Status of the DeeMe Experiment to search for μ-e Conversion at J-PARC MLF

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

Natsuki TESHIMA
Osaka City University NITEP

The 22nd International Workshop
on Neutrinos from Accelerators (NuFact2021)

Cagliari, Italy / online hybrid

The DeeMe Experiment

M. Aoki [1], D. Bryman [2], K. Hase [7], Y. Higashino [1],
M. Ikegami [3], Y. Irie [3], S. Ito [12], N. Kawamura [3], M. Kinsho [4],
S. Makimura [3], S. Meigo [4], T. Mibe [3], S. Mihara [3], Y. Miyake [3], D. Nagao [1],
Y. Nakatsugawa [5], H. Natori [3], H. Nishiguchi [3], T. Numao [6], C. Ohomori [3],
P. K. Saha [4], N. Saito [3], Y. Seiya [7], K. Shigaki [9], K. Shimomura [3],
P. Strasser [3], K. Sugita [1], N. Teshima [7,8], N. D. Thong [10],
N. M. Truong [11], T. Uematsu [7], K. Yamamoto [3], K. Yamamoto [7],
T. Yamazaki [3], M. Yoshii [3], K. Yoshimura [12]

(1) Osaka University (2) UBC (3) KEK (4) JAEA (5) IHEP (6) TRIUMF
(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

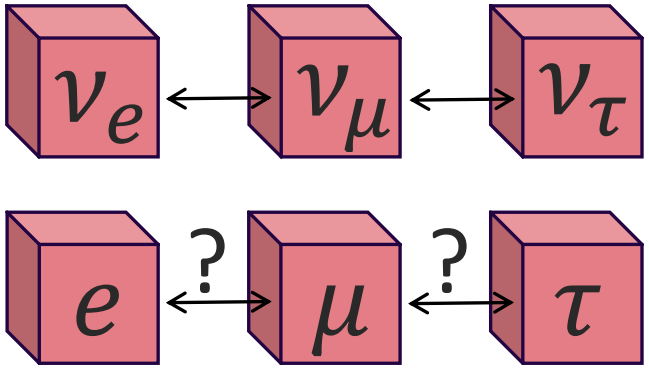
DeeMe Experiment

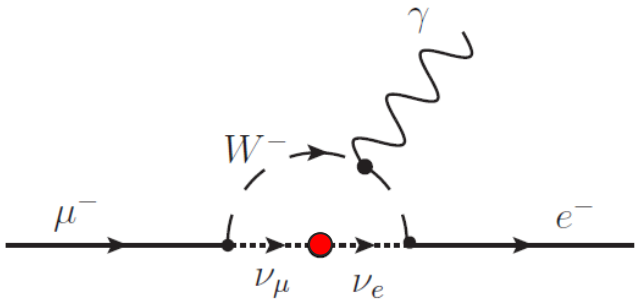
- Search for charged lepton flavor violating decay
  $\mu^- \mathrm{N} \rightarrow e^- \mathrm{N}$

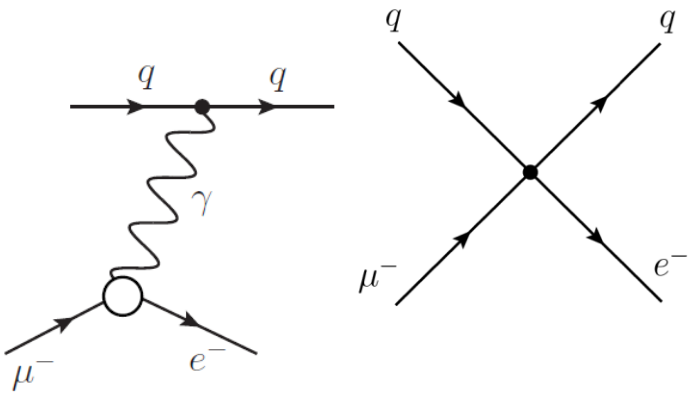
This talk

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

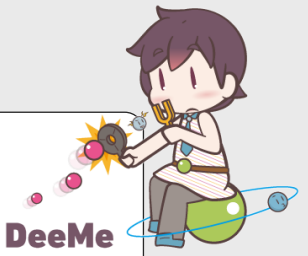
Charged Lepton Flavor Violation and New Physics







- Charged Lepton Flavor Violation (cLFV)
  - $\mu\mathrm{N} \rightarrow e\mathrm{N}, \mu \rightarrow e\gamma, \mu \rightarrow eee, \ldots$
- Branching ratio for $\mu \rightarrow e\gamma$ 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) $\mu^- \rightarrow e^- \nu_\mu \overline{\nu}_e$

  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

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

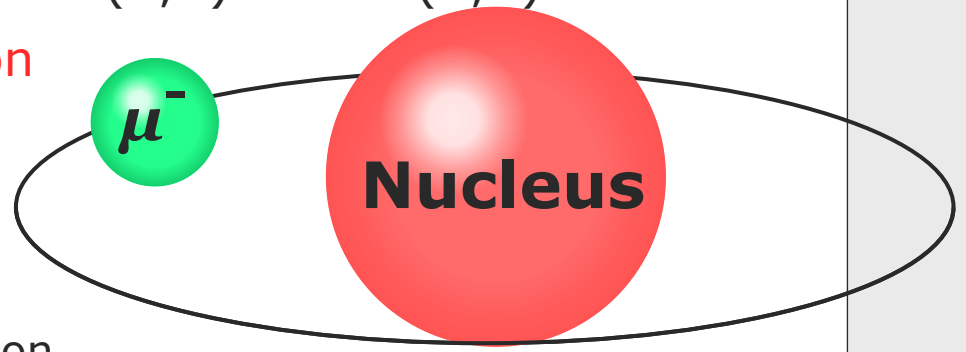
- Muon to electron conversion $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$

  Charged lepton flavor violation

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

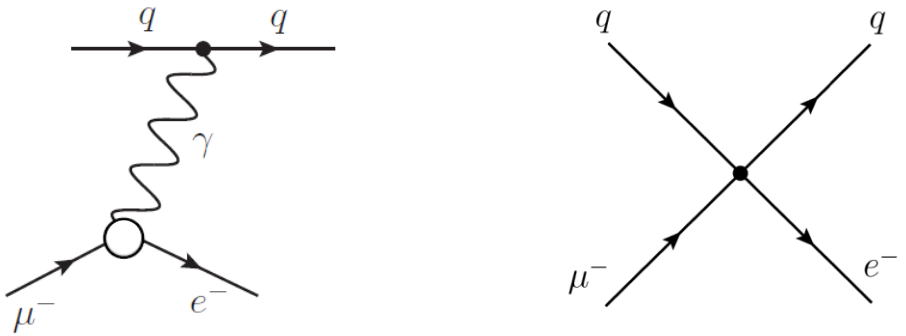
Search for cLFV in Photonic and Non-photonic Decays

