J-PARC TPC Lifetime

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Neutron Lifetime by Appearance

Kenji Mishima (J-PARC, KEK)
On behalf of
J-PARC neutron lifetime
collaboration

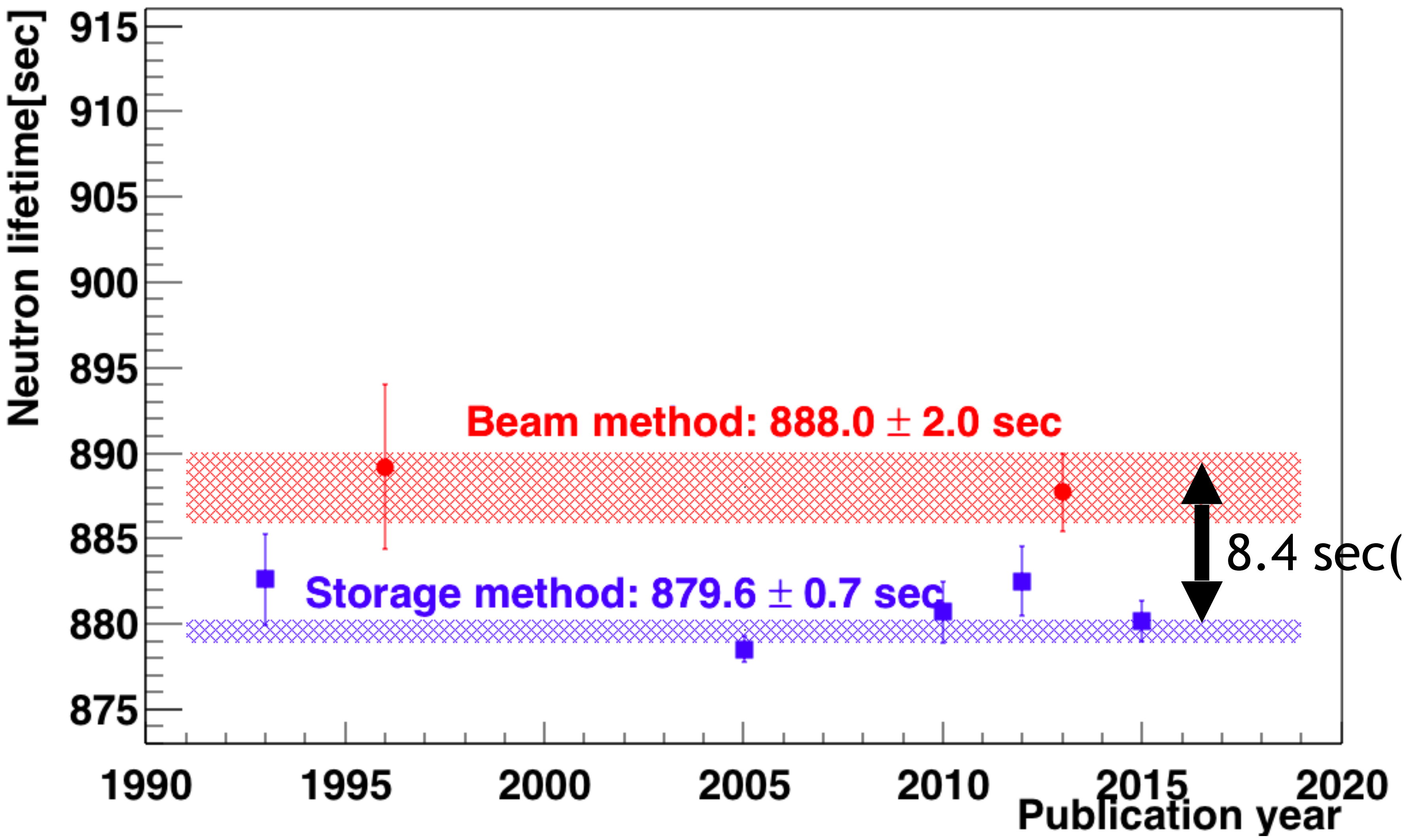
Particle Physics with Neutrons at the ESS, 2018/Dec/11th,
Stockholm university, Stockholm, Sweden

Neutron Lifetime

Neutron lifetime is an important parameter for both of particle physics and cosmology.

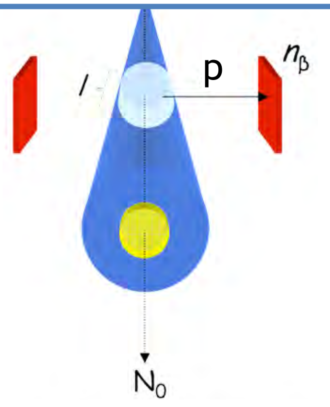
880.2±1.0 s (PDG2018)

There is 8.4 s (3.8 σ) deviation of the value of lifetime between two methods of measurement.

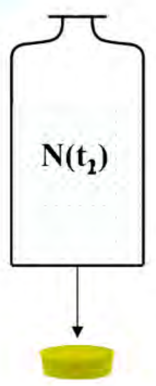


8.4 sec(3.8 σ)

In-beam method
Count the dead



Storage method
Count the living

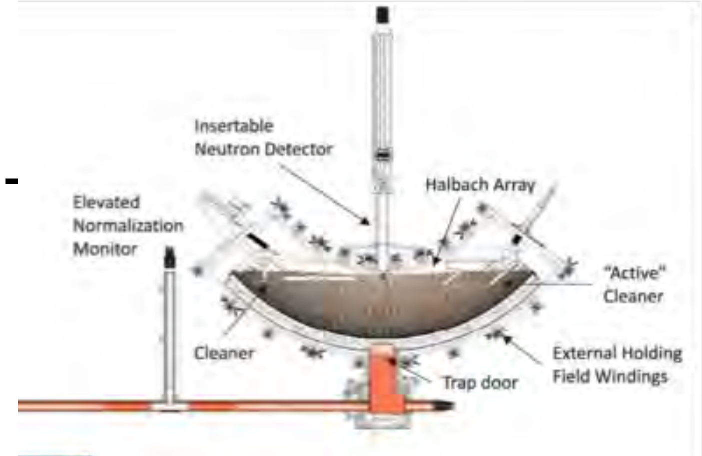


The Review of Particle Physics (2018)
M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

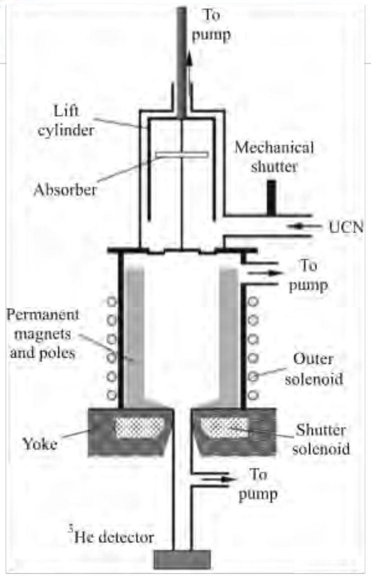
New results 2018:

(Storage method)

1. **PNPI/ILL Large storage bottle**
   - New neutron lifetime measurements with the big gravitational trap and review of neutron lifetime data.
   - Serebrov, A. P. et al., *KnE Energy & Physics*, *3*(1) (2018) 121-128.
   - τ_n = (881.5 ± 0.7 (stat) ± 0.6 (sys) sec



2. **LANL Magnetic Trap**
   - Measurement of the neutron lifetime using an asymmetric magneto-gravitational trap and in situ detection.
   - R. W. Pattie Jr. et al ., Science 10.1126/science.aan8895 (2018).
   - τ_n = (877.7 ± 0.7 (stat) $^{+0.4}/_{-0.2}$ (sys) sec



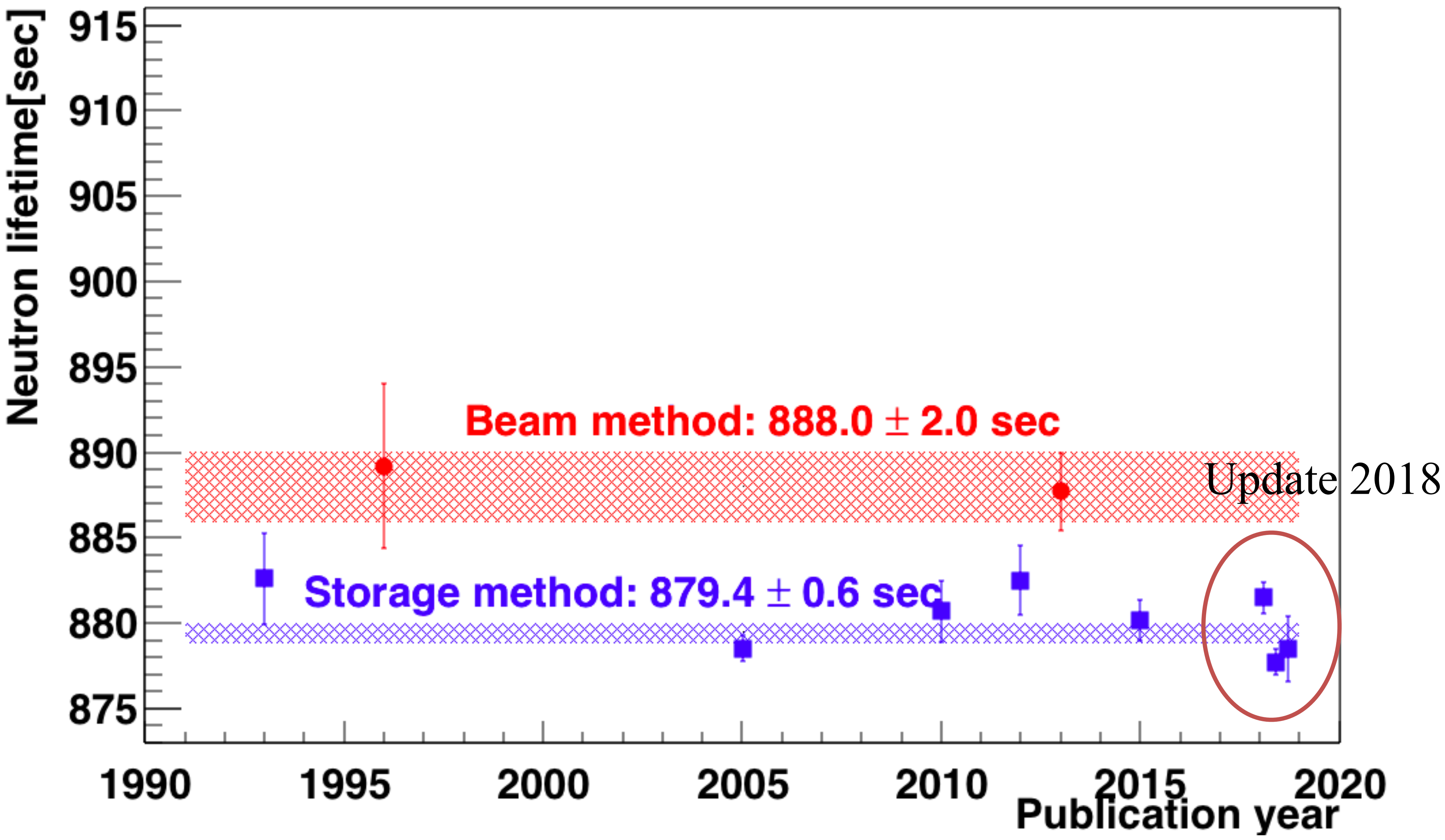
3. **PNPI/ILL Magnetic bottle**
   - Ezhov, V. F. et al., JETP Letters (2018) 1-6.
   - Measurement of the neutron lifetime with ultra-cold neutrons stored in a magneto-gravitational trap.
   - τ_n = (878.3 ± 1.6stat ± 1.0syst) sec

Neutron Lifetime

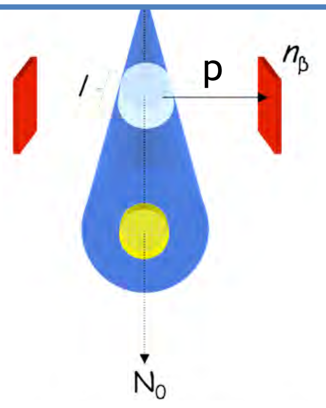
Neutron lifetime is an important parameter for both of particle physics and cosmology.

880.2±1.0 s (PDG2018)

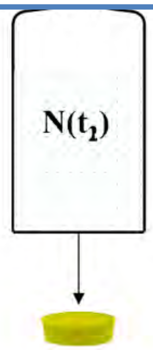
There is 8.6 s (4.0 σ) deviation of the value of lifetime between two methods of measurement.



