The LiNA experiment: Development of multi-layered time projection chamber

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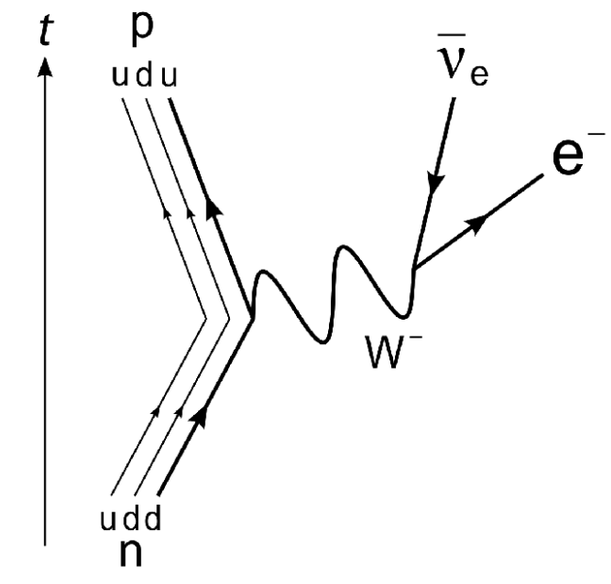
Introduction : Neutron lifetime

- Free neutrons decay to beta through weak interactions

$$n \rightarrow p + e^- + \bar{\nu}_e$$



- Neutron lifetimes have been measured by two different methods.
  - **Beam method：Counting decay neutrons**

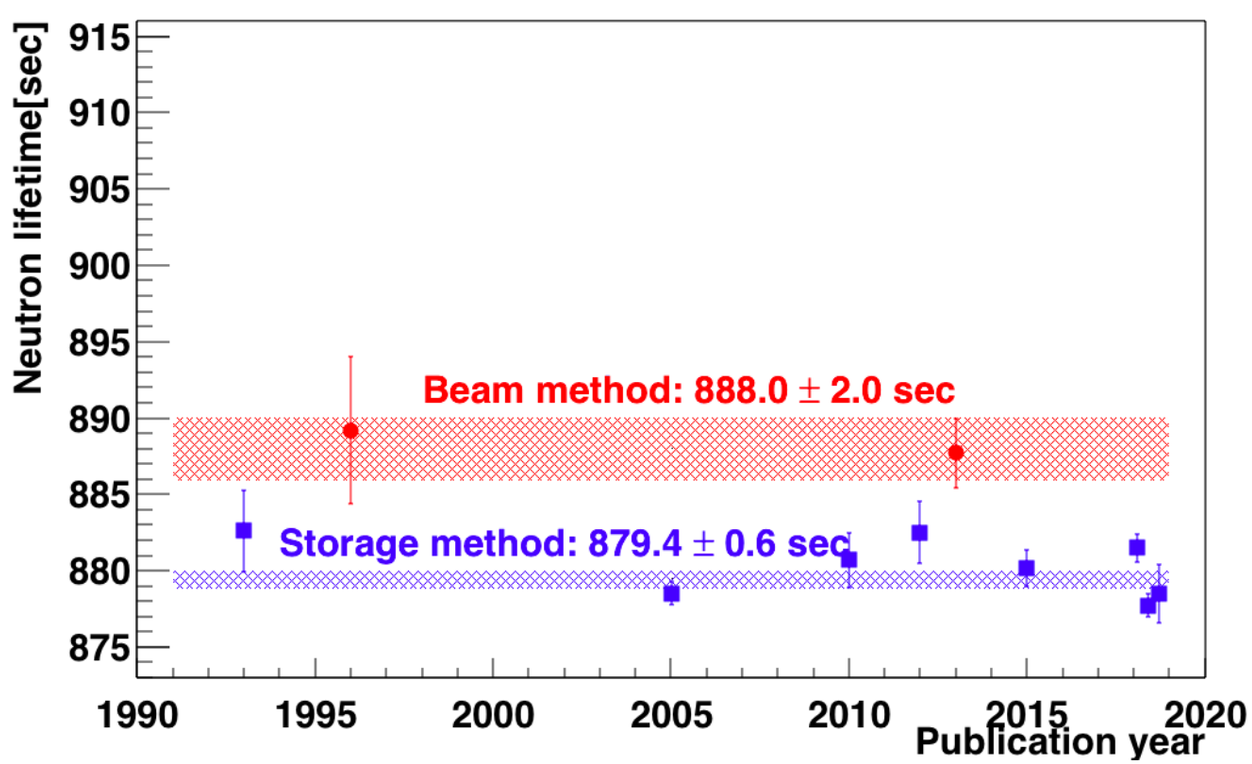
$$-\frac{dN}{dt} = \frac{N}{\tau}$$

  - **Storage method：Counting remaining neutrons**

$$\frac{N_1}{N_2} = e^{(t_1 - t_2)/\tau}$$

- **The cause of the discrepancy between the methods (8.6 s / 4.1σ) has not been understood for a long time.**

  ⇒ New measurements using beam methods are needed.

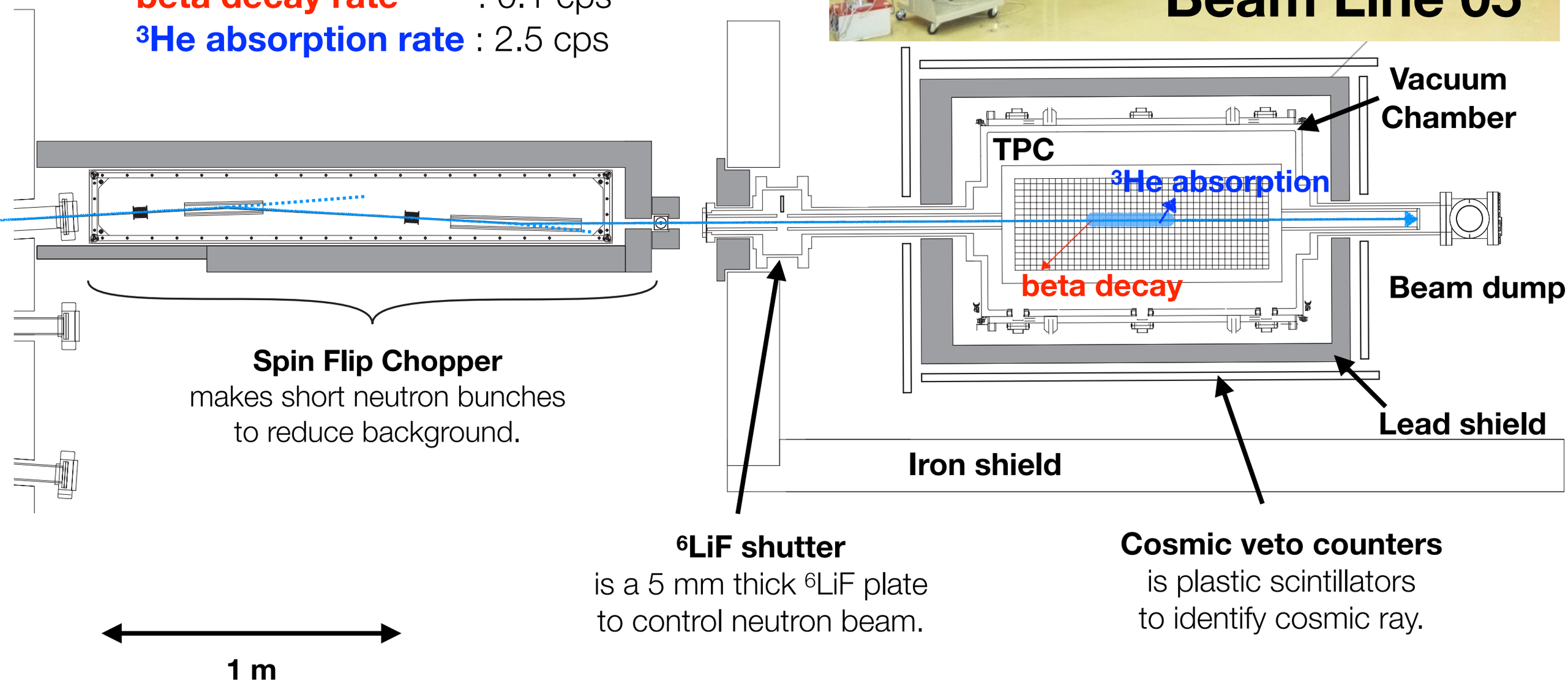


J-PARC MLF BL05

Neutron is produced
by injecting proton beam
to mercury target.

Beam line property

Neutron energy : ~10 meV
Neutron velocity : ~1000 m/s
beta decay rate : 0.1 cps
^{3}He absorption rate : 2.5 cps



Measurement principle

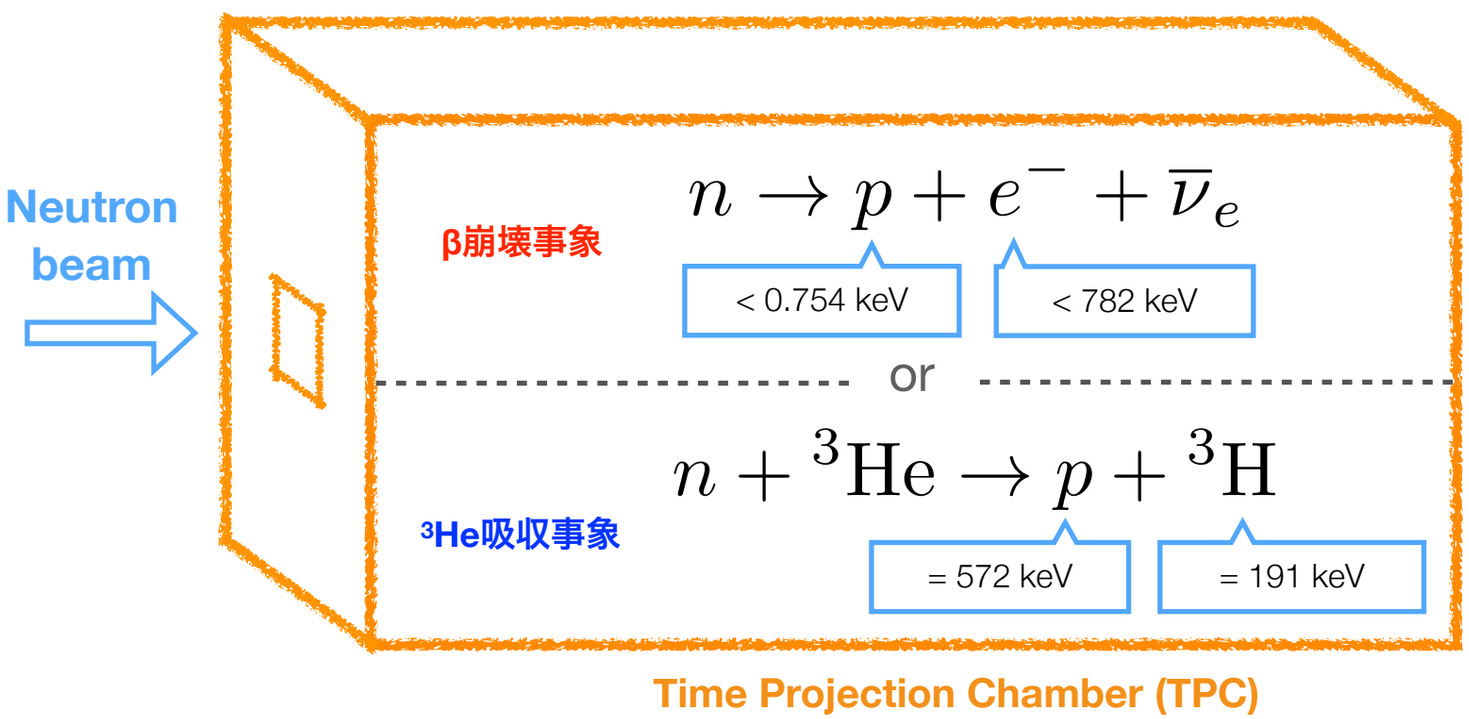
- Using a neutron beam, **beta decay events** and **^{3}He absorption events** are measured with a gas detector, Time Projection Chamber.

