A new results of neutron lifetime measurement with cold neutron beam at J-PARC

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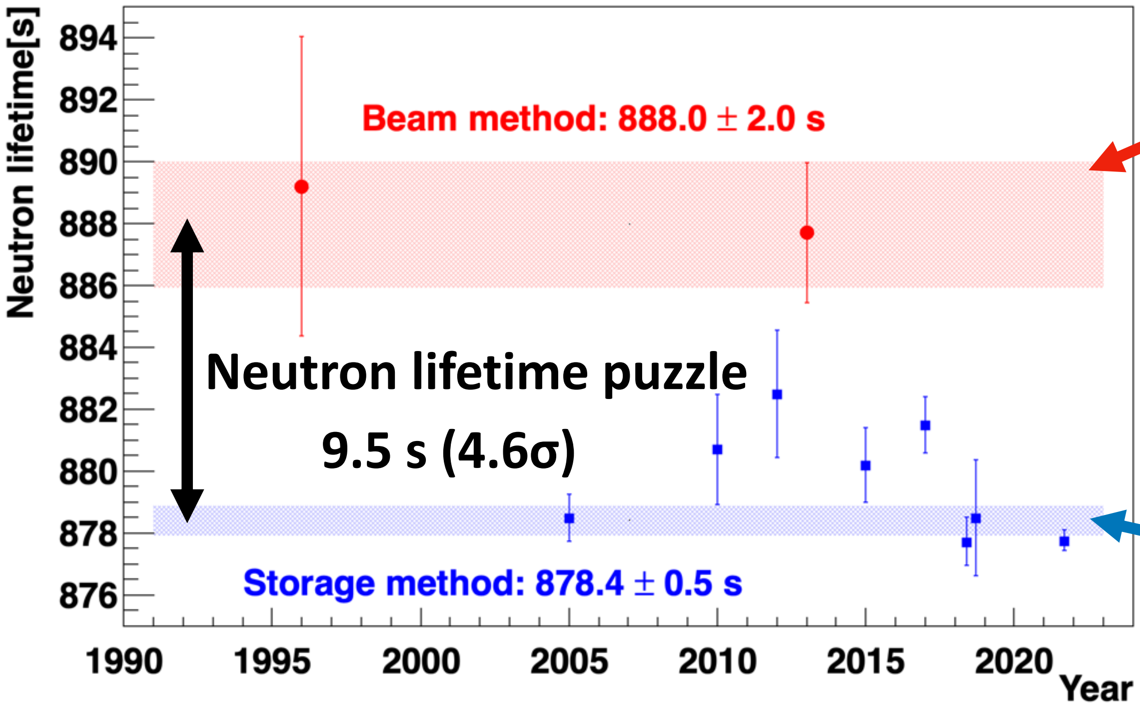
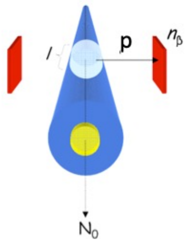
On behalf of J-PARC neutron lifetime collaboration

The 9th International Symposium on Symmetries in Subatomic Physics (SSP2025)
2025. Sep. 24th, Nara, Japan

Neutron Lifetime Puzzle

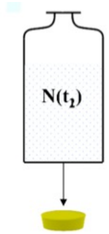


Beam method: Count the decay



$$-\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{N}{\tau}$$

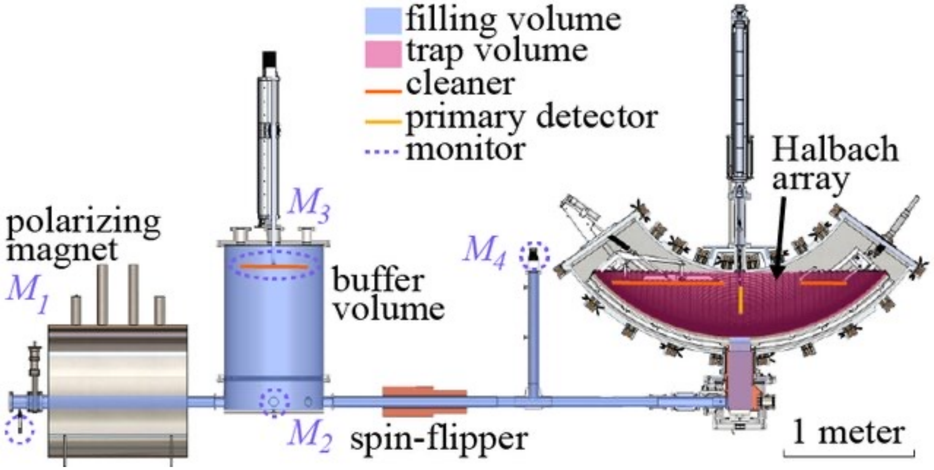
Storage method : Count the missing

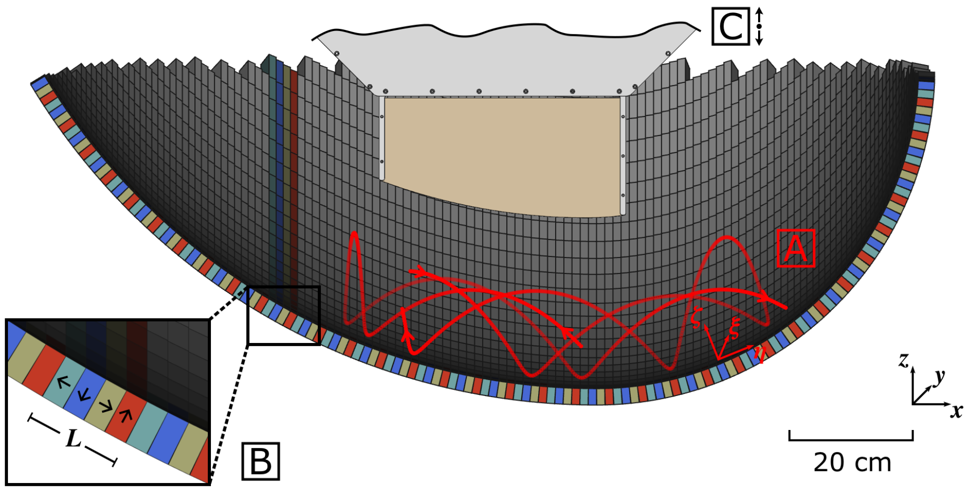


$$\frac{N_1}{N_2} = \mathrm{e}^{-(t_1 - t_2)/\tau}$$

- **Measured neutron lifetime values with beam method and storage method show significant discrepancy (more than 4.6σ)**
  - Experimental uncertainties that were not taken into account? (Phys. Rev. D **103**, 074010)
  - New physics?
    - Dark decay? (Mod. Phys. Lett. A **35**, 2030019 (2020))
    - Soft scattering with dark matter? (Phys. Rev. D **103**, 035014)
    - Mirror neutron oscillation? (EPJ C **79:** 484 (2019))

UCNτ experiment





N. Callahan *et al.* Phys. Rev. C **100**, 015501

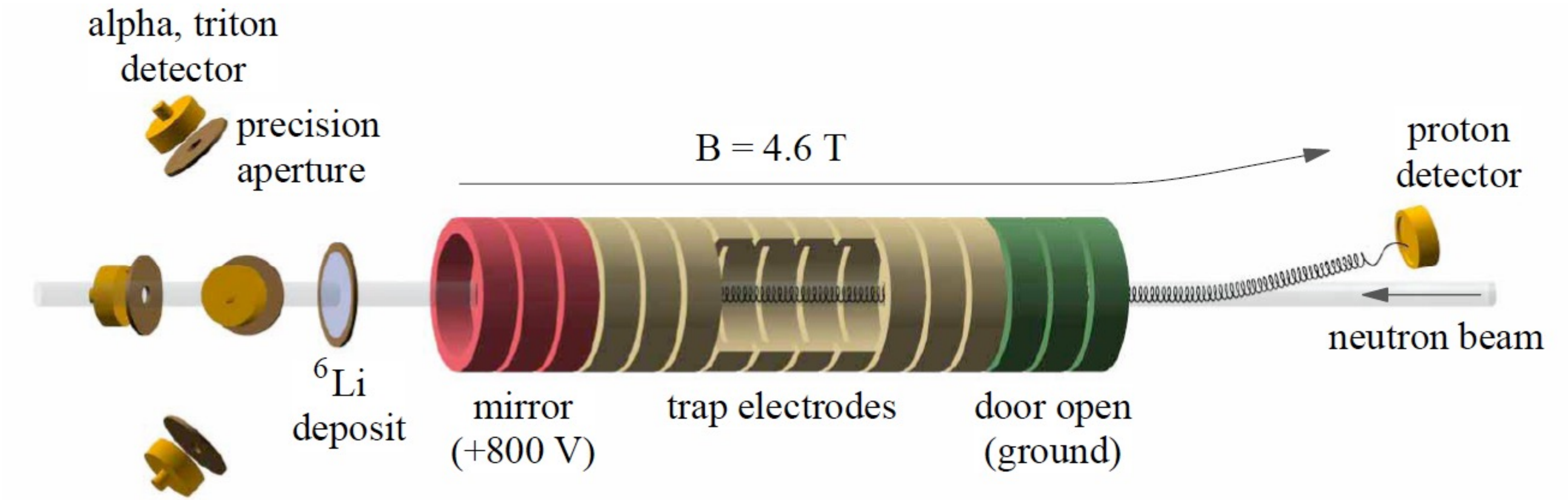
- The most accurate experiment have done in Los Alamos in 2021.

F. M. Gonzalez *et al* (UCN τ Collaboration), Phys. Rev. Lett. 127, 162501 (2021)

$$\tau_n = 877.7 \pm 0.28_{stat}{}^{+0.22}_{-0.16}{}_{syst}\ s$$

- Storing UCNs in magnetic bottle, and detecting with scintillation detector.

Beam method
NIST experiment by proton counting



1. Monochromatic beam is transported to the magnetic trap. Neutron flux is monitored by a well calibrated ^{6}Li/SSD detector.
2. Protons from the neutron decays captured in the magnetic trap with electrodes. Stored protons are released and detected by an SSD with thin surface layer.

$$\tau_n = 887.7 \pm 1.2\,[stat.] \pm 1.9\,[syst.]\,s \; = 887.7 \pm 2.3\,[combined]\,s$$

A. T. Yue et al., "Improved determination of the neutron lifetime." Physical review letters 111.22 (2013): 222501.
J. Nico et al., "Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam." Physical Review C 71.5 (2005): 055502.