In-beam method
Count the dead



Storage method
Count the living



Neutron Lifetime

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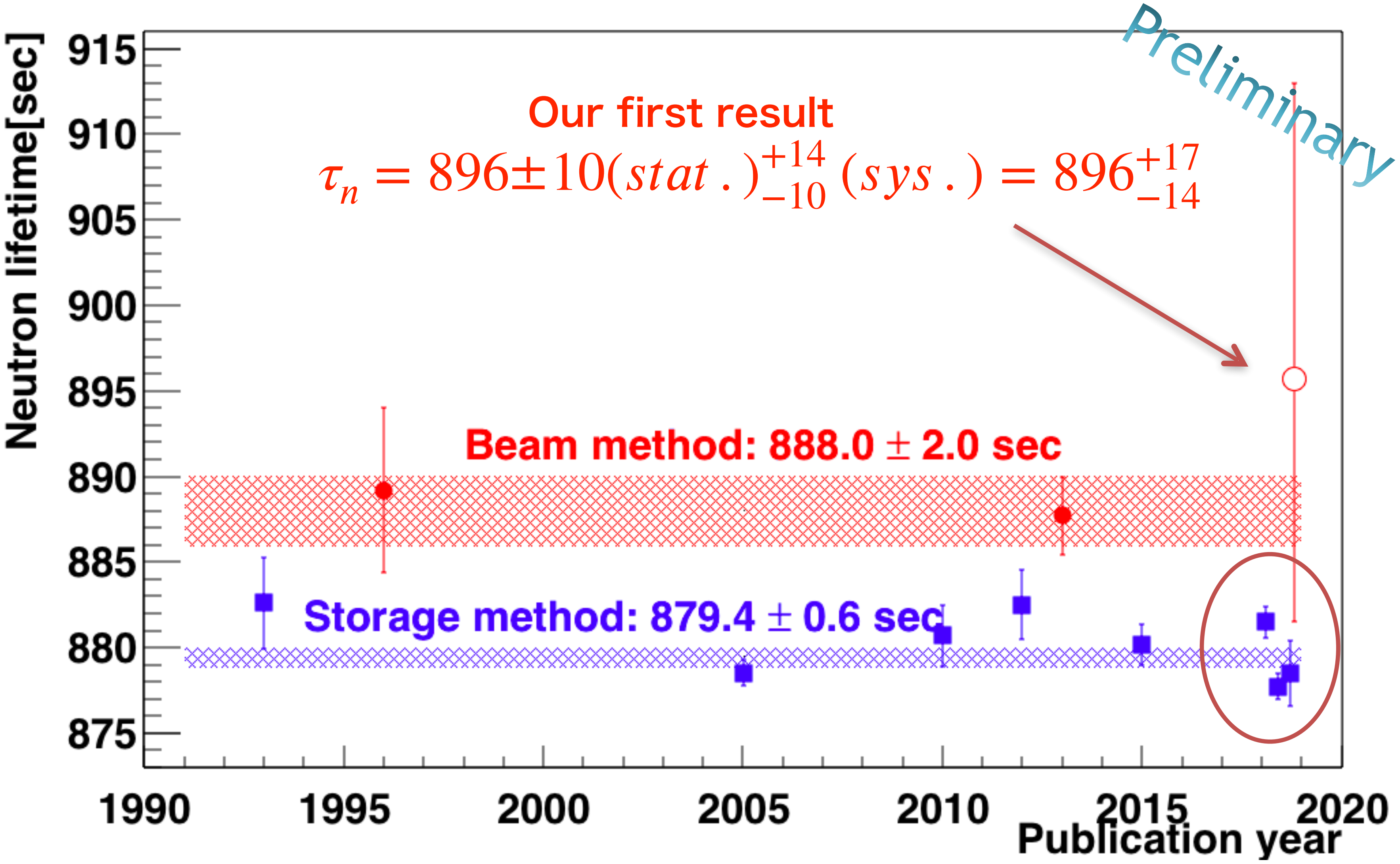
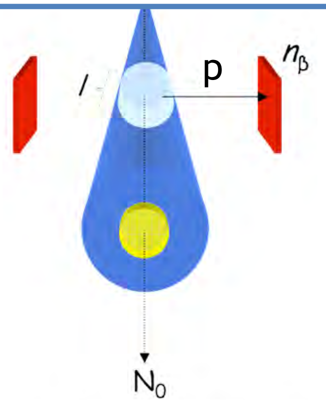


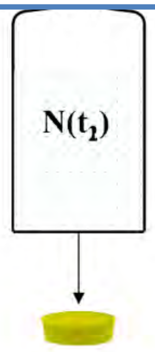
Our first result

$$\tau_n = 896 \pm 10(stat.)^{+14}_{-10}(sys.) = 896^{+17}_{-14}$$

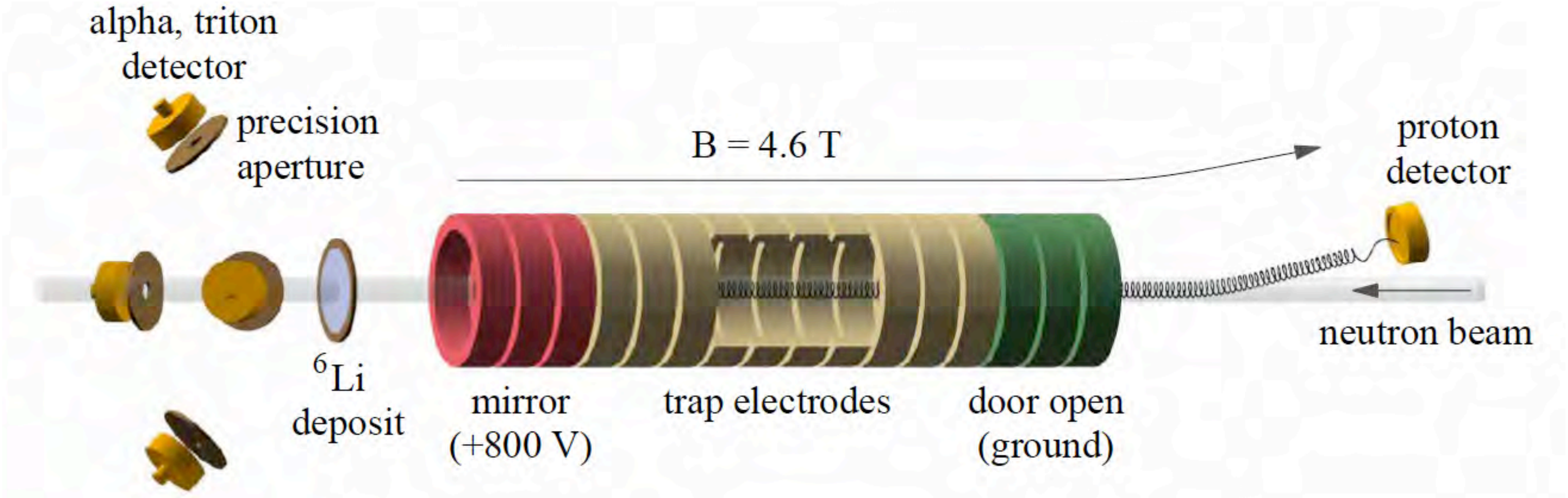
In-beam method
Count the dead



Storage method
Count the living



Beam method (Appearance)
NIST experiment: proton counting



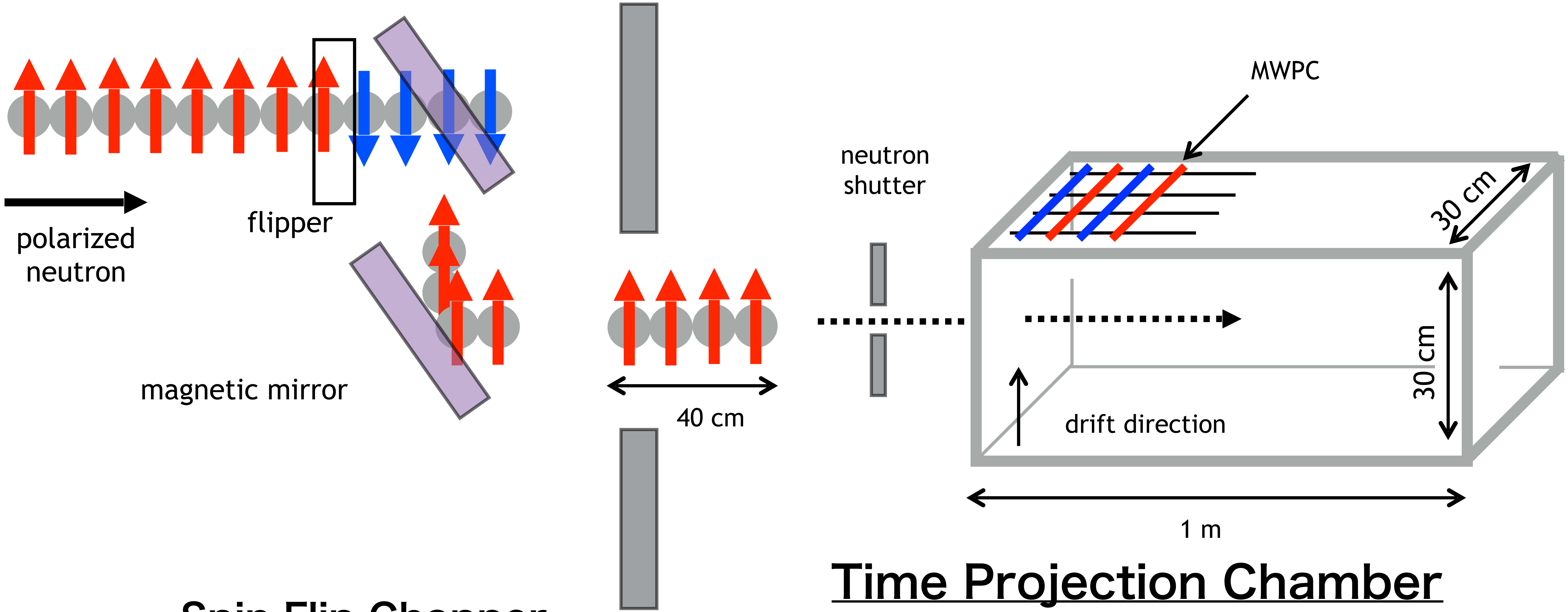
1. Monochromatic beam is transported to the magnetic trap. Neutron flux is monitored by a well calibrated ^{6}Li/SSD detector.
2. Protons from the neutron decays captured in the magnetic trap with electrodes. Stored protons are released and detected by a SSD with thin surface layer.

$$\tau_n = 887.7 \pm 1.2\,[stat.] \pm 1.9\,\left[syst.\right]\,s \;= 887.7 \pm 2.2\,[combined]\,s$$

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

J-PARC neutron lifetime experiment

- A beam method with pulsed neutron at J-PARC
- Simultaneous measurement of electrons from neutron decay and ^{3}He(n,p)^{3}H reaction



Spin Flip Chopper

form neutron bunches

Time Projection Chamber

He + CO_2 gas

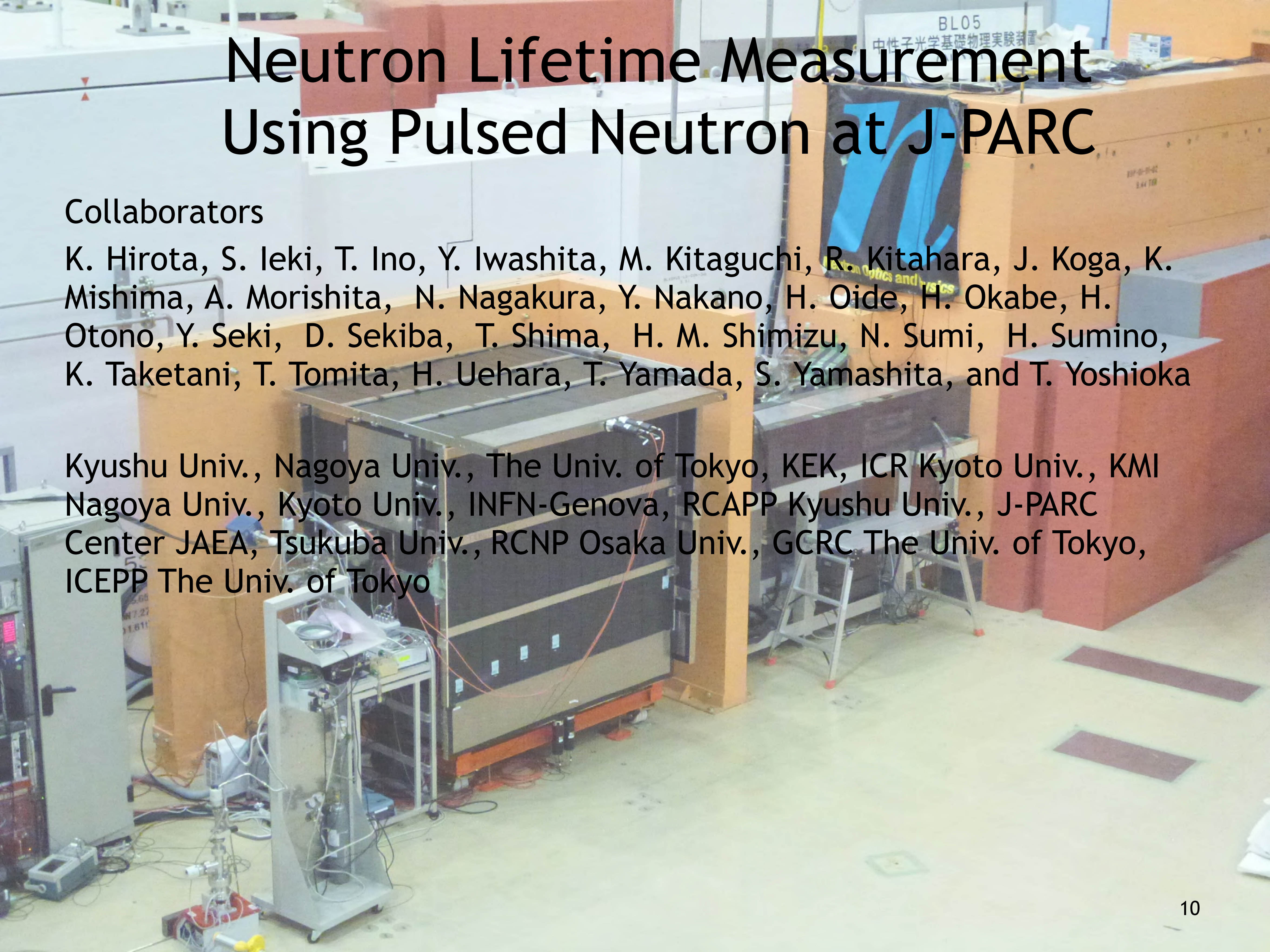
detect electron from the neutron decay

Beam / Storage Appearance/Disappearance

	Decay mode	UCN (Storage)	Proton trap (Beam)	Electron counting (Beam)
~1%		Sensitive	Sensitive	Sensitive
		Sensitive	Sensitive	Sensitive?
~10^{-6}		Sensitive	Insensitive	Insensitive
		Sensitive	Insensitive	Insensitive
Dark Decay		Sensitive	Insensitive	Insensitive?
		Sensitive	Insensitive	Insensitive
		Sensitive	Insensitive?	Sensitive?

