Current status of DeeMe

Daiki Nagao, Osaka Univ.
on behalf DeeMe collaborator
NuFACT2018 @Virginia Tech.

DeeMe Collaboration

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Outline

- Motivation
- DeeMe experiment
  - Concept
  - Background
  - Spectrometer
  - H-Line
- DIO spectrum measurement
  - DIO spectrum
  - Setup
  - Analysis
- Summary

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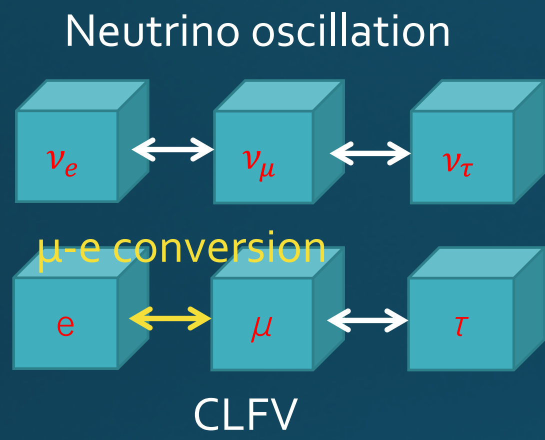
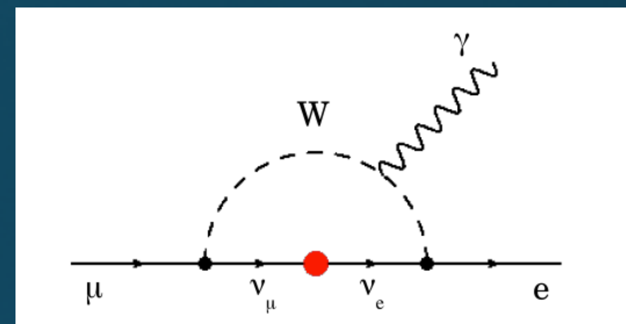
Lepton Flavor Violation





- Neutrino oscillation was observed by experiments.
- Charged Lepton Flavor Violation (CLFV) is heavily suppressed in the current Standard Model of particle physics with neutrino oscillation.
  - BR(μ→e) ~ 10^{-54} considering the neutrino oscillation

→ Too small to be observed!

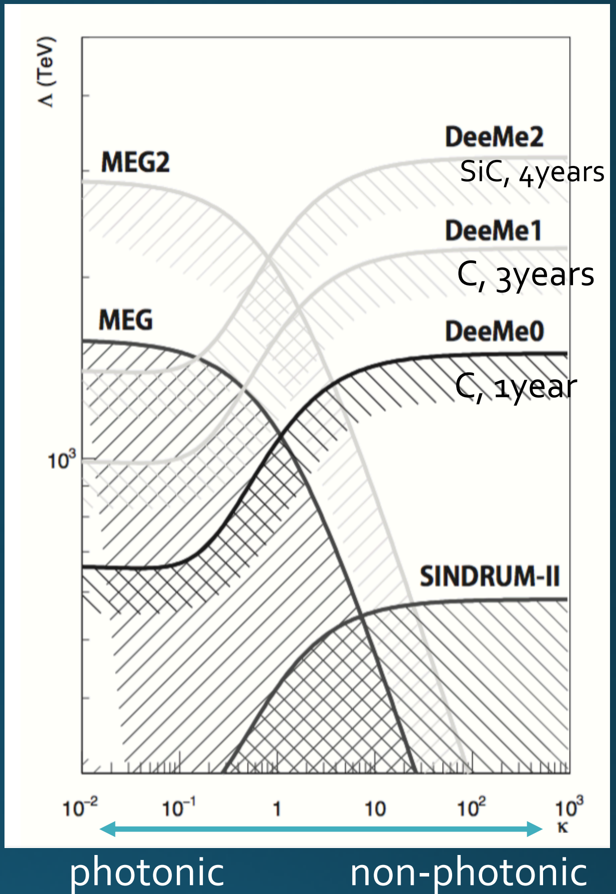
- Sizable Branching ratio predicted by theoretical models beyond SM
  - Observation of CLFV is the clear evidence of the new physics!

μ-e conversion

- CLFV
  - $\mu \to e\gamma$
  - $\mu N \to eN$
  - $\mu \to eee$
  - …

Lagrangian

$$L = \underbrace{\frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma^{\mu\nu}e_L F^{\mu\nu}}_{\text{photonic}} + \underbrace{\frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_L\gamma^\mu e_L)(\bar{q}_L\gamma_\mu q_L)}_{\text{non-photonic}}$$



- Current upper limit
  - $BR(\mu^- Ti \to e^- Ti) < 4.6\times10^{-12}$ (TRIUMF: 1988)
  - $BR(\mu^- Ti \to e^- Ti) < 4.3\times10^{-12}$ (SINDRUM-II: 1993)
  - $BR(\mu^- Au \to e^- Au) < 7\times10^{-13}$ (SINDRUM-II: 2011)
  - $BR(\mu^+ \to e^+\gamma) < 4.2\times10^{-13}$ (MEG: 2016)
  - $BR(\mu \to 3e) < 1.0\times10^{-12}$ (SINDRUM: 1988)

μ-e conversion

$$\mu^- + N(A,Z) \rightarrow \mathrm{e}^- + N(A,Z)$$

- The atom trapped a muon is called “muonic atom”.
- The muon in the muonic atom decays with one of the following processes,
  - Decay In Orbit (DIO): SM

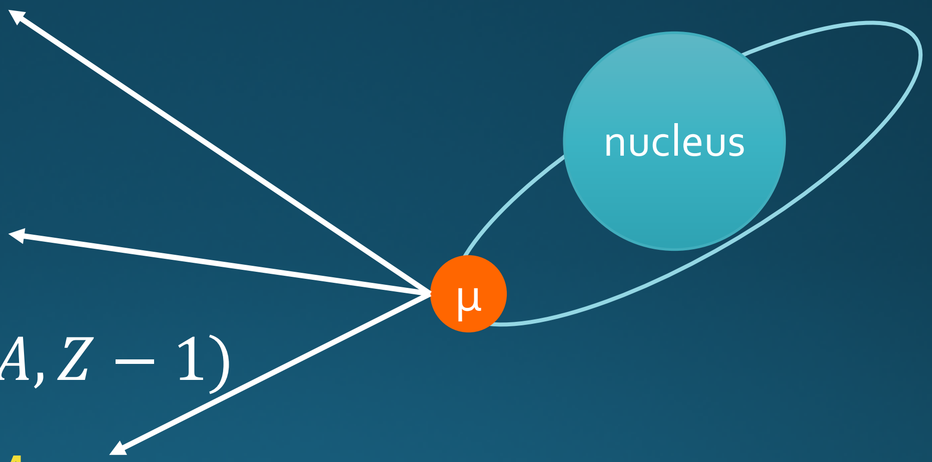
    $$\mu^- \rightarrow \mathrm{e}^- + \bar{\nu}_\mathrm{e} + \nu_\mu$$

