DeeMe Experiment

Search for Muon to Electron Conversion at J-PARC MLF

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For the DeeMe Collaboration

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

The 19th International Workshop
on Neutrinos from Accelerators (NUFACT2017)

Uppsala University, Sweden

DeeMe Collaboration

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(6) IHEP
(7) IBS
(8) TRIUMF
(9) PSI
(10) Okayama University

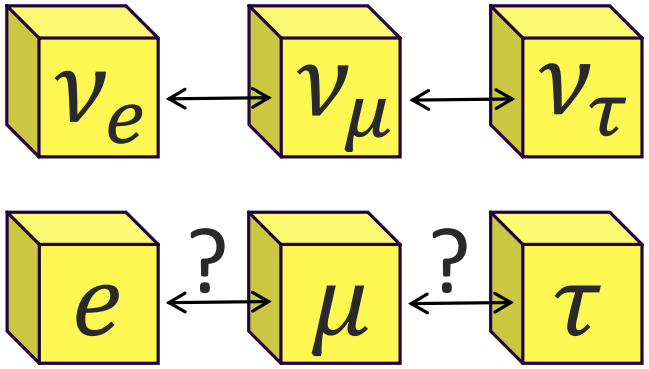
DeeMe Experiment

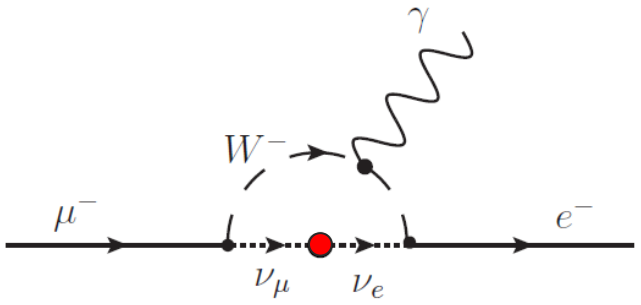
- Search for charged lepton flavor violating decay
  $\mu^- \mathrm{N} \rightarrow e^- \mathrm{N}$

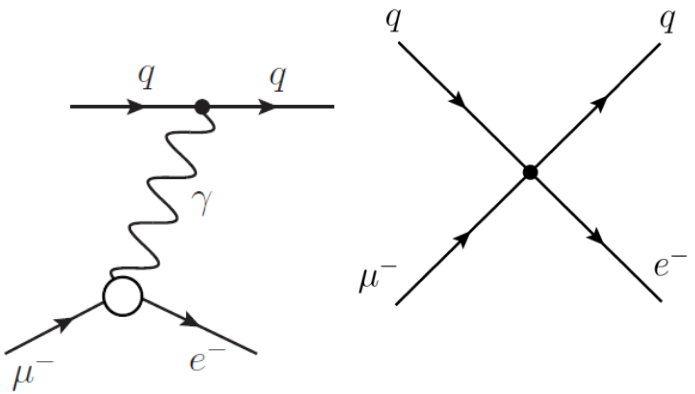
This talk

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

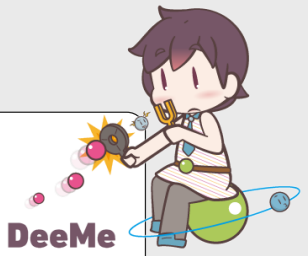
Charged Lepton Flavor Violation and New Physics







- 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 that there is 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, 33% for Si

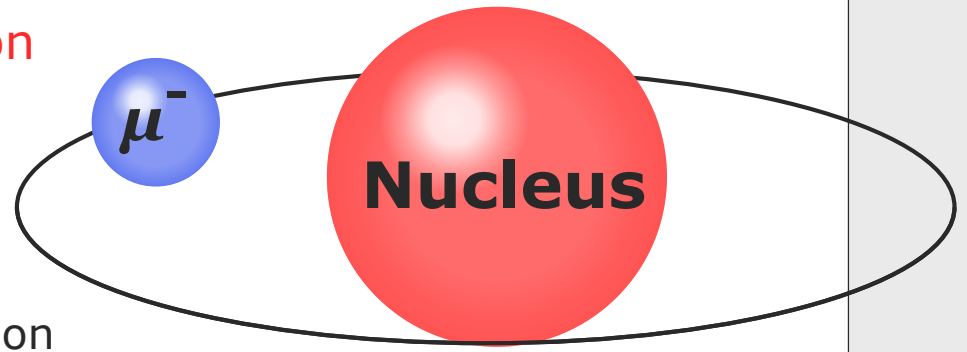
- Muon capture (MC) $\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$
  8% for C, 66% for Si

New physics

- Muon to electron conversion $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  Charged lepton flavor violation
  Monoenergetic e^-
  with ≈ 105 MeV for C 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

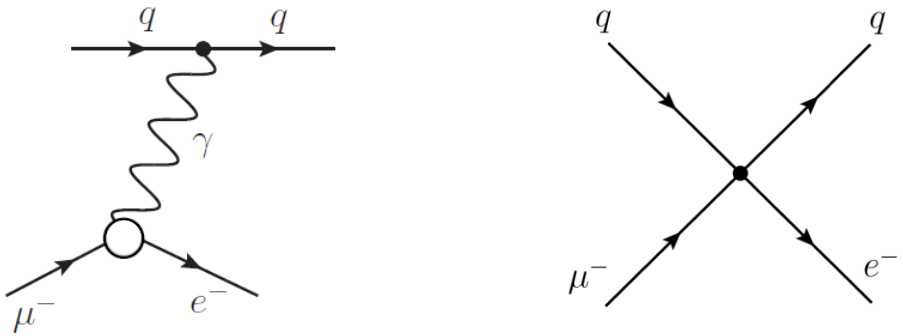
Search for cLFV in Photonic and Non-photonic Decays

- Possible processes for cLFV can be classified

Photonic

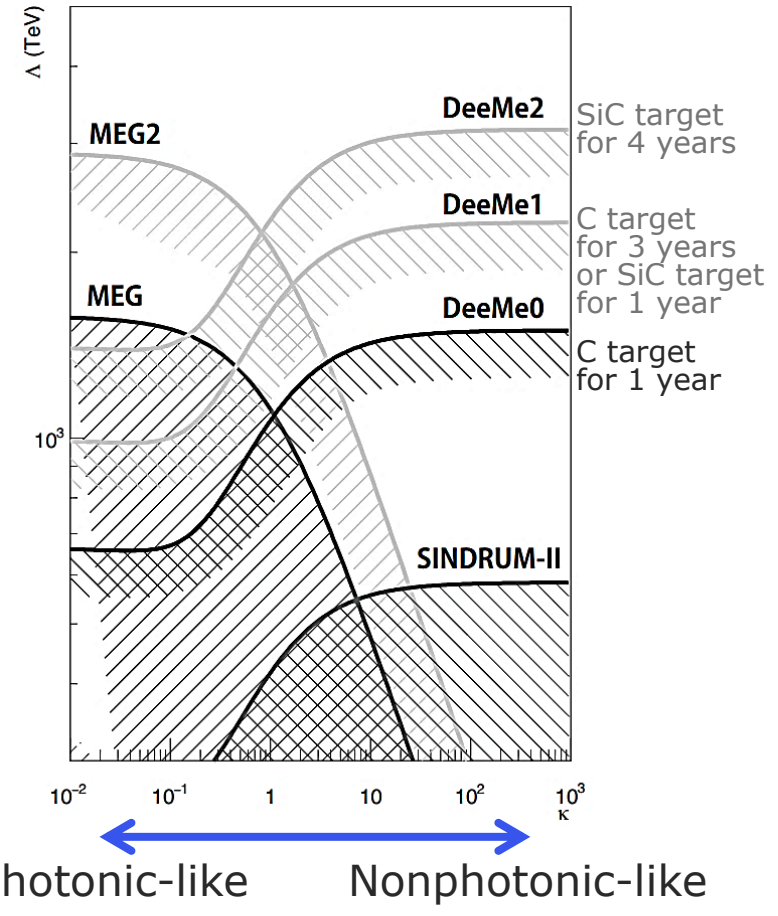
Non-photonic

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



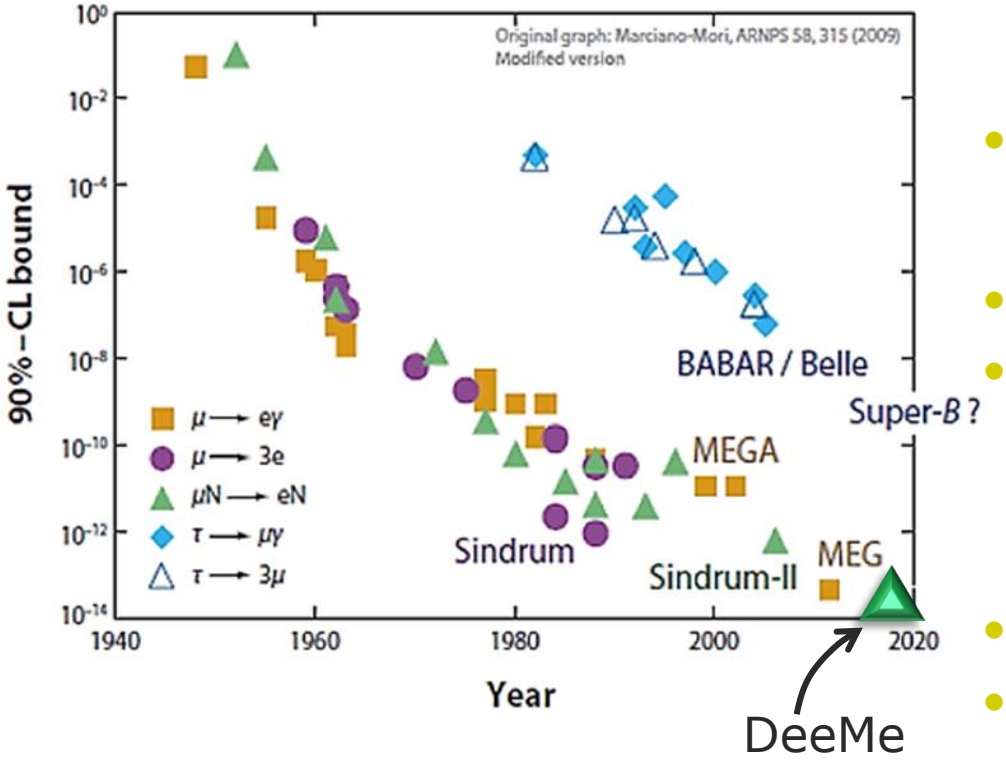
Branching ratio for $\mu\,\mathrm{N} \to e\,\mathrm{N}$
$\approx$ 1/100 of that for $\mu \to e\gamma$

