron detection efficiency ～3%

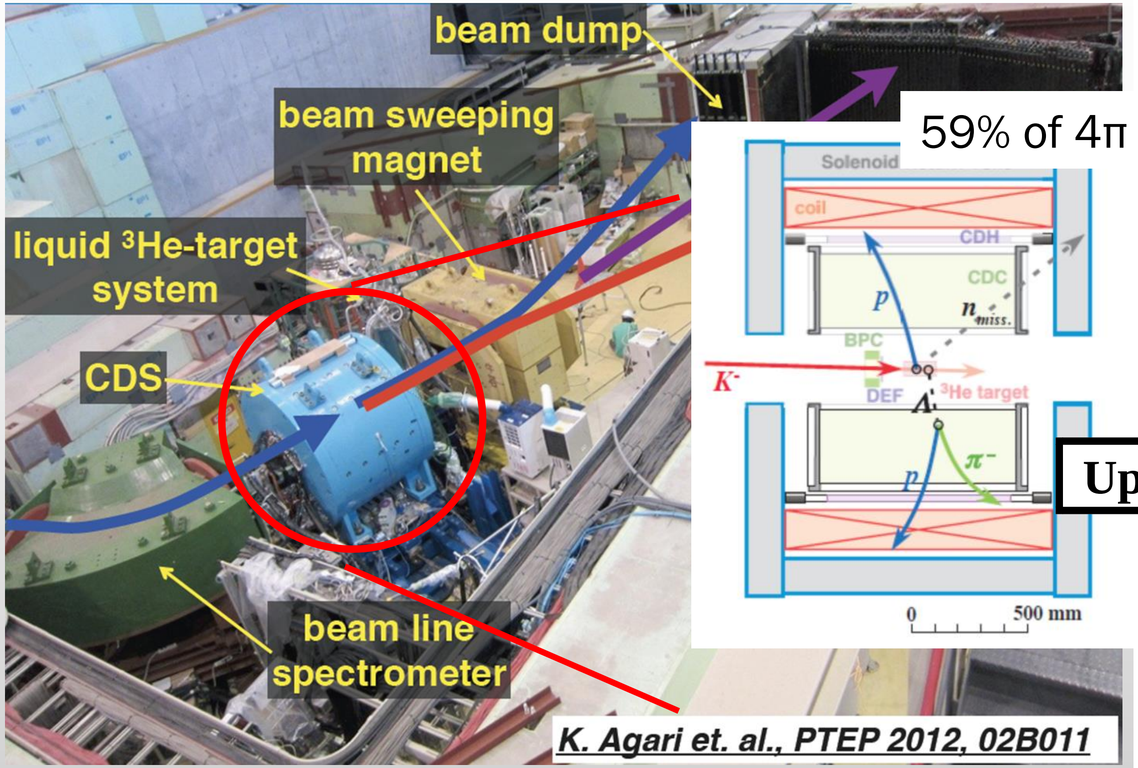


K. Agari et. al., PTEP 2012, 02B011

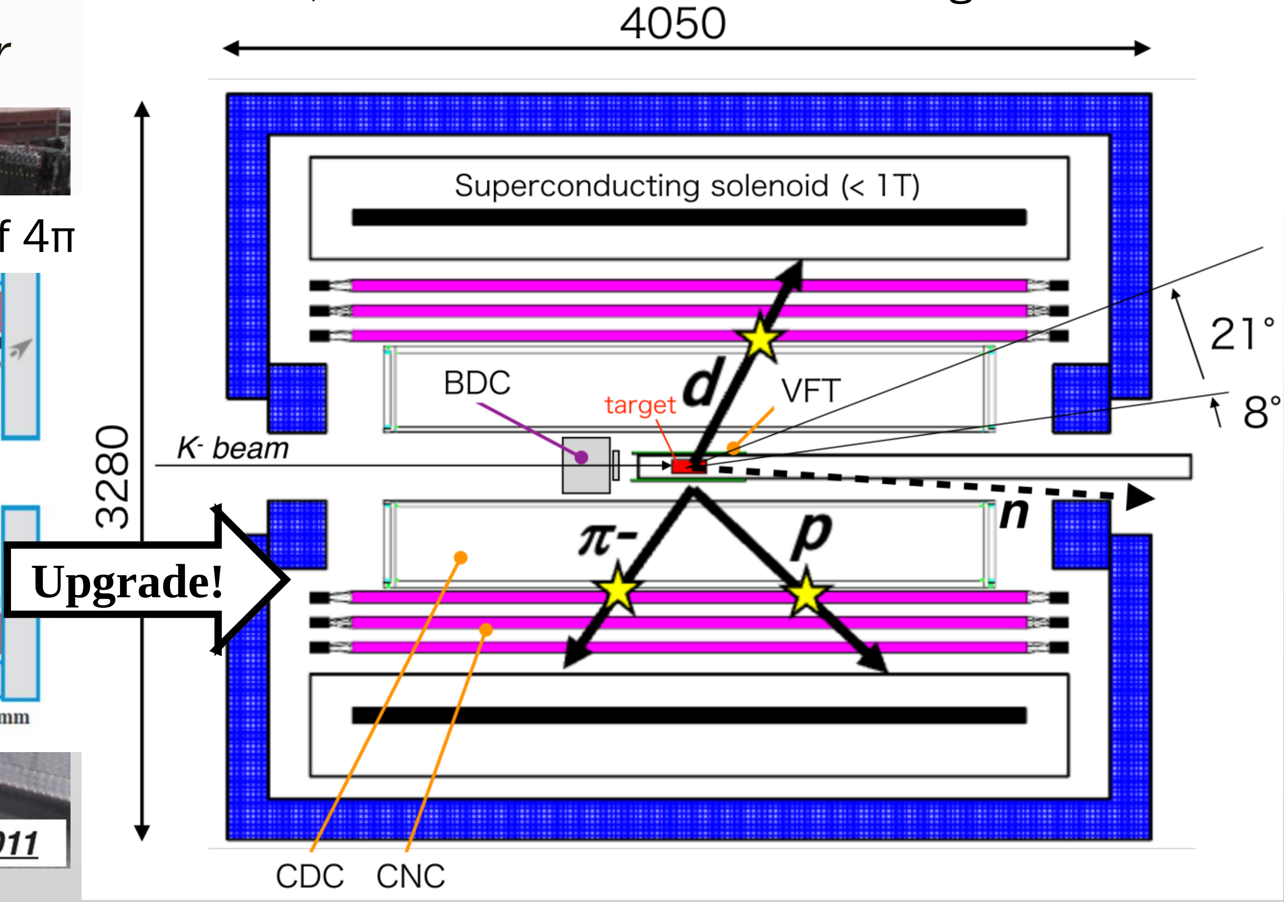
Upgrade plan of Spectrometer system @J-PARC

- solenoidal spectrometer with larger acceptance
  - *Superconducting solenoid magnet (0.7T over tracking volume)*
  - *CDC (Cylindrical Drift Chamber)*