- The neutron lifetime is derived from the ratio of both signals.

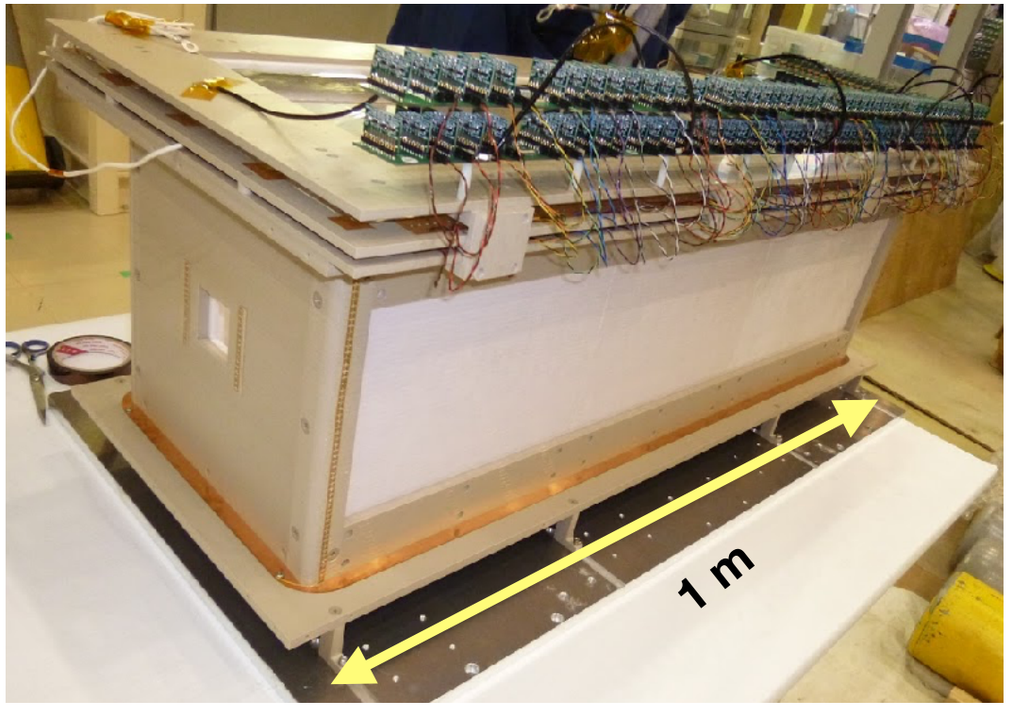
↓ **Signal number** ↓ **Efficiency**

$$\tau_n = \frac{1}{\rho\sigma v}\left(\frac{S_{\mathrm{He}}/\varepsilon_{\mathrm{He}}}{S_\beta/\varepsilon_\beta}\right)$$

^{3}He density ↑ **↑^{3}He cross section × neutron velocity**



TPC Gas ^{4}He:CO_2:^{3}He = 85 kPa:15 kPa: 100 mPa



TPC detector made of PEEK

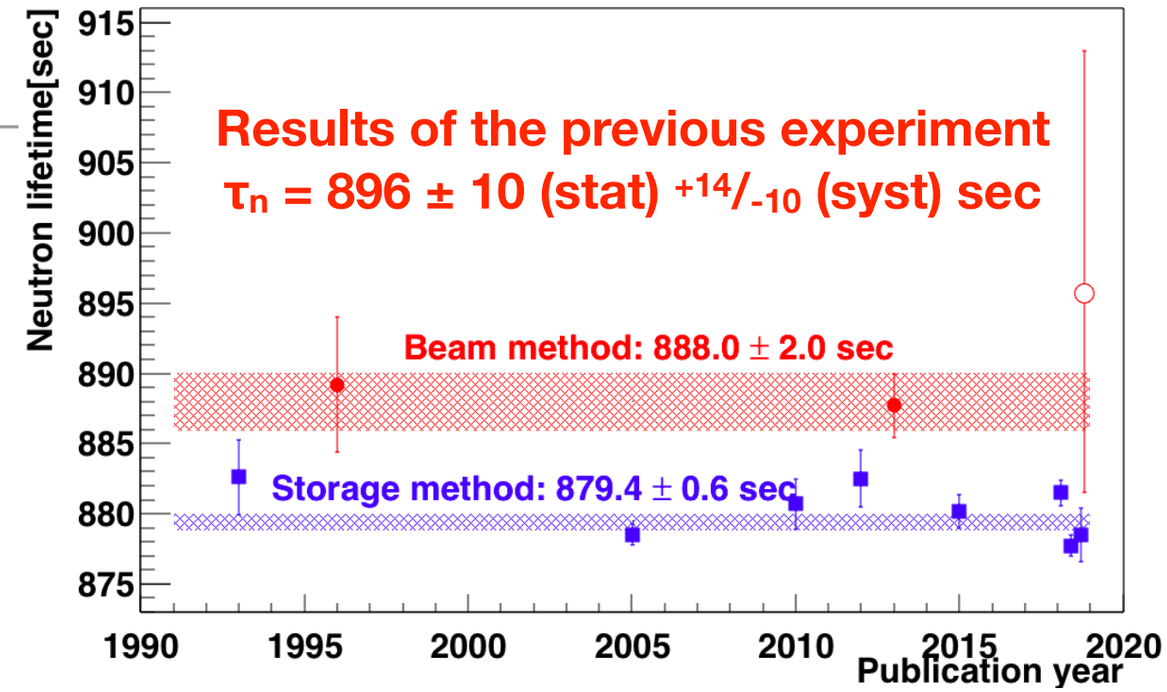
Measurement results

Large uncertainty in correction

↓ Signal number ↓ Efficiency

$$\tau_n = \frac{1}{\rho\sigma v}\left(\frac{S_{\mathrm{He}}/\varepsilon_{\mathrm{He}}}{S_\beta/\varepsilon_\beta}\right)$$

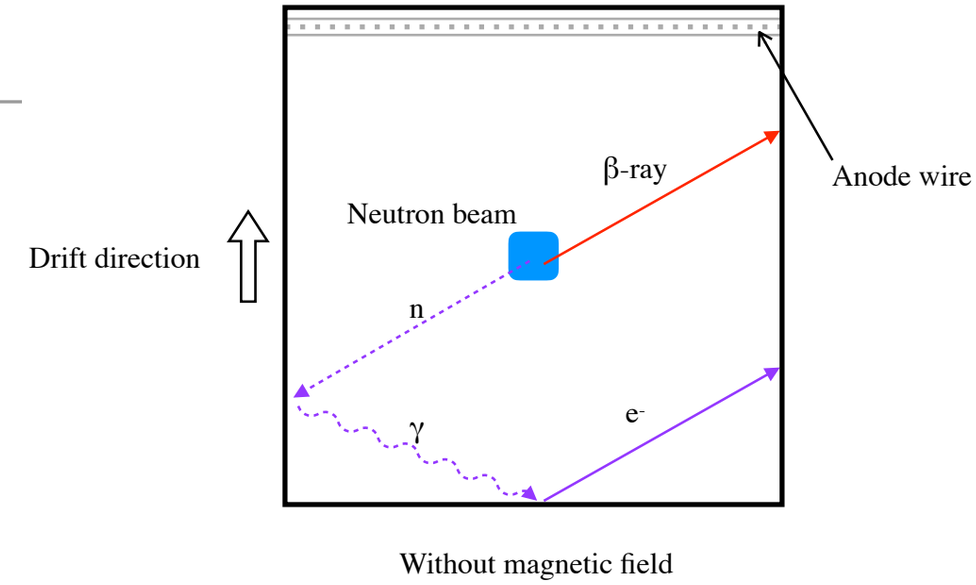
^{3}He density ↑ ↑^{3}He cross section × neutron velocity