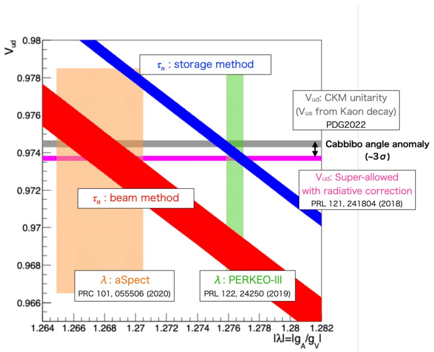
Neutron lifetime

➢ Test of standard model

- V_{ud} of the Cabibbo-Kobayashi-Maskawa (CKM) matrax can be calculated with:
  - Neutron lifetime (τ_n)
  - Axis/vector coupling constant $\lambda \equiv G_A/G_V$

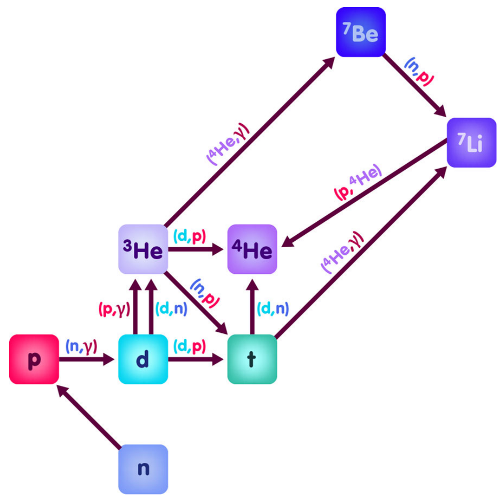
$$|V_{ud}|^2 = \frac{(4905.7 \pm 1.7)\ \mathrm{sec}}{\tau_n(1 + 3\lambda^2)}$$

→ Verification of the unitarity of the CKM matrix

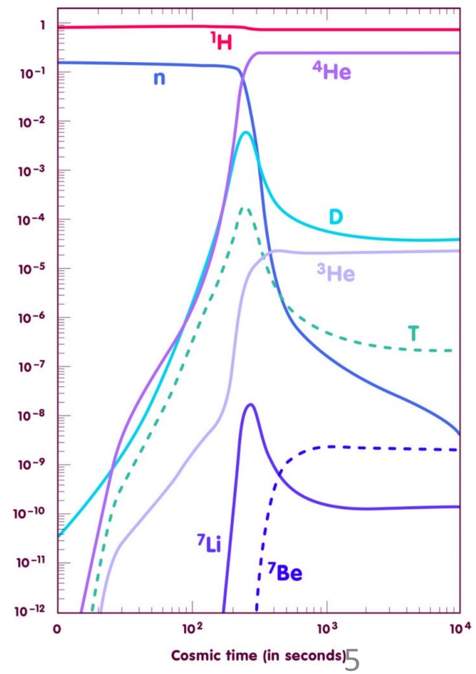


➢ An input parameters for the Big Bang Nucleosynthesis (BBN)

- Abundance of light elements in early universe can be calculated with:
  - Baryon-to-photon ratio
  - Nuclear cross sections
  - Neutron lifetime



https://www.einstein-online.info/en/spotlight/bbn_phys/

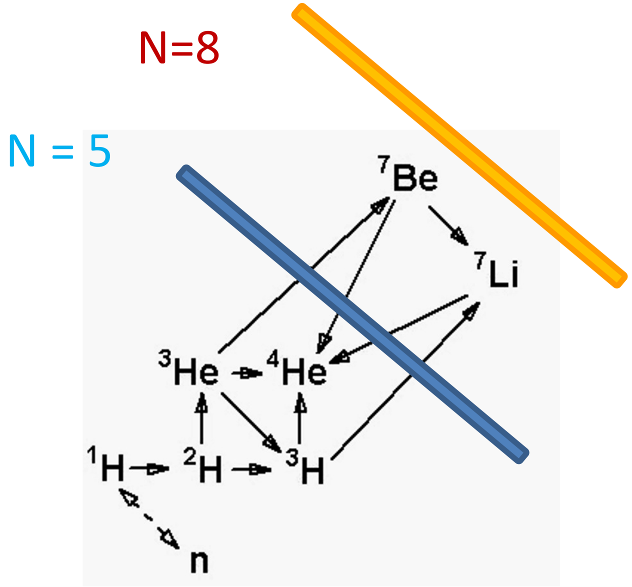


- The neutron lifetime is an important parameter for physics

Big Bang Nucleosynthesis from SUBARU Telescope

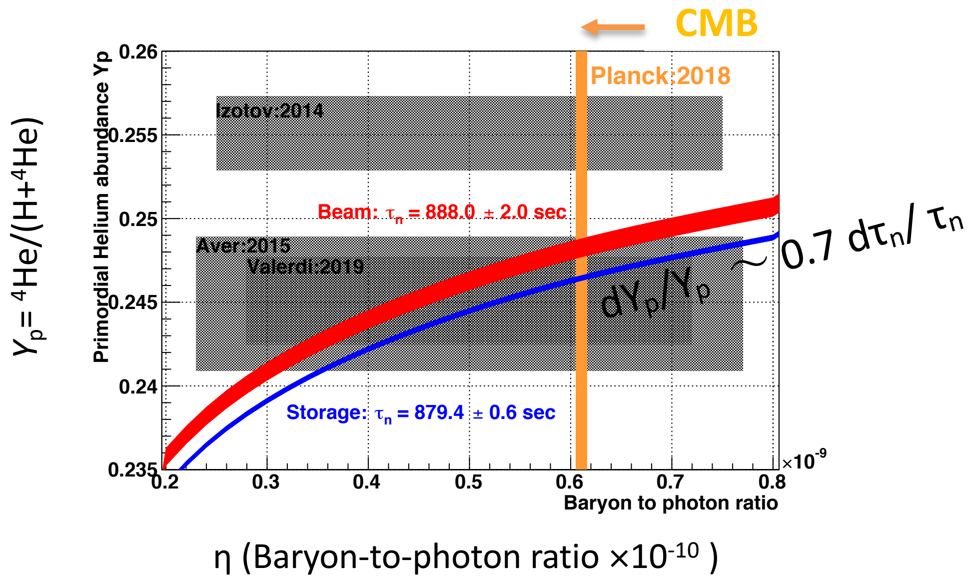
Big bang nucleosynthesis

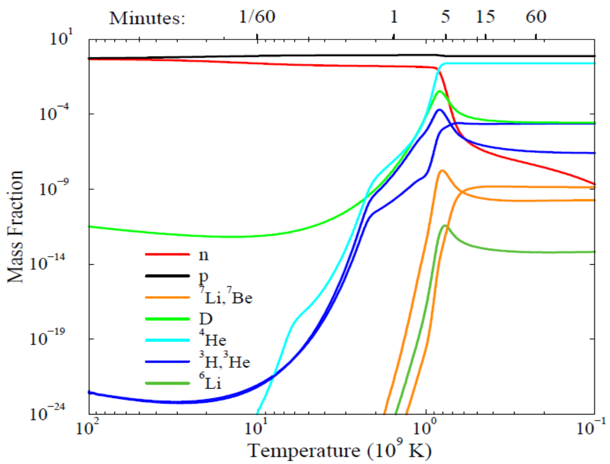
CMB & He/H & Neutron Lifetime



Light elements up to N=7 were created in 3 minute after the big bang (Big Bang Nucleosynthesis). Abundance of them can be calculated by baryon-to-photon ratio η, nuclear cross sections, and **the neutron lifetime**.

He/H observation of HII region in galaxies





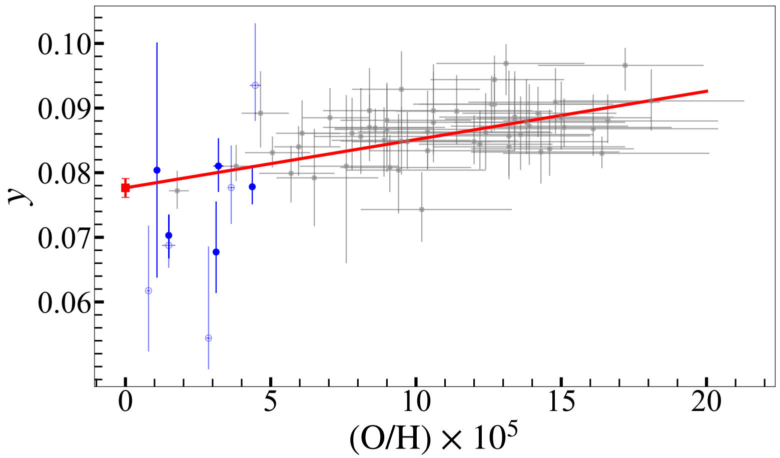
BBN model and η gives accurate prediction of the abundance of light elements, e.g. Y_p = ^{4}He/(H+^{4}He). Comparing with the Y_p predicted and observed enable testing the early universe.

1. Izotov, Y. I., G. Stasińska, and N. G. Guseva. "Primordial 4He abundance: a determination based on the largest sample of H II regions with a methodology tested on model H II regions." *Astronomy & Astrophysics* 558 (2013): A57.
2. Valentino E, et al., "Reconciling Planck with the local value of H0 in extended parameter space", Physics Letters B 761 (2016) 242–246.

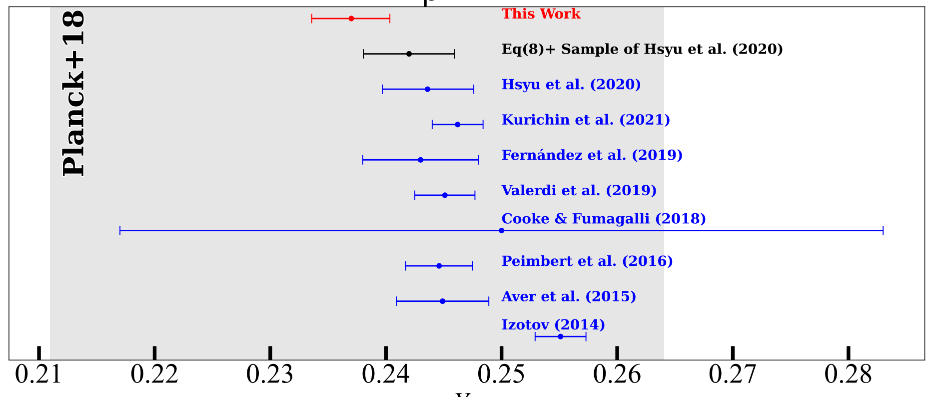
Recent observation by SUBARU telescope

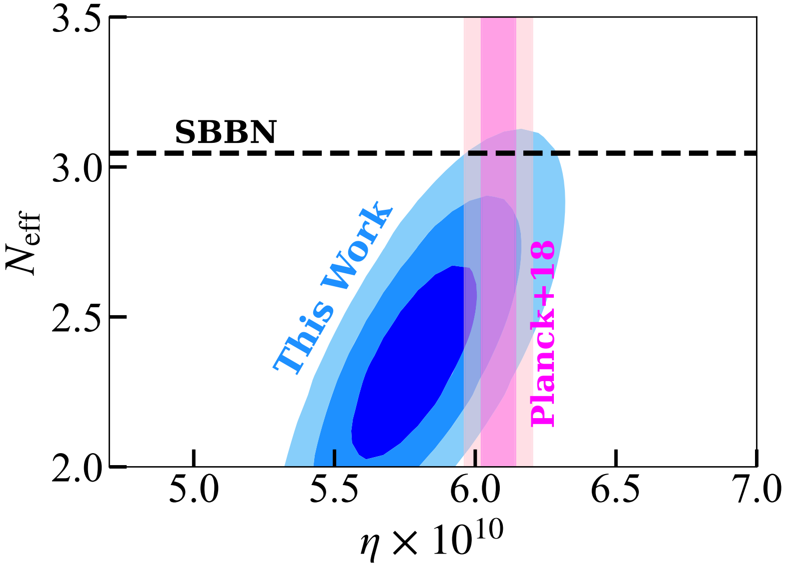
Resent observation from SUBARU telescope gives very small Y_p value.