- Possible processes for cLFV can be classified

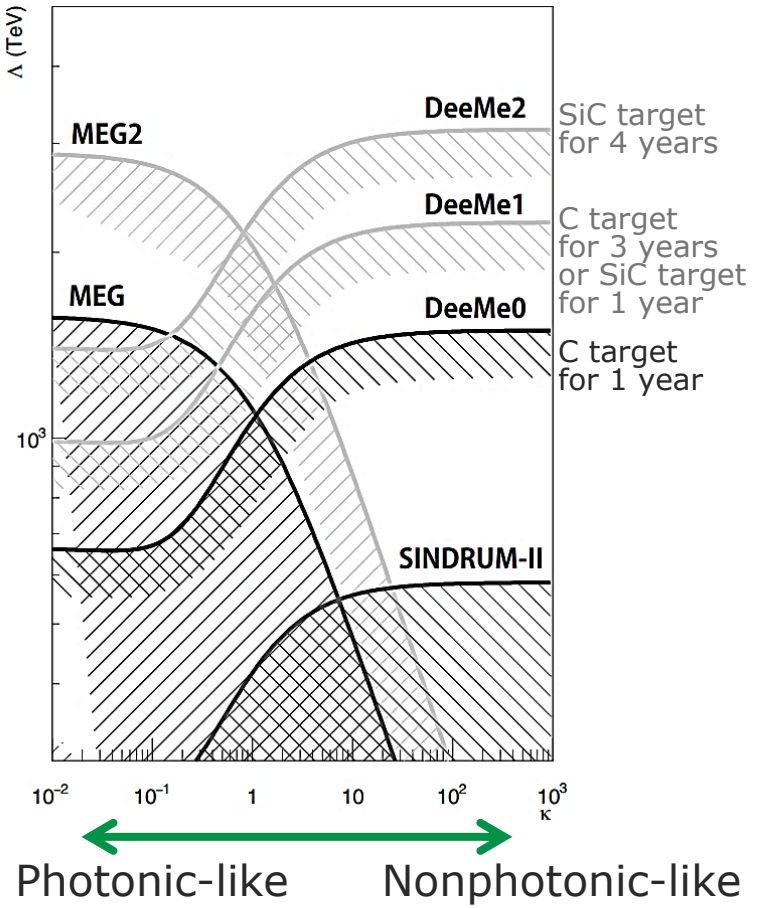
Photonic

Non-photonic

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



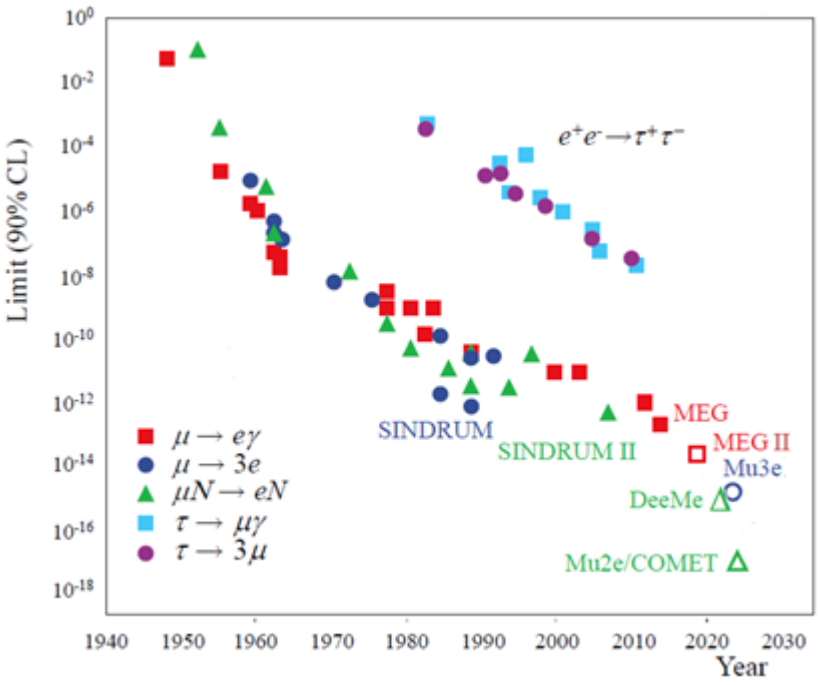
Branching ratio for $\mu\,\mathrm{N} \to e\,\mathrm{N}$
$\approx$ 1/100 of that for $\mu \to e\gamma$



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

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

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)

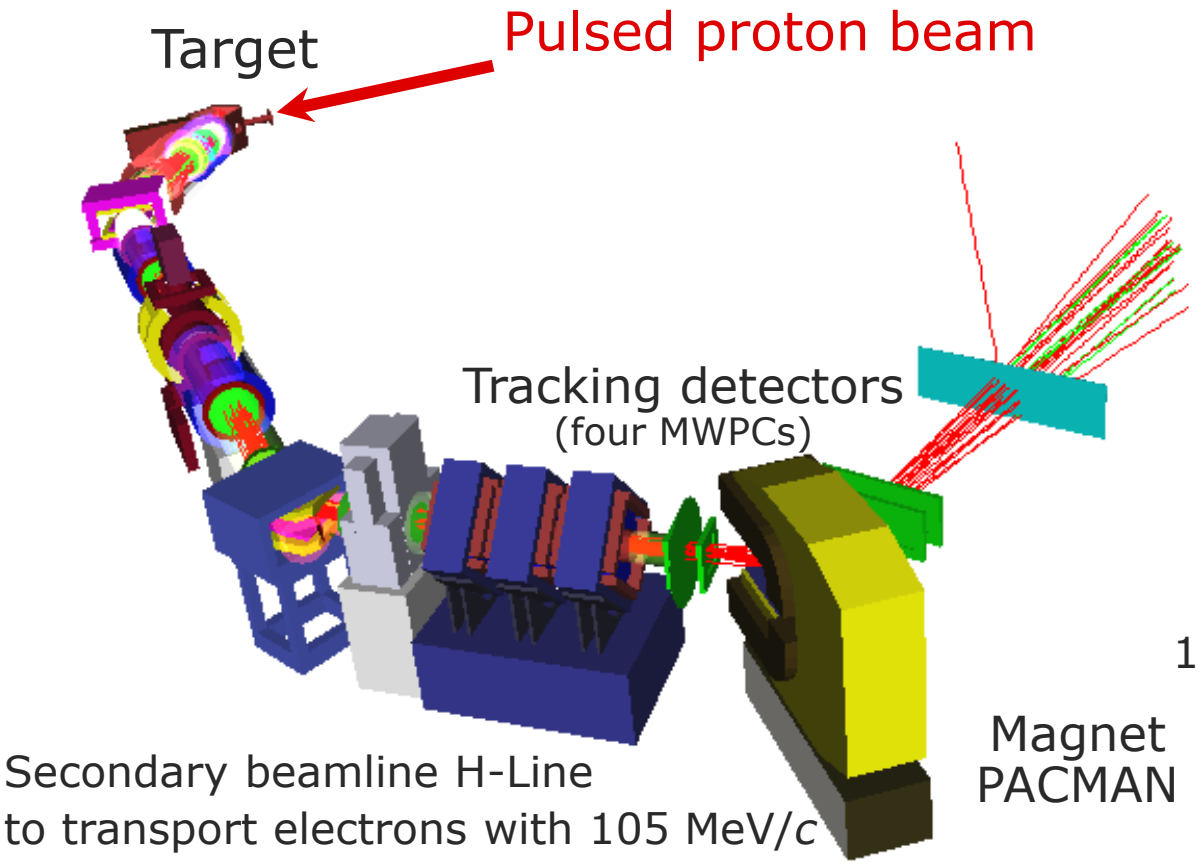
to observe the CLFV
or to improve the current limit
by ×10 or ×100

