Status of the DeeMe Experiment, an Experimental Search for *μ-e* Conversion at J-PARC MLF

from HiggsTan
(http://higgstan.com/)

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Osaka City University and NITEP

The 21st International Workshop
on Neutrinos from Accelerators (NUFACT2019)

The Grand Hotel, Daegu, Korea

The DeeMe Experiment

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(7) Osaka City University (8) NITEP (9) Hiroshima University
(10) Vietnam National University Ho Chi Minh City
(11) University of California, Davis (12) Okayama University

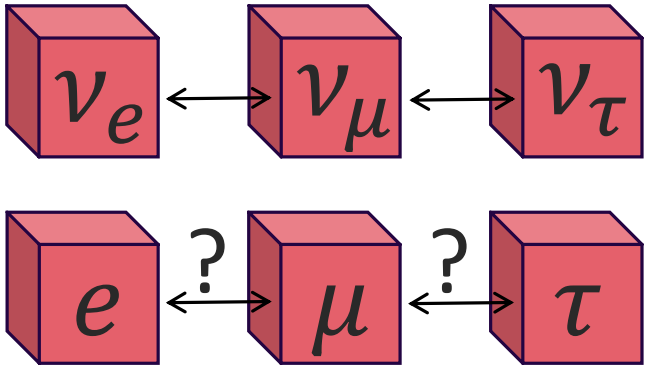
DeeMe Experiment

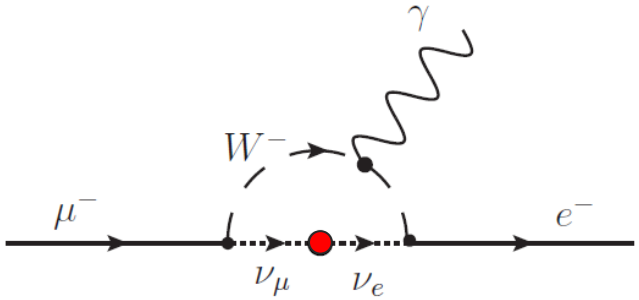
- Search for charged lepton flavor violating decay
  $\mu^- \mathrm{N} \rightarrow e^- \mathrm{N}$

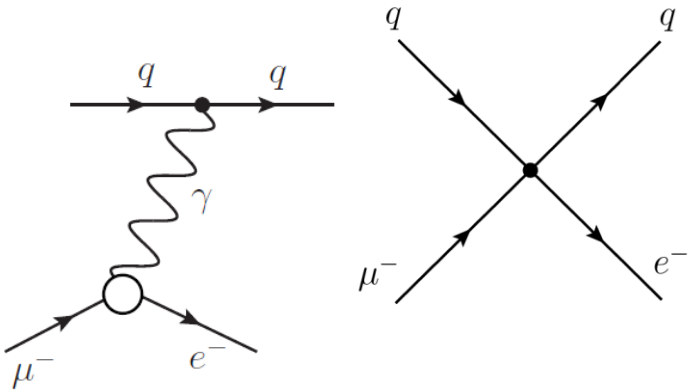
This talk

- Charged lepton flavor violation
- Experimental concept
- Current status
- Summary

Charged Lepton Flavor Violation and New Physics







- Charged Lepton Flavor Violation (cLFV)
  - $\mu N \to eN, \mu \to e\gamma, \mu \to eee, \ldots$
- Branching ratio for $\mu \to e\gamma$ suppressed in the Standard Model < 10^{-54}
  Nuclear Physics B (Proc. Suppl.) 188 (2009) 303-308
- Too low probability to observe
- Some theoretical models beyond the SM predict branching ratios 10^{-13} to 10^{-17}
  - SUSY-GUT, SUSY-seesaw, extended Higgs sector, etc.
- An observation of cLFV processes at large rates means the existence of new physics

What May Happen to Muonic Atoms

Standard Model

- Muon decay in orbit (DIO) $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$

  92% for C, 39% for Al, 33% for Si

- Muon capture (MC) $\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$

  8% for C, 61% for Al, 66% for Si

Life time: 2.0 μs, 0.86 μs, 0.76 μs

New physics

$$Branching\ ratio_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$$

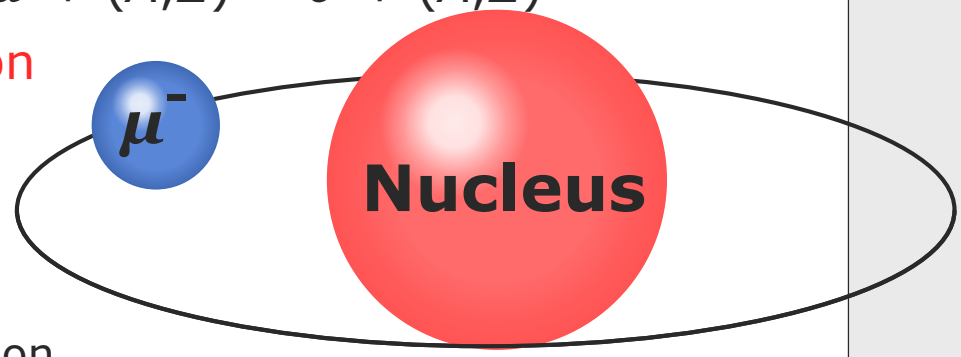
- Muon to electron conversion $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$

  Charged lepton flavor violation

  Monoenergetic e^-
  with ≈ 105 MeV for C or Al, Si

$$E = m_\mu - B_\mu - E_{\mathrm{rec}}$$

where B_μ : the binding energy of muon
E_{rec}: the nuclear recoil



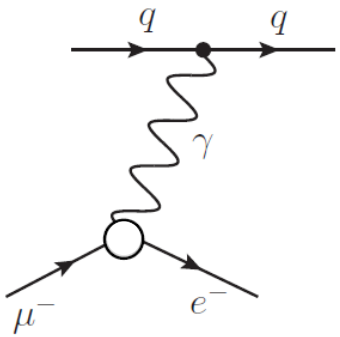
Muonic atom 1S bound state

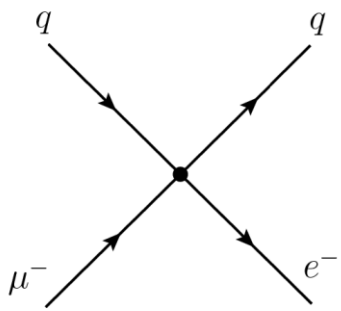
Search for cLFV in Photonic and Non-photonic Decays

- Possible processes for cLFV can be classified

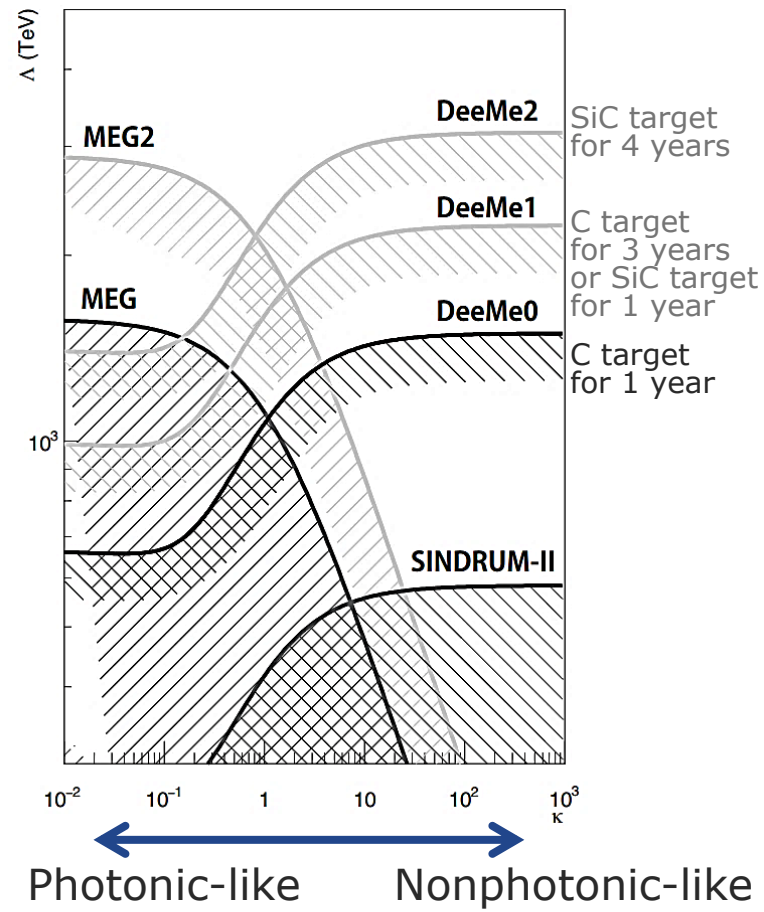
Photonic | Non-photonic

$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\overline{\mu_\mathrm{R}}\sigma^{\mu\nu}e_\mathrm{L}F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\overline{\mu_\mathrm{L}}\gamma^\mu e_\mathrm{L})(\overline{q_\mathrm{L}}\gamma_\mu q_\mathrm{L})$$