Correction of Metallicity



Y_p value





$$N_{\rm eff} = 3.11^{+0.34}_{-0.31},$$

$$\eta \times 10^{10} = 6.08^{+0.06}_{-0.06},$$

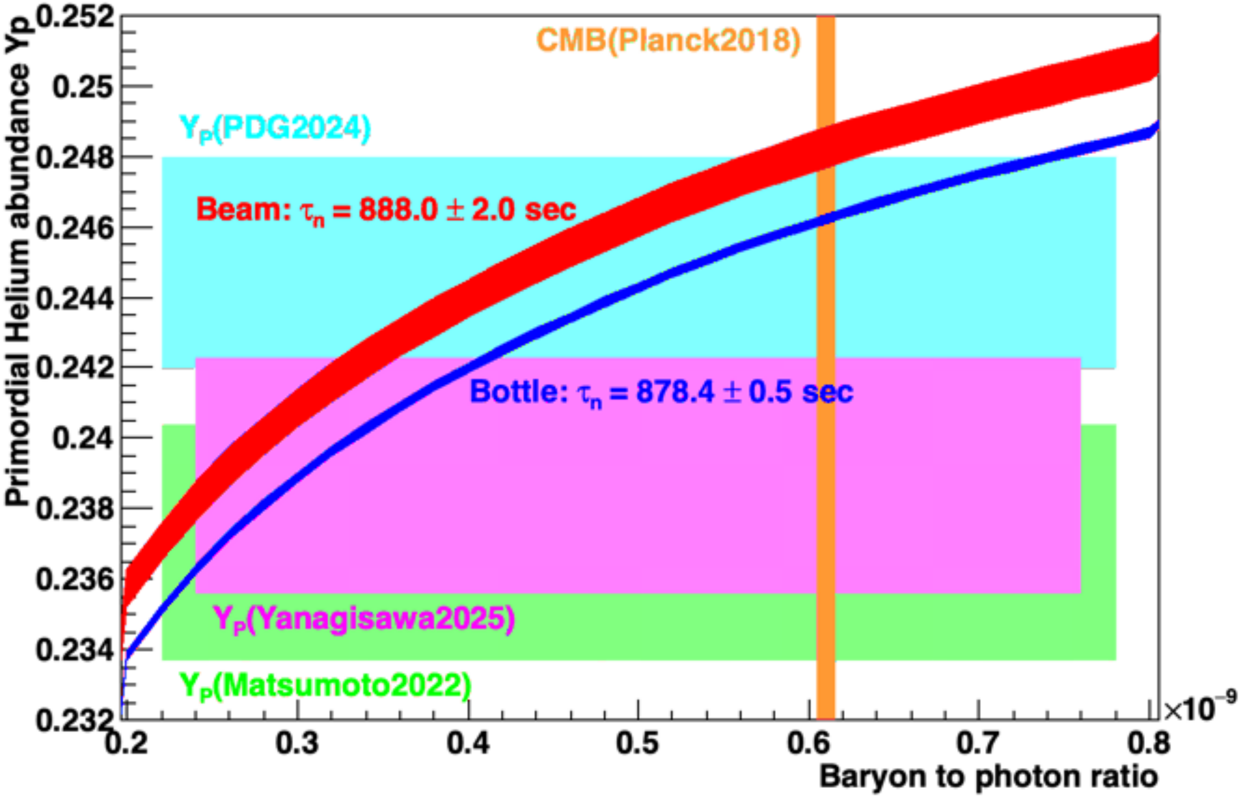
$$\xi_e = 0.05^{+0.03}_{-0.02}.$$

The degeneracy parameter of the electron neutrino ($\nu_e - \overline{\nu_e}$ asymmetry) is non-zero by more than 2σ.

Akinori Matsumoto *et al* 2022 *ApJ* **941** 167, https://doi.org/10.3847/1538-4357/ac9ea1

SUBARU update (2025)

An update of Y_p is now on arXiv.
H. Yanagisawa et al., "EMPRESS. XV. A New Determination of the Primordial Helium Abundance Suggesting a Moderately Low Y_P Value", arXiv (2025), https://doi.org/10.48550/arXiv.2506.24050



$$Y_p = 0.2387^{+0.0036}_{-0.0031}$$
$$N_{eff} = 2.54^{+0.21}_{-0.20}$$

If lepton asymmetry is allowed,

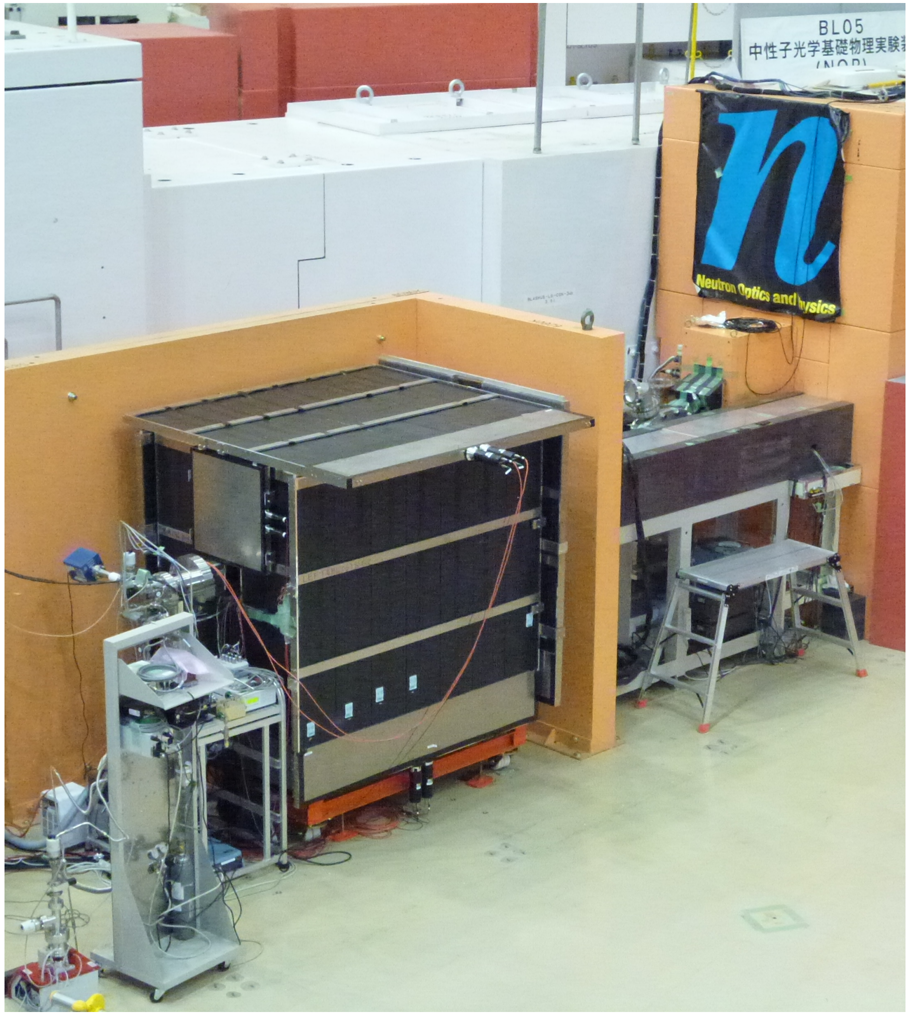
$$N_{eff} = 3.23^{+0.27}_{-0.26}$$
$$\xi_e = 0.05^{+0.02}_{-0.02}$$

These mitigates the Hubble tension.

Or Neutron lifetime of 845 s !

A new beam experiment at J-PARC by detecting electrons

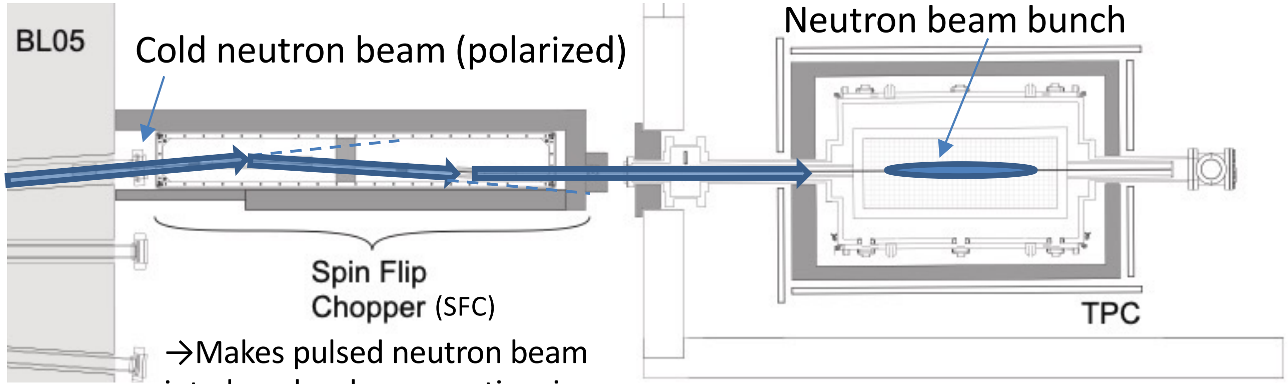
Neutron Lifetime experiment using pulsed neutron at J-PARC



K. Mishima[1], Y. Fuwa[2], T. Hasegawa[1], T. Hoshino[4], R. Hosokawa[4], G. Ichikawa[3], S. Ieki[5], T. Ino[3], Y. Iwashita[6], M. Kitaguchi[1], S. Makise[4], S. Matsuzaki[4], T. Mogi[7], K. Morikawa[1], N. Nagakura[7], H. Okabe[1], H. Otono[4], Y. Seki[5], D. Sekiba[8], T. Shima[9], H. E. Shimizu[10], H. M. Shimizu[1], N. Sumi[3], H. Sumino[6], M. Tanida[4], T. Tomita[4], H. Uehara[4], T. Yamada[6], S. Yamashita[11], K. Yano[4], T. Yoshioka[4]

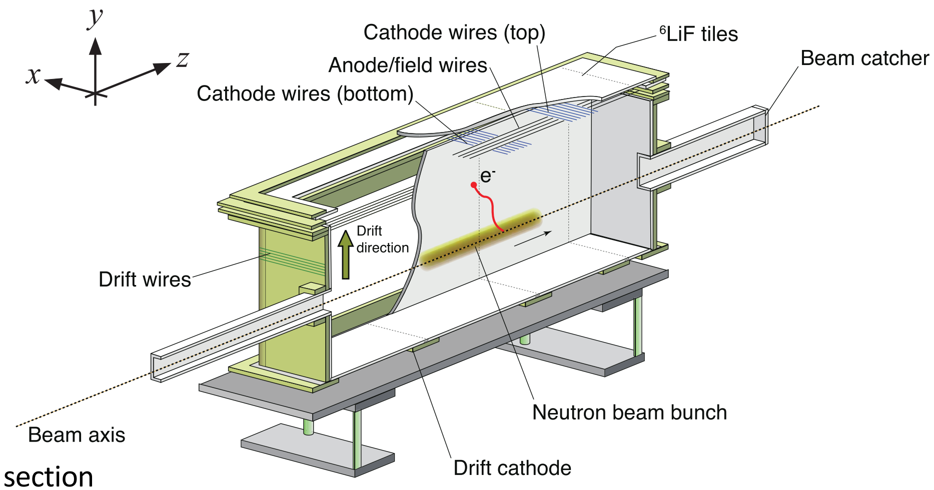
Nagoya Univ.[1], JAEA[2], KEK[3], Kyushu Univ.[4], Tohoku Univ.[5], Kyoto Univ.[6], The Univ. of Tokyo[7], Univ. of Tsukuba[8], Osaka Univ.[9], Sokendai[10], Iwate Pref. Univ.[11]