  - Muon Capture (MC): SM

    $$\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)$$

  - μ-e conversion: beyond SM

    $$\mu^- + N(A,Z) \rightarrow \mathrm{e}^- + N(A,Z)$$



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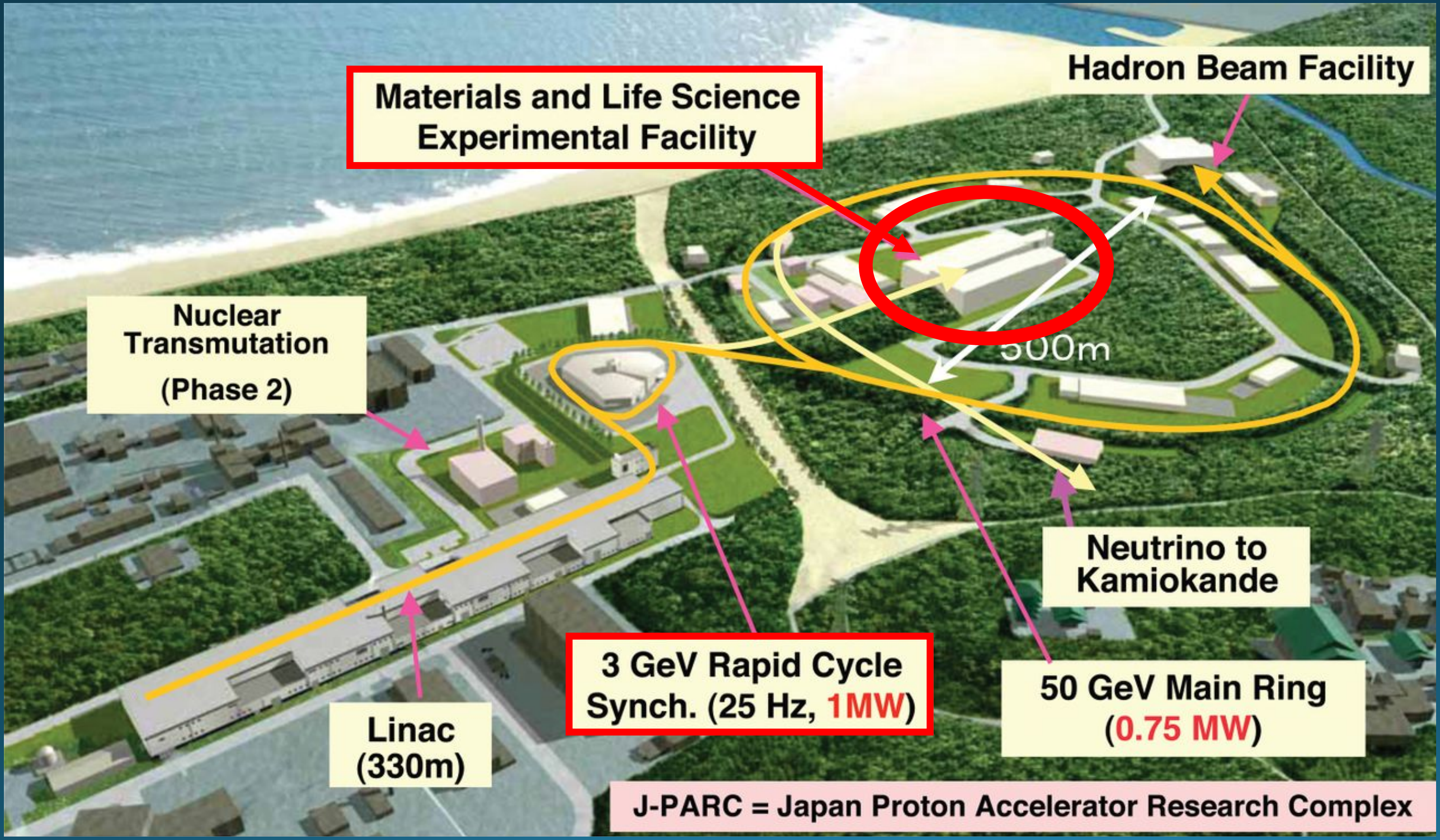
DeeMe experiment

μ-e conversion searching experiment at **J-PARC** MLF H-Line

Aiming to start DeeMe experiment from 2019!

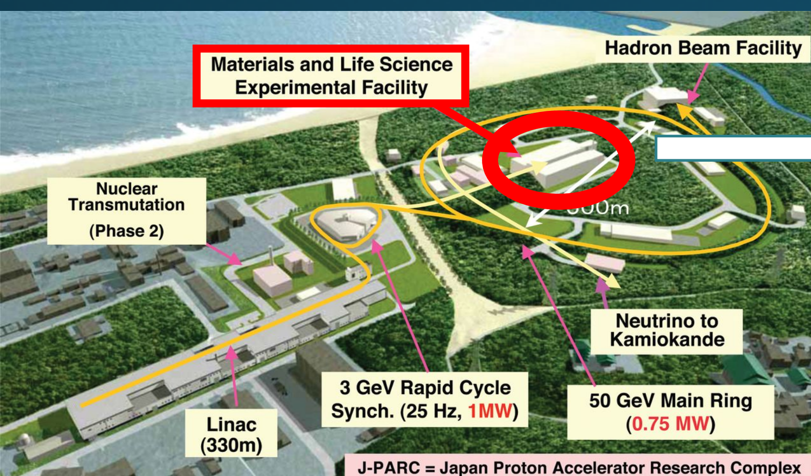


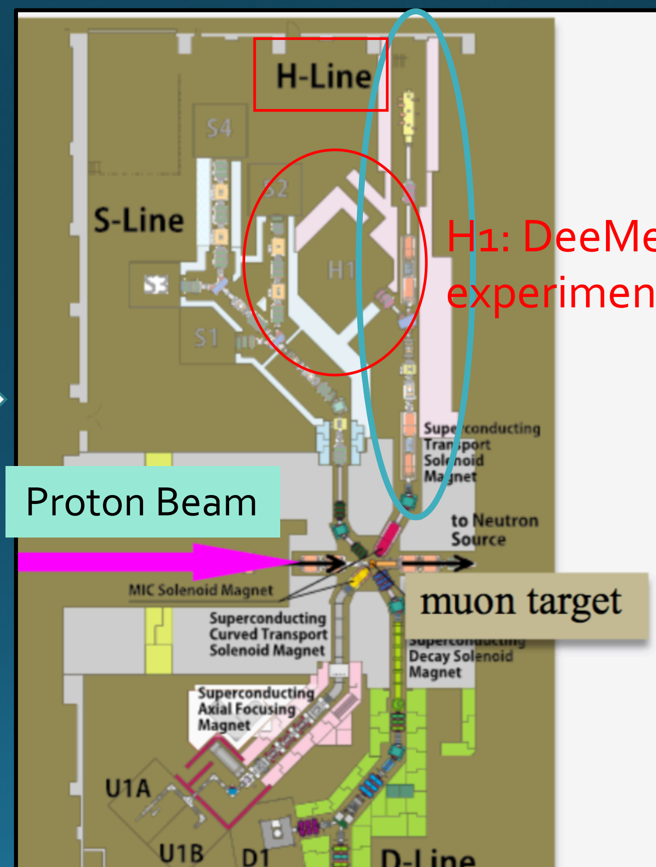
DeeMe experiment

μ-e conversion searching experiment at J-PARC **MLF H-Line**

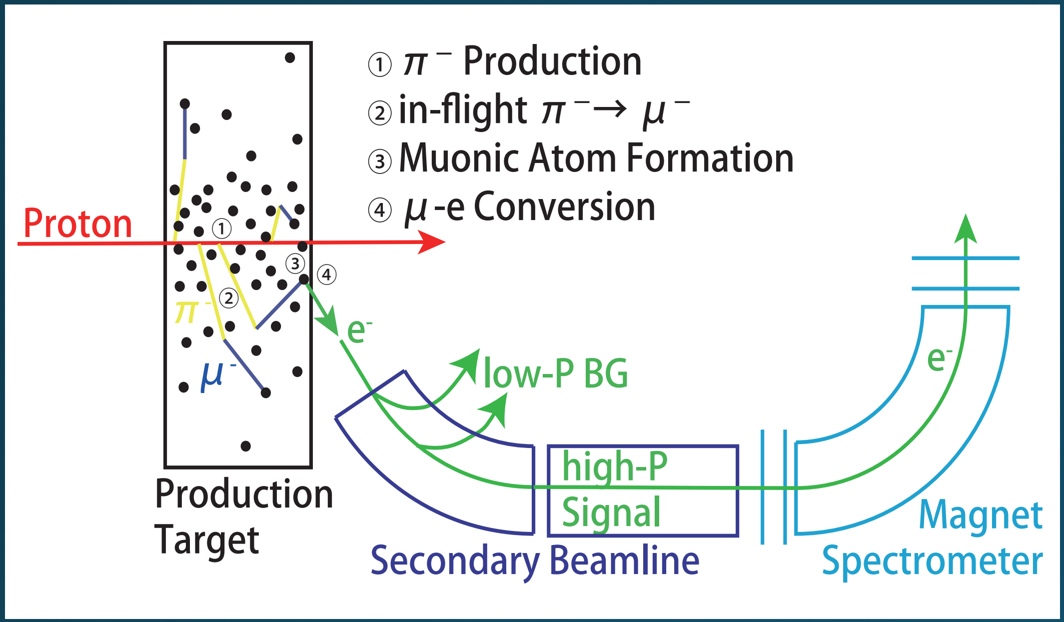
Aiming to start DeeMe experiment from 2019!