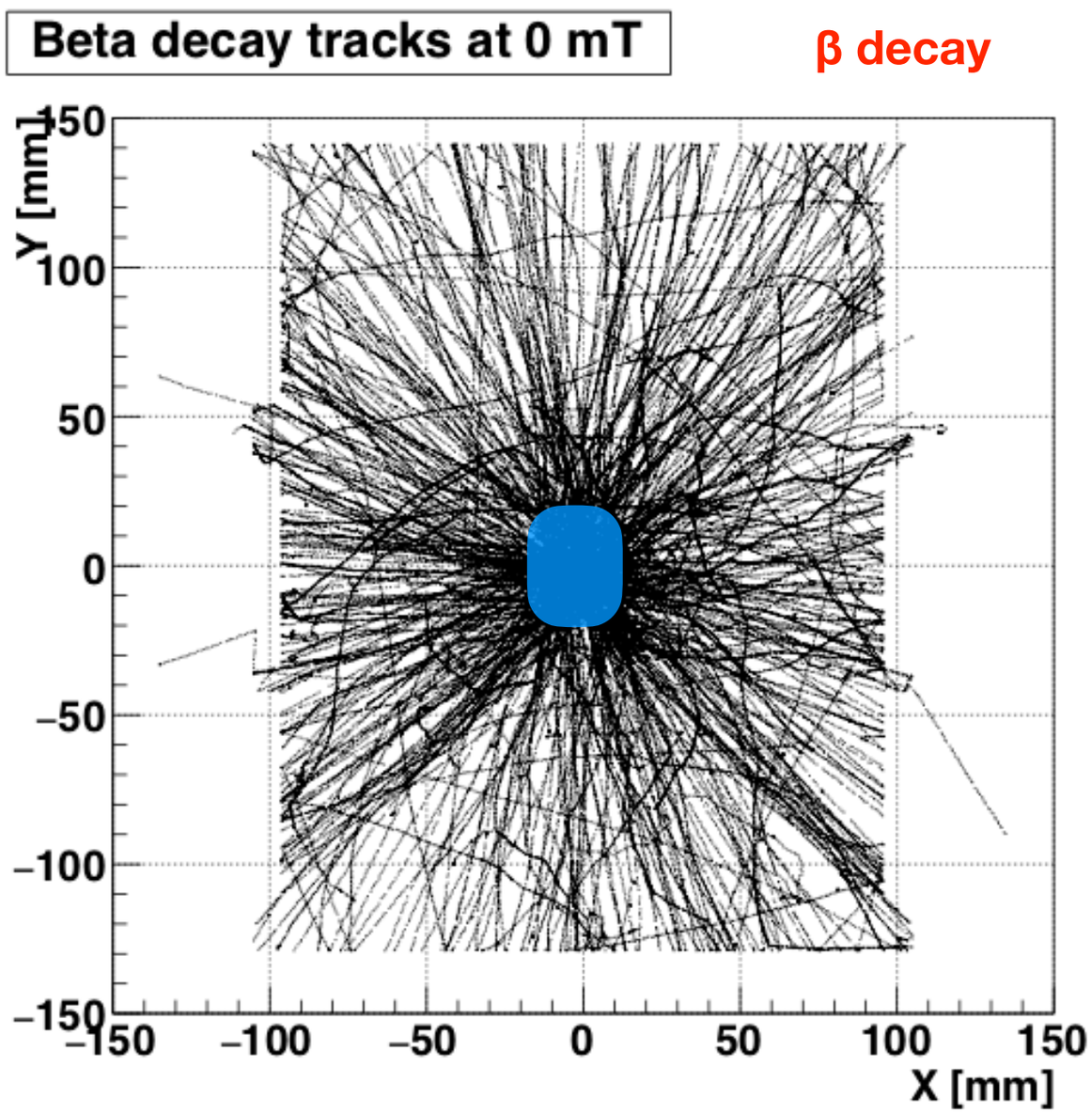


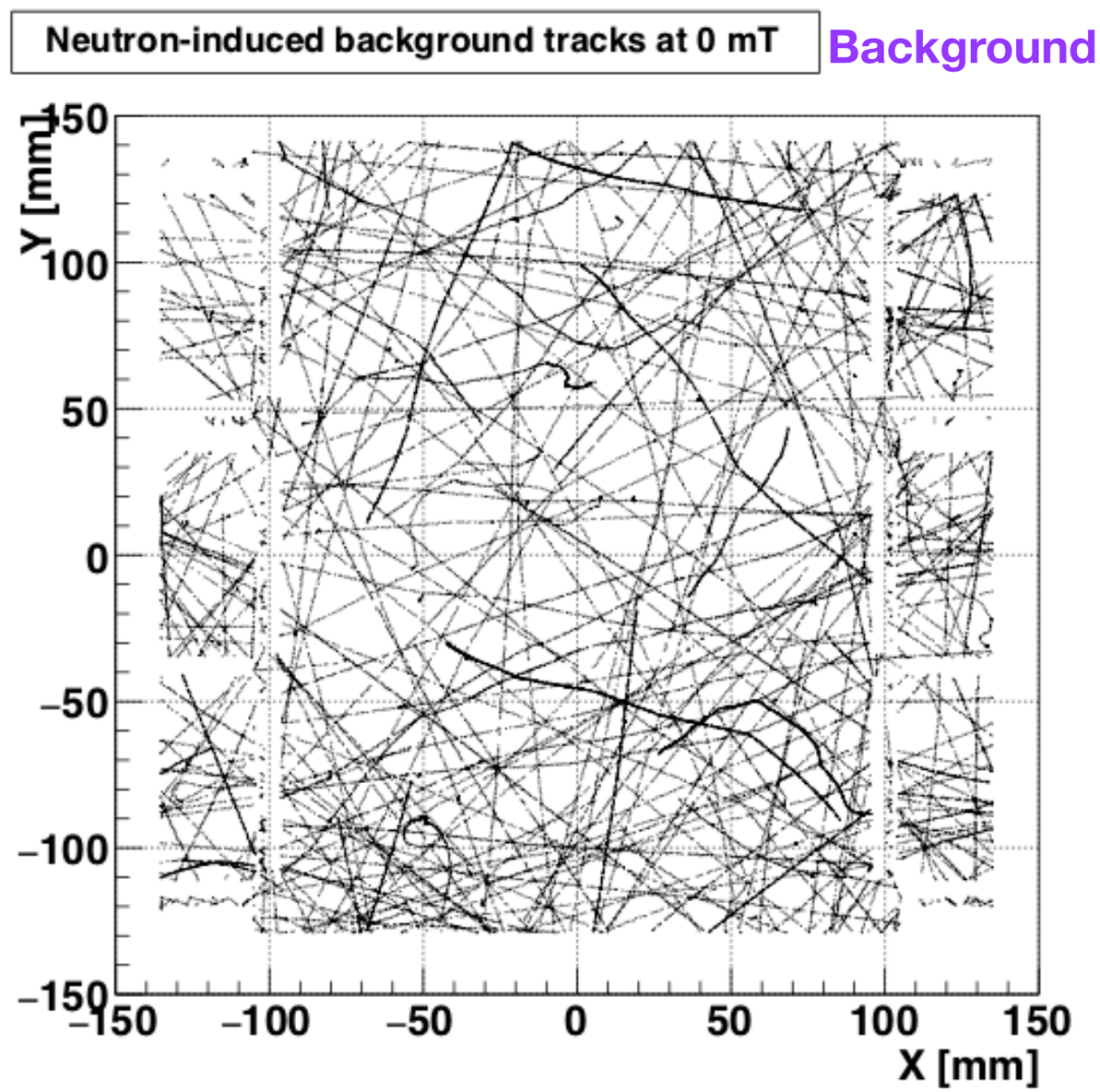
	Value	Correction	Uncertainty	Note
ρ	(2.08 ± 0.01)×10^{19} #/m^3	0	0.5%	Can be improved by the method of introducing ^{3}He gas
σv	5333 ± 7 barn × 2200 m/s	0	0.13%	Alternate measurement required
S_{He}	202993 ± 480 event	2672 ± 351 event	0.3%	Statistical accuracy dominates
S_β	8868 ± 151 event	463 ± 154 event	**2.6%**	Background event contamination **5.2%**
ε_{He}	100 - 0.014%	0 + 0.014%	0.014%	Enough accuracy
ε_β	94.5 ± 1.0%	+5.5 ± 1.0%	**1.0%**	Efficiency correction **5.5%**

Background contamination

- Beta decay and background events get mixed up.
  - **β decay** ：Radial distribution from beam axis
  - **Background**：Intrusion into beam axis