Places of Experiments

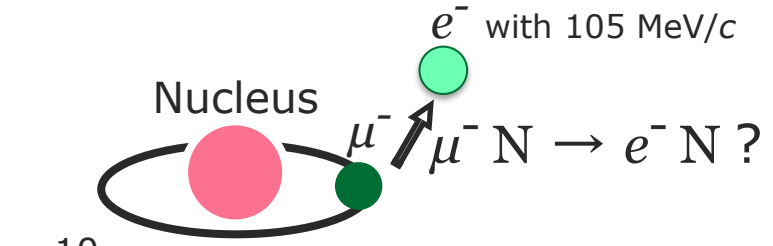
- DeeMe will be conducted at J-PARC Materials and Life Science Experimental Facility MUSE in Tokai Village, Japan
- Takes 1.5 hours by express train from Tokyo

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

Experimental Concept



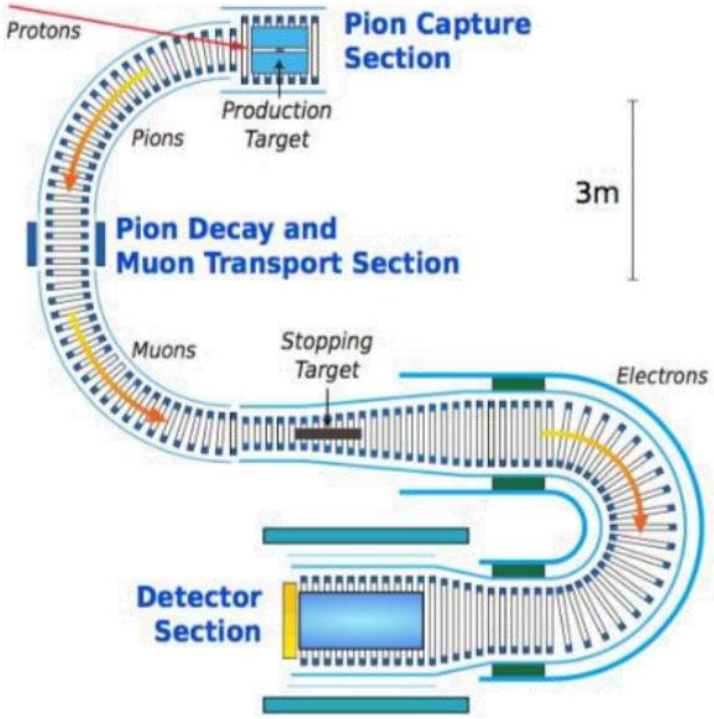
1. π^- production
2. π^- decay-in-flight into μ^-
3. Muonic atom formation



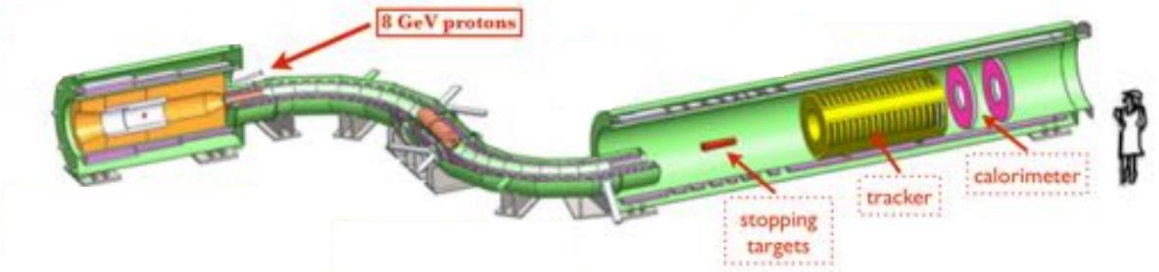
10^{10} muonic atoms/sec
with RCS 1 MW

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

COMET at J-PARC



Mu2e at Fermilab

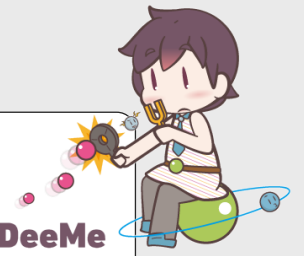


In larger-scale experiments,

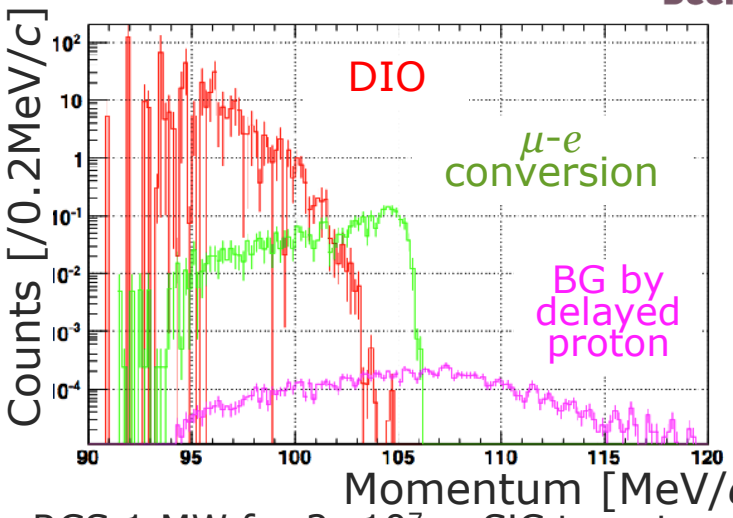
- Pion production target
- Pion decay and muon transport section
- Muon stopping target