  - *CNC (Cylindrical Neutron Counter)*
    - **5×3 cm thickness plastic scintillator array**
  - *VFT (Vertex Fiber Tracker)→new detector*

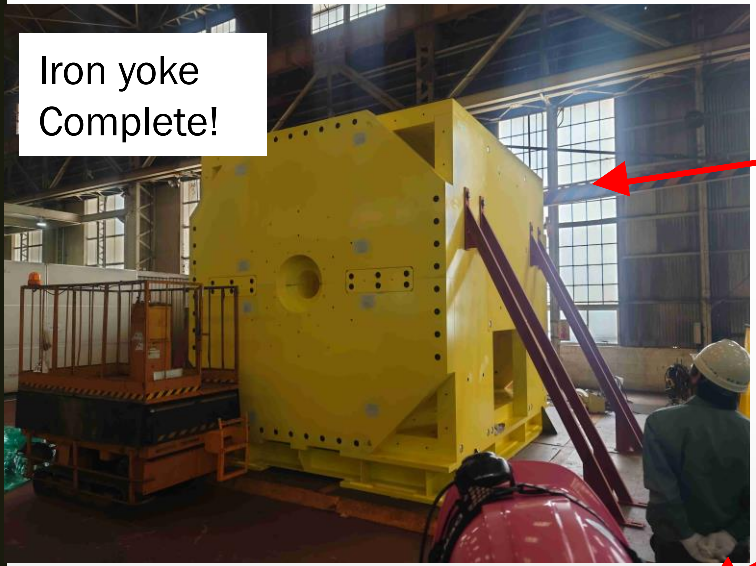
Momentum resolution **2-3 %** for p_T
Vertex resolution:
σ_r～2-3 mm, $\boldsymbol{\sigma_z}$**～1mm**
β resolution 0.5 %
Performances will retain or will be improved!