- We must study cLFV using different approaches



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

DeeMe Sensitivity Goal



COMET
Mu2e S. E. S. < 10^{-16}
in the future

Current limit for $\mu N \rightarrow eN$

TRIUMF

- 4.6×10^{-12} for a Ti target

SINDRUM-II at PSI

- 4.3×10^{-12} for a Ti target
- 7×10^{-13} for a Au target

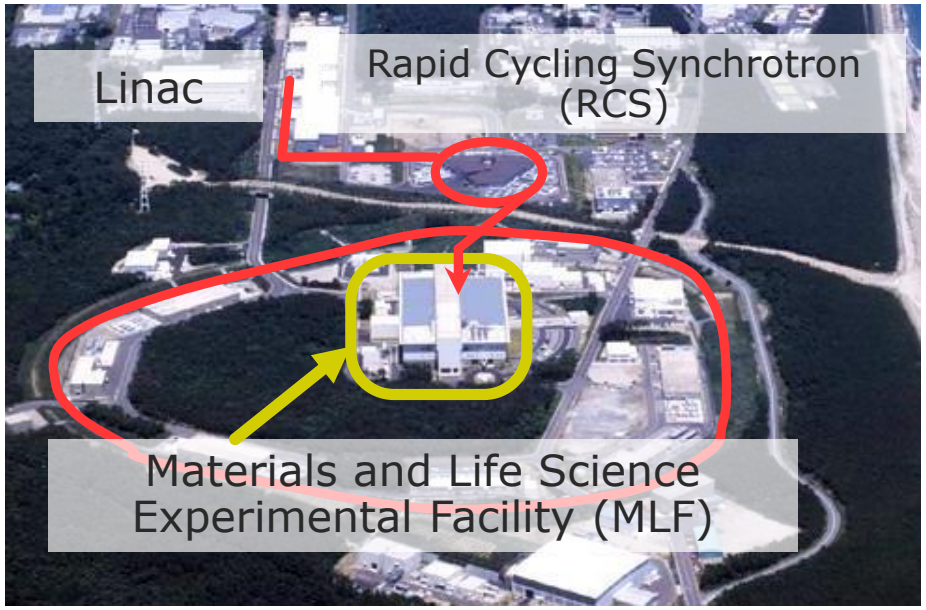
DeeMe

Aim to achieve

- S. E. S. < 1×10^{-13} for a C target
- S. E. S. < 2×10^{-14} for a SiC target

or to improve the current limit
by one or two orders of magnitude

J-PARC MLF MUSE



- J-PARC MLF MUSE (muon facility) in Tokai Village, Japan
- Take 1.5 hours by express train from Tokyo

High purity pulsed proton beam from RCS

- 3 GeV
- 500 kW → 1 MW (design power)
- Fast extraction
- 25 Hz double pulses

Experimental Concept

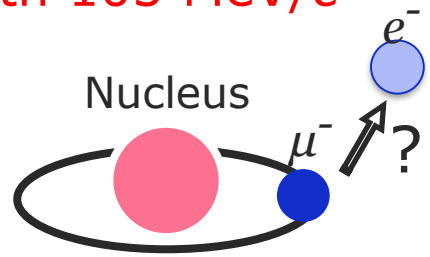
1. π^- production

Experimental Concept

1. π^- production
2. π^- decay-in-flight into μ^-

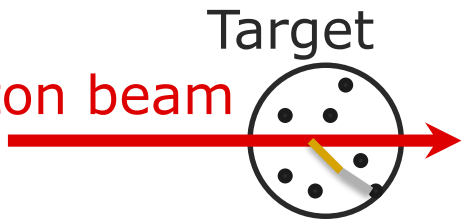
Experimental Concept

Signal: delayed monoenergetic e^- with 105 MeV/c



$\mu^- \mathrm{N} \rightarrow e^- \mathrm{N}$

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

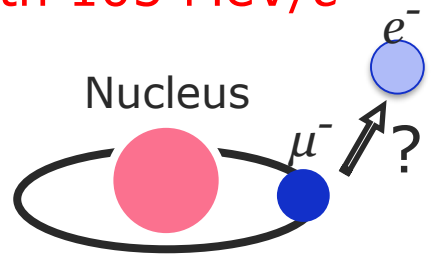


1. π^- production
2. π^- decay-in-flight into μ^-
3. Muonic atom formation

Experimental Concept

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

Signal: delayed monoenergetic e^- with 105 MeV/c



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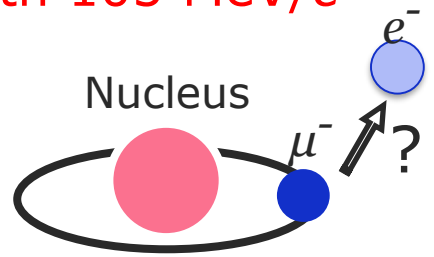
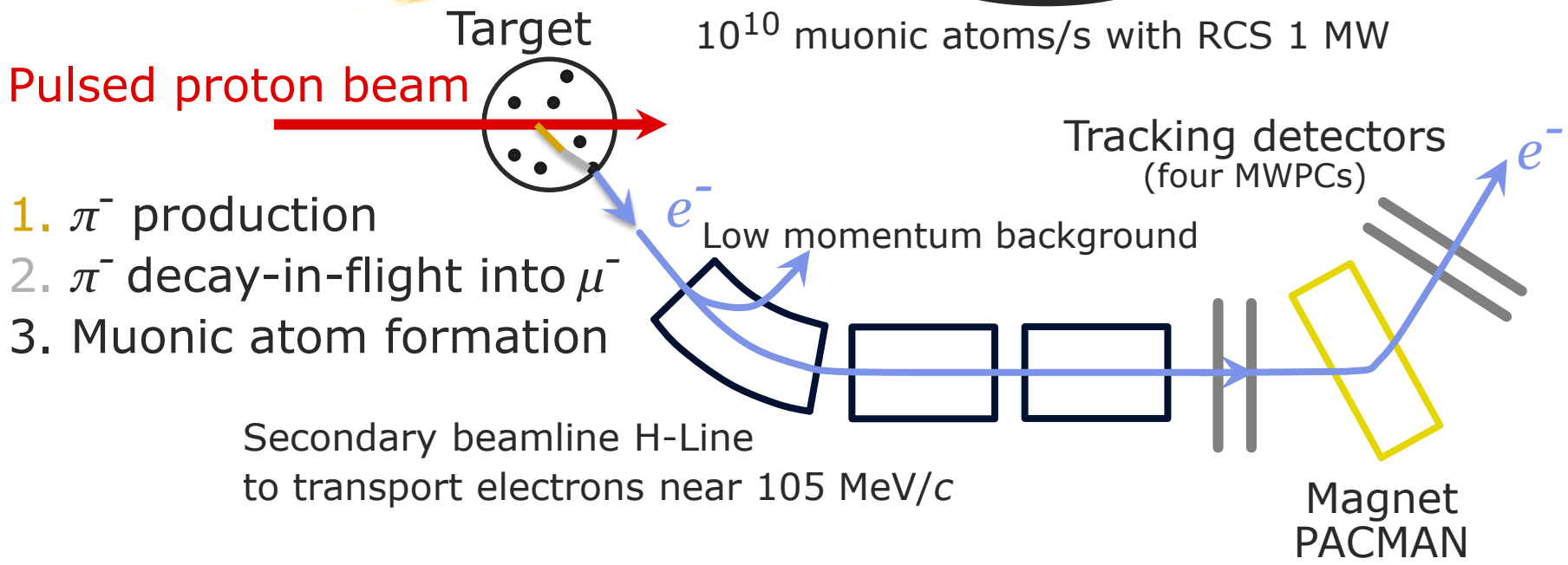


$\mu^- \mathrm{N} \rightarrow e^- \mathrm{N}$

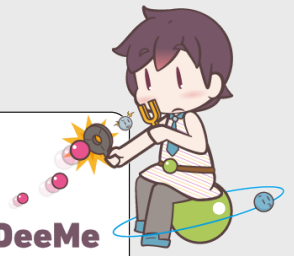
10^{10} muonic atoms/s with RCS 1 MW



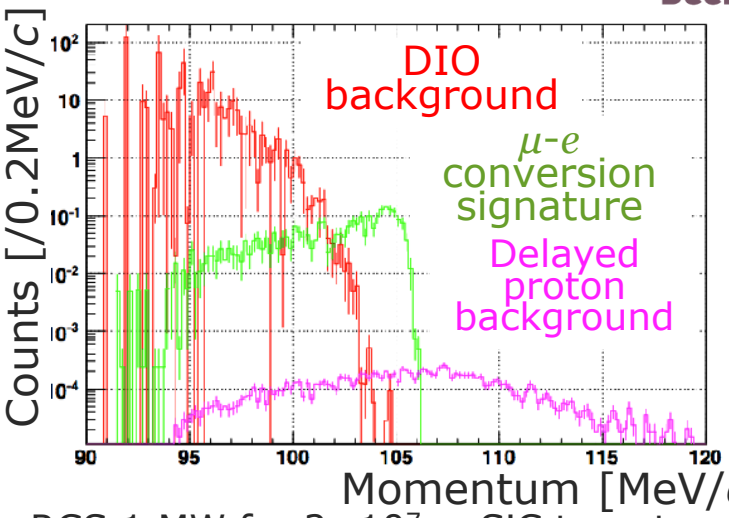
1. π^- production
2. π^- decay-in-flight into μ^-
3. Muonic atom formation