Sensitive: Short lifetime / Insensitive: Long lifetime

Neutron Lifetime Measurement Using Pulsed Neutron at J-PARC



Collaborators

K. Hirota, S. Ieki, T. Ino, Y. Iwashita, M. Kitaguchi, R. Kitahara, J. Koga, K. Mishima, A. Morishita, N. Nagakura, Y. Nakano, H. Oide, H. Okabe, H. Otono, Y. Seki, D. Sekiba, T. Shima, H. M. Shimizu, N. Sumi, H. Sumino, K. Taketani, T. Tomita, H. Uehara, T. Yamada, S. Yamashita, and T. Yoshioka

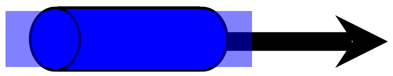
Kyushu Univ., Nagoya Univ., The Univ. of Tokyo, KEK, ICR Kyoto Univ., KMI Nagoya Univ., Kyoto Univ., INFN-Genova, RCAPP Kyushu Univ., J-PARC Center JAEA, Tsukuba Univ., RCNP Osaka Univ., GCRC The Univ. of Tokyo, ICEPP The Univ. of Tokyo

Principle of our experiment

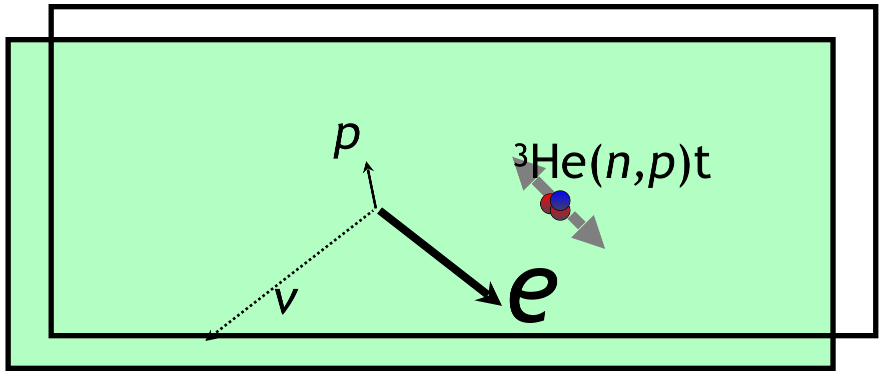
Cold neutrons are injected into a TPC.
The neutron decay and the ^{3}He(n,p)^{3}H reaction are measured simultaneously.

Principle (Kossakowski,1989)

Neutron bunch shorter than TPC



Count events during time of bunch in the TPC



Neutron bunch

$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\left(\frac{S_n/\epsilon_n}{S_\beta/\epsilon_\beta}\right)$$

β-decay $$S_\beta = \epsilon_e N \frac{L}{\tau_n v}$$

^{3}He(n,p)^{3}H $$S_n = \epsilon_n N \rho \sigma L$$

τ_n : lifetime of neutron
v : velocity of neutron
ε_e : detection efficiency of electron

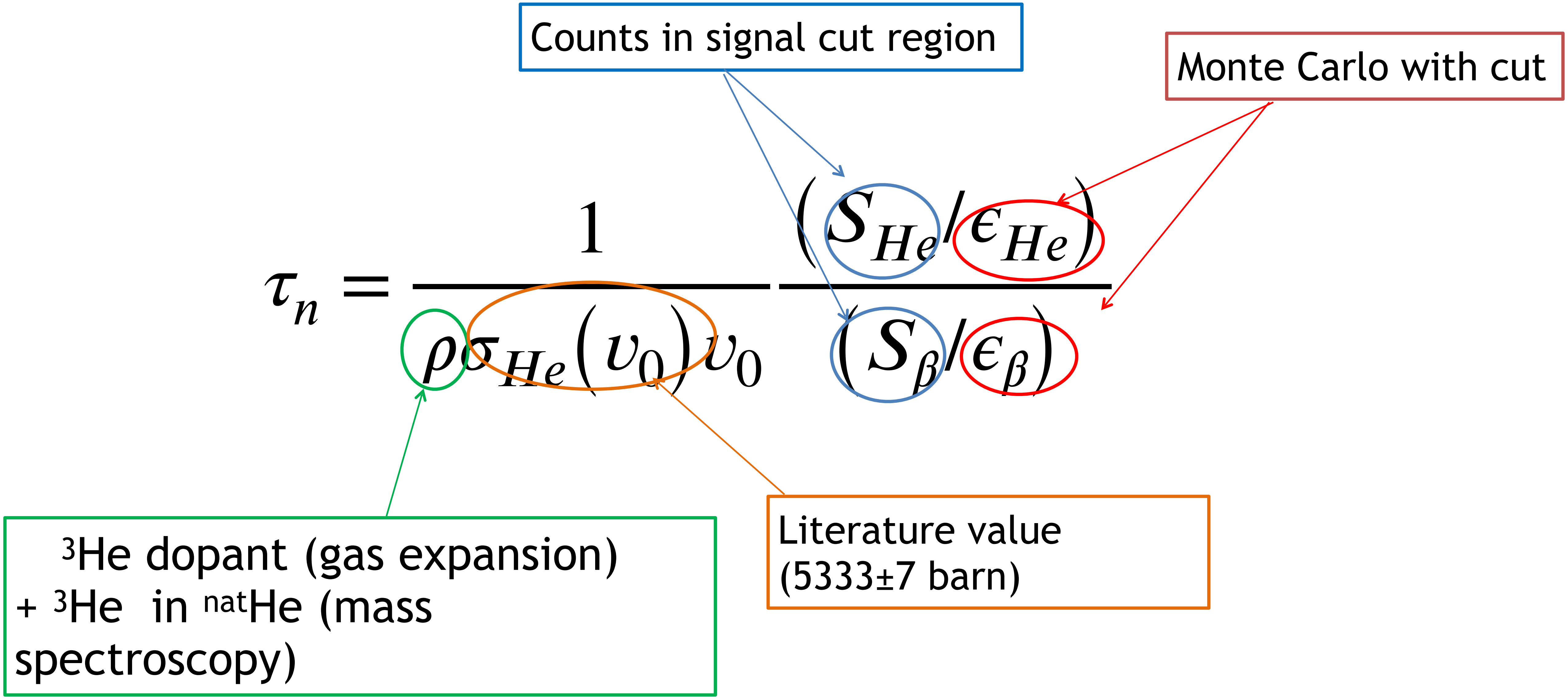
ε_n : detection efficiency of ^{3}He reaction
ρ : density of ^{3}He
σ : cross section of ^{3}He reaction

$$\sigma v = \sigma_0 v_0$$ σ_0=cross section@v_0, v_0=2200[m/s]

This method is free from the uncertainties due to external flux monitor, wall loss, depolarization, etc.

Our goal is measurement with 1 s uncertainty.

How to obtain the neutron lifetime



Counts in signal cut region

Monte Carlo with cut

$$\tau_n = \frac{1}{\rho\sigma_{He}(v_0)v_0}\frac{\left(S_{He}/\epsilon_{He}\right)}{\left(S_\beta/\epsilon_\beta\right)}$$

^{3}He dopant (gas expansion) + ^{3}He in ^{nat}He (mass spectroscopy)

Literature value (5333±7 barn)

Acquired data

we took physics data for 29 gas conditions in 2014～2018

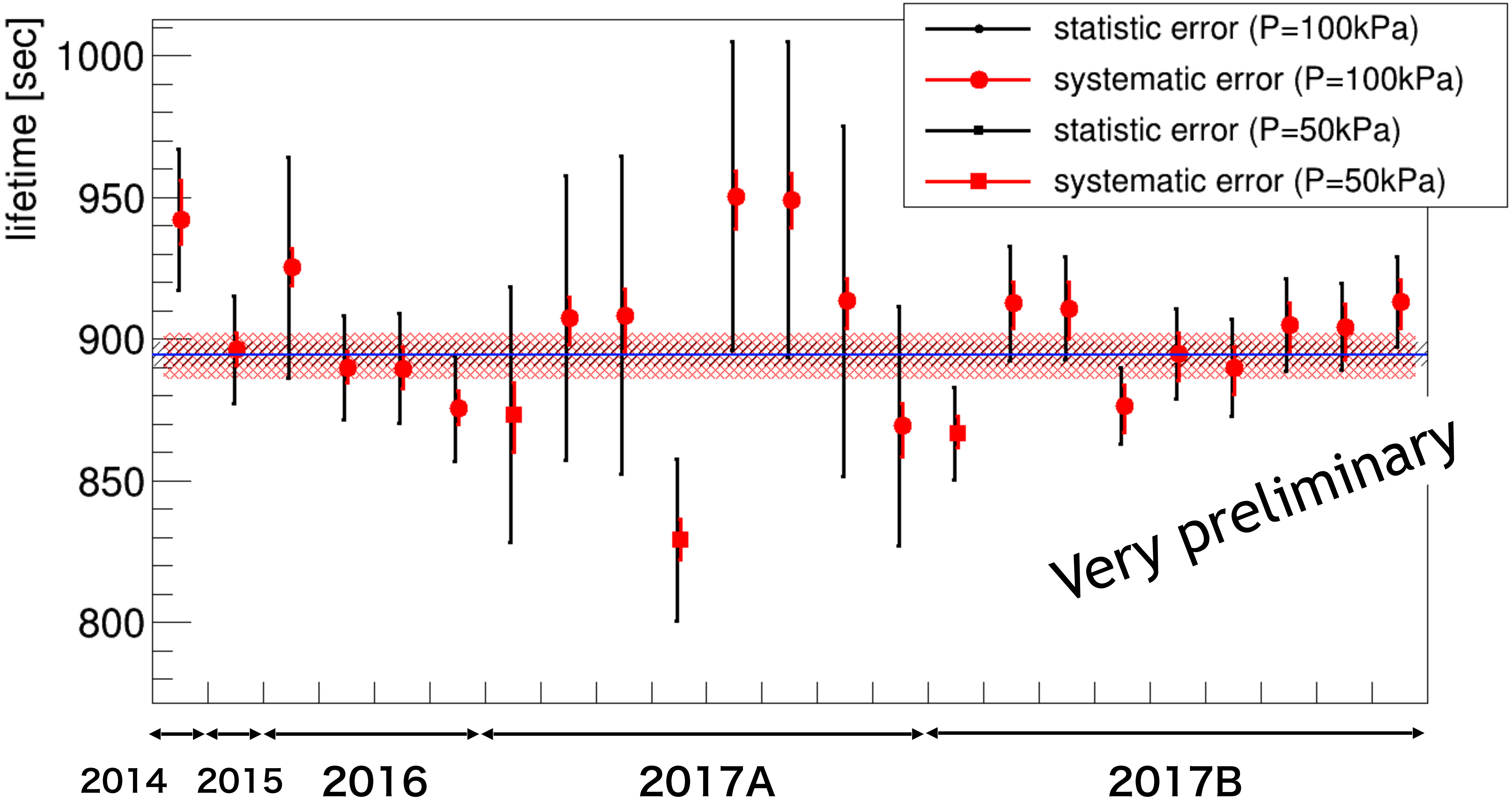
year	gas set number	MLF power [kW]	total incident neutron $[\times 10^{11}]$
2014A	1	300	0.2
2015A	1	500	0.2
2016A	4	200	1.2
2017A	8	150	0.8
2017B	9	300, 400	3.7
2018A	6	400, 500	～4

Data set for
the first result

Dataset use
for analysis

all combined statistical uncertainty ~4 sec (0.5%)

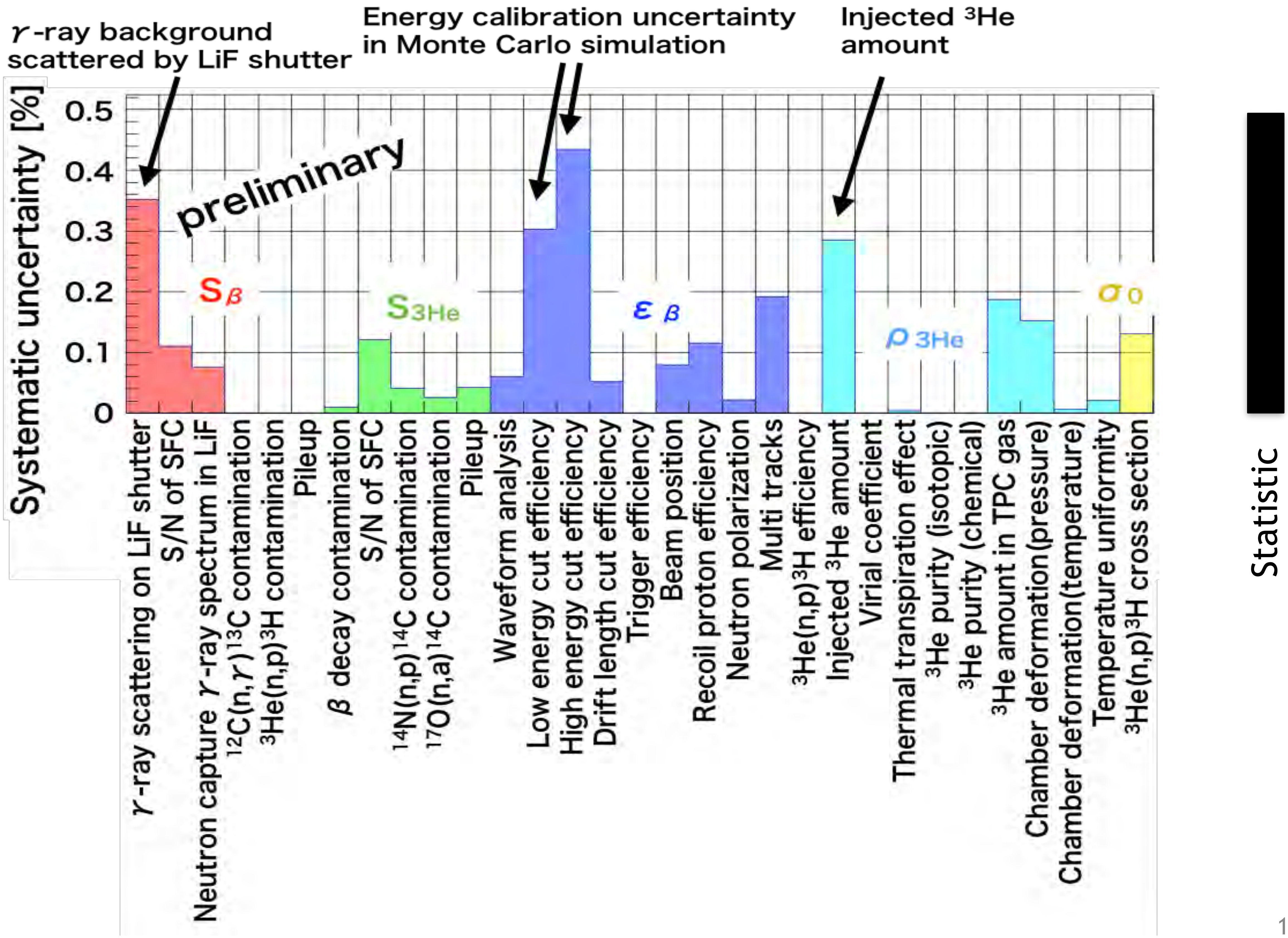
Combined results



all-combined results

$$\tau_n = \underline{894.6 \ \pm 4.4(\text{stat.}) \ {}^{+7.6}_{-8.6}(\text{sys.})} \ \ \text{sec}$$