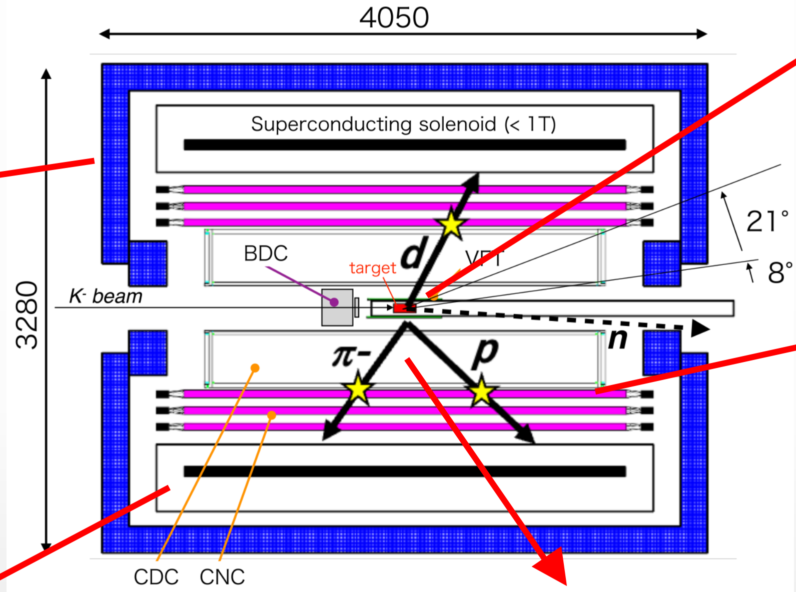


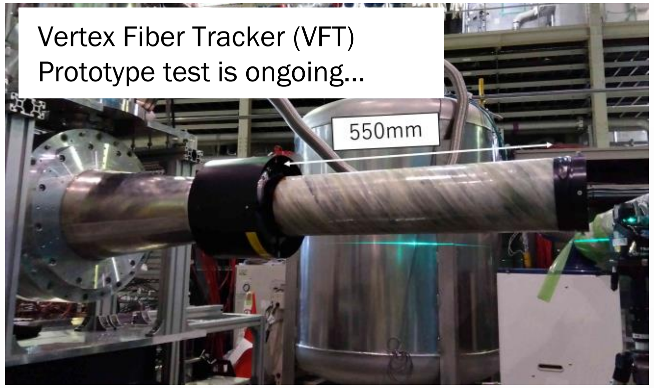
93% of 4π, detectors will be ～3 times longer