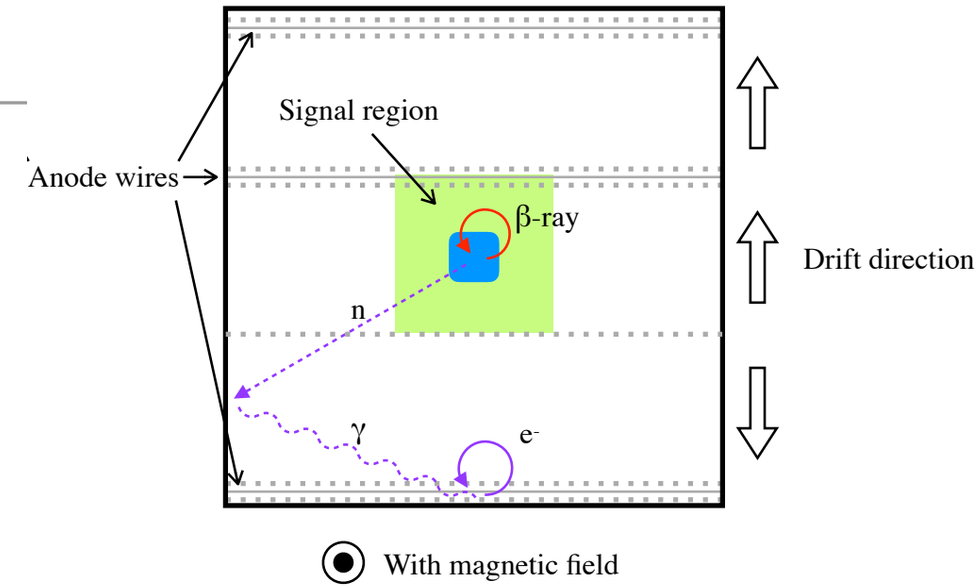


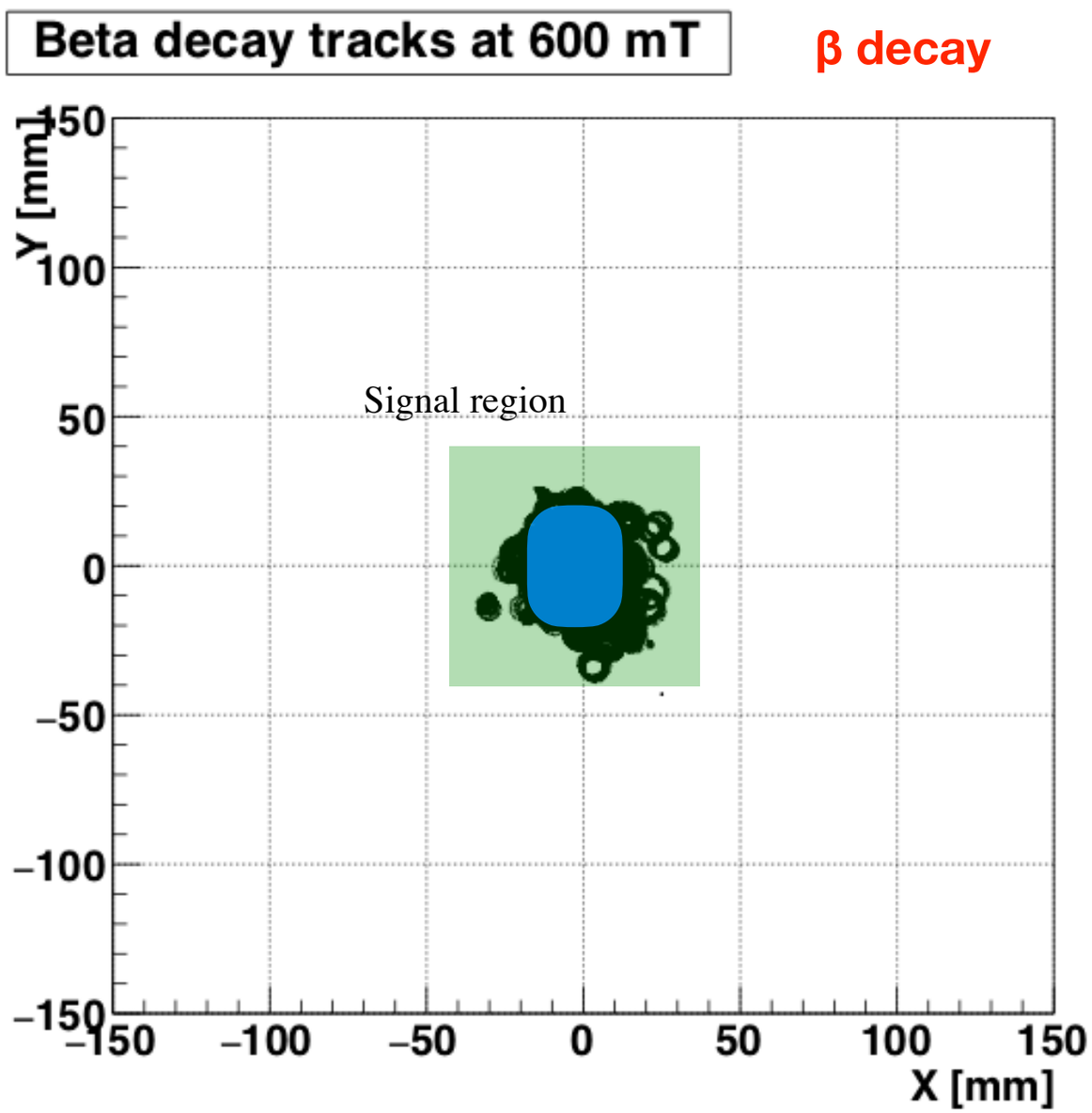


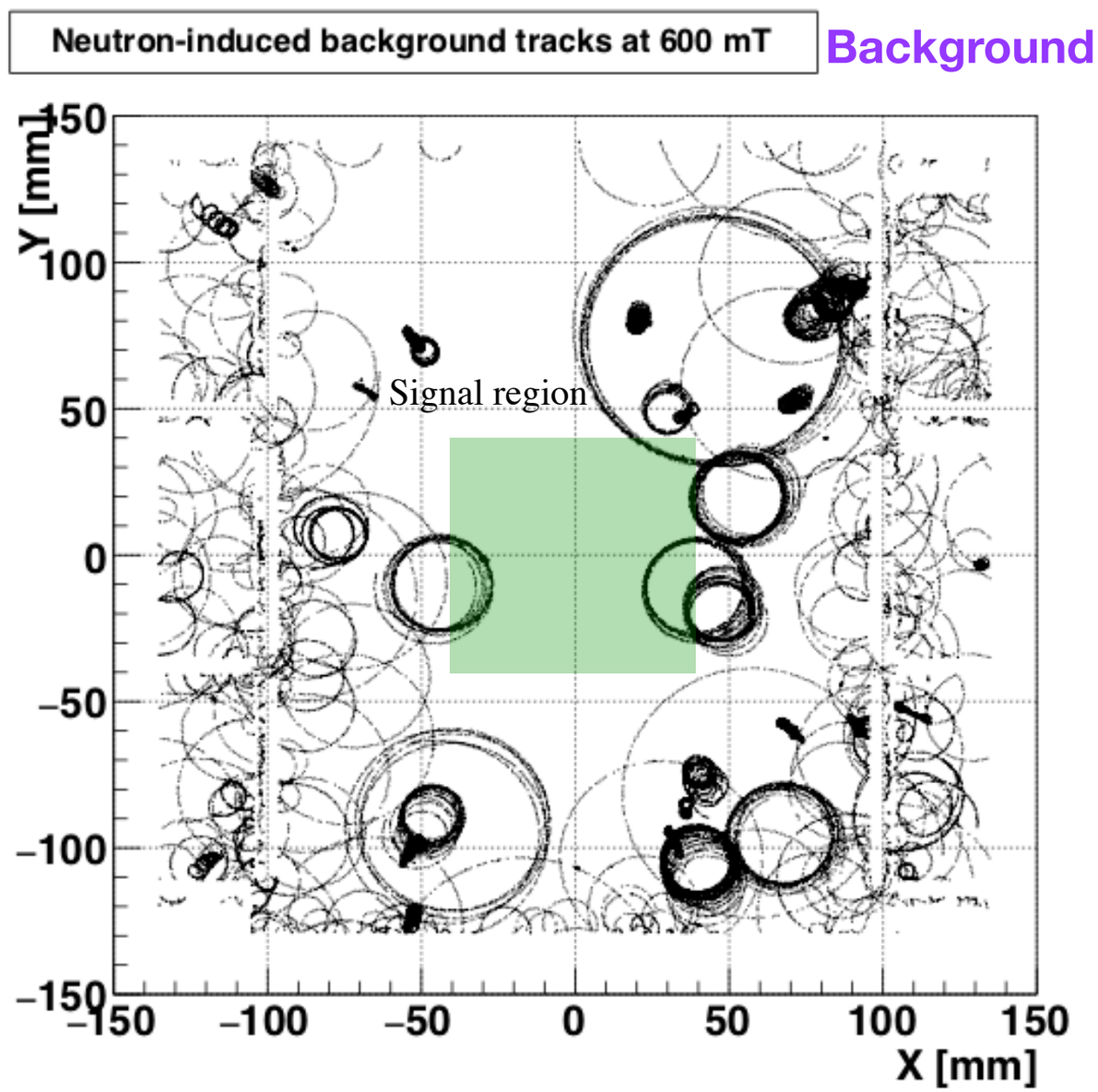


Solution using magnetic field

- Separating beta decay from background events
  - **β decay** ：Focus on beam axis
  - **Background**：No intrusion into beam axis



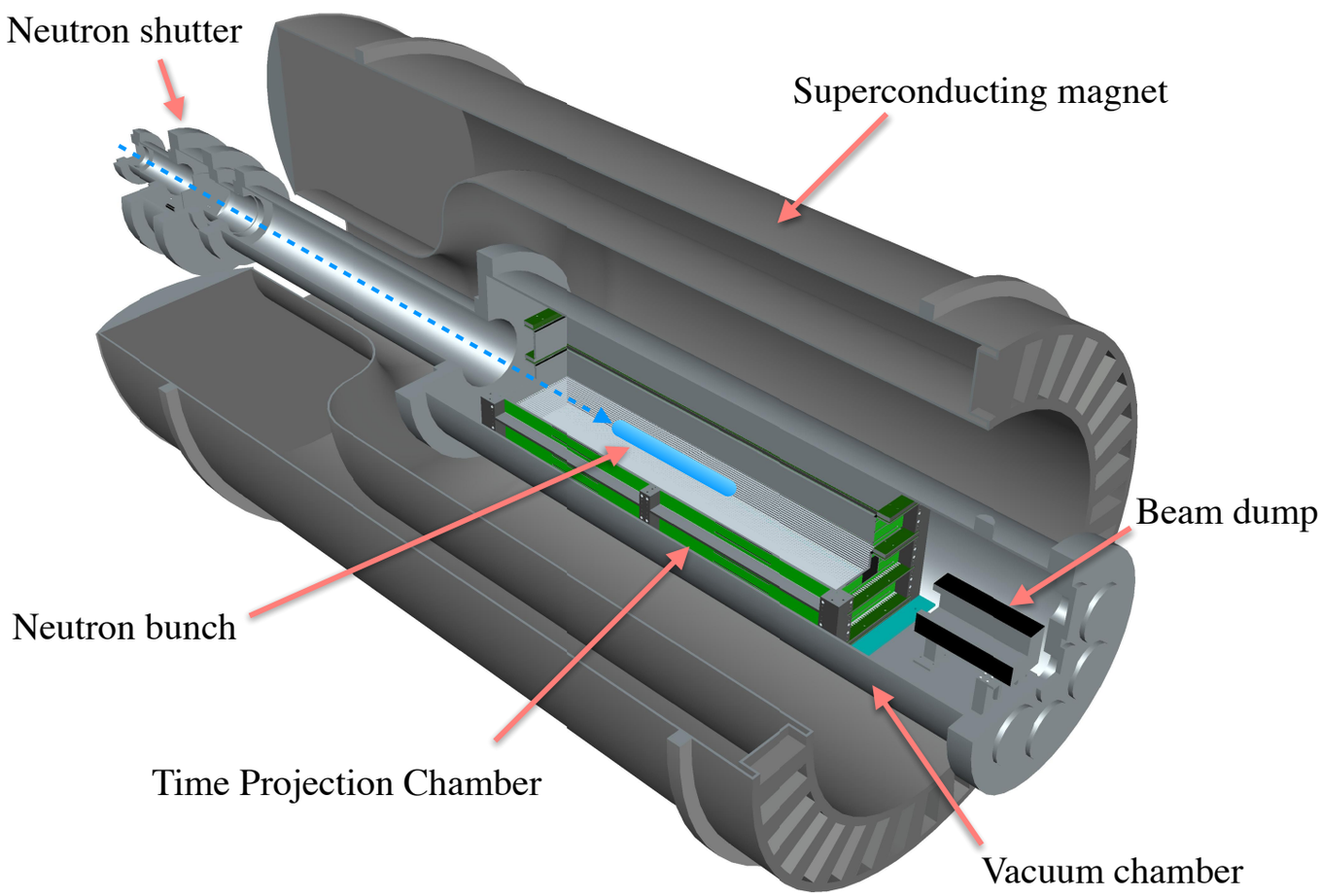


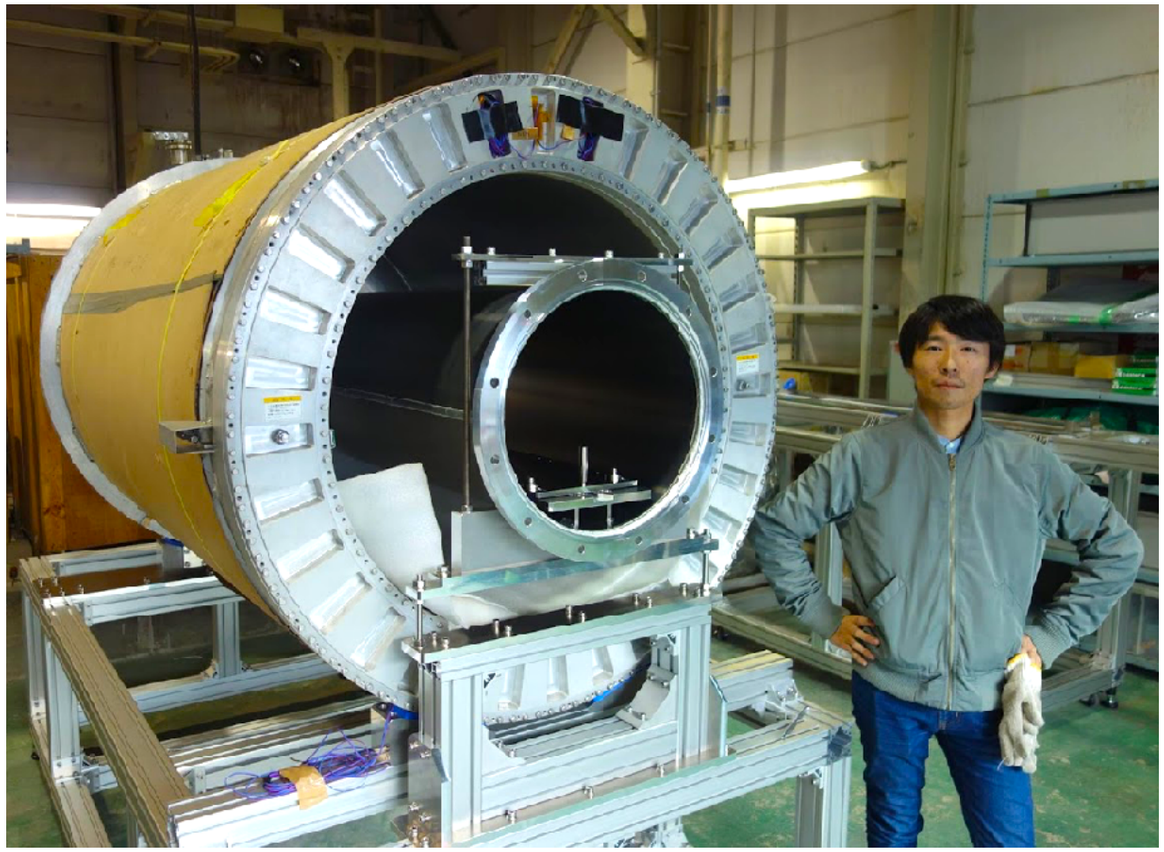


Superconducting magnet

- Using a spare superconducting magnet from the BESS experiment
  - Solenoid coil 920 mT @580 A
  - Coil **ϕ1000 mm × 1300 mm**
  - Superconducting wire NbTi:Cu:Al