Systematic uncertainties



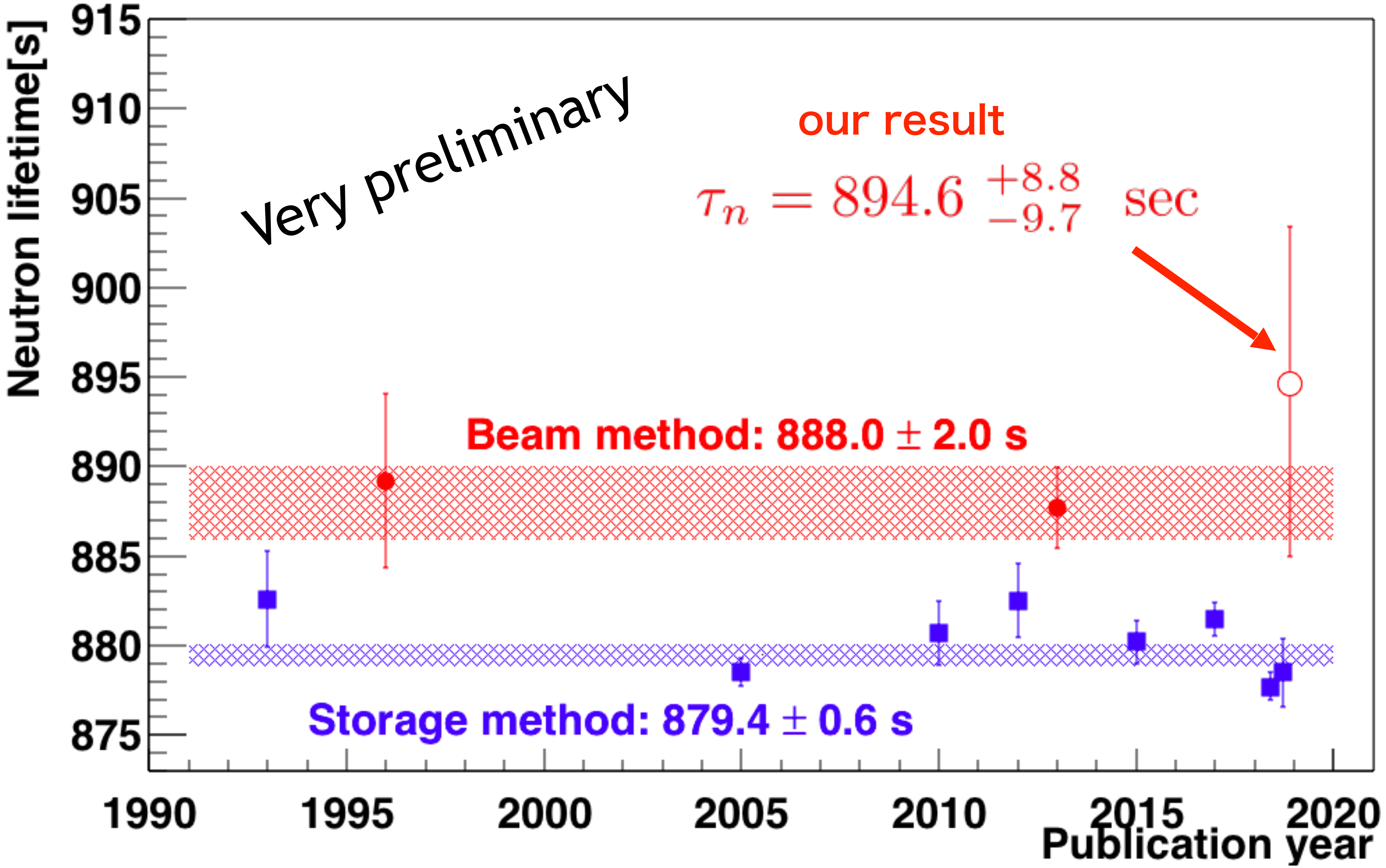
γ-ray background scattered by LiF shutter

Energy calibration uncertainty in Monte Carlo simulation

Injected ^{3}He amount

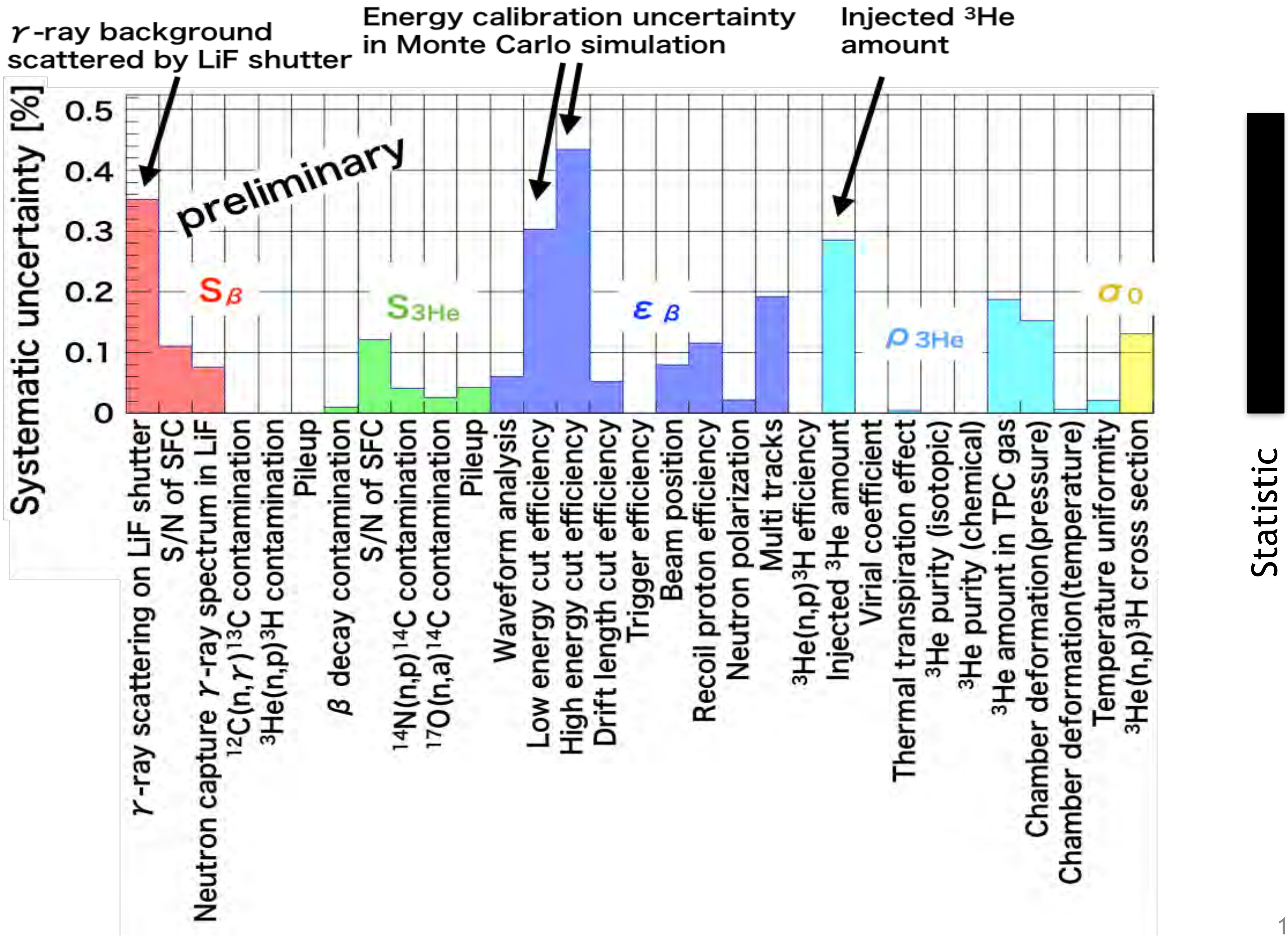
Statistic

Results



- **1.6σ with Storage method**
- upgrade projects are ongoing to achieve our goal precision of 1 sec

Systematic uncertainties



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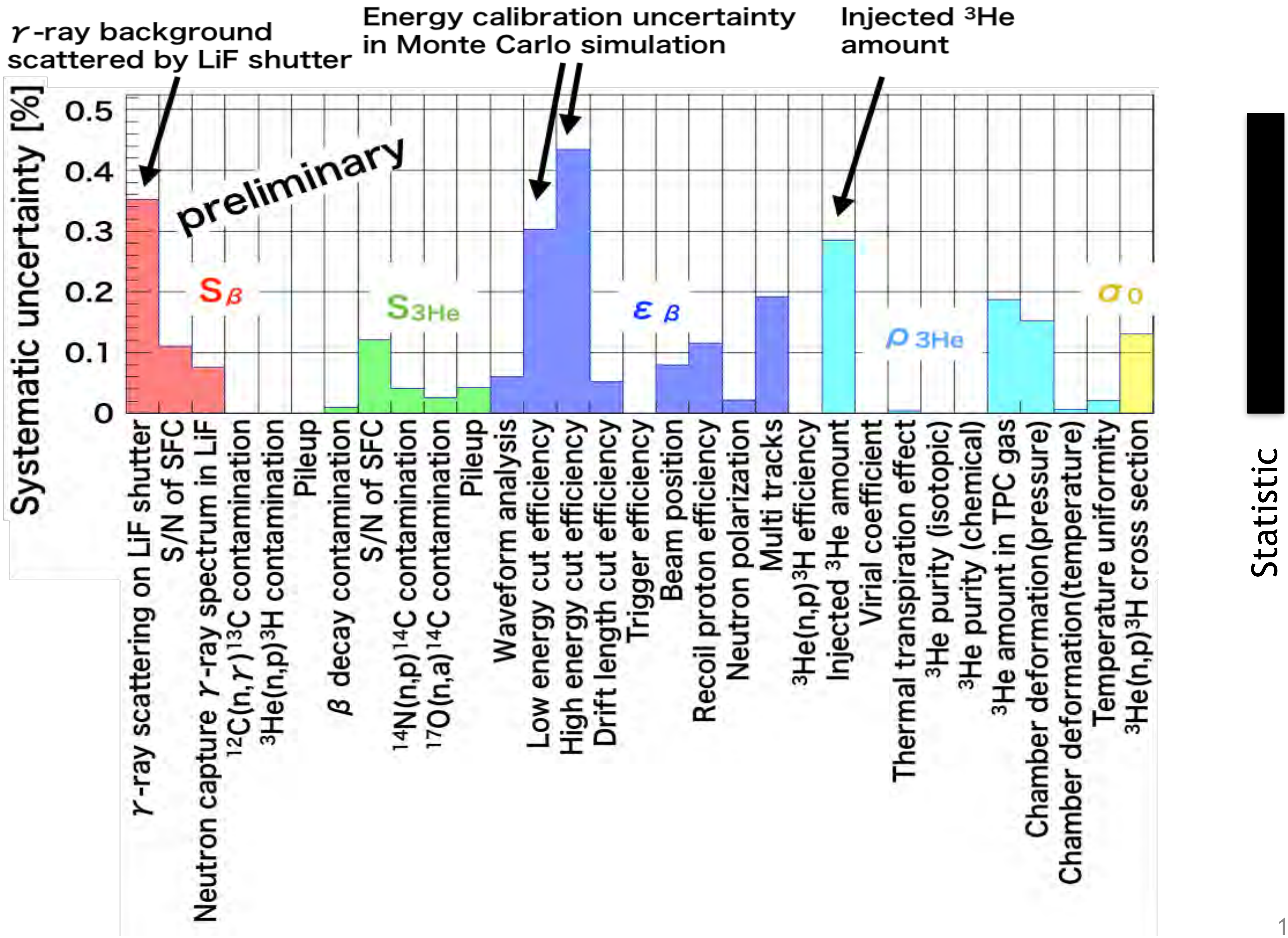
Energy calibration uncertainty in Monte Carlo simulation