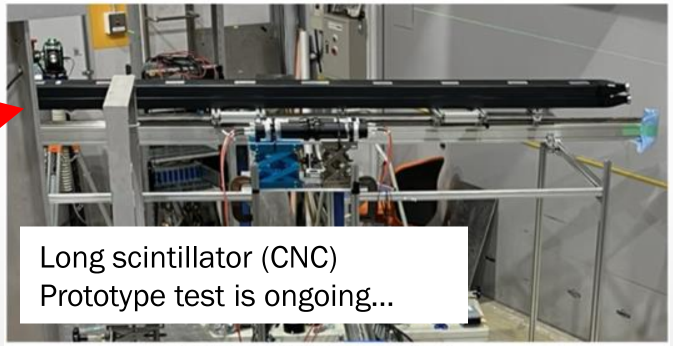


Development status of new spectrometer

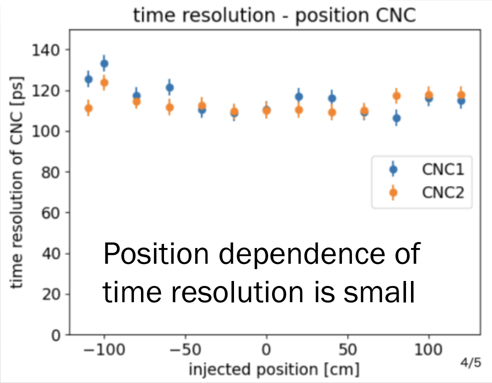


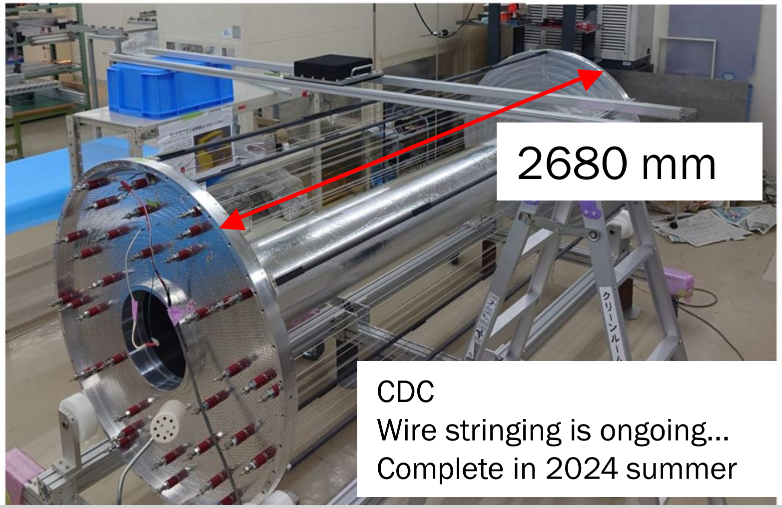






@ GeV-γ irradiation room in ELPH





Schedule

- Beam line upgrade and Installation new spectrometer will start 2025 summer
  - *After E73 ($^{3}_{\Lambda}H$ lifetime measurement) and E72 (Λ^{*} resonance search)*
- Commissioning run for new spectrometer will be performed in FY2026.
  - *LH_2 target, for about 1 week beamtime*
- physics run with new spectrometer will be started FY2026
  - ***1st step: J-PARC E80 experiment***
    - Search for KbarNNN via $^{4}He(1\ GeV/c\ K^{-},n)$ reaction

<table>
<tr><th rowspan="2"></th><th colspan="4">FY2022</th><th colspan="4">FY2023</th><th colspan="4">FY2024</th><th colspan="4">FY2025</th><th colspan="4">FY2026-</th></tr>
<tr><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th><th>Q1</th><th>Q2</th><th>Q3</th><th>Q4</th></tr>
<tr><td>SC Sorenoid</td><td colspan="2">Design</td><td colspan="2">Purchase (Yoke, SC wire)</td><td colspan="9">Construction</td><td colspan="2">Installation & test</td><td colspan="3" rowspan="4">Integration</td><td rowspan="4">Commissioning</td><td rowspan="4">Physics run</td></tr>
<tr><td>CNC</td><td colspan="10">Design & prototype test</td><td colspan="3">purchase & assemble</td><td colspan="2">test & commissioning</td></tr>
<tr><td>CDC</td><td colspan="7">Design</td><td colspan="2">Construction</td><td colspan="6">test & commissioning</td></tr>
<tr><td>VFT</td><td colspan="3"></td><td colspan="7">prototype test & performance evaluation</td><td colspan="3">production</td><td colspan="2">test & commissioning</td></tr>
<tr><td>K1.8BR beam line</td><td colspan="9">E73 (lifetime measurement of hypertriton) experiment</td><td colspan="4">E72 (Λ* resonance search with HypTPC)</td><td colspan="2">area rearrangement</td><td colspan="5">with new CDS</td></tr>
</table>