Magnetic spectrometer

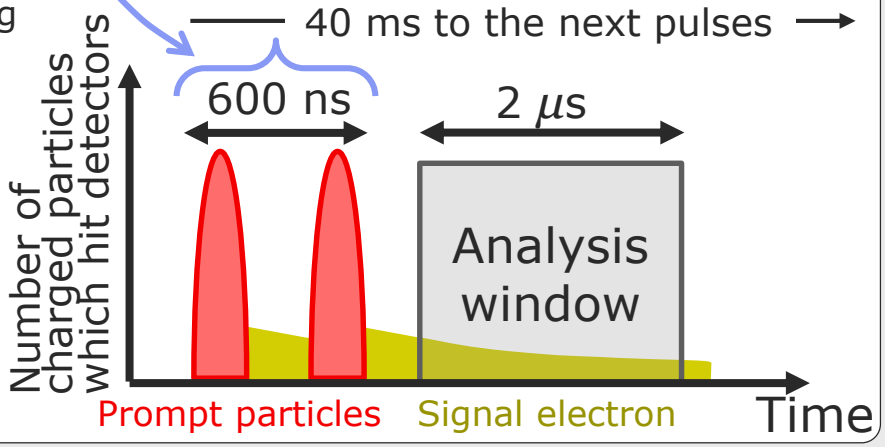
Backgrounds



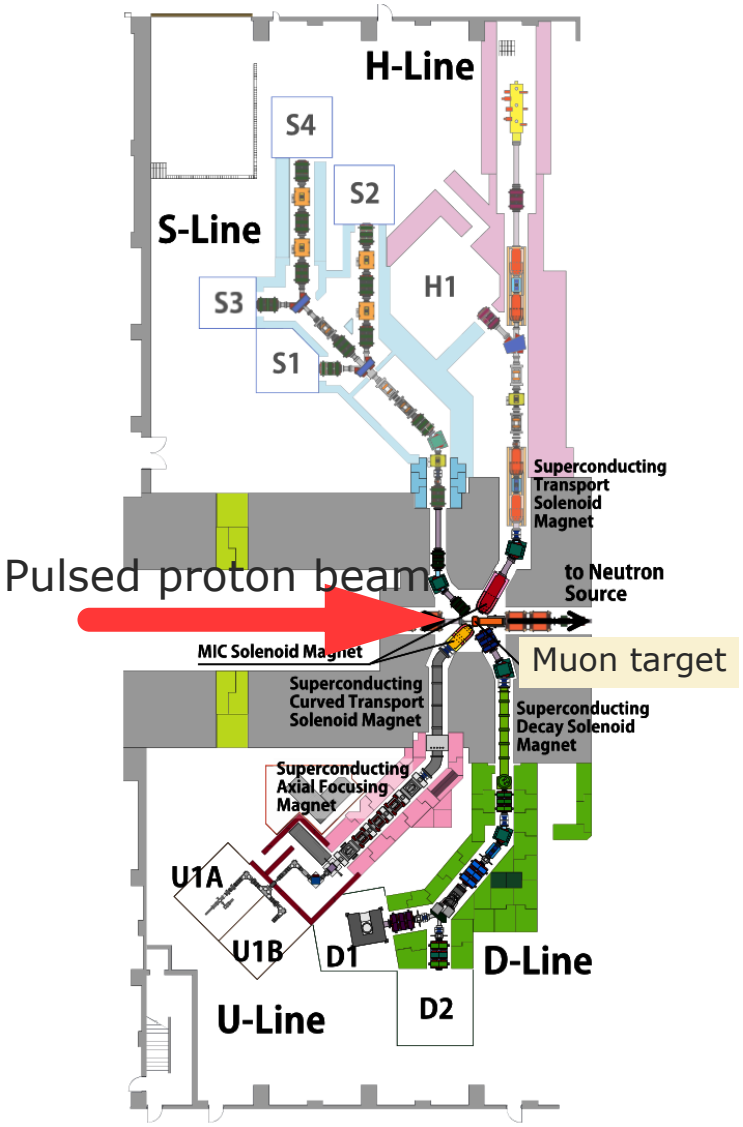
- Low-momentum background
  suppressed by the beamline
- High-momentum tail
  → need Δp < 1 MeV/c spectrometer
- Beam pion/muon capture
  $\pi^-/\mu^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$,
  $\gamma \rightarrow e^+ e^-$ at the beam-prompt timing
- Muon Decay in Orbit (DIO) 0.09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

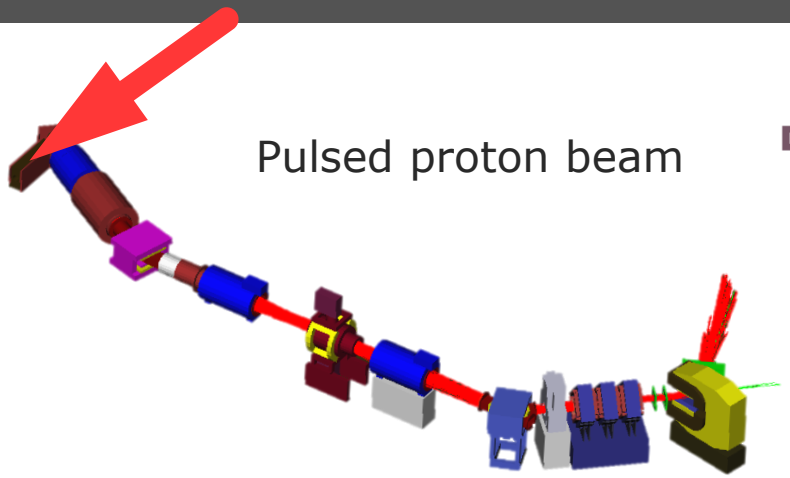


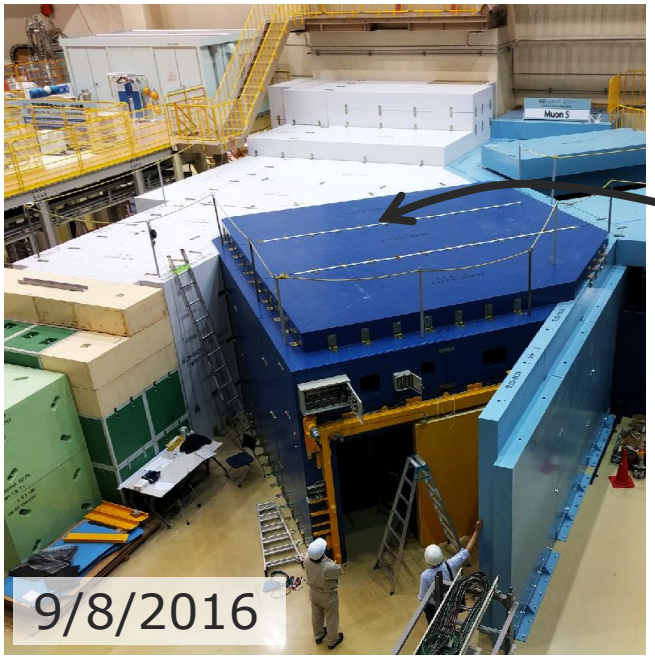
RCS 1 MW for 2×10^7 s, SiC target
BR 3×10^{-14}, delayed proton rate < 10^{-19}