Lifetime measurement at J-PARC/BL05 (Beam Line 05)



→Makes pulsed neutron beam into bunches by magnetic mirrors and spin flippers

Comparing e^- of neutron decay and $^3He(n,p)^3H$



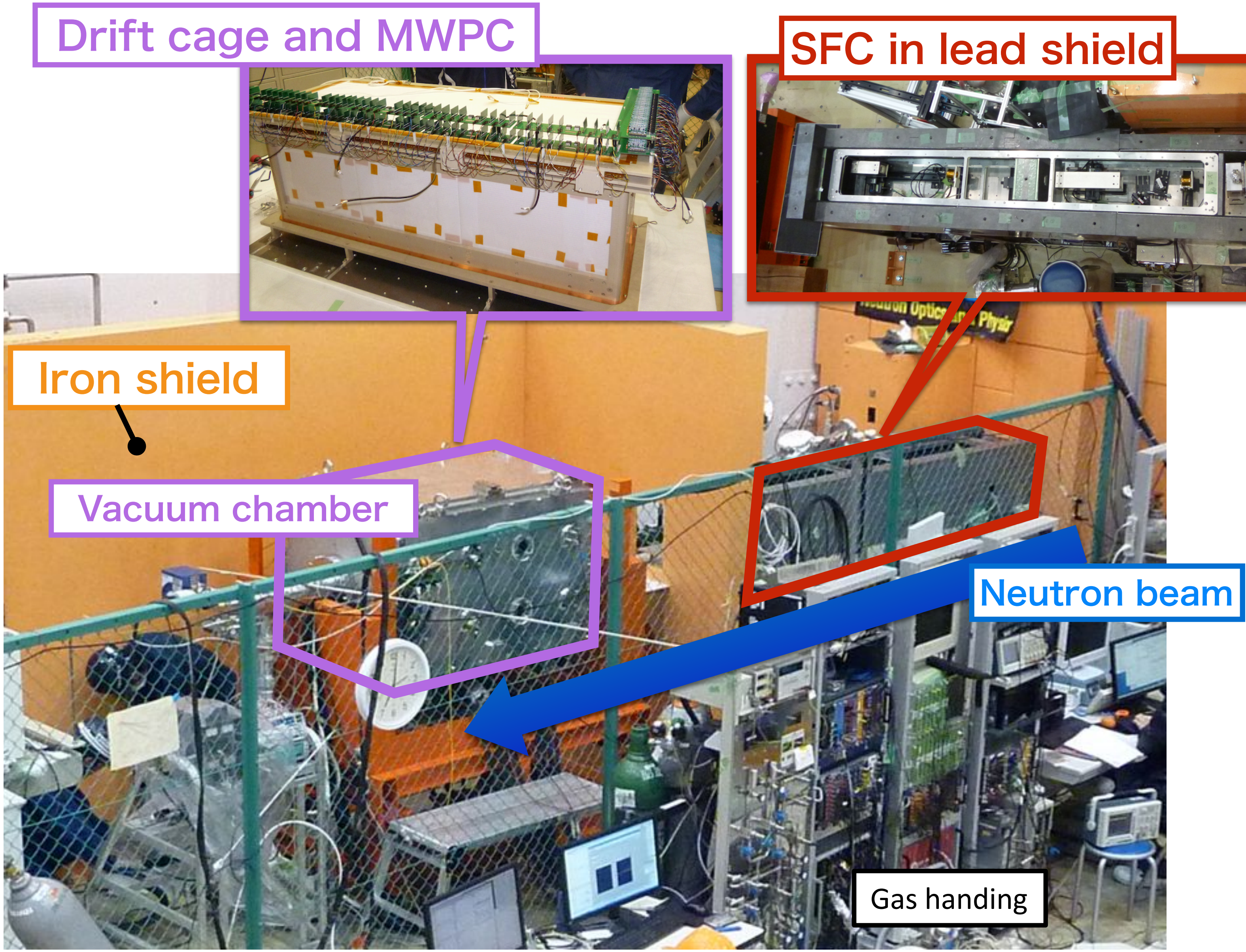
- Detector: Time Projection Chamber (TPC)
  - Gas: ^4He, CO_2, ^3He
    (~85%, ~15%, 0.5 - 2 ppm, respectively)
    Total pressure: 100 kPa or 50 kPa
  - Signals are detected with a Multi Wire Proportional Chamber (MWPC)

$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\frac{(S_{He}/\varepsilon_{He})}{(S_\beta/\varepsilon_\beta)}$$

ρ : ^{3}He dencity
σ_0 : ^{3}He neutron absorption cross section
v_0 : Velocity of neutron
S_{He} : Number of ^{3}He neutron absorption event
S_β : Number of neutron β decay
ε_{He}, ε_β : Efficiency

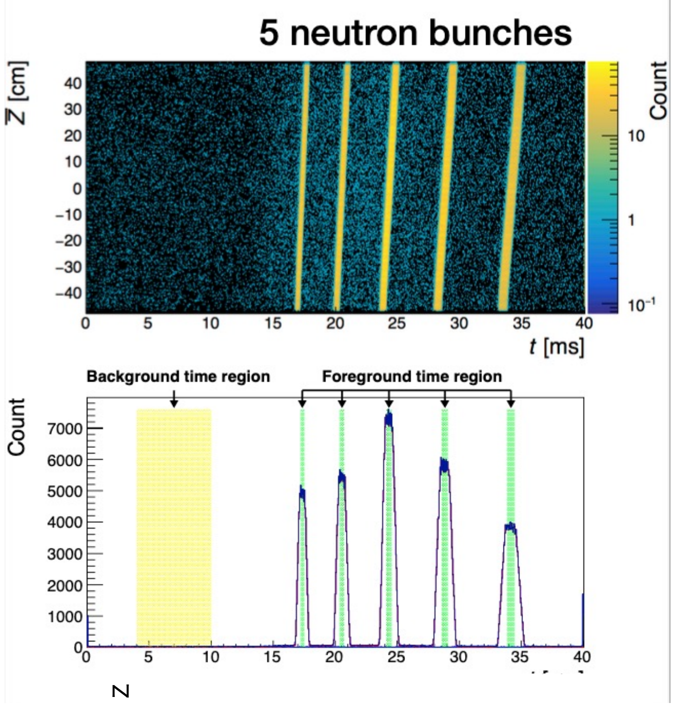
- We aim to provide the most precise experimental neutron lifetime value for beam method as an important piece to solve the neutron lifetime puzzle
  - **Goal: measurement with ~1 s accuracy**

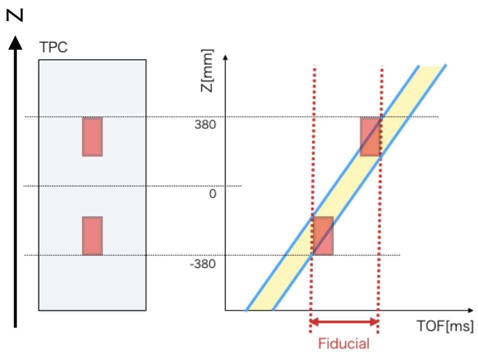
Experimental Setup



Analysis

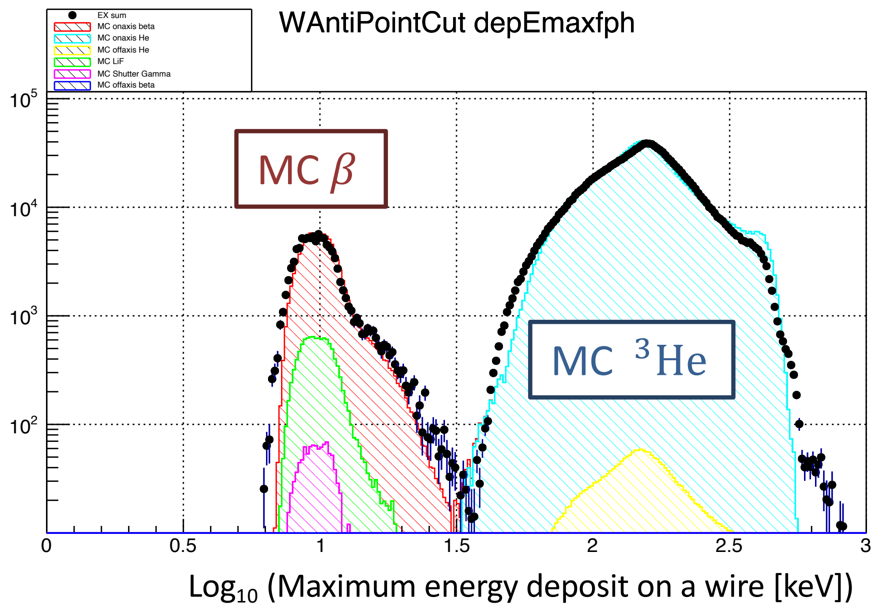
Selection by TOF





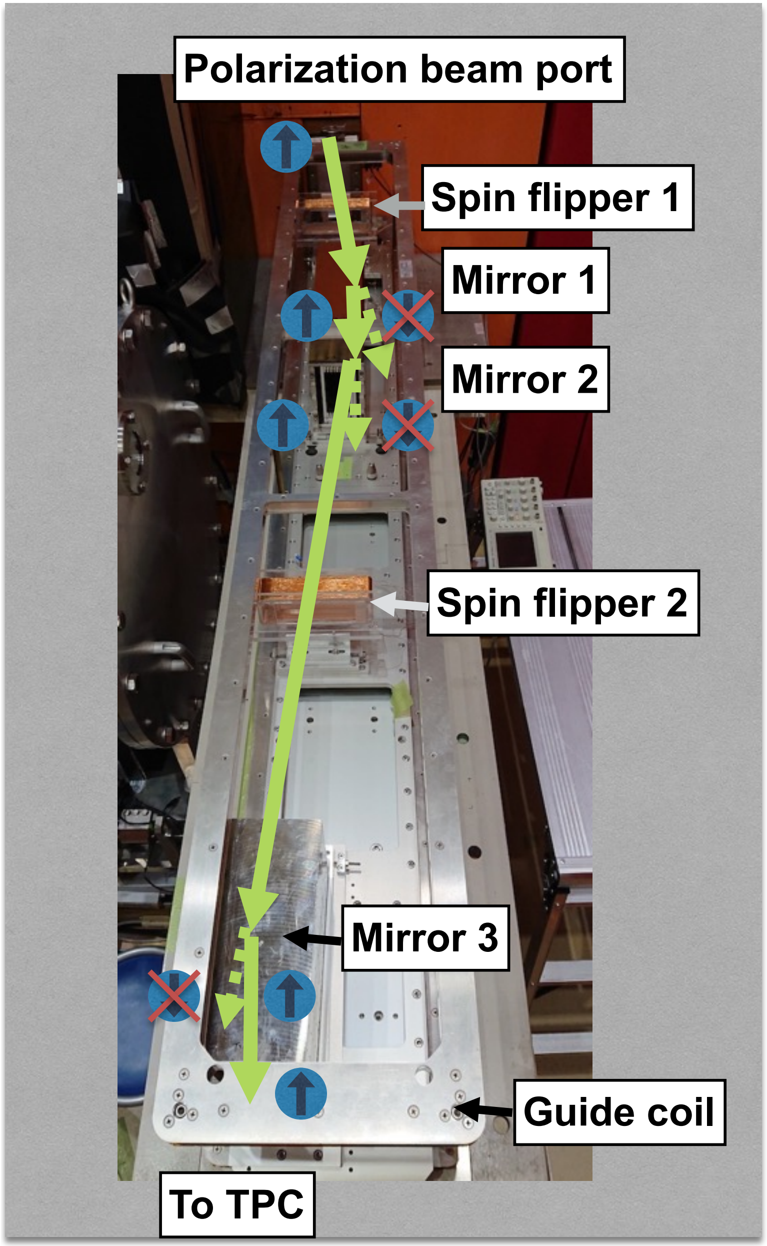
TOF cut applied when the neutron bunches are completely in the TPC.