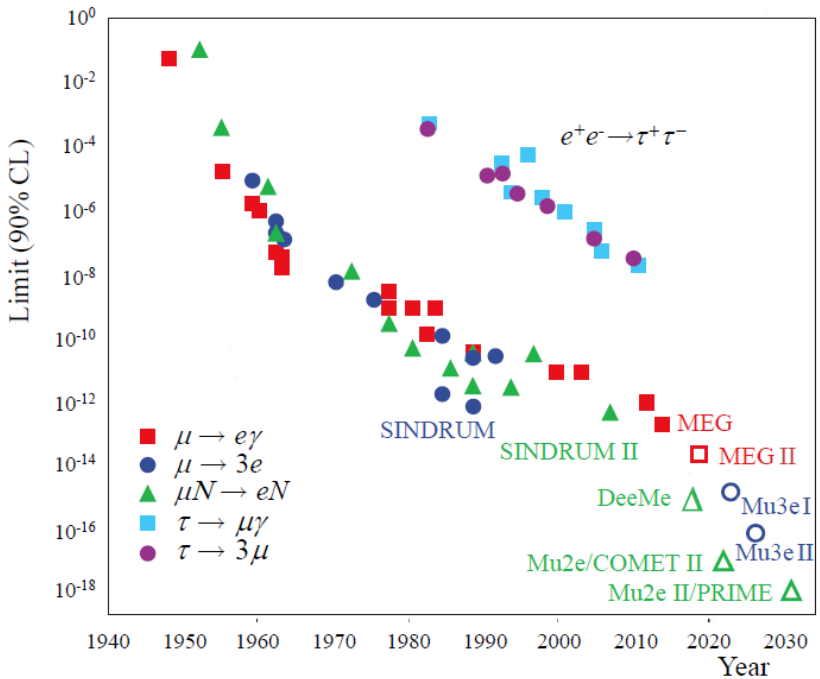
Branching ratio for $\mu\,\mathrm{N} \to e\,\mathrm{N}$
$\approx$ 1/100 of that for $\mu \to e\gamma$



Original graph by A. de Gouvêa, P. Vogel
Prog. Part. Nucl. Phys. 71, 75-92 (2013)

- It is important to probe the cLFV with as many different approaches as possible

Sensitivity Goals



Eur. Phys. J. C 78 (380) (2018)

Single event sensitivity:
branching ratio @ 1 event observation

Current upper limits for $\mu N \to eN$

TRIUMF

- $< 4.6\times10^{-12}$ (Ti target)

SINDRUM-II at PSI

- $< 4.3\times10^{-12}$ (Ti target)
- $< 7\times10^{-13}$ (Au target)

DeeMe

Aims to achieve

- S. E. S. $< 1\times10^{-13}$ (C target, 1 year)
- S. E. S. $< 2\times10^{-14}$ (SiC target, 1 year)

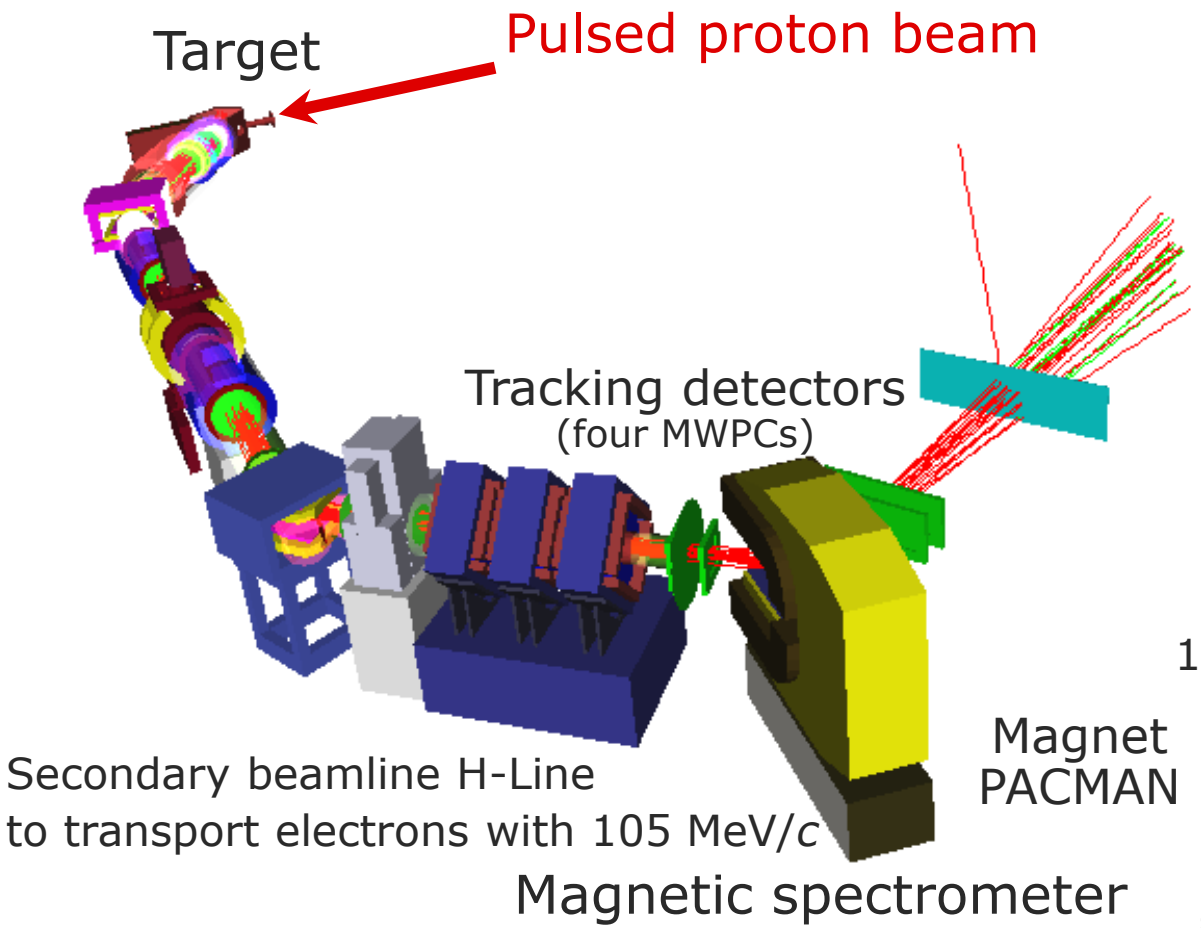
to observe the CLFV
or to improve the current limit
by ×10 or ×100

Places of Experiments

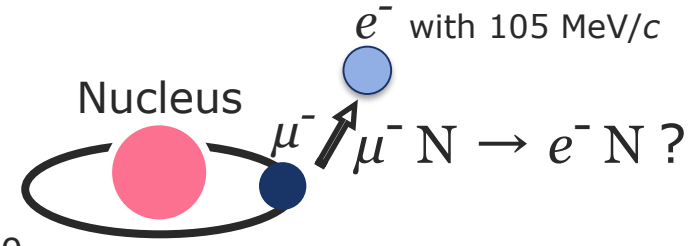
- DeeMe will be conducted at J-PARC Materials and Life Science Experimental Facility MUSE in Tokai Village, Japan
- Takes 1.5 hours by express train from Tokyo

- Pulsed proton beam from 3-GeV RCS
- Fast extraction
- 500 kW → 1 MW (design power)
- 25 Hz double pulses

Experimental Concept



1. π^- production
2. π^- decay-in-flight into μ^-
3. Muonic atom formation

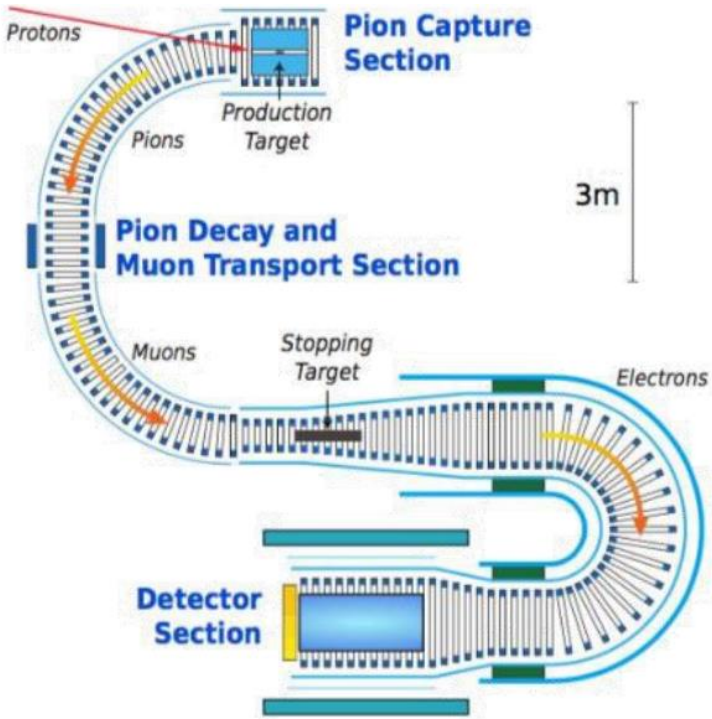


10^{10} muonic atoms/sec
with RCS 1 MW

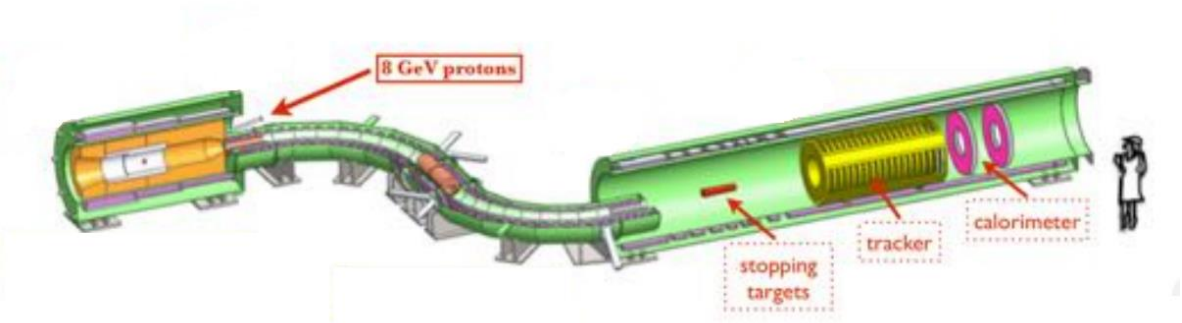
π^- production target
= π^--decay & μ^--transport section
= μ^- stopping target
in DeeMe experiment