Injected ^{3}He amount

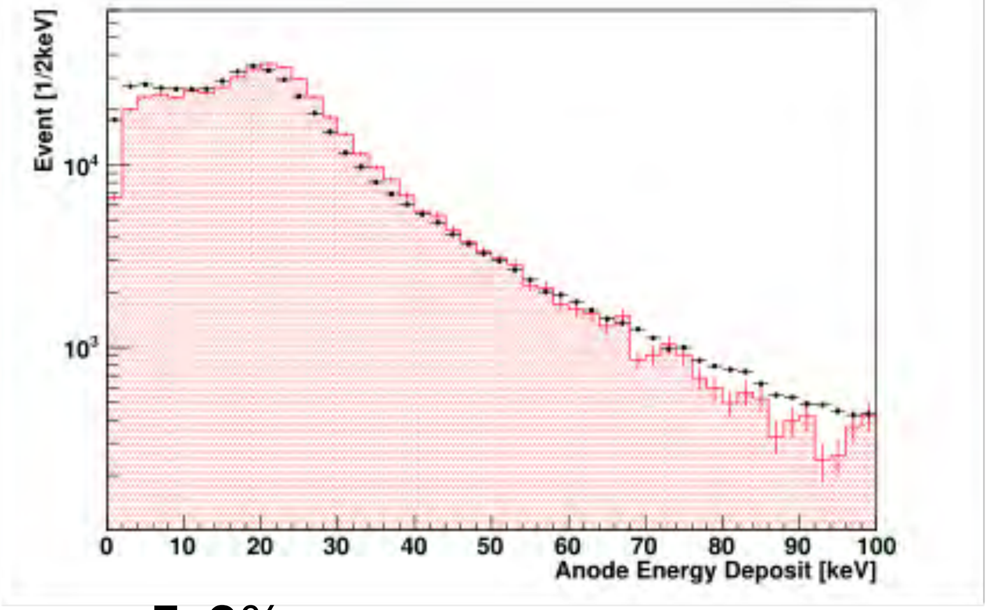
Upgrade plans

Systematic uncertainties

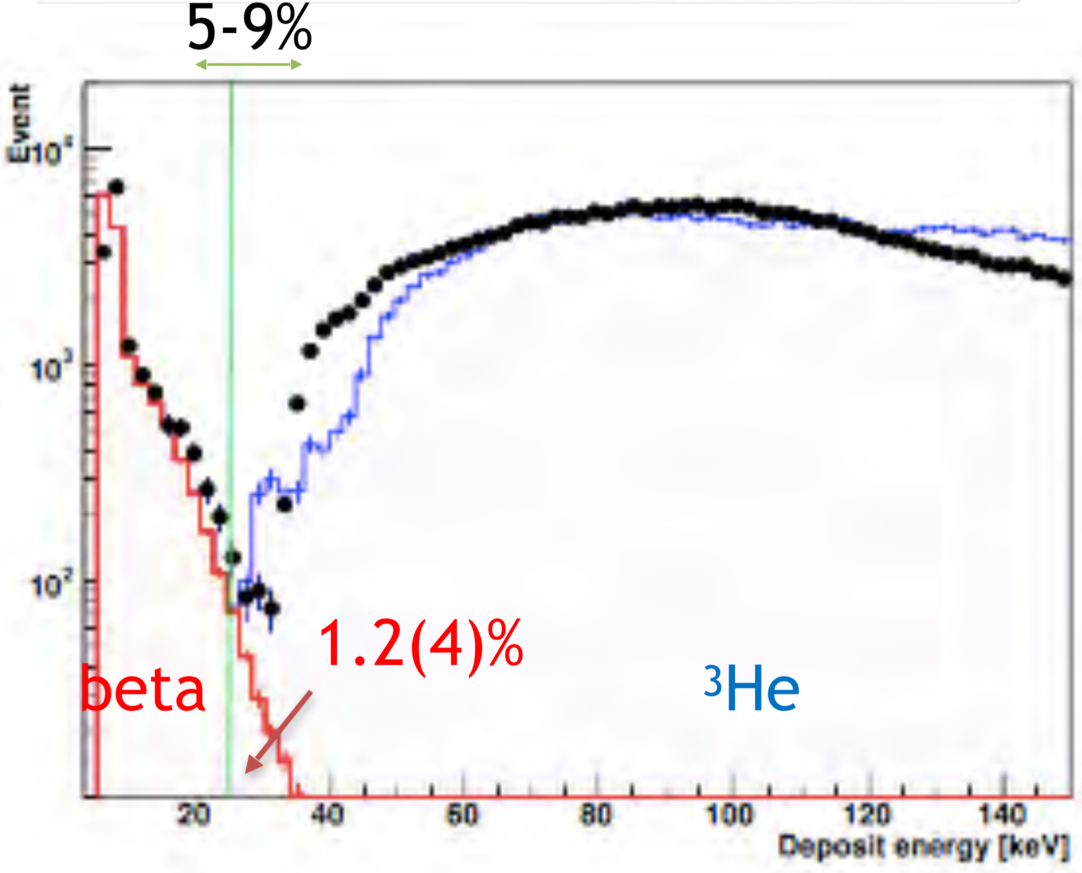


Energy cut uncertainty

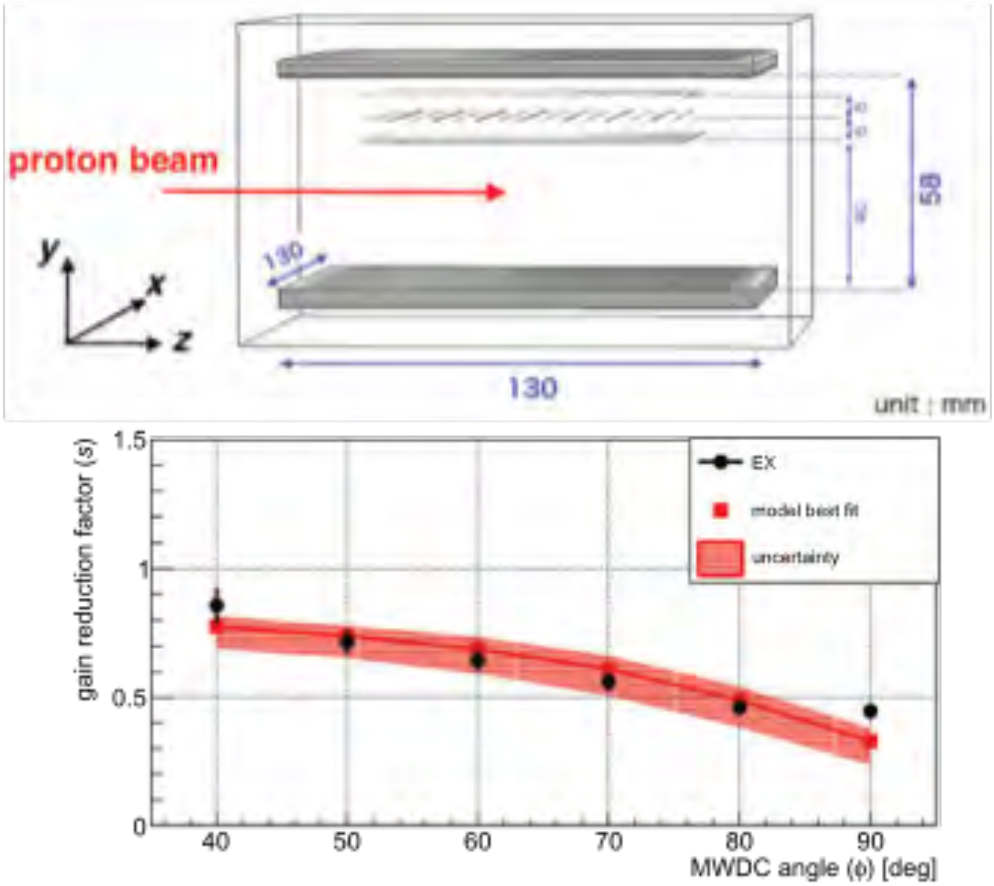
Energy distribution of cosmic rays



Energy uncertainty of the simulation was evaluated by agreement with cosmic rays.



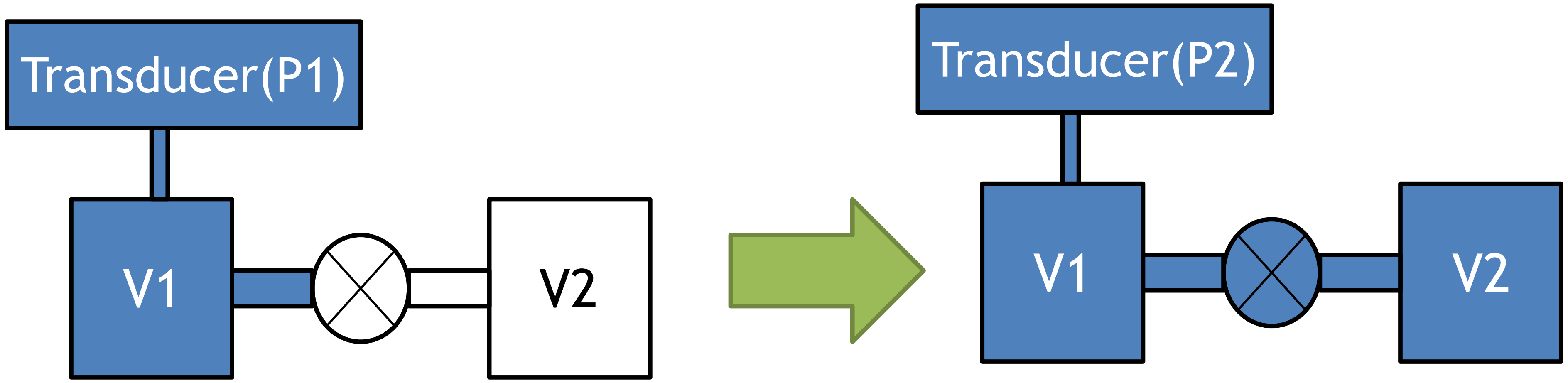
Experimental space charge evaluation



^{3}He(n,p)^{3}H reaction release 762 keV,
But space charge effect distorts the spectrum.

N. Nagakura, et al. "Experimental verification of a gain reduction model for the space charge effect in a wire chamber." Progress of Theoretical and Experimental Physics 2018.1 (2018): 013C01.

^{3}He injection



- The ^{3}He injection have 0.3% uncertainty.
  - It caused "Error propagations" of the pressure gauge.
  - Because we used 2 buffer volumes and 3 times of dilutions to obtain thin ^{3}He pressure (100 mPa) with high accuracy.
  - Two pressure gauges with different dynamic ranges, 500 kPa and 100 Pa can provide 100 mPa with 0.11%.

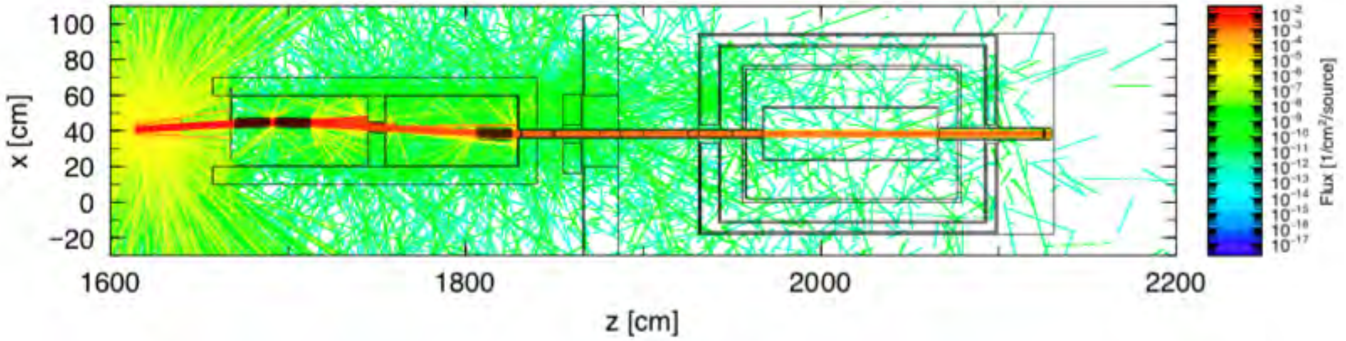
Beam optics upgrade

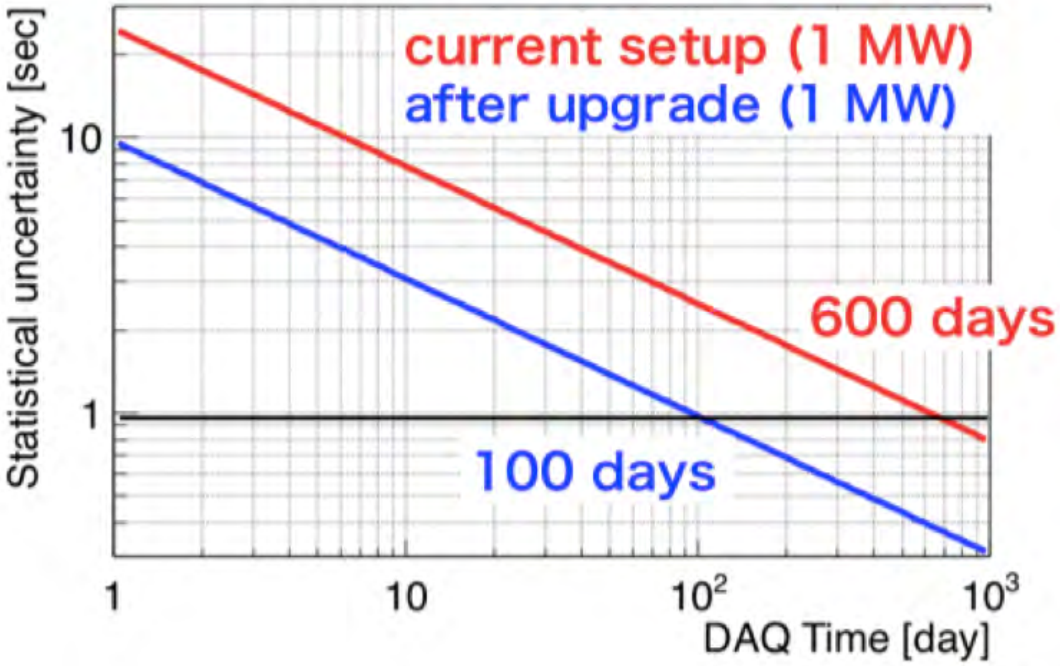
Enlarge beam size 2×2[cm] -> 3×10[cm] and focusing

Enlarged Supper Mirror

Vertical Focusing Mirror

Simulation expect 5 times beam increase without any other upgrade.