MLF Muon facility





DeeMe experiment



$\mu N \rightarrow eN$

signal electron

- single
- mono energetic
- delayed

The signal electron is identified by their momentum and time information

Start with Carbon target

- Lifetime of muonic atom ~ 2 μs
- Energy of electron from μ -e conversion = 105 MeV
- Single event sensitivity (1 year = 2×10^{7} sec)
  - 1×10^{-13}
  - 2.5×10^{-14} (4 years)

Upgrade to SiC

- 2×10^{-14}
- 5×10^{-15} (4 years)

Background

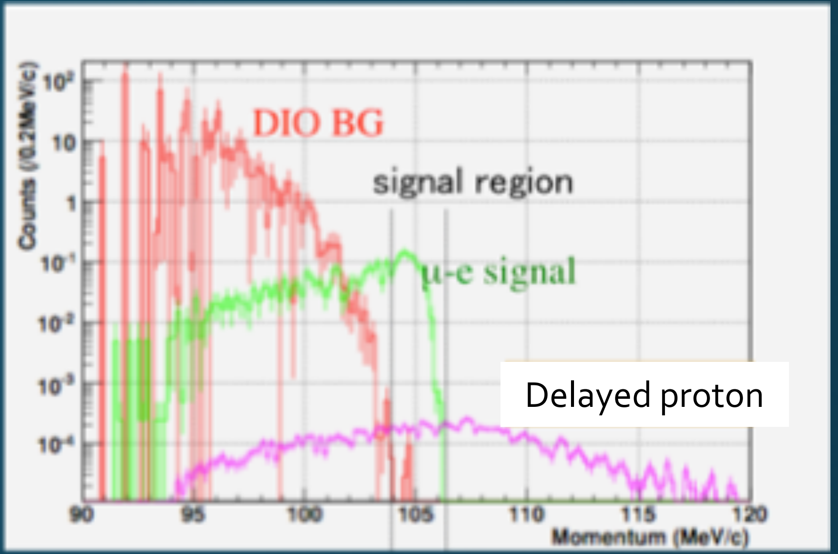
- Decay In Orbit 0.015 (event/year)
  - Distinguished by momentum
- prompt background <0.027(event/year)

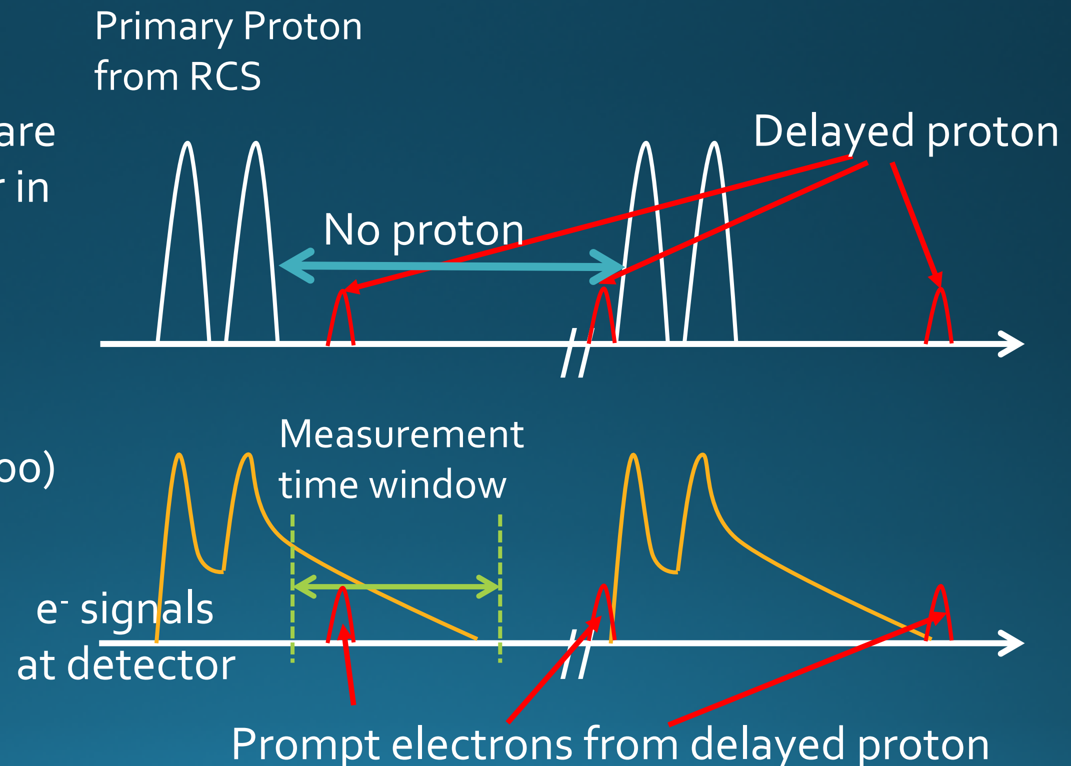
  (zero in principle)
  - Distinguished by time distribution
  - Delayed protons from main pulse are monitored by a beam loss monitor in RCS
- Cosmic-ray induced

  e: <0.018, μ: <0.001(event/year)
  - suppressed by duty factor(= 1/20000) and Horizontal tracking direction
- Anti-Proton
  - Zero in principle

    beam energy(=3 GeV)

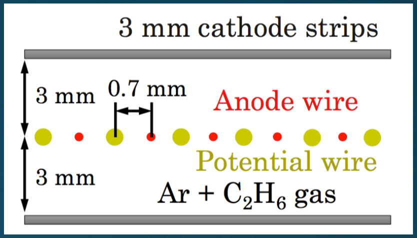
    < $\bar{p}$ production threshold

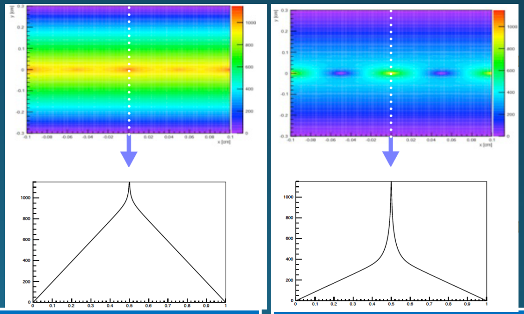




Spectrometer

- PACMAN Magnet
  - Central field = 0.4 T (at 300A) for 105 MeV/*c*, 70 degree bending
  - Transported from TRIUMF to J-PARC
  - Test operation and magnetic field measurement finished in J-PARC.
- Multi-Wire Proportional Chamber (MWPC)
  - exposed to prompt burst (10^8 particles/pulse)
    - Instantaneous hit rate ~ 100 GHz/mm^2
    - Usual detector saturated by this burst
  - Gas gain control with potential wire
  - Readout by cathode strip and store waveform with Flash ADC
  - Baseline oscillation was observed with Ar:C2H6=1:2