COMET at J-PARC and Mu2e at Fermilab

COMET at J-PARC



Mu2e at Fermilab



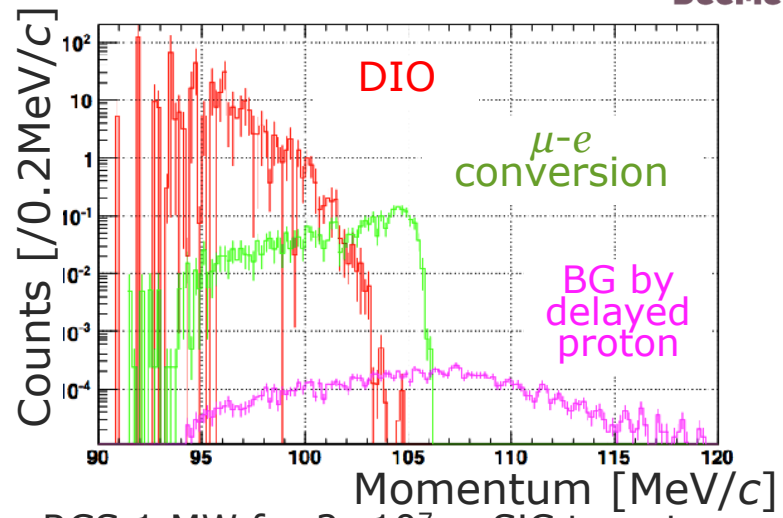
In larger-scale experiments,

- Pion production target
- Pion decay and muon transport section
- Muon stopping target

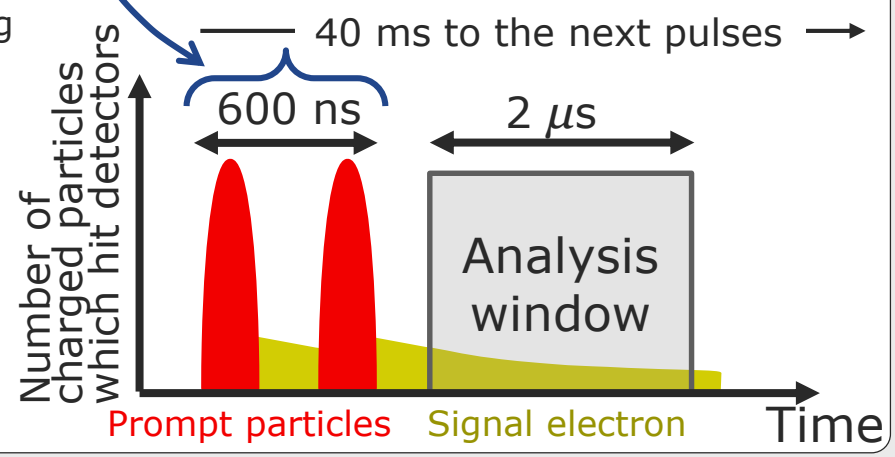
- Detectors

Backgrounds

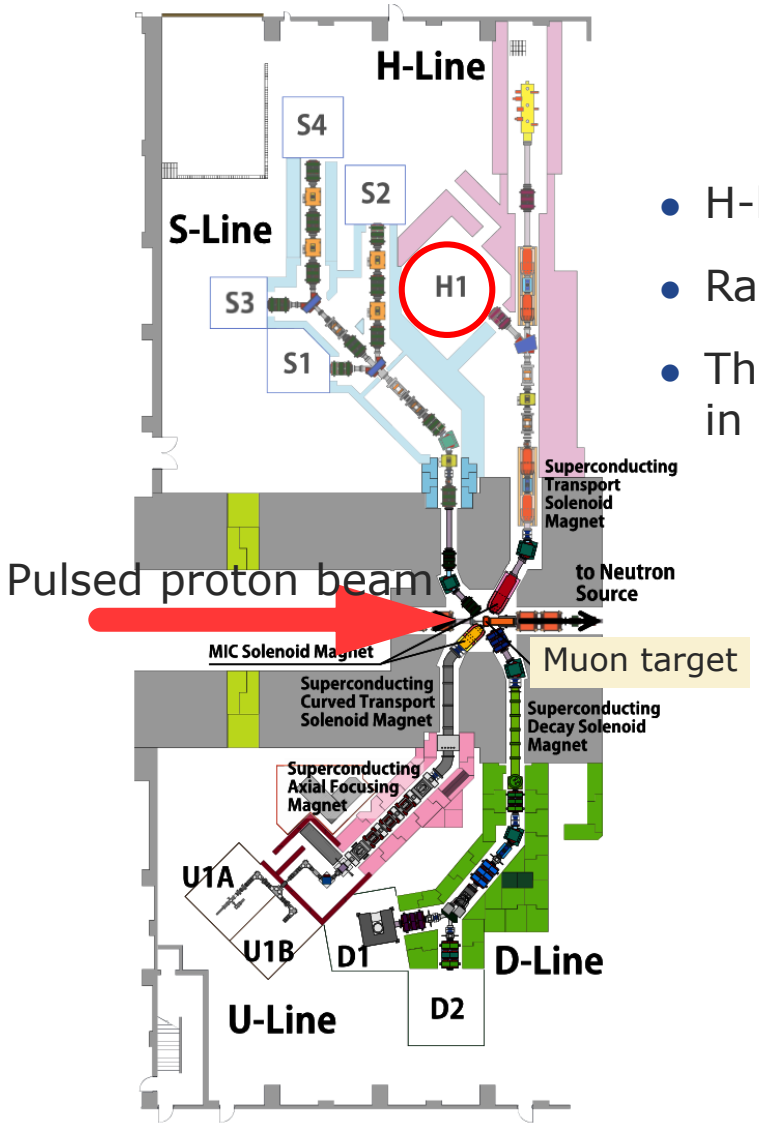
- Low-momentum background
  suppressed by the beamline
- High-momentum tail
  → need Δp < 0.4% spectrometer
- Beam pion capture
  $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$,
  $\gamma \rightarrow e^+ e^-$ at the beam-prompt timing
- Muon Decay in Orbit (DIO) 0.09
- Delayed protons at an irregular timing induce backgrounds
  < 0.027 (< 0.05 90%CL)
- Cosmic rays suppressed 2 μs/40 ms
  e: < 0.018, μ: < 0.001
- No antiprotons (T_p < 3 GeV)



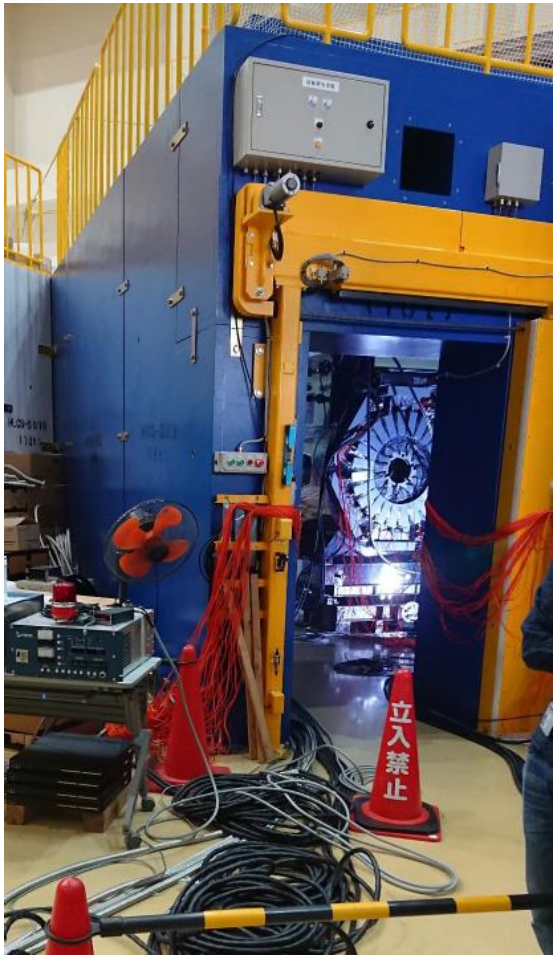
RCS 1 MW for 2×10^7 s, SiC target
BR 3×10^{-14}, delayed proton rate < 10^{-19}