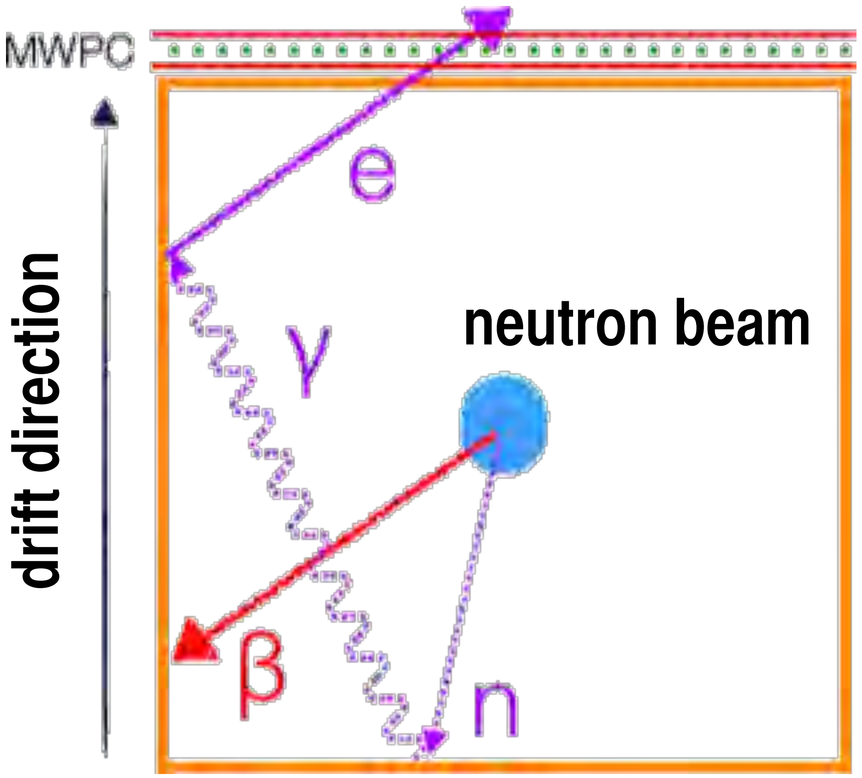


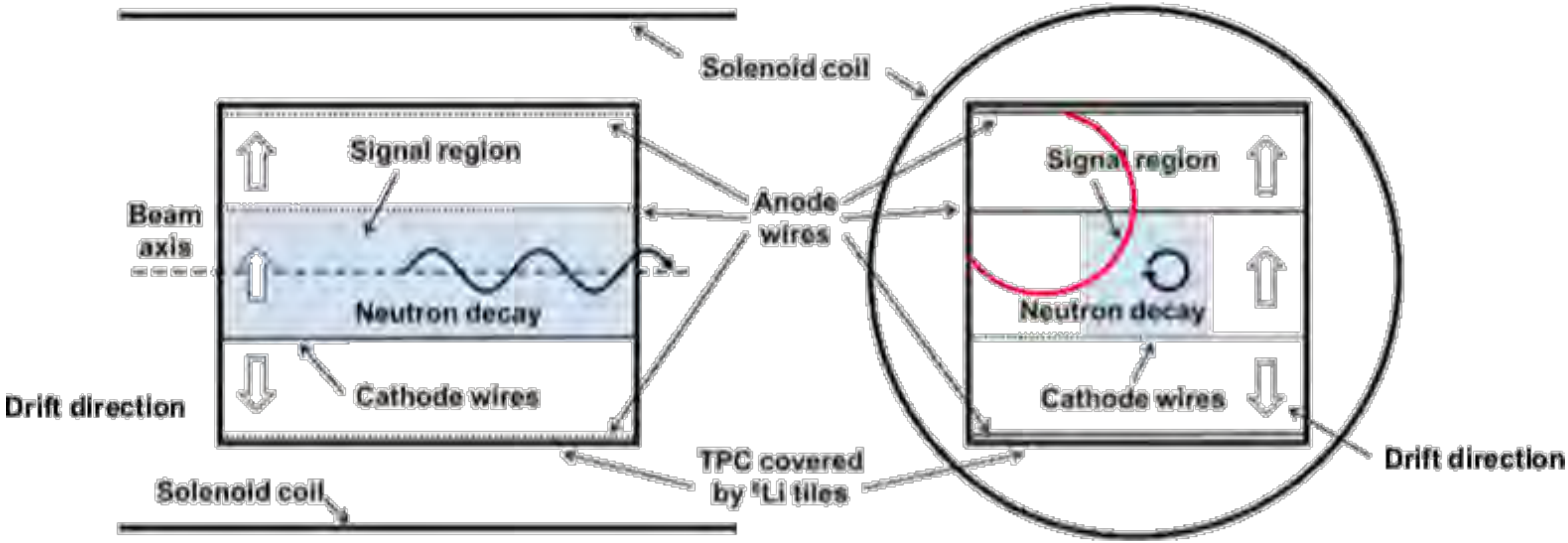
Summary

- Neutron lifetime is an important parameter, however there is 8.6 s (4.0σ) deviation of the value of lifetime between two methods of measurement.
- We are measuring the neutron lifetime at pulsed neutron beamline (BL05) at J-PARC.
  - **Electron counting beam experiment.**
  - Goal is 1 sec accuracy.
- We have not finalized the result. (to be finalized soon)
- Upgrades are undergoing.
  - Systematic uncertainty will be smaller with more intelligent cuts.
  - ^{3}He injection will be 0.11%.
  - Beam optics upgrade (Enlarging SFC mirror) makes beam intensity by 5 times.
  - Etc.

TPC in Solenoid Field

N.Sumi et al.
Kyushu Univ.





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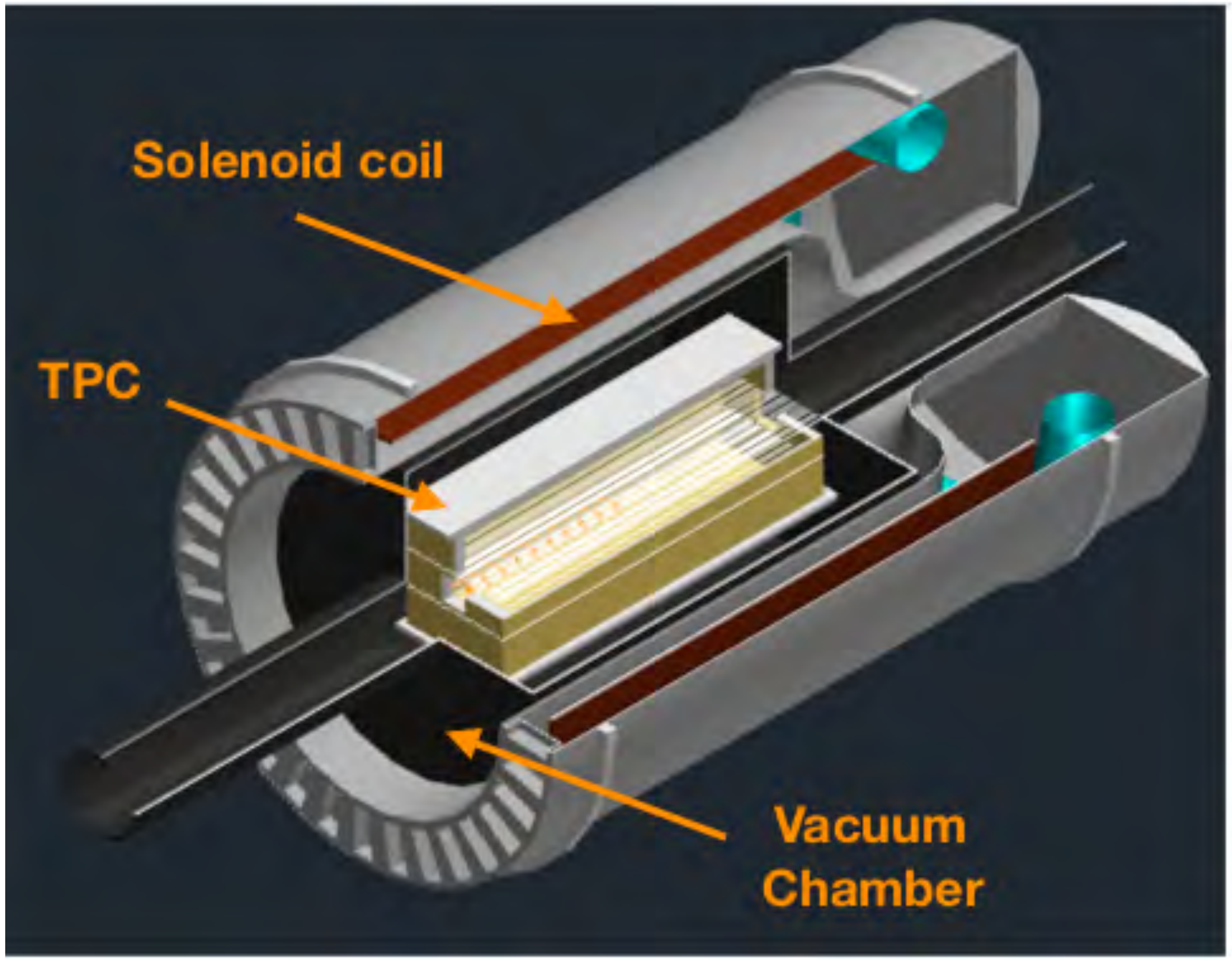
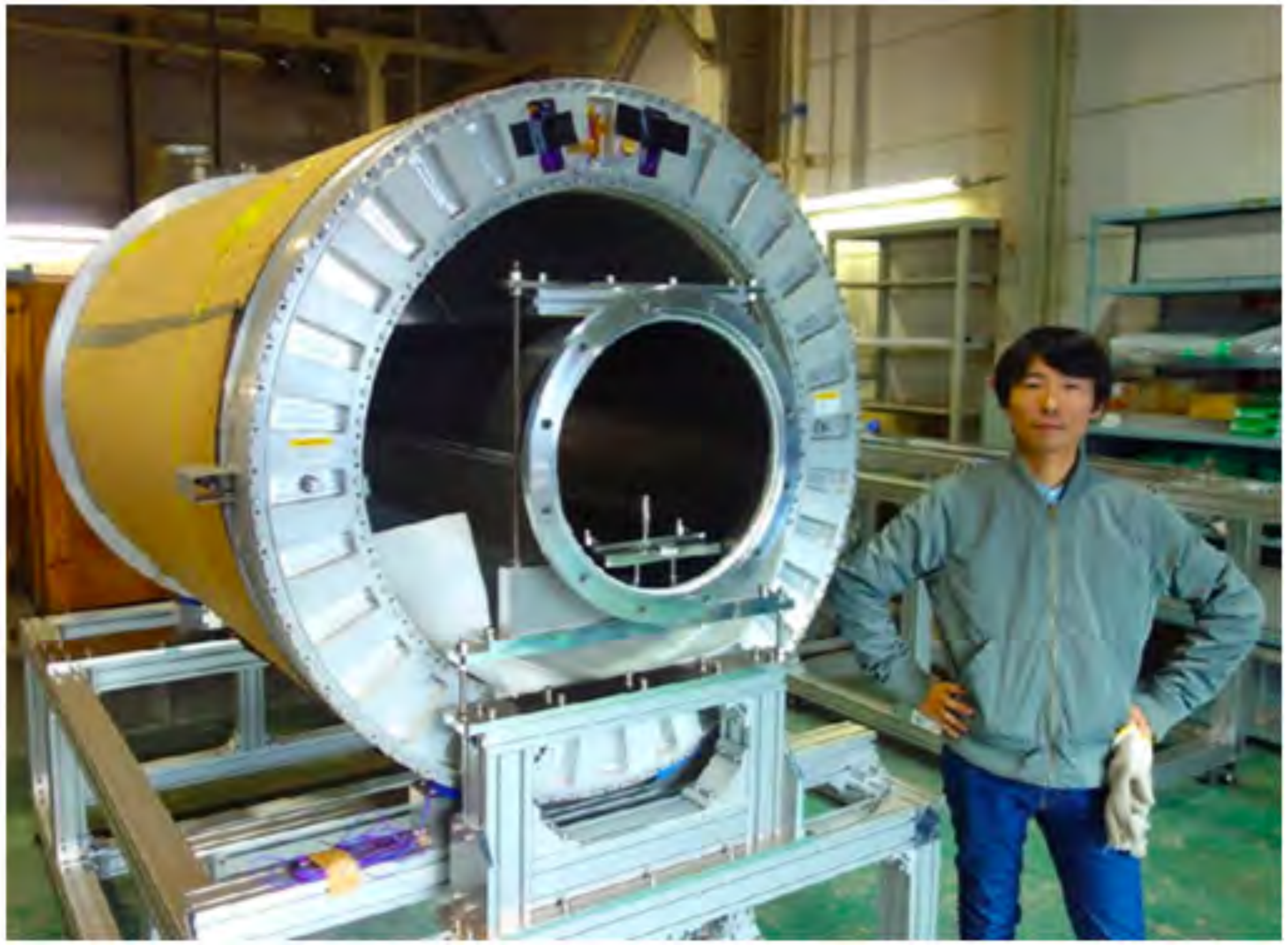