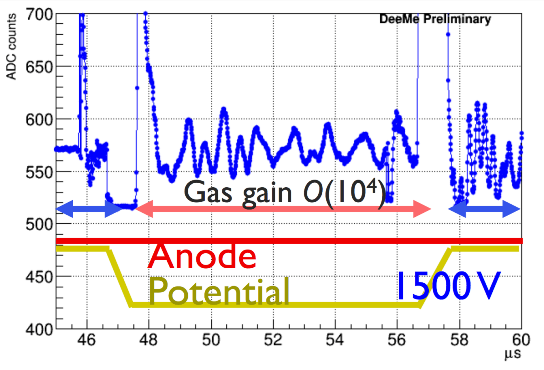


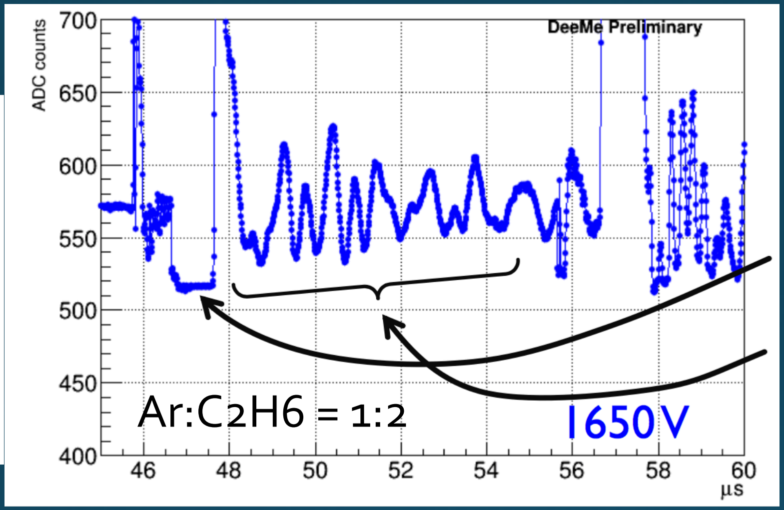


OFF	ON
Anode wire: 1450V	Anode wire: 1450V
Potential wire: 1450V	Potential wire: 0V
Gas gain: O(1)	Gas gain: O(10^4)

Publication: PTEP, Volume 2017, Issue 2, 023C01

MWPC optimization



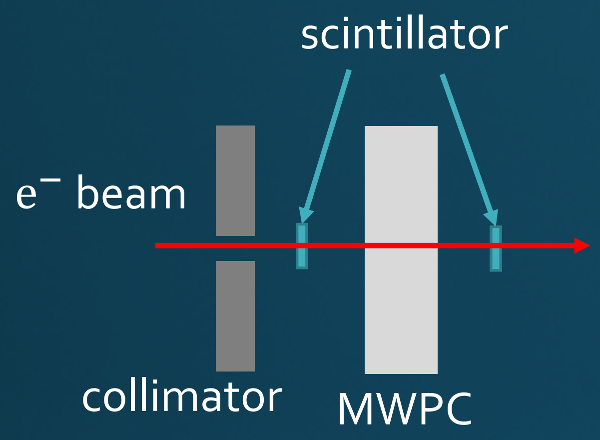


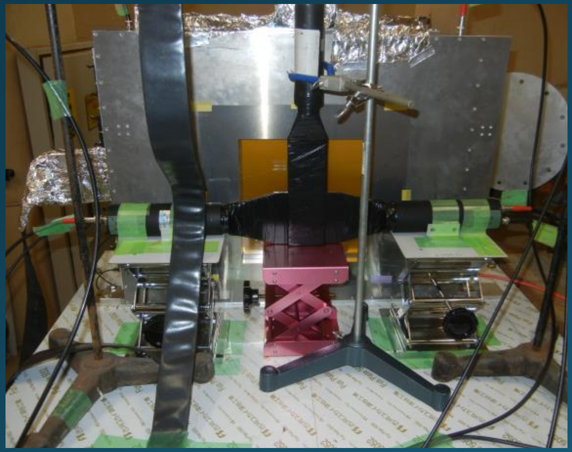
saturation of switching noise in preamp

baseline oscillation from switching noise

- Baseline oscillation makes efficiency suppressed
  - Lower HV application with same gas gain is required to suppress baseline oscillation
    - Use more powerful quencher to decrease volume of quenching gas
  - Improvement of preamplifier
    - Lower dynamic range of preamp was extended

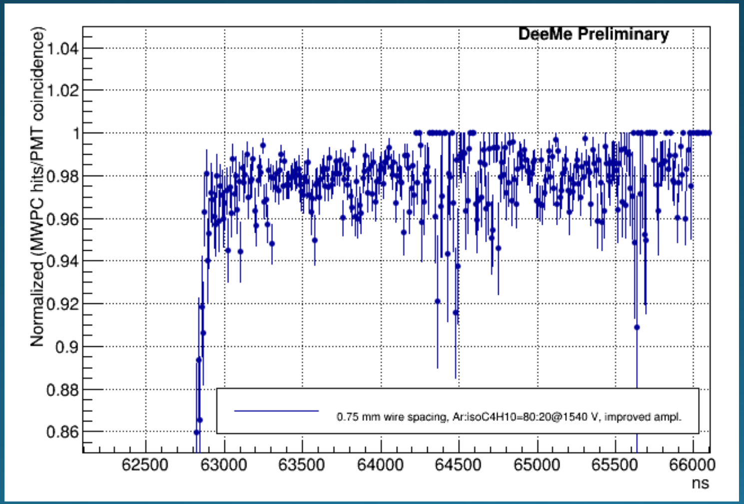
MWPC performance test





beamtime @Kyoto University Research Reactor Institute (KURRI) in Dec. 2017
test with prototype MWPC
Quencher C2H6 -> iC4H10
- efficiency improved
- time structure of efficiency was suppressed

beamtime @KURRI in Feb. 2018
test with definitive MWPC

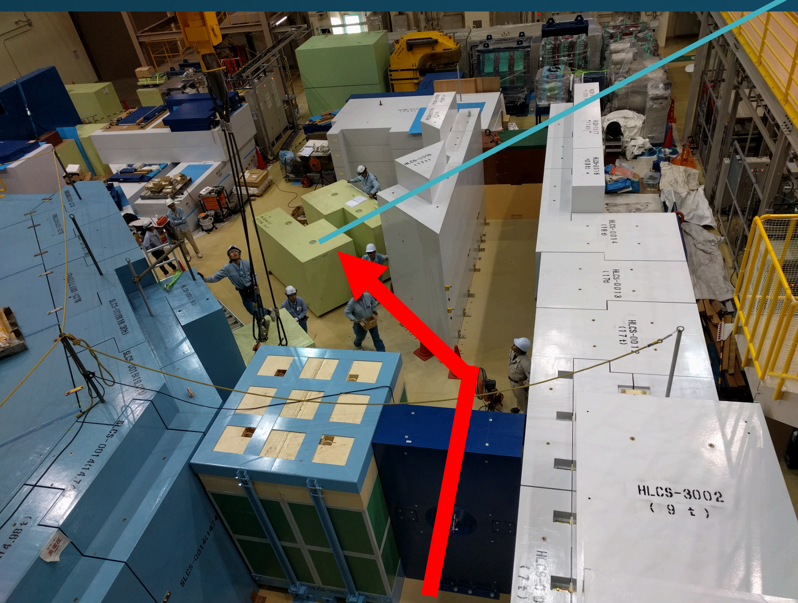


efficiency ~98% in switching-ON period

H1 experimental hall

H–Line

H-Line construction already started.
Beam is expected to be available at H1 area in 2019.



beam

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DIO spectrum

- Watanabe calculated the DIO momentum spectrum <90 MeV
- Then, Shanker calculated the spectrum of high momentum region including recoil energy

We call the combined momentum for mu-e conversion experiments “Watanabe-Shanker spectrum”

- “Czarnecki” spectrum
  - detail calculation including recoil and relativity effect