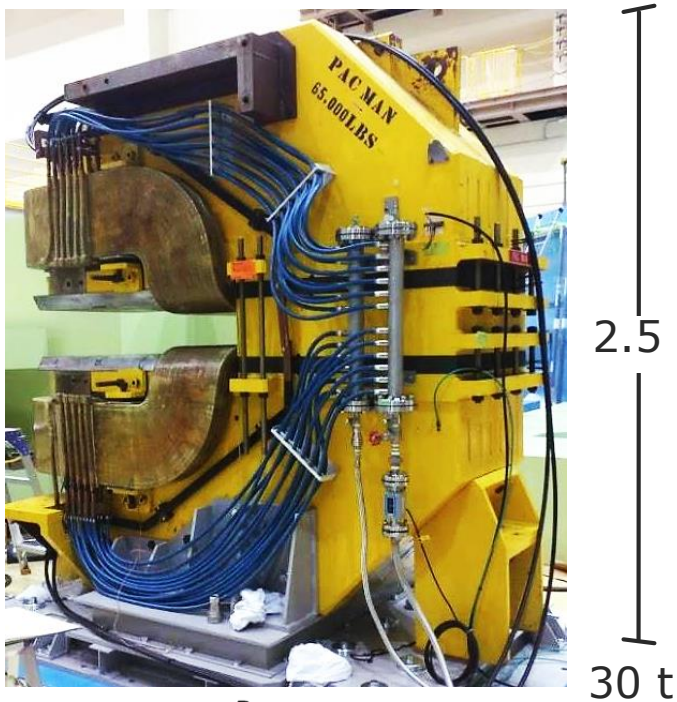
Status of Beamline, H Line at MLF



- H-line construction is ongoing
- Radiation shield built in 2016
- The spectrometer will be installed in H1 Area

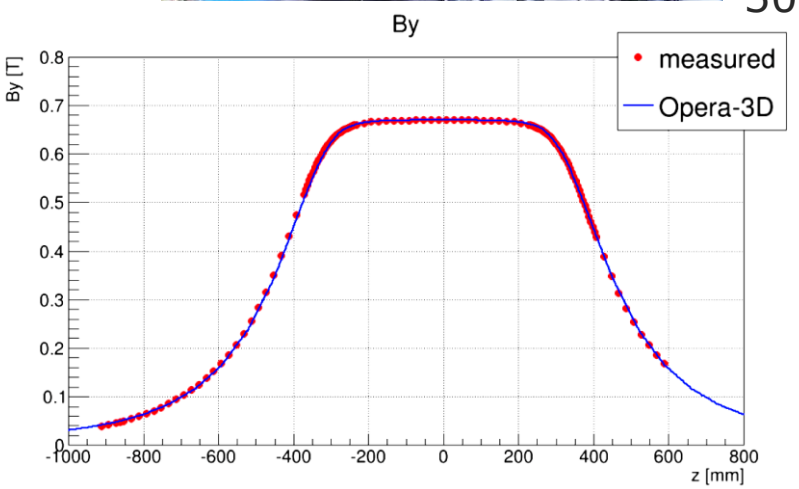


Status of Spectrometer Magnet, PACMAN



2.5 m

30 t

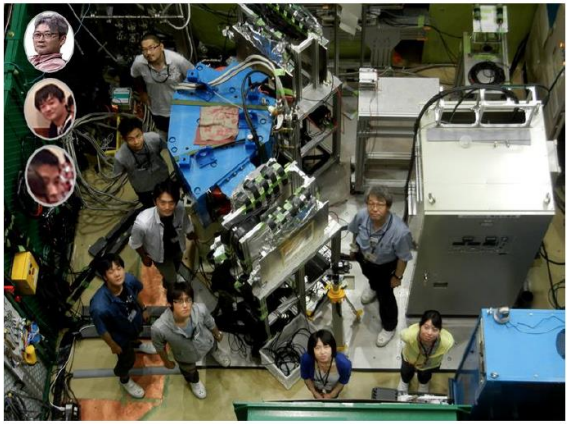


- Dipole magnet PACMAN
- Used in PIENU experiment in TRIUMF until 2012
- Shipped to J-PARC in 2014
- Nominal field strength: 0.4 T in the central part
  for electrons with 105 MeV/*c*
  bending 70 degrees
- Operation tested up to 500 A

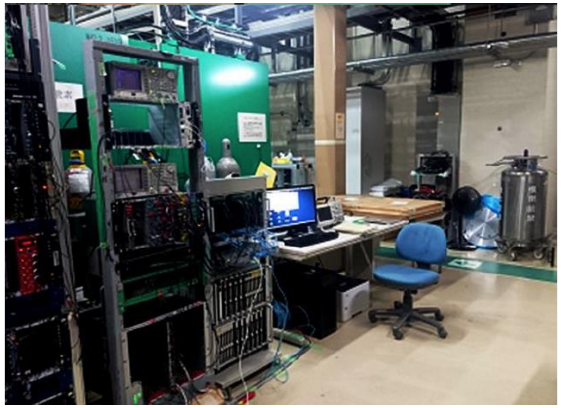
Status of Detectors

- Four MWPCs & ampls. & FADCs & DAQ work well

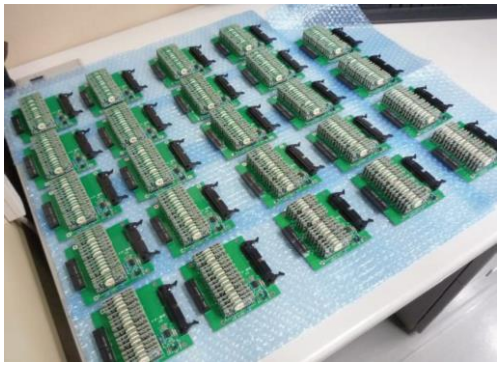
Four MWPCs manufactured in 2015-2017 are ready



DAQ efficiency ≃ 100%



Amplifiers for all channels ready



Publication on the MWPC:
Prog. Theor. Exp. Phys. 2017, 023C01

PTEP

Prog. Theor. Exp. Phys. **2017**, 023C01 (11 pages)
DOI: 10.1093/ptep/ptw193

A fast high-voltage switching multiwire proportional chamber

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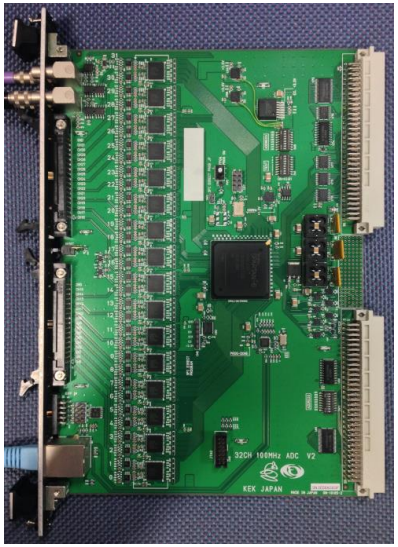
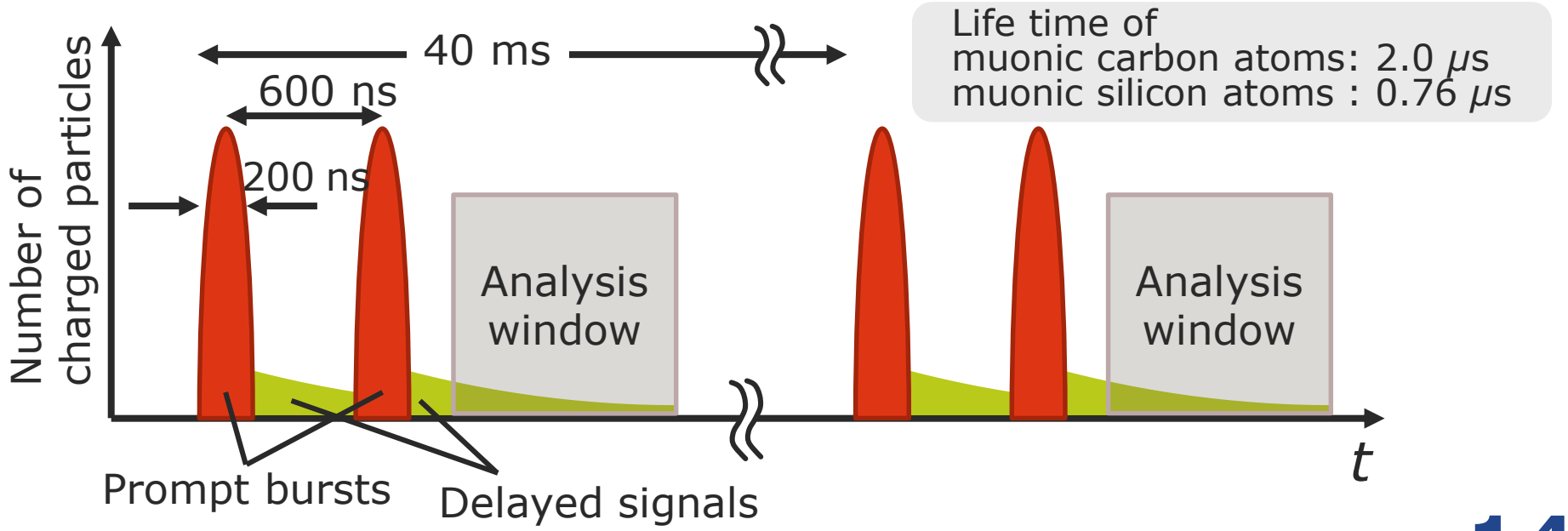