BESS experiment: Balloon launch

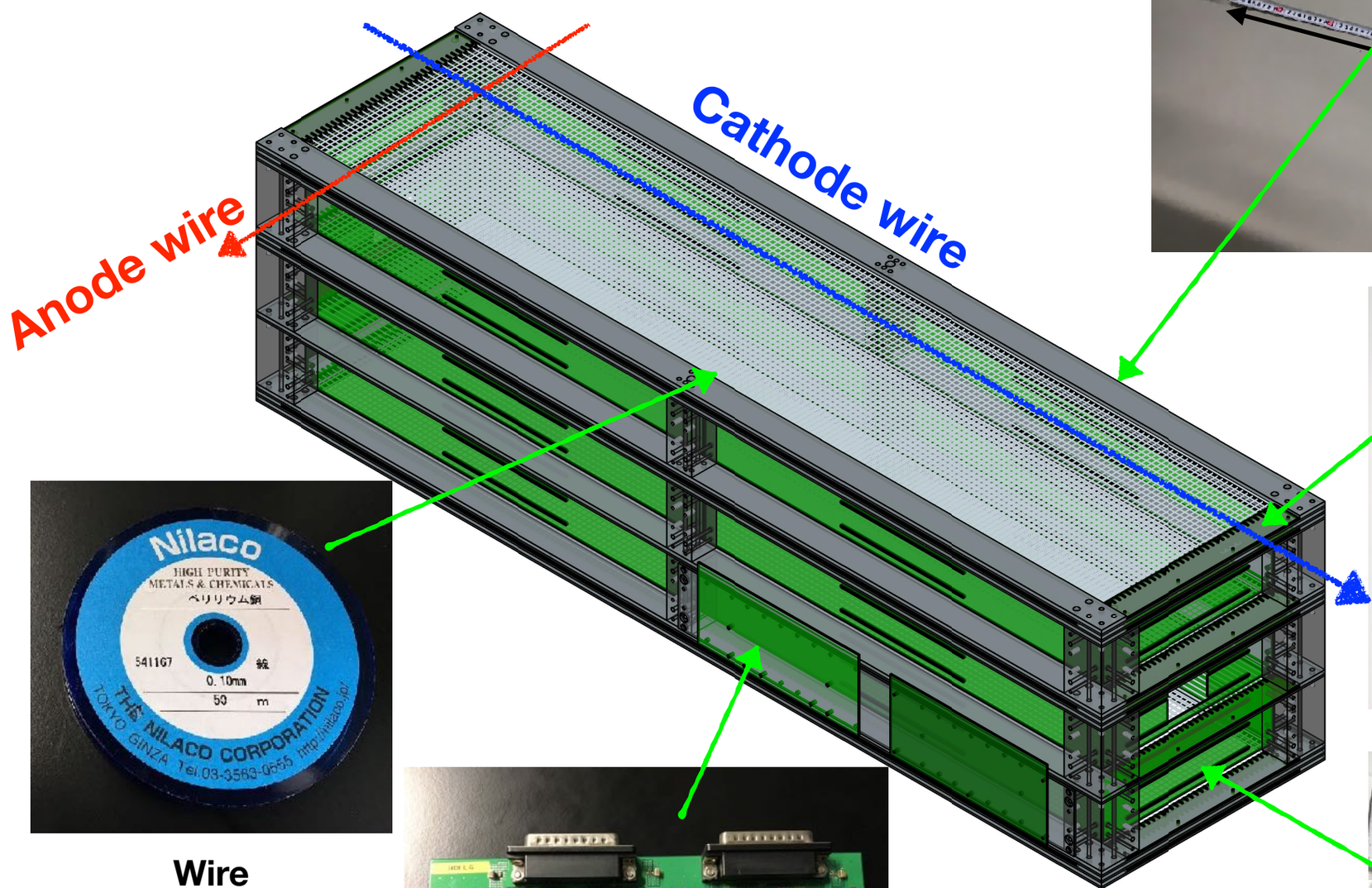


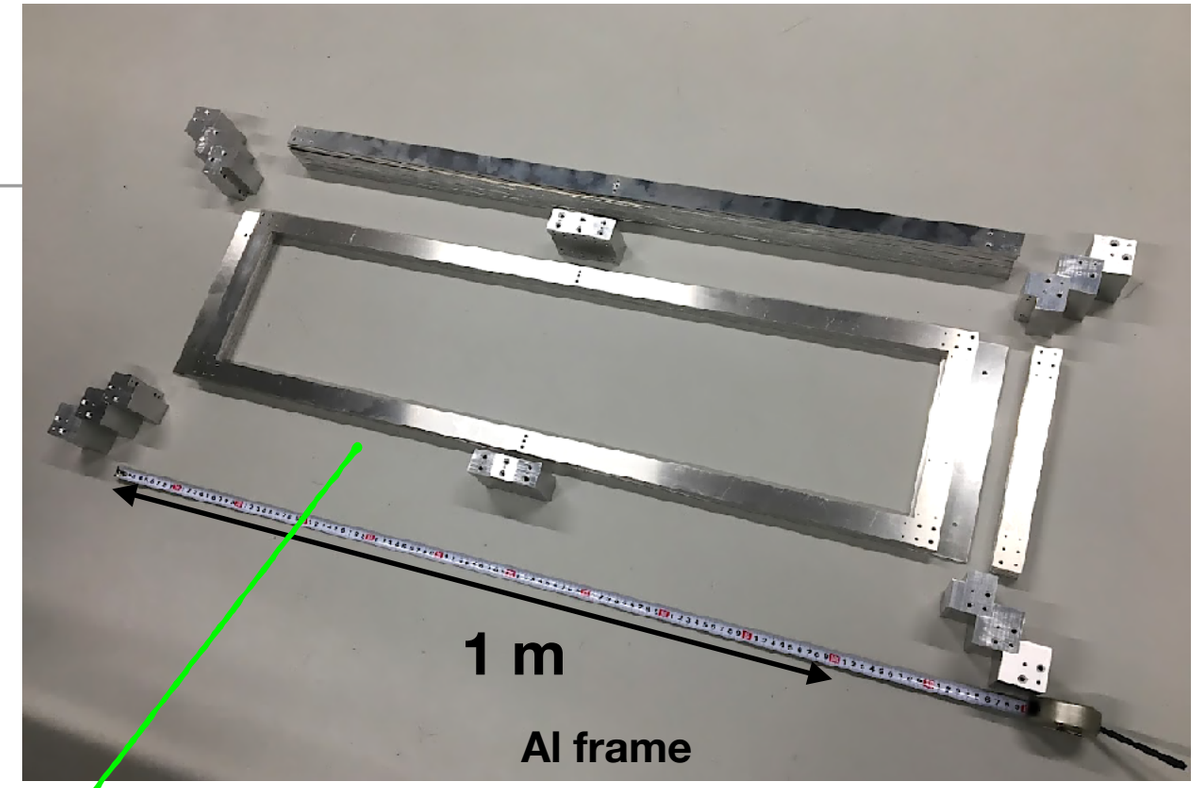


Magnet vessel, vacuum vessel and mount

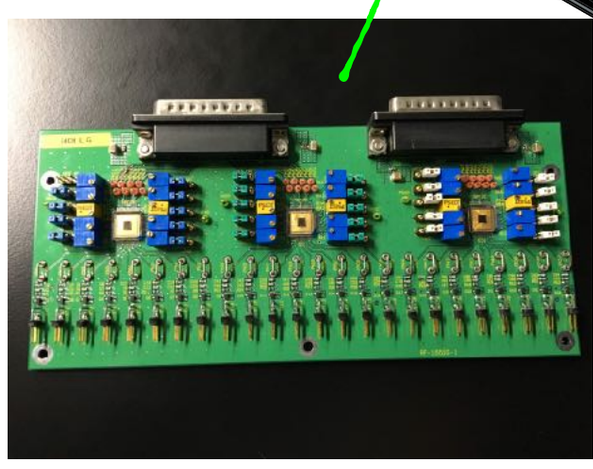
Detector Design

- **Using 3D CAD to design detectors**
  - Three-layer detector area
  - Select non-magnetic materials for components.