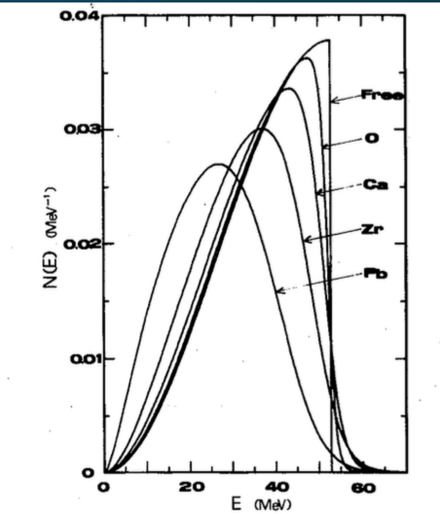
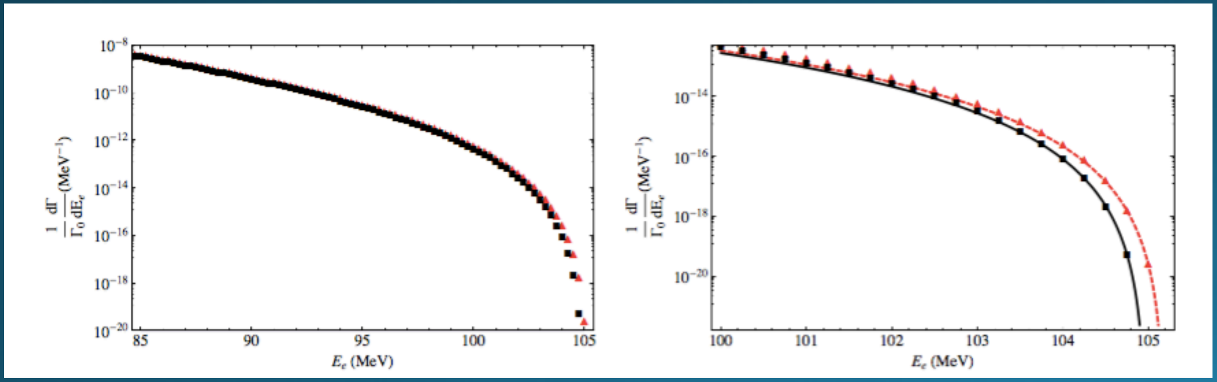


Fig. 1. Energy spectra $N(E)$ of electrons for the bound muon decays in ^{16}O, ^{40}Ca, ^{90}Zr and ^{208}Pb, and for the free muon decay. They are normalized so that $\int N(E)dE=1$ for the free muon decay.

Watanabe spectrum

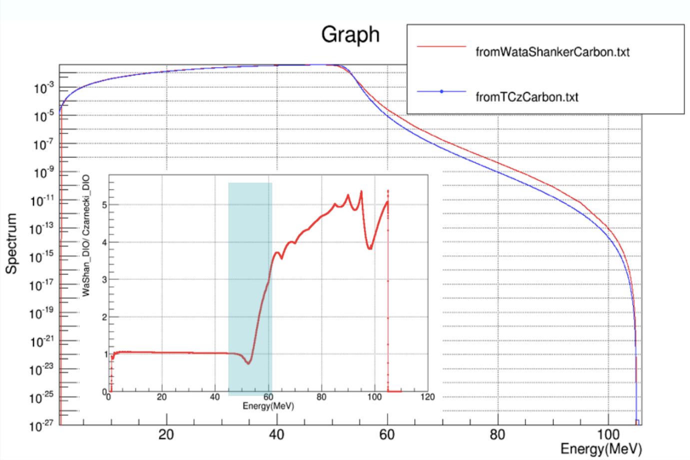


DIO spectrum with Al atom
Red: Watanabe spectrum
Black: Czarnecki spectrum

DIO measurement

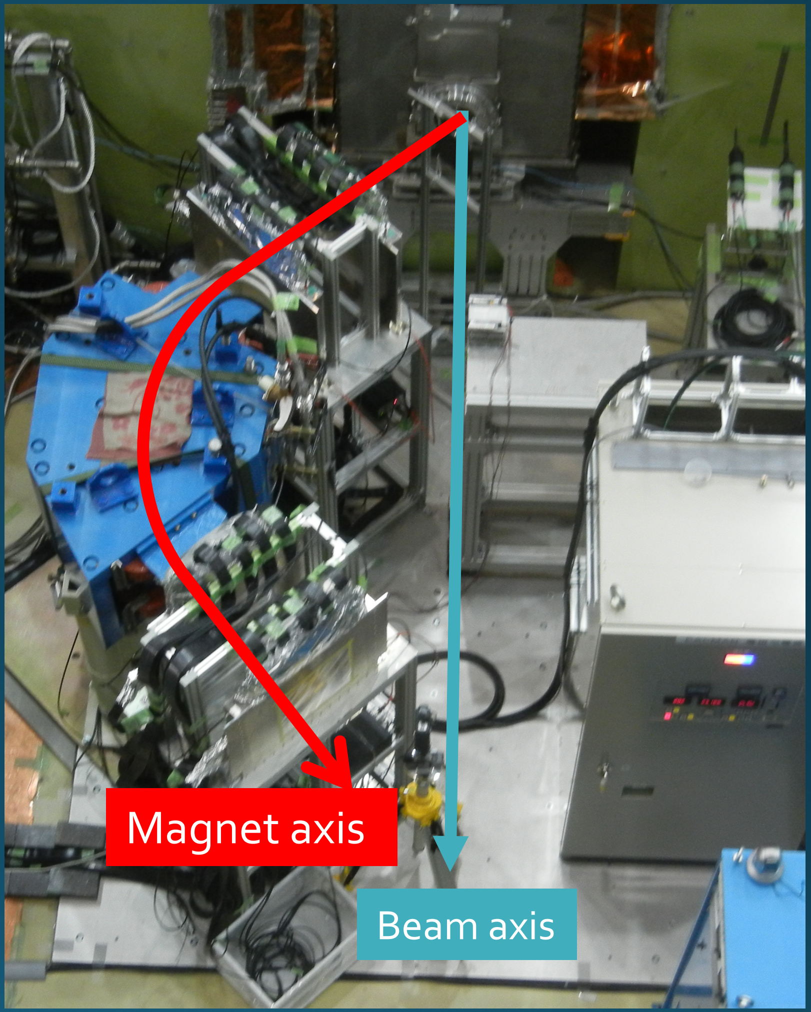
- Performance test of spectrometer system
  - DAQ test with 4 MWPCs
  - Development of tracking analysis codes with real data
- DIO spectrum analysis
  - Confirmation of Czarnecki C spectrum
- Experiment plan
  - J-PARC, MLF, D line
    - H line was not available
  - Full MWPC set and 90° bending sector magnet
    - PACMAN magnet is too large to install in D2 area
    - Maximum momentum range is =70 MeV/c with the sector magnet
  - Measurement energy = 55 MeV
    - The biggest difference between 2 spectra is the end point, but its factor ~5 and intensity decrease to O(10^{-12}) comparing with 55 MeV

Comparison between Czarnecki DIO spectrum and Watanabe-Shanker DIO spectrum in Carbon