FADCs of real-time lossless compression of waveforms ready

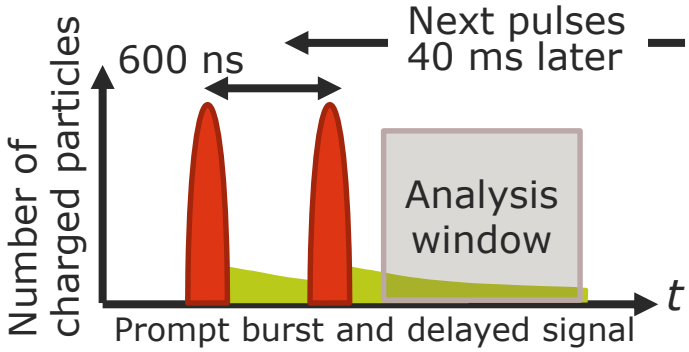
Publication on the FADC:
IEEE Trans. Nucl. Sci. 65, 2650 (2018)

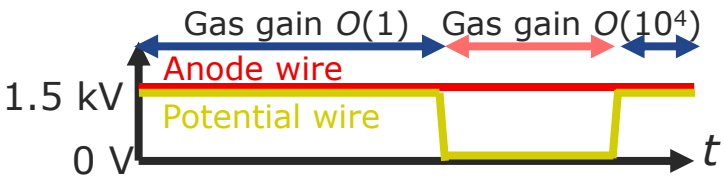
Detector Requirements

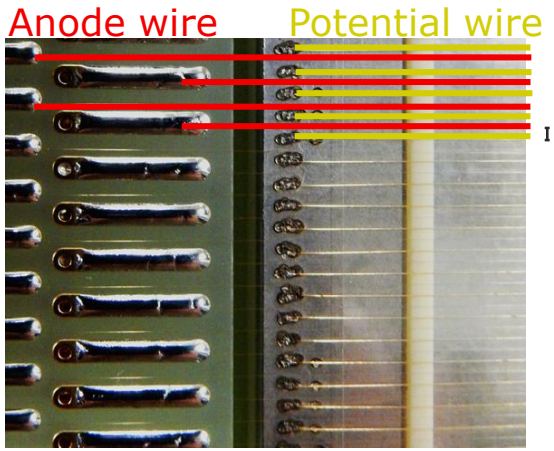
- Expected charged particles to hit the detectors
  - Prompt burst: produced by pulsed proton beams from RCS hitting the target, pass through the H Line
  - Mono-energetic delayed signal electrons: μ-e conversion
- $\approx$ 70 GHz/mm^2 (10^6 to 10^7 particles/readout) per prompt burst at most
- Need to detect a single electron soon after the prompt bursts



HV-switching MWPC to Control Gas Gain

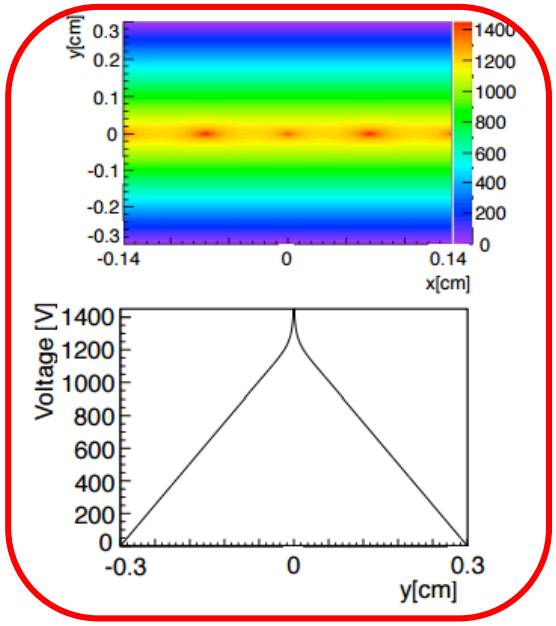




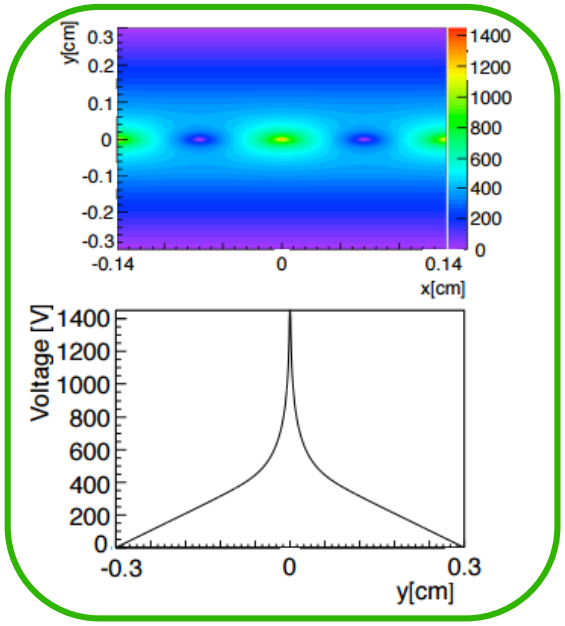


stretched alternately

Wire spacing
0.7 mm or 0.75 mm



OFF

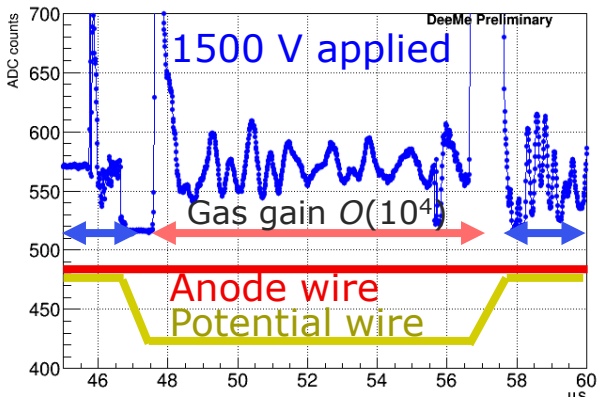


ON

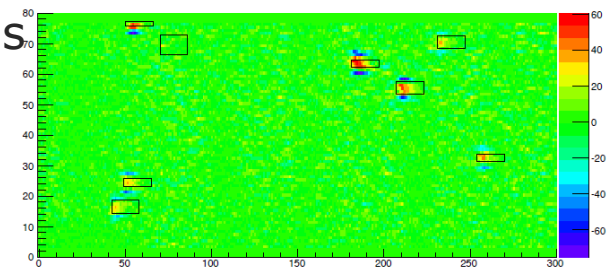
Dynamic gas-gain control by HV on the potential wires when $d_{\text{cath-wire}} \gg d_{\text{ano-po}}$

Analysis Process

- Output waveform
  - Oscillation caused by HV switching
  - Same shape in every trigger

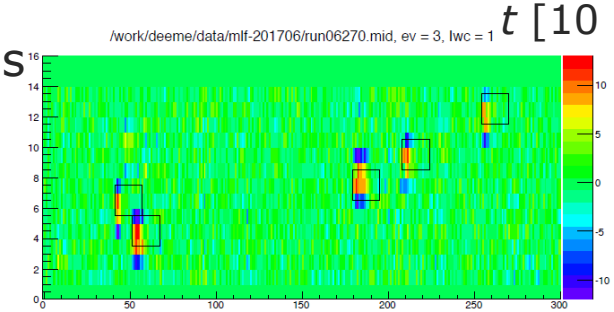


X-axis



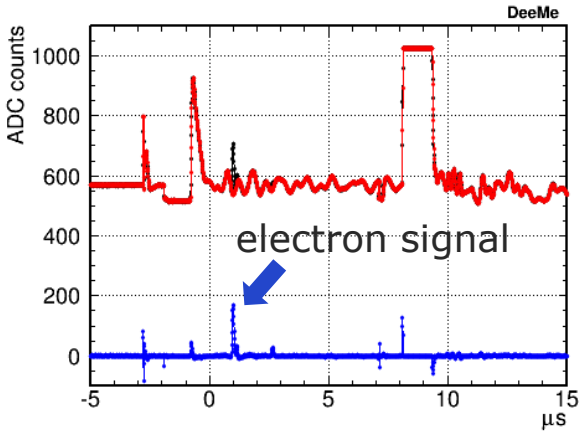
t [10 ns]

Y-axis



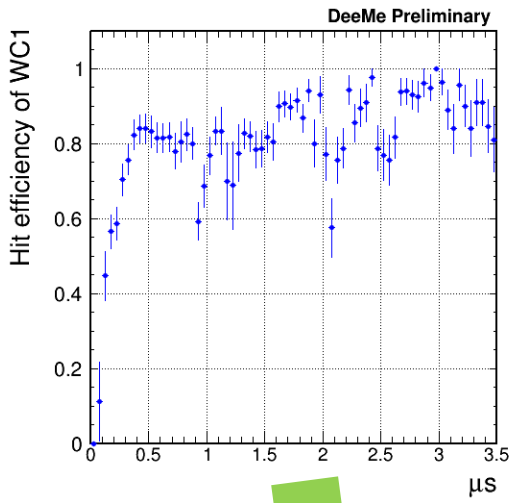
t [10 ns]