Current Status - H1 Area at H Line





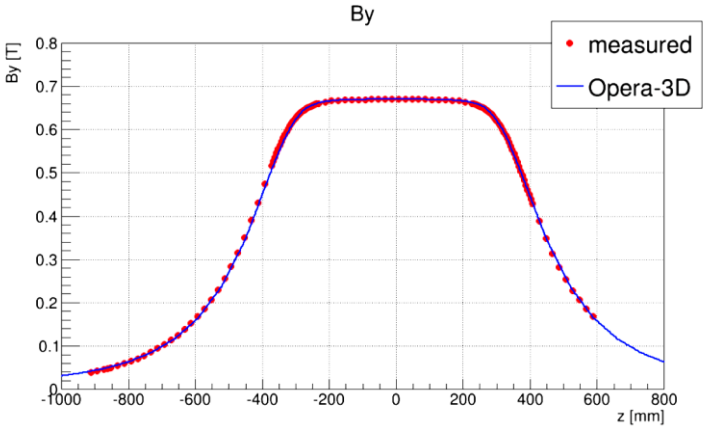


Experimental area
at H Line
(under construction)
in J-PARC MLF

Current Status - Spectrometer Magnet PACMAN

2.5 m

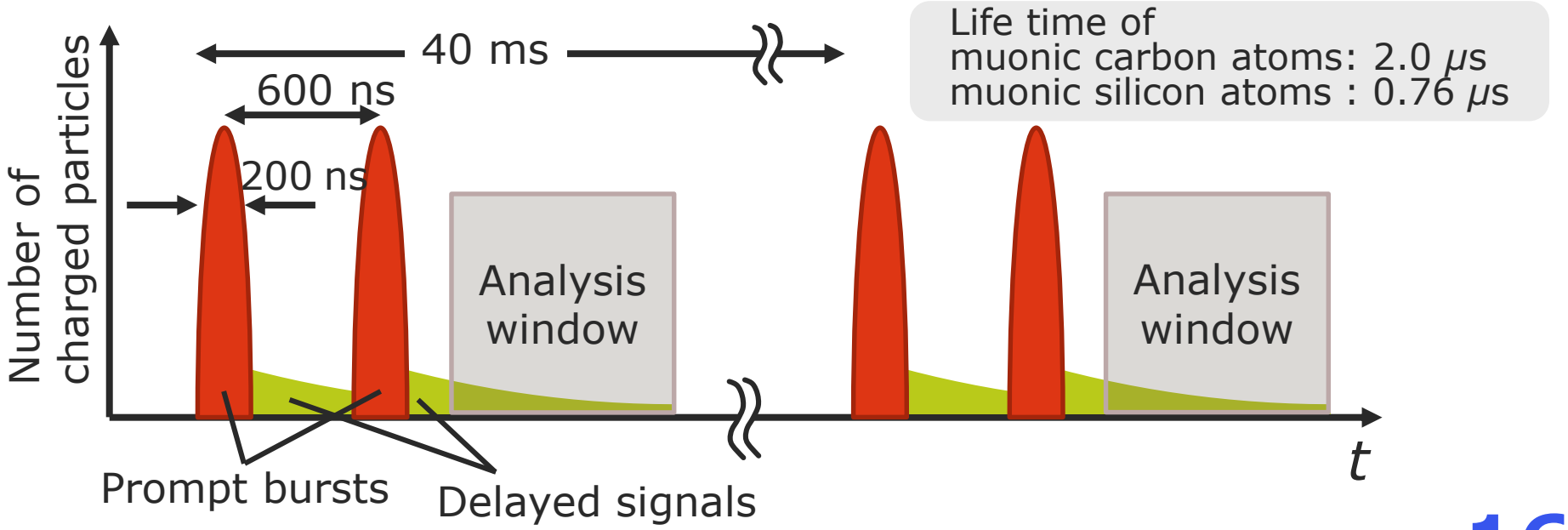
30 tons



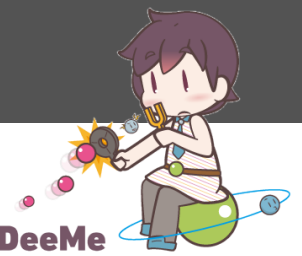
- Dipole magnet PACMAN
- Used in PIENU experiment in TRIUMF until 2012
- Lease agreement from 2014 to 2017
- Updated until 2020
- Nominal field strength: 0.4 T in the central part for electrons with 105 MeV/c bending 70 degrees
- Operation tested up to 500 A

Current Status - Detector Requirements

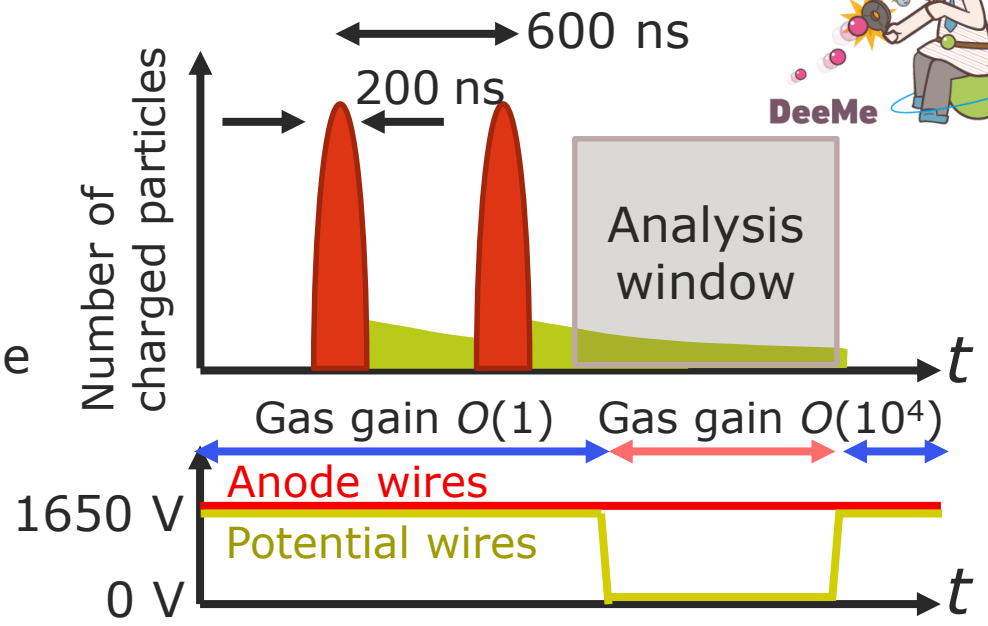
- Expected charged particles which hit the detectors
  - Prompt burst: produced by pulsed proton beams from RCS hitting the target, pass through the H Line
  - Mono-energetic delayed signal electrons: μ-e conversion
- $\approx$ 70 GHz/mm^2 (10^6 to 10^7 particles/readout) per prompt burst at most
- Need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

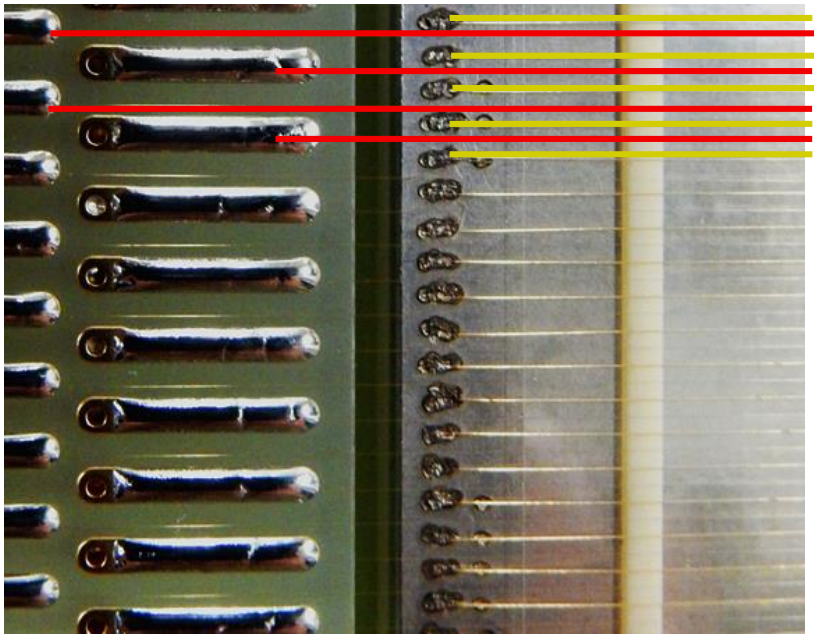


Current Status - Detector Structure



- Rapid gas-gain-switching MWPC
  by switching applied voltage
- Work well
  after it is hit by many particles
  equivalent to those in DeeMe at H Line
- Publication in 2017:
  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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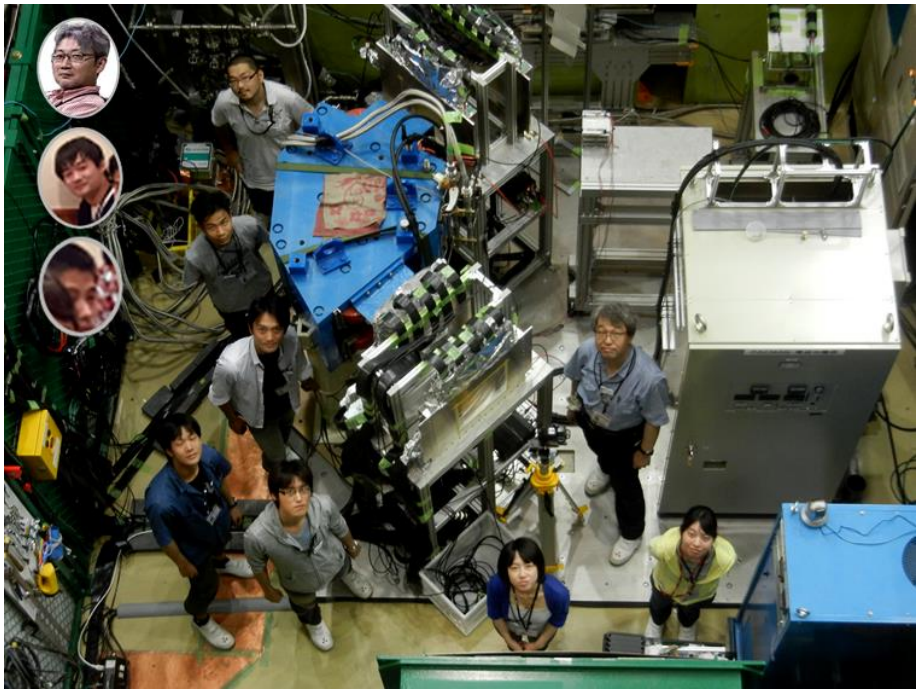
Current Status - Measurement of Muon Decay in Orbit