- Detectors

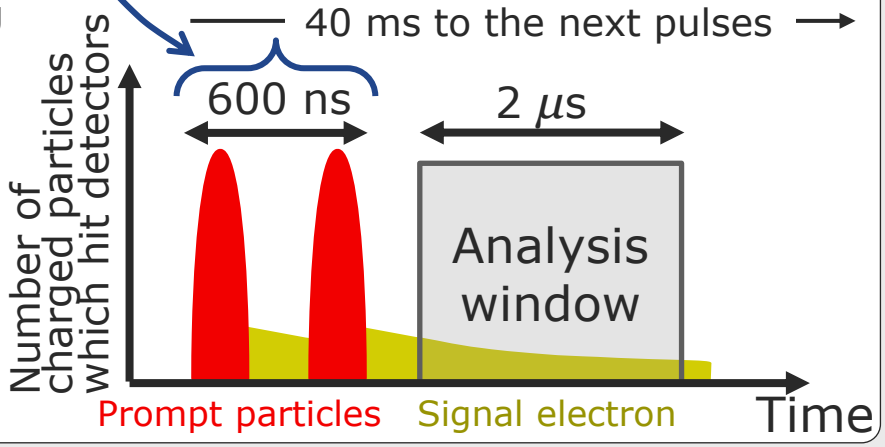
Backgrounds



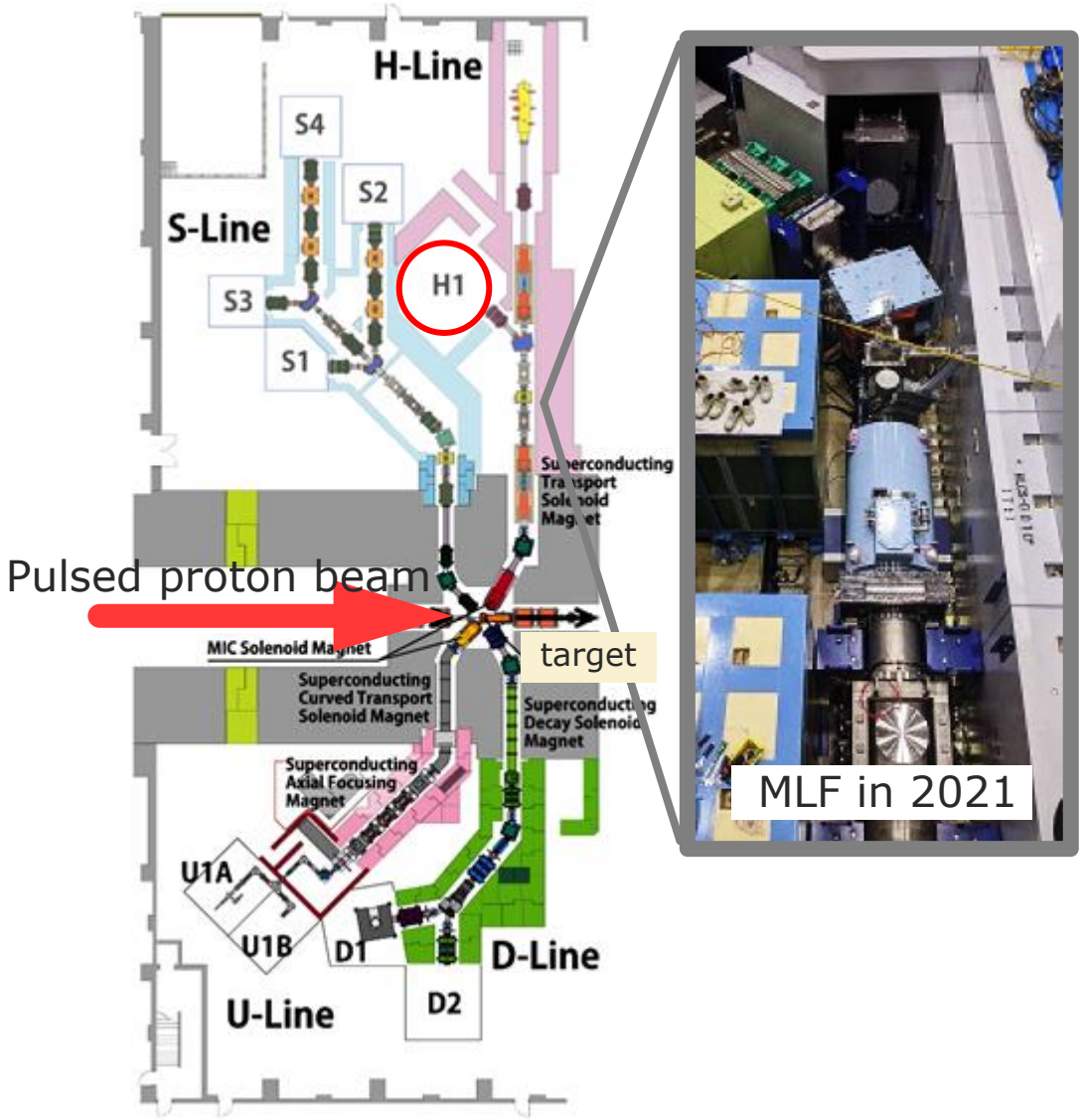
- Low-momentum background
  suppressed by the beamline
- High-momentum tail
  → need Δp < 0.5% spectrometer
- Beam pion capture
  $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$,
  $\gamma \rightarrow e^+ e^-$ at the beam-prompt timing
- Muon Decay in Orbit (DIO) 0.09
- Delayed protons 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}