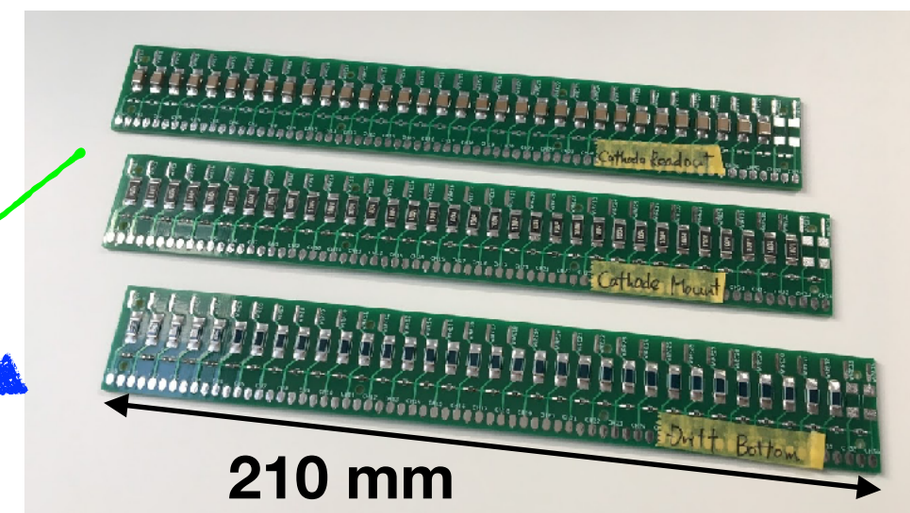




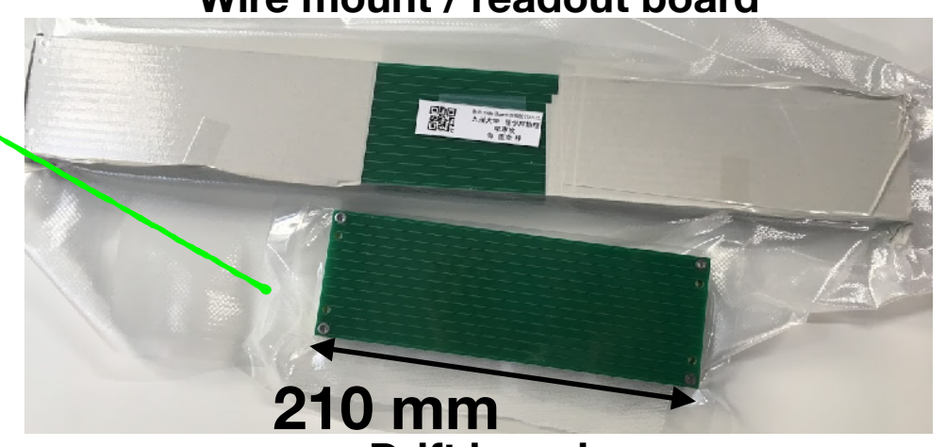
Wire



Preamp



Wire mount / readout board

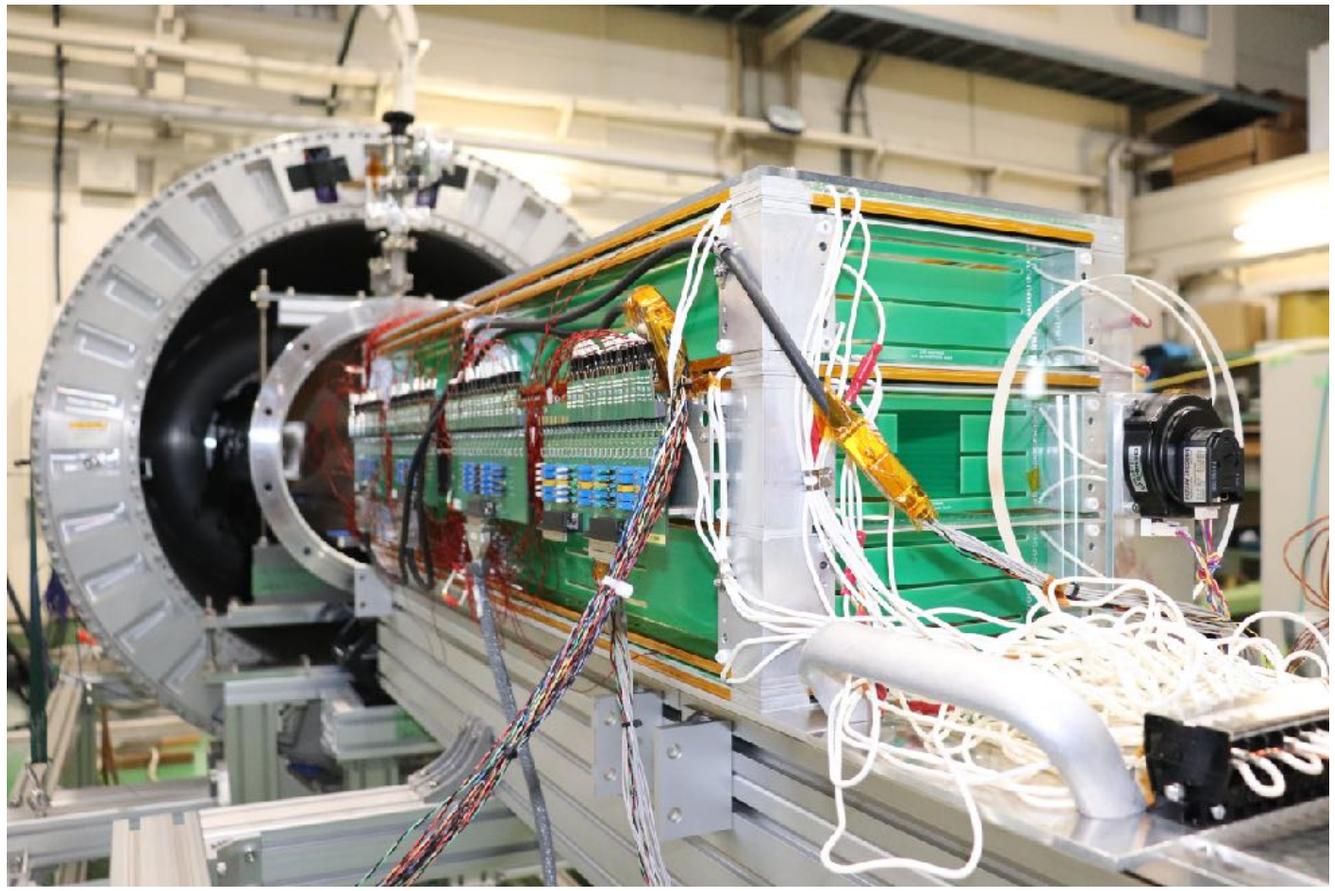


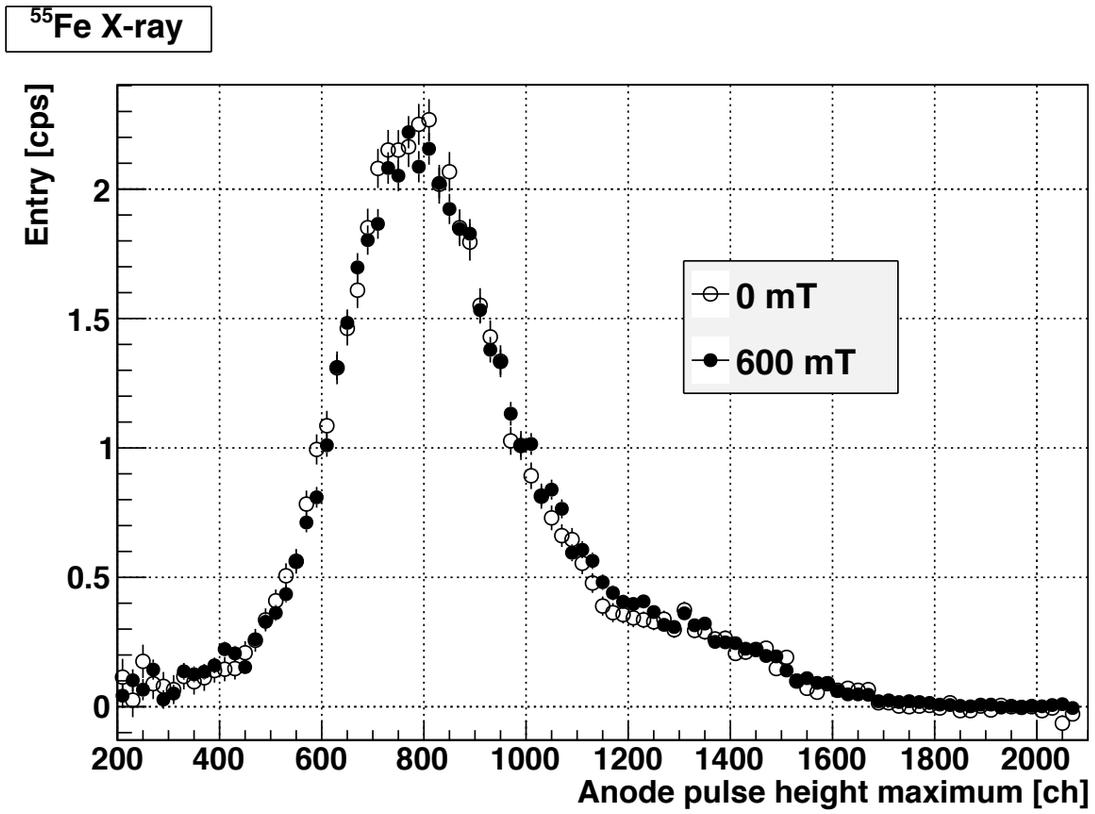
Drift board

Integration test with superconducting magnet

- Transport of fabricated detectors to KEK
  ⇒ Integration test of superconducting magnet and detector was carried out.
  - Detectors and amplifiers can operate in magnetic fields?
  - Performance evaluation of detectors using cosmic rays and sources

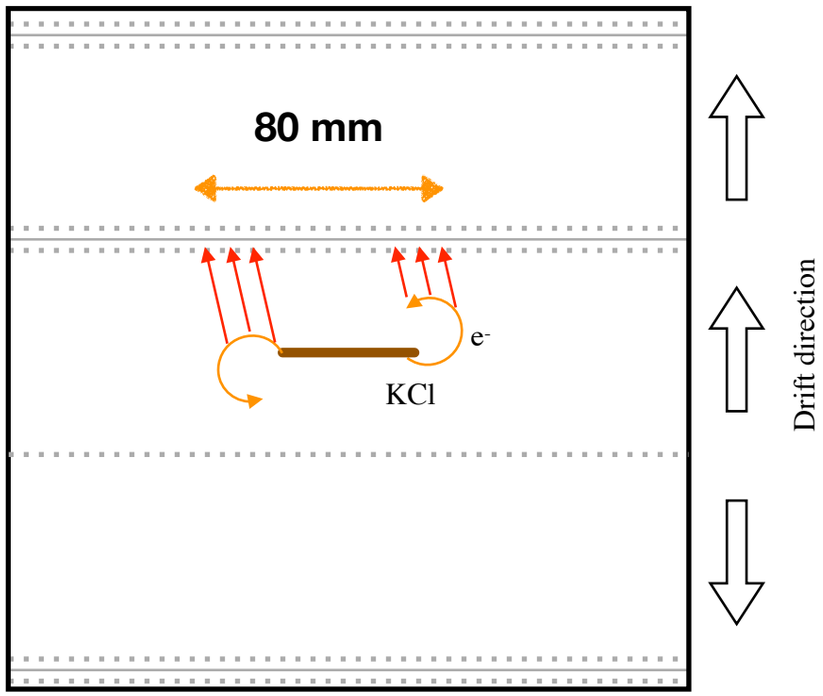
- Detector calibration using X-rays from a ^{55}Fe source
  - Sufficient gain and energy resolution at Anode HV +1.8 kV
    ⇒ No variation with or without magnetic field