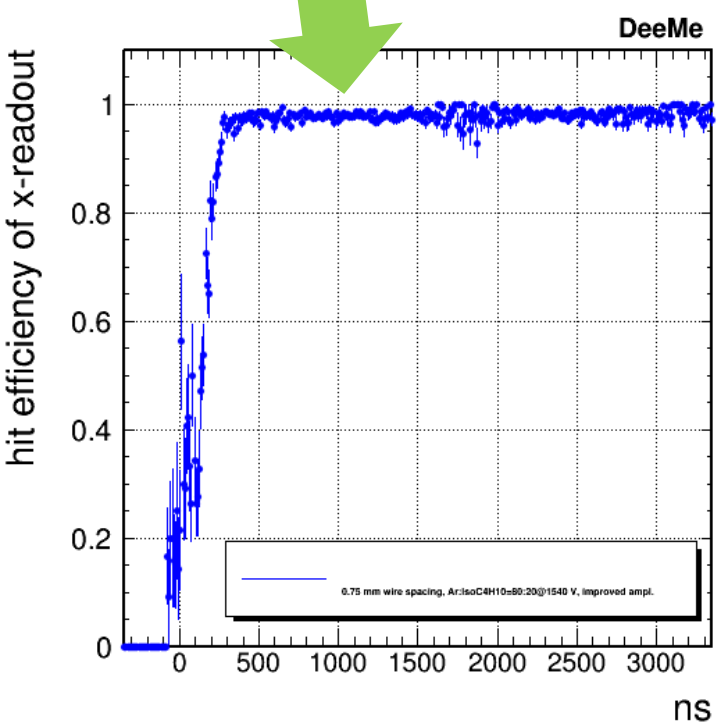
- Subtract a typical waveform (red) to find hits



- Select four hits and calculate the momentum using GENFIT: Journal of Physics: Conference Series **608** (2015) 012042

Current Status – Detector Development



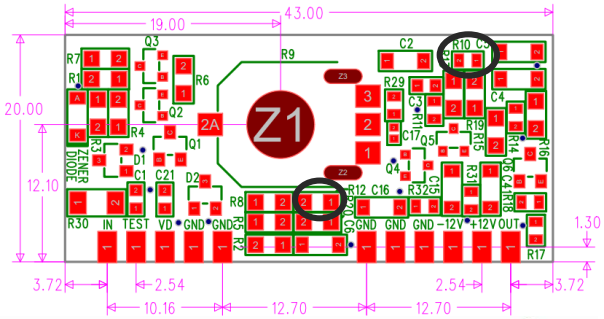


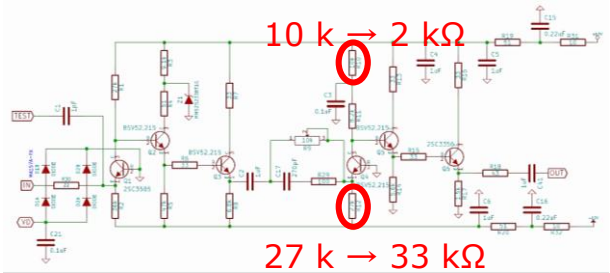
- Circuit of amplifiers was slightly modified
  - Increase the negative range
- Filling gas was changed
  - Ar (33%) C_2H_6 (67%), 1650 V applied → Ar (80%) $isoC_4H_{10}$ (20%), 1540 V applied

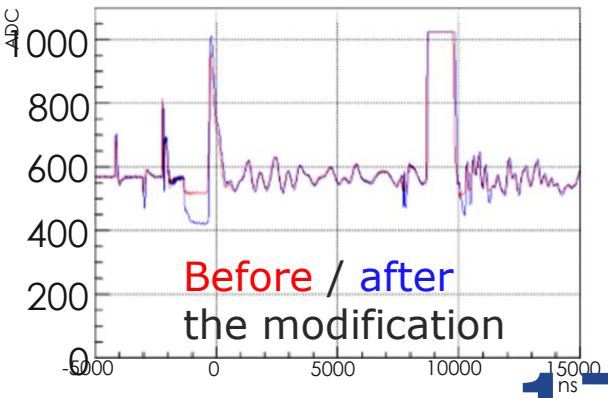
Hit efficiency improving

- 90%×90%×80%×80% ≃ 50%
- $(98\%)^4$ ≃ 90%

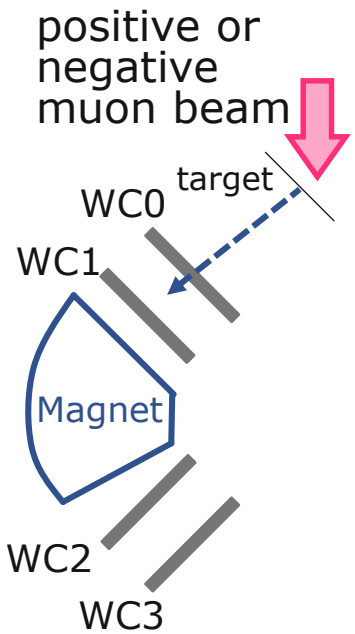
- Further optimization of the gas in progress

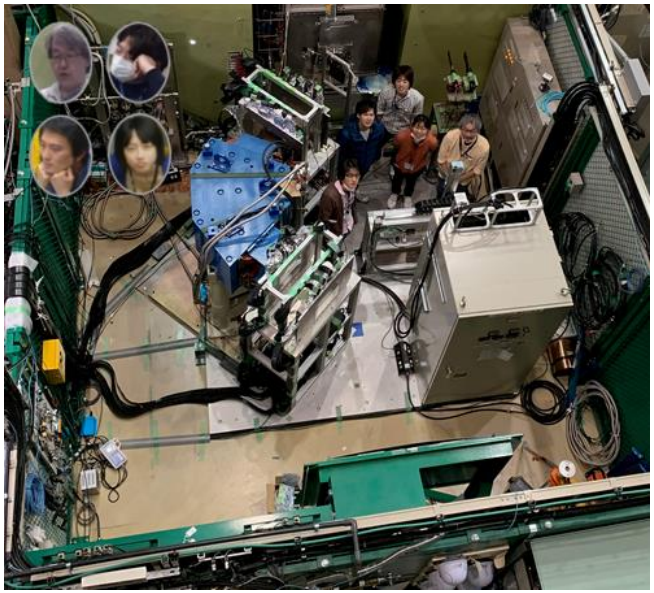






Current Status – Measurement of Muon DIO in 2019

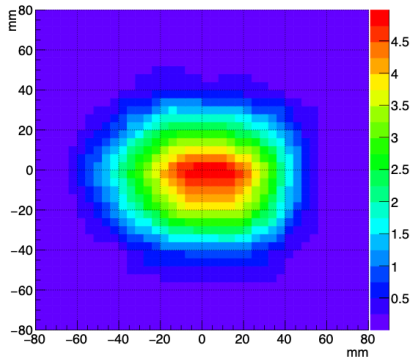




- Momentum (45 – 55 MeV/*c*) of electrons from muon DIO measurement
- D2 Area of D Line
- Mar. 7-13, 2019
- Carbon target

tracking eff. improving
Longer data taking

Measurement of
muon beam profile
using a plastic-tile scintillator + fiber



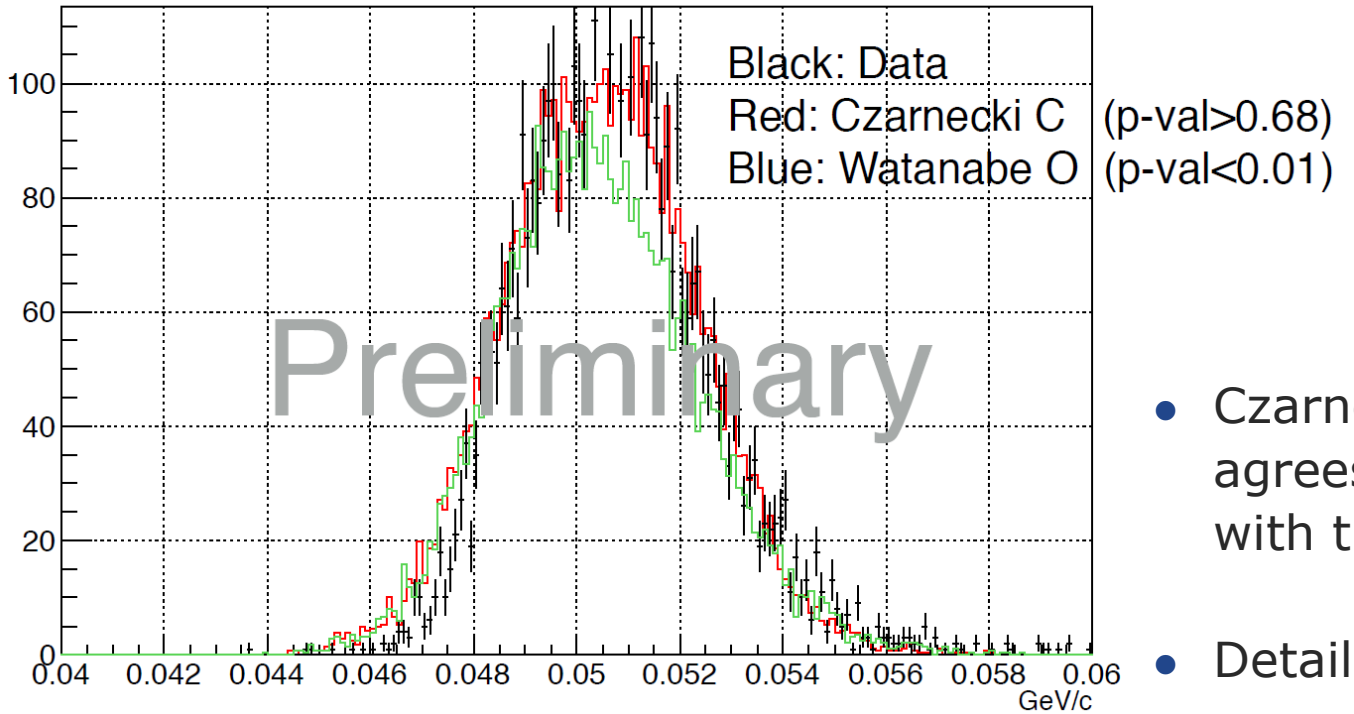
Mar. 2017 (2 days)