Proposed physics programs with upgraded experimental setup : E80 and P89

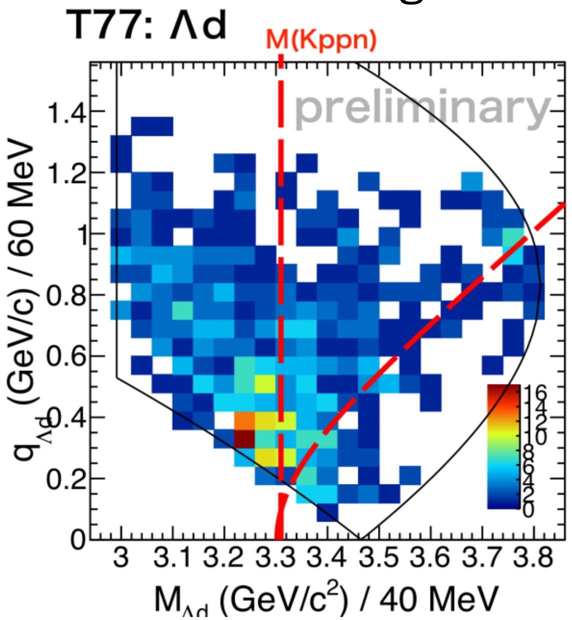
Proposed physics program-E80

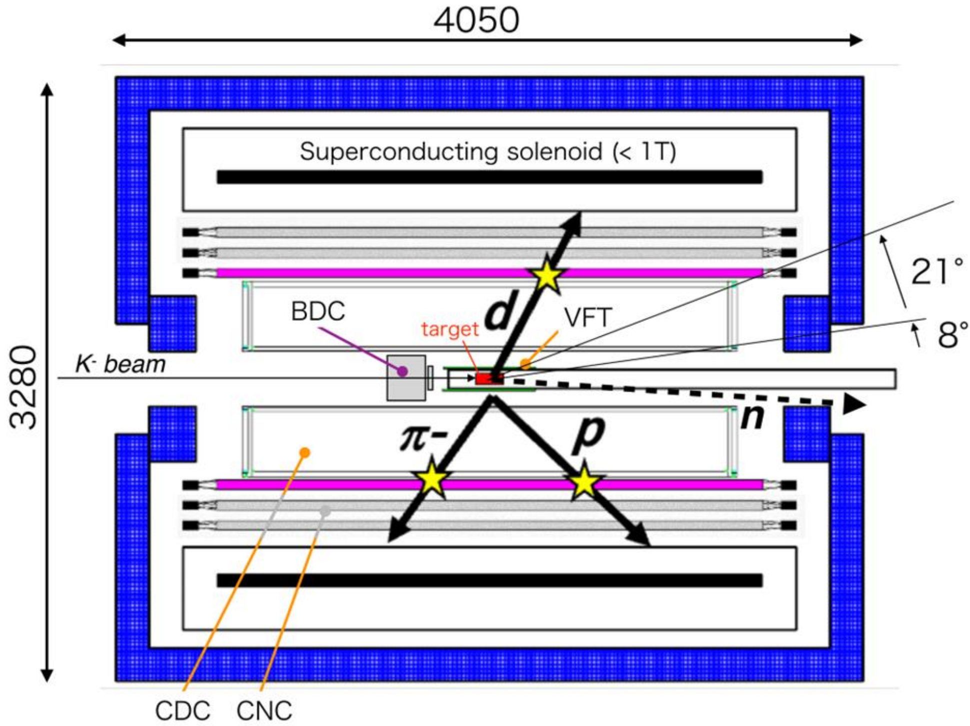
- Search for KbarNNN via ^{4}He(1 GeV/c K^-,n) reaction
  - *The K^-ppn state will be easily observed Via 2-body Λd decay*

  ->1st experiment of new CDS
    - Limited statistics data with Existing CDS
      - *J-PARC T77 biproduct, 6G K^-*
      - *Similar 2D plot to "K^-pp" case in E15*