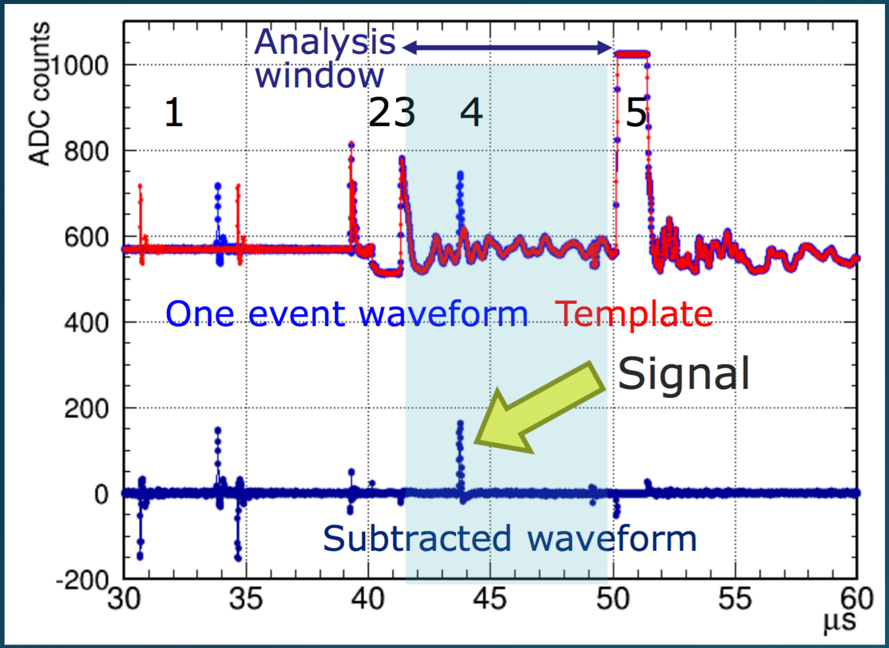
Setup

- Beam
  - 30 MeV/c decay muon
- Target
  - Right next to the beam window
  - 45° and 90° against to beam axis and magnet axis
- Spectrometer
  - 4 MWPCs and sector bending magnet
- Hodoscope
  - 2 scintillation counters
  - Counting electron from the target
- Trigger and DAQ
  - Trigger of DAQ synchronized with that of accelerator (trigger fired every 40 ms)
  - Waveform recorded by 12 32ch-100MHz-Flash ADC
    - ➢ Publication - DOI: 10.1109/TNS.2018.2861880



Waveform analysis

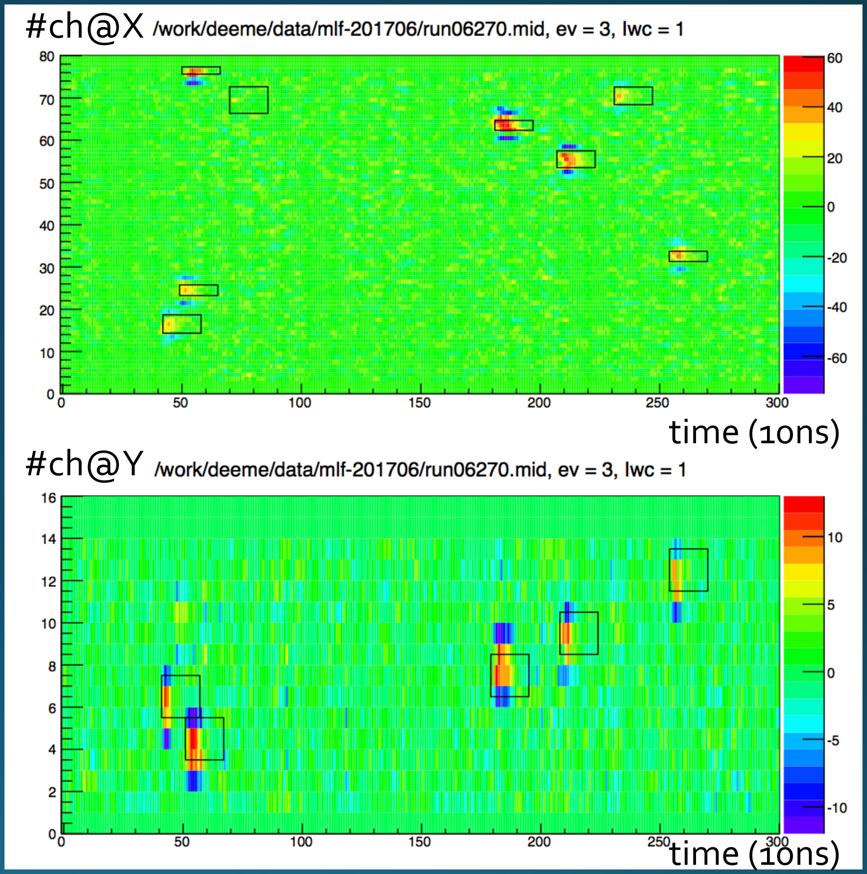
- Baseline subtraction



1. test pulse
2. HV-switching OFF->ON
3. over shoot by PZC circuit
4. signal
5. HV-switching ON->OFF

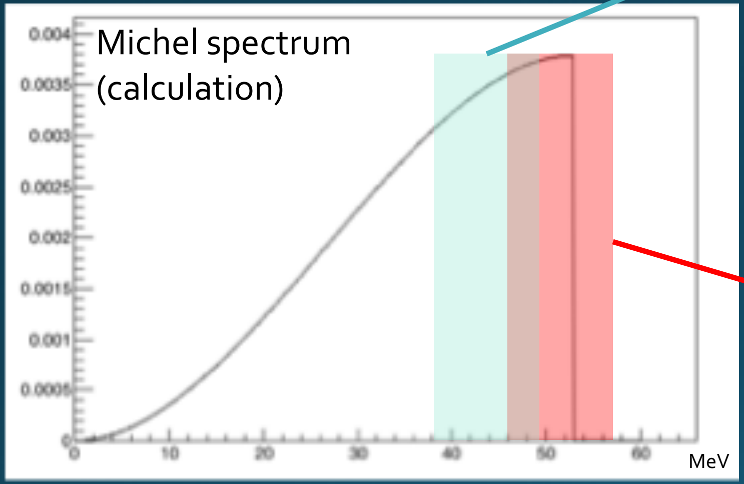
A template waveform is a set of most frequent value in each sample points

- Pulse finding

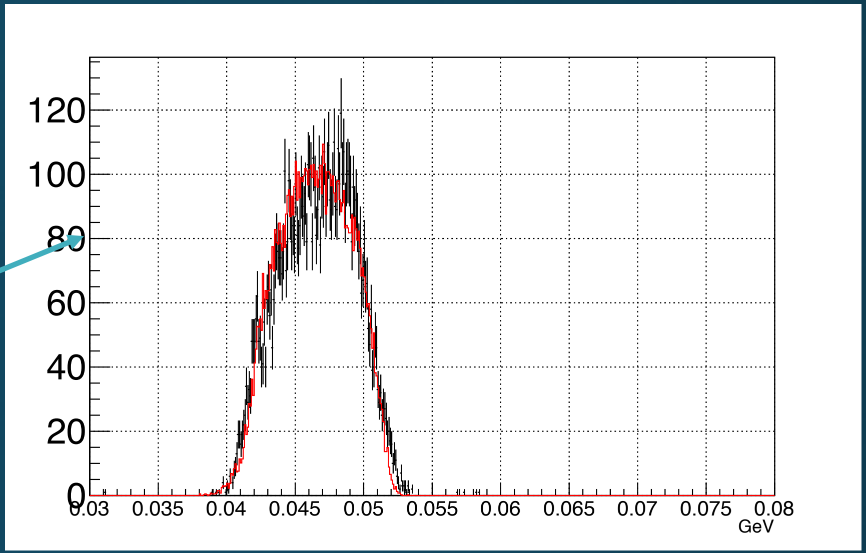


Analysis

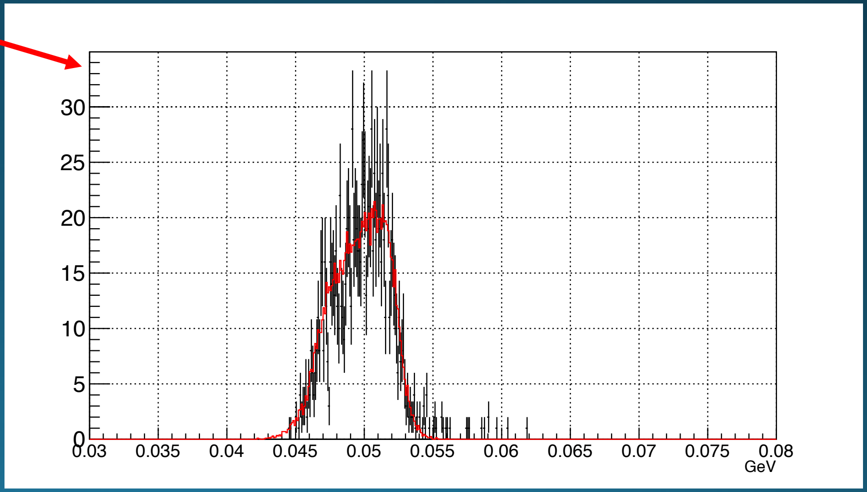
compared the shape of measured momentum spectrum with MC simulation