- 1.2×10^6 muon pulses on C, spectrometer set for 55 MeV/*c*

Jun. 2017 (5 days)

- 6.3×10^5 muon pulses on C, spectrometer set for 55 MeV/*c*

Analysis Result of Data in Jun. 2017

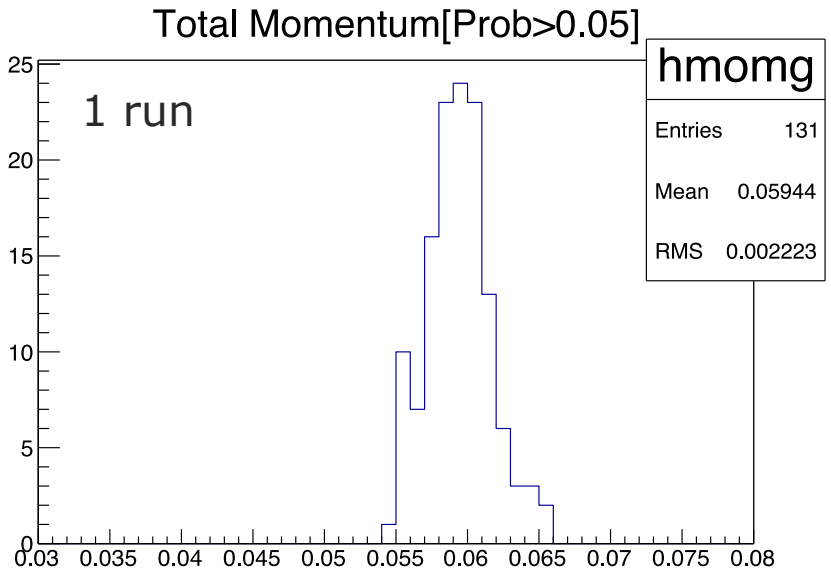


- Czarnecki-C calculation agrees well with the measurement
- Detailed analysis in progress

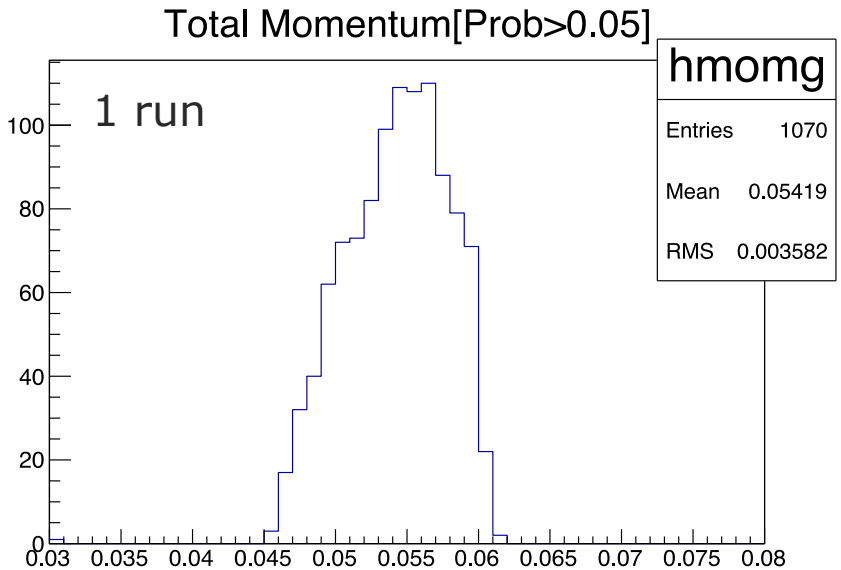
R. Watanabe, et al., Prog. Theor. Phys. 78, 114 (1987)
O. U. Shanker, Phys. Rev. D 25, 1847 (1982)
A. Czarnecki et al., Phys. Rev. D 90, 093002 (2014)

Current Status – Quick Analysis Result of Data in Mar. 2019

$\mu-$ on C, 55 MeV/c
for DIO measurement



$\mu+$ on C, 45 MeV/c
for getting acceptance curve



Mode	Jun. 2017	Mar. 2019	Ratio
Muon DIO ($\mu-$, 55 MeV/c)	5028 events (63 runs)	43769 events (346 runs)	8.7
Michel edge ($\mu+$, 52.5 MeV/c)	23 runs	35306 events (124 runs)	
Acceptance ($\mu+$, 45 MeV/c)	16062 events (46 runs)	86567 events (151 runs)	5.4

Tracking eff. improving by 1.6,
Longer data taking by 5.4

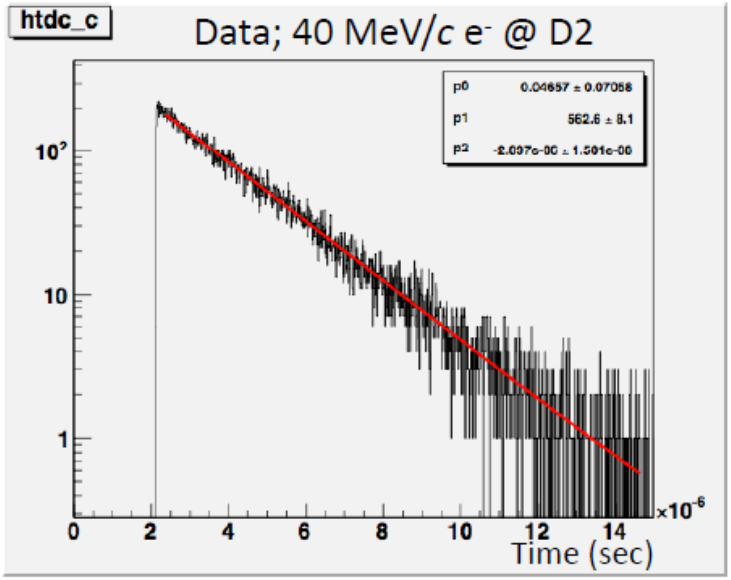
Tracking eff. improving by 1.6,
Longer data taking by 3.3

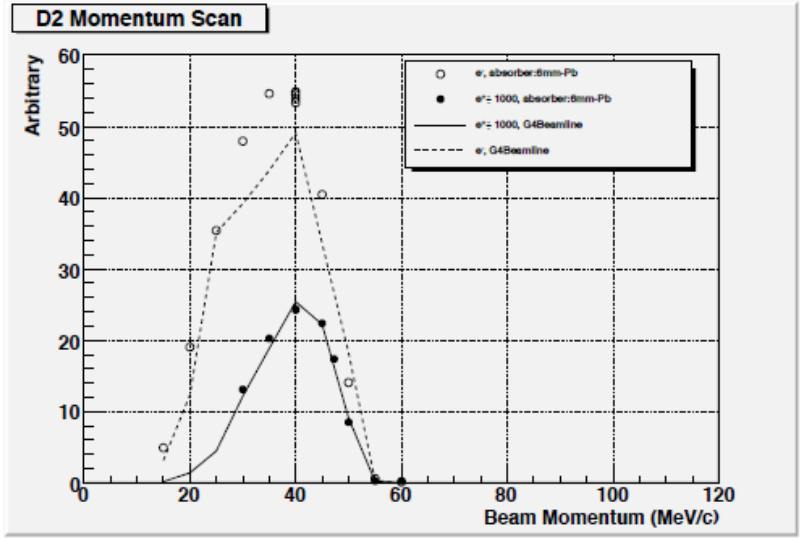
Summary

- DeeMe to search for $\mu^- \mathrm{N} \rightarrow e^- \mathrm{N}$ with a S. E. S. of 10^{-14}.
  Muon production target made of carbon (, or silicon carbide).
- The spectrometer is ready.
  - Optimizing filling gas of MWPCs for better performance.
- H-Line construction is in progress.
- Momentum (45-55 MeV/c) measurement of muon DIO from the carbon target.
  Detailed analysis ongoing.
- Plan to begin data taking for μ-e conversion soon after completing the construction of H Line.