  - *We also have a chance to reconstruct K^-ppn state via 3-body Λpn decay*

Result with existing CDC

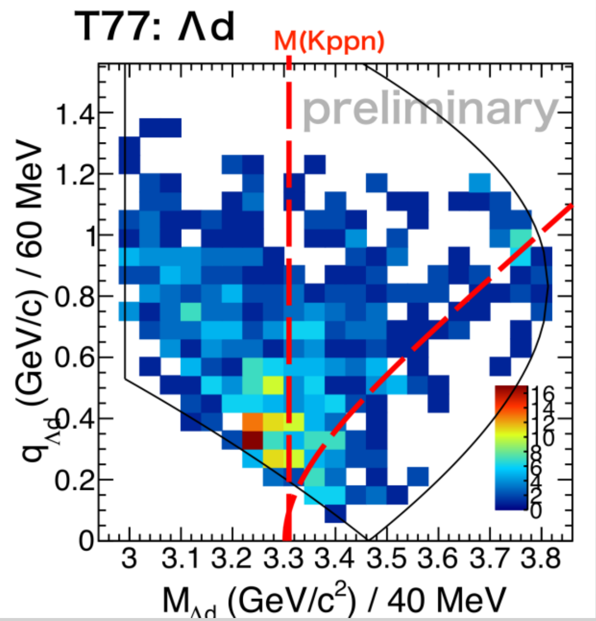


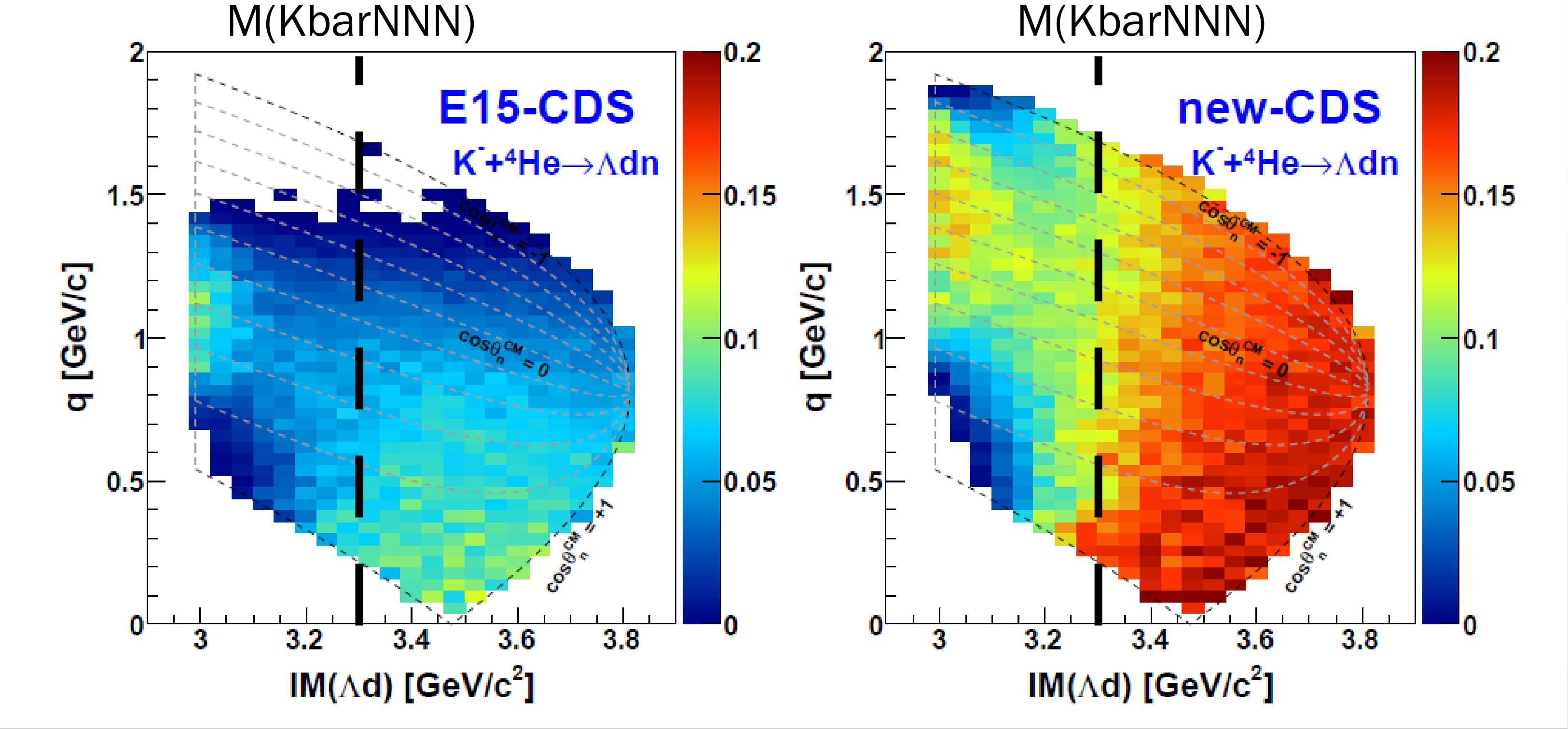


Proposed physics program-E80

- Search for KbarNNN via ^{4}He(1 GeV/c K^{-},n) reaction
  - *Detector acceptance for the Λd detection*
    - A few times larger than existing CDS!