Muon beam

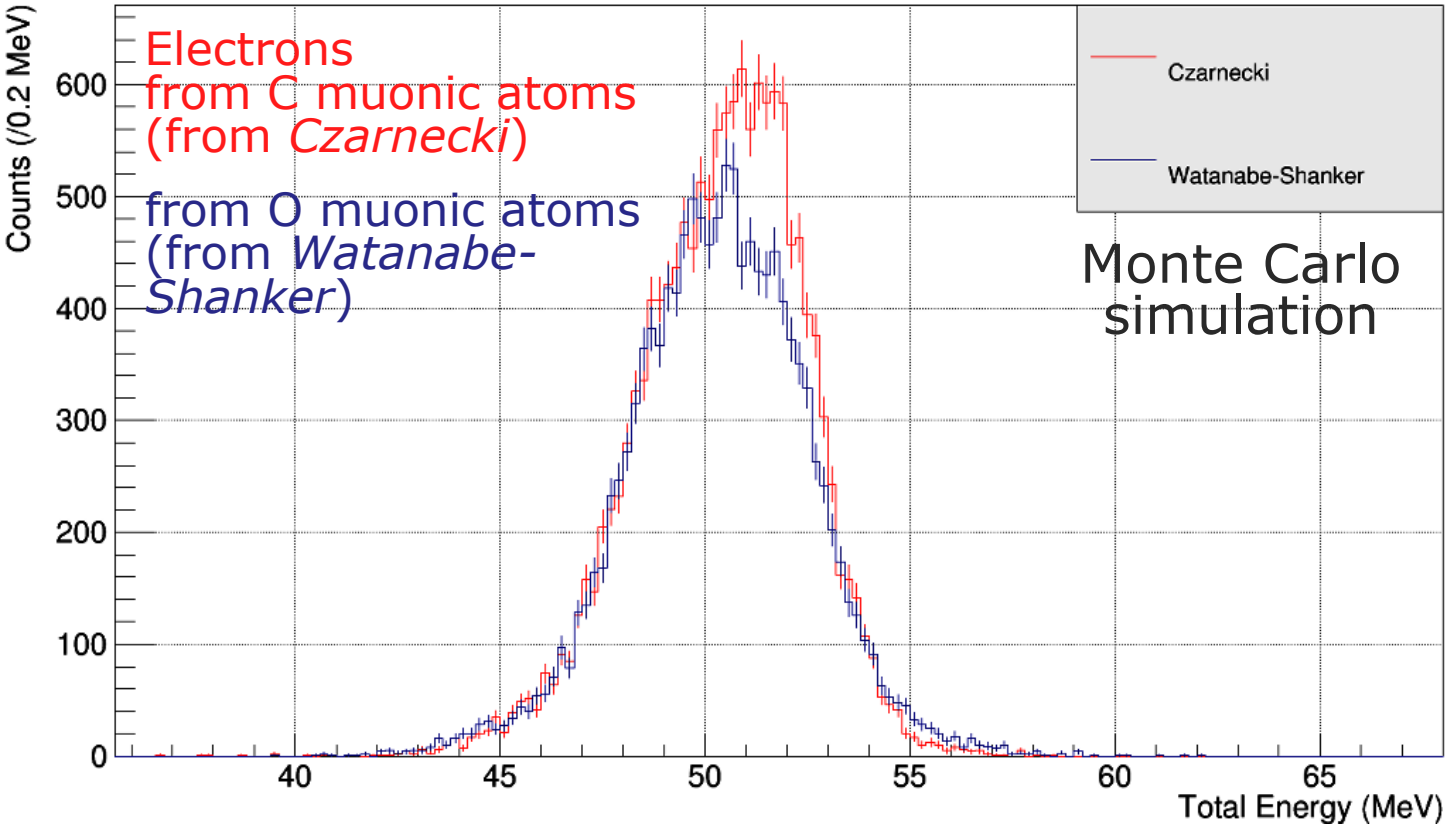


Motivation

- 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

Current Status – Monte Carlo Simulation of DIO

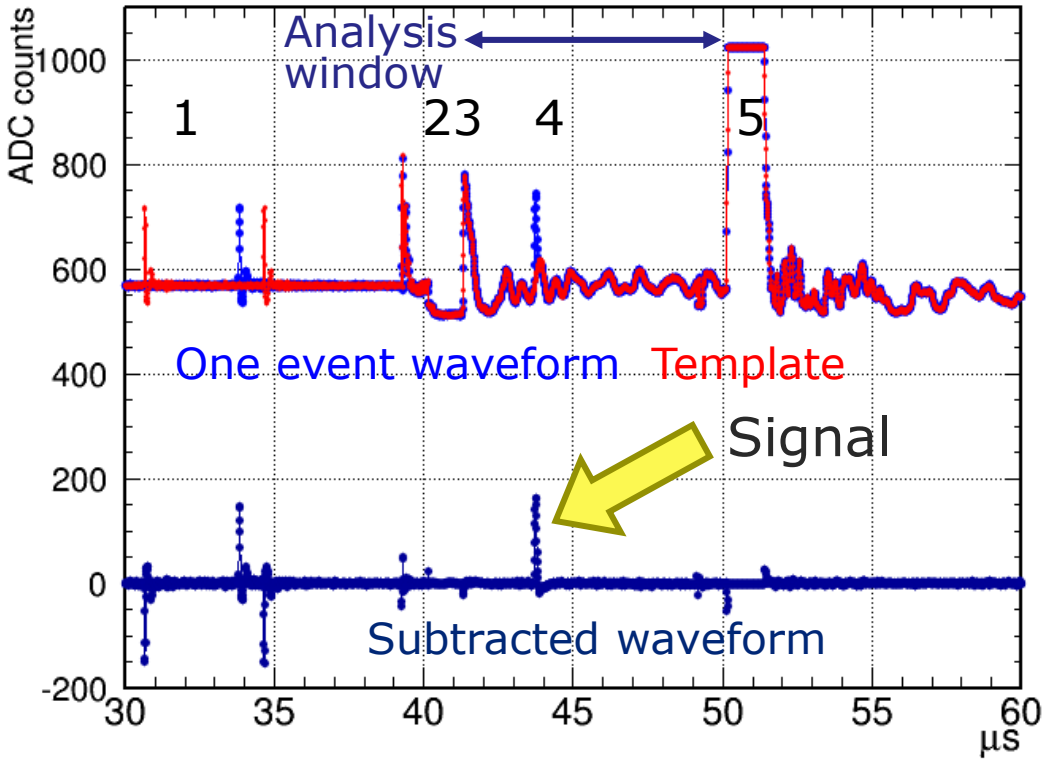
- At D Line, we measured the momentum with spectrometer momenta of 45, 52.5 (the edge), 55 MeV/*c*

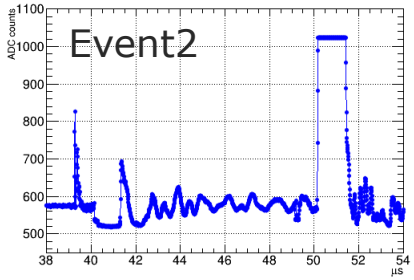


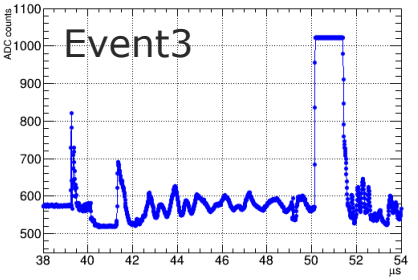
Current Status - Analysis of DIO Measurement

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

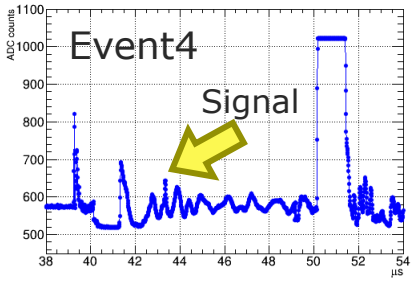
Test pulse[1], HV ramp down on potential wires[2], over shoot by PZC circuit[3], detector oscillation[4], HV ramp up on potential wires[5]