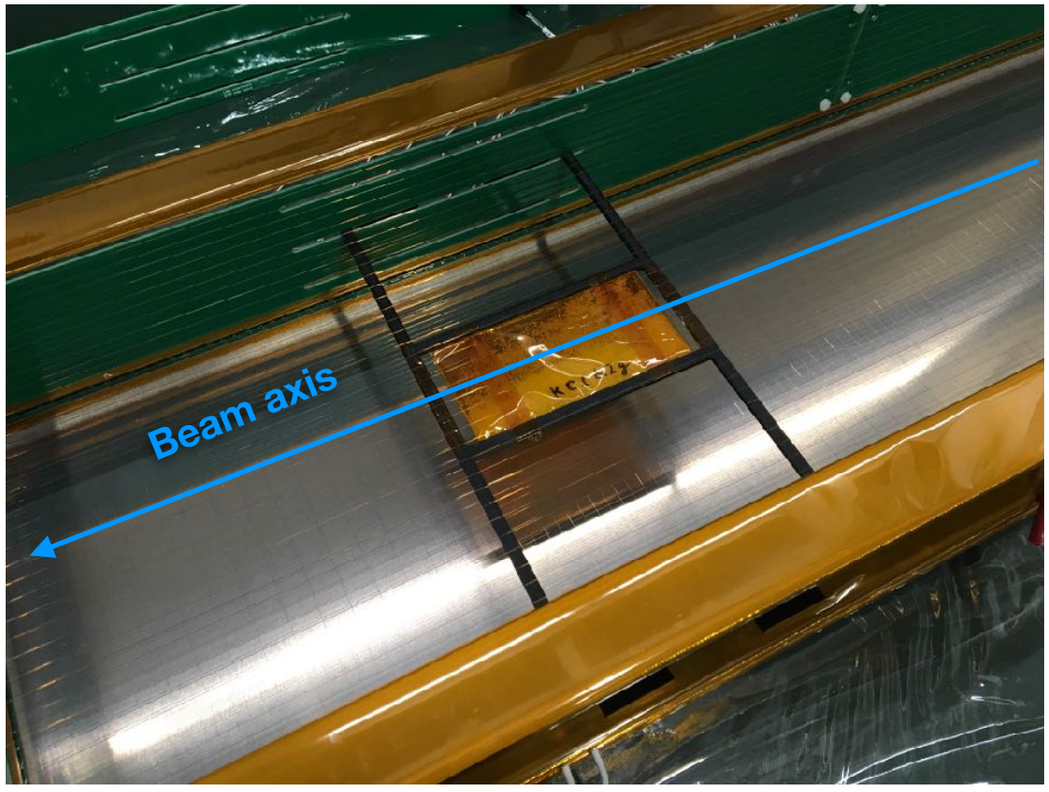


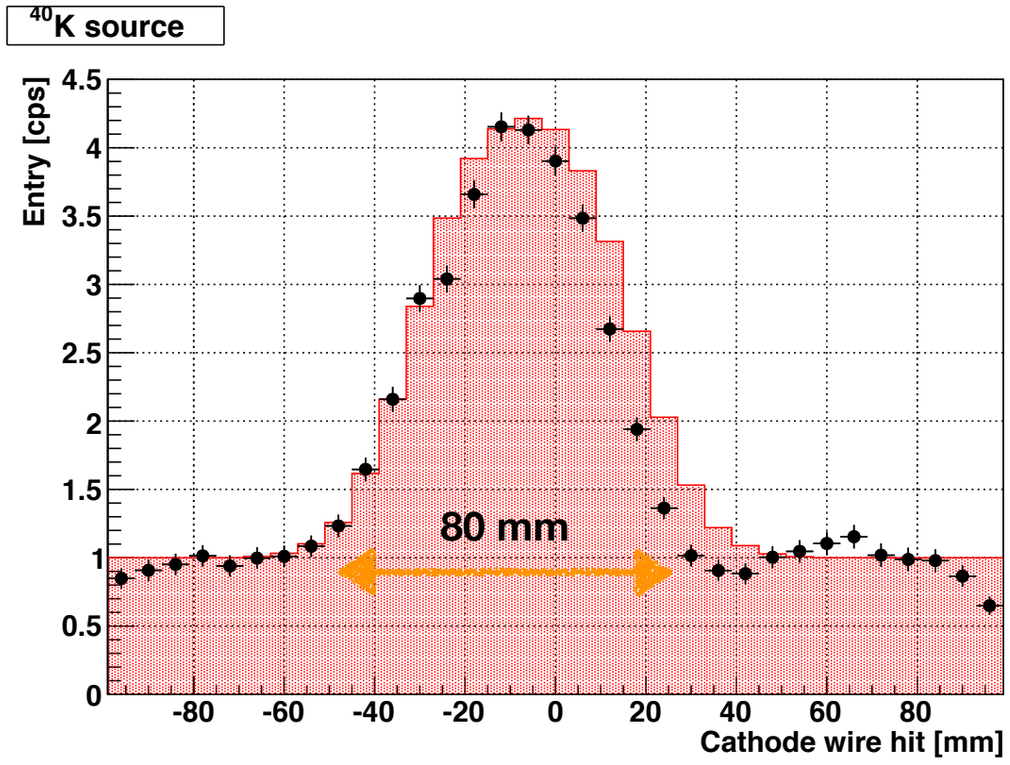


Pseudo neutron beam measurement

- We want to place the beta source on the beam axis to simulate a neutron beam.
  - Intensity of checking source is too high and saturates the detector
  - Difficult to get permission to use in a magnetic or electric field
    ⇒ We decided to use the natural isotope ^{40}K in KCl.
- KCl powder (6.2 g) is needed to make 100 Bq
  - Wrapped in Kapton sheet and placed in the center of the detector with a jig made with a 3D printer



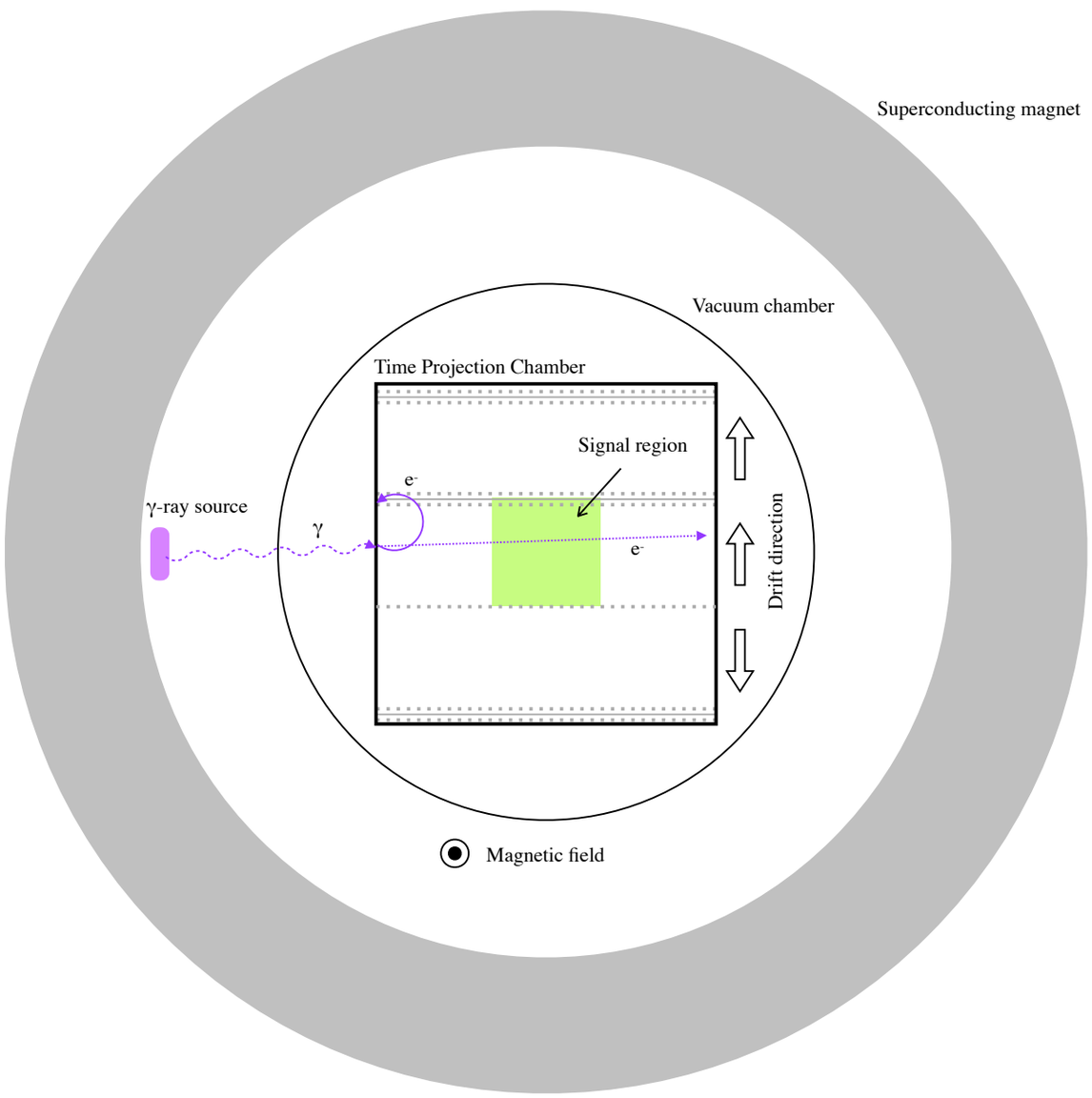


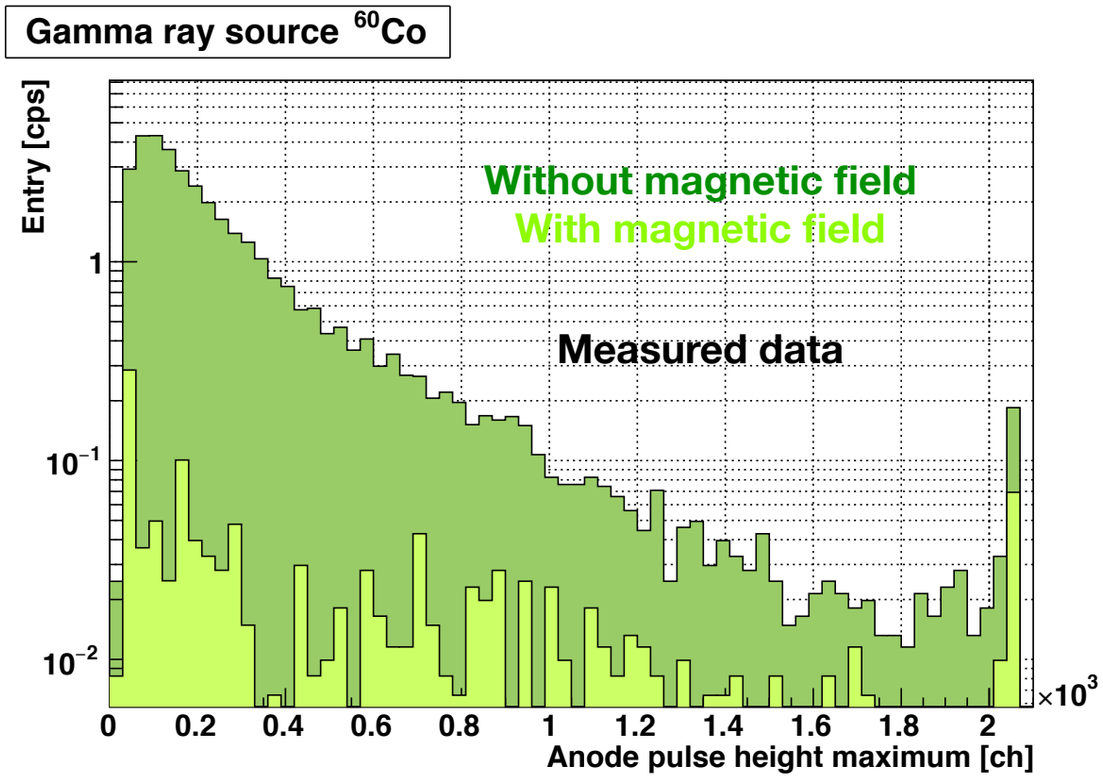


Pseudo background event measurement

- The gamma source is placed next to the detector to simulate a background event.
  - **Without magnetic field**：Electrons generated on the wall enter the signal region
  - **With magnetic field**：The electrons can't get to the signal field.