Result with existing CDC





Proposed physics program-E80

- Search for KbarNNN via ^{4}He(1 GeV/c K^-,n) reaction
  - *Yield estimation*

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

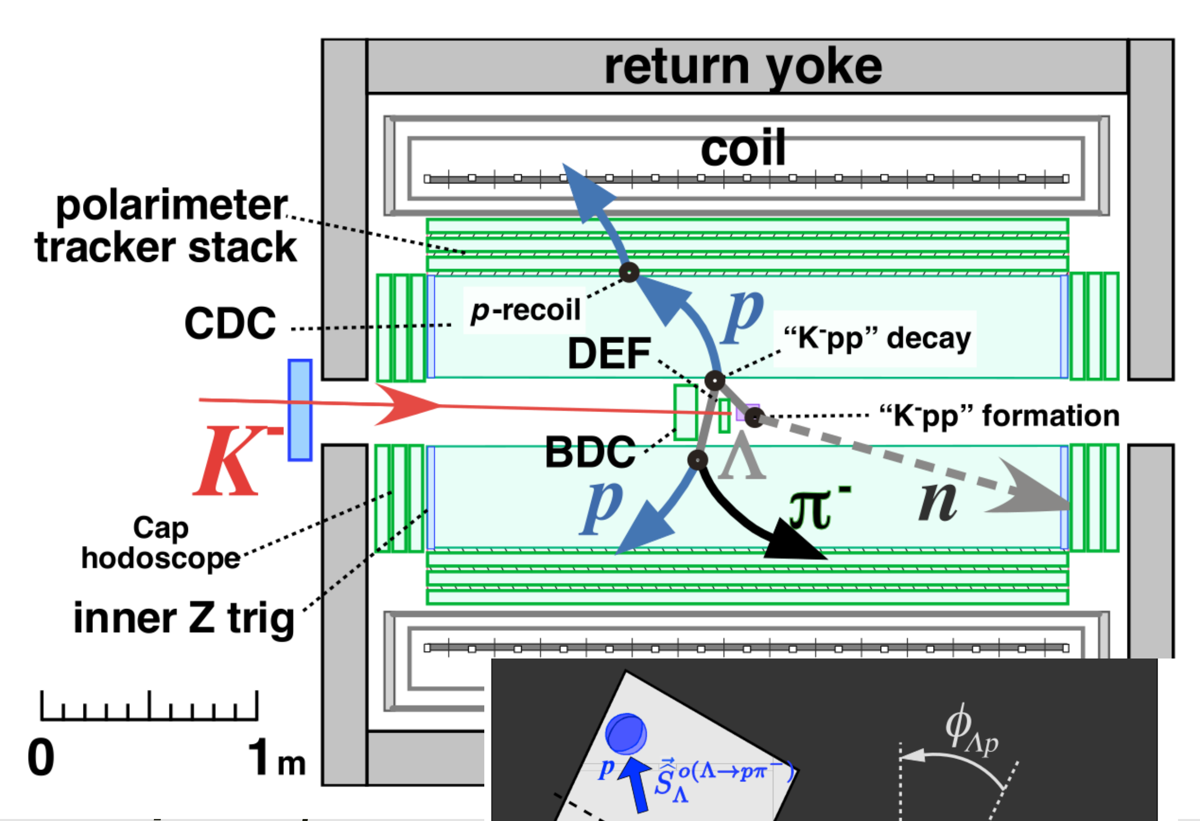
  - *N_{beam} = 100 G K^- on target*
    - Corresponding to ～3 weeks data taking
  - $\boldsymbol{\sigma(K^- ppn) \cdot Br(\Lambda d) \sim 5\ \mu b}$
    - Assumption From the T77 result
  - **N(K^-ppn→Λd) ~ 12 k events**
  - **N(K^-ppn→Λpn) ~ 1.5 k events**
    - 1.7 k "K^-pp"→Λp events in E15 (40 G K^-)

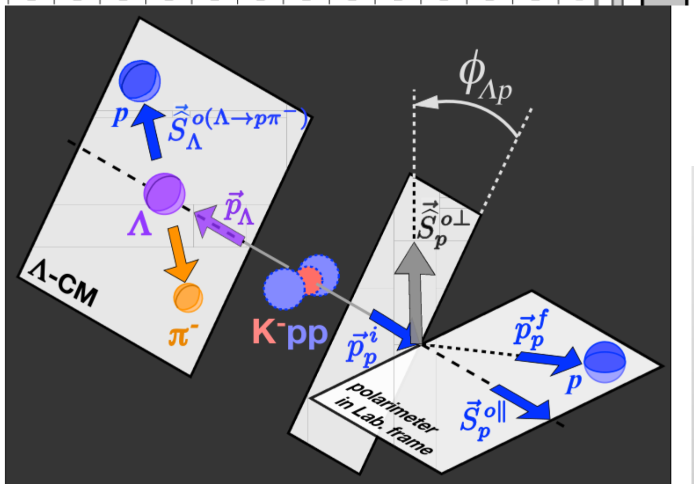
	Λd	Λpn
σ(K^-ppn)*Br	5 μb	5 μb
N(K^- on target)	100 G	100 G
N(target)	2.56 x 10^{23}	2.56 x 10^{23}
ε(DAQ)	0.92	0.92
ε(trigger)	0.98	0.98
ε(beam)	0.72	0.72
Ω(CDC)	0.23	0.06
ε(CDC)	0.6	0.3
N(K^-ppn)	12 k	1.5 k

Proposed physics program-P89

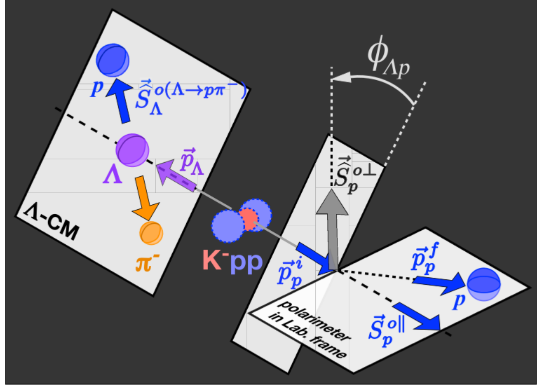
- Investigation of the spin and parity of the KbarNN state
  - *Measuring the spin-spin correlation between Λ and p from "K⁻pp"→Λp decay*
    - $\alpha_{\Lambda p}=1$ ($J^{\pi}=0^{-}$), $\alpha_{\Lambda p}=1/3$($J^{\pi}=1^{-}$)

  - *Spin direction of Λ can be Estimated from pπ⁻ decay*
  - *To measure the spin direction of the proton using p-C scattering, tracker stack should be additionally equipped*
    - Scintillating fiber?
    - Straw tube?