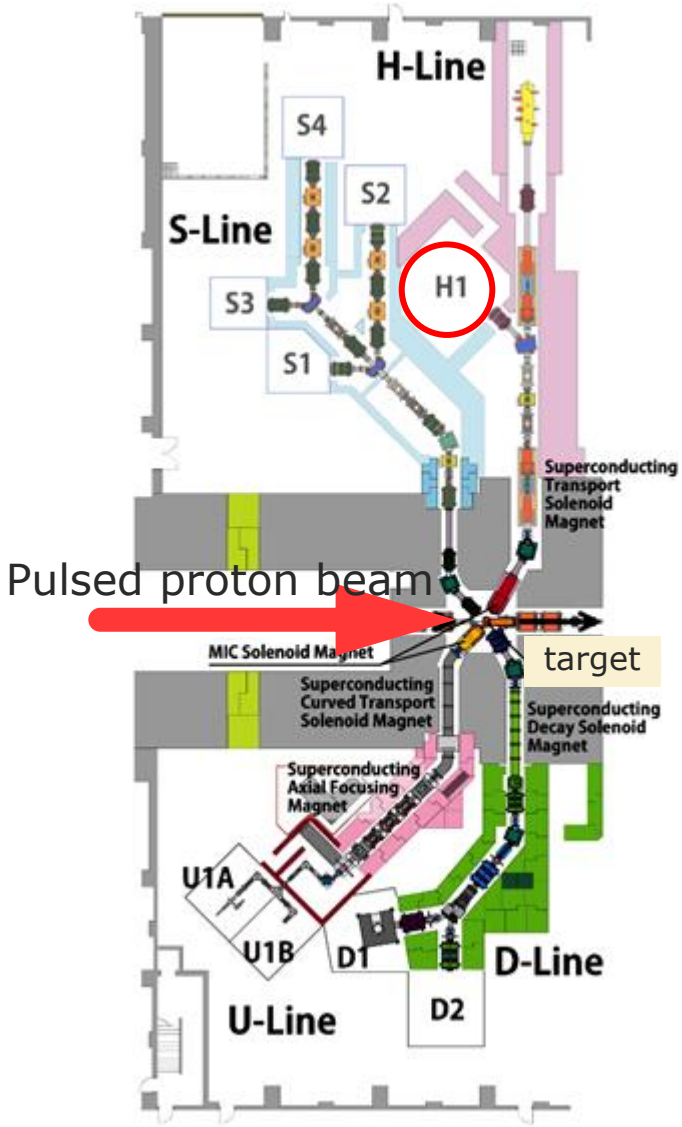


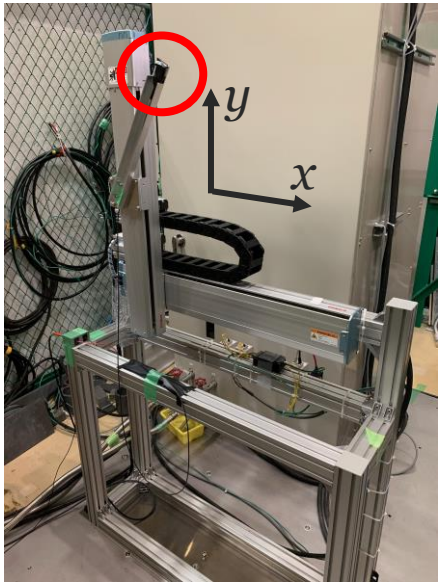
Status of Beamline, H Line at MLF

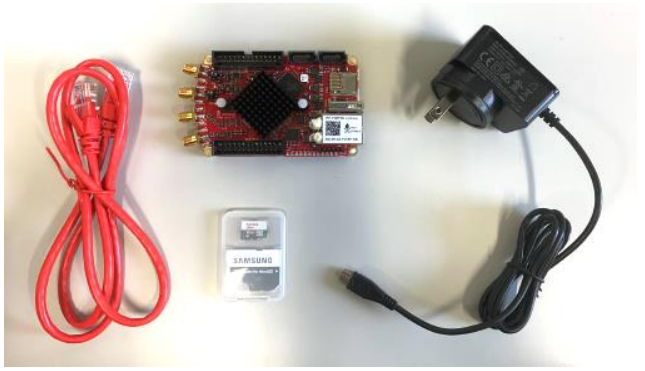


- Good progress in H Line construction
- Beam will come out after next January
- The spectrometer will be installed in H1 Area

Status of Beamline, H Line at MLF





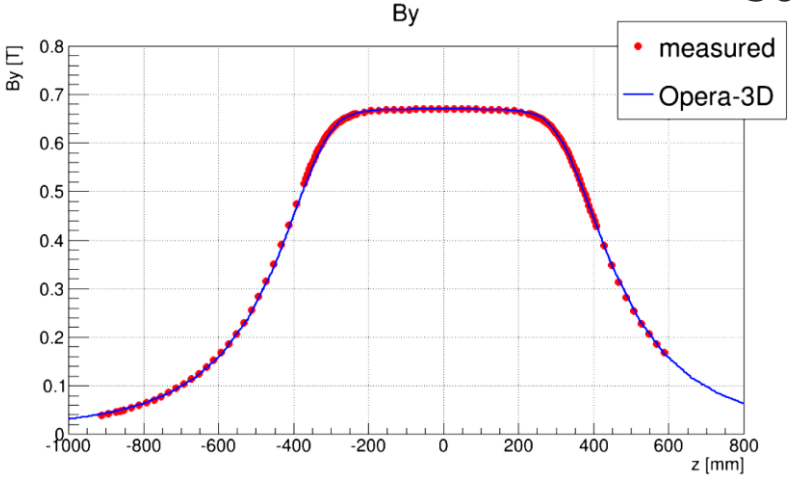


- 2-axis robot will be used for beam profile scanning
- Acrylic counter at the end of the arm
- Development of a system for waveform recording by Red Pitaya is ongoing

Status of Spectrometer Magnet, PACMAN

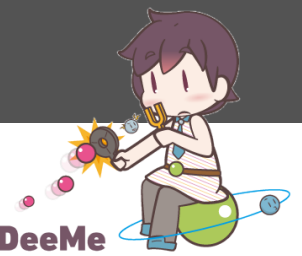
2.5 m

30 t

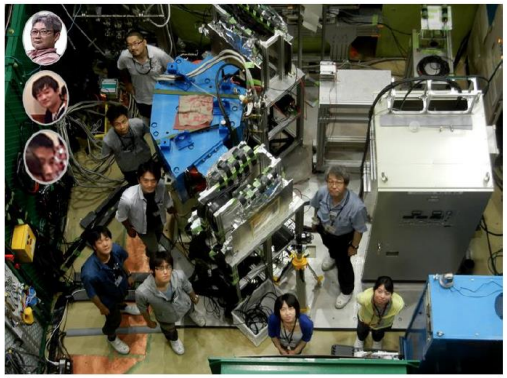


- Dipole magnet PACMAN
- Used in PIENU experiment in TRIUMF until 2012
- Shipped to J-PARC in 2014
- Nominal field strength: 0.4 T in the central part
  for electrons with 105 MeV/*c* bending 70 degrees
- Operation tested up to 500 A

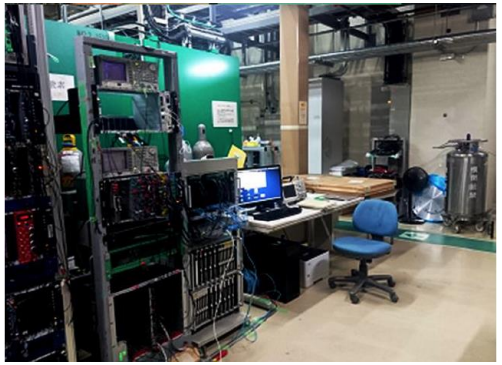
Status of Tracking Detectors



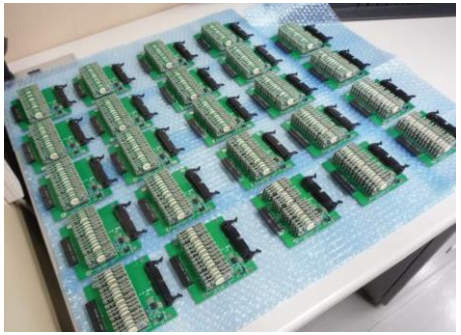
Four MWPCs manufactured in 2015-2017 are ready



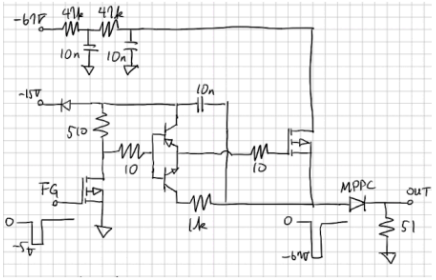
DAQ efficiency ≃ 100%



Amplifiers for all channels ready



Publication on the MWPC:
Prog. Theor. Exp. Phys. 2017, 023C01 (2017)
Nucl. Instrum. Meth. A, 999, 165228 (2021)