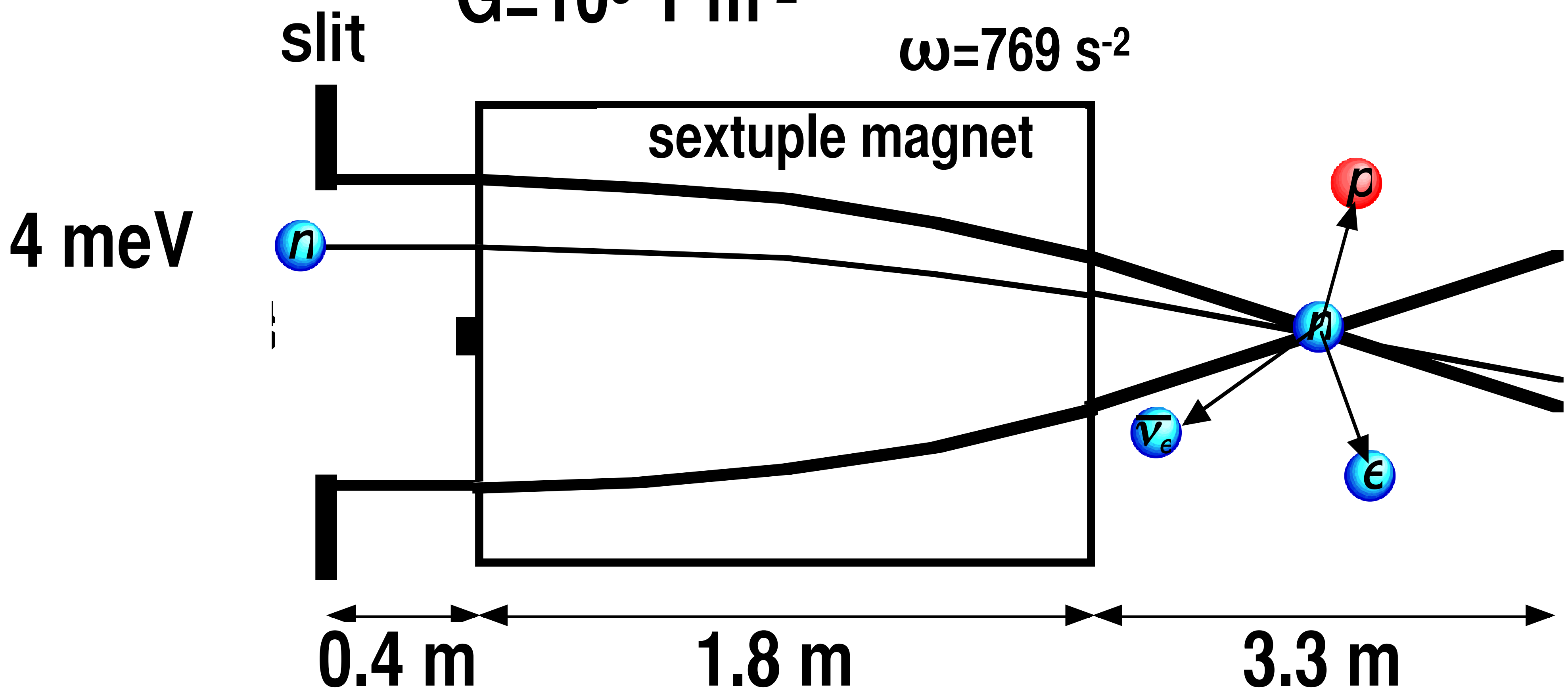
Magnetic Guide

Magnetic Focusing

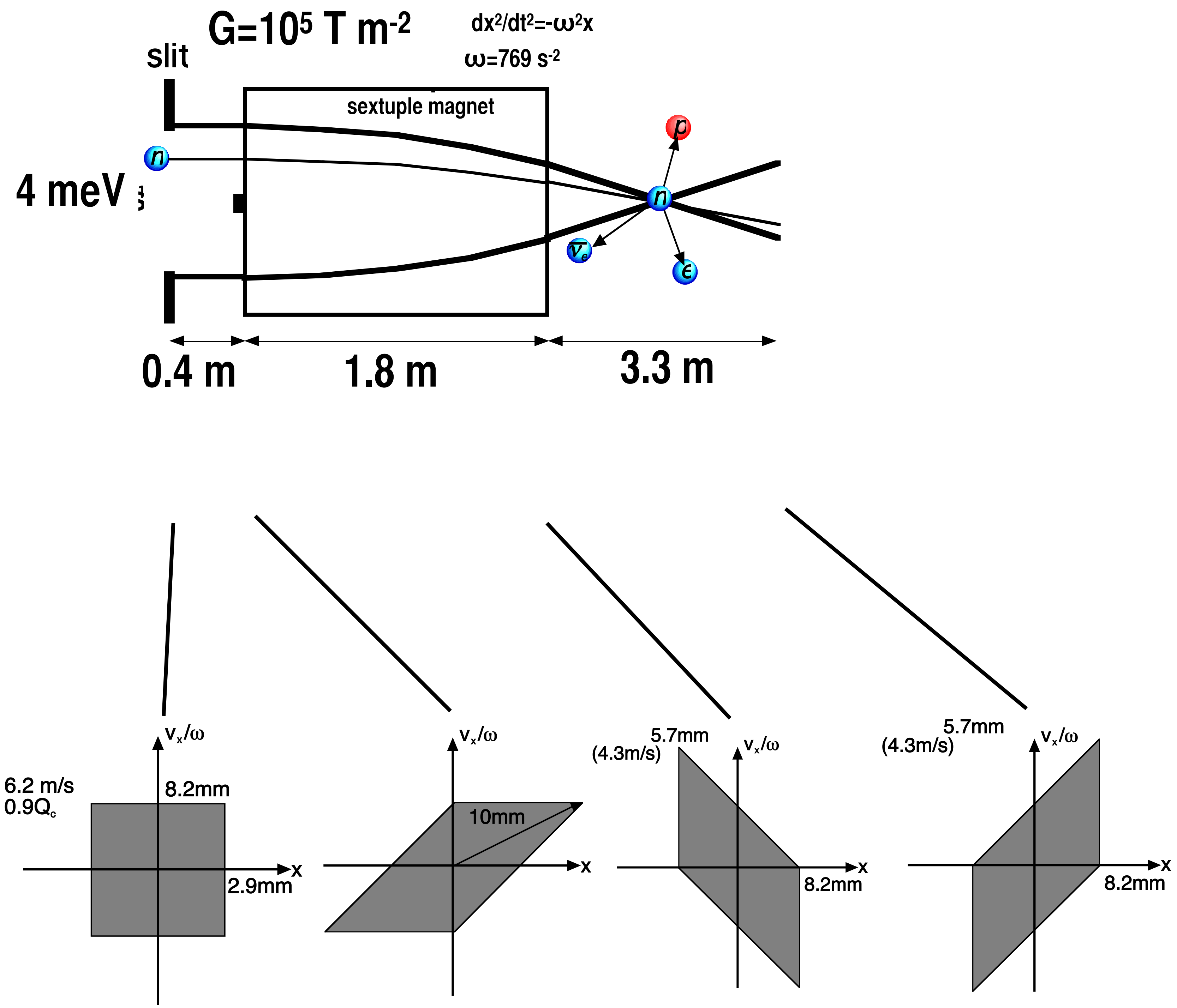
$G=10^5\ \mathrm{T\ m^{-2}}$

$dx^2/dt^2=-\omega^2 xG=10^5\ \mathrm{T\ m^{-2}}$

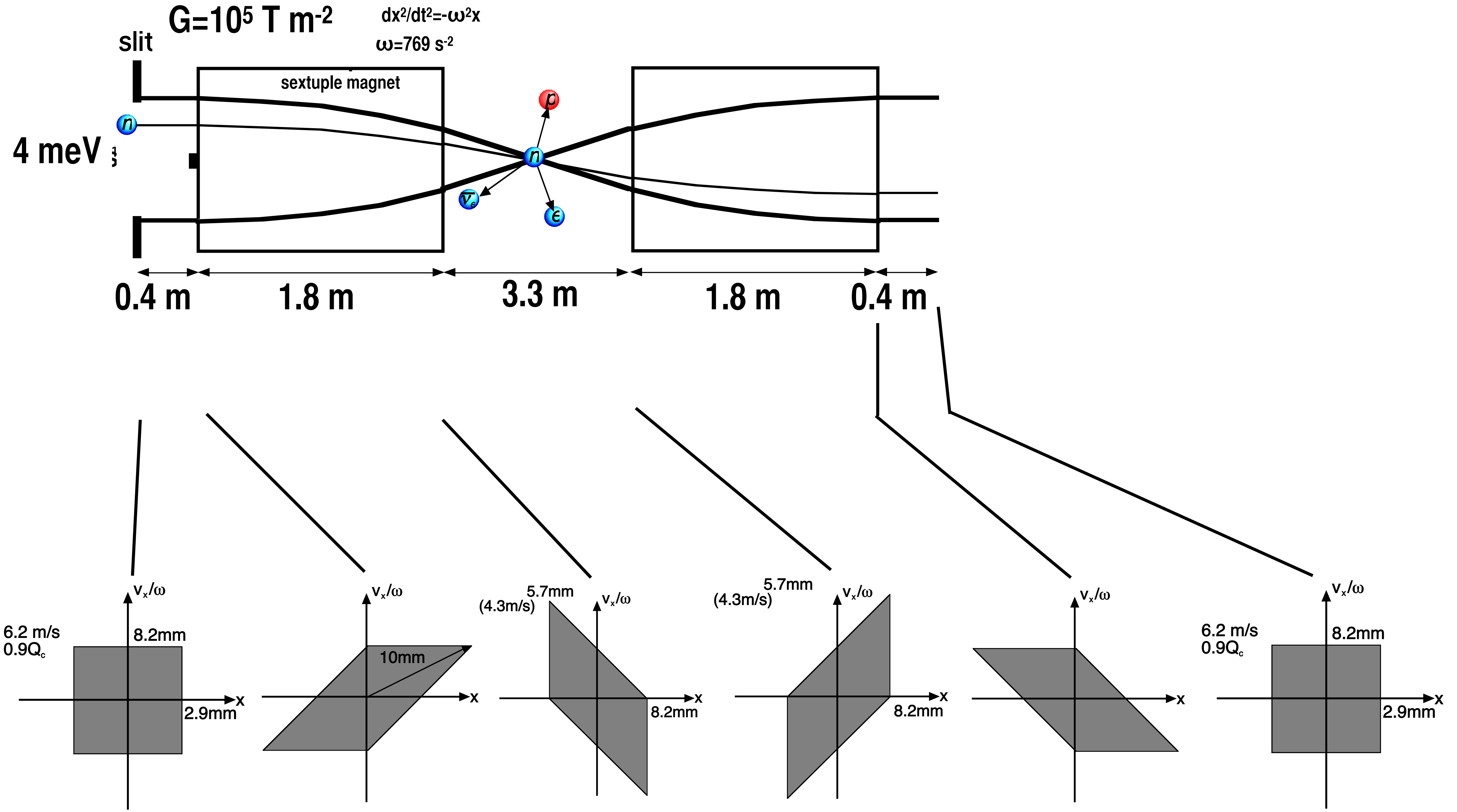
$\omega=769\ \mathrm{s^{-2}}$



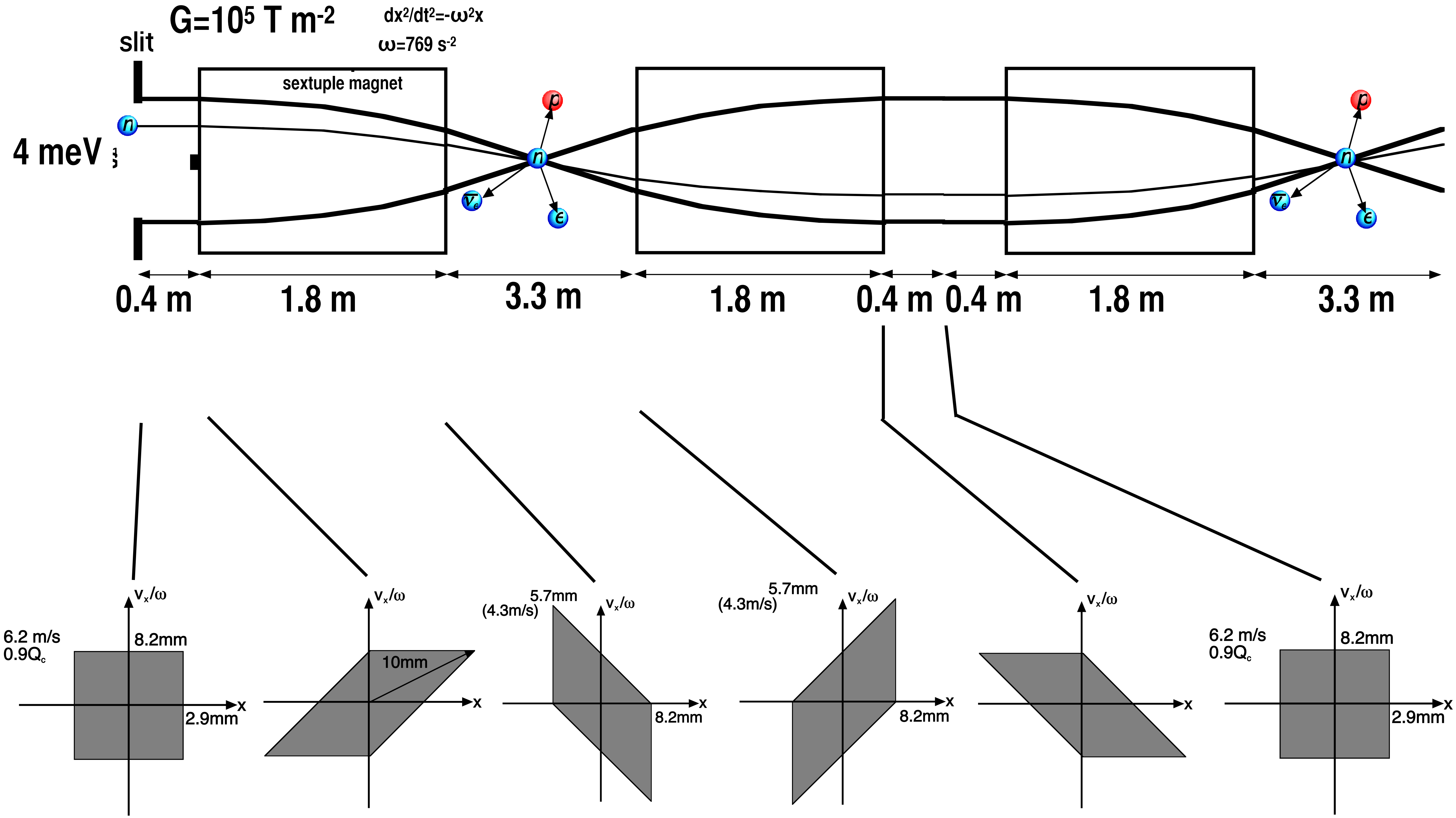
Refractive Focusing



Refractive Focusing



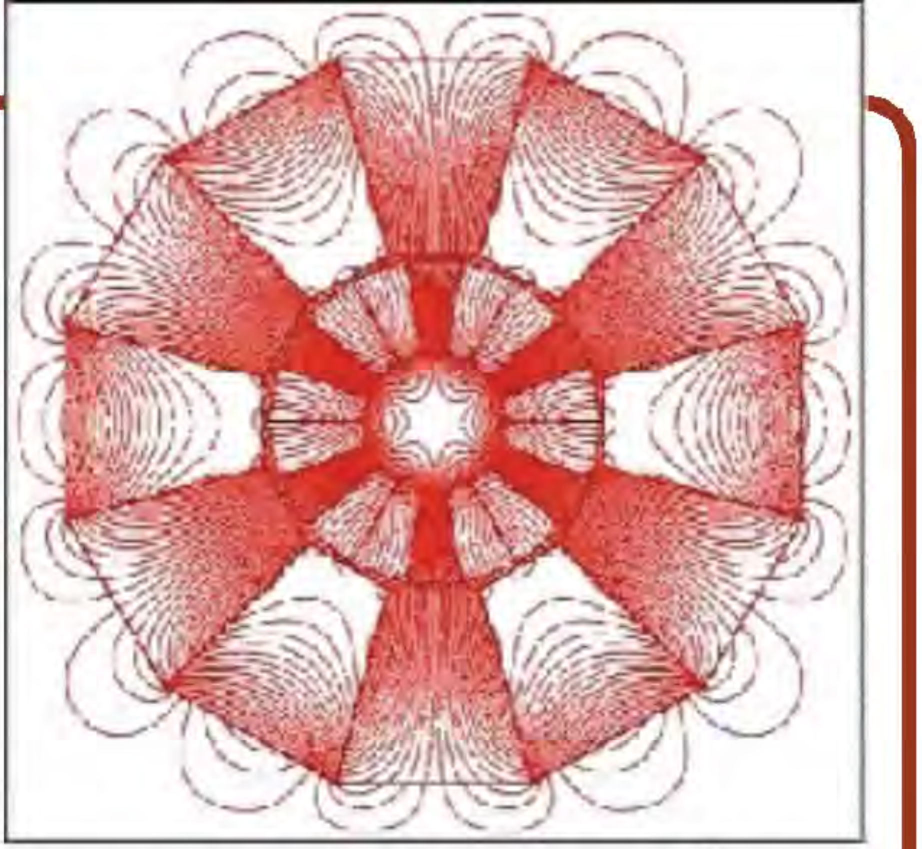
Refractive Focusing



Magnetic Lens for Pulsed Neutrons

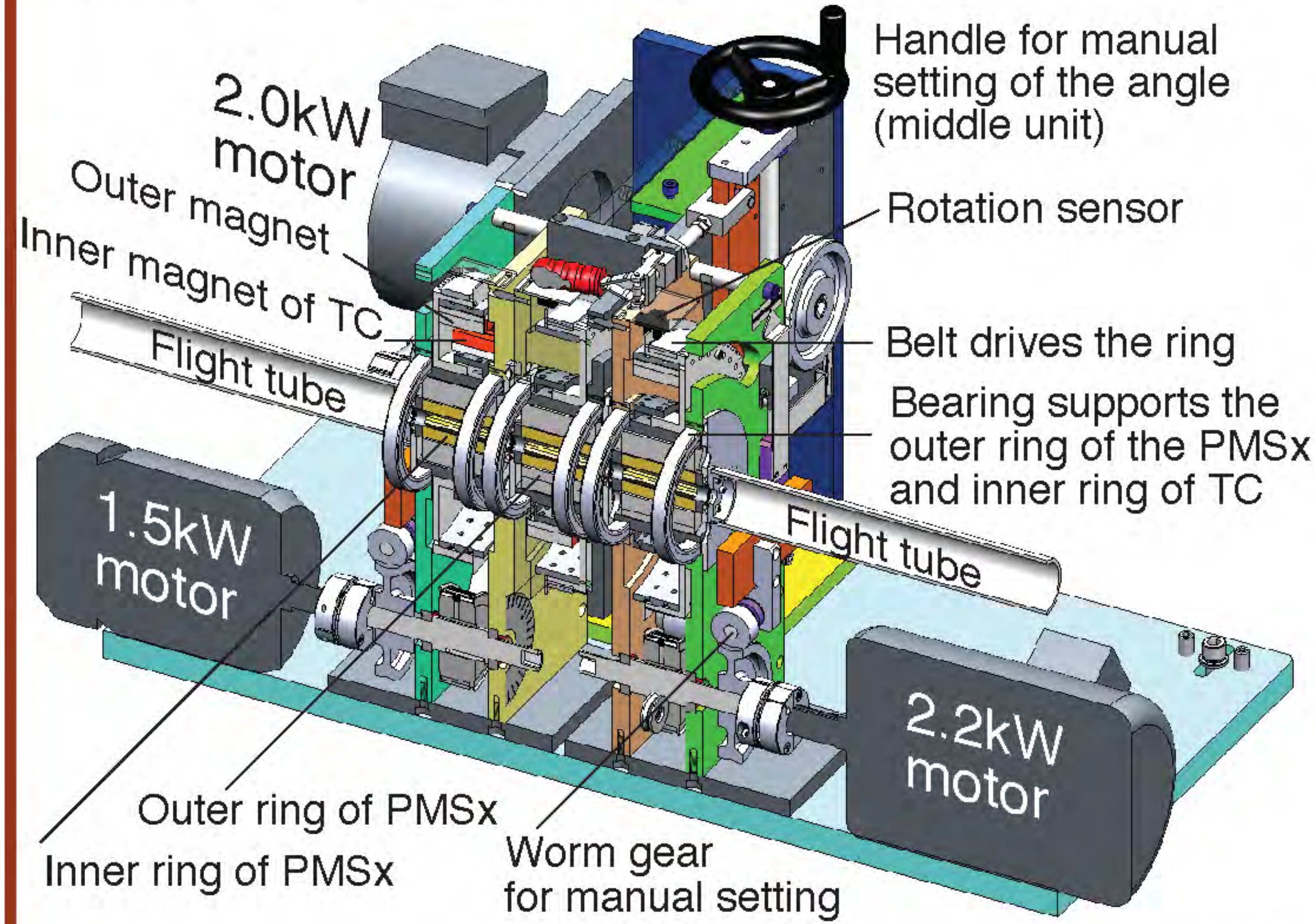
Permanent Magnet size

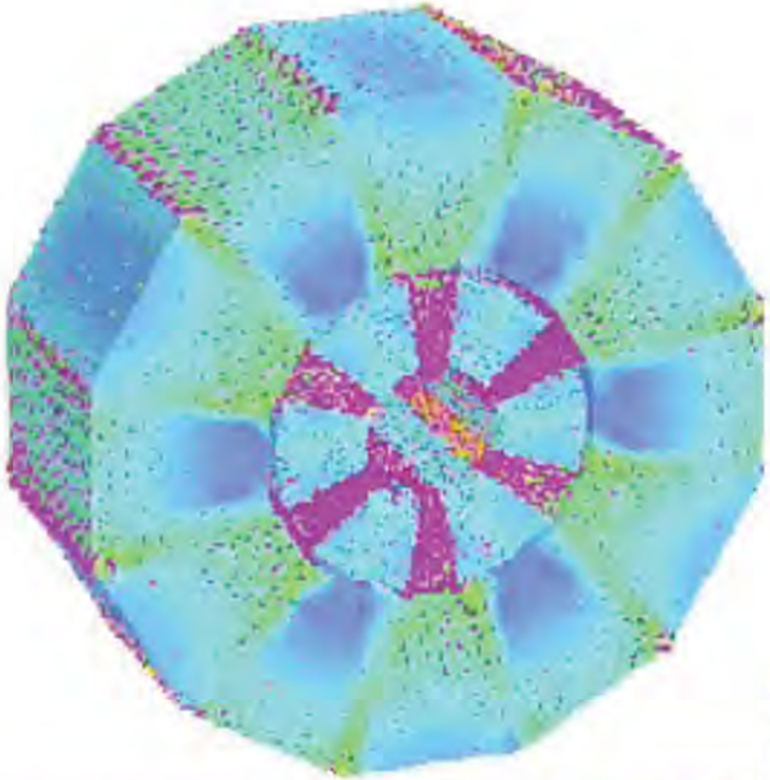
ID=15mm, OD=80mm



Inner: 18 sections

Outer: 12 sections





Early work demonstrated by Dr. M. Yamada

Summary

J-PARC TPC lifetime

to be finalized soon

upgrade: enlarging the acceptance etc.

TPC in Solenoid Field

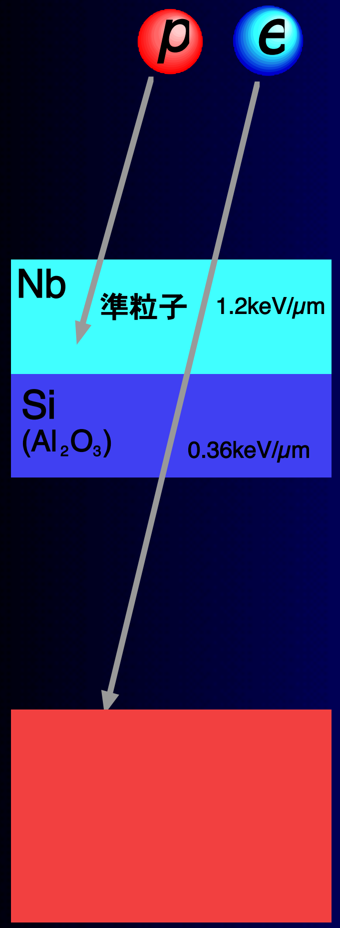
N.Sumi et al., Kyushu Univ.