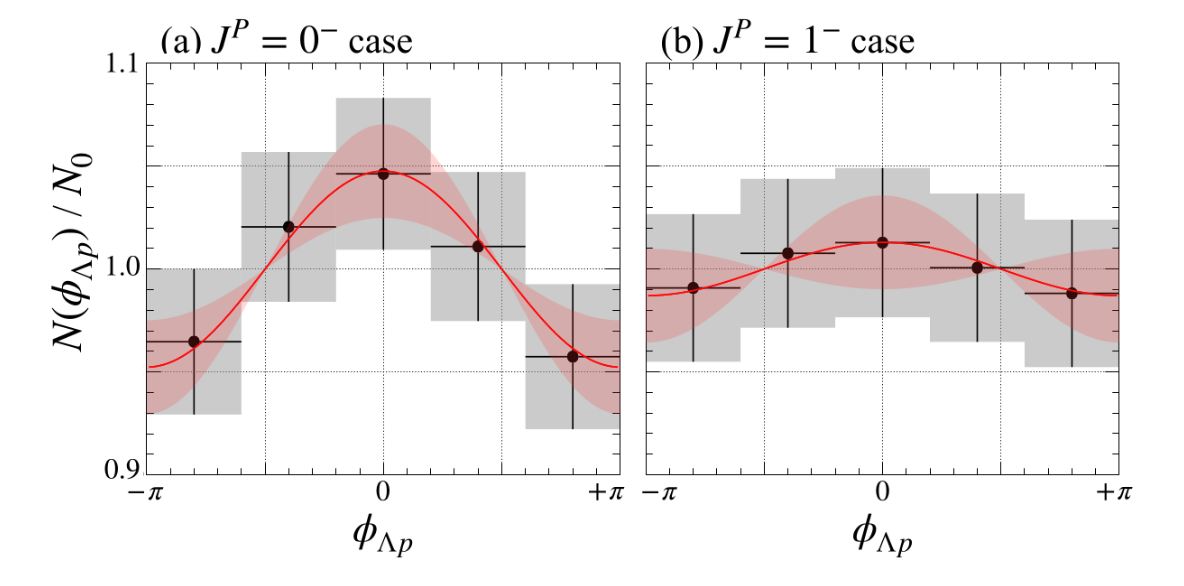




Proposed physics program-P89



- Investigation of the spin and parity of the KbarNN state
  - *Expected result for 8-week data taking*
    - $\alpha_{\Lambda p}$ measurement
      - *420 k "K-pp"→Λp events*
        - 250 times larger than E15
        - When J^P=0^- case, J^P= 1^- hypothesis Would be excluded more than 95% C. L.



    - "K^0bar nn" measurement
      - *^{3}He(K^-,p) reaction, Reconstruct from"K^0barnn"→Λn*
      - *Production cross section is expected to strongly depend on J^π due to spin-isospin selection rule.*
        - σ*BR～7μb/sr (1^- case), σ*BR～1.4μb/sr (0^- case)
    - These measurement would provide conclusive results of J^π!

Summary

- J-PARC E15 experiment @ K1.8 BR beamline successfully founded the existence of "$K^{-}pp$" states using the in-flight K^{-} +^{3}He reaction with an exclusive analysis of the Λpn final state.
- Further investigations for kaonic nuclei are needed
  - *Heavier systems (KbarNNN, KbarNNNN,…)*
  - *Spin and parity of the "$K^{-}pp$"?*
  - *Mesonic decay channel (πΛN, πΣN)*
- We are developing a new magnetic spectrometer
  - *Large solid angle (93 % of 4π)*
  - *thicker plastic scintillator (×5 neutron detection efficiency)*
  - *Momentum/position resolutions will retain or will be improved*
- Construction of new spectrometer in K1.8BR will be started in FY2025 and Physics run with new spectrometer will be started FY2026!
- If you are interested in or/and have ideas for the experiments with the spectrometer, we are welcome!