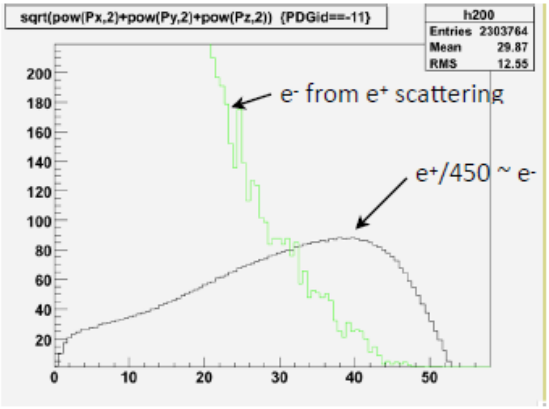
Backup

Measurement of Muonic Atom Yield



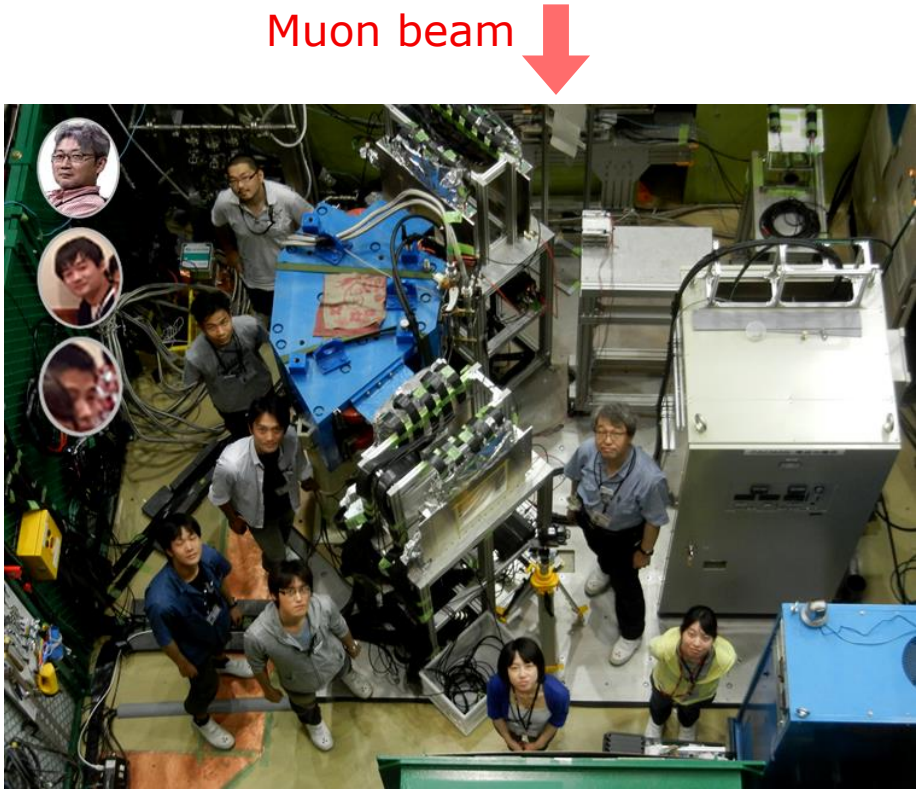


- p_e > 40 MeV/c: Dominated by e^- from μ^- decay.
- p_e ~ 50 MeV/c: Michel Edge
- p_e < 30 MeV/c: Dominated by e^- from e^+ scattering where the e^+ is coming from μ^+ Michel decay.
- → μ^- stopping rate = 5~6 × 10^9 /sec/MW in a fixed Target, confirmed.
- Good agreement with Geant4/G4Beamline Estimation.
  - 10^{10}/sec/MW for SiC Rotating-Target



Will be published!

Measurement of Muon Decay in Orbit Momentum in 2017



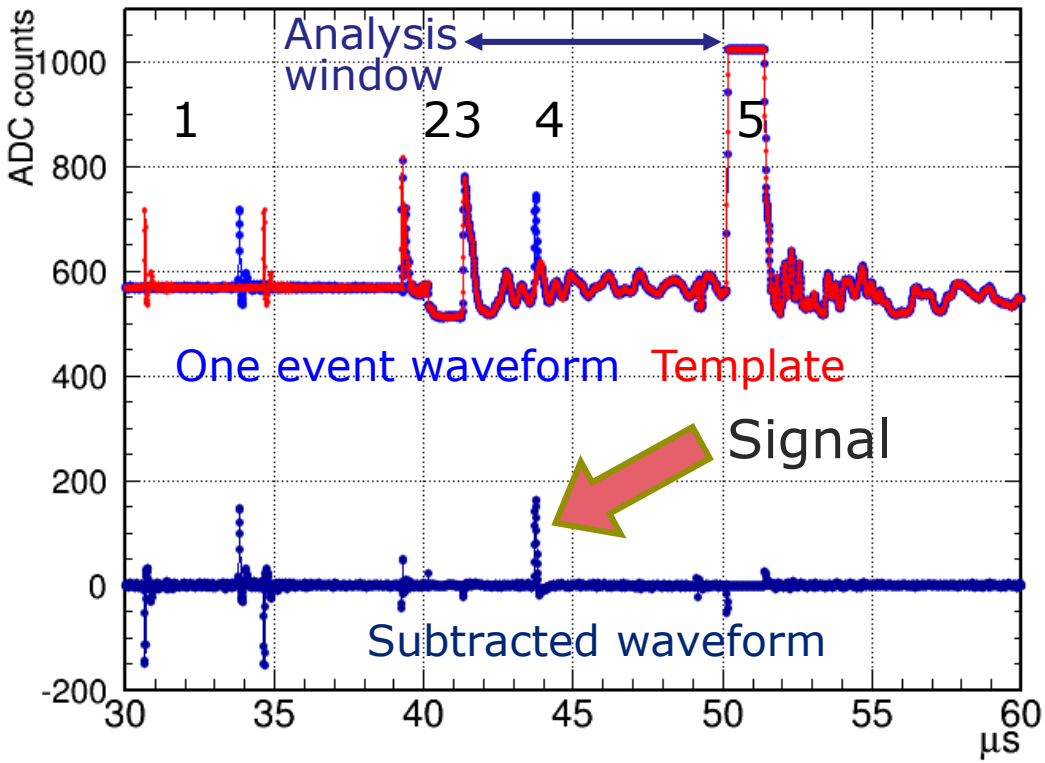
Motivation

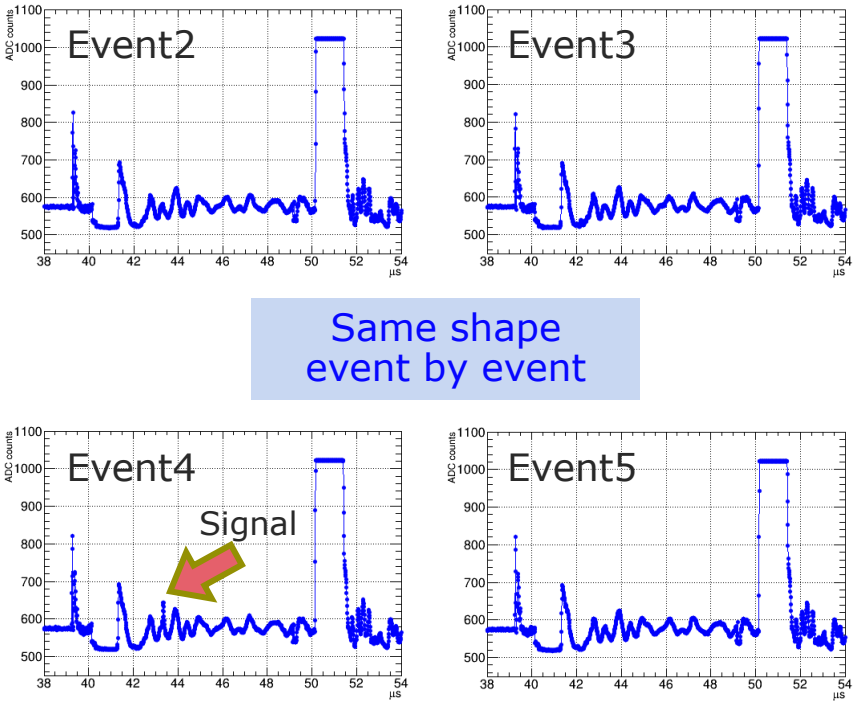
- To test magnetic spectrometer (4 MWPCs and DAQ) → worked well
- To confirm the medium-momentum region around 55 MeV/*c* of theoretical calculation by Czarnecki et al.
- At D Line up to 10^6 muons/s
- Measured the medium-region momentum spectrum of electrons from $\mu^- \rightarrow e^- \nu_\mu \overline{\nu}_e$
- Target: C, Si and SiC
- 2 days in Mar. 2017
- 5 days in Jun. 2017

Analysis of DIO Measurement

- Subtract a template from waveforms
- Sum up sample points in the time and strip direction

Test pulse[1], HV ramp down on potential wires[2], over shoot by PZC circuit[3], detector oscillation[4], HV ramp up on potential wires[5]



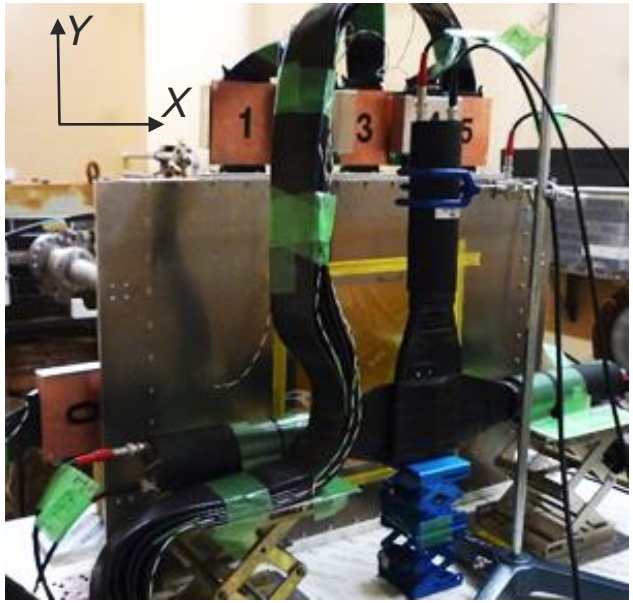


Same shape event by event

Detector Structure

MWPC

- Cathode strip readout
- X-axis readout 3 mm width strip
- Y-axis readout 5×3 mm width strip
- Active area: 250 mm×200 mm



Readout electronics

- Amplifiers with large current tolerance
- 10-bit FADCs
  with a sampling rate of 100 MHz

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