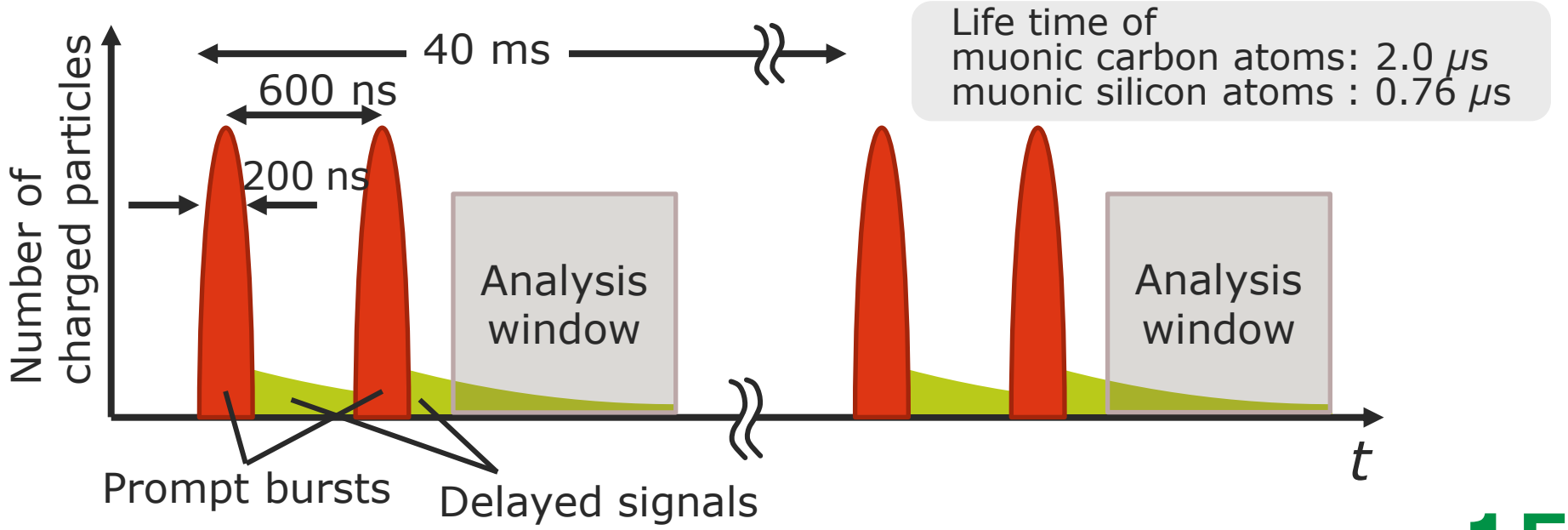
Unique scinti-fiber + MPPC detector with switchable applied voltage

FADCs of real-time lossless compression of waveforms ready

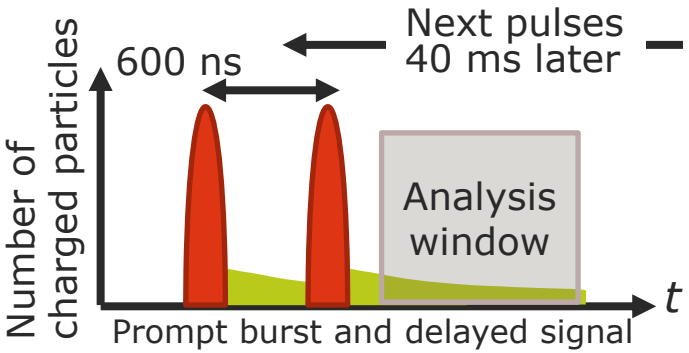
Publication on the FADC:
IEEE Trans. Nucl. Sci. 65, 2650 (2018)