Selection by maximum energy deposit



This cut can clearly distinguish β and $^3He(n,p)^3H$ events

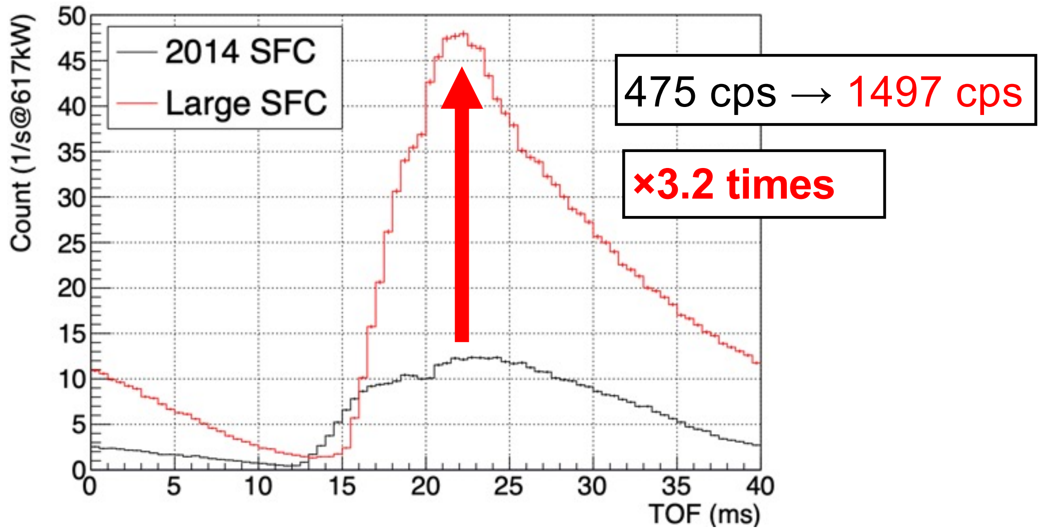
Upgrade of the Spin Flip Chopper



Spin Flip Chopper (SFC)

- The neutron intensity is limited by the size of the mirrors.
- Larger mirrors were installed in 2020.

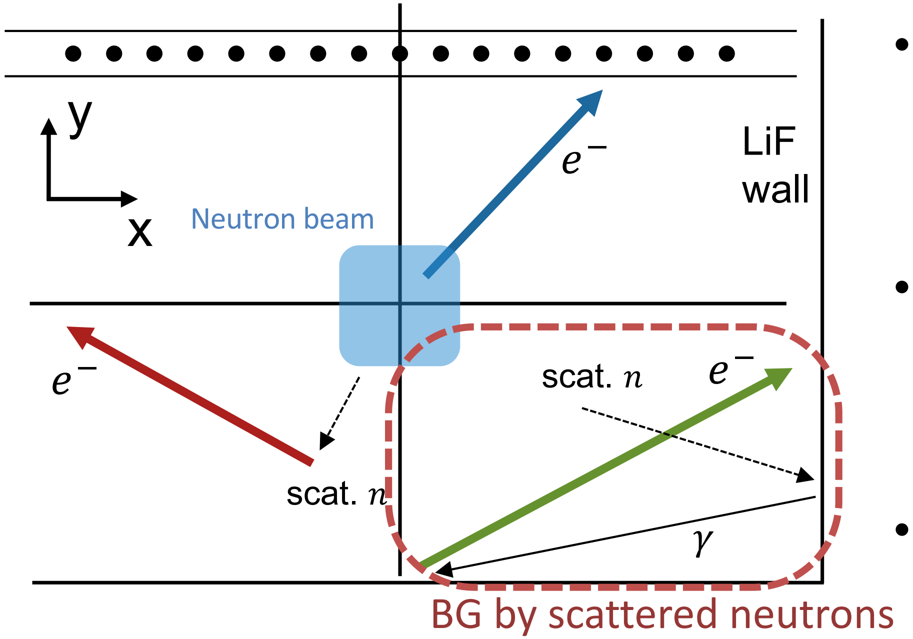
Magnetic mirror
25 mm×140 mm×15→100 mm×200 mm×26



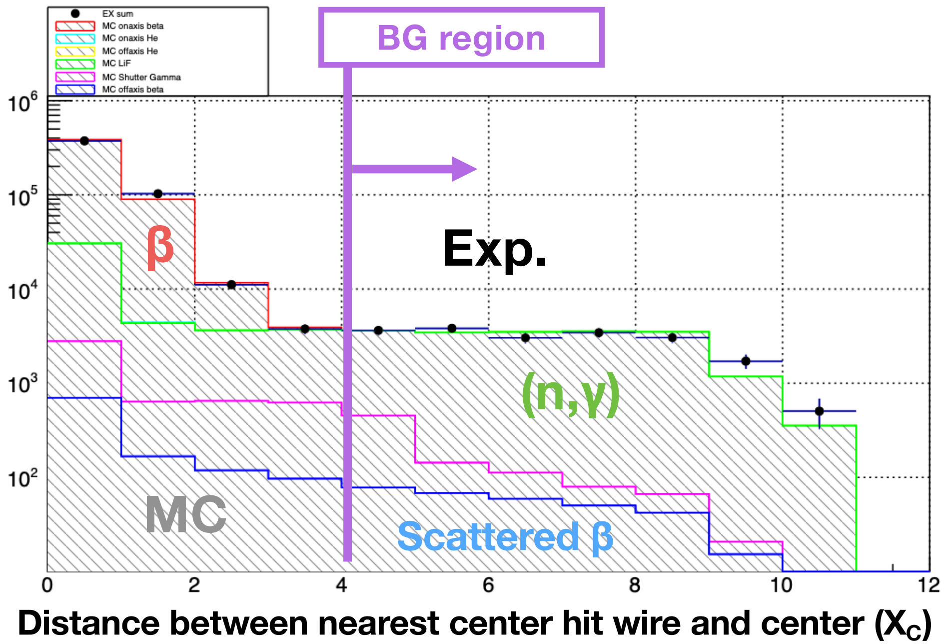
Neutron event rate at the exit of SFC

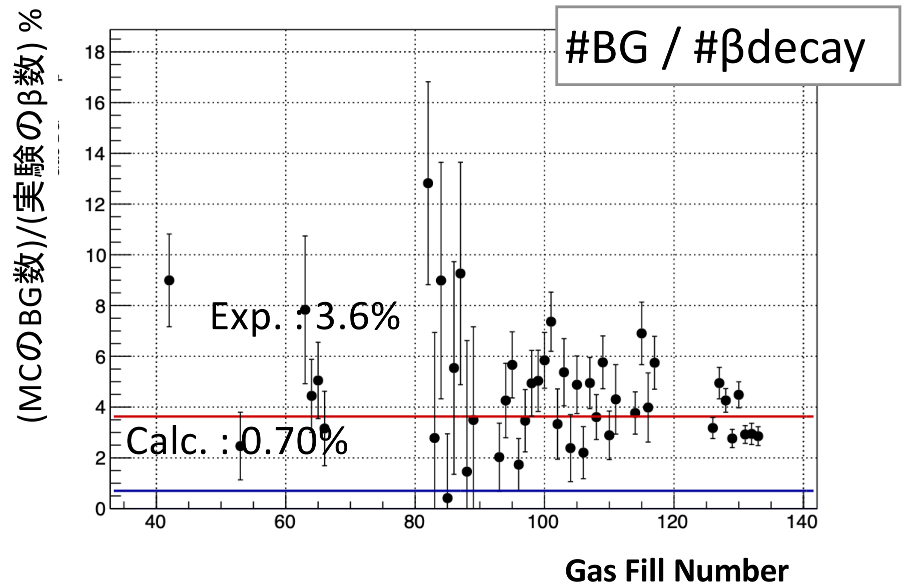
- Larger magnetic mirror increases intensity by 3.2 times
- Statistical accuracy of 1 s can be reached in 3 months of measurement
- Neutron polarization $P \sim 99\%$

Excess of background



- Neutrons scattered by the TPC operating gas are absorbed by the LiF inner wall, some of which emit γ-rays, creating (n,γ) background (BG) events.
- Although the events are created in the BG region close to the wall, the amount of the events was about five times larger than expected.
- The indeterminacy in the distribution of the (n,γ)BGs and the large uncertainty in the rate at which the BGs leak into the signal region were the largest sources of systematic error.





Low gas pressure operation

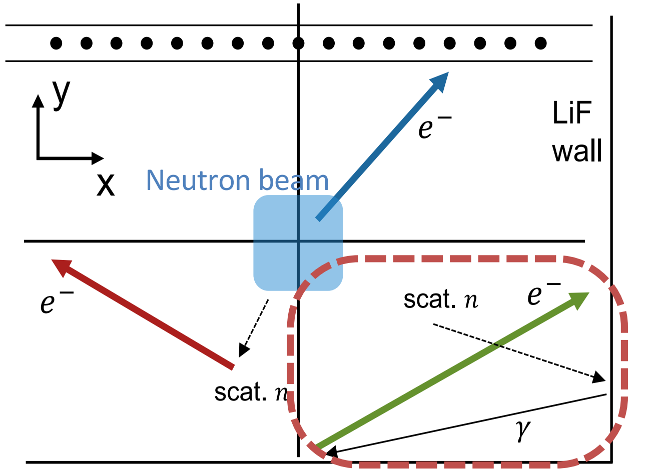
- First result (2014-2016): TPC gas pressure 100 kPa

($^4\mathrm{He} : \mathrm{CO_2} : {}^3\mathrm{He} = 85\ \mathrm{kPa} : 15\ \mathrm{kPa} : 50 - 200\ \mathrm{mPa}$)

- Number of background events due to gas scattering ∝ Number of scattered neutrons