  ⇒ **Background events suppressed to 2.9%.**





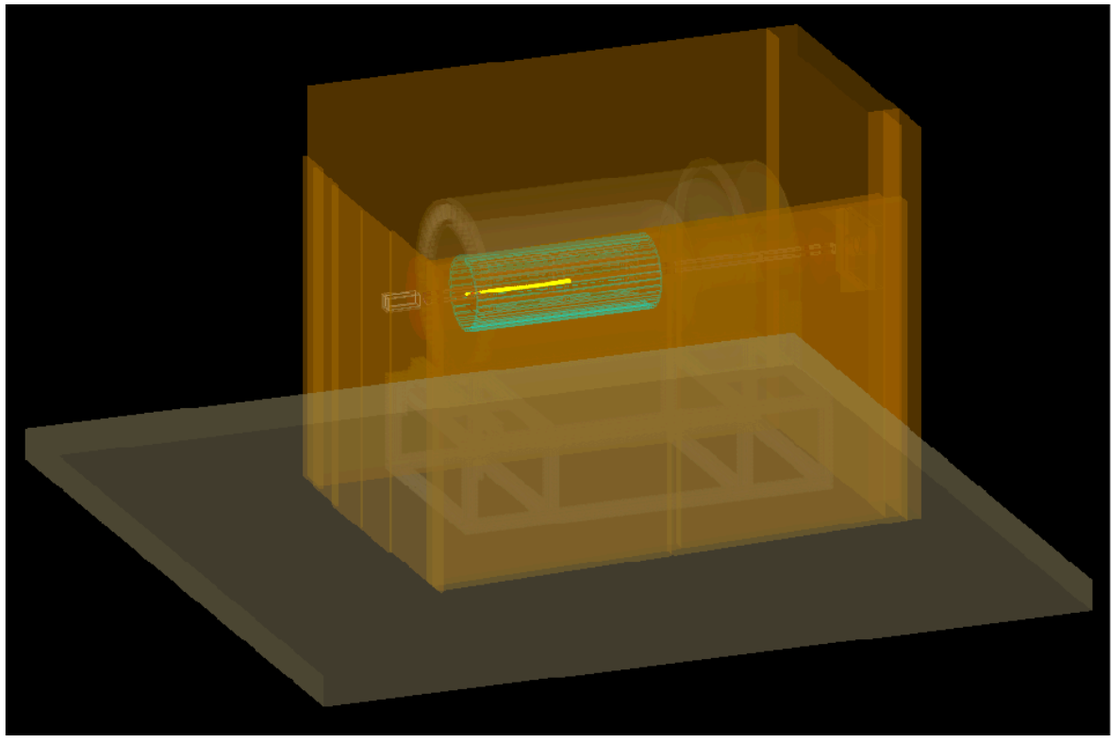
Estimation of measurement accuracy

- The measurement accuracy was estimated using Geant4 simulation.
  - A magnet and a detector are placed to inject a neutron beam.
  - Calibrate detector response with cosmic ray and source data

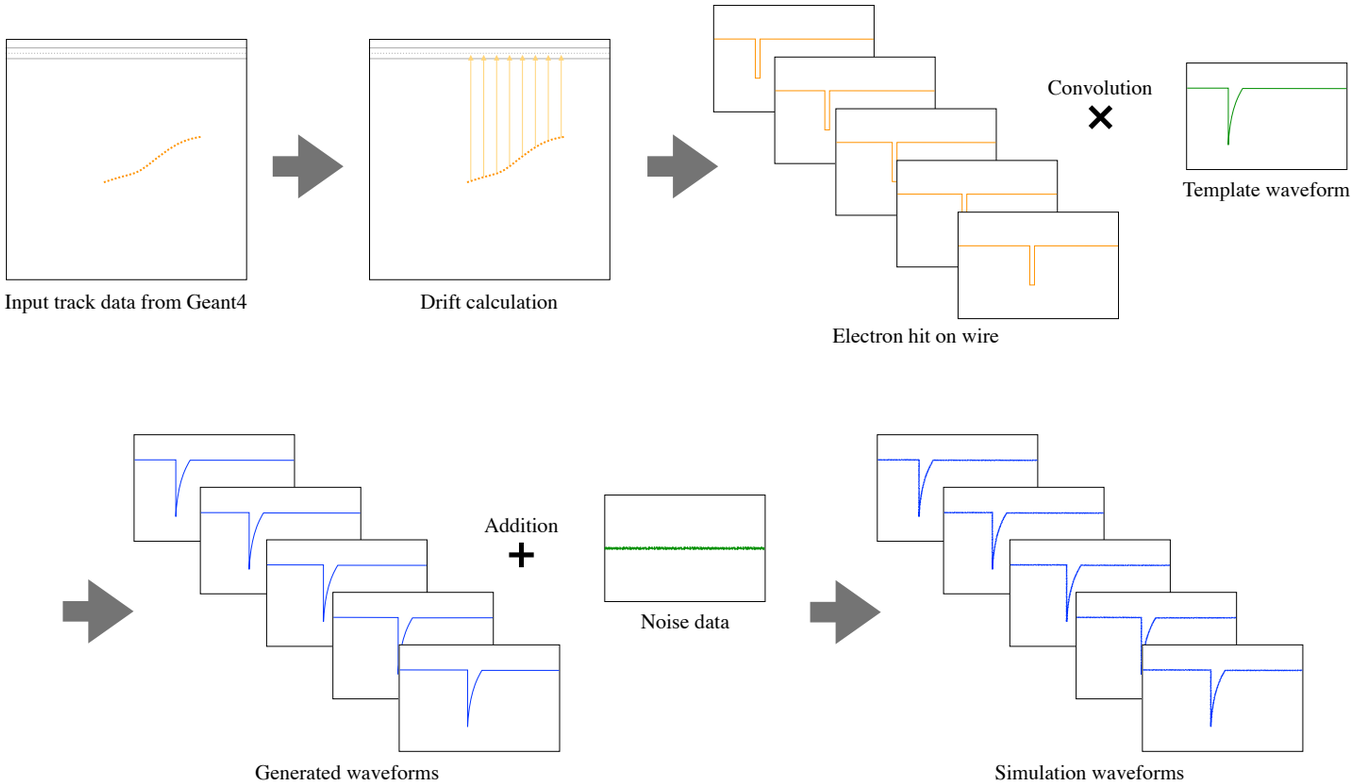
    ⇒ **Create the same waveform as the experimental data,**

    and calculate the lifetime
    using the same analysis as the experimental data.

$$\tau_{\mathrm{n}}(\mathrm{MC}) = 887.0 \pm 3.3\ (\mathrm{stat}) \pm 1.2\ (\mathrm{syst})\ \mathrm{sec} = 887.0 \pm 3.5\ \mathrm{sec}$$



Geant4 simulation



Flow of Simulation

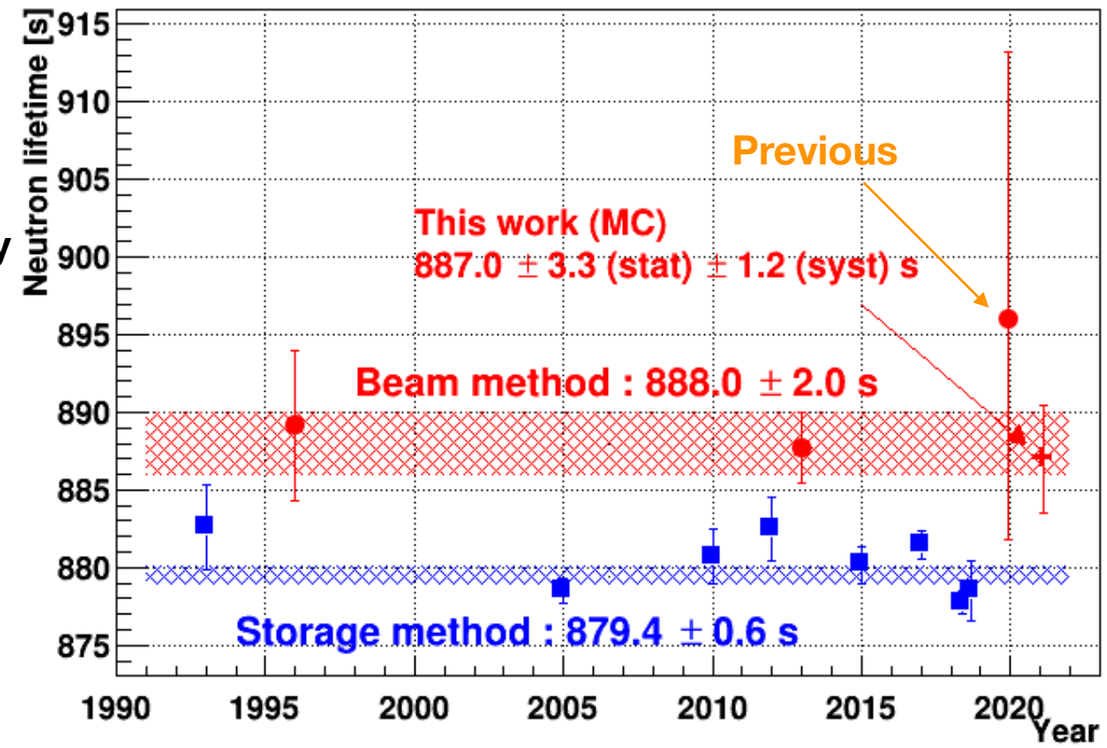
Estimation of accuracy

Decrease in indeterminacy as correctio

↓ Signal number ↓ Efficiency

$$\tau_n = \frac{1}{\rho\sigma v}\left(\frac{S_{\mathrm{He}}/\varepsilon_{\mathrm{He}}}{S_\beta/\varepsilon_\beta}\right)$$

^{3}He density ↑ ↑^{3}He cross section × neutron velocity



	Value	Correction	Uncertainty	Note
ρ	(2.3927 ± 0.002)×10^{19} #/m^3	0	0.1%	Can be improved by the method of introducing ^{3}He
σv	5333 ± 7 barn × 2200 m/s	0	0.13%	Alternate measurement required
S_{He}	1915609 ± 1384 event	9578 ± 575 event	0.3%	Statistical accuracy dominates
S_β	76611 ± 276 event	163 ± 12 event	**0.4%**	Correction **5.2%→0.21%**
ε_{He}	100 - 0.01%	0 + 0.01%	0.01%	Enough accuracy
ε_β	99.90 ± 0.01%	+0.10 ± 0.01%	**0.01%**	Correction **5.5%→0.10%**

Summary

- Discrepancies exist between the two neutron lifetime measurement methods, **the beam method** and **the storage method**.

- The previous experiment has large indefiniteness associated with the correction.
  ⇒ **Proposed measures to reduce corrections**

  and developed a new measurement system
  - Developed a detector and evaluated its performance in a magnetic field.

- Precise neutron lifetime measurement with reduced correction using this system