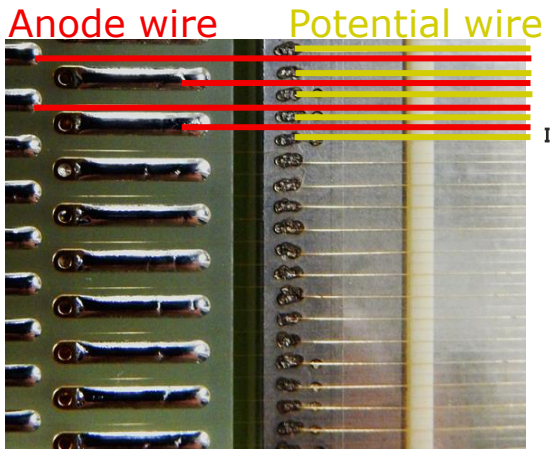
Detector Requirements

- 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



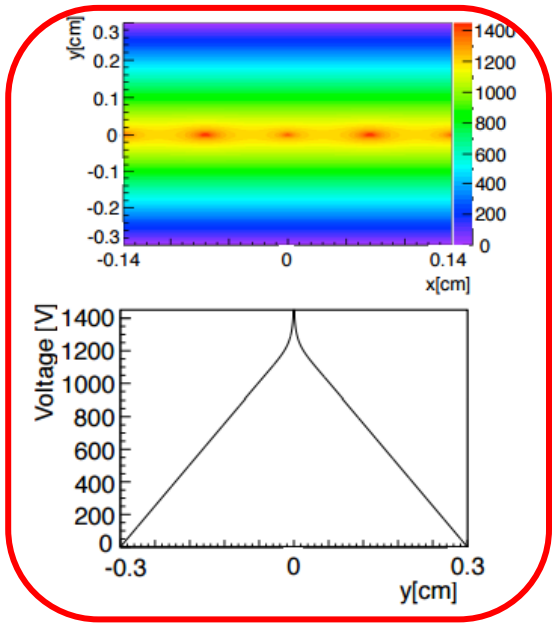
HV-switching MWPC to Control Gas Gain



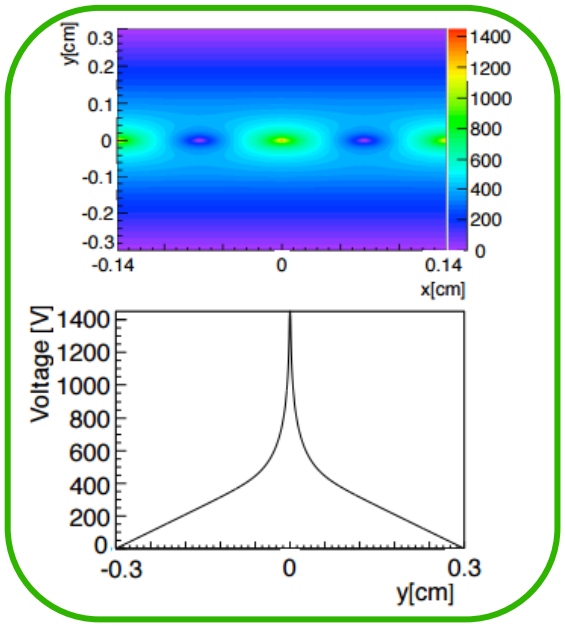


stretched alternately

Wire spacing
0.7 mm or 0.75 mm



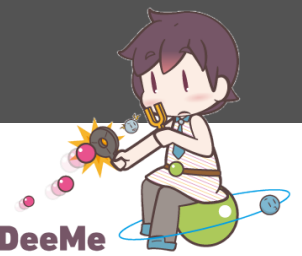
OFF



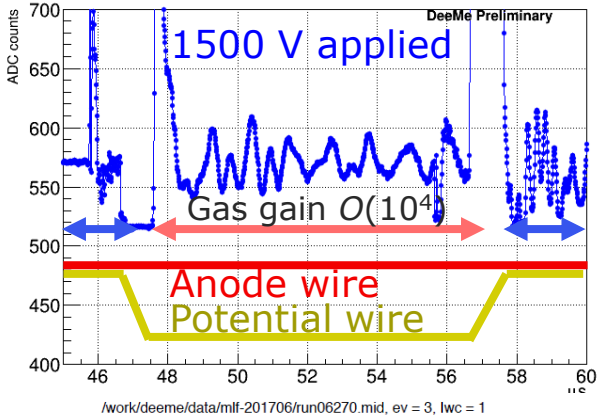
ON

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

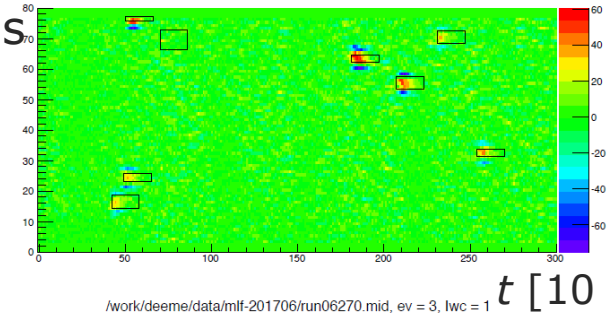
Analysis Process



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

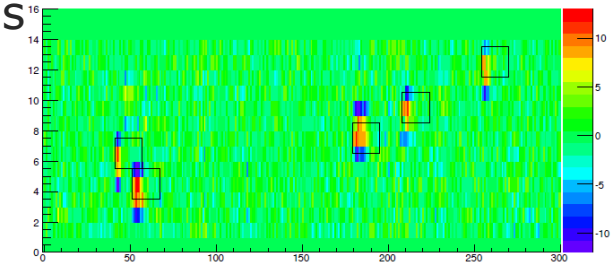


X-axis



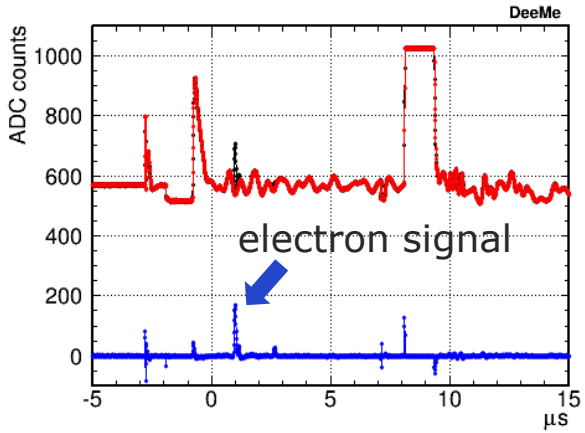
t [10 ns]

Y-axis



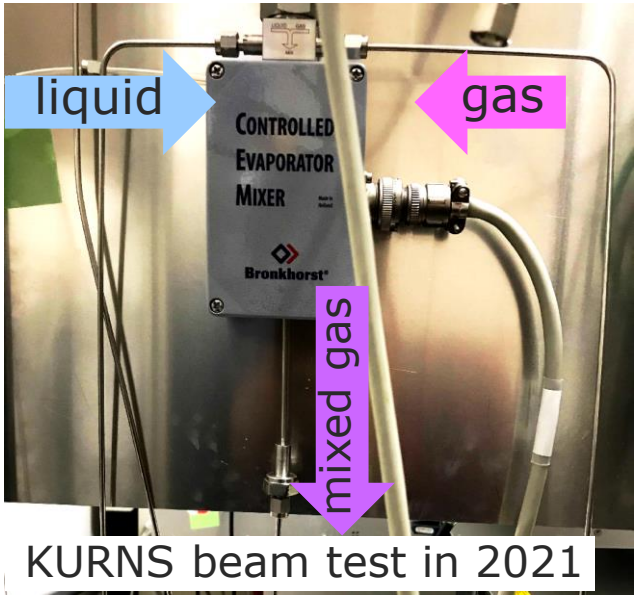
t [10 ns]

- Subtract a typical waveform (red) to find hits



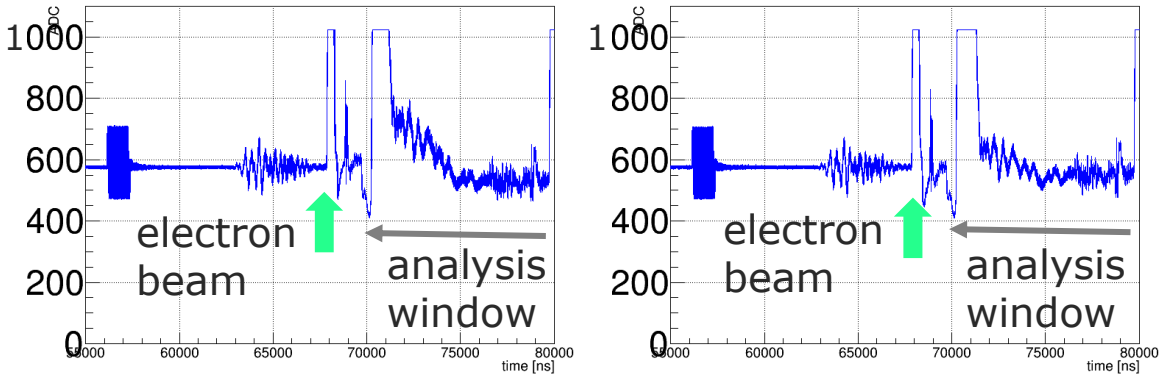
- Select four hits and calculate the momentum using GENFIT:
  Journal of Physics: Conference Series **608** (2015) 012042