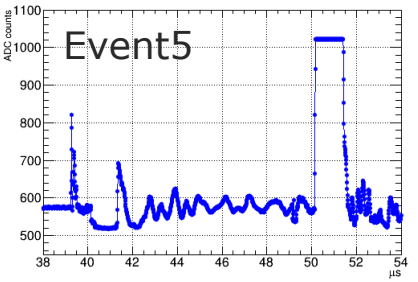






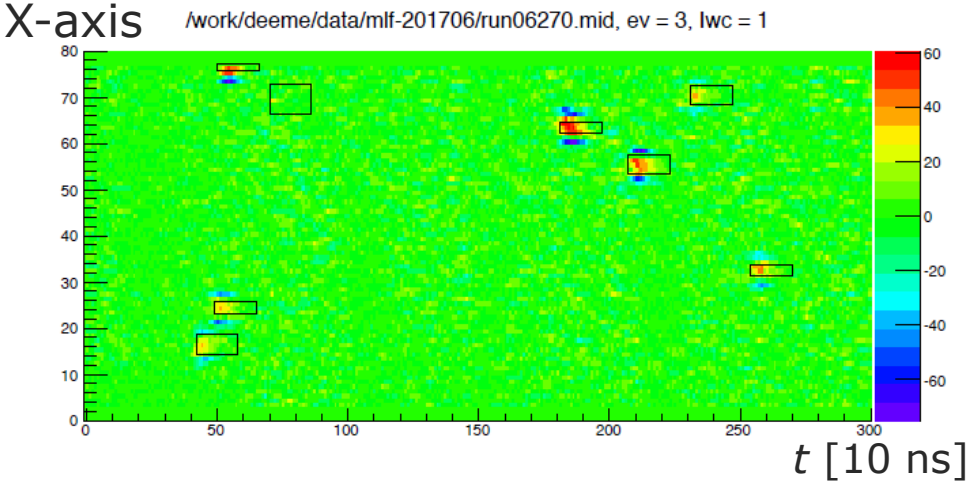
Same shape event by event



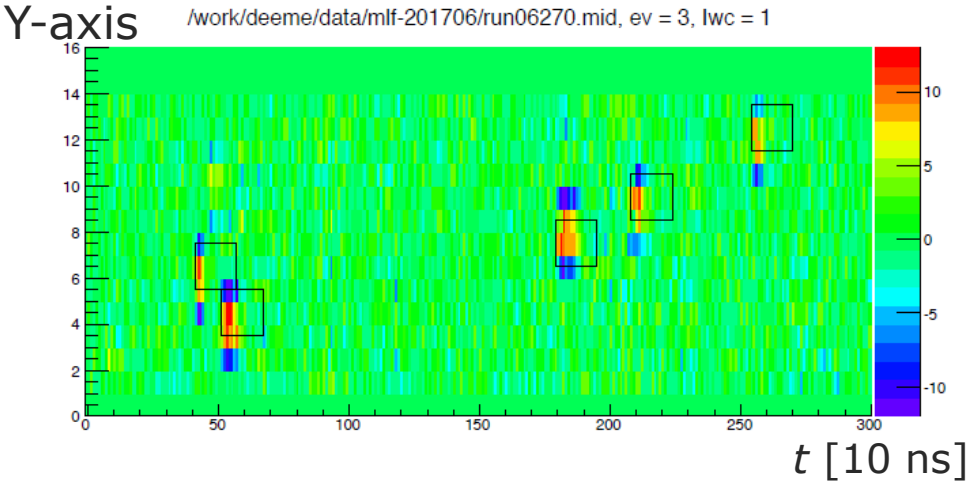


Current Status - Analysis of DIO Measurement

X-axis



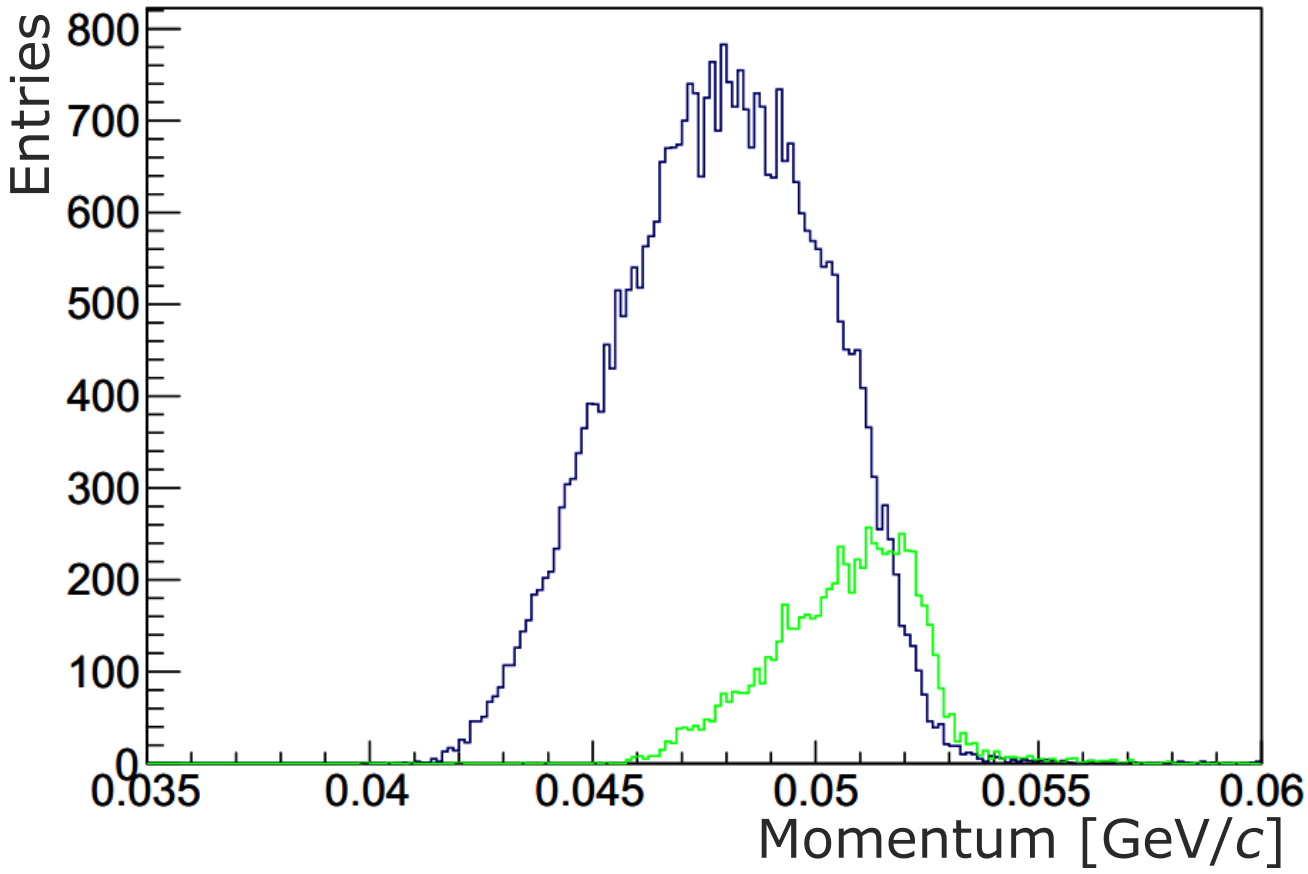
Y-axis



- Event display of one of the MWPCs
- Black rectangles show the hits
- We can see some hits
  both in X-axis and Y-axis channels

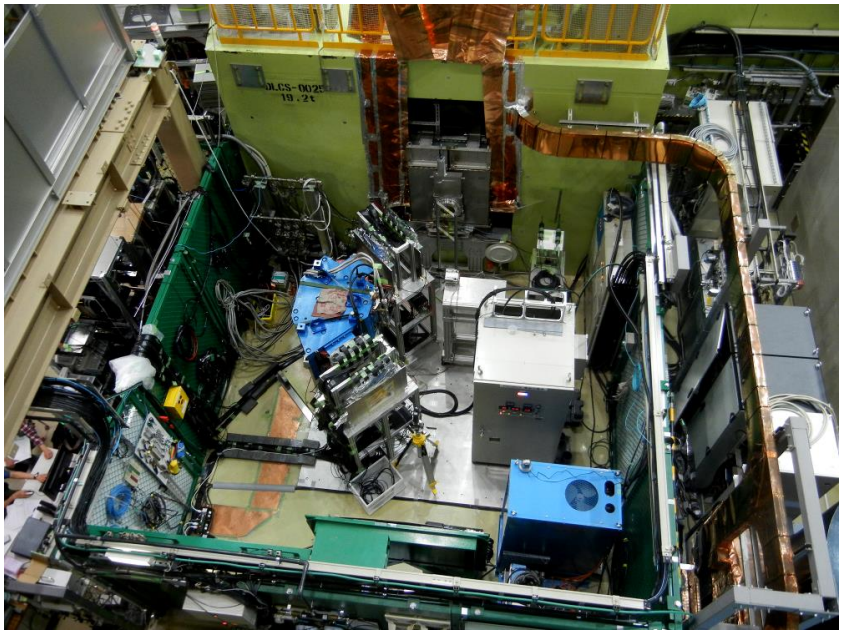
Current Status – Correction of Spectrometer

- For the momentum calibration using positive muons
- Set 45 MeV/c and 52.5 MeV/c (nominal) for the spectrometer
- The edge of 52.5 MeV seen



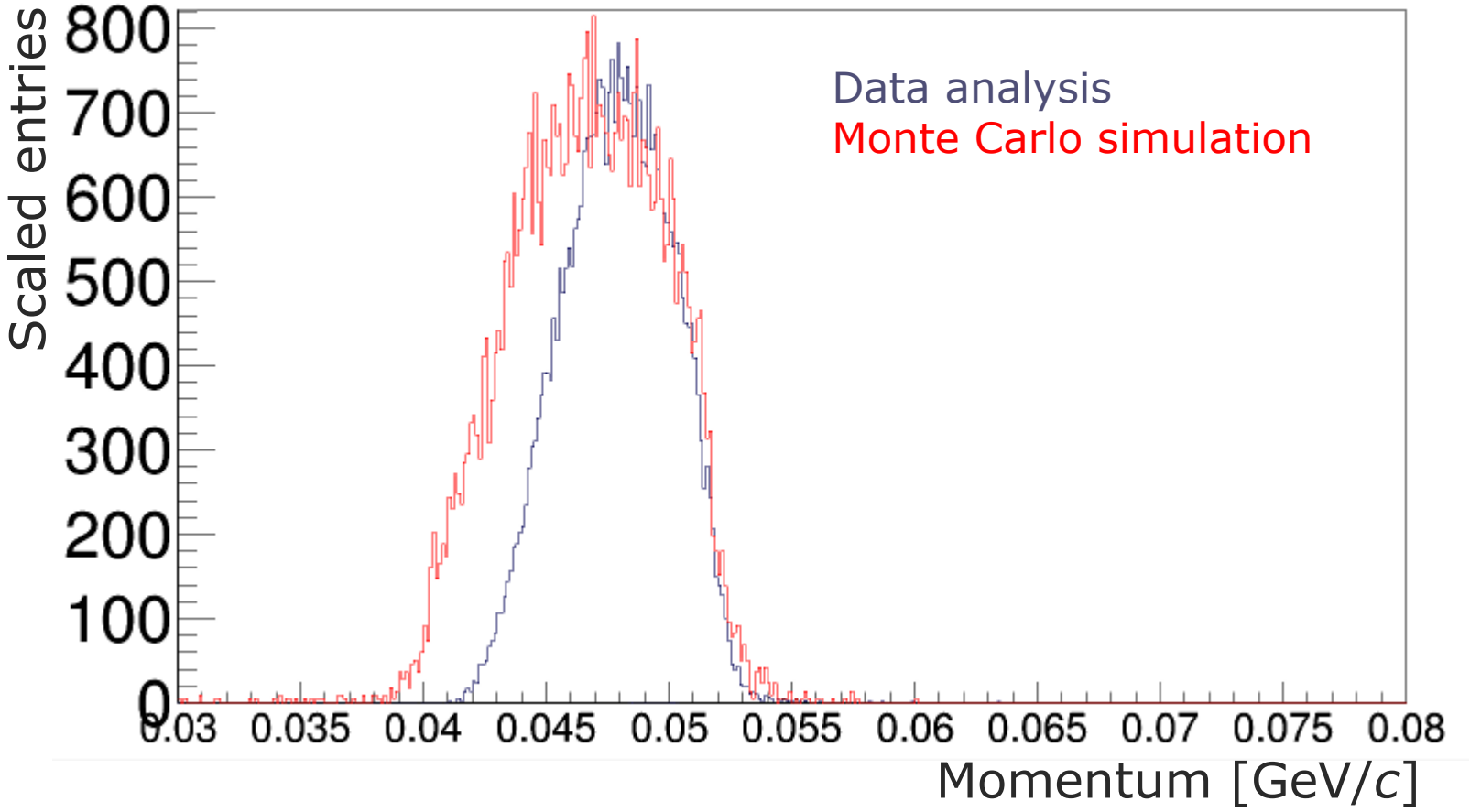
Summary

- Search for $\mu^- \mathrm{N} \rightarrow e^- \mathrm{N}$ with a sensitivity of 1×10^{-14}
- 10^{10} muonic atoms/s at H Line with RCS operating 1 MW
- 4 MWPCs have been manufactured
- Spectrometer magnet was tested in 2015
- We measured the DIO spectrum around 55 MeV/*c* at D Line in 2017
- Target: C, Si, and SiC
- Spectrometer system,
  including 4 MWPCs and DAQ,
  worked without any serious problems
- Analysis ongoing
- DeeMe experiment will start
  soon after completing
  the H Line construction