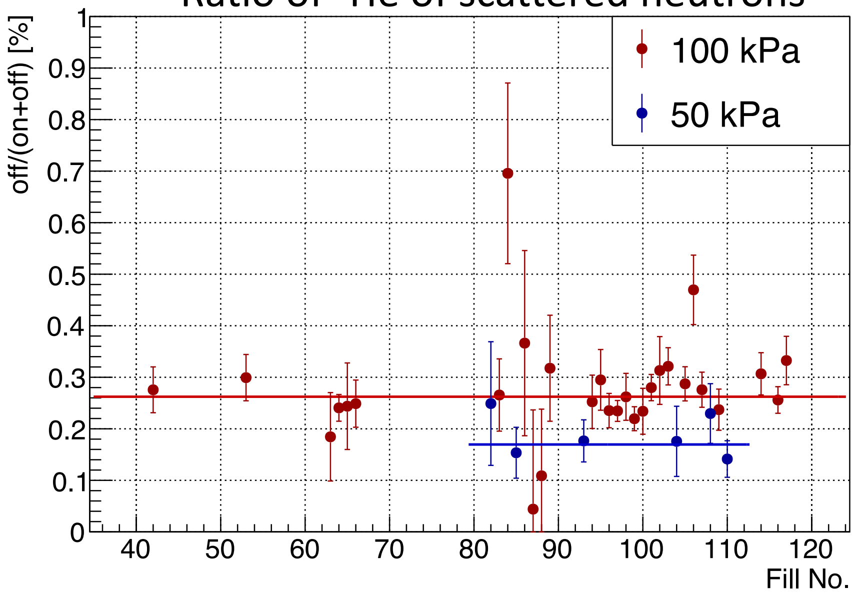
- Operation with gas pressure with **50 kPa** can reduce background

($^4\mathrm{He} : \mathrm{CO_2} : {}^3\mathrm{He} = 42.5\ \mathrm{kPa} : 7.5\ \mathrm{kPa} : 50 - 200\ \mathrm{mPa}$)

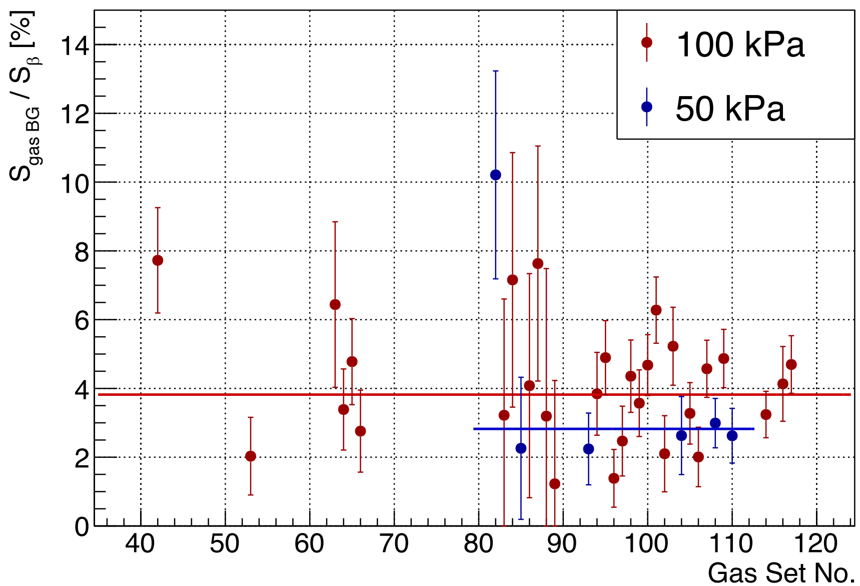


BG by scattered neutrons

Ratio of ^{3}He of scattered neutrons



Ratio of beta backgrounds



Measurement at 50 kPa reduces the number of background events due to gas scattering to 60% of that at 100 kPa.

Data obtained

Physics measurements taken on 49 gas sets in 2014 - 2023

- With 100 kPa

Acquisition year	Num. of Gas Set	MLF Power [kW]	DAQ time [h]	
2014	1	300	59	
2015	1	500	31	
2016	4	200	424	
2017	14	150, 300, 400	1303	(A)
2018	6	400, 500	614	
2019	3	500	348	
2021	1	700	38	
2022	3	700, 800	253	(B)
2023	1	800	126	

First result (stat. 10 s)

Statistic ~2.2 s

After SFC Upgrade

- With 50 kPa

Acquisition year	Num. of Gas Set	MLF Power [kW]	DAQ time [h]	
2017	3	150,300	253	
2018	3	400, 500	357	(C)
2021	1	700	86	
2022	7	700, 800	839	(D)
2023	1	800	155	

Statistic ~1.8 s

After SFC Upgrade

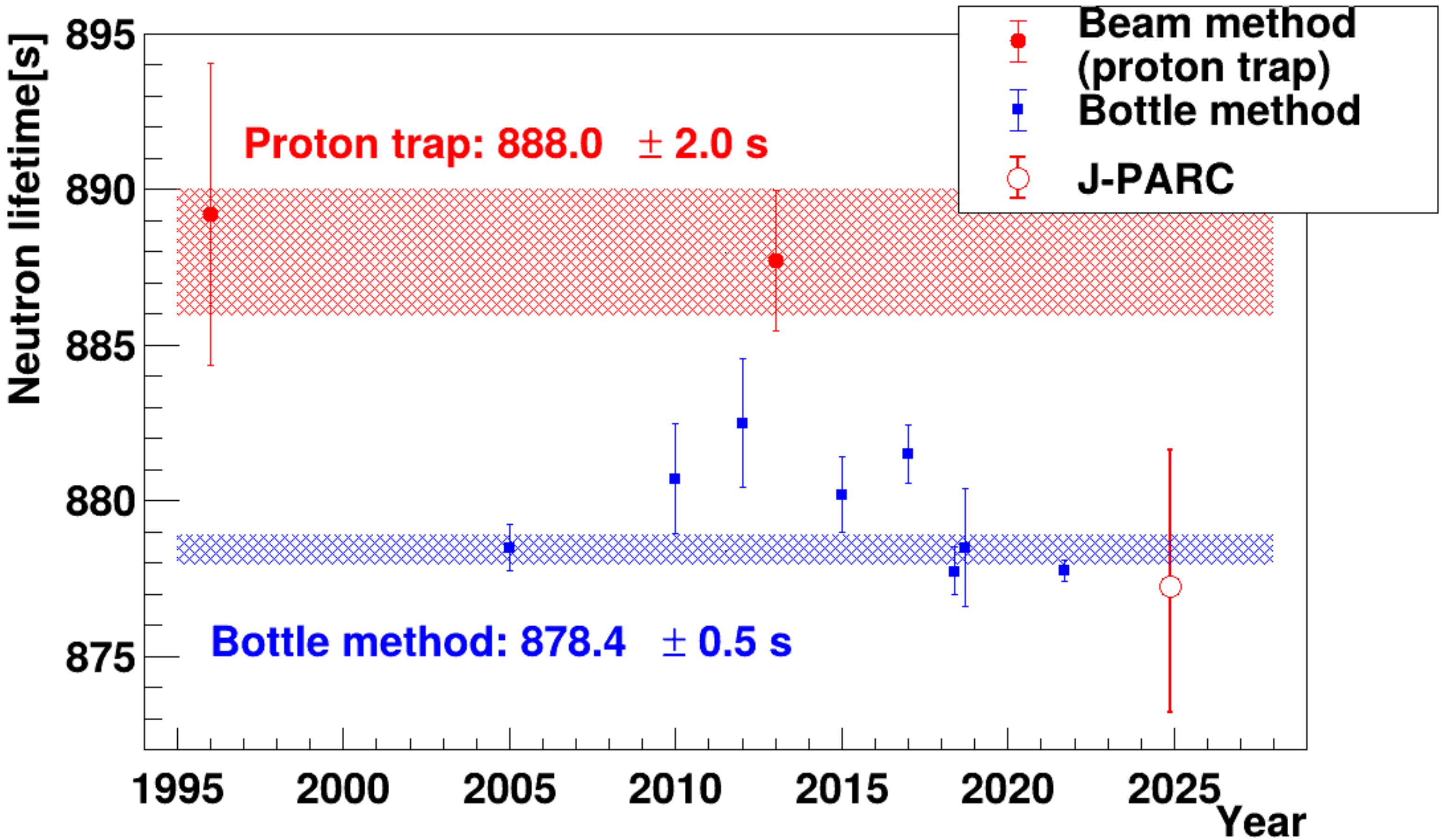
The combined Statistic is 1.4 s

A new result from J-PARC

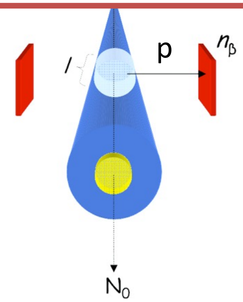
The improved results using data from 2014 to 2023 are as follows:

$$\tau_n = 877.2 \pm 1.7(stat.)^{+4.0}_{-3.6}(sys.) = 877.2^{+4.4}_{-4.0}\ \mathrm{s}$$

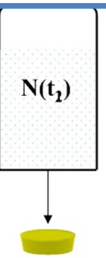
[Y. Fuwa et al., arXiv:2412.19519v1]