Current Status – Detector Development



KURNS beam test in 2021

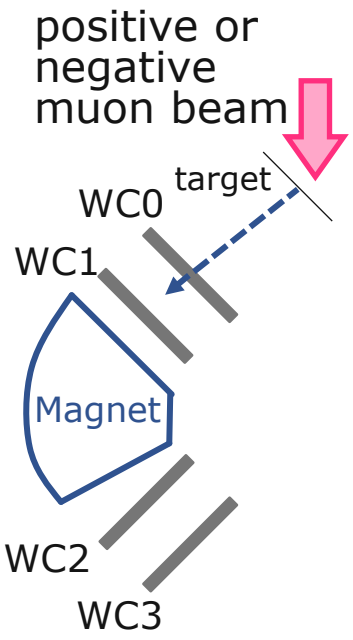
Overlaying 100 waveforms

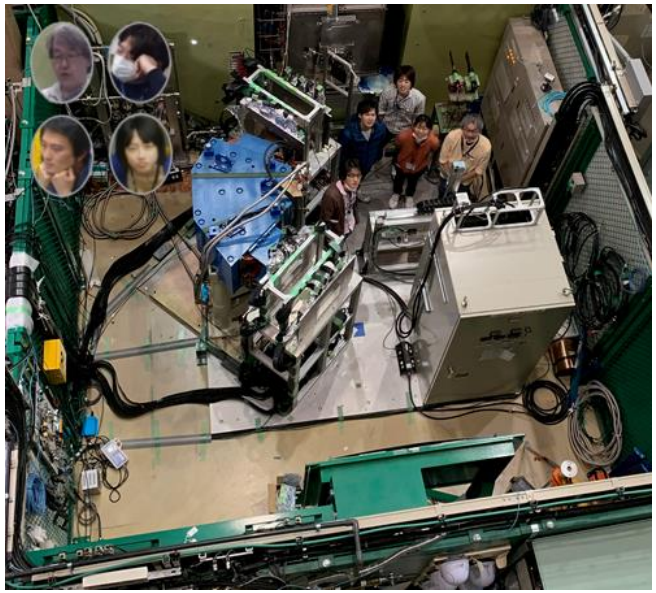


Controller for liquid mass flow and temperature

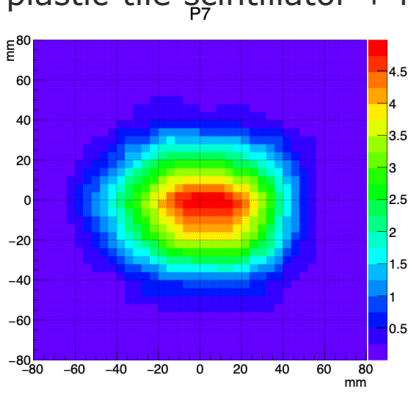
- Need to suppress delayed noise that occurs after the hitting of prompt charged particles
- Tested adding methylal to Ar + $isoC_4H_{10}$ gas
- Simulating the effect of accidental coincidence in H1 Area

Current Status – Measurement of Muon DIO





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



- 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

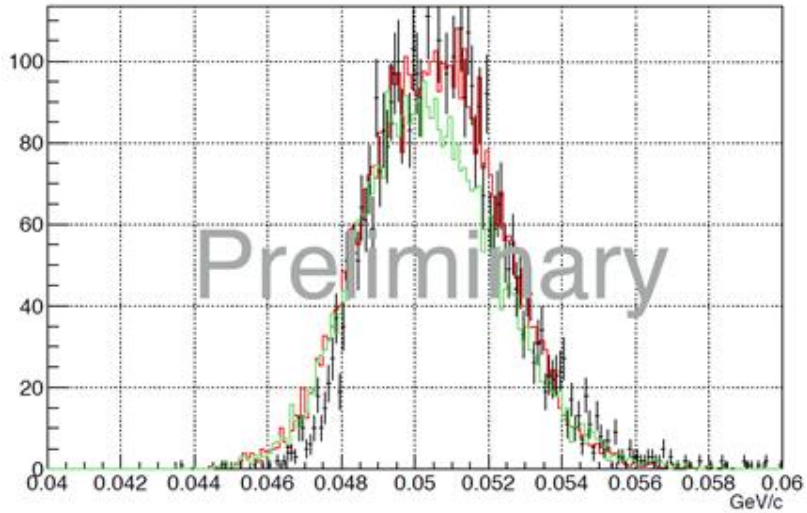
Mar. 2017 (2 days)

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

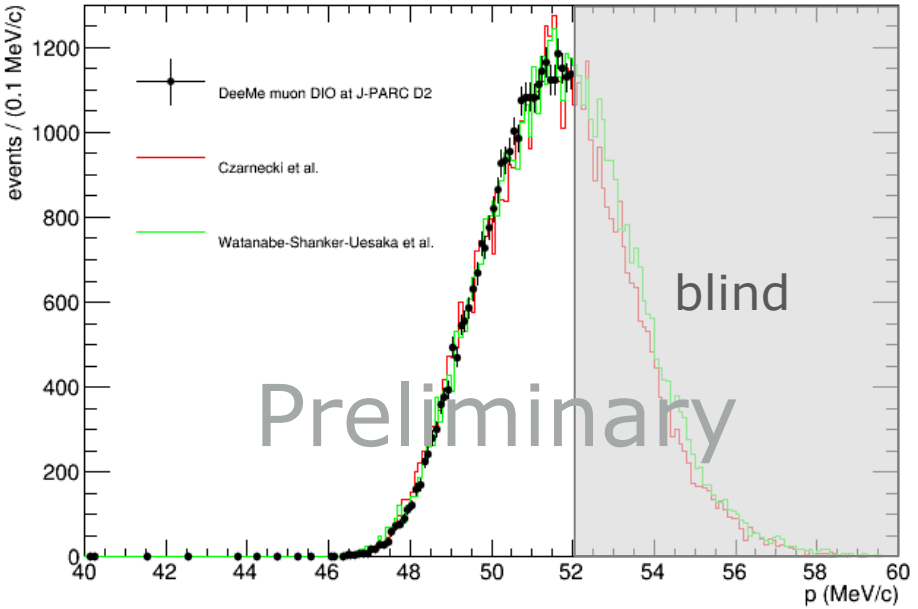
Jun. 2017 (5 days)

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

Analysis Result of Data at J-PARC MLF D Line

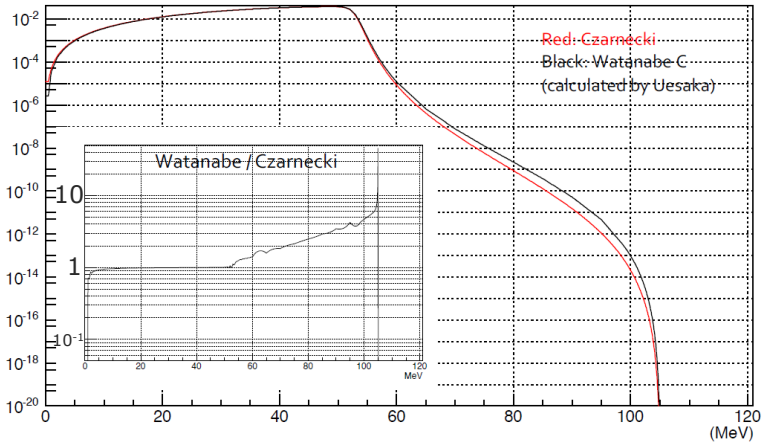


Measurement in 2017



Measurement in 2019

- Improved detection efficiency
  led to better statistics from 2017
- Studying analysis tools
  to prepare for the experiment in H1 Area



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Sept. 8th, 2021

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
- H Line has been built
  - Beams will be available after January of next year
- Data acquisition will start next year

- Feel free to contact
  teshima@hep.sci.osaka-cu.ac.jp

Backup