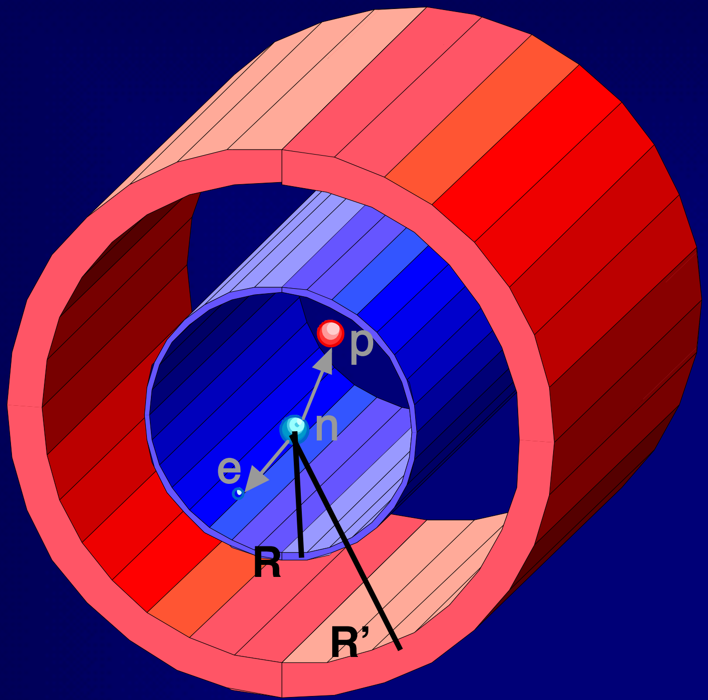
Magnetic Transport -> Lifetime

M.Kitaguchi et al., Nagoya Univ.

Superconducting Proton Detection

Simultaneous Measurement of Electron Momentum and Proton Energy



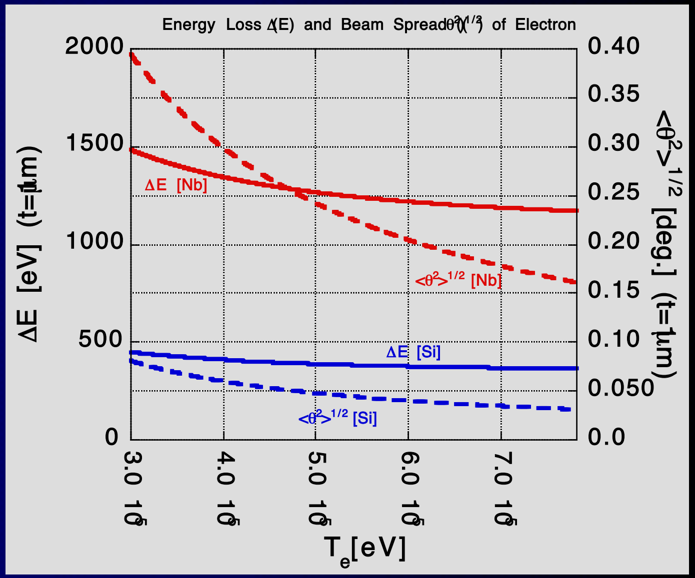


E_p, E_e
detected position
Δt : arrival time difference

vertex determination with Δt

momentum direction

kinematically complete measurement



Δx=1mm R=10mm R'=50mm	Δx=10μm R=100mm R'=200mm
ΔT_e=1keV @ T_e=100keV	ΔT_e=17eV @ T_e=100keV
ΔT_p=50eV @ T_p=500eV	ΔT_p=0.12eV @ T_p=500eV
Δt=10ns	Δt=2ps
↓	↓
Δθ=5.7deg	Δθ=0.006deg

radiative corrections to each correlation term may be measured as functions of electron energy

misalignment

↓

relative measurement of correlation terms

comparison between theoretical and experimental values of the final state interaction leads to T-violation search in neutron decay