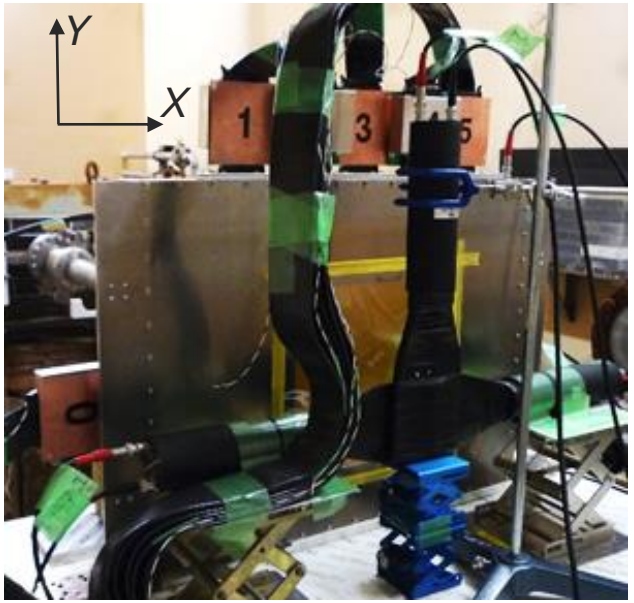
Backup

- Negative muon, C target
  with a spectrometer momentum of 45 MeV/*c*
  at D Line



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

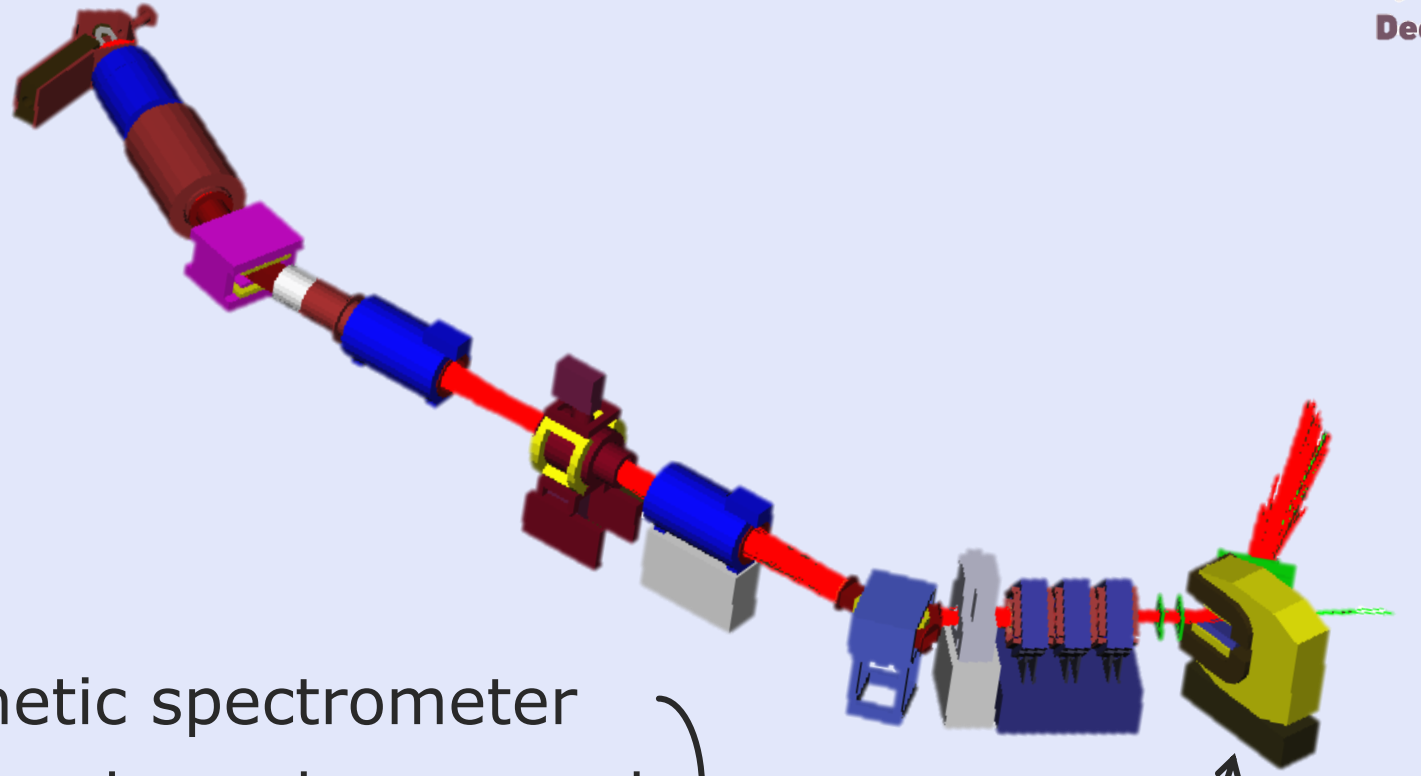


Readout electronics

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

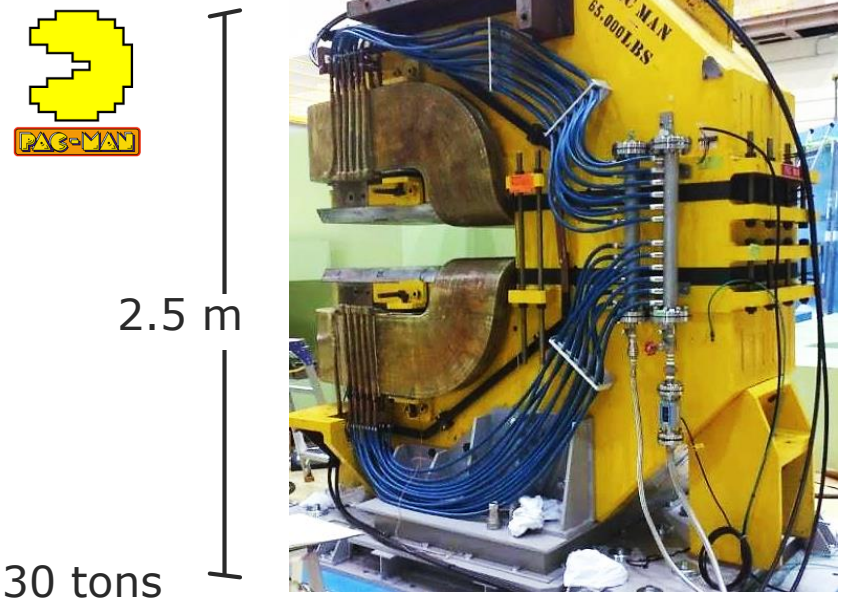
Firmware developed
by *N. M. Truong*

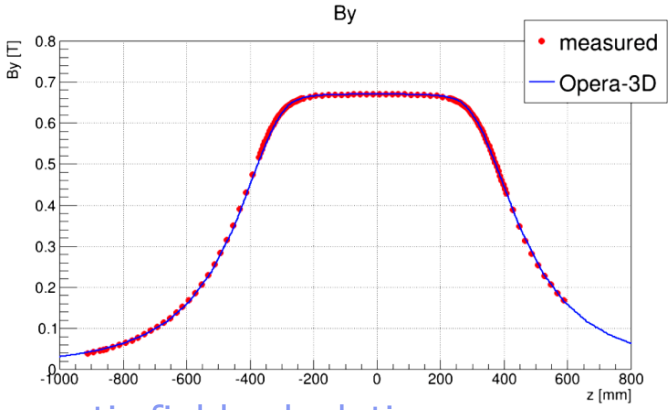
Current Status



- Magnetic spectrometer
  - Spectrometer magnet
  - Detectors (4 MWPCs)
- Muon Decay in Orbit (DIO) spectrum measurement