- C target, μ^+, 45 MeV



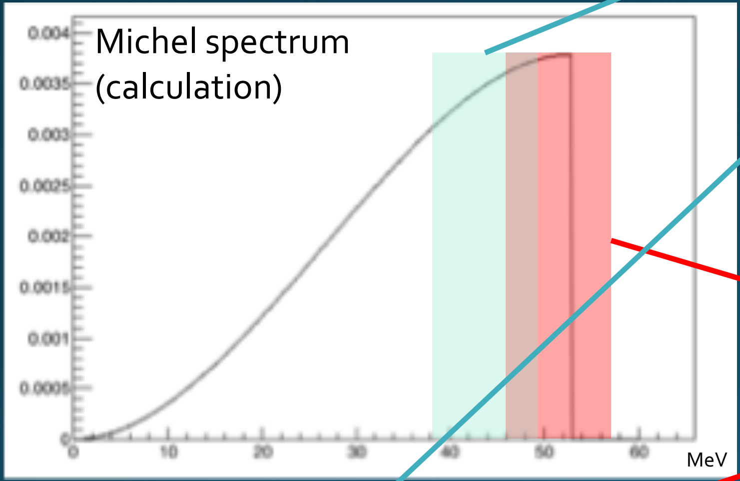
- C target, μ^+, 52.5 MeV



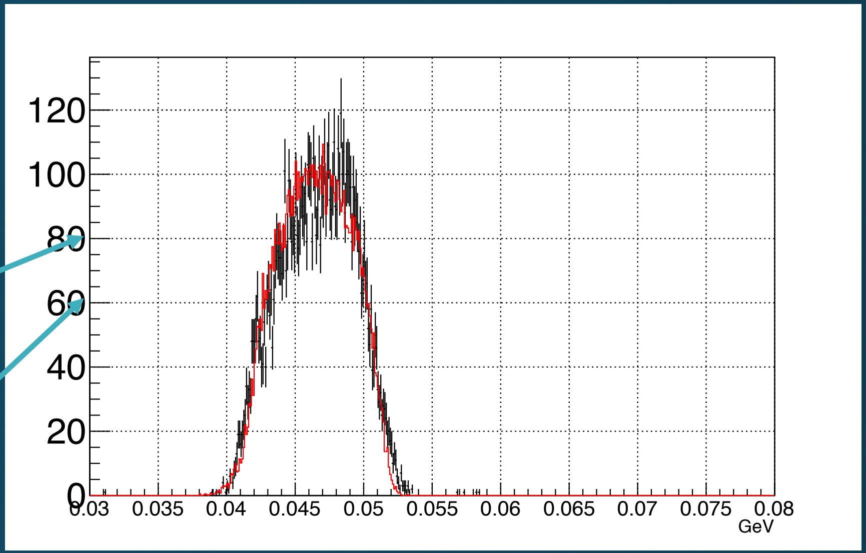
Momentum spectra of data are consistent to that of MC
Calibrated with MC spectrum

Analysis

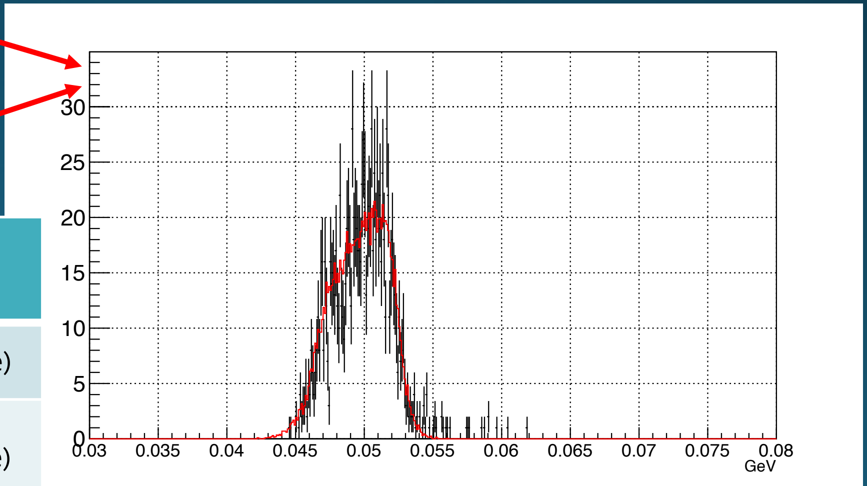
compared the shape of measured momentum spectrum with MC simulation



- C target, μ^+, 45 MeV



- C target, μ^+, 52.5 MeV



Purpose	Material of target	Polarity	Momentum of B field setting (MeV/c)	Number of trigger ($\times 10^5$ trig.)
Momentum calibration	C	+	55 (March)/ 52.5 (June)	0.6 (March) / 2.3 (June)
Acceptance and polarized spectrum measurement	C	+	45	2.0 (March) / 4.7 (June)

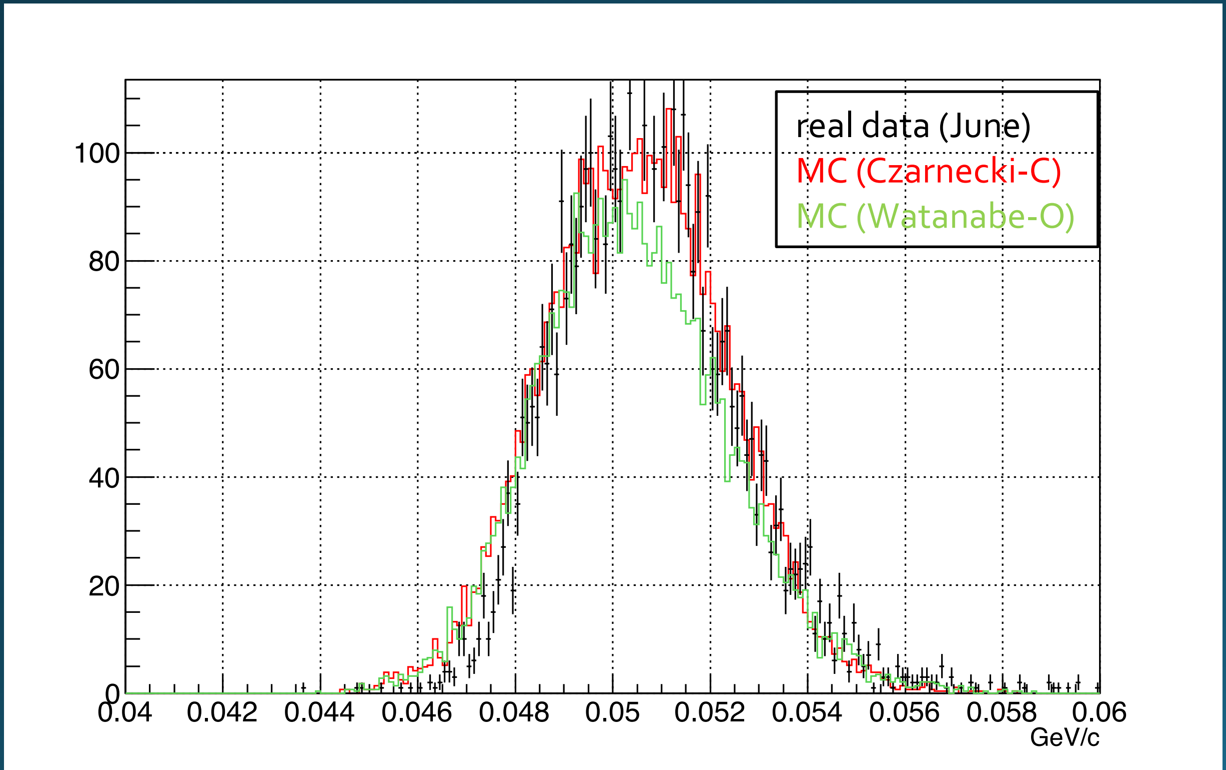
taken data set

DIO analysis

Purpose	Material of target	Polarity	Momentum of B field setting (MeV/c)	Number of trigger ($\times 10^5$ trig.)
Momentum calibration	C	+	55 (March)/ 52.5 (June)	0.6 (March) / 2.3 (June)
Acceptance and polarized spectrum measurement	C	+	45	2.0 (March) / 4.7 (June)
DIO spectrum measurement	C	-	55	12.4 (March) / 6.3 (June)
	Si	-	55	4.8
	SiC	-	55	17