Beam method (proton trap)
Count the dead



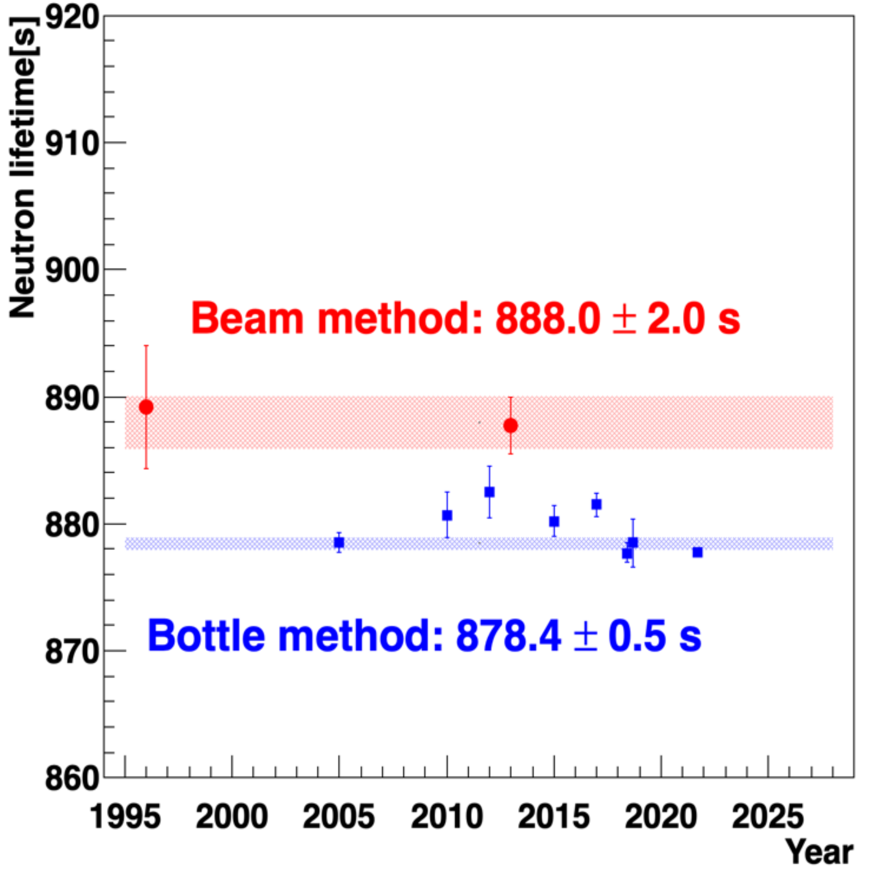
Bottle method
Count the living

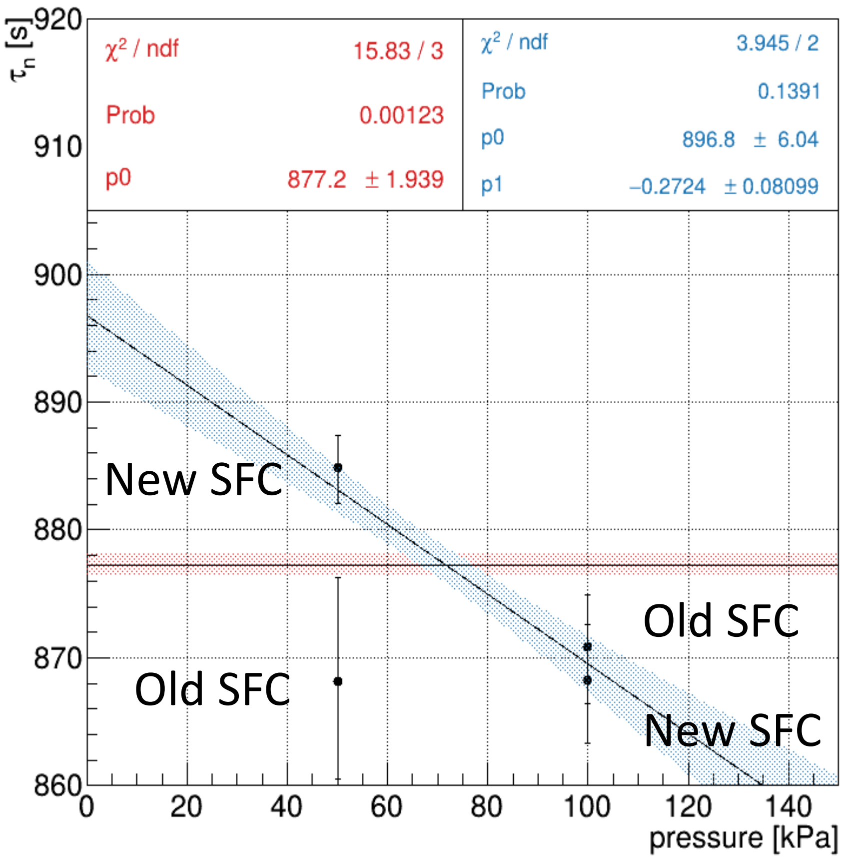


This value gives a 2.3σ tension with the average value obtained from the proton trap.

Discussion

- The χ^2/NDF of our fitting is large.
- If there is a pressure dependence, the fitting is going to be better, and then consistent with beam method.





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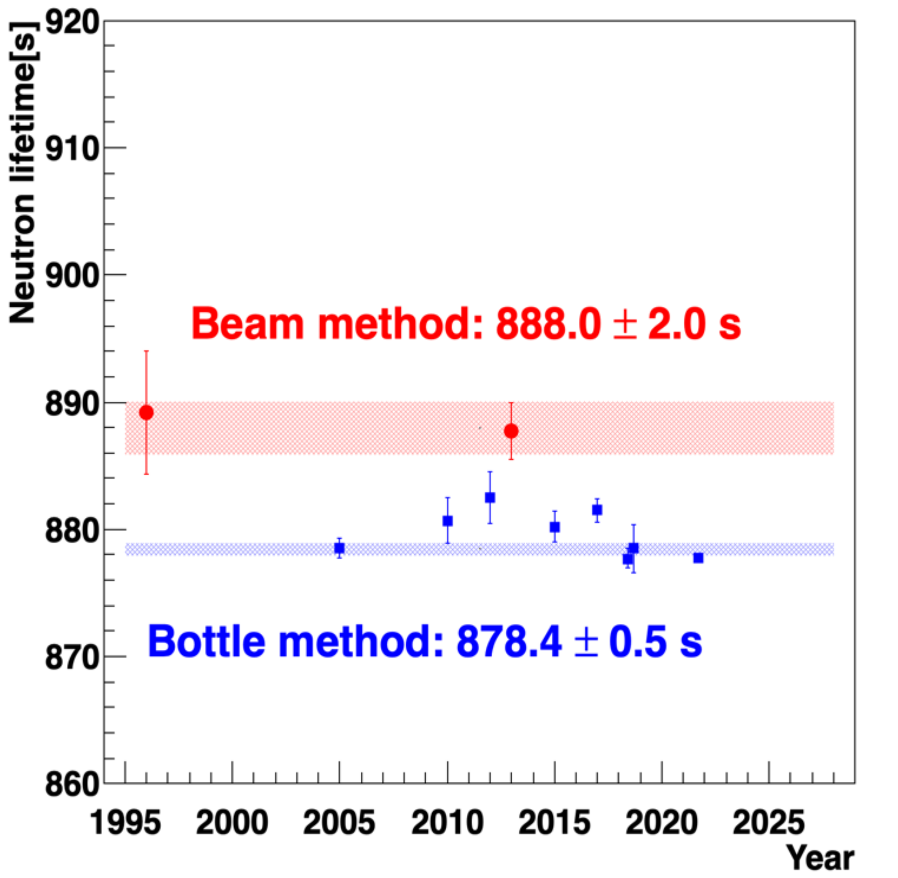
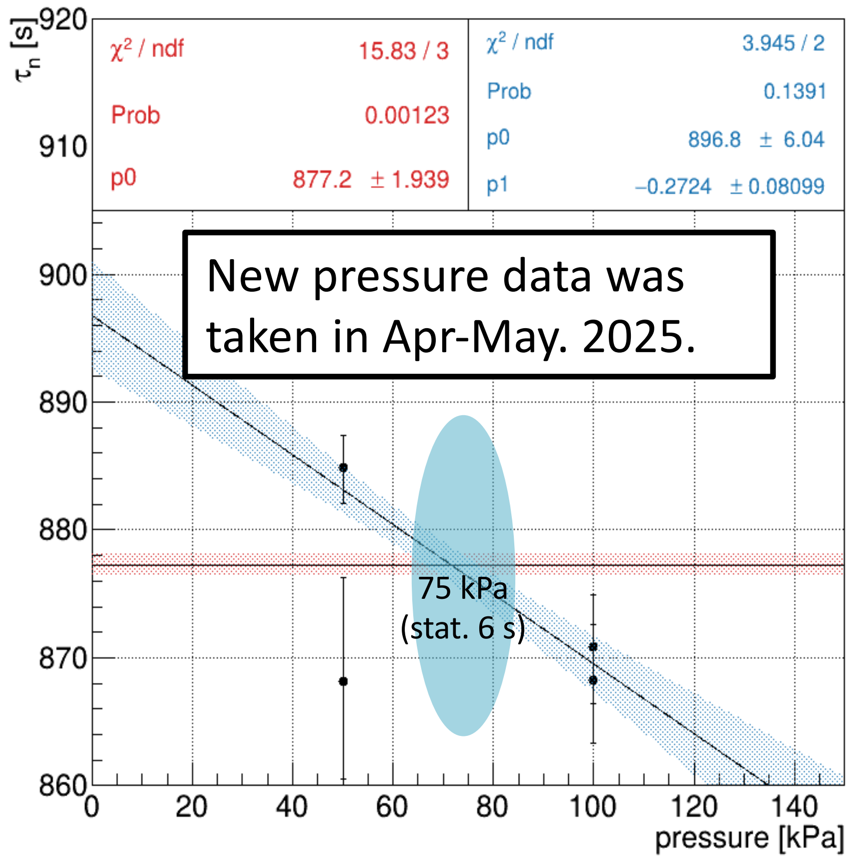




75 kPa and pure CO_2 run

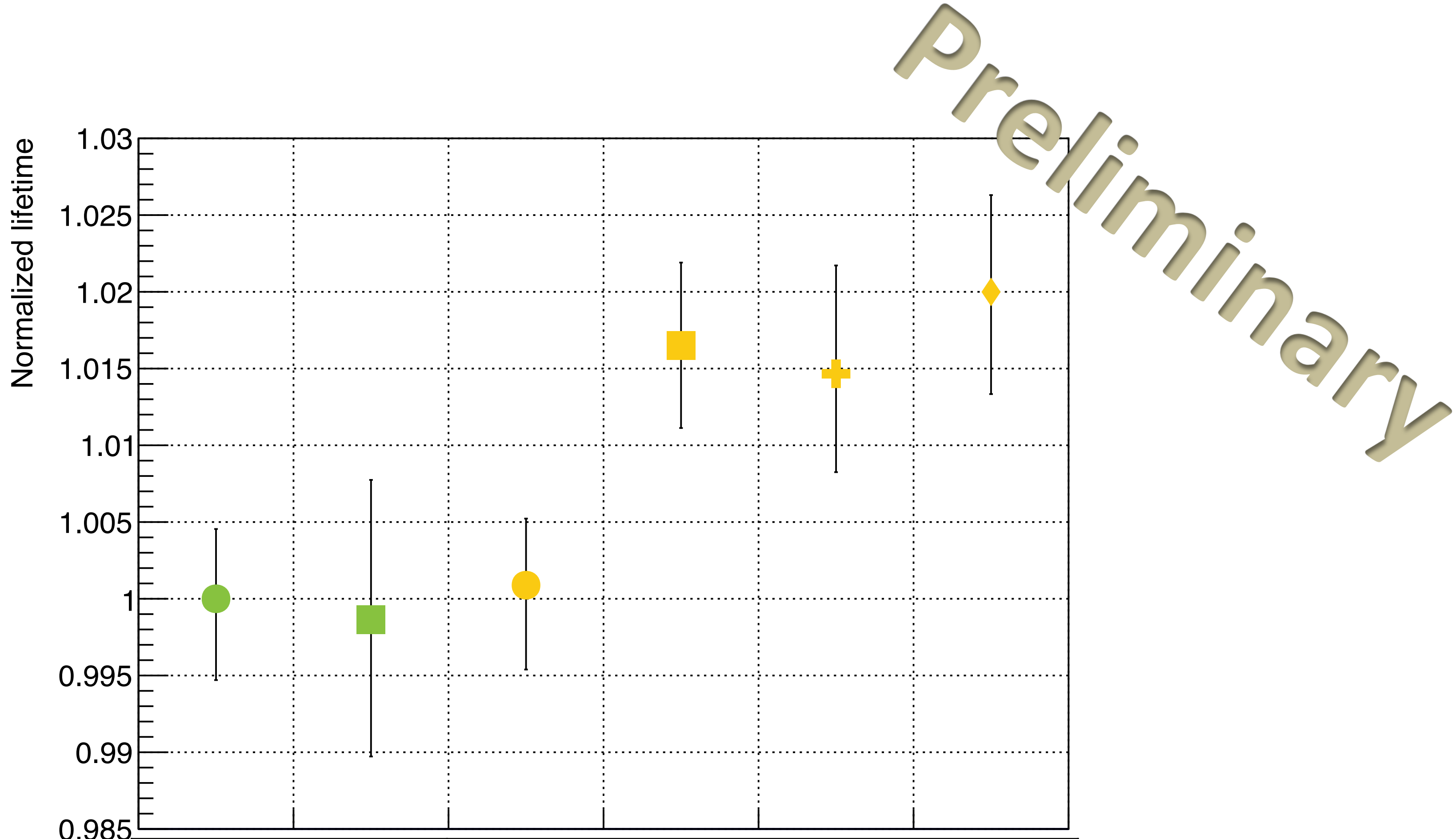
- We have used 100 and 50 kPa of $HeCO_2$ with mixture of 85%: 15%.
- In April in 2025, we took new data sets: with $HeCO_2$ of 75 kPa and 20 kPa of pure CO_2 run.
  - The amount of ^3He in the the He gas (G1He) must be corrected.
  - For pure CO_2 run, no need for the ^3He in the G1He correction.
    - ➢ After solved the discharging problem, we have succeeded to obtain a week of data taking.