Current Status - Spectrometer Magnet PACMAN



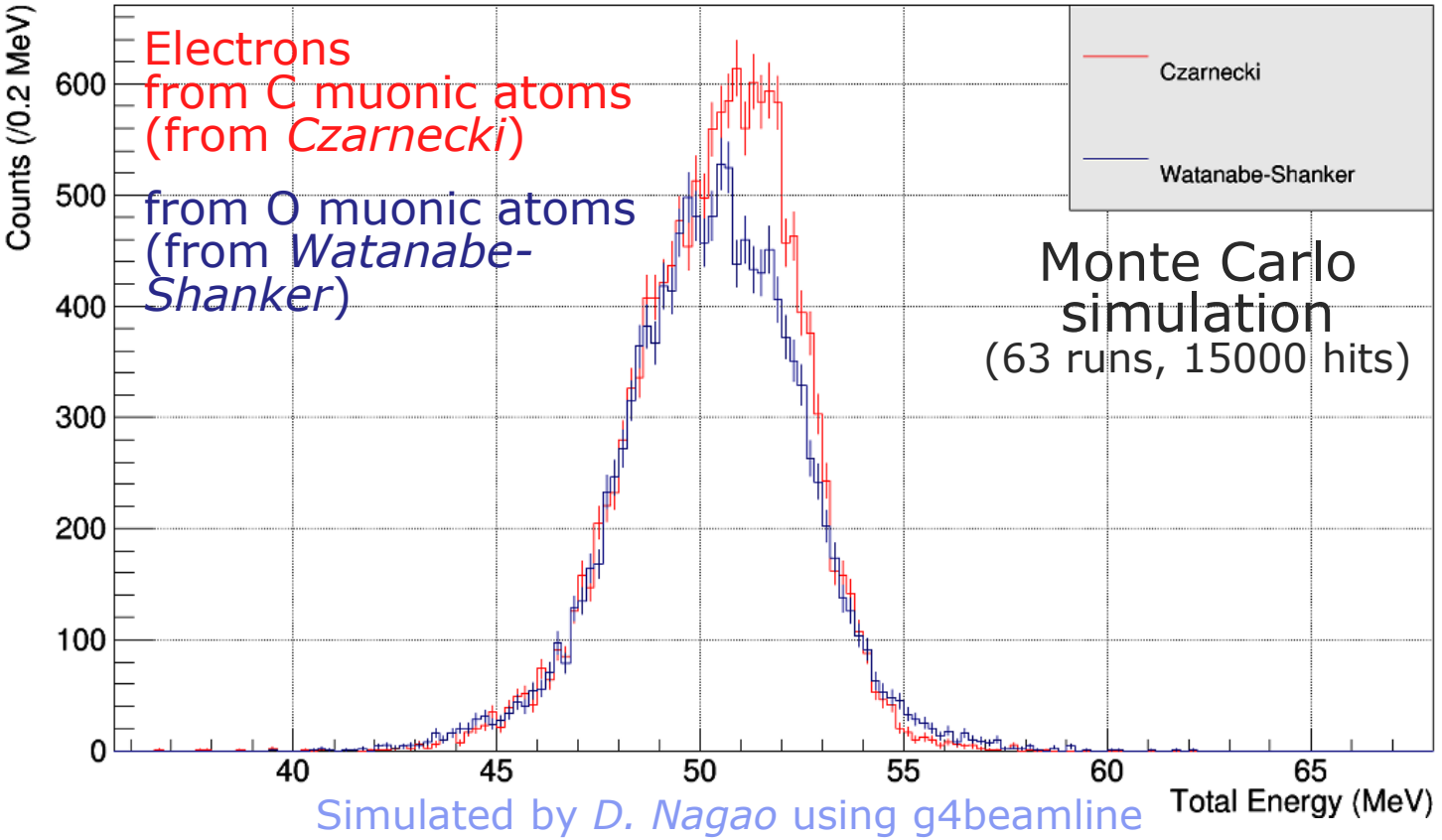


Magnetic field calculation
by *Y. Nakatsugawa* using OPERA-3d

- Dipole magnet PACMAN
- Used in PIENU experiment in TRIUMF until 2012
- Lease agreement from 2014 to 2017
- Updated until 2020
- 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

Current Status – Monte Carlo Simulation of DIO

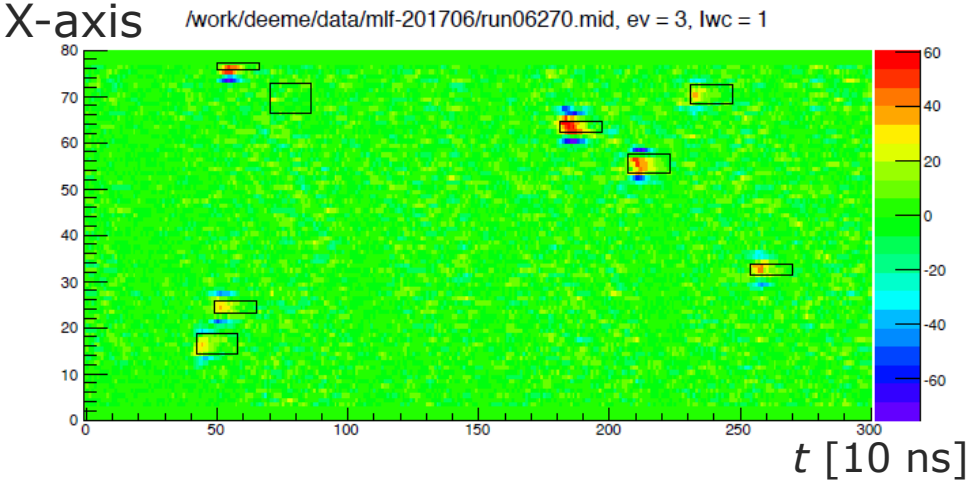
- At D Line, we measured the momentum with spectrometer momenta of 45, 52.5 (the edge), 55 MeV/*c*



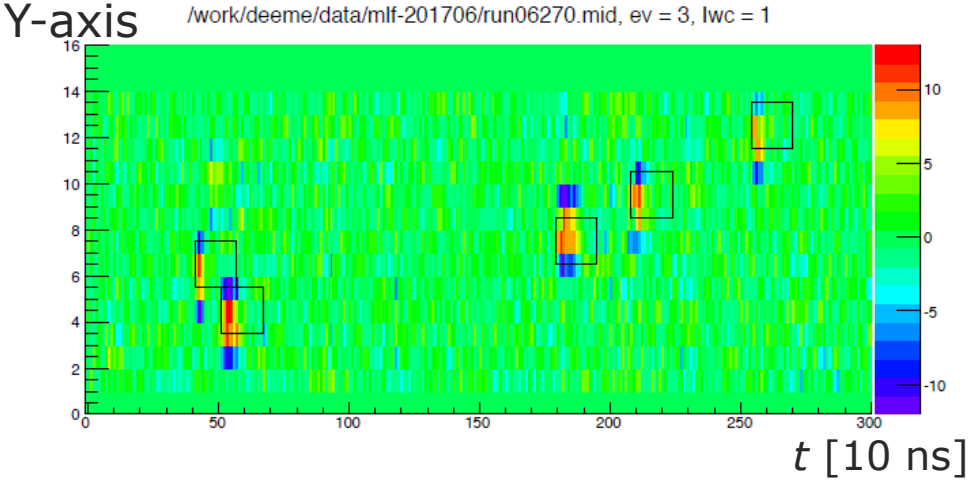
Simulated by *D. Nagao* using g4beamline

Current Status - Analysis of DIO Measurement

X-axis



Y-axis

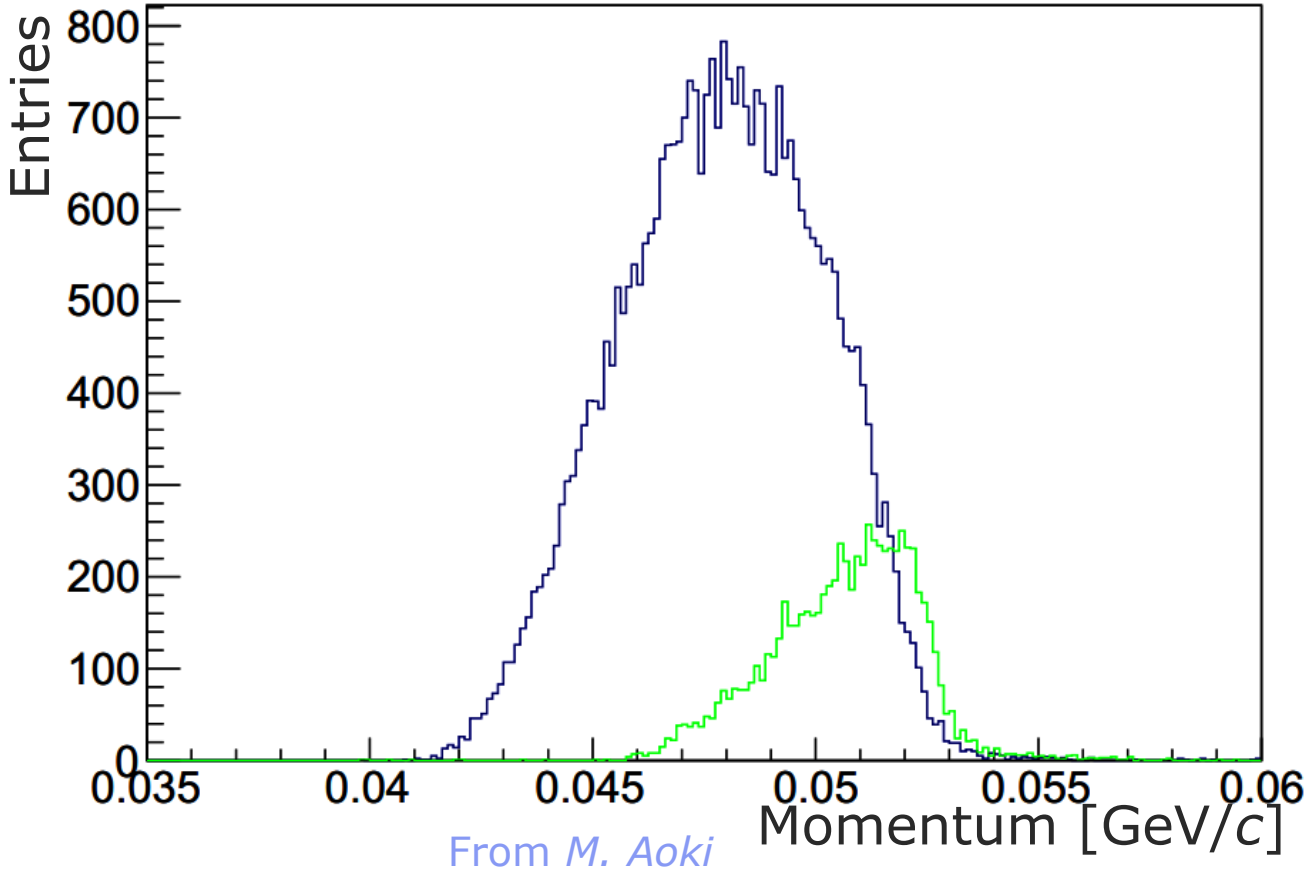


- Event display of one of the MWPCs
- Black rectangles show the hits
- We can see some hits
  both in X-axis and Y-axis channels

Coding by *M. Aoki*

Current Status – Correction of Spectrometer

- For the momentum calibration using positive muons
- Set 45 MeV/c and 52.5 MeV/c (nominal) for the spectrometer
- The edge of 52.5 MeV seen



From *M. Aoki*