DIO analysis

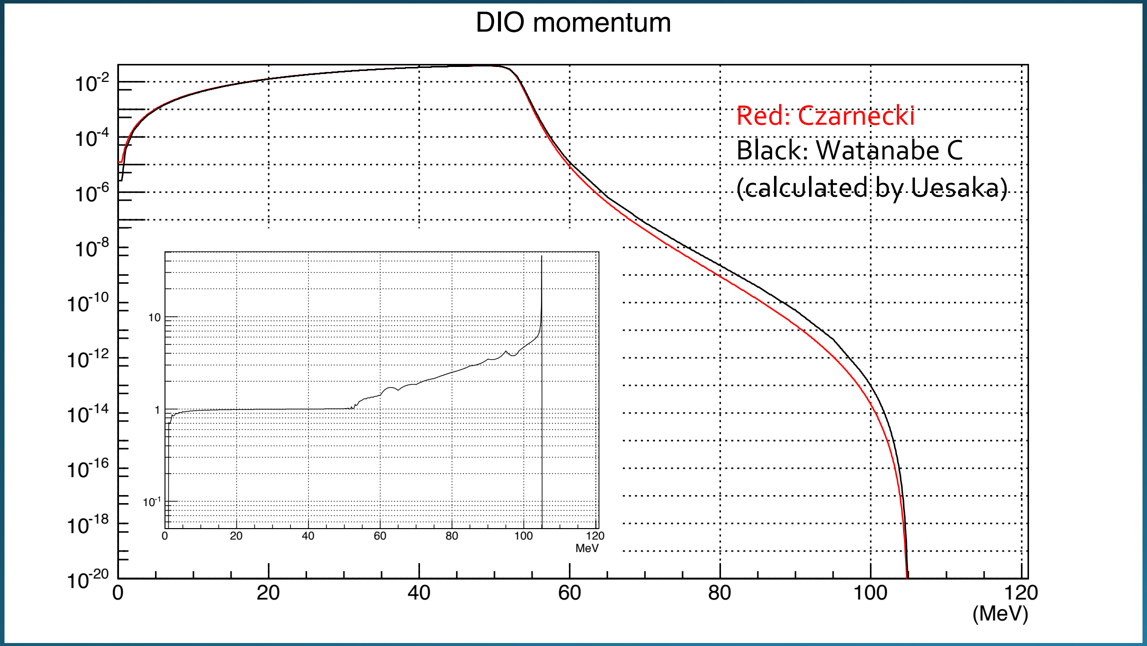
- C target, μ^-, 55 MeV (DIO data)



The shape of the momentum spectrum is not inconsistent with Czarnecki spectrum for the moment

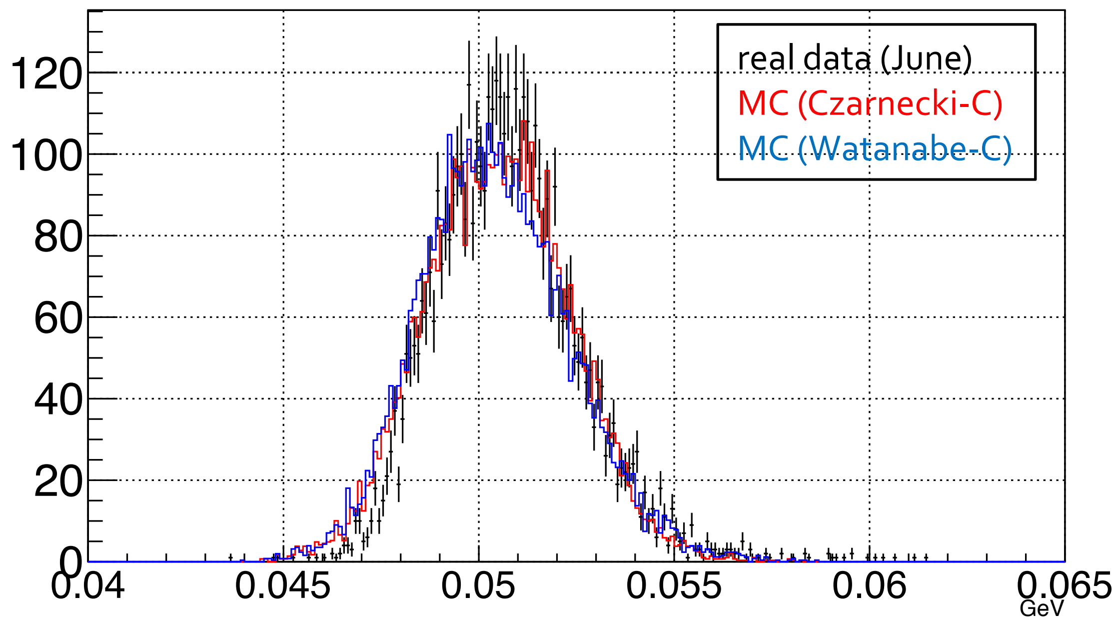
Update of Watanabe spectrum

- Original Watanabe spectrum was not calculated for C
  - We used Watanabe-O spectrum for C-target when we design DeeMe experiment in 2009
- These 2 spectrum cannot be compared truly, so I asked a theorist to calculate the spectrum for C with Watanabe's method



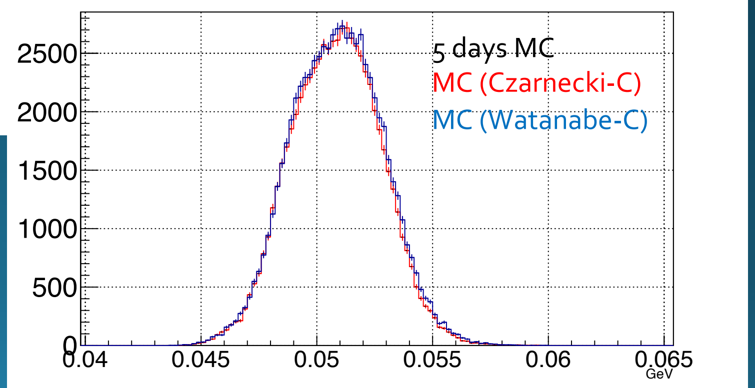
Analysis

- C target, μ^-, 55 MeV (DIO data)



By improving the statistics by factor 15, the difference between Czarnecki-C and Watanbe-C spectra becomes clear.
We submitted additional experiment to increase the number of event.

Difference between Czarnecki and Watanabe-C spectrum is expected to be observed with 5-days measurement by MC simulation.



Summary

- μ-e conversion is the clear evidence of the new physics
- DeeMe will start soon with the single event sensitivity of 1×10^{-13} for C
  - The single event sensitivity of 5×10^{-15} for SiC 4-years
- The spectrometer system is ready.
  - Gas mixture optimization ongoing
- H-Line construction ongoing
- DIO spectrum measured at J-PARC
  - Analysis tools were developed with real data
  - measured momentum is not inconsistent with Czarnecki spectrum (analysis is still ongoing)
  - A proposal to increase the statistics was submitted