Working gas conditions

New

	100 kPa	50 kPa	75 kPa	CO_2 20 kPa
CO_2	15 kPa	7.5 kPa	11.25 kPa	20 kPa
^4He	85 kPa	42.5 kPa	63.75	0 kPa

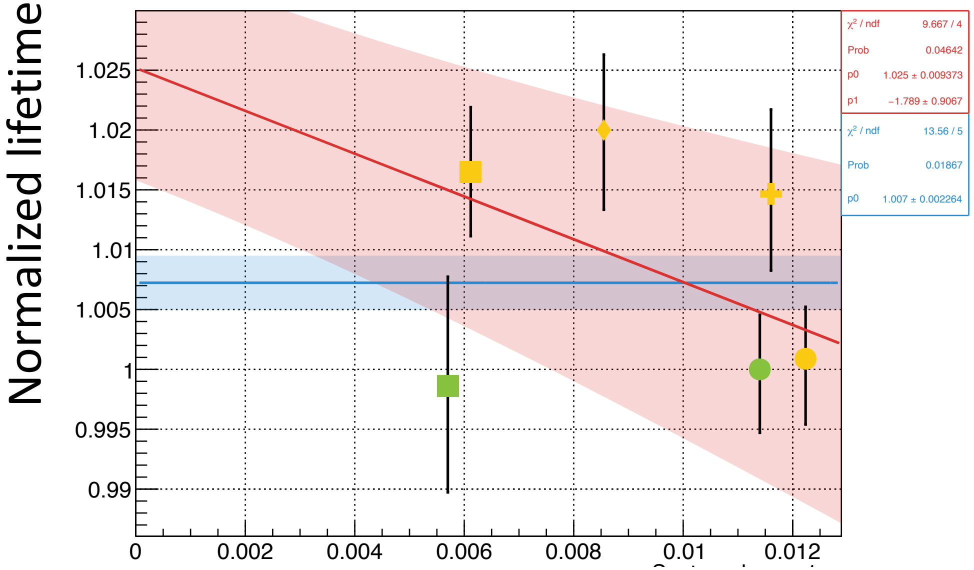
Results Preliminary



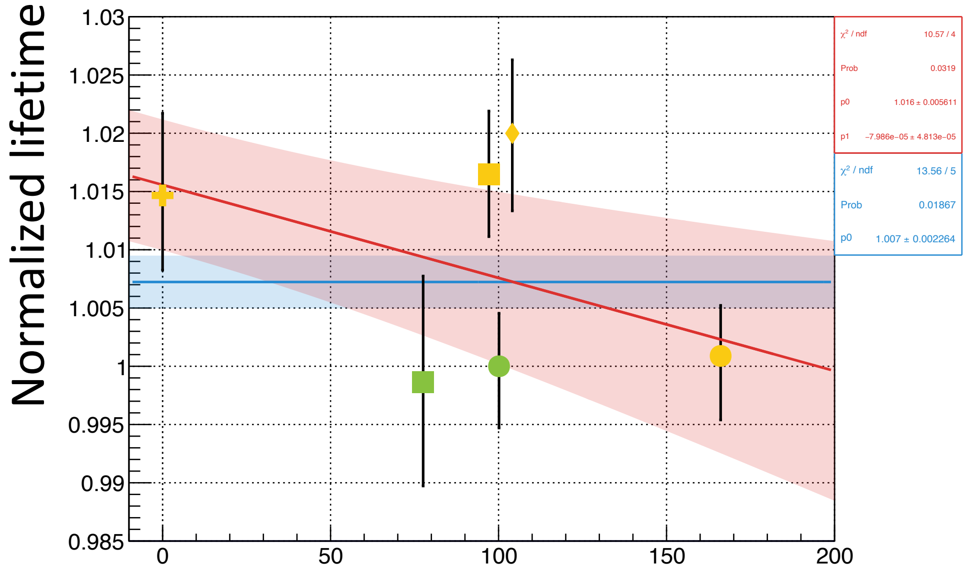
Old SFC		New SFC			
100 kPa	50 kPa	100 kPa	50 kPa	20 kPa (CO_2)	75 kPa

Dependency for Scattering Probability and ^{3}He amount in G1He

Preliminary



Neutron scattering probability per meter



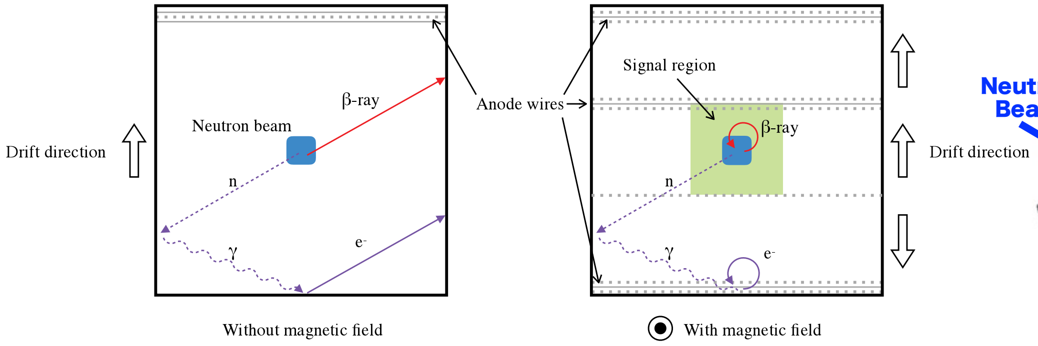
Correction for ^{3}He impurities in G1He (s)

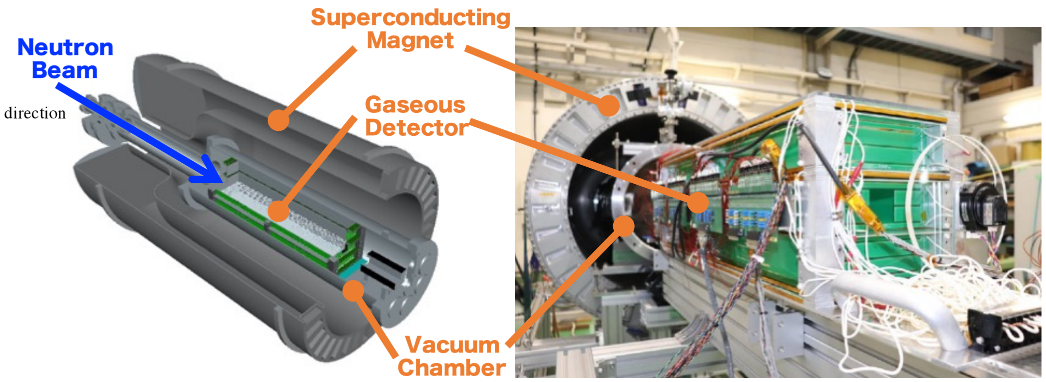
No clear dependencies were found.

Changes in gas conditions alter the scattering probability and electron path length.

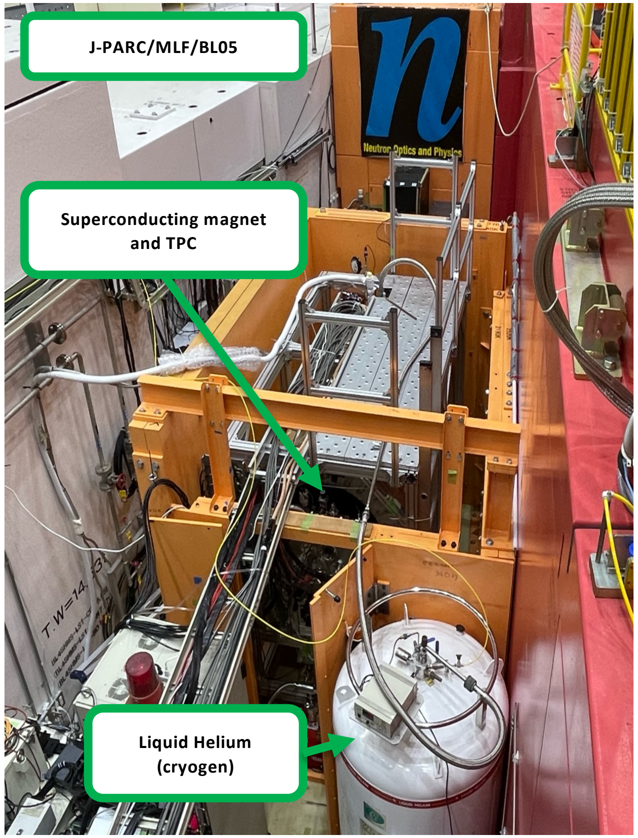
→This provides a clue for investigating consistency with MC.

Background suppression with solenoidal magnetic field

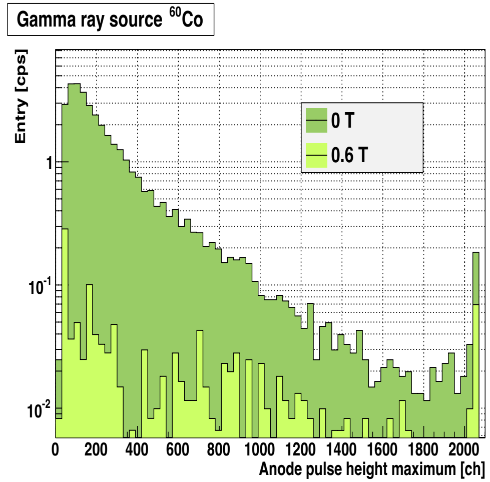




N. Sumi *et al.*, *Nucl. Inst. Meth. Phys. Res A* 1045 (2023) 167586.



To achieve 1 s, we are preparing for background suppression by using multi-layered TPC in a solenoid magnetic field. The magnetic field can suppress the gamma ray background to 1/50.



Gamma ray suppression with magnetic field

The first data was obtained on this apparatus in Feb. 2024. By analyzing 3 hours of run with the magnetic field, we obtained $\tau_n = 882 \pm 78$ [s] (no systematic considered). Experiment is planed in Dec. 2025.

Summary

- Neutron lifetime is an important parameter for particle, nuclear, and astro-physics.
- However, the value have 9.5 s (4.6σ) discrepancy with two method of measurements
  - **τ_n = 888.0 ± 2.0 （Beam method）**
  - **τ_n = 878.4 ± 0.5 （Storage method）**
- A new "beam" experiment is ongoing at J-PARC
  - We obtained physics data (statistic 1.7 s).
  - Analysis has been fixed and opened blind in Nov. 2024.
  - The result is now on arXiv:

    Y. Fuwa et al., arXiv:2412.19519v1

$$\boldsymbol{\tau_n} = 877.2 \pm 1.7\ (stat.)^{+4.0}_{-3.7}(sys.)\ [\mathrm{s}]$$

  - This result is consistent with bottle method measurements but exhibits a 2.3σ tension with the average value obtained from the proton-detection-based beam method.

- There is a still room for discussion in our results.
- Additional data will be taken with less background conditions.
- A new apparatus with a solenoid magnet is getting ready for physics measurements in December 2025.